Azimuthal Anisotropy of π^0 Production in Au + Au Collisions at \( \sqrt{s_{NN}} = 200 \) GeV: Path-Length Dependence of Jet Quenching and the Role of Initial Geometry


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We have measured the azimuthal anisotropy of \( \pi^0 \) production for \( 1 < p_T < 18 \) GeV/c for Au + Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV. The observed anisotropy shows a gradual decrease for \( 3 \leq p_T \leq 7-10 \) GeV/c, but remains positive beyond 10 GeV/c. The magnitude of this anisotropy is underpredicted, up to at least \( \sim 10 \) GeV/c, by current perturbative QCD (PQCD) energy-loss model calculations. An estimate of the increase in anisotropy expected from initial-geometry modification due to gluon saturation effects and fluctuations is insufficient to account for this discrepancy. Calculations that implement a path-length dependence steeper than what is implied by current PQCD energy-loss models show reasonable agreement with the data.

A central goal of high-energy nuclear physics is to understand the properties of the strongly coupled quark gluon plasma (SQGP), a new form of nuclear matter identified at the Relativistic Heavy Ion Collider (RHIC) [1]. A key tool for this goal is jet quenching or the suppression of high transverse momentum (p_T) hadron yields as a result of in-medium energy loss of high-p_T partons [2]. Such suppression was first observed in measurements of the nuclear modification factor for single hadron yield \( R_{AA} = \frac{dN_{AA}}{d\phi_{AA}d\sigma_{pp}} \) [3], where \( dN_{AA} \) is the differential yield in Au + Au collisions, \( d\sigma_{pp} \) is the differential cross section in p + p collisions for a given p_T, and \( \langle T_{AA} \rangle \) is the nuclear overlap integral for a given Au + Au centrality bin. Later on this effect was also observed in measurements of dihadron [4] and \( \gamma \)-hadron correlations [5].

Current theoretical descriptions of jet quenching are commonly based on a perturbative QCD (PQCD) framework [6], which assumes that the coupling of jets with the medium is weak, even though the medium itself is strongly coupled (large coupling constant \( \alpha_s \)). Prompted by the large amount of experimental data from RHIC, several sophisticated PQCD-based models have been developed in the last decade [2,6]. These models have provided initial estimates of the properties of the SQGP, such as the momentum broadening per mean free path, \( q = \langle k_T^2 \rangle / \lambda \), and the energy loss per unit length, \( dE/dl \) [6–8].

Despite these successes, the PQCD description of jet quenching faces several challenges [9]. Besides a large discrepancy among models of extracted medium properties such as \( q \) [8], the energy-loss models also disagree in their predictions of the azimuthal anisotropy of high \( p_T \) hadrons [8]. The latter characterizes hadron emission relative to the reaction plane (RP) angle \( \langle \Psi_{RP} \rangle \), \( dN/d\phi - \Psi_{RP} \approx (1 + 2\nu_2 \cos(2(\phi - \Psi_{RP})) \). Such azimuthal anisotropy ensues because the hadron yield is more suppressed along the long axis of the almond-shaped fireball than the short axis. Thus the magnitude of the anisotropy, \( \nu_2 \), is sensitive to the path-length \( (l) \) dependence of energy loss, which scales as \( \Delta E \sim l \) for collisional energy loss [10], \( \Delta E \sim l^2 \) for coherent radiative energy loss [10], and \( \Delta E \sim l^3 \) for a non-perturbative energy-loss calculation using AdS/CFT gravity-gauge dual theory [11]. However, our ability to probe such \( l \) dependences hinges not only on precision data at high \( p_T \), but also on a good understanding of the role of the initial collision geometry and space-time evolution of the medium. One geometry commonly used in energy-loss models is based on the optical Gluab model [12], which assumes a smooth Woods-Saxon nuclear geometry. Such geometry ignores the event-by-event shape distortion due to spatial fluctuations of participating nucleons [13], and a possible overall shape distortion due to gluon saturation effects, known as the CGC geometry [14].

The choice of collision geometry and medium evolution has been shown to be important for elliptic flow at low \( p_T \) [15,16], but their influences on high \( p_T \) \( \nu_2 \) are not well studied to date.

