Cold Nuclear Matter Effects at PHENIX

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Abstract

While the study of the quark-gluon plasma has been the primary focus of the RHIC experiments, much work has also been done to understand so-called cold nuclear matter (CNM) effects through d+Au collisions where no hot plasma is produced. Effects such as nuclear shadowing, Cronin enhancement, and initial-state parton energy loss, among others, are not only interesting in their own right, but have direct implications on QGP-related measurements in $A+A$ collisions.

Recently PHENIX has measured CNM effects at midrapidity in $\sqrt{s_{NN}}$ = 200 GeV d+Au collisions. Measurements of reconstructed jets reveal the centrality dependence of both jet suppression and broadening of the away-side jet. Meanwhile, single electrons from heavy flavor decays exhibit enhancement, increasing with centrality, over a broad p_T range. J/ψ and ψ' modification have also been measured and are quite different in magnitude, in contrast with our expectations. The above results are presented here and compared to our present understanding of CNM effects.

1. Introduction

p+A collisions have long been supplying us with interesting results that challenge us to provide explanation. After Cronin, *et al.* measured enhancement of π, K, and p production at moderate p_{T} in p+A at Fermilab [1], it was theorized that partons undergoing multiple scattering within the nucleus would lead to such enhancement [2, 3]. This reproduces the results at lower $\sqrt{s_{NN}}$ (than RHIC) relatively well, including the larger enhancement of protons compared to the mesons, due to the proton p_{T} spectrum being softer than that of the pions. At $\sqrt{s_{NN}}$=200 GeV at RHIC, however, the larger enhancement of protons persists, but the p/π ratio is relatively flat at $p_{\mathrm{T}} \lesssim 2$ GeV/c [4, 5]. An alternative theory involving production through recombination of final-state partons was proposed to try to explain this anomaly [6].

Later experiments showed that the parton distribution functions (PDFs) in nuclei are modified as compared to those in protons. The gluon PDF, in particular, shows substantial suppression at low x, referred to as shadowing; at larger values of x there is enhancement of gluons, referred to as anti-shadowing; at even larger values of x gluons are suppressed again in the "EMC Effect" region. These nuclear PDFs have been calculated using global fits to a variety of experimental results [7, 8, 9], and in the notable recent case of EPS09 [10] with multiple PDFs using variations in the weighting of the fit to allow the calculation of an uncertainty band. To date, however, we have no *a priori* knowledge of the spatial dependence (within the nucleus) of the PDF modification, although several attempts have been made to estimate this [11, 12].

[1]A list of members of the PHENIX Collaboration and acknowledgments can be found at the end of this issue.

