Mapping out the jet correlation landscape: a perspective from PHENIX experiment

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This is a status report on where PHENIX stands in terms of mapping out the landscape of jet correlation in $p_T$, hadron species, $\sqrt{s}$. We discuss separately high $p_T$ correlation results and low and intermediate $p_T$ correlation results. The former is sensitive to the quenching of the jet by medium, the later allows detailed study of the medium response to the (di-)jet.

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1. Introduction

One of the primary focuses of the RHIC program is to study the properties of the strongly interacting quark-gluon plasma (sQGP) with high transverse momentum ($p_T$) jet and dijets. The properties of the plasma can be deduced in two ways: on the one hand, the suppression of single jets and di-jets signals at high $p_T$ tells us about the stopping power or the transport properties of the medium. On the other hand, studying the response of the medium to the jets, especially their energy dissipation in the medium, can reveal the collective properties or equilibration process of the medium.

The studies of two particle azimuth correlation at RHIC have revealed detailed information on the jet interaction with the medium, beyond what we learned from the single particle spectra measurements. Experimentally, any deviations of the correlation pattern in heavy-ion collisions from that in baseline $p+p$ collisions are attributed to some sort of medium effects. Such deviations are found to be dependent on the $p_T$ of the trigger hadrons ($p_{T,T}$) and partner hadrons ($p_{T,A}$). Fig. 1 shows a schematic sketch of the landscape of the two particle correlations in $p_{T,T}$ or $p_{T,A}$. Based on existing experimental results and theoretical calculations, the $p_T$ range is divided into four regions, each of which is probably sensitive to different physics. At high $p_T$, STAR [1] shows that the away side jet magnitude is suppressed by a factor of 4-5 relative to $p+p$, but maintaining a relatively unmodified shape. It is consistent with the fragmentation of the primary jets that survive the medium either through tangential emission [2] or punching-through mechanisms [3] or both [4]. At intermediate $p_T$ range (1-4 GeV/c), the away side jet is broadened [5] or even concave like [6] in shape but its amplitude is enhanced relative to $p+p$ [7]. The features were believed to be the consequence of the response of the medium to the energy degradation of the high $p_T$ jets. Many theoretical scenarios have been proposed in the last few years to describe the energy dissipation processes, including gluon radiation [8], Cherenkov radiation [9][10], “Mach Shock” mechanism [11]. But deflected jet pictures such as hydrodynamical wake [12] or multiple scattering of the jet by the medium [13] were proposed as well. The first two models require additional particle production, whereas the other models require redistribution of the momentum/energy among existing particles.

In between these two $p_T$ regions, experimental data show an suppressed and possibly very flat away side with no visible peak structure [14]. This region (we call moderately high $p_T$ region) could have contributions from both jet fragmentation and responses of the medium. The flat but still positive structure could be the combined result of a fragmentation contribution concentrated around $\Delta \phi = \pi$ and a medium contribution centered at 1 radian away from $\pi$. The flat structure probably implies the two components have roughly equal yield at this $p_T$ region.

Lastly is the low $p_T$ region. In most jet quenching models [15][16], the bremsstrahlung radiation was believed to be largely contained in a narrow angular range (0.5 rad) around the jet axis. These gluons might be the precursor of
the collective medium response, but it is also conceivable that some gluons simply thermalized with the medium after additional scattering. In this picture, one would also expect an enhancement in the region around $\pi$ at low $p_T$ and it should have an exponential thermal shape.

Given that the correlation patterns depend strongly on the $p_T$ of both particles in the pairs, it is crucial to map out the away-side jet properties in a broad $p_T$ range and to identify the transition regions between different correlation patterns. We focus separately on the high $p_T$ region, which is ideal for studying jet quenching and jet tomography, and on intermediate $p_T$ region, which is dominated by the medium response. PHENIX results on hadron-hadron, identified hadron-hadron and three particle correlation are discussed in this context, with an emphasize on new results we have shown in QM2006.

2. $p_T$ evolution of correlation pattern

In correlation analysis, one correlate hadrons in one $p_T$ region ("trigger") with those in another $p_T$ window ("partner"). The hadron pairs from same jet tend to appear at $\Delta \phi = |\phi_A - \phi_B| \sim 0$ and those from for back-to-back dijet tend to appear at $\Delta \phi \sim \pi$. We are interested in the partner yield distribution per-trigger, $Y_{\text{jet}}(\text{PTY})$, which is defined in a way similar to the previous $d + Au$ and $p + p$ analysis, with the additional $2v_2^2\epsilon_2^2\cos 2\Delta\phi$ term to take into account the flow modulation of the background pairs in Au+Au collisions. $N_t$ is the number of trigger, $\epsilon$ is the efficiency for associated hadrons in full azimuth and in ±0.35 pseudo-rapidity. $N_{\text{fg}}(\Delta\phi)$ and $N_{\text{mix}}(\Delta\phi)$ are same-event pair and mixed-event pair distributions,

\[
Y_{\text{jet}} = \int \frac{d\Delta\phi N_{\text{mix}}^{\text{mix}}}{2\pi N_t \epsilon} \left( \frac{N_{\text{fg}}(\Delta\phi)}{N_{\text{mix}}(\Delta\phi)} - \xi \left( 1 + 2v_2^2\epsilon_2^2\cos 2\Delta\phi \right) \right)
\]
respectively. The superscript \( t \) and \( a \) stands for the trigger and partner particles. \( \xi \) is a normalization factor which is the ratio of the combinatorics pairs in the same event to those in the mixed event. \( \xi \) is typically bigger but very close to 1.

