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Scattering studies with low-energy kaon-proton femtoscopy in proton–proton collisions at the LHC

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Abstract

The study of the strength and behaviour of the antikaon-nucleon ($\overline{\mathrm{K}}$N) interaction constitutes one of the key focuses of the strangeness sector in low-energy Quantum Chromodynamics (QCD). In this letter a unique high-precision measurement of the strong interaction between kaons and protons, close and above the kinematic threshold, is presented. The femtoscopic measurements of the correlation function at low pair-frame relative momentum of ($\mathrm{K}^+\mathrm{p} \oplus \mathrm{K}^-\overline{\mathrm{p}}$) and ($\mathrm{K}^-\mathrm{p} \oplus \mathrm{K}^+\overline{\mathrm{p}}$) pairs measured in pp collisions at $\sqrt{s} = 5$, 7 and 13 TeV are reported. A structure observed around a relative momentum of 58 MeV/c in the measured correlation function of ($\mathrm{K}^-\mathrm{p} \oplus \mathrm{K}^+\overline{\mathrm{p}}$) with a significance of 4.4 σ constitutes the first experimental evidence for the opening of the ($\overline{\mathrm{K}}^0\mathrm{n} \oplus \mathrm{K}^0\overline{\mathrm{n}}$) isospin breaking channel due to the mass difference between charged and neutral kaons. The measured correlation functions have been compared to Jülich and Kyoto models in addition to the Coulomb potential. The high-precision data at low relative momenta presented in this work prove femtoscopy to be a powerful complementary tool to scattering experiments and provide new constraints above the $\overline{\mathrm{K}}$N threshold for low-energy QCD chiral models.

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[*] See Appendix A for the list of collaboration members

The kaon (K) nucleon (N) and anti-kaon ($\overline{\mathrm{K}}$)N interactions constitute the building blocks of low energy QCD with u, d and s quarks, since the effective theories aiming to describe hadron interactions in the non-perturbative energy regime are anchored to these interactions. Traditionally, the interaction of K and $\overline{\mathrm{K}}$ with protons and neutrons has been studied by performing scattering experiments at low energies. However, only few measurements exist and only in a limited energy range [1–5]. In such experiments the initial state is fixed, formed by a KN or $\overline{\mathrm{K}}$N pair, and cross-sections of elastic and inelastic final states are measured.

These data showed that the K and $\overline{\mathrm{K}}$ behavior with nucleons is very different: while the repulsive nature of K^+p, due to the strong and Coulomb interactions, is well established [6], the strong interacting term of the K^-p is instead deeply attractive and characterized by the presence of several coupled-channels, i.e. two-particle systems with energy close to the K^-p threshold and carrying the same quantum numbers. These coupled-channels contributions are already present in the initial $\overline{\mathrm{K}}$N scattering wave-function and hence influence both the inelastic and the elastic processes [7].

In the K^-p system, due to the strangeness $S = -1$ charge of the $\overline{\mathrm{K}}$, already two open coupled-channels appear below threshold: $\Lambda\pi$ and $\Sigma\pi$. Of particular interest is the coupling to the $\Sigma\pi$ channel since this, along with the attractive nature of the $\overline{\mathrm{K}}$N interaction, leads to the appearance of the $\Lambda(1405)$ resonance just 27 MeV/c^2 below threshold. Indeed, this resonance is interpreted as the only $\Sigma\pi$-$\overline{\mathrm{K}}$N molecular state [8–10]. The available theoretical approaches [11–20] are constrained above the $\overline{\mathrm{K}}$N threshold, but since the experimental data are scarce, these constraints are rather loose resulting in rather significant differences below threshold. Experimental constraints on the $\overline{\mathrm{K}}$N interaction and on the interplay between both $\overline{\mathrm{K}}$N and $\Sigma\pi$ poles, are fundamental to reproduce the properties of the $\Lambda(1405)$ [21–25].

