Azimuthal correlations between charged hadrons and direct photons at high-\(p_T\) in \(p + p\) and \(Au + Au\) collisions at \(\sqrt{s_{NN}} = 200\) GeV

A. M. Hamed (for the STAR Collaboration)
Texas A&M University, Physics Department, Cyclotron Institute, College Station, TX 77843, USA

Recent results of the STAR experiment on direct \(\gamma\)-charged hadron azimuthal correlations in heavy-ion collisions are presented. These correlations are used to study the color charge density of the medium through the medium-induced modification of high-\(p_T\) parton fragmentation. Azimuthal correlations of direct photons at high transverse energy \(8 < E_T < 16\) GeV with away-side charged hadrons of transverse momentum \(3 < p_T < 6\) GeV/c have been measured over a broad range of centrality for \(Au + Au\) collisions and \(p + p\) collisions at \(\sqrt{s_{NN}} = 200\) GeV in the STAR experiment. The per-trigger away-side hadron yield is smaller for direct \(\gamma\) triggers than for \(\pi^0\) triggers in the same centrality class.

I. INTRODUCTION

After various complementary measurements at the Relativistic Heavy Ion Collider (RHIC) have revealed the formation of a strongly coupled medium [1,2,3,4,5], the primary goal of the RHIC heavy-ion program progresses from qualitative statements about the formation of new matter to rigorous quantitative conclusions about the basic characteristics of such matter. One of the most important requirements for quantitative conclusions is the precise measurements of the medium color charge density. The color structure of the medium can be probed by its effect on the propagation of a fast parton, therefore the absorption of the high-\(p_T\) particles in the medium can be used to obtain a tomographic image of the color charge density of the medium [6]. Recognition of the importance of the high-\(p_T\) measurements in the heavy-ion program has resulted in some of the most important observations at RHIC such as the suppression of hadrons in central \(Au + Au\) collisions, compared to \(p + p\) collisions [7] and to cold nuclear matter [8] at high \(p_T\). Although this suppression has been placed on a firm experimental footing as a final state effect, many questions remain unanswered and await future measurements [9,10].

The \(\gamma\)-hadron azimuthal correlation measurement has been suggested as a powerful tool to quantify the partonic energy loss [11]. In the dominant QCD process of Compton-like scattering, the photon transverse momentum balances the parton initial transverse energy. In addition, due to the large mean free path of the photon compared to the system size formed in heavy-ion collision, the direct photon measurement doesn’t suffer from the same geometrical bias as that of single particle spectra and di-hadron azimuthal correlation measurements. In particular the \(\gamma\)-hadron azimuthal correlations provide a unique way to quantify the energy loss dependence on the initial parton energy and possibly the color factor. Combining the energy loss measurements from many probes of different geometrical biases and different coupling to the formed medium and comparing these measurements with different theoretical models is expected to lead to a successful quantitative interpretation of the heavy-ion data.

II. DATA ANALYSIS

The STAR experiment collected an integrated luminosity of 535 \(\mu b^{-1}\) of \(Au + Au\) collisions at \(\sqrt{s_{NN}} = 200\) GeV in 2007 using a level-2 high-\(p_T\) tower trigger. The level-2 trigger algorithm was implemented in the Barrel Electromagnetic Calorimeter (BEMC) and optimized based on the information of the direct \(\gamma/\pi^0\) ratio in \(Au + Au\) collisions [12], the \(\pi^0\) decay kinematics, and the electromagnetic shower profile characteristics. The BEMC has full azimuthal coverage and pseudorapidity coverage \(|\eta| \leq 1.0\). As a reference measurement we use \(p + p\) data at \(\sqrt{s_{NN}} = 200\) GeV taken in 2006 with integrated luminosity of 11 pb\(^{-1}\). The Time Projection Chamber (TPC) was used to detect charged particle tracks and measure their momenta. The charged track quality cuts are similar to previous STAR analyses [13]. For this analysis, events with at least one cluster with \(E_T > 8\) GeV were selected. To ensure
Au the purity of the photon-triggered sample, trigger towers were rejected if a track with Au for 40-80% and 0-10%

FIG. 1: Left: Azimuthal correlation histograms of high-p

Au + Au collisions. Right: Azimuthal correlation histograms of high-p

$$\gamma_{\text{trig}}$$ inclusive photons with associated hadrons for 40-80% and 0-10% Au + Au collisions

Au collisions. Right: Azimuthal correlation histograms of high-p

$$\gamma_{\text{trig}}$$ $$\pi^0$$-rich sample and $$\pi^0$$-sample with associated hadrons for 40-80% and 0-10% Au + Au collisions.

the purity of the photon-triggered sample, trigger towers were rejected if a track with $$p > 3 \text{ GeV/c}$$ points to it.

