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High $\mathrm{p_T}$ identified hadrons in large and small systems measured by PHENIX

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Abstract. The PHENIX experiment at RHIC measured identified hadrons in several collision systems and centrality classes. Measurements were performed in different years and independent decay modes. The mesons show universal high-p_T supression in the different collision systems which suggest no dependency on the size of the projectile. Yields of π^0 , η, K_S, K^* and Φ mesons measured in large systems show similar suppression pattern at $\sqrt{s_{NN}} = 200$ GeV for similar numbers of participant nucleons. In the intermediate p_T region, between 2 and 5 GeV/c, a significant enhancement of baryon-to-meson ratios compared to those measured in pp collisions is observed. In small systems an ordering ($R_{\mathrm{pA}} > R_{\mathrm{dA}} > R_{\mathrm{HeA}}$) for the mesons ($\pi^0$ and Φ) at mid-p_T was observed.

1. Introduction

One of the most important tools to study the properties of the Quark Gluon Plasma (QGP), formed in relativistic heavy ion collisions [1, 2, 3, 4], is the production of high p_{T} hadrons which as a rule are leading fragments of jets from hard scattered partons at the earliest stage of the collision [5]. Except for possible nuclear modifications of the parton distribution functions, the initial spectrum of the hard scattered partons is expected to be the same irrespective whether the scattering occurred in *pp* or nucleus-nucleus (NN) collision. However, if a hot, dense, colored medium is formed in NN, the scattered parton will traverse it and interact with it, losing energy [6]. Therefore, when it fragments into final state colorless particles, their average momentum, including that of the leading particle, will usually be smaller compared to the momenta of final state particles from a *pp* collision with similar hard scattering. As a result, the spectra of high p_{T} particles in NN will be shifted down with respect to the *pp* spectra scaled by the number of binary nucleon-nucleon collisions. The simplest observable to quantify this shift is the nuclear modification factor R_{AB} defined as

$$R_{AB}^{cent}(p_T) = \frac{1}{T_{AB}^{cent}} \frac{d{N_{AB}}^{cent}/dp_T}{d\sigma_{pp}/dp_T}$$

where A, B are the two nuclei, the upper index ^{cent} is the centrality of the collision as derived from the Glauber-model [7, 8], dN_{AB}^{cent} is the invariant yield of the observable (high p_T hadron), $d\sigma_{pp}/dp_T$ is the cross-section for production of the hadron in *pp* collisions, while T_{AB} is the nuclear overlap function, proportional to the the number of binary nucleon-nucleon collisions at a given centrality ($N_{coll} = T_{AB} * \sigma_{NN}^{inel}$). The volume of the overlap region is characterized by the number of "participating" nucleons N_{part} [9].

The energy loss of the hard scattered parton depends, among others, on the path-length in the medium, which in turn can be controlled to some extent with the collision geometry. The idea and its limitations are illustrated in Figure 1. Partons scattered near the surface of the overlap volume (color shaded area) often have little medium to traverse before they exit in the vacuum and fragment, on the other hand, less frequently, have unusually high path in the medium. (Note that this "surface bias" is a well-known phenomenon, that can be remedied studying the asymmetry of back-to-back dijets, but here we study single inclusive spectra.) The bias clearly increases with the surface to volume ratio, which in turn, for any fixed overlap volume (i.e. N_{part}) is maximum if the two colliding nuclei are of the same size (Au+Au in Figure 1). If one is much smaller than the other (Cu+Au), the same size (N_{part}) overlap volume is closer to spherical, decreasing the surface bias. Therefore, it is very interesting to compare R_{AB} as a function of N_{part} for same size (Au+Au) and different size (Cu+Au) nuclei. Note that both nuclei are spherical which makes determination of the overlap geometry (volume shape) relatively straightforward. The same is not true for U+U collisions; the nuclei are oblong, and their relative orientation can not be clearly determined event-by-event, also, N_{part} is no longer a reliable measure of the overlap volume. Fully aligned "tip-to-tip" or "body-to-body" collisions have the same N_{part}, but much smaller volume and higher energy density in case of "tip-to-tip", and vice versa for "body-to-body" collisions. Nonetheless, in extreme cases they provide the highest possible (at RHIC) energy density QGP, so measuring their R_{AA} is very important.

Another interesting question is to study whether the flavor content of the leading (highest p_{T}) hadron makes any difference in the R_{AB}. The results presented include R_{AB} of mesons with light quarks only, with hidden strangeness and with open strangeness.

