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Search for the onset of baryon anomaly at RHIC-PHENIX

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Abstract. The baryon production mechanism at the intermediate p_T (2 - 5 GeV/c) at RHIC is still not well understood. The beam energy scan data in Cu+Cu and Au+Au systems at RHIC may provide us a further insight on the origin of the baryon anomaly and its evolution as a function of $\sqrt{s_{NN}}$. In 2005 RHIC physics program, the PHENIX experiment accumulated the first intensive low beam energy data in Cu+Cu collisions. We present the preliminary results of identified charged hadron spectra in Cu+Cu at $\sqrt{s_{NN}} = 22.5$ and 62.4 GeV using the PHENIX detector. The centrality and beam energy dependences of (anti)proton to pion ratios and the nuclear modification factors for charged pions and (anti)protons are presented.

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1 Introduction

One of the most surprising observations at RHIC is a particle type dependence of hadron yield suppression at the intermediate transverse momentum p_T (2 - 5 GeV/c) [1,2]. In Au+Au central collisions at $\sqrt{s_{NN}} = 200$ GeV, yields for mesons are largely suppressed [3] with respect to the yields in proton-proton collisions in the intermediate p_T, while those for baryons are not suppressed, and show a binary nucleon-nucleon collision (N_{coll}) scaling.

In d+Au experiment at RHIC, there is also a particle type dependence in the nuclear modification factor R_{AA} [4]. The R_{AA} for protons in d+Au is larger than that for pions and kaons. This observations can be understood by Cronin effect [5,6]. It is found, however, that the particle species dependence in d+Au is not large enough to account for the absence of suppression for protons as seen in Au+Au central collisions at RHIC. This phenomena in Au+Au central collisions is called "Baryon Anomaly at RHIC". To explain the baryon anomaly, many theoretical models has been proposed, such as quark recombination models [7], and a hybrid model of hydrodynamics with a color glass condensate (CGC) and jet quenching [8]. All of these models are able to reproduce the experimental data qualitatively for both pions and protons.

On the elliptic flow (v_2) measurements, there is a also clear particle species dependence [9]. The number of constituent quark scaling of v_2 shows a clear universal curve regardless of the particle species, and these scaling properties support the quark recombination picture for the hadron production at RHIC.

In order to test the quark recombination picture, ϕ meson is one of the ideal test particles, because the mass is similar to protons', but it's a meson particle. If the hydrodynamical collective flow is a dominant source of baryon anomaly, ϕ meson's R_{AA} should follow the data for protons (no suppression) due to its heavy mass. Thanks to the high statistics data in Au+Au collisions at $\sqrt{s_{NN}} =$ 200 GeV taken in 2004 RHIC run, it is confirmed that the R_{AA} for ϕ mesons behaves like a meson [10], and its v_2 follows the same universal quark number scaling curve of all other particle species [11]. Giving the fact that ϕ mesons behave like a "meson", it is now widely believed that the quark recombination is one of the main mechanisms for the hadronization process at the intermediate p_T in central Au+Au collisions at RHIC.

Now the key questions are; where the onset of the baryon anomaly is, and how they evolve as a function of beam energy. In order to answer these questions, the lower energy beam data in Cu+Cu collisions were taken during the 2005 RHIC run by the PHENIX experiment. In this paper, we present the preliminary results of single particle p_T spectra for identified charged particles in Cu+Cu collisions at $\sqrt{s_{NN}} = 22.5$ GeV and 62.4 GeV measured by the PHENIX experiment. The beam energy and centrality dependences of the particle ratios and nuclear modification factors are presented and discussed.

2 PID charged particle spectra analysis

The low beam energy data sets in Cu+Cu have been taken during the 2005 RHIC run. We analyzed 5.2 M minimum bias events for 22.5 GeV Cu+Cu, and 66.5 M minimum bias events for 62.4 GeV Cu+Cu data set. We constructed the tracks within a collision vertex ± 30 cm from the center of the spectrometer.

