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Femtoscopic correlation studies between D^0 mesons and charged kaons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV by STAR

PRIYANKA ROY CHOWDHURY for the STAR COLLABORATION

Warsaw University of Technology, Faculty of Physics - Koszykowa 75, 00-662 Warsaw, Poland

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Summary. — Heavy quarks are produced in hard partonic scatterings at the very early stage of heavy-ion collisions and they experience the whole evolution of the Quark-Gluon Plasma medium. Femtoscopic correlation is defined as two particle correlation at low relative momentum which is sensitive to the final-state interaction as well as to the extent of the region from which the correlated particles emit. Study of such correlations between charmed mesons and identified charged hadrons could shed light on their interactions in the hadronic phase and the interaction of charm quarks with the medium. We report the first measurement of femtoscopic correlations between D^0 and kaon pairs at mid-rapidity in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV by the STAR experiment. The physics implications are discussed by comparing to theory calculations.

1. – Introduction

Relativistic collisions between heavy ions produce heavy quarks, like the charm (c) and its charge conjugate ($\bar{c}$) at very beginning. Their early emergence proves valuable in probing all phases of heavy-ion collision evolution, including Quark-Gluon-Plasma (QGP), chemical freeze-out, hadronization, kinetic freeze-out, and subsequent interactions leading to the final state [1-3]. $D^0/\overline{D}^0$ mesons (lifetime, $c\tau \approx 123$ μm [4]) contain one heavy ($c/\bar{c}$) quark and one light quark ($\bar{u}/u$). The STAR experiment at RHIC (Relativistic Heavy Ion Collider) is primarily focused on studying the properties of QGP [5-8], a deconfined state of quarks and gluons produced at sufficiently high energy density and temperature. Study of QGP helps us to understand the microsecond old universe just after the Big Bang and its space-time evolution. STAR reported a suppression of heavy-flavor hadrons at high p_{T} [9] and significant D^0 elliptic flow [10]. Several theoretical models with different assumptions quantitatively reproduced these data. To enhance our understanding of the interaction of heavy quarks (c, b) with the medium, it is necessary to measure new observables such as the two-particle momentum correlation function. This will help in constraining various model parameters. The two-particle femtoscopy technique allows the study of both the phase-space evolution of emission sources and the interactions occurring in the final state of heavy-ion collisions [11]. As D^0 is neutral particle, Coulomb interaction is absent in this measurement. The measured so-called area of homogeneity is believed to be sensitive to dynamics of QGP, for example, collective flow [11]. By definition, this homogeneity region represents shape and size of phase-space cloud of outgoing correlated pairs [12]. In case of strong correlation, size of area of homogeneity is significantly smaller than the size of fireball [11]. The configuration of the emission source is commonly described through a source function S(r), denoting a time-integrated distribution of emission points with a relative distance r. The radius (r) of the emission source can be determined employing the D^0K correlation function.

2. – Methodology

According to Koonin-Pratt formalism [11], femtoscopic correlation function $C(k^*)$ can be expressed as $C(k^*) = \int S(r)|\psi(k^*, r)|^2 \mathrm{d}^3 r$, where k^* is reduced momentum difference between a pair of particles emitted as correlated pair from an emission source of size r. $S(r)$ represents emission source function and $\psi(k^*, r)$ is the wave function of emitted pair. To calculate the correlation function using experimental data, we took the ratio of k^* of correlated $[A(k^*)]$ and uncorrelated $[B(k^*)]$ pairs of particles in the rest frame of their center of mass represented as eq. (1).

$$C(k^*) = N\frac{A(k^*)}{B(k^*)} \quad \text{and} \quad k^* = \frac{1}{2}(p_1 - p_2), \tag{1}$$

where N is normalization factor and p_1, p_2 are momenta of $D^0/\overline{D}^0$ and kaon tracks in the pair-rest frame. To calculate $A(k^*)$, both tracks were selected from the same event and in order to estimate $B(k^*)$, event mixing technique was applied to choose pair of tracks from different events within similar primary vertex-z position (V_z) and centrality range.

3. – Experiment setup and dataset

STAR consists of several detectors designed for specific purposes [13]. The Time Projection Chamber (TPC) and Time of Flight (TOF) are two main detectors for charge particle tracking and identifications. STAR installed Heavy Flavour Tracker (HFT) detector [14] dedicated to track open heavy-flavour hadrons in the year 2013 for commisioning purpose and included in data taking during Run 2014 to Run 2016. For this analysis, we used TOF and TPC detectors in order to identify primary $K^{\pm}$ and $\pi^{\pm}$, tracks and HFT detector to discriminate secondary vertex of $K^-\pi^+$ decay channel as D^0 daughters. In this proceeding, we report the first measurement of femtoscopic correlations between (D^0+$\overline{D}^0$) and ($K^{\pm}$) pairs at mid-rapidity in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV with 600 M events from RHIC Run 2014.