Contrary to mesons – where R_{AB} is everywhere at or below unity – baryons are typically enhanced at 2-3 GeV/c in p_{T}. This observation helps to shed light on the physics of hadronization. While at higher p_{T} virtually the sole possible source of hadrons is jet fragmentation, at lower p_{T} this is not the case. If a thermalized QGP was formed, up to a certain baryon p_{T} recombination of three quarks with momenta at the higher end of the thermal

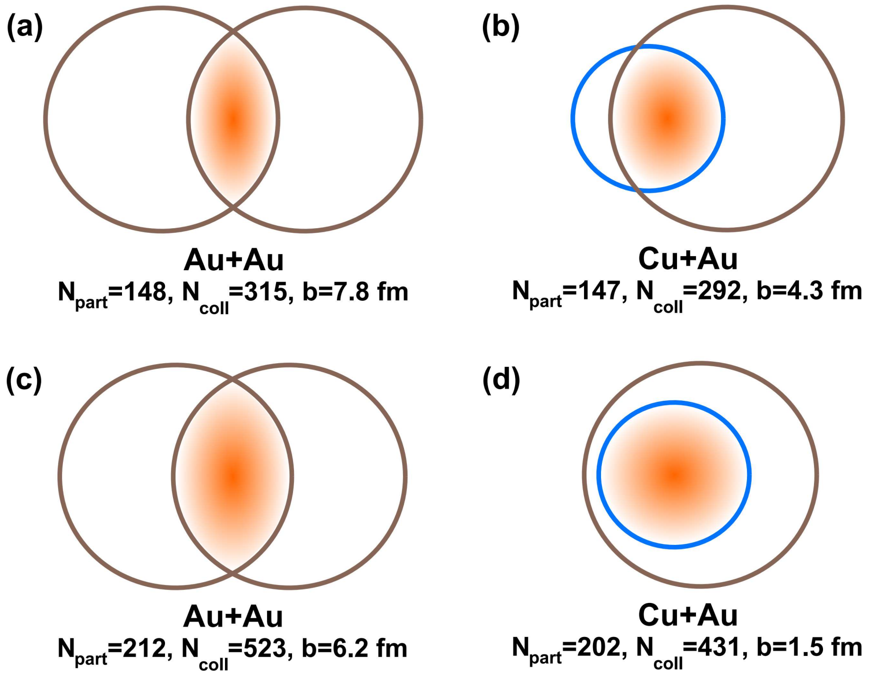

Figure 1. Cartoon showing Au+Au and Cu+Au collisions with comparable N_{part}. On panel (b) the overlap area is asymmetric, and part of the dilute surfaces of Au and Cu (corona) overlap.

distribution is a plausible source of moderate p_{T} baryons. Therefore, the observed "baryon enhancement" is a powerful constraint on the QGP equation of state and the recombination model.

A fourth line of inquiry is collisions of very small and large ions (p+Au, d+Au, ^{3}He+Au). Azimuthal asymmetries in particle emission at mid-rapidity indicated that formation of QGP even in such small systems is a plausible possibility. In large colliding systems such asymmetries always came hand in hand with strong suppression of high p_{T} leading hadrons (small R_{AB}). Therefore, it is paramount to study R_{AB} in small-on-large systems, too, although we should emphasize, that *lack of suppression in p/d/^{3}He+Au in itself does not disprove the creation of QGP in those systems.* Parton energy loss depends on path length in the medium, and even if droplets of QGP are formed, they might be too small to induce any measurable energy loss. – Also, at intermediate p_{T} (2-5 GeV/c) it is important to see whether a "Cronin-type" enhancement can be observed or not [10].

2. Experimental Details

All results presented are from data taken and analyzed by the PHENIX experiment (see Fig. 2) at the Relativistic Heavy Ion Collider (RHIC). The Cu+Au data were collected in 2012 [11], Au+Au in 2004 [12] and 2007 [13], Cu+Cu in 2005 [14], U+U in 2012 [15], p+Au in 2015, d+Au in 2003 [16] and 2008 [17], and ^{3}He+Au in 2014.

