Two-particle correlations with STAR

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Abstract. Recent results from two-particle correlations measured by the STAR experiment in heavy-ion collisions at RHIC are reported. Disappearance of the away-side for intermediate-$p_T$ associated particles, reappearance of back-to-back jet for high-$p_T$ associated particles and possible conical emission for low-$p_T$ particles is observed. Investigations of a long-ranged correlation in $\Delta \eta$ or “ridge” with unidentified and identified triggered two-particle correlations are presented.

1. Introduction
The final state of hard parton scattering in heavy-ion collision differs from that in a proton-proton one. In the latter, partons escape the collision system and hadronize in vacuum, which results in particles being described by a cone centred on the initial parton trajectory (jet). The end result in the detection system tends to be a jet and back-to-back jet (di-jet) in the plane transverse to the beam axis. In nucleus-nucleus collisions the hard parton scattering may be surrounded by other nucleons and additional interactions with other partons produced may occur.

There are many interesting experimental observations that support the creation of a dense partonic matter in heavy-ion collisions at RHIC [1]. Hard partons that traverse the medium act as a probe, and can be used to study the properties of that matter. This method is known as jet tomography [2]. One of the most successful experimental methods of jet tomography is two-particle correlation analysis. There are many different types of two-particle correlation analysis at STAR. Here we report results only from di-hadron correlations which employ a trigger particle.

1.1. Correlation technique
The general technique for calculation of triggered correlations is as follows: The particle with highest momentum in a specific $p_T$ range (trigger particle) in an event is selected. The particle is assumed to be related to the jet leading particle. Then the particles in the same event with transverse momentum in the interval $p_T^{\text{min}} < p_T < p_T^{\text{trig}}$ (associated particles) are selected and for each associated particle the angular (azimuthal, $\Delta \phi = \phi_{\text{asso}} - \phi_{\text{trig}}$ and polar represented by pseudo-rapidity variable $\eta$, $\Delta \eta = \eta_{\text{asso}} - \eta_{\text{trig}}$) correlations are calculated. The goal of this method is thus to find and investigate jet cones of both initial partons. In general we expect the trigger and associated particles to be correlated around $\Delta \phi = 0$ (near-side) and $\Delta \phi = \pi$ (away-side).

Due to the high multiplicity of low-$p_T$ particles in Au+Au events, jets cannot be reconstructed on an event-by-event basis but the correlation structures can be observed, after summing over millions of events, sitting atop huge background. Raw angular distributions are then normalized.
by the number of trigger particles, corrected for pair-wise detector acceptance and single particle reconstruction efficiency. Then a combinatorial background modulated by elliptic flow (present in Au+Au) is subtracted.

2. Triggered correlations with unidentified particles

2.1. Disappearance of away-side

One of the first and very famous results from correlation analysis at the STAR experiment is depicted in figure 1. For specific $p_T^{\text{trig}}$ (4-6 GeV/c) and $p_T^{\text{asso}}$ (2 GeV/c-$p_T^{\text{trig}}$) intervals a clear di-jet structure in $p+p$ and $d+Au$ data in $\Delta\phi$ distributions is seen. The similarity between azimuthal correlations in $p+p$ and $d+Au$ allows to use $d+Au$ as a reference distribution for a jet fragmentation in the vacuum. The correlations in $Au+Au$ are presented in the same figure. A clear suppression of away-side is observed. Apparently, there are no particles correlated on away-side for this specific momentum interval. This could be interpreted as a large degree attenuation of a parton in the medium.

2.2. Reappearance of away-side

Going to the high-$p_T$ region for trigger particles (8-15 GeV/c) and for associated particles (intervals 3-4 GeV/c, 4-6 GeV/c, 6 GeV/c-$p_T^{\text{trig}}$), di-jet structure reemerges in $Au+Au$ collisions with the away-side in $Au+Au$ being smaller than in $d+Au$ collisions. (Figure 2). This has been interpreted as evidence for the second parton to have lost a significant amount of its energy in the medium (the away-side peak in $Au+Au$ is much smaller than in $d+Au$) but survived to undergo fragmentation in the vacuum (existence of correlation peak on away-side).

