UCRL-PROC-207407

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High pT hadron spectra at RHIC: an overview

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October 21, 2004

Hot Quarks 2004: Workshop for young scientists on the physics of ultrarelativistic nucleus-nucleus collisions
Taos Valley, NM, United States
July 18, 2004 through July 24, 2004

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High p_T hadron spectra at RHIC: an overview

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Abstract. Recent results on high transverse momentum (p_T) hadron production in p+p, d+Au and Au+Au collisions at the Relativistic Heavy Ion Collider (RHIC) are reviewed. Comparison of the nuclear modification factors, $R_{dAu}(p_T)$ and $R_{AA}(p_T)$, demonstrates that the large suppression in central Au+Au collisions is due to strong final-state effects. Theoretical models which incorporate jet quenching via gluon Bremsstrahlung in the dense partonic medium that is expected in central Au+Au collisions at ultra-relativistic energies are shown to reproduce the shape and magnitude of the observed suppression over the range of collision energies so far studied at RHIC.

1. Introduction

There are now four years of beam data on high p_T hadron spectra available from the relativistic heavy ion collider (RHIC) covering multiple confi gurations (p+p, d+Au, Au+Au) and beam energies (62.4, 130, 200 GeV). The four RHIC experiments, BRAHMS, PHENIX, PHOBOS and STAR have observed and reported on several striking features from this new era of collider data, where the high cross-section for pQCD hard-scattering processes plays an important role in heavy ion collisions for the fi rst time. In particular, jets of high transverse momentum hadrons which come from the fragmentation of hard-scattered partons can be experimentally observed in heavy ion collisions using two-particle azimuthal correlations[1, 2].

The yield of single inclusive high p_T charged hadrons leading these jets is observed to be substantially suppressed (by a factor of 3-5 for $p_T>6$ GeV/c) in the most central Au+Au collisions at $\sqrt{s_{\rm NN}}$= 130 and 200 GeV compared to the expectation from scaling the yield in p+p collisions at the same beam energy by the average number of binary nucleon-nucleon collisions in Au+Au[3, 4, 5, 6]. The yields in d+Au collisions are slightly enhanced at intermediate p_T and consistent with binary-collision scaling for $p_T \gtrsim 7$ GeV/c[7, 8, 9, 10].

Detailed studies of the two-particle azimuthal correlations as a function of centrality in Au+Au collisions at $\sqrt{s_{\rm NN}}$= 200 GeV reveal that the correlations at $d\phi = \pi$ expected from the balancing partner jet created in the partonic hard-scattering become more and more suppressed in central Au+Au collisions in stark contrast to p+p and d+Au collisions. The back-to-back partner of the di-jet effectively "disappears" into the bulk matter soft hadronic background generated in the collision[2, 9].

These features, along with the observed large azimuthal anisotropy of hadron distributions at large p_T in non-central Au+Au collisions[1, 11], provide strong evidence that

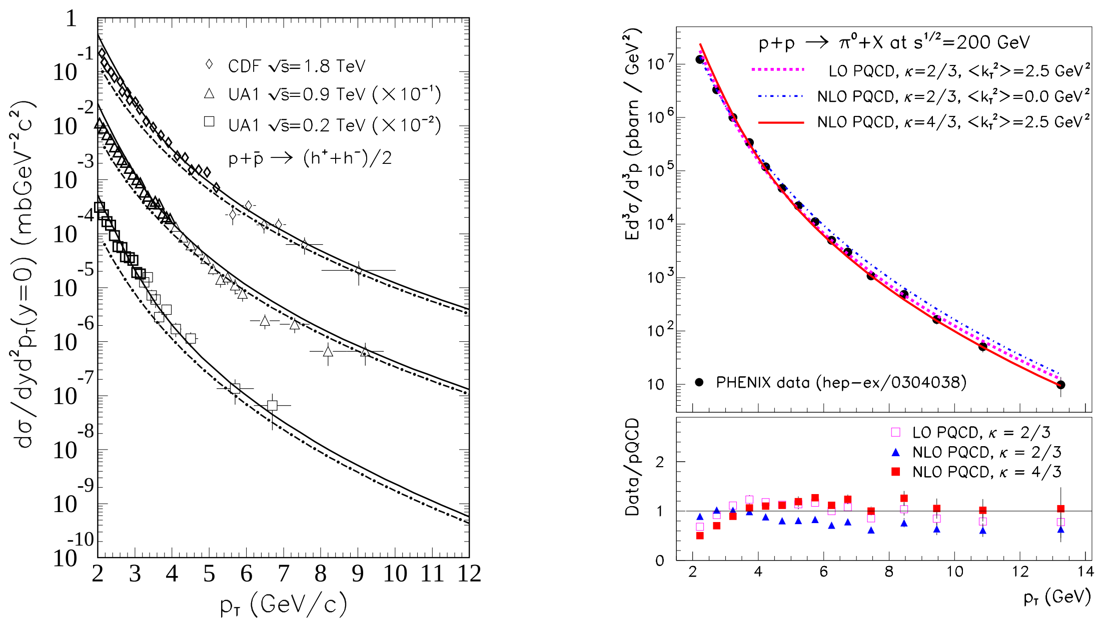

Figure 1. Comparisons of $h^{\pm}$ and π^0 spectra from p+p($\bar{p}$) collisions to leading order and next-to-leading order pQCD parton model calculations. The left panel is from [13] and the right panel is from [14].

a dense, strongly interacting medium is formed in Au+Au collisions at RHIC, substantially effecting the production and dynamics of jets which traverse it. In this article I review the available data on the transverse momentum spectra of leading hadrons in p+p, d+Au and Au+Au collisions and how the theoretical interpretations of these data contribute to our understanding of the dense nuclear medium created in central heavy ion collisions at RHIC.