Approximately 5 MeV above threshold, the $\overline{\mathrm{K}}^0$n channel opens up due to the breaking of the isospin symmetry. The $\overline{\mathrm{K}}$n-KN coupling is also very important to understand the interaction and structure of the $\Lambda(1405)$ and its effect should be visible in the total K^-p cross-section measured in scattering experiments as a clear cusp-like structure for a kaon incident momentum of $p_{\mathrm{lab}} = 89$ MeV/c [26]. However, this peak has not been experimentally observed yet due to the large uncertainties of the data [3, 5, 27].

In order to constrain the contributions of the coupled-channels and to provide a complete description of the $\overline{\mathrm{K}}$N interaction, precise data close to threshold are needed and effects of coupled-channels lying close to threshold must be explicitly taken into account in any process between a $\overline{\mathrm{K}}$ and a nucleon.

The measurement of kaonic hydrogen [28], which nowadays constitutes the most precise constraint at threshold, and the obtained results on the $\overline{\mathrm{K}}$N scattering parameters include the coupled-channel contributions only in an effective way.

Recently, the femtoscopy technique [29, 30], which measures the correlation of particle pairs at low relative momentum, has provided high precision data on different baryon–baryon pairs [31–33], indicating a great sensitivity to the underlying strong potential. Contrary to the scattering, in femtoscopy only the final state is measured and different initial states are allowed. In the K^-p system, this translates into an extreme sensitivity of the correlation function to the introduction of the different coupled-channels, which affect both shape and magnitude of the femtoscopic signal [34].

The femtoscopic measurement of Kp pairs (($\mathrm{K}^+\mathrm{p} \oplus \mathrm{K}^-\overline{\mathrm{p}}$) and ($\mathrm{K}^-\mathrm{p} \oplus \mathrm{K}^+\overline{\mathrm{p}}$)) from pp collisions at different energies presented in this Letter shows experimentally for the first time the impact of coupled-channels effect on the momentum correlation function. Comparison with recent models including or partially including coupled-channel contributions are presented. The same-charge pairs ($\mathrm{K}^+\mathrm{p} \oplus \mathrm{K}^-\overline{\mathrm{p}}$), because of the well described interaction and the lack of coupled-channel effects, are used as a benchmark to test the sensitivity of the correlation function to the strong interaction.

The analysis presented here is based on minimum bias triggered pp collisions collected by the ALICE experiment [35] at the LHC in 2010, 2015, 2016 and 2017 at three different collision energies ($\sqrt{s}$ = 5 TeV, 7 TeV, and 13 TeV). The correlation function $C(k^*)$ is measured as a function of the momentum difference of the pair $k^* = \frac{1}{2}(\vec{p}_1{}^* - \vec{p}_2{}^*)$, where $\vec{p}_1{}^*$ and $\vec{p}_2{}^*$ are the momenta of the two particles in the pair rest frame. It is defined as $C(k^*) = \mathcal{N}\, A(k^*)/B(k^*)$, where $A(k^*)$ is the measured distribution of pairs from the same event, $B(k^*)$ is the reference distribution of pairs from mixed events and $\mathcal{N}$ is a normalization parameter. The denominator, $B(k^*)$, is formed by mixing particles from one event with particles from a pool of other events with comparable number of charged particles at mid-rapidity [36] and comparable interval of the collision primary vertex coordinate along the beam axis, V_z interval ($\Delta V_z = 2$ cm). The normalization parameter $\mathcal{N}$ is chosen such that the mean value of the correlation function equals unity for $400 < k^* < 600$ MeV/c.

