INFLUENCE OF RESONANCE DECAY ON EMISSION ASYMMETRIES PROBED BY NON-IDENTICAL PARTICLE FEMTOSCOPY* **

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Non-identical particle femtoscopy is sensitive to relative emission asymmetries between particles of different masses. In heavy ion collisions observation of such asymmetries has been interpreted as a strong evidence of the collective behavior of matter. However, decays of resonances are also known to affect the asymmetries, mainly because they introduce a difference in average emission time, which is indistinguishable from the spatial shift coming from collective flow. We show that the effect of resonance decay processes on asymmetries are more complicated than the simple picture above. We show how resonance decay can result in the enhancement of the flow asymmetries, rather than its dilution.

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1. Introduction

Non-identical particle femtoscopy [1–5] has been used in low energy heavy-ion collisions to probe the emission asymmetries between emitted particles and nuclei fragments, measuring time differences of the order of up to hundreds of fm. The same technique has been applied to ultra relativistic heavy-ion collisions [6–11], but with different physics goal. The spatial asymmetry coming from the collective behavior of matter — radial flow, was being studied and the expected asymmetries were of the order of fm.

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However, the underlying uncertainty remained, where the measurable asymmetry $r^*_{\rm out}$ in the pair rest frame (PRF) is a combination of the spatial $r_{\rm out}$ (the interesting one) and temporal Δt (having more "trivial" origin) asymmetries in the longitudinally co-moving frame (LCMS):

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

the Lorentz transformation is done with pair transverse velocity β.

In heavy ion collisions at RHIC it was shown that the system can be well described by the hydrodynamic models; recently it was shown that even the space-time behavior can be adequately described if proper initial conditions, equation of state and hadronic resonance treatment is employed. We use the model that was successful in describing all the other observables to understand the emission asymmetries coming from radial flow and how particles coming from strong resonance decay affect it.

2. `LHYQUID` and `THERMINATOR` calculations

We base our work on the combination of `LHYQUID` hydrodynamics code and `THERMINATOR` package which implements freeze-out of particles, as well as resonance propagation and decay [12–16]. We use a particular `LHYQUID` calculation which was tuned to reproduce STAR central collisions data (pion, kaon and proton spectra as well as elliptic flow v_2). It also reproduces STAR pion femtoscopic radii [17]. The initial conditions include a Gaussian profile of initial energy density, its RMS is obtained from Glauber calculation. Equation of state combines the dependence obtained from lattice calculations above $T_{\rm c}$ and hadronic resonance gas below $T_{\rm c}$. There is no first order phase transition, but a smooth cross over in between the two. A single chemical and kinetic freeze-out temperature of 145 MeV is used. All known hadronic resonances are created at the freeze-out hypersurface (obtained from `LHYQUID`), and their propagation and decay (in cascades when necessary) is carried out by the `THERMINATOR` program. The simulation produces events, which consist of individual particles, making the application of all the experimental acceptance cuts straightforward.

2.1. Asymmetry from radial flow

Hydrodynamics calculation from `LHYQUID` naturally produces collective flow — *i.e.* all particles move with some collective velocity "outwards". This produces specific patterns in particle emission, that are of particular interest to non-identical particle femtoscopy. Let us consider two particles with similar velocity, but of different types, *e.g.* pion and kaon. Both will have the same collective velocity given by the velocity field from hydrodynamics. It will produce space–velocity direction correlations: velocities will point outwards — following the density gradient — away from the high density center. However, all particles are also affected by temperature, its net effect is that velocity will have an additional "thermal" component with random orientation. It will be relatively strong for light particles. Therefore for pions, the original correlation between position and velocity direction will be weak, so pions emitted in a given direction may come from the whole source. For kaons the position — velocity direction correlation will only be slightly diluted by temperature, as illustrated on right panels of Fig. 1, where particles have been rotated in such a way that their momentum is pointing in the positive x direction (hence the "out" label), and their emission points are plotted. A significant position–momentum correlation is apparent for both pions and kaons — emission points are shifted in the positive "out" direction. This correlation is stronger for kaons (note the mean x values) — confirming the expectation given above. This difference in the mean "out" emission point between particles of different mass is the main physics effect that we aim to observe with non-identical particle femtoscopy.

