Tilted emitting source in the heavy-ion collisions

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Abstract. The three-dimensional structure of the initial state in heavy-ion collisions has recently drawn a lot of attention. One of its key features is the tilt of the particle-emitting source away from the beam direction, which becomes more pronounced at lower collision energies. This tilt, set by the collision geometry, plays an important role in understanding observables like directed flow and particle polarization. Still, measuring the tilt directly in experiments is far from simple.

The azimuthally sensitive femtoscopy method makes it possible to study tilt by analyzing momentum correlations of pion pairs. In this work we apply it to Au+Au collisions at $\sqrt{s_{NN}}$= 7.7 GeV. While one might expect the tilt to change mainly with centrality, our results instead show a much stronger dependence on the pair momentum.

This provides a framework that STAR can use with the ongoing high-statistics BES-II data to extract tilt more precisely and to build a clearer picture of how the three-dimensional initial state shapes final observables.

1 Introduction

Understanding the three-dimensional structure of the initial state in heavy-ion collisions has become an important focus in recent years. It helps explain the origin of anisotropic flow and why boost invariance breaks down. One key feature of this structure is the tilt of the particle-emitting source away from the beam direction. This tilt is especially strong at collision energies of a few GeV and is closely linked to observables such as directed flow and particle polarization.

Several studies [1–3] have shown that introducing an initial tilt has a strong impact on both directed and elliptic flow, for light hadrons as well as heavy-flavor particles. For light hadrons, directed flow can often be reproduced without assuming a tilted source. For heavy particles, such as D mesons, the situation is different: one must start with a tilted energy density. In particular, [3] demonstrates that the rapidity-odd directed flow of open charm arises partly from a fireball tilted in the reaction plane, which then drives both D D-mesons through drag interactions with the medium.

This makes it essential to understand the tilt of the particle-emitting source. However, measuring this tilt directly is far from straightforward, and extracting it from experimental data remains a significant challenge.

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2 What can we measure?

So what can we actually measure in an experiment? Unfortunately, the initial tilt discussed in [1–3] cannot be accessed directly. In the detector, we only observe the particles that survive until kinetic freeze-out. What we reconstruct from these particles is therefore the final tilt of the emitting source, not the tilt of the hot, dense quark–gluon plasma in its earliest stages. The distributions of the pion freeze-out coordinates at $\sqrt{s_{NN}} = 7.7$ GeV are shown on Fig. 1.

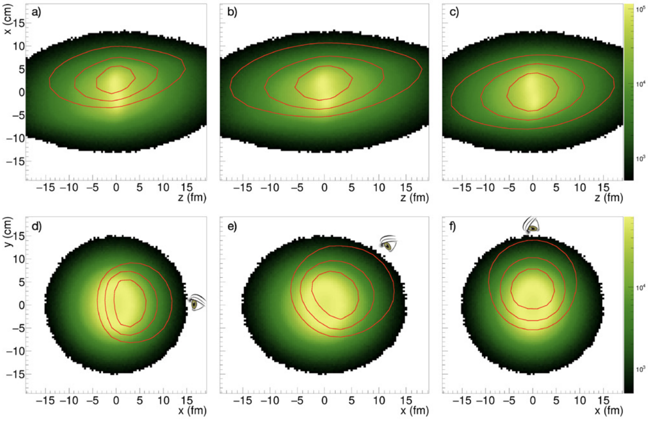

Figure 1. Two-dimensional projections of the three-dimensional freeze-out distribution of pion freeze-out coordinates from Au+Au collisions with b = 4-8 fm at $\sqrt{s_{NN}} = 7.7$ GeV obtained with the UrQMD model. Panels (a), (b), and (c) show the x–z projections, while panels (d), (e), and (f) show the transverse y–x projections. The red lines represent the contours of the same projections obtained under different conditions on the average azimuthal angle of the emitted particles: (a,d) $\langle\phi\rangle = 0°$, (b,e) $\langle\phi\rangle = 45°$, and (c,f) $\langle\phi\rangle = 90°$.

This distinction is important. The "initial tilt" refers to the geometry of the energy density distribution at very early times, before the system has undergone hydrodynamic expansion, interactions, and hadronization. By the time particles decouple, the system has evolved substantially. The final tilt that we can measure carries the imprint of the initial geometry, but it is modified by the full space–time dynamics of the medium, including collective expansion, pressure gradients, and rescattering.

3 Azimuthally sensitive femtoscopy

At present, only one experimental method exists to extract the tilt of the particle-emitting source. This method is azimuthally sensitive femtoscopy (asHBT)—that is, Hanbury Brown and Twiss (HBT) interferometry performed with respect to the reaction plane, using pairs of identical particles.

An important point to keep in mind is that femtoscopy does not probe the entire freeze-out source at once. Instead, it accesses so-called regions of homogeneity—the space-time regions that emit particles with similar velocities. By varying the average transverse momentum of the pair, $k_T = \frac{p_{T,1}+p_{T,2}}{2}$, one can effectively probe different homogeneity regions. It has been shown in the literature [4] that particles with higher k_T have smaller regions of homogeneity and are typically emitted at earlier times. This makes the k_T-dependence of femtoscopic observables, including the tilt angle, a valuable tool for disentangling the space-time structure of the emitting source.

AsHBT method is based on one main assumption: the source tilt does not depend on the azimuthal viewing angle. In other words, no matter from which side we look at the emitting source, the overall tilt should remain the same.

To illustrate this idea, consider analyzing only pairs of particles emitted at an average azimuthal angle of $\langle\phi\rangle = 45°$. The distribution of their freeze-out coordinates will show a tilt away from the z-axis. If we now analyze pairs at $\langle\phi\rangle = 90°$ the freeze-out distribution will again be tilted in essentially the same way. Thus, examining different azimuthal angles should lead to a consistent determination of the tilt.

