PHENIX Results on Jet Modification with $\pi^0$-, Photon-, and Isolated Photon-Triggereed Two Particle Correlations

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Abstract. PHENIX has measured $\pi^0$ and direct photon-triggered two-particle azimuthal correlations in a variety of collision systems ranging from $p+p$ to $Au+Au$ at 200 GeV. In $p+p$, $p+Au$, and $d+Au$ correlations, interesting new measurements related to angular correlation widths are made which may reveal 'cold' nuclear effects. In $Au+Au$ collisions, we have developed new methods to obtain isolated photons by using an isolation cut like those used in the smaller systems which provide for a cleaner sample of direct photons but reveal new challenges in the high multiplicity $Au+Au$ environment. We present first measurements of centrality-dependent isolated photon-hadron angular correlations that quantify the transition from low $z_T (=p_T^h/p_T^\gamma)$ enhancement to high $z_T$ suppression relative to $p+p$ collisions.

1. Introduction

Direct photon-hadron correlations are used because the direct photons are color neutral, they originate from the initial hard scattering, they are produced alone, meaning isolated and without other fragmentation products. Being color neutral means that they undergo no strong interactions and therefore no energy loss as they traverse the QGP. This means that their flow coefficients are close to zero. The direct photon energy can be used a proxy of the of the hadron jet energy because they are produced alone in the opposite direction of the jet. This allows the study of jet energy loss as they traverse the QGP. In the past, PHENIX has used two methods to obtain direct photons, a statistical subtraction method, for large systems, and an isolation cut method in small systems.

PHENIX has measured photon-hadron correlations in a variety of collision systems, $p+p$, $p+Au$, $d+Au$, and $Au+Au$. PHENIX consists of two central arms with azimuthal coverage $\pi$ and $|\eta| < 0.35$ [1]. The photons and $\pi^0$'s are measured in the electromagnetic calorimeter. The drift and pad chambers measure charged hadrons. Centrality is determined using beam-beam counters.

Most of the methods outlined below, outside of the isolation cut method used in $Au+Au$, have been already described in PHENIX publications [2, 3, 4]. Two-particle correlation (2PC) analyses measure the azimuthal correlation function between photons and hadrons. This correlation function, $C(\Delta\phi_{AB})$, has two contributions, the contribution from the jet, the jet
function, $J(\Delta \phi_{AB})$, and the background, $b_0 dN_{\text{comb}}^{AB}/d\Delta \phi_{AB}$; that is,

$$C(\Delta \phi_{AB}) = J(\Delta \phi_{AB}) + b_0 \frac{dN_{\text{comb}}^{AB}}{d\Delta \phi_{AB}},$$  \hspace{1cm} (1)$$

where A and B are the two correlated particles. The magnitude of the background, $b_0$, is usually found via zero yield at minimum or mean seeds mean partners [5]. The shape of the background, $dN_{\text{comb}}^{AB}/d\Delta \phi_{AB}$, comes from independent measurements of the single particle elliptic flow, that is,

$$\frac{dN_{\text{comb}}^{AB}}{d\Delta \phi_{AB}} \propto 1 + 2v_2^A v_2^B \cos(2\Delta \phi_{AB}).$$  \hspace{1cm} (2)$$

In small systems, just a flat (in $\phi$) background is subtracted—even though $v_2$ is found to be non-zero in $p+Au$ and $d+Au$ [6], the level of combinatoric background is so small that including $v_n$ makes a negligible difference. The elliptic flow shape is subtracted from Au+Au data. Higher order flow harmonics are not included in the Au+Au subtraction because direct measurements are not available in all $p_T$ bins used, and because the prompt photons have very small $v_n$, such that it is found that the effects of ignoring harmonics with $n > 2$ are negligible. Once the jet function is obtained for inclusive or isolated photon-hadron pairs, the statistical subtraction method can be applied to subtract the decay photon contribution from in order to find the direct photon-hadron yield. This is done using

$$Y_{\text{direct}} = \frac{R_\gamma Y_{\text{inclusive}} - Y_{\text{decay}}}{R_\gamma - 1},$$  \hspace{1cm} (3)$$

where $Y_{\text{direct}}$ is the direct photon-hadron pair yield, $Y_{\text{inclusive}}$ is the inclusive photon-hadron pair yield, $R_\gamma$ is the ratio of number of inclusive photons to number of decay photons, and $Y_{\text{decay}}$ is the decay photon-hadron pair yield that is found by mapping the $\pi^0$ to decay photons based on the probability of the $\pi^0$ of a specific $p_T$ to decay to two photons. When the isolation cut is applied, the statistical subtraction is identical except $Y_{\text{isolated}} = Y_{\text{inclusive}}$ in Equation 3 and $R_\gamma$ is modified to include the increased signal-to-background ratio for direct photons from the isolation cut. These methods are used in both small and, for the first time, large systems at RHIC.

