

Exploring the N-N coupled system with high precision correlation techniques at the LHC

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Exploring the N-N coupled system with high precision correlation techniques at the LHC / Acharya, S., Adamová, D., Adler, A., Adolfsson, J., Aglieri Rinella, G., Agnello, M., Agrawal, N., Ahammed, Z., Ahmad, S., Ahn, S.U., Ahuja, I., Akbar, Z., Akindinov, A., Al-Turany, M., Alam, S.N., Aleksandrov, D., Alessandro, B., Alfanda, H.M., Alfaro Molina, R., Ali, B., et al.. - In: PHYSICS LETTERS. SECTION B. - ISSN 0370-2693. - STAMPA. - 833:(2022), p. 137272. [10.1016/j.physletb.2022.137272]

*Availability:*

This version is available at: 11583/2971895 since: 2022-09-30T08:33:23Z

*Publisher:*

Elsevier

*Published*

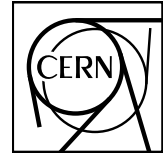
DOI:10.1016/j.physletb.2022.137272

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CERN-EP-2021-51  
30 March 2021

## Exploring the $N\Lambda$ – $N\Sigma$ coupled system with high precision correlation techniques at the LHC

ALICE Collaboration\*

### Abstract

The interaction of  $\Lambda$  and  $\Sigma$  hyperons ( $Y$ ) with nucleons ( $N$ ) is strongly influenced by the coupled-channel dynamics. Due to the small mass difference of the  $N\Lambda$  and  $N\Sigma$  systems, the coupling strength of the  $N\Sigma \leftrightarrow N\Lambda$  processes is non-negligible and constitutes a crucial element in the determination of the  $N\Lambda$  interaction. In this letter we present the most precise measurements on the interaction of  $p\Lambda$  pairs, from zero relative momentum up to the opening of the  $N\Sigma$  channel. The correlation function in the relative momentum space for  $p\Lambda \oplus \bar{p}\bar{\Lambda}$  pairs measured in high-multiplicity triggered  $pp$  collisions at  $\sqrt{s} = 13$  TeV at the LHC is reported. The opening of the inelastic  $N\Sigma$  channels is visible in the extracted correlation function as a cusp-like structure occurring at relative momentum  $k^* = 289$  MeV/ $c$ . This represents the first direct experimental observation of the  $N\Sigma \rightarrow N\Lambda$  coupled channel in the  $p\Lambda$  system. The correlation function is compared with recent chiral effective field theory calculations, based on different strengths of the  $N\Sigma \leftrightarrow N\Lambda$  transition potential. A weaker coupling, as possibly supported by the present measurement, would require a more repulsive three-body  $NN\Lambda$  interaction for a proper description of the  $\Lambda$  in-medium properties, which has implications on the nuclear equation of state and for the presence of hyperons inside neutron stars.

arXiv:2104.04427v1 [nucl-ex] 9 Apr 2021

The proton–Lambda ( $p\Lambda$ ) system is one of the best-known examples in hadron physics where the role of coupled-channel dynamics is crucial for the understanding of the two-body and three-body interaction, both in vacuum and at finite nuclear densities [1–4]. The coupling between the nucleon–Sigma ( $N\Sigma$ ) and  $N\Lambda$  systems arises from these baryon pairs having the same strangeness content and a small mass difference ( $\approx 70 \text{ MeV}/c^2$ ), and it is responsible for the dominant attractive  $p\Lambda$  interaction in the spin-triplet state of coupled-channel potentials [3, 5, 6].

The attractive nature of the interaction between a proton and a  $\Lambda$  was established from measurements of binding energies of light  $\Lambda$ -hypernuclei [7, 8] and scattering experiments at low energies [9–11]. The measured scattering cross sections are characterised by large uncertainties and limited to hyperon momenta above  $p_{\text{lab}} \sim 100 \text{ MeV}/c$ . In the region where the  $\Sigma^+n$  and  $\Sigma^0p$  channels open, which occurs around  $p_{\text{lab}} \approx 638 \text{ MeV}/c$ , the momentum resolution of the existing data is very poor [12, 13]. Thus it remains unclear whether there is any threshold structure in the  $p\Lambda$  cross section due to the coupling to the  $N\Sigma$  system. Experimental observations of a cusp-like structure at the  $N\Sigma$  threshold stem only from studies of the  $p\Lambda$  invariant mass spectrum in strangeness exchange processes such as  $K^-d \rightarrow \pi^-p\Lambda$  [14, 15] and more recently from measurements of the reaction  $pp \rightarrow K^+p\Lambda$  [16, 17].

It has been known for a long time that the strength of the  $N\Sigma \leftrightarrow N\Lambda$  conversion is of particular relevance for the behaviour of  $\Lambda$  hyperons in infinite nuclear matter [18–20]. This has been emphasised again in a recent study of the  $YN$  interaction based on chiral effective field theory ( $\chi$ EFT) [3]. Specifically, this work discussed the interplay between the  $N\Sigma \leftrightarrow N\Lambda$  conversion, the in-medium properties of the  $\Lambda$  and the role played by three-body forces. The abundant data on hypernuclei allowed the determination of the average attraction ( $-30 \text{ MeV}$ ) experienced by a  $\Lambda$  hyperon within symmetric nuclear matter at the nuclear saturation density ( $\rho_0 = 0.16 \text{ fm}^{-3}$ ) [21]. However, the interaction of hyperons, and in particular of the  $\Lambda$ , with the surrounding nucleons at larger baryonic densities ( $\rho > \rho_0$ ) is not known empirically. Pertinent calculations are afflicted by a certain degree of model dependence and the outcome strongly depends on the employed  $N\Lambda$  and  $NNA$  interactions in vacuum. These contributions are also directly correlated to the  $N\Sigma \leftrightarrow N\Lambda$  conversion, as the parameters driving the coupling strength in the theory can be tuned differently while still reproducing, at the same accuracy level, the existing experiments [3]. For example, compared to the original version of the NLO  $\chi$ EFT (NLO13) [2], the revisited version (NLO19) [3] involves a weaker  $N\Sigma \leftrightarrow N\Lambda$  transition potential. However, it still leads to practically identical results for  $N\Lambda$  two-body scattering, but to an enhanced attractive behaviour in the medium. This points to a stronger (and repulsive) three-body force needed within the latter realisation. The interplay between the  $N\Lambda$  and  $NNA$  interaction is relevant to the widely debated presence of  $\Lambda$  hyperons inside the core of neutron stars (NS), i.e. to the so-called hyperon puzzle [21–23]. The puzzle originates from the contraposition between the energetically favored production of hyperons in the interior of NS [24] and the subsequent softening of the corresponding equation of state (EoS). The latter does not support the existence of the heaviest observed NS of up to 2.2 solar masses [25–27]. Applications of the NLO19  $\chi$ EFT potentials in calculations of the EoS [4] demonstrated that a repulsive genuine  $NNA$  interaction causes a large increase in the chemical potential of  $\Lambda$  hyperons inside NS. Thus their appearance is suppressed, giving a more quantitative reference for the solution of the hyperon puzzle. In this context new experimental data of high precision with the aim to provide additional constraints on the  $N\Sigma \leftrightarrow N\Lambda$  dynamics are needed. This will result in a more reliable estimation of contributions from a genuine  $NNA$  interaction and to establish a tighter connection between the  $YN$  two- and three-body forces, and the EoS.