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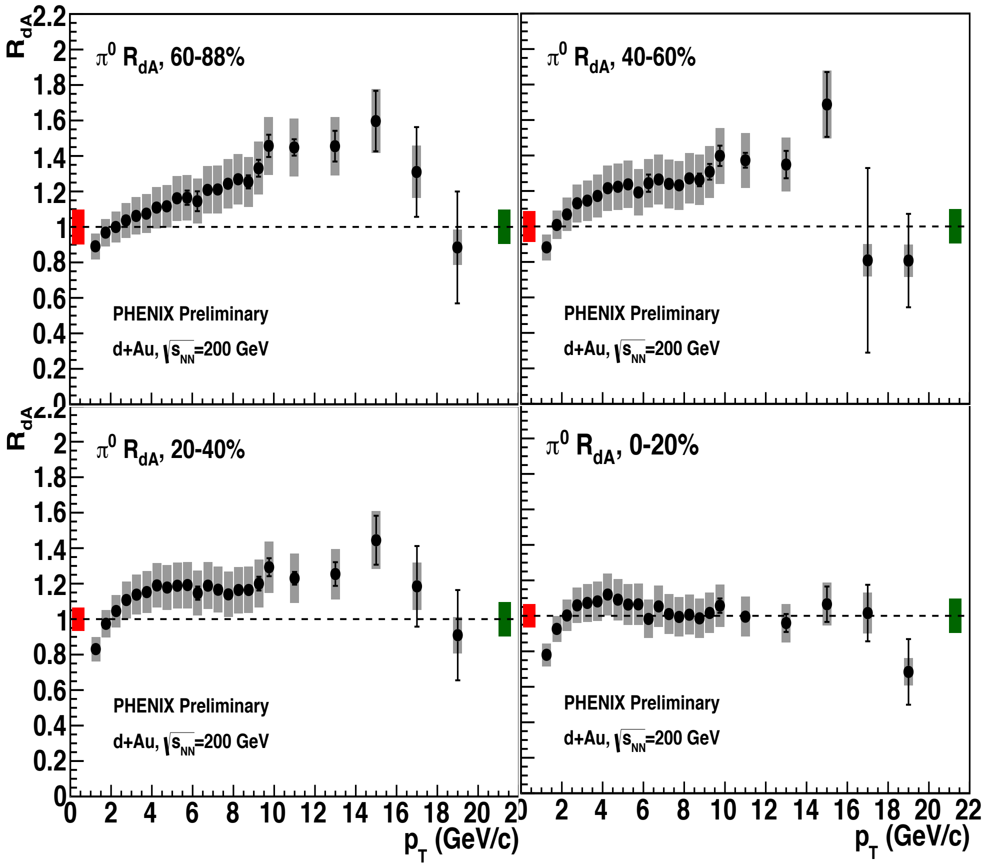

Figure 1: π^0 $R_{\rm dA}$ as a function of $p_{\rm T}$ in four centrality bins.

In addition to those listed above, there are several other possible cold nuclear matter (CNM) effects, including energy loss by initial-state partons interacting with the nucleus, saturation of gluon density at very low x, and final-state interactions with the nucleus leading to break-up of the bound state in the case of heavy quarkonia. Extensive experimental measurements are required to understand and quantify all of these effects in hadron-nucleus collisions.

To this end, PHENIX has made a comprehensive suite of CNM measurements using $\sqrt{s_{NN}}$ = 200 GeV d+Au collisions, first in 2003 and more recently in 2008 with much higher statistics. Several interesting results have already been released, such as the larger enhancement of protons than pions and kaons, and the strong suppression of particle production at low x_{Au} [13, 14]. The latter has been interpreted as possible evidence of gluon saturation, while the former remains unexplained.

