Hard spectra and QCD matter: experimental review

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Abstract. The most significant experimental results on hadron spectra at large transverse momentum available at the time of Quark Matter 2004 conference are reviewed. Emphasis is put on those measurements that provide insights on the properties of the QCD media, “Quark Gluon Plasma” and “Color Glass Condensate”, expected to be present in nucleus-nucleus collisions at collider energies.

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1. Introduction

Nucleus-nucleus collisions at relativistic energies aim at the study of the fundamental theory of the strong interaction, Quantum Chromo Dynamics (QCD), at extreme energy densities. The main goal of this physics program is the production and study under laboratory conditions of the plasma of quarks and gluons (QGP). The QGP is a deconfined and chirally symmetric state of strongly interacting matter predicted by QCD calculations on the lattice [1] for values of the energy density five times larger than those found in the nuclear ground state, $\epsilon \gtrsim 0.7 \pm 0.3$ GeV/fm$^3$. The combination of high center-of-mass energies and large nuclear systems in the initial-state of heavy-ion reactions provides, furthermore, favorable conditions for the study of the (non-linear) parton dynamics at small values of (Bjorken) fractional momentum $x$. In this regime (often dubbed “Color Glass Condensate”, CGC [2]), higher-twist effects are expected to saturate the rapidly increasing density of “wee” gluons observed at small-$x$ in the hadronic wave functions which would, otherwise, violate the unitarity limit of the theory.

In hadronic collisions the production of particles with high transverse momentum ($p_T \gtrsim 2$ GeV/$c$) results from hard parton-parton scattering processes with large momentum transfer $Q^2$ and, as such, is directly connected to the fundamental (quark and gluon) degrees of freedom of QCD. Since hard cross-sections can be theoretically computed by perturbative methods using the collinear factorization theorem [3], inclusive high $p_T$ hadroproduction, jets, direct photons, and heavy flavors, have

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long been considered sensitive and well calibrated probes of the small-distance QCD phenomena. This paper reviews the most interesting results on transverse spectra from $Au + Au$ reactions at RHIC collider energies ($\sqrt{s_{NN}} = 200$ GeV) in the high $p_T$ sector, where the production of hadrons in central collisions shows substantial differences compared to heavy-ion reactions at lower center-of-mass-energies ($\sqrt{s_{NN}} \approx 20$ GeV) as well as compared to more elementary reactions either in the “vacuum” ($p+p$, $e^+e^-$) or in a cold nuclear matter environment ($d$, $l+A$). Such differences are indicative of significant initial- and final- state effects and provide direct information on the properties of the QCD medium in which the hard scattering process has taken place.

2. Hard spectra in the QCD vacuum: $p + p$ collisions

High $p_T$ production in proton-proton collisions provides the baseline “free space” reference to which one compares heavy-ion results in order to extract information about the QCD medium properties. At RHIC, the differential cross-sections for $\pi^0$ \cite{5} and charged hadrons \cite{5, 6} above $p_T \approx 2$ GeV/c measured in $p + p$ collisions at $\sqrt{s} = 200$ GeV are well reproduced by standard next-to-leading-order (NLO) pQCD calculations (Figure 1). This is at variance with measurements at lower center-of-mass energies ($\sqrt{s} \lesssim 65$ GeV, Fig. 1 left) where the $p_T < 5$ GeV/c cross-sections in hadronic collisions at fixed-target and CERN-ISR collider energies are underpredicted \cite{7, 8} by pQCD calculations (even supplemented with soft-gluon resummation corrections \cite{9}), and additional non-perturbative effects (e.g. intrinsic $k_T$ \cite{10}) must be introduced to bring parton model analysis into agreement with data. Hard production in $p + p$ collisions in the collider regime of RHIC seems to be basically free of the “distortive” non-perturbative effects that are important at lower energies, and constitutes thus a experimentally and theoretically well calibrated baseline for heavy-ion studies.

