Quantum Chromo (many-body) Dynamics probed in the hard sector at RHIC

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The most significant experimental results on hard processes in heavy-ion collisions at RHIC collider energies are reviewed. Emphasis is put on measurements that provide insights on strongly interacting media like the “Quark Gluon Plasma” and the “Color Glass Condensate”.

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. Two aspects are of particular interest in this physics program:

1. The production and study under laboratory conditions of the plasma of quarks and gluons (QGP), a deconfined and chirally symmetric state of strongly interacting matter, predicted by QCD calculations on the lattice for values of the energy density $\epsilon \approx 1 \text{ GeV/fm}^3$.

2. The study of the (non-linear) evolution of the gluon density at small values of (Bjorken) fractional momentum $x$ in the nuclear and, in general, hadronic wave functions, as described e.g. in the “Color Glass Condensate” (CGC) framework.

In hadronic collisions, the production of particles with high transverse momentum (jets, single hadrons with $p_T \gtrsim 2 \text{ GeV/c}$, prompt $\gamma$) or large mass (heavy quarks) results from hard parton-parton scatterings with large momentum transfer $Q^2$ (“hard processes”). Such production processes provide, thus, direct information on the fundamental (quark and gluon) degrees of freedom of QCD. Since hard cross-sections can be theoretically computed by perturbative methods via the collinear factorization theorem, inclusive high $p_T$ hadroproduction, jets, direct photons, and heavy flavors, have long been considered sensitive and well calibrated probes of the small-distance QCD phenomena. This paper reviews the most interesting results on hard processes from $Au + Au$ reactions at RHIC collider energies ($\sqrt{s_{NN}} = 200 \text{ GeV}$), and compares them to more elementary reactions either in the “vacuum” ($p + p$, $e^+e^-$) or in a cold nuclear matter environment ($d, l + A$). Several substantial differences are found which are indicative of important initial- and final-state effects in $Au + Au$ reactions that can be directly connected to the properties of the QCD medium in which the hard scattering process has taken place.

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*The parton density in a high-energy (Lorentz-contracted) nucleus is enhanced by a $A^{1/3}$ factor compared to that in the proton and, thus, one has an experimental access to the $(x, Q^2)$ kinematical regime where higher-twist ($g+g$ fusion) processes are expected to set in and saturate the rapidly rising gluon distribution function at small-$x$. 
2 Hard processes in the QCD vacuum: \( p+p \) collisions @ \( \sqrt{s} = 200 \) GeV

Hard processes in proton-proton collisions provide the baseline “free space” reference to which one compares heavy-ion results in order to extract information about the properties of color many-body dynamics. At RHIC, the differential cross-sections in \( p+p \) collisions at \( \sqrt{s} = 200 \) GeV for neutral pions and charged hadrons above \( p_T = 2 \) GeV/c 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 (\( \sqrt{s} \approx 20 – 63 \) GeV at CERN-ISR and \( \sqrt{s} \approx 20 – 40 \) GeV in fixed-target at FNAL, Fig. 1 left), where the \( p_T < 5 \) GeV/c cross-sections are underpredicted by pQCD calculations (even supplemented with soft-gluon resummation corrections), and additional non-perturbative effects (e.g. intrinsic \( k_T \)) must be introduced to bring parton model analysis into agreement with data. Hard production in \( p+p \) collisions at RHIC collider energies seems to be 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 processes in dense QCD matter: central \( Au+Au \) reactions @ \( \sqrt{s_{NN}}=200 \) GeV

3.1 QCD factorization for hard cross-sections in \( A+A \) collisions.

In the absence of initial and final state interactions, QCD factorization (based on the implicit premise of incoherent parton scattering) implies that inclusive A+B cross-sections for hard processes should scale simply as \( A \cdot B \) times the corresponding \( p+p \) cross-sections:

\[
E d\sigma_{AB\to h}^{\text{hard}}/d^3p = A \cdot B \cdot E d\sigma_{pp\to h}^{\text{hard}}/d^3p. \tag{1}
\]

More generally, for a given centrality bin (or impact parameter \( b \)) in a nucleus-nucleus reaction, the relation between hard cross-sections in \( p+p \) and \( A+A \) collisions is:

\[
E dN_{AB\to h}^{\text{hard}}/d^3p(b) = \langle T_{AB}(b) \rangle \cdot E d\sigma_{pp\to h}^{\text{hard}}/d^3p, \tag{2}
\]

