Recent Heavy Ion Results from PHENIX

Carla M. Vale for the PHENIX Collaboration

Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

DOI: http://dx.doi.org/10.5689/UA-PROC-2010-09/36

The Relativistic Heavy Ion Collider, RHIC, began operation just over 10 years ago. Over this period, the PHENIX Collaboration has accumulated a wealth of results that provide an increasingly detailed picture of the hot and dense medium produced in central heavy ion collisions at RHIC. This contribution reviews some recent PHENIX results from the heavy ion runs.

1 Introduction

The first decade of RHIC running has brought both big surprises and the confirmation of some theoretical expectations. One such theoretical success was the prediction that a highly energetic parton produced in the first instants of the collision could lose energy, and perhaps even be fully absorbed, as it traversed the hot colored medium created in the collision [1]. Many experimental observables focus on the evaluation of this "jet quenching" mechanism at RHIC, from the single particle spectra and their suppression when compared to the appropriately scaled p+p measurement, to di-hadron correlations and the new attempts at full jet reconstruction in the difficult high-multiplicity heavy ion environment. All of these have contributed to establish that jet quenching is indeed happening at RHIC, but the mechanisms involved are yet to be determined, and only the full complement of measurements, as well as a move towards increased precision, both experimental and theoretical, will be able to resolve this issue.

2 Single particle spectra

Single particle transverse momentum spectra can be used as tools to study the suppression of high-momentum partons via the measurement of the Nuclear Modification Factor, denoted as R_{AA}, the ratio of the A+A single particle yield scaled by the average number of binary collisions in a given centrality bin, to the same yield in p+p collisions.

PHENIX has measured R_{AA} for a wide range of particle species, collision energies, and colliding species (Au+Au, Cu+Cu, and d+Au). The two key observations were that a factor of 5 suppression was reached for light mesons in the most central Au+Au collisions for $p_T > 3$, and that no such effect was seen in d+Au collisions, indicating that jet-quenching is a final state effect that takes place in the medium created in A+A collisions. The full range of PHENIX measurements for central Au+Au collisions is presented in Fig.1. Several interesting trends are worth noting:

- η: the recently published η R_{AA} [2] covers nearly the full p_T range of the original π^0

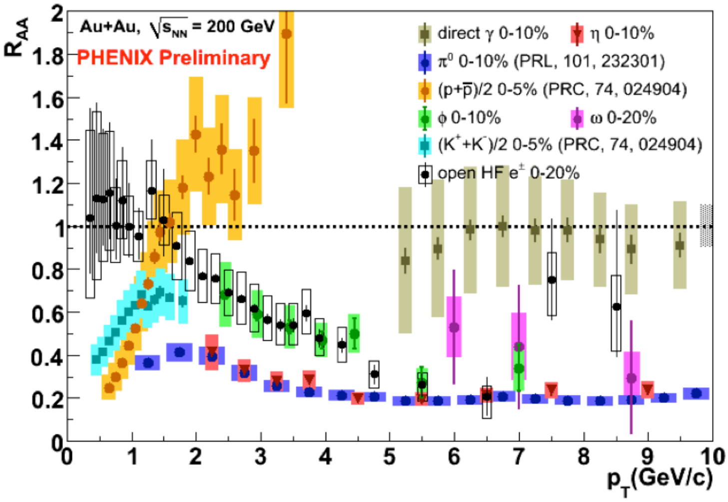

Figure 1: $R_{AA}(p_T)$ in central Au+Au collisions for several identified hadron species, electrons from heavy-flavor decays, and direct photons. (color online)

measurement, and shows that the two results are nearly identical, despite the different mass and flavor compositions of the η and π^0. From the experimental point of view, the η measurement suffers from fewer systematic uncertainties at high-p_T. This is because the two photons that result from the η decay are well enough separated to be independently resolved in the PHENIX electromagnetic calorimeter up to a p_T of more than 40 GeV/c, unlike the π^0, which starts to be affected by merging effects at p_Ts of about 20 GeV/c. This difference implies that future larger data samples, such as the one from the recent Run-10, will allow the p_T range of the R_{AA} measurement to be extended via the η.

- ϕ: results for the ϕ spectra and R_{AA}, measured using several different techniques, have also recently been published [3]. It is interesting that while clearly suppressed, ϕ mesons only reach the suppression level of the π^0 and η at $p_T > 5$ GeV/c, and also that they seem to follow a similar p_T evolution trend as other strange particles and even heavy-flavor electrons.

- heavy-flavor electrons: one of the big surprises at RHIC, even after the observation of jet quenching, was that the suppression for electrons resulting from heavy-flavor electrons (see [4] for the details of the measurement technique) was almost as strong as that observed for light mesons, despite the fact that heavy-flavor quarks were not expected to couple strongly to the medium. This strong coupling is one of the aspects of jet quenching that has attracted considerable theoretical attention, but no clear resolution.