3. Hard spectra in hot QCD matter: central $A + A$ collisions

3.1. QCD factorization in $A + A$ collisions

Implicitly at the root of the QCD description of high $p_T$ particle production in hadronic collisions is the idea that the large-$Q^2$ scattering between the two partons from each hadron is an incoherent process. Namely, that the characteristic time of the parton-parton interaction is much shorter than any long-distance interaction occurring before (among partons belonging to the same hadronic wave function) or after (during the evolution of the struck partons into their hadronic final-state) the hard collision itself. The “factorization theorem” \cite{3} reflects this mutual independence of QCD dynamics at different time (length) scales: the inelastic cross-section for the production of a given hadron $h$ in a hard process, $E d\sigma_{h}^{\text{hard}}/d^3p$, is the (factorized) product of long-distance (non-perturbative but universal parton distribution functions, $f_q,g$, and fragmentation functions, $D_{q,g}/h$) and short-distance (perturbatively computable parton-
Hard spectra and QCD matter: experimental review

Figure 1. Invariant cross-sections as a function of $p_T$ measured at midrapidity in $p+p$ collisions at $\sqrt{s} = 200$ GeV compared to NLO pQCD calculations (with scales $\mu = p_T$, solid lines, and $\mu = p_T/2$, dotted-dashed lines) for: $p+p \rightarrow \pi^0 + X$ (PHENIX data, left, compared to results at different $\sqrt{s}$ [8]), and $p+p \rightarrow h^\pm + X$ (STAR, right).

In nucleus-nucleus reactions, QCD factorization reads:

$$E \frac{d\sigma_{AB \rightarrow h}}{d^3p} = f_{a/A}(x, Q^2) \otimes f_{b/B}(x, Q^2) \otimes \frac{d\sigma_{ab \rightarrow c}}{d^3p} \otimes D_{c/h}(z, Q^2).$$

Since partons are effectively “frozen” during the hard scattering, one can treat each nucleus as a collection of free partons. Thus, with regard to high $p_T$ production, the density of partons in a nucleus with atomic number $A$ should be equivalent to the superposition of $A$ independent nucleons:

$$f_{a/A}(x, Q^2) = A \cdot f_{a/N}(x, Q^2).$$

From (1) and (2) it is clear that QCD factorization implies that hard inclusive cross-sections in a minimum-bias $A+B$ reaction scale simply as $A \cdot B$ times the corresponding $p+p$ cross-sections:

$$E d\sigma_{AB \rightarrow h}/d^3p = A \cdot B \cdot E d\sigma_{pp \rightarrow h}/d^3p.$$  (3)

Since nucleus-nucleus experiments usually measure invariant yields for a given centrality bin (or impact parameter $b$), one writes instead:

$$E dN_{AB \rightarrow h}/d^3p (b) = \langle T_{AB}(b) \rangle \cdot E dN_{pp \rightarrow h}/d^3p,$$  (4)

where $T_{AB}(b)$ is the Glauber geometrical nuclear overlap function at $b$. One can thus quantify the medium effects on the production of a given particle at high $p_T$ via the

Since the number of inelastic nucleon-nucleon collisions at $b$, $N_{\text{coll}}(b)$, is proportional to $T_{AB}$:

$$N_{\text{coll}}(b) = T_{AB}(b) \cdot \sigma_{pp}^{\text{inel}},$$

one also writes Eq. (4) as:

$$E dN_{AB \rightarrow h}/d^3p (b) = \langle N_{\text{coll}}(b) \rangle \cdot E dN_{pp \rightarrow h}/d^3p.$$
nuclear modification factor:

\[ R_{AB}(p_T, y) = \frac{\text{"hot QCD medium"}}{\text{"QCD vacuum"}} = \frac{d^2 N_{AB}/dydp_T}{\langle T_{AB}(b) \rangle \times d^2 \sigma_{pp}/dydp_T}, \] (5)

which measures the deviation of \( A+B \) at \( b \) from an incoherent superposition of nucleon-nucleon (NN) collisions, in terms of suppression (\( R_{AA} < 1 \)) or enhancement (\( R_{AA} > 1 \)).