The main sub-detectors used in this analysis are: the V0 detectors [37], which are used as trigger detectors, the Inner Tracking System (ITS) [38], the Time Projection Chamber (TPC) [39] and the Time-of-Flight (TOF) detector [40]. The ITS, TPC and TOF are located inside a 0.5 T solenoidal magnetic field and are used to track and identify charged particles. In order to ensure a uniform acceptance at mid-rapidity, events were selected by requiring the V_z of the event to be within 10 cm from the center of the ALICE detector. The rejection of pile-up is performed by exploiting the innermost silicon detector (SPD, part of ITS) vertexing capabilities, following the same procedure described in [33, 41]. After the application of the event selection criteria, about 874 million, 374 million, and 1 billion minimum bias pp events were analyzed at $\sqrt{s} = 5$ TeV, 7 TeV, and 13 TeV, respectively.

As recently proposed in [42], in order to reduce the contribution from the mini-jet background in pp collisions, the events were classified according to their transverse sphericity (S_{T}), an observable which is known to be correlated with the number of hard parton–parton interactions in each event [43]. An event with only one hard parton–parton interaction will generally produce a jet-like distribution that yields low sphericity, while an event with several independent hard parton–parton interactions can yield higher sphericity. To reduce the strong mini-jet background at low momenta, only events with S_{T}, defined as in [42], larger than 0.7 were considered in this analysis.

Charged particles were tracked and selected using the same criteria described in [33]. The charged kaons and protons were identified in a wide transverse momentum (p_{T}) interval ($0.15 < p_{\mathrm{T}} < 1.4$ GeV/c for kaons and $0.4 < p_{\mathrm{T}} < 3$ GeV/c for protons) using the information provided by the TPC and the TOF detectors. The deviation of the measured specific ionization energy loss (dE/dx) in the TPC from the Bethe-Bloch parametrization was required to be within three standard deviations (σ_{TPC}). For kaons with $p_{\mathrm{T}} > 0.4$ GeV/c and protons with $p_{\mathrm{T}} > 0.8$ GeV/c, a similar method was applied for the particle identification using the TOF, where, on top of TPC selection, a selection based on a maximum three standard deviation difference from the expected signal at a given momentum was applied. Tracks identified ambiguously as belonging to both a proton and a kaon, were discarded. In order to remove the large fraction of $\mathrm{e^+e^-}$ pairs that can affect the extraction of the correlation function of the opposite-charge pairs, a selection on the p_{T} of kaon and protons was applied: kaon candidates are excluded if $0.3 < p_{\mathrm{T}} < 0.4$ GeV/c, while proton candidates are excluded in the interval between $0.6 < p_{\mathrm{T}} < 0.8$ GeV/c. The purity of the selected particle samples, determined by Monte Carlo simulations, is larger than 99% in the considered p_{T} intervals for all the analyzed dataset. The systematic uncertainties of the measured $C(k^*)$ were evaluated for each k^* interval by varying event and track selection criteria. The event sample was varied by changing the selection on the V_z position from ± 10 cm to ± 7 cm and by varying the sphericity of the accepted events from $S_{\mathrm{T}} > 0.7$ to $S_{\mathrm{T}} > 0.6$ and $S_{\mathrm{T}} > 0.8$. Systematic uncertainties related to the track selection criteria were studied by varying the selection on the Distance of Closest Approach in the transverse plane direction within the experimental resolution. To study systematic effects related to particle identification, the number of standard deviations around the energy loss expected for kaons and protons in the TPC and, similarly, for the time-of-flight in the TOF was modified from 3σ to 2σ. For each source, the systematic uncertainty was estimated as the root-mean-square (RMS) of the deviations. The total systematic uncertainty was calculated as the quadratic sum of each source's contribution and amounts to about 3% in the considered k^* intervals.

