Jet studies in STAR via 2+1 correlations

Hua Pei, for the STAR collaboration
Post-doc research associate, 845 W Taylor St, MC 273, Dept. of Physics, University of Illinois at Chicago, Chicago, IL, 60607, U.S.A.
E-mail: hpei@uic.edu

Abstract.
This paper reports results from an analysis based on a new multi-hadron correlation technique. Jet-medium interactions and di-jet surface emission bias are explored at RHIC, via events tagged by back-to-back high transverse momentum hadrons pairs as proxy of di-jets, then studying the associated hadron distributions. In contrast with traditional two- and three-particle correlations with a single trigger particle, the associated hadron distribution at both trigger sides reveals no evident modification in either relative pseudo-rapidity, $\Delta \eta$, or relative azimuthal angle, $\Delta \phi$, from d+Au to central Au+Au collisions. This observation stands for either back-to-back triggers of similar kinematic selections (symmetric, of $5 < p_T < 10\text{GeV/c}$ and $4 < p_T < 10\text{GeV/c}$) or of highly different kinematic selections (asymmetric, of $10 < E_T < 15\text{GeV/c}$ and $4 < p_T < 10\text{GeV/c}$). The associated hadron yields and spectra are also measured on each trigger side, to gain additional insights of medium properties.

1. Introduction
Di-hadron correlation measurements in heavy ion collisions have provide deeper view of the hot and strongly interacting matter at RHIC in additional to inclusive single particle spectrum. The effects of jet-medium interactions are observed in the broad away-side distributions ($\Delta \phi \sim \pi$) of associated hadrons in di-hadron azimuthal correlations and their softened transverse momentum ($p_T$) spectra [1, 2, 3, 4]. For associated hadrons with transverse momentum between $1.0 < p_T < 2.0 \text{ GeV/c}$, in addition to the overall broadening of the away-side, a dip at $|\Delta \phi| \approx \pi$ is reported in [4, 5, 6]. Various scenarios and different mechanisms of jet-medium interactions have been proposed to explain the experimental observations [7, 8, 9, 10]. On the near-side ($\Delta \phi \sim 0$) modification of the correlation structure is also observed [2, 11, 12, 13]. In [12] the same side peak is described by two components: the ridge, a long-range $\Delta \eta$ plateau, and the small-$\Delta \eta$ jet-like peak. It is argued that the ridge might arise from jet-medium interactions. However, recent three-particle analyses in $\Delta \eta - \Delta \eta$ space has reported possible decoupling of the jet and ridge features [14]. On the other hand, the existing correlation analyses, even those three-particle ones, use a single high-$p_T$ trigger and do not specifically identify the away side jet, hence the pseudo-rapidity correlation relative to the away-side jet cannot be studied. Di-hadron azimuthal correlations of two high-$p_T$ hadrons have been observed to exhibit jet-like peaks in both near- and away-sides [15, 16]. Little modification is apparent in the shape of the peaks, but the amplitude of the away-side peak shows a strong suppression in central Au+Au collisions with respect to d+Au collisions. The data may be interpreted in two scenarios: in-medium energy loss followed by in-vacuum fragmentation, and finite probability to escape the medium without interactions. As jet-medium interactions manifest themselves via shape changes
of correlation structures predominately in the softer momentum range (below 2 GeV/c at RHIC),

it is important to investigate the modification dynamics in the same events where back-to-back
jets are already present. The analysis in this paper is using a new 3-particle \((2 + 1)\) correlation



technique, which measures the degree of correlation of a softer particle with a di-hadron trigger





pair as proxy of di-jets. The technique utilizes a second high-\(p_T\) trigger on the away-side of




the highest-\(p_T\) particle in the event as an estimate of the away-side jet axis direction. The




asymmetry between energies of two triggers are varied as an attempt to control the path length




each parton traveled in the medium, thus the difference between their final energy.




2. Analysis

2.1. Data selection

The analysis presented in this paper used data collected by the STAR (Solenoidal Tracker at





RHIC) experiment \cite{17} in the years 2003-2004, and 2007-2008. Data samples consist of events




from collisions with the center-of-mass per nucleon pair energy of 200 GeV, including 5.5M d+Au




of year 2003, 14M minimum bias Au+Au and 18M central triggered Au+Au of year 2004, 1.1M




high-energy BEMC (Barrel Electro-Magnetic Calorimeter) triggered Au+Au and 74M minimum




bias Au+Au of year 2007, 6M high-energy BEMC triggered d+Au and 46M minimum bias d+Au




of year 2008. Based on the charged track multiplicity at mid-rapidity \((|\eta| < 0.5)\) recorded by the




STAR Time Projection Chamber (TPC) \cite{18} the minimum bias Au+Au data are divided into




multiple centrality bins. They correspond to 0-20%, 20-40%, 40-60%, and 60-80% of the total




geometric cross-section. The central-trigger data represent approximately 12% of the total cross-




section. To express centrality dependences, the number of participating nucleons \((N_{coll})\) for each centrality bin used in the analysis are calculated via Monte-Carlo Glauber model. The charged tracks from TPC for the analysis have identical




quality cuts as in \cite{5}.