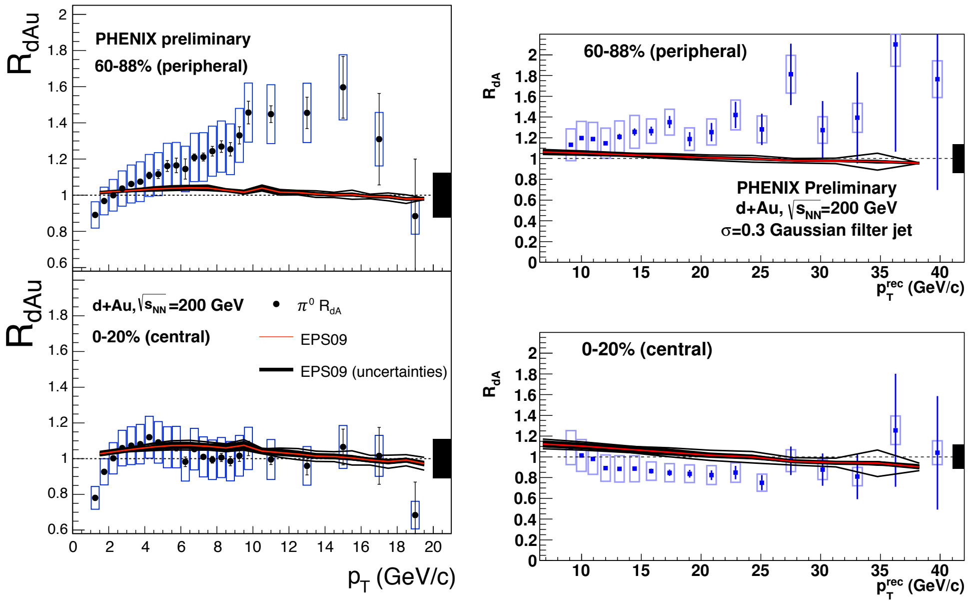

Figure 2: (color online) Left: π^0 R_{dA} as a function of p_{T} in the most peripheral and most central bins, with the simple shadowing calculation of Section 2 overlaid. Right: reconstructed jet R_{dA} as a function of p_{T} for the most peripheral (top) and most central (bottom) bins, with the PYTHIA+Glauber+EPS09 calculation overlaid.

2. π^0 Production

One of the most basic observables available experimentally is pion production. Figure 1 shows π^0 R_{dA} as a function of p_{T} in four centrality bins from the 2008 d+Au data [15]. This measurement has much higher statistics than the previous 2003 measurement, and thus the p_{T} range is extended by 5 GeV/c. The p+p reference data used in this preliminary result is from 2005, so some of the systematics that would normally cancel or be reduced in the ratio are not in this case.

As can be seen, the peripheral bins show the largest modification, while the central bins show the least, and is consistent with no modification at $p_{\mathrm{T}} > 2$ GeV/c. This is contrary to our basic expectation that nuclear modifications are stronger in central collisions, although one possibility is that there are competing nuclear effects which coincidentally cancel in the most central bin.

For comparison, we performed a simple shadowing calculation using PYTHIA 8 to get the (x, Q^2) sampling for each p_{T} bin, combined with the PHENIX Glauber Monte Carlo and EPS09 nuclear-modified PDFs, with the assumption that the PDF modification scales linearly with longitudinal nuclear thickness. The resulting curves are overlaid in Figure 2 (left). In the most central bin they match the data fairly well, but in the most peripheral bin they follow a different trend with p_{T}.

3. Reconstructed Jets

In addition to pions, PHENIX has recently measured reconstructed jets in d+Au collisions. Figure 2 (right) shows R_{dA} for jets reconstructed using the Gaussian filter algorithm with σ = 0.3 [16], as used previously in PHENIX on the 2005 Cu+Cu and p+p data [17]. As can be seen, the measured jets have a much higher p_{T} reach than the π^0. Similar to the π^0 case they are enhanced in peripheral collisions, and slightly suppressed in central collisions. While the obvservables are different between the two results, they are not totally unrelated, and it is still informative to compare them. As can be seen in Figure 3, the R_{dA} are actually quite similar in the overlapping region in p_{T}.

