First measurement of heavy flavour femtoscopy in Au+Au collisions at $\sqrt{s_{NN}}$ = 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 emit and 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 $\sqrt{s_{NN}}$ = 200 GeV. The discussion of the physics consequences involves a comparison to theory calculations.

1 Introduction

In the early stages of relativistic collisions involving heavy ions, heavy quarks such as the charm (c) and its charge conjugate ($\overline{c}$) are created. Probing all stages of the evolution of heavy-ion collisions by heavy-quarks, such as Quark-Gluon-Plasma (QGP), chemical freeze-out, hadronization, kinetic freeze-out, and subsequent interactions leading to the final state, is made possible by their early establishment [1]. The study of QGP contributes to our understanding of the universe's space-time evolution in the microseconds following the Big Bang. One heavy ($c/\overline{c}$) and one light (($\overline{u}/u$) quark make up $D^0/\overline{D}^0$ mesons (lifetime, $c\tau \approx 123$ μm [2]). These charmed mesons are useful to probe how heavy quarks interact with medium. The STAR experiment at RHIC (Relativistic Heavy Ion Collider) observed significant D^0 elliptic flow [3] and D^0 suppression at high p_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 paarticular interest. Phase-space evolution of emission source and final-state interactions of heavy-ion collisions, both can be studied with such measurements [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, $C(k^*) = \int S(r)|\psi(k^*, r)|^2 d^3r$, is a combination of emission source function, $S(r)$ and pair-wave func-

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tion, $\psi(k^*, r)$. 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 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].

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

where N is normalization factor and p_1, p_2 are momenta of $D^0/\overline{D}^0$ and $K/\pi/p$ 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). We used both TPC and TOF to select the primary tracks of considered charged hadrons (π, K and p). 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 with a branching ratio of 3.89% and set of topological criteria [4]. Using STAR data from Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV, Fig. 1 displays the reconstructed D^0 and $\overline{D}^0$ invariant mass distributions covering a range of 1.82 -1.91 GeV/c^2 [4]. We selected D^0 candidates (and their charge conjugates) for this study based on two criteria: $p_{\mathrm{T}} > 1$ 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. 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.

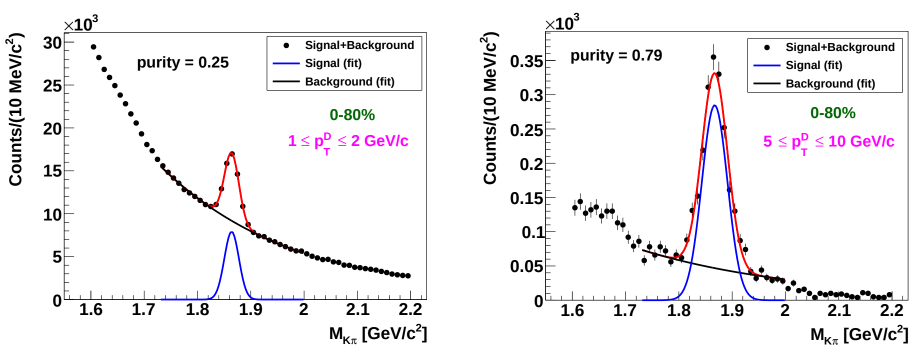

Figure 1. Invariant mass ($M_{K\pi}$) of D^0 and $\overline{D}^0$ candidates using STAR Run 2014 data. The black solid circles depict the D^0 ($\bar{D}^0$) signal from same-event (SE) unlike-sign (US) pairs mixed with combinatorial background from SE like-sign (LS) pairs. The red curve corresponds to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

3 Correlation function calculation

The correlation function's computed value may be impacted by incorrectly identifying correlated pairs. 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 eliminate the contribution from the background under D^0 signal peak and reduce contamination of the identified hadron sample with other particles 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 by performing corresponding $n\sigma$ fit in different momentum bins, utilizing the sum of Gaussian functions associated with other hadrons and electrons present in the system. 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 π 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