2. The baseline: high p_T particle spectra in elementary hadron collisions

Within the perturbative QCD (pQCD) parton model, the short-distance perturbatively calculable hard-scattering cross-section is assumed to factorize from the long-distance non-perturbative parton distribution functions (PDFs) and parton fragmentation functions, providing a way to describe high p_T particle production in elementary collisions[12]. The parton distribution functions are determined from deep inelastic scattering data, while the fragmentation functions are obtained from experimental studies of e+e- collisions. Within the pQCD parton model, the expression for the production of high transverse momentum hadrons in pp($\bar{p}$) collisions can be written

$$\frac{d\sigma^h_{pp}}{dyd^2p_T} = K\sum_{abcd}\int dx_a dx_b\, f_a(x_a,Q^2)\, f_b(x_b,Q^2)\frac{D^0_{h/c}(z_c,Q^2)}{\pi z_c}\frac{d\sigma^{(ab\to cd)}}{d\hat{t}}, \quad (1)$$

where $f_a(x_a,Q^2)$ and $f_b(x_b,Q^2)$ represent the distribution of partons carrying momentum fraction x within the incoming hadrons, $\frac{D^0_{h/c}(z_c,Q^2)}{\pi z_c}$ is the fragmentation function to convert

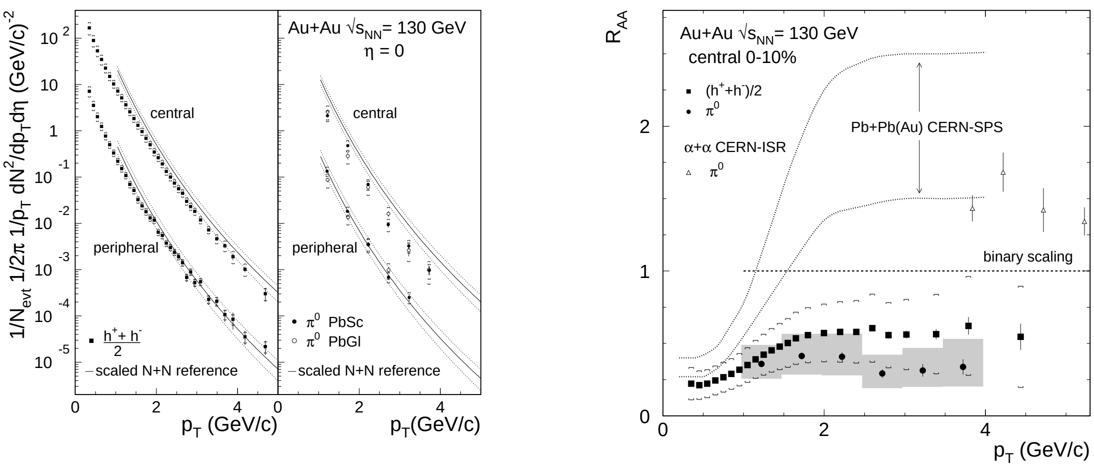

Figure 2. Transverse momentum spectra and nuclear modification factor R_{AA} of $h^{\pm}$ and π^0 measured by the PHENIX experiment for Au+Au collisions at $\sqrt{s_{NN}}$= 130 GeV[3].

parton c into colorless hadrons, h and $\frac{d\sigma^{(ab\to cd)}}{d\hat{t}}$ is the hard-scattering cross-section, which is calculable in a perturbative series expansion in powers of the strong coupling constant, α_s. Since the complexity of the calculation grows nonlinearly with the power of α_s, leading order calculations with a phenomenological K-factor to account for the next-to-leading order corrections are often used. For $\sqrt{s_{NN}}\gtrsim$50 GeV, these calculations agree impressively well with the experimental data. In the left panel of Figure 1, a parton model calculation is compared to data from pp($\bar{p}$) collisions at three collision energies[13]. The right panel of Figure 1 shows a comparison of both LO and NLO calculations to π^0 production in p+p collisions at RHIC[14]. The addition of terms to account for finite transverse momentum K_T of the partons within the nucleus improves the agreement with the experimental data in both cases. The success of this description in describing the hadron spectra in p+p($\bar{p}$) collisions suggests that a similar formalism may be a useful starting point for the more complex systems: p(d)+A and A+A.

3. Leading particle spectra in heavy ion collisions

In p(d)+A and A+A collisions, additional nuclear medium effects must be taken into account. The parton distribution functions in nuclei differ from those in free nucleons[15]. The distributions of partons with $x \lesssim 10^{-1}$ are suppressed relative to the same distributions in nucleons, a phenomenon known as "shadowing". For partons with $x \sim 1$ the distributions are enhanced or "anti-shadowed". In addition, multiple soft scattering of the projectile partons as they traverse a target nucleus may boost their transverse momentum slightly even before they undergo the hard-scattering or subsequent to it, leading to an enhancement of the yield at high p_T compared to p+p collisions[16]. These effects can be added to the factorized pQCD model expressed in Equation 1 as modifications to the PDF terms.

