

Measurements of $p - \Lambda$ and $d - \Lambda$ correlations in 3 GeV Au+Au collisions at STAR

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Abstract. Heavy-ion collisions provide a unique opportunity to explore nucleon-hyperon (N-Y) interactions through two-particle correlations. The $p - \Lambda$ and $d - \Lambda$ correlations shed light on both N-Y two-body and N-N-Y three-body interactions, which is crucial for understanding neutron star properties. We present the high precision measurement of $p - \Lambda$ and the first measurement of $d - \Lambda$ correlation with $\sqrt{s_{\text{NN}}} = 3$ GeV Au+Au collisions at STAR. Using the Lednicky-Lyuboshitz formalism, we characterized emission source size, the scattering length (f_0), and the effective range (d_0) of $p - \Lambda$ and $d - \Lambda$ interactions. Using the f_0 and d_0 extracted from two spin states in $d - \Lambda$ correlation, the parameters from the doublet state indicate the hypertriton binding energy is consistent with the current average of world measurements.

1 Introduction

While the nuclear force has been studied for many decades through classical scattering experiments, measuring the interactions between nucleon (N) and hyperon (Y) is found to be very challenging. Heavy-ion collisions is a well-designed laboratory to study the properties of the dense QCD matter. It offers us a new way to understand N-Y interactions by studying the two-particle correlation produced in a collision [1]. The correlations reveal valuable information about the space-time evolution of the particle-emitting source and final state interactions involving hyperons. That's the primary observable of interest in this proceedings.

The momentum correlation between two identified particles can be presented as follows,

$$C(\mathbf{p}_1, \mathbf{p}_2) \equiv \frac{P(\mathbf{p}_1, \mathbf{p}_2)}{P(\mathbf{p}_1) \cdot P(\mathbf{p}_2)}, \quad (1)$$

where the \mathbf{p}_1 and \mathbf{p}_2 are the momentum of particle 1 and 2. P is the probability of finding such particle or particle pair with that certain momentum. As for the experimental measurement, we used the following equation to get the correlation function, which is equivalent to Eq 1.

$$C(\mathbf{k}^*) = \mathcal{N} \frac{A(\mathbf{k}^*)}{B(\mathbf{k}^*)} = \int d^3r^* S(\mathbf{r}^*) |\Psi(\mathbf{r}^*, \mathbf{k}^*)|^2. \quad (2)$$

Here the $A(\mathbf{k}^*)$ is the distribution of \mathbf{k}^* with both particles from the same event, $B(\mathbf{k}^*)$ is for two particles from different events, and \mathcal{N} is the normalization factor. \mathbf{k}^* is the particle momentum in the pair rest frame. The correlation function can be expanded into the later

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31 part of Eq. 2. Here the $S(\mathbf{r}^*)$ is the distribution of the relative distance of particle pairs, the
 32 $\Psi(\mathbf{r}^*, \mathbf{k}^*)$ is the relative wave function of the particle pairs.

33 If we take a smoothness approximation for the source function and expand the wave
 34 function in the Eq. 2. We can get

$$C(\mathbf{k}^*) \approx 1 + \frac{|f(k)|^2}{2r_0^2} F(d_0) + \frac{2\text{Re}f(k)}{\sqrt{\pi}r_0} F_1(2kr_0) - \frac{\text{Im}f(k)}{r_0} F_2(2kr_0), \quad (3)$$

35 where,

$$\frac{1}{f(k)} \approx \frac{1}{f_0} + \frac{d_0 k^2}{2} - ik. \quad (4)$$

36 Here the r_0 is the radius parameter that defines the size of the source. In this study, the
 37 equivalent spherical Gaussian source radius of the particle pairs (R_G), which corresponds to
 38 the size of the emission source and r_0 , is used to compare the size between two correlation
 39 systems. f_0 and d_0 are the scattering length and effective range, which are the parameters to
 40 describe the interaction between two particles. F , F_1 , and F_2 are the parametric equations [2].
 41 This approach is called the Lednicky-Lyuboshitz (L-L) approach [3]. With this approach, we
 42 can characterize the source radius and final state interaction from the measured correlation
 43 function. For the correlation between two nonidentical particles, the system can have different
 44 spin states. The $p - \Lambda$ systems have singlet (S) and triplet (T) spin states [4], and the $d - \Lambda$
 45 systems have doublet (D) and quartet (Q) spin states [2]. The f_0 and d_0 can be different in two
 46 different systems. The effective f_0 and d_0 are also widely used to describe the correlations
 47 when the statistics cannot separate two different spin states.

