QCD HARD SCATTERING RESULTS FROM PHENIX AT RHIC

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Abstract
Data on hadron production at high transverse momentum ($p_T > 2$ GeV/c) in $p+p$, $d+Au$, and $Au+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV from the PHENIX experiment at RHIC are reviewed. The single inclusive spectrum of light hadrons produced in central $Au+Au$ reactions shows significant differences compared to $p+p$ and $d+Au$ collisions, and provides interesting information on the properties of the underlying QCD medium present in heavy-ion reactions at collider energies.

Keywords: Relativistic nucleus-nucleus collisions, QCD, hard scattering, PHENIX, RHIC

1. Introduction

The fundamental degrees of freedom of the theory of the strong interaction (Quantum Chromodynamics, QCD) are colored quarks (fermions) and gluons (gauge bosons). In the real world, however, quarks and gluons are not observed free but confined in color singlet states (hadrons). In addition, the observed effective constituent mass of the quarks ($m_{u,d} \approx 300$ MeV for the lightest $u$ and $d$ quarks) is much larger than the bare current mass of the QCD Lagrangian ($m_{u,d} \approx 2$ 8 MeV). Theoretically understanding from first principles these two basic properties of QCD: confinement and chiral symmetry breaking, remains in fact one of the most important problems in fundamental physics [1]. Lattice calculations of QCD in the bulk [2] predict that above an energy density of $\epsilon_{\text{crit}} \approx 0.7$, 0.3 GeV/fm$^3$, the (long range part of the) strong color potential becomes screened and, as a result, quarks and gluons can move freely with their bare mass within the deconfined medium. Experimentally accessing and studying the properties of this “Quark-Gluon Plasma” (QGP) phase is one of the main goals of the physics program of the PHENIX experiment at the Relativistic Heavy-Ion Collider (RHIC) at BNL. By colliding heavy nuclei at high energies one expects to produce a thermalized system of quarks and gluons.
with energy densities above \( \rho_{\text{crit}} \), albeit for very short time scales, \( \rho (10^{-23} \text{ s}) \) and small volumes, \( \rho (10^2 \text{ fm}^3) \). In the period 2000-2003, PHENIX collected data from Au+Au, d+Au and p+p collisions at \( \mathcal{P}_\text{NN} = (130)200 \text{ GeV} \).

The most interesting phenomena observed so far in the data are in the high \( p_T \) (\( p_T < 2 \text{ GeV/c} \)) sector where the production of hadrons in (non-peripheral) Au+Au collisions shows substantial differences compared to more elementary reactions either in free space (p+p, e+e-) or in a “cold” nuclear matter environment (d+Au). Hard scattering processes are an excellent experimental probe in heavy-ion collisions inasmuch as: (i) they are the result of violent (large \( Q^2 \)) short-distance (parton-parton) collisions in the first instants of the reaction (\( 1 = p_T = 0.1 \text{ fm/c} \)) and, as such, direct probes of the partonic phase(s) of the reaction; (ii) in the absence of medium effects, their cross section in A+A reactions is expected to scale simply with that measured in p+p collisions times the number of scattering centers (\( A^2 \), see discussion below); and (iii) their production yields can be theoretically calculable in QCD via standard perturbative (collinear factorization plus Glauber multiscattering [3]) or via “classical-field” (“Color-Glass-Condensate” approach [4]) methods.

2. The PHENIX experiment

The PHENIX detector [5] is specifically designed to measure hard QCD probes such as high \( p_T \) hadrons, direct photon radiation, lepton pairs, and heavy flavour production. PHENIX achieves good mass and PID resolution, and small granularity by combining 13 detector subsystems (350,000 channels) divided into: (i) 2 central arm spectrometers for electron, photon and hadron measurement at mid-rapidity (\( j_0 \leq 0.38, = 2 \)); (ii) 2 forward-backward (\( j_0 = 1.15 - 2.25, = 2 \)) spectrometers for muon detection; and (iii) 4 global (inner) detectors for trigger and centrality selection. Neutral mesons are reconstructed through invariant mass analysis of decay pairs detected in two types of electromagnetic calorimeters (15552 lead scintillator towers with 18X0, and 9216 lead glass modules with 14.4X0). The trajectories and momenta of charged hadrons in the axial central magnetic field (\( B_{\text{max}} = 1.15 \text{ T} \text{ m} \)) are measured by a drift chamber (DC) and three layers of MWPC’s with pad readout (PC). Hadron identification (\( \pi, K, \) and \( p; \pi \)) is achieved by matching the reconstructed tracks to hits in a time-of-flight wall (TOF).

