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 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, $N_{\rm part}$, $N_{\rm qp}$ and $dN_{\rm ch}/d\eta$, 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 $dN_{\rm ch}/d\eta$.

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 [1]. 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 [2]. The PHENIX experiment [3] has been exploring the highest p_T region with single π^0 mesons which are leading hadrons of jets. We show a calculation on the energy loss of partons published almost 20 years ago in Fig. 1(a). 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, $R_{\rm AA}$ ($\equiv (dN_{\rm AA}/dydp_T)/(\langle T_{\rm AA}\rangle d\sigma_{pp}/dydp_T)$), and quantified the energy loss effect via its suppression. We here present the momentum shift of high p_T hadrons instead of $R_{\rm AA}$.

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 partons using the hadron p_T spectra measured in $p+p$ and Au+Au collisions [4]. Since the number of data points is finite, a fit to the 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 inversely converting the quadratic sum of the uncertainties on the yields of Au+Au and $p+p$ points, using the $p+p$ fit function. Statistical and systematic uncertainties are individually calculated in the same way.

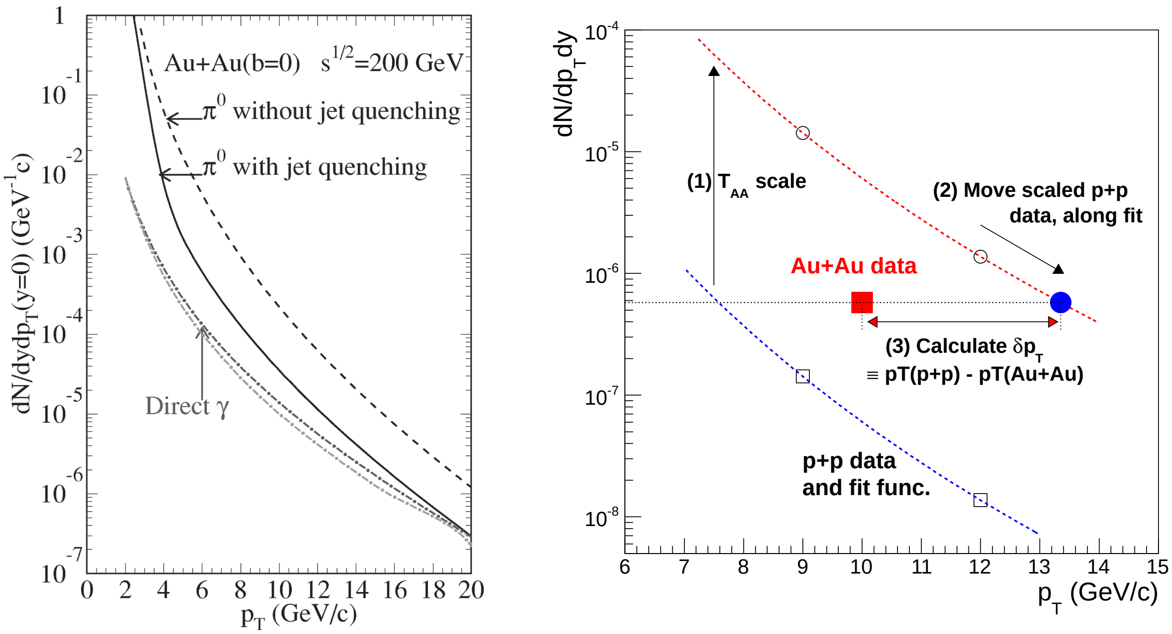

Figure 1. (a, left) A calculation demonstrating that the suppression of the π^0 yield is resulted in from the shift of the momentum spectra in A+A collisions. (b, right) Method of calculating average $\delta p_\mathrm{T}/p_\mathrm{T}$. We scaled the $p+p$ yield by T_AA corresponding to centrality selection of Au+Au data, shifted the $p+p$ points closest to Au+Au in yield, and calculated the momentum difference of $p+p$ and Au+Au points.

