Azimuthal elliptic anisotropy (v_2) of high-p_T direct γ in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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Abstract. Preliminary results from the STAR collaboration for the azimuthal elliptic anisotropy (v_2) of high transverse momentum (p_T) direct photons (γ_{dir}) produced at mid-rapidity ($|\eta^{\gamma_{dir}}| < 1$) in Au+Au collisions at center-of-mass energy $\sqrt{s_{NN}} = 200$ GeV are presented, and compared to the measured (v_2) of neutral pions (π^0) in the same kinematic range. The electromagnetic transverse shower profile is used to distinguish π^0 from direct photons. The measured $v_2^{\gamma_{dir}}(p_T)$ at high p_T ($8 < p_T^{\gamma_{dir}} < 20$ GeV/c) is found to be smaller than that of π^0 and consistent with zero when using the forward detectors in determining the event plane.

1. Introduction

The azimuthal distribution of the produced particles in heavy-ion collisions is expected to be sensitive to the initial geometric overlap of the colliding nuclei, and would result in anisotropic azimuthal distributions with respect to the event plane. The standard method to quantify the azimuthal elliptic anisotropy is to expand the particle azimuthal distributions in a Fourier series $\frac{dN}{d\phi}(p_T) = \frac{N}{2\pi}[1 + \sum_n 2v_n(p_T)\cos(n(\phi_{p_T} - \psi_{\rm EP}))]$, where ϕ_{p_T} is the azimuthal angle of the produced particle with certain value of p_T, $\psi_{\rm EP}$ is the azimuthal angle of the event plane, and v_n is the coefficient of the n^{th} harmonic. The 2^{nd} Fourier moment ($n = 2$) is referred to as the "elliptic flow" parameter in the context of the hydrodynamical descriptions, v_2 and its differential form is given by

$$v_2(p_T) = \langle\langle e^{2i(\phi_{p_T} - \psi_{\rm EP})}\rangle\rangle = \langle\langle \cos 2(\phi_{p_T} - \psi_{\rm EP})\rangle\rangle, \tag{1}$$

where the brackets denote statistical averaging over particles and events.

While RHIC data show large amount of elliptic flow as predicted by the hydrodynamic models at low p_T, the results at high p_T [1] are not expected to follow hydrodynamic behavior. The medium-induced radiative energy loss of partons (jet-quenching) has been proposed as the source for the large observed azimuthal elliptic anisotropy at high p_T, due to the path-length dependence of the parton energy loss [2]. The STAR results [3] show the amount of v_2 at high p_T is larger than the predicted values by pure jet-quenching models. Although recent measurements by PHENIX [4] show the produced π^0's in-plane outnumber those produced out-of-plane which may be consistent with the path-length dependence of energy loss, the event plane determination might have remaining bias toward the direction of the produced jets. On the other hand, STAR results on the suppression of direct γ-triggered vs. π^0-triggered correlated yields [5] show no sensitivity to the path length dependence of parton energy loss. If the $v_2^{\gamma_{dir}}$ can be measured without bias in the event-plane determination, then the measured value can help disentangle the various scenarios of direct photon production through the expected opposite contributions to the v_2 [6, 7, 8, 9], and therefore could help to confirm the observed binary scaling of the direct photon [10].

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 (ϕ). While the Barrel Electromagnetic Calorimeter (BEMC) [11] measures 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: $|\eta| < 1$) [12] identifies charged particles, measures their momenta, and allows for a charged-particle veto cut with the BEMC matching. The Forward Time Projection Chamber (FTPC: $2.4 < |\eta| < 4.0$) [13] is used to measure the charged particles momenta and to reconstruct the event plane angle in this analysis. Using the BEMC to select events (*i.e.* "trigger") with high-p_T γ, the STAR experiment collected an integrated luminosity of 535 μb^{-1} of Au+Au collisions in 2007 and 973 μb^{-1} of Au+Au collisions in 2011. In this analysis, events having primary vertex within $\pm$55 cm of the center of TPC along the beamline, and with at least one electromagnetic cluster with $E_T > 8$ GeV are selected. 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 $p > 3.0$ GeV/c pointing to it, which reduces the number of the electromagnetic clusters by only $\sim$ 7%.

