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# LATEST QCD RESULTS FROM PHENIX*

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The PHENIX experiment has produced an extensive array of measurements in heavy ion collisions in order to study the created strongly interacting medium. This medium is seen to modify the properties of many global and high-momentum observables; a strong suppression relative to that expected from $p+p$ collisions is observed. Initially scattered partons traverse the formed medium prior to fragmentation. A comparison of the final measured jet (a stream of particles with large transverse momenta in a localized region of phase space) in heavy ion and $p+p$ collisions reflects the energy loss of the partons within the medium. In order to systematically study the parton-medium interactions, PHENIX has used a suite of analysis methods. In these paper, I will present our latest QCD results, focusing on single-particle spectra, inclusive jet production and two-particle correlations in heavy ion collisions.

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## 1. Introduction

The overall goal of the PHENIX experiment is to investigate the properties of the hot, dense matter produced in heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC). High-$p_{\rm T}$ particles are an excellent probe with which to study the produced medium. As the hard partonic scattering occurs before the medium has formed, any modification to the parton energy and its fragmentation will be observed in the measured high-$p_{\rm T}$ particles.

We wish to quantify this modification and thus study the parton energy loss in the created medium. One approach to accomplish this is to create different initial conditions which turn on and off the hot, dense medium by colliding different nuclei at various collision energies. In our experiment, we can also vary the collison system size (centrality), dial the particular momentum of our probe, or choose to study particles of a certain type.

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## 2. A brief story of high-$p_{\mathrm{T}}$ at RHIC

Single-particle spectra are among the earliest QCD measurements at high-$p_{\mathrm{T}}$ at RHIC. The large suppression of hadrons at high-$p_{\mathrm{T}}$ in $\mathrm{Au}+\mathrm{Au}$ collisions with respect to that in $p+p$ was interpreted as parton energy loss in medium — referred to as jet quenching. Based on this measurement alone it is difficult to be quantitative in the level of the radiative *versus* collisional energy loss or the type of the process which may be perturbative or non-perturbative.

The disappearance of the backward jet in two particle correlations provided further evidence of jet quenching. This measurement in $\mathrm{Au}+\mathrm{Au}$ collisions was interpreted as suppression due to parton energy loss. The backward jet reappearance — a relative enhancement — at low momenta was observed later. There are uncertainties associated with two particle correlation measurements: in the energy scale of the jet and in the modification to the fragmentation function, where softening and broadening of the jet is expected. Further uncertainties are linked with the geometrical aspects of the measurements pertaining to the location of the hard scattering within the collision overlap area and the path-length traversed in the medium. It is difficult to determine if the energy loss is by the trigger or by the near side jet.

$\gamma$-jet measurements are considered to be the golden channel for heavy ion collisions. The jet yield is averaged over all possible path-lengths; the $\gamma$ trigger has no surface bias as it does not interact with the medium. As the energy of the jet is calibrated by the unmodified $\gamma$ energy, any modification of the jet fragmentation function is interpreted as parton energy loss in the medium. Full jets are a relatively recent probe at RHIC. They provide a direct observation of the parton-medium interaction and medium response.

In light of the $\mathrm{Au}+\mathrm{Au}$ collision results, the jet quenching hypothesis was further tested using $d+\mathrm{Au}$ collisions. This provided a control over the cold *versus* hot nuclear matter effects, which have ultimately shown that the suppression in central $\mathrm{Au}+\mathrm{Au}$ events is not apparent in $d+\mathrm{Au}$, thus confirming that the suppression in $\mathrm{Au}+\mathrm{Au}$ is a “final state” effect.

## 3. PHENIX spectra

The latest PHENIX QCD results augment the knowledge from the first RHIC measurements. The parton interaction with the created medium and the path-length traversed has been extensively studied at various collision energies and for different system sizes. New analysis techniques have been developed, as the ultimate goal is to understand biases associated with specific analysis probes.

### *3.1. Single-particle spectra*

A clear path-length (system size) dependence is observed in the single hadron particle spectra. The suppression of the nuclear modification factor ($R_{AA}$, see Eq. (1)) in 200 GeV Au + Au collisions is dependent on the number of participants, $N_{\rm part}$ [1][1]. A similar suppression is observed for $\pi^0$ and $h^{\pm}$ for $p_{\rm T} > 4.5$ GeV/$c$ for the same $N_{\rm part}$; a larger suppression is observed in more central collisions (fully overlapping nuclei). Such measurements provide us with an "averaged" parton suppression, as at a given $N_{\rm part}$ the measurement is integrated over the whole nuclei-overlap region of the collision

$$R_{AA} = \frac{1}{N_{\rm coll}} \frac{d^2N_{AA}/dydp_{\rm T}}{d^2N_{pp}/dydp_{\rm T}} \,. \tag{1}$$