3.2. High \( p_T \) suppression in central \( A + A \): \( \sqrt{s_{NN}} \) and \( p_T \) dependence

One of the most interesting results at RHIC so far is the breakdown of the expected incoherent parton scattering assumption for high \( p_T \) production, Eq. (4), observed in central \( Au + Au \). Figure 2 shows \( R_{AA} \) as a function of \( p_T \) for \( \pi^0 \) produced in nucleus-nucleus reactions at different center-of-mass energies. RHIC data at 200 GeV (circles) and 130 GeV (squares) [11, 12] are noticeably below unity in contrast to the enhanced production observed in \( \alpha + \alpha \) collisions at CERN-ISR [13] (stars). This enhanced production, observed first in \( p + A \) fixed-target experiments (“Cronin effect”) [14], is interpreted in terms of multiple initial-state soft and semi-hard interactions which broaden the transverse momentum of the colliding partons prior to the hard scattering. The situation at CERN-SPS is not completely clear. Whereas the original work [15]

![Figure 2. Nuclear modification factor, \( R_{AA}(p_T) \), for \( \pi^0 \) measured in central nucleus-nucleus reactions at SPS [15], ISR [13], and RHIC [11, 12]. The dashed (dotted) line is the expectation of “\( N_{coll} \) (\( N_{part} \)) scaling” for hard (soft) particle production.](image-url)

reported a strong Cronin enhancement, a recent reanalysis using a better \( p+p \rightarrow \pi^0 + X \) reference [16] shows that the 0–7% most central \( Pb+Pb \) data is consistent with \( R_{AA} \approx 1 \) (triangles in Fig. 2) and that the production in head-on \( Pb+Pb \) reactions (0–1% central) is actually suppressed (\( R_{AA} \approx 0.6 \)) indicating that some amount of “jet quenching” may already be present at \( \sqrt{s_{NN}} \approx 20 \text{ GeV} \). A concurrent measurement at RHIC of high \( p_T \)
hadron spectra in \( Au + Au \) and \( p + p \) collisions at these lower \( \sqrt{s} \) would definitely set the issue of the onset of the suppression in central \( A + A \) reactions.

The breakdown of the expectations from collinear factorization for high \( p_T \) production in central \( Au + Au \) collisions at RHIC, has been interpreted as indicative of:

(i) Strong **initial-state** effects: The parton distribution functions in the nuclei are strongly modified: \( f_{a/A} \ll A \cdot f_{a/p} \) in the relevant \( (x, Q^2) \) range, resulting in an effective reduction of the number of partonic scattering centers in the initial-state.

(ii) Strong **final-state** effects: The parton fragmentation functions (or, more generally, any post hard collision effect on the scattered partons) are strongly modified in the nuclear medium compared to free space.

Explanation (i) is usually invoked in the context of the “Color-Glass-Condensate” picture [2] which assumes that the kinematical conditions prevailing in the initial-state of an atomic nucleus boosted to RHIC energies are such that nonlinear QCD effects \( (g + g \rightarrow g \) processes, amplified by a \( A^{1/3} \) factor compared to the proton case) are important and lead to a saturation of the strongly rising small-\( x \) gluon densities in the nuclei. Leading-twist QCD factorization itself breaks down since the incoherence between long- and short-distance effects in which the product Eq. \( (1) \) relies upon, does not hold anymore. CGC calculations predict \( N_{part} \) (instead of \( N_{coll} \)) scaling at moderately high \( p_T \)'s, as approximately observed in the data (dotted line in Fig. 2). Explanation (ii) relies on the expectations of “jet quenching” [17] in a Quark Gluon Plasma in which the hard scattered partons lose energy by final-state “gluonstrahlung” in the dense partonic system formed in the reaction. After traversing the medium, the partons fragment into high \( p_T \) (leading) hadrons with a reduced energy compared to standard fragmentation in the “vacuum”. Different jet quenching calculations can reproduce the magnitude of the \( \pi^0 \) suppression assuming the formation of a hot and dense system characterized by different, but closely related, properties [17]: i) large initial gluon densities \( dN_g/dy \approx 1100 \), ii) large “transport coefficients” \( \hat{q}_0 \approx 3.5 \) GeV/fm\(^2\), iii) high opacities \( L/\lambda \approx 3.5 \), iv) effective parton energy losses of the order of \( dE/dx \approx 14 \) GeV/fm, or v) plasma temperatures of \( T \approx 0.4 \) GeV.

