High-$p_T$ Particle Production with Respect to the Reaction Plane

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Abstract. The PHENIX Run4 data-set provides a powerful opportunity for exploring the angular anisotropy of identified particle yields at high $p_T$. Complementing traditional $v_2$ measurements, we present π0 yields as a function of emission angle with respect to the reaction plane in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV/c. The centrality dependence of the angular anisotropy allows us to probe the density and path-length dependence of the energy loss of hard-scattered partons.

Keywords: heavy ion, π0, high-pt, reaction plane
PACS: 25.75.-q, 25.75.Dw, 25.75.Ld, 25.75.Nq

1. Introduction

Two of the greatest mysteries that have arisen from the RHIC physics program are the source of the apparent flatness of the high $p_T$ (> 5 GeV/c) suppression of $R_{AA}$ [1] and the source of non-zero $v_2$ at high $p_T$ [2]. The existence of intermediate to high $p_T$ $v_2$ was suggested early in the RHIC program [3], and has been the subject of many theoretical treatments (see [4, 5] for some additional examples). Traditional flow and parton energy loss pictures have failed to describe the magnitude of this anisotropy. Measurement of the azimuthal asymmetry $v_2$ at high $p_T$ will shed light on the contributions from flow, recombination, and energy loss, as well as the transition from soft to hard production mechanisms.

2. Measuring $v_2$ and π0 yields in PHENIX

The orientation of the reaction plane is measured event-by-event using the set of two PHENIX Beam-Beam Counters (BBCs), which reside at the region $3 < |\eta| < 4$. Each detector is an array of 64 hexagonal, close-packed quartz Cherenkov counters, located 150 cm from the interaction point. The charge measured by each counter
is proportional (on average) to the multiplicity of particles hitting it. The reaction plane angle $\Psi_{RP}$ is determined from the value of $\langle \cos 2\phi \rangle$. Because the two BBCs provide independent measurements of $\Psi_{RP}$, we can estimate the resolution of the combined measurement via standard techniques \[6\].

For measuring photons and $\pi^0$s, we use the Electromagnetic Calorimeter (EM-Cal) \[7\]. Candidate clusters are required to pass $\gamma$ identification cuts, and $m_{\text{inv}}$ distributions are formed from pairs of these clusters. The resulting yields are binned in angle with respect to the reaction plane ($\Delta \phi = \phi - \Psi_{RP}$). A similarly binned mixed event background is then subtracted. The counts in the remaining peak centered on the $\pi$ mass are integrated in a $\pm 2\sigma$ window (where $\sigma$ is the width of a Gaussian fit to the peak). Six bins in $\Delta \phi$ are used in the interval $[0 - \pi/2]$.

To measure $v_2$, we fit the $\Delta \phi$ distribution as $1 + 2v_2^{\text{raw}} \cos(2\Delta \phi)$. The resulting $v_2$ parameter needs to be corrected for the reaction plane measurement resolution, hence the designation $v_2^{\text{corr}}$. The resolution $\sigma_{RP}$ is determined for each centrality bin, and leads to the corrected value $v_2^{\text{corr}} = v_2^{\text{raw}} / \sigma_{RP}$. The yields as a function of $\Delta \phi$ can then be corrected with a factor

$$f(\Delta \phi) = \frac{1 + 2v_2^{\text{corr}} \cos 2\Delta \phi}{1 + 2v_2^{\text{raw}} \cos 2\Delta \phi}.$$  \hspace{1cm} (1)

3. Results and Discussion

To obtain $R_{AA}(\Delta \phi)$, we exploit the fact that the ratio of the yield at a given $\Delta \phi$ to the inclusive yield is equivalent to the ratio of the angle-dependent $R_{AA}$ to the inclusive $R_{AA}$. Thus multiplying these relative yields by an inclusive measured $R_{AA}$, we have:

$$R_{AA}(\Delta \phi) = \frac{\text{Yield}(\Delta \phi)}{\text{Yield}} \times R_{AA} \hspace{1cm} (2)$$

The $R_{AA}(\Delta \phi, p_T)$ as a function of $\langle N_{\text{part}} \rangle$ is shown in Figure 1(a). It is clear that there is non-trivial angular substructure of the $R_{AA}$, and that it varies with centrality. This feature is emphasized by plotting the data on a semi-log scale, showing that the $R_{AA}$ behaves differently in different $\Delta \phi$ bins.