4. – Event and track selection

In order to select good quality events with 0 - 80% centrality, following criteria were applied: primary vertex along z axis of TPC, $|V_z| < 6$ cm, primary vertex in transverse direction of TPC, $|V_{xy}| < 2$ cm, $|V_z$-$V_z^{\mathrm{VPD}}| < 3$ cm where V_z^{VPD} is the z-position vertex

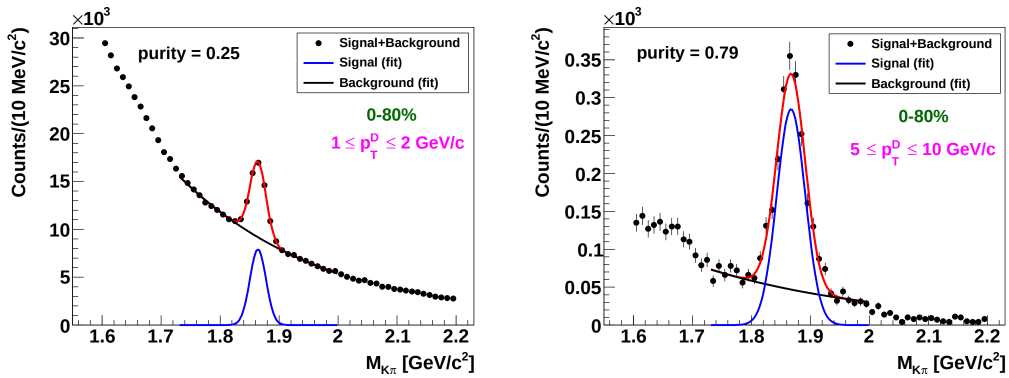

Fig. 1. – p_T integrated invariant mass ($M_{K\pi}$) distribution of ($D^0 + \overline{D}^0$) candidates from 0 - 80% centrality events where black solid circles represent D^0 ($\overline{D}^0$) signal [same event (SE), unlike sign (US)] mixed with combinatorial background [SE, like sign (LS)]. Red curve indicates Gaussian fit to D^0 ($\overline{D}^0$) signal and black line shows exponential fit to the background. Blue curve depicts D^0 ($\overline{D}^0$) signal fit with subtraction of SE, LS distributions within mass range 1.73 - 2.0 GeV/c^2

estimated from time difference measured between two sides of Vertex Position Detector (VPD).

Kaons and pions with pseudorapidity range of $|\eta| < 1$ were identified using information of ionization energy loss ($\frac{dE}{dx}$) with the TPC and time-of-flight from TOF detectors. Selection of K and π tracks was based on the criteria involving the deviation in resolution-normalized $\frac{dE}{dx}$ measured in the TPC from the expected value [9],$|n\sigma_K| < 3$ and $|n\sigma_\pi| < 2$. PID using TOF is based on $\Delta\frac{1}{\beta}$ for a given mass and momentum, where β is the relative speed of the particle and Δ represents deviation in measurement from the expected value. Applied cuts for both K and π are $|\Delta\frac{1}{\beta}| < 0.03$. All tracks were required to have the selection criteria of $20 \leq$ TPC hit points < 45 in order to achieve good momentum resolution.

5. – D^0 reconstruction and signal purity estimation

D^0 mesons were reconstructed via the $K^-\pi^+$ decay channel (and $\overline{D}^0 \to K^+\pi^-$) with a branching ratio of 3.89% using topological criteria [9] enabled by the HFT detector with excellent track pointing resolution. Figure 1 shows reconstructed $D^0 + \overline{D}^0$ invariant mass within a mass range of 1.82 -1.91 GeV/c^2 [9] using STAR data of Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from the Run 2014. Ratio of reconstructed D^0 ($\overline{D}^0$) signal (S) over the combinatorial background (B) under the D^0 peak, increases with increasing transverse momentum, p_T and for this study we selected D^0 (and its charge conjugate) candidates with $p_T > 1$ GeV/c with good S/B ratio. D^0 signal purity was calculated for each p_T bin (1-2, 2-3, 3-5 and 5-10 GeV/c) as purity $= \frac{S}{S+B}$.

In this study, centrality-inclusive femtoscopic correlation function was measured for D^0 ($\overline{D}^0$) with $p_T > 1$ GeV/c and $K^\pm$ momentum, $p < 1$ GeV/c with $D^0/\overline{D}^0$ rapidity (y) coverage of $|y| < 1.0$.