2.2. v_2 of neutral and charged particles

The v_2 is determined using the standard method (Eq. 1), which correlates each particle with the event plane determined from all charged particles with $p_T < 2$ GeV/c (minus the particle of interest). The event plane is determined by

$$\psi_{\mathrm{EP}} = \frac{1}{2}\tan^{-1}\left(\frac{\sum_i \sin(2\phi_i)}{\sum_i \cos(2\phi_i)}\right), \quad (2)$$

where ϕ_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 [14]. The event plane is measured using different techniques and detectors: 1) using all the selected tracks inside the TPC (full-TPC), 2) using the selected tracks in the opposite pseudorapidity side to the particle of interest (off-η), and 3) using all tracks inside the FTPC (full-FTPC) in order to reduce the "non-flow" contributions (azimuthal correlations not related to the event plane). Since the event plane is only an approximation to the true reaction plane, the observed correlation is divided by the event plane resolution. The event plane resolution is estimated using the sub-event method in which the full event is divided up randomly into two sub-events (for full-TPC, off-η, and full-FTPC separately) as described in [15]. Biases due to the finite acceptance of the detector, which cause the particles to be azimuthally anisotropic in the laboratory system are removed according to the method in [16].

2.3. Transverse shower profile analysis

A crucial part of the analysis is to discriminate between showers from γ_{dir} and two close γ's from high-p_T π^0 symmetric decays. At $p_T^{\pi^0} \sim 8$ 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

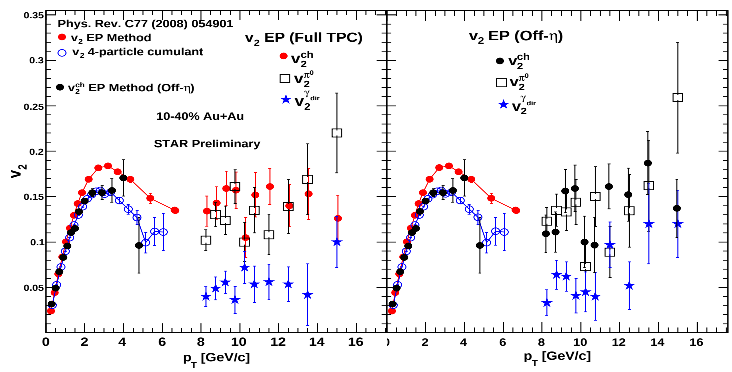

Figure 1. (Color online) For $p_T < 6$ GeV/c, (Au+Au 2007) both panels show previous STAR measurements [14] of v_2 as a function of p_T for charged particles with $|\eta| < 1$ in 10-40% $Au+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV using the Event-Plane method (closed red circles), and the 4-particle cumulant method (open circles). Also v_2 for charged particles ($|\eta| < 1$) using off-η event plane method is shown in closed black circles (this analysis). For $p_T > 6$ GeV/c: (Au+Au 2007) both panels show v_2 of charged particles, π^0, and γ_{dir} (circles, squares, stars respectively) using the full TPC (left panel) and using the off-η method (right panel).

shower. The BSMD is capable of $(2\gamma)/(1\gamma)$ separation up to $p_T^{\pi^0} \sim 20$ GeV/c due to its high granularity ($\Delta\eta \sim 0.007$, $\Delta\phi \sim 0.007$). 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 [5]. The shower profile cuts were tuned to obtain a nearly γ_{dir}-free (π^0_{rich}) sample and a sample rich in γ_{dir} (γ_{rich}). Since the shower-shape analysis is only effective for rejecting two close γ showers, the γ_{rich} sample contains a mixture of direct photons and contamination from fragmentation photons (γ_{frag}) and photons from asymmetric hadron (π^0 and η) decays.