A crucial step of the analysis is to discriminate between showers of direct $$\gamma$$ and two close $$\gamma$$'s from a high-$$p_T$$ $$\pi^0$$ decay. At $$p_T \sim 8 \text{ GeV/c}$$ the angular separation between the two photons resulting from a symmetric $$\pi^0$$ decay (both decays photons have similar energy, smallest opening angle) at the BEMC face is typically smaller than the tower size ($$\Delta \eta = 0.05, \Delta \phi = 0.05$$); but a $$\pi^0$$ shower is generally broader than a single $$\gamma$$ shower. The Barrel Shower Maximum Detector (BSMD), which resides at $$\sim 5X_0$$ inside the calorimeter towers, is well-suited for $$(2\gamma)/(1\gamma)$$ separation up to $$p_T \sim 26 \text{ GeV/c}$$ due to its fine segmentation ($$\Delta \eta \approx 0.007, \Delta \phi \approx 0.007$$). In this analysis the $$\pi^0/\gamma$$ discrimination was carried out by making cuts on the shower shape as measured by the BSMD, where the $$\pi^0$$ identification cut is adjusted in order to obtain a very pure sample of $$\pi^0$$ and a sample rich in direct $$\gamma$$ ($$\gamma_{\text{rich}}$$). The discrimination cuts are varied to determine the systematic uncertainties. To determine the combinatorial background level the relative azimuthal angular distribution of the associated particles with respect to the trigger particle is fitted with two Gaussian peaks and a constant. The near- and away-side yields, $$Y^n$$ and $$Y^a$$, of associated particles per trigger are extracted by integrating the $$(dN/d\Delta \phi)/(1 \text{ GeV/c})$$ distributions above background in $$|\Delta \phi| \leq 0.63$$ and $$|\Delta \phi - \pi| \leq 0.63$$ respectively. The yield is corrected for the tracking efficiency of associated charged particles as a function of multiplicity.

The shower shape cuts used to select a sample of direct photon “rich” triggers reject most of the $$\pi^0$$'s, but do not reject photons from highly asymmetric $$\pi^0$$ decays, $$\eta$$'s, and fragmentation photons. All of these sources of background are removed as follows from Eq.(1) below, but only within the systematic uncertainty on the assumption that their correlations are similar to those for $$\pi^0$$'s. Assuming zero near-side yield for direct photon triggers and a very pure sample of $$\pi^0$$, the away-side yield of hadrons correlated with the direct photon is extracted as

$$Y_{\gamma_{\text{direct}}+h} = \frac{Y_n^{\gamma_{\text{rich}}+h} - R Y_{\pi^0+h}^{\gamma_{\text{rich}}+h}}{1 - R}, \quad R = \frac{Y_n^{\gamma_{\text{rich}}+h}}{Y_{\pi^0+h}^{\gamma_{\text{rich}}+h}}$$

(1)

Where $$Y_n^{\gamma_{\text{rich}}+h}$$ and $$Y_n^{\gamma_{\text{rich}}+h}$$ are the away (near)-side yields of associated particles per $$\gamma_{\text{rich}}$$ and $$\pi^0$$ triggers respectively, so that $$R$$ is the fraction of $$\gamma_{\text{rich}}$$ triggers that are actually from $$\pi^0$$, $$\eta$$, and fragmentation photons.

III. RESULTS

Figure 1 (left) shows the azimuthal correlation for inclusive photon triggers for the most peripheral and central bins in Au + Au collisions. Parton energy loss in the medium causes the away-side to be increasingly suppressed with
centrality as it was previously reported [8,13]. The suppression of the near-side yield with centrality, which has not been observed in the charged hadron azimuthal correlation, is consistent with an increase of the $\gamma/\pi^0$ ratio with centrality at high $E_T^{trig}$. The shower shape analysis is used to distinguish between the $(2\gamma)/(1\gamma)$ showers as in Figure 1 (right) which shows the azimuthal correlation for $\gamma$-rich sample triggers and $\pi^0$ triggers for the most peripheral and central bins. The $\gamma$-rich sample has a lower near-side yield than $\pi^0$-triggered sample, but it is not zero. The non-zero near-side yield for the $\gamma$-rich sample is expected due to the remaining contributions of the widely separated photons from other sources, because the shower shape analysis is only effective for the two close $\gamma$ showers.

The purity of $\pi^0$ identification with the shower shape analysis is verified by comparing to previous measurements of azimuthal correlations between charged hadrons ($ch$) [13]. Figure 2 shows the $z_T$ dependence of the associated hadron yield normalized per $\pi^0$ trigger $D(z_T)$, where $z_T = p_T^{assoc}/p_T^{trig}$ [14], for the near-side and away-side compared to the result with charged trigger hadrons [13]. The near-side yield as in Figure 2 (left) shows no significant difference between $p+p$, $d+Au$, and $Au+Au$ indicating in-vacuum fragmentation even in heavy-ion collisions. However the medium effect is clearly seen in the away-side in Figure 2 (right) where the per trigger yield in $Au+Au$ is significantly suppressed compared to $p+p$ and $d+Au$. The general agreement between the results from this analysis ($\pi^0$-$ch$) and the previous analysis ($ch$) is clearly seen in both panels of Figure 2 which indicates the purity of the $\pi^0$ sample and therefore the effectiveness of the shower shape cut to identify $\pi^0$.

