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FEMTOSCOPY OF PION–PROTON SYSTEM AT 200 A GeV*

Marcin Zawisza

Warsaw University of Technology, Faculty of Physics, Warsaw, Poland

for the STAR Collaboration

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Correlations between non-identical particles at small relative velocity probe asymmetries in the average space-time emission points at freeze-out. Such asymmetries may arise from long-lived resonances, bulk collective effects, or differences in the freeze-out scenario for the different particle species. STAR has extracted pion–proton correlation functions from a high-statistics dataset of Au + Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV. We present a femtoscopic analysis (including spherical-harmonics decomposition) of pions and (anti-)protons for collisions of different centrality. Our results suggest that pions and protons have relatively shifted average space-time emission points. At the end we show `THERMINATOR` simulations which look quantitatively similar to the data.

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1. Introduction

Femtoscopy is the only experimental technique that provides possibility of measuring space time quantities of the order of 10^{-15} m and 10^{-23} s. It allows for investigation of evolution of nuclear matter created in heavy ion collisions. Two particles with small relative velocity emitted from source interact through strong and Coulomb interactions called final state interactions (FSI) which give correlation between them. Non identical correlations are sensitive to space-time asymmetry in particle emission [1]. By measuring them we can investigate which sort of particles are emitted earlier or later and what is the relative shift between average emission points.

Information about size and space-time asymmetry of the source can be extracted from correlation functions calculated with respect to sign of the *out*, *side* and *long* components. First such analysis has been already done for pion–kaon system by STAR collaboration for Au + Au collisions at $\sqrt{s_{\rm NN}} =$ 130 GeV [2].

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Information on the shapes and asymmetries of the pair separation distribution are most efficiently encoded in a spherical harmonic representation of the correlation function [3]. Recently a new technique has been developed that allows to calculate correlation function directly in spherical harmonics [4]. This method has some advantages especially important for analysis of non-identical particles. Function decomposed into spherical harmonics keeps more detailed information about the source. Big difference of masses between pions and protons cause that, due to limited momentum acceptance, some orientations in space of k^* vector (momentum of first particle in Pair Rest Frame) are not registered in the experiment. Functions calculated directly in spherical harmonics are less sensitive to this effect which gives us possibility to obtain more reliable results.

2. Experimental analysis

2.1. Data selection

In this work we analyze data coming from Au–Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV. Events taken with minimum-bias trigger are divided into three centrality groups: 0–10%, 10–30% and 30–50% of the total hadronic cross-sections. Only events with vertex position placed between ±30 cm from the center of the detector are analyzed. Particle identification is based on dE/dx data coming from the time projection chamber. Due to significant mass difference between pions and protons, selecting close velocity pairs requires wide range of momentum acceptance. To meet these requirements transverse momentum cuts have been set up to 0.1–0.5 GeV for pions and 0.5–1.25 GeV for protons. Both species of particles are selected in mid-rapidity region $|y| < 0.7$. The main problem in particle selection is caused by correlated electron–positron pairs coming from gamma conversion which are incorrectly identified as pion–proton pairs. In this analysis probability

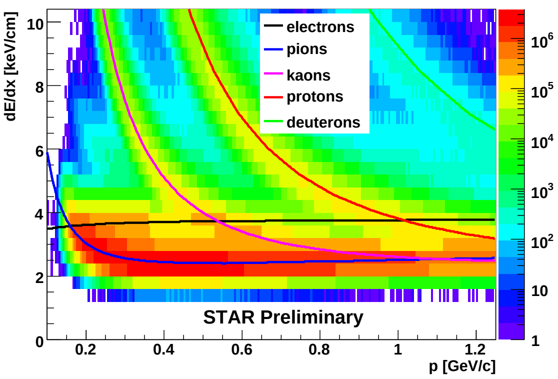

Fig. 1. Rate of energy loss *versus* magnetic rigidity.

of such misidentification is increased by the fact that pions dE/dx curve in momentum range which is used in our analysis intersect with electrons dE/dx (Fig. 1). The same is for protons. Thus to ensure high quality of data sample a topological cut is also applied to remove electron–positron pairs coming from gamma conversion, pairs with merged hits and pairs with low probability of being pion–proton pair.

