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 sizeable coupling strength of the $N\Sigma \leftrightarrow N\Lambda$ processes 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 $N\Sigma \leftrightarrow N\Lambda$ 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.

*See Appendix A for the list of collaboration members
1 Introduction

The proton–Lambda (pΛ) 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 (NΣ) and NA systems arises from these pairs having the same strangeness content and a small mass difference, and it is responsible for the dominant attractive pΛ interaction in the spin-triplet state of coupled-channel potentials [3,5,6].

The attractive nature of the interaction between a proton and a Λ was established from measurements of binding energies of light Λ-hypernuclei [7,8] and scattering experiments at low energies [9–11]. However, the available scattering cross sections are characterised by large uncertainties. Moreover, they are limited to hyperon momenta above $p_{lab} \sim 100$ MeV/c. Thus, a reliable determination of standard quantities like scattering lengths, which provide a simple quantitative measure for the strength of an interaction, is practically impossible. Furthermore, in the region $p_{lab} \approx 640$ MeV/c, where the NΣ+ and pΣ0 channels open, the momentum resolution of the existing data is poor [12,13]. Calculations based on NA-NΣ coupled-channel potentials [2,3,6] predict a narrow but sizeable enhancement of the pΛ cross section in that region which reflects the strength of the channel coupling and also that of the NΣ interaction. However, because of the poor resolution of the mentioned scattering data, the presence of such a structure could not be confirmed. New pΛ data that became available recently [14] cover only energies well above the NΣ threshold. Experimental observations of a cusp-like structure at the NΣ threshold stem only from studies of the pΛ invariant mass (IM) spectrum in strangeness exchange processes such as $K^-d \rightarrow \pi^-p\Lambda$ [15,16] and more recently from measurements of the reaction $pp \rightarrow K^+p\Lambda$ [17,18].

It is known that the strength of the NΣ ↔ NA conversion is relevant for the behaviour of Λ hyperons in infinite nuclear matter [19,21]. This has been emphasised in a recent study of the YN interaction based on chiral effective field theory (χEFT) [3]. Specifically, this work discussed the interplay between the NΣ ↔ NA conversion, the in-medium properties of the Λ and the role played by three-body forces. The abundant data on hypernuclei allowed the determination of the average attraction (∼30 MeV) experienced by a Λ hyperon within symmetric nuclear matter at the nuclear saturation density [22]. However, the interaction of hyperons with the surrounding nucleons at larger baryonic densities is not known empirically. The outcome of pertinent calculations depends on the employed NA and NNA interactions in vacuum. These contributions are directly correlated to the NΣ ↔ NA conversion, as the parameters driving the coupling strength in the theory can be tuned differently while still reproducing the existing experiments [3]. For example, compared to the original version of the next-to-leading order (NLO) χEFT (NLO13) [2], the revisited version (NLO19) [3] involves a weaker NΣ ↔ NA transition potential. However, it leads to practically identical results for NA two-body scattering, but to an enhanced attractive behaviour in the medium. This points to a stronger repulsive three-body force needed within the latter realisation. The interplay between the NA and NNA interaction is relevant to the debated presence of Λ hyperons inside the core of neutron stars (NS) [22,24]. The hyperon puzzle originates from the contraposition between the energetically favoured production of hyperons in the interior of NS [25] 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 [26,28]. Applications of the NLO19 χEFT potentials in calculations of the EoS [4] demonstrated that a repulsive genuine NNA interaction suppresses the appearance of Λ hyperons inside NS, giving a more quantitative reference for the solution of the hyperon puzzle. Thus new experimental data of high precision providing constraints on the NΣ ↔ NA dynamics are needed.

Recent studies of two-particle correlations in pp, p–Pb and Pb–Pb collisions have been successful in studying the final-state interaction (FSI) and in delivering high precision data on particle pairs of limited accessibility using traditional experimental techniques [29,39]. 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 pK– correlations [35, 40, 41]. In this letter we present the combined measurement of pΛ and pΛ̅ pairs in pp collisions with a high-multiplicity (HM) trigger at √s = 13 TeV [42, 43].