For the main (first) trigger, the highest-\(p_T\) particle in an event is selected, and is required to




be \(p_T^{trig1}\) between 5 to 10 GeV/c as a charged track in TPC for year 2003-2004, or \(E_T^{trig1}\)




between 10 to 15 GeV as a BEMC cluster for year 2007-2008. The second trigger is always a




charged track in TPC, and its \(p_T^{trig2}\) is selected to be above 4 GeV/c. Two high-\(p_T\) particles




are considered to be a di-jet-like pair if they conform to the requirement of relative azimuthal
difference of \(|\phi_{trig1} - \phi_{trig2} - \pi| < \alpha\). The \(\alpha\) is chosen to be 0.2 corresponding approximately to




1\(\sigma\) of the away-side peak width \(|\eta| < 1.5\) recorded by the




star particles \(|p_T < p_T^{assoc, trig1, trig1}\) is selected to coincide with the range where the away-side dip and the near-side ridge in di-hadron correlations are reported. The “raw” distribution is corrected for single-track efficiency and acceptance effects. This correction factor \(\epsilon_{pair}\) includes single track reconstruction efficiency, which depends on \(\eta, \phi, p_T\) and multiplicity. It also corrects for the pair acceptance obtained by the mixed-event
technique. The item \(d^2N_{assoc}/d\eta d\phi\) represents the total background, consisting of multiple terms. The

dominant background contribution is from random combinatorics between trigger and associates,




and is accounted for by mixing trigger pairs and associated hadrons from different events, selected
to have similar multiplicity and primary vertex position to minimize geometry variance. The
initially uniform distribution (apart from efficiency and acceptance effects) from mixing-events is then modulated by the flow term

\[ f(\Delta \phi) = 1 + \frac{2v_{2\text{trig}}^1 v_{2\text{assoc}}^2 + 2v_{2\text{trig}}^2 v_{2\text{assoc}}^1 \sin(2\alpha)}{1 + 2v_{2\text{trig}}^1 v_{2\text{trig}}^2 \sin(2\alpha)} \cos(2\Delta \phi) \]

where \( v_{2\text{trig}}^1, v_{2\text{trig}}^2, v_{2\text{assoc}}^2 \) are sample-averaged values of the elliptical flow coefficient for primary and secondary triggers, and associated hadrons, respectively, to account for elliptical flow effects, which are independent of \( \eta \) in the range studied [19, 20]. The multiplicity and \( p_T \) dependence of the elliptical flow coefficients (\( v_2 \)) for triggers and associated particles are obtained from averaging the results from the Event Plane and Four-particle Cumulant methods [19]. The background due to randomly associated triggers in the initial selection of the trigger pairs is also considered [6]. The di-hadron correlations for the appropriate kinematic selections are used to determine the per-trigger correlated background for such pairs, and trigger-trigger correlation is used to estimate the ratio of such pairs to total trigger pairs. The overall background level \( a_{zyam} \) is estimated with the Zero-Yield at Minimum (ZYAM) method [21, 6, 22]. For the 2+1 correlation the zero-yield region is chosen to be more than 3\( \sigma \) (corresponding to 1.3 radians) away from both jet-like peaks. A fit of double Gaussian plus a \( v_2 \)-modulated background is applied to estimate the systematic error due to the ZYAM method. The transverse momentum spectra for associated hadrons is measured by selecting the hadrons within 0.5 radians in relative azimuth and 0.5 in relative pseudorapidity of the respective trigger direction, with same procedure of removing background.

