Residual third-body Coulomb effect on identical charged pion correlations in Au+Au collisions at STAR

Vinh Ba Luong[1,*] for the STAR Collaboration

[1]Joint Institute for Nuclear Research, Dubna 141980

Abstract. We report the identical charged pion femtoscopic correlations measured by the STAR experiment in Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 3.0, 3.2, 3.5, 3.9, 4.5, 5.2, and 7.7 GeV. A clear collision energy dependence of the difference between $\pi^+\pi^+$ and $\pi^-\pi^-$ correlations is observed for $R_{\rm side}$ and $R_{\rm long}$ radii. Further study suggests the residual third-body Coulomb effect is the dominant source causing the difference.

1 Introduction

Measurements of identical pion femtoscopy offer insights into collision dynamics, such as collective expansion, geometry of the collision zone at freeze-out, etc. (see [1] for a review). In addition to the quantum interference between two pions within a pair, Coulomb interactions between the pair and the net positive charge in the emitting source affect the final measurements as well [2]. Furthermore, due to the imbalance of protons and neutrons inside the colliding nuclei, initial isospin, which plays an important role in determining the Equation of State (EoS) of the produced medium, also affects the correlation functions at high baryon density.

To extract the effect of the isospin, a systematic analysis of the identical charged pion femtoscopic correlations from $\sqrt{s_{\rm NN}}$ = 3.0, 3.2, 3.5, 3.9, 4.5, 5.2, and 7.7 GeV Au+Au collisions collected by the STAR experiment has been carried out. A new procedure has been developed to remove the residual effect from the third-body Coulomb force. We report collision energy dependence of the source size parameters extracted from the positive and negative charged pion correlation functions after removing the third-body Coulomb effect. UrQMD [3] transport model calculations with realistic experimental cuts are used to aid the discussions.

2 Analysis method

The two-particle correlation functions can experimentally be measured by the ratio: $C(\mathbf{q}) = N(\mathbf{q})/D(\mathbf{q})$, where $\mathbf{q} \equiv \mathbf{p}_1 - \mathbf{p}_2$ is the relative momenta of the first ($\mathbf{p}_1$) and the second ($\mathbf{p}_2$) particles from a pair. The numerator distribution ($N(\mathbf{q})$) is constructed from pairs, both particles of which are from the same event. The denominator distribution ($D(\mathbf{q})$) is constructed from pairs formed from particles coming from different events. For the case of pion correlation femtoscopy, while both $N(\mathbf{q})$ and $D(\mathbf{q})$ contain two-particle phase-space information,

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[*] e-mail: lbavinh@gmail.com

the $N(\mathbf{q})$ contains additional contributions from Bose-Einstein correlations and Coulomb interactions between the two pions.

To mitigate the two-track detector effects on measured correlation functions: track splitting and track merging, specific pair selection criteria are implemented. These pair selection criteria are applied to both $N(\mathbf{q})$ and $D(\mathbf{q})$ equally.

Particles forming the pair are boosted to the longitudinal comoving system (LCMS), where the longitudinal components of their momenta cancel each other, $p_{z,1} + p_{z,2} = 0$. The pair relative momentum is then decomposed into Bertsch-Pratt [4, 5] "out-side-long" coordinate system.

Pairs with transverse momentum: $0.15 < k_{\mathrm{T}} < 0.25$ GeV$/c$ and pair rapidity in the collision center-of-mass frame: $-0.5 < y^{\pi\pi}_{\mathrm{c.m.}} < 0$ are selected for this analysis.

