Two Particle Azimuthal Correlations in 4.2A GeV C+Ta Collisions

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Two particle azimuthal correlations are studied in 4.2A GeV C+Ta collisions observed with the 2-m propane bubble chamber exposed at JINR Dubna Synchrophasotron. The correlations are analyzed both for protons and negative pions, and their dependence on the collision centrality, rapidity and rapidity difference is investigated. It is found that protons show a weak back-to-back correlations, while a side-by-side correlations are observed for negative pions. Restricting both protons to the target or projectile fragmentation region, the side-by-side correlations are observed for protons also. Using the two particle correlation function, the flow analysis is performed and intensity of directed flow is determined without event-by-event estimation of the reaction plane.

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The measurement of azimuthal ($\Delta \phi$) correlations for charged hadrons is arguably one of the most important probes for high density nuclear matter created in relativistic nucleus-nucleus collisions [1]. Detailed and systematic measurements constitute an important step in good understanding of their mechanism origin and provide additional information to the methods, currently used to measure azimuthal anisotropies, which assume that all azimuthal correlations between particles result from their correlation with the reaction plane [2, 3, 4, 5, 6].

Here, we present a study of two particle azimuthal correlations in 4.2A GeV C+Ta collisions. The results are obtained by analyzing 2000 C+Ta events recorded with the 2-m propane bubble chamber exposed at JINR Dubna Synchrophasotron. Additionally, the same type of analysis is performed using 50000 events generated by the Quark Gluon String (QGS) model [3]. The two particle azimuthal correlations are studied both for protons and negative pions, and their dependence on the collision centrality, rapidity and rapidity difference is investigated. By assuming that azimuthal correlations between two particles are generated by the correlation of the azimuth of each particle with the reaction plane and without the admixture of unidentified fast electrons ($< 5\%$). All positive particles with momenta less than 0.5 GeV/c are classified either as protons or $\pi^+$ mesons according to their ionization density and range. Positive particles with momenta above 0.5 GeV/c are taken to be protons, and because of this, the admixture of $\pi^+$ of approximately $7\%$ is subtracted statistically using the procedure described in [1].

The experimental data are also corrected to the loss of particles emitted at small angles relative to the optical axes of chamber and to the loss of particles absorbed by the tantalum plates. The aim of this correction is to obtain isotropic distribution in azimuthal angle and smooth distribution in emission angle (both measured with respect to the direction of the incoming projectile).

Following the approach commonly used in interferometry studies, a two particle azimuthal correlation function [3, 10, 11, 12] is used to measure the distribution of the azimuthal angle difference between pairs of charged hadrons:

$$C(\Delta \phi) = \frac{N_{\text{cor}}(\Delta \phi)}{N_{\text{mix}}(\Delta \phi)},$$

where $\Delta \phi$ represents the angle between the transverse momenta of $i$-th and $j$-th particle in an event:

$$\Delta \phi = \arccos \frac{P_{Ti} \cdot P_{Tj}}{P_{Ti} P_{Tj}}.$$  

Here $N_{\text{cor}}(\Delta \phi)$ represents the experimentally observed $\Delta \phi$ distribution for particle pairs selected from the same event, and $N_{\text{mix}}(\Delta \phi)$ represents the $\Delta \phi$ distribution for uncorrelated particle pairs selected from the mixed events. Mixed events were obtained by randomly selecting each member of particle pair from different events having similar multiplicity. Essentially, $C(\Delta \phi)$ measures...
back-to-back correlations are stronger for peripheral collisions and decrease when going to semicentral collisions. The QGSM reproduces these experimental results, although it underestimates the magnitude of proton correlations in the projectile rapidity region. Negative pions, on the other hand, show anisotropic pion flow relative to the reaction plane, which is found in the target rapidity region, mid-rapidity region, and projectile fragmentation region, respectively.

For charged pions at 1A GeV/c Au+Au collisions, an anisotropic pion flow relative to the reaction plane was found ("pion squeeze-out") [12]. The side-by-side correlations in [13] increase both with target mass and with impact parameter of a collision and were consistently described by assuming strong rescattering phenomena, including pion absorption effects in the entire excited target nucleus. However, for 1A GeV/c Au+Au collisions, due to different reaction geometry in symmetric systems and a longer nuclear passing time, the spectator matter causes a stronger absorption and rescattering in reaction plane than out of reaction plane causing an appearance of the out-of-plane pion flow. The dependence of azimuthal correlations on the rapidity difference $\Delta y = y_1 - y_2$, between particles in a pair, is shown in Fig. 3. For pions emitted with $\Delta y > 1$, correlation function has a clear back-to-back structure. With decreasing $\Delta y$ the slope of $C(\Delta \phi)$ decreases, and for protons emitted with $\Delta y < 0.2$, the correlation function is flat within error bars. For $\Delta y < 0.1$, on this flat structure a superimposed peak at $\Delta \phi < 20^\circ$ appears. This peak can be attributed to the correlations arising from the effect of quantum (Fermi-Dirac) statistics, and final state interactions due to strong and Coulomb force. The peak disappears if protons with $q_T < 0.07$ GeV/c are removed [13], where $q = p_1 - p_2$ and $q_T$ is the component of $q$ in the direction perpendicular to $p_1 + p_2$. The QGSM reproduces changes of $C(\Delta \phi)$ with $\Delta y$ except the peak due to close pairing of protons.