2. Small Systems - $p+p$, $p+Au$, and $p+Al$ Results

Measuring photon-hadron correlations in small systems aims to study ‘cold’ nuclear matter effects in the modification of jets and jet fragmentation. It has been predicted that in transverse momentum dependent (TMD) framework, QCD factorization breaks [7]. TMD evolution predicts that the nonperturbative momentum widths increase with increasing hard scale interaction [8]. These momentum widths can be measured in PHENIX by measuring $p_{\text{out}} = p_T^{\text{assoc}} \sin \Delta \phi$, the component of the hadron transverse momentum perpendicular to the trigger direct photon or $\pi^0$ momentum vector, via direct photon-hadron and $\pi^0$-hadron correlations.

The $p_{\text{out}}$ distributions on the left side of Figure 1 show a Gaussian at small $p_{\text{out}}$ with power law tails at large $p_{\text{out}}$. The small $p_{\text{out}}$ region is fit to a Gaussian and the widths are plotted as a function of trigger $p_T$ shown on the right side of Figure 1. The away-side jet widths decrease with increasing hard scale ($p_{T}^{\text{trig}}$) for both $\pi^0 - h$ and $\gamma - h$ correlations. The lines show the slopes of the widths are different.

To check whether the trend of decreasing widths with increasing hard scale is ubiquitous across all collision species and energies, this analysis has been carried out on $p+p$, $p+Al$, and $p+Au$ collisions at $\sqrt{s_{NN}} = 200\text{GeV}$. The left side of Figure 2 shows the direct photon-hadron
**Figure 1.** (Left panel) $p_{\text{out}}$ distributions for $\pi^0$-hadron (open points) and direct photon-hadron correlations (closed points) in $p + p$ collisions at $\sqrt{s_{\text{NN}}} = 510\text{GeV}$. Each trigger $p_T$ bin is a different color that has been offset for clarity. The lines are Gaussian fits at small $p_{\text{out}}$ and power law fits at large $p_{\text{out}}$. (Right panel) Width of the low $p_{\text{out}}$ Gaussian fit as a function of $p_T^{\text{trig}}$ for $\pi^0$-hadron (open points) and direct photon-hadron correlations (closed points)[3].

$p_{\text{out}}$ Gaussian widths as a function of trigger $p_T$ for the $p+p$ collisions at $\sqrt{s_{\text{NN}}} = 510\text{GeV}$ shown on the right side of Figure 1 (red points) and $p + p$ collisions at $\sqrt{s_{\text{NN}}} = 200\text{GeV}$ (blue points). The decreasing trend is also shown in $p + p$ collisions at $\sqrt{s_{\text{NN}}} = 200\text{GeV}$ and the slopes of the widths seem similar. The right side of Figure 2 shows the direct photon-hadron $p_{\text{out}}$ Gaussian widths as a function of trigger $p_T$ for the $p+p$ (black points) and $p+Au$ (red points) collisions at $\sqrt{s_{\text{NN}}} = 200\text{GeV}$. The widths between these two collision systems are consistent and the slopes are similar, though it is harder to discern because of the large error bars.

**Figure 2.** (Left panel) Direct photon-hadron $p_{\text{out}}$ Gaussian width as a function of trigger $p_T$ for the $p + p$ collisions at $\sqrt{s_{\text{NN}}} = 510\text{GeV}$ shown on the right side of Figure 1 (red points) and $p + p$ collisions at $\sqrt{s_{\text{NN}}} = 200\text{GeV}$ (blue points). (Right panel) Direct photon-hadron $p_{\text{out}}$ Gaussian width as a function of $p_T^{\text{trig}}$ for the $p + p$ (black points) and $p + Au$ (red points) collisions at $\sqrt{s_{\text{NN}}} = 200\text{GeV}$.

