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 configurations ($p+p$, $d+Au$, $Au+Au$) 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 first 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 $\sqrt{s_{NN}}= 130$ 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 $\sqrt{s_{NN}}= 200$ 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].
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2

$10^{-10}$

$10^{-9}$

$10^{-8}$

$10^{-7}$

$10^{-6}$

$10^{-5}$

$10^{-4}$

$10^{-3}$

$10^{-2}$

$10^{-1}$

Figure 1. Comparisons of $h^\pm$ and $\pi^0$ 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].

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 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 factorizes 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

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

where $K$ is a constant and $f_a(x, Q^2)$ and $f_b(x, Q^2)$ are the parton distribution functions for quark $a$ and $b$, respectively. $D^{0}_{h/c}(z_c, Q^2)$ is the partonic fragmentation function for hadron $h$ from parton $c$, and $d\sigma^{(ab\rightarrow cd)}/dz_c$ is the partonic cross-section for the process $ab\rightarrow cd$. This expression is known as the QCD parton model, and it provides a framework for understanding the production of high $p_T$ hadrons in elementary collisions.
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, \( D_{\pi^0 c/c}(z, Q^2) \) is the fragmentation function to convert parton \( c \) into colorless hadrons, \( h \) and \( \frac{d\sigma}{dt}^{(ab\rightarrow cd)} \) is the hard-scattering cross-section, which is calculable in a perturbative series expansion in powers of the strong coupling constant, \( \alpha_s \). Since the complexity of the calculation grows nonlinearly with the power of \( \alpha_s \), 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\(^\text{13}\). The right panel of Figure 1 shows a comparison of both LO and NLO calculations to \( \pi^0 \) production in p+p collisions at RHIC\(^\text{14}\). 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\(^\text{15}\). 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\(^\text{16}\). These effects can be added to the factorized pQCD model expressed in Equation 1 as modifications to the PDF terms.

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\(^\text{17}\). This effect is often introduced in pQCD parton model calculations through a modified fragmentation function\(^\text{18, 19}\) or in the form of quenching weights\(^\text{20}\), 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\(^\text{19, 21}\). 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

$$R_{AB}(p_T, b) \equiv \frac{d\sigma_{AB}^{h}/dyd^2p_T(b)}{\langle N_{\text{binary}}(b) \rangle d\sigma_{pp}^{h}/dyd^2p_T},$$

where $d\sigma_{AB}^{h}/dyd^2p_T(b)$ is the differential cross-section for hadron production in a nuclear collision of impact parameter, $b$, $d\sigma_{pp}^{h}/dyd^2p_T$ is the corresponding quantity in p+p collisions and $\langle N_{\text{binary}}(b) \rangle$ 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 $\sqrt{s_{\text{NN}}}=130$ GeV, the PHENIX experiment showed that the production of high $p_T$ $h^\pm$ and $\pi^0$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. This stunning result, also seen in $h^\pm$ spectra by the STAR experiment\[4], 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 $\sqrt{s_{\text{NN}}}= 130$ GeV.

In RHIC Run II, this limitation was overcome when data from p+p and Au+Au collisions at $\sqrt{s_{\text{NN}}}= 200$ 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
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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.

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 $\sqrt{s_{NN}}=200$ GeV, with smaller uncertainties and higher $p_T$ reach than $\sqrt{s_{NN}}=130$ 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.

More recent model calculations are compared to the data in Figure 3. Two formulations 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 prior to and
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Figure 4. Nuclear modification factors $R_{dAu}$ in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Clockwise from the upper left: STAR $h^{\pm}$[9], PHENIX $\pi^0$[8], PHOBOS $h^{\pm}$[7] and BRAHMS $h^{\pm}$[10].

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

possibly after the hard-scattering which were 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 $R_{dA} \simeq 0.7$\cite{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\cite{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\cite{30}. The features of the data are indeed reproduced, but 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\cite{32,33}. Figure 6 shows results from PHENIX\cite{6} on the left and STAR\cite{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 $p_T$\cite{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 of the medium properties while minimizing complications from the dynamics of additional effects.

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\cite{10} and d+Au\cite{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\cite{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 $\eta = 3.2$\cite{31}. In addition, conventional nuclear shadowing corrections are also expected to result in a roughly 30% decrease of $R_{dAu}$ over the same range of pseudorapidity. The authors of\cite{31} find 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. More studies of the pseudorapidity dependence of \( R_{AB} \) and other high \( p_T \) observables such as di-hadron correlations are probably needed before a concrete understanding of the underlying dynamics emerges.

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 \([11]\). These values are both
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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].

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

well above the factor 3-5 expected for the onset of deconfinement and yet the yield of $\pi^0$ 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 $17 < \sqrt{s_{NN}} < 130$ GeV?

During RHIC Run IV, $Au+Au$ collisions at $\sqrt{s_{NN}} = 62.4$ 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 $\pi^0$ with $2<p_T<4$ GeV/c that is consistent (within large uncertainties) with binary collision scaling at $\sqrt{s_{NN}}=17$ 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 in May 2004 show that even at $\sqrt{s_{NN}}=62.4$ 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 $\sqrt{s_{NN}}=62.4$ 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 $\sqrt{s_{NN}}=200$ 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 $\sqrt{s_{NN}}=5.5$ 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 $\sqrt{s_{NN}}=62.4$ 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 $\sqrt{s_{NN}}=62.4$ 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
Figure 10. The \( p_T \) dependence of \( R_{AA} \) at high \( p_T \) compared to RHIC data at \( \sqrt{s_{NN}} = 200 \) GeV (left) and predictions for \( R_{AA} \) at \( \sqrt{s_{NN}} = 62.4 \) GeV within the same model from Ref.49 (right).

6. Conclusion

Systematic high-precision studies of single hadron inclusive spectra measured in \( p+p \), \( d+Au \) and \( Au+Au \) collisions at RHIC 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 \( 62.4 < \sqrt{s_{NN}} < 200 \) 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 developed. As the simplest and most investigated of the observables, the single hadron spectra provide a strong baseline for these more detailed and differential explorations of the medium. The quality and quantity of the spectra will grow and improve as the RHIC program proceeds, transforming them from the pool of discovery they provided in the first four years of RHIC running to a tool of precision for future high \( p_T \) studies in heavy ion collisions at RHIC and beyond.

Acknowledgments

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.
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