Measurements of $\Lambda \Lambda$ correlation function in heavy-ion collisions at RHIC

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Abstract. The information on the hyperon-hyperon interaction is crucial for our understanding of baryon-baryon interactions in hot and dense medium from high-energy nuclear collisions. In this proceeding we discuss the measurement of the $\Lambda \Lambda$ correlation function from the STAR experiment and the status of an $H$-dibaryon search based on this measurement.

1. Introduction

Based on a bag-model calculation, R. Jaffe [1] predicted a deeply bound state, $H$-dibaryon, with isospin ($I$) = 0 and strangeness ($S$) = -2. Lattice QCD calculations from the HAL [2] and NPLQCD [3] collaborations indicate existence of a bound $H$-dibaryon for pion masses larger than the physical mass, while chiral extrapolation to a physical quark mass leads to an unbound $H$-dibaryon [4]. Since its prediction, many experimental searches and theoretical calculations have been performed. Various experiments have explored the $\Lambda \Lambda$, $\Sigma p$ and $\Lambda p\pi$ invariant mass spectrum to look for an $H$-dibaryon signal. However the results from those experiments did not have enough statistical significance to establish any conclusion about its existence [5, 6, 7, 8].

At present, the constraint on the binding energy for the $H$-dibaryon comes from the so-called Nagara event: measurement of $6 \Lambda \Lambda$ He candidate with very small binding energy [9]. The observed enhancement in $\Lambda \Lambda$ invariant mass spectrum from the KEK-E522 experiment [5] showed that it is important to understand the interaction between two $\Lambda$s to extract an $H$-dibaryon signal.

At the densities in the interior of neutron stars, the neutron chemical potential exceeds the mass of various members of the baryon octet. Therefore, in addition to nucleons and electrons, abundant hyperons are expected to exist in neutron stars [10]. If the $\Lambda \Lambda$ interaction is attractive enough, a significant fraction of $\Lambda$s in a neutron star may combine to form $H$-dibaryons. If the densities are high enough, this could lead to the formation of $H$-matter in the core of moderately dense neutron stars [11]. The knowledge of the strength of the $\Lambda \Lambda$ interaction will improve our understanding of the equation of state for neutron stars.

Measurements of the correlation function for a pair of particles with small relative momenta have been used to get insight into the geometry and lifetime of the particle-emitting source in relativistic heavy-ion collisions [12]. These measurements are sensitive to the separation distribution of the source, as well as effects from quantum statistics (QS) and interactions in the final state (FSI). This allows one to use the measurement of a two particle correlation function to get information about the final state interactions between two particles and the $H$-dibaryon signal. In 2015, the STAR experiment published the first high statistics measurement of the $\Lambda \Lambda$ correlation function [13], which provided a better constraint on the $\Lambda \Lambda$ interaction parameters.
2. $\Lambda$ reconstruction

Identification and momentum determination for the $\Lambda$ particle was carried out with the Time Projection Chamber. The decay channel $\Lambda \rightarrow p\pi$ with a branching ratio of 63% was used for the reconstruction of $\Lambda$. The $\Lambda$ candidates were formed out of a pair of positive ($p$) and negative ($\pi$) tracks whose trajectories point to a common secondary decay vertex which was well separated from the primary vertex. The decay length of $\Lambda$ candidate was asked to be more than 5 cm and the distance of closest approach from the primary vertex was taken to be less than 0.4 cm. Approximately $2.87 \times 10^8$ events from the year 2010 run and $5.0 \times 10^8$ events from the year 2011 run were analyzed. The invariant mass distribution of the $\Lambda$ and $\bar{\Lambda}$ candidates at 0-80% centrality under these conditions are shown in Fig. 1. It has an excellent signal (S) to background (B) ratio of $S/(S+B) \approx 0.97$. All candidates with invariant mass between 1.112 and 1.120 GeV/$c^2$ were used in the correlation analysis.

3. $\Lambda\Lambda$ interactions

The combined $\Lambda\Lambda$ and $\bar{\Lambda}\bar{\Lambda}$ correlation function as a function of relative momentum (Q) for 0-80% centrality is shown in Fig. 2. The systematic error is shown separately as a shaded band in Fig. 2 and the dotted line corresponds to QS with a source size of 3.13 fm. The following
function from Lednický and Lyuboshitz analytical model [14] was used to fit the correlation function data

\[ C(Q) = N[1 + \lambda(\frac{1}{2} \exp(-r_0^2 Q^2) + \frac{1}{4} \frac{|f(k)|^2}{r_0^2}(1 - \frac{1}{2\sqrt{\pi}} \frac{d_0}{r_0}) + \frac{\text{Re} f(k)}{\sqrt{\pi}r_0} F_1(Qr_0) - \frac{\text{Im} f(k)}{2r_0} F_2(Qr_0))] \tag{1} \]

where \( k = Q/2 \), \( F_1(z) = \int_0^1 e^{x^2-z^2}/z \, dx \) and \( F_2(z) = (1 - e^{-z^2})/z \) in Eq. (1). The scattering amplitude is given by