### 2.2. Systematic errors

Various sources of systematic uncertainties on measured yields are evaluated. Single track reconstruction efficiency contributes 5% overall normalization uncertainty for the associated hadron yields in year 2003-2004. As for year 2007-2008, the study is still going on and a very conservative 15% uncertainty is applied. The systematic uncertainty in the pair-acceptance correction due to finite statistics of the mixed-events is estimated to be less than 5%. The uncertainty due to the elliptical flow correction is estimated from the difference in the \( v_2 \) results from the Event-Plane and Cumulant methods. The uncertainty is found to be 5% in most central, less than 1% in most peripheral and 9% in mid-central Au+Au events. This uncertainty is not applicable to d+Au events. Systematic uncertainty due to ZYAM normalization of the background level was estimated by varying the \( \Delta \phi \) range for minimum yield region, and is found to be \( \sim \)10% in the Au+Au data and less than 5% in d+Au events. The related uncertainty is correlated for comparison between same- and away-sides. Systematic uncertainty due to correlated background subtraction from the di-jet sample is determined to be less than 3% for both d+Au and Au+Au events. This error is correlated between the same- and away-sides, and was estimated by varying background normalization for the trigger-trigger correlation in a similar manner as for 2+1 correlation. Finally, the uncertainty in the di-hadron distributions used for estimating the correlated background term arises mainly from the uncertainty in \( v_2 \) and ZYAM normalization. This is evaluated in a similar manner and estimated to vary the final result from less than 1% in d+Au events to about 5% in central Au+Au data. The errors above are strongly correlated between same- and away-side distributions, and mostly cancel out for such comparisons.

### 3. Result

#### 3.1. Symmetric triggers

Figure 1 shows the work from most recent STAR 2+1 correlation publication [25]. The analysis was based on data from year 2003-2004. The \( \Delta \phi \) and \( \Delta \eta \) projections (symmetrized about 0) of
the correlation function are plotted, measured for central and mid-central Au+Au collisions and compared with the corresponding measurement from minimum bias d+Au data. The $\Delta \phi$ and $\Delta \eta$ projections in figure 1a and 1b reveal jet-like peaks on both the same- and away-sides. More important is that the observed structures from Au+Au data of all centralities are consistent within errors with the ones in d+Au collisions. This constitutes the first observation of not only the near-side, but also the away-side correlation structure in central Au+Au reproducing those of d+Au as a reference (without hot quark matter), in both $\Delta \phi$ and $\Delta \eta$, for the associated hadrons in this kinematic range. These results differ significantly from earlier di-hadron correlation observations, where substantial differences in both yields and shapes on both the same and away-sides were observed between Au+Au and d+Au data [5]. First, no evidence of the Mach-cone effect in the three particle (2+1) correlations studied is present in figure 1a. Second, the ridge properties is explored by looking at $\Delta \eta$ projections for di-jet triggered correlations for same-side as well as away-side triggers in figure 1b. The same-side integrated yields at 0.5 < $\Delta \eta$ < 1.5 are consistent with zero; however, statistical limitations ban exclusion of the small $\Delta \eta$ effects reported in [12]. As a conclusion, the 2+1 results provide no evidence of a “ridge” or “cone” associated with the direction of either of the high-$p_T$ triggers, consistent with lack of medium-induced effects on those di-jets selected by this analysis. The possible effects of radial flow on Mach-cone-like and ridge signals in di-hadron correlations have been studied in [23]. No such radial flow-related effects are expected for tangentially emitted trigger pairs.

The associated hadron spectra is further explored to complement the correlation shape analysis. Figure 1c shows same- and away-side associated hadron yields plotted vs transverse momentum in d+Au and 12% central Au+Au collisions. Within the uncertainties no difference is observed between associated hadron spectra on same-side or away-side, Au+Au or d+Au data samples. This differs from earlier measurements from di-hadron correlations in a similar kinematic range, where significant softening of the away-side associated hadron spectra are shown [2].

To check for the possible away-side softening which is indicative of energy deposition in the medium, the jet energy is estimated by summing the transverse momentum of trigger particle and the charged hadrons used for the spectra in the fiducial range, then compared between the same-
side and away-side for d+Au and Au+Au data. Such difference of energy estimates between the same-side and away-side results in a major improvement of systematic uncertainties as no background re-normalization/subtraction is needed and uncertainties on elliptical flow cancel. The result in the 12% central Au+Au data $\Delta(Au + Au) = \Sigma(p_T)^{same} - \Sigma(p_T)^{away} = 1.59 \pm 0.19$ GeV/c, similar to the minimum bias d+Au data value of $\Delta(d + Au) = 1.65 \pm 0.39$ GeV/c. The initial state kinematic effects are expected to cause similar differences \cite{26, 27}, and calculated theoretically to be 1.6 GeV/c. Note this 1.6 GeV/c is before partons lose energy into medium.

The absence of a jet quenching signal or a suppression of associated hadrons suggests that the 2 + 1 particle triplets considered in this analysis are biased towards surface jet emission, i.e. di-jet events where both jets are emitted nearly tangentially to the medium surface. In such a scenario, one would expect that di-jet production rates are determined by the surface area of the fireball. This possibility is investigated by studying the centrality dependence of jet and di-jet production rates in 200 GeV Au+Au data.

