UNVEILING FEMTOSCOPIC CORRELATIONS OF LIGHT HADRONS*

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The ALICE Collaboration has recently shown interest in analyzing femtoscopic correlations involving light hadrons. In this paper, we review how πK data can be well reproduced using realistic interactions, while accurately describing the $\kappa/K_0^*(700)$ resonance. For other light-hadron channels, qualitative insights into resonances such as ρ and a_0 can be obtained through femtoscopic correlations. Moreover, we present preliminary results on a framework to interpret femtoscopy from a Chiral Perturbation Theory perspective.

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1. Introduction

To fully understand hadrons, the study of hadron–hadron interactions is essential. In this regard, femtoscopy, originally focused on extracting information about the space-time characteristics of the particle-emitting source, is now seen as a powerful tool, capable of providing insights into the interaction when traditional techniques, such as scattering, are limited or infeasible [1]. Indeed, promising results using this technique for hyperon–hyperon, hyperon–nucleon, and kaon–nucleon systems have been reported [2]. Experiments involving correlations among lighter hadrons, such as pions and kaons, have also been conducted by ALICE at the LHC [3, 4].

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The correlation function is determined experimentally by the ratio of the momentum distribution of particle pairs produced in the same event over a reference distribution obtained from particles produced in different events. On the theory side, the theoretical correlation function is addressed using the Koonin–Pratt formula [5, 6], which can be rewritten, under some assumptions, as $C(k^*) = \int S(r)|\psi(k^*, r)|^2 \mathrm{d}^3 r$, where k^* is the relative momentum of the hadron pair.

2. $\pi^+ K_\mathrm{S}$ femtoscopic correlations

The ALICE measurements of $\pi^\pm K_\mathrm{S}$ femtoscopic correlations provide data of unprecedented statistical precision and aim to help understand better the properties of the $\kappa/K_0^*(700)$ resonance [3]. Thus, our work in [7] focuses on identifying and addressing improvements on the theoretical side of the analysis.

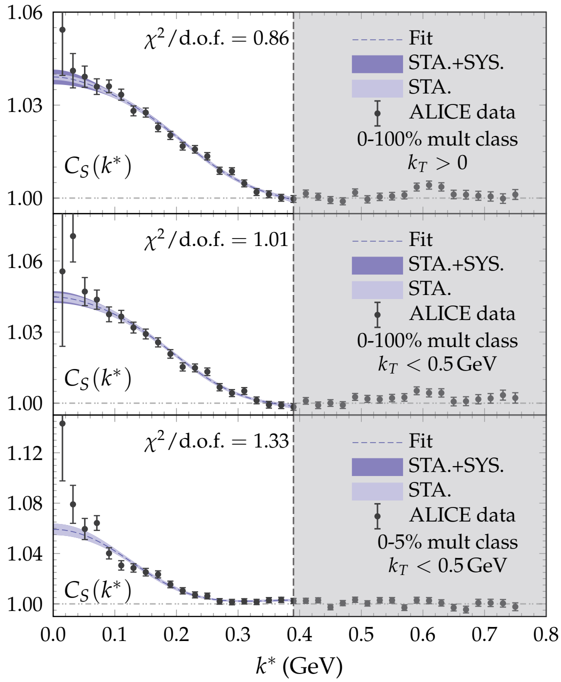

Fig. 1. (Color online) ALICE data on femtoscopic S-wave correlations [3]. Blue/gray lines show fits using realistic πK interactions within our model [7] with relativistic corrections. Data beyond the ηK threshold are only included for completeness. Picture taken from [7].

In particular, ALICE employs the non-relativistic Lednický–Lyuboshitz formalism [8], which uses on-shell factorization of the scattering amplitude. As for the πK interaction, it is assumed to be purely elastic and dominated by the $I = 1/2$ channel, modeled via a Breit–Wigner description. However, limitations such as a non-relativistic approximation for the light-pion mass, the neglect of the significant $I = 3/2$ contribution, and the low-energy dynamics dictated by chiral symmetry and dispersive constraints call into question the applicability of this simplified framework.

