EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

A new laboratory to study hadron–hadron interactions

ALICE Collaboration*

Abstract

One of the big challenges for nuclear physics today is to understand, starting from first principles, the effective interaction between hadrons with different quark content. First successes have been achieved utilizing techniques to solve the dynamics of quarks and gluons on discrete space-time lattices. Experimentally, the dynamics of the strong interaction have been studied by scattering hadrons off each other. Such scattering experiments are difficult or impossible for unstable hadrons and hence, high quality measurements exist only for hadrons containing up and down quarks. In this work, we demonstrate that measuring correlations in the momentum space between hadron pairs produced in ultrarelativistic proton–proton collisions at the CERN LHC provides a precise method to obtain the missing information on the interaction dynamics between any pair of unstable hadrons. Specifically, we discuss the case of the interaction of baryons containing strange quarks (hyperons). We demonstrate for the first time how, using precision measurements of p–Ω^- correlations, the effect of the strong interaction for this hadron–hadron pair can be studied and compared with predictions from lattice calculations.

---

*See Appendix for the list of Collaboration members

Introduction

Baryons are composite objects formed by three valence quarks bound together by means of the strong interaction mediated through the emission and absorption of gluons. Between baryons, the strong interaction leads to a residual force described by an effective strong potential. The most common example is the effective strong force among nucleons (N), that are baryons composed of u and d quarks: proton = uud and neutron = ddu. This force is responsible for the existence of atomic nuclei; it manifests itself in scattering experiments [1] and through the existence of a neutron–proton stable bound state, the deuteron.

The fundamental theory of the strong interaction is quantum chromodynamics (QCD) with quarks and gluons as the degrees of freedom. Perturbative techniques are used to calculate strong interaction phenomena in high-energy collisions with per cent level precision [2]. For baryons however, such techniques cannot be employed and the only possible approaches are numerical solutions on a finite space-time lattice. First attempts based on such lattice techniques have been carried out but do not yet reproduce the properties of the deuteron [3], and more reliable calculations are at the horizon. To date, the understanding of the nucleon–nucleon strong interaction relies heavily on effective theories [4], where the degrees of freedom are nucleons. These effective theories are constrained by scattering measurements and are successful in describing nuclear properties [5, 6].

Baryons containing s quarks, exclusively or combined with u and d quarks, are called hyperons (Y) and are denominated by capital greek letters: $\Lambda = uds$, $\Sigma^0 = uds$, $\Xi^- = dss$, $\Omega^- = sss$. Experimentally, little is known about Y–N and Y–Y interactions, but recently major steps forward in their understanding have been made within lattice QCD approaches [7–9]. The predictions available in this sector are characterized by smaller uncertainties because the lattice calculation becomes more stable for quarks with larger mass, such as the s quark. In particular, robust results are obtained for interactions involving the heaviest hyperons, such as Ξ and Ω, and precise measurements of the p–Ξ^- and p–Ω^- interactions are instrumental to validate these calculations. From an experimental point of view, the existence of nuclei where a nucleon is replaced by a hyperon (hypernuclei) demonstrates the presence of an attractive strong Λ–N interaction [10] and indicates the possibility of binding a Ξ^- to a nucleus [11, 12]. A direct and more precise measurement of the Y–N interaction requires scattering experiments, which are particularly challenging to perform with hyperons, since they are short-lived and travel only a few centimeters before decaying. Experiments with Λ and Σ hyperons on proton targets [13–15] delivered results that were two orders of magnitude less precise than those for nucleons, and such experiments are impossible to carry out with Ξ and Ω beams. The measurement of the Y–N and Y–Y interactions has further important implications for the possible formation of a Y–N or Y–Y bound state. Although numerous theoretical predictions exist [7, 16–19], so far no clear evidence for any of such bound states has been found, despite many experimental searches [20–24]. Real progress in this area calls for new experimental methods.

The ALICE collaboration has demonstrated that pp and p–Pb collisions at the LHC allow N–N and several Y–N interactions to be studied at low relative momentum [25–29]. Indeed, the collision energy and rate available at the LHC opens the phase space for an abundant production of any strange hadron [30], while the excellent momentum resolution and particle identification capabilities of the ALICE detector facilitate the investigation of correlations in momentum space. These correlations reflect the properties of the interaction and hence can be used to test theoretical predictions [31]. An important aspect in pp and p–Pb collisions at LHC energies is the fact that all hadrons originate from very small space-time volumes, with typical inter-hadron distances of about 1 fm. These small distances are linked through the uncertainty principle to a rather large relative momentum range (up to $200\,\mathrm{MeV}/c$) for the baryon pair.

Similar studies were carried out in ultrarelativistic Au–Au collisions at a center-of-mass energy of $200\,\mathrm{GeV}$ per nucleon pair by the STAR collaboration for Λ–Λ [32, 33] and p–Ω^- [34] interactions. This collision system leads to comparatively large particle emitting sources of 3–5 fm. The resulting

relative momentum range is below $40\,\mathrm{MeV}/c$, implying reduced sensitivity to interactions at distances shorter than 1 fm.

In this work, we present a precision study of the most exotic among the proton–hyperon interactions, obtained via the p–Ω^- correlation function in pp collisions at a center-of-mass energy $\sqrt{s} = 13$ TeV at the LHC. The comparison of the measured correlation function with first-principle calculations [7] and with a new precision measurement of the p–Ξ^- correlation in the same collision system demonstrates that the strong p–Ω^- interaction exceeds by far the strength of the p–Ξ^- interaction. The implications of the measured correlations for a possible p–Ω^- bound state are also discussed.

Our measurement opens a new chapter for experimental methods in hadron physics with the potential to pin down the strong interaction for all known proton–hyperon pairs.
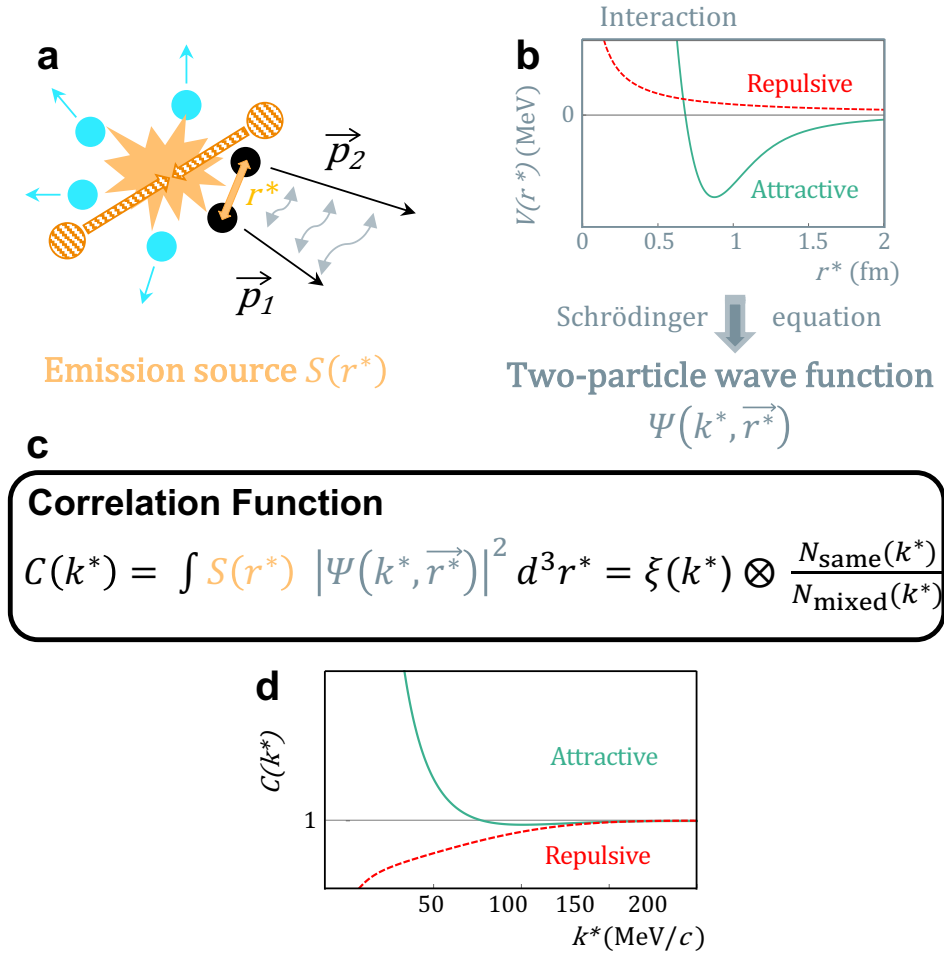

Figure 1: Schematic representation of the correlation method. a, A collision of two protons results in a particle source from which a hadron–hadron pair with momenta $\vec{p}_1$ and $\vec{p}_2$ emerges and can undergo final state interaction. Consequently, their relative momentum can be either reduced or increased via an attractive or a repulsive interaction, respectively. **b**, Two examples of attractive and repulsive interaction potentials, V(r^*). **c**, The formula of the theoretical and measured correlation function $C(k^*)$. **d**, The resulting shape of $C(k^*)$ as a function of the relative momentum k^* between the hadron–hadron pair for an attractive (green) and a repulsive (red) potential.

Analysis of the Correlation Function

Figure 1 shows a schematic representation of the correlation method used in this analysis. The correlation function can be expressed theoretically [35, 36] as $C(k^*) = \int d^3 r^* S(r^*) \times |\psi(\vec{k^*}, \vec{r^*})|^2$, where $S(r^*)$ is the distribution of the distance r^* at which particles are emitted (defining the source size), $\psi(\vec{k^*}, \vec{r^*})$ represents the wave function of the relative motion for the pair of interest and k^* is the reduced relative momentum of the pair ($k^* = |\vec{p_2^*} - \vec{p_1^*}|/2$). The asterisk indicates evaluation in the pair rest frame, where $p_1^* = -p_2^*$. Given an interaction potential between two hadrons as a function of their relative distance, a non-relativistic Schrödinger equation[1] can be employed [31] to obtain the corresponding wave function and hence also predict the expected correlation function. Experimentally, this correlation function is computed as $C(k^*) = \xi(k^*) \otimes \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}$, where $\xi(k^*)$ denotes the corrections for experimental effects, $N_{\text{same}}(k^*)$ is the number of pairs with a given k^* obtained by combining particles produced in the same collision (event), which constitute a sample of correlated pairs, and $N_{\text{mixed}}(k^*)$ is the number of uncorrelated pairs with the same k^*, obtained by combining particles produced in different collisions (the so-called mixed-event technique). Panel **d** in Fig. 1 shows how an attractive or repulsive interaction is mapped into the correlation function. For an attractive interaction the magnitude of the correlation function will be above unity for small values of k^*, while for a repulsive interaction it will be between zero and unity. In the former case, the presence of a bound state would create a depletion of the correlation function with a depth increasing with increasing binding energy.

