Two-particle correlations in Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV

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We present preliminary results on two new two-particle correlation analyses of Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV performed by the STAR collaboration. Two-pion interferometry with respect to the reaction plane shows that the pion source can be described as an ellipse extended out of the reaction plane. Analysing the pion-kaon correlation functions, we show that, on average, pions and kaons are not emitted at the same position and/or time. Both measurements are interpreted in the so-called blast wave model framework whose main feature is a strong flow.

I. INTRODUCTION

Two-particle interferometry is a sensitive probe of the space-time geometry of the particle emitting source. Using this technique, pion source sizes have been measured at every available relativistic heavy ion beam energy which led to the excitation function reported in [1]. Two-particle correlation also offers a large variety of observables combining different particle species. For example, particle correlation also offers a large variety of observables combining different particle species. For example, two-kaon and two-proton correlation functions have been measured and out, i.e. when the particles decouple. The step function, $\Theta$ confines the system inside a filled cylinder. Such a parametrisation had been used for several years to interpret transverse mass spectra assuming an azimuthally symmetric system.

In this extended blast wave framework, the probability of emitting a particle at a given space-time $X$ and energy-momentum $P$ is:

$$f(X, P) = \Theta(1 - \frac{(|r| \cos(\phi_s)|^2}{R_x^2} - \frac{(|r| \sin(\phi_s)|^2}{R_y^2}) .$$

This equation can be understood separating it in 3 parts:

- The step function, $\Theta$ confines the system inside a filled ellipse. $\phi_s$ is the spatial (momentum) azimuthal angle $\phi_s = 0$ for particle emitted in the reaction plane. $R_x$ and $R_y$ are the maximum radii of the system in plane and out of plane, respectively. To interpret the identified particle elliptic flow, the variable $s_2$ was introduced as a parameter that quantifies the spatial anisotropy of the particle emission in non-central collisions. We find, when $s_2 > 0$, $R_y > R_x$ which means that the source is described by an ellipse extended out of the reaction plane.

- The second term of the equation express the hydro-like behavior of the system. The expression was derived where the following functions are used: $\alpha(r, \phi_s, p_T) = \frac{1}{2} \eta \sinh(\rho(r, \phi_s))$ and $\beta(r, \phi_s, m_T) = \frac{1}{2} \eta \cosh(\rho(r, \phi_s))$. $\rho$ is the transverse rapidity boost that the particles feel.

II. THE EXTENDED BLAST WAVE MODEL

The extended blast wave model allows one to combine transverse mass spectra, elliptic flow and two-particle correlation analysis within a single framework. It is a simple parametrization of the system at kinetic freeze-out in terms of temperature, transverse flow, and source transverse radius. This approach focuses on the transverse plane, ignoring the longitudinal direction, i.e., the direction parallel to the beam. The blast wave model was introduced to [2] to interpret the identified particle elliptic flow from STAR. In this model, particles are emitted from a infinitely thin shell. To reproduce the pion source size measured, the model had to be extended to a filled cylinder.

Transverse mass spectra and elliptic flow analysis suggest that there is a strong collective motion of the particles in the Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV. Such flow introduces a strong correlation between the position and the momentum of the emitted particles, which reduces the apparent relative size. It could explain why the analysis of two-pion correlation functions published by STAR [3] shows no anomalously large pion source size which would have indicated the formation of the quark gluon plasma. Transverse flow must be accounted for in order to interpret the source size extracted from two-particle correlation analysis. We will introduce the so called "extended blast wave model" in order to investigate the effect of flow.

