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Femtoscopy with unlike-sign kaons at STAR in 200 GeV Au+Au collisions

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Abstract.
In the collisions of heavy ions the nuclear matter can undergo a phase transition from hadrons to a state of deconfined quarks and gluons called the Quak-Gluon Plasma. Femtoscopic measurements of two-particle correlations at small relative momenta reveal information about the space-time characteristics of the system at the moment of particle emission. The correlations result from quantum statistics, final-state Coulomb interactions, and the strong final-state interactions between the emitted particles.
It has been predicted that correlations due to the strong final-state interactions in a system where a narrow resonance is present will be sensitive, in the region of the resonance, to the source size and momentum-space correlations. Such a measurement can provide complementary information to the measurements at very low relative momenta. This paper presents the preliminary results of a STAR analysis of unlike-sign kaon femtoscopic correlations in Au+Au collisions at $\sqrt{s_{\rm NN}}$=200 GeV, including the region of $\phi(1020)$ resonance. The experimental results are compared to a theoretical prediction that includes the treatment of resonance formation due to the final-state interactions.

1 Introduction

In 1960 Goldhaber and collaborators observed in proton-antiproton annihilations an excess of pairs of identical pions produced at small relative momenta [1]. These observed correlations, as experimenters correctly asserted, came as a result of quantum statistics. Based on this observation the theoretical background of femtoscopy was developed by G. I. Kopylov and M. I. Podgoretsky in the 1970s [2]. Since then the femtoscopic measurements of two-particle correlations at low relative momenta became a standard tool for extracting the space-time extents of particle emitting sources. Nowadays femtoscopic studies include identical particles, as well as non-identical interacting particles [3–6].

The approach proposed by Lednicky [7] extends the femtoscopic formalisms to higher relative momenta between the two emitted particles in a system where the final-state interactions (FSI) contain a narrow, near-threshold, resonance. It is predicted that the correlation function will be more sensitive in the region of the resonance, where the strength of the correlation should change with the source size,

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r as $\sim r^{-3}$ in comparison with measurements at the very low relative momenta, where the correlation function depends on r^{-2} or r^{-1}. In addition, these measurements will be statistically advantageous, since the particle spectra fall rapidly at low relative momenta.

Pairs of unlike-sign kaons are ideally suited for such femtoscopic analysis as they contain the narrow $\phi(1020)$ resonance. The $\phi(1020)$ resonance is characterized by the decay width $\Gamma = 4.3$ MeV and the decay momentum in the rest frame $k^* = 126$ MeV/c. The use of kaons is also advantageous due to the fact that the emission source function is less affected by weak decays of resonances. From previous STAR source imaging analysis [4], the kaon source function is known to be well-described by a Gaussian form.

2 Data analysis

The data used for this analysis were collected in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV by the Solenoidal Tracker at RHIC (STAR) in 2011. The STAR [8] is a multi-purpose detector, which excels in tracking and identification of charged particles at mid-rapidity with full coverage in azimuthal angle. The most important subdetectors for this analysis are the Time Projection Chamber (TPC) [9] and the Time of Flight (ToF) [10]. The TPC records charged particle tracks and measures their momentum p and identifies them via specific ionization loss dE/dx. For kaon selection, the particles were required to have $|n\sigma_K| < 3$, where $n\sigma_K$ is the distance from the expected mean $<\mathrm{d}E/\mathrm{d}x>$ expressed in terms of standard deviation units σ_K. The ToF measures particle velocity β which is used to calculate particle mass m according to the relation

$$\frac{1}{\beta} = \sqrt{1 + m^2/p^2}, \tag{1}$$

where the momentum p is measured by the TPC. Due to a good time resolution, which is less than 100 ps, the ToF is able to separate charged kaons from other hadrons up to $p \sim 1.55$ GeV/c, as shown in Figure 1. Due to this fact, only primary tracks at mid-rapidity $|\eta| < 1$ with momentum $p \in [0.15, 1.55]$