In this Letter we present a new measurement of the \( \pi^0 \) anisotropy in \( \sqrt{s_{NN}} = 200 \) GeV Au + Au collisions. This measurement complements our prior results [17–19], but significantly increases both the \( p_T \) reach and the statistical precision above 6 GeV/c, allowing for quantitative comparisons to energy-loss models, as well as detailed investigations of the role of the initial collision geometry.

Results were obtained from \( \sim 3.5 \times 10^9 \) minimum bias events taken in 2007. Event centrality was determined by the number of charged particles detected in the Beam-Beam Counters (BBC, \( 3.0 < \eta < 3.9 \)). A Monte Carlo (MC) Gluab model [12] was used to estimate the average number of participating nucleons (\( N_{\text{part}} \)) and \( \langle T_{AA} \rangle \) for each centrality class.
Previous PHENIX analyses [19] estimated the RP using the charged particles detected in the BBC. Several new detectors, installed symmetrically on both sides of the beam line, provided additional RP measurements in 2007: the Muon Piston Calorimeters (MPC, $3.1 < |\eta| < 3.9$) and the Reaction Plane detectors in two $\eta$ ranges, RXN$_{in}$ (RXN$_{out}$) in $1.5(1.0) < |\eta| < 2.8(1.5)$. Each MPC is equipped with PbWO$_4$ crystal scintillators to detect both charged and neutral particles. Each RXN consists of 12 azimuthally segmented paddle scintillators. This analysis estimates the RP angle using both the MPC and RXN$_{in}$ to provide good resolution, while minimizing the potential biases from jets and dijets [20]. The error on the RP angle $\Delta \Psi$, and the RP dispersion factor $\sigma_{RP} = \langle \cos 2\Delta \Psi \rangle$ are estimated by the subevent method [19], giving $\sigma_{RP} \sim 0.52$ and 0.73 in central and midcentral collisions, respectively, which is $\sim 80\%$ better than that for the BBC. The large data set and improved $\sigma_{RP}$ give an equivalent of $\sim 15$-fold increase in statistics over the previous measurement of $v_2$ [19].

The methodology for $v_2$ extraction follows our previous work [19]. We reconstruct the neutral pions via the $\pi^0 \rightarrow \gamma + \gamma$ decay channel with photons detected in the Electromagnetic Calorimeter (EMCal, $|\eta| < 0.35$). We apply shower shape and pair asymmetry cuts to reduce the combinatorial background. The remaining background is subtracted by the mixed event method [19]. The azimuthal distribution of the $\pi^0$ yields relative to the estimated RP angle, $\Delta \phi = \phi - \Psi_{RP}$, is divided into 6 bins in $[0, \pi/2]$ and fit to $N_0(1 + 2v_2^{raw}\cos(2\Delta \phi))$ (higher order harmonics are found to be small and do not influence $v_2$ value). The $v_2$ is then obtained by applying the dispersion correction $v_2 = v_2^{raw}/\sigma_{RP}$ for each centrality and $p_T$ selection. The main sources of systematic uncertainties come from $\sigma_{RP}$ and $v_2^{raw}$. The former is estimated by comparing measurements from different RP detectors, giving $\sim 10\%$ for central and peripheral collisions and $\sim 5\%$ for midcentral collisions. The latter accounts for dependence of $v_2$ on $p_T$ identification cuts, different sectors of EMCal, and different run groups, and is correlated in $p_T$; it is estimated to be $10\%$ for central collisions and $3\%$ for other collisions.

Figures 1(a)–1(f) show $v_2(p_T)$ for six centrality bins, spanning 1–18 GeV/$c$. In the 10%–50% centrality range, where the signal is large and the uncertainty is small, the $v_2$ values above 3 GeV/$c$ indicate a slow decrease up to 7–10 GeV/$c$, and remain significantly above zero at higher $p_T$. The ratios in Figs. 1(g)–1(i) confirm the consistency of $v_2$ measured using the RP from the MPC or the RXN$_{in}$, and imply that the influence of rapidity dependent jet bias to the RP, if any, is within the statistical or systematic uncertainty of the measurement.

