Detailed study of parton energy loss via measurement of fractional momentum loss of high $p_T$ hadrons in heavy ion collisions

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Abstract. PHENIX measurement of the fractional momentum loss ($\delta p_T/p_T$) of high $p_T$ identified hadrons are presented. The $\delta p_T/p_T$ of high $p_T$ $\pi^0$ which are computed from 39 GeV Au+Au up to 2.76 TeV Pb+Pb are found to vary by a factor of six. We plotted the $\delta p_T/p_T$ against several global variables, $N_{part}$, $N_{np}$ and $dN_{ch}/d\eta$, and found global features. It was found that 200 GeV Au+Au points are merging into the central 2.76 TeV Pb+Pb points when plotting $\delta p_T/p_T$ against $dN_{ch}/d\eta$.

1. Introduction
The interaction of hard scattered partons with the medium created by heavy ion collisions (i.e., quark-gluon plasma, QGP) has been of interest since the beginning of the RHIC running. A large suppression of the yields of high transverse momentum ($p_T$) hadrons which are the fragments of such partons was observed, suggesting that the matter is sufficiently dense to cause parton-energy loss prior to hadronization [1]. The PHENIX experiment [2] has been exploring the highest $p_T$ region with single $\pi^0$ mesons which are leading hadrons of jets. We show a calculation of the energy loss of partons published almost 20 years ago in Fig. 1(a) [3]. Although the measurement of the momentum shift is the ultimate goal, the paper suggested looking at the ratio of the high $p_T$ single hadrons in Au+Au and p+p collisions as an alternate way. Since then, most of the experiments including PHENIX have looked at the nuclear modification factors, $R_{AA}$ ($\equiv (dN_{AA}/dydp_T)/(\langle T_{AA}\rangle d\sigma_{pp}/dydp_T)$), and quantified the energy loss effect via its suppression. In the present analysis, we evaluate the momentum shift of high $p_T$ hadrons instead of $R_{AA}$.

2. Fractional momentum loss $\delta p_T/p_T$
With a larger statistics of both $p + p$ and Au+Au data recently collected, it became possible to measure the momentum shift directly. Fig. 1(b) depicts the method to compute such shift. We have statistically extracted the fractional momentum loss ($\delta p_T/p_T$, $\delta p_T \equiv p_T - p_T'$, where $p_T$ is the transverse momentum of the $p + p$ data, and $p_T'$ is that of the Au+Au data) of the of the hadrons using their $p_T$ spectra measured in $p + p$ and Au+Au collisions [4]. Since the number of data points is finite, a fit to scaled $p + p$ is needed to evaluate $\delta p_T/p_T$ at a given Au+Au invariant yield. The uncertainty of the $\delta p_T/p_T$ is calculated by converting the quadratic sum of the uncertainties on the yields of Au+Au and $p + p$ points, using the $p + p$ fit function. Statistical
Figure 1. (a, left) A calculation demonstrating that the suppression of the $\pi^0$ yield can be modeled by a relative transverse momentum shift of the transverse momentum spectra in A+A collisions. (b, right) Method of calculating average $\delta p_T/p_T$. We scale the differential cross-section measured in $p+p$ by $T_{AA}$ (yields are scaled by $N_{coll}$ corresponding to the centrality class of Au+Au data, shift the $p+p$ points closest to Au+Au in yield, and calculate the momentum difference of $p+p$ and Au+Au points.

and systematic uncertainties are individually calculated in the same way. The uncertainties on $T_{AA}$ and $p+p$ luminosity are not plotted but indicated in the legend. Fig. 2(a) show the $R_{AA}$ for the $\pi^0$'s in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from the RHIC Year-7 run. Using this method, we obtained the $\delta p_T/p_T$ for the same dataset as shown in Fig. 2(b). Similarly, the $R_{AA}$ for the $\pi^0$'s in 0-10 % Au+Au collisions at $\sqrt{s_{NN}} = 39, 62$ and 200 GeV from the RHIC Year-7 and Year-10 runs shown in Fig. 3(a) are replotted in the form of $\delta p_T/p_T$ as shown in Fig. 3(b). The $R_{AA}$'s don’t change as much as the change in cms energies as seen in Fig. 3(a). However, when we look at $\delta p_T/p_T$ for the corresponding dataset, we found that the $\delta p_T/p_T$ changes by a factor of three from 39 to 200 GeV as shown in Fig. 3(b) [5].

