Study of azimuthal anisotropy of high-$p_T$ charged particles in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV with RHIC-PHENIX†

Risa Nishitani 1 for the PHENIX Collaboration

1 Department of Physics, Nara Women’s University, Nara 630-8506, Japan.; rar_nishitani@cc.nara-wu.ac.jp

† Presented at Hot Quarks 2018 - Workshop for young scientists on the physics of ultra relativistic nucleus-nucleus collisions, Texel, The Netherlands, September 7-14 2018

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 $\Delta p_T$ 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 $\Delta p_T$ 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 $\Delta p_T$ 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 ($p + p$) collisions [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.

\[ \frac{dN}{d\phi} \propto 1 + 2v_2 \cos(2\phi) \]  

(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 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 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.](image1)

![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.](image2)
Fig. 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 Eq. (2), where $P_0$, $P_1$, $P_2$, $P_3$, $P_4$ are parameters to be determined by a fit.

$$f(p_T) = P_0(p_T/e^{P_1p_T}) + P_2(1.0 + p_T/P_3)P_4$$ (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 $p_T^s$, $p_T^{in}$ 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 $\Delta p_T = p_T^{in} - p_T^{out}$ as the estimator of the energy-loss within QGP for given $p_T$.

![Azimuthal distribution](image)

**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 $\Delta p_T$ are shown in Fig. 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 $\Delta p_T$ and the horizontal is the in-plane $p_T$.

For low $p_T$ the $\Delta p_T$ increases as $p_T$ increases. On the other hand, at high $p_T$, $\Delta p_T$ is almost constant, i.e. $\Delta p_T$ does not depend on its own $p_T$. The results indicate that the mechanisms causing the $\Delta p_T$ 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 $\Delta p_T$ as centrality goes up, and for 30 - 50% centrality it increases more gently.

In order to study the relation between the $\Delta p_T$ 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 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 $\Delta p_T$ at higher $p_T$, 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 $p_T$ spectra and the $v_2$ measurement using our previous results. From these yields, we estimate the transverse momentum loss, $\Delta p_T$, as a function of $p_T$ (in-plane) for the centrality 0 to 50 %. The $\Delta p_T$ 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 $\Delta p_T$ results.
Figure 4. $\Delta p_T$ 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.

References

1. A. Adare et al., (PHENIX Collaboration), Phys. Rev. C 87, 034911 (2013).
2. M. Shimomura, (PHENIX Collaboration), Nucl. Phys. A 967 405-408 (2017).
3. A. Takeda (PHENIX Collaboration), Master thesis at Nara Women’s University p57 (2017)
   http://webhepl.cc.nara-wu.ac.jp/thesis/master.html (in Japanese).
4. S. S. Addler et al., (PHENIX Collaboration), Phys. Rev. C 69, 034910 (2004).
5. T. Renk and J. Ruppert, Phys. Rev. C 72, 044901 (2005).
6. K. Adcox et al., (PHENIX Collaboration), Nucl. Phys. A 757, 184-283 (2005).

© 2018 by the authors. Submitted to Proceedings for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).