High-$p_T$ Direct Photon Azimuthal Correlation Measurements

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Abstract
The azimuthal correlations of direct photons ($\gamma_{\text{dir}}$) with high transverse momentum ($p_T$), produced at mid-rapidity ($|\eta_{\gamma_{\text{dir}}}| < 1$) in Au+Au collisions at center-of-mass energy $\sqrt{s_{\text{NN}}} = 200$ GeV, are measured and compared to those of neutral pions ($\pi_0$) in the same kinematic range. The measured azimuthal elliptic anisotropy of direct photon, $v_2^{\gamma_{\text{dir}}}$, at high $p_T$ ($8 < p_T^{\gamma_{\text{dir}}} < 20$ GeV/$c$) is found to be smaller than that of $\pi_0$ and consistent with zero when using the forward detectors ($2.4 < |\eta| < 4.0$) in reconstructing the event plane. The associated charged hadron spectra recoiled from $\gamma_{\text{dir}}$ show more suppression than those recoiled from $\pi_0$ ($p_T^{\gamma_{\text{dir}}, \pi_0} < 24$ GeV/$c$ and $3 < p_T^{\text{assoc}} < 24$ GeV/$c$).

Keywords: Electromagnetic probes, high-$p_T$ direct photons, STAR

1. Introduction
A major goal of measurements at the Relativistic Heavy Ion Collider (RHIC) is to quantify the properties of the QCD matter created in heavy-ion collisions at high energy [1]. Unlike quarks and gluons, photons do not fragment into hadrons and can be directly observed as a final state particle. Furthermore, due to their negligible coupling to the QCD matter in contrast to hadrons, direct photons are considered as a calibrated probe for the QCD medium.

The previous measurements at RHIC indicate unexpected finite values of azimuthal elliptic anisotropy parameter $v_2$ of charged hadrons at high-$p_T$ [2]. The measured $v_2$ at high-$p_T$ is beyond the applicability of hydrodynamic models, and the path-length dependence of jet quenching is the only proposed explanation of $v_2$ at high-$p_T$ [3]. The $v_2^{\gamma_{\text{dir}}}$ measurement would provide a gauge for the energy loss at high-$p_T$.

The high-$p_T$ $\gamma_{\text{dir}}$ sample unbiased spatial distribution of the hard scattering vertices in the QCD medium [4], in contrast to hadrons which suffer from the geometric biases. Therefore, a comparison between the spectra of the away-side charged hadrons associated with $\gamma_{\text{dir}}$ vs. $\pi_0$ can provide a benchmark for the energy loss and its dependence on the path-length. Although the previous measurements have indicated similar level and pattern of suppression for the away-side of $\gamma_{\text{dir}}$ and $\pi_0$ [5], the current work explores a softer region in the fragmentation functions where a more significant difference is expected [6].

2. Analysis and Results
2.1. Electromagnetic neutral clusters
The STAR detector is well suited for measuring azimuthal angular correlations due to the large coverage in pseudorapidity and full coverage in azimuth ($\phi$). While the Barrel Electromagnetic Calorimeter (BEMC) [7] measures

\footnote{A list of members of the STAR Collaboration and acknowledgements can be found at the end of this issue.}
the electromagnetic energy with high resolution, the Barrel Shower Maximum Detector (BSMD) provides fine spatial resolution and enhances the rejection power for the hadrons. The Time Projection Chamber (TPC: |η| < 1) [8] identifies charged particles, measures their momenta, and allows for a charged-particle veto cut with the BEMC matching. The Forward Time Projection Chamber (FTPC: 2.4 < |η| < 4.0) [9] is used to measure the charged particles’ momenta and to reconstruct the event plane angle. Using the BEMC to select events (i.e., “trigger”) with high-\(p_T\) γ, the STAR experiment collected an integrated luminosity of 23 \(pb^{-1}\) of \(p+p\) collisions in 2009 and 973 \(μb^{-1}\) of \(Au+Au\) collisions in 2011. In this analysis, events having a primary vertex within ±55 cm of the center of the TPC along the beamline in Au+Au and ±80 cm in \(p+p\) are selected. In addition, each event must have at least one electromagnetic cluster with \(E_γ > 8\) GeV for the event plane correlation analysis and \(E_γ > 12\) GeV for the charged hadron correlation analysis. More than 97% of these clusters have deposited energy greater than 0.5 GeV in each layer of the BSMD. A trigger tower is rejected if it has a track with \(p > 8\) GeV/c pointing to it, which reduces the number of the electromagnetic clusters by only ~ 7%.