To examine path-length effects of the partonic energy loss more closely, it is possible to constrain the in-medium distance through which a parton must travel by selecting in-plane and out-of-plane angles (see Fig. 1 (right) for an illustration). In-plane the particles will traverse less medium than out-of-plane, as for mid-central collisions, the overlap-almond shape has its semi-minor axis along the plane of the collision. The measurements of $\pi^0$ in Au + Au collisions at 200 GeV [2] *versus* reaction plane show a clear path-length dependence. Similarly in- *versus* out-of-plane dependencies of the $R_{AA}$ are observed in central and mid-central collisions. The $R_{AA}$ suppression is found to be strongly correlated to the path length traversed, not just to the overall system size ($N_{\rm part}$).

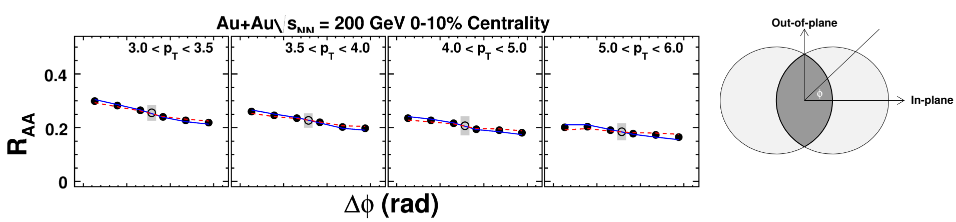


Fig. 1. The left panels show the reaction-plane dependence $R_{AA}$ in mid-central Au + Au collisions at 200 GeV. The right panel defines the angle $\phi$ relative to the collision event plane.

### *3.2. Direct-$\gamma$ spectra*

As the $\gamma$s do not couple to the created medium, direct-$\gamma$s are a unique probe which could answer the question of whether the observed $R_{AA}$ suppression in heavy ion collisions is due to the created medium or not. It was

[1] $N_{\rm part}$ is a measure of the collision system size and is proportional to the the traversed path-lengths.

observed that in Au + Au collisions at 200 GeV [3] the $R_{AA}$ of the direct-$\gamma$s at $p_{\rm T}$>6 GeV/$c$ is close to unity for all centralities. This intimates that the underlying $\gamma$ production is the same as that expected from collision-scaled $p + p$.

### 3.3. Energy scan

The energy scan at RHIC provides the opportunity to further test the parton energy loss path-length dependence at different collision energies. Our latest result [4] on measured $\pi^0$s shows that suppression is observed in central collisions at three different Au + Au energies: 200, 62.4 and 39 GeV. (A Cronin-like enhancement is observed in peripheral collisions at 39 GeV.) The path-length dependence is found to be similar for both 200 and 62.4 GeV. At high-$p_{\rm T}$, the $R_{AA}$ measured in 39 GeV data shows a similar path-length trend (peripheral to central) as the other two higher energies but with less suppression, see Fig. 2. The ultimate "high" energy scan was performed at the LHC. Surprisingly, when the PHENIX $\pi^0$ and hadron $R_{AA}$ is compared to that measured in ALICE, the results look strikingly similar! Note that the difference in collision energies is over an order of magnitude.

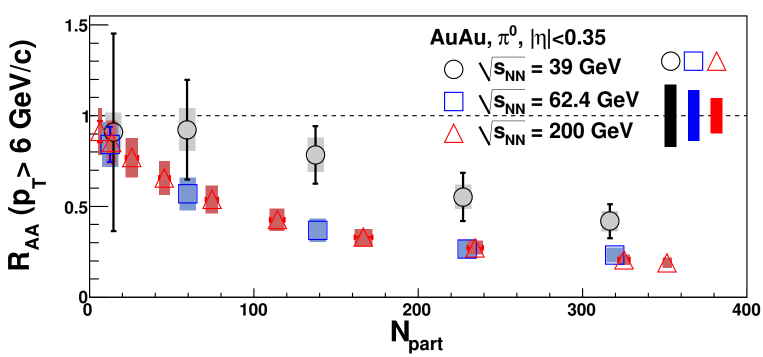


Fig. 2. Nuclear modification factor *versus* the number of participants for high-$p_{\rm T}$ $\pi^0$s in 200 (red triangles), 62.4 (blue squares), and 39 GeV (black circles) collisions.

## 4. Triggered correlations

Triggered two particle hadron–hadron correlations provide different advantages and challenges when used to study the parton-medium interactions. The most important advantage is that they probe jet-like correlation features in the data which are closer to the initial parton. We can also tune the trigger and associated particles to probe different kinematic regions. The main disadvantage is that these measurements call for larger statistics when collecting data as the jet-like correlated signal resides within a large background.