6. – Correlation function extraction

Misidentification of correlated pairs could potentially affect the calculated value of correlation function. We mitigated possible TPC detector effects by excluding self-correlation between D^0 daughters and eliminating splitted hadron track which can influence the number of correlated pairs. Another feasible detector effect is merging of two separate tracks as one, but our analysis revealed that the contribution from merged tracks was minimal. In order to get rid off the contribution from combinatorial background of D^0 signal and contamination of identified kaon sample with other hadrons, we applied D^0K pair purity correction using the formula [15]:

$$C(k^*) = \frac{C_{\text{measured}}(k^*) - 1}{\text{PairPurity}} + 1, \tag{2}$$

where $C(k^*)$ is the purity-corrected final correlation function, $C_{\text{measured}}(k^*)$ is the calculated correlation function with corrections due to detector effects and Pair Purity is a product of D^0 signal purity and the average purity of the kaon sample. Purity of hadron sample ($K^{\pm}$) was obtained by $n\sigma_K$ fit in momentum bins using sum of three Gaussian function for K, π and proton. We consider kaons with momenta < 1 GeV/c because above this threshold value, they cannot be efficiently distinguished from electrons and other hadrons. The average purity of the kaon sample is estimated to be $\sim 0.97 \pm 0.03$, within considered momentum range ($p_K < 1$ GeV/c). For conducting systematic uncertainty studies, we varied the topological cuts for D^0 reconstruction [9] and included uncertainty on purity estimation for D^0K pairs. The resulting systematic uncertainty is found to be less than 8%.

7. – Results and discussions

Figure 2 shows the correlation function for all possible combination of DK pairs (D^0K^+, D^0K^-, $\overline{D}^0K^+$ and $\overline{D}^0K^-$) after pair-purity correction. The $C(k^*)$ distribution is around unity which implies no correlation and large fluctuations appear due to non-adequate statistics. Strength of correlation is related to the source size [11, 12]. Weak

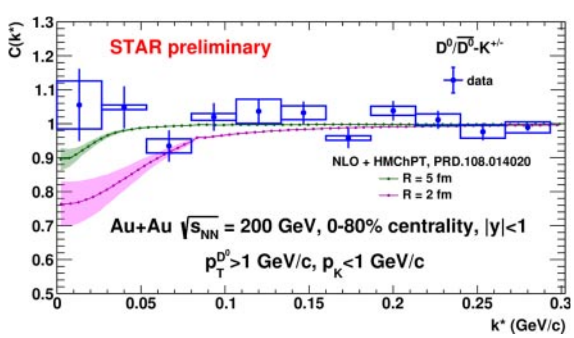

Fig. 2. – Correlation function between $D^0/\overline{D}^0$ and $K^{\pm}$ pairs using minimum bias Au+Au collision at $\sqrt{s_{\text{NN}}} = 200$ Gev with $|\eta| < 1$. Blue solid circles and corresponding boxes represent the STAR data and systematic uncertainties, respectively. Green and pink bands show $C(k^*)$ values from reference model predictions for source sizes of 5 fm and 2 fm, respectively.

or no correlation implies a large size of emission source from which considered DK pairs emitted.

We made a comparison between STAR data and available theory predictions of correlation functions with emission source size dependency for the mixture of D^0K^+ and D^+K^0. Both DK channels give equal contributions to the theoretical correlation functions ($C_x(k^*)$, where $x = D^0K^+$ or D^+K^0) [16]. None of these channels involves the Coulomb interaction. Result from STAR data analysis and theory prediction are consistent with a emission source size of 5 fm or larger. Typically for strong correlation, 1-D source radius could be expected ~ 1 fm [17]. Reference correlation functions were obtained using NLO (next-to-leading order) HMChPT (Heavy Meson Chiral Perturbation Theory) scheme [16, 18, 19]. D^0K^+ channel has a threshold around 0.083 GeV where a cusp effect can be seen [16]. The prediction demonstrates a pronounced depletion at the origin, attributed to the presence of the $D^*_{S0}(2317)^{\pm}$ bound state, which intensifies as the source radius decreases. Resonance effect of this state is not visible in STAR result due to large source size or large experimental uncertainties.

Estimation of the same observable, $C(k^*)$ between other D^0-hadron pairs, *i.e.*, using p and π are ongoing and we expect the results using combined data from the Run 2014 and 2016 will increase the precision of the measurement of correlation functions and will provide more decisive conclusion about the source size. Theoretical inputs are required for better understanding of these data.

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