The uncertainties on T_AA and p+p luminosity are not plotted but mentioned in plots. Fig. 2(a) show the R_{AA} for the π^0's in Au+Au collisions at $\sqrt{s_\mathrm{NN}}$ =200 GeV from the RHIC Year-7 run. Using the $\delta p_\mathrm{T}/p_\mathrm{T}$ calculation method, we obtained the $\delta p_\mathrm{T}/p_\mathrm{T}$ 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 $\sqrt{s_\mathrm{NN}}$ =39, 62 and

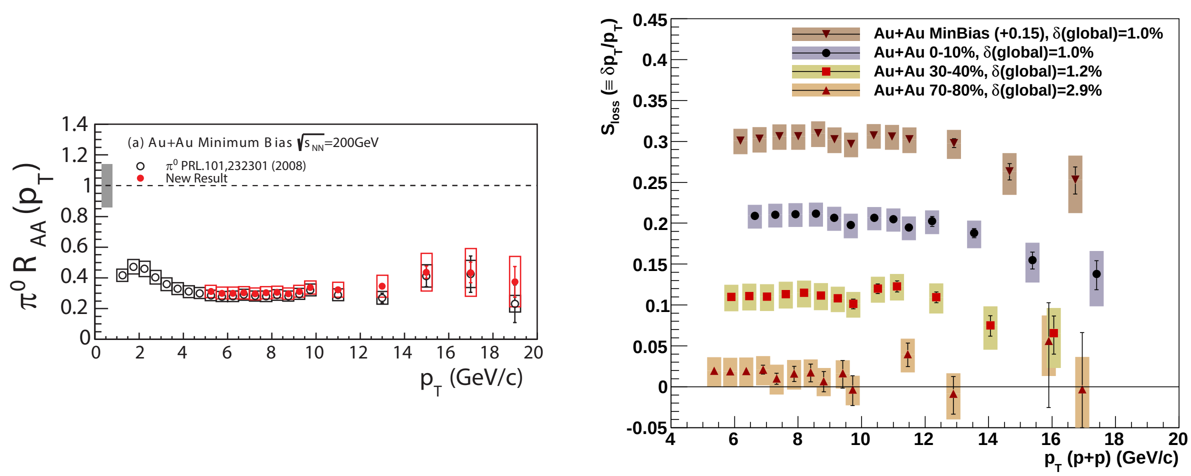

Figure 2. (a, left) R_{AA} of π^0's for 200 GeV Au+Au collisions obtained from RHIC Year-7 run. (b, right) $\delta p_\mathrm{T}/p_\mathrm{T}$ for the same dataset.

200 GeV from the RHIC Year-7 and Year-10 runs shown in Fig. 3(a) are replotted in the form of $\delta p_{\mathrm{T}}/p_{\mathrm{T}}$ as shown in Fig. 3(b). The R_{AA}'s look similar even the cms energies are changed