3.2. Comparison with surface-bias model simulation

Figure 2. Comparison between data and model \cite{25}. a) Relative production rates for jets and di-jets in year 2004 Au+Au collisions of different centralities with respect to year 2003 d+Au data. b) Calculations of the Glauber-based core/corona model that accommodates inclusive hadron suppression and single jet production rate results. c) Conditional di-jet survival probability in Au+Au data compared to d+Au reference. The band shows the expectations from Glauber-based core/corona model described in the text. Error bars in a) and c) are the quadrature sum of the statistical and systematic uncertainties.

Figure 2 is also from most recent STAR 2+1 correlation publication \cite{25}. In figure 2a shows the centrality dependence of the nuclear modification factors $R_{d+Au}^{Au+Au}$ (ratio of binary-scaled per-event trigger counts in Au+Au and d+Au data) for the primary (single) triggers and di-jet triggers. The observed $R_{d+Au}^{Au+Au}$ for single triggers is consistent with the suppression factors observed in inclusive charged hadron measurements \cite{24}, while correlated trigger pair production rates are suppressed even further.

To examine if these results are consistent with the purely tangential jet production scenario, a Monte Carlo Glauber calculations is applied to find the spatial distribution of hard scattering were performed for each centrality bin. Here a simplistic scenario is assumed where the interaction zone in heavy-ion collisions consists of a completely opaque core (full jet attenuation) surrounded by a permeable corona (no jet-medium interactions). Participant eccentricity for the medium core shape has been used. This has been found most suitable for elliptical flow results \cite{29}. Energy loss fluctuations as discussed in \cite{28} have not been taken into account. The size of the core is estimated directly from the $R_{AA}$ suppression measurements \cite{30, 24} and the calculated core eccentricity. It is important to note that this $R_{AA}$ is the only input of data to tune this MC-model. The model then calculates the di-jet rate and $R_{d+Au}^{Au+Au}$ on its own as predictions, and compare with the experimental data to test its validity. In the tuning of core/corona size, the
total size of the interaction area is calculated by requiring the integrated collision density inside this area to be 99% of the total \( N_{\text{coll}} \). It is further assumed that all observed trigger hadrons come from the corona. Core/corona sizes that accommodate the inclusive hadron suppression results are shown in figure 2b. The gray band shows propagation of uncertainties in the published \( R_{\text{AA}} \) values into our calculations.

In figure 2c displays the conditional di-jet survival rates. The expected rates from core/corona model are shown as a band, where the width reflects the uncertainty in the published \( R_{\text{AA}} \) data. The conditional di-jet survival probability in the data are shown as points, which indicate the double ratio \( \frac{I^{\text{Au+Au}}_{d+Au}}{I^{\text{d+Au}}_{d+Au}} = \frac{R_{\text{AA}}(\text{triggerpairs})}{R_{\text{AA}}(\text{single triggers})} \). Both data and MC-model calculations reflect any changes in probability to find an away-side trigger for each primary trigger in Au+Au data relative to d+Au, i.e., the conditional di-jet survival probability. For example, at 12% most central Au+Au data such probability is approximately 20% \( \pm 2(\text{stat}) \pm 4.5(\text{syst}) \) compared to d+Au, as is shown the symbols in figure 2c for comparison with the above model. However, it must be pointed out that core emission where neither of the di-jets interacted with the medium cannot be ruled out by this analysis.

3.3. Asymmetric triggers

While surface emission model works well with the experimental data, it is important to understand how path-length dependent energy-loss models adapt to the 2+1 correlation measurement. In a scenario where in-medium energy loss followed by in-vacuum fragmentation, selecting trigger pairs of similar \( p_T (\text{GeV/c vs. } \text{GeV/c}) > 5 \) can possibly bias towards partons losing similar energy, assuming both near-/away-side triggers from not fully surface biased partons. Since both partons travel similar path length of medium then fragment in the medium, they reach similar energy loss or survival probability. This argument can be tested by picking up those trigger pairs of high and asymmetric \( p_T \) cuts, as proxy of di-jets which have big asymmetry in energy loss, and measure the relative difference between Au+Au and d+Au for comparison of near-/away-sides.

