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Studying the strong interaction with baryon-(anti)baryon femtoscopy in Pb-Pb collisions measured by ALICE

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Abstract.
The shape of the baryon-(anti)baryon femtoscopic correlation function is influenced by the size of the emission source, strong and Coulomb interactions and Quantum Statistics. Another factor introducing additional correlation structures is related to the residual correlations, which are related to the fact that baryons may come from decays of heavier particles. The correlation function of a given pair of baryons (for example $p\bar{p}$) is closely connected with correlation functions of other particles (such as $p\bar{\Lambda}$).
Analysing correlation functions of multiple baryon pairs simultaneously can further constrain measured strong scattering parameters. A newly developed fitting procedure allowing for a combined fit of several correlation functions is presented. The procedure was applied to 2.76 TeV and 5.02 TeV Pb-Pb data measured by ALICE. The analysis was performed for all combinations of (anti)protons and (anti)lambdas for different collision centralities.
Measured strong interaction parameters for $p\bar{\Lambda}$, $\Lambda\bar{\Lambda}$ and heavier baryon-antibaryon ($b\bar{b}$) pairs are shown and possible underlying physical processes are discussed.

1 Introduction

The strong interaction for (anti)baryons (particles composed of three quarks) is not well know. There have been only a few cross section measurements performed for baryon-baryon pairs: pp, pn, pd, $p\Lambda$ and $p\Sigma^-$ [1]. For baryon-antibaryon pairs there are even less data - measurements exist only for $p\bar{p}$, $\bar{p}n$ and $d\bar{p}$ [1]. This is mainly caused by the technical difficulty to form, accelerate and collide beams of heavier, short lived (anti)particles.

Heavy-ion collisions at relativistic energies allow for a study of interactions between (anti)baryons by looking at the collisions products, rather than at the particles scattered from the incoming beams. Experiments such as ALICE at the LHC detect nearly the same number of baryons and antibaryons at midrapidity, hence they are well suited for the study of the strong interaction.

What motivate the research presented in this work are several unanswered questions concerning the interaction between baryons and antibaryons, such as "is the strong potential attractive or repulsive for $b\bar{b}$ pairs?", "do pairs of non-identical baryons annihilate?" or "do bound states of baryon-antibaryon exist?". It will be shown that the recent measurements of ALICE and analysis method based on the femtoscopic correlations may help to find answers to these questions.

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1.1 Two-particle correlations at low relative momenta

The analysis performed in this study is based on femtoscopy - a technique of measuring correlation functions with respect to the relative momenta of particle pairs. Such distributions depend on the shape and size of the emission source, as well as on the interactions between the particles. The two-particle femtoscopic correlation function can be formally written as [2]:

$$C(k^*) = \int S(\bar{r^*}) \left|\Psi(\bar{k}^*, \bar{r}^*)\right|^2 d^4\bar{r^*} \tag{1}$$

where $S(\bar{r^*})$ is a source emission function, defining probability of producing two particles with given space-time separation $\bar{r^*}$ and $\Psi(\bar{k}^*, \bar{r}^*)$ is a pair wave function. The $\bar{k^*}$ vector is a momentum of one of the particles in the Pair Rest Frame (PRF).

In case of small relative momenta and spherically-symmetric potential, the pair wave function can be defined as the sum of the incoming plane wave and the outgoing spherical wave [3]:

$$\Psi(\bar{k^*}, \bar{r^*}) = e^{-i\bar{k}^*\bar{r}^*} + f(k^*)\frac{e^{ik^*r^*}}{r^*} \tag{2}$$

where $f(k^*)$ is the scattering amplitude that for small momenta and small potential length scales (the so-called effective range approximation) can be expressed in the following way [4]:

$$f(k^*) = \left[\frac{1}{f_0} + \frac{d_0 k^{*2}}{2} - ik^*\right]^{-1} \tag{3}$$

The scattering length f_0 and the effective range d_0 are parameters describing the strong potential. Measurement of these parameters is crucial to understand whether the strong interaction for the studied pairs is attractive or repulsive, whether annihilation channels for non-identical particles exist or not, and whether the creation of bound states is possible.