We present two new analyses that are potentially more sensitive to flow effects. They both provide new independent insights on how the system looks at kinetic freeze-out, i.e. when the particles decouple.
at a given emission point. In order to describe non-
azimuthally symmetric systems, we have modified its orig-
inal expression to include its dependence on the az-
nimuthal angle: \[
\rho(r, \phi) = \frac{1}{\pi} \int \frac{\rho_0}{(r_0 + \rho_0 \cos(2\phi))} r^2 dr,
\]
where \( r = \sqrt{(r \cdot \sin(\phi))^2 + \eta^2 (r \cdot \cos(\phi))^2} \) is the "elliptical
radius". I.e. all points on an ellipse have a constant \( r \). \( \rho_0 > 0 \) means that there is a stronger boost in
the reaction plane than out of it. Since in an ellipse 
the radial vector and the vector normal to the surface
of the ellipse are not aligned we introduce the variable
\( \phi_0 = \tan^{-1}(\tan(\phi_3)/\eta^2) \). Indeed, in the Cooper-Frye
prescription that the blast wave model follows, the
transverse boost that the particles acquire has to be nor-
mal to the freeze-out surface.

The third term of the equation accounts for the dura-
tion of particle emission using a single parameter \( \tau \). This
term is particularly important when interpreting the pion
source size. It has no effect, however, on the transverse
mass spectra and elliptic flow.

In the azimuthally symmetric case, this formula simpli-
fies to:

\[
f(X, P) = f(r, \phi, t, p_T, p_p, m)
\]
\[
= \Theta(R - r) \cdot K_1(\beta(r, m_T)) \cdot e^{\alpha(r, p_T) \cdot \cos(\phi - \phi_p)} \cdot e^{-t^2/\tau^2}
\]
with \( \rho(r) = \frac{3}{2} \rho_0 r \). The system is now confined to a
cylinder of radius \( R \). There are four parameters: the tem-
perature \( T \), the magnitude of the flow transverse boost
\( \rho_0 \), the radius of the cylinder \( R \), and the emission dura-
tion \( \tau \). The parameters that quantify the anisotropy of
the system \( s_2 \) and \( \rho_0 \) vanish.

From the phase space density, \( f(X, P) \), it is straight-
forward to calculate transverse mass spectra and source radii. Both the pion source radii and the pion, kaon and
proton transverse mass spectra are well reproduced with
\( \rho_0 = 0.6, T = 110 \text{ MeV}, R = 13 \text{ fm and } \tau = 1.5 \text{ fm/c}. \) It is
interesting to notice that to keep the ratio \( R_{out}/R_{side} \)
as a function of \( p_T \) comparable with the values measured
by STAR which are close or even below one, the emis-
sion duration must be on the order of 1 or 2 fm. Indeed,
in the usual Bertsch-Pratt parameterization, \( R_{out} \)
is the radius component parallel to the transverse mo-
mentum of the pair \( k_T \) while \( R_{side} \) is normal to \( k_T \), the
emission duration increases \( R_{out} \) while leaving \( R_{side} \)
unchanged. Such a short emission duration is not currently
achieved by any realistic microscopic or hydrodynamic
model.

The parameters that best fit the identified particle el-
niptic flow measured by STAR are \( \rho_0 = 0.61 \pm 0.05, T = 101 \pm 24 \text{ MeV}, \rho_0 = 0.04 \pm 0.01 \) and \( s_2 = 0.04 \pm 0.02 \). The flow rapidity and temperature are consistent with
the values obtained from transverse mass spectra and pion source size. The system is best described when both
\( \rho_0 \) and \( s_2 \) differ from zero, i.e. when the system exhibit
an asymmetry in momentum and space.

### III. PION SOURCE GEOMETRY WITH RESPECT TO THE REACTION PLANE

The identified particle elliptic flow favours a system
that is asymmetric both in space and momentum. The
pion source should reflect such an asymmetry. It is thus
interesting to study the pion source geometry as a func-
tion of the angle between the particle momenta and the
reaction plane.

Such analysis was performed by the E895 collabora-
tion at the AGS. The important difference between
STAR and E895 is that directed flow \( (v_1) \) cannot yet be
measured by STAR, which means that only the radii
within the transverse plane are relevant. The available
radii are \( R_{out}, R_{side} \) and the cross term \( R_{outside} \). For the
theoretical aspect of the analysis see [10].

