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In-Medium Jet Modification Measured by PHENIX Via Two-Particle Correlations and High p_T Hadrons in $A + A$ Collisions

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Abstract

The first evidence of jet quenching was observed at RHIC via suppression of single high p_T hadron R_{AA} and the disappearance of the away-side jet peak in two-particle correlations. Since then, hadron R_{AA} and two-particle correlations continue to be useful probes of the QGP in heavy ion collisions, since the particles involved are fragments of the jets produced in the initial hard scattering. PHENIX recently improved the width measurements extracted from π^0-hadron correlations after removing the higher order flow terms in the underlying event subtraction. Measurements of the away-side jet correlated with high p_T neutral pions show an increase in low p_T particle production at wide angles consistent with theoretical expectations for energy loss. The system size dependence of energy loss is further investigated at PHENIX by measuring the absolute yield and R_{AA} for various hadron species at high p_T in several collision systems including $U + U$ and $Cu + Au$. These proceedings will present the newest PHENIX R_{AA} and two-particle correlation measurements and their role in our understanding of jet quenching and medium response in heavy ion collisions.

Keywords: Jets, Two-Particle Correlations, RAA, Hadrons, Heavy Ion Collisions, Quark Gluon Plasma

1. Introduction

High energy heavy ion collisions produced at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) provide a unique environment to study Quantum Chromodynamics (QCD). In heavy ion collisions, a hot, dense state of matter, known as a Quark Gluon Plasma (QGP), is formed in which quarks and gluons have their own degrees of freedom. After the initial hard scatterings in the early stages of the collision, the now deconfined quarks and gluons propagate through the QGP medium and lose energy. This results in a modification to the yields of several particle species relative to their yields in $p+p$ collisions, with the notable exception of the direct photon, which escapes the plasma unmodified. One area of research is quantifying how energy is dissipated through the QGP via either gluon radiation or by secondary partonic collisions within the QGP. These proceedings detail new results on energy loss studies from PHENIX using two techniques: measurements of the single particle R_{AA} and two-particle correlations.

2. Single Particle R_{AA}

The R_{AA}, or nuclear modification factor, of a given particle species quantifies the extent to which the yield of a given particle species in $A+A$ collisions is modified relative to the yield in $p+p$ scaled by the number of binary collisions. The definition of R_{AA} is given in Eqn. (1).

$$R_{AA} = \frac{1}{\langle T_{AA}\rangle} \frac{d^2N^{AA}/dp_T d\eta}{d^2\sigma_{pp}/dp_T d\eta} \tag{1}$$

PHENIX has measured the R_{AA} for several meson species in $Cu+Au$ at $\sqrt{s_{NN}} = 200$ GeV and $U+U$ $\sqrt{s_{NN}} = 192$ GeV, with the $U+U$ results shown in Fig. 1. The R_{AA} is plotted on the y-axis as a function of the transverse p_T on the x-axis. In both collision systems in the most central collisions, there is a separation between the ϕ and K^* R_{AA} and the π^0 and the η R_{AA} at low p_T. All species remain suppressed relative to the $p+p$ baseline across all p_T, however. This separation may be attributable to strangeness enhancement which reflects the quark content of the species shown. The ϕ, for instance, is entirely composed of strange quarks ($s\bar{s}$), whereas the π^0 ((($u\bar{u}$) + ($d\bar{d}$))/ $\sqrt{2}$) has no contribution to its makeup from strange quarks and, thus, would not see this effect. The dominant source of systematic uncertainty (represented by the empty boxes around the data points) is the uncertainty in the raw yield extraction and in the reconstruction efficiency.

