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Systematic study of energy loss in the quark-gluon plasma at RHIC-PHENIX

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This article discusses an estimation of the energy loss of partons in QGP in various collision systems using PHENIX data. We study the energy loss by two different methods, the fractional momentum losses $S_{\mathrm{loss}} = (p_{\mathrm{T}}^{\mathrm{pp}} - p_{\mathrm{T}}^{\mathrm{AA}})/p_{\mathrm{T}}^{\mathrm{pp}}$ and $S'_{\mathrm{loss}} = (p_{\mathrm{T}}^{\mathrm{AA,in}} - p_{\mathrm{T}}^{\mathrm{AA,out}})/p_{\mathrm{T}}^{\mathrm{AA,in}}$. S_{loss} is obtained by comparing the inclusive p_{T} spectra in the AA and pp collisions. In contrast, S'_{loss} is obtained by comparing in-plane and out-of-plane spectra using azimuthal anisotropy v_2. These quantities are extracted from the data in AuAu, CuAu, and CuCu collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV for π^0s, and the AuAu collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV for charged hadrons. The results show that S_{loss} is almost constant for a given centrality and does not depend on p_{T}. In addition, S_{loss} is proportional to the squared path-length of the parton in the reaction area. In contrast, the results show that S'_{loss} slightly decreases up to $p_{\mathrm{T}} \sim 6$ GeV and is almost constant at higher p_{T} for a given centrality class. In addition, unlike S_{loss}, S'_{loss} is not proportional to the difference of squared path-length in-plane and out-of-plane in the reaction area.

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1. Introduction

The phase transition from hadronic material to quark-gluon plasma (QGP) is a phenomenon that occurs under extreme conditions of high temperature and high density. PHENIX, one of the relativistic heavy ion collider (RHIC) experiments at Brookhaven National Laboratory, aims to measure various QGP signals from nuclear collision reactions. There are two primary pieces of evidence of QGP generation observed at RHIC. One is the high-p_T hadron yield suppression in AuAu comparing pp [1]. This suppression is expected to be caused by an energy loss of high momentum partons in QGP. The other is a large azimuthal anisotropy. At low p_T, the anisotropy is caused by a pressure gradient of an early stage of collision. Whereas, at high p_T, it is caused by a parton energy loss in QGP. From this evidence, the parton energy loss during passage is crucial for understanding the critical characteristics of QGP.

In the analysis of the energy loss in QGP, the quantity, S_loss, is often used in the literature. S_loss is defined as the fractional momentum loss of high-p_T hadrons, and the value is obtained by comparing the p_T spectra of hadrons in AA collisions and pp collisions. The previous study found that (1) S_loss does not strongly depend on p_T and decreases as the centrality increases [1]. (2) S_loss increases with L_ϵ, an effective radius of the collision [2]. In addition to S_loss, we study another quantity derived from the azimuthal anisotropy of the particle momentum spectrum. We name it S'_loss. Due to the characteristic almondlike shape of the overlapping matter produced in AA reactions with finite impact parameter, partons traversing the produced medium along the direction perpendicular to the reaction plane ("out-of-plane") will comparatively go through more matter than those going parallel to it ("in-plane") and therefore are expected to lose more energy [2]. Thus, S'_loss includes the difference in energy loss between in-plane and out-of-plane in the fractional momentum loss. The detailed definitions of S_loss and S'_loss are described in Section 2.1.

2. Analysis method

2.1 S_loss and S'_loss

The purpose of this study is to estimate the energy loss of parton in QGP systematically. We study the energy loss with two approaches using two different quantities, S_loss and S'_loss.

For approach 1, we compare particle yield in AA and pp collisions and measure S_loss in the same way of the previous analysis [1] but using new data. S_loss is defined as $S_\mathrm{loss} = (p_\mathrm{T}^\mathrm{pp} - p_\mathrm{T}^\mathrm{AA})/p_\mathrm{T}^\mathrm{pp}$, where p_T^pp and p_T^AA are the transverse momentum of scaled-pp and AA yield, respectively. In S_loss calculation, we firstly scale pp-spectra from [3, 4] by the number of binary collisions in AA collisions. The number of binary collisions in AA collisions can be easily obtained [5, 6]. Then we compare it with AA-spectra from [4, 7, 8] and obtain the transverse momentum, p_T^pp and p_T^AA, that give the same scaled-pp and AA yields, respectively. Finally, we calculate S_loss by subtracting p_T^AA from p_T^pp and dividing it by p_T^pp. In this calculation, we use the same fitting function in the previous study [9] to extract spectra in AA collisions at a given p_T.

