NON-IDENTICAL PARTICLE CORRELATIONS IN STAR AS A PROBE OF EMISSION ASYMMETRIES AND RADIAL FLOW*

Adam Kisiel, Piotr Szarwas

Faculty of Physics, Warsaw University of Technology
Koszykowa 75, 00-662 Warsaw, Poland

and Fabrice Retière

Lawrence Berkeley National Laboratory, Berkeley, CA, USA

for the STAR Collaboration

(Received November 18, 2003)

Non-identical particle correlations offer new methods of probing the dynamics of the heavy-ion collision. In STAR we have performed a correlation analysis of pion–kaon and pion–proton pairs for 130 AGeV AuAu collisions. The results show that average emission space-time points of these particle species are not the same. These asymmetries are interpreted as a consequence of space-momentum correlations produced by rapid transverse radial expansion of the system. The effects of emission time differences, coming from the decay of resonances, are also investigated with the help of rescattering models, and explain only part of the asymmetry. Therefore our measurements represent an independent confirmation of the existence of transverse radial flow.

PACS numbers: 25.75.Gz, 25.75.Ld

1. Introduction

One of the main physics goals of the Relativistic Heavy-Ion Collider operating in the Brookhaven National Laboratory is the search for a new state of matter, where quarks and gluons are deconfined and form a Quark-Gluon Plasma (QGP). Many experimental observables have been proposed

* Presented at the XXXIII International Symposium on Multiparticle Dynamics, Kraków, Poland, September 5–11, 2003.

as evidence of the existence of such phase. One of them is the collective behavior of matter (flows) at a partonic level. Such flows at the early stage of the collision produce flows at the final stage, one of them being transverse radial flow. Non-identical particle correlations [1–3] have been proposed [4] as a measure of such flow as well as asymmetries in particle emission from the expanding system produced in the heavy-ion collision.

2. Non-identical particle correlations technique

Identical particle correlations (HBT) have been used to study the space-time characteristics of the system produced in heavy-ion collisions, also in STAR [5]. Non-identical particle correlations have been proposed as a method giving supplementary information as well as providing new insights into the dynamics of the collision [4].

2.1. Correlation functions

The correlation function for non-identical particles reflects final state (after last elastic collision) Coulomb (for charged particles) and strong (for hadrons) interactions. We construct the correlation functions for pairs of particles with close relative momentum k^*, which corresponds to close velocities in the source rest frame. The height and width of the correlation carry the information about the size of the emission region.

2.2. "Double ratios"

The correlation functions of non-identical particles also carry a qualitatively new piece of information — the emission asymmetries [1]. The technique uses the fact that both particles are quantum-mechanically distinguishable. We divide particle pairs in two groups — with $k^*_x > 0$ and $k^*_x < 0$, where k^*_x is the component of the relative momentum of the first particle in one of the following directions: out — the direction of pair momentum, long — the direction of beam axis or side — perpendicular to both previous ones. We can then construct two correlation functions: $C^x_+(k^*)$ for pairs with $k^*_x > 0$, and $C^x_-(k^*)$ for pairs with $k^*_x < 0$. It can be shown that these two functions should be identical if the average emission points of the two particle species are the same. However if there is a non-zero difference Δr_x between average emission points r_x of the particle species in the given direction x, the functions C^x_+ and C^x_- will be different, and their "double ratio" $C^x_+(k^*)/C^x_-(k^*)$ will be proportional to this Δr_x at $k^* = 0$ [3].

By symmetry considerations it can be shown that $\langle \Delta r_{\mathrm{side}} \rangle = 0$. For a symmetric system with a symmetric rapidity coverage (as is the case in AuAu collisions at STAR) we also have $\langle \Delta r_{\mathrm{long}} \rangle = 0$. The only direction where we expect the asymmetry is out. It can be written:

$$\langle \Delta r^*_{\rm out} \rangle = \langle \gamma(\langle \Delta r_{\rm out} \rangle - \beta \langle \Delta t \rangle) \rangle \ , \tag{1}$$