3.3. High \( p_T \) suppression in central \( A + A \): particle species dependence

Another intriguing result of the RHIC program is the different suppression pattern of baryons and mesons at moderately high \( p_T \). Figure 3 shows the \( N_{coll} \) scaled central to peripheral yield ratios\(^\dagger\), \( R_{cp} \), for baryons (left) and mesons (right). In the range \( p_T \approx 2 - 4 \) GeV/c the (anti)protons are not suppressed \( (R_{cp} \sim 1) \) at variance with the pions which are reduced by a factor of 2 – 3. The resulting baryon/meson\( \sim 0.8 \) ratio is clearly at odds with the “perturbative” \( \sim 0.2 \) ratio measured in \( p + p \) or \( e^+e^- \) collisions. Such a particle composition is inconsistent with standard fragmentation functions, and points \(^\dagger\) Since the peripheral \( Au + Au \) (inclusive and identified) spectra scale with \( N_{coll} \) when compared to the \( p + p \) yields, the ratio \( R_{cp} \) carries basically the same information as the nuclear modif. factor \( R_{AA} \).
to an additional non-perturbative mechanism for baryon production in central $Au + Au$ reactions in this intermediate $p_T$ range. In the recombination picture [18], the quarks present in the dense environment coalesce and with the addition of their momenta, the soft production of baryons extends to larger $p_T$ values than that for mesons. Beyond $p_T \approx 5$ GeV/c fragmentation becomes the dominant production mechanism for all species. Estimates of the formation time of the (leading) hadrons qualitatively support this scenario. A hard scattered parton with momentum $p = 3$ (10) GeV/c hadronizes into a fully formed meson of radius $R_h \approx 0.8$ fm in a time [19] $\tau_h \approx p \cdot R_h^2 \approx 10$ (30) fm/c. The total lifetime of the strongly interacting system produced in $Au + Au$ reactions is $\tau \approx 15$ fm/c as extracted from different experimental observables [20]. Thus, partons with moderate energies (leading to hadrons with $p_T \approx 2 - 4$ GeV/c) will not fragment in the vacuum, as do the more energetic ones, but in a environment where they can still recombine with other surrounding particles.

4. Hard spectra in cold QCD matter: $d + A$ and $l + A$ collisions

Hard scattering in lepton- and proton- (or deuteron-) nucleus collisions allows the study of the properties of the nuclear wave-function with minimal final-state distortions due to dense QCD medium effects. In 2003, RHIC run $d + Au$ collisions as a “control” experiment in order to disentangle between the two different scenarios (QGP and CGC) proposed to explain the high $p_T$ deficit observed in central $Au + Au$ at mid-rapidity.

4.1. High $p_T$ production at midrapidity: Cronin enhancement

The results of high $p_T$ pion production at $y = 0$ in $d + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV do not show any indication of suppression (Fig. 4 left). On the contrary, pion yields appear
Cronin enhanced \( (R_{cp} > 1) \) compared to the expectations of collinear factorization\(^*\). This result indicates, in a model-independent way, that the observed suppression in \( Au + Au \) central collisions is not an initial-state effect arising from strong modifications of the gluon distribution function in nuclei as proposed by CGC approaches, but results instead from a final-state effect in the produced dense medium. The Cronin enhancement is also observed above \( p_T^2 \approx 1 \text{ GeV}^2/c^2 \) in the HERMES and EMC deep-inelastic “hadron multiplicity ratio” \( R_M^h \) (ratio of the number of hadrons of type \( h \) produced per DIS event on a nuclear target to that from a deuterium target) for \(^{14}N, Cu \) and \( Kr \) nuclei \[^{21}\] (Fig. 4 right). Two points are worth noticing here: (i) at such relatively high values of \( p_T^2 \), the exchanged virtual photon interacts directly with the partonic constituents of the nucleus, and (ii) any \( p_T \) broadening is due to multiple scattering of the outgoing quark propagating inside the (cold) nuclear medium. Thus, the observed Cronin effect in lepton-nucleus collisions is due to final-state partonic multiple scattering.

