Two-Pion HBT Analysis on Central Au+Al Fixed Target Collisions at STAR

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Collisions between gold nuclei and the aluminum beam pipe at RHIC have been registered by the STAR detector. Particles produced in these background collisions have been identified and used in various analyses. In this case, Hanbury-Brown Twiss (HBT) correlations between negatively charged pions were produced. Preliminary results of the correlation functions produced in this analysis suggest that information regarding the particle emission region can be extracted in a fixed target configuration at STAR.

I. Heavy-Ion Physics at RHIC

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab has been accelerating and colliding nuclei such as gold, copper, and uranium since 2001 in an effort to study a phase of nuclear matter called the Quark-Gluon Plasma (QGP). Studying the QGP is an important task, as it is the only way to experimentally study Quantum Chromodynamics, the theory of the Strong Force, in the lab. The QGP exists at extreme temperatures and densities, which are only attainable in the lab by colliding heavy nuclei moving at relativistic speeds.

A. Fixed Target Collisions at STAR

As a result of there being multiple phases of nuclear matter, it is of interest to study transitions between these phases. It is possible that a first-order phase transition exists between the QGP and hadronic gas at energies lower than currently attainable through the Beam Energy Scan (BES) at RHIC. Fortunately, there is a relatively simple approach to reaching lower energies: collide nuclei with a fixed target. But before installing a target, it is worthwhile to understand the types of analyses that can be done in a fixed target setup. This is essential when considering that the Solenoidal Tracker at RHIC (STAR) detector, which is the focus of this analysis and the site of the proposed gold target, was designed solely for beam-on-beam collisions. One analysis of interest reveals spatial and temporal information about the particle emission region from a collision via the Hanbury-Brown Twiss Effect.

II. Theory behind HBT Analysis [3]

The fireballs resulting from nuclear collisions are on the femtometer scale, so there needs to be an indirect way of gaining information about these particle emission regions. One such method of measuring the size of these regions is through the HBT effect, which was originally applied to finding the angular size of distant stars. The Hanbury-Brown Twiss effect is the space-time or energy-momentum correlation of detected identical particles emitted from an extended source [1]. In regard to the analysis, this means that if a pion is emitted, it is likely that another pion was emitted with similar momentum. HBT correlations only exist with chaotic sources, and the emission of pions from a heavy-ion collision is considered to be chaotic [1]. The difference between a coherent and chaotic pion source is analogous to the difference between a laser and a star in regard to light sources; one extreme consists of particles with identical phases, while the other extreme has particles of completely random phases.

Ultimately, the momentum correlation comes as a consequence of studying identical particles. The correlation function comes from taking into account the propagation (i.e., the wavefunction) of two pions at two separate production points to two detection points and the symmetry from exchanging the identical particles. The correlation function $C_2(\mathbf{p_1}, \mathbf{p_2})$ is defined as the ratio of the probability of coincidence of measuring particles with momenta $\mathbf{p_1}$ and $\mathbf{p_2}$ relative to observing $\mathbf{p_1}$ and $\mathbf{p_2}$ separately [1],

$$C_2(\mathbf{p_1}, \mathbf{p_2}) = \frac{P(\mathbf{p_1}, \mathbf{p_2})}{P(\mathbf{p_1})P(\mathbf{p_2})}. \tag{1}$$

From analyzing the probability amplitude of the identical particles propagating from two production points to two detection points, the correlation function is shown to have the form [1]

$$C_2(\mathbf{p_1}, \mathbf{p_2}) = 1 + |\tilde{\rho}(q, \mathbf{p_1}\mathbf{p_2})|^2, \tag{2}$$

where $\tilde{\rho}$ is the Fourier transform of the effective density of the chaotic source and q is the relative 4-momentum between a pair of pions. This density function is related to the phase-space configuration at the time of emission, so when the correlation function is known, information about the phase-space can be extracted.