where values with asterisk (*) are in the pair rest frame and therefore can be measured directly through the correlation function, while values without the asterisk are in the source rest frame. From equation (1) one can see that the observable asymmetry can come from space and/or time component. For now we concentrate on the origin of the space asymmetry. For simplicity we only consider the transverse plane. Let us assume that a velocity $\vec{\beta}$ of the particle has a flow component $\vec{\beta}^{\rm F}$, which is aligned with the vector $\vec{r}$, which describes that particle's emission point. It also has a thermal component $\vec{\beta}^{\rm T}$, which has a random direction ϕ. Since the out direction (here denoted by $\hat{x}$) is determined by the direction of the observed velocity $\vec{\beta} = \vec{\beta}^{\rm F} + \vec{\beta}^{\rm T}$, the average out component of $\vec{r}$ can be written as:

$$\langle r_{\rm out} \rangle = \langle \vec{r}\hat{x} \rangle = \left\langle r \frac{\beta^{\rm F} + \beta^{\rm T}\cos(\phi)}{\beta_\perp} \right\rangle \approx \left\langle r \frac{\beta^{\rm F}}{\sqrt{{\beta^{\rm F}}^2 + {\beta^{\rm T}}^2}} \right\rangle . \tag{2}$$

For hydrodynamics-like flow, the flow velocity of all types of particles is the same. However the thermal component depends on particle momenta and is different for different mass particles. Therefore, if we consider pairs of particles with different masses (*e.g.* pion–kaon) we expect a non-zero shift:

$$\langle \Delta r_{\rm out} \rangle = \langle r_{{\rm out},\pi} - r_{{\rm out},K} \rangle \approx \langle r_{{\rm out},\pi} \rangle - \langle r_{{\rm out},K} \rangle \ . \tag{3}$$

In order for this shift to be significant, the flow and thermal component of the velocities should be comparable. Specifically if the flow component $\beta_{\rm F} = 0$, the shift should be zero.

3. Results from the STAR experiment

Non-identical particle correlations have been studied by the STAR experiment [6]. The rapidity and azimuthal angle coverage of the detector is ideally suited for such a measurement. In this preliminary analysis we have used pions, kaons and protons identified in the STAR Time Projection Chamber (TPC) detector [7]. Only central (13% of the total hadronic cross-section) AuAu collisions at 130 AGeV were studied, with the exception of kaon–proton correlations, where only in 200 AGeV data sample sufficient statistics was available. Based on the dE/dx and momentum information, a probability for each particle to be a pion, kaon, proton and electron has been calculated. Only particles within the central rapidity region ($-0.5 < y < 0.5$) were used in this analysis. The momentum ranges (in GeV) were: (0.08, 0.5) for pions, (0.3,1.0) for kaons and (0.3,1.2) for protons. The reconstruction purity of the pair was calculated with the help of the dE/dx information. Only the pairs with at least 60% chance of being a right pair were accepted for the analysis. Also special care has been taken to eliminate $e^+ - e^-$ pairs, as the pairs coming from γ decays were found to significantly distort the correlation functions for opposite-charge pairs. Two-track effects were also taken into account: a cut was applied to eliminate pairs of tracks which shared more than 10% of their hits in the TPC. Momentum resolution and purity corrections [6] were also applied to the pion–kaon and pion–proton correlation functions.

In Fig. 1 we present the correlation functions for all combinations of pion–kaon, pion–proton and identical-charge kaon–proton pairs. Please note that all results except pion–kaon are preliminary. Opposite-charge kaon–proton correlations are not shown, because $e^+ - e^-$ and purity effects for these pairs are still under study. It can be seen that the correlation functions for all like-sign and opposite-sign combinations agree, which suggests that the emission mechanisms for opposite charge pions, kaons and protons are the same.