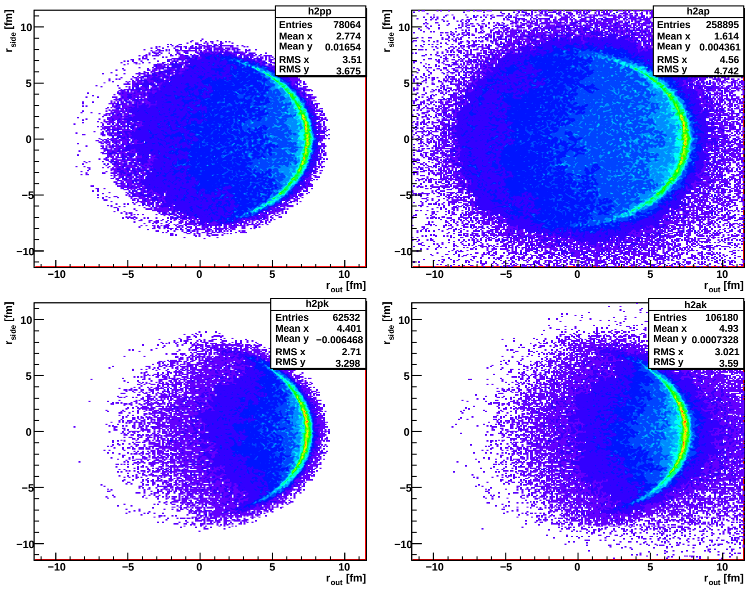

Fig. 1. Emission points of pions (top) and kaons (bottom) from the `THERMINATOR` model (central RHIC collisions). Primordial particles on the left panels, all particles on the right panels. Particles have velocities in the range 0.62 to 0.77.

2.2. Resonances influence on the emission asymmetries

Resonance propagation and decay has been of particular interest for non-identical particle femtoscopy, since it is expected to introduce emission time differences between particles of different type. This will influence the observed emission asymmetry, as per Eq. (1). However, the exact influence will depend on details of branching ratios and decay momenta, so it is interesting to see how adding resonance decay products will influence the asymmetry. The effect is shown in Fig. 1 on the right panels. One expected effect is seen — the overall size of the system grows both for pions and kaons — this has also been seen in identical pion femtoscopy. The result on space asymmetry is puzzling and appears to be counter-intuitive. Resonances seem to push pion emission point more to the center, while they have an opposite effect for kaons. So they significantly enhance the spatial asymmetry, which we originally associated with radial flow. Two important question arise: what is the origin of this effect and does it invalidate/question the radial flow interpretation of the asymmetry observed in the data?

In order to understand the effect, let us discuss the mechanics of the particle emission via resonance decay. We start from the original resonance, created at the freeze-out hypersurface. Since it is coming from the flowing medium, its velocity is correlated with position. It travels some distance in that direction, before it decays. The decay process can be reduced in our case to a randomization of direction of the daughter particle. How strong this randomization is, depends on the kinematics of a given decay process. Mathematically the decay momentum has precisely the same effect as temperature in the hydro consideration above. The higher this momentum is with respect to the daughter particle rest mass, the stronger is the randomization of direction.

Let us then do a simple calculation: to see how the particle emission points behave for pions and kaons, if they are coming from the strongly decaying resonance which has the rest mass closest to theirs. This study will be particularly useful, since such a resonance will also have the lowest possible mass, and therefore will be most abundant in the chemical model, so its relative effect on the particle of interest will be strongest. For pions we look at the ρ resonance, for kaons — at the K^*. According to the PDG, their width and decay momenta into particles of interest (pions and kaons, respectively) are: 150.3 MeV and 364 MeV/c for ρ and 50.8 MeV and 289 MeV/c for the K^*.

The result of the calculation is shown in Fig. 2. On the left panels, for comparison, emission points of primordial pions and kaons are shown. In the middle panels, emission points of the corresponding resonances. On the right panels — emission points of secondary pions and kaons. One can see that emission points of the resonances follow the expectations — both are strongly shifted outwards. Even though the decay kinematics are similar, the decay process has dramatically different results on pions and on kaons. The decay momentum for ρ is almost three times bigger than pion mass,