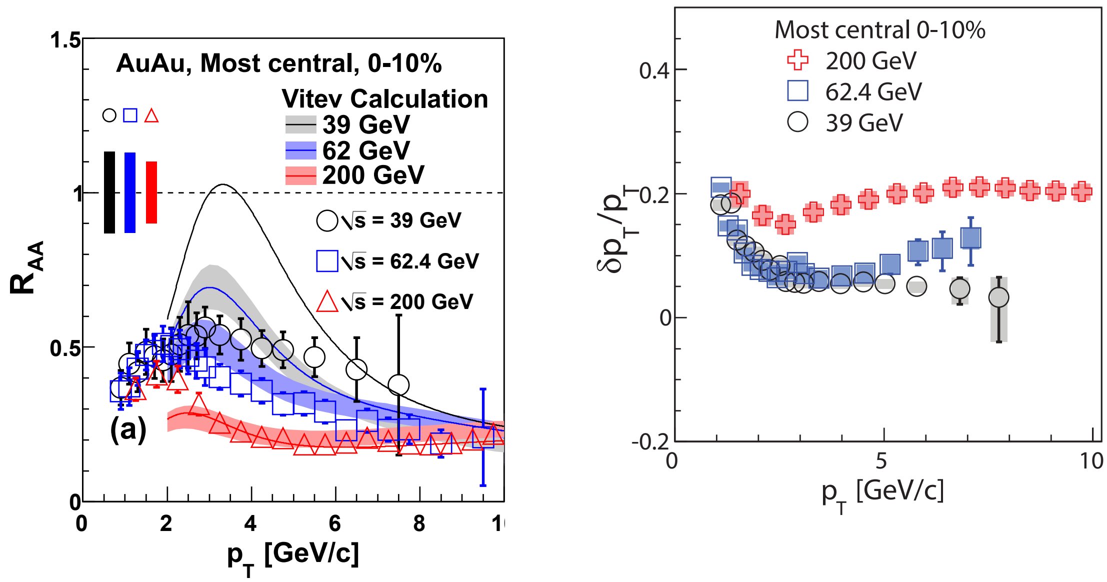

Figure 3. (a, left) R_{AA} of π^0's for 39, 62 in 0-10 % Au+Au collisions obtained from RHIC Year-10 run and in 0-10 % 200 GeV Au+Au collisions from RHIC Year-10 run. (b, right) $\delta p_{\mathrm{T}}/p_{\mathrm{T}}$ for the same dataset.

by a factor of 5 as seen in Fig. 3(a). However, when we look at $\delta p_{\mathrm{T}}/p_{\mathrm{T}}$ for the corresponding dataset, we found that the $\delta p_{\mathrm{T}}/p_{\mathrm{T}}$ changes by a factor of three from 39 to 200 GeV as shown in Fig. 3(b) [5].

The R_{AA}'s also look similar between RHIC and LHC (Fig. 4(a)). Similarly, the $\delta p_{\mathrm{T}}/p_{\mathrm{T}}$ 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 are similar, the $\delta p_{\mathrm{T}}/p_{\mathrm{T}}$'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 $\delta p_{\mathrm{T}}/p_{\mathrm{T}}$

In order to study the systematics of $\delta p_{\mathrm{T}}/p_{\mathrm{T}}$, we plot the $\delta p_{\mathrm{T}}/p_{\mathrm{T}}$ against several global variables such as N_{part}, N_{qp} (number of quark participants) and $dN_{\mathrm{ch}}/d\eta$. We first plotted the $\delta p_{\mathrm{T}}/p_{\mathrm{T}}$ against N_{part} as shown in Fig. 5. All the plots shown in this section are at $p_{\mathrm{T}}(p+p) = 7$ GeV/c in order to reach the hard scattering regime. In the N_{part} scaling we see that the Cu+Cu and Au+Au are nicely lined up, implying that within the same cms energy, the $\delta p_{\mathrm{T}}/p_{\mathrm{T}}$ scales with N_{part}. This is consistent with the fact that R_{AA} is similar at same N_{part} between Cu+Cu and 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 $\delta p_{\mathrm{T}}/p_{\mathrm{T}}$ 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 ($\sigma_{qq}^{\mathrm{inel}}$) for each collision energy such that the inelastic nucleon-nucleon cross section ($\sigma_{NN}^{\mathrm{inel}}$) is reproduced. Then the model is modified to 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

