# First measurement of heavy flavour femtoscopy in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV by STAR

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**Abstract.** In the very beginning stages of heavy-ion collisions, hard partonic scatterings yield heavy quarks, which go through the entire Quark-Gluon Plasma medium evolution. Femtoscopic correlation is characterized as a two particle correlation at low relative momentum that depends on the size of the region from which the correlated particles are emitted and on the final-state interaction. Such correlations between identifiable charged hadrons and charmed mesons could provide insights into their interactions with the medium and charm quarks in the hadronic phase. We describe the first femtoscopic correlation measurements made by the STAR experiment between $D^0/\overline{D^0} - \pi^{\pm}$, $D^0/\overline{D^0} - K^{\pm}$ and $D^0/\overline{D^0} - p^{\pm}$ pairs at mid-rapidity in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV. The discussion of the physics consequences involves a comparison to theory calculations.

## 1 Introduction

Heavy quarks such as charm (c) and its charge conjugate ($\overline{c}$) are created in the early stages of ultra-relativistic collisions of heavy ions. Therefore, they probe all stages of the evolution of heavy-ion collisions - Quark-Gluon Plasma (QGP), hadronization, chemical and kinetic freeze-out. [1] One heavy ($c/\overline{c}$) and one light (($\overline{u}/u$) quark make up $D^0/\overline{D}^0$ mesons (lifetime, $c\tau \approx 123\ \mu$m [2]). These charmed mesons are useful to probe how heavy quarks interact with QGP medium. The STAR experiment at RHIC (Relativistic Heavy Ion Collider) observed significant $D^0$ elliptic flow [3] and $D^0$ suppression at high $p_{\mathrm{T}}$ [4] in heavy-ion collisions. Numerous theoretical models with varying assumptions were able to quantitatively describe these findings. In order to improve our comprehension of heavy quarks ($c, b$) interactions with the medium, new observables like the two-particle momentum correlation functions are of particular interest. Phase-space evolution of emission source and final-state interactions can be both studied with such measurements in heavy-ion collisions [5]. According to theory, phase-space cloud of outgoing correlated pairs or so-called area of homogeneity is responsive to QGP dynamics, such as collective flow [5, 6]. Size of area of homogeneity is substantially lower than the size of fireball in cases of strong correlation [5].

According to Koonin-Pratt equation [5], femtoscopic correlation function, $C(k^*) = \int S(r)|\psi(k^*, r)|^2 \mathrm{d}^3 r$, is a combination of emission source function, $S(r)$ and pair-wave function, $\psi(k^*, r)$. Here $k^*$ represents the reduced momentum difference between correlated particle pairs emitting from a source of size $r$. We computed $C(k^*)$ by taking the $k^*$ ratio of

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correlated $[A(k^*)]$ and uncorrelated $[B(k^*)]$ $D^0$-hadron pairs in the rest frame of their center of mass given in Eq. 1 [5].

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

where $N$ is normalization factor and $p_1$, $p_2$ are momenta of $D^0/\overline{D}^0$ and $K/\pi/p$ tracks in the pair-rest frame. Two tracks were chosen from the same event in order to compute $A(k^*)$. $B(k^*)$ was calculated using event mixing technique to select a pair of tracks from different events chosen within a similar primary z-vertex position ($V_z$) and centrality range as the same-event pairs.

## 2 $D^0/\overline{D}^0$ reconstruction and signal purity estimation

STAR is made up of multiple detectors with distinct functions [7]. The two primary detectors for tracking and identifying charge particles are the Time Projection Chamber (TPC) and Time of Flight (TOF). The HFT detector with outstanding track pointing resolution was used for the reconstruction of $D^0/\overline{D}^0$ mesons via the $K^{\mp}\pi^{\pm}$ decay channel using the set of topological criteria [4]. Fig. 1 shows the reconstructed $D^0$ and $\overline{D^0}$ invariant mass distributions using STAR data of Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [4]. We selected $D^0$ candidates (and their charge conjugates) based on two criteria: $p_T > 1$ GeV/$c$ and the ratio of signal-to-combinatorial background under $D^0$ peak (S/B) had to exceed 30% in the lowest $p_T$ bin. $D^0$ ($\overline{D^0}$) signal peak lies between 1.82 to 1.91 GeV/$c^2$ mass range. With rising transverse momentum, $p_T$, the $S/B$ ratio increases. The $D^0$ signal purity ($\frac{S}{S+B}$) was calculated for each $p_T$ bin (1-2, 2-3, 3-5, and 5-10 GeV/$c$). In the lowest $p_T$ bin, the purity is 25% , gradually increasing to 80% in the highest $p_T$ bin. $D^0$ purity is used to calculate the pair purity as discussed in detail in Sec. 3.

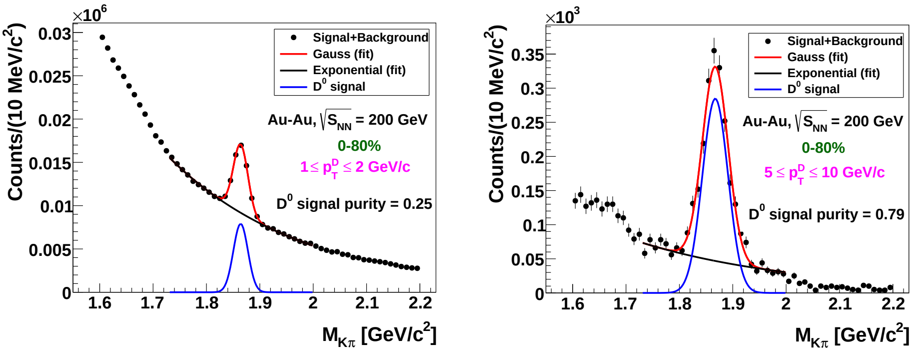

**Figure 1.** Invariant mass ($M_{K\pi}$) of $D^0$ and $\overline{D}^0$ candidates using STAR Run 2014 data. The black solid circles depict the invariant mass of unlike-sign (US) $K\pi$ pairs. The red curve corresponds to a Gaussian fit, while the black line shows an exponential fit to the US pairs. The blue curve illustrates the fit to the $D^0$ ($\bar{D}^0$) signal within the mass range of 1.73 to 2.0 GeV/$c^2$.