2.2. Events mixing

In femtoscopic analysis it is very important to ensure constructing background (mixing) from events with similar characteristics. In this analysis events with vertex position separated not more than 4 cm are mixed. Each centrality bin is also divided into 6 multiplicity bins and 3 event mean p_{T} bins what assures that mixed pairs are constructed only from events with similar multiplicity and mean p_{T}. This procedure removes undesirable effect of slope of the correlation function for large k^* (non-flat correlation function for large k^*).

2.3. Pair purity correction

Due to experimental reasons not all of the particles taken into analysis are primary pions and protons. This results in a fact that not all of the pairs are correlated. To reduce undesirable influence of this effect we calculate pair purity that is defined as a fraction of primary pion–proton pair (obtained from THERMINATOR) multiplied by pion–proton pair identification probability (product for pion and proton individual dE/dx probabilities). The correlation based on such k^* dependent purity function is applied to measured correlation function according to the Eq. (1).

$$C_{\mathrm{real}}(k^*) = \frac{C_{\mathrm{measured}}(k^*) - 1}{\mathrm{Purity}(k^*)} + 1\,. \tag{1}$$

2.4. Correlation functions

After applying these methods of data selection and events mixing we can construct proper correlation functions. Such preliminary functions have been calculated by STAR for π^+–p (Fig. 2), π^-–$\bar{p}$ (Fig. 3), π^+–$\bar{p}$ (Fig. 4) and π^-–p (Fig. 5) for three centralities. Obtained results show clear dependence on centrality of the size of the system. For central events correlation effect is weaker because size of the system is bigger. Correlation is getting stronger in next centrality bins as the size of the system is getting smaller. Double ratios [1] calculated with respect to sign of *out* component of k^* vector carry information about space-time asymmetry of the source in particle emission. For like sign pairs asymmetry of the source is clearly reflected on calculated *out* double ratios. Unlike sign pairs do not show asymmetry which could be related to experimental issues and requires more study to understand. *Side* and *long* double ratios are not plotted because they vanish due to symmetry reasons.

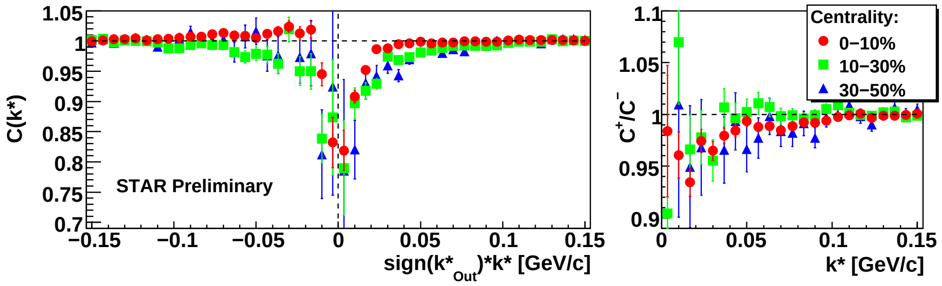

Fig. 2. π–p correlation functions and double ratios as a functions of k^*.

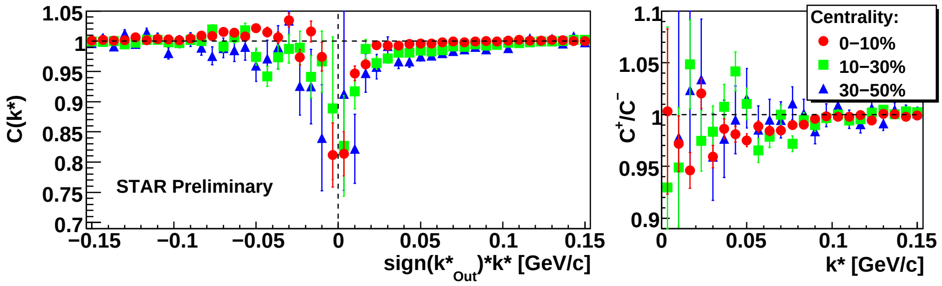

Fig. 3. π^-–$\bar{p}$ correlation functions and double ratios as a functions of k^*.