On the other hand, the $R_{AA}$'s look similar between RHIC and LHC (Fig. 4(a)). The $\delta p_T/p_T$ is found to change by a factor of $\sim 1.5$ from 200 to 2.76 TeV (Fig. 4(b)). To summarize, even the $R_{AA}$'s don’t change as much as the change in the cms energies, the $\delta p_T/p_T$'s show a factor of six variation from 39 GeV to 2.76 TeV. This fact has not been found by looking at $R_{AA}$.

3. Scaling property of $\delta p_T/p_T$

In order to study the systematics of $\delta p_T/p_T$, we plot the $\delta p_T/p_T$ against several global variables such as $N_{part}$, $N_{qp}$ (number of quark participants) and $dN_{ch}/d\eta$. We first plotted the $\delta p_T/p_T$ against $N_{part}$ as shown in Fig. 5. All the plots shown in this section are at $p_T(p+p) = 7$ GeV/c in order to reach the hard scattering regime. For the $N_{part}$ dependence we see that the Cu+Cu and Au+Au are nicely lined up, implying that for the same cms energy, the $\delta p/T/p_T$ scales with $N_{part}$. This is consistent with the fact that $R_{AA}$ is similar at the same $N_{part}$ between Cu+Cu and
Figure 2. (a, left) $R_{AA}$ of $\pi^0$'s for 200 GeV Au+Au collisions obtained from RHIC Year-7 run. The gray bars around the unity shows the quadratic sum of p+p luminosity and $T_{AA}$ uncertainties. (b, right) $\delta p_T/p_T$ for the same dataset.

Figure 3. (a, left) $R_{AA}$ of $\pi^0$'s for 39, 62 in 0-10 % Au+Au collisions obtained from RHIC Year-10 run and in 0-10 % 200 GeV Au+Au collisions from RHIC Year-10 run. The bands around the unity shows the quadratic sum of p+p luminosity and $T_{AA}$ uncertainties for each cms energies. (b, right) $\delta p_T/p_T$ for the same dataset.

Au+Au collisions [7]. The Pb+Pb points are consistently off the trend of 200 GeV points, but the slopes of both systems look similar. Fig. 6 shows $\delta p_T/p_T$ against $N_{qp}$. The detail description of how the number of quark participants are obtained can be found in the literature [8]. We employed a Monte-Carlo-Glauber (MC-Glauber) model to calculate the numbers. We first determine the quark-quark inelastic cross section ($\sigma_{qq}^{inel}$) for each collision energy such that the inelastic nucleon-nucleon cross section ($\sigma_{NN}^{inel}$) is reproduced. Then the model is modified to
Figure 4. (a, left) $R_{AA}$ of $\pi^0$'s for 200 GeV Au+Au collisions obtained from RHIC Year-7 run and charged hadrons for 2.76 TeV Pb+Pb collisions obtained by the ALICE experiment at LHC [6]. (b, right) $\delta p_T/p_T$ for the same dataset.