For approach 2, we compare particle yield in-plane and out-of-plane in AA collisions and measure S'_loss, a new quantity for approach 2 corresponding to S_loss. S'_loss is defined as $S'_\mathrm{loss} = (p_\mathrm{T}^\mathrm{AA,in} - p_\mathrm{T}^\mathrm{AA,out})/p_\mathrm{T}^\mathrm{AA,in}$, where $p_\mathrm{T}^\mathrm{AA,in}$ and $p_\mathrm{T}^\mathrm{AA,out}$ are the transverse momentum in-plane and out-of-plane in AA collisions, respectively. In S'_loss calculation, we firstly divide AA-spectra from [4, 7, 8] into the direction of in-plane and out-of-plane using azimuthal anisotropy, v_2, from [10, 11]. We then compare in-plane and out-of-plane p_T-spectra and calculate the difference of p_T, $p_T^{AA,in} - p_T^{AA,out}$. $p_T^{AA,in}$ and $p_T^{AA,out}$ give the same in-plane and out-of-plane yields, respectively. Finally, we divide the difference value by $p_T^{AA,in}$. This calculation uses the same function [9] to extract spectra in-plane in AA collisions at a given p_T.

2.2 Parton path-length in QGP

In order to study the path-length dependences of the S_{loss} and S'_{loss}, path-length in the collided matter is calculated using Glauber Monte Carlo simulation [5]. We define the in-plane (out-plane) length L_{in} (L_{out}) as the distances from each nucleon-nucleon collision point to the edge of the reaction area along the direction parallel (perpendicular) to the reaction plane. First, we calculate L_{in} and L_{out} for all nucleon-nucleon collisions generated by 30,000 nucleon-nucleon collisions. Then calculate the average L_{in} ("$\overline{L_{in}}$") and the average L_{out} ("$\overline{L_{out}}$") for each nuclear-nuclear collision center. Then we calculate $L = (\overline{L_{in}} + \overline{L_{out}})/2$. The Nth power of path-length dependence of energy loss is crucial observable, and the previous study [2, 12] reports that the S_{loss} tend to be proportional to the L^2. In this study, we calculate L^2 for various collision systems and centralities to study its dependence of S_{loss}. We also calculate $\Delta L^2 = \overline{L_{out}}^2 - \overline{L_{in}}^2$ to study its dependence of S'_{loss}, where ΔL^2 for S'_{loss} corresponds to L^2 for S_{loss}. Fig. 1 shows the result of the centrality dependence of L^2 and that of ΔL^2 in Au+Au.

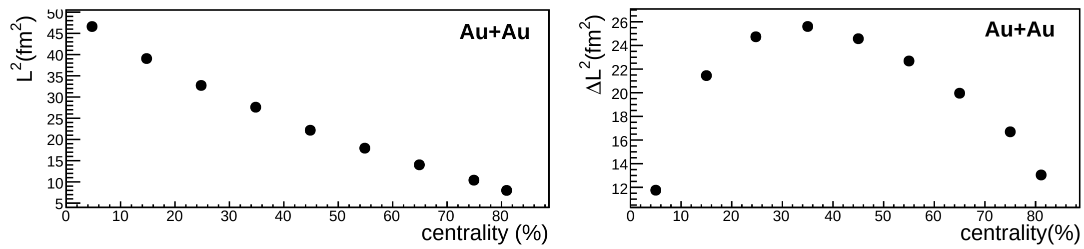

Figure 1: The centrality dependence of L^2 and that of ΔL^2 in Au+Au.

3. Results

We present our results on the p_T and path-length dependences of S_{loss} and S'_{loss} for various reactions. Fig. 2 and Fig. 3 show the p_T dependence of S_{loss}. The legend shows the centrality class. The solid error bars show the statistic error, and the filled box error bars show the systematic error. For charged hadrons in AuAu collisions, S_{loss} increases in central collisions and almost constants in peripheral collisions. From comparing this result and π^0s in AuAu collisions, there is no significant difference between charged hadrons and π^0s within uncertainty. For π^0s in CuAu, S_{loss} is almost constant up to $p_T \sim 12$ GeV and decreases at higher p_T. From Fig. 2 and Fig. 3, one can see that the S_{loss} shows the same tendency in AuAu and CuAu. Fig. 4 shows the p_T dependence of S'_{loss}. For charged hadrons and π^0 in AuAu collisions, S'_{loss} slightly decreases up to $p_T \sim 6$ GeV and seems almost constant at higher p_T. Furthermore, there is no significant difference between

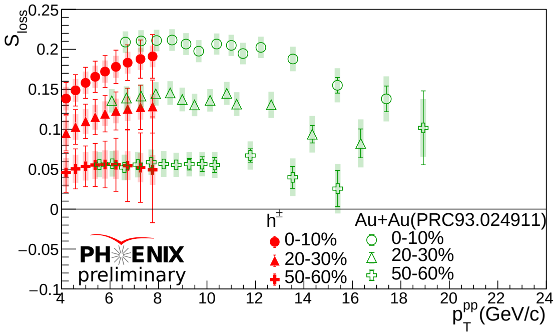

Figure 2: The p_{T} dependence of S_{loss} for charged hadrons in AuAu collisions for various centralities.

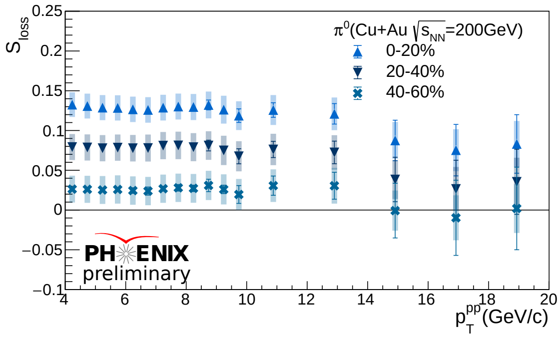

Figure 3: The p_{T} dependence of S_{loss} for π^0s in CuAu collisions.