48 2 Correlation function and discussions

49 The STAR (Solenoidal Tracker at RHIC) detector at RHIC (Relativistic Heavy Ion Collider)
 50 has collected many collision energies and systems over the two decades. For this study,
 51 we analyzed about 250M Au+Au collision events at center of mass energies per nucleon
 52 pair, $\sqrt{s_{NN}} = 3$ GeV which were collected in 2018 under the Fixed Target setup. We use the
 53 Time Projection Chamber (TPC) and the Time of Flight (ToF) detector to identify the pions
 54 (π), protons (p), and deuterons (d). We reconstructed the Λ with the KFPARTICLE package [5]
 55 using the π and p .

56 For the $p - \Lambda$ correlation measurement, we selected the p_T from 0.5 GeV/c to 2 GeV/c
 57 for both p and reconstructed Λ . We measured the correlation function in three rapidity ranges
 58 (-0.5 to 0 , -0.75 to -0.5 , and -1 to -0.75), and three different centralities (0-10%, 10-20%,
 59 and 20-60%). The measured functions are corrected based on particle purity, feed-down
 60 contributions, track splitting effect, track merging effect, and momentum smearing effect.
 61 The examples of corrected correlation functions in $-0.5 < y < 0$ for different centralities are
 62 shown in Figure 1. We applied a simultaneous fit to data in three different centralities and
 63 three different rapidities. The f_0 and d_0 are assumed to be the same for different centralities
 64 and rapidities, while the R_G are assumed to be different for different centralities and rapidities
 65 in the fitting. We got the spin-averaged $f_0 = 2.32_{-0.11}^{+0.12}$ fm and $d_0 = 3.5_{-1.3}^{+2.7}$ fm.

66 For the $d - \Lambda$ correlation measurement, we used the d selected in 0.6 GeV/c to 3 GeV/c,
 67 Λ in 0.4 GeV/c to 2.2 GeV/c for the p_T , and from -1 to 0 for the rapidity range. The mea-
 68 surements are corrected for particle purity, track splitting, and merging effect. The ${}^3_\Lambda H$ con-
 69 tamination (${}^3_\Lambda H \rightarrow d + p + \pi^-$) is also subtracted due to the indistinguishable experimental
 70 $p + \pi^-$ contribution to the Λ reconstruction. Evaluation with the measured ${}^3_\Lambda H$ yields show
 71 $4 \sim 8\%$ of the $d - \Lambda$ entries come from ${}^3_\Lambda H$ decay at $k^* < 100$ MeV/c in 10-20% centrality [6].
 72 The corrected $d - \Lambda$ correlation functions are shown in Figure 2. A simultaneous fit to data

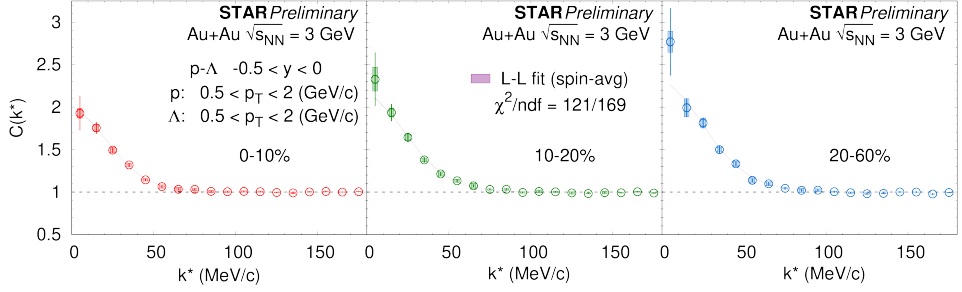


Figure 1. $p - \Lambda$ correlation measured in $-0.5 < y < 0$, and $0.5 < p_T < 2$ GeV. The purple band shows the spin-averaged fitting results.

73 in different centralities is shown in purple color. The fitting indicates $f_0(D) = -20^{+3}_{-3}$ fm,
 74 $d_0(D) = 3^{+2}_{-1}$ fm, $f_0(Q) = 16^{+2}_{-1}$ fm, and $d_0(Q) = 2^{+1}_{-1}$ fm.

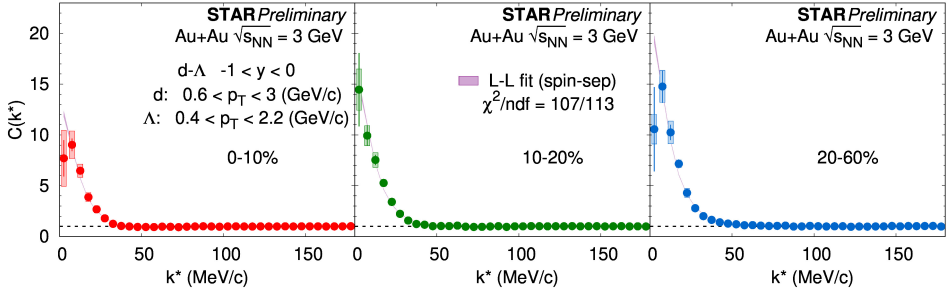


Figure 2. $d - \Lambda$ correlation measured in $-1 < y < 0$. The purple band shows the spin-separated fit for both D and Q states.