2.2. \(v_2\) of neutral particles

The \(v_2\) is determined using the standard method [10]:

\[
v_2(p_γ) = \langle\cos 2(\phi_{p_γ} - ψ_{EP})\rangle,
\]

where the brackets denote statistical averaging over particles and events, \(\phi_{p_γ}\) is the azimuthal angle of the neutral particle with certain value of \(p_γ\), and \(ψ_{EP}\) is the azimuthal angle of the event plane. The event plane is reconstructed from charged particles, within the detector acceptance, with \(p_γ < 2\) GeV/c, and determined by

\[
ψ_{EP} = \frac{1}{2} \tan^{-1}(\frac{1}{2}\sum_i \sin(2\phi_i) \sum_i \cos(2\phi_i)),
\]

where \(\phi_i\) are the azimuthal angles of all the particles used to define the event plane. In this analysis, the charged-track quality criteria are similar to those used in previous STAR analyses [11].

2.3. Azimuthal correlations of a neutral trigger particle with charged hadrons

The azimuthal correlations of a neutral trigger particle with charged hadrons, measured as the number of associated particles per neutral cluster per \(Δφ\) (“correlation functions”), are used in both \(p+p\) and \(Au+Au\) collisions to determine the (jet) associated particle yields in the near- (\(Δφ \sim 0\)) and away-sides (\(Δφ \sim π\)). The near- and away-side yields, \(Y^n\) and \(Y^w\), of associated particles per trigger are extracted by integrating the \((1/N_{γγ})dN/d(Δφ)\) distributions over \(|Δφ| \leq 0.63\) and \(|Δφ - π| \leq 0.63\), respectively. The yield is corrected for the tracking efficiency of charged particles as a function of event multiplicity.

2.4. Transverse shower profile analysis

A crucial part of the analysis is to discriminate between showers from \(γ_{er}\) and two close \(γ\’s\) from high-\(p_T\) \(π^0\) symmetric decays. At \(p_T^{γ} \sim 8\) GeV/c, the angular separation between the two \(γ\’s\) resulting from a \(π^0\) decay is small, but a \(π^0\) shower is generally broader than a single \(γ\) shower. The BSMD is capable of 2\(γ/1γ\) separation up to \(p_T^{γ} \sim 24\) GeV/c due to its high granularity (\(Δη \sim 0.007, Δφ \sim 0.007\)). The shower shape is quantified as the cluster energy, measured by the BEMC, normalized by the position-weighted energy moment, measured by the BSMD strips [3].

The shower profile cuts were tuned to obtain a nearly \(γ_{er}\)-free (\(π^0_{nah}\)) sample and a sample rich in \(γ_{er}\) (\(γ_{nah}\)). Since the shower-shape analysis is only effective for rejecting two close \(γ\) showers, the \(γ_{nah}\) sample contains a mixture of direct photons and contamination from fragmentation photons (\(γ_{frag}\)) and photons from asymmetric hadron (\(π^0\) and \(η\)) decays.