Fig. 2 shows the PTY for various combination of trigger and partner \( p_T \) in central Au+Au collisions, in comparison with p+p. The partner \( p_T \) is constrained to be less than trigger \( p_T \). From left to right and top to bottom, the \( p_T \) ranges of one or both particles increase, going from \( 3 - 4 \times 0.4 - 1 \text{ GeV/c} \) (trigger \( p_T \) vs partner \( p_T \)) to \( 5 - 10 \times 5 - 10 \text{ GeV/c} \). The solid lines around the points represent the error due to the elliptic flow uncertainty, which peaks at 0 and \( \pi \) and is the dominating error at \( p_T < 3 \text{ GeV/c} \). The shaded bands indicate the error due to uncertainty on the background level which is fixed by the Zero Yield At Minimum (ZYAM) method. This error depends on the statistical uncertainty at the ZYAM minimum and is the dominating at \( p_T > 3 \text{ GeV/c} \).

![Fig. 2](image)

**Fig. 2.** The yield of associated hadron per-trigger in \( \Delta \phi \) for successively increasing \( p_{T,T} \) and \( p_{T,A} \) in 0-20% Au+Au collisions. The two lines around the data indicate the errors due to uncertainty of elliptic flow; the shaded bands around 0 indicate the uncertainty from ZYAM method.

The top row shows the jet yield in three successive partner \( p_T \) ranges covering 0.4 to 3 GeV/c with trigger \( p_T \) fixed in 3-4 GeV/c. The away side jet shapes are dramatically different between Au+Au and p+p. The p+p data always peak at \( \pi \); The Au+Au data show a concave shape with a dip around \( \pi \) and two side peaks around 1 radian from \( \pi \). The concaveness grows with increasing partner \( p_T \), however the location of the side peaks is not changing. To characterize the
distorted away side jet shape, we divided the away side into a “Head” region \((\pi/6 < |\Delta \phi - \pi|)\) and a “Shoulder” region \((\pi/6 < |\Delta \phi - \pi| < \pi/2)\), as illustrated in Fig.1c.

They are so named because for normal jet as in p+p, the “Head” region contains bulk of the jet fragmentation, whereas the “Shoulder” contains the tail of the jet fragmentation and the radiative contribution. The “Head” region is sensitive to the level of jet quenching while the “Shoulder” region is suitable for studying the medium response. Clearly, the behavior of the Au+Au data in the two regions are dramatically different from that of p+p. Namely there a suppression in the “Head” region and an enhancement in the “Shoulder” region. The suppression in the “Head” region sets in around 1 GeV/c and grows with larger partner \(p_T\), while the enhancement in the “Shoulder” region persists up to 4 GeV/c.

In the bottom panels of Fig.2, as the \(p_T\) of both hadrons are further increased, the awayside “displaced” peaks in Au+Au data seem to be compressed relative to p+p and the Au+Au near side. This reflects the fact that the away side yield drops faster than the near side with increasing partner \(p_T\). In 4-5 GeV/c bin, the Au+Au away side is broader than p+p but is no concave. At the highest \(p_T\) bin (5-10 GeV/c), the away side turns into a convex shape, similar in shape to p+p but it’s magnitude is largely suppressed.

Note that medium modification is on the pairs. Thus the shape of the away side should be symmetric with respect to the trigger \(p_T\) and partner \(p_T\). Fig.2 suggests that the away side can be categorized in following four regions depends on its shape: 1) a flat region at \(p_T,T\) or \(p_T,A\) < 1 GeV/c; 2) a concave shape region at 1 < \(p_T,T\), \(p_T,A\) < 4 GeV/c; 3) a convex region \(p_T,T\), \(p_T,A\) > 5 GeV/c; 4) a transition region (almost flat away side) \(p_T,T(p_T,A) \geq 5 GeV/c p_T,A(p_T,T)\) < 3 GeV/c.

3. Medium response
3.1. Hadron-hadron correlation

PHENIX have tried different methods to quantify the behavior of the away side concave shape at intermediate \(p_T\). The location of the side peaks are characterized by “D” \(^6\), the distance of the peak to \(\pi\). “D” is found by triple gauss function fit of the away side:

\[
J(\Delta \phi) = G_N(\Delta \phi) + G_A(\Delta \phi - \pi - D) + G_A(\Delta \phi - \pi + D)
\]  

Fig.3 show D for several collision systems and collisions energies. The position of the peaks was found to be around 1 radian from \(\pi\) independent of the centrality \(N_{\text{part}} > 100\), collision energy and system size. In addition, “D” was found to be relatively insensitive to the change of partner \(p_T\) \(^6\), which is also confirmed in Fig.2. This suggests that “D” reflects some kind of universal properties of the medium, such as the speed of sound as suggested by the Mach Cone mechanism. It can’t be described by Cherenkov gluon radiation models \(^9\, ^{10}\) or most of the deflected
jet models such as hydrodynamical wake\textsuperscript{12} or Markov random scattering\textsuperscript{13}. Such mechanisms would predict narrowing of the peak angle with increasing $p_T$. 

PHENIX also try to characterize the convexity of the away side jet shape with the ratio of average jet yield in the “Head” region to that in the “Shoulder” region, $R_{HS}$, 

$$R_{HS} = \frac{\int_{\text{Head}} d\Delta \phi Y_{\text{jet}}(\Delta \phi)}{\int_{\text{Shoulder}} d\Delta \phi Y_{\text{jet}}(\Delta \phi)}$$ \hspace{1cm} (2)

Each of the distribution in Fig\textsuperscript{2} produces one value of $R_{HS}$ that captures essence the the away side jet shape. In general, one expect $R_{HS} < 1$ for a concave shape, $R_{HS} \approx 1$ for a flat distribution and $R_{HS} > 1$ for a convex shape. Thus $R_{HS}$ is an ideal quantity for studying the transition between the “Shoulder” dominated region to “Head” dominated region in $p_T$. Note $R_{HS}$ is purely a shape variable, thus it is symmetric with respect to $p_{T,T}$ and $p_{T,A}$, i.e. $R_{HS}(p_{T,T}, p_{T,A}) = R_{HS}(p_{T,A}, p_{T,T})$. 