Figures 2(a) and 2(b) show the centrality dependence of $v_2$ in two high-$p_T$ selections. They are compared with four PQCD jet-quenching model calculations, AMY, HT, and ASW from [8] and WHDG from [21].

The WHDG model was calculated for gluon density $\frac{dN_g}{dy} = 1000–1600$, a range constrained by 0%–5% ($N_{part} \sim 351$) $\pi^0 R_{AA}$ data [7]; it assumes analytical Woods-Saxon nuclear geometry with a longitudinal Bjorken expansion. The AMY, HT, and ASW models were fitted independently to the 0-5% $\pi^0 R_{AA}$ data [8]; they were implemented in a 3D ideal hydrodynamic code with identical initial Wood-Saxon nuclear geometry, medium evolution and fragmentation functions. The HT and ASW models include only coherent radiative energy loss, while the AMY and WHDG also include collisional energy loss. The ASW and WHDG models predict sizable but similar $v_2$, while the HT and AMY models tend to give much smaller $v_2$. However, all models significantly underpredict the $v_2$ data in $6 < p_T < 9$ GeV/$c$ range. For $p_T > 9$ GeV/$c$, ASW and WHDG results show a better agree-

![FIG. 1. (a)–(f) $\pi^0$ $v_2$ using combined reaction plane for MPC and RXN$_{in}$ as a function of $p_T$ for different centralities. (g)–(i) ratios of $v_2$ measured separately using MPC (solid triangles) and RXN$_{in}$ (open triangles) to the combined result; the dashed lines indicate the systematic error. Note that the MPC and RXN$_{in}$ are combined at the raw hit level before the RP flattening correlation [19] which unfolds for nonuniform detector acceptance; thus the combined $v_2$ is not a simple weighted average of $v_2^{MPC}$ and $v_2^{RXN_{in}}$.](142301-4)
ment with the 20%–30% \((N_{\text{part}} \sim 167)\) centrality bin due to a slow decrease of \(v_2\) with \(p_T\) [see Fig. 1(b)]. This is accidental, because the \(v_2\) values for the other centrality bins remain large, and are significantly above the WHDG calculations (the \(p\) value for the agreement is \(<10^{-4}\)).

In all these models, the inclusive suppression \(R_{AA}\) and \(v_2\) are anticorrelated; i.e., a smaller \(R_{AA}\) implies a larger \(v_2\) and vice versa. Consequently, more information can be obtained by comparing the data with a given model for both \(R_{AA}\) and \(v_2\). Figures 2(c) and 2(d) compare the centrality dependence of \(\pi^0\) \(R_{AA}\) data to four model calculations for the same two \(p_T\) ranges [22]. The calculations are available for a broad centrality range for WHDG, but only in 0%–5% and 20%–30% centrality bins for AMY, HT and ASW. The level of agreement varies among the models. The HT calculations are slightly above the data in the most central bin, while WHDG systematically underpredicts the data over the full centrality range, though better agreement with the data is obtained for \(p_T > 9\) GeV/c. On the other hand, ASW and AMY calculations agree with the data very well in both \(p_T\) ranges. The different levels of agreement among the models are partially due to their different trends of \(R_{AA}\) with \(p_T\): WHDG and ASW results have stronger \(p_T\) dependences than what is found in the data, and tend to deviate at low \(p_T\) when fitted to the full \(p_T\) range [7,8].

Given the larger fractional systematic error for \(R_{AA}\) measurements compared to the \(v_2\) measurements, the deviation of \(v_2(N_{\text{part}})\) from the data is more dramatic than that for \(R_{AA}(N_{\text{part}})\). Nevertheless, Fig. 2 clearly shows the importance for any model to simultaneously describe the \(R_{AA}\) and the azimuthal anisotropy of the data.