2 Data analysis

The relevant observable in this analysis is the two-particle correlation function C(k∗). This is related to an effective particle emission source S(r∗) and to the wave function Ψ(k∗, r∗) of the particle pair, by means of the relation C(k∗) = ∫ S(r∗)|Ψ(k∗, r∗)|2 d3r∗ [44], where the relative distance r∗ and relative momentum q∗ = 2k∗ are evaluated in the pair rest frame. The experimental correlation is defined as

\[
C(k^*) = N \cdot N(k^*) / M(k^*),
\]

where N(k∗) is the distribution of pairs where both reconstructed particles are measured in the same event, M(k∗) is the reference distribution of uncorrelated pairs sampled from different (mixed) events and N is a normalisation factor. The uncorrelated sample in the denominator, M(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 Vc along the beam axis (z).

The ALICE experiment excels in correlation studies thanks to its good tracking and particle identification (PID) [42, 43]. These capabilities are related to the three subdetectors, the inner tracking system (ITS) [45], the time projection chamber (TPC) [46] and the time-of-flight detector (TOF) [47]. 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 < η < 5.1) and backward (−3.7 < η < −1.7) pseudorapidities [48]. The selected HM events correspond to 0.17% of all events with at least one measured charged particle within |η| < 1 (INEL > 0). This condition results in an average of 30 charged particles in the range |η| < 0.5 [34]. Compared to a minimum-bias trigger, HM events provide not only a larger number of particles per event, but an overall higher production rate of particles containing strangeness, such a Λ hyperons [49]. Consequently, the HM sample offers a tenfold increase in the amount of pΛ pairs reconstructed below k∗ of 200 MeV/c, leading to a total of 1.3 million pairs within the same event sample. 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. Pile-up events with multiple primary vertices are removed following the procedure described in [29, 30, 33, 34]. The final number of selected HM events reaches approximately 109. Charged particles, such as protons and pions, are directly measured, while the Λ candidates are reconstructed based on the IM of the decay products. The correlation functions obtained for particles (pΛ) and anti-particles (pΛ̅) are identical within uncertainties, thus the final result is presented as their weighted sum pΛ + pΛ̅.

Both the protons and the Λ candidates are reconstructed using the procedure described in [30], while the related systematic uncertainties are evaluated by varying the kinematic and topological observables used in the reconstruction. For the purpose of correlation studies it is essential to differentiate between primary particles, which participate in the FSI, and secondary (feed-down) particles, which stem from weak or electromagnetic decays. Experimentally, the former can be selected by demanding the particle candidates to be close to the PV of the event, while the latter have to be associated with a secondary vertex within the event. In the following text, the systematic variations are enclosed in parentheses. The primary proton candidates are selected in the momentum interval 0.5 (0.4, 0.6) < pT < 4.05 GeV/c and |η| < 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 σ(pT, PD). For protons with pT < 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 \( p_T > 0.75 \text{ GeV}/c \) 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. Nevertheless, due to the limited resolution of the reconstruction, the selected primary proton candidates will contain certain amount of secondaries, stemming from weak decays, and misidentifications. These contributions are extracted using Monte Carlo (MC) template fits to the measured distributions of the DCA to the PV \([29]\). The resulting proton purity is 99.4\% with a 82.3\% fraction of primaries.

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. 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 three-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 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 \([31]\). The final \( \Lambda \) candidates are selected in a 4 MeV/c^2 mass window around the nominal mass \([50]\), where the width of the IM peak is c.a. 1.6 MeV/c^2. 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 fraction of primary \( \Lambda \) hyperons is 57.6 (52.1, 60.6)\% and 19.2 (15.4, 21.9)\% originate from the electromagnetic decays of \( \Sigma^0 \).

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 \([51]\) and measurements of the corresponding production ratios \([52][54]\). Further, each of the weak decays of \( \Sigma^- \) and \( \Sigma^0 \) contributes with 11.6 (13.5)\% to the yield of \( \Lambda \) hyperons. The purity of \( \Lambda \) and \( \bar{\Lambda} \) was extracted by fitting, as a function of \( k^* \), the 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 result was averaged for \( k^* < 480 \text{ MeV}/c \), leading to a purity \( P_\Lambda = 95.3\% \). The systematic variations include a modelling of the signal using the sum of three Gaussians, leading to a purity of 96.3\%. The effect of misidentified \( \Lambda \) candidates (\( \tilde{\Lambda} \)) can be accounted for by the relations

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

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

where the signal is decomposed into its ingredients, weighted by the corresponding \( \lambda \) parameters and corrected for the non-FSI baseline \( B(k^*) \).