Fig\textsuperscript{4} summarize the $p_{T,T}$ and $p_{T,A}$ dependence of $R_{HS}$ in p+p and central Au+Au collisions. It is presented in fine bins of partner $p_T$ for three trigger $p_T$ regions. The wide red shaded error bars represent the elliptic flow error, which is correlated in $p_T$; The narrow green shaded bar represent the ZYAM error, which can vary from point to point. In p+p collisions, $R_{HS}$ is always above one and increases with $p_{T,A}$. This suggests that the away side is always peaked around $\pi$ in p+p and its width narrows with increasing $p_{T,A}$. The same ratio in 0-5\% central Au+Au collisions are drastically different. For trigger $p_T$ in 2-3 GeV/c, $R_{HS}$ decrease from around 1 at $p_{T,A} < 1$ GeV/c to a level of $0.3 \pm 0.1$ at 3-4 GeV/c. For trigger $p_T$ in 4-5 GeV/c, the decrease of $R_{HS}$ is less significant. The level at low partner $p_T$ is around 1, relatively insensitive to the trigger $p_T$. This suggests that away side is
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Flat at low partner $p_T$ independent of the trigger $p_T$.

$$R_{HS} = \frac{\int_{\Delta\phi \in W} d\Delta\phi Y_{jet}^{Au+Au}}{\int_{\Delta\phi \in W} d\Delta\phi Y_{jet}^{p+p}}$$

The top panels Figs. 2 show the $I_{AA}$ as function of partner $p_T$ at away side ($|\Delta\phi - \pi| < \pi/2$) for three trigger $p_T$ bins. $I_{AA}$ is greater than 1 at low partner $p_T$ but drops towards high partner $p_T$. This implies that central Au+Au data have a significant enhancement at low partner $p_T$ and a strong suppression at high partner $p_T$. For higher trigger $p_T$, the enhancement at low partner $p_T$ is smaller and the suppression at high partner $p_T$ is stronger. The point where $I_{AA}$ cross 1 shifts to lower partner $p_T$, indicating a stronger decrease of $I_{AA}$ in partner $p_T$ for higher trigger $p_T$. The observed $p_T,T$ and $p_T,A$ dependence is a consequence of the competition between the enhancement in the “Shoulder” region and the suppression in the “Head” region shown in Fig. 2. At low $p_T,A$, the away side is (thus $I_{AA}$) is dominated by the “Shoulder” region; at sufficiently high $p_T,A$, the away side is dominated by the “Head” region. The point where $I_{AA} = 1$ would depend on both trigger and partner $p_T$. For 4-5 GeV/c trigger, the suppression level seems to saturates around 0.3 at $p_{T,A} > 3$, close to the $R_{AA}$ value for 4-5 GeV/c inclusive hadrons.

The bottom panels of Fig. 2 show the $I_{AA}$ as function of partner $p_T$ at away side ($|\Delta\phi| < \pi/3$) for the same three trigger $p_T$ bins. We see similar enhancement at low partner $p_T$, and the enhancement diminishes towards high partner $p_T$. As one increase the trigger $p_T$, the dependence on partner $p_T$ weakens, and the $I_{AA}$ distributions become flatter in partner $p_T$. The near side enhancement has been
observed by STAR \[ ^7 \] and PHENIX \[ ^19, 15 \], this enhancement was attributed by STAR to the ridge contribution which extends out in $\Delta \eta$ up to $\pm 2$. The ridge contribution seen by STAR in $|\Delta \eta| \approx 1.7$ is about a factor of three compared to the pure jet contribution, and was argued to be the reason for the near side enhancement. The enhancement seen in PHENIX is smaller than observed in STAR, because of the ridge yield in PHENIX’s limited $\eta$ acceptance is smaller. The decrease of the enhancement with increasing trigger $p_T$ suggests that the ridge component is softer than the jet component. The $p_T$ range where the ridge yield is important seems to be in $p_T, T, p_T, A < 4 \text{ GeV/c}$, very similar to the range for the enhancement at the away side. PHENIX have also observed a broadening of the near side jet width in central Au+Au collisions \[ ^20 \] at intermediate $p_T$, the broadening was found to disappear at high trigger $p_T$ \[ ^21 \] (also see Fig.6). These observations are summarized in Fig.6. The width results are also suggestive of a ridge contribution that is important at intermediate $p_T$ but disappears at large $p_T$. Due to its limited $\eta$ acceptance, PHENIX so far haven’t be able to observe the ridge signature directly. However, the detailed study of near side jet shape and yield in broad $p_T$ range can provide indirect but still valuable constraints on the properties of the ridge.

PHENIX have carried out the intermediate $p_T$ correlation analysis at both $\sqrt{s_{NN}} = 200$ and 62.4 GeV \[ ^{10} \]. CERES also carried out similar analysis at $\sqrt{s_{NN}} = 17.2$ GeV selection \[ ^{22} \]. The results from the three collision energies for

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**Fig. 5.** $I_{AA}$ for three different trigger bins in the away side (top panels) and the near side (bottom panels) in 0-20% central Au+Au collisions at 200 GeV.
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Fig. 6. Centrality dependence of the near side gauss width in 200 GeV Au+Au collisions at intermediate $p_T$ of $2.5 - 4 \times 2 - 3$ GeV/c (Left) and at various high $p_T$ bins above 5 GeV/c (Right).

$1 < p_{T,A} < 2.5 < p_{T,T} < 4$ GeV/c are summarized in the Fig[7]. The middle panel[8] shows the “jet fraction”, so the scale can’t be compared directly with the other two panels which show the per-trigger yield. But the jet shape can be directly compared among the three distributions. Fig[7] indicate a clear modification of away side jet at all energies. They all have displaced peaks around 1 radian from $\pi$, the concaveness of the away side distributions seems to decrease for lower $\sqrt{s}$. Since the trigger selection are similar, we expect the away side jet energy would be mostly determined by the trigger $p_T$, modulo a weak $\sqrt{s}$ dependence of the trigger bias (reflected by $\langle z \rangle$) due to the $\sqrt{s}$ dependence of the parton spectra shape. CERES Time Projection Chamber $\eta$ range is 2.1-2.7 in lab frame, which corresponds to 0.1-0.7 in CM frame. Thus its rapidity range is 0.6 and is close to PHENIX range of 0.7. Thus the jet yield at 17.3 GeV can be compared directly with that at 200 GeV after multiplied by 0.7/0.6 = 1.17 to correct for the difference in $\eta$ acceptance.