## 3 Correlation function calculation

The computed value of the correlation function can be affected by incorrectly identified correlated pairs. We used both TPC and TOF to select the primary tracks of considered charged hadrons ($\pi$, $K$ and $p$). We eliminated splitted hadron tracks and excluded self-correlation between $D^0$ daughters in order to reduce the potential effects of the TPC detector. Combining two different tracks into one is another possible detector impact, however our investigation showed that the contribution from merged tracks was negligible. To account for the contribution from the background under $D^0$ signal peak and impurity of the selected $\pi$, $K$ and $p$ samples with other hadrons and electrons present in the system, we implemented a purity correction for $D^0$-hadron pairs using a specific formula [8]:

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

where $C(k^*)$ is the final correlation function after purity correction, $C_{\text{measured}}(k^*)$ represents the correlation function after correcting possible detector effects, while Pair Purity is determined by multiplying the $D^0$ signal purity with the average purity of the hadron sample. The purity of the hadron sample was determined using standard approach in STAR [9]. Hadrons were selected with momentum criteria, $p_\pi < 1$ GeV/$c$, $p_p < 1.2$ GeV/$c$ and $p_K < 1$ GeV/$c$ as they become difficult to distinguish from electrons and other hadrons beyond the mentioned thresholds respectively. Within selected momentum range, average purity of $\pi$ and $p$ are $(99.5 \pm 0.5)\%$ while for $K$ sample, purity is $(97 \pm 3)\%$ . Systematic uncertainty studies were made by variations in the topological cuts used for $D^0$ reconstruction [4], and by including the uncertainties in the purity estimation of $D^0$-hadron pairs.

## 4 Results and discussions

Figure 2 presents the final correlation function of $D^0/\overline{D^0} - \pi^\pm$, $D^0/\overline{D^0} - p^\pm$ and $D^0/\overline{D^0} - K^\pm$ pairs using STAR data from minimum bias Au+Au collision at $\sqrt{s_{\text{NN}}} = 200$ GeV within $|\eta| < 1$. The $C(k^*)$ distribution is consistent with unity, indicating an absence of significant correlation, with large statistical fluctuations. The strength of the correlation is linked to the size of the source [5, 6]. A weak or absent correlation suggests that the emission source from which the $D$-hadron pairs are produced is relatively large in size. In left and right panel, STAR data are compared with $C(k^*)$ calculated using NLO (next-to-leading order)-HMChPT (Heavy Meson Chiral Perturbation Theory) scheme [10–12]. In the left panel, the

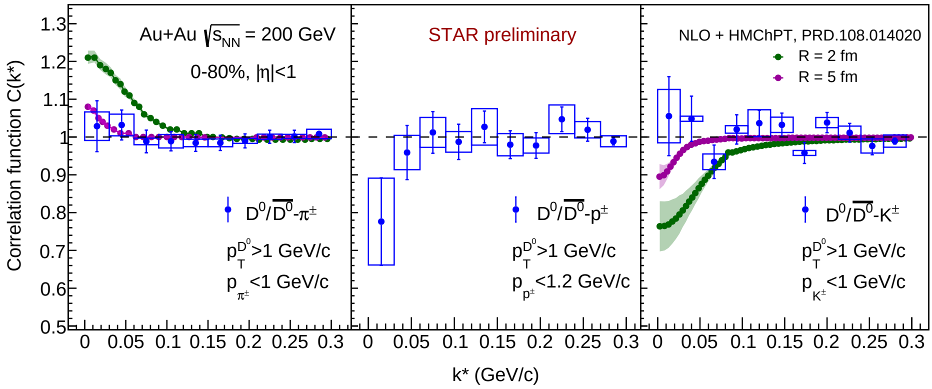

**Figure 2.** $C(k^*)$ for (left) $D^0/\overline{D^0} - \pi^\pm$, (mid) $D^0/\overline{D^0} - p^\pm$ and (right) $D^0/\overline{D^0} - K^\pm$ pairs. The blue solid circles, along with the boxes, indicate the STAR data and the associated systematic uncertainties. The green and pink bands illustrate the $C(k^*)$ values predicted by NLO + HMChPT model for source sizes of 2 fm and 5 fm, respectively.

theory predictions are for $D^0 - \pi^+$ and $D^+ - \pi^0$ pairs while in the right panel, for $D^0 - K^+$ pairs [10]. Neither of these channels includes Coulomb interaction. The STAR data and theoretical predictions align with an emission source size of 5 fm or more. The $D^0K^+$ channel exhibits a threshold near 0.083 GeV where a cusp effect is observed. The prediction shows a marked depletion around $k^*$ between 0 to 0.05 GeV/c, which is attributed to the $D_S^*(2317)^\pm$ bound state and becomes more pronounced as the source radius decreases [10]. However, the resonance effect of this state is not evident in the STAR results due to either the large source size or significant experimental uncertainties. As a next step, we plan to update these results by combining data from Runs 2014 and 2016. This approach is expected to improve the precision of the correlation function measurements and offer more definitive conclusions about the source size. Additionally, theoretical inputs are necessary for a better interpretation of these data.

## 5 Acknowledgement

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