Recent studies of two-particle correlations in  $pp$ ,  $p$ – $\text{Pb}$  and  $\text{Pb}$ – $\text{Pb}$  collisions have been successful in studying the final-state interaction (FSI) and in delivering high precision data on particle pairs which have a very limited accessibility using traditional experimental techniques [28–36]. Most prominently, the multi-strange sector was studied via  $p$ – $\Xi^-$  and  $p$ – $\Omega^-$  correlations [37, 38]. Performing such measurements in small collision systems results in a stronger sensitivity of the experimental correlation to

the coupled-channel dynamics, as recently proven by means of  $\text{p}\text{--}\text{K}^-$  correlations measured by ALICE in pp collisions [32, 39, 40].

In this letter we present the combined measurement of  $\text{p}\Lambda$  and  $\bar{\text{p}}\bar{\Lambda}$  pairs in pp collisions with a high-multiplicity (HM) trigger at  $\sqrt{s} = 13$  TeV [41, 42]. The obtained results represent the most precise measurement of the  $\text{p}\Lambda$  interaction, leading to relevant implications for astrophysical studies. Further, they provide the first experimental evidence for a threshold effect at the opening of the  $\text{N}\Sigma$  ( $\text{p}\Sigma^0$ ,  $\text{n}\Sigma^+$ ) channel in the  $\text{p}\Lambda$  two-body final state. Comparisons with recent  $\chi\text{EFT}$  calculations are presented, along with a different modelling of the interaction for the residual  $\text{p}\Sigma^0$  contributions.

The relevant observable in this analysis is the measured two-particle correlation function  $C(k^*)$ . This is related to an effective particle emission source  $S(r^*)$  and to the wave function  $\Psi(\vec{k}^*, \vec{r}^*)$  of the relative motion of the particle pair, by means of the Koonin-Pratt equation  $C(k^*) = \int S(r^*) |\Psi(\vec{k}^*, \vec{r}^*)|^2 d^3 r^*$  [43], where the relative distance  $r^*$  and relative momentum  $q^* = 2k^*$  between the two particles are evaluated in the pair rest frame. The experimental correlation is defined as  $C(k^*) = \mathcal{N} N_{\text{SE}}(k^*) / N_{\text{ME}}(k^*)$ , where  $N_{\text{SE}}(k^*)$  is the distribution of pairs where both tracks are measured in the same event and  $N_{\text{ME}}(k^*)$  is the reference distribution of uncorrelated pairs sampled from different (mixed) events. The uncorrelated sample in the denominator,  $N_{\text{ME}}(k^*)$ , is obtained by combining particles from one event with particles from a set of other events. The two events are required to have comparable number of charged particles at midrapidity and a similar primary vertex coordinate  $V_z$  along the beam axis ( $z$ ). The normalisation factor  $\mathcal{N}$  is dimensionless and arbitrary, since it will be absorbed by the non-FSI background present in Eq. 2.

The ALICE experiment excels in correlation studies thanks to its good tracking and particle identification (PID) [41, 42]. These capabilities are related to the three subdetectors, the inner tracking system (ITS) [44], the time projection chamber (TPC) [45] and the time-of-flight detector (TOF) [46] that are located in a solenoidal magnet that provides a uniform field of 0.5 T parallel to the beam line. The event trigger is based on the measured amplitude in the V0 detector system, consisting of two arrays of plastic scintillators located at forward ( $2.8 < \eta < 5.1$ ) and backward ( $-3.7 < \eta < -1.7$ ) pseudorapidities [47]. The selected HM events correspond to 0.17% of all events with at least one measured charged particle within  $|\eta| < 1$  ( $\text{INEL} > 0$ ). This condition results in an average of 30 charged particles in the range  $|\eta| < 0.5$  [38]. The reconstructed primary vertex (PV) of the event is required to have a maximal displacement with respect to the nominal interaction point of 10 cm along the beam axis, in order to ensure a uniform acceptance. The innermost silicon detector (SPD, part of ITS) [44] is used to remove pile-up events with multiple primary vertices following the procedure described in [28, 29, 37, 38]. The final number of selected HM events reaches approximately  $10^9$ . Charged particles, such as protons and pions, are directly measured, while the  $\Lambda$  candidates are reconstructed based on the invariant mass of the decay products (protons and pions). The correlation functions obtained for particles ( $\text{p}\Lambda$ ) and anti-particles ( $\bar{\text{p}}\bar{\Lambda}$ ) are identical within uncertainties, thus the final result is presented as their weighted sum  $\text{p}\Lambda \oplus \bar{\text{p}}\bar{\Lambda}$ .

Both the protons and the  $\Lambda$  candidates are reconstructed using the procedure described in [29], while the related systematic uncertainties are evaluated by varying several of the kinematic and topological observables used in the reconstruction process. In the following text, the systematic variations are enclosed in parentheses. The primary protons are selected in the momentum interval  $0.5$  ( $0.4, 0.6$ )  $< p_{\text{T}} < 4.05$  GeV/ $c$  and  $|\eta| < 0.8$  ( $0.77, 0.85$ ). To improve the quality of the tracks a minimum of 80 (70, 90) out of the 159 possible spatial points (hits) inside the TPC are required. The candidates are selected by comparing the measurements in the TPC and TOF detectors to the expected distributions for a proton candidate. The agreement is expressed in terms of the detector resolution  $\sigma$  ( $n_{\sigma}^{\text{PID}}$ ). For protons with  $p_{\text{T}} < 0.75$  GeV/ $c$  the  $n_{\sigma}^{\text{PID}}$  is evaluated only based on the energy loss and track measurements in the TPC, while for  $p_{\text{T}} > 0.75$  GeV/ $c$  a combined TPC and TOF PID selection is applied ( $n_{\sigma}^{\text{PID}} = \sqrt{n_{\sigma, \text{TPC}}^2 + n_{\sigma, \text{TOF}}^2}$ ). The  $n_{\sigma}^{\text{PID}}$  of the accepted candidates is required to be within 3 (2.5, 3.5). To reject non-primary particles the distance of closest approach (DCA) to the PV of the tracks is required to

be less than 0.1 cm in the transverse plane and less than 0.2 cm along the beam axis. The contribution of secondary protons stemming from weak decays, of misidentified candidates, and of protons interacting with the detector material are extracted using Monte Carlo (MC) template fits to the measured distributions of the DCA to the PV [28]. The resulting proton purity is 99.4% with a 82.3% fraction of primaries. The associated uncertainties are negligible.

