Direct photon-charged particle coincidence measurements in STAR

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The multiplicities of charged-particles of $3 < p_T^{h^\pm} < 16$ GeV/c and pseudorapidity $\mid \eta \mid \leq 1.0$ associated with direct photons and π^0 of $8 < p_T^{\gamma,\pi^0} < 16$ GeV/c at mid-rapidity $\mid \eta \mid \leq 0.9$ have been measured for $Au + Au$ and $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV in the STAR experiment. A transverse shower-shape analysis in the STAR Barrel Electromagnetic Calorimeter Shower Maximum Detector is used to discriminate between the shower of single photon and that of photons from the decays of high p_T π^0s. The relative azimuthal positions of the charged particles with respect to the trigger particle are constructed and the associated charged particle yields per direct γ and π^0 are extracted. The observed suppression for the associated charged-particles per trigger in central $Au + Au$ relative to peripheral $Au + Au$ collision is similar for both direct γ-trigger and π^0-trigger. Within the current uncertainties, the suppression is similar to the previously observed suppression of single-particle yields as well as of hadron-triggered associated-particle yields.

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1. Introduction

High-p_T direct γ, photons unaccompanied by additional hadrons, produced in high-energy collisions are of special importance for the formalism of perturbative Quantum Chromodynamics (pQCD). This is because the point-like coupling of the γ to the hard interaction, in principle, makes this process ideally free from uncertainties inherent in jet reconstruction (as in the case of jet production) or in fragmentation of partons into hadrons (as in inclusive hadron production), and hence a clean probe of the hard-scattering dynamics. The direct γ-hadron azimuthal correlation measurement has been suggested as a powerful tool to quantify the energy loss in the medium created at relativistic heavy ion collisions [1]. Unlike quarks and gluons, the photon does not have to fragment into hadrons and can be directly observed as a final state particle carrying the total energy of the parton. Furthermore, in heavy-ion collisions these particles are formed early in the collisions dynamics (prompt production) and therefore represent an ideal tool for probing the early stage of the evolution of a short-lived (≈ 10 fm/c) and small size (≈ 5 fm^3) medium created in the collisions.

In the dominant QCD process of Compton-like scattering ($q + g \rightarrow q + \gamma$), indeed the photon transverse momentum balances the parton initial transverse energy $p_T^\gamma = p_T^{parton}$, modulo negligible corrections from initial state radiation. In addition, due to the large mean free path of the photon compared to the system size formed in heavy-ion collision, direct photons decouple from the medium upon creation without any further interaction with the medium, and therefore the direct-photon measurement doesn't suffer from the same geometrical bias of that of single particle spectra and di-hadron azimuthal correlation measurements. In particular the direct γ-hadron azimuthal correlations provide a unique way to quantify the energy-loss dependence on the initial parton energy and possibly the color factor [2]. A comparison of direct γ-hadron azimuthal correlations with di-hadron azimuthal correlations impart better constraint on the path length dependence of energy loss; since the former average over the volume while the latter average over the surface of the formed medium.

2. Data Analysis

This paper reports on the measurements of azimuthal correlations at mid-rapidity of direct photons at high transverse momentum $8 < p_T^{\gamma,\pi^0} < 16$ GeV/c with away-side charged hadrons of transverse momentum $3 < p_T^{h^\pm} < 6$ GeV/c over a broad range of centralities for $Au + Au$ collisions and $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV in the STAR experiment. Unfortunately direct photons have a rather small cross-section, making it a difficult measurement requiring a high-statistics data set. Using a level-2 high-E_T tower trigger to tag γ-jet events, in 2007 the STAR experiment collected an integrated luminosity of 535 μb^{-1} of $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. The level-2 trigger algorithm was implemented in the Barrel Electromagnetic Calorimeter (BEMC) [3] and optimized based on the information of the direct γ/π^0 ratio in $Au + Au$ collisions [4], the π^0 decay kinematics, and the electromagnetic shower profile characteristics. The BEMC has full azimuthal coverage and pseudorapidity coverage of $|\eta| \leq 1.0$. As a reference measurement, we have analyzed $p + p$ data at $\sqrt{s_{NN}} = 200$ GeV taken in 2006 with integrated luminosity of 11 pb^{-1}. The Time Projection Chamber (TPC) [5] was used to detect charged-particle tracks and measure their momenta. The

charged track quality cuts are similar to previous STAR analyses [6]. For this analysis, events with at least one cluster with $E_T > 8$ GeV were selected. To ensure the purity of the photon-triggered sample, trigger towers were rejected for which a track with $p > 3$ GeV/c pointed to it. To avoid the energy leakage near the edges of the BEMC acceptance in pseudorapidity, the trigger towers were restricted to a pseudorapidity of $\mid \eta \mid \leq 0.9$.