III. Event Selection

The data used in the analysis come from several thousand events over many runs at RHIC. The events were recognized as collisions between gold nuclei and the aluminum beam pipe. The collisions occurred at the lowest energies of the BES-I, 7.7, 11.5, and 19.6 GeV, which correspond to center of mass energies of 3.0, 3.5, and 4.5 GeV, respectively. All events occurred between -200 cm $\leq V_z \leq -150$ cm from the center of STAR Time Projection Chamber (TPC) and 2 cm $\leq V_r \leq 5$ cm from the center of the beam in the radial direction. Particles were also required to have $\sum_{Tracks} p_z$(momentum in the direction of the beam) > 0, meaning the particles were traversing from the left side of the detector to the right. The requirements on z-vertex and z-momentum ensured sufficient distance for particle identification in the TPC, while radial requirement for the vertex meant that these were beam pipe events. Additionally, the 10% most central collisions, determined by pion multiplicity, were studied. The centrality cut provides confidence that we are looking at nucleus-nucleus collisions and not a collision between a nucleus and a fragment of another nucleus.

IV. HBT Correlations from Experimental Data

In order to produce a correlation function using experimental data, one uses equation (1). The probability of measuring the particles in coincidence is simply referred to as the numerator, and the probability of measuring them separately is the denominator. The numerator is found by calculating the relative 4-momentum of pairs of pions in an event. In a given event, there is expected to be an enhanced probability of measuring pions with similar momenta, or small relative momentum. On the other hand, the denominator is formed by finding the relative momentum of pions in different events. The background is formed by looking at different events because pions produced in different events are not related and thus should not have similar momenta.

A. Particle Identification

Since producing an HBT correlation relies on comparing identical particles, the first task is to identify particles and select only the ones that are to be compared. Pions are of interest not only because they are the most common type of particle emitted, but also since they are bosons. The fact that pions are bosons means they can exist in the same quantum state and have similar momenta. In this particular analysis, negatively charged pions were compared, so the first criterion was for the particle to be negatively charged. Some of the remaining electrons were removed using a cut on the number of standard deviations away from the ideal pion curve on an energy loss plot. Particles falling beyond 1.5 times the standard deviation were rejected. The results of making cuts are visualized on two different plots, which can verify the identity of a particle.

1. Energy Loss vs. Momentum

One way of visually checking cuts made on particles is through an energy loss per unit distance versus momentum plot. The basis for this plot is that at the same momentum, different particles will have different rates of energy loss; that is, they will ionize gas in the TPC differently. This means there will be separate curves for each type of particle that was registered by the STAR detector. Figure 1 shows curves for all the particles detected in 3.0 GeV Au+Al collisions and figure 2 shows the remaining pion band after making cuts.

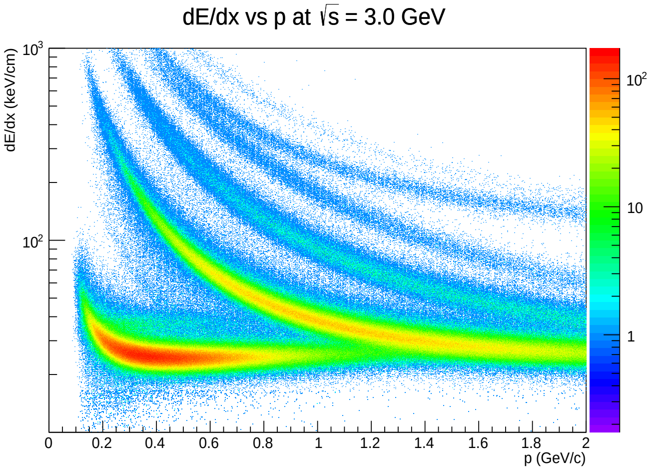

FIG. 1. Plot of energy loss in the TPC for all charged particles.