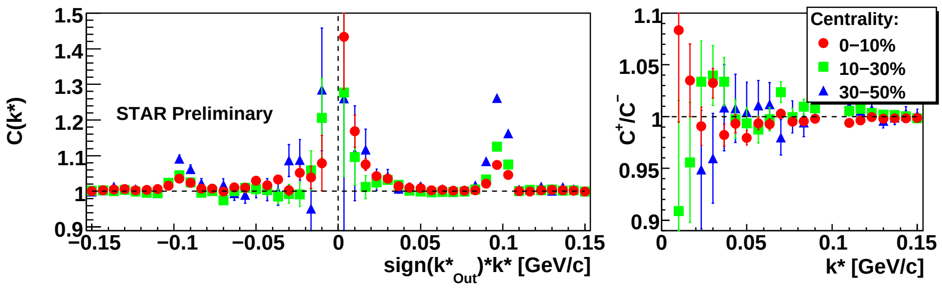

Fig. 4. π–$\bar{p}$ correlation functions and double ratios as a functions of k^*.

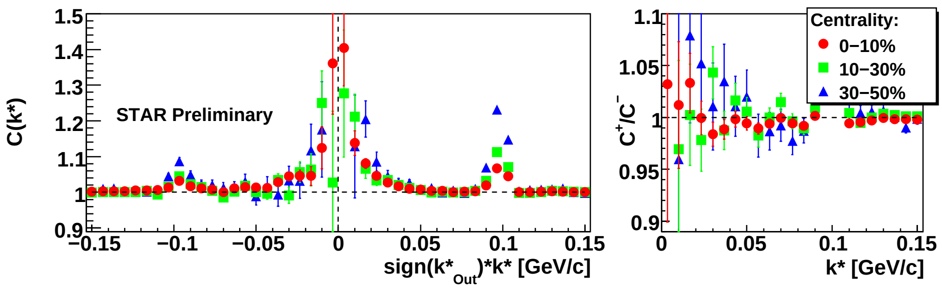

Fig. 5. π^-–p correlation functions and double ratios as a functions of k^*.

2.5. Correlation functions in spherical harmonics

Information about asymmetry can be also extracted from correlation functions calculated in spherical harmonics. Fig. 6 presents such functions calculated for central events. C_0^0 components reflects size of the system and C_1^1 reflects space-time asymmetry of the source. Correlation functions calculated directly in spherical harmonics are more efficient in describing geometry of the source so they are a good supplement to previous results. Presented functions for π^+–p (red circles) and π^-–$\bar{p}$ (blue squares) as well as π^+–$\bar{p}$ (green triangles) and π^-–p (black inverted triangles) seem to show some trend which can be interpreted as an evidence of asymmetry in the observed source.

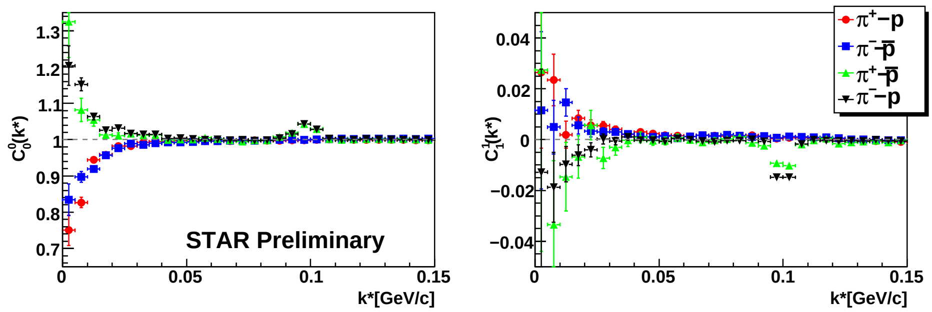

Fig. 6. Correlation function in spherical harmonics *versus* k^* for π^+–p (red circles), π^-–$\bar{p}$ (blue squares), π^+–$\bar{p}$ (green triangles), π^-–p (black inverted triangles).

3. Simulations with THERMINATOR

For better understanding of our experimental results we performed similar study with the THERMINATOR 2.0 beta [5] with hydrodynamical evolution which includes all effects, important for asymmetry measurement in non-identical systems, like resonance decays and collective flow. Parameters of the model used in this work have been set to the values provided by the authors of THERMINATOR in [6]. Figs. 7 and 8 show simulated correlation functions for unlike sign pairs and like sign pairs correspondingly. Figs. 9 and 10 show simulated correlation functions binned in spherical harmonics. Both methods of calculating correlation functions from simulated data show functions similar to our experimental results.