A crucial step of the analysis is to discriminate between showers of direct γ and two close γ's from a high-p_T π^0 symmetric decay. At $p_T \sim 8$ GeV/c the angular separation between the two photons resulting from a π^0 symmetric decay (both decay 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 π^0 shower is generally broader than a single γ shower. The Barrel Shower Maximum Detector (BSMD) [3], which resides at approximately 5.6 radiation lengths (X_0), at $\eta = 0$, inside the calorimeter towers, is well-suited for $(2\gamma)/(1\gamma)$ separation up to $p_T \sim 26$ GeV/c due to its fine segmentation ($\Delta\eta \approx 0.007, \Delta\phi \approx 0.007$). In this analysis the π^0/γ discrimination was carried out by making cuts on the shower shape as measured by the BSMD, where the π^0 identification cut was adjusted in order to obtain a very pure sample of π^0 and a sample rich in direct γ (γ_{rich}). The discrimination cuts were 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 $1/N_{trig}dN/d(\Delta\phi)$ distributions in $\mid \Delta\phi \mid \leq 0.63$ and $\mid \Delta\phi - \pi \mid \leq 0.63$ 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 π^0's, but do not reject photons from highly asymmetric π^0 decays, η's, and fragmentation photons. All of these sources of background are removed as follows (Eq. 2.1), but only within the systematic uncertainty resulting from the assumption that their correlations are similar to those for π^0's. Assuming zero near-side yield for direct photon triggers and a very pure sample of π^0, which is verified by the π^0-charged yields in Fig. 3, the away-side yield of hadrons correlated with the direct photon is extracted as

$$Y_{\gamma_{direct}+h} = \frac{Y^a_{\gamma_{rich}+h} - rY^n_{\gamma_{rich}+h}}{1-R}, \quad r = \frac{Y^a_{\pi^0+h}}{Y^n_{\pi^0+h}}, \text{ and } 1-R = \frac{N^{\gamma_{dir}}}{N^{\gamma_{rich}}}. \tag{2.1}$$

Here $Y^{a(n)}_{\gamma_{rich}+h}$ and $Y^{a(n)}_{\pi^0+h}$ are the away (near)-side yields of associated particles per γ_{rich} and π^0 triggers, respectively, the ratio R is equivalent to the fraction of "background" triggers (π^0, η, and fragmentation photons) in the γ_{rich} trigger sample, and $N^{\gamma_{dir}}$ and $N^{\gamma_{rich}}$ are the trigger number of direct γ and γ_{rich} respectively.

3. 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 [6,7]. The suppression of the near-side yield with centrality, which has not been observed in the charged hadron
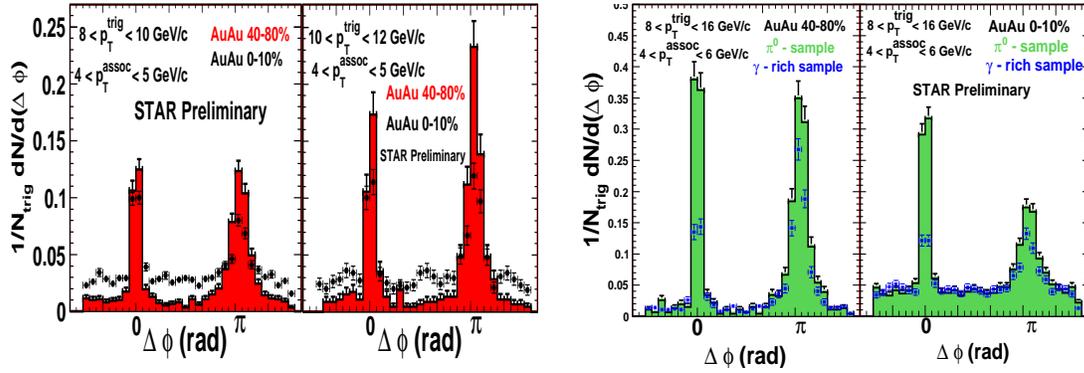
Figure 1: Left: Azimuthal correlation histograms of high p_T^{trig} inclusive photons with associated hadrons for 40-80% and 0-10% $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Right: Azimuthal correlation histograms of high p_T^{trig} γ_{rich} sample and π^0-sample with associated hadrons for 40-80% and 0-10% $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV.