- direct photons: the direct photons serve also as a control measurement, as they are not expected to interact with the medium. It therefore comes as no surprise that their measured R_{AA} value is one. At higher p_T (not shown in the figure), there are hints of a deviation from unity, which can be due to contributions from isospin effects and/or fragmentation photons.

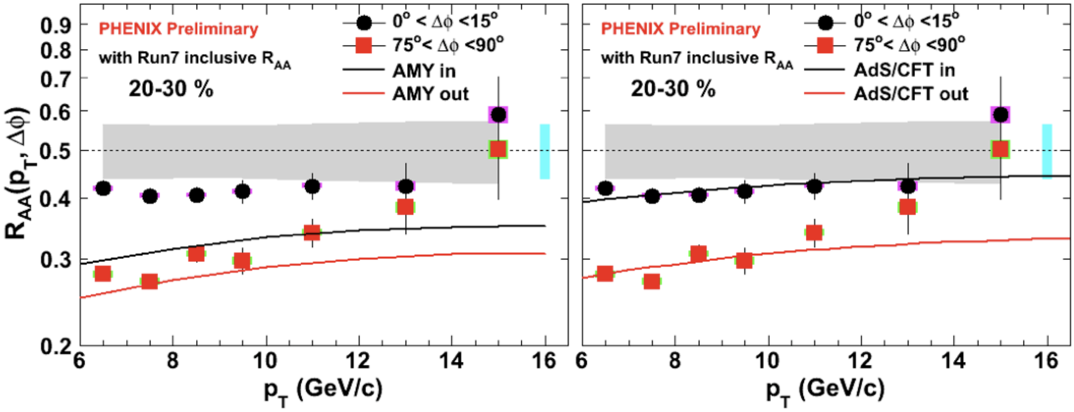

Figure 2: π^0 $R_{AA}(p_T, \Delta\phi)$, in-plane (black) and out-of-plane (red), compared to model calculations: [6] (left) and [7] (right). (color online)

3 Azimuthal Asymmetry

Even within measurements of single particle spectra, it is possible to obtain a more differential picture of jet quenching by looking at the azimuthal dependence of the suppression, relative to the reaction plane. The reaction plane is formed by the impact parameter vectors of the two colliding nuclei. The almond shaped region created by their overlap is thinnest in-plane and thickest out-of-plane. Therefore, since all proposed jet quenching mechanisms have a path-length dependence built-in (though the strength of this dependence varies across models), it should be possible to identify different suppression levels between high-p_T particles that emerge along the reaction plane and perpendicular to it. Figure 2 shows a sample of the PHENIX results [5] for azimuthally-dependent R_{AA}, in- and out-of-plane, together with two of the model comparisons. The best agreement so far is obtained by an AdS/CFT inspired calculation [7], which corresponds to a path-length dependence proportional to l^3, the strongest dependence considered.

4 Di-hadron Correlations and $\gamma-$jet

When studying di-hadron correlations, the focus is again on finding deviations from the two-peak distribution that is attributed to back-to-back jets in p+p collisions. Since jets are expected to be modified by the medium in A+A collisions, these modifications should be apparent in the shapes and yields of the two peaks when compared to p+p, and able to be more differentially analyzed than in single particle spectra studies. Di-hadron correlations are built by requiring a (typically high-p_T) trigger particle, and pairing it with every other track (within a given p_T range) in the event. After correcting for acceptance and azimuthal correlations due to elliptical flow, a correlation function is obtained, and the yields and shapes of near-side and away-side peaks can be extracted.

PHENIX has recently published results [8] on the yield and shape modification for di-hadrons where the trigger particles are identified π^0 with transverse momentum in the range

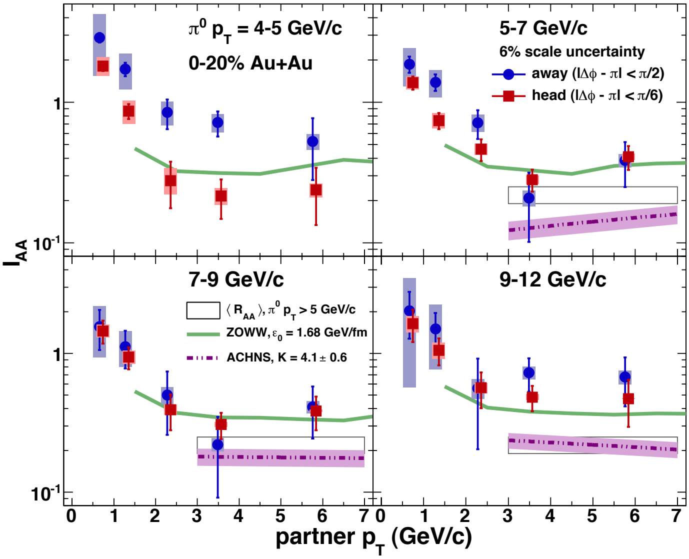

Figure 3: Away-side I_{AA} for "head" region ($|\Delta\phi - \pi| < \pi/6$), squares, and full away-side ($|\Delta\phi - \pi| < \pi/2$), circles, for several trigger and partner momentum selections. Calculations from [9] and [10] are included for comparison, as well as the π^0 R_{AA}. (color online)