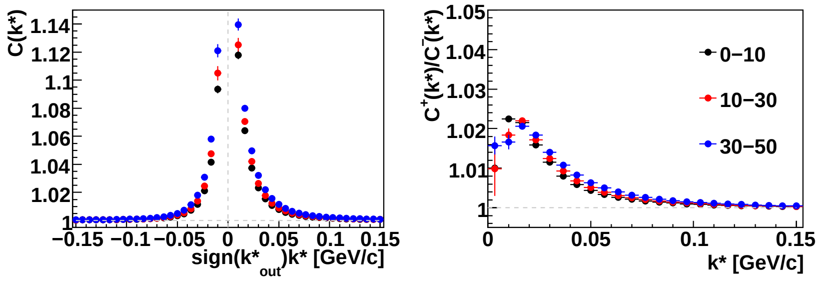

Fig. 7. Correlation functions and corresponding double ratios for unlike sign pairs (THERMINATOR).

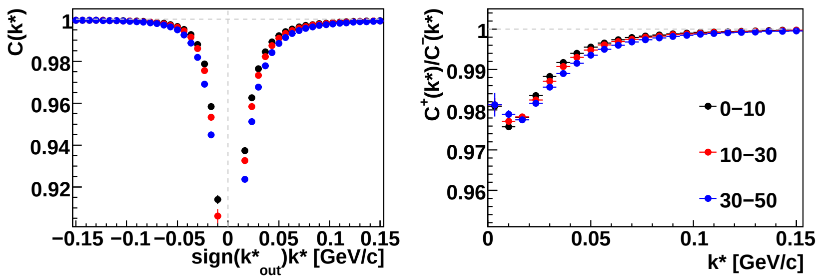

Fig. 8. Correlation functions and corresponding double ratios for like sign pairs (THERMINATOR).

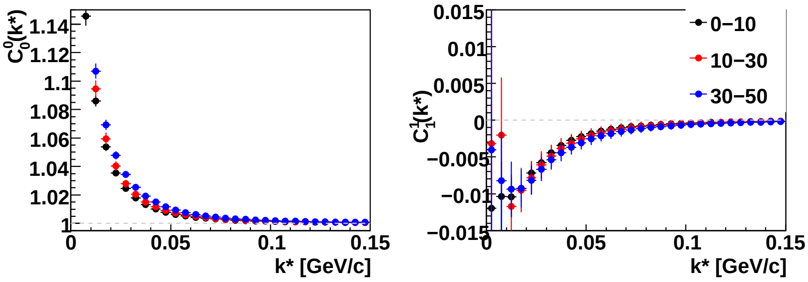

Fig. 9. Correlation functions in spherical harmonics for unlike sign pairs (THERMINATOR).

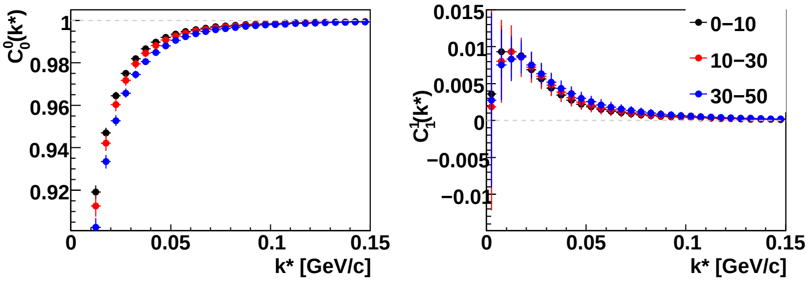

Fig. 10. Correlation functions in spherical harmonics for like sign pairs (`THERMINATOR`).

4. Summary

We presented preliminary results of pion–proton femtoscopy for AuAu collisions at $\sqrt{200}$ GeV at RHIC. Correlation functions and corresponding double ratios calculated in *out* direction for like sign pairs show asymmetry in average space-time emission points for pion–proton system. We cannot make any statement (based on *out* double ratio) on asymmetry for unlike sign pairs. This is due to limited momentum acceptance and still present electron–positron contamination. Similar information can be extracted from decomposition of correlation function into spherical harmonics. This technique is more efficient thus computed results are more valuable. Based on C_1^1 components we can make conclusion that we observe asymmetry in all charge combinations. Qualitative comparisons with earlier model predictions [7, 8] and those done in this work allow us to claim that average emission points of pions and protons are relatively shifted. Average emission points of pions are distributed over almost the whole source and average emission point of protons is shifted towards outside of the source.

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