Such analysis is done from STAR year 2007 Au+Au and 2008 d+Au data. Benefited from the much improved coverage of BEMC since year 2007, the first trigger is now selected as those high-energy BEMC tower clusters, whose transverse energy \( E_T \) can be pushed to very high region of \( 10 < E_T^{\text{first}} < 15 \) GeV, while still maintaining a good energy resolution. The triggered events are mostly within 0-20% centrality in Au+Au. They are mainly \( \pi^0 \)'s because of the big coverage of single tower 0.5x0.5 in \( \Delta \psi \) that include both decay photons, while there can be up to 30% contribution from direct photons of same \( E_T \) in most central Au+Au. On the other hand, such direct gamma contamination won’t affect the validity of asymmetric trigger test by comparing the summed energy on both trigger sides, since the direct gamma is expected to not losing energy in the medium. Thus away-side parton has to lose more energy and make away-side summed energy (trigger and associates) smaller if path-length dependence stands. The second trigger is still selected to be charged tracks of \( 4 \text{ GeV/c } < p_T^{\text{trigger 2}} < 10 \text{ GeV/c} \), so as to satisfy large \( \Delta p_T \) between two triggers.

As is shown in the figure 3 and 4, even with such asymmetric trigger selections, the correlation functions shown evident jet-like structures, and they are still of similar shape and magnitude from d+Au to central Au+Au collisions, at both same-/away-sides. The systematic errors previously discussed are not shown on the plots. While they strongly correlated between near-/away-sides, these errors could affect the relative difference of both trigger sides between Au+Au and d+Au. No evident ridge or dip structure is observed at near-/away-side of Au+Au data. The away-side magnitude is higher than near-side in both Au+Au and d+Au, and this difference is possibly due to the direct-gamma contamination. On the other hand, if the surviving di-jets with their jet-like structure sustained mainly come from partons losing energy or escaping from deep within the medium, picking up asymmetric trigger pairs would sample asymmetric parton (jet) energies,
i.e., different levels of surface-bias. By comparing such difference between Au+Au and d+Au, the measurement doesn’t indicate the asymmetry in energy loss of parton pairs expected from path-length dependence model [26].

Also noted is that even with the conservative systematic errors we assigned, most of them are strongly correlated between near-/away-sides. That is, even if we did shift either Au+Au or d+Au points by 20%, any strong asymmetry between near-/away-sides of Au+Au relative to d+Au won’t be hidden.

The spectrum of associates at either trigger side is further analyzed to explore the jet-like structures. Same as Figure 1c, associated hadrons are selected within 0.5 radians in $\Delta \phi$ and 0.5 in $\Delta \eta$ of the respective trigger. Figure 5 and 6 shows the ratios of such spectrum of Au+Au divided by d+Au. The ratio is consistent with flat and close to unity at either trigger side, showing no evidence of softening or strong suppression. This measurement further supports the assumption of strong surface-bias whenever a jet-like structure is observed.

4. Summary
To summarize: the mechanisms of jet-medium interactions in ultra-relativistic heavy ion collisions was investigated using a novel technique involving three particle (2+1) correlations of hadrons associated with a correlated pair of back-to-back high $p_T$ particles. Both same-side and away-side peaks of di-jet triggered correlations from central Au+Au data are found similar to the structures observed in d+Au collisions at the same energy, and same in multiple centrality bins of minimum bias Au+Au data. The associated hadron spectra on each side of a di-jet primary
trigger are also found to be of similar, in shapes and integrated yields, in central Au+Au data between same- and away -sides, and are consistent with those measured in d+Au data. Also no modification is observed in correlations of associated hadrons in the momentum range of $p_{T}^{assoc} > 1.5 \text{ GeV}/c$ with the kinematic selection studied. All these are in contrast with earlier measurements with a single trigger. Systematic assessment of di-jet production rates supports tangential emission bias in a simplistic core/corona scenario, showing no evidence for di-jets interacting with the core. For the purpose of complement, the measurement was done in both cases of symmetric to very asymmetric trigger pairs, to test the possible asymmetry of energy loss predicted by path-length dependence models. No such asymmetry is observed at this stage within the errors.

We thank the RHIC Operations Group and RCF at BNL, the NERSC Center at LBNL and the Open Science Grid consortium for providing resources and support. This work was supported in part by the Offices of NP and HEP within the U.S. DOE Office of Science, the U.S. NSF, the Sloan Foundation, the DFG cluster of excellence ‘Origin and Structure of the Universe’of Germany, CNRS/IN2P3, FAPESP CNPq of Brazil, Ministry of Ed. and Sci. of the Russian Federation, NNSFC, CAS, MoST, and MoE of China, GA and MSMT of the Czech Republic, FOM and NWO of the Netherlands, DAE, DST, and CSIR of India, Polish Ministry of Sci. and Higher Ed., Korea Research Foundation, Ministry of Sci., Ed. and Sports of the Rep. Of Croatia, and RosAtom of Russia.

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