The resulting $\pi^0$ $v_2$ is shown in Figure 1(b). For the first time we observe $v_2$ up to 10 GeV/c. While the value of the $v_2$ decreases beyond intermediate $p_T$, it nonetheless shows a substantial and perhaps constant value out to the highest measured transverse momenta.

To gain insight into the $v_2$ mechanisms at work at high $p_T$, we turn to models. We compare the $\pi^0$ $v_2$ to two models, a calculation done by Turbide et al. \[8\] (using an Arnold-Moore-Yaffe (AMY) formalism \[9\]) and the Molnar Parton Cascade (MPC) model \[10\]. Figure 2 shows calculations from these models, plotted alongside data for similar centralities. The AMY calculation contains energy loss mechanisms only, and we see that the data appear to decrease to a value at high $p_T$ that is consistent with this model; the level of agreement is most striking in the 20-40% bin.
The MPC model has a number of mechanisms, including corona effects, energy loss, and the ability to boost lower $p_T$ partons to higher $p_T$ (a unique feature). The calculation shown in Figure 2 does a better job of reproducing the overall shape of the $v_2$, though it is systematically low. It is important to note that this calculation is done for one set of parameters, so it should be very interesting to see if the MPC can better reproduce the data for a different set of parameters (the opacity of the medium, for example).

The prevailing thought is that the high $p_T$ behavior of the $v_2$ is due to energy loss mechanisms. If this is true, the $R_{AA}$ should be sensitive to the geometry of the collision. To test this behavior, we seek to reparameterize the two handles we have on geometry (centrality, or collision overlap, and angle of emission) into a single parameter, a quantity which we will refer to as “$\rho \cdot L \cdot dL$”. Details of the calculation are described in [11]. This effective path length is calculated from the parton-density weighted average of the length from hard-scattering origin to edge of an ellipse and includes the Bjorken 1-D longitudinal expansion. We perform a Glauber Monte Carlo sampling of starting points to account for fluctuations in the location of the hard-scattering origin of the particles’ paths within the region of overlap between the colliding nuclei. The crucial feature of $\rho \cdot L \cdot dL$ is that it is proportional to the energy loss sustained by the parton as it traverses the medium.

The result of plotting $R_{AA}$ for all centralities and angles vs. $\rho \cdot L \cdot dL$ is shown in Figure 3. If the observed $R_{AA}$ arose from only geometric effects, we would expect the data to exhibit a universal dependence on $\rho \cdot L \cdot dL$. For low $p_T$, this is clearly not the case; something more than just energy loss is taking place there. However, when the $p_T$ reaches 7 GeV/c and above, the $R_{AA}$ data do indeed appear to have a dependence on a single $\rho \cdot L \cdot dL$ curve. This apparent scaling strongly suggests that the dominant effect on $R_{AA}$ at high-$p_T$ is radiative energy loss.

4. Conclusions

We have presented the first measurement of high $p_T$ $v_2$ for $\pi^0$s. It is now clear that the $v_2$ at high $p_T$ does decrease but to a non-zero value. Comparison of $v_2$ with models suggest that the dominant mechanism at work at high $p_T$ is energy loss. In addition, we have presented the first measurement of $\pi^0$ $R_{AA}$ as a function of angle with respect to the reaction plane. The $R_{AA}(\Delta \phi, p_T)$ exhibits interesting angular substructure. Furthermore, when the $R_{AA}$ data are plotted as a function of an effective path length through the medium, the scaling that arises at high $p_T$ also argues for energy loss as the dominant mechanism at work.

References

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Fig. 1. $\pi^0 R_{AA}$ and $v_2$: (a) shows $R_{AA}(p_T)$ as a function of $\langle N_{\text{part}} \rangle$ for each $\Delta\phi$ bin; the panels are for different $p_T$ bins. (b) Shows the $\pi^0 v_2(p_T)$, with each panel corresponding to a centrality bin. The grey bands indicate the systematic error due to the reaction plane resolution correction.
Fig. 2. Comparison of $\pi^0 v_2$ with models. The top three panels show the AMY calculation with data for three centralities \cite{8}. The bottom two panels compare two centralities with the $b = 8$ fm calculation of the MPC model \cite{11}.

Fig. 3. $R_{AA}(\Delta \phi, p_T)$ vs. $\rho \ L / \tau \ dL$. The panels correspond to different $p_T$ ranges. The solid circles are the most peripheral events, while the solid stars are the most central events.