75 The left plot of Figure 3 shows the R_G extracted from the correlation functions. We
 76 successfully separated the emission source from the final state interaction. The observed
 77 R_G is larger in more central collisions than the peripheral collisions. We also observed at a
 78 certain centrality, the R_G for $d - \Lambda$ correlation is slightly smaller than for the $p - \Lambda$ correlation.
 79 These observations generally agree with our naive collision dynamics pictures that the central
 80 collision creates a bigger source, and if all the particles are produced at the same moment, the
 81 heavier particles fly slower so that the corresponding equivalent source is smaller for $d - \Lambda$.

82 The right-side plot of Figure 3 shows the 1σ , 2σ , and 3σ contour of the f_0 and d_0 for
 83 both systems. The green solid points show the theory predictions of the f_0 and d_0 for S and
 84 T states in $p - \Lambda$ [4], and the purple points show the theory predicted D and Q states for
 85 $d - \Lambda$ [2]. The constraint of the d_0 is weaker because it characterizes the second order effect
 86 as shown in Eq. 4. The larger magnitude f_0 in $d - \Lambda$ indicates a much stronger correlation
 87 and larger cross-section than the $p - \Lambda$. The negative $f_0(D)$ indicates a bound state for $d - \Lambda$
 88 systems which is the $^3_{\Lambda}\text{H}$.

89 Using $f_0(D)$, $d_0(D)$, and the Bethe formula from Effective Range Expansion (ERE), we
 90 could estimate the $^3_{\Lambda}\text{H}$ binding energy. We got $^3_{\Lambda}\text{H } B_{\Lambda} = [0.04, 0.33]$ (MeV) at 95% CL. The
 91 result is consistent with the current world average [7]. This measurement provides us with a
 92 new way to constrain the $^3_{\Lambda}\text{H}$ structure.

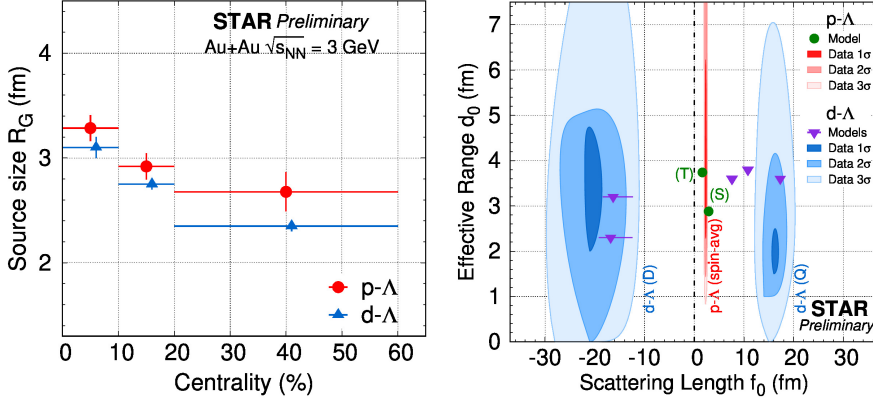


Figure 3. Left: Spherical Gaussian source of pairs (R_G); Right: scattering length (f_0) and effective range (d_0) with 1σ , 2σ , and 3σ from $p-\Lambda$ and $d-\Lambda$ correlations. The parameters are estimated using the Lednicky-Lyuboshitz (L-L) approach. Bezier smooth is applied to the right side contour plot for $d-\Lambda$ correlation to improve the visibility.

3 Summary

The $p-\Lambda$ correlation function is measured using the $\sqrt{s_{NN}} = 3$ GeV Au+Au collisions from RHIC Beam Energy Scan II. The $d-\Lambda$ correlation is measured for the first time in the experiment. The emission source is successfully separated from the final state interactions. The R_G is larger in central than peripheral collision, and slightly smaller in $d-\Lambda$ correlation than $p-\Lambda$ correlation. The spin-averaged f_0 and d_0 is extracted to be $2.32^{+0.12}_{-0.11}$ fm and $3.5^{+2.7}_{-1.3}$ fm in $p-\Lambda$ correlation. The effective fit showed $f_0(D) = -20^{+3}_{-3}$ fm, $d_0(D) = 3^{+2}_{-1}$ fm, $f_0(Q) = 16^{+2}_{-1}$ fm, and $d_0(Q) = 2^{+1}_{-1}$ fm in $d-\Lambda$ correlation. This measurement indicates the ${}^3_{\Lambda}\text{H}$ binding energy to be 0.04 to 0.33 MeV at 95% CL, which provides a new method to study the hypernuclei structure in the heavy-ion collision experiment.

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