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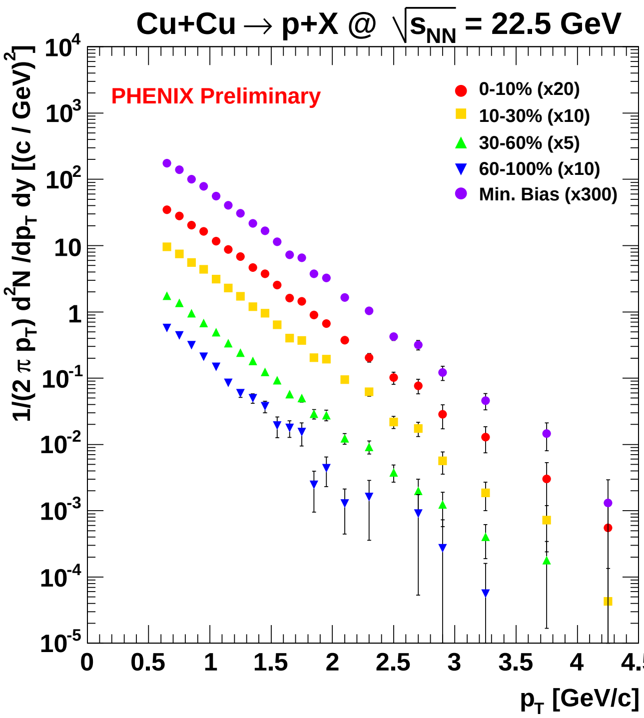

Fig. 1. Centrality dependence of p_T spectra for protons in Cu+Cu collisions at $\sqrt{s_{NN}} = 22.5$ GeV. No feeddown correction is applied.

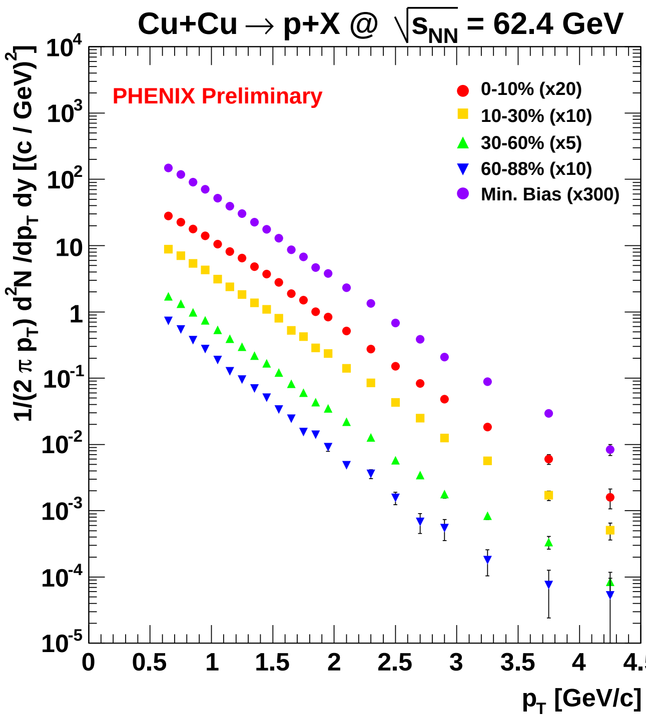

Fig. 2. Centrality dependence of p_T spectra for protons in Cu+Cu collisions at $\sqrt{s_{NN}} = 62.4$ GeV. No feeddown correction is applied.