![Figure 1](image1.png)

**Figure 1.** (a) Efficiency corrected two-particle azimuthal distributions for minimum bias and central $d+Au$ collisions, and for $p+p$ collisions. (b) Comparison of two-particle azimuthal distributions for central $d+Au$ collisions to those seen in $p+p$ and central $Au+Au$ collisions. The respective pedestals have been subtracted. [3]

![Figure 2](image2.png)

**Figure 2.** Azimuthal correlation histograms of high-$p_T$ charged hadrons for $8 < p_T^{\text{trig}} < 15$ GeV/c, for $d+Au$, 20%-40% $Au+Au$, and 0%-5% $Au+Au$ events. $p_T^{\text{asso}}$ increases from top to bottom. [4]

2.3. Modified away-side at low $p_T$

It was shown in the two previous sub-sections that for azimuthal correlations in intermediate and high-$p_T$ regions, no away-side or very small away-side yield in comparison to the near-side
yield is seen. Due to momentum conversation this deficit should appear in different $p_T$ regions. Going to lower $p_T^{\text{trig}}$ and $p_T^{\text{asso}}$ another interesting effect is observed (Figure 3).

![Figure 3](image)

**Figure 3.** (Color online) Azimuthal distributions for $2.5 < p_T^{\text{trig}} < 4.0$ GeV/c and $1.0 < p_T^{\text{asso}} < 2.5$ GeV/c, for the full acceptance (blue circles) and for $0.72 < |\Delta\eta| < 1.44$ (orange circles) relative to the trigger particle. d+Au results (black triangles) are shown for reference. The bands around the data points show the systematic uncertainty from flow determination.

The near-side peak is enhanced in Au+Au in comparison to d+Au. This effect will be investigated in the next sub-section. The away-side yield is also enhanced and wider than near-side with possible dip at $\Delta\phi=\pi$. The origin of the dip is a source of much speculation. It could be explained by Mach cones [5], jet deflection by expanding medium or Cherenkov radiation of high $p_T$ parton [6]. The most appropriate analysis technique for the investigation of the dip’s origin seems to be three-particle azimuthal correlations where one trigger and two associated particles are involved. The aim of this method is to distinguish between large acoplanarity of jets (for example from jet deflection by expanding medium) and two bumps structure from conical emission. Two methods have been developed at STAR for studying those effects: three-particle cumulant method [7] and two-component subtraction method [8]. The latter method found evidence for conical emission, however, this method is model dependent.

### 2.4. Near-side study - the ridge

As it was seen in the previous sub-section, the near-side yield in corrected $\Delta\phi$ distribution and integrated over $\Delta\eta$ is enhanced in Au+Au collisions in comparison to d+Au. Looking at the two-dimensional angular correlations for d+Au (figure 4(a)) and for Au+Au (figure 4(b)), the enhancement is seen to be caused by long-ranged correlation in $\Delta\eta$ on the near-side which, together with the original jet signal, contributes to the final near-side signal in $\Delta\phi$ distribution. Because of the characteristic shape, it is called the “ridge”. Assuming flatness of the ridge in $\Delta\eta$, the yield at large $\Delta\eta$ was separated out as having only a ridge contribution (in this analysis $0.7 < |\Delta\eta| < 1.4$) and this used to subtract the ridge contribution from the yield at small $|\Delta\eta|$ to obtain the yield in the jet-like peak. In this analysis a scaling by the number of trigger particles is performed, thus the jet and ridge yields are proportional to the average number of associated particles per trigger particle.

Dependence of the jet and ridge yields on system size, represented by $N_{\text{part}}$ (number of nucleons participated in the reaction), is depicted on figure 5(a). The ridge yield increases with system size. On the contrary, the jet yield is independent of centrality and resembles correlations in d+Au. This can be interpreted as a confirmation of similarity of the parton hard scattering in d+Au and in the Au+Au with fragmentation in vacuum for both systems.
When increasing the $p_T$ of trigger particles, the ridge persists to high $p_T$ ($\sim 9$ GeV/c) (figure 5(b)). This very interesting behaviour could indicate a connection between jet production and the ridge.

Looking at the momentum distribution of the associated particles, i.e. particles in the jet and in the ridge for various intervals of $p_T^{\text{trig}}$, as in figure 6, shows that the momentum spectra of jet particles are harder relative to inclusive particle momenta in the same $p_T$ interval. In contrast, ridge spectra are very similar to inclusive which could be explained by a common origin of medium and ridge particles. There are many theoretical interpretations of the ridge origin [9–13]. One of the basic ideas is [9]: a high-$p_T$ parton interacts with the dense partonic medium in the presence of strong longitudinal collective flow which leads to a breaking of the rotational symmetry of the average jet energy and multiplicity distribution in the $\eta \times \phi$ plane. This will in turn cause a medium-induced broadening of gluon radiation in pseudo-rapidity and form a ridge in $\Delta \eta$.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Two-particle angular correlations ($\Delta \phi, \Delta \eta$) in d+Au (a) and central (0-10\%) Au+Au (b) collisions at $\sqrt{s_{NN}} = 200$ GeV for $3 < p_T^{\text{trig}} < 6$ GeV/c and $2$ GeV/c $< p_T^{\text{assoc}} < p_T^{\text{trig}}$}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{(a) Jet+ridge yield (black squares) in $\Delta \phi$ and jet yield (triangles in $\Delta \phi$ and circles in $\Delta \eta$) as a function of $N_{\text{part}}$ with $3 < p_T^{\text{trig}} < 4$ GeV/c and $p_T^{\text{assoc}} > 2$ GeV/c. Bands indicate systematics errors from flow subtraction. (b) Ridge yield for different centralities as a function of $p_T^{\text{trig}}$ for $p_T^{\text{assoc}} > 2$ GeV/c in Au+Au.}
\end{figure}
Figure 6. Ridge/jet-like yield (filled/open symbols) as a function of $p_T^{asso}$ for different $p_T^{trig}$ in 0-10% central Au+Au collisions. The inclusive spectrum (0-5% central Au+Au, stars) is also shown.