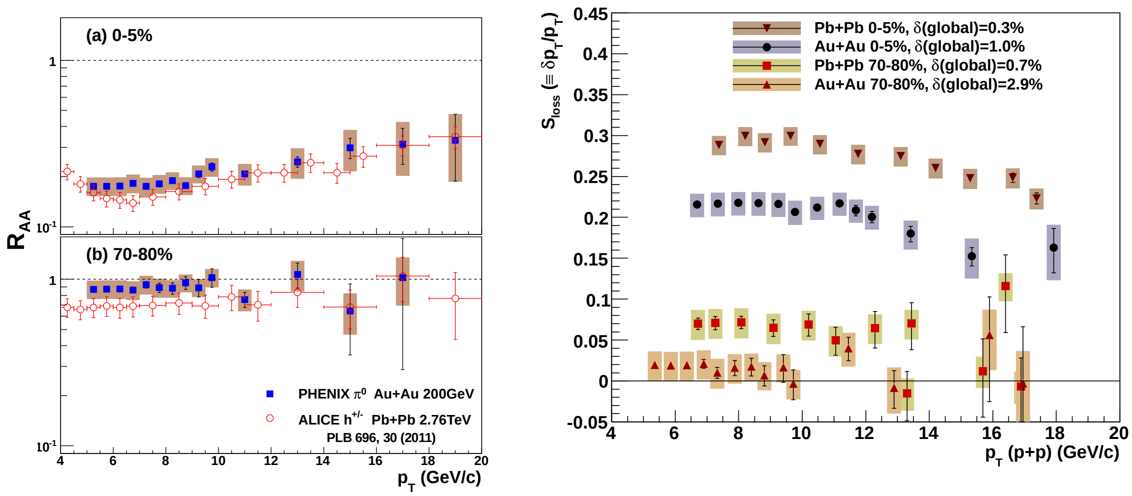

Figure 4. (a, left) R_{AA} of π^0's for 200 GeV Au+Au collisions obtained from RHIC Year-7 run and charged hadrons for 2.76 TeV Pb+Pb collisions obtained by the ALICE experiment at LHC [6]. (b, right) $\delta p_{\mathrm{T}}/p_{\mathrm{T}}$ for the same dataset.

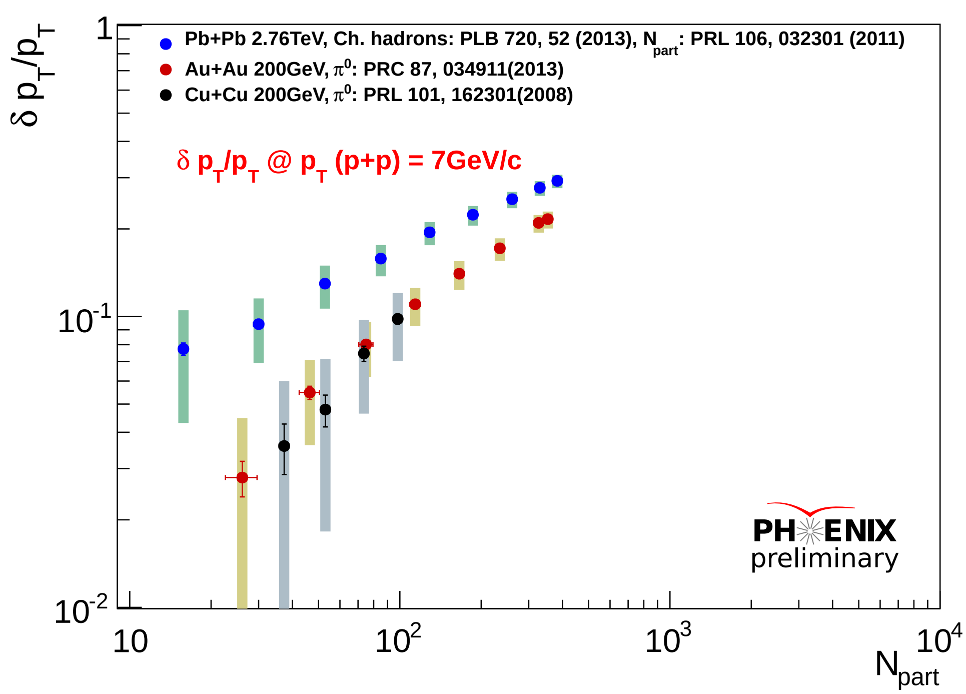

Figure 5. $\delta p_{\mathrm{T}}/p_{\mathrm{T}}$ as a function of N_{part} for π^0's in 200 GeV Au+Au and Cu+Cu collisions measured by PHENIX and charged hadrons in 2.76 TeV Pb+Pb collisions measured by ALICE.

nucleon following the distribution of:

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

where $a = \sqrt{12}/r_m = 4.27\,\mathrm{fm}^{-1}$ and $r_m = 0.81\,\mathrm{fm}$ 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