4.2. High \( p_T \) production at forward rapidities: searching for gluon saturation

In a sense, the apparent absence of gluon saturation effects in hard \( d + Au \) cross-sections at \( y = 0 \) at RHIC is not completely surprising inasmuch as the kinematical range probed corresponds to relatively moderate values of Bjorken \( x \approx 2 p_T/\sqrt{s} \approx 10^{-2} \) where standard DGLAP evolution describes well the DIS data at HERA. A simple way to probe smaller values of \( x \) in the Au nucleus consists in looking at hadron production in the forward direction. Since \( x_{1,2} = p_T/\sqrt{s}(e^{x_{y_1}} + e^{x_{y_2}}) \) for a \( 2 \rightarrow 2 \) process, \( x \) decreases by a factor of \( \sim 10 \) for every 2-units of rapidity one moves away from \( y = 0 \). BRAMHS \[^{6}\] and PHENIX \[^{22}\] results on high \( p_T \) charged hadron production at pseudorapidities \( \eta \)

\(^*\) Note in Fig. 4 left, that the Cronin effect seems to disappear \( (R_{cp} \approx 1) \) above \( p_T \approx 8 \text{ GeV}/c \), a result found also in \( p + A \) collisions at fixed-target energies \[^{14}\].
Hard spectra and QCD matter: experimental review

Figure 5. Left: Ratio of central over peripheral $N_{	ext{coll}}$ scaled yields, $R_{cp}$, as a function of $p_T$ for charged hadrons measured by BRAHMS at $\eta = 0$ (dots) and $\eta = 3.2$ (open circles) in $d+Au$ at $\sqrt{s_{NN}} = 200$ GeV [6]. Right: Kinematical range in the $x$-$Q^2$ plane probed in nuclear DIS and DY processes, and in $d+Au$ at forward rapidities at RHIC.

$\eta = 3.2$ and $\eta = 1.8$ (corresponding to $x \approx O(10^{-4})$ and $O(10^{-3})$ respectively) show a suppression instead of an enhancement as found at $\eta = 0$ (Fig. 5 left). Interestingly, this is the first time that the nuclear PDFs are probed at such small values of $x$ in the perturbative domain ($Q^2 \approx p_T^2 > 1$ GeV$^2$/c$^2$) (Fig. 5 right). BRAHMS $R_{cp} \approx 0.5$ result seems to indicate that the ratio of $Au$ over $p$ gluon densities is $R_{Au}^{G}(x \approx 10^{-4}, Q^2 \approx 2$ GeV$^2$/c$^2) \approx 0.5$, whereas standard leading-twist DGLAP analysis of the nuclear PDFs (based on global fits of the DIS and Drell-Yan data above $Q^2 = 1$ GeV$^2$/c$^2$ shown in Fig. 5 right) indicate a less significant amount of gluon “shadowing” in this range: $R_{Au}^{G} \approx 0.8$ [23, 24]. Whether this larger suppression is due to soft physics (the global $dN/dy$ distributions in lower energy $p+A$ collisions are also found to be depleted at forward $\eta$ [25]) or a genuine CGC effect, is still matter of discussion at this point.

5. Summary

During its first four years of operation, RHIC has provided many new and exciting results on the many-body dynamics of QCD at high energies. The suppressed high $p_T$ hadroproduction observed in central $Au+Au$ reactions and in $d+Au$ collisions at forward-rapidities is inconsistent with the basic QCD factorization expectations that describe particle production in $p+p$ at $\sqrt{s} = 200$ GeV. The factor of 4–5 suppression in central $Au+Au$ is unambiguously due to final-state effects (since no such an effect is seen in $d+Au$ collisions at $y = 0$) and can be reproduced by calculations of parton energy loss in a strongly interacting medium with energy densities well above those where lattice QCD predicts a transition to a Quark Gluon Plasma. The factor of $\sim 2$ deficit observed at $y \approx 3$ in $d+Au$ reactions may be the first empirical indication of higher-twist (non-linear) QCD effects at small Bjorken-$x$ in the hadronic wave functions.
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