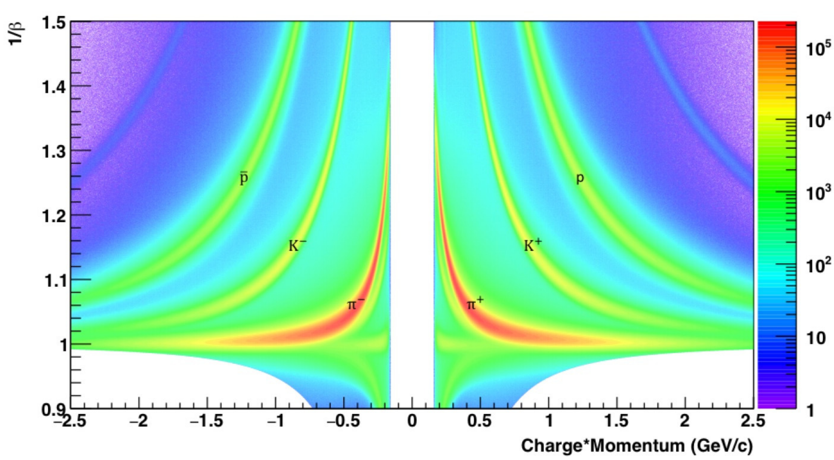

Figure 1. The relative velocity$1/\beta$ (from ToF) of charged particle as a function of momentum p (from TPC).

GeV/c, which have signal from the ToF and satisfy cut criteria on mass: $0.21 < m^2 < 0.28$ GeV^2/c^4 were used here.

3 Construction of correlation function

Experimentally, the two-particle correlation function $CF(q_{inv})$ is constructed as a ratio of the correlated two-particle distribution from the same event, $N_{same}(q_{inv})$, and the uncorrelated two-particle distribution from mixed events, $N_{mixed}(q_{inv})$:

$$CF\left(q_{inv}\right) = \frac{N_{same}(q_{inv})}{N_{mixed}(q_{inv})} = \frac{real\ pairs}{mixed\ pairs}, \tag{2}$$

where $q_{inv}^2 = -(p_1^\mu - p_2^\mu)^2$. In the pair rest frame $q_{inv} = 2k^*$. The technique of event mixing is used to obtain the uncorrelated two-particle distribution. The events are mixed within sub-classes with similar values of the primary vertex position along the beam direction and the multiplicity.

4 Unlike-sign 1D correlation functions

In this analysis, the correlation functions are constructed for 5 centralities and 4 different bins of transverse pair momentum $k_T = (\vec{p_1} + \vec{p_2})_T /2$, where $\vec{p_1}$ and $\vec{p_2}$ are the momenta of the first particle and the second particle, respectively. In Figure 2 there are the STAR preliminary results of K^+K^- correlation functions from Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV. While at the low q_{inv}, the attractive Coulomb interaction and strong interaction in s-wave can be observed, in the region of $q_{inv} \sim 0.25$GeV/c the strong interaction in p-wave via $\phi(1020)$ resonance in FSI is present. As can be seen, the correlation function is sensitive to the source size. In particular, a strong dependence on collision centrality and on the pair k_T is observed in the resonance region.

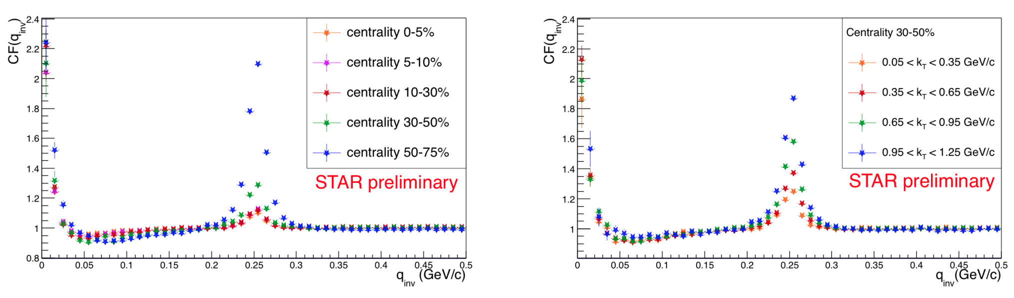

Figure 2. Left: Centrality dependence of one dimensional unlike-sign correlation function from Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV. Right: k_T dependence of one-dimensional unlike-sign correlation function for centrality 30-50% from Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV.

