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# Event Plane Dependence of Di-hadron Correlations with Event Shape Engineering at the STAR Experiment

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**Abstract**

In high-energy-nuclear collisions, di-hadron correlations are used as a probe to study energy-loss mechanisms of jets in the Quark-Gluon Plasma (QGP). In order to understand the interplay between jet-medium interaction and medium expansion, we measured di-hadron correlations where events were classified by the trigger-hadron's angle with respect to the event plane. We further constrained the collision geometry using event-shape engineering based on the magnitude of the reduced flow vector $q_2$. This measurement provides new and unique constraints for the dependence of energy loss of jets on in-medium path length and the role of flow.

## 1. Introduction

In heavy-ion collisions, two-body scatterings can occur with large momentum transfer. The scattered partons are created back-to-back and fragment into di-jet pairs. Jets lose their energy by interacting with the Quark-Gluon Plasma (QGP). Thus, jets are a good probe to study energy-loss mechanisms of jets in the QGP. Di-hadron correlations with high-$p_T$ trigger particles as proxies for the jets are established-robust method to investigate energy loss of jets. The correlation function is calculated as:

$$C(\Delta\phi) = \frac{\int(\Delta\phi)N^{mix}(\Delta\phi)}{\int(\Delta\phi)N^{real}(\Delta\phi)} \cdot \frac{N^{real}(\Delta\phi)}{N^{mix}(\Delta\phi)}, \tag{1}$$

where $\Delta\phi = \phi^{asso} - \phi^{trig}$ is the relative angle of associated particles with respect to the trigger particle and $N^{real}$ and $N^{mix}$ are the number of pairs from real events and from mixed events, respectively. Rapidity-independent background is subtracted via:

$$J(\Delta\phi) = \frac{N^{pair}}{N^{trig}} \cdot (C(\Delta\phi) - b_0 F(\Delta\phi)), \tag{2}$$

where $N^{pair}$ and $N^{trig}$ are the number of pairs and the number of particles, respectively, $b_0$ is a normalization factor determined by assuming zero correlated yield at minimum, and $F(\Delta\phi)$ is a background term including

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$v_2$, $v_3$ and $v_4$ contributions [2]. While the magnitude of the rapidity-odd $v_1$ at mid-rapidity is small and its contribution to the measured correlation function may be neglected [3], the rapidity-even $v_1$ has a non-zero value and its contribution is not negligible [4]. However, the measured rapidity-even $v_1$ includes momentum conservation due to di-jet production which forms part of the signal we are trying to observe. Therefore the $v_1$ contribution is not included in the background term.

The data were collected by the STAR detectors [5] in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV in 2011. Charged hadrons are reconstructed with the Time Projection Chamber (TPC) [6]. In this analysis, di-hadron correlations are measured in one half of the TPC, while the event plane is determined in the other half with a gap of 0.5 units in pseudorapidity $\eta$; e.g. $C(\Delta\phi)$ is calculated in $-1 < \eta < 0$ for an event where the event plane was determined in $0.5 < \eta < 1$. Azimuthal anisotropy $v_n$ for background components are determined by the TPC [1], with a pseudorapidity gap of 1.0 units in order to reduce the non-flow contribution e.g. $v_n$ is measured in $-1 < \eta < -0.5$ with respect to the event plane determined in $0.5 < \eta < 1$.