For Year-2004 data collision centrality was determined from the correlation between the number of charged particles detected in the Beam-Beam Counters (BBC, $3.0 < |\eta| < 3.9$) and the energy measured in the Zero Degree Calorimeters (ZDC). For all other data the centrality classification was done solely with the total charge observed in the BBC. The two central spectrometer arms cover $|\eta| < 0.35$ and an azimuthal angle range of $\pi/2$ each. The

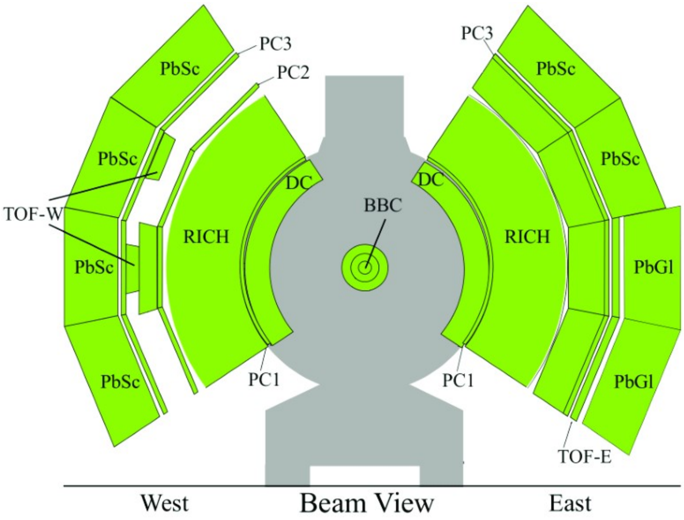

Figure 2. Layout of the PHENIX detector

electromagnetic calorimeter (EMCal) consists of eight sectors, two are composed of lead-glass (PbGl) towers in the bottom sectors of the east arm while the remaining six are composed of lead-scintillator (PbSc) modules. Requiring energy-momentum matching with an associated hit in the Ring Imaging Čerenkov Counter (RICH) provides a hadron rejection factor of better than 10^4 up to 4.9 GeV/c momentum, thus providing good electron identification. Each arm is instrumented with a drift chamber (DC) and pad chambers (PCs) that determine the trajectories, and together with a magnetic field, measure the momenta of charged particles. The Time-of-Flight (TOF) detector identifies charged hadrons, i.e. pions, kaons and protons. Neutral pions and η are measured via the $\pi^0(\eta) \to \gamma\gamma$ decay channel. The K^0_S meson is reconstructed via the $K^0_S \to \pi^0\pi^0 \to 4\gamma$ decay mode. The K^0 and $\overline{K^0}$ mesons are reconstructed via the $K^0 \to K^+\pi^-$ and $\overline{K^0} \to K^-\pi^+$ decay modes, respectively. Φ is reconstructed in the K^+K^- decay channel.

3. Results for large systems

In central Cu+Au collisions the Cu nucleus is fully submerged in the Au nucleus, which results in the reduction of nucleon-nucleon interactions in the corona region of the collision (see Fig. 1). In semi-central Cu+Au collisions an asymmetry of the nuclear overlap region is present along the axis connecting the centers of the interacting nuclei. These features make Cu+Au collision system an important part of the systematic study of the final-state effects in heavy-ion collisions.

Measurements of the production of different types of mesons (π^0, η, K, ϕ) allow a systematic study of jet quenching with respect to the fragmentation function and quantum numbers (mass, flavour, spin, etc.) of the final state hadrons. The nuclear modification factor $R_{\rm AB}$ of π^0, η, K* and Φ mesons as functions of $p_{\rm T}$ are shown in Fig. 3 for different Cu+Au centrality intervals. For both π^0 and η $R_{\rm AB}$ is consistent within uncertainties in the whole $p_{\rm T}$ range for every analyzed centrality interval of Cu+Au collisions. For open or pure strangeness mesons the $R_{\rm AB}$ is larger at low $p_{\rm T}$ but the difference disappears at higher $p_{\rm T}$.