azimuthal correlation, is consistent with an increase of the γ/π^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 γ_{rich} sample triggers and π^0 triggers for the most peripheral and central bins. The γ_{rich} sample has lower near-side yield than π^0 but not zero. The non-zero near-side yield for the γ_{rich} sample is expected due to the remaining contributions of the widely separated photons from other sources. The shower shape analysis is only effective for the two close γ showers.

The purity of using the shower shape analysis in π^0 identification is verified by comparing to previous measurements of azimuthal correlations between charged hadrons ($ch - ch$) [6]. Figure 2 shows the z_T dependence of the associated hadron yield normalized per π^0 trigger $D(z_T)$, where $z_T = p_T^{assoc}/p_T^{trig}$ [8], for the near-side and away-side compared to the per charged hadron trigger [6]. The near-side yield as in Figure 2 (left) shows no significant difference over the shown z_T range between $p + p$, $d + Au$, and $Au + Au$ indicating in-vacuum fragmentation even in heavy ion collisions, which reveals the surface bias as generated in several model calculations [9-12]. 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 ($ch - ch$) is clearly seen in both panels of Figure 2 which indicates the purity of the π^0 sample and therefore the effectiveness of shower shape analysis in π^0 identifications. An overall agreement for the p_T^{assoc} dependence of the near-side associated yields for ($\pi^0 - ch$) correlations compared to that of ($ch - ch$) have been reported earlier [13].

The away-side yield of hadrons correlated with the direct γ triggers $8 < p_T^\gamma < 16$ GeV/c is extracted as indicated by Eq. 2.1 in $p + p$ and $Au + Au$ collisions for $3 < p_T^{h^\pm} < 4$ GeV/c and $4 < p_T^{h^\pm} < 6$ GeV/c of charged hadrons. In order to quantify the away-side suppression, we calculate the quantity I_{AA}, which is defined as the ratio of the integrated yield of the away-side associated particles per trigger particle (direct γ) in $Au + Au$ relative to $p + p$ collisions. Figure 3 shows the
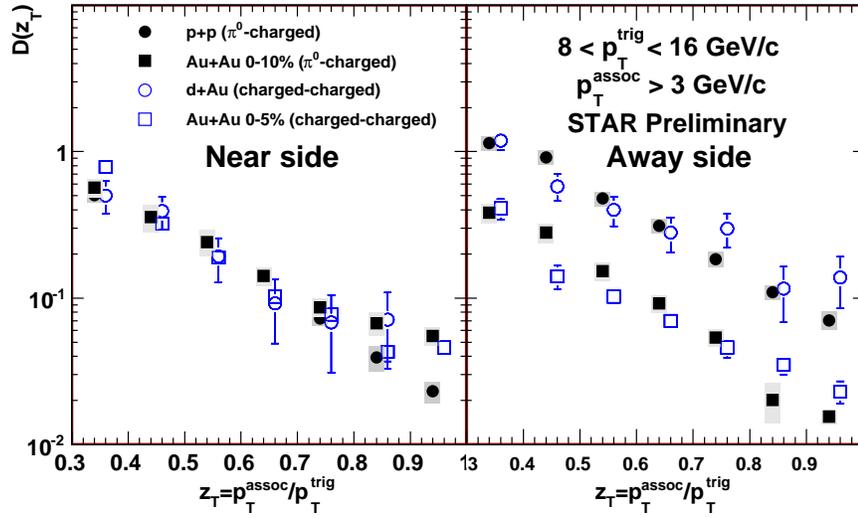
Figure 2: z_T dependence of $\pi^0 - ch$ and $ch - ch$ [6] near-side (left panel) and away-side (right panel) associated particle yields. Boxes show the systematic uncertainties. All collisions are at $\sqrt{s_{NN}} = 200$ GeV.
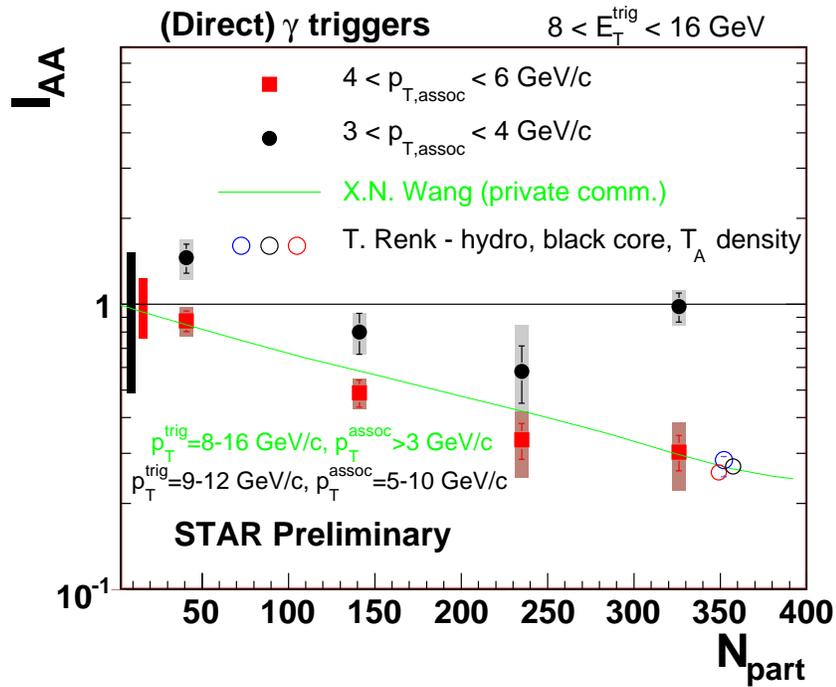