## 2. Di-hadron Correlations with Respect to the Second Order Event Plane

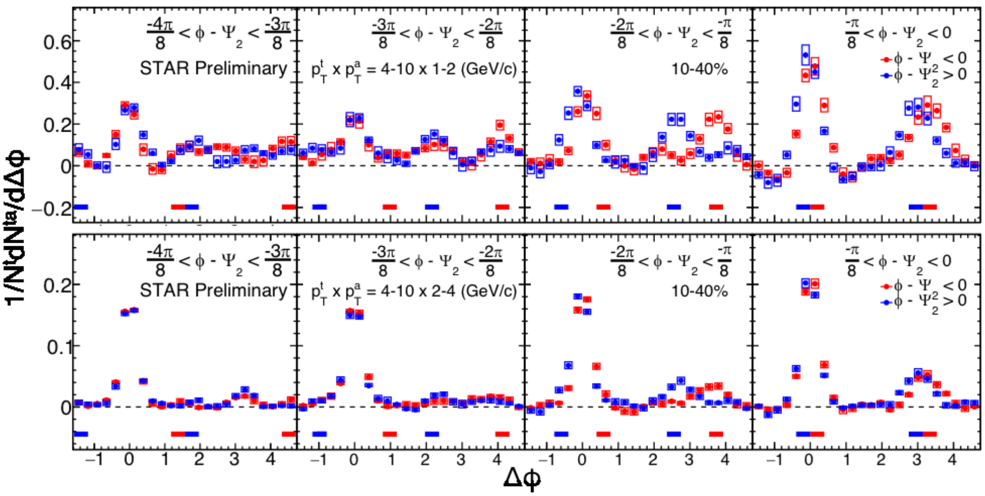


Fig. 1. (Color online) Di-hadron correlations in bins of trigger angle with respect to the second order event plane at $\sqrt{s_{NN}}$ = 200 GeV in 10-40% centrality, ranging from out-of-plane (left) to in-plane (right). Trigger particles are selected with $4 < p_T^{trig} < 10$ GeV/$c$ and associate particles are selected with $1 < p_T^{asso} < 2$ GeV/$c$ (upper panels) and $2 < p_T^{asso} < 4$ GeV/$c$ (bottom panels). The trigger angle is measured to the left ($\phi - \Psi_2 < 0$, red marker) and right ($\phi - \Psi_2 > 0$, blue marker) of $\Psi_2$. Statistical errors may be smaller than the symbol size, systematic uncertainties are indicated as colored boxes. The bars at $y \sim 0.2$ indicate the event-plane directions.

The correlations with left ($\phi - \Psi_2 < 0$) / right ($\phi - \Psi_2 > 0$) separated trigger-angle selections can provide more information about away-side modification than previous measurements at STAR [2]. Figure 1 shows di-hadron correlations with left and right separated trigger-angle selections with respect to the second order event plane in 10-40% centrality. An asymmetric shape is observed because of different path lengths while traversing the medium. Moreover, mirror-symmetric correlation shape between left and right triggers is observed because mirror-symmetric path lengths are expected with mirror-symmetric selection for trigger angle. When the trigger particle's direction changes from the in-plane to out-of-plane direction, the heights of both the near-side (same side as trigger particle's direction) and away-side (back-to-back direction to trigger particle's direction) peaks decrease, and the away-side peak for low-$p_T$ associate particles broadens toward the in-plane direction. The change in the peak height indicates that jets can penetrate more in the

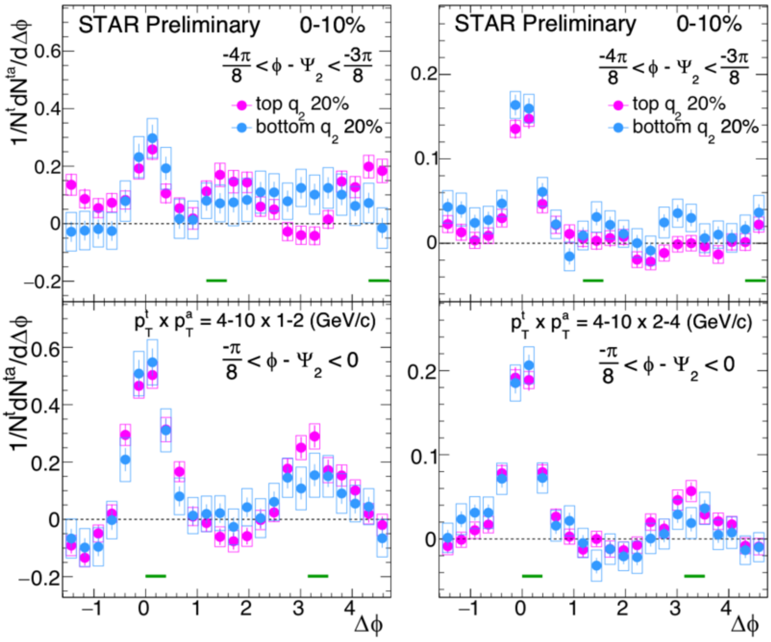


Fig. 2. (Color online) Di-hadron correlations in bins of trigger angle to the second-order event plane at $\sqrt{s_{NN}}$ = 200 GeV in 0-10% Au+Au, with top-$q_2$ 20% (magenta markers) and bottom-$q_2$ 20% (azure markers), with out-of-plane (top panels) and in-plane trigger (bottom panels). Trigger particles are selected with $4 < p_T^{trig} < 10$ GeV/$c$ and associate particles are selected with $1 < p_T^{asso} < 2$ GeV/$c$ (left panels) and $2 < p_T^{asso} < 4$ GeV/$c$ (right panels). Statistical errors may be smaller than the symbol size, systematic uncertainties are indicated as colored boxes. The bars at $y \sim 0.2$ indicate the event-plane directions.

in-plane direction, while the change in the position of away-side peak suggests that the lost energy of the jets is redistributed to low-$p_T$ particles in the in-plane direction. This observation could be a possible sign of conical emission or stronger flow with longer path length.