Correlations can occur in nature either because of quantum-mechanical interference, resonances, conservation laws or final-state interactions. Here, the latter contributes predominantly at low relative momentum and we focus in this work on the strong and Coulomb interactions in pairs composed of a proton and either a Ξ^- or a Ω^- hyperon.

Protons do not decay and can hence be directly identified within the ALICE detector, but Ξ^- and Ω^- baryons are detected through their weak decays, $\Xi^- \to \Lambda + \pi^-$ and $\Omega^- \to \Lambda + K^-$. The identification and momentum measurement of protons, Ξ^-, Ω^- and their respective antiparticles are described in Methods. Figure 2 shows a sketch of the Ω^- decay and the invariant mass distribution of the ΛK^- and $\overline{\Lambda} K^+$ pairs. The clear peak corresponding to the rare Ω^- and $\overline{\Omega}^+$ baryons demonstrates the excellent identification capability which is the key ingredient for this measurement. The contamination from misidentification is $\leq 5\%$. Similar results are obtained for the Ξ^- ($\overline{\Xi}^+$) baryon [28].
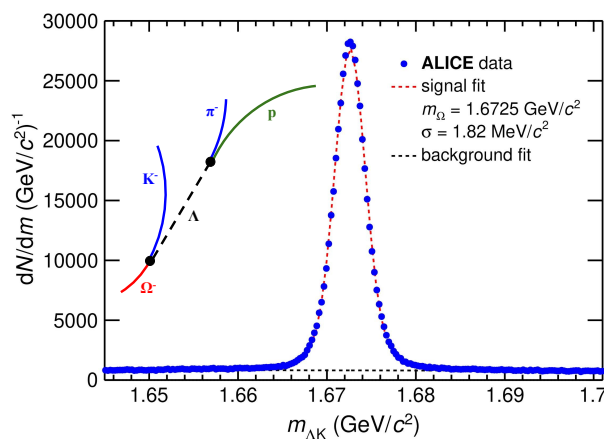

Figure 2: Reconstruction of the Ω^- and $\overline{\Omega}^+$ signals. Sketch of the Ω^- decay and invariant mass distribution of ΛK^- and $\overline{\Lambda} K^+$ combinations.

---

[1]The choice of a non-relativistic Schrödinger equation is motivated by the fact that typical relative momenta relevant for the strong final state interaction have a maximal value of $200\,\text{MeV}/c$.

4

Once the p, Ω^- and Ξ^- candidates and charge conjugates are selected and their 3-momenta measured, the correlation functions can be built. Since we assume that the same interaction governs baryon–baryon and antibaryon–antibaryon pairs [25], we consider in the following the sum of particles and antiparticles ($\mathrm{p}–\Xi^- \oplus \overline{\mathrm{p}}–\overline{\Xi}^+ \equiv \mathrm{p}–\Xi^-$ and $\mathrm{p}–\Omega^- \oplus \overline{\mathrm{p}}–\overline{\Omega}^+ \equiv \mathrm{p}–\Omega^-$). The determination of the correction $\xi(k^*)$ and the evaluation of the systematic uncertainties are described in Methods.

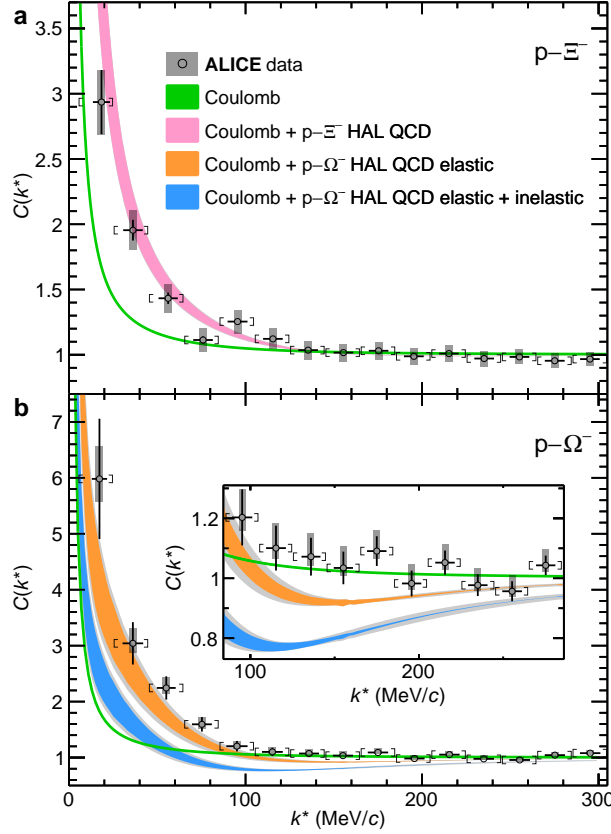**Figure 3: Experimental p–Ξ^- and p–Ω^- correlation functions.** Measured p–Ξ^- (**a**) and p–Ω^- (**b**) correlation functions in pp collisions at $\sqrt{s} = 13$ TeV. The experimental data are shown as black symbols. The black vertical bars and the grey boxes represent the statistical and systematic uncertainties, and the square brackets show the bin width. The measurements are compared with theoretical predictions, shown as coloured bands, that assume either Coulomb or Coulomb+strong HAL QCD interactions. The width of the curves including HAL QCD predictions represents the uncertainty associated to the calculation and the grey shaded band represents, in addition, the uncertainties associated with the determination of the source radius.

Comparison of the p–Ξ^- and p–Ω^- interactions

The obtained correlation functions are shown in panels **a** and **b** of Fig. 3 for the p–Ξ^- and p–Ω^- pairs, respectively, along with the statistical and systematic uncertainties. The fact that both correlations are well above unity implies the presence of an attractive interaction for both systems. For opposite-charge pairs, as considered here, the Coulomb interaction is attractive and its effect on the correlation function is illustrated by the green curves in both panels of Fig. 3. These curves have been obtained by solving the Schrödinger equation for p–Ξ^- and p–Ω^- pairs using the CATS equation solver [31], considering only the Coulomb interaction and assuming that the shape of the source follows a Gaussian distribution with a width equal to 1.02 ± 0.05 fm for the p–Ξ^- and to 0.95 ± 0.06 fm for the p–Ω^- system, respectively. The source-size values have been determined via an independent analysis of p–p correlations [37], where

5

modifications of the source distribution due to strong decays of short-lived resonances are taken into account as described in Methods. The difference in size between the source of the p–Ξ^- and p–Ω^- pairs might reflect the contribution of collective effects such as (an)isotropic flow. The width of the green curves in Fig. 3 reflects the quoted uncertainty of the measured source radius. The correlations obtained accounting only for the Coulomb interaction significantly underestimate the strength of both measured correlations. This implies, in both cases, that an attractive interaction exists and exceeds the strength of the Coulomb interaction.

In order to discuss the comparison of the experimental data with the predictions from lattice QCD, it is useful to first focus on the distinct characteristics of the p–Ξ^- and p–Ω^- interactions. Figure 4 exhibits the radial shapes obtained for the strong interaction potentials calculated from first principles by the HAL QCD (Hadrons to Atomic nuclei from Lattice QCD) collaboration for the p–Ξ^- [8] and the p–Ω^- systems [7], see Methods for details. For the p–Ξ^- channel only the most attractive of the four components [8] of the interaction (isospin $I = 0$ and spin $S = 0$) is shown. One can see that aside from an attractive component, the interaction contains also a repulsive core starting at very small distances, below 0.2 fm. For the p–Ω^- system no repulsive core is visible and the interaction is purely attractive. This very attractive interaction can accommodate a p–Ω^- bound state, with a binding energy of about 2.5 MeV, considering the Coulomb and strong forces [7]. The p–Ξ^- and p–Ω^- interactions look very similar to each other above a distance of 1 fm.
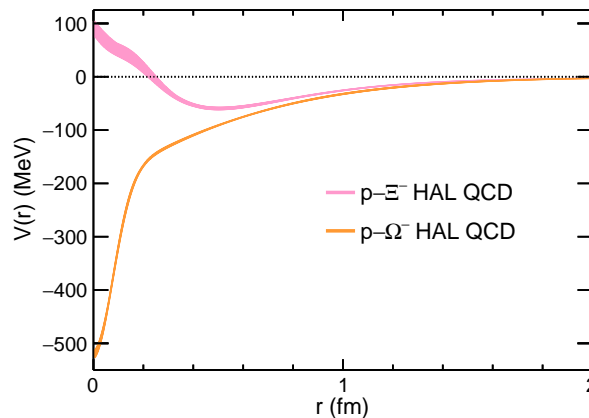

Figure 4: p–Ξ^- and p–Ω^- potentials. p–Ξ^- (pink) and p–Ω^- (orange) interaction potentials as a function of the pair distance predicted by the HAL QCD collaboration [7, 8]. Only the isospin $I = 0$ and spin $S = 0$ component is shown for p–Ξ^-. The widths of the curves correspond to the uncertainties associated with the calculations.

The measured p–Ξ^- and p–Ω^- correlation functions displayed in Fig. 3 reflect the difference in strength between the two interactions. The less attractive p–Ξ^- interaction translates into a correlation function that reaches values of 3 in comparison with the much higher values of up to 6 visible for the p–Ω^- correlation. The hierarchy in the interactions predicted by first-principle calculations is validated by the correlation functions, as demonstrated in Figs. 3 and 4.

Regarding the p–Ξ^- interaction, it should be considered that strangeness-rearrangement processes such as p$\Xi^- \to \Lambda\Lambda, \Sigma\Sigma, \Lambda\Sigma$ can occur. This means that the inverse processes (e.g. $\Lambda\Lambda \to$ pΞ^-) can also occur and modify the p–Ξ^- correlation function. These contributions are accounted for within lattice calculations by exploiting the well known quark symmetries [8] and are found to be very small. Moreover, the ALICE collaboration measured the Λ–Λ correlation in pp and p–Pb collisions [27] and good agreement with the shallow interaction predicted by the HAL QCD collaboration was found.