$4 - 12$ GeV/c and the associated particles are charged hadrons with $p_T = 0.5 - 7$ GeV/c. The near-side shape in Au+Au collisions is found to be consistent with the one observed in p+p, over the full range of trigger and associated p_T. The away-side side yield, however, is modified: at low p_T it exhibits a broad, non-gaussian shape, while for higher p_T pairs the shape of the peak is similar to p+p but its magnitude is suppressed. The away-side modification can be quantified by measurements of I_{AA}, the ratio of the conditional jet pair yield in a given $\Delta\phi$ range in A+A to the same yield in p+p, shown in Figure 3 for central Au+Au collisions. The R_{AA} for single π^0 is also shown for comparison, as well as two theoretical calculations. For the lowest p_T pairs, the shape modification is visible through the difference in the I_{AA} values measured for the two different angular intervals considered. Such a difference disappears for the higher p_T pairs. The suppression in I_{AA} is lower than that observed for the π^0 R_{AA}, which is likely to result from two competing effects: the first is the surface bias induced by requiring a high-p_T trigger particle, which means that the away-side parton will have a larger path through the medium; the second is the relatively softer spectrum observed for the away-side hadrons, when compared to the single inclusive hadron spectrum, which will translate in a stronger suppression in R_{AA} for an equivalent spectral shift.

Correlations between direct photons and hadrons are especially interesting as the photon is able to emerge from the medium without having interacted with it, and therefore the measured photon's momentum should almost exactly correspond to that of the opposing jet. The measurement is obtained by correlating inclusive photons with high-momentum hadrons, and then statistically subtracting the decay photon component from the correlation function [11]. As expected, results show that the away-side yield is suppressed, notably at a level which is consistent with that seen for single particles, as shown in Fig. 4. The slopes of the away side yield as a function of $z_T = p_T^h/p_T^{jet} \sim p_T^h/p_T^\gamma$ in p+p and central Au+Au collisions are 6.89 ± 0.64 and 9.49 ± 1.37, respectively, which corresponds to a 1.3σ increase in Au+Au, suggesting that the fragmentation function in Au+Au is indeed modified.

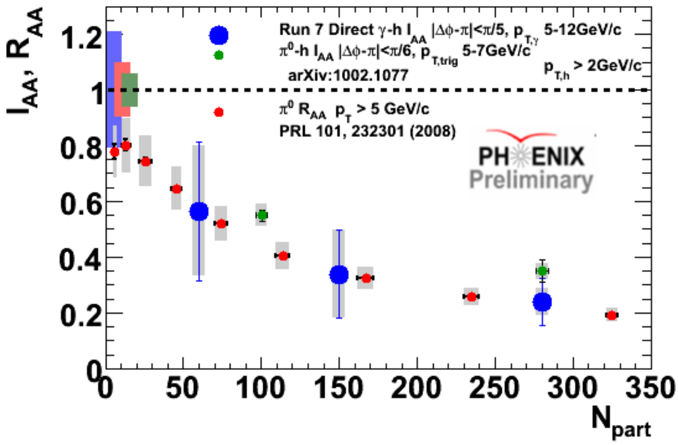

Figure 4: Away-side I_{AA} for direct $\gamma-$jet, π^0-hadron and single π^0 R_{AA} as a function of number of participants for Au+Au collisions. (color online)

5 Jet Reconstruction

A recent advance in the study of jets and energy loss at RHIC is the use of full jet reconstruction algorithms, developed originally for p+p collisions, in the analysis of heavy ion events. PHENIX has pursued these studies using a Gaussian filter algorithm [12], which has been applied to p+p and Cu+Cu collisions so far [13]. Fluctuations in the underlying event can also produce fake jets, especially given the large soft background at RHIC. These are removed by requiring a minimum energy in the jet core. This fake rejection scheme has been shown to be effective in heavy ion collision environments using HIJING. The jet spectra obtained for p+p collisions using this method are consistent with NLO calculations and PYTHIA. Figure 5 shows the jet R_{AA}, obtained from the jet reconstruction measurements for Cu+Cu and p+p collisions in PHENIX. For comparison, the R_{AA} for π^0 is also shown. The observed jet R_{AA} is approximately 0.6, which is consistent with that seen for single π^0 in central Cu+Cu collisions.