Charged particle tracks are reconstructed by the Drift Chamber (DC) based on a combinatorial Hough transform. The first layer of Pad Chamber (PC1) is used to measure the position of the hit in the longitudinal direction (along the beam axis). When combined with the location of the collision vertex along the beam axis (from the Beam-Beam Counter(BBC)), the PC1 hit gives the polar angle of the track. Only tracks with valid information from both the DC and PC1 are used in the analysis. In order to associate a track with a hit on the high resolution Time-of-Flight detector (TOF), the track is projected to its expected hit location on the TOF. Tracks are required to have a hit on the TOF within $\pm 2\sigma$ of the expected hit location in both the azimuthal and beam directions. The charged particle identification (PID) is performed by using the combination of three measurements: time-of-flight from the BBC and the TOF, momentum from the DC, and flight path length from the collision vertex point to the hit position on the TOF.

The geometrical acceptance and the in-flight decay are corrected by the GEANT based Monte Carlo simulation. No occupancy correction (detector inefficiency correction due to the high track densities) is applied. The expected occupancy correction is below 4% in Cu+Cu 62.4 GeV at the most central events and less for peripheral collisions, the correction is negligible. No weak decay feeddown correction is applied for proton and antiproton spectra in this analysis.

The centrality determination in Cu+Cu 22.5 GeV is purely based on the PC1 hit multiplicity in order to avoid an effect of the spectator nucleons. Since at $\sqrt{s_{NN}} =$ 22 GeV the beam rapidity gap is quite narrower than those at the higher beam energy, the BBC (located in $3.0 < |\eta| < 3.9$) is able to see the spectator nucleons. The PC1 multiplicity distribution with the BBC z vertex correction is subdivided by four centrality bins. For Cu+Cu 62.4 GeV data, we use the charge distribution measured by the BBC. We obtain the number of binary collisions (N_{coll}) and the number of participant nucleons (N_{part}) for each data set and each centrality bin by the Glauber Monte Carlo calculation in PHENIX.

3 Results

We present the following preliminary results in Cu+Cu collisions at $\sqrt{s_{NN}} = 22.5$ GeV and 62.4 GeV, measured by the PHENIX experiment. (1) the identified charged particle p_T spectra, (2) particle ratios (p/π^+, $\overline{p}/\pi^-$) as a function of p_T for each centrality class, and (3) the nuclear modification factor R_{AA} for pions and (anti)protons as a function of p_T.

3.1 p_T spectra

Fig. 1 and Fig. 2 are the centrality dependences of p_T spectra for protons in Cu+Cu collisions at $\sqrt{s_{NN}} = 22.5$ GeV

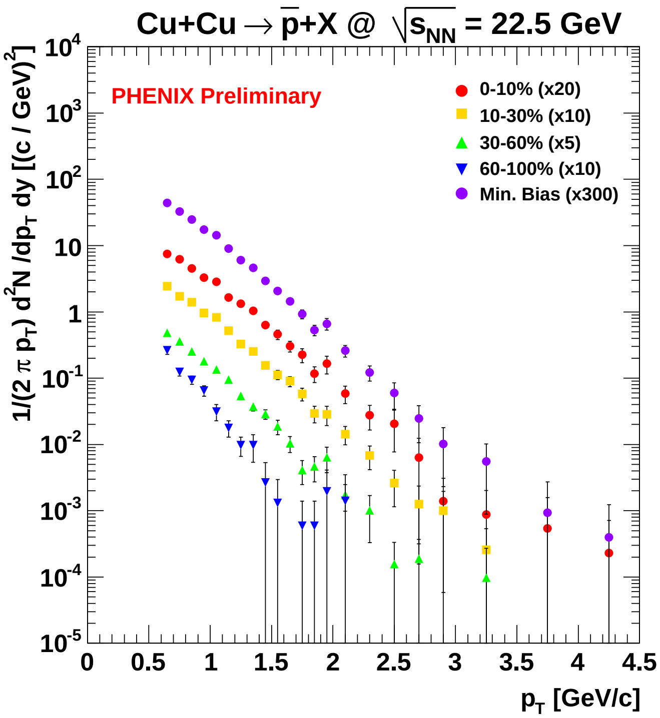

Fig. 3. Centrality dependence of p_T spectra for $\overline{p}$ in Cu+Cu collisions at $\sqrt{s_{NN}}$ = 22.5 GeV. No feeddown correction is applied.