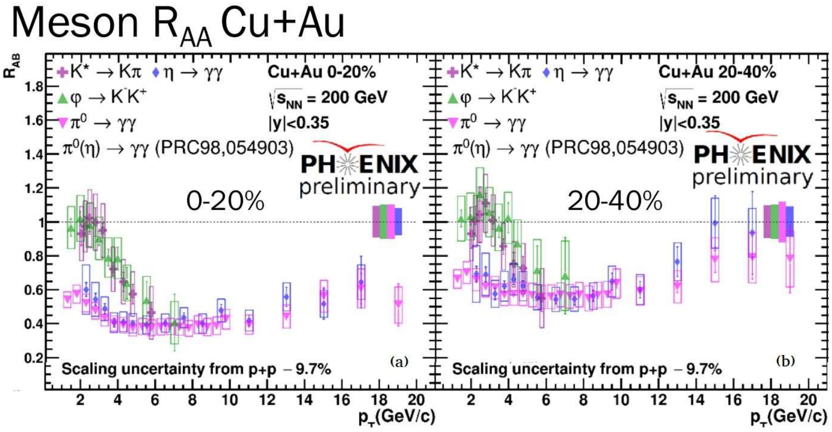

Figure 3. R_{AB} for K^* and Φ meson $>$ R_{AB} for π^0 and η at low p_T in central events, difference disappears at high p_T

The nuclear modification factor R_{AA} of π^0, η, K_S, K^* and Φ mesons as functions of p_{T} is shown in Fig. 4 for different U+U centrality intervals. The absolute values are smaller than those in Cu+Au, but the pattern of separation of the π^0 and η from the open or pure strangeness mesons is similar, as is the p_{T} where the difference between them disappears.

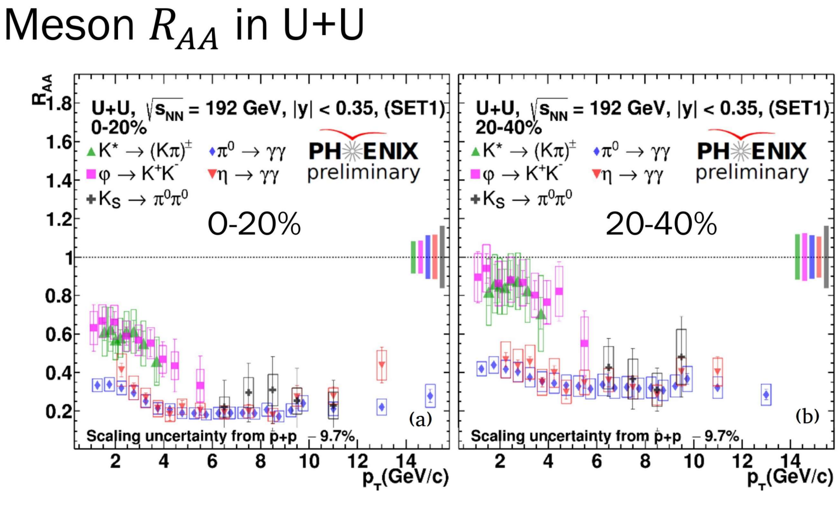

Figure 4. R_{AA} of π^0, η, K^*, K_S and Φ mesons measured as a function of p_{T} in different centrality intervals of U+U collisions at $\sqrt{s_{NN}} = 192$ GeV.

Fig. 5 compares R_{AB} of π^0 mesons measured as a function of p_{T} in Cu+Au, Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV and at similar N_{part}. In central and semi-central Cu+Au collisions the π^0 R_{AB} is consistent with those measured in Au+Au and Cu+Cu, if applicable, which suggests that π^0 suppression mostly depends on the energy density and size of the produced medium. Since in the most central collisions the Cu ion is fully submerged in Au, without any "corona", but the suppression is the same as in Au+Au at comparable N_{part}, the corona-effect is either non-existent or very small compared to the uncertainties of the measurement.

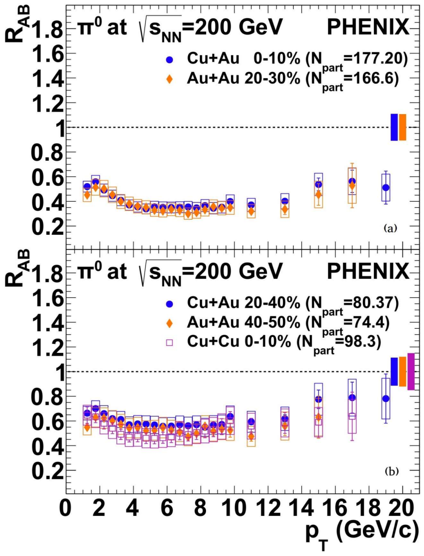

Figure 5. Comparison of π^0 R$_{AB}$ measured in Cu+Au, Au+Au and Cu+Cu collisions.