For these reasons, we introduce the following improvements. First, we incorporate relativistic corrections through a Bethe–Salpeter-like construction of the pair wavefunction. Second, we utilize a realistic description of πK scattering based on dispersive analyses (CFD) [9], which encode the correct low-energy dynamics. Finally, we introduce the full isospin structure, accounting for both $I = 1/2$ and $I = 3/2$ channels.

Fits to data, with χ^2/d.o.f (≈ 1), using our improved framework using realistic πK interactions, are shown in Fig. 1. From the physical standpoint, the fits yield smaller source radii [10] and larger correlation strengths than those obtained in the ALICE crude analysis.

3. Predictions for other light-hadronic channels

The same formalism developed in the previous section can be employed to gain insight into other light-hadronic channels; in particular, this can be applied to $\pi^+\pi^0$, K^+K_S, and $\pi^+\eta$. Here, we present preliminary results. First, regarding $\pi^+\pi^0$, we have computed up to P-wave contributions to the correlation functions to reproduce fairly well the $\rho(770)$. In fact, since this resonance lies in the $I = 1$ isospin channel, the Bose symmetry requires an odd-angular-momentum contribution. For the interaction, we use a dispersive parametrization of the $\pi\pi$ channels involved, extracted from [11]. In the right panel of Fig. 2, we show the S and P contributions to $C_{\pi^+\pi^0} - 1$, denoted δC_S and δC_P, respectively. The $\rho(770)$ effect is visible as a dip around $k^* \approx 0.35$ GeV ($\sim m_\rho/2$) in δC_P.

For $\eta\pi^+$ and K^+K_S, we restrict ourselves to S-wave correlations. Moreover, we neglect CP violation, so $|K_\mathrm{S}\rangle \equiv \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle)$. Then, a coupled-channel formalism, involving a phenomenological description of the $I = 1$ $\eta\pi, K\bar{K}$ channels given in [12], and a Chew–Mandelstam representation for the K^+K^0 scattering amplitude, is implemented. In Fig. 2, we observe in $C_{\pi^+\eta}$ a hint of the $a_0(980)$ resonance around $k^* \approx 0.3$–0.35 GeV. This approach lays the foundations for further studies, in which we will also include the correction to the asymptotic wavefunction (usually denoted ΔC) and consider the case in which two channels with different physical thresholds take place.

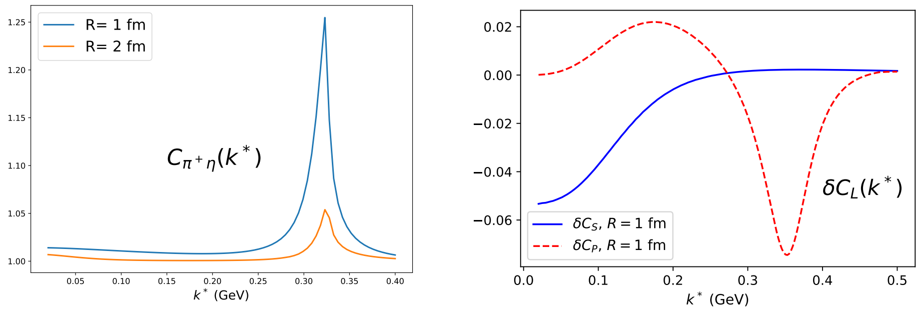

Fig. 2. Our preliminary results for: $C(k^*)$ for $\pi^+\eta$ (left) and S- and P-wave contributions to $C(k^*) - 1$ for $\pi^+\pi^0$ (right).

4. Femtoscopy from a ChPT perspective

The framework proposed above showcases two important caveats: the on-shell factorization of the scattering amplitude and the non-relativistic approach to deal with the particle-emitting source and intermediate propagators. In the following, we present preliminary results on how to absorb the source off-shell divergences when working with the Chiral Perturbation Theory (ChPT) amplitudes in the low-energy regime, while keeping the relativistic formalism.