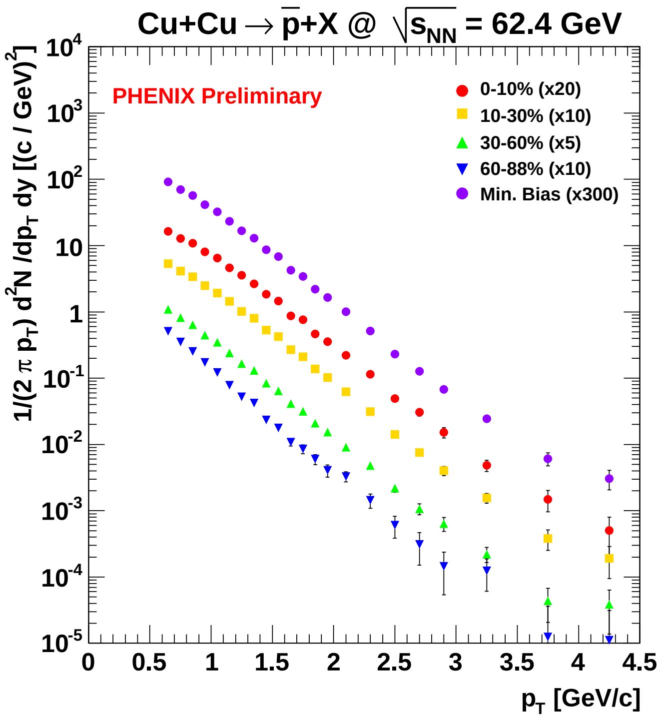

Fig. 4. Centrality dependence of p_T spectra for $\overline{p}$ in Cu+Cu collisions at $\sqrt{s_{NN}}$ = 62.4 GeV. No feeddown correction is applied.

and 62.4 GeV, respectively. The p_T spectra for antiprotons are shown in Fig. 3 and 4. No weak decay feeddown correction is applied for both protons and antiprotons spectra and both beam energies. We measured the spectra in four centrality bins (0-10%, 10-30%, 30-60%, 60-88 or 60-100%) and in the minimum bias events. The p_T spectra for each centrality bin for $\pi^{\pm}$ and $K^{\pm}$ are also measured at both beam energies (see [12]).

3.2 Particle ratios (p/π^+ and $\overline{p}/\pi^-$)

Fig. 5 shows the centrality dependence of p/π^+ and $\overline{p}/\pi^-$ ratios as a function of p_T in Cu+Cu collisions at $\sqrt{s_{NN}} =$ 22.5 GeV. The similar plots for Cu+Cu at 62.4 GeV is shown in Fig. 6.

In 22.5 GeV Cu+Cu data, p/π^+ ratio is significantly larger than those in the higher beam energy in Au+Au [1], and it is increasing as a function of collision centrality. This large p/π^+ ratios can be understood by the influence of the incoming nucleons from the beams. For $\overline{p}/\pi^-$ ratios, (almost) no centrality dependence is observed, and the ratios are constant at the value of 0.3 - 0.4 at $p_T = 2.0$ GeV/c, which is close to the expected values in the fragmentation and the data in p+p collisions.

In 62.4 GeV Cu+Cu data, the influence of incoming proton are smaller than those in Cu+Cu 22.5 GeV, as seen in p/π^+ ratios in Fig. 6. The centrality dependence of $\overline{p}/\pi^-$ is seen. In the most central collisions, $\overline{p}/\pi^-$ ratio is about 0.6 at $p_T = 2$ GeV/c, and in the peripheral collisions, the value becomes consistent with that for p+p collisions.