The maximum and minimum value is 0.17 and 0.07 for 0-5% central Au+Au collisions at 200 GeV (Fig[7a]) and 0.08 and 0.07 for 0-5% Pb+Pb collisions at 17.3 GeV after the acceptance correlation (Fig[7c]). Thus the amplitude of the displaced peak in CERES is about factor 2 lower than PHENIX value, whereas the level at the “Head” region in CERES is surprisingly close to PHENIX value. This probably suggests that the yield in the “Head” region is dominated by fragments from jet. The jet multiplicity are somewhat higher at RHIC due to smaller $\langle z \rangle$, but jet quenching is stronger at RHIC than that in SPS. The yield at “Shoulder” region is significantly smaller at SPS than at RHIC, possibly suggesting a weaker medium effect. Clearly detailed study of the $\sqrt{s}$ dependence of the “Head” and “Shoulder” yield can provide crucial constrains on interplay between jet quenching and medium response.

PHENIX also obtained some interesting but puzzling results for correlations between very low $p_T$ hadrons ($0.2 < p_T < 0.4$ GeV/c)[23] Fig[9] shows azimuthal
correlation in 0-5% Au+Au collisions for like-sign pairs (left) and unlike-sign pairs (right). The like-sign correlation shows a near side peak consistent with HBT correlation, whereas unlike-sign correlation does not. What is surprising is the observation of a displaced peak at a location that is consistent with what has been observed for high \( p_T \) correlation. Whether it has the same physics origin is not clear. If this is due to correlation between soft particle in the jets or mini-jets, why the unlike-sign correlation does not show any enhancement at the near side as well (the ridge argument)? It is also worth pointing out that the displaced peak mostly concentrated in a very narrow window of \(|\Delta \eta| < 0.1\) and that the peak only shows up in large \( N_{\text{part}} \geq 100 \) and is insensitive to the collision energy. It is observed at 0-5% Au+Au at 62.4 GeV but not in central Cu+Cu collisions at 200 or 62.4 GeV. Further characterization of the shape and yield of this away side peak is underway to clarify the picture.

Fig. 8. Low \( p_T \) like-sign (left) and unlike-sign correlation function for 0-5% central 200 GeV Au+Au collisions.
3.2. Three particle correlation

Three-particle correlation can provide direct topological features on the interaction of the jets with the medium, thus potentially allows clear distinction of various modification patterns such as Mach-cones and Deflected jets which can’t be directly differentiated with two particle correlation method. There are four independent angular variables among the three particles, \( \Delta \phi_{12} = \phi_1 - \phi_2, \Delta \phi_{13} = \phi_1 - \phi_3, \Delta \eta_{12} \) and \( \Delta \eta_{13} \). If one is mainly interested in the azimuthal correlation, as is done in STAR \( ^{24} \) and in earlier PHENIX measurements \( ^{25} \), then there are only two independent variable \( \Delta \phi_{12} \) and \( \Delta \phi_{13} \). Recently PHENIX has chosen to characterize three particle correlations through the use a local polar coordinate system where the trigger direction is the z axis (see insert of Fig.9) \( ^{20} \). In this scheme, the four independent variables are \( \theta^*_1, \theta^*_2, \phi^*_1 \) and \( \phi^*_2 \). Note that the coordinate system is defined for each trigger so it changes trigger by trigger relative to the global frame. In the data analysis, PHENIX chose \( \Delta \theta^* = \theta^*_1 - \theta^*_2 \) and \( \Delta \phi^* = \phi^*_1 - \phi^*_2 \) as the two independent variables. These two variables combine the information of all four angles, thus provide a very different way of presenting the jet signal.

![Fig. 9. (Left) Full \( \Delta \phi^*, \Delta \theta^* \) correlation surface in 10-20% Au+Au collisions. (Middle insert) Schematic illustration of coordinate system. (Right) the 1-D projection of along \( \Delta \phi^* \) for \( 1.65 < \Delta \theta^* < 2.2 \) rad.](image)

Left panel of Fig.9 shows the resulting three-particle correlation function in \( \Delta \theta^* \) and \( \Delta \phi^* \). The soft-soft and soft-hard flow backgrounds have been subtracted, but it still includes the 2+1 (two particles from di-jet and one from background) flow background. It is important to note that this correlation function as generated also contains the effect of the PHENIX acceptance. One can see three peaks in the ring region (1.65 < \( \Delta \theta^* < 2.2 \) rad) between the two gray circles, located at \( \Delta \phi^* \approx 0 \) and...
$\Delta \phi^* \approx \pm \pi/2$. These peaks were not observed for simulation where only normal di-jet is included, thus are signatures for the medium effects. After removing the 2+1 flow contributions, right panel of Fig. shows the projection along the ring on the $\Delta \phi^*$ axis, together with expectation of simplistic cone jet and deflected jet scenarios given by Monte-Carlo simulations. In both scenarios, one expected a narrow peak around $\Delta \phi^* \approx 0$ and a broad peak around $\Delta \phi^* \approx \pi/2$. The difference is that the deflected jet scenario predicts a bigger jet amplitude at $\Delta \phi^* \approx 0$ than that for the cone jet. From right panel of Fig. it appears that the PHENIX measurements are most consistent with the excitation of a Mach cone in the medium and not consistent with a deflected jet hypothesis.

3.3. Identified hadron-hadron correlation

Previous results indicate that the jet properties at the nearside, away-side “Head” and away-side “Shoulder” regions are quite different. The near side is consist of a ridge component along $\Delta \eta$ and a jet fragmentation contribution. The away-side “Shoulder” region is dominated by collective medium response and the “Head” region seems to be consist of jet fragmentation plus possible feedback from the radiated gluons. Given the complexity of the problem and many theoretical possibilities, one need additional handles to test this picture. Correlation with identified particles can reveal the composition or the chemistry of the jet yield in the three regions, thus provide valuable constraints on the underlying physics.