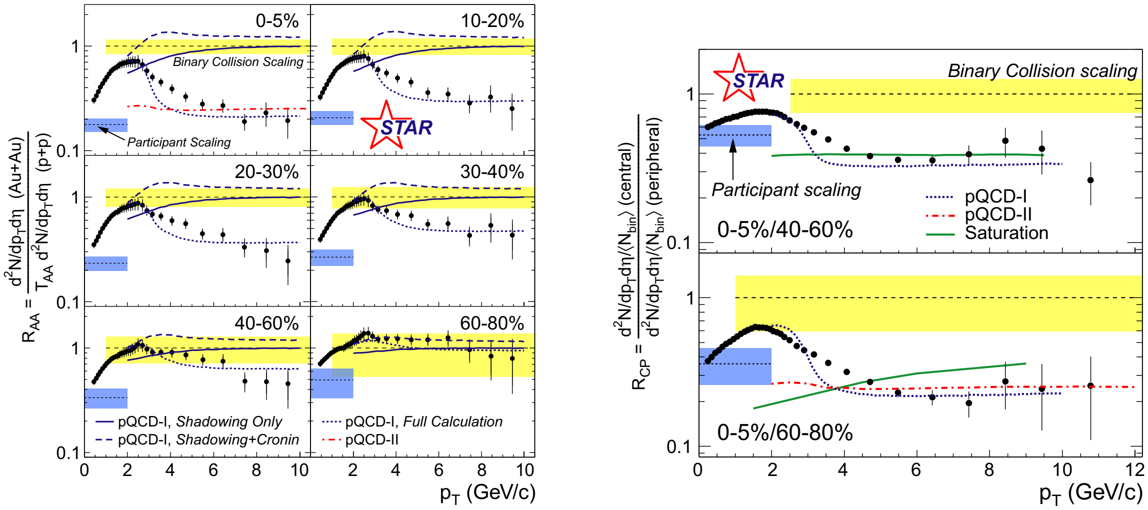

Figure 3. Nuclear modification factors, R_{AA} (left) and R_{CP} (right) for $h^{\pm}$ measured by the STAR experiment in Au+Au collisions at $\sqrt{s_{NN}}$= 200 GeV[5].

Finally, the nuclear medium produced in a collision might influence the production of high p_T hadrons, either through hard partonic or hadronic re-interactions in the final-state after the hard-scattering. Partonic interactions with a colored medium induce gluon Bremsstrahlung radiation, reducing the parton's energy before it fragments into hadrons[17]. This effect is often introduced in pQCD parton model calculations through a modified fragmentation function[18, 19] or in the form of quenching weights[20], for example.

By comparing the yields in p(d)+A and A+A collisions to that in p+p collisions, with a scaling factor to take into account the nuclear geometry, one can test the assumption that a nucleus-nucleus collision is a simple superposition of incoherent nucleon-nucleon scatterings and explore these nuclear effects. The magnitude and shape of deviations from this scaling in Au+Au collisions may be used to infer information about the properties of the medium[19, 21]. This is the fundamental goal of studying high p_T particle production and dynamics in heavy ion collisions: What can be learned about the medium from these "hard probes"?

The nuclear modification factor, R_{AB}, is defined as

$$R_{AB}(p_T,b) \equiv \frac{d\sigma^h_{AB}/dyd^2p_T(b)}{\langle N_{\rm binary}(b)\rangle d\sigma^h_{pp}/dyd^2p_T}. \qquad (2)$$

where $d\sigma^h_{AB}/dyd^2p_T(b)$ is the differential cross-section for hadron production in a nuclear collision of impact parameter, b, $d\sigma^h_{pp}/dyd^2p_T$ is the corresponding quantity in p+p collisions and $\langle N_{\rm binary}(b)\rangle$ is the average number of binary nucleon-nucleon collisions, often calculated using the Glauber model for the nuclear overlap with given impact parameter[22].

In the first collision data from RHIC at $\sqrt{s_{NN}}$=130 GeV, the PHENIX experiment showed that the production of high p_T $h^{\pm}$ and π^0's was suppressed by a factor of $\sim$3 in central Au+Au collisions compared to the expectation from binary-scaled p+p collisions, as seen in Figure 2 [3]. This stunning result, also seen in $h^{\pm}$ spectra by the STAR experiment[4],

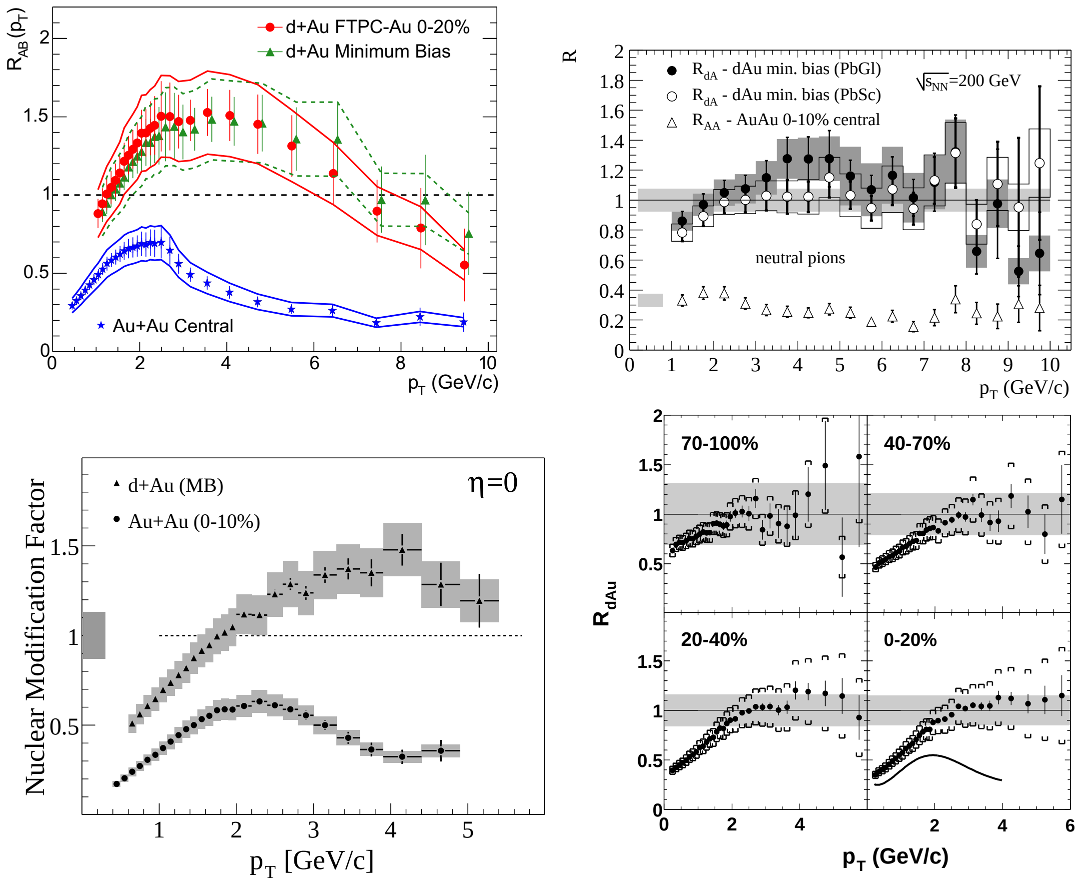

Figure 4. Nuclear modification factors R_{dAu} in d+Au collisions at $\sqrt{s_{\rm NN}}$= 200 GeV. Clockwise from the upper left: STAR $h^{\pm}$[9], PHENIX π^0[8], PHOBOS $h^{\pm}$[7] and BRAHMS $h^{\pm}$[10].