Figure 3: I_{AA} for direct γ triggers (see text). Boxes on the left show the scale uncertainty due to $p + p$ measurements. Boxes around the points show the systematic uncertainties. All collisions are at $\sqrt{s_{NN}} = 200$ GeV.
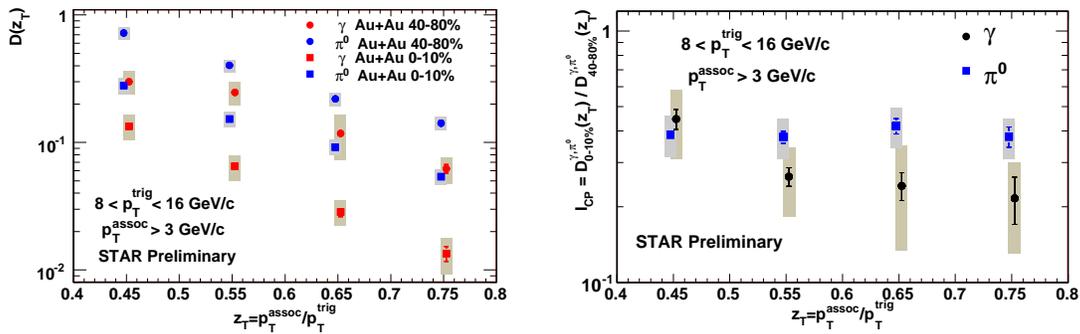
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Figure 4: (Left) z_T dependence of π^0 triggers and direct γ triggers associated particle yields for 40-80% and 0-10% $Au+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. (Right) z_T dependence of I_{CP} for direct γ triggers and π^0 triggers (see text). Boxes show the systematic uncertainties.

$I_{AA}^{\gamma h^{\pm}}(N_{part.})$ for direct γ triggers as a function of centrality. The ratio would be unity if there were no medium effects on the parton fragmentation; and indeed the most peripheral bin shows a ratio close to unity. The ratio decreases with centrality for more central events in a similar fashion for different ranges of p_T^{assoc}. The statistical and systematic uncertainties on the $p+p$ measurement result in a rather large scale uncertainty, which can be reduced with larger data samples in the future. The value of $I_{AA}^{\gamma h^{\pm}}$ for γ-hadron correlations in the most central events is found to be similar to the values observed for di-hadron $I_{AA}^{h^{\pm} h^{\pm}}$ correlations and for single-particle suppression (R_{AA}^h) [14,15], and agrees well with theoretical calculations in which the energy loss is tuned to the single- and di-hadron measurements [16,17].