The  $\Lambda$  candidates are reconstructed via the weak decay  $\Lambda \rightarrow p\pi^-$ . The secondary daughter tracks are subject to similar selection criteria as for the primary protons regarding the  $|\eta|$  and number of hits in the TPC. However, the particle identification criterion is loosened to  $|n_{\sigma}^{\text{PID}}| < 5$  (4). In addition, the daughter tracks are required to have a DCA to the PV of at least 0.05 (0.06) cm. The DCA of the corresponding  $\Lambda$  candidates to the PV has to be below 1.5 (1.2) cm. The cosine of the pointing angle (CPA) between the vector connecting the PV to the decay vertex and the 3-momentum of the  $\Lambda$  candidate is required to be larger than 0.99 (0.995). To reject unphysical secondary vertices, reconstructed with tracks stemming from collisions corresponding to different (bunch) crossings of the beam, the decay tracks are required to possess a hit in one of the SPD or SSD detectors or a matched TOF signal [30]. The final  $\Lambda$  candidates are selected in a 4 MeV/ $c^2$  mass window around the nominal mass [48]. The number of primary and secondary contributions for  $\Lambda$  are extracted similarly as for protons, using the CPA as an observable for the template fits. The average fractions of  $\Lambda$  hyperons produced from primary interactions are 57.6 (52.1, 60.6)% and 19.2 (15.4, 21.9)% originate from the electromagnetic decays of  $\Sigma^0$ . The systematic variations are enclosed in parentheses, where the number of  $\Sigma^0$  particles is related to their ratio to the  $\Lambda$  hyperons, which is fixed to 0.33 (0.27, 0.40). These values are based on predictions from the isospin symmetry, thermal model calculations using the Thermal-FIST package [49] and measurements of production ratios between these two hadrons [50–52]. This ratio is also related to the size of the cusp at the  $\Lambda$  threshold present in the  $p\Lambda$  correlation, as discussed below. Further, each of the weak decays of  $\Xi^-$  and  $\Xi^0$  contributes with 11.6 (13.5)% to the yield of  $\Lambda$  hyperons. The number of secondaries stemming from a  $\Xi$  depends on the  $k^*$  of the  $p\Lambda$  pair and is, by default, averaged over all pairs, while the systematic variation considers the pairs with  $k^*$  below 480 MeV/ $c$  only. The purity of  $\Lambda$  and  $\bar{\Lambda}$  was extracted by fitting, as a function of  $k^*$ , the invariant mass (IM) spectra of candidates selected in the mixed-event sample. The fits were performed in the IM range of 1088 to 1144 MeV/ $c^2$  using a double Gaussian for the signal and a third-order spline for the background. The resulting  $k^*$  dependence is negligible, thus the result was averaged for  $k^* < 480$  MeV/ $c$ , leading to a purity  $P_{\Lambda} = 95.3\%$ . Due to an imperfect fit quality, the systematic variations include a modelling of the signal using the sum of three Gaussians, which leads to an improved  $\chi^2$  of the fit and a purity of 96.3%. The effect of misidentified  $\Lambda$  candidates ( $\tilde{\Lambda}$ ) can be accounted for by the relations

$$C_{\text{exp}}(k^*) = P_{\Lambda}C_{\text{corrected}}(k^*) + (1 - P_{\Lambda})C_{p\tilde{\Lambda}}, \quad (1)$$

$$C_{\text{corrected}}(k^*) = B(k^*) \left[ \lambda_{p\Lambda}C_{p\Lambda}(k^*) + \lambda_{p(\Sigma^0)}C_{p(\Sigma^0)}(k^*) + \lambda_{p(\Xi)}C_{p(\Xi)}(k^*) + \lambda_{\text{ff}} + \lambda_{\tilde{p}\Lambda} \right], \quad (2)$$

where the signal is decomposed into its ingredients, weighted by the corresponding  $\lambda$  parameters and corrected for the non-FSI baseline  $B(k^*)$ . The correlation function, shown in Fig. 1, is corrected by subtracting the contribution  $C_{p\tilde{\Lambda}}$  from the measured  $C_{\text{exp}}(k^*)$ . The former is obtained experimentally by using the sideband technique [31], that pairs the reconstructed protons with misidentified  $\tilde{\Lambda}$  candidates, characterised by a  $p\pi$  invariant mass 3–8 $\sigma$  away from the nominal  $\Lambda$  mass. The resulting corrected correlation function  $C_{\text{corrected}}(k^*)$  consists of an admixture of the genuine  $p\Lambda$  signal  $C_{p\Lambda}(k^*)$ , the residual (feed-down) contributions for which at least one of the particles of the pair stems from weak or electromagnetic decays, and a small fraction of pairs related to misidentified protons  $\tilde{p}$ . The latter is assumed to have a negligible (flat) contribution, thus accounted for by the constant factor  $\lambda_{\tilde{p}\Lambda}$ . In this study only the feed-down from  $\Sigma^0$  and  $\Xi$  ( $\Xi^- \oplus \Xi^0$ ) into  $\Lambda$  is explicitly modelled, as all other contributions are expected to produce an approximately flat correlation signal. The corresponding contributions are denoted by the subindices  $p(\Sigma^0)$ ,  $p(\Xi)$  and flat feed-down (ff). The residual contributions  $C_{p(\Sigma^0)}(k^*)$  and  $C_{p(\Xi)}(k^*)$  are

**Table 1:** Weight parameters of the individual components of the  $p\Lambda$  correlation function. The two last rows correspond to the minimum and maximum value of the  $\lambda$  parameters within the systematic variations.

