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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 $\pi^0$-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 momentum 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 has been 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).

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

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 momentum on the x-axis. In both collision species in the most central collisions, there is a separation between the $\phi$ and $K^*$ $R_{AA}$ and the $\pi^0$ and the $\eta$ $R_{AA}$ 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 $\phi$, for instance, is entirely composed of strange quarks ($s \bar{s}$), whereas the $\pi^0$ ($(uu) + (dd)/\sqrt{2}$) has no contribution to its makeup from strange quarks and, thus, would not see this effect.

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 both 0–20% and 20–40% centrality bins which disappears at higher $p_T$.

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 momentum 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 $\pi^0$) 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

$$\frac{1}{N'_t} \frac{dN^{Pair}}{d\Delta \phi} = \frac{1}{N'_t} \frac{N^{Pair}}{\epsilon \int \Delta \phi} \left( \frac{dN^{Pair}_{Same}/d\Delta \phi}{dN^{Pair}_{Mix}/d\Delta \phi} - \xi(1 + \sum_{n=2}^{4} 2(v'_n)(v''_n) \cos(n\Delta \phi)) \right) \tag{2}$$

Here, $N'_t$ and $N^{Pair}$ refer to the number of trigger $\pi^0$s and correlated pairs, respectively. “Same” denotes a $n^{th}$-hadron pair that came from the same event, whereas pairs denoted “Mix” came from two separate events and are used to correct for detector effects via event mixing. $\epsilon$ is the charged hadron efficiency, and $\xi$ represents the magnitude of the correlated background due to flow, calculated using the absolute background subtraction method [1]. Lastly, $v'_n$ and $v''_n$ 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 momentum on the $x$-axis in two different trigger $p_T$ ranges. $I_{AA}$ 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: $Y_{AA} = Y^{AA}/Y^{pp} \approx D^{AA}(z)/D^{PP}(z)$. Additionally, the measurement of $I_{AA}$ as a function of $\Delta \phi$, shown in Fig. 5, probes modification to the fragmentation function spatially as well as in $p_T$.

The $I_{AA}$ measurement shown in Fig. 5 shows an enhancement in the yield of low momentum associate particles, and a suppression in the yield of high momentum 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, $\sigma$, as previously shown in Fig. 4. The result of this measurement is shown in Fig. 4 with the jet width, $\sigma$, 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 momentum. 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 Fig. 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 even further to track the lost energy in $\Delta \phi$ space in a new PHENIX result. 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 $|\Delta \phi - \pi| < \pi/3$, 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 momentum 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 momentum 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 $\Delta \phi = \pi$, 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.

![Graph showing $I_{AA}$ as a function of $\Delta \phi$ in four trigger $p_T$ bins. Each color represents a different associate particle momentum 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.](image)

**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 momentum 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. The $R_{AA}$ of protons in Au+Au and Cu+Au were found to be consistent at similar $N_{part}$, which is a proxy for the system size. 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 $\pi^0$-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 $\sigma$ 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.

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