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Study of Azimuthal Anisotropy of High-p_T Charged Particles in Au + Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV with RHIC-PHENIX †

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Abstract: We study the path length dependence of energy-loss in the Quark Gluon Plasma (QGP) by measuring the azimuthal anisotropy coefficient and transverse momentum (p_T) spectra for charged hadrons in Au + Au at $\sqrt{s_{NN}}$ = 200 GeV at the RHIC-PHENIX experiment. To estimate the strength of the energy-loss as a function of p_T, we use the Δp_T which is the difference of p_T which provide the same yields at in-plane and out-of-plane directions. The results indicate that there are different structures between low-p_T and high-p_T regions. At high-p_T, the size of Δp_T increases as the centrality goes up. We also calculate the difference of the path length of in-plane and out-of-plane directions for each centrality. The difference of the path length increases along with the centrality and the tendency is the same with the Δp_T results.

Keywords: Quark Gluon Plasma; Azimuthal anisotropy; energy-loss; high transverse momentum

1. Introduction

In high energy heavy ion collisions, hard scattered partons can loose their energy because of the interaction with QGP. From the previous results of the nuclear modification factor R_{AA}, it is suggested that the energy-loss plays an important role for the suppression of the yields in QGP relative to nucleon scattering. The previous study in PHENIX by using Au + Au collisions and proton + proton (p + p) collsions [1] has been focused on understanding the strength of energy loss. It compares the strength of the energy loss as a function of transverse momentum (p_T) in Au + Au collision from the central collision to the peripheral to that in p + p. The study indicates that the amount of the energy loss at all centralities tends to be independent of the p_T. In this research, we intend to clarify the path-length dependence of the QGP energy-loss. The hard scattered partons have different QGP path-lengths depending on the azimuthal angle of the particle emission. The yield difference at the different azimuthal angle for high-p_T particles in the momentum space can be seen as a result of the different amount of energy-loss in the QGP since the original emission angle should be isotropic, azimuthally. In this analysis, we use the azimuthal anisotropy coefficient (v_2) to estimate the azimuthal-angle dependence of the particle yield. The analysis using v_2 is unique and has advantages that cancel the systematic errors comparing to the previous method [1], since this method uses only the Au + Au collision system. The strength of energy loss can be investigated by measuring the v_2 at high p_T, and we can calculate it more accurately.

2. Analysis Methods

We assume that the azimuthal distribution follows the Equation (1) since we consider only v_2 component in this analysis.

$$dN/d\phi \propto 1 + 2v_2 cos(2\phi) \tag{1}$$

We use two previous results, inclusive p_T spectra and the azimuthal anisotropy v_2 for charged hadrons, to obtain the "in-plane yield" and the "out-of-plane yield". The "in-plane" means the plane parallel to the reaction plane direction while the "out-of-plane" is the one perpendicular to that. For this study, we use preliminary results of the azimuthal anisotropy v_2 measured by the PHENIX experiment in Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV in 2014 data shown in Figure 1 [2,3].

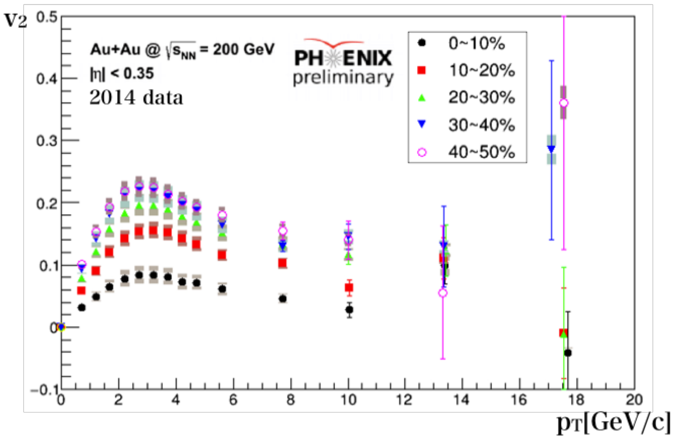

Figure 1. Azimuthal anisotropy coefficient v_2 as a function of p_T in Au + Au at $\sqrt{s_{NN}}$ = 200 GeV (PHENIX preliminary results [3], for different region of the centrality from 0–10% to 40–50%. The results are shown by different symbols as explained in the legend.). Bars indicate the statistical errors and boxes indicate the systematic errors.