Regarding the centrality dependence, where the correlation functions are integrated over all k_T, the height of the ϕ peak decreases significantly with centrality. Similarly a strong dependence is observed as a function of k_T, as shown on right panel of Figure 2 for centrality $30-50\%$, mid-peripheral events. The k_T dependence of femtoscopic correlations reflects the dynamics of the system. The observed increase in the correlation strength with the k_T qualitatively agrees with the effects expected from a system undergoing a transverse expansion where pairs with the larger transverse momentum are emitted from a smaller effective source than the pairs with the smaller k_T [11].

For comparison to the theoretical prediction of [7], additional physical effects have to be taken into account, since they decrease the strength of the measured correlation function. These effects are contained in the so-called correlation strength, the λ parameter. In this analysis, the λ parameter is obtained from fitting an experimental correlation function of like-sign kaons. The effects of momentum resolution, feed-down and residual correlations have not been studied yet.

5 Like-sign 1D correlation functions and fitting

The one-dimensional like-sign correlation functions were constructed by the same method as the unlike-sign correlation functions introduced in the previous sections. Figure 3 shows STAR preliminary results of K^+K^+ and K^-K^- correlation functions from Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV. As the pairs consist of two identical particles with the same charge, the repulsive Coulomb interaction and Bose-Einstein statistics can be observed at low q_{inv}.

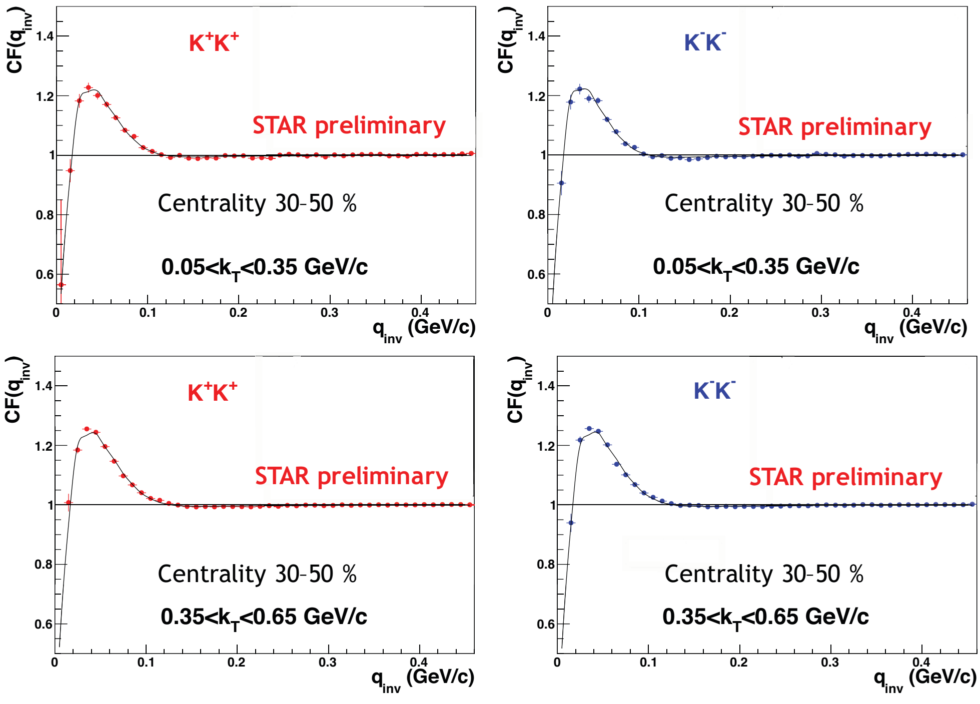

Figure 3. One dimensional K^+K^+ and K^-K^- correlation function from 30-50% central collisions for positive(top) and negative(bottom) kaons for two k_T bins: $0.05 < k_T < 0.35$ GeV/c and $0.35 < k_T < 0.65$ GeV/c. The lines represent the best fits to the data by using the Eq. 3.

