PHENIX measurements of nuclear modification factor of hadrons in d+Au and A+A collision

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High momentum partons, traversing through the colored medium created in heavy ion collisions (A+A), lose significant amount of energy, resulting in suppression of high p_T particle yields generally quantified by the 'nuclear modification factor (R_{AA})'. Particle production is also modified in the presence of cold nuclear matter effects which are studied in d+Au collisions, and quantified by a quantity R_{dAu}. The quantities, R_{AA} and R_{dAu} are defined as the ratio of the yields in A+A and d+Au collisions respectively to the yield in $p+p$ collisions, scaled by the number of binary collisions in respective collision systems. In this proceeding the recent R_{AA} and R_{dAu} results from PHENIX are presented, along with the comparison among the wide variety of particles, spanning from the light quark mesons(π^0, $\pi^{\pm}$), strange quark mesons ($K^{\pm}$, K^0_S, K^{*0}, ϕ), baryons (p) to the electrons from heavy flavor and direct photons.

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[†]A footnote may follow.

1. Introduction

Hard partons coming from the early stage of collisions, are a sensitive probe to study the hot/dense matter created [1] in high energy heavy ion collisions. These hard partons are predicted to loose energy [2] via multiple scattering and gluon radiation. This energy loss results in modification and softening of spectra of final state hadrons. The modification due to presence of medium is quantified by the 'nuclear modification factor (R_{AB})' which is defined as the particle yield in heavy ion collisions ($A+B$) to the particle yield in $p+p$ collisions, scaled by number of binary collisions. The measurements in $p+A$ (or $d+A$) collision systems are important for studying the initial state effects (e.g. shadowing, Cronin effect, etc.) and distinguishing them from the final state effects.

PHENIX [3] experiment has performed a systematic study of nuclear modification factor for particles with various quark contents (e.g. pions, kaons, protons etc.) for different collision species ($p+p$, $d+$Au, Au+Au and Cu+Cu) and also at different collision energies. These measurements help to estimate the parton energy loss in the medium as a function of particle species, system size and collision energies. In the following sections, PHENIX results are presented in details.

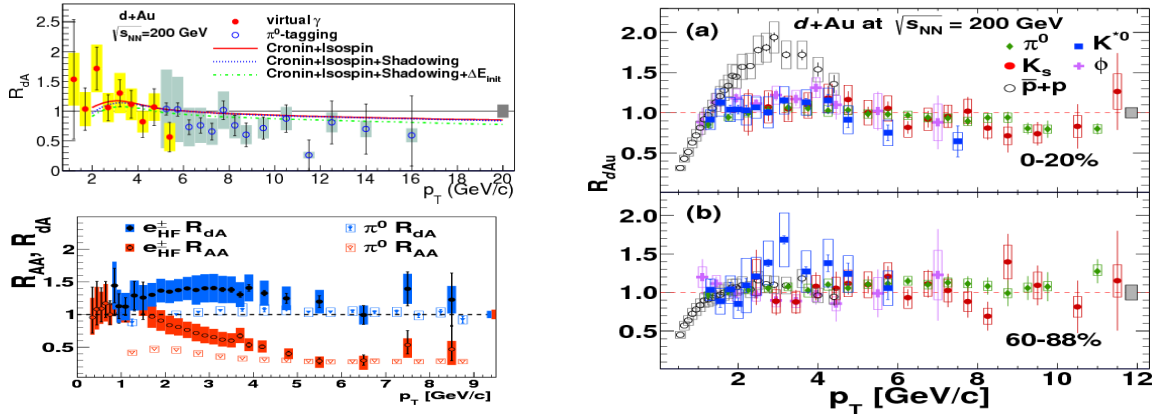## 2. R_{AB} measurements in $d+$Au collisions

Figure 1: Nuclear modification factor as a function of p_T for photons [5], electrons from heavy flavor [4], light and strange mesons [6] and also protons [7] (for the (a) most central and (b) peripheral centrality bin) in $d+$Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The statistical errors are shown by bars and the systematic errors are shown by boxes.

Figure 1 shows the nuclear modification factor of photons [5], electrons from heavy flavor (e_{HF}^-) [4], light mesons, strange mesons [6, 7] and protons in $d+$Au collisions at $\sqrt{s_{NN}} = 200$ GeV. It is observed that for photons and light mesons, $R_{dAu} \sim 1$ within uncertainties, for $p_T > 2$ GeV/c, which indicates that these particles do not suffer any kind of cold nuclear matter effects. The electrons from heavy flavors and protons suffer an enhancement at intermediate p_T range (2 - 5 GeV/c) which is generally explained by the rescattering in the initial state and also by recombination model [8]. However, at high p_T, $R_{dAu} \sim 1$ within uncertainties for e_{HF}^-.