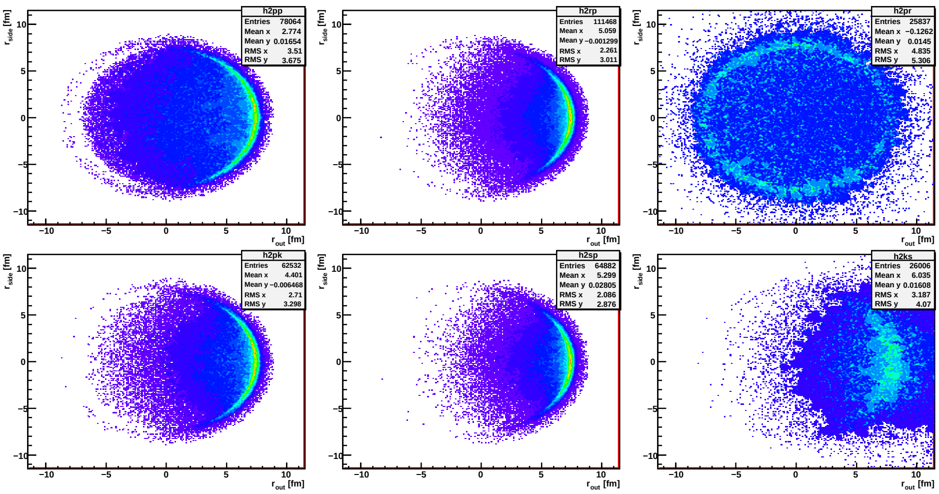

Fig. 2. Emission points of pions (top) and kaons (bottom) from the THERMINATOR model (central RHIC collisions). Primordial particles on the left panels, original resonance ρ top-middle panel, K^*, bottom-middle panel. Particles coming from the resonance on the right panels. Particles have velocities in the range 0.62 to 0.77.

hence the direction randomization is dramatic. The correlation between emission position and momentum direction, still visible in the original ρ, is completely lost. For these pions, which have particularly low momentum one can say that they come from the whole source. For kaons the situation is qualitatively different. Decay momentum introduces some, but not very strong randomization of direction. In fact the resonance travels some distance before it decays, pushing the emission point even more outwards than the average point for the K^* resonance. Having the above in mind, the overall picture shown in Fig 1, which includes contributions from all resonances, becomes understandable. But how does this explanation affect the radial flow interpretation of the asymmetry? Considering the mechanism in detail one comes to the conclusion that the increase in the emission asymmetry between pions and kaons produced by resonance decay is, in its origin, flow driven. The original K^* resonance emission direction is correlated with its emission point through flow, and the subsequent decay process only keeps this correlation. It cannot produce it on its own, so it cannot be used as an alternative explanation of the asymmetry. Therefore the resonance decay only serves to magnify the spatial asymmetries coming from flow, and therefore strengthens the flow interpretation of the emission asymmetry.

2.3. Separation distributions

Femtoscopy is sensitive to emission asymmetries between two particle species, it probes not the single-particle distributions shown above, but the separation distributions. The two are connected by:

$$\begin{aligned} S_{\pi K}(\boldsymbol{r}^*, k^*) \; &= \; S_\pi(\boldsymbol{x}_1, p_1) S_K(\boldsymbol{x}_2, p_2) \delta(\boldsymbol{r} - \boldsymbol{x}_1 + \boldsymbol{x}_2) \\ &\quad \times \delta\left(k^* - \tfrac{1}{2}(p_1 + p_2)\right) d^4\boldsymbol{x}_1 d^4\boldsymbol{x}_2 \, . \end{aligned} \tag{2}$$

The separation distributions for pion–kaon pairs are shown in Fig. 3. Dashed lines show primordial pairs, solid lines — all pairs, including resonance decays products. One can see no asymmetry in "side" and "long" directions, and modest increase in source size due to resonance contribution. In the "out" direction the size increase is also visible. The mean emission point shift in the PRF, the value of which is most interesting since it is directly measurable, is increased, from approximately -4 fm to -6 fm, the exact value depending on the way that it is determined (mean of the histogram, position of the peak *etc.*). This is consistent with the increase observed in the discussion above.

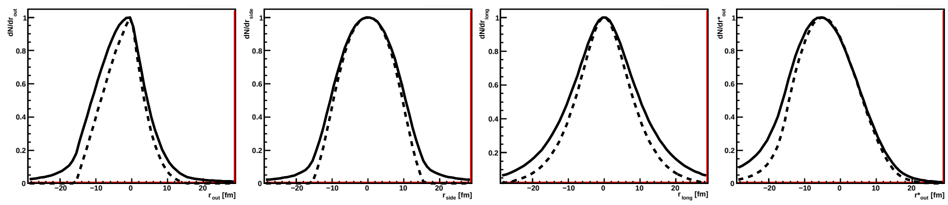

Fig. 3. Emission separation distributions for pion–kaon pairs in LHYQUID + THERMINATOR calculation for central AuAu collisions at RHIC. Left panel shows "out" component in LCMS, middle panels show "side" and "long" components, right panel shows the observable "out" component in PRF.

3. Conclusion

We have shown that collective behavior of matter inherent in hydrodynamics produces specific emission patterns for particles of different masses in heavy ion collisions. Lower mass particles (*e.g.* pions) appear to be emitted closer to the center than heavier mass particles (*e.g.* kaons). Introducing resonance propagation and decay was found to have a particular and unexpected effect on the asymmetry: it increased it. This effect was found to be intimately related to the collective flow of matter. Therefore this study shows that if the emission asymmetry is observed between pions and kaon in heavy ion collisions, it can be uniquely interpreted as a consequence of the collective radial flow and that the realistic inclusion of the propagation and decay of resonances into the modeling only strengthens this interpretation.

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