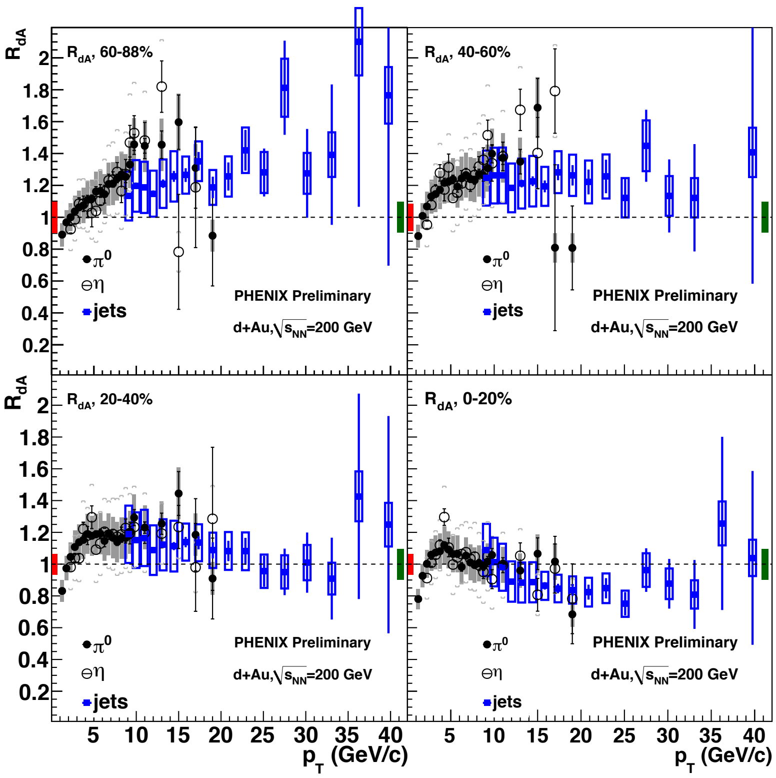

Figure 3: (color online) π^0 and reconstructed jet R_{dA} vs. p_{T} plotted together in four centrality bins.

We can also perform the same comparison to the simple shadowing calculation as we did in the pion case in Section 2. The resulting curves can be seen overlaid in Figure 2. Because the p_{T} range here sample the x region of the nuclear PDFs transitioning from antishadowing to the EMC effect, there is a corresponding transition from enhancement to suppression with increasing p_{T}. The trend of the central bin is reproduced, at least qualitatively, but the same decreasing-with-p_{T} trend appears in the peripheral bin, where the data trends towards enhancement with p_{T}. Also similar to the π^0 case, there is no obvious explanation for this contrast, and further studies will

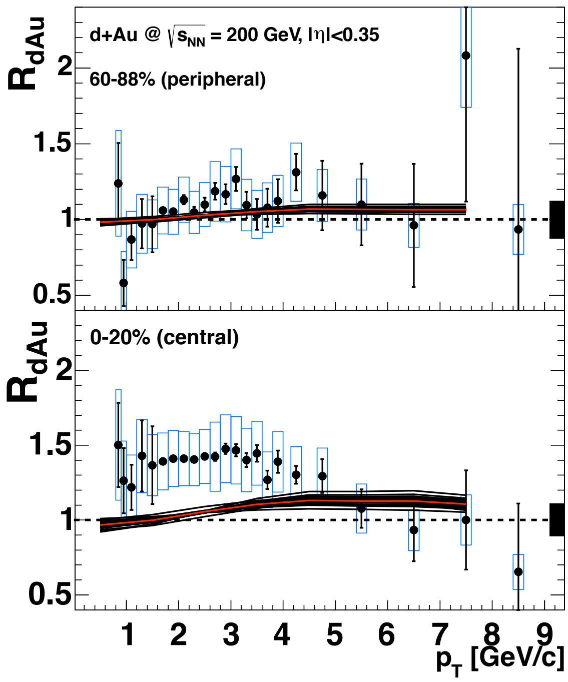

Figure 4: (color online) Heavy flavor single electron R_{dA} as a function of p_{T} in the most peripheral (top) and most central (bottom) bins, with the PYTHIA+Glauber+EPS09 calculation overlaid.

be required to understand if this represents new physics effects in the nucleus or indicates some unaccounted-for additional bias in events which include jets or very high-p_{T} particles.

4. Heavy Flavor Single Electrons

A rather different probe that PHENIX has frequently measured is R_{AA} of single electrons from heavy flavor decays at midrapidity. In central Au+Au collisions it was observed that the heavy flavor electrons are strongly suppressed [18]. The corresponding R_{dA} from the 2008 d+Au data [19] is shown in Figure 4. In the case of peripheral collisions there is little modification, while in central collisions the heavy flavor electrons are enhanced in the intermediate p_{T} region (0.8 GeV/c < p_{T} < 5 GeV/c). There is no suppression in either case, which may suggest that the effect seen in Au+Au collisions is entirely due to a hot medium, although it is impossible to be certain without extending the d+Au measurement down to the lowest p_{T}.