The inclusive p_T spectrum in Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV shown as black points in Figure 2, is taken from [4]. For the given p_T range, one can get the azimuthal distribution, Equation (1), illustrated by the black line in the left panel of Figure 3. Here, we define the in-plane yield (out-of-plane yield) as the yield where the azimuthal distribution is assumed to be flat and has a constant value of $1 + 2v_2$ $(1 - 2v_2)$ which is the value at $\phi = 0$ $(\phi = \pi/2)$. The integral value of the black line is equal to the that of the yellow flat line indicated by "inclusive". The right panel in Figure 3 shows a cartoon of the inclusive, in-plane and out-of-plane yields as a function of p_T. These three lines can be obtained from the corresponding distributions for a given p_T in the left panel.

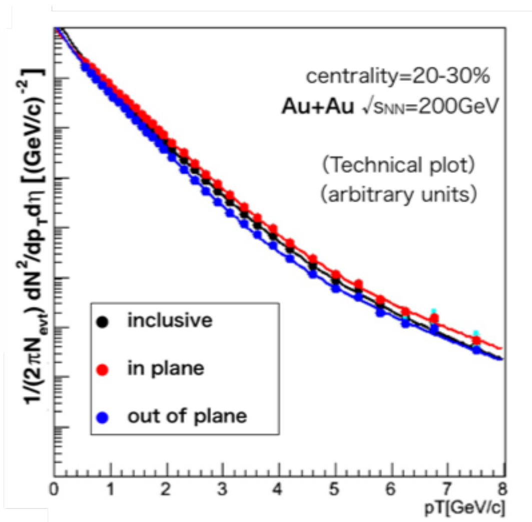

Figure 2. Inclusive, in-plane and out-of-plane yields as a function of p_T for the centrality 20–30% in the Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Bars indicate the statistical errors.

Figure 2 shows the differential yield as a function of the p_T in the case of centrality 20 to 30% in Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. The black points are the inclusive yield, while the red and the blue points show the particle yields in the in-plane and the out-of-plane, respectively. We fit these yields by a function, f(p_T), given in Equation (2), where P_0, P_1, P_2, P_3, P_4 are parameters to be determined by a fit.

$$f(p_T) = P_0(p_T/e^{P_1 p_T}) + P_2(1.0 + p_T/P_3)^{P_4} \tag{2}$$

We determine the values of these parameters, separately, by fitting the inclusive in-plane and out-of-plane yield. By using the fitting results, one can obtain the values of p_Ts, $p_{T,in}$ and $p_{T,out}$, that give the same in-plane and out-of-plane yields, respectively ($f(p_{T,in}) = f'(p_{T,out})$). We define the difference Δp_T = $p_{T,in}$ - $p_{T,out}$ as the estimator of the energy-loss within QGP for given p_T.

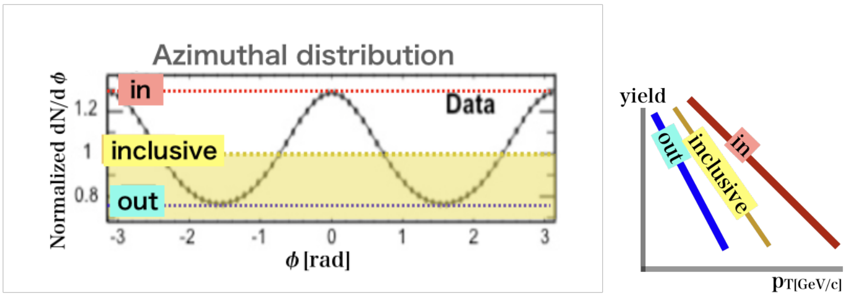

Figure 3. Left: A typical inclusive azimuthal anisotropic distribution. Right: Cartoon of the inclusive, in-plane and out-of-plane yields as a function of p_T.

3. Results

The obtained values of Δp_T are shown in Figure 4 as a function of p_T for the various centrality regions from 0 to 50% in 10% steps. In each figure, the vertical axis is Δp_T and the horizontal is the in-plane p_T. For low p_T the Δp_T increases as p_T increases. On the other hand, at high p_T, Δp_T is almost constant, i.e., Δp_T does not depend on its own p_T. The results indicate that the mechanisms causing the Δp_T seem to be different between low p_T and high p_T. This is consistent with the previous pictures that the yield difference between in and out of plane at low p_T is due to the elliptic flow [5] and that at high p_T is due to the parton energy loss described in the introduction. The results also indicate that although the shapes are similar for each centrality, for 0–30% centrality, it tends to increase Δp_T as centrality goes up, and for 30–50% centrality it increases more gently.