confirmed that a qualitatively new kind of system with intriguing properties is generated in these collisions. However these first data are *quantitatively* limited by the parameterized p+p reference spectrum used for the comparison. The reference had to be derived from a compilation of the world's data on hadron production in p+p($\bar{p}$) collisions over a broad range of collision energies because no data exist at $\sqrt{s_{\rm NN}}$= 130 GeV.

In RHIC Run II, this limitation was overcome when data from p+p and Au+Au collisions at $\sqrt{s_{\rm NN}}$= 200 GeV were collected[5, 23, 24, 10]. Figure 3 shows results for $h^{\pm}$ R_{AA} on the left and a similar measure, R_{CP}, the binary collision-scaled yield in central Au+Au compared to the scaled yield in peripheral Au+Au collisions[5] on the right. This comparison, which is motivated by the observed binary collision-scaling in peripheral Au+Au collisions for p_T>2 GeV/c seen in the lower panels of the left side of Figure 3, extends the p_T reach of the measurement with smaller systematic uncertainties than R_{AA}. The high statistics data sample at $\sqrt{s_{\rm NN}}$= 200 GeV, with smaller uncertainties and higher p_T reach than $\sqrt{s_{\rm NN}}$= 130 GeV, reveals the feature that for all hadrons with 6<p_T<12 GeV/c, the suppression is approximately independent of p_T. This p_T-independence was largely unexpected in model predictions prior to the availability of the data[13].

More recent model calculations are compared to the data in Figure 3. Two formulations

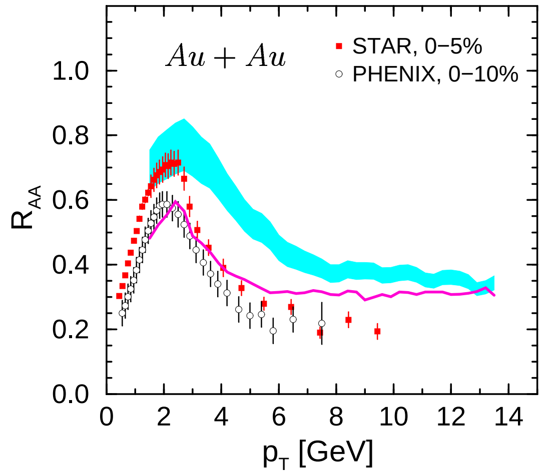

Figure 5. A comparison of results from the Hadron-String-Dynamics model[30] to RHIC data on R_{AA} in Au+Au collisions at $\sqrt{s_{\rm NN}}$= 200 GeV.

of a pQCD parton model incorporating partonic energy loss, labeled pQCD-I[25] and pQCD-II[21] are shown. The influence of nuclear gluon shadowing is shown within pQCD-I as the dashed lines of the left panel of Figure 3. It is the subtle interplay of the shadowing, initial state multiple scattering and jet quenching which results in the observed p_T-independence in these models. In addition, the right panel of Figure 3 also shows a calculation from the parton saturation model which extends initial-state gluon saturation beyond the saturation scale, Q_s to high p_T at midrapidity[26]. This model is also seen to reproduce the suppression pattern for p_T>5 GeV/c in the upper panel. The fact that two models based on entirely different physics, one incorporating strong initial-state effects and one with strong final-state effects, can both explain the suppression data was the primary reason that d+Au collisions were run at RHIC. Initial-state nuclear effects are present in both d+Au and Au+Au collisions, while final-state effects are expected only in Au+Au.

Figure 4 shows results on R_{dAu} from each of the four RHIC experiments[7, 8, 9, 10]. The enhancement observed for 2<p_T<6 GeV/c is similar to the enhancement seen in p+A collisions at lower energies[27], called the “Cronin effect”. The standard explanation of this observed enhancement is the multiple soft interactions independent of the hard-scattering discussed in the first section[16].

In contrast, the gluon saturation model shown in the right panel of Figure 3 predicted a suppression for central d+Au collisions of $R_{dA}\simeq$0.7[26]. Clearly no such suppression is present in Figure 4. The factor 4-5 suppression in central Au+Au collisions must be attributed to final-state, not initial-state nuclear effects.

Although the data in Figure 3 compare quite well with models incorporating final-state partonic energy loss, final state hadronic re-scattering may play some role in generating the observed suppression and many theoretical investigations of this possibility have been undertaken[28, 29, 31]. In Figure 5, a comparison is made between RHIC data and a Hadron-String-Dynamics (HSD) model which incorporates quark, diquark, string and hadronic interactions with the medium[30]. The features of the data are indeed reproduced, but