The resulting prediction for the correlation function, obtained solving the Schrödinger equation for the

single p–Ξ^- channel including the HAL QCD strong and Coulomb interactions, is shown in the panel **a** of Fig. 3. The first measurement of the p–Ξ^- interaction using p–Pb collisions [28] showed a qualitative agreement to lattice QCD predictions. The improved precision of the data in the current analysis of pp collisions is also in agreement with calculations that include both the HAL QCD and Coulomb interactions.

Detailed Study of the p–Ω^- Correlation

Concerning the p–Ω^- interaction, strangeness-rearrangement processes such as p$\Omega^- \rightarrow \Xi\Lambda$, $\Xi\Sigma$ can also occur [38]. Such processes might affect the p–Ω^- interaction in a different way depending on the relative orientation of the total spin and angular momentum of the pair. Since the proton has $J_p = 1/2$ and the Ω has $J_\Omega = 3/2$ and the orbital angular momentum L can be neglected for correlation studies implying low relative momentum, the total angular momentum J equals the total spin S and can take on values of $J = 2$ or $J = 1$. The $J = 2$ state cannot couple to the strangeness-rearrangement processes discussed above, except through D-wave processes which are strongly suppressed. For the $J = 1$ state only two limiting cases can be discussed in the absence of measurements of the p$\Omega^- \rightarrow \Xi\Lambda$, $\Xi\Sigma$ cross sections.

The first case assumes that the effect of the inelastic channel is negligible for both configurations and the radial behaviour of the interaction is driven by elastic processes, following the lattice QCD potential (see Fig. 4), for both the $J = 2$ and $J = 1$ channels. This results in a prediction shown by the orange curve in panel **b** of Fig. 3, that is close to the data in the low k^* region. The second limiting case assumes, following the prescription shown in [38], that the $J = 1$ configuration is completely dominated by strangeness-rearrangement processes. The obtained correlation function is shown by the blue curve in panel **b** of Fig. 3. This curve clearly deviates from the data. Both theoretical calculations also include the effect of the Coulomb interaction and they predict the existence of a p–Ω^- bound state with a binding energy of 2.5 MeV, which causes a depletion in the correlation function in the k^* region between 100 and 300 MeV/c, since pairs that form a bound state are lost to the correlation yield. The inset in Fig. 3 shows that in this k^* region the data are consistent with unity and do not follow either of the two theoretical predictions.

At the moment, the lattice QCD predictions underestimate the data, but in order to draw a firm conclusion on the existence of the bound state, additional measurements are necessary. Measurements of Λ–Ξ^- and Σ^0–Ξ^- correlations will verify experimentally the strength of possible non-elastic contributions. Measurements of the p–Ω^- correlation function in collision systems with slightly larger size (e.g. p–Pb collisions at the LHC [28]) will clarify the possible presence of a depletion in $C(k^*)$. Indeed, the appearance of a depletion in the correlation function depends on the interplay between the average intra-particle distance (source size) and the scattering length[2] associated to the p–Ω^- interaction [38].

Summary

We have shown that the hyperon–proton interaction can be studied in unprecedented detail in pp collisions at $\sqrt{s} = 13$ TeV at the LHC. We have demonstrated, in particular, that even the so far unknown p–Ω^- interaction can be investigated with significant precision. The comparison of the measured correlation functions shows that the p–Ω^- signal is up to a factor two larger than the p–Ξ^- signal. This reflects the large difference in the strong-attractive interaction predicted by the first-principle calculations by the HAL QCD collaboration. The correlation functions predicted by HAL QCD are in agreement with the measurements for the p–Ξ^- interaction. For the p–Ω^- interaction, the inelastic channels are not yet accounted for quantitatively within the lattice QCD calculations. Additionally, the depletion in the correlation function visible in the calculations around $k^* = 150$ MeV/c, due to the presence of a p–Ω^- bound

---

[2]The scattering length expresses the strength of the interaction in terms of an effective geometrical cross section and hence has the dimension of a length.

state, is not observed in the measured correlation. In order to draw quantitative conclusions concerning the existence of a p–Ω^- bound state, we plan a direct measurement of the Λ–Ξ^- and Σ^0–Ξ^- correlations and a study of the p–Ω^- correlation in p–Pb collisions in the near future. Indeed, with the upgraded ALICE apparatus [39] and the increased data sample size expected from the high luminosity phase of the LHC Run 3 and Run 4 [40], the missing interactions involving hyperons will be measured in pp and p–Pb collisions and this should allow us to answer the question about the existence of a new baryon-baryon bound state. Since this method can be extended to almost any hadron–hadron pair, an unexpected avenue for high-precision tests of the strong interaction at the LHC has been opened.

Acknowledgements

References

[1] V. Stoks and J. de Swart, "Comparison of potential models with the pp scattering data below 350 MeV", *Phys. Rev. C* **47** (1993) 761–767.

[2] T. Klijnsma, S. Bethke, G. Dissertori, and G. P. Salam, "Determination of the strong coupling constant $\alpha_s(m_Z)$ from measurements of the total cross section for top-antitop quark production", *Eur. Phys. J. C* **77** (2017) 778.

[3] K. Orginos, A. Parreno, M. J. Savage, S. R. Beane, E. Chang, and W. Detmold, "Two nucleon systems at $m_\pi \sim 450$ MeV from lattice QCD", *Phys. Rev. D* **92** (2015) 114512.

[4] E. Epelbaum, H.-W. Hammer, and U.-G. Meissner, "Modern Theory of Nuclear Forces", *Rev. Mod. Phys.* **81** (2009) 1773–1825.

[5] K. Hebeler, J. Holt, J. Menendez, and A. Schwenk, "Nuclear forces and their impact on neutron-rich nuclei and neutron-rich matter", *Ann. Rev. Nucl. Part. Sci.* **65** (2015) 457–484.

[6] E. Gebrerufael, K. Vobig, H. Hergert, and R. Roth, "Ab Initio Description of Open-Shell Nuclei: Merging No-Core Shell Model and In-Medium Similarity Renormalization Group", *Phys. Rev. Lett.* **118** (2017) 152503.

[7] **HAL QCD** Collaboration, T. Iritani *et al.*, "$N\Omega$ dibaryon from lattice QCD near the physical point", *Phys. Lett. B* **792** (2019) 284–289.

[8] K. Sasaki *et al.*, "$\Lambda\Lambda$ and NΞ interactions from Lattice QCD near the physical point", *Nucl. Phys. A* **998** (2020) 121737.

[9] T. Hatsuda, "Lattice quantum chromodynamics and baryon-baryon interactions", *Front. Phys. (Beijing)* **13** (2018) 132105.

[10] O. Hashimoto and H. Tamura, "Spectroscopy of Λ hypernuclei", *Prog. Part. Nucl. Phys.* **57** (2006) 564–653.

[11] K. Nakazawa *et al.*, "The first evidence of a deeply bound state of Xi$^-$–^{14}N system", *PTEP* **2015** (2015) 033D02.

[12] T. Nagae *et al.*, "Search For A Ξ Bound State In The ^{12}C(K^-,K^+)X Reaction At 1.8 GeV/c in J-PARC", *PoS* **INPC2016** (2017) 038.

[13] F. Eisele, H. Filthuth, W. Foehlisch, V. Hepp, and G. Zech, "Elastic $\Sigma^{\pm}$p scattering at low energies", *Phys. Lett. B* **37** (1971) 204–206.

[14] G. Alexander, U. Karshon, A. Shapira, G. Yekutieli, R. Engelmann, H. Filthuth, and W. Lughofer, "Study of the Λ–N system in low-energy Λ–p elastic scattering", *Phys. Rev.* **173** (1968) 1452–1460.

[15] B. Sechi-Zorn, B. Kehoe, J. Twitty, and R. Burnstein, "Low-energy Λ–proton elastic scattering", *Phys. Rev.* **175** (1968) 1735–1740.

[16] R. L. Jaffe, "Perhaps a Stable Dihyperon", *Phys. Rev. Lett.* **38** (1977) 195–198. [Erratum: Phys.Rev.Lett. 38, 617 (1977)].

[17] M. M. Nagels, T. A. Rijken, and J. J. de Swart, "Baryon-baryon scattering in a one-boson-exchange-potential approach. II. Hyperon-nucleon scattering", *Phys. Rev. D* **15** (1977) 2547–2564.

[18] M. M. Nagels, T. A. Rijken, and J. J. de Swart, "Baryon-baryon scattering in a one-boson-exchange-potential approach. III. A nucleon-nucleon and hyperon-nucleon analysis including contributions of a nonet of scalar mesons", *Phys. Rev. D* **20** (1979) 1633–1645.

[19] S. Gongyo *et al.*, "Most Strange Dibaryon from Lattice QCD", *Phys. Rev. Lett.* **120** no. 21, (2018) 212001, `arXiv:1709.00654 [hep-lat]`.

[20] **ALICE** Collaboration, J. Adam *et al.*, "Search for weakly decaying $\overline{\Lambda}$n and $\Lambda\Lambda$ exotic bound states in central Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV", *Phys. Lett. B* **752** (2016) 267–277.

[21] **Belle** Collaboration, B. Kim *et al.*, "Search for an H-dibaryon with mass near $2m_\Lambda$ in $\Upsilon(1S)$ and $\Upsilon(2S)$ decays", *Phys. Rev. Lett.* **110** (2013) 222002.

[22] R. Chrien, "H particle searches at Brookhaven", *Nucl. Phys. A* **629** (1998) 388C–397C.

[23] C. Yoon *et al.*, "Search for the H-dibaryon resonance in ^{12}C $(K^-, K^+\Lambda\Lambda X)$", *Phys. Rev. C* **75** (2007) 022201.

[24] **KEK-PS E224** Collaboration, J. Ahn *et al.*, "Enhanced $\Lambda\Lambda$ production near threshold in the ^{12}C(K^-,K^+) reaction", *Phys. Lett. B* **444** (1998) 267–272.