1.2 Measuring correlation functions in ALICE

ALICE [5] is one of the four major experiments at the LHC, designed to study heavy-ion collisions at relativistic energies. With its six-layer silicon tracker, Time Projection Chamber, Time Of Flight and Transition Radiation Detector, ALICE excels in the precise particle identification at low-momenta. As an example, a visualisation of a Pb-Pb collision registered by ALICE is shown in Fig.1.

Thanks to the similar amount of matter and antimatter being produced in heavy-ion collisions at the LHC and the great capability of the detector to measure particle momenta and to perform precise identification, ALICE is a perfect experiment for the study of interactions between baryons and antibaryons.

The experimental two-particle correlation function can be measured for particles produced in heavy-ion collisions using:

$$C(p_1, p_2) = \frac{P(p_1, p_2)}{P(p_1)P(p_2)} \tag{4}$$

where $P(p_1, p_2)$ is a probability of observing particles with momenta p_1 and p_2 in the same event, while $P(p_1)$ and $P(p_2)$ are probabilities of observing particles with such momenta independently. With this definition of the correlation function, some detector effects (e.g. connected to the limited detector's acceptance) cancel out in the ratio.

Correlation functions were measured for all combinations of (anti)protons and (anti)lambda baryons, at two collision energies in six centrality bins. This gives in total 72 correlation functions, including 36 baryon-antibaryon correlation functions. An example of the measured functions is presented in Fig.2.

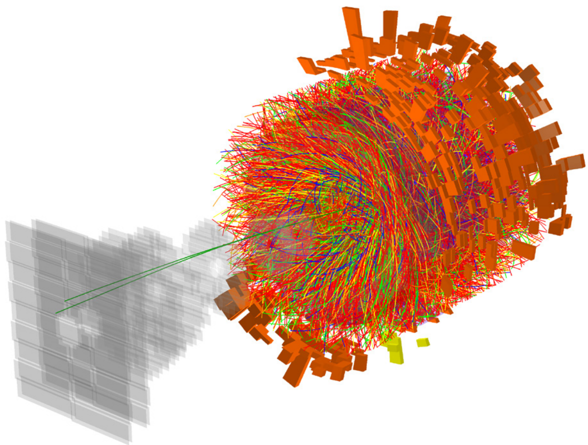

Figure 1. Visualisation of one of the first lead-lead collisions at 5.02 TeV per nucleon pair as seen by ALICE.

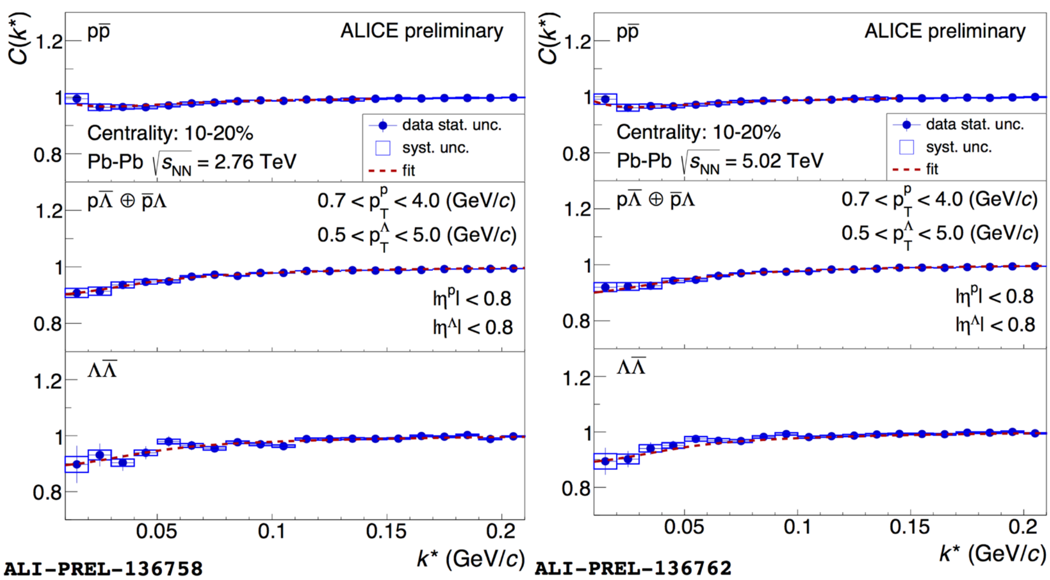

Figure 2. Example of baryon-antibaryon correlation functions measured by ALICE.