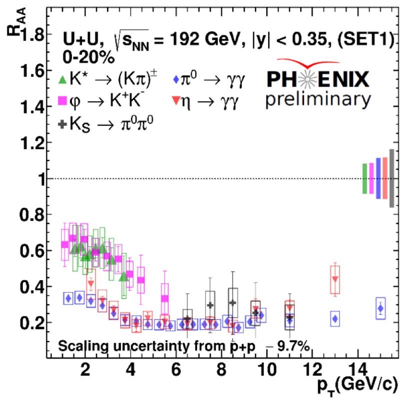

Fig. 1: R_{AA} for various meson species as a function of p_T in $U+U$ at 192 GeV collisions. One can see features of possible strangeness enhancement at low p_T in the 0–20% centrality bin which disappears at higher p_T

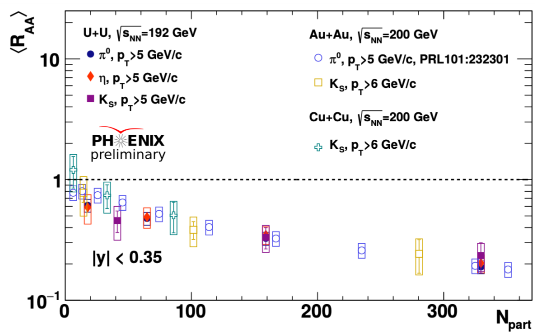

Fig. 2: Integrated R_{AA}'s for different meson species and collision systems for $p_T > 5$ GeV/c

The p_T integrated $\langle R_{AA}\rangle$ across $Au+Au$, $Cu+Au$, and $U+U$ as a function of the system size N_{part} and for various mesons is shown in Fig. 2, with the $\langle R_{AA}\rangle$ on the y-axis and the transverse p_T on the x-axis. The different data points correspond to different particle species. When only looking at the high p_T region ($p_T > 5$ GeV/c), effects due to strangeness enhancement disappear, and the integrated $\langle R_{AA}\rangle$ for all meson species across the different collision species follow the same trend. This shows that at high p_T, energy loss is the dominant QGP-related effect.

3. Two-Particle Correlations

Measurement of two-particle correlations allows one to study the modification of both the particle yield and shape of recoil jets in $A+A$ relative to a $p+p$ baseline. In this method, we correlate all the charged hadrons in an event to a high p_T trigger particle (in this case, the π^0) and measure the angular separation in the azimuthal direction, $\Delta\phi$. This results in a distribution with two prominent peaks at $\Delta\phi = 0$ and at $\Delta\phi = \pi$, which are called the near and away-side peaks, respectively. From here, subtraction of correlations due to flow (in this analysis flow harmonics up to $n = 4$ are subtracted) yields the jet function, defined in Eqn. 2.

$$\frac{1}{N^t}\frac{dN^{Pair}}{d\Delta\phi} = \frac{1}{N^t}\frac{N^{Pair}}{\epsilon\int\Delta\phi}\left\{\frac{dN^{Pair}_{Same}/d\Delta\phi}{dN^{Pair}_{Mix}/d\Delta\phi} - \xi(1+\sum_{n=2}^{4}2\langle v_n^t\rangle\langle v_n^a\rangle\cos(n\Delta\phi))\right\} \tag{2}$$

Here, N^t and N^{Pair} refer to the number of trigger π^0's and correlated pairs, respectively. "Same" denotes a π^0-hadron pair that come from the same event, whereas pairs denoted "Mix" come from two separate events and are used to correct for detector effects via event mixing. ϵ is the charged hadron efficiency, and ξ represents the magnitude of the correlated background due to flow, calculated using the absolute background subtraction method [1]. Lastly, v_n^t and v_n^a represent the flow harmonic values for both the trigger and the associated hadron, respectively. Both are taken from previous PHENIX analyses [2, 3].

