High-$p_T$ $\pi^0$ Production with Respect to the Reaction Plane Using the PHENIX Detector at RHIC

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Abstract. The origin of the azimuthal anisotropy in particle yields at high $p_T$ ($p_T > 5$ GeV/c) in RHIC collisions remains an intriguing puzzle. Traditional flow and parton energy loss models have failed to completely explain the large $v_2$ observed at high $p_T$. Measurement of this parameter at high $p_T$ will help to gain an understanding of the interplay between flow, recombination and energy loss, and the role they play in the transition from soft to hard physics. Neutral mesons measured in the PHENIX experiment provide an ideal observable for such studies. We present recent measurements of $\pi^0$ yields with respect to the reaction plane, and discuss the impact current models have on our understanding of these mechanisms.

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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 $R_{AA}$ \cite{1} and the source of non-zero $v_2$ at high $p_T$ \cite{2}. The existence of intermediate to high $p_T$ $v_2$ was suggested early in the RHIC program \cite{3}, and has been the subject of many theoretical treatments (see \cite{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 $\pi^0$ 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 $\langle \cos 2\theta \rangle$. Because the two BBCs provide independent measurements of $\Psi_{RP}$, we can estimate the resolution of the combined measurement via standard techniques \cite{6}.

For measuring photons and $\pi^0$s, we use the Electromagnetic Calorimeter (EMCal) \cite{7}. Candidate clusters are required to pass $\gamma$ identification cuts, and $m_{raw}$ 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 raw (uncorrected) $\Delta \phi$ distribution $Y(\Delta \phi)$ as

$$Y_{raw}(\Delta \phi) \propto 1 + 2v_2^{raw} \cos(2\Delta \phi). \quad (1)$$

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

$$Y(\Delta \phi) = Y_{raw}(\Delta \phi) \times \frac{1 + 2v_2^{corr} \cos 2\Delta \phi}{1 + 2v_2^{raw} \cos 2\Delta \phi}. \quad (2)$$

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:

$$R_{AA}(\Delta \phi) = Y(\Delta \phi)/Y \times R_{AA} \quad (3)$$

The $R_{AA}(\Delta \phi, p_T)$ as a function of $\langle N_{part} \rangle$ is shown in Figure \textsuperscript{1}. We note that there appears to be a slightly
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 combine the two traditional geometric parameters (centrality, or collision overlap, and angle of emission) into a single parameter, a quantity which we will refer to as "\( \rho L dL \)." Details of the calculation are described in [11], as well as below.

The Guylassy-Levai-Vitev (GLV) formalism can be used to calculate jet energy loss for a set of scattering centers \( \{x_i\} \), where \( x_i = (t_i, \tau_i) \). In practice, an average over these centers is performed. As shown in Figure 1 if a static uniform color charge density within some region \( \rho(x) = \rho_0 \) and zero outside the region is assumed, the resulting energy loss is \( \Delta E_{QCD} \propto \rho_0 L_{\text{max}}^2 \). More realistically, if the density seen by the particle changes along the path, we have \( \Delta E_{QCD} \propto \int_0^L \rho(L)dL \) (which reduces to the quadratic \( L \) dependence for a constant density). Application of this to a 1D Bjorken expansion, with

\[
\rho(r, \tau) = \rho(0, \tau_0) \frac{\tau_0}{\tau} \tag{4}
\]

and given a jet trajectory \( r(\tau) = r_0 + v(\tau - \tau_0) \) (assuming \( v \approx c \approx 1 \) for the jet), we have

\[
L(\tau) = |r(\tau) - r_0| = \tau - \tau_0 \tag{5}
\]

Therefore we have

\[
\Delta E_{QCD} \propto \int_{0}^{L_{\text{max}}} \rho(r, \tau) L dL \tag{6}
\]

\[
\int_{0}^{L_{\text{max}}} \frac{\rho(r, \tau_0) \tau_0 L}{\tau_0 + L} dL \tag{7}
\]

This effective energy loss is calculated from the parton-density weighted average of the length from hard-scattering origin to edge of an ellipse. Additionally, 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 \( \rho L dL \)
is that it is proportional to the energy loss sustained by the parton as it traverses the medium.

The resulting dependence of $R_{AA}$ for all centralities and angles on $\rho L dL$ is shown in Figure 4. If the observed $R_{AA}$ arose from only geometric effects, we would expect the data to exhibit a universal dependence on $\rho L dL$. 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 $\rho L dL$ curve. This apparent scaling strongly suggests that the dominant effect on $R_{AA}$ at high-$p_T$ is energy loss. These data can help to constrain energy loss models, and perhaps help to understand the nature of that energy loss (is it radiative, collisional, or some combination of both?).

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. When the $R_{AA}$ data are examined 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.

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Fig. 5. $R_{AA} (\Delta \phi, p_T)$ vs. $\rho \ L \ dL$. 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.