

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 π^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_{qp} and $dN_{\text{ch}}/d\eta$, 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 $dN_{\text{ch}}/d\eta$.

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 π^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} ($\equiv (dN_{\text{AA}}/dydp_T)/(\langle T_{\text{AA}} \rangle d\sigma_{pp}/dydp_T)$), 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



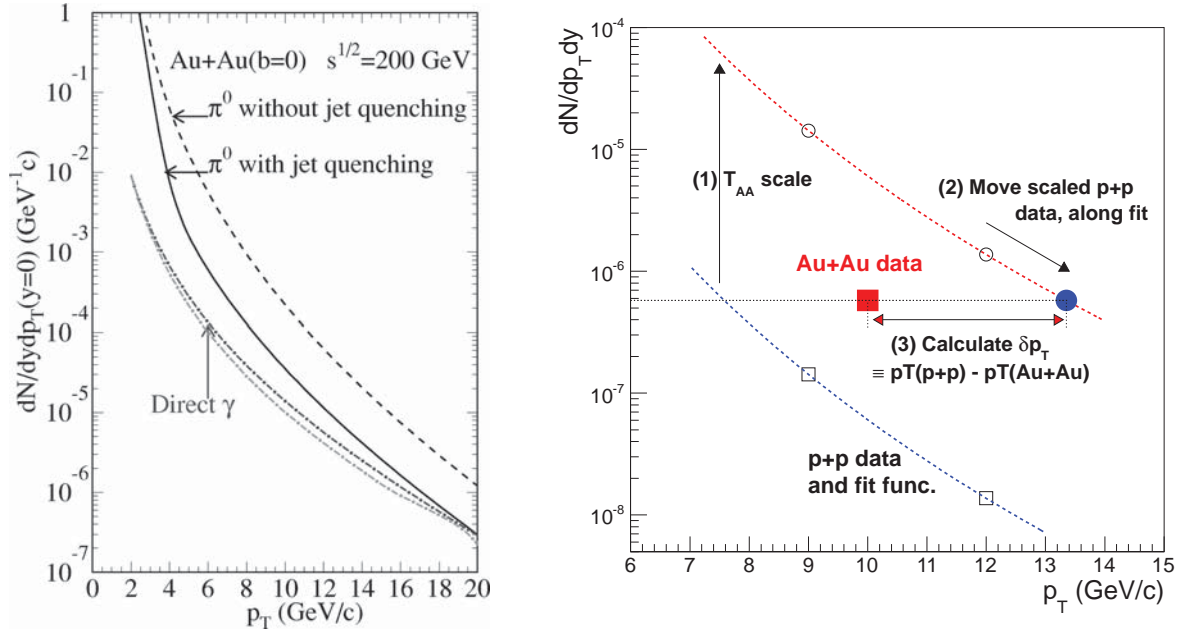


Figure 1. (a, left) A calculation demonstrating that the suppression of the π^0 yield can be modeled by a relative transverse momentum shift of the transverse momentum spectra in A+A collisions. (b, right) Method of calculating average $\delta p_T/p_T$. We scale the differential cross-section measured 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 π^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 π^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 ~ 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