The measured correlation functions for ($\mathrm{K^+p} \oplus \mathrm{K^-\overline{p}}$) and ($\mathrm{K^-p} \oplus \mathrm{K^+\overline{p}}$) are shown in the upper panels of Fig. 1 and Fig. 2. In both figures, each panel corresponds to a different collision energy, as indicated in the legend. The structure that can be seen in the ($\mathrm{K^-p} \oplus \mathrm{K^+\overline{p}}$) correlation function at k^* around 240 MeV/c

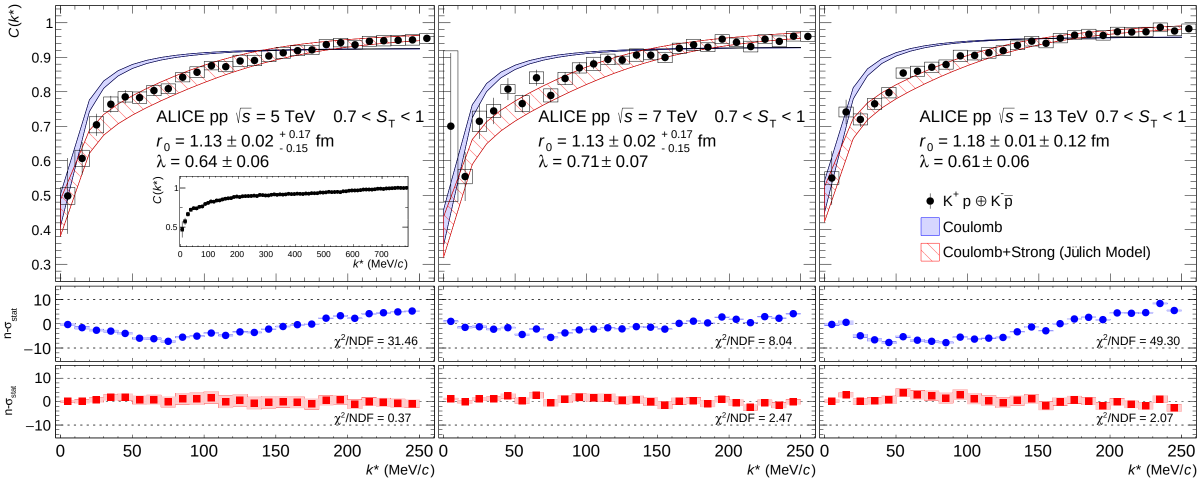

Fig. 1: $(K^+p \oplus K^-\overline{p})$ correlation functions obtained from pp collisions at $\sqrt{s}$ = 5 TeV (left), 7 TeV (middle) and 13 TeV (right). The inset shows the correlation function evaluated for pp collisions at $\sqrt{s}$ = 5 TeV in a wider k^*interval. The measurement is shown by the black markers, the vertical lines and the boxes represent the statistical and systematic uncertainties respectively. Bottom panels represent comparison with models as described in the text.