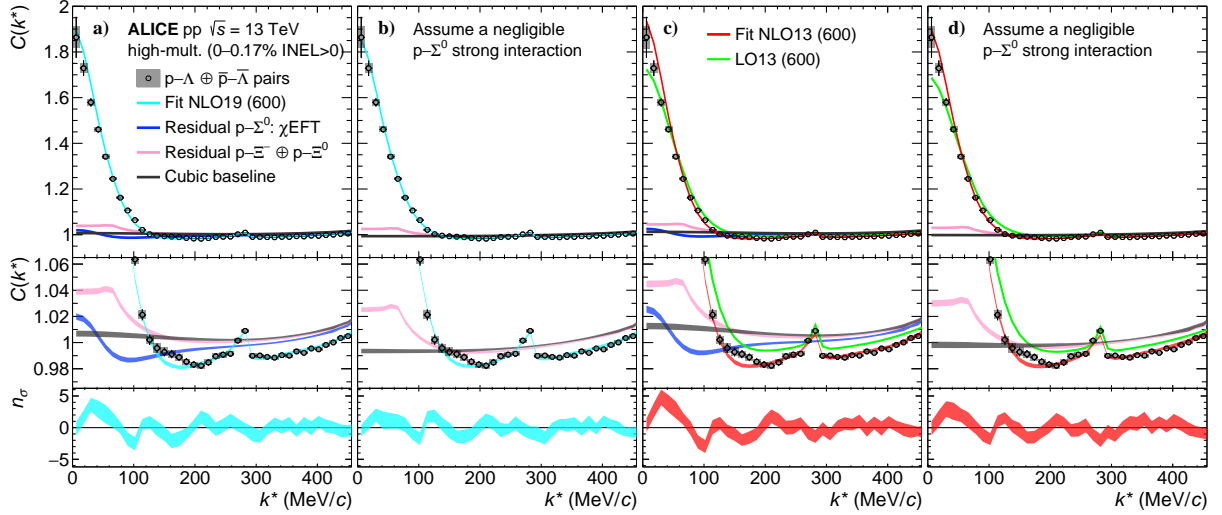
| Pair                                | $p\Lambda$ | $p(\Sigma^0)$ | $p(\Xi)$ | Flat feed-down | $\bar{p}\Lambda$ |
|-------------------------------------|------------|---------------|----------|----------------|------------------|
| $\lambda_{\text{Pair}}$ (%)         | 47.1       | 15.7          | 19.0     | 17.6           | 0.6              |
| $\min\{\lambda_{\text{Pair}}\}$ (%) | 42.7       | 12.6          | –        | –              | –                |
| $\max\{\lambda_{\text{Pair}}\}$ (%) | 49.6       | 18.0          | 22.1     | –              | –                |

obtained by transforming the corresponding genuine correlation functions to the basis of the  $p\Lambda$  interaction, using the formalism described in [53] and [28]. The  $\lambda$  weight factors are the product of single particle purities and fractions, both determined as described above. The resulting values are summarised in Table 1.

Recent correlation studies of the  $p$ – $\Sigma^0$  system showed that the interaction between these two baryons is rather weak [31]. This channel contributes with  $C_{p(\Sigma^0)}(k^*)$  and a weight  $\lambda_{p(\Sigma^0)} = 15.7\%$  to the total  $p\Lambda$  correlation function and is modelled assuming either a flat function or employing results from the same  $\chi$ EFT calculations used for the genuine  $p\Lambda$  interaction [3]. The contribution from the  $p$ – $\Xi$  ( $p$ – $\Xi^- \oplus p$ – $\Xi^0$ ) channel  $C_{p(\Xi)}(k^*)$  ( $\lambda_{p(\Xi)} = 19.0\%$ ) is modelled employing the lattice potentials from the HAL QCD collaboration [54]. They were experimentally validated by comparison with high precision ALICE measurements of  $p\Xi^-$  pairs in  $pp$  and  $p$ – $Pb$  collisions [37, 38].

The non-FSI background (baseline) is parameterised by a third-order polynomial  $B(k^*)$  constrained to be flat at  $k^* \rightarrow 0$  and fitted to the data (Eq. 2). A similar fit, excluding the FSI, was performed on MC simulations based on Pythia 8.2 [55] showing an agreement between the two approaches in the  $k^*$  range up to 200 MeV/ $c$ , with  $B(k^*) \approx \text{const}$ . By default, the fit is performed for  $k^* \in [0, 456]$  MeV/ $c$ , with systematic variations of the upper limit to 432 and 480 MeV/ $c$ . Further, due to the observation of a flat baseline at low  $k^*$ , a systematic cross-check has been performed by assuming the hypothesis of a constant  $B(k^*)$  and fitting the correlation function for  $k^*$  below 336 MeV/ $c$ . The measured correlation function for  $p\Lambda \oplus \bar{p}\bar{\Lambda}$  is shown in Fig. 1. The presented data are unfolded for the detector momentum resolution, which affects the correlation function up to 3% only in the momentum region of  $k^* < 60$  MeV/ $c$ . The theoretical correlation functions in Eq. (2) ( $p\Lambda$ ,  $p$ – $\Xi^-$ ,  $p$ – $\Xi^0$ ,  $p$ – $\Sigma^0$ ) were evaluated using the CATS framework [56]. The size of the emitting source employed in the calculation was fixed from independent studies of proton pairs [29], which demonstrate a common primordial (core) Gaussian source for  $pp$  and  $p\Lambda$  pairs when the contribution of strongly decaying resonances is explicitly accounted for [29]. This source exhibits a pronounced  $m_T$  dependence and considering the average transverse mass  $\langle m_T \rangle = 1.55$  GeV of the measured  $p\Lambda$  pairs a corresponding core source radius of  $r_{\text{core}}(\langle m_T \rangle) = 1.02 \pm 0.04$  fm is obtained. The total source function can be approximated by an effective Gaussian emission source of size 1.23 fm. The upper panels in Fig.1 present the correlation function in the whole  $k^*$  range, while the middle panels show the region where the  $N\Sigma$  channels ( $\Sigma^+n$ ,  $\Sigma^0p$ ) open, clearly visible as a cusp structure occurring at  $k^* = 289$  MeV/ $c$ . This result represents the first direct experimental evidence of the  $N\Sigma \rightarrow N\Lambda$  coupling in a two-body final state. The genuine  $p\Lambda$  correlation function was modelled by two different versions of  $\chi$ EFT hyperon-nucleon potentials (with the default cut-off parameter of 600 MeV). In panels a) and b) of Fig. 1 the comparison with the latest NLO calculation (NLO19) [2, 3] is shown and in panels c) and d) both LO and NLO results of the previous  $\chi$ EFT computation (LO13, NLO13) [1, 2] are presented. The residual  $p$ – $\Sigma^0$  contribution was modelled according to the  $\chi$ EFT calculations and assuming a flat correlation, corresponding to a weaker  $p\Sigma^0$  interaction than predicted. The deviation between data and prediction, expressed in terms of numbers of standard deviations  $n_\sigma$ , is shown in the bottom panels of Fig.1 and the deviations, evaluated up to  $k^* = 300$  MeV/ $c$ , for the different interaction hypotheses are summarised in Table 2.