[25] **ALICE** Collaboration, S. Acharya *et al.*, "p-p, p-Λ and Λ-Λ correlations studied via femtoscopy in pp reactions at $\sqrt{s}$ = 7 TeV", *Phys. Rev. C* **99** (2019) 024001.

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

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

[28] **ALICE** Collaboration, S. Acharya *et al.*, "First Observation of an Attractive Interaction between a Proton and a Cascade Baryon", *Phys. Rev. Lett.* **123** (2019) 112002.

[29] **ALICE** Collaboration, S. Acharya *et al.*, "Investigation of the p-Σ^0 interaction via femtoscopy in pp collisions", *Phys. Lett. B* **805** (2020) 135419.

[30] **ALICE** Collaboration, J. Adam *et al.*, "Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions", *Nature Phys.* **13** (2017) 535–539.

[31] D. Mihaylov, V. Mantovani Sarti, O. Arnold, L. Fabbietti, B. Hohlweger, and A. Mathis, "A femtoscopic Correlation Analysis Tool using the Schrödinger equation (CATS)", *Eur. Phys. J. C* **78** (2018) 394.

[32] **STAR** Collaboration, L. Adamczyk *et al.*, "ΛΛ Correlation Function in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV", *Phys. Rev. Lett.* **114** (2015) 022301.

[33] K. Morita, T. Furumoto, and A. Ohnishi, "ΛΛ interaction from relativistic heavy-ion collisions", *Phys. Rev. C* **91** (2015) 024916.

[34] **STAR** Collaboration, J. Adam *et al.*, "The Proton-Ω correlation function in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV", *Phys. Lett. B* **790** (2019) 490–497.

[35] S. Pratt, "Pion Interferometry of Quark-Gluon Plasma", *Phys. Rev. D* **33** (1986) 1314–1327.

[36] M. A. Lisa, S. Pratt, R. Soltz, and U. Wiedemann, "Femtoscopy in relativistic heavy ion collisions", *Ann. Rev. Nucl. Part. Sci.* **55** (2005) 357–402.

[37] **ALICE** Collaboration, S. Acharya *et al.*, "Search for a common baryon source in high-multiplicity pp collisions at the LHC", `arXiv:2004.08018 [nucl-ex]`. Submitted to *Phys.Lett.B*.

[38] K. Morita, S. Gongyo, T. Hatsuda, T. Hyodo, Y. Kamiya, and A. Ohnishi, "Probing ΩΩ and pΩ dibaryons with femtoscopic correlations in relativistic heavy-ion collisions", *Phys. Rev. C* **101** (2020) 015201.

[39] **ALICE** Collaboration, B. Abelev *et al.*, "Upgrade of the ALICE Experiment: Letter Of Intent", *J. Phys. G* **41** (2014) 087001.

[40] Z. Citron *et al.*, "Report from Working Group 5: Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams", *CERN Yellow Rep. Monogr.* **7** (2019) 1159–1410.

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

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

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

[44] **ALICE** Collaboration, S. Acharya *et al.*, "Multiplicity dependence of (multi-)strange hadron production in proton-proton collisions at $\sqrt{s} = 13$ TeV", *Eur. Phys. J. C* **80** (2020) 167.

[45] **ALICE** Collaboration, K. Aamodt *et al.*, "Alignment of the ALICE Inner Tracking System with cosmic-ray tracks", *JINST* **5** (2010) P03003.

[46] J. Alme *et al.*, "The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events", *Nucl. Instrum. Meth. A* **622** (2010) 316–367.

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

[48] **Particle Data Group** Collaboration, M. Tanabashi *et al.*, "Review of Particle Physics", *Phys. Rev. D* **D98** (2018) 030001.

[49] **ALICE** Collaboration, K. Aamodt *et al.*, "Strange particle production in proton-proton collisions at sqrt(s) = 0.9 TeV with ALICE at the LHC", *Eur. Phys. J. C* **71** (2011) 1594.

[50] A. Kisiel, H. Zbroszczyk, and M. Szymański, "Extracting baryon-antibaryon strong-interaction potentials from $p\overline{\Lambda}$ femtoscopic correlation functions", *Phys. Rev. C* **89** (2014) 054916.

Methods

Event Selection

Events were recorded from inelastic pp collisions by ALICE [41, 42] at the LHC. A trigger that requires the total signal amplitude measured in the V0 detector [43] to exceed a certain threshold was employed to select high-multiplicity (HM) events. The V0 detector comprises two plastic scintillator arrays placed on both sides of the interaction point at pseudorapidities $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$. The pseudorapidity is defined as $\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$, where θ is the polar angle of the particle with respect to the proton beam axis.

At $\sqrt{s} = 13$ TeV, in the HM events on average 30 charged particles in the range $|\eta| < 0.5$ are produced. This η range corresponds to the region within 26 degrees of the transverse plane that is perpendicular to the beam axis. The HM events are rather rare, constituting 0.17% of the pp collisions that produce at least one charged particle in the pseudorapidity range $|\eta| < 1.0$. It was shown [30] that HM events contain an enhanced yield of hyperons, which facilitates this analysis. The yield of Ω^- in HM events is at least a factor 5 larger, on average, compared with the one in total inelastic collisions [44]. A total of 1×10^9 HM events were analyzed. Additional details on the HM event selection can be found in [29].

Particle Tracking and Identification

For the identification and momentum measurement of charged particles, the Inner Tracking System (ITS) [45], Time Projection Chamber (TPC) [46], and Time-Of-Flight (TOF) [47] detectors of ALICE are employed. All three detectors are located inside a solenoid magnetic field (0.5 T) leading to a bending of the trajectories of charged particles. The measurement of the curvature is used to reconstruct the particle momenta. Typical transverse momentum (p_T) resolutions for protons, pions and kaons vary from about 2% for tracks with $p_T = 10\,\mathrm{GeV}/c$ to below 1% for $p_T < 1\,\mathrm{GeV}/c$. The particle identity is determined by the energy lost per unit of track length inside the TPC detector and, in some cases, by the particle velocity measured in the TOF detector. For additional experimental details see [42].

Protons are selected within a transverse momentum range of $0.5 < p_T < 4.05\,\mathrm{GeV}/c$. They are identified requiring TPC information for candidate tracks with momentum $p < 0.75\,\mathrm{GeV}/c$, while TPC and TOF information are both required for candidates with $p > 0.75\,\mathrm{GeV}/c$. An incorrect identification of primary protons occurs in 1% of the cases, as evaluated by Monte Carlo simulations.

Direct tracking and identification is not possible for Ξ^- and Ω^- hyperons and their antiparticles, since they are unstable and decay because of the weak interaction within a few centimeters after their production. The mean-decay distances (evaluated as $c \times \tau$, where τ is the particle lifetime) of $\Xi^-(\overline{\Xi}^+) \rightarrow \Lambda(\overline{\Lambda}) + \pi^-(\pi^+)$ and $\Omega^-(\overline{\Omega}^+) \rightarrow \Lambda(\overline{\Lambda}) + K^-(K^+)$ are 4.9 and 2.5 cm, respectively [48]. Both decays are followed by a second decay of the unstable $\Lambda(\overline{\Lambda})$ hyperon: $\Lambda(\overline{\Lambda}) \rightarrow p(\bar{p}) + \pi^-(\pi^+)$, with an average decay path of 7.9 cm [48]. Consequently, pions ($\pi^\pm$), kaons ($K^\pm$), and protons have to be detected and then combined to search for $\Xi^-(\overline{\Xi}^+)$ and $\Omega^-(\overline{\Omega}^+)$ candidates. Those secondary particles are identified by the TPC information in the case of the reconstruction of $\Xi^-(\overline{\Xi}^+)$, while in the case of $\Omega^-(\overline{\Omega}^+)$, it is additionally required that the secondary protons and kaons are identified in the TOF detector. To measure the $\Xi^-(\overline{\Xi}^+)$ and $\Omega^-(\overline{\Omega}^+)$ hyperons, the two successive weak decays need to be reconstructed. The reconstruction procedure is very similar for both hyperons and is described in detail in [49]. Topological

selections are performed to reduce the combinatorial background, evaluated via a fit to the invariant mass distribution.

Determination of the source size

The widths of the Gaussian distributions constituting $S(r^*)$, and defining the source size, are calculated on the basis of the results of the analysis of the p–p correlation function in pp collisions at $\sqrt{s} = 13$ TeV by the ALICE collaboration [37]. Assuming a common source for all baryons, its size was studied as a function of the transverse mass of the baryon–baryon pair, $m_T = \left(k_T^2 + m^2\right)^{1/2}$, where m is the average mass and $k_T = |\vec{p}_{T,1} + \vec{p}_{T,2}|/2$ is the transverse momentum of the pair. The source size decreases with increasing mass. This effect could be due to the collective evolution of the system. For p–Ξ^- and p–Ω^- pairs, the average $\langle m_T \rangle$ is 1.9 GeV$/c$ and 2.2 GeV$/c$, respectively. For these values, the source size is determined via a parametrization of the results from p–p correlations shown in Figure 5 in [37] by a function composed of an exponential multiplied with a polynomial of first order.

In pp collisions at $\sqrt{s} = 13$ TeV, Ξ^- and Ω^- baryons are produced mostly as primary particles, but about 2/3 of the protons originate from the decay of short-lived resonances with a lifetime of a few fm$/c$. As a result, the source of both p–Ξ^- and p–Ω^- is equally modified. This effect is taken into account by folding the Gaussian source with an exponential distribution following [37]. The resulting source distribution can still be parametrized by a Gaussian distribution, which yields an effective Gaussian source size equal to 1.02 ± 0.05 fm for p–Ξ^- pairs and to 0.95 ± 0.06 fm for p–Ω^- pairs. The quoted uncertainties correspond to variations of the parametrization of the p–p results according to their systematic and statistical uncertainties.

Corrections of the Correlation Function

The correction factor $\xi(k^*)$ accounts for the normalisation of the k^* distribution of pairs from mixed-events, for effects produced by finite momentum resolution and for the influence of residual correlations.

The mixed-event distribution, $N_{\text{mixed}}(k^*)$, has to be scaled down since the number of pairs available from mixed-events is much higher than the number of pairs produced in the same collision used in $N_{\text{same}}(k^*)$. The normalisation parameter $\mathcal{N}$ is chosen such that the mean value of the correlation function equals to unity in a region of k^* values where the effect of final-state interactions are negligible, $500 < k^* < 800$ MeV$/c$.