3. Triggered correlations with identified particles

3.1. Identified trigger particles

For identified particle correlation we report jet and the ridge study with identified trigger particles $\Lambda$, $\Xi$, and $K_S^0$. For $p_T^{trig}$ dependence (figures 7(a) and 7(b)) the jet yield for identified strange and unidentified charged trigger particles is increasing with $p_T^{trig}$. This is expected - jet yield in this analysis is proportional to number of associated particles per trigger therefore with higher jet energy it is more probable to have higher particle production from fragmentation. For ridge yield it is hard to claim there is some clear dependence. Also there is not any obvious trigger species dependence in either component.

Figure 7. Dependence of the ridge (a) and jet (b) yield on $p_T^{trig}$ for various trigger species in central (0–10%) Au+Au collisions. The bands indicate systematic errors on the ridge yield due to the flow subtraction.

The study of momentum spectra of associated particles with identified triggers reaches similar conclusion to the unidentified one [14]. In correlations with multi-strange trigger particles ($\Xi^-$, $\Omega^-$) a near-side peak which is furthermore independent of strange content figure 8(a) is observed. This is interesting because according to the recombination model [10], the $\Omega$s included in this $p_T$ interval should come almost entirely from thermal quarks. (Because of a lack of statistics jet and ridge components have not been separated.)
3.2. Identified associated particles
Identification of associated particles could reveal the composition of jet and ridge. Calculating
the ratio of the jet yields for \( \Lambda \) and \( K_S^0 \) and the same ratio for ridge yields and then comparing
those ratios with inclusive spectra (figure 8(b)), shows that for jets the ratio is similar to p+p
spectra. This suggests that the particles in the jet cone originate from fragmentation. On
the other hand the ridge value is approximately halfway between p+p and Au+Au values i.e.
between two different production regimes. It could be interpreted as particles from the ridge
coming partly from fragmentation and partly from recombination.

![Corrected azimuthal correlations with \( \Lambda \), \( \Xi \) and \( \Omega \) for \( p_T^{jet} = 2.5-4.5 \text{ GeV/c} \) in 0–10% central
Au+Au collisions. (b): \( \Lambda/K_S^0 \) ratio measured in inclusive \( p_T \) distributions, near-side jet and ridge-like correlation
peaks in Au+Au collisions together with this ratio obtained from inclusive \( p_T \) spectra in p+p collisions.](image)

![Corrected azimuthal correlations with \( \Lambda \), \( \Xi \) and \( \Omega \) for \( p_T^{jet} = 2.5-4.5 \text{ GeV/c} \) in 0–10% central
Au+Au collisions. (b): \( \Lambda/K_S^0 \) ratio measured in inclusive \( p_T \) distributions, near-side jet and ridge-like correlation
peaks in Au+Au collisions together with this ratio obtained from inclusive \( p_T \) spectra in p+p collisions.](image)

**Figure 8.** (a): Corrected azimuthal correlations with \( \Lambda \), \( \Xi \) and \( \Omega \) for \( p_T^{jet} = 2.5-4.5 \text{ GeV/c} \) in 0–10% central
Au+Au collisions. (b): \( \Lambda/K_S^0 \) ratio measured in inclusive \( p_T \) distributions, near-side jet and ridge-like correlation
peaks in Au+Au collisions together with this ratio obtained from inclusive \( p_T \) spectra in p+p collisions.

4. Summary
In recent years the two-particle correlations were established as a very powerful tool for studying
heavy-ion collisions. All presented results: disappearance of away-side for intermediate-\( p_T \),
reappearance for high-\( p_T \), possible conical emission for low-\( p_T \) particles and the ridge study on
the near-side confirm that the idea of using hard partons as a probe could give many interesting
insights for studying the dense partonic medium created at RHIC.

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