Such a decomposition is required \([29]\), as the experimental signal contains correlations complementing the genuine \( p\Lambda \) signal \( C_{p\Lambda}(k^*) \). In the present analysis the contribution \( C_{p\Lambda} \) related to misidentified \( \Lambda \) candidates (\( \tilde{\Lambda} \)) is explicitly measured and subtracted from the total correlation \( C_{\exp}(k^*) \). This is achieved by performing a sideband analysis \([32]\), which relies on purposefully selecting \( \Lambda \) candidates incompatible with the true \( \Lambda \) mass by more than 5\( \sigma \).

The corrected correlation \( C_{\text{corrected}}(k^*) \) has an effective \( \Lambda \) purity of 100\%, and the remaining contributions (Eq. \([3]\)) are the genuine signal of interest \( C_{p\Lambda}(k^*) \), the residual (feed-down) correlation \( C_{p(\Sigma^0)} \) of \( \Lambda \) particles originating from the decay of a \( \Sigma^0 \), the residual signal \( C_{p(\Xi)} \) related to \( \Xi^- (\Sigma^- \mp \Xi^0) \) decaying into \( \Lambda \), other sub-dominant (flat) sources of feed-down correlations \( C_{ff} \approx 1 \), and contamination \( C_{p\Lambda} \) stemming from misidentified protons. Each of these contributions is weighted by a statistical factor \( \lambda \), evaluated as the product of the purities and fractions (primary or secondary) of the set particles \([29]\). These weight factors
are summarised in Table 1. The contribution \( C_{\bar{p}A} \) cannot be modelled, however the associated \( \lambda_{\bar{p}A} \) is only 0.6%, justifying the assumption \( \lambda_{\bar{p}A} C_{\bar{p}A} \approx \lambda_{\bar{p}A} \) within the uncertainties of \( C_{\text{corrected}}(k^*) \). By contrast, the residual correlations \( C_{p(\Sigma^0)} \) and \( C_{p(\Xi^0)} \) are significant, but in these cases their interactions with protons can be described by theory. Recent correlation studies of the \( p\Sigma^0 \) system showed that this interaction is rather weak [32]. This channel is modelled assuming either a flat function or employing the same \( \chi^2 \)EFT calculations used for the genuine \( p\Lambda \) interaction [3]. The contribution from the \( p\Xi^- (p\Xi^- \oplus p\Xi^0) \) channel is modelled employing the lattice potentials from the HAL QCD collaboration [55]. They were experimentally validated by comparison with precision measurements of \( p\Xi^- \) correlations [33, 34]. The residual contributions \( C_{p(\Sigma^0)}(k^*) \) and \( C_{p(\Xi^0)}(k^*) \) are obtained by transforming the corresponding genuine correlation functions to the basis of the \( p\Xi^- \) interaction, using the formalism described in [29] and [56] applied to the phase space of the measured pairs.

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. 3). 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 expectation 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 correlation function (Eq. 3) is given as a function of the measured \( k^* \), which is not identical to the true relative momentum of the pair due to the effects of momentum resolution. Thus, to compare the experimental results with theoretical predictions an unfolding of the data is required. Both the same- and mixed-event samples \( \langle N(k^*), M(k^*) \rangle \) are biased by the resolution of the detector. They relate to their true underlying distributions by

\[
N(k^*) = \int_0^\infty T(k^*, k^*_\text{true})N_{\text{true}}(k^*_\text{true})dk^*_\text{true}
\]

(4)

and

\[
M(k^*) = \int_0^\infty T(k^*, k^*_\text{true})M_{\text{true}}(k^*_\text{true})dk^*_\text{true},
\]

(5)

where \( T(k^*, k^*_\text{true}) \) is the detector response matrix. The latter is a two-dimensional matrix corresponding to the probability of having a true value \( k^*_\text{true} \) given a measured \( k^* \). By using a full scale simulation of the detector, involving Pythia 8 [57] as an event generator and Geant3 [58] to model the detector response, the matrix \( T(k^*, k^*_\text{true}) \) has been determined. The resulting spread in the distribution of \( k^* \) for a fixed \( k^*_\text{true} \) is, on average, 4.2 MeV/c. Using \( N_{\text{true}}(k^*_\text{true}) = M_{\text{true}}(k^*_\text{true})C(k^*_\text{true}) \) and defining \( W(k^*, k^*_\text{true}) = T(k^*, k^*_\text{true})M_{\text{true}}(k^*_\text{true})/M(k^*) \), Eq. 1 becomes equivalent to

\[
C_{\exp}(k^*) = N \int_0^\infty W(k^*, k^*_\text{true})C_{\text{true}}(k^*_\text{true})dk^*_\text{true},
\]