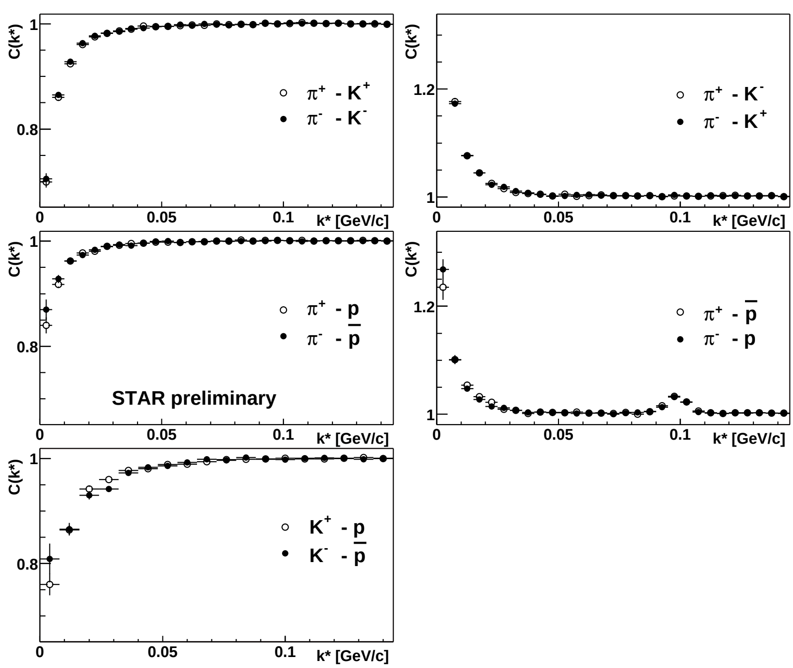

Fig. 1. The correlation functions for (from top to bottom) pion–kaon, pion–proton and kaon–proton pairs. On the left identical charge combinations are plotted, on the right — opposite charge.

In Fig. 2 we present the "double" ratios in the out direction for pion–kaon, pion–proton and kaon–proton pairs. They clearly deviate from unity for all the combinations, showing that pions, kaons and protons are not emitted from the same average space-time point.

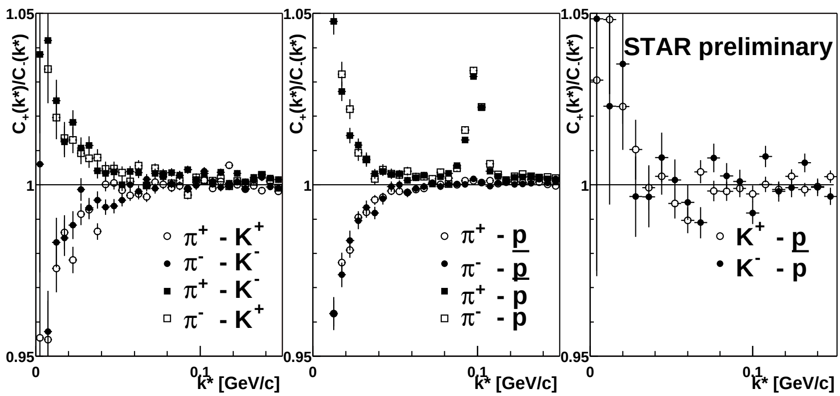

Fig. 2. The "double" ratios in the out direction for (from left to right) pion–kaon, pion–proton and kaon–proton pairs.

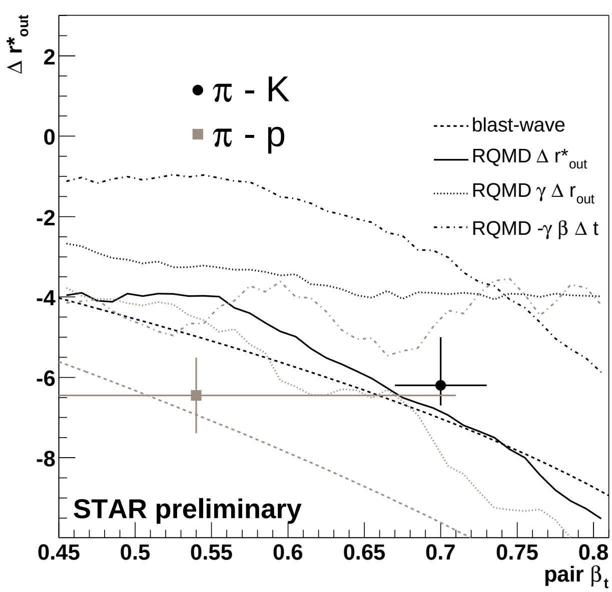

Fig. 3. Comparing pion–kaon (black) and pion–proton (grey) correlation function fit results with the predictions of models: blast-wave parameterization (dashed line) and RQMD (solid line). We also show a space(dotted line) and time (dashed-dotted line) component of the asymmetry from RQMD separately.