The $\pi^0$-hadron correlations have more statistics so the error bars are smaller. Figure 3 shows the $p_{\text{out}}$ Gaussian width for $\pi^0$-hadron correlations as a function of trigger $p_T$ for various collision species and energies. The left and middle panel of this figure shows the Gaussian widths decrease in $p + p$, $p+Au$, and $p+Al$ collisions but with different slopes. The right panel of Figure 3 shows the centrality dependence of the $p_{\text{out}}$ Gaussian width in $p+Au$ and $p+Al$ collisions. There is a definite broadening from peripheral to central events and the effect is stronger in $p+Au$ than $p+Al$. 
Figure 3. (Left panel) $\pi^0$-hadron $p_{out}$ Gaussian width as a function of $p_{T}^{trig}$ for the $p+p$ collisions at $\sqrt{s_{NN}} = 510$GeV shown on the right side of Figure 1 (black points) and $p+Al$ (blue points) collisions at $\sqrt{s_{NN}} = 200$GeV. (Middle panel) $\pi^0$-hadron $p_{out}$ Gaussian width as a function of $p_{T}^{trig}$ for the $p+p$ collisions at $\sqrt{s_{NN}} = 510$GeV shown on the right side of Figure 1 (red points) and $p+p$ collisions at $\sqrt{s_{NN}} = 200$GeV (black points). (Right panel) $\pi^0$-hadron $p_{out}$ Gaussian width as a function of $p_{T}^{trig}$ for 0-20% central $p+Al$ (black circles), 60-84% central $p+Au$ (black squares), 0-20% central $p+Al$ (green circles), and 60-72% central $p+Al$ (green squares) collisions.

3. Small and Large System Comparison - Non Isolation Method $d+Au$ and $Au+Au$ Results

Photon-hadron correlations in large systems are used to measure jet energy loss in the QGP. This is done by measuring jet functions and comparing their away-side yields to the same measurement in $p+p$ collisions. Doing this is complicated by the presence of the sizable underlying event, for example in $Au+Au$ collisions, the elliptic flow of the particles involved in the correlation cannot be neglected.

The upper panel of Figure 4 shows the integrated $\pi/2$ away-side yield in $p+p$ (blue points), $d+Au$ (purple points), and $Au+Au$ (black points) collisions as a function of $\xi = ln(1/\zeta_T)$ where $\zeta_T = p_T^h/p_T^{\gamma}$. The ratio of the $d+Au$ and $Au+Au$ yield to the $p+p$ yield, that is, the $I_{AA} = Y_{Au+Au}/Y_{p+p}$ and $I_{dA} = Y_{d+Au}/Y_{p+p}$ is shown in the lower panel of Figure 4. The $I_{dA}$ shows that there is little or no fragmentation function modification in $d+Au$ collisions. The $I_{AA}$ result confirms the previous PHENIX result from Reference [9]. This also concludes that there is enhancement of the fragmentation function at low $\zeta_T$, which is interpreted as recovered energy from the jet energy loss. This is confirmed with better statistical precision.

Figure 4. (Upper panel) Integrated $\pi/2$ away-side yield in $p+p$ (blue points), $d+Au$ (purple points), and $Au+Au$ (black points) collisions as a function of $\xi = ln(1/\zeta_T)$ where $\zeta_T = p_T^h/p_T^{\gamma}$. (Lower panel) $Au+Au$ and $d+Au$ $\pi/2$ away-side $I_{AA}$ as a function of $\xi$ [10].
4. Centrality Dependence of Jet Energy Loss Effects: Isolation Method Au+Au Results

We have also developed a new isolation cut method in Au+Au. As usual for isolation methods, photons in each event are used to define a cone surrounding with a specific sized radius according to \( R_{\text{cone}} = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} \). The energy of all other particles inside the cone is then measured, and if it is smaller than the threshold energy, the photon is classified as isolated. If the energy is greater, the photon is not isolated and probably originated from decay products of jet fragments. In our method, the cone threshold energy is determined by \( E_{TH} = aE_\gamma + b \), where \( E_\gamma \) is the central photon’s total energy and \( a \) and \( b \) are parameters vary with centrality due to the magnitude of the underlying event.