(6)

In the present analysis the unfolding is performed as a two-step process, first obtaining \( M_{\text{true}}(k^*) \) from Eq. 5 second using Eq. 6 to obtain \( C_{\text{true}}(k^*) \). Each step is performed by using a cubic spline to parameterise the true functions, which are fitted to their measured counterparts. The splines are defined for \( k^* < 1000 \) MeV/c, using a total of 32 knots. The quality of the procedure is validated by transforming the unfolded functions backwards using Eq. 5 and Eq. 6 which ideally should restore the input distributions (\( \chi^2 = 0 \)). In case the resulting \( \chi^2 \) per data point is larger than 0.2, the value of each \( C_{\text{true}}(k^*) \) bin is
perturbed using a bootstrap procedure \cite{59}, until a better \( \chi^2 \) is achieved. This is iteratively repeated until obtaining the desired precision, and until no single bin deviates by more than half of their uncertainty.

3 Results and discussion

The corrected and unfolded experimental correlation function for \( p\Lambda \oplus \bar{p}\bar{\Lambda} \) is shown in Figs. 1 and 2. The correlation function is measured with high-precision in the low momentum region down to \( k^* = 6 \text{ MeV}/c \), in contrast to existing \( p\Lambda \) scattering data which cover the region \( k^* > 60 \text{ MeV}/c \). The precision achieved for \( k^* < 110 \text{ MeV}/c \) is better than 1\%, which corresponds to an improvement of factor up to 25 compared to previous scattering data \cite{9,11}. The theoretical correlation functions in Eq. 3 were evaluated using the CATS framework \cite{60}. The size of the emitting source employed in the calculation was fixed compared to previous scattering data \cite{9–11}. The genuine \( p\Lambda \) correlation data \cite{2,3}. The size of the emission source employed in the calculation was fixed from independent studies of proton pairs \cite{30}, 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 \cite{30}. This source exhibits a pronounced \( m_T \) dependence and considering the average transverse mass \( \langle m_T \rangle = 1.55 \text{ GeV} \) of the measured \( p\Lambda \) pairs a corresponding core source radius of \( r_{\text{core}}(\langle m_T \rangle) = 1.02 \pm 0.04 \text{ fm} \) is obtained. The total source function can be approximated by an effective Gaussian emission source of size 1.23 fm. The genuine \( p\Lambda \) correlation function is modelled by \( \chi^EFT \) hyperon-nucleon potentials, considering the leading-order (LO) interaction \cite{1} and two NLO versions (NLO13 \cite{2} and NLO19 \cite{3}). For the NLO interactions the variation with the underlying cut-off parameter (cf. Ref. \cite{2}) is explored, while \( \Lambda = 600 \text{ MeV} \) is chosen as a default value. Both NLO versions provide an excellent description of the available scattering data, having a \( \chi^2 \approx 16 \) for the considered 36 data points \cite{3}.

Figures 1 and 2 show the total fit functions (red and cyan) to the present data. The non-FSI baseline \( B(k^*) \) is depicted as a dark grey line, while the individual contributions related to feed-down from \( F = \{ \Sigma^0, \Xi^0 \} \) are drawn as royal blue and pink lines, corresponding to \( B(k^*) \left[ \lambda_{p(F)}C_{p(F)}(k^*) + 1 - \lambda_{\bar{p}(F)} \right] \). The latter relation is derived by setting all \( C_i \) terms within Eq. 3 apart from \( C_{p(F)} \), equal to unity. The upper panels in Figs. 1 and 2 present the correlation function in the whole \( k^* \) range, while the middle panels show the region where the \( \Sigma \) channels open, clearly visible as a cusp structure occurring at \( k^* = 289 \text{ MeV}/c \). The deviation between data and prediction, expressed in terms of number of standard deviations \( n_{\sigma} \), is shown in the bottom panels. The discrepancy between theory and data is largest in the momentum region \( k^* < 110 \text{ MeV}/c \), while, due to the presence of the \( \Sigma \) cusp, the sensitivity of the correlation function to the properties of the strong interaction extends up to 300 MeV/c. The deviations for the interaction hypotheses are summarised in Table 2 where the left two columns show the \( n_{\sigma} \) only in the low momentum region, and the right two columns represent the deviation evaluated for \( k^* \in [0, 300] \text{ MeV}/c \).

