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Bridging nuclear physics and neutron stars at the LHC

Dimitar Mihaylov[a,*]

[a] *Faculty of Physics, University of Sofia,*
5 J. Bourchier Blvd., 1164 Sofia, Bulgaria

E-mail: dimitar.lubomirov.mihaylov@cern.ch

Two-particle correlations (femtoscopy) of hadrons produced in high-energy collisions provide a powerful tool for probing final-state interactions. At the LHC, the femtoscopic technique has been applied to systems involving strange baryons (hyperons), yielding high-precision constraints on their interactions. This work summarizes the recent efforts exploiting these state-of-the-art data to construct a data-constrained nuclear equation of state and to derive the corresponding mass–radius relation of neutron stars.

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*Speaker

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1. Introduction

The properties of the strong interaction between nucleons (N) and strange baryons, known as hyperons (Y = Λ, Σ, Ξ), play an important role in determining the high-density behavior of nuclear matter. This topic is of particular relevance for studies of the nuclear equation of state (EoS) and the physics of neutron stars. Recent observations of gravitational waves [1], together with results from the NICER mission [2], have sparked renewed interest in this subject.

Over the past five to six decades, experimental efforts to constrain the properties of the nucleon–hyperon (NY) final-state interaction (FSI) have relied primarily on scattering experiments and measurements of hypernuclei. These studies have provided important insights into both the attractive nature of the two-body NY force and the likely presence of repulsive three-body NNY contributions. Nevertheless, the experimental challenges associated with such measurements have led to a limited sensitivity to the FSI, particularly at low relative momenta. This limitation has been addressed in recent years by adapting the Hanbury Brown–Twiss technique to the study of two-particle correlations in high-energy collisions, under the assumption of a well-characterized particle emission source [3]. Pioneering work in this direction has been carried out by the ALICE Collaboration, which has reported measurements of, among others, the pΛ, ΛΛ and NΞ correlation functions [4–6]. Several subsequent studies [7, 8] have exploited these data to quantify the improved constraints they provide on chiral effective field theory (χEFT) descriptions of the NY interaction, as well as the resulting implications for the two-body contribution to the EoS. The present work provides an overview of these ongoing efforts and summarizes the obtained results.

2. Femtoscopy

Femtoscopy is a well-established technique that relates particle correlations to the properties of the emission source and the final-state interaction. Its theoretical foundation is provided by the Koonin–Pratt formalism [3], which describes the modeling of two-particle correlation functions measured in heavy-ion (HI) collisions. Experimentally, the correlation function is constructed from the pair-wise distribution $N(k^*)$ of the particle species of interest as a function of the single-particle momentum in the pair rest frame, k^*. This distribution contains information on the available phase space for particle emission, as well as correlations arising from final-state interactions and, in the case of identical particles, wave-function symmetrization effects.

The correlation function $C(k^*)$ is obtained by dividing $N(k^*)$ by a reference distribution $M(k^*)$, which is constructed to be free of correlations. Such a reference sample is typically obtained using event mixing, where each particle in a pair originates from a different collision event. The Koonin–Pratt equation relates the measured correlation function to the relative wave function of the motion of the pair, $\Psi(\vec{k}^*, \vec{r}^*)$, and to the source function $S(r^*)$, which describes the probability of emitting two particles at a relative distance r^*,

$$C(k^*) = \frac{N(k^*)}{M(k^*)} = \int S(r^*) \left|\Psi(\vec{k}^*, \vec{r}^*)\right|^2 d^3r^*. \tag{1}$$

Traditionally, this relation has been employed to study the properties of the emission source using identical particle correlations with negligible strong interactions, such as $\pi\pi$ pairs. Over the past decade, however, significant progress has been achieved in reversing this paradigm by exploiting Eq. 1 to access information on the strong interaction encoded in $\left|\Psi(\vec{k}^*, \vec{r}^*)\right|^2$. This approach requires a precise characterization of the emission source $S(r^*)$, as well as a reliable framework for modeling the underlying interaction.

A robust methodology for describing the source function has been developed in proton–proton (pp) collision systems by assuming a common emission region for all particle species [9]. This assumption has been validated by disentangling contributions from primordial hadronization and feed-down from short-lived, strongly decaying resonances. These effects were first incorporated within the Resonance Source Model (RSM) [9] and later refined in the CECA model [10]. While the RSM provides an effective description at the pair level without explicit single-particle kinematics, the CECA model derives $S(r^*)$ from single-particle emission properties. This allows for the inclusion of experimentally observed kinematic effects, such as the scaling of the source size with the pair transverse momentum k_T.