3. R_{AB} measurements in heavy-ion collisions

The results from Cu+Cu and Au+Au collisions at various collision energies are presented in this section. The results are discussed as a function of p_T, collision energies and collision system size. To understand the reason behind the different behavior among various particles, the fractional energy loss is also studied as a function of collision energy and system size.
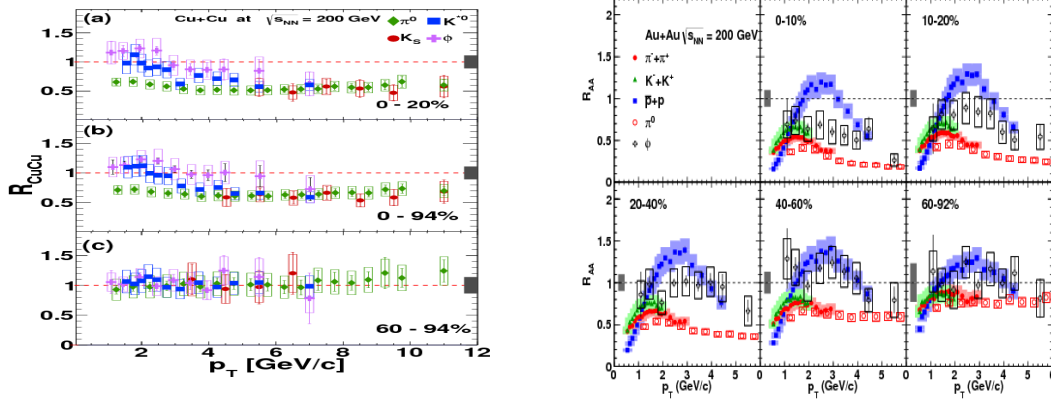

Figure 2: Left panel: Nuclear modification factor as a function of p_T is shown for K^{*0} and K_S^0 mesons in Cu+Cu [6] collisions at $\sqrt{s_{NN}} = 200\,\text{GeV}$ for three centrality bins. Right panel: Nuclear modifications for charged kaons, charged pions and protons in Au+Au [7] collisions at $\sqrt{s_{NN}} = 200\,\text{GeV}$ are shown for various centrality bins. The results for π^0 and ϕ are also shown for the both collision systems.

3.1 Studying R_{AB} as a function of p_T for various system sizes

Figure 2 shows the nuclear modification factor for K^{*0} and K_S^0 in Cu+Cu collisions at $\sqrt{s_{NN}}$ = 200 GeV along with the nuclear modification factor of charged hadrons (e.g. pions, kaons and protons) in Au+Au collisions at $\sqrt{s_{NN}} = 200\,\text{GeV}$, for different centrality bins. Also a comparison is shown with π^0 and ϕ meson. It is observed that in the most peripheral collisions, no significant modification has taken place with $R_{AB} \sim 1$ within uncertainties in the measured kinematic range for all the measured particles. In central collisions production of particles is significantly suppressed. For $p_T > 5\,\text{GeV}/c$, the suppression for the light meson, strange mesons and e_{HF}^- (Fig. 1) is similar in the most central collisions. This points to the fact that, at high p_T, energy loss takes place at partonic level and are independent of particle quark content. The medium effects at intermediate p_T ($2 < p_T$ (GeV/c) < 5) is quite interesting as one can see a certain hierarchy in suppression pattern. The π^0 s are the most suppressed, the protons are enhanced and the strange mesons lie in between of these two. The colorless photons do not interact with the colored medium and hence are not at all suppressed within uncertainties in the measured p_T range.

3.2 Studying R_{AB} as a function of $\sqrt{s_{NN}}$

The modification in particle yield in heavy-ion collision has been studied for π^0 meson in Au+Au collisions at $\sqrt{s_{NN}}$ = 39, 62 and 200 GeV [9]. The PHENIX measurement of π^0 meson suppression has been compared [10] to that of ALICE measurement of charged hadrons. These results are shown in Fig. 3 in the left and right panels respectively. It is seen that suppression
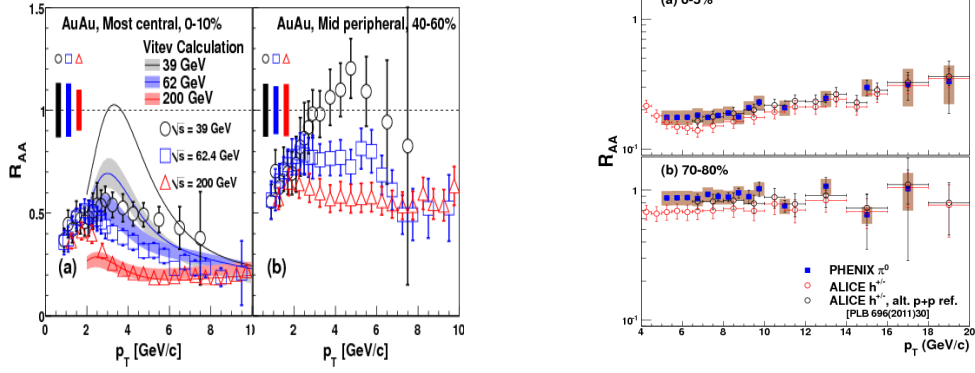
Figure 3: Left panel: Nuclear modification factor for π^0 meson as a function of p_T in Au+Au collisions at $\sqrt{s_{NN}}$ = 39, 62 and 200 GeV, for the central and mid-peripheral centrality bins [9]. Right panel: Comparison [10] of π^0 meson suppression in Au+Au $\sqrt{s_{NN}}$ = 200 GeV with that of the charged hadrons in Pb+Pb $\sqrt{s_{NN}}$ = 2.76 TeV.