Fig. 7 shows the beam energy dependence of p/π^+ and $\overline{p}/\pi^-$ ratios in Cu+Cu collisions from $\sqrt{s_{NN}} = 22.5$ GeV to 200 GeV [13]. There is a clear beam energy dependence in Cu+Cu from 22.5 GeV to 200 GeV, i.e. p/π^+ ($\overline{p}/\pi^-$) decreases (increases) as a function of $\sqrt{s_{NN}}$, respectively.

For the study of the baryon anomaly at the lower beam energies at RHIC, $\overline{p}/\pi^-$ ratios would be a good measure, because antiprotons are "produced particles", but measured protons are the mixture of produced particles and the incoming protons from the beams. The absence of centrality dependence in $\overline{p}/\pi^-$ ratio in Cu+Cu 22.5 GeV may suggest that there is no baryon anomaly at this beam energy. To conclude this observation, the high statistics data with the heavier collisions system like Au+Au at around 22.5 GeV is necessary in the future RHIC run.

3.3 Nuclear modification factor: R_{AA}

To obtain the nuclear modification factors at the lower energy, we used the p_T spectra at mid-rapidity in p+p collisions at $\sqrt{s}$ = 23 GeV and 63 GeV for kaons and (anti)protons as the reference spectra, measured by the British-Scandinavian Collaboration [14]. Those data are fitted by the empirical functional form (see [12] in detail). For pions, we use the parameterization as described in [15]. The nuclear modification factor R_{AA} is defined as the following equation;

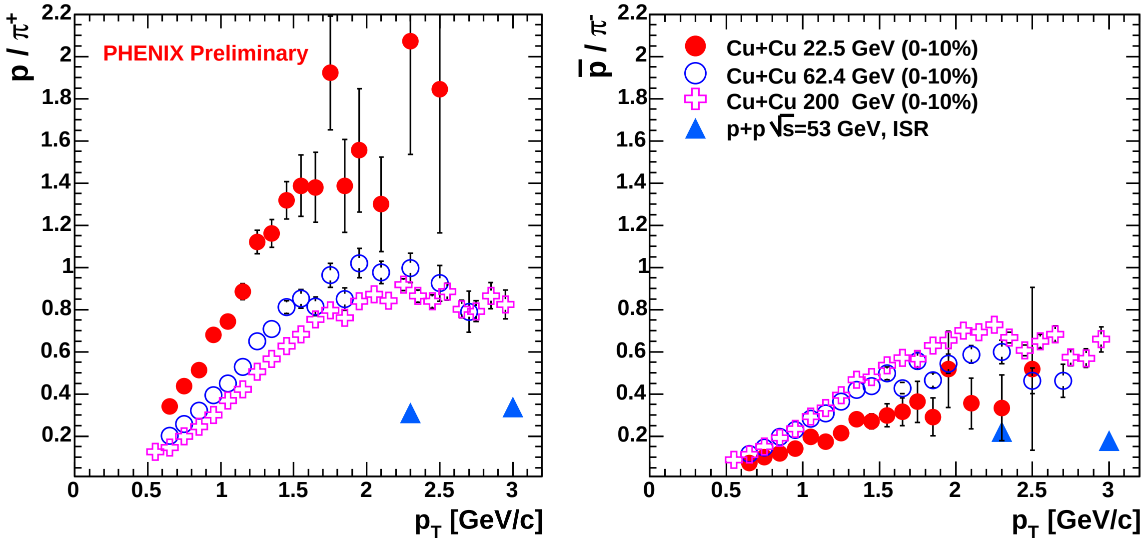

Fig. 7. Beam energy dependence of p/π^+ (left) and $\overline{p}/\pi^-$ (right) ratios as a function of p_T in Cu+Cu collisions from $\sqrt{s_{NN}} =$ 22.5 GeV to 200 GeV. The data for 200 GeV Cu+Cu is taken from the PHENIX preliminary data [13].