The strong interaction is incorporated into the modeling through the wave function, either by evaluating it explicitly within a given theoretical framework, for example based on an interaction potential, or by using its asymptotic behavior for a given set of scattering parameters. The latter approach allows for an analytic solution provided by the Lednicky–Lyuboshitz (LL) model [11], which represents an approximation valid for relatively large emission sources, such as those encountered in heavy-ion collisions. It is worth noting that the LL model relates the correlation function to the scattering amplitude f, and that for small values of k^* it contains both linear and quadratic terms in $|f/R|$, where R denotes the width of an effective Gaussian source. This implies that, for a sufficiently large source, the amplitude of the correlation signal scales linearly with the scattering amplitude, in contrast to scattering experiments where the measured cross section exhibits a quadratic dependence on f.

For smaller source sizes, such as those typically realized in pp collisions, both the linear and quadratic terms may contribute to the correlation function. As a result, the measured correlation does not exhibit a purely linear or quadratic scaling with the scattering amplitude. This feature is particularly relevant for the interpretation of spin-averaged results commonly quoted in femtoscopy studies, which are obtained by fitting a correlation function composed of multiple spin states with a single effective set of scattering parameters. Such results cannot be directly compared to spin-averaged scattering data unless the correlations between the different spin channels are explicitly investigated and quantified.

In the following discussion of pΛ correlations, the spin-averaged properties are therefore examined by exploring the correlated scattering lengths f_0 and f_1 in the spin 0 (singlet) and spin 1 (triplet) channels, respectively. The final results are expressed either as

$$\langle f_S \rangle = \frac{1}{4} f_0 + \frac{3}{4} f_1, \tag{2}$$

corresponding to a purely linear scaling of the spin-averaged parameters, or as

$$\langle f_{\mathrm{RMS}} \rangle = \sqrt{\frac{1}{4} f_0^2 + \frac{3}{4} f_1^2}, \tag{3}$$

corresponding to a quadratic scaling of the spin-averaged parameters.

3. YN, YY interactions and hyperonic matter

The study of matter with hyperonic degrees of freedom is of relevance for the description of the properties of neutron stars, as the behavior of EoS is driven by the properties of baryons and hyperons at large densities. The resulting stiffness of the EoS determines the maximum allowed mass of neutron stars. The interaction between pairs of nucleons is well understood through scattering experiments, and the role of three-body forces has been established from the binding energies of nuclear systems, the position of the neutron drip line, and related observables. In fact, a purely nucleonic EoS is able to support and explain the existence of neutron stars with masses above twice the mass of the Sun ($2\,M_\odot$). However, the introduction of hyperonic degrees of freedom typically leads to a significant softening of the EoS, resulting in an inability to model heavy neutron stars. This issue, commonly referred to as the hyperon puzzle, has spurred extensive experimental and theoretical efforts aimed at improving our understanding of dense matter. One promising way to resolve this puzzle is the introduction of repulsive three-body forces, which can provide sufficient stiffness to the EoS at large densities, potentially disfavoring the presence of hyperons in neutron stars and thereby resolving the hyperon puzzle [12]. Nevertheless, an ultimate conclusion on this topic will only be possible through a quantitative experimental determination of both two- and three-body forces among nucleons and hyperons, followed by a theoretical calculation of the corresponding EoS.

The experimental challenge of constraining YN interactions has been largely addressed by recent high-precision measurements of several hyperon–nucleon correlation functions performed by the ALICE Collaboration [4–6]. In particular, it has been demonstrated that measurements of the pΛ correlation function, performed differentially in k_T in high-multiplicity pp collisions at $\sqrt{s}$ = 13 TeV, can significantly reduce the uncertainties associated with the two-body scattering parameters [7]. Moreover, these results have been complemented by measurements of three-body ppΛ correlations [13]. Together with recent theoretical advances in the modeling of three-body interactions [14], this opens the possibility for a more complete and quantitative description of hyperonic matter.

The application of correlation data to the construction of the nuclear equation of state was conceptually introduced in Ref. [8], where available femtoscopy measurements from the two-body strangeness sector [4–6] were employed to derive a data-driven EoS. The procedure involved the use of the Brueckner–Hartree–Fock (BHF) approach [15] to extrapolate the interaction to densities beyond nuclear saturation density (ρ_0 = 0.17 fm^{-3}), employing NN, YN, and YY G-matrices, and enforcing β-equilibrium and charge neutrality. This framework allows the use of the Tolman–Oppenheimer–Volkoff (TOV) [16] equations to evaluate the corresponding mass–radius relation of neutron stars. The two-body NN interaction is modeled using the well-established Argonne V18 potential [17], while the hyperonic channels are described by effective potentials that have been successfully used to reproduce the corresponding femtoscopic measurements. The effects of three-body forces involving hyperons are omitted due to the lack of sufficiently precise and reliable experimental constraints. However, the NNN interaction is effectively included through the introduction of a correction term in the energy density, which depends on density and isospin and is tuned to reproduce the binding energy $E_0 = -16$ MeV of symmetric nuclear matter at ρ_0 and the nuclear incompressibility K_0. The latter is set to two extreme values, K_0 = 160 MeV and

K_0 = 270 MeV, based on current experimental uncertainties.