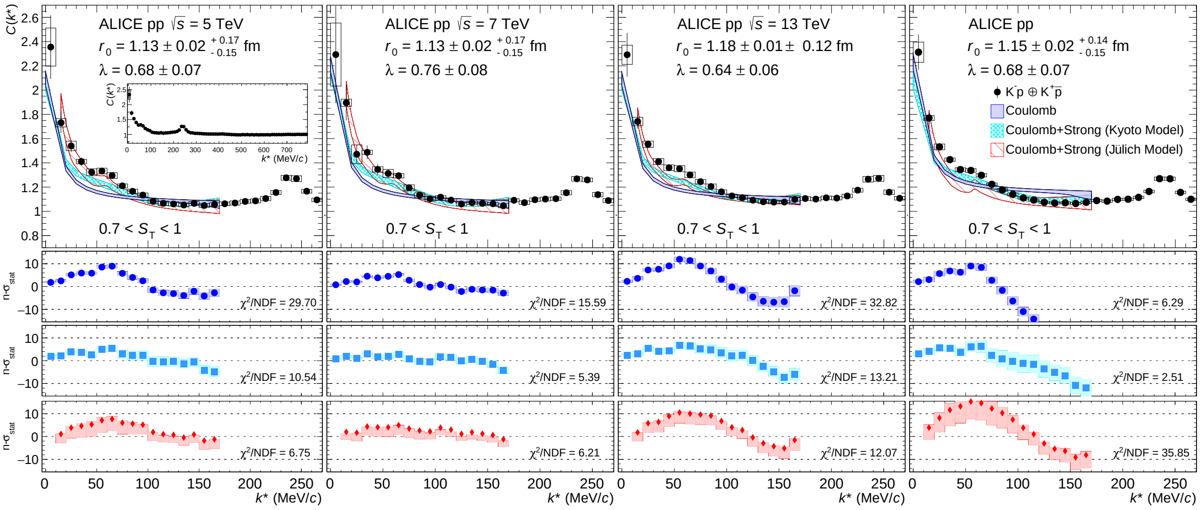

Fig. 2: $(K^-p \oplus K^+\overline{p})$ correlation functions obtained (from left to right) from pp collisions at $\sqrt{s}$ = 5 TeV, 7 TeV, 13 TeV. The fourth panel shows the combined results at the three colliding energies, The number of pairs in each data sample as been used as weight. The inset shows the correlation function evaluated for pp collisions at $\sqrt{s}$ = 5 TeV in a wider k^*interval. The measurement is presented by the black markers, the vertical lines and the boxes represent the statistical and systematic uncertainties respectively. Bottom panels represent comparison with models as described in the text.

in Fig. 2 is consistent with the $\Lambda(1520)$ which decays into K^-p, with a center-of-mass momentum for the particle pair of 243 MeV/c [44]. The correlation function of $(K^-p \oplus K^+\overline{p})$ exhibits also a clear structure between 50 and 60 MeV/c for the three collision energies. The k^* position of the structure is consistent with the threshold of the $\overline{K}^0n$ $(K^0\overline{n})$ channel opening at p_{lab} = 89 MeV/c [3, 5, 27] which corresponds to k^* = 58 MeV/c. In order to quantify the significance of this structure, and since the three measured distributions are mutually compatible, the $C(k^*)$ measured at the three different energies were summed using the number of pairs in each data sample as a weight. The resulting $C(k^*)$ was interpolated with a spline considering the statistical uncertainties and the derivative of the spline was then evaluated [36]. A change in the slope of the derivative consistent with a cusp effect in the k^* region between 50 and 60 MeV/c at the level of 4.4σ has been observed, to be compared with a significance of 30σ for $\Lambda(1520)$. The measurement presented here is therefore the first experimental evidence for the opening of the $\overline{\mathrm{K}}^0\mathrm{n}$ ($\mathrm{K}^0\overline{\mathrm{n}}$) channel, showing that the femtoscopy technique is a unique tool to study the $\overline{\mathrm{K}}\mathrm{p}$ interaction and coupled-channel effects.

The experimental correlation functions were also used to test different potentials to describe the interaction between $\mathrm{K}^+\mathrm{p}$ ($\mathrm{K}^-\overline{\mathrm{p}}$) and $\mathrm{K}^-\mathrm{p}$ ($\mathrm{K}^+\overline{\mathrm{p}}$). The measured correlation function $C(k^*)$ is compared with a theoretical function using the following equation

$$C(k^*) = (a + b \cdot k^*) \cdot \left[1 + \lambda \cdot (C(k^*)^{theoretical} - 1)\right], \tag{1}$$

where the baseline $(a + b \cdot k^*)$ is introduced to take into account the remaining non-femtoscopic background contributions related to momentum-energy conservation which might be present also after the S_{T} selection. The slope, b, of the baseline is fixed from Monte Carlo simulations based on PYTHIA 6 [45] and PYTHIA 8 [46], while the normalization, a, is a free parameter. In order to assign a systematic uncertainty related to the slope of the baseline, the b parameter has been varied by its uncertainty as obtained from the Monte Carlo simulation (± 10%) and the fit repeated. The parameter λ represents the fraction of primary pairs in the analyzed sample multiplied by the purity of the same sample and is fixed by fitting Monte Carlo (MC) templates to the experimental distributions of DCA_{xy} of kaons and protons, similarly to what is described in [33].