The \(γ_{nah}\) triggers \(Y(γ_{nah})^n+h\) and \(Y(γ_{nah})^w+h\) are measured as discussed in section 2.3.
2.5. \( v_z \) of direct photons

Assuming zero near-side yield for \( \gamma_{\text{dir}} \) triggers and a sample of \( \pi_{\text{rich}}^0 \) free of \( \gamma_{\text{dir}} \), the \( v_z^{\gamma_{\text{dir}}} \) is given by:

\[
v_z^{\gamma_{\text{dir}}} = \frac{v_z^{\gamma_{\text{dir}}} - R \cdot v_z^{\pi_{\text{rich}}}}{1 - R},
\]

where \( R = \frac{N_{\pi_{\text{rich}}}^{\gamma_{\text{dir}}}}{N_{\gamma_{\text{dir}}}^{\pi_{\text{rich}}}} \), and the numbers of \( \pi_{\text{rich}}^0 \) and \( \gamma_{\text{rich}} \) triggers are represented by \( N_{\pi_{\text{rich}}}^{\gamma_{\text{dir}}} \) and \( N_{\gamma_{\text{rich}}}^{\pi_{\text{rich}}} \) respectively. Although the \( R \) quantity approximates all background triggers in the \( \gamma_{\text{rich}} \) sample to the measured \( \pi_{\text{rich}}^0 \) triggers, all background triggers have the same correlation function as the \( \pi_{\text{rich}}^0 \) sample [5]. The value of \( R \) is measured in [3] and found to be \( \sim 30\% \) in central Au+Au. In Eq. 3 all background sources for \( \gamma_{\text{dir}} \) are assumed to have the same \( v_z \) as the measured \( \pi_{\text{rich}}^0 \).

![Figure 1. \( v_z \) of \( \pi^0 \) and \( \gamma_{\text{dir}} \) in 10-40% centrality of Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) using TPC. Boxes show the systematic errors.](image1)

![Figure 2. \( v_z \) of \( \pi^0 \) and \( \gamma_{\text{dir}} \) in 10-40% centrality of Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) using FTPC. Boxes show the systematic errors.](image2)

![Figure 3. The \( z_p \) dependence of \( I_{\text{assoc}} \) for \( \gamma_{\text{dir}} \) and \( \pi^0 \) triggers in Au+Au 0-10% centrality. Boxes show the systematic errors.](image3)

Figures 1 and 2 show the \( v_z^{\pi^0} \) and \( v_z^{\gamma_{\text{dir}}} \) for \( 8 < p_{\text{Tdir}}^0 < 20 \text{ GeV/c} \) from Au+Au data set of Run 2011 using the TPC (\(|\eta| < 1\)) and FTPC (\(2.4 < |\eta| < 4.0\)). The results of Fig. 1 are consistent with those from different STAR data set of Run 2007 [13], and the results of Fig. 2 agree with other measurements [14, 15]. While using the FTPC in determining the event plane (Fig. 2) the \( v_z^{\gamma_{\text{dir}}} \) is consistent with zero. Assuming the dominant source of direct photons is prompt hard production, the zero value implies no remaining bias in the event-plane determination. Accordingly, the measured value of \( v_z^{\gamma_{\text{dir}}} \) would be the effect of path-length dependent energy loss.

2.6. Extraction of \( \gamma_{\text{dir}} \) associated yields

Assuming zero near-side yield for \( \gamma_{\text{dir}} \) triggers and a sample of \( \pi_{\text{rich}}^0 \) free of \( \gamma_{\text{dir}} \), the away-side yield of hadrons correlated with the \( \gamma_{\text{dir}} \) is extracted as

\[
Y_{\gamma_{\text{dir}} h} = \frac{Y_{\gamma_{\text{dir}} h} - R Y_{\pi_{\text{rich}} h}^{\gamma_{\text{dir}}}}{1 - R},
\]

where \( R = \frac{N_{\pi_{\text{rich}}}^{\gamma_{\text{dir}}}}{N_{\gamma_{\text{rich}}}^{\pi_{\text{rich}}}} = \frac{Y_{\gamma_{\text{dir}} h} - Y_{\pi_{\text{rich}} h}^{\gamma_{\text{dir}}}}{Y_{\pi_{\text{rich}} h}^{\gamma_{\text{dir}}}} \), and \( 1 - R = \frac{N_{\gamma_{\text{dir}}}^{\pi_{\text{rich}}}}{N_{\gamma_{\text{rich}}}^{\pi_{\text{rich}}}} \).