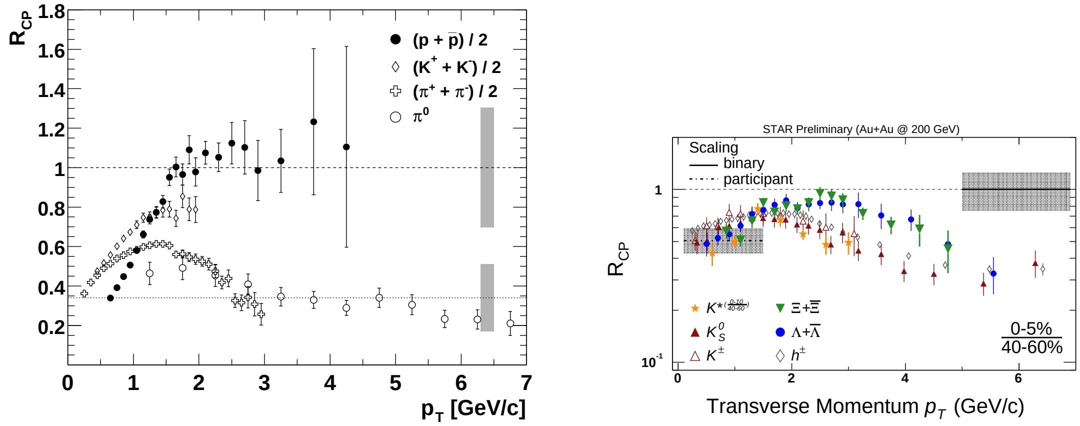

Figure 6. Nuclear modification factor R_{CP} for identified hadrons from PHENIX[6] on the left and STAR[34] on the right.

hadronic interactions are found to contribute very little to the suppression for $p_T > 6$ GeV/c, where inelastic, possibly colored partonic interactions of leading "pre-hadrons" with the dense medium are responsible for the observed suppression.

4. Identified particle spectra and pseudorapidity dependence of R_{AA}

The particle composition at intermediate p_T has been observed to contain an unusually bountiful baryon population in Au+Au collisions at RHIC[32, 33]. Figure 6 shows results from PHENIX[6] on the left and STAR[34] on the right for R_{CP} of identified hadrons. The difference between meson and baryon R_{CP} is most pronounced for $2 < p_T < 6$ GeV/c. Several models relying on parton recombination and coalescence have been proposed to explain the "baryon anomaly" at intermediate p_T[35]. From the right panel of Figure 6, it appears that the mesons and baryons converge for $p_T > 6$ GeV/c, where parton fragmentation dynamics dominate and no difference between mesons and baryons is expected. Interesting dynamics are clearly at play in the intermediate p_T region, which should be investigated more thoroughly. What is also clear is the importance of carrying all leading hadron observables, such as spectra, di-hadron correlations and azimuthal anisotropies to the highest p_T available and at minimum for $p_T > 6$ GeV/c. This ensures that they can be used as reliable hard probes and minimizes complications from competing effects in evaluating the medium properties.

In Figures 7 and 8, data from the BRAHMS collaboration on R_{AA} and R_{CP} at forward rapidities are compared to the results at mid-rapidity in Au+Au[10] and d+Au[36] collisions. From Figure 7 it appears that there is no strong evolution of the suppression pattern as a function of pseudorapidity in Au+Au, while in Figure 8 there is a clear change from Cronin enhancement at midrapidity to a suppression at forward rapidities in the Au-going direction of d+Au collisions. Such a pattern is expected in saturation models[37, 38, 26, 39] but may not be a unique signature of gluon saturation. In fact, energy-momentum conservation in the hadron fragmentation region alone should result in a reduction of R_{dAu} of about 30% between $\eta = 0$ and $\eta = 3.2$[31]. In addition, conventional nuclear shadowing corrections are also

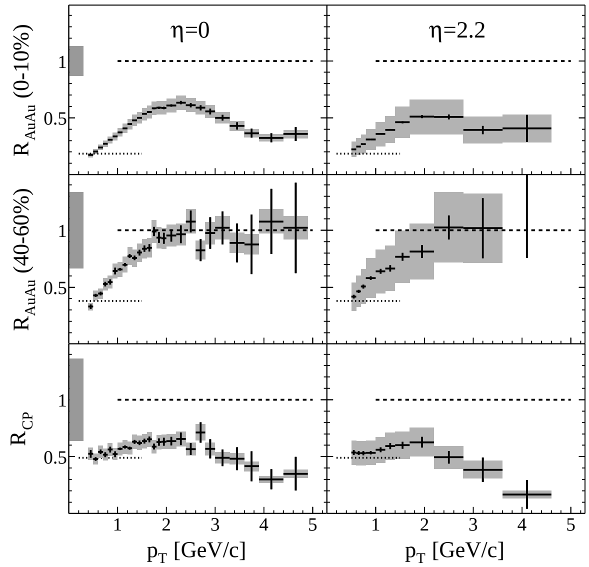

Figure 7. Nuclear modification factors R_{AA} and R_{CP} in Au+Au collisions at $\sqrt{s_{NN}}$= 200 GeV for midrapidity (right) and forward rapidity (left) measured by the BRAHMS collaboration[10].

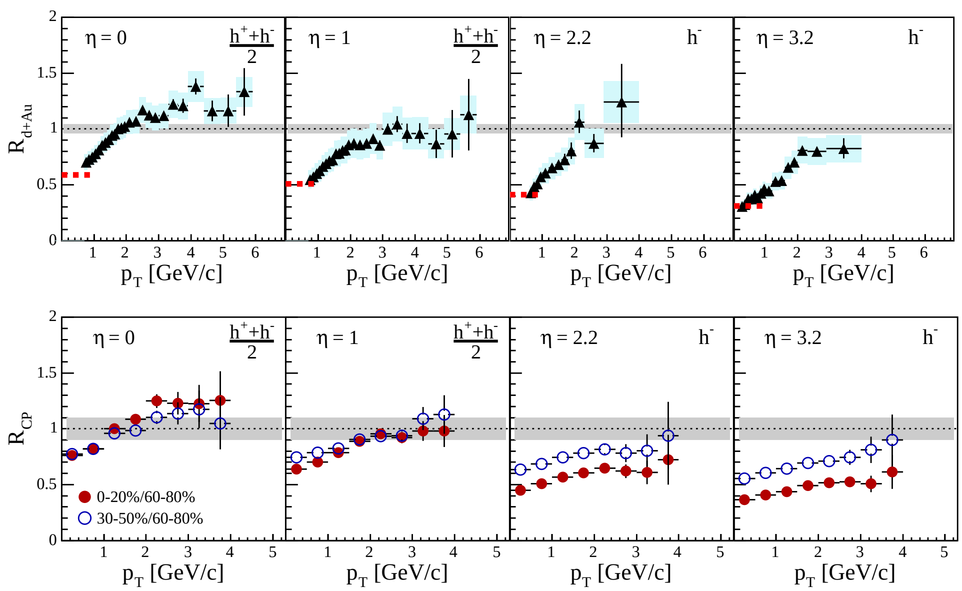

Figure 8. Nuclear modification factors R_{dAu} (top) and R_{CP}^{dAu} (bottom) for four rapidity intervals in d+Au collisions at $\sqrt{s_{NN}}$= 200 GeV measured by the BRAHMS Collaboration[36].