The away-side associated yields per trigger photon for direct $\gamma$-charged hadron correlations are extracted using Eq. 1. Figure 3 (left) shows the $z_T$ dependence of the trigger-normalized fragmentation function $D(z_T)$ for $\pi^0$-charged correlations ($\pi^0$-$ch$) compared to measurements with direct $\gamma$-charged correlations ($\gamma$-$ch$). The away-side yield per trigger of direct-$\gamma$ is smaller than with $\pi^0$ trigger at the same centrality class. This difference is due to the fact that the $\pi^0$ originates from higher initial parton energy and therefore has a larger associated jet multiplicity.

In order to quantify the away-side suppression, we calculate the quantity $I_{CP}$, which is defined as the ratio of the integrated yield of the away-side associated particles per trigger particle in $Au+Au$ central (0-10% of the geometrical cross section) relative to $Au+Au$ peripheral (40-80% of the geometrical cross section) collisions. Figure 3 (right) shows the $I_{CP}$ for $\pi^0$ triggers and for direct $\gamma$ triggers as a function of $z_T$. The ratio would be unity if there were no medium effects on the parton fragmentation; the observed ratio deviates from unity by a factor of $\sim 2.5$. The ratio for the $\pi^0$ trigger is approximately independent of $z_T$ for the shown range in agreement with the previous results from ($ch$) measurements [13]. Within the current systematic uncertainty the $I_{CP}$ of direct $\gamma$ and $\pi^0$ are similar. The $I_{CP}$ values of direct $\gamma$ agree well with the theoretical predictions within the current uncertainties, however more reduction in the systematic and statistical uncertainties is needed to distinguish between different color

FIG. 2: $z_T$ dependence of the associated charged hadron yield with high-$p_T$ $\pi^0$ and charged particle triggers on the near side (left panel) and away side (right panel).
FIG. 3: (Left) $z_T$ dependence of associated recoil yield with $\pi^0$ and direct $\gamma$ triggers for 40-80% and 0-10% $Au+Au$ collisions. (Right) $z_T$ dependence of $I_{CP}$ for direct $\gamma$ triggers and $\pi^0$ triggers (see text). Boxes show the systematic uncertainties.

charge densities [15].

Suppression ratios with respect to the p+p reference, $I_{AA}$, have been reported earlier [16]. The values of $I_{AA}$ are smaller than for $I_{CP}$, indicating finite suppression in the peripheral 40-80% data, but the statistical uncertainties are large due to the small $\gamma/\pi^0$ ratio in p+p as previously reported [17]. Nevertheless, the value of $I_{AA}$ is found to be similar to the values observed for di-hadron correlations and for single-particle suppression $R_{AA}$.

In summary, the first measurement of fragment distributions for jets with energy controlled via $\gamma$-jet in $Au+Au$ collisions has been performed by the STAR experiment. The STAR detector is unique to perform such correlation measurements due to the full coverage in azimuth. Within the current uncertainty the recoil suppression ratio $I_{CP}$ of direct $\gamma$ and $\pi^0$ are similar. A full analysis of the systematic uncertainties is under way and may lead to a reduction of the total uncertainty. Future RHIC runs will provide larger data samples to further reduce the uncertainties and extend the $z_T$ range.

[1] I. Arsene et al., Nucl. Phys. A757, 1 (2005); B. B. Back et al., ibid. A757, 28 (2005); J. Adams et al., ibid. A757, 102 (2005); K. Adcox et al., ibid. A757, 184 (2005).
[2] U.W. Heinz and P. F. Kolb, Nucl. Phys. A702, 269 (2002).
[3] D. Teaney, Phys. Rev. C 68, 034913 (2003).
[4] P. K. Kovtun, D. T. Son, and A. O. Starinets, Phys. Rev. Lett. 94, 111601 (2005).
[5] G. Policastro, D. T. Son, and A. O. Starinets, Phys. Rev. Lett. 87, 081601 (2001).
[6] X. N. Wang and M. Gyulassy, Phys. Rev. Lett. 68, 1480 (1992).
[7] S. Adler et al., Phys. Rev. Lett. 91 072303 (2003).
[8] J. Adams et al., Phys. Rev. Lett. 91 072304 (2003).
[9] B.I. Abelev et al., Phys. Rev. Lett. 98 192301 (2007).
[10] B.I. Abelev et al., Phys. Lett. B 655, 104 (2007).
[11] X.N.Wang, Z. Huang, and I. Sarcevic, Phys. Rev. Lett. 77 231 (1996).
[12] K. Filimonov, Acta Phys.Hung. A25:363-370 (2006).
[13] J. Adams et al., Phys. Rev. Lett. 97 162301 (2006).
[14] X.N.Wang, Phys. Lett. B 595, 165 (2004).
[15] A. M. Hamed (STAR) Hard Probes08 proceedings, arXiv:0809.1462
[16] A. M. Hamed (STAR) J. Phys. G 35 104120 (2008), arXiv: 0806.2190.
[17] S. Chattopadhyay (STAR) J. Phys. G: Nucl. Part. Phys. 34, S985-S988 (2007) .