Here, \( Y_{\gamma_{\text{dir}} h}^{(a)} \) and \( Y_{\pi_{\text{rich}} h}^{(a)} \) are the away (near)-side yields of associated particles per \( \gamma_{\text{rich}} \) and \( \pi_{\text{rich}}^0 \) triggers, respectively. The ratio \( R \) is equivalent to the fraction of “background” triggers in the \( \gamma_{\text{rich}} \) trigger sample, and \( N_{\gamma_{\text{dir}}}^{\pi_{\text{rich}}} \) and \( N_{\gamma_{\text{rich}}}^{\pi_{\text{rich}}} \) are the
numbers of $\gamma_{\text{dir}}$ and $\gamma_{\text{assoc}}$ triggers, respectively. The value of $\mathcal{R}$ is found to be $\sim 55\%$ in p+p and decreases to $\sim 30\%$ in central Au+Au with little dependence on $p_T$. All background to $\gamma_{\text{dir}}$ is subtracted with the assumption that the background triggers have the same correlation function as the $\pi^0$ sample.

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 in Au+Au to that in p+p collisions. The values of $I_{AA}^{\gamma_{\text{dir}}}$ and $I_{AA}^{\gamma_{\text{assoc}}}$, as shown in Fig. 3, are $z_T$ ($z_T = p_T^{\text{assoc}}/p_T^{\text{dir}}$) independent in agreement with results of [5] where the recoiled parton from $\gamma_{\text{dir}}$ and $\pi^0$ experience constant fractional energy loss in the QCD medium. It is also observed that the charged hadron spectra recoiled from $\gamma_{\text{dir}}$ show unexpectedly more suppression than those recoiled from $\pi^0$ ($I_{AA}^{\gamma_{\text{dir}}-\pi^0} < I_{AA}^{\gamma_{\text{assoc}}-\pi^0}$) within the covered kinematics range $12 < p_T^{\gamma_{\text{dir}}} < 24 \text{ GeV/c}$ and $3 < p_T^{\pi^0} < 24 \text{ GeV/c}$.

3. Conclusions

The STAR experiment has reported the first $v_2^{\gamma_{\text{dir}}}$ at high-$p_T$ ($8 < p_T^{\gamma_{\text{dir}}} < 20 \text{ GeV/c}$), and explored new kinematic range ($12 < p_T^{\gamma_{\text{dir}}} < 24 \text{ GeV/c}$) and ($3 < p_T^{\pi^0} < 24 \text{ GeV/c}$) for $I_{AA}$ measurements of $\gamma_{\text{dir}} - h$ correlations at $\sqrt{s_{NN}} = 200 \text{ GeV}$. Using the mid-rapidity detectors in determining the event plane, the measured value of $v_2^{\gamma_{\text{dir}}}$ is non-zero, and is probably due to biases in the event-plane determination. Using the forward detectors in determining the event plane could eliminate remaining biases, and the measured $v_2^{\gamma_{\text{dir}}}$ is consistent with zero. The zero value of $v_2^{\gamma_{\text{dir}}}$ suggests a negligible contribution of jet-medium photons [17], and negligible effects of $\gamma_{\text{assoc}}$ [16] on the $v_2^{\gamma_{\text{dir}}}$ over the covered kinematics range. The measured finite value of $v_2^{\pi^0}$, using the forward detectors in determining the event plane, is apparently due to the path-length dependence of energy loss. The $\gamma_{\text{dir}} - h$ correlation results indicate that the associated charged hadron spectra recoiled from $\gamma_{\text{dir}}$ show more suppression than those recoiled from $\pi^0$ ($I_{AA}^{\gamma_{\text{dir}}-\pi^0} < I_{AA}^{\gamma_{\text{assoc}}-\pi^0}$) within the covered kinematic range, in contrast to the theoretical predictions [18]. The disagreement with the theoretical expectations may indicate that the lost energy is distributed to lower $p_T$ of the associated particles in the case of a $\gamma_{\text{dir}}$ trigger than a $\pi^0$ trigger. To further test this, one must explore the region of low $p_T^{\pi^0}$ and $z_T$.

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