

Direct photon-hadron correlations with the PHENIX detector

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Abstract. Direct photon tagged jets, in the form of photon-hadron correlations, are well suited to provide unique insight into how jets interact with the quark gluon plasma. Since photons do not interact strongly with medium produced at RHIC, at leading order the measured photon momentum approximately balances that of the away-side parton. The modification to the effective fragmentation function can be measured by comparing integrated away-side yields in direct photon-hadron correlations in Au+Au collisions to those in p+p. By varying the away-side integration range, the angular dependence of the observed modification can also be studied. Direct photon-hadron correlations have been measured with PHENIX in p+p and Au+Au using a statistical subtraction technique to remove the decay photon contribution from the inclusive photon-hadron correlations, with an additional isolation cut applied in p+p to reduce uncertainties. Recently published results showing a significant modification to the fragmentation function with an azimuthal angle dependence indicative of broadening are discussed in the context of related theoretical models and complementary results from other experiments.

1. Introduction

A variety of single-particle and two-particle correlation measurements illustrate well the suppression of high p_T hadrons, which is understood to be due to the energy loss of the parent parton as it traverses the medium produced in heavy-ion collisions. However, the details of parton-medium interactions going into such measurements are difficult to decouple due in part to lack of access to the original parton energy. The study of high p_T direct photons, which do not interact strongly with the medium and therefore escape unmodified and at leading order are produced back-to-back with a parton, predominately through the QCD Compton process, provides unique access to the energy of the parton (in this case a quark) prior to medium interaction. Through direct photon-hadron correlation measurements, the fragmentation function (FF) for the opposing jet, $D(z)$ where $z = p_h/p_{jet}$, can be estimated by measuring $z_T = p_{h,T}/p_{\gamma,T} \approx z$. This is only an approximation due to initial state effects, such as the initial transverse momenta of the colliding partons in the nucleons, k_T , which can introduce a momentum imbalance between the photon and the opposing jet. Based on hadron-hadron correlation results, k_T has been measured to be ~ 3 GeV/ c in both p+p and d+Au collisions, with no significant difference in the resulting smearing [1, 2]. This suggests that p+p should provide a good baseline estimate for the FF when studying medium modification to the effective fragmentation function in Au+Au.



2. Method

Photon-hadron correlations are constructed by measuring the azimuthal angle, $\Delta\phi$, between trigger photons and associated charged hadrons in an event, with detector acceptance effects being corrected for by mixing trigger photons with associated hadrons not from the same event. The corrected correlations are then assumed to be a combination of jet constituents, the jet function, and a background of combinatorial pairs that are un-correlated, or correlated only due to event-level effects. In $p+p$ collisions, where hard scattering processes dominate and event multiplicities are low, this background should result only in a small flat pedestal that can be estimated based on the zero-yield-at-minimum (ZYAM) assumption. In heavy-ion collisions, the high multiplicity of the event leaves a large background which includes an angular correlation between particles due to bulk anisotropies leading to flow. The total level of the background, b_0 , is determined using the absolute normalization method [3]. The flow modulation can be decomposed into Fourier components, v_n , which can be measured independently [4] and included as additional terms in the background subtraction, as described in Eqn. 2. In the results discussed here only v_2 is included, with higher order effects estimated as an additional systematic uncertainty on the final results. The charged hadron efficiency, ϵ_a , is determined via a full GEANT simulation of the detector.

$$\frac{1}{N_t} \frac{dN^{pair}}{d\Delta\phi} = \frac{1}{N_t \epsilon^a} \frac{N_{real}^{pair}}{\int \Delta\phi} \left\{ \frac{dN_{real}^{pair}/d\Delta\phi}{dN_{mix}^{pair}/d\Delta\phi} - b_0 [1 + 2\langle v_2^t v_2^a \rangle \cos(2\Delta\phi)] \right\}. \quad (1)$$

Ultimately, it is the yield of hadrons associated only with direct photons that will provide information about the fragmentation function. However, the trigger photons used to construct the jet functions, or per-trigger yields, are a combination of such direct photons and a large background of photons produced from meson decays, predominately from π^0 decays. To estimate this decay photon background, π^0 -h correlations are measured and mapped to decay photon-hadron correlations according to the probability for a π^0 to decay into a photon within the relevant p_T range, as determined by a Monte Carlo study. The decay photon jet functions are then determined in the same way as the inclusive according to Eqn. 2. The γ_{direct} -h can then be extracted from the inclusive correlations using Eqn. 2

$$Y_{dir} = \frac{R_\gamma Y_{inc} - Y_{dec}}{R_\gamma - 1}, \quad (2)$$

where Y are the per trigger yields and R_γ is the ratio of the number of inclusive photons to the number of decay photons, which has been measured previously [5].