The amplitude of the cusp is determined by the properties of the interaction, and further modified by



**Figure 1:** Upper panels:  $p\Lambda$  correlation function (circles) with statistical (vertical bars) and systematic (grey boxes) uncertainties. Middle panels: zoom on the region with the cusp-like signal at  $k^* = 289$  MeV/ $c$  due to the  $N\Sigma \leftrightarrow N\Lambda$  coupling. Lower panels: The deviation between data and predictions, expressed in terms of  $n_\sigma$ . The fit is performed using NLO13 (red) and NLO19 (cyan)  $\chi$ EFT potentials with a cut-off parameter of 600 MeV [2, 3] and using a cubic baseline (dark grey). The residual  $p-\Xi^- \oplus p-\Xi^0$  (pink) and  $p-\Sigma^0$  (royal blue) correlations are modelled using, respectively, a lattice potential from the HAL QCD collaboration [37,54] and a  $\chi$ EFT potential [2]. Both contributions are plotted relative to the baseline, while in panels b) and d) the strong interaction of  $p-\Sigma^0$  is neglected.

the relative amount of  $N\Sigma$  and  $p\Lambda$  initial state pairs leading to the final state (measured)  $p\Lambda$  pairs. The amount of initial state pairs was fixed by the above-mentioned  $\Sigma:\Lambda$  ratio, enabling the direct test of the strong interaction. The LO chiral calculation [1], predicting a smaller  $N\Sigma$  cusp with respect to the NLO, was already ruled out from scattering data, and the results shown in Fig. 1 confirm this. The updated NLO19 calculation with a cut-off parameter of 600 MeV gives the best description of the  $p\Lambda$  correlation function, in particular of the cusp, independently of the assumed  $p\Sigma^0$  interaction and of the baseline. The assumption of a constant baseline leads to the same conclusions and similar  $n_\sigma$  values. For both NLO13 and NLO19 the best agreement with the data is achieved at the same cut-off value (550–650 MeV) which also provide the best description of the available scattering and hypertriton data [2, 3]. However, unlike the previously existing experimental data, the present results have the sensitivity to discriminate between the NLO13 and NLO19 version of  $\chi$ EFT, showing a slight preference towards the latter. The best  $n_\sigma = 3.7$  achieved by  $\chi$ EFT suggests that further improvements in the theory are needed. The main discrepancy stems from the slight difference in the slope of the experimental and theoretical correlations at low  $k^*$ . The  $\chi$ EFT NLO19 potential seems to still predict a too large two-body  $p\Lambda$  attraction with respect to the present experimental data. Possibly, an even weaker coupling to  $N\Sigma$  could be needed in order to reduce the disagreement, but it would lead to an overestimation of the  $\Lambda$  single-particle potential in nuclear matter, necessitating an increased three-body repulsion that can be modelled approximately by the theory. In turn, this would disfavour the production of these strange hadrons in neutron stars and result in a stiffer EoS [4]. Nevertheless, the same kinematic region at low  $k^*$  is influenced by the  $p-\Sigma^0$  residual correlation and the compatibility to the data can be improved by assuming a weaker (flat)  $p\Sigma^0$  interaction ( $n_\sigma = 1.6$ ). At present the  $p\Lambda$  and  $p-\Sigma^0$  signals cannot be disentangled in a model independent way due to the insufficient precision of the direct  $p-\Sigma^0$  measurement [31]. The situation will improve in the upcoming LHC Run 3 due to the expected increase in statistics [57].

In conclusion, two-particle correlation techniques were used to study the final state interaction in the  $N\Sigma \leftrightarrow N\Lambda$  coupled system. This was achieved by studying the  $p\Lambda$  correlation function at low relative

**Table 2:** The deviation, expressed in terms of  $n_\sigma$ , between data and prediction for the different interaction hypotheses of  $p$ - $\Lambda$  and  $p$ - $\Sigma^0$ , evaluated for  $k^* \in [0, 300]$  MeV/ $c$ . The default values correspond to the fit with a cubic baseline and the values in parentheses represent the results using a constant baseline. The default interaction (in bold) is the  $\chi$ EFT NLO19 calculation [3], at a cut-off parameter of 600 MeV. Each row corresponds to a different variation of the  $\chi$ EFT used for the  $p\Lambda$  correlation, while the columns discriminate between the two assumptions on the  $p$ - $\Sigma^0$  correlation.

| $p$ - $\Sigma^0$ ( $\leftrightarrow$ )<br>$p$ - $\Lambda$ ( $\downarrow$ ) | Standard deviation ( $n_\sigma$ ) |                |
|--|-----------------------------------|----------------|
|  | $\chi$ EFT                        | Negligible FSI |
| LO13-600   | 5.6 (7.5)                         | 10.2 (10.3)    |
| NLO13-500  | 7.3 (10.3)                        | 4.5 (5.3)      |
| NLO13-550  | 4.4 (6.5)                         | 2.1 (2.2)      |
| NLO13-600  | 5.8 (5.8)                         | 3.3 (3.6)      |
| NLO13-650  | 5.5 (5.5)                         | 4.2 (5.0)      |
| NLO19-500  | 5.6 (7.2)                         | 3.0 (3.0)      |
| NLO19-550  | 4.5 (4.3)                         | 1.8 (2.2)      |
| <b>NLO19-600</b>   | 3.7 (3.9)                         | 1.6 (3.0)      |
| NLO19-650  | 3.7 (3.7)                         | 2.3 (4.1)      |

momenta with an unprecedented precision. The significance of the coupling of  $p\Lambda$  to  $N\Sigma$  is manifested as a cusp-like enhancement present at the corresponding threshold energy, which is the first direct experimental observation of this structure. Further, using different modellings for the  $p$ - $\Sigma^0$  feed-down leads to a statistically significant modification of the measured  $p\Lambda$  correlation, implying an indirect sensitivity to the genuine  $p$ - $\Sigma^0$  correlation in convolution with the direct  $p\Lambda$  signal. The final results, presented in Table 2, exhibit a slightly better compatibility with the updated version of  $\chi$ EFT (NLO19), compared to the NLO13 prediction. The former involves a weaker  $N\Sigma \leftrightarrow N\Lambda$  transition potential and a more attractive two-body interaction of the  $\Lambda$  hyperon in the medium. The latter requires a stronger repulsive  $NNA$  three-body force, in order to achieve a stiffening of the EoS at large densities [4]. The large value of the best  $n_\sigma = 3.7$  indicates that the presented ALICE data increase the constraining power on the  $p\Lambda$  interaction and provide an opportunity to improve the existing theoretical calculations for the  $N\Sigma \leftrightarrow N\Lambda$  coupled system. The existing constraints from hypernuclei data relate the problem to the  $\Lambda$  properties in the dense medium.

## Acknowledgements

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 Atomic Energy Agency (TAEK), Turkey; National Academy of Sciences of Ukraine, Ukraine; Science and Technology Facilities Council (STFC), United Kingdom; National Science Foundation of the United States of America (NSF) and United States Department of Energy, Office of Nuclear Physics (DOE NP), United States of America.