The presented results are the first direct experimental evidence of the \( \Sigma \leftrightarrow \Lambda \) coupling in a two-body final state. The signal of the cusp is determined by the properties of the interaction, and further modified by the relative amount of \( \Sigma \) 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 a direct test of the strong interaction. The LO chiral potential \cite{1} predicts a too small \( \Sigma \) cusp with respect to the measurement, the green line in Fig. 1 while both NLO interactions provide a satisfactory description of the cusp structure. On the other hand, in the momentum region below 110 MeV/c there is a tension between the data and the theory predictions for all considered interactions. In particular, the results for the two NLO potentials are not that well in line with the measured correlation function, despite of the fact that these interactions reproduce the low-energy \( p\Lambda \) scattering data perfectly \cite{3}. The best result is provided by the NLO19 potential with \( \Lambda = 600–650 \text{ MeV} \), though the deviation of \( n_{\sigma} = 3.2 \) from the experiment is substantial. For NLO13 this deviation is even larger and amounts to \( n_{\sigma} = 4.2 \). Further, it is observed that for NLO13 and NLO19 the best agreement with the data is achieved within the same range of cut-off values (550–650 MeV) which also provide the best description of the available scattering and hypertriton data \cite{2,3}.
The discrepancy between the data and χEFT at low momenta could be an indication for a weaker genuine pΛ interaction, but it could also signal that the pΣ\(^0\) correlation is very small. As visible in the right panels of Figs. 1,2 and Table 2 adopting the hypothesis of a negligible pΣ\(^0\) correlation leads to a better agreement with the present pΛ data (n\(_\sigma\) = 2.2). At the moment it is impossible to differentiate between these two cases because the existing direct measurement of the pΣ\(^0\) channel is not precise enough for drawing pertinent conclusions [32]. The pΣ\(^0\) measurement is compatible with both the NLO predictions (of a weakly attractive pΣ\(^0\) interaction) and with a flat correlation (negligible pΣ\(^0\) interaction). A precision measurement of the genuine pΣ\(^0\) channel, expected to be achieved in the upcoming LHC Run 3 [61], should provide clarification. Then the actual strength of the NA interaction can be pinned down in a model independent way by a dedicated theoretical analysis of the pΛ data.

All the conclusions of the present analysis remain the same under the alternative hypothesis of a constant baseline, or in case the deviation is evaluated for k\(^*\) < 300 MeV/c. Within that momentum region, the NLO19 provides a satisfactory description of the data, with a deviation of n\(_\sigma\) = 2.8, while the NLO13 still results in a larger discrepancy (n\(_\sigma\) = 3.6).
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Figure 2: Similar representation as in Fig. [1] where the pΛ interaction is modelled using NLO19 (cyan) $\chi$EFT potentials with cut-off $\Lambda = 600$ MeV [2][3]. This leads to an improved description of the low momentum region. The reduced $\chi^2$, for $k^* < 300$ MeV/c, equals 2.0 in case the pΣ⁰ is modelled by $\chi$EFT (panel a) and 1.8 in case the pΣ⁰ final state interaction is ignored (panel b).