A similar comparison to the simple shadowing calculation of Section 2, now with heavy flavor electrons instead of pions (the curves in Figure 4), shows that in this case the calculation agrees quite well with the peripheral data, but cannot reproduce the result from central collisions (even qualitatively). The calculated modification is consistent with our naive expectation, as the data at $p_{\mathrm{T}} \sim 5.2$ GeV/c corresponds to $\langle x \rangle \sim 0.1$, which is right in the antishadowing region of

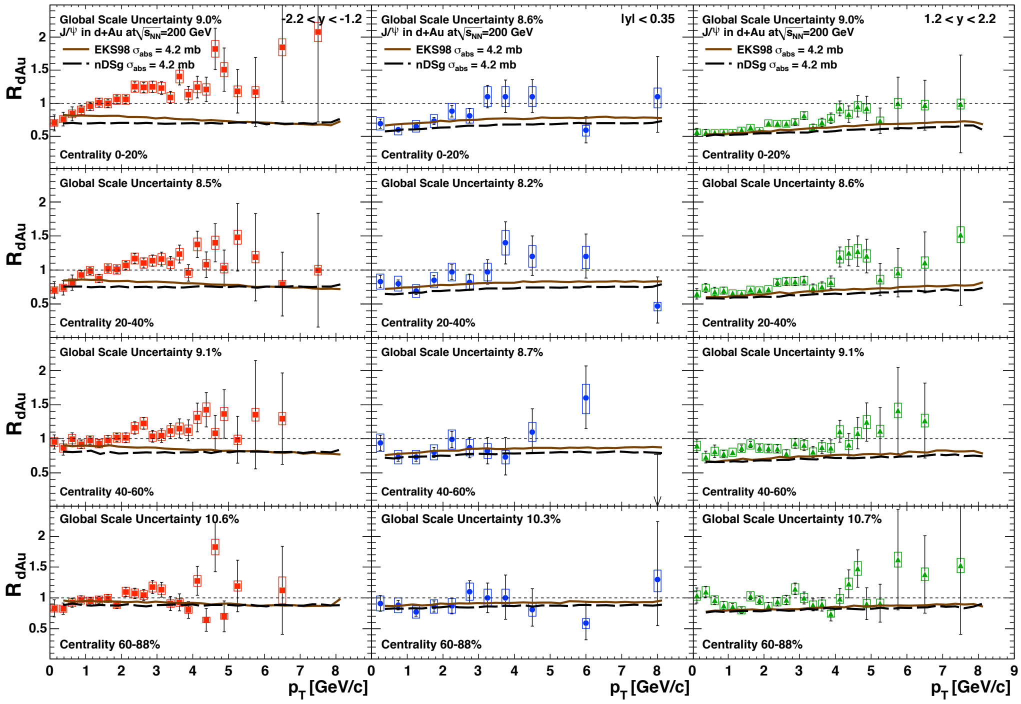

Figure 5: (color online) J/ψ R_{dA} as a function of p_{T} in four centrality bins at backward (left), mid- (center), and forward (right) rapidities.

the EPS09 gluon PDF. This comparison could imply that there is additional physics going on beyond simply shadowing.

5. J/ψ Modification

In the case of CNM effects on charmonia, there is an additional suppression due to the breakup of the $c\bar{c}$ pair as it transits the outgoing nucleus. This is usually included in calculations as a break-up cross section (σ_{br}). PHENIX has previously measured J/ψ R_{dAu} as function of centrality and rapidity and found that the turn-on of the suppression with centrality occurs much faster than the simple assumption that it occurs roughly linearly with the longitudinal thickness of the nucleus at the site of the binary collision [13].

