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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 Fig.1 [2] [3]. The inclusive p_T spectrum

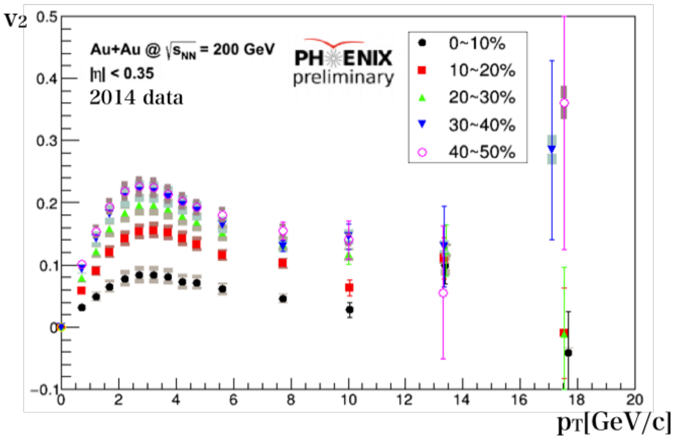

Figure 1. Azimuthal anisotropy coefficient v_2 as a function of p_T in Au + Au at $\sqrt{s_{NN}}$ = 200 GeV (PHENIX preliminary results [3], for different region of the centrality from $0-10\%$ to $40-50\%$. The results are shown by different symbols as explained in the legend.). Bars indicate the statistical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

in Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV shown as black points in Fig.2, is taken from [4]. For the given p_T range, one can get the azimuthal distribution, Eq.1, illustrated by the black line in the left panel of Fig.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 Fig.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.

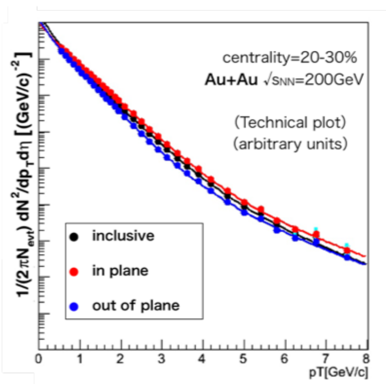

Figure 2. Inclusive, in-plane and out-of-plane yields as a function of p_T for the centrality 20-30% in the Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Bars indicate the statistical errors.

Fig.2 shows the differential yield as a function of the $p_{\rm T}$ 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($p_{\rm T}$), given in Eq.(2), where P_0, P_1, P_2, P_3, P_4 are parameters to be determined by a fit.

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

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 $p_{\rm T}$s, $p_{\rm T,in}$ and $p_{\rm T,out}$, that give the same in-plane and out-of-plane yields, respectively ($f(p_{\rm T,in}) = f'(p_{\rm T,out})$). We define the difference $\Delta p_{\rm T}$ = $p_{\rm T,in}$ - $p_{\rm T,out}$ as the estimator of the energy-loss within QGP for given $p_{\rm T}$.

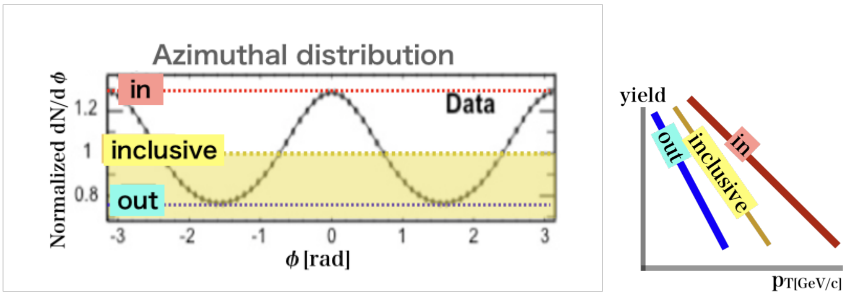

Figure 3. Left: A typical inclusive azimuthal anisotropic distribution. Right: Cartoon of the inclusive, in-plane and out-of-plane yields as a function of $p_{\rm T}$