\( ^6 \)Incoming quarks and gluons undergoing hard scattering are “free” in a collinear factorized approach, i.e. with regard to hard production the density of partons in a nucleus with atomic number \( A \) should be equivalent to the superposition of \( A \) independent nucleons, or \( f_{a/A}(x, Q^2) = A f_{a/p}(x, Q^2) \) in terms of parton distribution functions.
where $T_{AB}(b)$ is the Glauber (eikonal) nuclear overlap function at $b$. Since the number of nucleon-nucleon ($NN$) collisions at $b$ is: $N_{\text{coll}}(b) = T_{AB}(b) \cdot \sigma_{\text{inel}}^{pp}$, one can write also Eq. (2) in terms of invariant yields as: $E dN_{AB \to h}^{\text{hard}}/d^3p(b) = \langle N_{\text{coll}}(b) \rangle \cdot E dN_{pp \to h}^{\text{hard}}/d^3p$ (“$N_{\text{coll}}$ scaling”). Usually, the standard method to quantify the effects of the medium in the production of a given hard probe is provided by the nuclear modification factor:

$$R_{AB}(p_T, y; b) = \frac{\text{“hot QCD medium”}}{\text{“QCD vacuum”}} = \frac{d^2N_{AB}/dydp_T}{(T_{AB}(b)) \times d^2\sigma_{pp}/dydp_T},$$

which measures the deviation of $A + B$ at $b$ from an incoherent superposition of $NN$ collisions.

The expectations of QCD factorization, Eqs. (1)–(2), are indeed fulfilled by hard processes in $Au + Au$ collisions at RHIC. The measured spectra of direct photons and single electrons from heavy quark decays (Figure 2) is consistent with the $N_{\text{coll}}$ (or $A^2$) scaling expected for hard scattering in the absence of medium effects$^6$.

![Figure 2: Hard spectra in $Au + Au$ at $\sqrt{s_{NN}} = 200$ GeV. (a) Direct photon “excess” (given by the ratio $dN_{\gamma_{total}}/dydp_T$ over $dN_{\gamma_{decay}}/dydp_T$, normalized by the $\pi^0$ spectra) measured in central $Au + Au$ compared to NLO pQCD yields scaled by $N_{\text{coll}}$ (red curve)$^{10}$ (b) “Non-photonic” single electron spectrum (mostly from open charm and beauty semi-leptonic decays) measured in min.bias $Au + Au$ compared to the $p+p$ spectrum scaled by $A^2$ (black curve)$^{11}$](image)

### 3.2 High $p_T$ suppression of (light flavored) hadron spectra in central $Au + Au$

High $p_T$ light flavored hadrons emitted in $Au + Au$ collisions result from the fragmentation of hard scattered (light) quarks and gluons and, thus, their yields should follow the $N_{\text{coll}}$ scaling for incoherent parton scattering seen in direct $\gamma$ and heavy-quark cross-sections$^6$. One of the most significant results at RHIC so far is the observation that the high $p_T$ cross-sections of neutral pions and inclusive charged hadrons in central $Au + Au$ are strongly suppressed compared to these expectations. Figure 3 (left) 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)$^{12}$ are noticeably below unity in contrast to the “Cronin” enhanced production observed in $\alpha + \alpha$ collisions at CERN-ISR$^{13}$ (stars) and to the CERN-SPS central Pb+Pb data$^{15}$ consistent, within errors, with $N_{\text{coll}}$ scaling$^{16}$ (triangles). The same factor of 4–5 suppression is observed above $p_T \approx 5$ GeV/$c$ in the spectra of charged hadrons (Fig. 3 right). This marked

$^6$Note that although the yield of single $e^\pm$ in $Au + Au$ seems to be suppressed at high $p_T$ with respect to the $p + p$ scaled reference (Fig. 2 right), the overall differential and integrated cross-sections$^{11}$ are consistent with $N_{\text{coll}}$ scaling in the whole $p_T$ range covered, as expected for $e^\pm$ coming from hard (heavy-quark) processes.
breakdown of the expectations from collinear factorization in central Au+Au collisions, together with the unsuppressed production of colorless hard probes (direct photons, Fig. 2 left), is clearly indicative of strong final-state effects affecting high $p_T$ Au+Au hadroproduction at RHIC. In “jet quenching” scenarios, the scattered partons lose energy via gluon radiation in the dense partonic system formed in the reaction and the resulting high $p_T$ (leading) hadrons have a reduced energy compared to standard fragmentation in the vacuum. Theoretical calculations reproduce the observed suppression pattern assuming the formation of a strongly interacting (expanding) system with very large initial gluon densities $dN^g/dy \approx 1100$.

### 3.3 Suppression of back-to-back dijet correlations in central Au+Au.

A second prominent RHIC result is the disappearance of jet-like azimuthal correlations in the away-side hemisphere of trigger particles with $p_T = 4 - 6$ GeV/$c$. Figure 4 (right) shows the azimuthal distribution of associated particles (with $2 \text{ GeV/c} < p_T < p_T^{18}$) in Au+Au (after subtraction of the collective elliptic flow component) compared with $p+p$ reference data. The near-side ($|\Delta \phi| \lesssim 0.5$) correlations measured in Au+Au are clearly jet-like as those in $p+p$ collisions. The back-to-back correlations ($|\Delta \phi - 2\pi| \lesssim 0.7$) in Au+Au collisions for trigger particles emitted parallel to the reaction plane (“in plane”) are suppressed compared to $p+p$, and even more suppressed for the “out of plane” trigger particles. Such behavior can be explained...
3.4 Enhanced baryon production at intermediate $p_T$.