More recently PHENIX has extended this measurement to include R_{dAu} vs. p_{T} in three rapidity and four centrality bins [20]. As can be seen in Figure 5, R_{dAu} exhibits a flat or rising trend with p_{T} in all twelve bins, with stronger modification in the more central bins. Included in the figures are two calculations using EKS98 (solid line) and nDSg (dashed line) shadowing parametrizations along with σ_{br} = 4.2 mb. In the most central bins it can be seen that shadowing models cannot completely reproduce the modification seen. At backward rapidity, in particular, the trend with p_{T} is completely wrong due to the gluon x that is being sampled moving from the antishadowing region of enhancement into the EMC region of suppression with increasing

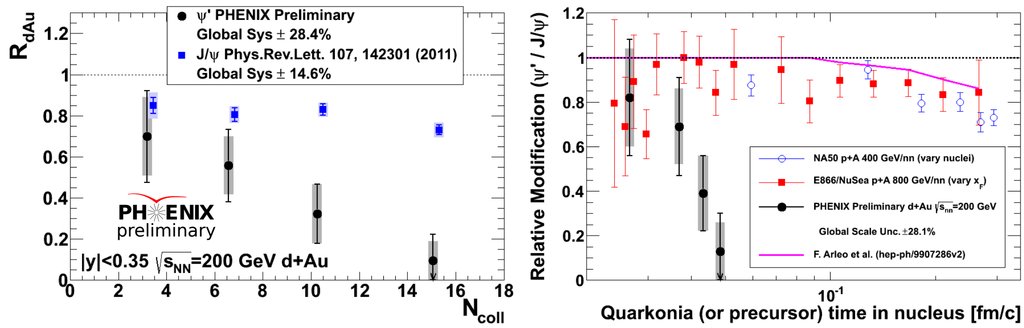

Figure 6: (color online) Left: ψ' (circles) and J/ψ (squares) R_{dA} at midrapidity as a function of N_{coll}. Right: Relative modification of $\psi'/J/\psi$ as a function of time spent in the nucleus by the $c\bar{c}$, as measured at several different $\sqrt{s_{NN}}$.

p_{T}. Some additional effect is needed to interpret the modification here, possibly some kind of initial-state scattering, as has been proposed to explain Cronin enhancement [3].

6. ψ' Suppression

Using the 2008 data PHENIX has for the first time measured ψ' production in d+Au collisions [21]. ψ' R_{dAu} vs. N_{coll} is plotted in Figure 6 at midrapidity, and it is notable that the ψ' suppression is stronger than that of the J/ψ, and increases with centrality (whereas the J/ψ suppression at midrapidity is roughly flat with centrality). This is in stark contrast to the expectation that CNM effects would be nearly identical for J/ψ and ψ' mesons, since at RHIC energies the final meson state is formed after the $c\bar{c}$ have escaped from the Au nucleus, and therefore the CNM effects in both cases would operate on the $c\bar{c}$ precursor to the final state.

The relative modification between ψ' and J/ψ can be compared to previous measurements at lower $\sqrt{s_{NN}}$ by replotting it in terms of the time spent in the nucleus by the $c\bar{c}$ pair. As can be seen in Figure 6, the lower-$\sqrt{s_{NN}}$ results conform nicely with the picture described above, while the PHENIX measurements are completely at odds with this scenario.

This has direct implications for the use of heavy quarkonia as a temperature probe of the medium. In particular, CNM measurements of the Υ 1S, 2S, and 3S states will be a requirement to any interpretation of their suppression in A+A collisions at either the LHC or RHIC.

7. Summary

PHENIX has made a comprehensive set of CNM measurements using the 2008 $\sqrt{s_{NN}} = 200$ GeV d+Au data. While some of the results match our prior expectations, many more provide questions that need to be answered. In particular:

- Why are protons so much more enhanced than pions and kaons in 200 GeV d+Au?
- Why don't the π^0 and jet modifications get stronger in central collisions?
- What causes the heavy flavor electron enhancement at $p_{\mathrm{T}} < 4$ GeV/c?

- Why does J/ψ suppression turn on so steeply with nuclear thickness?
- What causes the rising R_{dAu} vs. p_{T} for J/ψs at backward rapidity?
- Why is the ψ' CNM suppression so much stronger than J/ψ CNM suppression?

These questions are even more compelling on the eve of the first long p+Pb run at the LHC, and their answers will both require and result in a more complete understanding of CNM effects than we currently have.

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