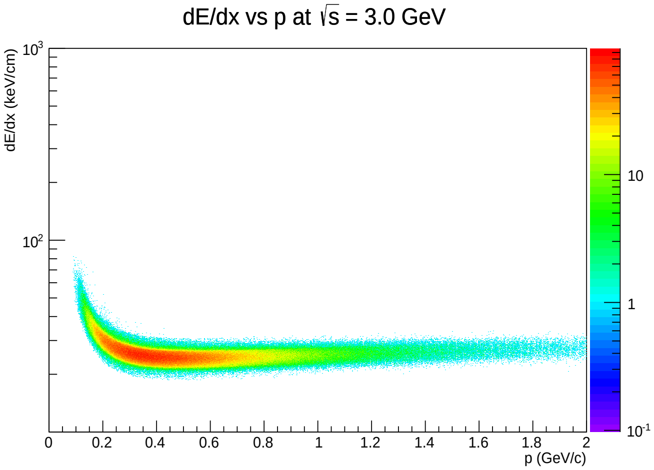

FIG. 2. Plot of energy loss in the TPC for negatively charged pions.

2. Time of Flight vs. Momentum

Another way of accomplishing particle identitification is by comparing $1/\beta$ with momentum, where $\beta = \frac{v}{c}$. From the definition of relativistic momentum, one can easily show

$$\frac{1}{\beta} = \frac{\sqrt{m^2 + \mathbf{p}^2}}{|\mathbf{p}|}. \tag{3}$$

Using the relationship in equation (3), a particle's identity can be verified by substituting the mass of the particle. Figure 3 verifies that the criteria used to identify pions are correct, since substituting $m_{\pi^-} = 0.1396$ GeV$/c^2$ into equation (3) nicely fits the remaining band.

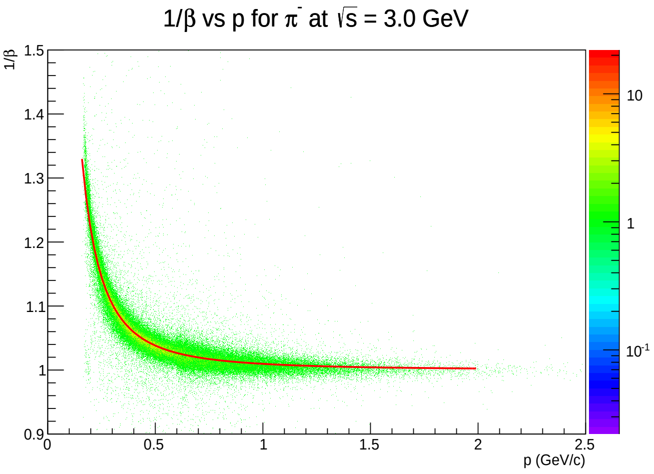

FIG. 3. The red line is the predicted pion curve.

B. Sorting Particles by Event

The particles identified as pions are sorted by event. Since the numerator and denominator of the correlation function depend on comparing particles in specific events, one must know exactly what particles belong to which events.

C. Producing the Numerator, Denominator, and Correlation Function

The magnitude of the relative 4-momentum q_{inv} of pairs of particles can be computed by [4]

$$q_{inv} = \sqrt{(E_1 - E_2)^2 - (\mathbf{p_1} - \mathbf{p_2})^2}. \tag{4}$$

The components of momentum in the transverse and longitudinal directions are recorded by the detector, and the energy of a particle is computed from its momentum and mass. For the numerator, one calculates q_{inv} for each possible pair within a single event. For the denominator, an event is selected, and the relative momentum is calculated for each possible pair of particles between the selected event and the following ten events. Histograms for the numerator and denominator are shown in figures 4 and 5, respectively. The histogram for the numerator is divided by the histogram for the denominator, and this results in another histogram - the correlation function.

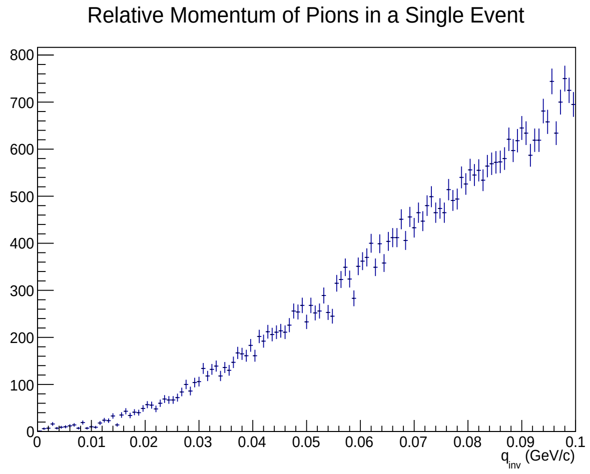

FIG. 4. The numerator of the correlation function produced from pairs within events.