A third intriguing observation at RHIC is the different suppression pattern for baryons and mesons at moderate $p_T$ values. Fig. 5 shows the $N_{\text{coll}}$-scaled central to peripheral ratio $R_{cp}$, for baryons and mesons measured by PHENIX [19] (left) and STAR [20] (right). In the range $p_T \approx 2 - 4$ GeV/$c$, (anti)baryons (p, $\Lambda$, $\Xi$) are not (or barely) suppressed ($R_{cp} \sim 1$) at variance with mesons ($\pi^0, K^\pm, K^0_S, \phi$) which are reduced by a factor of 2 – 3. The resulting $p/\pi \sim 1$ ($\Lambda/K^0_S \sim 1.5$) ratio in this $p_T$ range is clearly at odds with the “perturbative” $p/\pi \sim 0.2$ ($\Lambda/K^0_S \sim 0.5$) value measured in $p+p$ or $e^+e^-$ collisions. Such a particle composition is inconsistent with standard fragmentation functions, and points to an additional non-perturbative mechanism for baryon production in central $Au+Au$ in this intermediate $p_T$ range. Enhanced production due to

mass-dependent boost effects (e.g. due to collective hydrodynamic flow) seems to be excluded since mesons as heavy as the proton ($\phi, K^*$) are as equally suppressed as lighter mesons. Recombination models [21], on the other hand, where hadronization occurs mainly via quark coalescence, predict such enhanced baryon over meson yields (due simply to the extra momentum gained by the addition of a third constituent quark). Beyond $p_T \approx 5$ GeV/$c$ fragmentation becomes the dominant production mechanism for all species in agreement with the data.

4 Hard spectra in cold QCD matter: $d+Au$ collisions @ $\sqrt{s_{NN}} = 200$ GeV

4.1 High $p_T$ production at midrapidity: Cronin enhancement

High $p_T$ pion production at $y = 0$ in $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV (Fig. 6) is not suppressed but enhanced ($R_{cp} > 1$) compared to the expectations of QCD factorization. Such a result was first observed in $p+Au$ fixed-target experiments at $\sqrt{s_{NN}} = 20 – 40$ GeV ("Cronin effect" [14]) (Fig. 6, right) and is usually interpreted in terms of multiple soft and semi-hard interactions which broaden the transverse momentum of the colliding partons on their way in/out the traversed nucleus. This result confirms that the high $p_T$ deficit in central $Au+Au$ collisions is by jet quenching models [17], where the energy loss of a parton depends on the distance traveled through the dense medium (note that in non-central reactions the overlap nucleus-nucleus region has an almond-like shape with shorter length in the in-plane than in the out-of-plane direction, Fig. 1 left).
collisions (Fig. 3) 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.

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

At variance with \( Au + Au \) collisions, lepton- and proton- (or deuteron-) nucleus collisions allow to probe the nuclear parton distribution functions (PDF) with minimal distortions due to final-state effects. Small values of parton fractional momenta, \( x_2 \), in the \( Au \) nucleus (where gluons are overly dominant) can be probed studying hard production in the forward direction. Since \( x_{1,2} = p_T/z\sqrt{s}(e^{±y_1} + e^{±y_2}) \) for a \( 2 \to 2 \) scattering, \( x \) decreases by a factor of \( ∼10 \) 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 \( η = 3.2 \) and \( η = 1.8 \), corresponding to \( x ≈ O(10^{-4}) \) and \( O(10^{-3}) \) respectively, show a suppression instead of an enhancement as found at \( η = 0 \) (Fig. 6 left). This is the first time that nuclear “shadowing” is observed at such low-\( x \) values in the perturbative domain (\( Q^2 ≈ p_T^2 > 1 \text{ GeV}^2/c^2 \)) (Fig. 7 right). BRAHMS \( R_{cp} \approx 0.5 \) result would indicate that the ratio of \( Au \) over \( p \) gluon densities is \( R_G^{Au}(x ≈ 10^{-4}, Q^2 ≈ 2 \text{ GeV}^2/c^2) ≈ 0.5 \), whereas standard leading-twist DGLAP analysis of the nuclear PDFs [23] (based on global fits of the DIS and Drell-Yan data above \( Q^2 = 1 \text{ GeV}^2/c^2 \) shown in Fig. 7 right) indicate a less significant amount of gluon shadowing in this kinematical range: \( R_G^{Au} ≈ 0.8 \).

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 \( \sqrt{s} = 200 \text{ GeV} \). 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 electromagnetic probes, insensitive to the colored final-state, are not depleted in \( Au + Au \) 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 \( ∼2 \) deficit observed at \( y ≈ 3 \) in \( d + Au \) reactions may be the first empirical indication of higher-twist
Figure 7: Left: Ratio of central over peripheral $N_{coll}$-scaled yields, $R_{cp}$, versus $p_T$ 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. Right: Kinematical $x$-$Q^2$ domain probed in nuclear DIS and DY at fixed-target energies, and in $d + Au$ at forward rapidities at RHIC.

(non-linear) QCD effects at small Bjorken-$x$ in the hadronic wave functions, as described in “Color Glass Condensate” approaches.

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