Figure 5. $\delta p_T/p_T$ as a function of $N_{\text{part}}$ for $\pi^0$'s in 200 GeV Au+Au and Cu+Cu collisions measured by PHENIX and charged hadrons in 2.76 TeV Pb+Pb collisions measured by ALICE.

handle the quark-quark rather than nucleon-nucleon collisions. The nuclei are placed according to a Woods-Saxon distribution and then three quarks are distributed around the center of each nucleon following the distribution of:

$$\rho^{\text{proton}}(r) = \rho_0^{\text{proton}} \times e^{-ar}$$
where \( a = \sqrt{12}/r_m = 4.27 \text{ fm}^{-1} \) and \( r_m = 0.81 \text{ fm} \) is the rms charge radius of the proton. A pair of quarks, one from each nucleus, interact with each other if their distance \( d \) in the plane transverse to the beam axis satisfies the condition of \( d < \sqrt{\sigma_{qq}^{\text{inel}}/\pi} \). The number of quark participants as a function of the number of nucleon participants is nonlinear, especially for low values of \( N_{\text{part}} \). In Fig. 6, the similar feature as the previous plot is seen. Since the \( N_{\text{part}} \) is a factor of 2-3 higher than \( N_{qp} \), all the points are systematically moved to the right. We expected that the \( N_{qp} \) dependence show a different trend compared to \( N_{\text{part}} \) dependence since the \( N_{qp} \) involves the partonic degree of freedom, which should play a role in the energy loss mechanism. However, it turned out that trend is very similar between \( N_{\text{part}} \) and \( N_{qp} \) dependence. Finally, we plotted the \( \delta p_T/p_T \) against the charged multiplicity, \( dN_{\text{ch}}/d\eta \), as shown in Fig. 7. In this plot, we added one 62 GeV Au+Au point which is 0-10 % centrality. We expect that \( dN_{\text{ch}}/d\eta \) well represents the energy density of the system. It is interesting to note that the most central Au+Au 200 GeV points tend to merge into the most central points of Pb+Pb collisions, while they deviate from each other as going to lower \( dN_{\text{ch}}/d\eta \). This systematic trend has not been found by looking at \( R_{AA} \)'s which look similar across the systems. In order to cross-check this new result, we have performed a power-law fit to \( \delta p_T/p_T \) vs \( dN_{\text{ch}}/d\eta \) points from 200 GeV Au+Au collisions, and compared the power with the result obtained from a different method [9]. We fitted the points of this work with \( \delta p_T/p_T = \beta (dN_{\text{ch}}/d\eta)^{\alpha/1.19} \) assuming \( dN_{\text{ch}}/d\eta \propto (N_{\text{part}})^{1.19} \) [10], and obtained \( \alpha \) as 0.64±0.07. Assuming the spectra shape follows a power-law with the power \( n \), one can write the relation between \( \delta p_T/p_T \) and \( R_{AA} \) as:

\[
S_{\text{loss}} \equiv \delta p_T/p_T = \beta N_{\text{part}}^\alpha, R_{AA} = (1 - S_{\text{loss}})^{n-2} = (1 - \beta N_{\text{part}}^\alpha)^{n-2}
\]

Following this relation, we obtained the power \( \alpha \) as 0.57±0.13 from the fit to the integrated \( R_{AA} \) as a function of \( N_{\text{part}} \) in the literature [9]. We therefore confirmed that the powers obtained by the two methods are consistent.
4. Summary

We presented PHENIX measurement of the fractional momentum loss ($\delta p_T/p_T$) of high $p_T$ identified hadrons. By looking at the $\delta p_T/p_T$ instead of $R_{AA}$, we found many interesting features. The $\delta p_T/p_T$ of high $p_T$ $\pi^0$ which are computed from 39 GeV Au+Au over to 2.76 TeV Pb+Pb are found to vary by a factor of six. We plotted the $\delta p_T/p_T$ against several global variables, $N_{\text{part}}$, $N_{\text{qp}}$ and $dN_{\text{ch}}/d\eta$. It was found that 200 GeV Au+Au points are merging into the central 2.76 TeV Pb+Pb points when plotting $\delta p_T/p_T$ against $dN_{\text{ch}}/d\eta$. We performed a power-law fit to the $\delta p_T/p_T$ vs $dN_{\text{ch}}/d\eta$, and obtained a power that is consistent with the one obtained from the fit to the integrated $R_{AA}$. We are going to add points from other systems to systematically investigate the $\delta p_T/p_T$.

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