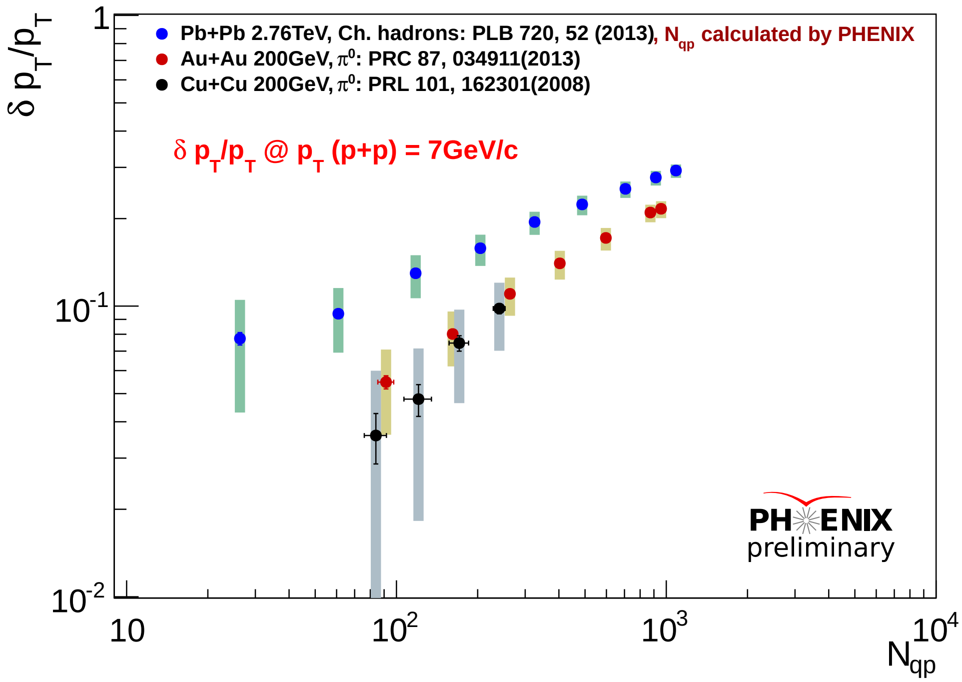

Figure 6. $\delta p_{\mathrm{T}}/p_{\mathrm{T}}$ as a function of N_{qp} for π^0's in 200 GeV Au+Au and Cu+Cu collisions measured by PHENIX and charged hadrons in 2.76 TeV Pb+Pb collisions measured by ALICE.

transverse to the beam axis satisfies the condition of $d < \sqrt{\sigma_{qq}^{\mathrm{inel}}/\pi}$. 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. Finally, we plotted the $\delta p_{\mathrm{T}}/p_{\mathrm{T}}$ against the charged multiplicity, $dN_{\mathrm{ch}}/d\eta$, as shown in Fig. 7. In this plot, we added one 62 GeV Au+Au point which is 0-10 % centrality. We expect that $dN_{\mathrm{ch}}/d\eta$ 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 each other as going to lower $dN_{\mathrm{ch}}/d\eta$. 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 $\delta p_{\mathrm{T}}/p_{\mathrm{T}}$ vs $dN_{\mathrm{ch}}/d\eta$ 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 $\delta p_{\mathrm{T}}/p_{\mathrm{T}} = \beta(dN_{\mathrm{ch}}/d\eta)^{\alpha/1.19}$ assuming $dN_{\mathrm{ch}}/d\eta \propto (N_{\mathrm{part}})^{1.19}$ [10], and obtained α as 0.64$\pm$0.07. Assuming the spectra shape follows a power-law with the power n, one can write the relation between $\delta p_{\mathrm{T}}/p_{\mathrm{T}}$ and R_{AA} as:

$$S_{\mathrm{loss}} \equiv \delta p_{\mathrm{T}}/p_{\mathrm{T}} = \beta {N_{\mathrm{part}}}^{\alpha}, R_{\mathrm{AA}} = (1 - S_{\mathrm{loss}})^{n-2} = (1 - \beta {N_{\mathrm{part}}}^{\alpha})^{n-2}$$

Following this relation, we obtained the power α as 0.57$\pm$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.

4. Summary

We presented PHENIX measurement of the fractional momentum loss ($\delta p_{\mathrm{T}}/p_{\mathrm{T}}$) of high p_{T} identified hadrons. By looking at the $\delta p_{\mathrm{T}}/p_{\mathrm{T}}$ instead of R_{AA}, we found many interesting features.

