Physics of Elementary Particles and Atomic Nuclei

# One-dimensional pion femtoscopy in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from STAR

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Femtoscopy is an important tool to measure the spatial and temporal characteristics of the collision system. In this talk, the results of one-dimensional pion femtoscopic analysis performed for d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV are shown. We present dependence of the invariant radii on pair transverse momentum at the different charged particle multiplicity per event. The physics implications of the resulting radius from the 1D pion femtoscopic analysis in this small system are discussed.

Фемтоскопия, это важный инструмент для измерения пространственных и временных характеристик системы, образующейся вследствие столкновения. В данной работе показаны результаты одномерной пионной фемтоскопии выполненной для столкновений d+Au при энергии $\sqrt{s_{NN}} = 200$ ГэВ. Показаны зависимости инвариантных радиусов от поперечного импульса пары частиц при разной множественности частиц в событии. Физическое применение полученных 1D пионных фемтоскопических радиусов обсуждается.

## 1. Introduction

The femtoscopy technique is based on two-particle correlations at low relative momenta. These correlations arise due to quantum statistics and final state interactions. Femtoscopy can be used to extract the space-time characteristics of the particle emitting source which is created in p+p, p+A or A+A collisions [1–4].

The femtoscopic radii, extracted from these correlations, describe the emission source at the moment of kinetic freeze-out (the last stage of collision) and correspond to the regions of homogeneity [5]. The particles are emitted with similar velocities from such a region. The study of the femtoscopic radii dependence on the pair transverse momentum ($k_T = \frac{|p_{1T}+p_{2T}|}{2}$) allows one to probe different regions of homogeneity. The presence of this dependence is the signature of the hydrodynamic expansion in heavy-ion collisions [6]. Recent theoretical [7,8] and experimental [9,10] studies show the presence of the collective flow in the small systems, like p+p or p+A. The presence of the collective effects in small systems may indicate the creation of QGP droplet.

In this work, we present invariant radii of charged pions obtained for d+Au collision at $\sqrt{s_{NN}} = 200$ GeV collected by the STAR experiment at the RHIC. The dependence of the invariant radii on pair transverse momentum for different charged particle multiplicity is presented.

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## 2. Femtoscopy

The main idea behind the femtoscopy technique is quantum statistical correlations between two identical particles. In order to extract one-dimensional radii ($R_{inv}$) of the particle emission source, the correlation function needs to be constructed, which is defined as:

$$C(Q_{inv}) = \frac{A(Q_{inv})}{B(Q_{inv})}. \tag{1}$$

Here $Q_{inv}$ is relative four-momentum of a pair which is defined as:

$$Q_{inv} = \sqrt{(\mathbf{p_1} - \mathbf{p_2})^2 - (E_1 - E_2)^2}, \tag{2}$$

where $\mathbf{p_1}$ ($E_1$) and $\mathbf{p_2}$ ($E_2$) correspond to 3-momenta (energy) of first and second particles respectively. In Eq. 1 the $A(Q_{inv})$ is a distribution of two-particle relative four-momentum in an event. This distribution contains quantum statistics and final-state interactions (Coulomb and strong interactions). $B(Q_{inv})$ is the reference distribution with all experimental effects except for quantum statistics and final-state interactions as in $A(Q_{inv})$. In this work, to reconstruct the $B(Q_{inv})$ distribution the event mixing technique [11] was used.

The one-dimensional femtoscopic radii are obtained from the Bowler-Sinyukov fit to the correlation functions [12, 13]:

$$C(Q_{inv}) = N(1 - \lambda + \lambda K_{Coul}(Q_{inv})(1 + G(Q_{inv})))D(Q_{inv}), \tag{3}$$

where $N$ is a normalization factor, $\lambda$ is a correlation strength parameter, $D(Q_{inv})$ is a non-femtoscopic correlations (in this work $D(Q_{inv}) = 1$), $K_{Coul}(Q_{inv})$ is a Coulomb correction factor obtained by a squared like-sign pion pair Coulomb wave-function integrated over a spherical Gaussian source [14, 15], and $G(Q_{inv}) = e^{-Q_{inv}^2 R_{inv}^2}$ – Gaussian form of the emission source.

## 3. Analysis details

Data for this analysis were collected by the STAR [16] experiment at the RHIC. The analysis presented in this work was performed for the identical pion pairs ($\pi^{\pm}\pi^{\pm}$) produced in the d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

The collision events were selected with a collision vertex z-position within 40 cm from the center of the Time Projection Chamber (TPC) [17] and with a radial component of the collision vertex within 2 cm. In the collider, during the readout of the event in the gas volume of the TPC, several collisions may occur which may lead to the pile-up. In this work, to remove the pile-up the TPC and VPD [18] detectors were used. The events with the difference of the collision vertex z-positions, from the TPC and VPD detectors, larger than 5 cm in absolute value were removed from the analysis.