Fig. shows the partner meson and baryon yield in 1-1.3 GeV/$c$ (top panels) and 1.6-2.0 GeV/$c$ (bottom panels) for unidentified trigger in 2.5-4 GeV/$c$. Results for 0-20% and 20-40% Au+Au collisions are shown in the left panels and right panels, respectively. The partner baryon yields are scaled to approximately match the partner meson yields. Clearly, the away side shows a concave shape for both partner mesons and baryons. This is not surprising for partner meson since it dominates the charged hadrons. But it is interesting to see that partner baryons also have a similar but less concave shape (higher in the head region and lower in the shoulder region in the figure).

Fig. shows the ratios of the partner baryon/meson yield as function of partner $p_T$ for several centrality bins at the near side (left panel) and away side (right panel). The ratios are compared with that for the inclusive spectra and $e^+e^-$ collisions. The ratio for the near and away side jet grow steadily with increasing partner $p_T$ in all centralities, similar to inclusive hadrons and normal jet fragmentation measured in $e^+e^-$ collisions. But the increase is a little bit stronger in central Au+Au collisions as well as for the away side. The $p/(\pi + k)$ ratio is about 0.1 for pure jet fragmentation and $\sim 0.4$ for inclusive spectra in central Au+Au collisions. The $p/(\pi + k)$ ratio for the away side jet is somewhere in between. If the Mach-cone scenario is true, it is conceivable that the jet excites the medium at the away side, which then fragments in the usual recombination prescription. This would naturally lead to the centrality dependent baryon/meson ratio in the away side.
Fig. 10. The associated meson and baryon $\Delta \phi$ distribution for unidentified charged hadron triggers.

Fig. 11. Ratio of partner baryon to meson at the near side (left panel) and away side (right panel). It is plotted as function of partner $p_T$ for 0-20%, 20-40% and 70-90% centrality bin. Trigger particles are charged hadrons with $2.5 < p_T < 4.0$ GeV/c.

Fig. 12 shows the near side yield where the trigger is identified in PHENIX (left) compared with results from STAR (right). PHENIX Results show a steady increase with centrality, except a quick drop of the yield for trigger baryon at $N_{part} > 250$. The increase trend is qualitatively consistent with results
obtained from hadron-hadron correlation (see Fig. 5), which was argued to be due to the ridge in $\Delta \eta$. Similar trend is also observed by STAR in the right panels, except that in their case, the yield for trigger baryon is significantly larger than for trigger mesons and yield for trigger baryon does not drop in central collisions. However we should note that the trigger $p_T$ in STAR is different from PHENIX and they also include more ridge contribution due to a much larger $\Delta \eta$ coverage. In any case, a good theoretical model should be able to simultaneously explain single particle yields, elliptic flow and as well as these PID correlation results. Quark recombination (thermal-thermal and thermal-shower) was quite successful in describing the spectra and elliptic flow, but so far was not very successful in describing the jet correlation yield, especially the centrality dependence\footnote{27}.

3.4. Comments on $v_2$ background subtraction

One of the important systematic errors in the jet correlation comes from elliptic flow background subtraction (see Eq. 1). In the past years, many different methods have been developed to measure the $v_2$: Reaction-Plane (RP) Method ($v_2\{\text{RP}\}$), 2 particle commulant method ($v_2\{2\}$), 4 particle commulant method ($v_2\{4\}$), and SMD-ZDC method (Reaction-plane for direct flow $v_1$). These measurements have quite different sensitivities on the non-flow effects and eccentricity fluctuation\footnote{29,30,31,32}. The obvious question to ask is what $v_2$ one should use in the jet correlation analysis?

The two particle correlation method and two particle commulant method are closely related. Naturally, all non-flow effects and event by event fluctuations that affects the commulant $v_2$ would also contribute to the two particle azimuthal correlation. Thus it seems that $v_2\{2\}$ should be used in the background subtraction except that one would like to remove the jet bias to $v_2\{2\}$ since it is the signal. PHENIX use the $v_2\{\text{RP}\}$ in all correlation analysis. The $v_2\{\text{RP}\}$ is determined by

\begin{align*}
\text{STAR: Jet + Ridge}
\end{align*}
the BBC which sits in the forward region ($3 < |\eta| < 4$). The RP method measures separately the average $v_2$ for the triggers ($\langle v_2^t \rangle$) and partners ($\langle v_2^a \rangle$). Due to eccentricity fluctuation, the $v_2$ of the triggers and partners fluctuate in the same direction event by event. This intrinsic fluctuation would lead to $\langle v_2^t v_2^a \rangle \neq \langle v_2^t \rangle \langle v_2^a \rangle$. Both PHOBOS$^{[33]}$ and STAR$^{[34]}$ found a substantial eccentricity fluctuation, around 40%. From it, the additional correction factor can be roughly estimated to be (assuming a gauss shape for the fluctuation):

$$\sqrt{\langle v_2^2 \rangle} \approx \langle v_2 \rangle \left( \sqrt{1 + \frac{(\delta v_2)}{(v_2)}} \right)^2 \approx 1.08 \langle v_2 \rangle \quad (4)$$

So this suggest that the $v_2\{\text{RP}\}$ should be increased by 8% in order to account for the correlated fluctuation between triggers and partners. However, PHENIX have measured both the $v_2\{2\}$ $v_2\{\text{RP}\}$. The agreements between the two methods are better than 8%. Note that Eq(4) is very sensitive to the $\delta v_2$ used in the calculation and as well as the gauss smearing assumption. The correction factor would be only 4.5% for a 30% input $v_2$ fluctuation. So probably the estimation of Eq(4) is too simplistic.

In many jet correlation analyses in STAR, the used $v_2$ is an average between TPC $v_2\{\text{RP}\}$ and $v_2\{4\}$. Since the $v_2\{4\}$ reduces non-flow as well as fluctuation effects, it is smaller than $v_2\{2\}$. This probably explains why their away side jet shape at intermediate $p_T$ is less concave comparing to PHENIX.