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## A The ALICE Collaboration

S. Acharya<sup>143</sup>, D. Adamová<sup>98</sup>, A. Adler<sup>76</sup>, J. Adolfsson<sup>83</sup>, G. Aglieri Rinella<sup>35</sup>, M. Agnello<sup>31</sup>, N. Agrawal<sup>55</sup>, Z. Ahammed<sup>143</sup>, S. Ahmad<sup>16</sup>, S.U. Ahn<sup>78</sup>, I. Ahuja<sup>39</sup>, Z. Akbar<sup>52</sup>, A. Akindinov<sup>95</sup>, M. Al-Turany<sup>110</sup>, D. Aleksandrov<sup>91</sup>, B. Alessandro<sup>60</sup>, H.M. Alfanda<sup>7</sup>, R. Alfaro Molina<sup>73</sup>, B. Ali<sup>16</sup>, Y. Ali<sup>14</sup>, A. Alici<sup>26</sup>, N. Alizadehvandchali<sup>127</sup>, A. Alkin<sup>35</sup>, J. Alme<sup>21</sup>, T. Alt<sup>70</sup>, L. Altenkamper<sup>21</sup>, I. Altsybeev<sup>115</sup>, M.N. Anaam<sup>7</sup>, C. Andrei<sup>49</sup>, D. Andreou<sup>93</sup>, A. Andronic<sup>146</sup>, M. Angeletti<sup>35</sup>, V. Anguelov<sup>107</sup>, F. Antinori<sup>58</sup>, P. Antonioli<sup>55</sup>, C. Anuj<sup>16</sup>, N. Apadula<sup>82</sup>, L. Aphecetche<sup>117</sup>, H. Appelshäuser<sup>70</sup>, S. Arcelli<sup>26</sup>, R. Arnaldi<sup>60</sup>, I.C. Arsene<sup>20</sup>, M. Arslandok<sup>148,107</sup>, A. Augustinus<sup>35</sup>, R. Averbeck<sup>110</sup>, S. Aziz<sup>80</sup>, M.D. Azmi<sup>16</sup>, A. Badalà<sup>57</sup>, Y.W. Baek<sup>42</sup>, X. Bai<sup>110</sup>, R. Bailhache<sup>70</sup>, Y. Bailung<sup>51</sup>, R. Bala<sup>104</sup>, A. Balbino<sup>31</sup>, A. Baldisseri<sup>140</sup>, M. Ball<sup>44</sup>, D. Banerjee<sup>4</sup>, R. Barbera<sup>27</sup>, L. Barioglio<sup>108,25</sup>, M. Barlou<sup>87</sup>, G.G. Barnaföldi<sup>147</sup>, L.S. Barnby<sup>97</sup>, V. Barret<sup>137</sup>, C. Bartels<sup>130</sup>, K. Barth<sup>35</sup>, E. Bartsch<sup>70</sup>, F. Baruffaldi<sup>28</sup>, N. Bastid<sup>137</sup>, S. Basu<sup>83,145</sup>, G. Batigne<sup>117</sup>, B. Batyunya<sup>77</sup>, D. Bauri<sup>50</sup>, J.L. Bazo Alba<sup>114</sup>, I.G. Bearden<sup>92</sup>, C. Beattie<sup>148</sup>, I. Belikov<sup>139</sup>, A.D.C. Bell Hechavarria<sup>146</sup>, F. Bellini<sup>26,35</sup>, R. Bellwied<sup>127</sup>, S. Belokurova<sup>115</sup>, V. Belyaev<sup>96</sup>, G. Bencedi<sup>71</sup>, S. Beole<sup>25</sup>, A. Bercuci<sup>49</sup>, Y. Berdnikov<sup>101</sup>, A. Berdnikova<sup>107</sup>, D. Berenyi<sup>147</sup>, L. Bergmann<sup>107</sup>, M.G. Besoiu<sup>69</sup>, L. Betev<sup>35</sup>, P.P. Bhaduri<sup>143</sup>, A. Bhasin<sup>104</sup>, I.R. Bhat<sup>104</sup>, M.A. Bhat<sup>4</sup>, B. Bhattacharjee<sup>43</sup>, P. Bhattacharya<sup>23</sup>, L. Bianchi<sup>25</sup>, N. Bianchi<sup>53</sup>, J. Bielčik<sup>38</sup>, J. Bielčiková<sup>98</sup>, J. Biernat<sup>120</sup>, A. Bilandžić<sup>108</sup>, G. Biro<sup>147</sup>, S. Biswas<sup>4</sup>, J.T. Blair<sup>121</sup>, D. Blau<sup>91</sup>, M.B. Blidaru<sup>110</sup>, C. Blume<sup>70</sup>, G. Boca<sup>29</sup>, F. Bock<sup>99</sup>, A. Bogdanov<sup>96</sup>, S. Boi<sup>23</sup>, J. Bok<sup>62</sup>, L. Boldizsár<sup>147</sup>, A. 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F. Ronchetti<sup>53</sup>, A. Rosano<sup>33,57</sup>, E.D. Rosas<sup>71</sup>, A. Rossi<sup>58</sup>, A. Rotondi<sup>29</sup>, A. Roy<sup>51</sup>, P. Roy<sup>112</sup>, S. Roy<sup>50</sup>, N. Rubini<sup>26</sup>, O.V. Rueda<sup>83</sup>, R. Rui<sup>24</sup>, B. Rumyantsev<sup>77</sup>, A. Rustamov<sup>90</sup>, E. Ryabinkin<sup>91</sup>, Y. Ryabov<sup>101</sup>, A. Rybicki<sup>120</sup>, H. Rytkonen<sup>128</sup>, W. Rzesza<sup>144</sup>, O.A.M. Saarimaki<sup>45</sup>, R. Sadek<sup>117</sup>, S. Sadovsky<sup>94</sup>, J. Saetre<sup>21</sup>, K. Šafařík<sup>38</sup>, S.K. Saha<sup>143</sup>, S. Saha<sup>89</sup>, B. Sahoo<sup>50</sup>, P. Sahoo<sup>50</sup>, R. Sahoo<sup>51</sup>, S. Sahoo<sup>67</sup>, D. Sahu<sup>51</sup>, P.K. Sahu<sup>67</sup>, J. Saini<sup>143</sup>, S. Sakai<sup>136</sup>, S. Sambyal<sup>104</sup>, V. Samsonov<sup>101,96,i</sup>, D. Sarkar<sup>145</sup>, N. Sarkar<sup>143</sup>, P. Sarma<sup>43</sup>, V.M. Sarti<sup>108</sup>, M.H.P. Sas<sup>148</sup>, J. Schambach<sup>99,121</sup>, H.S. Scheid<sup>70</sup>, C. Schiaua<sup>49</sup>, R. Schicker<sup>107</sup>, A. Schmah<sup>107</sup>, C. Schmidt<sup>110</sup>, H.R. Schmidt<sup>106</sup>, M.O. Schmidt<sup>107</sup>, M. Schmidt<sup>106</sup>, N.V. Schmidt<sup>99,70</sup>, A.R. Schmier<sup>133</sup>, R. Schotter<sup>139</sup>, J. Schukraft<sup>35</sup>, Y. Schutz<sup>139</sup>, K. Schwarz<sup>110</sup>, K. Schweda<sup>110</sup>, G. Scioli<sup>26</sup>, E. Scomparin<sup>60</sup>, J.E. Seger<sup>15</sup>, Y. Sekiguchi<sup>135</sup>, D. Sekihata<sup>135</sup>, I. Selyuzhenkov<sup>110,96</sup>, S. Senyukov<sup>139</sup>, J.J. Seo<sup>62</sup>, D. Serebryakov<sup>65</sup>, L. Šerkšnytė<sup>108</sup>, A. Sevcenco<sup>69</sup>, T.J. Shaba<sup>74</sup>, A. Shabanov<sup>65</sup>, A. Shabetai<sup>117</sup>, R. Shahoyan<sup>35</sup>, W. Shaikh<sup>112</sup>, A. Shangaraev<sup>94</sup>, A. Sharma<sup>103</sup>, H. Sharma<sup>120</sup>, M. Sharma<sup>104</sup>, N. Sharma<sup>103</sup>, S. Sharma<sup>104</sup>, O. Sheibani<sup>127</sup>, K. Shigaki<sup>47</sup>, M. Shimomura<sup>86</sup>, S. Shirinkin<sup>95</sup>, Q. Shou<sup>41</sup>, Y. Sibiraki<sup>91</sup>, S. Siddhanta<sup>56</sup>, T. Siemiarczuk<sup>88</sup>, T.F. Silva<sup>123</sup>, D. Silvermyr<sup>83</sup>, G. Simonetti<sup>35</sup>, B. Singh<sup>108</sup>, R. Singh<sup>89</sup>, R. Singh<sup>104</sup>, R. Singh<sup>51</sup>, V.K. Singh<sup>143</sup>, V. Singhal<sup>143</sup>, T. Sinha<sup>112</sup>, B. Sitar<sup>13</sup>, M. Sitta<sup>32</sup>, T.B. Skaali<sup>20</sup>, G. Skorodumovs<sup>107</sup>, M. Slupecki<sup>45</sup>, N. Smirnov<sup>148</sup>, R.J.M. Snellings<sup>64</sup>, C. Soncco<sup>114</sup>, J. Song<sup>127</sup>, A. Songmoolnak<sup>118</sup>, F. Soramel<sup>28</sup>, S. Sorensen<sup>133</sup>, I. Sputowska<sup>120</sup>, J. Stachel<sup>107</sup>, I. Stan<sup>69</sup>, P.J. Steffanic<sup>133</sup>, S.F. Stiefelmaier<sup>107</sup>, D. Stocco<sup>117</sup>, M.M. Storetvedt<sup>37</sup>, C.P. Stylianidis<sup>93</sup>, A.A.P. Suaide<sup>123</sup>, T. Sugitate<sup>47</sup>, C. Suire<sup>80</sup>, M. Suljic<sup>35</sup>, R. Sultanov<sup>95</sup>, M. Šumbera<sup>98</sup>, V. Sumberia<sup>104</sup>, S. Sumowidagdo<sup>52</sup>, S. Swain<sup>67</sup>, A. Szabo<sup>13</sup>, I. Szarka<sup>13</sup>, U. Tabassam<sup>14</sup>, S.F. Taghavi<sup>108</sup>, G. Taillepied<sup>137</sup>, J. Takahashi<sup>124</sup>, G.J. Tambave<sup>21</sup>, S. Tang<sup>137,7</sup>, Z. Tang<sup>131</sup>, M. Tarhini<sup>117</sup>, M.G. Tarzila<sup>49</sup>, A. Tauro<sup>35</sup>, G. Tejada Muñoz<sup>46</sup>, A. Telesca<sup>35</sup>, L. Terlizzi<sup>25</sup>, C. Terrevoli<sup>127</sup>, G. Tersimonov<sup>3</sup>, S. Thakur<sup>143</sup>, D. Thomas<sup>121</sup>, R. Tieulent<sup>138</sup>, A. Tikhonov<sup>65</sup>, A.R. Timmins<sup>127</sup>, M. Tkacik<sup>119</sup>, A. Toia<sup>70</sup>, N. Topilskaya<sup>65</sup>, M. Toppi<sup>53</sup>, F. Torres-Acosta<sup>19</sup>, S.R. Torres<sup>38</sup>, A. Trifiro<sup>33,57</sup>, S. Tripathy<sup>55,71</sup>, T. Tripathy<sup>50</sup>, S. Trogolo<sup>35,28</sup>, G. Trombetta<sup>34</sup>, V. Trubnikov<sup>3</sup>, W.H. Trzaska<sup>128</sup>, T.P. Trzcinski<sup>144</sup>, B.A. Trzeciak<sup>38</sup>, A. Tumkin<sup>111</sup>, R. Turrisi<sup>58</sup>, T.S. Tveter<sup>20</sup>, K. Ullaland<sup>21</sup>, A. Uras<sup>138</sup>, M. Urioni<sup>142</sup>, G.L. Usai<sup>23</sup>, M. Vala<sup>39</sup>, N. Valle<sup>29</sup>, S. Vallerio<sup>60</sup>, N. van der Kolk<sup>64</sup>, L.V.R. van Doremalen<sup>64</sup>, M. van Leeuwen<sup>93</sup>, P. Vande Vyvre<sup>35</sup>, D. Varga<sup>147</sup>, Z. Varga<sup>147</sup>, M. Varga-Kofarago<sup>147</sup>, A. Vargas<sup>46</sup>, M. Vasileiou<sup>87</sup>, A. Vasiliev<sup>91</sup>, O. Vázquez Doce<sup>108</sup>, V. Vechernin<sup>115</sup>, E. Vercellin<sup>25</sup>, S. Vergara Limón<sup>46</sup>, L. Vermunt<sup>64</sup>, R. Vértesi<sup>147</sup>, M. Verweij<sup>64</sup>, L. Vickovic<sup>36</sup>, Z. Vilakazi<sup>134</sup>, O. Villalobos Baillie<sup>113</sup>, G. Vino<sup>54</sup>, A. Vinogradov<sup>91</sup>, T. Virgili<sup>30</sup>, V. Vislavicius<sup>92</sup>, A. Vodopyanov<sup>77</sup>, B. Volkel<sup>35</sup>, M.A. Völkl<sup>107</sup>, K. Voloshin<sup>95</sup>, S.A. Voloshin<sup>145</sup>, G. Volpe<sup>34</sup>, B. von Haller<sup>35</sup>, I. Vorobyev<sup>108</sup>, D. Voscek<sup>119</sup>, J. Vrláková<sup>39</sup>, B. Wagner<sup>21</sup>, C. Wang<sup>41</sup>, D. Wang<sup>41</sup>, M. Weber<sup>116</sup>, A. Wegrzynek<sup>35</sup>, S.C. Wenzel<sup>35</sup>, J.P. Wessels<sup>146</sup>, J. Wiechula<sup>70</sup>, J. Wikne<sup>20</sup>, G. Wilk<sup>88</sup>, J. Wilkinson<sup>110</sup>, G.A. Willems<sup>146</sup>, E. Willsher<sup>113</sup>, B. Windelband<sup>107</sup>, M. Winn<sup>140</sup>, W.E. Witt<sup>133</sup>, J.R. Wright<sup>121</sup>, W. Wu<sup>41</sup>, Y. Wu<sup>131</sup>, R. Xu<sup>7</sup>, S. Yalcin<sup>79</sup>, Y. Yamaguchi<sup>47</sup>, K. Yamakawa<sup>47</sup>, S. Yang<sup>21</sup>, S. Yano<sup>47,140</sup>, Z. Yin<sup>7</sup>, H. Yokoyama<sup>64</sup>, I.-K. Yoo<sup>17</sup>, J.H. Yoon<sup>62</sup>, S. Yuan<sup>21</sup>, A. Yuncu<sup>107</sup>, V. Zaccolo<sup>24</sup>, A. Zaman<sup>14</sup>, C. Zampolli<sup>35</sup>, H.J.C. Zanoli<sup>64</sup>, N. Zardoshti<sup>35</sup>, A. Zarochentsev<sup>115</sup>, P. Závada<sup>68</sup>, N. Zaviyalov<sup>111</sup>, H. Zbroszczyk<sup>144</sup>, M. Zhalov<sup>101</sup>, S. Zhang<sup>41</sup>, X. Zhang<sup>7</sup>, Y. Zhang<sup>131</sup>, V. Zherebchevskii<sup>115</sup>, Y. Zhi<sup>11</sup>, D. Zhou<sup>7</sup>, Y. Zhou<sup>92</sup>, J. Zhu<sup>7,110</sup>, A. Zichichi<sup>26</sup>, G. Zinovjev<sup>3</sup>, N. Zurlo<sup>142</sup>,