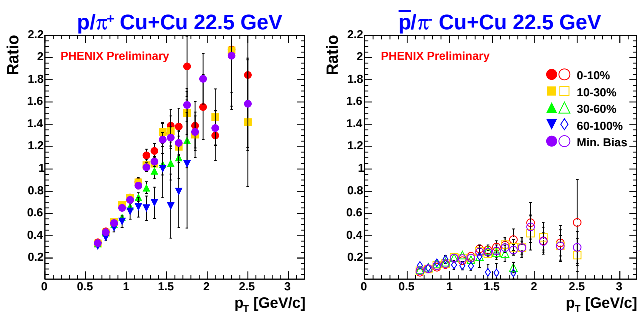

Fig. 5. Centrality dependence of p/π^+ (left) and $\overline{p}/\pi^-$ (right) ratios as a function of p_T in Cu+Cu collisions at $\sqrt{s_{NN}} = 22.5$ GeV. No feeddown correction is applied.

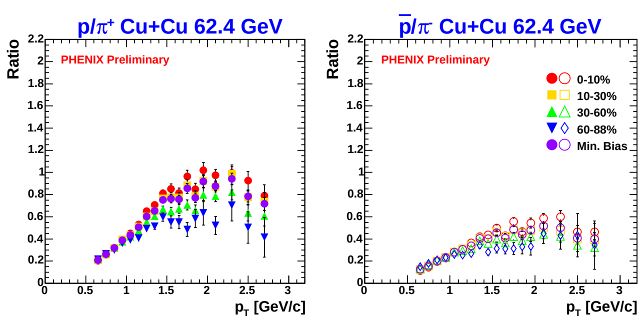

Fig. 6. Centrality dependence of p/π^+ (left) and $\overline{p}/\pi^-$ (right) ratios as a function of p_T in Cu+Cu collisions at $\sqrt{s_{NN}} = 62.4$ GeV. No feeddown correction is applied.

$$R_{AA}(p_T) = \frac{(1/N_{AA}^{evt})\, d^2N_{AA}/dp_T dy}{\langle N_{coll}\rangle/\sigma_{pp}^{inel} \times d^2\sigma_{pp}/dp_T dy}, \qquad (1)$$

where the $\langle N_{coll}\rangle/\sigma_{pp}^{inel}$ is the average Glauber nuclear overlap function, $\langle T_{AuAu}\rangle$.

The R_{AA} for pions and (anti)protons are shown in Fig. 8 for 22.5 GeV Cu+Cu, and in Fig. 9 for 62.4 GeV Cu+Cu. The centrality selection for R_{AA} is 0-10% central collisions for both beam energies. The valules of the average number of collisions used here are $\langle N_{coll}\rangle$ =140.7 ($\sigma_{inel} = 32.2$ mb) for 22.5 GeV Cu+Cu, and $\langle N_{coll}\rangle$ =152.3 ($\sigma_{inel} = 35.6$ mb) for 62.4 GeV Cu+Cu. The systematic error on R_{AA} consists of; (1) $< N_{coll} >$ uncertainty (one σ error as shown in dotted-lines above and below $R_{AA} = 1$), (2) combined systematic errors from p+p reference data and Cu+Cu spectra (not shown in the figures). The statistical errors are shown in the error bars on each data point.

The data shows that there is no suppression on charged pions for both 22.5 and 62.4 GeV Cu+Cu central collisions. For proton's R_{AA}, a clear enhancement is seen and it can be attribute to the effect from the incoming beam nucleons. The value of proton's R_{AA} in 62.4 GeV is slightly smaller than that in 22.5 GeV. The R_{AA} for antiprotons is almost unity at the intermediate p_T for both 22.5 and 62.4 GeV, and they are very similar to those for pions.

In 2006, the PHENIX experiment has successfully collected the new reference p+p data at $\sqrt{s_{NN}} = 62.4$ GeV. The precision of R_{AA} measurements at 62.4 GeV for both Cu+Cu and Au+Au are expected to be improved by using this new p+p data set.

