Baryon-(anti-)baryon and baryon-meson interaction cross-section measurement with femtoscopy technique in heavy-ion collisions

Adam Kisiel,
Warsaw University of Technology

Supported by Polish National Science Centre grant 2014/13/B/ST2/04054

Abstract: Interaction cross-sections for baryon pairs are of fundamental interest and they are actively investigated theoretically. They are known well for pairs of common (anti-)baryons, however there is a lack of precise data for heavier baryons, including the ones carrying strangeness. The so-called kaonic atoms are also investigated theoretically and their properties crucially depend on the kaon-nucleon interaction. The two-particle correlation formalism (femtoscopy) is sensitive to the interaction kernel for a pair of particles, which is related to the pair interaction cross-section [1]. The formalism is extensively used to measure two-particle correlations in heavy-ion collisions. In particular the collisions at RHIC and LHC produce simultaneously large number of baryons and anti-baryons and even larger number of kaons. We show how this formalism can be used to extract the cross-sections from the femtoscopic baryon-(anti-)baryon correlation functions [2], as well as from proton-charged kaon functions. The analysis is complicated by the presence of the so-called "residual correlations" arising from weak decay products in the measured sample. We show how this effect can be exploited to gain further insight into the cross-sections of even heavier baryons. We discuss the limitations of the measurement technique and estimate the discovery potential of currently available and soon-to-be-collected heavy-ion collision datasets at RHIC and at the LHC.

Formalism

The correlation function is a ratio of the conditional probability to observe two particles together, divided by the product of probabilities to observe each of them separately. Experimentally it is measured by dividing the distribution of relative momentum of pairs of particles detected in the same collision (event) by an equivalent distribution for pairs where each particle is taken from a different collision.

The femtoscopy technique focuses on the mutual two-particle interaction. For two identical particles the wave-function is (anti-)symmetrized. The Final State Interaction (FSI) are the Coulomb when both particles are charged and strong fot two hadrons. Out of those the Strong interaction is of particular interest, as for some pair types it is still not fully understood. This is the focus of this work.

In femtoscopy an assumption is made that the FSI of the pairs of particles is independent from their production. The two-particle correlation can then be written as [1,2]:

$$C(\boldsymbol{k}^*)=\frac{\int S(r^*,\boldsymbol{k}^*)|\Psi^S_{k^*}(r^*,\boldsymbol{k}^*)|^2}{\int S(r^*,\boldsymbol{k}^*)}$$

where r^* is the pair relative separation at creation, k^* is the momentum of the first particle in the Pair Rest Frame, S is the source function giving the probability to emit a given pair from at a given separation. Ψ describes the interaction. For the Strong component it is the solution of the Quantum scatttering problem with the inverse time direction.

$$\Psi^S_{k^*}(r^*,\boldsymbol{k}^*)=e^{-ik^*r^*}+f^S(k^*)\frac{e^{-ik^*r^*}}{r^*}$$

where f is the scattering amplitude and the S superscript denotes spin dependence. Coulomb modifies this formula slightly, and it is (anti-)symmetrized for identical particles. The femtoscopic correlation function is then the particle emitting source viewed through the interaction lens.