The finite experimental momentum resolution modifies the measured correlation functions at most by 8% at low k^*. A correction for this effect is applied. Resolution effects due to the merging of tracks that are very close to each other were evaluated and found to be negligible.

The two measured correlation functions are dominated by the contribution of the interaction between p–Ξ^- and p–Ω^- pairs. Nevertheless, other contributions also influence the measured correlation function. They originate either from incorrectly identified particles or from particles stemming from other weak decays (such as protons from $\Lambda \to p + \pi^-$ decays) combined with primary particles. Since weak decays occur typically some centimeters away from the collision vertex, there is no final-state interaction between their decay products and the primary particles of interest. Hence, the resulting correlation function will be either completely flat or will carry the residual signature of the interaction between the particles before the decay. A method to determine the exact shape and relative yields of the residual correlations was developed in [25, 50] and it is employed in this analysis. Such contributions are subtracted from the measured p–Ξ^- and p–Ω^- correlations in order to obtain the genuine correlation functions. The residual correlation stemming from mis-identification is evaluated experimentally [28] and its contribution is also subtracted from the measured correlation function.

The systematic uncertainties associated to the genuine correlation function arise from the following sources: i) the selection of the proton, Ξ^- ($\overline{\Xi}^+$) and Ω^- ($\overline{\Omega}^+$), ii) the normalisation of the mixed-event

distributions, iii) uncertainties on the residual contributions, and iv) uncertainties due to the finite momentum resolution. To evaluate the associated systematic uncertainties: i) all single-particle and topological selection criteria are varied with respect to their default values, ii) the k^* normalisation range of the mixed-events is varied, and a linear function of k^* is also used for an alternative normalisation, iii) the shape of the residual correlations and its relative contribution are altered, iv) the momentum resolution and the employed correction method are changed. The total systematic uncertainties associated to the genuine correlation function are maximal at low k^*, reaching a value of 9% and 8% for p–Ξ^- and p–Ω^-, correspondingly.

HAL QCD potentials

Results from calculations by the HAL QCD Collaboration for the p–Ξ^- [8] and p–Ω^- [7] interactions are shown in Fig. 3 and Fig. 4. Such interactions were studied via (2+1)-flavor lattice QCD simulations with nearly physical quark masses ($m_\pi = 146$ MeV/c^2).

In Fig. 4, the p–Ξ^- and p–Ω^- potentials are shown for calculations with $t/a = 12$, being t the Euclidean time and a the lattice spacing of the calculations. The HAL QCD Collaboration provided 23 and 20 sets of parameters for the description of the shape of the p–Ξ^- and p–Ω^- potentials, respectively. Such parametrizations result from applying the jackknife method in order to take into account the statistical uncertainty of the calculations. The width of the curves in Fig. 4 corresponds to the maximum variations observed in the potential shape by using the different sets of parameters.

To obtain the correlation functions shown in Fig. 3 we consider the calculations with $t/a = 12$, both for p–Ξ^- and p–Ω^-. The statistical uncertainty of the calculations is evaluated using the jackknife variations, and a systematic uncertainty is added in quadrature evaluated by considering calculations with $t/a = 11$ and $t/a = 13$.

The ALICE Collaboration

S. Acharya[141] , D. Adamová[95] , A. Adler[74] , J. Adolfsson[81] , M.M. Aggarwal[100] , G. Aglieri Rinella[34] ,
M. Agnello[30] , N. Agrawal[10 ,54] , Z. Ahammed[141] , S. Ahmad[16] , S.U. Ahn[76] , Z. Akbar[51] , A. Akindinov[92] ,
M. Al-Turany[107] , S.N. Alam[40 ,141] , D.S.D. Albuquerque[122] , D. Aleksandrov[88] , B. Alessandro[59] ,
H.M. Alfanda[6] , R. Alfaro Molina[71] , B. Ali[16] , Y. Ali[14] , A. Alici[10 ,26 ,54] , N. Alizadehvandchali[125] ,
A. Alkin[2 ,34] , J. Alme[21] , T. Alt[68] , L. Altenkamper[21] , I. Altsybeev[113] , M.N. Anaam[6] , C. Andrei[48] ,
D. Andreou[34] , A. Andronic[144] , M. Angeletti[34] , V. Anguelov[104] , C. Anson[15] , T. Antičić[108] , F. Antinori[57] ,
P. Antonioli[54] , N. Apadula[80] , L. Aphecetche[115] , H. Appelshäuser[68] , S. Arcelli[26] , R. Arnaldi[59] , M. Arratia[80] ,
I.C. Arsene[20] , M. Arslandok[104] , A. Augustinus[34] , R. Averbeck[107] , S. Aziz[78] , M.D. Azmi[16] , A. Badalà[56] ,
Y.W. Baek[41] , S. Bagnasco[59] , X. Bai[107] , R. Bailhache[68] , R. Bala[101] , A. Balbino[30] , A. Baldisseri[137] , M. Ball[43] ,
S. Balouza[105] , D. Banerjee[3] , R. Barbera[27] , L. Barioglio[25] , G.G. Barnaföldi[145] , L.S. Barnby[94] , V. Barret[134] ,
P. Bartalini[6] , C. Bartels[127] , K. Barth[34] , E. Bartsch[68] , F. Baruffaldi[28] , N. Bastid[134] , S. Basu[143] , G. Batigne[115] ,
B. Batyunya[75] , D. Bauri[49] , J.L. Bazo Alba[112] , I.G. Bearden[89] , C. Beattie[146] , C. Bedda[63] , N.K. Behera[61] ,
I. Belikov[136] , A.D.C. Bell Hechavarria[144] , F. Bellini[34] , R. Bellwied[125] , V. Belyaev[93] , G. Bencedi[145] ,
S. Beole[25] , A. Bercuci[48] , Y. Berdnikov[98] , D. Berenyi[145] , R.A. Bertens[130] , D. Berzano[59] , M.G. Besoiu[67] ,
L. Betev[34] , A. Bhasin[101] , I.R. Bhat[101] , M.A. Bhat[3] , H. Bhatt[49] , B. Bhattacharjee[42] , A. Bianchi[25] ,
L. Bianchi[25] , N. Bianchi[52] , J. Bielčík[37] , J. Bielčíková[95] , A. Bilandzic[105] , G. Biro[145] , R. Biswas[3] , S. Biswas[3] ,
J.T. Blair[119] , D. Blau[88] , C. Blume[68] , G. Boca[139] , F. Bock[96] , A. Bogdanov[93] , S. Boi[23] , J. Bok[61] ,
L. Boldizsár[145] , A. Bolozdynya[93] , M. Bombara[38] , G. Bonomi[140] , H. Borel[137] , A. Borissov[93] , H. Bossi[146] ,
E. Botta[25] , L. Bratrud[68] , P. Braun-Munzinger[107] , M. Bregant[121] , M. Broz[37] , E. Bruna[59] , G.E. Bruno[33 ,106] ,
M.D. Buckland[127] , D. Budnikov[109] , H. Buesching[68] , S. Bufalino[30] , O. Bugnon[115] , P. Buhler[114] , P. Buncic[34] ,
Z. Buthelezi[72 ,131] , J.B. Butt[14] , S.A. Bysiak[118] , D. Caffarri[90] , A. Caliva[107] , E. Calvo Villar[112] ,
J.M.M. Camacho[120] , R.S. Camacho[45] , P. Camerini[24] , F.D.M. Canedo[121] , A.A. Capon[114] , F. Carnesecchi[26] ,
R. Caron[137] , J. Castillo Castellanos[137] , A.J. Castro[130] , E.A.R. Casula[55] , F. Catalano[30] , C. Ceballos Sanchez[75] ,
P. Chakraborty[49] , S. Chandra[141] , W. Chang[6] , S. Chapeland[34] , M. Chartier[127] , S. Chattopadhyay[141] ,
S. Chattopadhyay[110] , A. Chauvin[23] , C. Cheshkov[135] , B. Cheynis[135] , V. Chibante Barroso[34] ,
D.D. Chinellato[122] , S. Cho[61] , P. Chochula[34] , T. Chowdhury[134] , P. Christakoglou[90] , C.H. Christensen[89] ,
P. Christiansen[81] , T. Chujo[133] , C. Cicalo[55] , L. Cifarelli[10 ,26] , L.D. Cilladi[25] , F. Cindolo[54] , M.R. Ciupek[107] ,
G. Clai[54 ,ii] , J. Cleymans[124] , F. Colamaria[53] , D. Colella[53] , A. Collu[80] , M. Colocci[26] , M. Concas[59 ,iii] , G. Conesa
Balbastre[79] , Z. Conesa del Valle[78] , G. Contin[24 ,60] , J.G. Contreras[37] , T.M. Cormier[96] , Y. Corrales Morales[25] ,
P. Cortese[31] , M.R. Cosentino[123] , F. Costa[34] , S. Costanza[139] , P. Crochet[134] , E. Cuautle[69] , P. Cui[6] ,
L. Cunqueiro[96] , D. Dabrowski[142] , T. Dahms[105] , A. Dainese[57] , F.P.A. Damas[115 ,137] , M.C. Danisch[104] ,
A. Danu[67] , D. Das[110] , I. Das[110] , P. Das[86] , P. Das[3] , S. Das[3] , A. Dash[86] , S. Dash[49] , S. De[86] , A. De Caro[29] ,
G. de Cataldo[53] , J. de Cuveland[39] , A. De Falco[23] , D. De Gruttola[10] , N. De Marco[59] , S. De Pasquale[29] ,
S. Deb[50] , H.F. Degenhardt[121] , K.R. Deja[142] , A. Deloff[85] , S. Delsanto[25 ,131] , W. Deng[6] , P. Dhankher[49] , D. Di
Bari[33] , A. Di Mauro[34] , R.A. Diaz[8] , T. Dietel[124] , P. Dillenseger[68] , Y. Ding[6] , R. Divià[34] , D.U. Dixit[19] ,
Ø. Djuvsland[21] , U. Dmitrieva[62] , A. Dobrin[67] , B. Dönigus[68] , O. Dordic[20] , A.K. Dubey[141] , A. Dubla[90 ,107] ,
S. Dudi[100] , M. Dukhishyam[86] , P. Dupieux[134] , R.J. Ehlers[96] , V.N. Eikeland[21] , D. Elia[53] , B. Erazmus[115] ,
F. Erhardt[99] , A. Erokhin[113] , M.R. Ersdal[21] , B. Espagnon[78] , G. Eulisse[34] , D. Evans[111] , S. Evdokimov[91] ,
L. Fabbietti[105] , M. Faggin[28] , J. Faivre[79] , F. Fan[6] , A. Fantoni[52] , M. Fasel[96] , P. Fecchio[30] , A. Feliciello[59] ,
G. Feofilov[113] , A. Fernández Téllez[45] , A. Ferrero[137] , A. Ferretti[25] , A. Festanti[34] , V.J.G. Feuillard[104] ,
J. Figiel[118] , S. Filchagin[109] , D. Finogeev[62] , F.M. Fionda[21] , G. Fiorenza[53] , F. Flor[125] , A.N. Flores[119] ,
S. Foertsch[72] , P. Foka[107] , S. Fokin[88] , E. Fragiacomo[60] , U. Frankenfeld[107] , U. Fuchs[34] , C. Furget[79] , A. Furs[62] ,
M. Fusco Girard[29] , J.J. Gaardhøje[89] , M. Gagliardi[25] , A.M. Gago[112] , A. Gal[136] , C.D. Galvan[120] , P. Ganoti[84] ,
C. Garabatos[107] , J.R.A. Garcia[45] , E. Garcia-Solis[11] , K. Garg[115] , C. Gargiulo[34] , A. Garibli[87] , K. Garner[144] ,
P. Gasik[105 ,107] , E.F. Gauger[119] , M.B. Gay Ducati[70] , M. Germain[115] , J. Ghosh[110] , P. Ghosh[141] , S.K. Ghosh[3] ,
M. Giacalone[26] , P. Gianotti[52] , P. Giubellino[59 ,107] , P. Giubilato[28] , A.M.C. Glaenzer[137] , P. Glässel[104] , A. Gomez
Ramirez[74] , V. Gonzalez[107 ,143] , L.H. González-Trueba[71] , S. Gorbunov[39] , L. Görlich[118] , A. Goswami[49] ,
S. Gotovac[35] , V. Grabski[71] , L.K. Graczykowski[142] , K.L. Graham[111] , L. Greiner[80] , A. Grelli[63] , C. Grigoras[34] ,
V. Grigoriev[93] , A. Grigoryan[1] , S. Grigoryan[75] , O.S. Groettvik[21] , F. Grosa[30 ,59] , J.F. Grosse-Oetringhaus[34] ,
R. Grosso[107] , R. Guernane[79] , M. Guittiere[115] , K. Gulbrandsen[89] , T. Gunji[132] , A. Gupta[101] , R. Gupta[101] ,
I.B. Guzman[45] , R. Haake[146] , M.K. Habib[107] , C. Hadjidakis[78] , H. Hamagaki[82] , G. Hamar[145] , M. Hamid[6] ,
R. Hannigan[119] , M.R. Haque[63 ,86] , A. Harlenderova[107] , J.W. Harris[146] , A. Harton[11] , J.A. Hasenbichler[34] ,
H. Hassan[96] , Q.U. Hassan[14] , D. Hatzifotiadou[10 ,54] , P. Hauer[43] , L.B. Havener[146] , S. Hayashi[132] ,
S.T. Heckel[105] , E. Hellbär[68] , H. Helstrup[36] , A. Herghelegiu[48] , T. Herman[37] , E.G. Hernandez[45] , G. Herrera
Corral[9] , F. Herrmann[144] , K.F. Hetland[36] , H. Hillemanns[34] , C. Hills[127] , B. Hippolyte[136] , B. Hohlweger[105] ,