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

where \( f_0 = a_0 \) is the scattering length and \( d_0 = r_{\text{eff}} \) is the effective range. Note that a universal sign convention is used rather than the traditional sign convention for the s-wave scattering length, \( a_0 = -f_0 \) for baryon-baryon systems. More details about the model can be found in Ref. [14]. The free parameters of the LL model are the normalization \((N)\), a suppression parameter \((\lambda)\), an emission radius \((r_0)\), scattering length \((a_0)\) and effective radius \((r_{\text{eff}})\). In the absence of FSI, \( \lambda \) equals unity for a fully chaotic Gaussian source. The impurity in the sample used and finite momentum resolution can suppress the value of \( \lambda \)-parameter. In addition to this the non-Gaussian form of the correlation function and the FSI between particles can affect (suppress or enhance) its value.

A fit to data using the above equation gives a larger \( \chi^2/\text{NDF} \) (dashed line in Fig. 2). Also, the obtained \( r_0 \) is much smaller than the expected \( r_0 \) from previous measurements [15, 16, 17], which suggests that the measured correlation is wider than that indicated by the fit in this scenario.

One possible explanation for this is the presence of a negative residual correlation in the data, which is expected to be wider than the correlation from the parent particles like \( \Sigma^0 \) and \( \Xi \). Therefore a Gaussian term \( a_{\text{res}} \exp(-Q^2 r_{\text{res}}^2) \) is added in Eq. (1), shown as the solid line in Fig. 2, where \( a_{\text{res}} \) is the residual amplitude and \( r_{\text{res}} \) is the width of the Gaussian. A negative residual correlation contribution is required with \( a_{\text{res}} = -0.044 \pm 0.004^{+0.048}_{-0.009} \) and \( r_{\text{res}} = 0.43 \pm 0.04^{+0.43}_{-0.03} \) fm. The fit parameters obtained with the residual correlation term are \( N = 1.006 \pm 0.001, \lambda = 0.18^{+0.05+0.12}_{-0.05-0.06}, a_0 = -1.10^{+0.37+0.68}_{-0.27-0.08} \) fm, \( r_{\text{eff}} = 8.52^{+2.56+2.99}_{-2.56-0.74} \) fm and \( r_0 = 2.96^{+0.38+0.96}_{-0.38-0.32} \) fm with \( \chi^2/\text{NDF} = 0.56 \).

From the scattering length and the effective radius obtained from the model fit we conclude that \( |a_{\Lambda\Lambda}| < |a_{p\Lambda}| < |a_{NN}| \), as shown in Fig. 3. This means that a weaker interaction exists between \( \Lambda \Lambda \) pairs compared to nucleon-nucleon and proton-hyperon. In case of a resonance state that decays to two \( \Lambda \) particles, one would expect to observe a peak structure in the two-particle correlations [22]. However, our data does not show such a peak in the correlation function for the relative momentum above 0.3 GeV/c. Numerical analysis of the final-state interaction effect using an s-wave scattering amplitude suggests the non-existence of a \( \Lambda \Lambda \) resonance saturating the s-wave below the \( N\Xi \) and \( \Sigma\Sigma \) thresholds (for more details please refer to ref [13]).

Assuming that \( H \)-dibaryons are produced through coalescence of \( \Lambda \Lambda \) pairs, the yield for the \( H \)-dibaryon can be related to the \( \Lambda \) yield by \( d^2N_H/(2\pi p_Tdp_Tdy) = 16B(d^2N_\Lambda/(2\pi p_Tdp_Tdy))^2 \), where \( B \) is a constant known as the coalescence coefficient. We obtain the upper limit for the \( p_T \)-integrated \( dN_H/dy = (1.23 \pm 0.47_{\text{stat}} \pm 0.61_{\text{sys}}) \times 10^{-4} \) [13].
4. Summary
We report \( \Lambda \Lambda \) correlation function from Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) at RHIC. Weakly attractive interaction between \( \Lambda \) is observed. The measured interaction parameter suggests the non-existence of \( \Lambda \Lambda \) resonance below the \( N \Xi \) and \( \Sigma \Sigma \) thresholds. We also obtained an upper limit on the \( H \)-dibaryon cross section in such collisions [13].

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