Events were selected using a minimum bias trigger
which covers 85% of the whole centrality range. It is
mandatory to include peripheral events where the ellip-
tic flow is maximal. Pion tracks are reconstructed and
identified in the STAR TPC in the momentum range:
\( 0.1 < p_T < 0.6 \text{ GeV/c} \) and \( -0.5 < Y < 0.5 \). The reaction
plane is reconstructed as described in [5]. Pion pairs are
sorted into four different bins depending on the angle be-
tween the pair momentum and the reaction plane. \( R_{out}, R_{side} \)
and \( R_{outside} \) are extracted fitting the four different
correlation functions constructed with each pair sample.
Figure 3 shows the squared radii \( R_{out}^2, R_{side}^2 \) and \( R_{outside}^2 \)
as a function of the mean angle of the pairs with respect
to the reaction plane.

A clear oscillation of the radii is observed. The line in
the figure is a blast wave model calculation using the pa-
rameters \( \rho_0 = 0.6, T = 100 \text{ MeV}, \rho_0 = 0.05, s_2 = 0.05, R = 10 \text{ fm, and } \tau = 2 \text{ fm/c}. \) These parameters were
chosen so that they are consistent with the ones extracted
from identified particle elliptic flow and two-pion inter-
ferometry. A non zero value of the space asymmetry
parameter \( s_2 \) is necessary to reproduce the data. When
\( s_2 \) is equal to zero the momentum asymmetry expressed
by \( \rho_0 \) is not sufficient to reproduce the oscillation of the radii.
Thus, since \( s_2 > 0 \), this analysis indicates that the
pion source geometry is an ellipse extended out of the
reaction plane.

### IV. PION-KAON CORRELATION FUNCTION

The correlation of non-identical particles can be used
to study the relative mean separation between the emis-
sion time and/or position of different particle species [12].
This technique is based on the comparison of two
different correlation functions. If one assumes that kaons
and pions are not emitted, on average, at the same time
or position, for each pion-kaon pair there are two configu-
rations: the pion and kaon get closer to each other or they
move away from one another. The correlation between
the two particles will be stronger in the first configura-
tion than in the second one. It is shown in [12] that
these two configurations correspond to \( \overline{v}_{\text{pair}} \cdot \vec{k} \) either positive or negative (\( \overline{v}_{\text{pair}} \) is the velocity of the pair and \( \vec{k} \) is the momentum of either the kaon or the pion in the rest frame of the pair). Two correlation functions can be constructed: \( C_+ (| \vec{k}^2 |) \) for pairs with \( \overline{v}_{\text{pair}} \cdot \vec{k} > 0 \) and \( C_- (| \vec{k}^2 |) \) for \( \overline{v}_{\text{pair}} \cdot \vec{k} < 0 \). If both correlation functions are not identical, it implies that there is a difference in the average space-time emission point of pions and kaons, or in other words, there is a space-time asymmetry in the emission process of pions and kaons. Thus, to study whether or not pions and kaons are emitted at the same time we calculate the ratio \( C_- (k^*) / C_+(k^*) \) as a function of \( k^* = | \vec{k} | \).

In this analysis, only the most central events are selected. They represent 12% of the total hadronic cross section. Pions and kaons are identified by their specific energy loss in the STAR TPC. The acceptance of the pions is: \( 0.1 < p_T < 0.6 \text{ GeV/c} \) and \( -0.5 < Y < 0.5 \), and \( 0.3 < p_T < 0.8 \text{ GeV/c} \) and \( -0.5 < Y < 0.5 \) for the kaons. Electrons and positrons are carefully removed to avoid contamination of the \( \pi^+ - K^- \), and \( \pi^- - K^+ \) pairs by \( e^+ - e^- \) pairs which are correlated in a non-trivial way. Special care is taken to remove two-track merging effect since it noticeably influences the \( \pi^+ - K^- \) and \( \pi^- - K^- \) correlation functions. The purity of the pion and kaon sample needs to be precisely known in order to estimate source size parameters from the correlation function. Indeed misidentified particles, or secondary particles such as pions from \( K^0 \) decay lower the correlation strength. To first order, this effect is equivalent to increasing the source size which also lowers the average correlation strength. The purity analysis is still under way which prevents us from making any quantitative statement from this analysis.