4 Conclusions

In summary, we have measured p_T spectra for $\pi^{\pm}$, $K^{\pm}$, p, $\overline{p}$ in Cu+Cu collisions at $\sqrt{s_{NN}} = 22.5$ and 62.4 GeV.

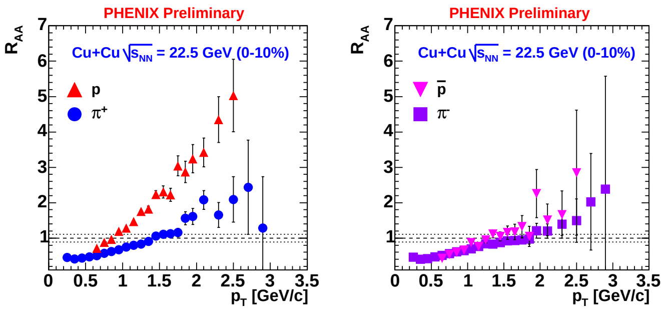

Fig. 8. Nuclear modification factor R_{AA} (0-10%) for charged pions and (anti)protons in Cu+Cu collisions at $\sqrt{s_{NN}} = 22.5$ GeV. The positively charged particles are shown in the left panel, and the negatively charged particles are shown in the right panel.

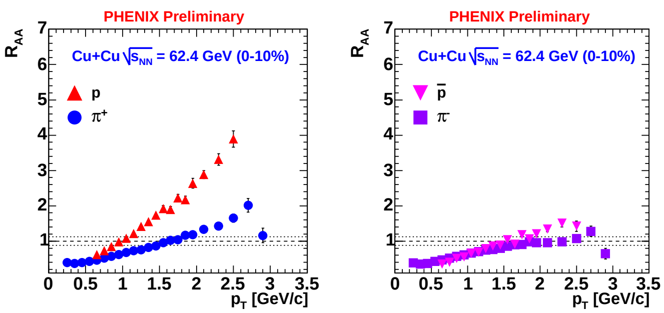

Fig. 9. Nuclear modification factor R_{AA} (0-10%) for charged pions and (anti)protons in Cu+Cu collisions at $\sqrt{s_{NN}} = 62.4$ GeV. The positively charged particles are shown in the left panel, and the negatively charged particles are shown in the right panel.

In 22.5 GeV Cu+Cu data, we observed a larger p/π^+ ratio compared to those at the higher beam energy in Au+Au, and it's increasing as a function of collision centrality. For $\overline{p}/\pi^-$ ratio, almost no centrality dependence is seen, and the ratio is about 0.3 - 0.4 at $p_T = 2.0$ GeV/c, which is close to the value in p+p collisions. In 62.4 GeV Cu+Cu data, p/π^+ ratios are reduced, compared to those in Cu+Cu 22.5 GeV, and the centrality dependence of $\overline{p}/\pi^-$ is seen. There is a clear beam energy dependence on those ratios in Cu+Cu from 22.5 GeV to 200 GeV, i.e. p/π^+ ($\overline{p}/\pi^-$) decreases (increases) as a function of $\sqrt{s_{NN}}$, respectively. The observed $\overline{p}/\pi^-$ ratio may suggest there is no baryon anomaly at 22.5 GeV Cu+Cu collisions. To make this point clearer, a further data set (a high statistics low beam energy data in heavy collision system) is necessary in the future RHIC run.

For the R_{AA}, no suppression is observed for charged pions for both 22.5 and 62.4 GeV in Cu+Cu central collisions. For protons R_{AA}, there is a clear enhancement, which can be attribute to the incoming beam nucleons. The R_{AA} in 62.4 GeV is slightly smaller than that in 22 GeV. The antiprotons R_{AA} is almost unity at the intermediate p_T region for both beam energies.

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