We analyzed charged particle tracks reconstructed in the TPC with momentum in the range from 0.15 GeV/$c$ to 0.8 GeV/$c$ within the pseudorapidity range $|\eta| < 0.5$. The upper value of the momentum cut was chosen based on the maximum possible value allowing the reasonable separation of pions and kaons in TPC. Also, similar selection criteria were used in previous analysis in p+p system [19]. The particle identification was performed using the information about the ionization energy loss of charged particles in the TPC gas.

The two-track effects, such as track splitting and track merging, may distort the correlation function. Track splitting occurs when two tracks are reconstructed from the ionization clusters (hits) that belong to the same physical track. This effect increases the number of the track pairs with low relative momenta. Track merging occurs when two tracks close to each other in the phase-space and reconstructed as one track due to the fusion of the ionization cluster. This effect decreases the number of the track pairs with low relative momenta. To remove the track-splitting and track-merging effects the splitting level and fraction of merged hits [20] along with the average separation between two tracks were used. The splitting level (SL) is a quantity that estimates whether the two tracks are real or possibly one track reconstructed as two tracks with similar momenta and the fraction of merged hits (FMH) is a quantity that estimates the opposite effect. In this work only tracks with splitting level in the range $-0.5 < SL < 0.6$, fraction of merged hits in the range $-1.1 < FMH < 0.1$ and average separation of two tracks within TPC volume $> 10$ cm were used.

The effects of various sources of systematic uncertainty on the extracted parameters were studied for different multiplicity and pair transverse momentum ranges. The total systematic error was calculated as a quadratic sum of the systematic errors from different sources. The variation of the primary vertex position cut ranges leads to the spread of the femtoscopic parameters up to 5%; momentum of the tracks and tracking efficiencies - up to 6%; two track effects (merging and splitting) - up to 2%; $Q_{inv}$ ranges for the fit procedure - up to 3%; and Coulomb radius variation in the Eq. 3 - up to 3%.

To extract the one-dimensional femtoscopic radii of the emission source the correlation functions were constructed using Eq. 1 and fitted with the Eq. 3.

## 4. Results

Figure 1 represents an example of the constructed correlation function in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV for multiplicity range $31 < N_{ch}^{|\eta|<0.5} < 40$, pair transverse momentum range $k_T \in [0.15, 0.25]$ GeV/$c$, and $k_T \in [0.45, 0.55]$ GeV/$c$. The fit to the correlation function is presented in Fig. 1 with two assumptions. Figure 1(a,b) shows the fit to the correlation function, assuming that the emission source has a Gaussian shape. With this assumption, the fit to the correlation function was performed with Eq. 1 where $G(Q_{inv}) = e^{-Q_{inv}^2 R_{inv}^2}$ has a Gaussian form. Another assumption is that the emission source has a Lorentzian shape, and it is presented in Fig. 1(c,d) where the correlation function was fitted with the same Eq. 3, but $G(Q_{inv}) = e^{-Q_{inv} R_{inv}}$ has exponential form. These two assumptions were considered for testing whether the emitting source has a Gaussian or Lorentzian shape. Further in this analysis only Gaussian assumption was used. It is seen that the fits reasonably describe the correlation functions.