From the jet function, we extract the yield of the away-side jet peak by integrating the region $|\Delta\phi - \pi| < \pi/2$. We then take the integrated yields in $A + A$ and $p + p$, Y_{AA} and Y_{pp}, respectively, and calculate the $I_{AA} = Y^{AA}/Y^{pp}$. Fig. 3 shows the I_{AA} on the y-axis plotted as a function of the associate particle p_T on the x-axis in two different trigger p_T ranges. The empty boxes around the data points in Fig. 3, 4, and 5 represent the systematic uncertainties and stem from the π^0 combinatorial background, the estimation of the background level ξ, and from the flow harmonic measurements themselves from [2, 3]. Additionally, the blue box shown at unity in Fig. 3 and 5 represents a global scale uncertainty primarily coming from the charged hadron tracking efficiency correction, ϵ. I_{AA} is an important observable in two-particle correlations because it allows us to directly study modifications to the fragmentation function, $D(z)$, due to the fact that the integrated yields are approximately equivalent to the fragmentation functions; that is to say: $I_{AA} = Y^{AA}/Y^{pp} \approx D^{AA}(z)/D^{pp}(z)$.

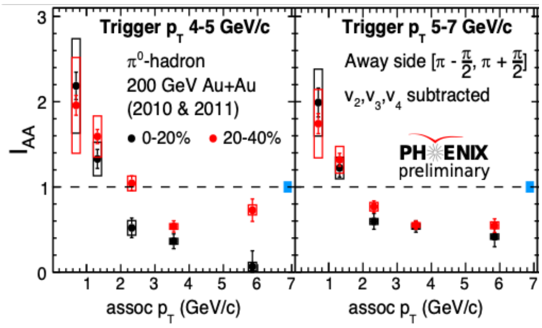

Fig. 3: I_{AA} as a function of the associate particle p_T in two trigger p_T bins, and in 0–20% (black) and 20–40% (red) centrality classes.

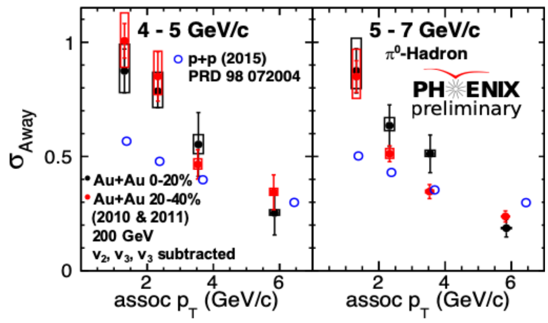

Fig. 4: Extracted away-side Gaussian widths plotted as a function of the associate partilce p_T in 0–20% (black) and 20–40% (red) centrality classes. The blue points are the $p + p$ baseline.

The I_{AA} measurement shown in Fig. 3 shows an enhancement in the yield of low p_T associate particles, and a suppression in the yield of high p_T associate particles. This trend is consistent across the two trigger p_T bins shown and in the 0–20% and 20–40% centrality bins. Additionally, the width of the away-side jet peak was measured by fitting it with a Gaussian and extracting the width, σ, as previously shown in [4]. The result of this measurement is shown in Fig. 4, with the jet width, σ, on the y-axis and the associate particle p_T on the x-axis. The away-side widths in $Au + Au$ collisions are broader than those in $p + p$ at low associate particle p_T. At high p_T, the $Au + Au$ jet widths converge to the $p + p$ baseline in both centrality bins.

The broadening of the away-side at low p_T seen in [4] coupled with the enhancement in the away-side yield at low p_T in Fig. 3 show us that the mechanism behind energy loss within the QGP is consistent with gluon bremsstrahlung being radiated at wide angles relative to the recoil parton trajectory. We extend this analysis further to track the lost energy in $\Delta\phi$ space. To do this, we plot the I_{AA} in a given trigger p_T bin as a function of the separation angle $\Delta\phi$ over the range $|\Delta\phi - \pi| \lesssim \pi/3$, encompassing the away-side jet peak. The result is shown in Fig. 5. Each of the different sets of color points represents a different associate particle p_T range, with red being the lowest (0.5–1 GeV/c) and black being the highest (5–7 GeV/c). The I_{AA}