As for baryons, Fig. 6 shows $R_{\rm AB}$ of $(p+\bar{p})/2$ as a function of $p_{\rm T}$ in different centrality classes in Cu+Au and Au+Au [18] at $\sqrt{s_{NN}}$ = 200 GeV and similar $N_{\rm part}$. Baryon enhancement is present in both systems, it reaches a maximum value above unity between 2 and 3 GeV, but above 3 GeV the $R_{\rm AB}$ values decrease and a suppression pattern emerges. The peripheral proton $R_{\rm AB}$– smaller to begin with – decreases more slowly than the central proton $R_{\rm AB}$ and they reach unity at about the same $p_{\rm T}$.

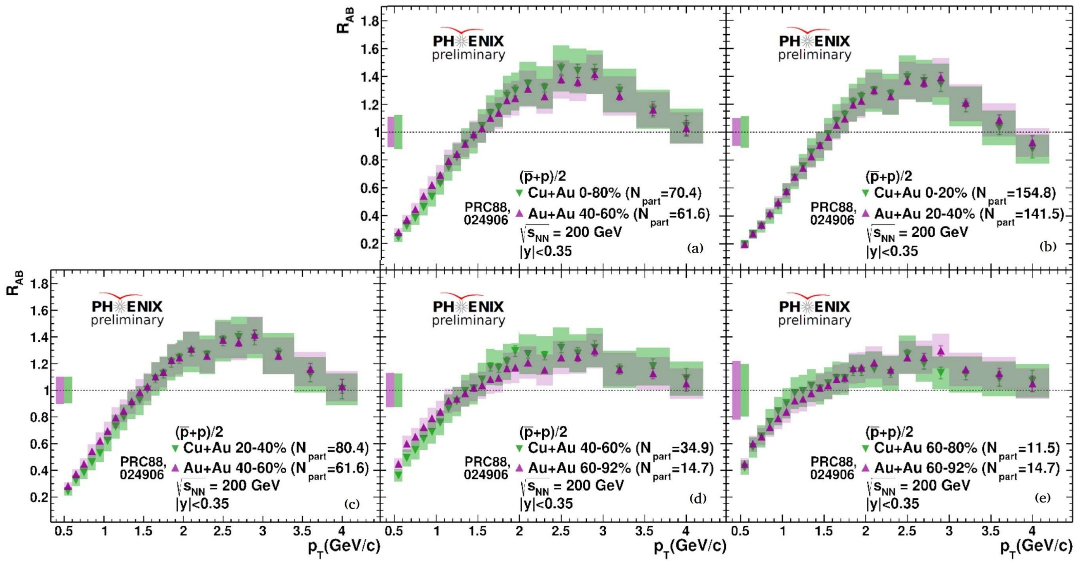

Figure 6. $R_{\rm AB}$ of $(p+\bar{p})/2$ consistent across Cu+Au and Au+Au [18] at similar N$_{part}$

4. Results for small systems

Since π^0 $R_{\rm AB}$ has been widely investigated in all large collision systems and up to a high $p_{\rm T}$, it is a natural first candidate to investigate the nuclear modification factor of leading hadrons of jets in small system collisions, too. PHENIX measured the $R_{\rm AB}$ of π^0 in in p+Au (preliminary), d+Au [19] and ^{3}He+Au (preliminary) collisions at $\sqrt{s_{NN}}$ = 200 GeV, shown in Fig. 7. In central collisions a clear enhancement is observed at $p_{\rm T}$ about 5 GeV/c in p+Au collisions, while it disappears in the d+Au and ^{3}He+Au collisions. Note that if the enhancement in p+Au is indeed a "Cronin-peak", it shows up at higher $p_{\rm T}$ than expected [10]. On the other hand at high $p_{\rm T}$ all three systems show a comparable suppression. The high-$p_{\rm T}$ nuclear modification is very comparable in the different collision systems: it appears to be independent on the projectile (p, d or ^{3}He).