2 Description of the fitting procedure

The fitting was performed for all baryon-antibaryon correlation functions simultaneously. An appropriate form of the theoretical function was chosen depending on the type of particles, taking into account strong and Coulomb interactions and Quantum Statistics. Three sets of parameters were introduced, for $p\bar{\Lambda}$, $\Lambda\bar{\Lambda}$ and effective parameters for heavier $b\bar{b}$ pairs. In each set, three parameters were free in the fit: the real and imaginary part of the scattering length and the effective range.

The fitting procedure fully takes into account so-called residual correlations that are the consequence of the fact that a fraction of measured particles comes from decays of heavier ones. This is illustrated in Fig.3 on the example of pp correlation function. In this case, two protons are observed in the experiment and influence the shape of proton-proton correlation functions, but the interaction actually took place between the proton and the Λ baryon, which then decayed into proton and pion. Due to this effect, the final correlation function will be a sum of all residual components:

$$C(k^*) = 1 + \sum_i \lambda_i \left[C_i(k^*) - 1\right] \tag{5}$$

where $C(k^*)$ is the measured correlation function, λ_i are fractions of different residual components and $C_i(k^*)$ is the correlation function of the pair i.

The residual correlations significantly complicate the analysis, but they also allow to link different systems - for example, strong interaction parameters extracted from $\Lambda\bar{\Lambda}$ functions can be used for the residual components of the $p\bar{\Lambda}$ and $p\bar{p}$ functions (see Fig.3).

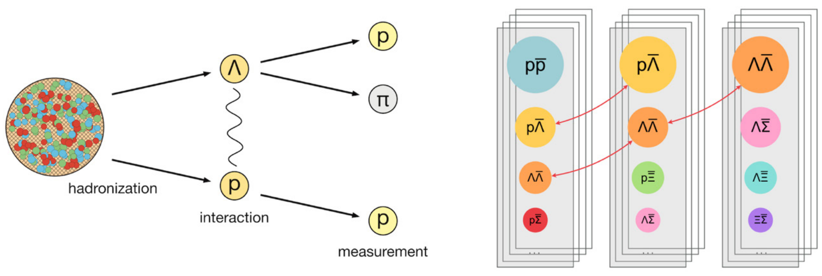

Figure 3. Left: Illustration of the residual correlations mechanism. Right: Illustration of the interlinks between different correlation functions through the residual components.

The source sizes were fixed in the fit. The femtoscopic radii scale as the cube root of multiplicity, which in turn depends on the collision centrality. This allows to link correlation functions for different centralities through the source sizes. An approximate scaling with the transverse mass m_T was also used to determine radii for baryon-antibaryon pairs based on previous measurements for pions, kaons and protons performed by ALICE [6]. In this analysis, the same scaling was used for the source sizes of the residual pairs, while previously the same radius was used for all residual components [7][8]. The functions were suitably normalised and non-femtoscopic background was corrected before fitting. The decay kinematics were taken into account for the residual components. The theoretical correlation functions were modified to take into account the limited momentum resolution of the detector [8].

3 Results of the analysis

Preliminary values of the measured strong interaction parameters for $p\bar{\Lambda}$, $\Lambda\bar{\Lambda}$ and heavier $b\bar{b}$, together with statistical and systematic uncertainties, are presented in Fig.4. A direct comparison with the values obtained from previous experiments and model predictions reveals good relative precision of the measurement. The extracted values of the interaction parameters for all baryon-antibaryon pairs are similar, the real part of the scattering amplitude is negative, the imaginary part is positive and the effective range is non-zero.