In $p+p$ collisions, the significantly lower multiplicities make possible some additional event-by-event level cuts that can improve the signal to background for direct photons prior to estimating and subtracting the decay photon yield. First, photons are excluded which, when paired with another photon in the event, fall within the π^0 or η mass windows. Second, an isolation cut is applied requiring the total momentum and energy within a 0.3 rad cone around the trigger photon to be $< 10\% E_\gamma$. This restriction further reduces the contamination from decay photons, with the additional advantage that the contribution from fragmentation photons is greatly reduced [6]. These techniques greatly improve the measurement uncertainties while remaining consistent with the more straightforward statistical subtraction. Though an isolation cut is unfeasible in heavy-ion collisions, lack of a significant near-side yield, in conjunction with the consistency in the $p+p$ results with and without this requirement, gives confidence that any observed modification is due to medium effects on the opposing jet.

3. Results

3.1. The $p+p$ baseline

The yield on the away-side, $|\Delta\phi\pi| < \pi/2$, of direct photon-hadron correlations in $p+p$ collisions is plotted as a function of $\xi = -\ln(x_E)$ in Fig. 1, where $x_E = \frac{p_{h,T}\cos\Delta\phi}{p_{g,T}} \approx z_T$. All the data points appear to lie on a universal curve, and agree well with the quark FF as measured by TASSO in e^+e^- collisions. Additionally, when plotted simply as a function of x_E and fit to an exponential, $dN/dz_T = Ne^{-bz_T}$, a slope of $b = 8.2 \pm 0.3$ is obtained, which is consistent with the expectation for quark jets of $b = 8$ [6]. These results support the claim that direct photon-hadron correlations indeed provide an effective measure of the quark FF. Furthermore, Fig. 2 shows the k_T vs p_T^{trig} values obtained from $\gamma_{\text{dir}}\text{-h}$ correlations by fitting the $\sqrt{\langle p_{\text{out}}^2 \rangle}$ results extracted from the $\Delta\phi$ distributions with a selection of LO+ k_T smearing models. The measured k_T effect is consistent with that measured for $\pi^0\text{-h}$ correlations and previous results, supporting the claim that any observed modification to the FF measured in $p+p$ versus Au+Au will be dominated by medium effects.

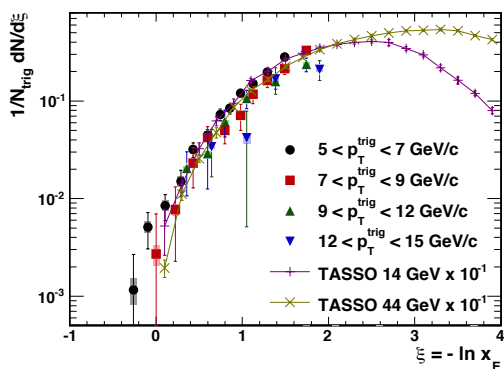


Figure 1. $p+p$ integrated away-side yields as a function of $\xi(x_E)$ compared to e^+e^- TASSO data scaled to match the PHENIX acceptance.

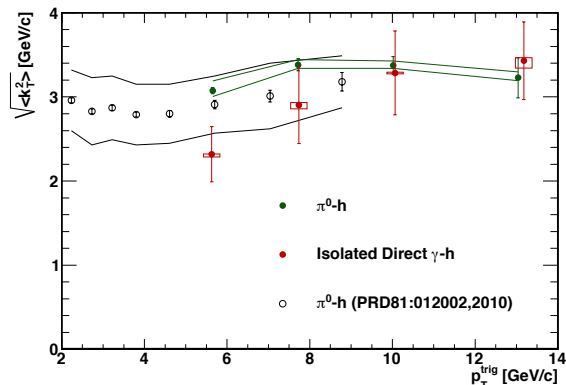


Figure 2. The k_T root-mean-square extracted from a LO+ k_T smearing models for $\pi^0\text{-h}$ (green) and $\gamma_{\text{dir}}\text{-h}$ (red) correlations, compared to previous $\pi^0 - h$ results.