4 Summary

In conclusion, two-particle correlation techniques were used to study the final state interaction in the NΣ ↔ NA coupled system. This was achieved by studying the pΛ correlation function at low relative momenta with an unprecedented precision. The significance of the coupling of pΛ to NΣ 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 modelings for the pΣ⁰ feed-down leads to a statistically significant modification of the measured pΛ correlation, implying an indirect sensitivity to the genuine pΣ⁰ correlation. In the momentum range $k^* \in [110, 300]$ MeV/c all of the tested NLO $\chi$EFT interactions are compatible with the data, however a significant deviation is present at lower values. The detailed analysis, presented in Table[2] reveals a deviation of at least $n_\sigma = 3.2$, for $k^* < 110$ MeV/c, for the considered $\chi$EFT interactions. The result for NLO19 exhibits an overall better compatibility, compared to the NLO13 prediction. The former involves a weaker NΣ ↔ NA transition potential and a more attractive two-body interaction of the Λ hyperon in the medium. This requires a stronger repulsive NNA three-body force, which leads to a stiffening of the EoS at large densities [4] and a disfavoured production of these strange hadrons in neutron stars. The presented data provide an opportunity to improve the theoretical calculations for the NΣ ↔ NA coupled system, including the low-energy properties of NA. The successful use of correlation techniques in the two-body sector can be extended to measure directly the three-body correlations [62]. The increased amount of statistics during the third running period of the LHC [61] will allow for such measurements.
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 $k^* \in [0, 110] \text{ MeV/c}$ (first two columns) and $k^* \in [0, 300] \text{ MeV/c}$ (last two columns). 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 $\chi_{\text{EFT}}$ NLO19 potential with cut-off $\Lambda = 600 \text{ MeV}$ \cite{3}. Each row corresponds to a different variant of the $\chi_{\text{EFT}}$ interaction used for evaluating the $p\Lambda$ correlation. The first and third column correspond to the case of modelling the $p\Sigma^0$ using $\chi_{\text{EFT}}$, while the second and fourth column represent the case of negligible $p\Sigma^0$ final state interaction.

| $p\Sigma^0 \rightarrow p\Lambda$ | Standard deviation ($n_\sigma$) | $k^* \in [0, 110] \text{ MeV/c}$ | $k^* \in [0, 300] \text{ MeV/c}$ |
|-------------------------------|---------------------------------|---------------------------------|---------------------------------|
|                               | $\chi_{\text{EFT}}$ Negligible $p\Sigma^0$ FSI | $\chi_{\text{EFT}}$ Negligible $p\Sigma^0$ FSI |
| LO-600                        | 4.7 (4.9)                        | 7.2 (8.7)                        | 10.3 (10.3)                     |
| NLO13-500                     | 5.9 (8.0)                        | 6.6 (10.3)                       | 4.9 (7.6)                       |
| NLO13-550                     | 4.5 (5.8)                        | 4.1 (7.2)                        | 2.8 (3.4)                       |
| NLO13-600                     | 5.5 (5.3)                        | 3.9 (5.1)                        | 2.9 (3.0)                       |
| NLO19-500                     | 4.3 (5.7)                        | 3.6 (4.1)                        | 2.8 (3.3)                       |
| NLO19-550                     | 3.6 (5.2)                        | 4.4 (7.6)                        | 3.4 (4.3)                       |
| NLO19-600                     | 3.2 (3.6)                        | 3.0 (4.4)                        | 2.2 (2.7)                       |
| NLO19-650                     | 3.2 (3.2)                        | 2.8 (3.2)                        | 2.7 (3.5)                       |

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Exploring the NA–N̅S system with high precision correlation techniques