This behavior can be seen in Fig. 1, where freeze-out distributions of pion pairs are shown for several azimuthal angles with red contour lines. Although the detailed shapes of the distributions vary somewhat with ϕ, they are all tilted in the same direction away from the z-axis.

Although our goal is to determine the spatial tilt of the source, the only quantities directly available in the experiment are the momenta of the detected particles. Femtoscopy provides the crucial link between these two domains: it allows us to access space–time characteristics of the emitting source through momentum correlations of particle pairs.

The key idea is that identical bosons (such as pions) exhibit enhanced correlations at small relative momentum due to quantum statistical (Bose–Einstein) interference. The shape and strength of these correlations depend on the relative separation of the particles at freeze-out. In this way, femtoscopy translates measurable momentum-space structures into information about the size, shape, and orientation of the homogeneity regions of the source.

Now one can analyze momentum correlations for different azimuthal angles. From the correlation function analysis, it is possible to extract six femtoscopic parameters for each azimuthal bin. Assuming that the analysis is performed in the Bertsch–Pratt coordinate system, three of these parameters correspond to the 3D sizes of the homogeneity region ($R_{\text{out}}, R_{\text{side}}, R_{\text{long}}$), while the other three represent the cross-term correlations (R_{os}, R_{ol}, R_{sl}). The latter essentially reflect tilts of the emission ellipsoid in momentum space.

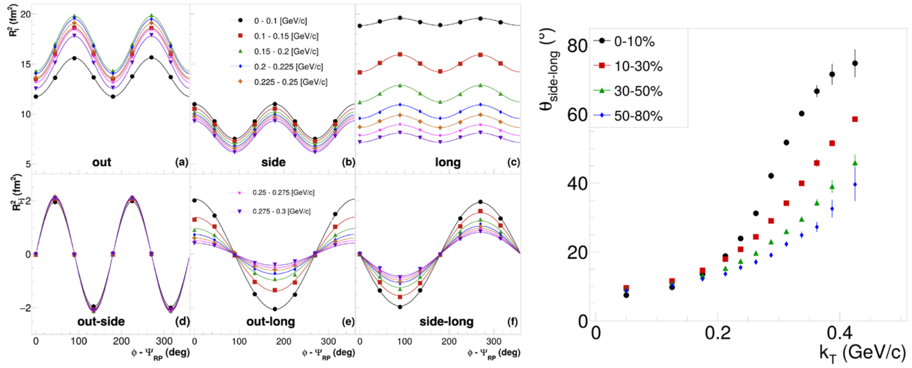

Figure 2. Femtoscopic parameters as a function of the azimuthal angle of pion pairs in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7 GeV with centrality 30–50%. Different colors correspond to different transverse momenta of the pion pairs. The lines represent fits to the oscillations of the femtoscopic parameters using Eq. (6) from [5]. On the right side of the plot one can see dependence of the homogeneity region tilt, extracted according to Eq. (8) from [5], on the transverse momentum of pion pairs in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7 GeV for multiple centrality classes.

In a naive picture, the freeze-out distribution can be thought of as an expanding ellipsoid. When such a source is analyzed as a function of azimuthal angle, one expects to observe oscillations in both the size parameters and their cross-terms. This expectation is indeed confirmed in model studies: results from the UrQMD 3.4 (Cascade) model, shown on the left side of the Fig. 2 [5]. Same effect one can expect from the experimental data.

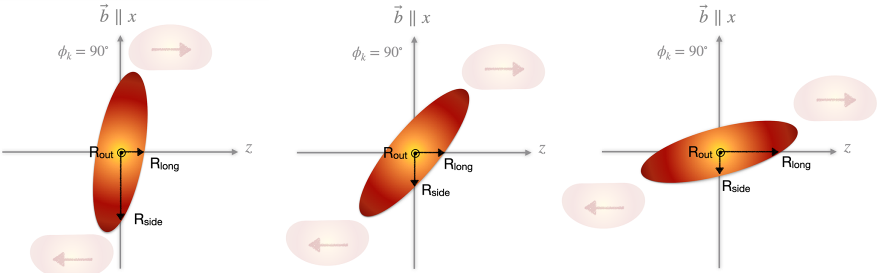

Figure 3. Schematic representation of the orientation of the homogeneity region with respect to the fixed STAR coordinate system. The example shown corresponds to a pion pair with azimuthal angle $\phi_k = 90°$. In this configuration, the beam direction is along the z axis, the impact parameter vector is aligned with the x axis, and the y axis is perpendicular to the reaction plane. The femtoscopic radii are oriented such that R_{long} is parallel to the z axis, R_{out} points out of the page, and R_{side} is perpendicular to both R_{long} and R_{out}. The three cases illustrate different tilts of the homogeneity region, corresponding to different emission times and values of k_T, increasing from left to right.

By combining data from all azimuthal angles, basically fitting azimutal dependence of the radii, one can extract the tilt of the considered homogeneity region. Naively, one would expect the tilt to vary mainly with the centrality of the collision. What was less expected is the clear k_T dependence of the tilt parameter. Both trends are illustrated on the right side of the Fig. 2: the centrality dependence can be seen from the different colors of the markers, while the k_T dependence is shown explicitly. It is evident that the k_T dependence is much stronger than the centrality dependence. This behavior can be interpreted as an evolution of the tilt with time, since, as mentioned earlier, particles with higher k_T are typically emitted at earlier stages of the collision. A schematic representation of this idea is shown in Fig. 3.

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