In order to study the relation between the Δp_T and the parton path length within the QGP, we calculate the distance from the center of the collision to the collision surface in-plane direction (L_{in}) and the out-of-plane direction (L_{out}) as the simplest case. We calculate L_{in} and L_{out} geometrically from the relationship between the centrality and the impact parameter of gold nuclei, and take the difference ($dL = L_{out} - L_{in}$) between them as shown in the left panel of Figure 5. The radius of the gold nuclei is taken to be 7.27×10^{-15} m . The right panel of Figure 5 shows the calculated dL as a function of the centrality from 0 to 50%. One can clearly see that dL increases with the centrality up to 30%. This behavior is in line with the result for Δp_T at higher p_T, supporting the interpretation based on a path length dependent energy loss.

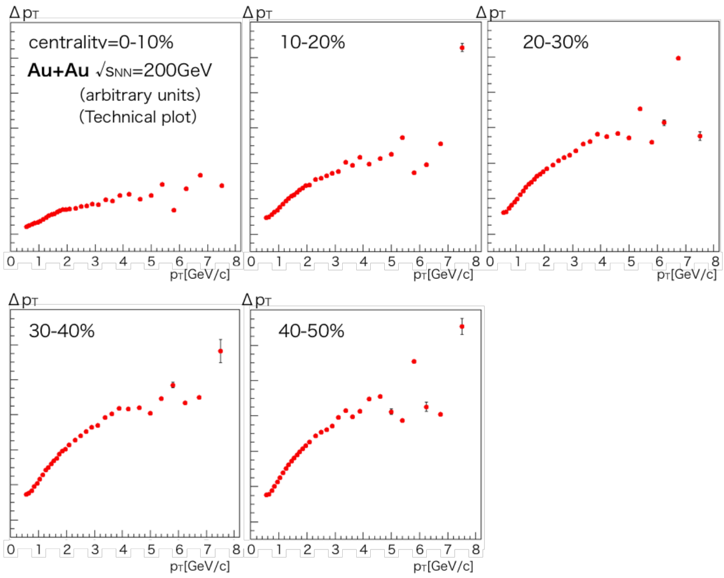

Figure 4. Δp_T vs. p_T of in-plane in Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV for the centrality region from 0% to 50% by a 10% step. In this proceeding, we are using an arbitrary scale for the vertical axis. Error bars indicate statistical errors.

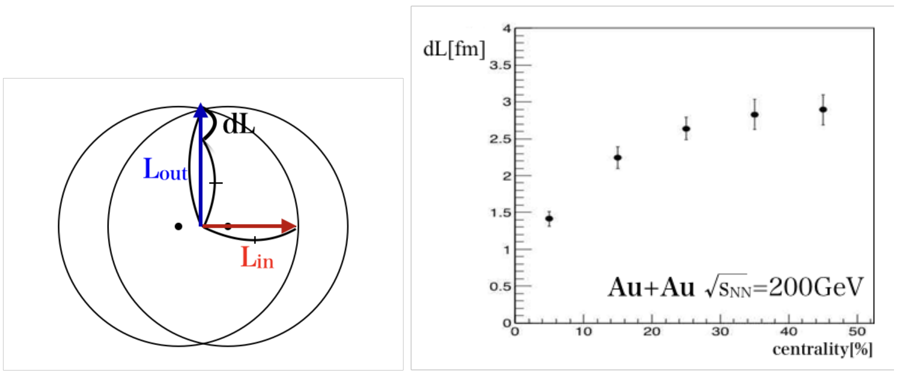

Figure 5. Left: Definition of L_{in}, L_{out} and dL. **Right**: The value of the path-length difference dL as a function of the centrality in Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Error bars indicate the statistical errors.

4. Conclusions

We obtain the in-plane and out-of-plane yields from the inclusive p_T spectra and the v_2 measurement using our previous results. From these yields, we estimate the transverse momentum loss, Δp_T, as a function of p_T (in-plane) for the centrality 0 to 50%. The Δp_T seems to be independent of its p_T at high p_T. The dL increases along with the centrality and the tendency is the same as for the Δp_T results.

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