J. Honermann[144] , D. Horak[37] , A. Hornung[68] , S. Hornung[107] , R. Hosokawa[15 ,133] , P. Hristov[34] , C. Huang[78] ,
C. Hughes[130] , P. Huhn[68] , T.J. Humanic[97] , H. Hushnud[110] , L.A. Husova[144] , N. Hussain[42] , S.A. Hussain[14] ,
D. Hutter[39] , J.P. Iddon[34 ,127] , R. Ilkaev[109] , H. Ilyas[14] , M. Inaba[133] , G.M. Innocenti[34] , M. Ippolitov[88] ,
A. Isakov[95] , M.S. Islam[110] , M. Ivanov[107] , V. Ivanov[98] , V. Izucheev[91] , B. Jacak[80] , N. Jacazio[34 ,54] ,
P.M. Jacobs[80] , S. Jadlovska[117] , J. Jadlovsky[117] , S. Jaelani[63] , C. Jahnke[121] , M.J. Jakubowska[142] ,
M.A. Janik[142] , T. Janson[74] , M. Jercic[99] , O. Jevons[111] , M. Jin[125] , F. Jonas[96 ,144] , P.G. Jones[111] , J. Jung[68] ,
M. Jung[68] , A. Jusko[111] , P. Kalinak[64] , A. Kalweit[34] , V. Kaplin[93] , S. Kar[6] , A. Karasu Uysal[77] , D. Karatovic[99] ,
O. Karavichev[62] , T. Karavicheva[62] , P. Karczmarczyk[142] , E. Karpechev[62] , A. Kazantsev[88] , U. Kebschull[74] ,
R. Keidel[47] , M. Keil[34] , B. Ketzer[43] , Z. Khabanova[90] , A.M. Khan[6] , S. Khan[16] , A. Khanzadeev[98] ,
Y. Kharlov[91] , A. Khatun[16] , A. Khuntia[118] , B. Kileng[36] , B. Kim[61] , B. Kim[133] , D. Kim[147] , D.J. Kim[126] ,
E.J. Kim[73] , H. Kim[17] , J. Kim[147] , J.S. Kim[41] , J. Kim[104] , J. Kim[147] , J. Kim[73] , M. Kim[104] , S. Kim[18] ,
T. Kim[147] , T. Kim[147] , S. Kirsch[68] , I. Kisel[39] , S. Kiselev[92] , A. Kisiel[142] , J.L. Klay[5] , C. Klein[68] , J. Klein[34 ,59] ,
S. Klein[80] , C. Klein-Bösing[144] , M. Kleiner[68] , A. Kluge[34] , M.L. Knichel[34] , A.G. Knospe[125] , C. Kobdaj[116] ,
M.K. Köhler[104] , T. Kollegger[107] , A. Kondratyev[75] , N. Kondratyeva[93] , E. Kondratyuk[91] , J. Konig[68] ,
S.A. Konigstorfer[105] , P.J. Konopka[34] , G. Kornakov[142] , L. Koska[117] , O. Kovalenko[85] , V. Kovalenko[113] ,
M. Kowalski[118] , I. Králik[64] , A. Kravčáková[38] , L. Kreis[107] , M. Krivda[64 ,111] , F. Krizek[95] ,
K. Krizkova Gajdosova[37] , M. Krüger[68] , E. Kryshen[98] , M. Krzewicki[39] , A.M. Kubera[97] , V. Kučera[34 ,61] ,
C. Kuhn[136] , P.G. Kuijer[90] , L. Kumar[100] , S. Kundu[86] , P. Kurashvili[85] , A. Kurepin[62] , A.B. Kurepin[62] ,
A. Kuryakin[109] , S. Kushpil[95] , J. Kvapil[111] , M.J. Kweon[61] , J.Y. Kwon[61] , Y. Kwon[147] , S.L. La Pointe[39] , P. La
Rocca[27] , Y.S. Lai[80] , M. Lamanna[34] , R. Langoy[129] , K. Lapidus[34] , A. Lardeux[20] , P. Larionov[52] , E. Laudi[34] ,
R. Lavicka[37] , T. Lazareva[113] , R. Lea[24] , L. Leardini[104] , J. Lee[133] , S. Lee[147] , S. Lehner[114] , J. Lehrbach[39] ,
R.C. Lemmon[94] , I. León Monzón[120] , E.D. Lesser[19] , M. Lettrich[34] , P. Lévai[145] , X. Li[12] , X.L. Li[6] , J. Lien[129] ,
R. Lietava[111] , B. Lim[17] , V. Lindenstruth[39] , A. Lindner[48] , C. Lippmann[107] , M.A. Lisa[97] , A. Liu[19] , J. Liu[127] ,
S. Liu[97] , W.J. Llope[143] , I.M. Lofnes[21] , V. Loginov[93] , C. Loizides[96] , P. Loncar[35] , J.A. Lopez[104] , X. Lopez[134] ,
E. López Torres[8] , J.R. Luhder[144] , M. Lunardon[28] , G. Luparello[60] , Y.G. Ma[40] , A. Maevskaya[62] , M. Mager[34] ,
S.M. Mahmood[20] , T. Mahmoud[43] , A. Maire[136] , R.D. Majka[146 ,i] , M. Malaev[98] , Q.W. Malik[20] , L. Malinina[75 ,iv] ,
D. Mal'Kevich[92] , P. Malzacher[107] , G. Mandaglio[32 ,56] , V. Manko[88] , F. Manso[134] , V. Manzari[53] , Y. Mao[6] ,
M. Marchisone[135] , J. Mareš[66] , G.V. Margagliotti[24] , A. Margotti[54] , A. Marín[107] , C. Markert[119] ,
M. Marquard[68] , C.D. Martin[24] , N.A. Martin[104] , P. Martinengo[34] , J.L. Martinez[125] , M.I. Martínez[45] ,
G. Martínez García[115] , S. Masciocchi[107] , M. Masera[25] , A. Masoni[55] , L. Massacrier[78] , E. Masson[115] ,
A. Mastroserio[53 ,138] , A.M. Mathis[105] , O. Matonoha[81] , P.F.T. Matuoka[121] , A. Matyja[118] , C. Mayer[118] ,
F. Mazzaschi[25] , M. Mazzilli[53] , M.A. Mazzoni[58] , A.F. Mechler[68] , F. Meddi[22] , Y. Melikyan[62 ,93] ,
A. Menchaca-Rocha[71] , C. Mengke[6] , E. Meninno[29 ,114] , A.S. Menon[125] , M. Meres[13] , S. Mhlanga[124] ,
Y. Miake[133] , L. Micheletti[25] , L.C. Migliorin[135] , D.L. Mihaylov[105] , K. Mikhaylov[75 ,92] , A.N. Mishra[69] ,
D. Miśkowiec[107] , A. Modak[3] , N. Mohammadi[34] , A.P. Mohanty[63] , B. Mohanty[86] , M. Mohisin Khan[16 ,v] ,
Z. Moravcova[89] , C. Mordasini[105] , D.A. Moreira De Godoy[144] , L.A.P. Moreno[45] , I. Morozov[62] , A. Morsch[34] ,
T. Mrnjavac[34] , V. Muccifora[52] , E. Mudnic[35] , D. Mühlheim[144] , S. Muhuri[141] , J.D. Mulligan[80] , A. Mulliri[23 ,55] ,
M.G. Munhoz[121] , R.H. Munzer[68] , H. Murakami[132] , S. Murray[124] , L. Musa[34] , J. Musinsky[64] , C.J. Myers[125] ,
J.W. Myrcha[142] , B. Naik[49] , R. Nair[85] , B.K. Nandi[49] , R. Nania[10 ,54] , E. Nappi[53] , M.U. Naru[14] ,
A.F. Nassirpour[81] , C. Nattrass[130] , R. Nayak[49] , T.K. Nayak[86] , S. Nazarenko[109] , A. Neagu[20] , R.A. Negrao De
Oliveira[68] , L. Nellen[69] , S.V. Nesbo[36] , G. Neskovic[39] , D. Nesterov[113] , L.T. Neumann[142] , B.S. Nielsen[89] ,
S. Nikolaev[88] , S. Nikulin[88] , V. Nikulin[98] , F. Noferini[10 ,54] , P. Nomokonov[75] , J. Norman[79 ,127] , N. Novitzky[133] ,
P. Nowakowski[142] , A. Nyanin[88] , J. Nystrand[21] , M. Ogino[82] , A. Ohlson[81 ,104] , J. Oleniacz[142] , A.C. Oliveira Da
Silva[130] , M.H. Oliver[146] , C. Oppedisano[59] , A. Ortiz Velasquez[69] , A. Oskarsson[81] , J. Otwinowski[118] ,
K. Oyama[82] , Y. Pachmayer[104] , V. Pacik[89] , S. Padhan[49] , D. Pagano[140] , G. Paić[69] , J. Pan[143] , S. Panebianco[137] ,
P. Pareek[50 ,141] , J. Park[61] , J.E. Parkkila[126] , S. Parmar[100] , S.P. Pathak[125] , B. Paul[23] , J. Pazzini[140] , H. Pei[6] ,
T. Peitzmann[63] , X. Peng[6] , L.G. Pereira[70] , H. Pereira Da Costa[137] , D. Peresunko[88] , G.M. Perez[8] , S. Perrin[137] ,
Y. Pestov[4] , V. Petráček[37] , M. Petrovici[48] , R.P. Pezzi[70] , S. Piano[60] , M. Pikna[13] , P. Pillot[115] , O. Pinazza[34 ,54] ,
L. Pinsky[125] , C. Pinto[27] , S. Pisano[10 ,52] , D. Pistone[56] , M. Płoskoń[80] , M. Planinic[99] , F. Pliquett[68] ,
M.G. Poghosyan[96] , B. Polichtchouk[91] , N. Poljak[99] , A. Pop[48] , S. Porteboeuf-Houssais[134] , V. Pozdniakov[75] ,
S.K. Prasad[3] , R. Preghenella[54] , F. Prino[59] , C.A. Pruneau[143] , I. Pshenichnov[62] , M. Puccio[34] , J. Putschke[143] ,
S. Qiu[90] , L. Quaglia[25] , R.E. Quishpe[125] , S. Ragoni[111] , S. Raha[3] , S. Rajput[101] , J. Rak[126] ,
A. Rakotozafindrabe[137] , L. Ramello[31] , F. Rami[136] , S.A.R. Ramirez[45] , R. Raniwala[102] , S. Raniwala[102] ,
S.S. Räsänen[44] , R. Rath[50] , V. Ratza[43] , I. Ravasenga[90] , K.F. Read[96 ,130] , A.R. Redelbach[39] , K. Redlich[85 ,vi] ,
A. Rehman[21] , P. Reichelt[68] , F. Reidt[34] , X. Ren[6] , R. Renfordt[68] , Z. Rescakova[38] , K. Reygers[104] , A. Riabov[98] ,
V. Riabov[98] , T. Richert[81 ,89] , M. Richter[20] , P. Riedler[34] , W. Riegler[34] , F. Riggi[27] , C. Ristea[67] , S.P. Rode[50] ,