3. Results

The obtained values of $\Delta p_{\rm T}$ are shown in Fig.4 as a function of $p_{\rm T}$ for the various centrality regions from 0 to 50% in 10% steps. In each figure, the vertical axis is $\Delta p_{\rm T}$ and the horizontal is the in-plane $p_{\rm T}$. For low $p_{\rm T}$ the $\Delta p_{\rm T}$ increases as $p_{\rm T}$ increases. On the other hand, at high $p_{\rm T}$, $\Delta p_{\rm T}$ is almost constant, i.e. $\Delta p_{\rm T}$ does not depend on its own $p_{\rm T}$. The results indicate that the mechanisms causing the $\Delta p_{\rm T}$ seem to be different between low $p_{\rm T}$ and high $p_{\rm T}$. This is consistent with the previous pictures that the yield difference between in and out of plane at low $p_{\rm T}$ is due to the elliptic flow [5] and that at high $p_{\rm T}$ 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 $\Delta p_{\rm T}$ 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 ($L_{\rm in}$) and the out-of-plane direction ($L_{\rm out}$) as the simplest case. We calculate $L_{\rm in}$ and $L_{\rm out}$ geometrically from the relationship between the centrality and the impact parameter of gold nuclei, and take the difference ($dL = L_{\rm out} - L_{\rm in}$) between them as shown in the left panel of Fig.5. The radius of the gold nuclei is taken to be 7.27 $\times$ 10^{-15}m . The right panel of Fig.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 $\Delta p_{\rm T}$ at higher $p_{\rm T}$, supporting the interpretation based on a path length dependent energy loss.

4. Conclusions

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

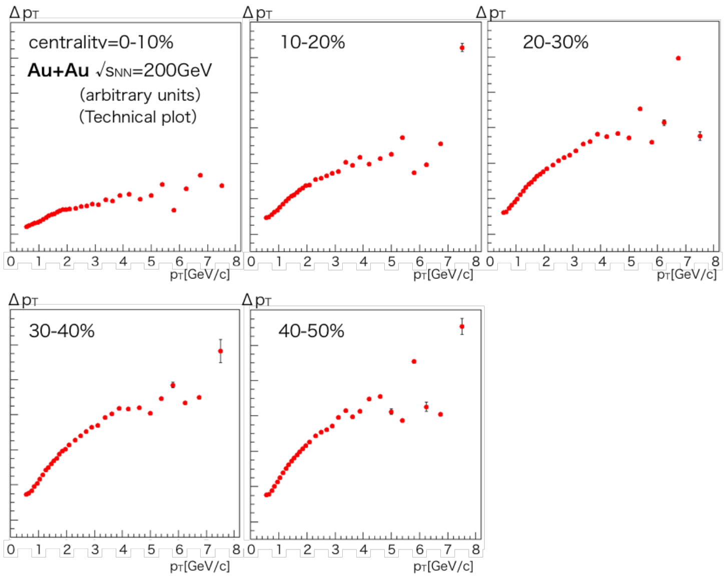

Figure 4. Δp_T v.s. p_T of in-plane in Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV for the centrality region from 0% to 50% by a 10% step. In this proceeding, we are using an arbitrary scale for the vertical axis. Error bars indicate statistical errors.

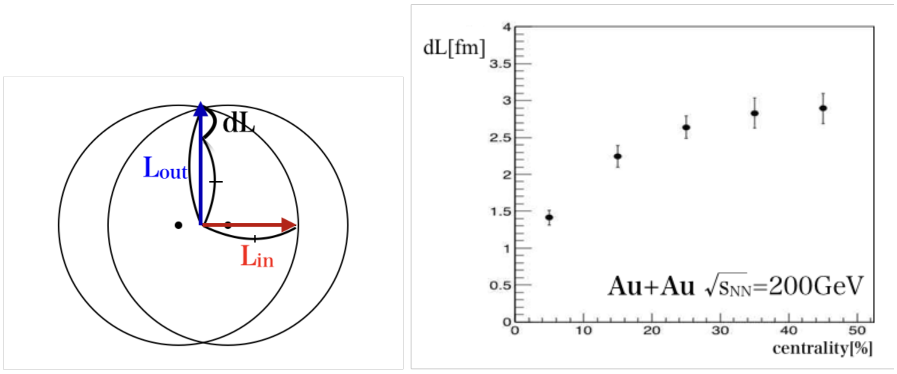

Figure 5. Left: Definition of L_{in}, L_{out} and dL. Right: The value of the path-length difference dL as a function of the centrality in Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Error bars indicate the statistical errors.

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