expected to result in a roughly 30% decrease of R_{dAu} over the same range of pseudorapidity. The authors of [31] fi nd that they can reproduce the data over all rapidities incorporating these effects into a hadronic absorption model without invoking substantial gluon saturation in the initial wave-function of the nucleus.

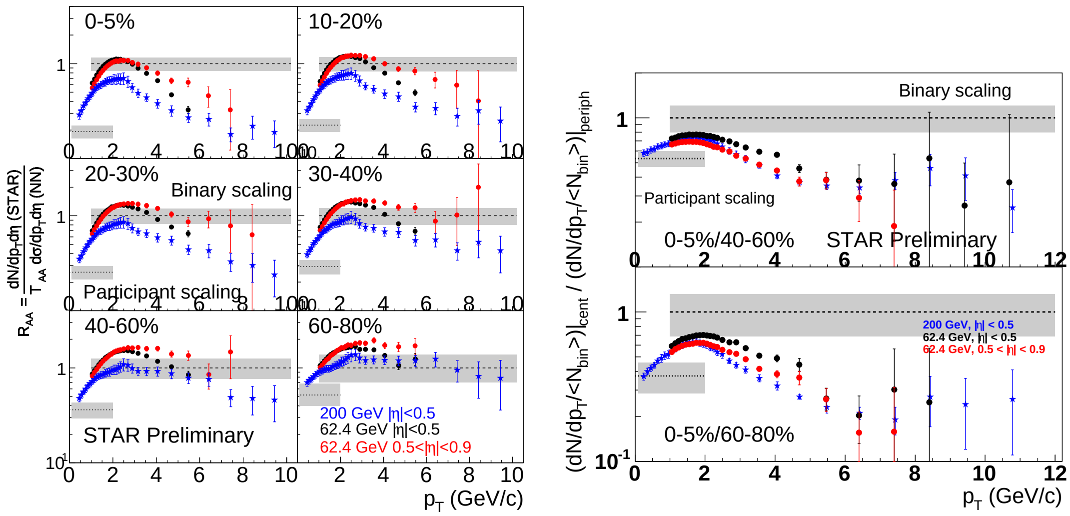

Figure 9. Preliminary results from the STAR Experiment on R_{AA} and R_{CP} in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$= 62.4 GeV[45].

5. Evolution of R_{AA} with beam energy: Enhancement vs. Suppression?

A Bjorken model estimate of the initial energy density achieved in central Au+Au collisions at RHIC yields values 30 times that in cold nuclear matter[40] while at the SPS the corresponding value is approximately a factor of 20[41]. These values are both well above the factor 3-5 expected for the onset of deconfinement and yet the yield of π^0 measured at the SPS appears enhanced by a factor of 2-4 relative to binary collision scaling[42]. Is there a transition from enhancement to suppression somewhere between $17<\sqrt{s_{\mathrm{NN}}}<130$ GeV?

During RHIC Run IV, Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$= 62.4 GeV were run to search for such a transition. The choice of beam energy was motivated by the fact that it lies roughly halfway between the SPS and RHIC top energies on a logarithmic scale and there exists a large body of reference data from p+p collisions at the ISR at this beam energy[43]. As it turns out, two key findings underscoring the importance of a reliable reference dataset have emerged from this exploration.

First, a recent re-analysis of the parameterization used for the SPS R_{AA} reference reveals large variations in the extracted R_{AA} depending on the choice of data and functional form used to fit them[44]. In fact, a parameterization using the best fit to all of the available data results in R_{AA} for π^0 with $2<p_T<4$ GeV/c that is consistent (within large uncertainties) with binary collision scaling at $\sqrt{s_{\mathrm{NN}}}$=17 GeV. R_{CP} may even be slightly suppressed at the SPS[44].

Second, it is challenging to find a reference spectrum within the ISR datasets[43] that has systematic uncertainties at the same level of precision as the RHIC data. Even compiling a composite spectrum from all available publications results in minimum systematic uncertainties of 20-30%. Therefore, the significance of R_{AA} measurements at this beam energy may remain small until a reference run at RHIC can be performed. Nevertheless, given these large uncertainties, preliminary results presented at the RHIC/AGS Users Meeting

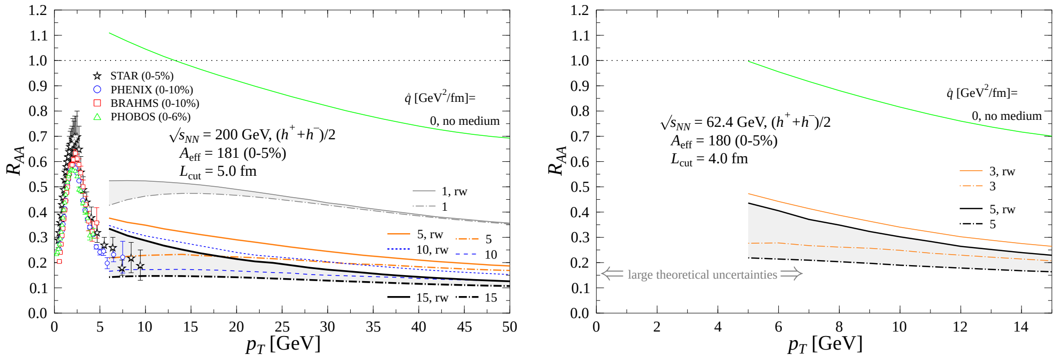

Figure 10. The p_T dependence of R_{AA} at high p_T compared to RHIC data at $\sqrt{s_{\rm NN}}$= 200 GeV (left) and predictions for R_{AA} at $\sqrt{s_{\rm NN}}$= 62.4 GeV within the same model from Ref.[49] (right).