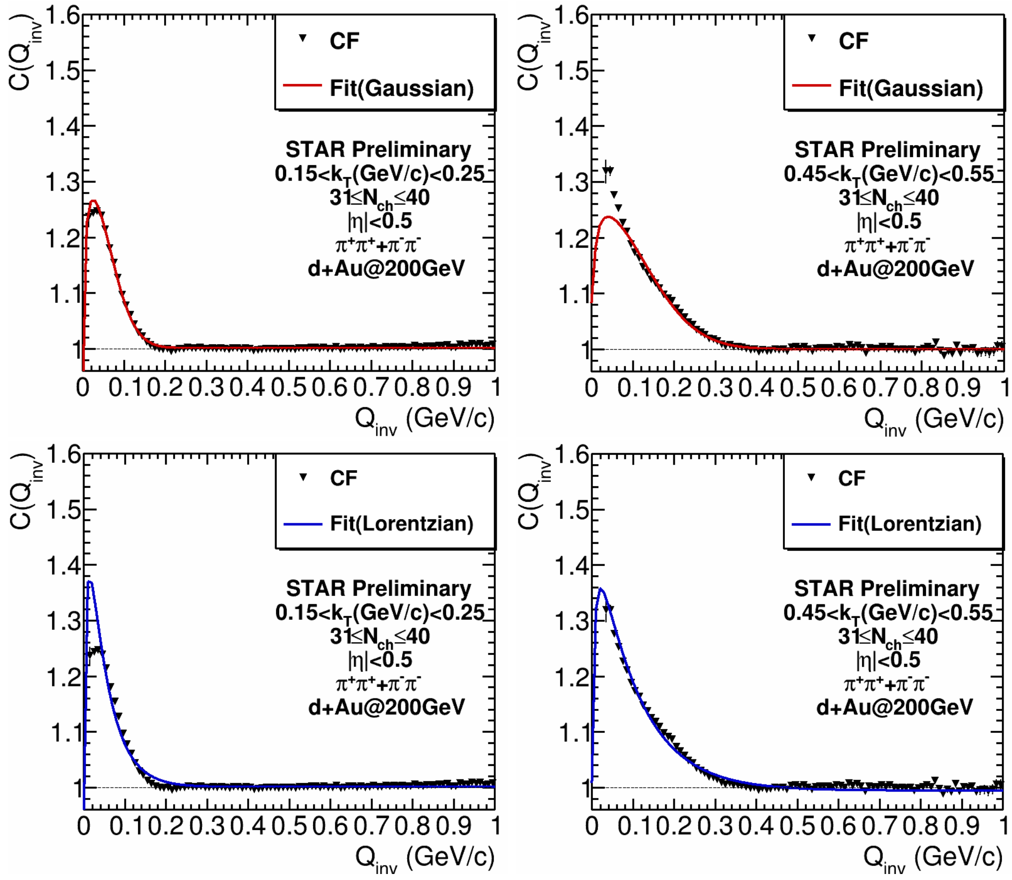

Figure 1. (Color online) Fit with Gaussian (a,b) and exponential (c,d) forms to the correlation functions constructed for identical charged pion pairs from d+Au collisions at $\sqrt{s_{NN}} =$ 200 GeV for the multiplicity range $31 < N_{ch}^{|\eta|<0.5} < 40$ and transverse momentum range $k_T \in [0.15, 0.25]$ GeV/$c$ (a,c), and $k_T \in [0.45, 0.55]$ GeV/$c$ (b,d).

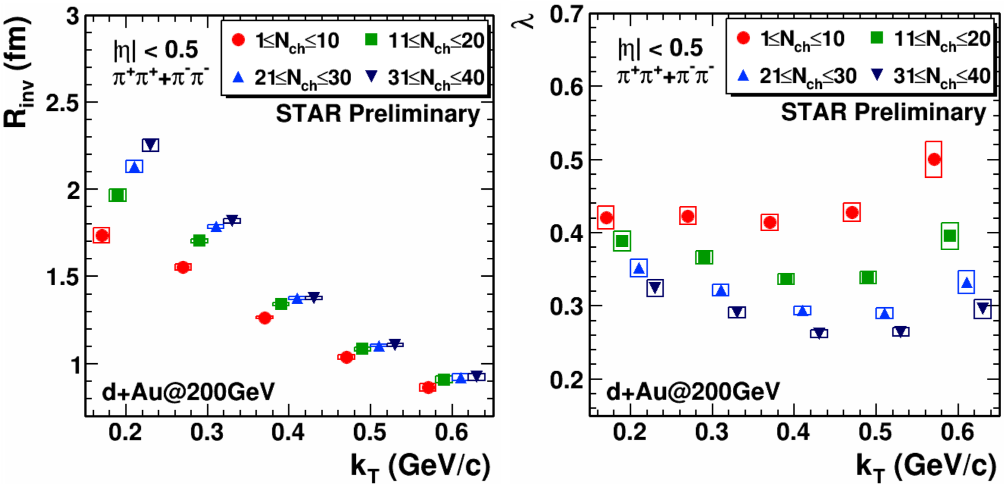

Figure 2. (Color online) Transverse momentum ($k_T$) dependence of charged pion invariant radii (left panel) and correlation strength parameter (right panel) for different multiplicity bins in d+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. The vertical lines and boxes represent the statistical and systematic uncertainties respectively. For almost all cases the statistical uncertainties are smaller than the marker size.

Figure 2 shows the dependence of the one-dimensional femtoscopic radii and correlation strength parameter on the transverse momentum of pion pairs for d+Au collision system at $\sqrt{s_{NN}} = 200$ GeV. The radii increase with increasing multiplicity, as one would expect from the simple geometric picture of the collisions. The correlation strength parameter decreases with increasing multiplicity. The decrease of the radii with increasing $k_T$ indicates the presence of the collective radial flow [21].