M. Rodríguez Cahuantzi[45] , K. Røed[20] , R. Rogalev[91] , E. Rogochaya[75] , D. Rohr[34] , D. Röhrich[21] , P.F. Rojas[45] , P.S. Rokita[142] , F. Ronchetti[52] , A. Rosano[56] , E.D. Rosas[69] , K. Roslon[142] , A. Rossi[28 ,57] , A. Rotondi[139] , A. Roy[50] , P. Roy[110] , O.V. Rueda[81] , R. Rui[24] , B. Rumyantsev[75] , A. Rustamov[87] , E. Ryabinkin[88] , Y. Ryabov[98] , A. Rybicki[118] , H. Rytkonen[126] , O.A.M. Saarimaki[44] , R. Sadek[115] , S. Sadhu[141] , S. Sadovsky[91] , K. Šafařík[37] , S.K. Saha[141] , B. Sahoo[49] , P. Sahoo[49] , R. Sahoo[50] , S. Sahoo[65] , P.K. Sahu[65] , J. Saini[141] , S. Sakai[133] , S. Sambyal[101] , V. Samsonov[93 ,98] , D. Sarkar[143] , N. Sarkar[141] , P. Sarma[42] , V.M. Sarti[105] , M.H.P. Sas[63] , E. Scapparone[54] , J. Schambach[119] , H.S. Scheid[68] , C. Schiaua[48] , R. Schicker[104] , A. Schmah[104] , C. Schmidt[107] , H.R. Schmidt[103] , M.O. Schmidt[104] , M. Schmidt[103] , N.V. Schmidt[68 ,96] , A.R. Schmier[130] , J. Schukraft[89] , Y. Schutz[136] , K. Schwarz[107] , K. Schweda[107] , G. Scioli[26] , E. Scomparin[59] , J.E. Seger[15] , Y. Sekiguchi[132] , D. Sekihata[132] , I. Selyuzhenkov[93 ,107] , S. Senyukov[136] , D. Serebryakov[62] , A. Sevcenco[67] , A. Shabanov[62] , A. Shabetai[115] , R. Shahoyan[34] , W. Shaikh[110] , A. Shangaraev[91] , A. Sharma[100] , A. Sharma[101] , H. Sharma[118] , M. Sharma[101] , N. Sharma[100] , S. Sharma[101] , O. Sheibani[125] , K. Shigaki[46] , M. Shimomura[83] , S. Shirinkin[92] , Q. Shou[40] , Y. Sibiriak[88] , S. Siddhanta[55] , T. Siemiarczuk[85] , D. Silvermyr[81] , G. Simatovic[90] , G. Simonetti[34] , B. Singh[105] , R. Singh[86] , R. Singh[101] , R. Singh[50] , V.K. Singh[141] , V. Singhal[141] , T. Sinha[110] , B. Sitar[13] , M. Sitta[31] , T.B. Skaali[20] , M. Slupecki[44] , N. Smirnov[146] , R.J.M. Snellings[63] , C. Soncco[112] , J. Song[125] , A. Songmoolnak[116] , F. Soramel[28] , S. Sorensen[130] , I. Sputowska[118] , J. Stachel[104] , I. Stan[67] , P.J. Steffanic[130] , E. Stenlund[81] , S.F. Stiefelmaier[104] , D. Stocco[115] , M.M. Storetvedt[36] , L.D. Stritto[29] , A.A.P. Suaide[121] , T. Sugitate[46] , C. Suire[78] , M. Suleymanov[14] , M. Suljic[34] , R. Sultanov[92] , M. Šumbera[95] , V. Sumberia[101] , S. Sumowidagdo[51] , S. Swain[65] , A. Szabo[13] , I. Szarka[13] , U. Tabassam[14] , S.F. Taghavi[105] , G. Taillepied[134] , J. Takahashi[122] , G.J. Tambave[21] , S. Tang[6 ,134] , M. Tarhini[115] , M.G. Tarzila[48] , A. Tauro[34] , G. Tejeda Muñoz[45] , A. Telesca[34] , L. Terlizzi[25] , C. Terrevoli[125] , D. Thakur[50] , S. Thakur[141] , D. Thomas[119] , F. Thoresen[89] , R. Tieulent[135] , A. Tikhonov[62] , A.R. Timmins[125] , A. Toia[68] , N. Topilskaya[62] , M. Toppi[52] , F. Torales-Acosta[19] , S.R. Torres[37] , A. Trifiró[32 ,56] , S. Tripathy[50 ,69] , T. Tripathy[49] , S. Trogolo[28] , G. Trombetta[33] , L. Tropp[38] , V. Trubnikov[2] , W.H. Trzaska[126] , T.P. Trzcinski[142] , B.A. Trzeciak[37 ,63] , A. Tumkin[109] , R. Turrisi[57] , T.S. Tveter[20] , K. Ullaland[21] , E.N. Umaka[125] , A. Uras[135] , G.L. Usai[23] , M. Vala[38] , N. Valle[139] , S. Vallero[59] , N. van der Kolk[63] , L.V.R. van Doremalen[63] , M. van Leeuwen[63] , P. Vande Vyvre[34] , D. Varga[145] , Z. Varga[145] , M. Varga-Kofarago[145] , A. Vargas[45] , M. Vasileiou[84] , A. Vasiliev[88] , O. Vázquez Doce[105] , V. Vechernin[113] , E. Vercellin[25] , S. Vergara Limón[45] , L. Vermunt[63] , R. Vernet[7] , R. Vértesi[145] , L. Vickovic[35] , Z. Vilakazi[131] , O. Villalobos Baillie[111] , G. Vino[53] , A. Vinogradov[88] , T. Virgili[29] , V. Vislavicius[89] , A. Vodopyanov[75] , B. Volkel[34] , M.A. Völkl[103] , K. Voloshin[92] , S.A. Voloshin[143] , G. Volpe[33] , B. von Haller[34] , I. Vorobyev[105] , D. Voscek[117] , J. Vrláková[38] , B. Wagner[21] , M. Weber[114] , S.G. Weber[144] , A. Wegrzynek[34] , S.C. Wenzel[34] , J.P. Wessels[144] , J. Wiechula[68] , J. Wikne[20] , G. Wilk[85] , J. Wilkinson[10 ,54] , G.A. Willems[144] , E. Willsher[111] , B. Windelband[104] , M. Winn[137] , W.E. Witt[130] , J.R. Wright[119] , Y. Wu[128] , R. Xu[6] , S. Yalcin[77] , Y. Yamaguchi[46] , K. Yamakawa[46] , S. Yang[21] , S. Yano[137] , Z. Yin[6] , H. Yokoyama[63] , I.-K. Yoo[17] , J.H. Yoon[61] , S. Yuan[21] , A. Yuncu[104] , V. Yurchenko[2] , V. Zaccolo[24] , A. Zaman[14] , C. Zampolli[34] , H.J.C. Zanoli[63] , N. Zardoshti[34] , A. Zarochentsev[113] , P. Závada[66] , N. Zaviyalov[109] , H. Zbroszczyk[142] , M. Zhalov[98] , S. Zhang[40] , X. Zhang[6] , Z. Zhang[6] , V. Zherebchevskii[113] , Y. Zhi[12] , D. Zhou[6] , Y. Zhou[89] , Z. Zhou[21] , J. Zhu[6 ,107] , Y. Zhu[6] , A. Zichichi[10 ,26] , G. Zinovjev[2] , N. Zurlo[140] ,