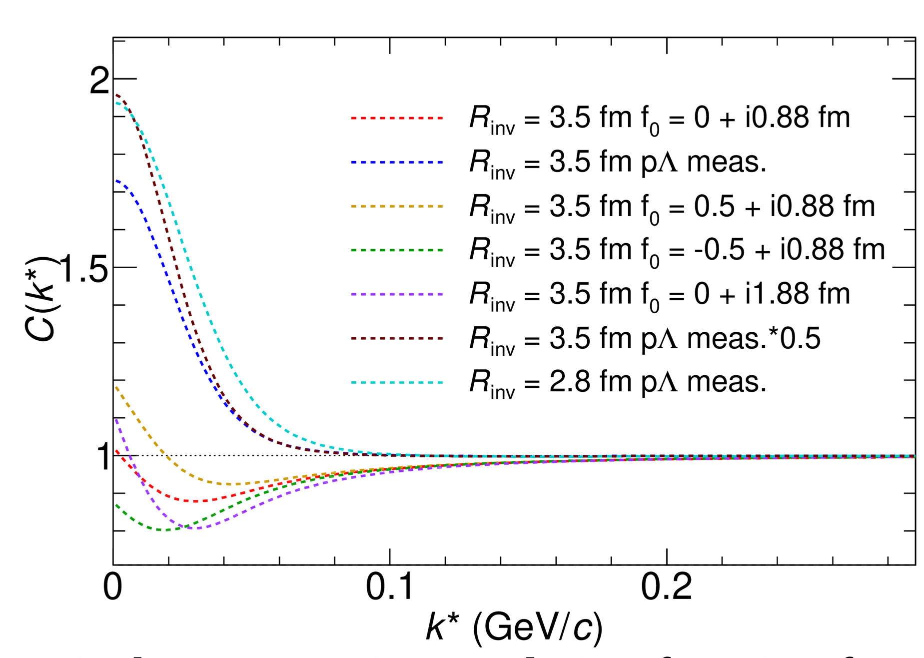

Figure 1 The strong FSI correlation function for selected interaction parameter sets.

Connection to cross-section

In the effective range approximation the scattering amplitude in the s-wave can be expressed as:

$$f^S(k^*)=\left(\frac{1}{f_0}+\frac{1}{2}d_0 k^{*2}-ik^*\right)^{-1}$$

where f_0 is the scattering length and d_0 is the effective range. The interaction cross-section σ is then simply:

$$\sigma=4\pi|f^S|^2$$

For a Gaussian source with directionally-averaged radius (width) r_0 the correlation function is then given analytically (F_1 and F_2 are known functions [2]):

$$C(k^*)=1+\sum_S \rho_S\left[\frac{1}{2}\left|\frac{f^S}{r_0}\right|^2\left(1-\frac{d_0}{2\sqrt{\pi}r_0}\right)+\frac{2\Re f^S}{\sqrt{\pi}r_0}F_1(2k^*r_0)-\frac{\Im f^S}{r_0}F_2(2k^*r_0)\right]$$

This functional form is fitted to the experimental femtoscopic correlation function and the f_0 and d_0 can be extracted as fitting parameters. However simultaneous fitting of r_0 as well is not possible. Fig. 1 shows that the function is sensitive to the value of the interaction parameters (for pΛ the known interaction parameters from experiment were used). The system size must be fixed in the fitting process, based on precise femtoscopic measurements for other pairs as well as on model assumptions on how the size changes between pairs of different mass. With that assumption the parameters can be extracted.

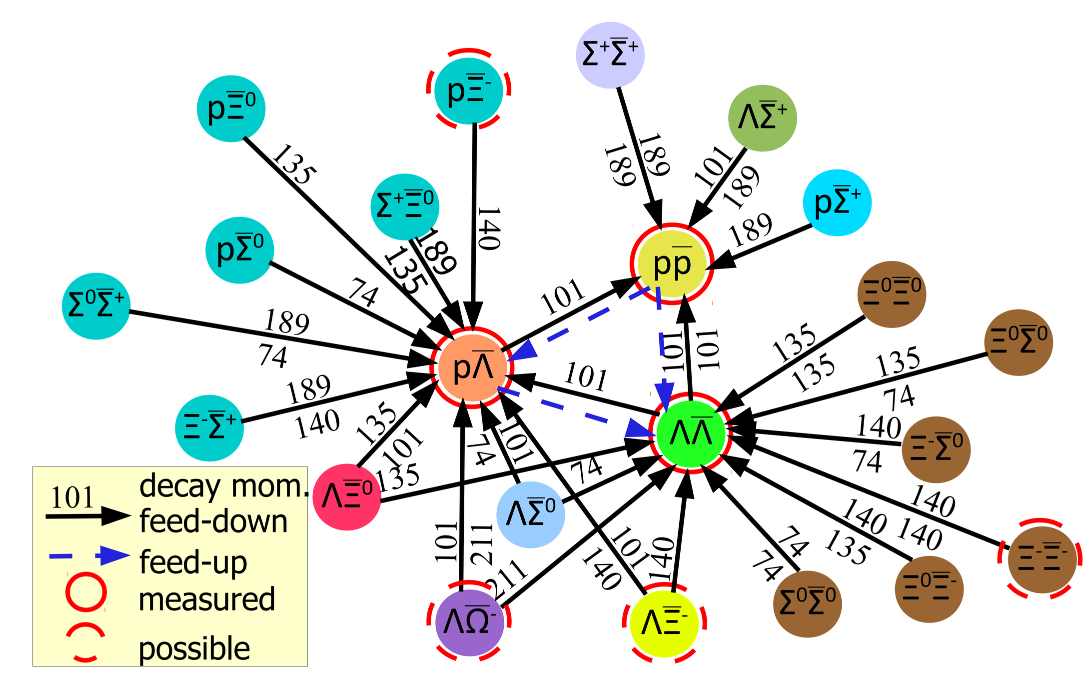

Figure 2: Residual correlation conributions

Residual correlations

A daughter of the weakly decaying baryon moves in a direction similar to the parent. Then the correlations for parent pairs are still visible for daugher pairs, which are a combination of several contributions of different possible parent pairs, as shown in Fig. 2. The effect is imporant if (a) the given decay produces significant percentage of the daughter particles and (b) the decay momentum is small with respect to daughter mass and (c) the parent interaction is strong. All three conditions are met for baryon pairs. The residual correlations are then taken into account in dedicated procedure [1] and can also provide some constraints on the interaction strength for parent pairs.

