Direct-photon Hadron Correlations at $\sqrt{s} = 200$ GeV with PHENIX

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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 high momentum photons are unmodified by the strongly coupled medium produced at RHIC, the measured photon momentum approximately balances that of the away-side parton. Therefore, the effective modification to the 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 modification to the effective fragmentation function 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. These recently published results are discussed in light of complementary results from STAR and the LHC, as well as qualitative comparisons with theoretical predictions.

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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, in part as a result of the inability to directly access the original parton energy. Alternatively, direct photons do not show any such suppression, as expected since they do not interact strongly with the medium, and therefore escape the medium unmodified. Additionally, the production of direct photons at high momentum is dominated by the leading order QCD Compton process, i.e. back-to-back with a quark. As a result, high-p_T direct photons provide unique access to the energy of the quark prior to any medium interaction.

Through measurements of hadrons associated with a direct photon, the fragmentation function (FF) for the opposing jet, D($z = p_h/p_{jet}$), 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 studing medium modification to the effective fragmentation function in Au+Au.

2. Method

The correlation of photons and hadrons produced as a result of a hard scattering in the collision can be studied by measuring the azimuthal angle, $\Delta\phi$, between trigger photons and associated charged hadrons in an event. Detector acceptance effects are then corrected for by mixing trigger photons with associated hadrons from different events. These corrected correlations are then assumed to be a combination of jet constituents and a background of combinatorial pairs that are un-correlated, or correlated only due to bulk effects. In p+p collisions, where hard scattering processes dominate, this background should result in a small flat pedastal 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 event-level 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 are measured independently [4] and included as additional terms in the background subtraction, as described in Eqn. 2.

$$\frac{1}{N_t}\frac{dN^{pair}}{d\Delta\phi} = \frac{1}{N_t}\frac{N^{pair}_{real}}{\varepsilon^a \int \Delta\phi}\left\{\frac{dN^{pair}_{real}/d\Delta\phi}{dN^{pair}_{mix}/d\Delta\phi} - b_0[1+2\langle v_2^t v_2^a\rangle cos(2\Delta\phi)]\right\} \tag{2.1}$$

In the results discussed here only v_2 is included, with higher order effects estimated as an additional systematic uncertainty on the final results. Finally, the invariant yield of associated hadrons is obtained by scaling this background-subtracted pair distribution by the number of trigger photons, N_t, and correcting for the charged hadron efficiency, ε_a, determined via a full GEANT simulation.

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 per-trigger yields are a combination of such direct photons and a large background of photons produced from meson decays, predominately π^0 decays. To estimate this decay 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 yield can then be extracted from the inclusive using Eqn. 2

$$Y_{dir} = \frac{R_\gamma Y_{inc} - Y_{dec}}{R_\gamma - 1}, \tag{2.2}$$

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 such as an isolation requirement on the trigger photon and tagging of π^0 and η decay photons to improve the signal to background for direct photons [6]. These techniques greatly improve the measurement uncertainties while remaining consistent with the more straightforward statistical subtraction.

3. Results

3.1 The p+p baseline

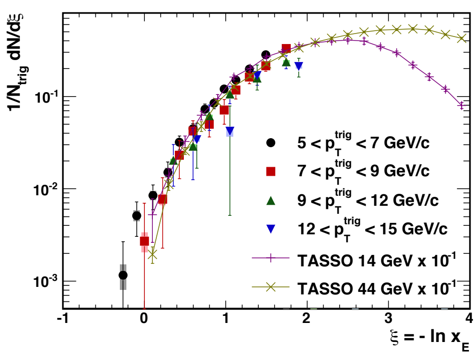

Figure 1: p+p integrated away-side yields as a function of $\xi(x_E)$ compared to e^+e^- TASSO data scaled to match the PHENIX acceptance [6].

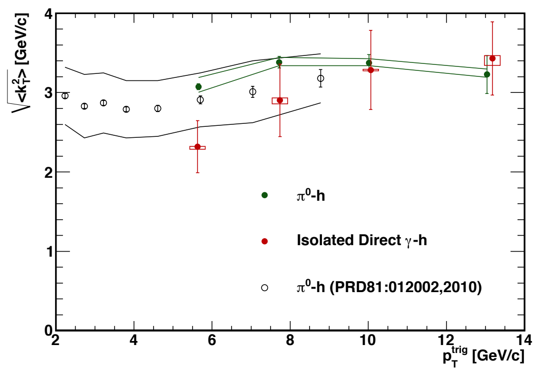

Figure 2: The k_T root-mean-square extracted from a LO+k_T smearing models for π^0-h (green) and γ_{dir}-h (red) correlations, compared to previous $\pi^0 - h$ results [6].

The yield on the awayside, $|\Delta\phi\pi| < \pi/2$, 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 γ_{dir}-h correlations by fitting the $\sqrt{< p_{out}^2 >}$ 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 π^0-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.