3.2. The modified FF

Based on the approximate x_E scaling in $p+p$, to improve statistics we use a wide trigger p_T bin of 5 – 9 GeV/c for the purposes of comparing $p+p$ and Au+Au results. The $\Delta\phi$ dependent per-trigger yields for $p+p$ and Au+Au are shown in Fig. 3 as blue squares and open black circles respectively. Already a clear modification to the away-side distribution going from $p+p$ to Au+Au is clear. On the other hand, the near-side distribution in Au+Au remains consistent with $p+p$, with an integrated yield within one sigma of zero, indicating that this measurement is not sensitive to the contribution from fragmentation photons. The ξ distribution (now defined based on z_T rather than x_E) obtained by integrating the full away-side ($|\Delta\phi - \pi| < \pi/2$) is shown in Fig. 4. At low ξ there is a clear suppression of the Au+Au relative to $p+p$, while at higher ξ there appears to be an enhancement. To further quantify this, the ratio of the yield in Au+Au to that in $p+p$, $I_{AA} = Y_{AA}/Y_{pp}$, is shown in the lower panel of Fig. 4. The suppression at low ξ is consistent with previous results [7], while the increased statistics and extended range achieved with these new results reveal a significant enhancement at high ξ . Also shown are two theoretical predictions based on models that track the redistribution of lost parton energy into

enhanced soft particle production [8, 9]. The general trend anticipated by theory is consistent with what the data show, though quantitative comparison will require more direct calculations based on the relevant kinematic ranges achievable with the available statistics.

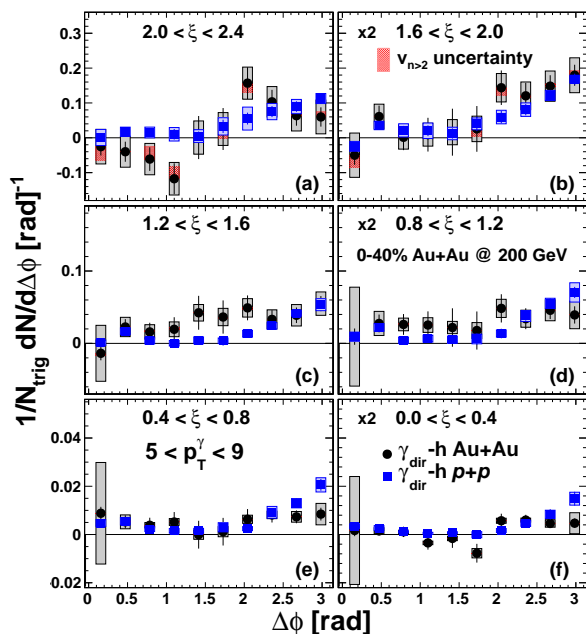


Figure 3. Direct photon-hadron $\Delta\phi$ dependent per-trigger yields in Au+Au (circles) and $p+p$ (squares) in 0.4 ξ bins from 0 to 2.4. Systematic uncertainties due to potential unsubtracted flow effects shown separately.

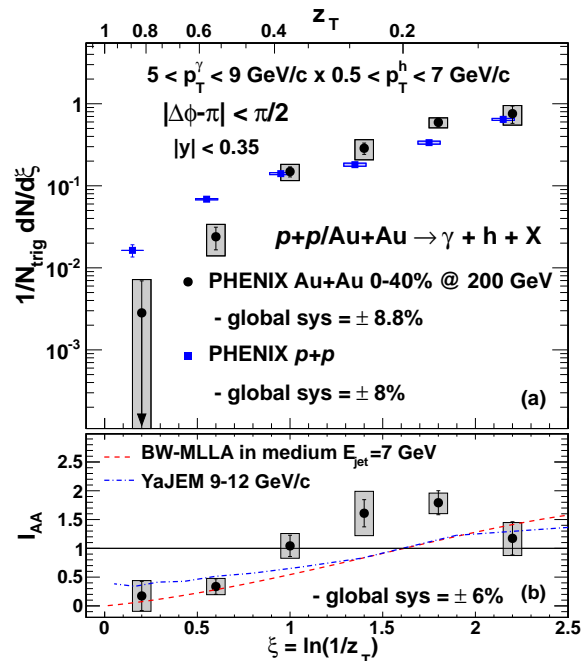


Figure 4. (a) The ξ dependent integrated away-side ($|\Delta\phi - \pi| < \pi/2$) per-trigger yields for Au+Au (circles) and $p+p$ (squares). (b) The Au+Au to $p+p$ ratio, I_{AA} , with comparison to BW-MLLA (dash) and YaJEM (dash-dot) calculations.