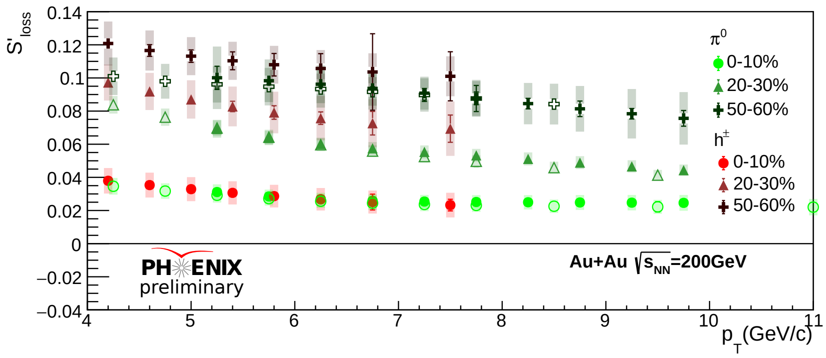

Figure 4: The p_{T} dependence of S'_{loss} for charged hadrons and π^0s in AuAu collisions.

charged hadrons and π^0s. From Fig. 2, Fig. 3, and Fig. 4, one can see that S_{loss} decreases as centrality increases, while S'_{loss} increases as centrality increases up to 60%.

Fig. 5 shows the L^2 dependence of S_{loss}. S_{loss} is proportional to L^2 for charged hadrons in AuAu and π^0s in CuAu collisions. This result can be understood that the overlapping matter produced in AA reactions gets smaller as centrality increases, as shown in Fig. 1. These results indicate that the gluon radiative loss seems to be dominant in this p_{T} region [13]. Fig. 6 shows the $\Delta L^2 = (\overline{L_{\mathrm{out}}}^2 - \overline{L_{\mathrm{in}}}^2)$ dependence of S'_{loss}. For charged hadrons and π^0s in AuAu collisions, S'_{loss} is not proportional to ΔL^2 and exhibits a different tendency from S_{loss}. We suspect one of the causes of this result is that ΔL^2 does not change monotonically for the centrality class, shown in Fig. 1. From this result, S'_{loss} is expected to include the detailed characteristics of energy loss in the QGP. Furthermore, from a comparison of charged hadrons and π^0s, there is no significant difference between them within uncertainly.

4. Summary

We have measured S_{loss} for π^0s in CuAu and charged hadrons in AuAu, and S'_{loss} for charged hadrons and π^0s in AuAu. S'_{loss} is a quantity defined in this study for a new approach that compares yield in-plane and out-of-plane. For both S_{loss} and S'_{loss}, we have confirmed no significant difference

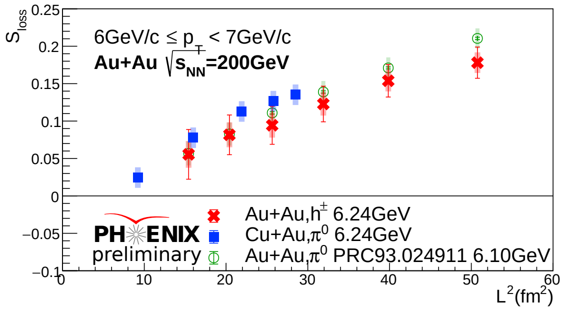

Figure 5: L^2 dependence of S_{loss} for charged hadrons in AuAu and π^0s in CuAu with that for π^0s in AuAu, measured in Ref. [1].

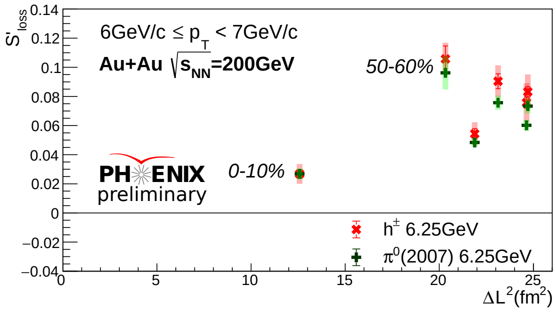

Figure 6: ΔL^2 dependence of S'_{loss} for charged hadrons and that for π^0s in AuAu. Percentage value written next to the plot shows the centrality class.

between π^0s and charged hadrons within uncertainty. We have also confirmed that all measured S_{loss} tend to be proportional to L^2, which may imply that radiative energy loss of gluon is dominant. However, S'_{loss} is not proportional to ΔL^2, which is different behavior from S_{loss}. This result may be due to the nonuniformity of gluon density in QGP. S'_{loss} is expected to provide more detailed information than S_{loss} about the effective path-length depending on the azimuthal angle. Further studies with more realistic models may be essential to estimate the path-length dependence of S_{loss} and S'_{loss}, which will give us more precise information about the parton energy-loss mechanism.

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