The source radii R_{inv} and the λ parameters are obtained from fitting experimental correlation functions with a standard Bowler-Sinyukov form of one dimensional correlation function

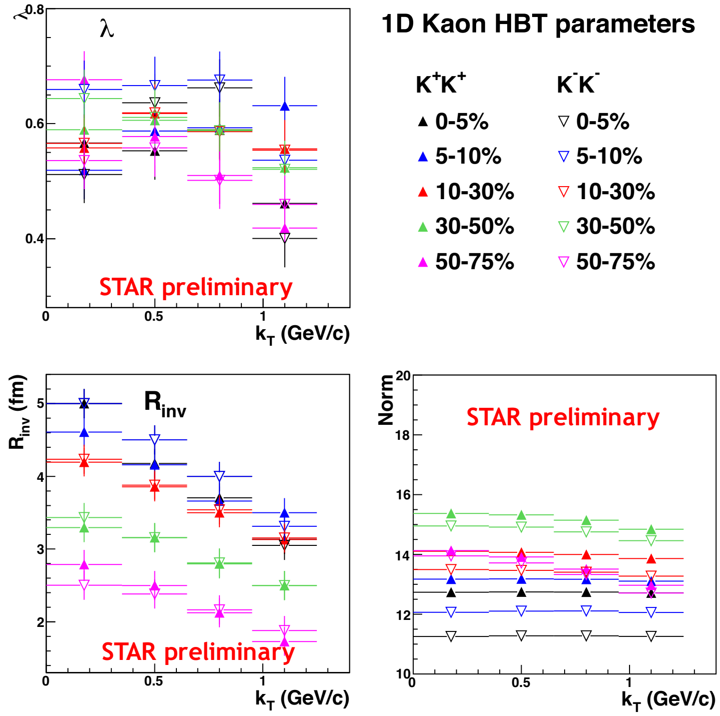

Figure 4. Fit results: λ parameter and source radius R_{inv} as a function of k_T and centrality.

$$CF(q_{inv}) = \left[(1-\lambda) + \lambda K(q_{inv})\, e^{-R_{inv}^2 q_{inv}^2}\right] N, \tag{3}$$

where N is normalization and $K(q_{inv})$ is Coulomb function integrated over source of size R_{inv}. The extracted parameters are shown in Figure 4. As can be seen, the source radii R_{inv} increase with the centrality and decrease with the pair transverse momentum k_T. The errors of fit results are dominated by systematic uncertainties which were estimated by varying the fit ranges. Study of other systematic uncertainties is underway.

6 Comparison of unlike-sign 1D correlation function to Lednicky model

The experimental results of the unlike-sign one-dimensional correlation function can be now compared to the theoretical prediction from Lednicky [7] using a relation:

$$CF(q_{inv}) = \int d^3r S(r, k^*) \left|\psi_{1,2}(r, k^*)\right|^2, \tag{4}$$

where $S(r, k^*)$ is the source function describing emission of two particles at a relative distance r with the relative momentum k^* in the pair rest frame (PRF). The interaction between the two emitted particles is characterized by their wave function $\psi_{1,2}(r, k^*)$.

Similarly, as assumed for eq. (3), the source is described by one-dimensional Gaussian in the PRF with a parameter R_{inv}. Here the individual R_{inv} are those extracted from fitting like-sign correlation functions (Figure 4). The used FSI model of Lednicky [7] includes the treatment of $\phi(1020)$ resonance in the final state. The model also introduces a generalized form of smoothness approximation which is needed for correct description of the correlation function in the region of the resonance. Since the theoretical function does not include effects contained in the experimental λ parameter, it is scaled for the comparison according to

$$CF = \left(CF^{theor} - 1\right)\lambda + 1, \tag{5}$$

where λ parameter was obtained from the fit to the like-sign correlation function.

Comparison of unlike-sign one-dimensional correlation functions to model calculations for two collision centralities is shown in Figs. 5 and 6. As can be seen, the model reproduces the overall structure of the observed correlation functions, both at low q_{inv} where the Coulomb and strong interaction in s-wave are present, as well as in the region of $\phi(1020)$ resonance. The agreement in the ϕ region is very good for central collisions, however with decreasing source size the height of the resonance peak is underestimated.