As Fig. 3 illustrates, the shape of the $\Delta\phi$ distribution in Au+Au appears modified relative to $p+p$. To quantify this effect beyond the examination of the integrated full away-side ($|\Delta\phi - \pi| < \pi/2$), two more restricted away-side integration ranges were selected, $|\Delta\phi - \pi| < \pi/3$ and $|\Delta\phi - \pi| < \pi/6$. The corresponding I_{AA} for these three integration ranges is shown in Fig. 5, as black circles blue squares and red triangles respectively. The suppression seen at low ξ is consistent for the three away-side definitions, while the relative enhancement seen at high ξ appears to be predominately at larger $\Delta\phi$, where the I_{AA} for the narrow ($|\Delta\phi - \pi| < \pi/6$) away-side remains consistent with one. The chosen integration ranges overlap, leading to correlation between the statistical and systematic uncertainties shown in the corresponding I_{AA} distributions. Therefore, to fully quantify the variation in I_{AA} , the ratio of the I_{AA} for the full away-side to the narrow away-side, in which these correlations will cancel, is shown in the bottom panel. A significant variation in the I_{AA} for $\xi > 1.0$ can be seen.

4. Conclusions

Evidence for modification to the jet fragmentation function due to medium interactions in heavy-ion collisions has been shown through comparison of direct photon-hadron correlations in $\sqrt{s_{NN}} = 200$ GeV Au+Au to $p+p$, using the photon as a proxy for the initial parton energy. Looking at the ratio of per-trigger yields we find a strong suppression at low ξ or high momentum fraction, z_T , consistent with previous results [7, 10]. The increased statistics and

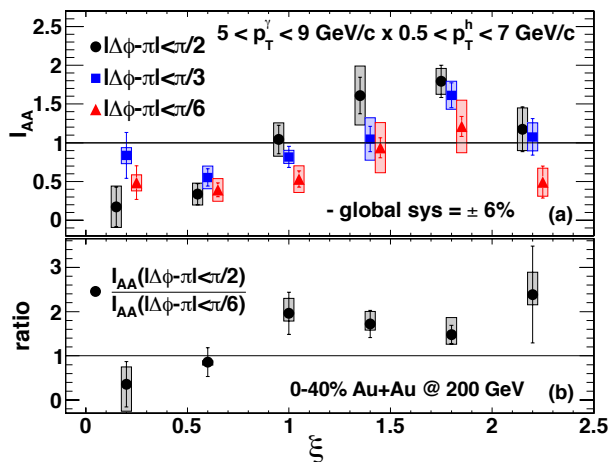


Figure 5. (a) The ξ dependent I_{AA} for different away-side integration ranges: $|\Delta\phi - \pi| < \pi/2$ (black circles), $|\Delta\phi - \pi| < \pi/3$ (blue squares), and $|\Delta\phi - \pi| < \pi/6$ (red triangles). (b) The ratio of the I_{AA} for the full ($|\Delta\phi - \pi| < \pi/2$) and narrow ($|\Delta\phi - \pi| < \pi/6$) away-side integration ranges.

larger z_T range accessed using a combination of data from 2007 and 2010 and going down to 0.5 in associated hadron p_T reveals an enhancement at high ξ indicative of increased soft particle production in response to the propagation of the initial parton through the medium. This enhancement is qualitatively consistent with the trend seen at the LHC through direct comparison of the fragmentation function for fully reconstructed jets in peripheral and central Pb+Pb [11, 12], and also with complementary measurements of jet-hadron correlations [13]. When the range of azimuthal angle integration of the away-side is restricted, this enhancement is reduced significantly, consistent with a broadening of the away-side distribution. Related measurements at LHC energies do not show a broadening of the distributions of fully reconstructed jets with respect to direct photon triggers [14]. However, evidence for the broadening of the jets themselves has been seen through studies of the jet profile, $\rho(r)$ [12], and the relative suppression of larger jet sizes ($R=0.5, 0.4, 0.3$) to a narrow baseline ($R=0.2$) [15]. Thus the angular dependence of the modification to I_{AA} shown here suggests that the medium enhances the production of soft jet fragments at large angles relative to the jet axis.

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