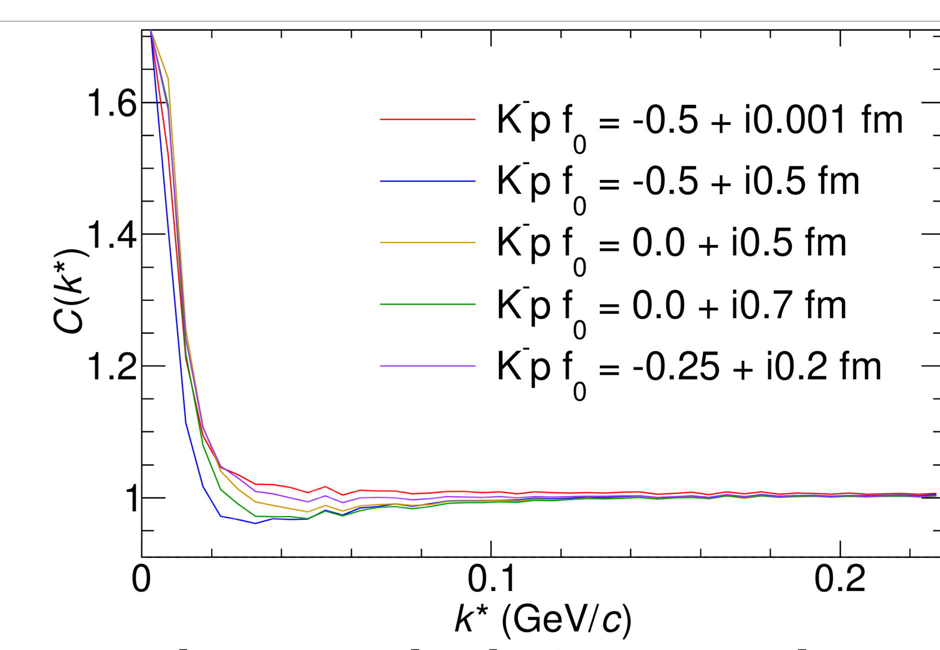

Figure 3: The K^-p Coulomb+Strong correlation function sensitive to interaction parameters

Kaon-proton correlation

The correlation for K^-p pairs comes from Coulomb interaction as well as the strong interaction containing the meson-baryon annihilation channel. This is the strangeness-baryonic matter interaction that is also the focus of intense investigation via the „kaonic atom" studies. In Fig. 3 example correlation functions are shown for different sets of interaction parameters. The correlation is clearly sensitive to the interaction cross-section. At LHC is should be possible to obtain data precise enough to distinguish between the values. It should be possible to measure in AA collisions at ALICE the real and imaginary component of f_0 to at least 0.5 fm precision.

Summary: The femtoscopic correlation function is directly sensitive to the parameters of the strong interaction potential parametrization and the interaction cross-section. For pairs of baryons the residual correlations coming from heavier (strange) baryon pairs must also be taken into account. Current experimental setup and datasample should allow for measurements of interactions of protons and lambdas in STAR and ALICE. Similarly the K^-p femtoscopic correlation function can be used to measure the relevant strong interaction, which may have direct consequences for the so-called „kaonic atom" studies, and the strangeness-baryon matter interaction problem. ALICE and STAR should enable such measurement with at least 0.5 fm precision for real and imaginary part of f_0.

References:

[1] A. Kisiel, H. Zbroszczyk, M. Szymański; "Extracting baryon-antibaryon strong interaction potentials from p$\bar{\Lambda}$ femtoscopic correlation functions"; Phys.Rev. C89 (2014) 5, 054916

[2] R. Lednicky, V.L. Lyuboshits; "Final State Interaction Effect on Pairing Correlations Between Particles with Small Relative Momenta"; Sov.J.Nucl.Phys. 35 (1982) 770, Yad.Fiz. 35 (1981) 1316-1330