6 Summary and Outlook

PHENIX continues to put together a full picture of energy loss through detailed measurements of many complementary signals, from higher p_T single identified particle spectra to di-hadron correlations and full jet reconstruction in p+p and heavy-ion collisions. This emphasis on precision measurements will continue over the next few years as the installation of dedicated detector upgrades takes place. The Hadron Blind Detector was part of the 2010 data taking run, and should soon provide results on the di-electron continuum and resonances. The 2011 run will be the first for the Silicon Vertex Detector, which will contribute to the understanding of heavy-flavor energy loss through measurements that separate the bottom and charm components, and will be complemented at forward rapidities by the Foward Vertex Detector, to be installed next year. Further into the future, the collaboration intends to pursue a large scale upgrade ("sPHENIX")[14], including a mid-rapidity ($\Delta\eta \pm 1$, $\Delta\phi = 2\pi$) full-coverage detector optimized for jet measurements, and a forward-rapidity detector with the ability to identify electrons, photons and hadrons.

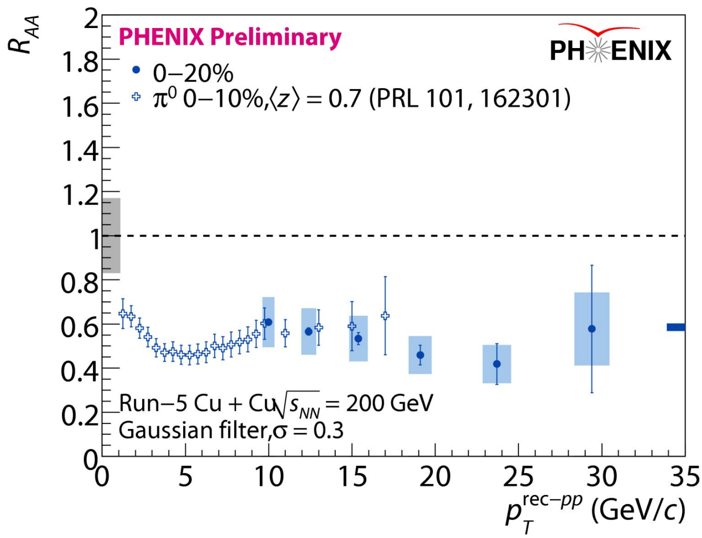

Figure 5: Jet R_{AA} for central Cu+Cu collisions at $\sqrt{s_{NN}} =$ 200 GeV/c, compared to π^0 R_{AA}. Shaded box on left indicates systematic uncertainty in the jet energy scale, box on the right indicates centrality dependent uncertainty associated with the measurement methods.(color online)

References

[1] X. N. Wang and M. Gyulassy, Phys. Rev. Lett. **68**, 1480 (1992).

[2] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. C **82**, 011902 (2010) arXiv:1005.4916 [nucl-ex].

[3] A. Adare *et al.* [PHENIX Collaboration], arXiv:1004.3532 [nucl-ex].

[4] A. Adare *et al.* [PHENIX Collaboration], arXiv:1005.1627 [nucl-ex].

[5] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **105**, 142301 (2010) arXiv:1006.3740 [nucl-ex].

[6] S. A. Bass, C. Gale, A. Majumder, C. Nonaka, G. Y. Qin, T. Renk and J. Ruppert, Phys. Rev. C **79**, 024901 (2009) arXiv:0808.0908 [nucl-th].

[7] C. Marquet and T. Renk, Phys. Lett. B **685**, 270 (2010) arXiv:0908.0880 [hep-ph].

[8] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **104**, 252301 (2010) arXiv:1002.1077 [nucl-ex].

[9] N. Armesto, M. Cacciari, T. Hirano, J. L. Nagle and C. A. Salgado, J. Phys. G **37**, 025104 (2010) arXiv:0907.0667 [hep-ph].

[10] H. Zhang, J. F. Owens, E. Wang and X. N. Wang, Phys. Rev. Lett. **98**, 212301 (2007) [arXiv:nucl-th/0701045].

[11] M. Connors [PHENIX Collaboration], Nucl. Phys. A **830**, 447C (2009) arXiv:0907.4571 [nucl-ex].

[12] Y. S. Lai and B. A. Cole, arXiv:0806.1499 [nucl-ex].

[13] Y. S. Lai [PHENIX collaboration], arXiv:0911.3399 [nucl-ex].

[14] PHENIX collaboration Decadal Plan 2011-2020, `http://www.phenix.bnl.gov/phenix/WWW/docs/decadal/2010/phenix_decadal10_full_refs.pdf`