in May 2004 show that even at $\sqrt{s_{\rm NN}}$= 62.4 GeV there is substantial suppression for p_T>6 GeV/c[45, 46, 47, 48]. Figure 9 shows preliminary results on R_{AA} (left) and R_{CP} (right) for $h^{\pm}$ measured by the STAR experiment at midrapidity ($|\eta| < 0.5$) and slightly forward ($0.9 < |\eta| < 0.5$)[45]. The intermediate p_T region is less suppressed at $\sqrt{s_{\rm NN}}$=62.4 GeV than 200 GeV, but for p_T>6 GeV/c, the suppression is comparable and may also be approximately p_T-independent.

This beam energy and p_T-independence of R_{AA} is intriguing. One possibility is that it may be due simply to the interplay of the evolving power-law shape of the underlying partonic spectrum and the medium-induced energy loss for media of varying size and density[49]. For central Au+Au at $\sqrt{s_{\rm NN}}$=200 GeV, calculations with a time-averaged transport coefficient of $\hat{q}$=5-15 GeV^2/fm for the medium and a pQCD parton spectrum from PYTHIA reproduce the observed R_{AA} for p_T>5 GeV/c and are p_T-independent even to the highest accessible p_T. This has intriguing consequences for R_{AA} at the LHC: the strong suppression in the denser, more opaque system expected in Pb+Pb collisions at $\sqrt{s_{\rm NN}}$= 5.5 TeV is balanced by the shallower partonic spectrum, which results in more high p_T hadrons from hard-scatterings near the surface. The overall effect is R_{AA} with similar shape and magnitude at RHIC and LHC, in contrast to other models[21]. It is suggested that R_{AA} may only be able to set a lower limit for the system density when $\hat{q} \geq 4$ GeV^2/fm[49].

At $\sqrt{s_{\rm NN}}$= 62.4 GeV, the transport coefficient is probably reduced somewhat and may offer more sensitivity to the medium properties, but again it competes with the steeper partonic spectrum. Figure 10 shows R_{AA} expected for $\sqrt{s_{\rm NN}}$= 62.4 GeV Au+Au assuming $\hat{q} \simeq$ 3-5 GeV^2/fm[49]. The suppression is substantial, p_T-independent and reasonably consistent with the preliminary data for p_T>6 GeV/c and with several other recently published predictions[50]. Clearly, the body of data collected at RHIC over many systems and beam energies provides important feedback for testing and refining these models so that reliable estimates of the medium properties may be extracted from them.

6. Conclusion

Systematic high-precision studies of single hadron inclusive spectra measured in p+p, d+Au and Au+Au collisions at RHIC have have yielded several exciting observations: the p_T-independent factor 4-5 suppression for p_T>6 GeV/c, the complex composition of hadron species at intermediate 2<p_T<6 GeV/c and the possible beam energy independence of $R_{AA}(p_T>6\text{GeV/c})$ for 62.4<$\sqrt{s_{\rm NN}}$<200 GeV. These features have stimulated extensive theoretical feedback to explain their origins. The body of data supports the idea that strong final-state partonic interactions are at work in the dense medium created in these collisions. In order to take this qualitative statement closer to quantitative evaluation of the medium properties, a comprehensive, coherent explanation of all the high p_T phenomena: single inclusive hadron spectra, di-hadron correlations/modifications and azimuthal anisotropic emission at high p_T must be undertaken. As the simplest and most investigated of the observables, the single hadron spectra provide a strong baseline from which to attempt further explorations. The quality and quantity of the spectra will only improve and grow as the RHIC program proceeds, transforming them from a pool of discovery to a tool of precision for future high p_T studies at RHIC and beyond.

References

[1] C. Adler *et al* (STAR Collaboration), Phys. Rev. Lett. **90**, 032301 (2003).
[2] C. Adler *et al* (STAR Collaboration), Phys. Rev. Lett. **90**, 082302 (2003).
[3] K. Adcox *et al* (PHENIX Collaboration), Phys. Rev. Lett. **88**, 022301 (2002).
[4] C. Adler *et al* (STAR Collaboration), Phys. Rev. Lett. **89**, 202301 (2002); J. Adams *et al* (STAR Collaboration), nucl-ex/0404020.
[5] J. Adams *et al* (STAR Collaboration), Phys. Rev. Lett. **91**, 172302 (2003).
[6] S.S. Adler *et al* (PHENIX Collaboration), Phys. Rev. **C69**, 034910 (2004).
[7] B.B. Back *et al* (PHOBOS Collaboration), Phys. Rev. Lett. **91**, 072302 (2003).
[8] S.S. Adler *et al* (PHENIX Collaboration), Phys. Rev. Lett. **91**, 072303 (2003).
[9] J. Adams *et al* (STAR Collaboration), Phys. Rev. Lett. **91**, 072304 (2003).
[10] I. Arsene *et al* (BRAHMS Collaboration), Phys. Rev. Lett. **91**, 072305 (2003).
[11] J. Adams *et al* (STAR Collaboration), nucl-ex/0407007.
[12] John C. Collins, Davison E. Soper and George Sterman, Nucl. Phys. **B261**, 104 (1985).
[13] Xin-Nian Wang, Phys. Rev. **C61**, 064910 (2000).
[14] P. Levai, G. Papp, G.G. Barnafoldi and George I. Fai, nucl-th/0306019.
[15] V. Emel'yanov, A. Khodinov, S.R. Klein and R. Vogt, Phys. Rev. **C61**, 044904 (2000).
[16] M. Lev and B. Petersson, Z. Phys. **C21**, 155 (1983); T. Ochiai, S. Date and H. Sumiyoshi, Prog. Theor. Phys. **75**, 288 (1986).
[17] R. Baier, D. Schiff and B.G. Zakharov, Ann. Rev. Nucl. Sci. **50**, 37 (2000); Miklos Gyulassy, Ivan Vitev, Xin-Nian Wang and Ben-Wei Zhang, nucl-th/0302077
[18] Xin-Nian Wang and Zheng Huang, Phys. Rev. **C55**, 3047 (1997); Xin-Nian Wang, Zheng Huang and Ina Sarcevic, Phys. Rev. Lett. **77**, 231 (1996).
[19] Xin-Nian Wang, Phys. Rev. **C58**, 2321 (1998).
[20] Carlos A. Salgado and Urs Achim Wiedemann, Phys. Rev. **D68**, 014008 (2003).
[21] Ivan Vitev and Miklos Gyulassy, Phys. Rev. Lett. **89**, 252301 (2002).
[22] R.J. Glauber, in Lectures in Theoretical Physics, edited by W.E. Brittin and L.G. Dunham (Interscience, N.Y., 1959), Vol. 1, p. 315.