Due to its composition $\Phi(s\bar{s})$ is a very sensitive probe of the formation and evolution of the QGP both when compared to non-strange mesons and double-strange baryons [20]. For central collisions the $R_{\rm AB}$ of Φ shows enhancement at p+Au and d+Au [17] at $p_{\rm T}$ about 5 GeV, in

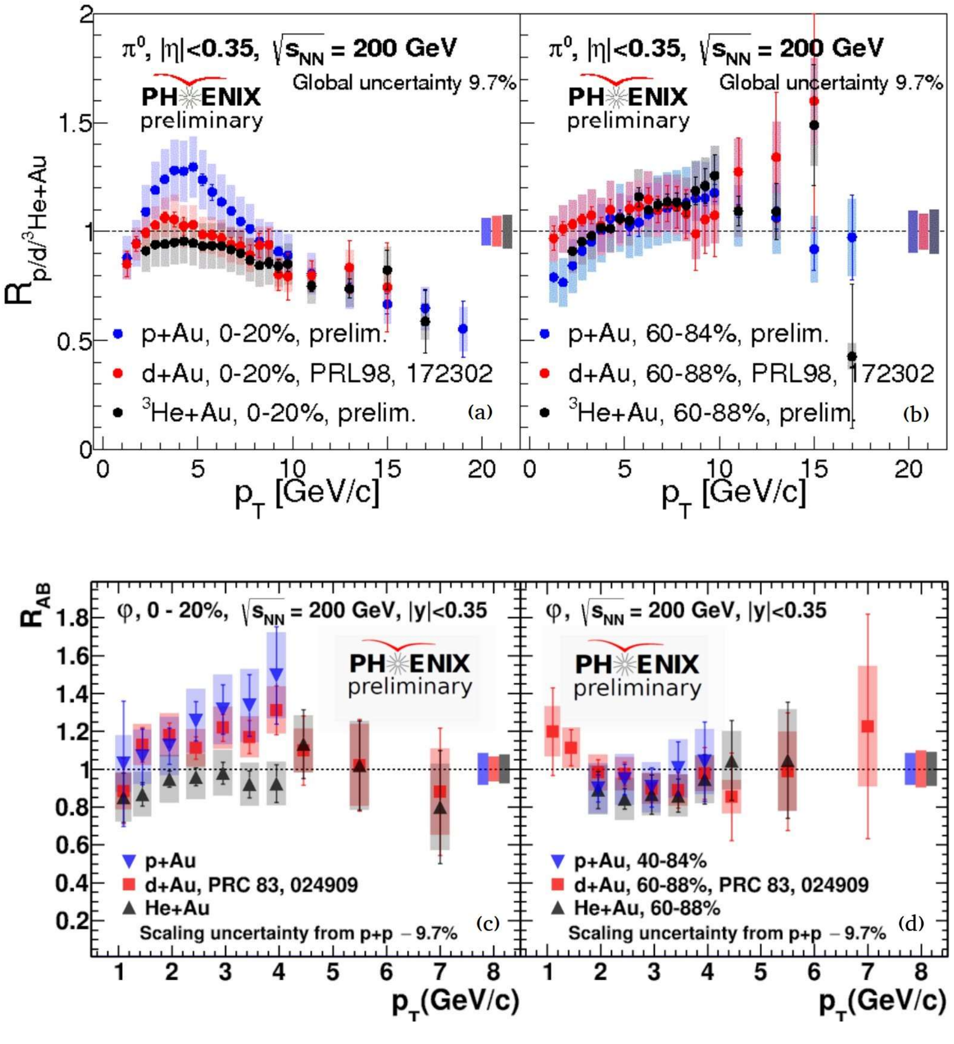

Figure 7. $R_{\rm AB}$ of π^0, Φ mesons measured as a function of $p_{\rm T}$ in small systems in central and peripheral collisions

peripheral collisions the data are also consistent with unity within the experimental uncertainties.

5. Summary

In the Au+Au, Cu+Au, Cu+Cu and U+U collisions we observed an universal high p_{T} suppression for all measured mesons, which suggests that the QGP medium produced in these collisions either does not affect the jet fragmentation into light mesons or it affects them the same way. The nuclear modification factor of the mesons mostly depends on the energy density and size of the produced medium, characterized by N_{part}. At low p_{T} the strange mesons show an intermediate suppression between the more suppressed π^0 and the unsuppressed baryons. In the intermediate p_{T} region, between 2 and 5 GeV, a significant enhancement of baryon-to-meson ratios compared to those measured in *pp* collisions is observed. In small systems the data suggest an ordering ($R_{\mathrm{pA}} > R_{\mathrm{dA}} > R_{\mathrm{HeA}}$) between the different collision systems for the mesons at mid-p_{T}. At high-p_{T} the nuclear modification factor is very similar between the different collision systems which suggest no dependency on the size of the projectile.

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