3.2 The modified FF

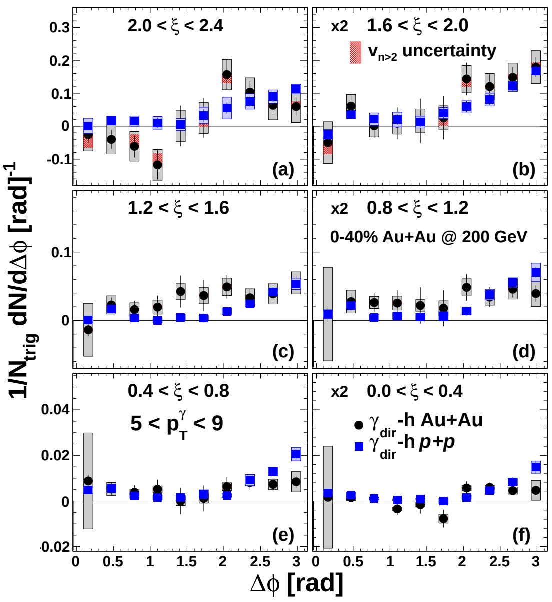

Figure 3: Direct photon-hadron $\Delta\phi$ dependent per-trigger yields in Au+Au (circles) and p+p (squares) in 0.4 ξ bins from 0 to 2.4. Systematic uncertainties due to potential unsubtracted flow effects shown separetly [7].

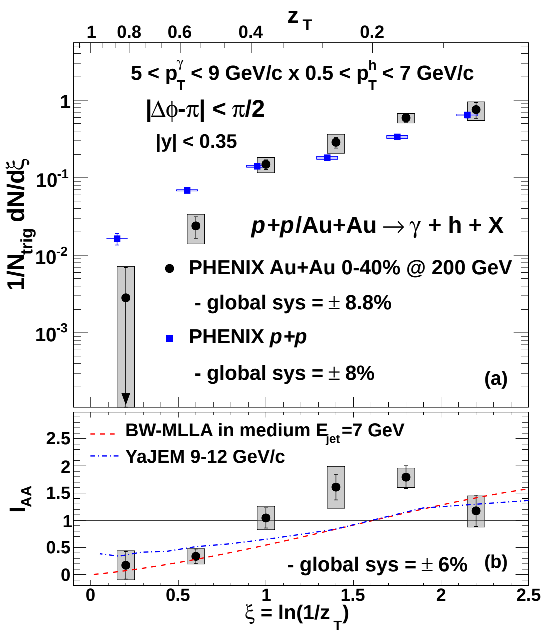

Figure 4: (a) The ξ dependent integrated away-side ($|\Delta\phi - \pi| < \pi/2$) per-trigger yields for Au+Au (circles) and p+p (squares). (b) The Au+Au to p+p ratio, I_{AA}, with comparison to BW-MLLA (dash) and YaJEM (dash-dot) calculations [7].

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, while the near-side distribution in Au+Au remains consistent with p+p. The ξ distribution (now defined in terms of z_T) obtained by integrating the full away-side ($|\Delta\phi - \pi| < \pi/2$) is shown in Fig. 4(a). A clear modification of the Au+Au distrubtion relative to p+p is seen, whic can be better quantified by taking the ratio of the yields, $I_{AA} = Y_{AA}/Y_p$, as shown in Fig. 4(b). The suppression at low ξ is consistent with previous results [8], while the inclreased sensi ivity of this result reveals a significant enhancement at high ξ. Also shown are two theoretical predictions based on models that tra k the redistribution of lost parton energy into enhanced soft particle production [9, 10].

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.

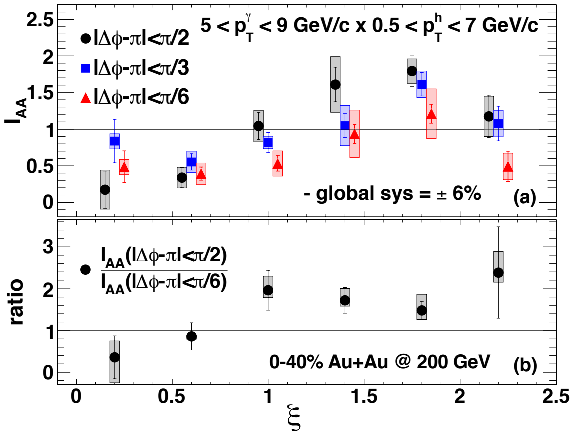

Figure 5: (a) The ξ dependent I_{AA} for different away-side integration ranges: $|\Delta\phi-\pi| < \pi/2$ (black circles), $|\Delta\phi-\pi| < \pi/3$ (blue squares), and $|\Delta\phi-\pi| < \pi/6$ (red triangles). (b) The ratio of the I_{AA} for the full ($|\Delta\phi-\pi| < \pi/2$) and narrow ($|\Delta\phi-\pi| < \pi/6$) away-side integration ranges [7].

As Fig. 3 illustrates, the shape of the $\Delta\phi$ distributions in Au+Au appear modified relative to p+p, motivating a closer look at the $\Delta\phi$ dependence of the I_{AA}. To that end, two more restricted away-side integration ranges were selected, $|\Delta\phi-\pi| < \pi/3$ and $|\Delta\phi-\pi| < \pi/6$ were studied and compared to the full away-side ($|\Delta\phi-\pi| < \pi/2$). The corresponding I_{AA} for these three integration ranges is shown in Fig. 5(a) as blue squares, red triangles, and black circles 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 $\Delta\phi$. 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 Fig. 5(b). 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 [8, 11]. The increased statistics and 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 [12, 13], and also with complementary measurements of jet-hadron correlations at RHIC[14]. 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 [15]. However, evidence for the broadening of the jets themselves has been seen through studies of

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the jet profile, $\rho(r)$ [13], and the relative suppression of larger jet sizes (R=0.5,0.4,0.3) to a narrow baseline (R=0.2) [16]. 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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