The Bowler-Sinyukov [6, 7] procedure is applied to fit and extract the femtoscopic parameters from the correlation functions:

$$C(\mathbf{q}) = N\left[(1-\lambda) + \lambda K_{\mathrm{Coul}}(q_{\mathrm{inv}})G(\mathbf{q})\right] \tag{1}$$

where

$$G(\mathbf{q}) = 1 + \exp(-q^2_{\mathrm{out}}R^2_{\mathrm{out}} - q^2_{\mathrm{side}}R^2_{\mathrm{side}} - q^2_{\mathrm{long}}R^2_{\mathrm{long}} - 2q_{\mathrm{out}}q_{\mathrm{long}}R^2_{\mathrm{out-long}}) \tag{2}$$

is the quantum-statistical part of the correlation function, N is the normalization factor, λ is the correlation strength, K_{Coul} is the correlation funtion accounting for the Coulomb interaction between the two pions within the pair. Femtoscopic radii: R_{out}, R_{side}, R_{long} give the length of homogeneity regions in the "out", "side", and "long" directions, respectively. $R^2_{\mathrm{out-long}}$ is the off-diagonal element accounting for the asymmetric acceptance w.r.t. midrapidity $y_{\mathrm{c.m.}} = 0$.

In this work, we propose a procedure to correct for the effect of the residual third-body Coulomb interactions on the measurements of femtoscopic correlations. First, the values of effective residual third-body Coulomb charge ($Z^{\mathrm{eff}}_{\mathrm{res.ch.}}$) are estimated. At $\sqrt{s_{\mathrm{NN}}} = 3.0$ GeV, $Z^{\mathrm{eff}}_{\mathrm{res.ch.}}$ is extracted from π^-/π^+ p_{T}-spectra ratio by matching data with UrQMD. Assuming third-body Coulomb is a point-like source, the pion momenta in UrQMD are distorted depending on the freeze-out distance from the collision's center. Such an approach yields $Z^{\mathrm{eff}}_{\mathrm{res.ch.}} = 50$ at $\sqrt{s_{\mathrm{NN}}} = 3.0$ GeV. For other energies, $Z^{\mathrm{eff}}_{\mathrm{res.ch.}}$ are scaled down by the overlapping time of the two colliding nuclei (τ_{overlap}). Values of the estimated $Z^{\mathrm{eff}}_{\mathrm{res.ch.}}$ are listed in Table 1.

Table 1. $Z^{\mathrm{eff}}_{\mathrm{res.ch.}}$ values used for third-body Coulomb correction for 0–10% central Au+Au collisions.

$\sqrt{s_{\mathrm{NN}}}$ (GeV)	3.0	3.2	3.5	3.9	4.5	5.2	7.7
τ_{overlap} (fm/c)	10.1	9.1	8.0	7.0	5.8	4.9	3.2
$Z^{\mathrm{eff}}_{\mathrm{res.ch.}}$	50	45	40	34	29	24	16

To correct for the third-body Coulomb, the magnitude of the momentum vector of each single π^+ (π^-) is reduced (increased) by an amount of Δp_{π^+} (Δp_{π^-}). The values of Δp_{π^+} and Δp_{π^-} are quantified from UrQMD simulations, where the third-body Coulomb is incorporated using the quantum relativistic approach described in Ref. [9] with estimated $Z^{\mathrm{eff}}_{\mathrm{res.ch.}}$ values. The momentum shift needed for correction is the value such that the original femtoscopic radii R_{side} without third-body are recovered. An illustration of this procedure is depicted in Fig. 1. Finally, the determined Δp_{π^+} and Δp_{π^-} at each $\sqrt{s_{\mathrm{NN}}}$ are applied to the data for third-body Coulomb correction.