The fact that the high \(p_T\) \(v_2\) at RHIC exceeds expectations of PQCD jet-quenching models was first pointed out in Ref. [23] in 2002. This was not a serious issue back then since the \(p_T\) reach of early measurements was rather limited, and the \(v_2\) could be strongly influenced, up to 6 GeV/c for pions, by collective flow and recombination effects rather than jet quenching [24]. Figure 2 clearly shows that the \(v_2\) at \(p_T > 6\) or even 9 GeV/c still exceeds the PQCD-based energy-loss models. It is possible that geometrical effects due to fluctuations and CGC effects, ignored in these models, can increase the calculated \(v_2\); it is also possible that the energy-loss process in the SQGP has a steeper \(l\) dependence (e.g., AdS/CFT) than what is currently implemented in these models.

To test whether these two ideas could bridge the difference between data and theory, we compare the data with the JW model from [25]. This model is based on a naïve jet absorption picture with an exponential survival probability \(e^{-\tau l}\) for jets, where the line integral \(I = \int dl\rho\) is chosen...
for a quadratic dependence ($-\int dl$) of energy loss in a longitudinally expanding medium ($-1/l$), and $\kappa$ is tuned to reproduce the central $R_{AA}$ data. The medium density $\rho$ is given by two leading candidates of the initial geometry: MC Glauber geometry $\rho_{GL}(x, y) = 0.43\rho_{part}(x, y) + 0.14\rho_{coll}(x, y)$, i.e., a mixture of participant density profile and binary collision profile from PHOBOS [26]; and MC CGC geometry $\rho_{CGC}(x, y)$ of Drescher and Nara [14]. The effect of fluctuations for both profiles were included via the standard rotation procedure [13]. The short-dashed curves in Fig. 3(a) show that the result for Glauber geometry without rotation ($\rho_{GL}$) compares reasonably well with those from WHDG [21] and a version of ASW model from [27]. Consequently, we use the JW model to estimate the shape distortions due to fluctuations and CGC effects. The results for Glauber geometry with rotation ($\rho_{GL}^{\text{Rot}}$) and CGC geometry with rotation ($\rho_{CGC}^{\text{Rot}}$) each lead to a $\sim$15%–20% increase of $v_2$ in midcentral collisions. However, these calculated results still fall below the data.

Figure 3(b) compares the same data with three JW models for the same matter profiles, but calculated for a line integral motivated by AdS/CFT correspondence $I = \int dl l p$. The stronger $l$ dependence for $\rho_{GL}$ significantly increases (by $\gtrsim50\%$) the calculated $v_2$, and brings it close to the data for midcentral collisions. However, a sizable fractional difference in the central bin seems to require an additional increase from fluctuations and CGC geometry. Figure 3(b) also shows a MR model from [27], which implements the AdS/CFT $l$ dependence within the ASW framework [28]; it compares reasonably well with the JW model for $\rho_{GL}$ (short-dashed curves). Note that the MR and JW models in Fig. 3 have been tuned independently to reproduce the 0–5% $\pi^0 R_{AA}$ data, and they all describe the centrality dependence of $R_{AA}$ very well [see Figs. 3(c) and 3(d)]. On the other hand, these models predict a stronger suppression for dihadrons than for single hadrons, opposite to experimental findings [29]; thus a global confrontation of any model with all experimental observables is warranted.

In summary, we presented results on $\pi^0$ azimuthal anisotropy ($v_2$) in $1 < p_T < 18$ GeV/$c$ in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The measurements indicate sizable $v_2(p_T)$ that decreases gradually for $3 \lesssim p_T \lesssim 7–10$ GeV/$c$, but remains positive for $p_T > 10$ GeV/$c$. This large $v_2$ exceeds expectations of PQCD energy-loss models even at $p_T \sim 10$ GeV/$c$. Estimates of the $v_2$ increase due to modifications of initial geometry from gluon saturation effects and fluctuations indicate that they are insufficient to reconcile data and theory. Incorporating an AdS/CFT-like path-length dependence for jet quenching in a PQCD-based framework [27] and a schematic model [25] both compare well with the data. However, more detailed study beyond these simplified models are required to quantify the nature of the path-length dependence. Our precision data provide key constraints on the initial geometry, medium space-time evolution, and the jet-quenching mechanisms.

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[28] The two MR models (ASW and AdS/CFT) in Fig. 3 are based on a 3D ideal hydrodynamic code slightly different from that of the ASW model shown in Fig. 2.