The correlation between the pions and kaons arises mainly from their Coulomb attraction if they have opposite charge or repulsion if they have the same charge. The \( \pi^+ - K^+, \pi^- - K^-, \pi^+ - K^- \) and \( \pi^- - K^+ \) correlation functions shown in figure 3 exhibit such a behaviour. A direct comparison to the blast wave model cannot be performed because these correlation functions depend not only on the transverse source size but also on the longitudinal one, which is not accounted for in the blast wave framework.

The blast wave predictions can however be compared to the ratio of correlation functions \( C_-(k^*) / C_+(k^*) \) shown in figure 3. Indeed, the acceptance of each particle species is symmetric about mid-rapidity, which cancels out any effect that would be due to a difference in the emission position along the longitudinal direction. To improve the statistics, we have combined the \( \pi^+ - K^+ \) and \( \pi^- - K^- \) correlation functions and the \( \pi^+ - K^- \) and \( \pi^- - K^+ \) correlation functions. The ratio \( C_-(k^*) / C_+(k^*) \) is significantly different from unity for both like sign and unlike sign pairs which leads us to the conclusion that pions and kaons are not emitted at the same space or/and time.

The extended blast wave model calculations compare
well with the data. The calculation was done with $p_0 = 0.6$, $T = 110$ MeV, $R = 13$ fm, and $\tau = 0$ fm/c. We showed in section II that, with these parameters, the extended blast wave model describes well the transverse mass spectra and the pion source size. It is striking to notice that the extended blast wave model reproduces the data without the need of any extra parameters such as one representing the difference between the average emission time of pions and kaons. Why does the blast wave model predict an asymmetry between the emission point of the pions and kaons? To answer this question it is important to notice that at low $k^*$, pions and kaons have the same velocity but not the same momentum. Indeed, at low $k^*$ the pion average $p_T$ is equal to 0.1 GeV/c while it is equal to 0.4 GeV/c for the kaons. In the blast wave model, if the temperature is equal to zero, particles are emitted at radii that depend only on their transverse velocity not on their mass. In this case, pions and kaons would be emitted at the same radii. However, switching on the temperature decreases the position-momentum correlation, which leaves the particles more freedom to fill the cylinder volume. Thus, the thermal motion pulls the average emission radius away from the edge of the cylinder, towards the centre of the system. Kaons, being less affected by the thermal motion due to their high mass compare to the temperature, are more likely to be emitted close to the edge of the cylinder than pions. In other words, on average, kaons are emitted further from the centre of the source than pions which is why the ratio $C_-(k^*)/C_+(k^*)$ calculated in the extended blast wave framework, shown on figure 3 deviates from unity.

The interplay between the temperature and transverse flow built in the blast wave model introduces an asymmetry in the emission of the pions and kaons that is in qualitative agreement with the data. The non-identical particle correlation function can be used to constrain the temperature and flow parameters of the extended blast wave model. However, at this stage, given the statistical and systematic uncertainties we only conclude that the blast wave model is in agreement with the data when using the same parameters that reproduce the transverse mass spectra and the pion source radii.

V. CONCLUSIONS

We have shown two new analyses from the STAR experiment at RHIC. The analysis of the pion source geometry with respect to the reaction plane led to the conclusion that the source is an ellipse extended out of plane. The study of the pion-kaon correlation functions allows us to state that $<p_T> = 0.1$ GeV/c pions and $<p_T> = 0.4$ GeV/c kaons are not emitted at the same position or/and time.

We have interpreted our results in the framework of the extended blast wave model. We show that the pion source geometry, and the pion-kaon space-time emission asymmetry can be described by the same set of parameters which are also used to interpret the transverse mass spectra and the elliptic flow measured by STAR. The picture that emerges from this model is a system with a strong collective expansion that freezes out in a few fm/c. Such a scenario is not currently achieved by any realistic models, hydrodynamic or microscopic.

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