For pions, the observed side-by-side correlations are roughly independent of the value of the rapidity difference. However, effect of close pairing of $\pi^-$ mesons, due to Bose-Einstein statistics, can also be observed in the structure of correlation function at $\Delta \phi < 20^\circ$ for $\Delta y < 0.6$ (Fig. 3 bottom). This peak disappears if pions with $q < 0.160$ GeV are removed [15]. Since 11% pion and 0.8% proton pairs contribute to quantum correlations, their effect on overall azimuthal correlations is negligible.

Assuming that all side-by-side correlations between
two particles are generated by the correlations of the azimuth of each particle with the reaction plane, we can extract the magnitude of the directed flow $v_1$ by fitting $C(\Delta \phi)$ with $^{11,12}$:

$$C(\Delta \phi) \propto 1 + 2v_1^2 \cos(\Delta \phi).$$

The fit of the correlation function is shown in Fig. 2, while the extracted values of the directed flow are summarized in Table 1.

The extracted values of directed flow can be compared with the values $^8$ obtained from the Fourier expansion of the azimuthal distribution of particles with respect to the reaction plane. The latter method predicts that for $y > 1$ ($y < 0$) the protons show a positive (negative) directed flow with magnitude $v_1 \simeq 0.17$ ($v_1 \simeq -0.07$). For $0 \leq y \leq 1$ the coefficient $v_1$ changes the sign, with the zero crossing at $y \simeq 0.5$ that corresponds to the average rapidity of protons. We can see that both methods give consistent values of the directed flow, with exception that from two particle azimuthal correlations we cannot determine the sign of the $v_1$ coefficient. For the pions, the method which involves the reaction plane gives positive $v_1$ for all rapidities. In the region $0 \leq y \leq 1$, where the statistics is largest, one has $v_1 \simeq 0.10$. Comparing the results of both methods we see that two particle azimuthal correlations overestimate the flow of pions.

**FIG. 2:** Correlation function for $pp$ and $\pi^-\pi^-$ pairs, for three rapidity intervals: $y < 0$, $0 \leq y \leq 1$ and $y > 1$.

**FIG. 3:** Correlation function for $pp$ and $\pi^-\pi^-$ pairs, for various $\Delta y$ values with (full circles) and without (open circles) contributions from quantum correlations.

**TABLE I:** Magnitude of directed flow, $v_1$, of protons and negative pions determined from the two-particle azimuthal correlation functions.

|       | $y < 0$ | $0 \leq y \leq 1$ | $y > 1$ |
|-------|---------|-------------------|---------|
| $pp$ (exp) | $0.13 \pm 0.05$ | - | $0.18 \pm 0.03$ |
| $pp$ (QGSM) | $(0.13 \pm 0.04)$ | - | $(0.08 \pm 0.01)$ |
| $\pi^-\pi^-$ (exp) | $0.26 \pm 0.06$ | $0.21 \pm 0.03$ | $0.13 \pm 0.06$ |
| $\pi^-\pi^-$ (QGSM) | $(0.11 \pm 0.01)$ | $(0.12 \pm 0.01)$ | $(0.08 \pm 0.01)$ |
In conclusion, in this paper the two particle azimuthal correlations are studied for \( pp \) and \( \pi^-\pi^- \) pairs in 4.2 A GeV C+Ta collisions. Their dependence on collision centrality, rapidity and rapidity difference is studied. When both protons in the pair cover the whole rapidity range, they show very weak back-to-back correlations, while side-by-side correlations are observed when both protons are restricted to the target or projectile fragmentation region. Pions always show side-by-side correlations, with slight decrease in magnitude when going from the target to the projectile rapidity region. While back-to-back correlations can be attributed to the transverse momentum conservation, all side-by-side correlations can be attributed to the flow effects since the contribution of quantum correlations to the overall azimuthal correlations is negligible. The underlying mechanism that leads to the different magnitudes and dependence on rapidity for the directed flow of protons and pions, involves strong rescattering and absorption of pions emitted into direction of the huge tantalum nucleus. At the later stage of collision, when the spectator matter leaves the collision zone, rescattering of protons near the beam (target) rapidity region is small, while the pions are influenced by the shadowing effect of the participant nucleons trough both pion rescattering and absorption. Assuming that observed side-by-side correlations can be attributed to flow effects, the intensity of the directed flow is determined from the two particle azimuthal correlations without event-by-event estimation of the reaction plane. It was found that both two-particle azimuthal correlations and Fourier expansion of the azimuthal distribution of particles with respect to the reaction plane give the consistent prediction for the directed flow of protons and pions.

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