## 5. Conclusions

The results of the $\pi^{\pm}\pi^{\pm}$ one-dimensional femtoscopic radii dependence on the pair transverse momentum and multiplicity for d+Au collision at $\sqrt{s_{NN}}$ = 200 GeV have been presented. It was shown that the radii increase with increasing multiplicity, which would be expected from the simple geometric picture of the collisions. For each of the studied multiplicity ranges the radii decrease with increasing transverse momentum of the pion pair. This dependence indicates the presence of the collective radial flow.

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## References

1. *Goldhaber G., Fowler W. B., Goldhaber S., Hoang T.F.* Pion-pion correlations in antiproton annihilation events // Phys. Rev. Lett. 1959. V. 3. P. 181-183.

2. *Goldhaber G., Goldhaber S., Lee W.-Y., Pais A.* Influence of Bose-Einstein statistics on the anti-proton proton annihilation process // Phys. Rev. 1960. V. 120. P. 300-312.

3. *Kopylov G.I., Podgoretsky M.I.* Correlations of identical particles emitted by highly excited nuclei // Sov. J. Nucl. Phys. 1972. V. 15. P. 219-223.

4. *Kopylov G.I., Podgoretsky M.I.* Multiple production and interference of particles emitted by moving sources // Sov. J. Nucl. Phys. 1974. V. 18. P. 336-341.

5. *Akkelin S.V., Sinyukov Yu.M.* The HBT interferometry of expanding sources // Phys. Lett. B. 1995. V. 356. P. 525-530.

6. *Lisa M.A., Pratt S., Soltz R., Wiedemann U.* Femtoscopy in relativistic heavy ion collisions // Ann. Rev. Nucl. Part. Sci. 2005. V. 55. P. 357-402.

7. *Bzdak A., Schenke B., Tribedy P., Venugopalan R.* Initial state geometry and the role of hydrodynamics in proton-proton, proton-nucleus and deuteron-nucleus collisions // Phys. Rev. C. 2013. V. 87. P. 10.

8. *Plumberg C.* Hanbury Brown–Twiss Interferometry and Collectivity in Small Systems // arXiv:2008.01709

9. *Aidala C. et al. (PHENIX Collaboration)* Creation of quark–gluon plasma droplets with three distinct geometries // Nature Phys. 2019. V. 15. P. 214-220.

10. *Betty B.A. et al. (ALICE Collaboration)* Multiplicity Dependence of Pion, Kaon, Proton and Lambda Production in p-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV // Phys. Lett. B. 2014. V. 728. P. 25-38.

11. *Kopylov G.I.* Like particle correlations as a tool to study the multiple production mechanism // Phys. Lett. B. 1974. V. 50. P. 472-474.

12. *Bowler M.G.* Coulomb corrections to Bose-Einstein correlations have been greatly exaggerated // Phys. Lett. B. 1991. V. 270. P. 69-74.

13. *Sinyukov Yu., Lednicky R., Akkelin S.V., Pluta J., Erazmus B.* Coulomb corrections for interferometry analysis of expanding hadron systems // Phys. Lett. B. 1998. V. 432. P. 248-257.

14. *Bowler M.G.* Coulomb corrections to Bose-Einstein correlations have been greatly exaggerated // Phys. Lett. B. 1998. V. 270. P. 69-74.

15. *Sinyukov Yu., Lednicky R., Akkelin S.V., Pluta J., Erazmus B.* Coulomb corrections for interferometry analysis of expanding hadron systems // Phys. Lett. B. 1998. V. 432. P. 248-257.

16. *Ackermann K.H. et al. (STAR Collaboration)* STAR detector overview // Nucl. Instrum. Meth. A. 2003. V. 499. P. 624-632.

17. *Anderson M. et al.* The Star time projection chamber: A Unique tool for studying high multiplicity events at RHIC // Nucl. Instrum. Meth. A. 2003. V. 499. P. 659-678.

18. *Llope W.J. et al* The STAR Vertex Position Detector // Nucl. Instrum. Meth. A. 2014. V. 759. P. 23-28.

19. *Aggarwal M.M. et al. (STAR Collaboration)* Pion femtoscopy in $p + p$ collisions at $\sqrt{s} = 200$ GeV // Phys. Rev. C. 2011. V. 83. P. 064905.

20. *Adams J. et al. (STAR Collaboration)* Pion interferometry in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV // Phys. Rev. C. 2005. V. 71. P 25.

21. *Makhlin A.N, Sinyukov Yu.M.* Hydrodynamics of Hadron Matter Under Pion Interferometric Microscope // Z. Phys. C. 1988. V. 39. P. 13.