[23] S.S. Adler *et al* (PHENIX Collaboration), Phys. Rev. Lett. **91**, 072301 (2003).
[24] B.B. Back *et al* (PHOBOS Collaboration), Phys. Lett. **B578**, 297 (2004).
[25] Xin-Nian Wang, Phys. Lett. **B595**, 165 (2004).
[26] Dmitri Kharzeev, Eugene Levin and Larry McLerran, Phys. Lett. **B561**, 93 (2003).
[27] J.W. Cronin *et al* , Phys. Rev. **D11**, 3105 (1975); D. Antreasyan *et al* , Phys. Rev. **D19**, 764 (1979).
[28] K. Gallmeister, C. Greiner and Z. Xu, Phys. Rev **C67**, 044905 (2003).
[29] Roman Lietava, Jan Pisut, Neva Pisutova and Boris Tomasik, Eur. Phys. J. **C28**, 119 (2003).
[30] W. Cassing, K. Gallmeister and C. Greiner, Nucl. Phys. **A735**, 277 (2004).
[31] A. Capella, E.G. Ferreiro, A.B. Kaidalov and D. Sousa, hep-ph/0403081.
[32] S.S. Adler *et al* (PHENIX Collaboration), Phys. Rev. Lett. **91**, 172301 (2003).
[33] J. Adams *et al* (STAR Collaboration), Phys. Rev. Lett. **92**, 052302 (2004).
[34] M.A.C. Lamont (STAR Collaboration), J. Phys. **G30**, S963 (2004).
[35] Rudolph C. Hwa and C.B. Yang, Phys. Rev. **C67**, 064902 (2003); R.J. Fries, B. Muller, C. Nonaka and S.A. Bass, Phys. Rev. Lett. **90**, 202303 (2003); V. Greco, C.M. Ko and P. Levai, Phys. Rev. Lett. **90**, 202302 (2003).
[36] I. Arsene *et al* (BRAHMS Collaboration), nucl-ex/0403005.
[37] Rudolf Baier, Alexander Kovner and Urs Achim Wiedemann, Phys. Rev. **D68**, 054009 (2003); Javier L. Albacete *et al* , Phys. Rev. Lett. **92**, 082001 (2004).
[38] Dmitri Kharzeev, Yuri V. Kovchegov and Kirill Tuchin, Phys. Rev. **D68**, 094013 (2003).
[39] Jamal Jalilian-Marian, Yasushi Nara and Raju Venugopalan, Phys. Lett. **B577**, 54 (2003); Adrian Dumitru and Jamal Jalilian-Marian, Phys. Rev. Lett. **89**, 022301 (2002).
[40] K. Adcox *et al* (PHENIX Collaboration), Phys. Rev. Lett. **87**, 052301 (2001).
[41] S. Margetis *et al* (NA49 Collaboration), Phys. Rev. Lett. **75**, 3814 (1995).
[42] M.M. Aggarwal *et al* (WA98 Collaboration), Eur. Phys. J. **C23**, 225 (2002).
[43] T. Akesson *et al* , Nucl. Phys. **B209**, 309 (1982); A. Breakstone *et al* , Z. Phys. **C69**, 55, (1995); D. Drijard *et al* , Nucl. Phys. **B208**, 1 (1982); A.L.S. Angelis *et al* , Phys. Lett. **B79**, 505 (1978); F.W. Busser *et al* , Nucl. Phys. **B106**, 1 (1976); T. Akesson *et al* , Nucl. Phys. **B246**, 408, (1984); K. Eggert *et al* , Nucl. Phys. **B98**, 49 (1975); B. Alper *et al* , Nucl. Phys. **B100**, 237 (1975); B. Alper *et al* , Nucl. Phys. **B87**, 19 (1975).
[44] David d'Enterria, Phys. Lett. **B596**, 32 (2004).
[45] J. Dunlop (STAR Collaboration), *Plenary talk at the RHIC & AGS Annual Users Meeting, May 10-14, 2004.*
[46] T. Awes (PHENIX Collaboration), *Plenary talk at the RHIC & AGS Annual Users Meeting, May 10-14, 2004.*
[47] M. Baker (PHOBOS Collaboration), *Plenary talk at the RHIC & AGS Annual Users Meeting, May 10-14, 2004.*
[48] B.B. Back *et al* (PHOBOS Collaboration), nucl-ex/0405003.
[49] K.J. Eskola, H. Honkanen, C.A. Salgado, U.A. Wiedemann, hep-ph/0406319.
[50] Ivan Vitev, nucl-th/0404052; Azfar Adil and Miklos Gyulassy, nucl-th/0405036; Xin-Nian Wang, Phys. Rev. **C70**, 031901 (2004).

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.