We begin by redefining the four-dimensional Koonin–Pratt formula, $C(k^*) = \int \mathrm{d}^4x S(x,k^*)|\psi(x,k^*)|^2$, in terms of a four-dimensional Bethe–Salpeter amplitude

$$\psi(x,k^*) = \mathrm{e}^{-ik^*x} + \int \frac{\mathrm{d}^4q}{(2\pi)^4} \frac{\mathrm{e}^{-iqx}T(P,q,k^*)}{\left(\left(\frac{P}{2}-q\right)^2 - m_1^2\right)\left(\left(\left(\frac{P}{2}+q\right)^2 - m_2^2\right)\right)}\,, \quad (1)$$

and allowing for a possible momentum-dependent source. Here, P denotes the center-of-mass four-momentum.

Then, we perform a chiral expansion of the amplitude, which leads to

$$C(k^*) = S_{k^*}(0) + 2\,\mathrm{Re} \int \frac{\mathrm{d}^4q}{(2\pi)^4} \frac{S_{k^*}(k^*-q)T(P,q,k^*)}{\left(\left(\frac{P}{2}-q\right)^2 - m_1^2\right)\left(\left(\left(\frac{P}{2}+q\right)^2 - m_2^2\right)\right)}\,, \quad (2)$$

where $S_k(q) = \int \mathrm{e}^{iqx} S(x,k)\, \mathrm{d}^4x$. Finally, we expand in momenta, $S_{k^*}(k^*-q) \approx S_{k^*}(0) + S'_{k^*}(0)(k^*-q)^2 + \ldots$. Following these guidelines and substituting $\pi\pi$ and πK scattering amplitudes with their LO ChPT expressions, we arrive at the simple functional form

$$C(k^*) = 1 + P\left(s, m_i^2\right) + 2\, T_{\mathrm{on}}(s)\, \mathrm{Re}\, J(s)\,, \quad (3)$$

where $T_{\rm on}$ denotes the on-shell amplitude, P is a polynomial in s and the masses coming from renormalizing through the source, and $J(s)$ is the usual loop function. In the end, we can test this model by comparing with $C_{\pi K}(k^*)$ in [3].

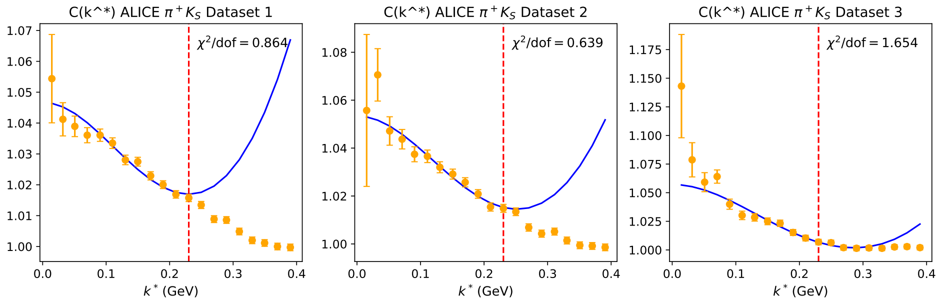

Fig. 3. (Color online) Preliminary results of our low-energy chiral approach in Eq. (3) *versus* ALICE data [3]. The dashed vertical red line signals the approximate energy where LO ChPT still gives an acceptable description of the S-wave πK scattering data, where the LO approach makes sense. Beyond that region, unitarity is badly violated and the LO approach is not applicable.

5. Conclusions

To summarize, in this paper, we have reviewed our successful description of the $\pi^{\pm} K_{\rm S}$ femtoscopic correlations using realistic meson–meson interactions, and preliminary results for other processes. We have also addressed a possible interpretation of the off-shell factorization within a low-energy chiral expansion.

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