Figure 4 (left) shows the z_T dependence of the trigger-normalized fragmentation function for π^0−charged correlations ($\pi^0 - ch$) compared to measurements with direct γ−charged correlations ($\gamma - ch$). The away-side yield per trigger of direct γ is smaller than with π^0 trigger at the same centrality class. This difference can be due to the fact that the π^0 originates from higher initial parton energy and therefore supports the energy loss at the parton level before fragmentation as it was previously reported [18] or it can be explained if a large fraction of direct γ is produced via $qg \rightarrow \gamma q$ constituent scattering.

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 4 (right) shows the I_{CP} for π^0 triggers and for direct γ triggers as a function of z_T. The medium effect on the parton fragmentation is obvious; and indeed the ratio deviates from unity by a factor of ~ 2.5. The ratio for the π^0 trigger is approximately independent of z_T for the shown range in agreement with the previous results from ($ch - ch$) measurements [6]. Within the current systematic uncertainty the I_{CP} of direct γ and π^0 are similar.

Suppression ratios with respect to the $p+p$ reference, I_{AA}, have been shown in Fig. 3. 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 γ/π^0 ratio in $p+p$ as previously reported [19]. Although the value of I_{AA} is found to be similar to the values observed for di-hadron correlations
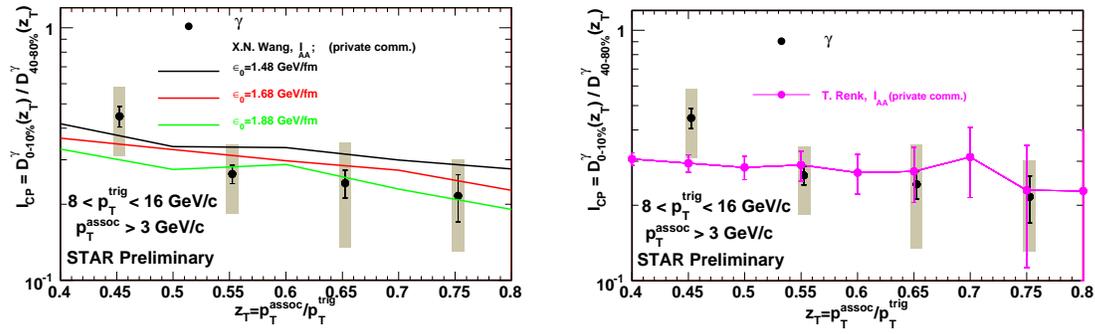
Figure 5: z_T dependence of I_{CP} for direct γ triggers associated particle yields compared with theoretical calculations (private communication). (Left) I_{AA} of 0-10% $Au+Au$ collisions (Only Annihilation and Compton processes to NLO are considered) at $\sqrt{s_{NN}} = 200$ GeV with three different initial gluon densities where $7 < p_T^{trig} < 9$ GeV/c and $p_T^{assoc} > 5$ GeV/c, (Right) I_{AA} where $8 < p_T^{trig} < 16$ GeV/c and $p_T^{assoc} > 3$ GeV/c. Boxes show the systematic uncertainties.

and for single-particle suppression R_{AA}.

A comparison of I_{CP} of direct γ with two different theoretical model calculations of I_{AA} of direct γ is shown in Figure 5. The I_{CP} values agree well with the two different theoretical predictions within the current uncertainties. Although the two models work in the pQCD framework but the detailed calculations and the medium modeling are quite different. Figure 5 (left) indicates the need for more reduction in the systematic and statistical uncertainties in order to distinguish between different color charge densities.

4. Summary and Outlook

In summary, the $\gamma-$charged hadron coincidence measurements in $Au+Au$ collisions have been performed and reported by the STAR experiment. The STAR detector is unique to perform such correlation measurements due to the full coverage in azimuth. The $I_{AA}^{\gamma h^{\pm}}$ and $I_{AA}^{\pi^0 h^{\pm}}$ show similar suppression to that of $I_{AA}^{h^{\pm} h^{\pm}}$, $R_{AA}^{\pi^0}$, and $R_{AA}^{h^{\pm}}$ of light and heavy quarks. The energy loss dependence of parton initial energy can be studied precisely through the $\gamma-$charged hadron results. Within the current uncertainty the recoil suppression ratio I_{CP} of direct γ and π^0 trigger are similar, which doesn't allow to study the path length dependence of energy loss. This can be better studied via $\gamma-$hadron coincidence measurements in- and out- of reaction plane. 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.

5. Acknowledgments

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