To quantify that shift in space-time emission point a fitting procedure is applied to the data. A source is assumed to be a Gaussian in $r^*_{\rm out}$, width σ and shift $\Delta r^*_{\rm out}$ of this distribution are taken as parameters of the fit. For each value of these parameters, with the use of experimental momentum distribution, a theoretical correlation function is constructed. Then a χ^2 value is calculated for each of these generated correlation functions. The one with the lowest χ^2 value is taken as the "best fit". The results of this fitting procedure are shown in Fig. 3. As the corrections for kaon–proton pairs were not ready yet, the fitting was not done for their correlation functions.

4. Understanding space-time asymmetries from models

Heavy-ion reaction models, which study the dynamics of the collision, provide a description of the emitting source. They also give the predictions for the emission asymmetries, which can be directly compared to our experimental results, and used to gain a better understanding of the reaction.

4.1. Blast-wave parameterization

The blast-wave parameterization [8] inspired by hydrodynamic calculations provides a simple way of describing a system with strong transverse radial flow. The asymmetry comes from the interplay between a flow velocity and thermal smearing of the emission point. This model shows that radial flows do produce the emission asymmetry that we expect. Moreover, the blast-wave calculation done with the parameters fixed by other measurements (elliptic flow — v_2 [9], $\pi\pi$ HBT [5], single particle spectra [10]) predict an asymmetry which is consistent with the data.

4.2. Rescattering models

We also studied the predictions of the RQMD model [11], which produces radial flows through hadronic rescatterings. In addition it allows for a complete treatment of resonances. Their decay can be a source of delayed (relative to the direct production) emission of pions, kaons and protons. Since the average delays are different for different particle species, we see a resulting average time shift between pions, kaons and protons, which produces emission asymmetries which sum with the spatial asymmetry coming from flow (see Eq. (1)). The relative weight of both components is shown in Fig. 3.

It is impossible to disentangle experimentally space and time contributions to the observed asymmetry. However the study of rescattering models shows, that neither flow, nor time difference alone are able to explain the magnitude of asymmetries observed in the data. Therefore we conclude that both effects are necessary to explain our measurements.

5. Conclusions

We have presented the preliminary results of pion–kaon, pion–proton and kaon–proton correlations measurements from the STAR experiment. The technique of measuring emission asymmetries has been described and applied to the STAR data. The emission asymmetry between pions and kaons as well as pions and protons has been measured, and the evidence for asymmetry between kaons and protons have been seen. They are shown to be consistent with the hypothesis of transverse radial flow produced in heavy-ion collisions, as seen *e.g.* in the blast-wave parameterization. Rescattering models were used to study the effect of emission time differences, which were found to be important, but not sufficient to explain the observed asymmetry. Therefore our measurements provide an independent confirmation of the existence transverse radial flow in AuAu collisions at RHIC.

REFERENCES

[1] R. Lednický, V.I. Lyuboshitz, B. Erazmus, D. Nouais, *Phys. Lett.* **B373**, 30 (1996).

[2] R. Lednický, V.L. Lyuboshitz, *Sov. J. Nucl. Phys.* **35**, 770 (1982); *Proc. CORINNE 90, Nantes, France*, 1990, ed. D. Ardouin, World Scientific, 1990, p. 42; *Heavy Ion Physisc* **3**, 93 (1996).

[3] S. Voloshin, R. Lednický, S. Panitkin, N. Xu, *Phys. Rev. Lett.* **79**, 30 (1997).

[4] R. Lednický `nucl-th/0305027`.

[5] C. Adler *et al. Phys. Rev. Lett.* **87**, 082301 (2001).

[6] J. Adams *et al.*, accepted for publication in *Phys. Rev. Lett.* July 31, 2003, `nucl-ex/0307025`.

[7] F. Retiere (STAR Collaboration), *Nucl. Phys.* **A698**, 408 (2000).

[8] B. Tomášik, U. Achim Wiedemann, U. Heinz, *Heavy Ion Phys.* **17**, 105 (2003); F. Retière, M. Lisa, in preparation.

[9] C. Adler *et al.*, *Phys. Rev. Lett.* **87**, 182301 (2001).

[10] C. Adler *et al.*, *Phys. Rev. Lett.* **87**, 112303 (2001).

[11] H. Sorge, *Phys. Rev.* **C52**, 3291 (1995).