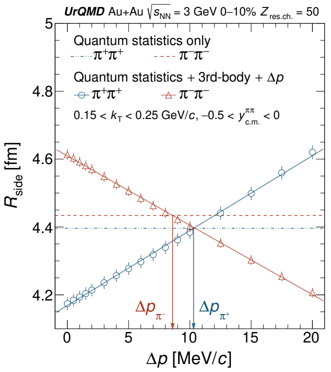

Figure 1. $R_{\rm side}$ as a function of Δp for third-body Coulomb correction for $\pi^+\pi^+$ (circles) and $\pi^-\pi^-$ (triangles) pairs from UrQMD calculations from 0–10% central Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 3 GeV. Third-body Coulomb is incorporated into UrQMD using a quantum relativistic approach [9] with $Z^{\rm eff}_{\rm res.ch.}$ = 50. Horizontal dash lines denote the original $R_{\rm side}$ with only quantum statistics included. Vertical arrows indicate the intercepts at Δp_{π^+} (Δp_{π^-}), for which the original $R_{\rm side}$ radii for each charged pion pair are restored.

3 Charged pion femtoscopy results without third-body correction

Figure 2 illustrates the projections of the 3-dimensional correlation functions measured for pion pairs with $0.15 < k_{\rm T} < 0.25$ GeV/c and $-0.5 < y^{\pi\pi}_{\rm c.m.} < 0$ from 0–10% central Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 3.2 GeV. A difference of a few percentage at low-q is observed in the correlation functions between positively and negatively charged pion pairs.

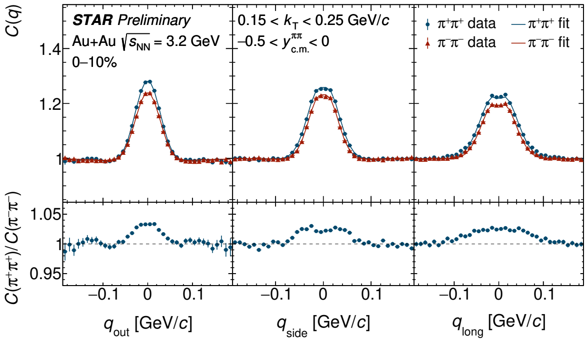

Figure 2. Top: Projections of the correlation functions onto $q_{\rm out}$, $q_{\rm side}$, and $q_{\rm long}$ for $\pi^+\pi^+$ (circles) and $\pi^-\pi^-$ (triangles) pairs for $0.15 < k_{\rm T} < 0.25$ GeV/c and $-0.5 < y^{\pi\pi}_{\rm c.m.} < 0$ from 0–10% central Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 3.2 GeV. The curves show the projections of the 3-dimensional fit to the correlation functions. Bottom: Ratios of the correlation functions between $\pi^+\pi^+$ and $\pi^-\pi^-$ pairs. Errors are statistical only.

The collision energy dependence of $R_{\rm out}$, $R_{\rm side}$, $R_{\rm long}$ femtoscopic radii is shown in Fig. 3. $R_{\rm out}$ radii show insignificant difference between $\pi^+\pi^+$ and $\pi^-\pi^-$ within uncertainties. On the other hand, a clear collision energy dependence of the charge-sign difference is observed for $R_{\rm side}$ and $R_{\rm long}$ radii. The charge splitting effect is most prominent at low $\sqrt{s_{\rm NN}}$. For comparison, HADES measurements at $\sqrt{s_{\rm NN}}$ = 2.4 GeV [8] are shown as triangles in Fig. 3.

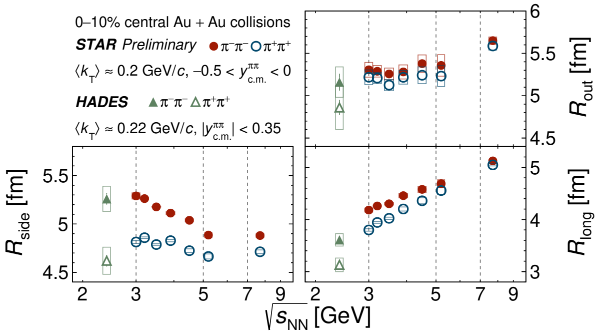

Figure 3. $\sqrt{s_{\rm NN}}$-dependence of extracted femtoscopic radii of midrapidity $\pi^-\pi^-$ (filled markers) and $\pi^+\pi^+$ (open markers) at low-$k_{\rm T}$ from 0–10% central Au+Au collisions. For STAR data, statistical uncertainty is smaller than the marker size. Boxes depict systematic uncertainties. HADES data are taken from Ref. [8].