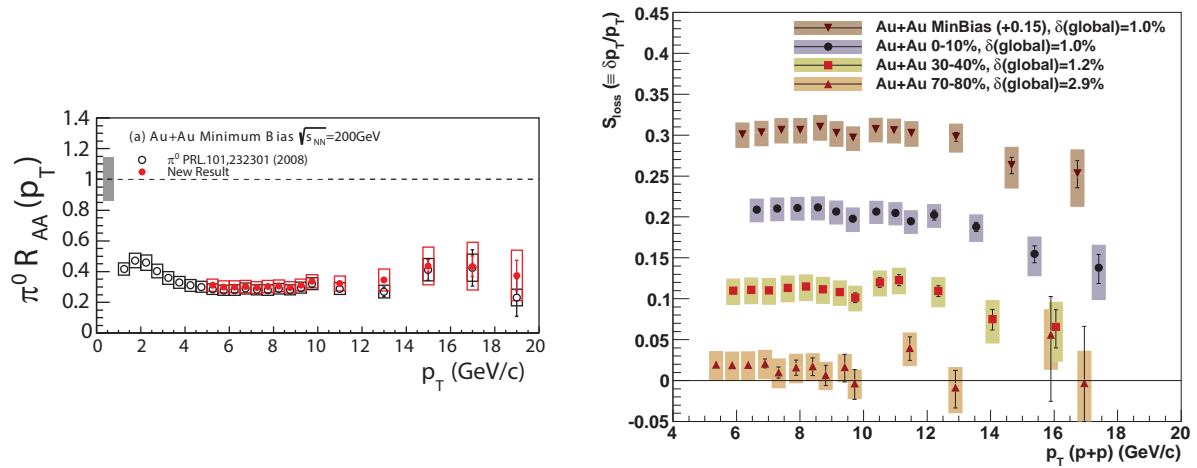


Figure 2. (a, left) R_{AA} of π^0 's for 200 GeV Au+Au collisions obtained from RHIC Year-7 run. The gray bars around the unity shows the quadratic sum of p+p luminosity and T_{AA} uncertainties. (b, right) $\delta p_T/p_T$ for the same dataset.

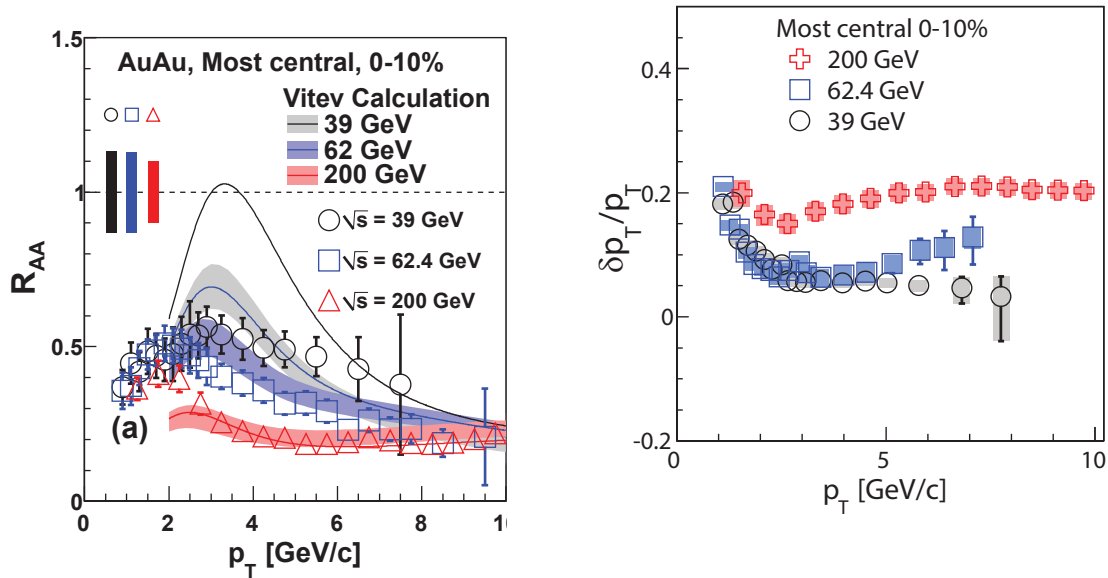


Figure 3. (a, left) R_{AA} of π^0 's for 39, 62 in 0-10 % Au+Au collisions obtained from RHIC Year-10 run and in 0-10 % 200 GeV Au+Au collisions from RHIC Year-10 run. The bands around the unity shows the quadratic sum of p+p luminosity and T_{AA} uncertainties for each cms energies. (b, right) $\delta p_T/p_T$ 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 (σ_{qq}^{inel}) for each collision energy such that the inelastic nucleon-nucleon cross section (σ_{NN}^{inel}) is reproduced. Then the model is modified to