The imaginary part of the scattering length is associated with inelastic processes, in which the types of particles change [9]. The obtained results suggest that inelastic channels are present for all baryon-antibaryon pairs (even non-identical ones, such as $p\bar{\Lambda}$) and they have similar magnitude.

The negative real part of the scattering amplitude means that either strong interaction for baryon-antibaryon pairs is repulsive, or that bound states exist (such as $p\bar{\Lambda}$, $\bar{p}\Lambda$, $\Lambda\bar{\Lambda}$, $\Xi\bar{\Sigma}$ etc.). In the low energy limit there is no way to distinguish between these two interpretations. However, existence of the inelastic channels favors the bound state scenario, in which baryon-antibaryon form a bound state (negative $\Re f_0$) and then decay into e.g. three mesons (non-zero $\Im f_0$) [10].

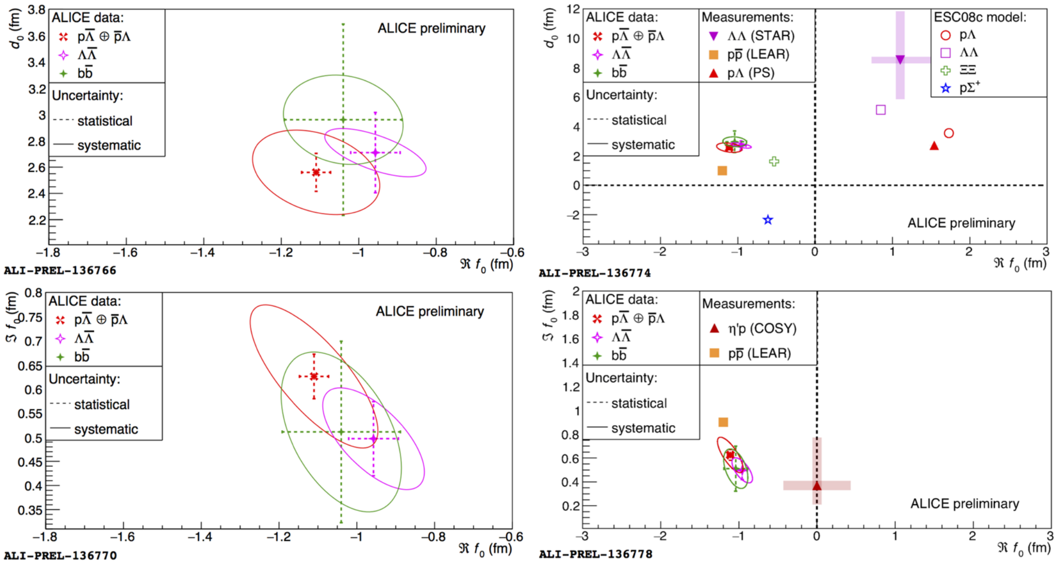

Figure 4. Left: Strong interaction parameters for different baryon-antibaryon pairs measured by ALICE. Right: Comparison of the obtained values with previous measurements and model predictions. Statistical and systematic uncertainties are shown with dashed and continuous lines respectively.

4 Conclusions

The correlation functions for all combinations of (anti)protons and (anti)lambda baryons were measured by ALICE in Pb-Pb collisions at 2.76 TeV and 5.02 TeV per nucleon pair. A new procedure was developed to fit simultaneously several systems, in centrality bins, taking into account residual correlations. The strong interaction parameters were measured for $p\bar{\Lambda}$, $\Lambda\bar{\Lambda}$ and heavier $b\bar{b}$ pairs.

The values of parameters which were obtained suggest that strong interaction for all $b\bar{b}$ pairs has similar properties and it is either repulsive, or it causes the formation of bound states. Inelastic channels are present for all $b\bar{b}$ pairs, including non-identical ones.

The presented results and their interpretation open further research paths in the direction of the bound states searching, or possible subtle spatial separation of baryons and antibaryons in heavy-ion collisions caused by a repulsive strong interaction.

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