The new and interesting feature of this measurement is the surface bias, which could be considered as an advantage *and* a disadvantage with respect to the single-particle spectra measurements. In the single-particle spectra, we do not have a "trigger" particle — we measure all particles produced in the collisions, independent of where the hard-scattering occurred. The traversed path-length was not fixed — there is no surface bias. In the triggered correlations, we have to take into account the geometrical aspect of the collisions; the point where the hard scattering occurred. Having a trigger results in a trigger bias as we may preferentially select interactions, where the hard scattering occurred at the edge of the medium. This fixes the associated particle path-length.

The studies of correlations between high-$p_T$ triggers with high-$p_T$ associates in PHENIX show that the away-side jet is suppressed relative to $p+p$ collisions [5]. To better study the medium, the conditional nuclear modification factor of the near and the away-side jet ($I_{AA}$) is used. Figure 3 shows the in- and out-of-plane dependence for three centrality bins. The associated $I_{AA}$ shows a clear path-length dependence. There is also a $p_T$ dependence. The $I_{AA}$ of the trigger shows no path-length dependence (in- or out-of-plane) and no system size dependence. This may hint to the presence of a surface bias.

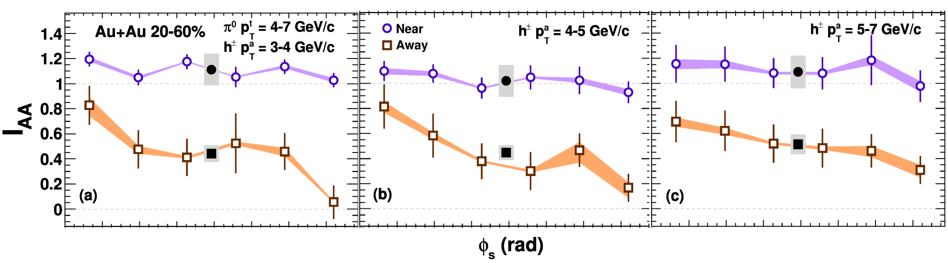


Fig. 3. Reaction-plane dependence of the conditional nuclear modification factor, $I_{AA}$, for trigger (light grey/purple) and associate (dark grey/orange) particles.

More interesting is the comparison to the single-particle $R_{AA}$, Fig. 1, with the $I_{AA}$ of the associated particles, Fig. 4. They are very similar in magnitude although we were expecting to sample *more* medium with the triggered correlations for a given system size and path-length due to the surface bias of the trigger. To avoid ambiguities of the triggered correlations we could look at the $\gamma$-jet correlation results.

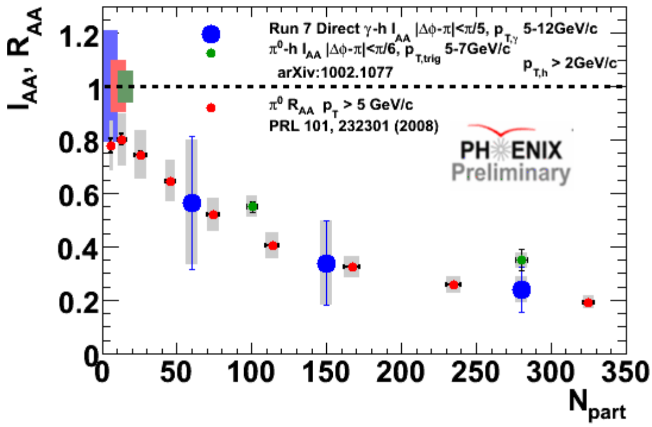


Fig. 4. A comparison of the nuclear modification factor for $\pi^0$s (cross symbols) and jets in central Au + Au collision events at 200 GeV. (Note that the centrality selections are not precisely the same.)

## 5. Jet studies

### *5.1. γ-jet*

As $\gamma$s do not interact with the created medium, there are two advantages: no trigger surface bias, and the energy of the associated jet is calibrated by the energy of $\gamma$. With no surface bias, the associated (jet) path-length is not fixed. As the trigger ($\gamma$) may come from any geometrical point within the medium, the average path-length of the away-side jet is expected to be smaller than that of the away-side jet in hadron–hadron correlations. As a result, a smaller modification to the away side is expected. Medium modification of the jet fragmentation function in heavy-ion collisions is a direct measure of the parton energy loss.

The hadronic jet fragmentation function in Au + Au collisions at 200 GeV is extracted from a narrow region on the away side ($|\Delta\,\phi-\pi|<\pi/4\,\mathrm{rad}$) of the $\gamma$-hadron correlation [11, 12]. The fragmentation function in Au + Au and $p+p$ collisions were reconstructed in different $p_{\mathrm{T}}$-bins of the reconstructed $\gamma(p_{\mathrm{T}},\gamma)$, from $p_{\mathrm{T}} = 5$ to 15 GeV/$c$. The fragmentation functions, within a collision system, were found to have the same behavior with $z_{\mathrm{T}}$, independent of $p_{\mathrm{T}}$. This $z_{\mathrm{T}}$ scaling is expected in $p+p$ collisions. Its presence in Au + Au shows that the created medium in heavy-ion collisions modifies the hadronic part of the jet fragmentation function in the same way, independent of the energy scale. As the $\gamma$-jet events are not expected to have a surface bias, the observed $z_{\mathrm{T}}$ scaling in heavy-ions is somewhat surprising.