The model correlation function, $C(k^*)^{theoretical}$, is evaluated using the CATS framework [47]. The λ parameters obtained for each analyzed dataset are reported in each panel of Fig. 1 and Fig. 2 for same-charge and opposite-charge Kp pairs, and vary from 0.61 to 0.76 for each considered set. A systematic uncertainty of ±10% is associated with the λ parameters. This uncertainty was estimated by varying the Monte Carlo templates used in the feed-down estimation procedure based on PYTHIA 6 [45] for the analysis at $\sqrt{s}$ = 7 TeV and based on PYTHIA 8 [46] for the analyses performed at $\sqrt{s}$ = 5 TeV and 13 TeV, and varying the transport code used in the simulation from GEANT3 [48] to GEANT4 [49].
The effects related to momentum resolution effects are accounted for by correcting the theoretical correlation function, similarly to what shown in [33] and [41]. The theoretical correlation function $C(k^*)^{theoretical}$ depends not only on the interaction between particles, but also on the profile and the size of the particle emitting source. Under the assumption that there is a common Gaussian source for all particle pairs produced in pp collisions at a fixed energy, the size of the source considered in the present analysis is fixed from the baryon–baryon analyses described in [33] and [41]. The impact of strongly decaying resonances (mainly K^* decaying into K and Δ decaying into p) on the determination of the radius for Kp pairs was studied using different Monte Carlo simulations [45, 46] and found to be 10%. This contribution was linearly added to the systematic uncertainty associated with the radius. The radii of the considered Gaussian sources are $r_0 = 1.13 \pm 0.02^{+0.17}_{-0.15}$ fm [33] for collisions at $\sqrt{s}$ = 5 and 7 TeV, and $r_0 = 1.18 \pm 0.01 \pm 0.12$ fm [41] for the $\sqrt{s}$ = 13 TeV collisions.

The comparison of the measured $C(k^*)$ for same-charge Kp pairs with different models is shown in Fig. 1. Each panel presents the results at different collision energy and the comparison with two different scenarios. The blue band represents the correlation function evaluated as described in Eq. (1), assuming only the presence of the Coulomb potential to evaluate the $C(k^*)^{theoretical}$ term. The red band represents the correlation function assuming the strong potential implemented in the Jülich model [50] in addition to the Coulomb potential. The latter has been implemented using the Gamow factor [51]. In the bottom panels, the difference between data and model evaluated in the middle of each k^* interval, and divided by statistical error of data for the three considered collision energies are shown. The width of the bands represents the n-σ range associated to the model variations. The reduced χ^2 are also shown. This comparison reveals that the Coulomb interaction is not able to describe the data points, as expected, while the introduction of a strong potential allows to reproduce consistently the data when the same source radius as for baryon-baryon pairs is considered. Hence, the measured correlation functions are sensitive to the strong interaction and can be used to test different strong potentials for the $\mathrm{K^-p}$ system, assuming a common source for all the Kp pairs produced in a collision.