## 3. Further Constraints from Event Shape Engineering

The evolution of the system is sensitive to fluctuations of the initial geometry of the participant region. Recently, event-shape engineering (ESE) was proposed as a useful tool to select the initial geometry of the system by utilizing the fluctuations of the magnitude of the reduced flow vector $q_2$ [7]. The combination of centrality selection and ESE allows us to control the initial geometry while keeping the average energy density fixed. Measurements of di-hadron correlations with event-shape engineering open up the potential to disentangle the respective roles of event geometry and activity and allow new differential insight into energy-loss mechanism of jets as a function of initial energy density and shape.

Figure 2 shows di-hadron correlations with trigger-angle selection with respect to the second-order event plane with top-$q_2$ 20% and bottom-$q_2$ 20% selections in 0-10% centrality. Azimuthal anisotropy for the background component is measured independently in each event class. We expect shorter path lengths for in-plane triggers in namely, large-$q_2$ events than out-of-plane triggers in small-$q_2$ events because large-$q_2$ events are expected to have a more elliptic shape. Out-of-plane triggers show a behavior consistent with these expectations, namely, large-$q_2$ events show more suppressed peaks around $\Delta\phi \sim \pi$ for both $p_T$ ranges while the low-$p_T$ yield is enhanced in the shorter direction around $\Delta\phi \sim \pi/2$ and $\Delta\phi \sim 3\pi/2$. On the other hand, in-plane triggers show only a small difference between large-$q_2$ and small-$q_2$ events within current systematic uncertainties. The peak height around $\Delta\phi \sim \pi$ is higher with lower associate $p_T$ in large-$q_2$ events but the results with lower associated-particle $p_T$ are consistent with those with high associated-particle $p_T$ within systematic uncertainties.

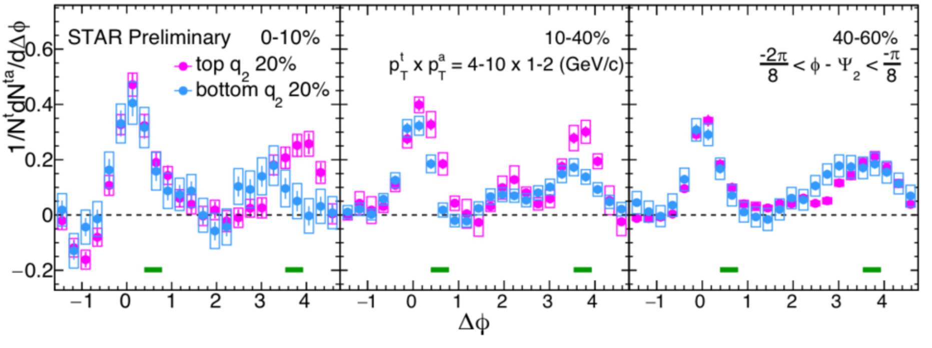


Fig. 3. (Color online) Di-hadron correlations with trigger angle selected to mid-plane ($-2\pi/8 < \phi - \Psi_2 < -\pi/8$) with respect to the second order event plane with top-$q_2$ 20% (magenta markers) and bottom-$q_2$ 20% (azure markers) selections in 0-10, 10-40 and 40-60% centrality. Trigger particle's $p_T$ range is $4 < p_T^{trig} < 10$ GeV/$c$ and associate particle's $p_T$ range is $1 < p_T^{asso} < 2$ GeV/$c$. Statistical errors may be smaller than the symbol size, systematic uncertainties are indicated as colored boxes. The bars at $y \sim 0.2$ indicate the event-plane directions.

In Figure 3, we focus on the centrality dependence of mid-plane region ($-2\pi/8 < \phi - \Psi_2 < -\pi/8$) with large-$q_2$ and small-$q_2$ selections in 0-10, 10-40 and 40-60% centrality. Larger shift of a peak position in the away side is observed in large-$q_2$ events in 0-10 and 10-40% centrality and the difference is larger in central events, but no $q_2$ dependence is observed in 40-60% within systematic uncertainties. The difference of correlation shapes between large-$q_2$ and small-$q_2$ events might be due to the difference in the strength of elliptic flow, and the difference is larger in lower-$p_T$ associate particles. This might be a hint of quenched jets coupling with the expanding medium.

## 4. Summary

The latest STAR results of di-hadron correlations with trigger-angle selections and event-shape engineering in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV are presented. Di-hadron correlations with left- and right-separated trigger angle selections have clear asymmetric yield and display significant dependence on the trigger angle with respect to the event plane. Di-hadron correlations with different trigger angle and $q_2$ selections have different correlation shapes. This observations might be explained by coupling of quenched jets and the expanding medium. Additionally, constraining the event shape using the $q_2$ variable leads to strong amplification of the observed effects. These results will provide more information about jet-medium interaction in the expanding system.

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