## Affiliation notes

<sup>i</sup> Deceased

<sup>ii</sup> Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Bologna, Italy

<sup>iii</sup> Dipartimento DET del Politecnico di Torino, Turin, Italy

<sup>iv</sup> M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear Physics, Moscow, Russia

<sup>v</sup> Institute of Theoretical Physics, University of Wrocław, Poland

## Collaboration Institutes

<sup>1</sup> A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia

<sup>2</sup> AGH University of Science and Technology, Cracow, Poland

<sup>3</sup> Bogolyubov Institute for Theoretical Physics, National Academy of Sciences of Ukraine, Kiev, Ukraine

<sup>4</sup> Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India

<sup>5</sup> Budker Institute for Nuclear Physics, Novosibirsk, Russia

<sup>6</sup> California Polytechnic State University, San Luis Obispo, California, United States

<sup>7</sup> Central China Normal University, Wuhan, China

- <sup>8</sup> Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba
- <sup>9</sup> Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico
- <sup>10</sup> Chicago State University, Chicago, Illinois, United States
- <sup>11</sup> China Institute of Atomic Energy, Beijing, China
- <sup>12</sup> Chungbuk National University, Cheongju, Republic of Korea
- <sup>13</sup> Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics, Bratislava, Slovakia
- <sup>14</sup> COMSATS University Islamabad, Islamabad, Pakistan
- <sup>15</sup> Creighton University, Omaha, Nebraska, United States
- <sup>16</sup> Department of Physics, Aligarh Muslim University, Aligarh, India
- <sup>17</sup> Department of Physics, Pusan National University, Pusan, Republic of Korea
- <sup>18</sup> Department of Physics, Sejong University, Seoul, Republic of Korea
- <sup>19</sup> Department of Physics, University of California, Berkeley, California, United States
- <sup>20</sup> Department of Physics, University of Oslo, Oslo, Norway
- <sup>21</sup> Department of Physics and Technology, University of Bergen, Bergen, Norway
- <sup>22</sup> Dipartimento di Fisica dell'Università 'La Sapienza' and Sezione INFN, Rome, Italy
- <sup>23</sup> Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy
- <sup>24</sup> Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy
- <sup>25</sup> Dipartimento di Fisica dell'Università and Sezione INFN, Turin, Italy
- <sup>26</sup> Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Bologna, Italy
- <sup>27</sup> Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Catania, Italy
- <sup>28</sup> Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Padova, Italy
- <sup>29</sup> Dipartimento di Fisica e Nucleare e Teorica, Università di Pavia, Pavia, Italy
- <sup>30</sup> Dipartimento di Fisica 'E.R. Caianiello' dell'Università and Gruppo Collegato INFN, Salerno, Italy
- <sup>31</sup> Dipartimento DISAT del Politecnico and Sezione INFN, Turin, Italy
- <sup>32</sup> Dipartimento di Scienze e Innovazione Tecnologica dell'Università del Piemonte Orientale and INFN Sezione di Torino, Alessandria, Italy
- <sup>33</sup> Dipartimento di Scienze MIFT, Università di Messina, Messina, Italy
- <sup>34</sup> Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy
- <sup>35</sup> European Organization for Nuclear Research (CERN), Geneva, Switzerland
- <sup>36</sup> Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, Croatia
- <sup>37</sup> Faculty of Engineering and Science, Western Norway University of Applied Sciences, Bergen, Norway
- <sup>38</sup> Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
- <sup>39</sup> Faculty of Science, P.J. Šafárik University, Košice, Slovakia
- <sup>40</sup> Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
- <sup>41</sup> Fudan University, Shanghai, China
- <sup>42</sup> Gangneung-Wonju National University, Gangneung, Republic of Korea
- <sup>43</sup> Gauhati University, Department of Physics, Guwahati, India
- <sup>44</sup> Helmholtz-Institut für Strahlen- und Kernphysik, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn, Germany
- <sup>45</sup> Helsinki Institute of Physics (HIP), Helsinki, Finland
- <sup>46</sup> High Energy Physics Group, Universidad Autónoma de Puebla, Puebla, Mexico
- <sup>47</sup> Hiroshima University, Hiroshima, Japan
- <sup>48</sup> Hochschule Worms, Zentrum für Technologietransfer und Telekommunikation (ZTT), Worms, Germany
- <sup>49</sup> Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
- <sup>50</sup> Indian Institute of Technology Bombay (IIT), Mumbai, India
- <sup>51</sup> Indian Institute of Technology Indore, Indore, India
- <sup>52</sup> Indonesian Institute of Sciences, Jakarta, Indonesia
- <sup>53</sup> INFN, Laboratori Nazionali di Frascati, Frascati, Italy
- <sup>54</sup> INFN, Sezione di Bari, Bari, Italy
- <sup>55</sup> INFN, Sezione di Bologna, Bologna, Italy
- <sup>56</sup> INFN, Sezione di Cagliari, Cagliari, Italy
- <sup>57</sup> INFN, Sezione di Catania, Catania, Italy
- <sup>58</sup> INFN, Sezione di Padova, Padova, Italy

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

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