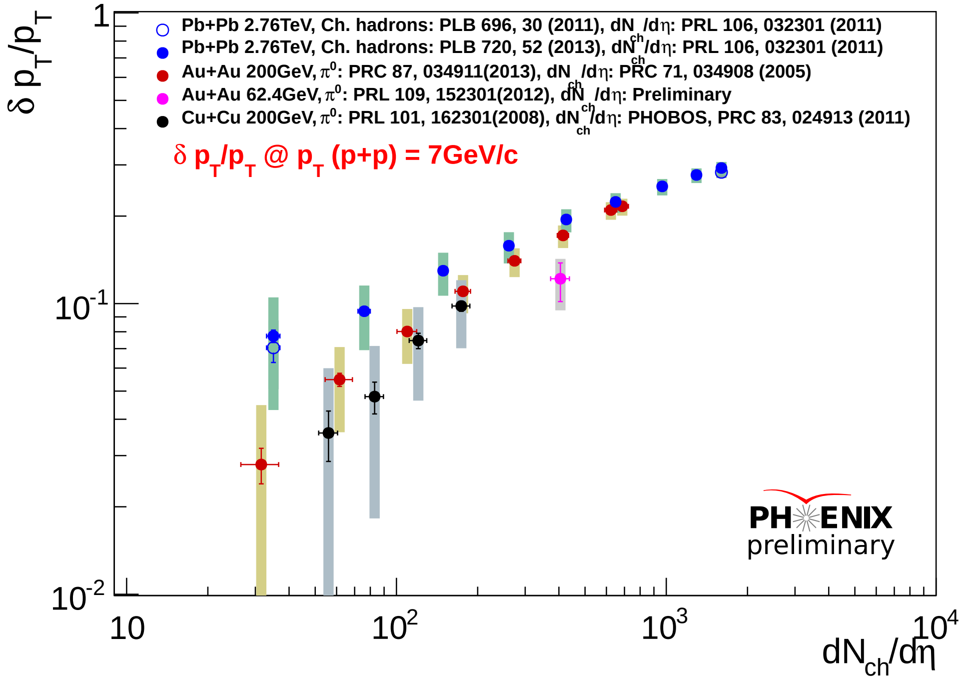

Figure 7. $\delta p_{\rm T}/p_{\rm T}$ as a function of $dN_{\rm ch}/d\eta$ for π^0's in Au+Au collisions at 200 GeV and 62.4 GeV, and in Cu+Cu collisions at 200 GeV measured by PHENIX and charged hadrons in 2.76 TeV Pb+Pb collisions measured by ALICE.

The $\delta p_{\rm T}/p_{\rm T}$ of high $p_{\rm T}$ 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 $\delta p_{\rm T}/p_{\rm T}$ against several global variables, $N_{\rm part}$, $N_{\rm qp}$ and $dN_{\rm ch}/d\eta$. It was found that 200 GeV Au+Au points are merging into the central 2.76 TeV Pb+Pb points when plotting $\delta p_{\rm T}/p_{\rm T}$ against $dN_{\rm ch}/d\eta$. We performed a power-law fit to the $\delta p_{\rm T}/p_{\rm T}$ vs $dN_{\rm ch}/d\eta$, and obtained a power that is consistent with the one obtained from the fit to the integrated $R_{\rm AA}$. We are going to add points from other systems to systematically investigate the $\delta p_{\rm T}/p_{\rm T}$.

References

[1] X. -N. Wang, Phys. Rev. C **58**, 2321 (1998).
[2] S. S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **91**, 072301 (2003).
[3] K. Adcox *et al.* [PHENIX Collaboration], Nucl. Instrum. Meth. A **499**, 469 (2003).
[4] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. C **87**, 034911 (2013).
[5] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **109**, 152301 (2012).
[6] K. Aamodt *et al.* [ALICE Collaboration], Phys. Lett. B **696**, 30 (2011).
[7] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **101**, 162301 (2008) [arXiv:0801.4555 [nucl-ex]].
[8] S. S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. C **89**, no. 4, 044905 (2014).
[9] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **101**, 232301 (2008).
[10] S. S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. C **71**, 034908 (2005) [Erratum-ibid. C **71**, 049901 (2005)].