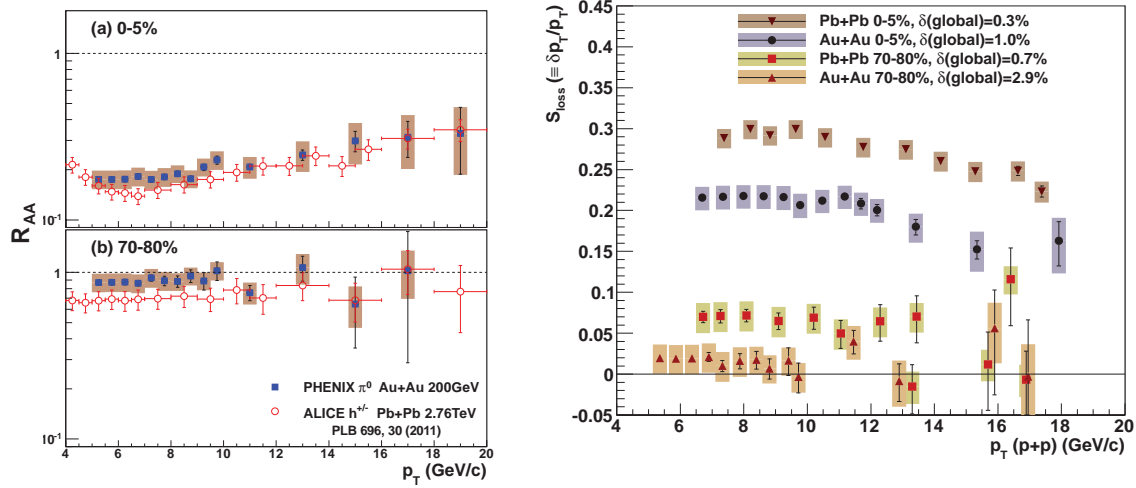


Figure 4. (a, left) R_{AA} of π^0 's for 200 GeV Au+Au collisions obtained from RHIC Year-7 run and charged hadrons for 2.76 TeV Pb+Pb collisions obtained by the ALICE experiment at LHC [6]. (b, right) $\delta p_T/p_T$ for the same dataset.

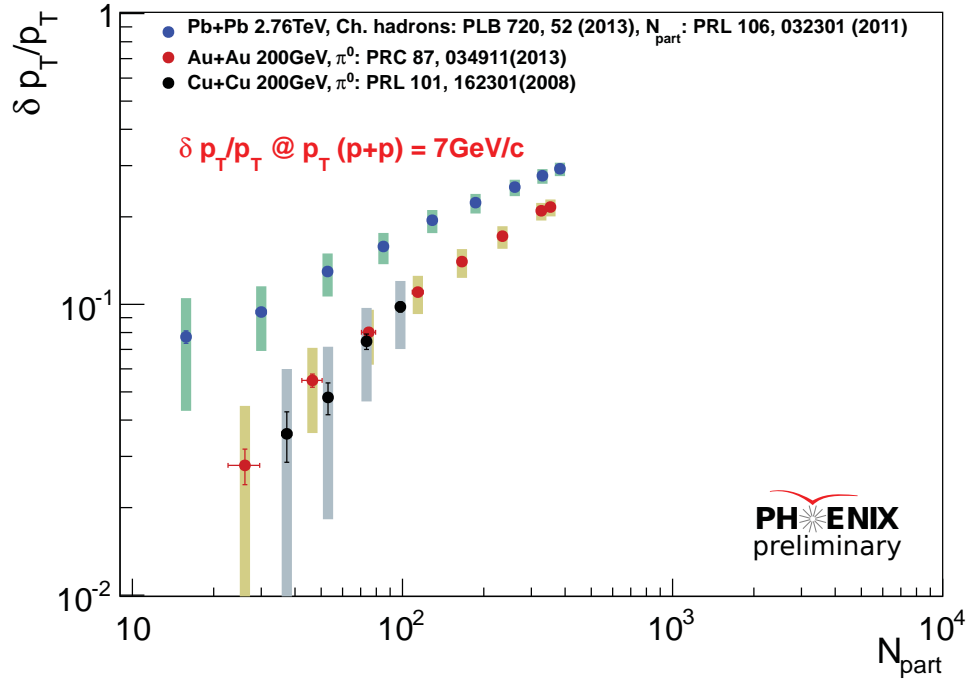


Figure 5. $\delta p_T/p_T$ as a function of N_{part} for π^0 's in 200 GeV Au+Au and Cu+Cu collisions measured by PHENIX and charged hadrons in 2.76 TeV Pb+Pb collisions measured by ALICE.

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:

$$\rho^{\text{proton}}(r) = \rho_0^{\text{proton}} \times e^{-ar}$$

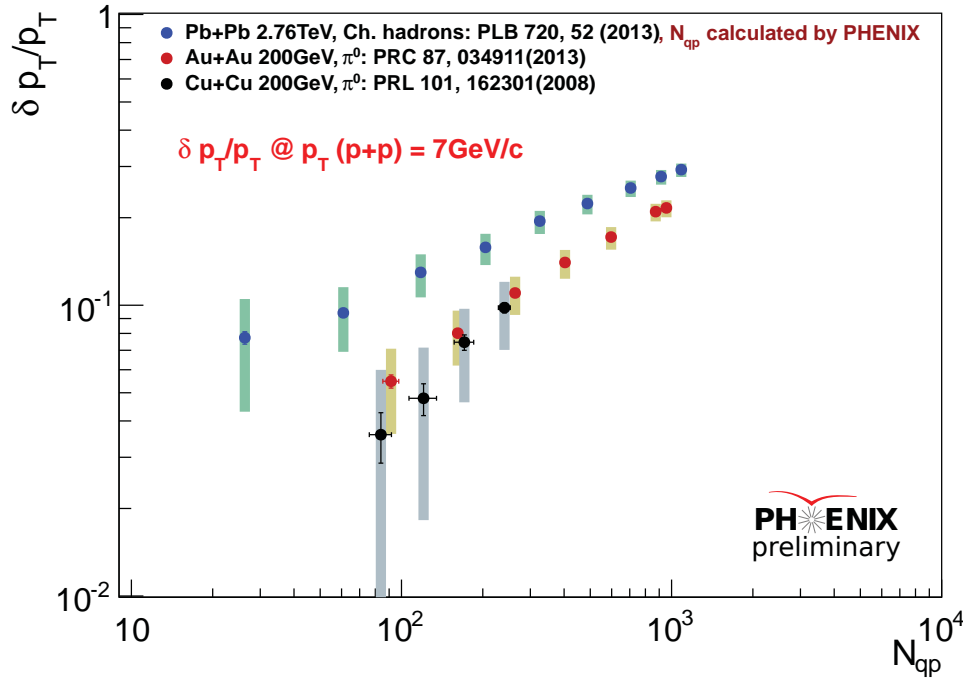


Figure 6. $\delta p_T/p_T$ as a function of N_{qp} for π^0 's in 200 GeV Au+Au and Cu+Cu collisions measured by PHENIX and charged hadrons in 2.76 TeV Pb+Pb collisions measured by ALICE.

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_{part} . In Fig. 6, the similar feature as the previous plot is seen. Since the N_{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_{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_{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 α 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 α as 0.57 ± 0.13 from the fit to the integrated R_{AA} as a function of N_{part} in the literature [9]. We therefore confirmed that the powers obtained by the two methods are consistent.

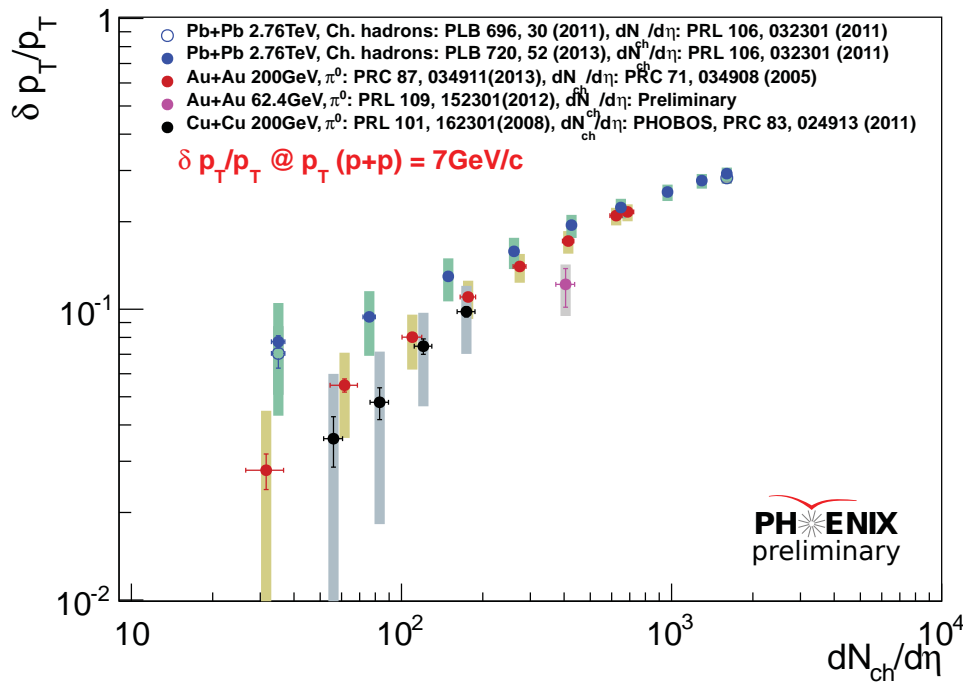


Figure 7. $\delta p_T/p_T$ as a function of $dN_{ch}/d\eta$ for π^0 's in Au+Au collisions at 200 GeV and 62.4 GeV, and in Cu+Cu collisions at 200 GeV measured by PHENIX and charged hadrons in 2.76 TeV Pb+Pb collisions measured by ALICE.

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 π^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_{part} , N_{qp} and $dN_{ch}/d\eta$. 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 $dN_{ch}/d\eta$. We performed a power-law fit to the $\delta p_T/p_T$ vs $dN_{ch}/d\eta$, 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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