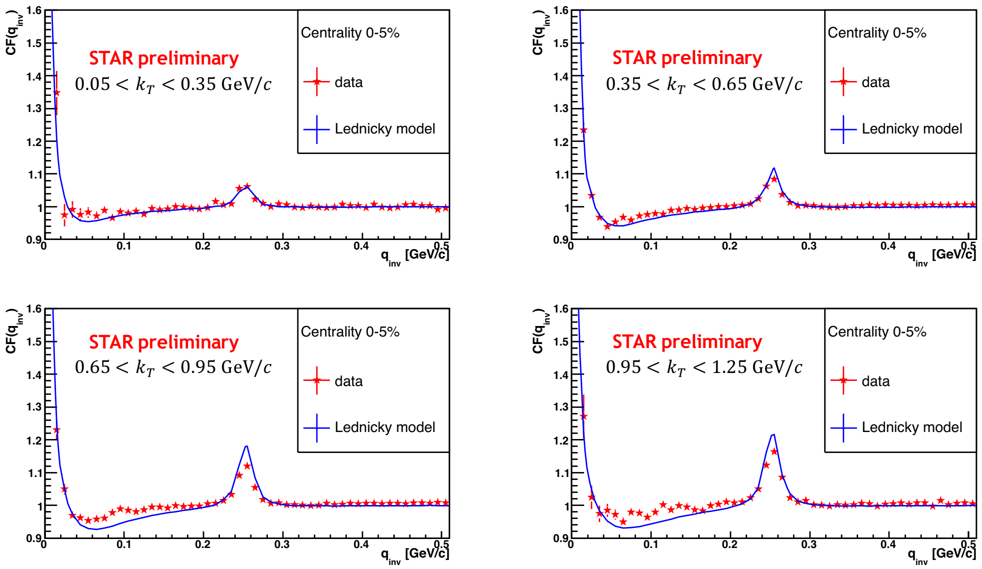

Figure 5. Comparison of experimental K^+K^- correlation functions from Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV to theoretical calculations for 0-5% centrality for 4 different k_T bins.

7 Summary

In this paper, the preliminary results of a STAR analysis of unlike-sign kaon femtoscopic correlations in Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV have been presented. The measured K^+K^- correlation function exhibits strong centrality and k_T dependence in the region of $\phi(1020)$ resonance. The obtained correlation function has been compared to a theoretical FSI model with parameters R_{inv}, λ obtained from like-sign correlation functions. The Lednicky FSI model reproduces the correlation function in

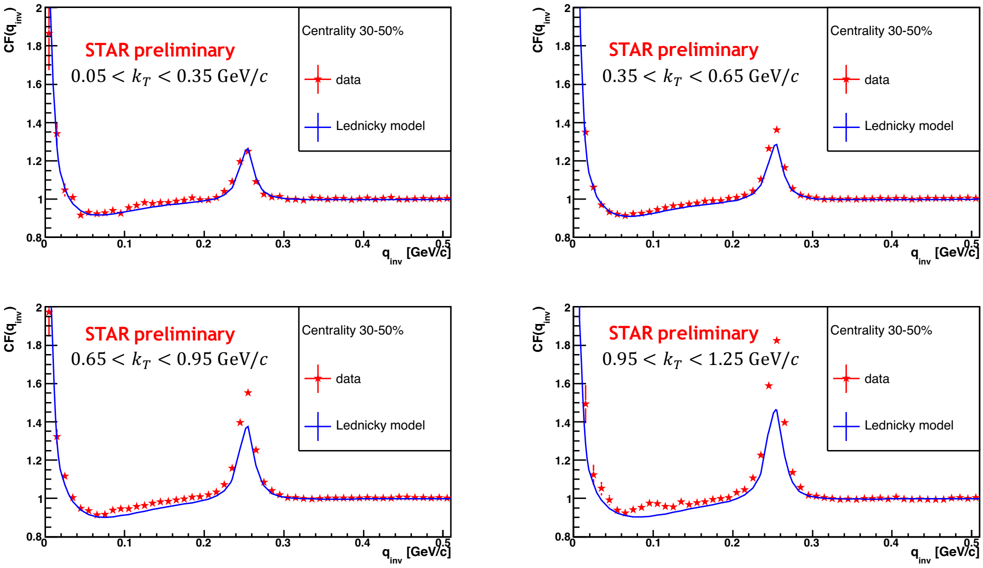

Figure 6. Comparison of experimental K^+K^- correlation functions from Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV to theoretical calculations for 30-50% centrality for 4 different k_T bins.

central collisions, but underpredicts the strength of correlation in the $\phi(1020)$ region for peripheral collisions.

Acknowledgments

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