4 Third-body Coulomb corrected radii

Figure 4 illustrates the $\pi^-\pi^-/\pi^+\pi^+$ ratios of R_{out}, R_{side}, and R_{long}. After residual third-body Coulomb correction, all three femtoscopic radii ratios are found to be consistent with unity within uncertainties. This observation suggests residual third-body Coulomb plays a key role among effects giving rise to the difference between $\pi^+\pi^+$ and $\pi^-\pi^-$ femtoscopic correlations. The isospin effect is observed to be small in the data. The UrQMD calculations including only quantum statistics effect predict the charge-sign difference is most prominent for the R_{long} radii at low $\sqrt{s_{\text{NN}}}$.

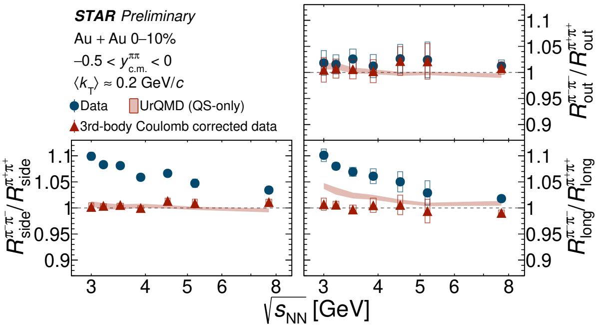

Figure 4. $\pi^-\pi^-/\pi^+\pi^+$ radii ratios as a function of $\sqrt{s_{\text{NN}}}$ for midrapidity pions at low-k_T from 0–10% central Au+Au collisions. Statistical uncertainty is smaller than the marker size. Boxes depict systematic uncertainties. Circles (triangles) depict the data without (with) the third-body Coulomb correction. Shaded bands correspond to UrQMD calculations including only quantum statistics.

5 Summary

The charged pion femtoscopic correlations are measured in Au+Au collisions at $\sqrt{s_{\text{NN}}}$ = 3.0, 3.2, 3.5, 3.9, 4.5, 5.2, and 7.7 GeV by the STAR experiment. The difference between $\pi^+\pi^+$ and $\pi^-\pi^-$ observed in the correlation functions and subsequently in R_{side}, R_{long} radii increases as collision energy decreases. The $\pi^-\pi^-/\pi^+\pi^+$ radii ratios after third-body Coulomb correction are consistent with unity within uncertainties. Within the approach of this work, these results suggest the residual third-body Coulomb is the dominant source causing the difference between $\pi^+\pi^+$ and $\pi^-\pi^-$ in the measured charged pion femtoscopic correlations, and the contribution of the isospin effect to the correlation functions is small.

References

[1] M. A. Lisa, S. Pratt, R. Soltz, U. Wiedemann, Ann. Rev. Nucl. Part. Sci. **55**, 357 (2005)
[2] J. Adamczewski-Musch *et al.* (HADES Collaboration), Eur. Phys. J. A **58**, 166 (2022)
[3] M. Bleicher *et al.*, J. Phys. G **25**, 1859 (1999)
[4] S. Pratt, Phys. Rev. D **33**, 1314 (1986)
[5] G. Bertsch, M. Gong, M. Tohyama, Phys. Rev. C **37**, 1896 (1988)
[6] M. G. Bowler, Phys. Lett. B **270**, 69 (1991)
[7] Y. Sinyukov, R. Lednicky, S. V. Akkelin *et al.*, Phys. Lett. B **432**, 248 (1998)
[8] J. Adamczewski-Musch *et al.* (HADES Collaboration), Phys. Lett. B **795**, 446 (2019)
[9] R. Lednicky, Phys. Part. Nucl. **40**, 307 (2009)