PHENIX Measurement of Particle Yields at High $p_T$ with Respect to Reaction Plane in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

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The PHENIX Run 4 Au+Au dataset provides a powerful opportunity for exploring the angular anisotropy of identified particle yields at high $p_T$. Complementing traditional $v_2$ measurements, we present $\pi^0$ yields as a function of angle with reaction plane, up to $p_T$ 10 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. We will discuss various mechanisms for particle production in this high $p_T$ region.

1. Introduction

One of the most intriguing puzzles in RHIC physics is the origin of the azimuthal anisotropy of particle yields at high $p_T$ ($> 5$ GeV/$c$) \cite{1,2}. Parton energy loss, which can reproduce the flat, suppressed $R_{AA}$ in single particle spectra \cite{3}, fails to reproduce the required $v_2$ at intermediate $p_T$ \cite{4,5}. The complicated interplay between soft and hard physics (for example, recombination, flow, and energy loss) at intermediate $p_T$ makes it critical to measure $v_2$ at high $p_T$, where we expect the only contribution to be from energy loss. We report here on the measurement of the $\pi^0$ azimuthal asymmetry, and discuss what it tells us about the source(s) of high $p_T$ $v_2$. First we describe the method by which we measure $R_{AA}$ as a function of angle with respect the reaction plane and $v_2$ for $\pi^0$s in PHENIX. We then discuss two model calculations that help to shed light on the mechanisms giving rise to the high $p_T$ $v_2$.

2. Measuring $\pi^0$ yields and $v_2$ in PHENIX

During Run 4, PHENIX recorded 1.5 billion minimum bias Au+Au events at $\sqrt{s} = 200$ GeV/$c$; the data presented here is taken from 1 billion of those events. For measuring photons and $\pi^0$s, we use the Electromagnetic Calorimeter (EmCal) \cite{6}. The angle of the reaction plane is measured event-by-event using the Beam-Beam Counters. Pairs of clusters that pass $\gamma$ identification cuts 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 are integrated in a $\pm 2\sigma$ window, determined by a gaussian fit. Six bins in $\Delta\phi$ are used from $0 - \pi/2$.

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

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

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:

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

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 substructure to the angular dependence of the $R_{AA}$, and that it varies with centralities. 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, and we see a clear decrease at high $p_T$, then a leveling off to a finite value.

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, an Arnold-Moore-Yaffe (AMY) calculation [7] done by Turbide et al. and the Molnar Parton Cascade (MPC) model [8]. 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 agreement is most striking in the 20-30% bin.

The MPC model has a number of mechanisms in it, 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 prevailing mechanism for high $p_T$ $v_2$ is parton energy loss in the dense medium. If this is true, the $R_{AA}$ should be sensitive only to the geometry of the collision. To test this behavior, we seek to reparametrize the two handles we have on geometry (centrality, or collision overlap, and angle of emission) into a single parameter, an effective path length which we will refer to as $L_{\text{eff}}$. Details of the calculation are described in [9]. In essence, it is proportional to the parton-density weighted average of the length from origin to edge of an ellipse. We also 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.

The result of plotting $R_{AA}$ for all centralities and angles vs. $L_{\text{eff}}$ 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 $L_{\text{eff}}$. 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 $L_{\text{eff}}$ curve.
4. Summary

We have presented the first measurement of high $p_T v_2$ for $\pi^0$ and charged hadrons. It is now clear that the $v_2$ at $p_T > 7$ GeV/c decreases to a small but non-trivial value. Comparison with models suggest that the dominant mechanism at work at high $p_T$ is energy loss. In addition, we have also 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, they exhibit a universal behavior at $p_T > 7$ GeV/c.

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