![Fig. 13. The fake $v_2$ of the leading particle from jet as function of centrality using the EP determined in four $\eta$ windows. The embedded jet is at mid-rapidity ($|\eta| < 0.35$).](image)
One of the advantages of the PHENIX RP $v_2$ measurement comes from the large pseudo-rapidity gap between BBC and the central arm. This gap greatly reduce the effects of the jet bias on the RP $v_2$. PHENIX have perform detailed Monte Carlo simulation to estimate the bias effect. Fig. 13 shows the centrality dependence of jet induced fake $v_2$ for various pseudo-rapidity window used to determine the RP. The fake $v_2$ decreases as the $\eta$ window used to determine the RP angle is further away from mid-rapidity. For the $\eta$ window in BBC acceptance ($3 < |\eta| < 4$), the fake $v_2$ is almost negligible. Further details can be found in 36.

PHENIX have measured the jet yield as function of angle with respect to the reaction plane at intermediate $p_T$. Due to the smearing effect due to relatively poor RP resolution of BBC and possibly a small jet signal, we see little jet like difference of the per-trigger yield in the in-plane direction relative to the out-plane direction (see Fig. 6 of 20 and discussions.). We can use this special property to constrain the $v_2$ simultaneously using CFs measured at different angular direction. Fig. 14a shows the CFs in 0-5% central Au+Au collisions for 6 angular bins in 15° steps. Fig. 14b shows the jet yield after subtracting the flow terms which can be calculated according to simple equation 20. Although the CFs change dramatically from in plane to out of plane, the calculated flow term tracks the true flow background nicely. Given the small eccentricity in 0-5%, we can safely assume that the jet yield, jet yield should not depend on the trigger direction. Thus the relatively good agreements between 6 measurements is an independent confirmation of the $v_2$ used in the correlation measurement. The small remaining difference between the jet functions in Fig. 14b can be used to further constrain the $v_2$.

**3.5. The meaning of per-trigger yield**

In two particle correlation analysis, typically one correlate particles in a high $p_T$ window (type $a$) with those in a low $p_T$ window (type $b$). The distinction between
Jet correlation results from PHENIX

There is a simple relation between the PTY using the high $p_T$ particles as triggers and that using low $p_T$ particles as triggers:

$$R_{AA}^a I_{AA}^a = R_{AA}^b I_{AA}^b = \frac{\text{JetPairs}_{AA}}{N_{\text{coll}} \times \text{JetPairs}_{pp}} \equiv J_{AA}(p_T^a, p_T^b)$$

(5)

where $\text{JetPairs}_{AA}$ and $\text{JetPairs}_{pp}$ represent the average number of jet pairs in one A+A collision and one p+p collision, respectively. The $R_{AA}^a$ represents $R_{AA}$ for type a particles and $I_{AA}^a$ represents PTY using type a particles as triggers. In naive jet quenching picture, the observed triggers are biased close to the surface, the corresponding away side companions have a larger medium to traverse. One expects $I_{AA} < R_{AA}$ or $J_{AA} < R_{AA} I_{AA}$. In direct photon-jet correlation, since direct photons are not modified by the medium, the away side jet would behave exactly as the single jet suppression: $I_{AA} = R_{AA}$.

In correlation analysis, we are interested in studying the modification of the away side jet tagged by the triggering jet, i.e the per-jet yield. In reality we study the modification on the per-trigger yield, represented by $I_{AA}$. The physics interpretation of this quantity are complicated by the modifications on the triggers. In general there can be two types of modifications of the triggers:

1. Additional triggers not coming from jet: such as thermal-thermal recombination, boost of soft particles due to flow. They tend to dilution the PTY.
2. Pure medium modifications of the triggers: jet quenching, enhancement due to energy dissipation such as radiative gluons/Mach-cone/Cherekov. They either does not affect or increase the PTY.

(2) represents the effects we hope to study, which are complicated by (1). Both can change $I_{AA}$, but relation Eq(5) always holds. Fig15 illustrates this idea by showing the PTYs from Au+Au and p+p, where the two hadrons are selected from non-overlapping $p_T$ ranges. In the left panel, 2-3 GeV/c hadrons and 3-4 GeV/c hadrons are used as triggers (a) and partners (b), respectively. In the right panel, the role of triggers and partners are swapped. Clearly, the vertical scale of the left panel is less than that in the right panel, simply because there are many more hadrons in 2-3 GeV/c than 3-4 GeV/c. In the left panel, the nearside Au+Au data points are close to those for p+p; whereas in the right panel, the nearside Au+Au data are higher. This is the case because $R_{AA}$ is smaller in 3-4 GeV/c than in 2-3 GeV/c. More suppression means less number of triggers for fixed number of pairs, thus the PTY increase relative to the p+p value.

Either (1) or (2) can explain this example. We can argue that most of type-a particles come from recombination without jet correlation, thus $I_{AA}$ for type-a is smaller than that for type-b. We can also argue that type-a particles come from jet but are less suppressed than type-b, thus $I_{AA}$ for type-b is larger than that for type-a. $v_2$ and spectra measurements suggest that a large fraction (more than 50%) of the particles in 2-4 GeV/c come from recombination. However the measured
Fig. 15. The per-trigger yield for 2-3 and 3-4 GeV/c correlation, a) using 2-3 GeV/c particles as trigger, b) using 3-4 GeV/c particles as trigger.

per-trigger yield is significantly enhanced at $p_T < 4$ GeV/c as shown by Fig.5. This suggests that either triggers are dominated by the shower-thermal recombination, hence maintaining the jet correlation, or the enhancement of the jet multiplicity is much bigger than the dilution to the triggers. PID correlation measurement can help to clarify this issue. Fig.12 indeed shows some differences between baryon and meson triggers on the near side and possibly also on the away side. This trend is not consistent with the dilution from pure thermal-thermal recombination model predictions. Further high statistics detailed measurement of the PID correlation in intermediate $p_T$ can help clarify the origin of the enhancement.