Because we choose the parameters \( a \) and \( b \) as constant anywhere in a given event, the isolation cut preferentially accepts particles emitted “out-of-plane” with respect to the event plane as isolated since the underlying event modulates lower there. The converse is also true, it finds less isolated particles oriented “in-plane” relative to the event plane. This creates a bias when trying to measure the elliptic flow of the isolated particles. This bias can be parameterized by \( 1 + v_2^2 \cos \Delta \phi \) where the underlying event \( v_2 \), \( v_{2E} \), is typically negative. This distribution can be derived by folding into the typical underlying event distribution to obtain

\[
\frac{dN_{\text{STSE}}}{d\Delta \phi} = I \left( 1 + 2J \cos(2\Delta \phi) + K \cos^2(2\Delta \phi) - 4L \cos(4\Delta \phi) \right),
\]

where \( I \) is a normalization factor, \( J = v_{2T} + v_{2E} \cos(2\delta \Psi) \), \( K = v_{2T}v_{2E} \), and \( L \propto v_{2T}^2 \). The \( \langle \cos(2\delta \Psi) \rangle \) factor is the typical event plane resolution correction.

In Figure 5, we show the extracted isolated photon \( v_2 \) (taken from parameter \( J \)) as a function of \( p_T \) for two centrality bins in Au+Au collisions, along with direct and inclusive photon \( v_2 \). One can see that the isolated photon \( v_2 \) (black points) is less than the inclusive photon \( v_2 \) (brown points) and consistent with the direct photon \( v_2 \) (red points). It is important to remember when comparing these \( v_2 \) that some decay photons survive the isolation cut so the black points are still a mixture of direct and decay photons, albeit with reduced decay contributions. The underlying event \( v_{2E} \) has not been corrected for here because the 2PC correlation functions also have this effect that must be subtracted, in Equation 2. This allows the net \( v_2 \) to even be slightly negative in some cases, because the true \( v_2 \) can be negligible for photons compared to the isolation-induced negative \( v_2 \).

![Figure 5](image_url)

Figure 5. Isolated direct + decay photon \( v_2 \) \((v_{2T} + v_{2E})\) as a function of \( p_T \) for 0-20\% (left) and 20-40\% (middle) central events in Au+Au collisions. The boxes are systematic error bars. The red points are the direct photon \( v_2 \) and the brown points are inclusive photon \( v_2 \) for 0-20\% and 20-40\% central events that are taken from Reference [11].

An example isolated photon-hadron correlation function is shown in Figure 6. The black points are the correlation function, the black line is the background level, and the red lines show
the error on the black line. Notice that the background shape is a negative cosine distribution for this momentum bin. This is due to the negative isolated photon $v_2$ discussed above. Once this background is subtracted from the correlation function, jet functions are obtained. These are shown in Figure 7 for four centrality bins in Au+Au collisions. The black points are $\gamma_{iso} - h$ pairs, the red points are $\gamma_{dec} - h$ pairs, and the blue points are $\gamma_{dir} - h$ pairs found using Equation 3.

Figure 6. A Au+Au $\gamma_{iso} - h$ correlation function. The background shape is opposite of the expected shape because the isolated photon has negative $v_2$.

Figure 7. Au+Au $\gamma_{iso} - h$ (black points), $\gamma_{dec} - h$ (red points), and $\gamma_{dir} - h$ (blue points) jet functions for $5 \leq p_T^{\text{trigger}} \leq 7$ and $3 \leq p_T^{\text{associated}} \leq 5$ for four centrality bins.

The direct photon-hadron jet functions can be integrated and compared to jet functions in $p+p$ collisions to find $I_{AA}$. Figure 8 shows the $\pi/2$ away-side region $I_{AA}$ as a function of $z_T$ for four centrality bins. Each trigger photon $p_T$ bin is a different color. In each centrality bin, there is suppression of high $z_T$ particles. By contrast there is no suppression of low $z_T$ particles and in some cases even enhancement. This has been seen in other Au+Au correlation analyses [9, 10, 12]. To quantify this contrasting behavior, the low and high $z_T$ regions are fit to constants (purple lines).

To see how the suppression varies with centrality, we plot the high $z_T$ average $I_{AA}$ as a function of $N_{part}$ for the $\pi/3$ (Figure 9 left) and $\pi/5$ (Figure 9 right) away-side integration regions. The gray bands in these figures is the $\pi^0 R_{AA}$ for $\pi^0$'s with $p_T > 5\text{GeV/c}$. The high $z_T I_{AA}$ approximately matches the $\pi^0 R_{AA}$ which is expected because the energy loss geometry of the QGP is the same as the single inclusive jet geometry if other effects besides geometry are sub-dominant.