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F. Ronchetti1, A. Rosani2, E.D. Rosa3, A. Ross4, A. Rotondo1, A. Roy5, P. Roj6, S. Ros7, N. Rubin8, O.V. Rueda9, R. Rui3, B. Runyan10, A. Rusanov11, E. Ryabinkin12, Y. Ryabov12, A. Rybicki13, H. Rytkonen14, W. Rzesiū15, O.A.M. Saarimäki16, R. Sadel17, S. Sadovsky12, J. Saetre18, K. Šafář19, S.K. Sahai20, S. Sahai19, B. Sahod21, P. Saho22, R. Sahod21, S. Sahod21, D. Sahod21, P.K. Sahai23, J. Sain24, S. Sakali25, N. Samborsky26, V. Samsonov27, D. Sarkar28, N. Sarkar28, P. Sarmiento29, V.M. Sartor10, M.H.P. Sas10, J. Schambach10, H.S. Scheid10, C. Schiaua10, R. Schicker10, A. Schmied10, C. Schmid11, H.R. Schmid11, M.O. Schmid11, M. Schmid11, N.V. Schmid11, A.R. Schmiegel11, R. Schottelius11, J. Schukraft11, Y. Schutz11, K. Schwab11, K. Schwed11, G. Sciolli11, E. Scomparin11, E. Sege11, Y. Sekiguchi11, D. Sekihata11, I. Selyuzhenko11, 11, S. Senyukov112, 112, J.J. Seo113, D. Serebryakov114, L. Serkšnytė115, A. Sevence116, T.J. Shabad117, A. Shabanov118, A. Shabetai119, R. Shahoyan120, W. Shaik121, A. Shangaraev122, A. Sharma123, H. Sharma124, M. Sharma125, M. Sharma126, N. Sharma127, S. Sharma128, O. Sheibani129, K. Shigak130, M. Shimomura131, S. Shirkennak132, Q. Shou133, Y. Sibiriak134, S. Siddhant135, T. Siemiarczuk136, T.F. Silva137, D. Silvermyr138, G. Simonetti139, B. Singh140, R. Singh141, R. Singh142, V.K. Singh143, V. Singhal144, T. Singhal145, B. Sitar146, M. Sitta147, T.B. Skaali148, G. Skorodumov149, M. Slupecki150, N. Smirnov151, R.J.M. Snellings152, C. Soncco153, J. Sonn154, A. Songmoolnak155, R. Sultanov156, R. Sultanov157, M. Šumber158, V. Sumberia159, S. Sumbowidaga160, S. Swann161, A. Szabó162, J. Szarka163, U. Tabassian164, S.F. Taghavi165, G. Taillepied166, J. Takahashi167, G.J. Tambave168, S. Tang169, Z. Tang170, M. Tarhini171, M.G. Tarzila172, A. Tauro173, G. Tejeda Muñoz174, A. Telles175, L. Terliizzi176, C. Terrevol177, G. Tersimov178, S. Thakur179, D. Thomas180, R. Tieu181, A. Tikhonov182, A.R. Timmins183, M. Tkaci184, A. Ton185, N. Topilskaya186, M. Topp187, F. Torales-Acosta188, S.R. Torres189, A. Trifin190, L. Tripathy191, T. Tripathy192, G. Trombetta193, V. Trubnikov194, W.H. Trzaska195, T.P. Trzciński196, B.A. Trzebiak197, A. Tumin198, R. Tursi199, T.S. Tveten200, K. Ullaland201, A. Uras202, M. Urion203, G.L. Usal204, M. Velázquez205, N. Valle206, S. Valledor207, N. van der Kolk208, L.V.R. van Doremalen209, M. van Leeuwen210, P. Vande Vyvre211, D. Varga212, Z. Varga213, M. Varga-Kofarad214, A. Varga215, M. Vasileio216, A. Vasilei217, O. Vázquez Docer218, V. Vecherin219, E. Vercellin220, S. Vergara Limó221, L. Verme222, R. Vértés223, M. Verweij224, L. Vickovic225, Z. Vilakazi226, O. Villabolos Baillir227, G. Vind228, A. Vinograd229, T. Virgili230, V. Vršalovic231, A. Vodopyanov232, B. Volkov233, M.A. Volk234, K. Voloshin235, S.A. Voloshinsh236, G. Volpe237, B. von Haller238, I. Vorobyev239, D. Vosco240, J. Vrček241, B. Wagner242, C. Wang243, D. Wang244, M. Webe245, A. Wegrzyn246, S.C. Wenze247, J.P. Wessels248, J. Wiechula249, J. Wiik250, G. Wij251, J. Wilkinson252, G.A. Willen253, E. Willshe254, B. Windelband255, M. Wijn196, W.E. Wi197, J.R. Wright256, W. Wlo198, Y. Wu257, R. Xu258, S. Yalcin259, M. Yamaguchi260, K. Yamakawa261, S. Yang262, S. Yang263, Z. Yin264, H. Yokouchi265, I.-K. Yoon266, J.H. Yoon267, S. Yuan268, A. Yusuf269, V. Zaccor270, A. Zaman271, C. Zampolli272, Y. Zhao273, D. Zhou274, Y. Zhou275, J. Zhu276, A. Zichichi277, G. Zinovje278, N. Zur279

Affiliation notes
1 Deceased
34 Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Bologna, Italy
35 Dipartimento DET del Politecnico di Torino, Turin, Italy
36 M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear Physics, Moscow, Russia
37 Institute of Theoretical Physics, University of Wrocław, Poland

Collaboration Institutes
1 A.I. Alipkhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia
2 AGH University of Science and Technology, Cracow, Poland
3 Bogolyubov Institute for Theoretical Physics, National Academy of Sciences of Ukraine, Kiev, Ukraine
4 Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India
5 Budker Institute for Nuclear Physics, Novosibirsk, Russia
6 California Polytechnic State University, San Luis Obispo, California, United States
7 Central China Normal University, Wuhan, China
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ALICE Collaboration

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, Bhabaneswar, 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 INP, 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