4. Jet quenching

4.1. hadron-hadron and $\pi^0$-hadron correlation at high $p_T$

At high $p_T$, the situation is a lot more cleaner. The dilution to jet yield due to recombination or flow (if there is any) become negligible. Since each jet fragments into one high $p_T$ trigger, the per-trigger-yield at the away side is the same as the per-jet yield. Fig.16 show the centrality dependence of the jet yield for 5-10 GeV/c trigger and 3-10 GeV/c partner in 200 GeV Au+Au collisions. The shape and yield at the near side show very little centrality dependence. The away side jet is clearly peaked at $\pi$, but the magnitude is significantly suppressed in central Au+Au collisions comparing to that in peripheral collisions, consistent with strong quenching or absorption of the away side jet.

PHENIX also carried out detailed study of the jet correlation analysis in Cu+Cu collisions at 200 GeV. The jet correlation measurements in Cu+Cu offer several unique advantages. In terms of $N_{\text{part}}$, Cu+Cu collisions cover from peripheral to 30-40% central Au+Au collisions. $N_{\text{part}}$ can be determined with better precision that in Au+Au, thus allows a more detailed mapping of the centrality dependence.
of the onset of the jet quenching. Secondly, systematic error from $v_2$ on the jet yield is much smaller in Cu+Cu due to a smaller combinatoric background.

The measurement was carried with 5-10 GeV/c $\pi^0$ as triggers and charged hadrons in several ranges in 0.4-10 GeV/c as partners. Fig.[17] show the correlation function in 0-20% Cu+Cu compared with that in p+p. A clear away side excess can be seen in all partner $p_T$ ranges. No concave shape is expected even after the $v_2$ background subtraction. At partner $p_T > 2$ GeV/c, the away side can be well fitted with a gauss function. Fig[18] shows the near side and away side jet width as function of partner $p_T$ for p+p, 0-20% and 20-40% Cu+Cu collisions. No apparent differences can be seen between Cu+Cu and p+p, suggesting partners come mostly from jet fragmentation in the $p_T$ range under consideration (all $p_T$ on the near side and $p_T >2$ GeV/c on the away side).

Comparing the top and the bottom panels of Fig[17] one notices that there is a larger asymmetry between the near and away side in Cu+Cu than in p+p. To quantify the medium modifications, we extract the PTY for Cu+Cu and p+p and construct the $I_{AA}$ as function of $x_E$ ($x_E = p_{T,A}/p_{T,T} \cos(\Delta\phi)$). The results
from 0-20% central Cu+Cu collisions are shown in the left panel of Fig.19. \( I_{AA} \) at the near side is consistent with 1 in the full \( x_E \) range of 0.1-1.4; the away side \( I_{AA} \) starts at slightly above 1 at small \( x_E \), and gradually decreases towards larger \( x_E \), at \( x_E > 0.4 \) the suppression value approaches a constant of 0.5. This constant behavior is also seen by STAR in Au+Au collisions with \( N_{\text{part}} \). The level of suppression was found to be similar to single particle \( R_{AA} \). Since the single particle \( R_{AA} \) in Au+Au and Cu+Cu collisions follows \( N_{\text{part}} \) scaling, we can ask whether \( I_{AA} \) also has similar scaling behavior. The right panel of Fig.19 shows the integrated \( I_{AA} \) in 0.4 < \( x_E \) < 1 as function \( N_{\text{part}} \), comparing with the integrated \( R_{AA} \) for the single particle. Assuming \( \langle z \rangle \sim 0.7 \) for leading \( \pi^0 \)s, the original jets should be around 5/0.7=7 GeV/c. Thus the \( I_{AA} \) of the away side should be directly comparable to the single particle at \( p_T > 7 \) GeV/c. In reality, since the \( \pi^0 \) \( R_{AA} \) is flat at \( p_T > 4 \) GeV/c, the exact values of the jet energy for high \( p_T \) \( \pi^0 \)s are not important. Near side \( I_{AA} \) is around one in all centralities, consistent with surface emission picture. Away side \( I_{AA} \) shows a suppression that has a similar centrality dependence in \( N_{\text{part}} \) relative to single particle suppression. This is rather surprising given that the away side jet travels more medium than the single particles in the naive jet absorption picture. Probably suggesting that the simple geometrical bias argument in Section 3.5 is too naive. In jet quenching picture, the suppression is due to the energy degradation of the high \( p_T \) jets. The suppression factor \( R_{AA} \) depends on both the energy loss itself as well as on the input parton spectra shape. For the single particle, the expected \( N_{\text{binary}} \) scaled p+p spectra have a typical power-law shape with a power of 8. In the di-hadron correlation, the away side spectra associated with the leading particles have much flatter distribution with a much smaller power. Thus for the same amount of energy loss for single jet and away side jet conditional to the near side jet, the suppression level observed for \( I_{AA} \) could be well less than...
Jet correlation results from PHENIX

Fig. 19. a) The $I_{AA}$ as function of $x_E$ in p+p and Au+Au for near and away side; b) The $I_{AA}$ for yield integrated in 0.4-1 as function of $N_{part}$, compared with suppression factor for high $p_T$ $\pi^0$.

If we follow the prescription in Ref. 38, the fractional energy loss $S_{loss}$ is related to $R_{AA}$ as:

$$S_{loss} = 1 - R_{AA}(p_T)^{1/(n-1)} \quad \text{or} \quad R_{AA} = (1 - S_{loss})^{n-1}$$

(6)

The power “n” is 7.1 for single particle spectra in $dN/dp_T$. The power for the away side associated spectra can be determined from $p+p$ data \cite{17} and it is about 4.8 in $dN/dp_T$. If the away side jet have same fraction energy loss as single particle, then we would expect:

$$S_{loss} = 1 - R_{AA}(p_T)^{1/(n_R-1)} = 1 - I_{AA}(p_T)^{1/(n_I-1)}.$$ (7)

$R_{AA} = 0.2$ in central Au+Au collisions would lead to $I_{AA} = R_{AA}^{(n_I-1)/(n_R-1)} = 0.37$, much bigger than $R_{AA}$. On the other hand, if we require $I_{AA} = R_{AA}$, then the away hadron energy loss fraction would be $S_{loss}^I = 1 - I_{AA}(p_T)^{1/(n_I-1)} = 0.345$, much bigger than the single hadron energy loss fraction $S_{loss}^R = 0.23$, as expected (about 50% more energy loss). If we apply the same trick to central Cu+Cu collisions, assuming $I_{AA} = R_{AA} = 0.5$, the fractional energy loss is would be $S_{loss}^I = 0.107$ and $S_{loss}^R = 0.167$ for single particle and away side jet, respectively.