Similar to Fig. 1 for like-sign pairs, Fig. 2 shows the data-model comparison for unlike-sign pairs. The measured $C(k^*)$ is reported for the three different collision energies and the $C(k^*)$ distributions were compared with different interaction models. Since all the models considered in this letter do not take the presence of $\Lambda(1520)$ into account, only the region below 170 MeV/c is considered in the comparison. The blue bands show results obtained using CATS with a Coulomb potential only.
The remaining curves include, on top of the Coulomb attraction, different descriptions of the $\mathrm{\overline{K}N}$ strong interaction. The width of each band accounts for the uncertainties in the λ parameters, the source radius and the baseline. The light blue bands corresponds to the Kyoto model calculations with approximate boundary conditions on the $\mathrm{K^-p}$ wave-function which neglect the contributions from $\Sigma\pi$ and $\Lambda\pi$ coupled-channels [26, 52–55]. Moreover, this version of the Kyoto model is performed in the so-called isospin basis and hence does not include the mass difference between $\mathrm{K^-}$ and $\mathrm{\overline{K}^0}$: no cusp-like structure are foreseen by the model in $C(k^*)$.
The introduction of coupled-channel contributions in the correlation function has been shown to result in additional attractive terms enhancing the signal, in particular in the low k^* region [34]. As expected, the Kyoto results clearly underestimate the data at low momenta where the $\Sigma\pi$ channel is particularly relevant.
The red bands indicate results obtained with the Jülich strong potential, recently updated to reproduce the kaonic atom results from SIDDHARTA collaboration [34]. This model includes explicitly both $\Sigma\pi$ and $\Lambda\pi$ coupled-channels below threshold and the $\mathrm{K^-}$– $\mathrm{\overline{K}^0}$ mass difference, reflected in the presence of a cusp structure. Accordingly, the comparison with data shows a better agreement with respect to the Kyoto model, but the region of k^* below 100 MeV/c is nevertheless not fully reproduced and the shape of the correlation function deviate from the data around the cusp.
The overall tension between data and the models is not surprising since the latter were fitted to only reproduce scattering data above threshold (providing constraints for $k^* \geq 70$ MeV/c) and the SIDDHARTA results at threshold [28].

To test the stability of the results, the measured $C(k^*)$ without any S_T cut was used and the background from mini-jets and other kinetically correlated pairs was subtracted by using a Monte Carlo simulation based on PYTHIA 8 [46], using a procedure similar to the one described in [56]. Applying this method the comparison between data and models is consistent within statistical uncertainties with the one obtained using the sphericity selection.

To summarize, the momentum dependent correlations of same-charge and opposite-charge Kp pairs ($(\mathrm{K^+p} \oplus \mathrm{K^-\overline{p}})$ and $(\mathrm{K^-p} \oplus \mathrm{K^+\overline{p}})$) were measured using the two-particle correlation function in pp collisions at different collision energies. A structure around $k^* = 58$ MeV/c in the measured correlation function of $(\mathrm{K^-p} \oplus \mathrm{K^+\overline{p}})$ was observed. The significance of such a structure was evaluated by combining the results from the three analyzed datasets and by interpolating the total correlation function with a spline. By studying the variation in the slope of the derivative of such spline in the range $50 \leq k^* \leq 60$ MeV/c, the kinematic cusp was assessed at a 4.4σ level. The observed structure is consistent with the opening of the $\mathrm{\overline{K}^0n}$ channel ($p_\mathrm{lab} \sim 89$ MeV/c). This measurement represents the first experimental evidence for the $\mathrm{\overline{K}^0n}$ ($\mathrm{K^0\overline{n}}$) isospin breaking coupled-channel and shows experimentally the effect of coupled-channel contributions on the correlation function.
The measured $C(k^*)$ were compared to different interaction scenarios. The $(\mathrm{K^+p} \oplus \mathrm{K^-\overline{p}})$ correlation functions were proven to be sensitive to the strong interaction, since a Coulomb-only hypothesis is in-

sufficient to describe the data. The inclusion of the strong interaction via the Jülich model results in a reasonable description of the data within uncertainties. The ($\mathrm{K^-p} \oplus \mathrm{K^+\overline{p}}$) correlation functions at low k^* cannot be fully reproduced by the considered potentials. Nevertheless, model including explicitly coupled-channel contributions shows a better agreement with data. The data presented here represent the most precise experimental information for the KN interaction and provide new constraints for future low-energy phenomenological QCD calculations can be used to shed light on the nature of the $\overline{\mathrm{K}}\mathrm{N}$ interaction.

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