is larger in the central collisions than that in the peripheral collisions. The suppression increases with the increasing $\sqrt{s_{NN}}$. The bands represents the theoretical estimations. For 39 GeV, in mid-peripheral collisions, R_{AA} has an increasing trend. In the higher p_T range, similar suppression is observed for all energies. A recent analysis [10] shows that, despite of the difference in collision energies, the suppression of π^0 meson at $\sqrt{s_{NN}}$ = 200 GeV is similar to the suppression of charged hadrons measured at $\sqrt{s_{NN}}$ = 2.76 TeV, both in the central and peripheral collisions.

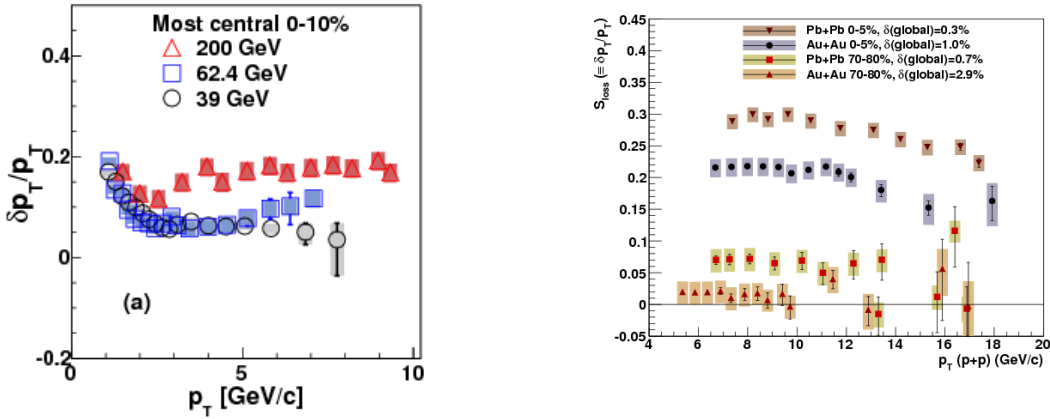## 4. Studying R_{AB} as a function of fractional energy loss

Figure 4: Left panel: Fractional energy loss of π^0 meson as a function of p_T in Au+Au collisions at $\sqrt{s_{NN}}$ 39, 62 and 200 GeV, in the central collisions [9]. Right panel: Comparison [10] of fractional energy loss of π^0 meson in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV with that of the charged hadrons in Pb+Pb at $\sqrt{s_{NN}}$ = 2.76 TeV, for central and peripheral data.

The fractional energy loss of π^0 meson as a function of p_T for different $\sqrt{s_{NN}}$ is shown in Fig. 4. Both plots show that the fractional energy loss increases with the increasing collisional

energy. This can be understood from the steepness of the particle spectra in $p + p$ collisions at the same energies. Recently is has been also studied that that the fractional energy loss ($\delta p_T / p_T$) increases with increasing multiplicity and also with increasing system size but are different for different collision species. For large enough multiplicties, $\delta p_T / p_T$ is independent of collision energy and species. The $\delta p_T / p_T$ is same for the same system size and independent of collision species.

5. Summary

In heavy-ion collisions, the hadrons are more suppressed in central collisions and magnitude of suppression is larger for higher collision energies. For $p_T > 5$ GeV/c, all the hadrons suffer similar suppression within uncertainty for the same heavy-ion collision species. At intermediate p_T, light mesons are the most suppressed and strange meson are suppressed more than protons but lesser than light mesons. The fractional energy loss of particles increases with the collision energy and system size and also depends on collision species. In p+A collisions, mesons of different masses do not suffer any kind of cold-nuclear matter effects and consistent with each other. Protons show an enhancement in the most central collisions in the intermediate p_T range.

References

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