4.2. $\gamma$-hadron correlation

In high $p_T$ hadron - hadron or $\pi^0$-hadron correlation, the total jet energy is not known. Trigger hadron from normal jet fragmentation carries on average about 60-70% ($\langle z \rangle$) of the total jet energy. This effect is known as the trigger bias, which have been studied in detail in p+p and d+Au collisions \cite{39,17}. The energy loss of triggering jet in the medium leads to additional bias effects, and since the energy
loss is dependent on path length, the trigger bias effects would also coupled with the collision geometry. Thus complicates the extraction of the medium effects. Direct photon (γ_{dir})-hadron correlation does not suffer from such limitations. γ_{dir} serves as the gauge of the jet energy and jet direction, allowing the direct study of the medium modification of the away side jets. In reality, γ_{dir} - h correlation has its own difficulties and limitations. In particular, once have to deal with large decay γ background, non-hard-scattering contributions such as the fragmentation and bremsstrahlung and thermal radiation and small rate.

PHENIX has observed a p_T dependent direct photon excess above the decay background in central Au+Au collisions. A statistical subtraction method combined with the knowledge on the direct γ excess^{37} is used to obtain the γ_{dir} - h signal. Fig. 20 show the hadron yield associated with direct photons in p+p collisions for two partner p_T ranges. Near side is consistent with zero, and away side shows some finite excess. The p+p data are compared with the expected values from the PYTHIA6.1 calculation with k_T=2.5 GeV/c. Within the large systematic uncertainties, the data qualitatively agrees with the PYTHIA value.

Fig. 20. The direct γ-h signal in p+p collisions compared with PYTHIA simulation for 7-9 GeV/c trigger γ and two partner p_T ranges.

Left panel of Fig. 21^{40} shows the comparison of the Δφ distribution of the PTY in p+p and 0-20% central Au+Au collisions. The Au+Au data have smaller systematic errors, however the measurements are currently statistics limited, especially at around Δφ = π/2 region. The Au+Au data seems to show a small positive yield at π, but the significance is only about 1 σ level. One can reduce the statistic errors by integrating the away side yield in π/2 < Δφ < 3π/2. The right panel of Fig. 21 show the integrated yield for several trigger p_T regions with partner p_T fixed in 2-5 GeV/c. p+p data suggest a gradual increase of the PTY towards larger trigger p_T,
5. Conclusion and outlook

PHENIX have mapped out the landscape of two particle azimuth correlation in heavy ion collisions as function of $p_{T,T}$, $p_{T,A}$, centrality, hadron species, $\sqrt{s}$ and collision systems in different $\Delta \phi$ regions. The background subtracted “jet” pairs seems to come from four different components concentrated in different $\Delta \phi$ regions with their characteristic dependence on $p_T$, PID, $\sqrt{s}$ etc. 1) A hard component around $\Delta \phi = 0$ that is consistent with jet fragmentation; 2) A soft and broad component around $\Delta \phi = 0$ that is consistent with the “Ridge” seen by STAR; 3) A hard component (“Head”) around $\Delta \phi = \pi$ consistent with fragmentation of away side jet; and 4) a soft component centered at $|\Delta \phi - \pi| \sim 1$ (“Shoulder”). The hard components are sensitive to the “quenching” of the (di-)jets by the medium. The hard component at the near side shows little modification, whereas the hard component at the away side are strongly suppressed, up to factor of 5 in central Au+Au collisions. The soft components (“Ridge” and “Shoulder”) represent the response of the medium to the jets, appearing as distortions of the shape and enhancements of the yield. These components are shown to be important at $p_T < 4 \text{ GeV}/c$ and have a particle composition that is closer to the bulk medium. The non-trivial evolutions of the near and away side shape/yield with $p_T$ and $\sqrt{s}$ are the results of the detailed interplay between the soft and hard components.

The four different components can have very different geometrical bias and
trigger bias. In a simple jet absorption picture where a very opaque medium is assumed, the near side hard component is emitted from the surface, \( \langle L \rangle \sim 0 \); the near side “Ridge” comes from jet close to the surface, \( \langle L \rangle < R \) (\( R \) is the average radius of the medium); the away side “Shoulder” results from jet that traverses a large path length, \( \langle L \rangle > R \); the path length for away side hard component can vary dramatically depends whether it is tangential emission or punch-through, \( 0 < \langle L \rangle < 2R \). One of the important future directions of the jet correlation is to quantitatively separate the four different components; and to study the detailed properties of each components. To fully understand the medium response, one need to address the question that whether the near side “Ridge” and away side “Shoulder” are of the same origin or not. A detailed mapping of the \( p_T \), PID, charge and \( \sqrt{s} \) dependence would be very helpful in this regard. One can dial the path length by triggering on two high \( p_T \) triggers and correlate with the third soft hadrons, the “displaced” peak might be seen on both the near and away side. However this is only possible if the high \( p_T \) have a significant punch-through component and the medium can not be very opaque. On the jet quenching part, high \( p_T \) correlation remains to be a good tomographic tool since it is less affected by the surface bias. Both the centrality and reaction plane dependence of the jet correlation at high \( p_T \) would be very helpful in constraining the transport properties of the medium. In the meanwhile, we should continue to pursue the gamma-jet correlation with increased statistics and refined analysis techniques. Since it is less affected by the geometrical bias and trigger bias, even a statistics limited result could be very powerful in constraining various jet quenching models.

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