Affiliation notes

[i] Deceased

[ii] Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Bologna, Italy

[iii] Dipartimento DET del Politecnico di Torino, Turin, Italy

[iv] M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear, Physics, Moscow, Russia

[v] Department of Applied Physics, Aligarh Muslim University, Aligarh, India

[vi] Institute of Theoretical Physics, University of Wroclaw, Poland

Collaboration Institutes

[1] A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia

[2] Bogolyubov Institute for Theoretical Physics, National Academy of Sciences of Ukraine, Kiev, Ukraine

[3] Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India

[4] Budker Institute for Nuclear Physics, Novosibirsk, Russia

[5] California Polytechnic State University, San Luis Obispo, California, United States

[6] Central China Normal University, Wuhan, China

[7] Centre de Calcul de l'IN2P3, Villeurbanne, Lyon, France

[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] Centro Fermi - Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi', Rome, Italy

[11] Chicago State University, Chicago, Illinois, United States

[12] China Institute of Atomic Energy, Beijing, China

[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.R. Caianiello' dell'Università and Gruppo Collegato INFN, Salerno, Italy

[30] Dipartimento DISAT del Politecnico and Sezione INFN, Turin, Italy

[31] Dipartimento di Scienze e Innovazione Tecnologica dell'Università del Piemonte Orientale and INFN Sezione di Torino, Alessandria, Italy

[32] Dipartimento di Scienze MIFT, Università di Messina, Messina, Italy

[33] Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy

[34] European Organization for Nuclear Research (CERN), Geneva, Switzerland

[35] Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, Croatia

[36] Faculty of Engineering and Science, Western Norway University of Applied Sciences, Bergen, Norway

[37] Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic

[38] Faculty of Science, P.J. Šafárik University, Košice, Slovakia

[39] Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany

[40] Fudan University, Shanghai, China

[41] Gangneung-Wonju National University, Gangneung, Republic of Korea

[42] Gauhati University, Department of Physics, Guwahati, India

[43] Helmholtz-Institut für Strahlen- und Kernphysik, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn, Germany

[44] Helsinki Institute of Physics (HIP), Helsinki, Finland

[45] High Energy Physics Group, Universidad Autónoma de Puebla, Puebla, Mexico

[46] Hiroshima University, Hiroshima, Japan

[47] Hochschule Worms, Zentrum für Technologietransfer und Telekommunikation (ZTT), Worms, Germany

[48] Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania

[49] Indian Institute of Technology Bombay (IIT), Mumbai, India

[50] Indian Institute of Technology Indore, Indore, India

[51] Indonesian Institute of Sciences, Jakarta, Indonesia

[52] INFN, Laboratori Nazionali di Frascati, Frascati, Italy

[53] INFN, Sezione di Bari, Bari, Italy

[54] INFN, Sezione di Bologna, Bologna, Italy

[55] INFN, Sezione di Cagliari, Cagliari, Italy

[56] INFN, Sezione di Catania, Catania, Italy

[57] INFN, Sezione di Padova, Padova, Italy

[58] INFN, Sezione di Roma, Rome, Italy

[59] INFN, Sezione di Torino, Turin, Italy

[60] INFN, Sezione di Trieste, Trieste, Italy

[61] Inha University, Incheon, Republic of Korea

[62] Institute for Nuclear Research, Academy of Sciences, Moscow, Russia

[63] Institute for Subatomic Physics, Utrecht University/Nikhef, Utrecht, Netherlands

[64] Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia

[65] Institute of Physics, Homi Bhabha National Institute, Bhubaneswar, India

[66] Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic

[67] Institute of Space Science (ISS), Bucharest, Romania

[68] Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany

[69] Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico

[70] Instituto de Física, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Brazil

[71] Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico

[72] iThemba LABS, National Research Foundation, Somerset West, South Africa

[73] Jeonbuk National University, Jeonju, Republic of Korea

[74] Johann-Wolfgang-Goethe Universität Frankfurt Institut für Informatik, Fachbereich Informatik und Mathematik, Frankfurt, Germany

[75] Joint Institute for Nuclear Research (JINR), Dubna, Russia

[76] Korea Institute of Science and Technology Information, Daejeon, Republic of Korea

[77] KTO Karatay University, Konya, Turkey

[78] Laboratoire de Physique des 2 Infinis, Irène Joliot-Curie, Orsay, France

[79] Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3, Grenoble, France

[80] Lawrence Berkeley National Laboratory, Berkeley, California, United States

[81] Lund University Department of Physics, Division of Particle Physics, Lund, Sweden

[82] Nagasaki Institute of Applied Science, Nagasaki, Japan

[83] Nara Women's University (NWU), Nara, Japan

[84] National and Kapodistrian University of Athens, School of Science, Department of Physics , Athens, Greece

[85] National Centre for Nuclear Research, Warsaw, Poland

[86] National Institute of Science Education and Research, Homi Bhabha National Institute, Jatni, India

[87] National Nuclear Research Center, Baku, Azerbaijan

[88] National Research Centre Kurchatov Institute, Moscow, Russia

[89] Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

[90] Nikhef, National institute for subatomic physics, Amsterdam, Netherlands

[91] NRC Kurchatov Institute IHEP, Protvino, Russia

[92] NRC «Kurchatov» Institute - ITEP, Moscow, Russia

[93] NRNU Moscow Engineering Physics Institute, Moscow, Russia

[94] Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom

[95] Nuclear Physics Institute of the Czech Academy of Sciences, Řež u Prahy, Czech Republic

[96] Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States

[97] Ohio State University, Columbus, Ohio, United States

[98] Petersburg Nuclear Physics Institute, Gatchina, Russia

[99] Physics department, Faculty of science, University of Zagreb, Zagreb, Croatia

[100] Physics Department, Panjab University, Chandigarh, India

[101] Physics Department, University of Jammu, Jammu, India

[102] Physics Department, University of Rajasthan, Jaipur, India

[103] Physikalisches Institut, Eberhard-Karls-Universität Tübingen, Tübingen, Germany

[104] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

[105] Physik Department, Technische Universität München, Munich, Germany

[106] Politecnico di Bari, Bari, Italy

[107] Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

[108] Rudjer Bošković Institute, Zagreb, Croatia

[109] Russian Federal Nuclear Center (VNIIEF), Sarov, Russia
[110] Saha Institute of Nuclear Physics, Homi Bhabha National Institute, Kolkata, India
[111] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[112] Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
[113] St. Petersburg State University, St. Petersburg, Russia
[114] Stefan Meyer Institut für Subatomare Physik (SMI), Vienna, Austria
[115] SUBATECH, IMT Atlantique, Université de Nantes, CNRS-IN2P3, Nantes, France
[116] Suranaree University of Technology, Nakhon Ratchasima, Thailand
[117] Technical University of Košice, Košice, Slovakia
[118] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland
[119] The University of Texas at Austin, Austin, Texas, United States
[120] Universidad Autónoma de Sinaloa, Culiacán, Mexico
[121] Universidade de São Paulo (USP), São Paulo, Brazil
[122] Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
[123] Universidade Federal do ABC, Santo Andre, Brazil
[124] University of Cape Town, Cape Town, South Africa
[125] University of Houston, Houston, Texas, United States
[126] University of Jyväskylä, Jyväskylä, Finland
[127] University of Liverpool, Liverpool, United Kingdom
[128] University of Science and Technology of China, Hefei, China
[129] University of South-Eastern Norway, Tonsberg, Norway
[130] University of Tennessee, Knoxville, Tennessee, United States
[131] University of the Witwatersrand, Johannesburg, South Africa
[132] University of Tokyo, Tokyo, Japan
[133] University of Tsukuba, Tsukuba, Japan
[134] Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
[135] Université de Lyon, Université Lyon 1, CNRS/IN2P3, IPN-Lyon, Villeurbanne, Lyon, France
[136] Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France, Strasbourg, France
[137] Université Paris-Saclay Centre d'Etudes de Saclay (CEA), IRFU, Départment de Physique Nucléaire (DPhN), Saclay, France
[138] Università degli Studi di Foggia, Foggia, Italy
[139] Università degli Studi di Pavia, Pavia, Italy
[140] Università di Brescia, Brescia, Italy
[141] Variable Energy Cyclotron Centre, Homi Bhabha National Institute, Kolkata, India
[142] Warsaw University of Technology, Warsaw, Poland
[143] Wayne State University, Detroit, Michigan, United States
[144] Westfälische Wilhelms-Universität Münster, Institut für Kernphysik, Münster, Germany
[145] Wigner Research Centre for Physics, Budapest, Hungary
[146] Yale University, New Haven, Connecticut, United States
[147] Yonsei University, Seoul, Republic of Korea