for the highest p_T associate particles, (i.e. the 5–7 GeV/c and 3–5 GeV/c bins), is suppressed by nearly the same amount across the $\Delta\phi$ range. As the p_T of the associate particle decreases, however, the I_{AA} begins to take on a $\Delta\phi$ dependence, showing enhancement at wide angles relative to the away-side jet peak ($\Delta\phi = \pi$), as is seen in the 0.5–1 GeV/c and 1–2 GeV/c bins. Near $\Delta\phi \approx \pi$, however, the I_{AA} for the 1–2 GeV/c bin appears to be consistent with one, whereas the 0.5–1 Gev/c shows enhancement across almost all $\Delta\phi$ bins on the away-side. Lastly, there appear to be no major changes in the measurement when looking at different trigger p_T bins.

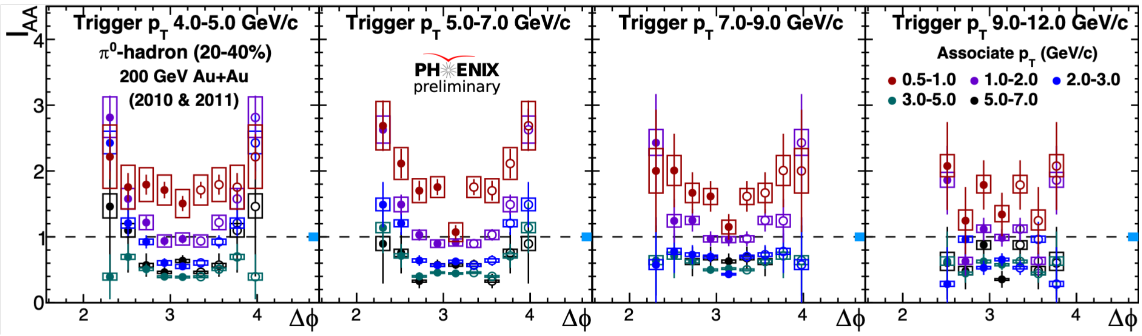

Fig. 5: I_{AA} as a function of the separation angle $\Delta\phi$ in four trigger p_T bins. Each color represents a different associate particle p_T range. The filled points are calculated directly by dividing a given $Au + Au$ jet function by the same bin in the $p + p$ baseline. These points are then mirrored across $\Delta\phi = \pi$, which is represented by the open points.

4. Conclusions

Single particle R_{AA} measurements have been performed by PHENIX in $A + A(B)$ collisions at $\sqrt{s_{NN}}$ = 200 GeV and 193 GeV. At high p_T, the integrated R_{AA}'s for several meson species were found to follow the same trend as a function of N_{Part}, showing that the modification in their yield is dependent only on N_{Part} and not the collision species nor meson species. This means that modifications to single particle yields at high p_T are dominantly due to energy loss.

Measurements of π^0-triggered two-particle correlations from PHENIX in $Au + Au$ collisions at $\sqrt{s_{NN}}$ = 200 GeV from RHIC Year-10 and 11 datasets show modification to the away-side jet peak's width and yield relative to the $p + p$ baseline. Extraction of the I_{AA} and jet width σ show that, at low associate particle p_T, recoil jets in $Au + Au$ are broader and have a larger particle yield than in $p + p$. Meanwhile, at high associate particle p_T, these jets are as collimated as their $p + p$ counterparts, and their particle yield is suppressed relative to the $p + p$ baseline. Lastly, a new measurement, the I_{AA} as a function of $\Delta\phi$, shows that high p_T associate particles are suppressed at the same level in $\Delta\phi$ space, whereas the enhancement of low p_T associate particles has a $\Delta\phi$ dependence and is most prominent at large angles relative to the away-side jet peak. The two-particle correlation studies presented in this analysis will be expanded upon by adding the statistics of two of PHENIX's largest $Au + Au$ at $\sqrt{s_{NN}}$ = 200 GeV datasets, Run 14 and Run 16, as well as including direct photon triggered correlations.

Acknowledgements

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