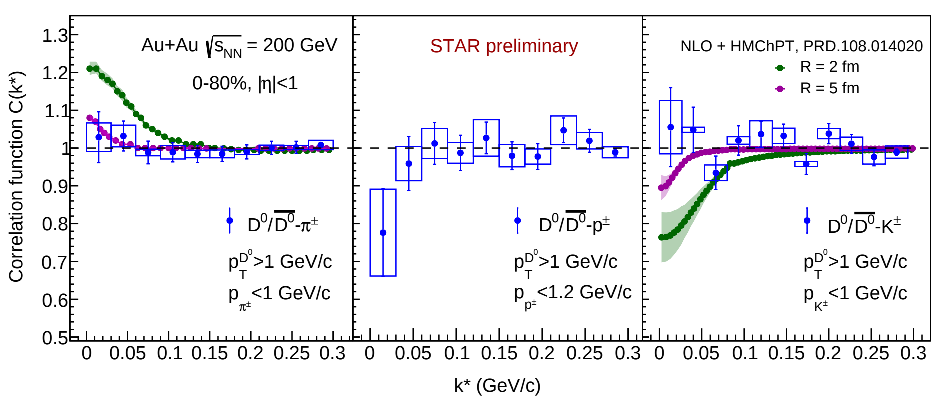

Figure 2. $C(k^*)$ for (left) $D^0/\overline{D^0} - \pi^\pm$, (mid) $D^0/\overline{D^0} - p^\pm$ and (right) $D^0/\overline{D^0} - K^\pm$ pairs. The blue solid circles, along with the boxes, indicate the STAR data and the associated systematic uncertainties. The green and pink bands illustrate the $C(k^*)$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

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 [9–11]. Theory calculations considered a mixture of (left) $D^0 - \pi^+$ and $D^+ - \pi^0$ pairs while (right) $D^0 - K^+$ pairs [9]. 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 at the origin, which is attributed to the $D^*_S(2317)^\pm$ bound state and becomes more pronounced as the source radius decreases [9]. 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.

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References

[1] X. Dong *et al.*, Open Heavy-Flavor Production in Heavy-Ion Collisions, Ann. Rev. Nucl. Part. Sci. **69**, 417-445 (2019).

[2] R. L. Workman *et al.* [Particle Data Group], Review of Particle Physics, PTEP **2022**, 083C01 (2022).

[3] L. Adamczyk *et al.* [STAR], Measurement of D^0 Azimuthal Anisotropy at Midrapidity in Au+Au Collisions at $\sqrt{s_{NN}}$=200 GeV, Phys. Rev. Lett. **118**, no.21, 212301 (2017).

[4] J. Adam *et al.* [STAR], Centrality and transverse momentum dependence of D^0-meson production at mid-rapidity in Au+Au collisions at $\sqrt{s_{\rm NN}} = 200\,$GeV, Phys. Rev. C **99**, no.3, 034908 (2019).

[5] M. A. Lisa *et al.*, Femtoscopy in relativistic heavy ion collisions, Ann. Rev. Nucl. Part. Sci. **55**, 357-402 (2005).

[6] S. V. Akkelin and Y. M. Sinyukov, The HBT interferometry of expanding sources, Phys. Lett. B **356**, 525-530 (1995).

[7] Special Issue on RHIC and Its Detectors, edited by M. Harrison, T. Ludlam and S. Ozaki, Nucl. Instrum. Methods Phys. Res., Sect. A **499**, no.2–3 (2003).

[8] J. Adams *et al.* [STAR], Proton - lambda correlations in central Au+Au collisions at S(NN)**(1/2) = 200-GeV, Phys. Rev. C **74**, 064906 (2006).

[9] M. Albaladejo, J. Nieves and E. Ruiz-Arriola, Femtoscopic signatures of the lightest S-wave scalar open-charm mesons, Phys. Rev. D **108**, no.1, 014020 (2023).

[10] F. K. Guo, C. Hanhart and U. G. Meissner, Interactions between heavy mesons and Goldstone bosons from chiral dynamics, Eur. Phys. J. A **40**, 171-179 (2009).

[11] L. S. Geng, N. Kaiser, J. Martin-Camalich and W. Weise, Low-energy interactions of Nambu-Goldstone bosons with *D* mesons in covariant chiral perturbation theory, Phys. Rev. D **82**, 054022 (2010).