4. Results and discussion

The two main achievements presented in Refs. [7, 8] are the improved precision with which the pΛ scattering parameters can be constrained [7], and the combination of these results with measurements of ΛΛ and pΞ^- correlations [5, 6] to construct a data-constrained EoS [8].

The left panel in Fig. 1 shows the allowed values for the scattering lengths f_0 and f_1 of the pΛ system, after accounting for the constraints using both scattering and femtoscopy data. The spin-averaged values of the scattering length can be obtained by applying Eqs. 2, 3 to the 1 σ contour region of the combined result. The corresponding results are $\langle f_S \rangle$ = 1.69 ± 0.10 fm and $\langle f_{\mathrm{RMS}} \rangle$ = 1.77 ± 0.18 fm. As discussed in the femtoscopy section, the correlation function contains both linear and quadratic terms of the scattering amplitude, thus using $\langle f_S \rangle$ or $\langle f_{\mathrm{RMS}} \rangle$ to obtain an effective description of femtoscopy data should be avoided.

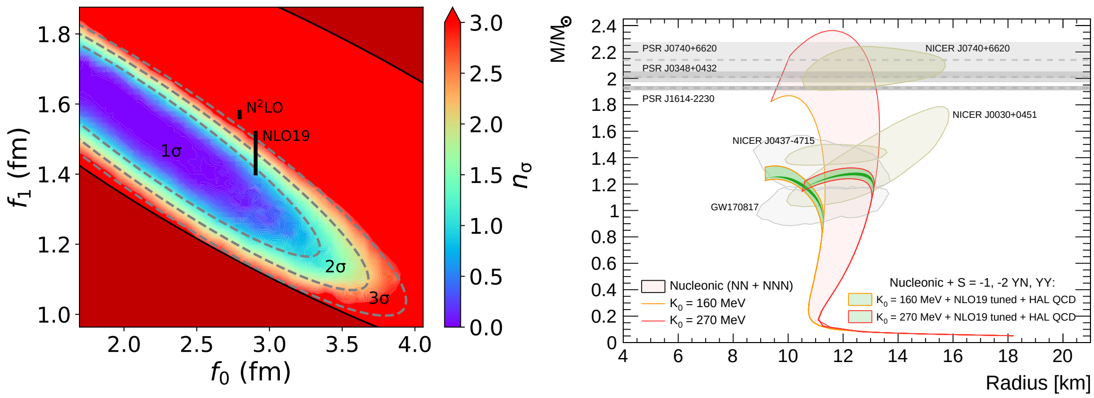

Figure 1: The left panel depicts the exclusion plot for the singlet (f_0) and triplet (f_1) pΛ scattering lengths based on the combined analysis of cross section and correlation data. The black lines separating the shaded region correspond to the 3 σ contour in the case of considering only the scattering data. For details consult the original work [7]. The right panel shows the mass-radius relation for neutron stars, based on the data-driven equation of state obtained in [8]. The details on the exact parameterization of the potentials used to model the included NΛ, NΣ, ΛΛ and NΞ interactions are described in detail in the original work [8].

The right panel in Fig. 1 shows the mass-radius relation for neutron stars, based on the data-driven equation of state obtained in [8], which utilizes the latest nucleon-hyperon and hyperon-hyperon femtoscopic measurements to improve the existing constraints on the final-state interaction. The details on the exact parameterization of the potentials used to model the included NΛ, NΣ, ΛΛ and NΞ interactions are described in detail in the original work [8].

The result reconfirms the state-of-the-art understanding of the hyperon puzzle, in which the inclusion of two-body forces is insufficient to provide the required stiffness of the EoS for modeling heavy neutron stars. Thus, the ultimate resolution of the puzzle remains an open question, with repulsive three-body forces representing the most likely explanation, although more experimental constraints are required. Nevertheless, exotic scenarios, such as the presence of QCD axions in neutron stars [18], could provide mechanisms for supporting heavier neutron stars and should be investigated further in the future.

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