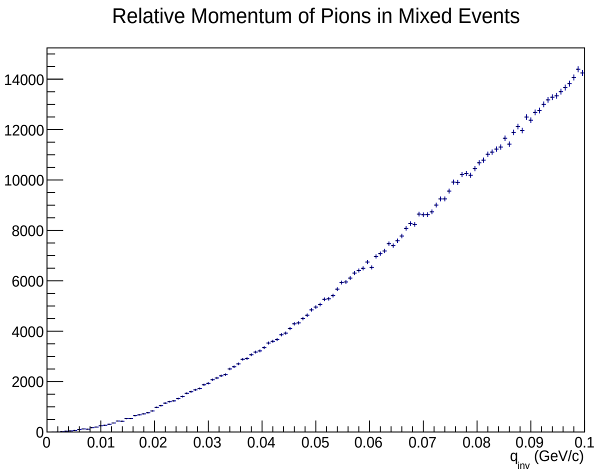

FIG. 5. The denominator of the correlation function produced from mixed pairs.

D. Extracting Results from Correlation Function

The resulting histogram is fit with a Gaussian centered at zero and its parameters are extracted. The width of the Gaussian is extracted to obtain information such as

R_{inv}, the radius of the region of homogeneity and τ, the mean lifetime of the emission region.

V. Results

At this point, results regarding the size of the emission regions in fixed Au+Al collisions are not conclusive. While correlation functions produced during the course of this research have general features of a typical two-pion correlation, fits to the current plots do not yield results similar to those from previous experiments. The Gaussian fit to the correlation function should have an amplitude of at most 1 and is expected to be wider than it currently is. Further work is needed to improve results.

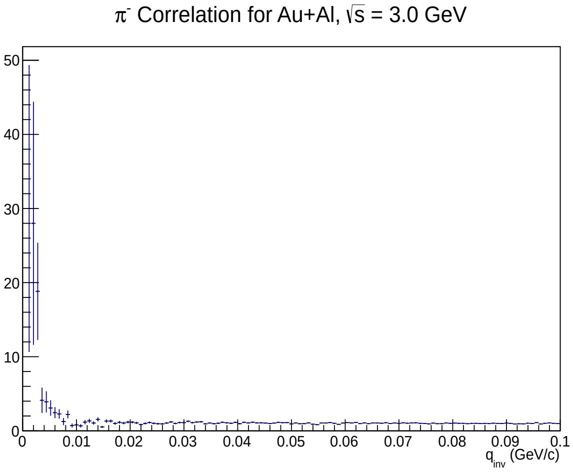

FIG. 6. The correlation function produced from the numerator and denominator histograms.

VI. Future Work

A. Split and Merged Tracks

One of the main concerns while performing HBT analyses is producing artificial correlations or anticorrelations through mixing certain pairs of particles. For instance, a single particle may be read by the detector as two separate tracks, which of course will both have nearly the same momentum. Another concern is when two particles in separate events nearly overlap one another. In a given event, the detector does not actually have the resolution to distinguish two tracks that lie on top of one another. Therefore, pairs that lie on top of one another in mixed events need to be eliminated. In either case, data sets including the spatial coordinates of each track in the TPC need to be used as the analysis is continued to eliminate possible detector effects.

B. Comparison to Simulated Data

Simulations of Au+Al collisions under similar conditions have been done in both UrQMD and GEANT. It has been shown that data from UrQMD can be used appropriately for two-pion HBT correlations [2]. Knowing this, the UrQMD data obtained for Au+Al collisions can be used for the HBT analysis and compared to results from the experimental data.

VII. Acknowledgements

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