Figure 4 shows the centrality dependence of the $\gamma$-hadron $I_{AA}$ along with the result obtained from $\pi^0$-hadron correlations. The results are consistent. The results are also consistent with $\pi^0$ $R_{AA}$. The same level of suppression for the same system size ($N_{\rm part}$) from all these probes is puzzling. We may ask ourselves if there is any surface bias in our $\gamma$-hadron correlations? Where is the difference due to the different path-length between these measurements?

### *5.2. Full jet reconstruction*

The full jet measurements provide a handle on the total energy loss of the parton with no ambiguity from the fragmentation function or the energy scale of the jet. PHENIX has reconstructed full jets in $p+p$ and Cu + Cu collisions at 200 GeV [6, 7].

The jet nuclear modification factor, $R_{AA}$, and its centrality dependence is shown in the left panel of Fig. 5. Indeed, the maximum difference between the jet spectrum in $p+p$ and Cu + Cu systems is observed in central collisions. This suppression lessens for mid-central and appears to be unmodified in peripheral collisions.

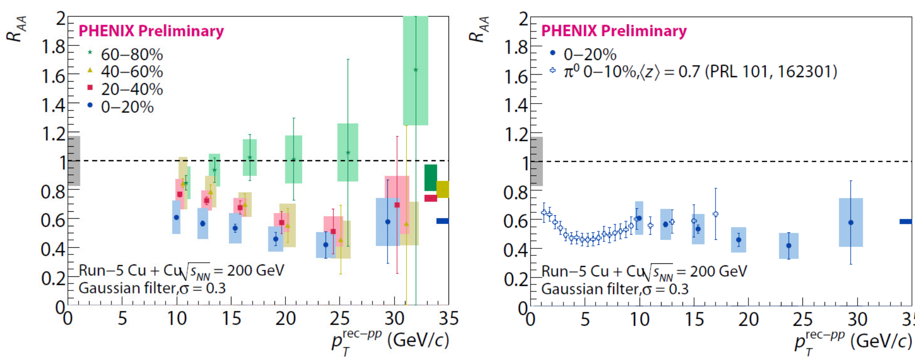


Fig. 5. The left panel shows the nuclear modification factor for full jets reconstructed in Cu + Cu collisions at 200 GeV. The right panel shows a comparison of the nuclear modification factor for $\pi^0$s (cross symbols) and jets in central Au + Au collision events at 200 GeV. (Note that the centrality selections and the energy scale are not precisely the same.)

The strong jet $R_{AA}$ suppression in central Cu + Cu collisions is found to be at the same level as the one for single-$\pi^0$ spectra, right panel of Fig. 5, for the overlapping $p_{\rm T}$ range. It should be noted that the $R_{AA}$ for single-$\pi^0$ spectra is at a different energy scale than the reconstructed jets.

## 6. Summary

PHENIX has made a wide range of high-$p_{\mathrm{T}}$ measurements. Our latest results provide systematic studies at different systems and collision energies using different probes as single particle spectra, triggered di-hadron correlations, $\gamma$-jet correlations as well as full jet reconstruction.

We have observed a clear path-length dependence to the modification of the spectra relative to $p+p$ interactions.

Many measurements show a path-length dependencies which are surprisingly similar and not fully meeting our initial expectations. We continue our systematic studies to gain a more comprehensive understanding of the parton energy loss in heavy-ion collisions.

## REFERENCES

[1] S.S. Adler *et al.* [PHENIX Collaboration], *Phys. Rev.* **C69**, 034910 (2004).
[2] S. Afanasiev *et al.* [PHENIX Collaboration], *Phys. Rev.* **C80**, 054907 (2009).
[3] S.S. Adler *et al.* [PHENIX Collaboration], *Phys. Rev. Lett.* **94**, 232301 (2005).
[4] A. Adare *et al.*, `arXiv:1204.1526v1 [nucl-ex]`, accepted in *Phys. Rev. Lett.*
[5] A. Adare *et al.* [PHENIX Collaboration], *Phys. Rev.* **C78**, 014901 (2008).
[6] Y. Lai [PHENIX Collaboration], *Nucl. Phys.* **A830**, 251 (2009).
[7] Y. Lai [PHENIX Collaboration], `arXiv:0911.3399v1 [nucl-ex]`.