To see how both the high $z_T$ suppression and low $z_T$ non-suppression/enhancement vary with centrality, we plot the low and high $z_T$ direct photon $I_{AA}$ constant fit values as a function of $N_{part}$ for three away-side integration regions, $\pi/2$ (Figure 10 left), $\pi/3$ (Figure 10 middle), and $\pi/5$ (Figure 10 right) away-side integration regions. Immediately obvious is that the low and high $z_T$ behaviors are different. There is high $z_T$ suppression for all centrality bins while the low $z_T$ points are not suppressed, so they are relatively flat with centrality. The low $z_T$ behavior has previously been interpreted as being a signal of energy loss recovery by the medium. This is because the high $z_T$ particle’s energy loss enhances the production of low $z_T$ particles. There is increasing low $z_T$ enhancement for wider integration regions, the blue points increase right.
Figure 8. $I_{AA}$ as a function of $z_T$ for the $\pi/2$ away-side integration region for four centrality bins. Each photon $p_T$ bin is a different color, $5 < p_T^{\text{trigger}} < 7$ GeV/c (black), $7 < p_T^{\text{trigger}} < 9$ GeV/c (red), $9 < p_T^{\text{trigger}} < 12$ GeV/c (green), and $12 < p_T^{\text{trigger}} < 15$ GeV/c (blue). The purple lines are constant fits to two $z_T$ regions with the statistical error on the fit in light purple.

Figure 9. High $z_T$ average $I_{AA}$ as a function of $N_{\text{part}}$ for the $\pi/3$ (left) and $\pi/5$ (right) away-side integration region $\pi/3$. The gray band is the $\pi^0$ $R_{AA}$ for $\pi^0$ with $p_T > 5$GeV/c from [13].

to left. The isolation cut method allows for a more precise analysis of the semi-peripheral and peripheral centralities. This is the first measurement of the centrality dependence of the low $z_T$ enhancement.

To judge true centrality dependence of enhancement however, we must account for overall reduction of jets due to suppression, because our normalization of the yields is made per trigger photon, and therefore includes the jet suppression factor--which is why the high $z_T$ yields have $I_{AA} < 1$. For this reason, low $z_T$ $I_{AA}$ values in this observable, even if they do not exceed $I_{AA} = 1$ can reasonably described as ”enhancement” as long as they are substantially higher than the overall suppression level measured by the high $z_T$ $I_{AA}$. To quantify this, the ratio is made of the low $z_T$ to high $z_T$ average $I_{AA}$ values, which we call the energy recovery factor (ERF) and is shown in the bottom panel of Figure 10. One can see that this ratio monotonically increasing towards central events for all away-side integration regions, qualitatively matching expectations of having low $z_T$ energy recovery scaling inversely to the amount of energy loss/suppression.
Figure 10. Average $I_{AA}$ as a function of $N_{\text{part}}$ for each away-side integration region $\pi/2$ (left), $\pi/3$ (middle), and $\pi/5$ (right). The red points in the top panels is the high $z_T$ average and the blue points are the low $z_T$ average. The bottom panels show the centrality dependence of ratio of high to low $z_T$ average $I_{AA}$, the energy recovery factor.

5. Conclusion

PHENIX has measured nonpreturbative momentum widths and has seen a decrease with increasing hard scale. This has been measured in $p+p$ at $\sqrt{s_{NN}} = 510\text{GeV}$ and $\sqrt{s_{NN}} = 200\text{GeV}$, as well as $p+\text{Au}$, and $p+\text{Al}$ collisions. This is opposite of TMD factorization expectations [3].

PHENIX has measured direct photon-hadron correlations in $d+\text{Au}$ and $\text{Au+Au}$ collisions. There is no modification in $d+\text{Au}$ collisions within uncertainties when compared to $p+p$ collisions. The centrality integrated $\text{Au+Au}$ result confirms the previously measured pattern of suppression to low $z_T$ enhancement in Reference [9].

Finally, PHENIX has developed a new isolation cut method in $\text{Au+Au}$ that allows for more precise analysis of the semi-peripheral and peripheral centralities. This method has lead to the first ever study of low $z_T$ enhancement as a function of centrality. This enhancement, when properly accounting for the overall jet suppression level through the ERF ratio, is found qualitatively to be monotonic with centrality and scaling inversely to the jet-suppression centrality dependence. PHENIX still has high statistics datasets from RHIC Run-14 and Run-16 that need to be analyzed which should be promising for application of our new isolation method.

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