2.4. v_2 of direct photons

The $v_2^{\gamma_{dir}}$ is given by:

$$v_2^{\gamma_{dir}} = \frac{v_2^{\gamma_{rich}} - \mathcal{R} v_2^{\pi^0}}{1 - \mathcal{R}}, \tag{3}$$

where $\mathcal{R}=\frac{N^{\pi^0}}{N^{\gamma_{rich}}}$, and the numbers of π^0 and γ_{rich} triggers are represented by N^{π^0} and $N^{\gamma_{rich}}$ respectively. The value of $\mathcal{R}$ is measured in [5] and found to be $\sim 30\%$ in central Au+Au. In Eq. 3 all background sources for γ_{dir} are assumed to have the same v_2 as π^0. Thus, all remaining background is subtracted under the assumption that the background particles have the same correlation functions as that measured for π^0 triggers. Figure 1 (both panels) shows the v_2 of charged particles (v_2^{ch}) at low p_T ($p_T < 6$ GeV/c) using the event plane method (off-η) compared to previous STAR measurements [14], and the v_2 of the charged particles, neutral pions and direct photons using the full-TPC and off-η event plane methods at high p_T ($p_T > 6$ GeV/c). At low p_T the v_2^{ch}(off-η) is smaller than the v_2 using the full TPC and agrees well with the $v_2\{4\}$ (4-particle cumulant) method, in which the contribution of the non-flow is expected to be small. At high p_T the two different methods (full TPC and off-η) for the event plane measurements give similar results , which might indicate that the off-η method is not free from a bias in the event-plane determination. While the $v_2^{\pi^0}$ and v_2^{ch} are similar ($\sim 12\%$), the $v_2^{\gamma_{dir}}$ is systematically lower than that of hadrons. The similarity of the v_2 results using the

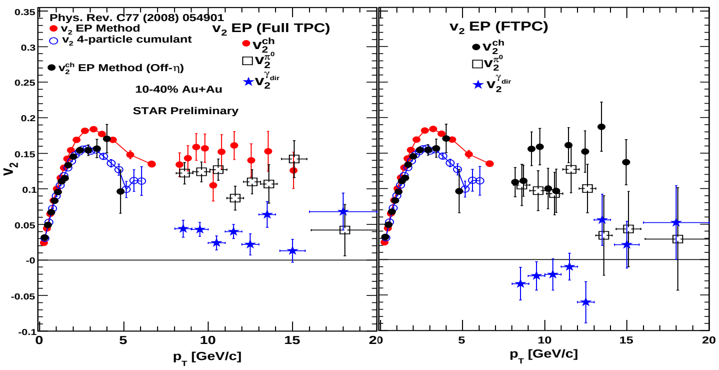

Figure 2. (Color online) For $p_T < 6$ GeV/c, (Au+Au 2007) both panels show measurements as in Fig. 1. For $p_T > 6$ GeV/c, (Au+Au 2011 for π^0 and γ_{dir}) both panels show v_2 of charged particles, π^0, and γ_{dir} (circles, squares, stars respectively) using the full TPC (left panel) and using full FTPC (right panel).

full-TPC and off-η at high p_T, along with the non-zero value of $v_2^{\gamma_{dir}}$, indicate a remaining bias in the event-plane determination.

Figure 2 (left and right panels) shows the $v_2^{\pi^0}$ and $v_2^{\gamma_{dir}}$ for ($8 < p_T^{\gamma_{dir}} < 20$ GeV/c) from Au+Au 2011 data using the full-TPC ($|\eta| < 1$) and full-FTPC ($2.4 < |\eta| < 4.0$). The results from two different data sets (Au+Au 2007 and Au+Au 2011) are consistent (left panels of Fig. 1 and Fig. 2) using the full-TPC. While using the FTPC in determining the event plane (Fig. 2 - right panel) the $v_2^{\gamma_{dir}}$ 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 $v_2^{\pi^0}$ would be the effect of path-length dependent energy loss. Systematic studies are currently in progress.

3. Conclusions

The STAR experiment has reported the first $v_2^{\gamma_{dir}}$ at high-p_T ($8 < p_T^{\gamma_{dir}} < 20$ GeV/c) at RHIC. Using the mid-rapidity detectors in determining the event plane, the measured value of $v_2^{\gamma_{dir}}$ 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 $v_2^{\gamma_{dir}}$ is consistent with zero. The zero value of $v_2^{\gamma_{dir}}$ suggests a negligible contribution of jet-medium photons [7], and negligible effects of γ_{frag} [6] on the $v_2^{\gamma_{dir}}$ over the covered kinematics range. The measured 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.

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