The occurrence of a p+p, d+Au or Au+Au collision (with vertex position \( j_z < 60 \text{ cm} \) within the center of the detector) is triggered by a coincidence between the two Beam-Beam Counters (BBC)\(^1\) which cover \( j_0 \leq 3.0 - 3.9 \). These minimum bias triggers accept respectively (52 4%) (88 4%), and (92 3%) of the total inelastic cross-sections (in \( \text{pp} \) 42 mb, in \( \text{dAu} \) 2150 mb, and

\(^1\) Plus the Zero Degree Calorimeters, ZDC, at \( j_0 < 2 \text{ mrad} \) in the case of Au+Au.
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$\text{inel}_{\text{Au+Au}}$ (6850 mb). Since hard probes are rare, high luminosities are required. PHENIX is an efficient high interaction rate experiment with a state-of-the-art data acquisition system capable of recording 120 MB/s to disk with event sizes of 100 KB, and event rates of 1-2 KHz. A total of 0.2 $10^9$, 5.5 $10^9$, and 4.0 $10^9$ events have been sampled in Au+Au, d+Au, and p+p collisions respectively at $\sqrt{s_{NN}} = 200$ GeV.

3. Scaling of yields and cross-sections from p+p to A+B

Insights on the mechanisms of particle production (and “destruction”) in nucleus-nucleus (A+B) collisions are obtained from the study of the scaling behavior of their yields with respect to p+p collisions. Depending on the \(p_T\) range in which they are produced, two different “scaling laws” are relevant:

**Soft particle production**

At low \(p_T\) (\(p_T < 1\) GeV/c) in A+B reactions is dominated by non-perturbative nucleon-nucleon collisions with small momentum transfers. Since those collisions occur in “parallel” and with large probabilities, they suffer destructive interference which effectively limits the maximal number of processes that can lead to secondary particle production [6]. As a result soft particle yields turn out to be proportional to the average number of participating (or “wounded”) nucleons, i.e. nucleons which undergo at least one inelastic collision [7]. Thus, in a A+B reaction at impact parameter \(b\):

$$E \frac{dN_{\text{soft}}}{d^3p} = h N_{\text{part}}(b) \frac{dN_{\text{soft}}}{d^3p};$$

where \(N_{\text{part}}(b)\) can be obtained from the nuclear thickness functions \(T_{\text{nuc}}(z,b)\) (normalized to A ; B resp.) via a Glauber model\(^2\). Such a “participant scaling” is indeed approximately observed in the total multiplicities measured in heavy-ion collisions [8]. Integrating \(N_{\text{part}}(b)\) over impact parameter one obtains the average number of participant nucleons in a minimum bias A+B collision:

$$h N_{\text{part}}_{\text{MB}} = \langle N_{\text{part}} \rangle_{\text{MB}} = \frac{1}{A+B} \left( \frac{A_{\text{inel}} p_A + B_{\text{inel}} p_B}{p_A} \right)_{\text{inel}} \frac{1}{A+B} \left( \frac{A_{\text{inel}} p_A + B_{\text{inel}} p_B}{p_B} \right)_{\text{inel}}.$$

Using this expression, Eq. (1), and \(dN_{\text{soft}}/d^3p\) in a symmetric A+A minimum bias collision\(^3\) are related to the corresponding p+p ones via:

$$E \frac{dN_{\text{soft}}}{d^3p} = \frac{2A_{\text{inel}}}{A_{\text{inel}}} \frac{dN_{\text{soft}}}{d^3p}; \quad \text{and} \quad E \frac{d^2}{d^3p} = \frac{2A_{\text{inel}}}{A_{\text{inel}}} \frac{d^2}{d^3p}.$$

**Hard particle production**

At high \(p_T\) (\(p_T > 2\) GeV/c) results from incoherent parton-parton scatterings with large \(Q^2\). In this regime, the pQCD “fac-

\(^2\)The corresponding formulas can be found e.g. in [7].

\(^3\)Also, for min. bias A+A collisions:

$$\langle N_{\text{part}} \rangle_{\text{MB}} = \frac{1}{A+B} \left( \frac{A_{\text{inel}} p_A + B_{\text{inel}} p_B}{p_A} \right)_{\text{inel}} \frac{1}{A+B} \left( \frac{A_{\text{inel}} p_A + B_{\text{inel}} p_B}{p_B} \right)_{\text{inel}}.$$
torization theorem” [9] holds and the inelastic cross-section for the production of a given particle can be separated in the product of long-distance (non-perturbative parton distribution functions, \( f_{a=A} \), and fragmentation functions, \( D_{c=1} \)) and short-distance (parton-parton scattering) contributions:

\[
E \frac{d^{\text{hard}}}{d^3p} = f_{a=A} (x; \mu^2) \cdot f_{b=B} (x; \mu^2) \cdot \frac{d^{\text{abl}}}{d^3p} \cdot D_{c=1} (z; \mu^2); \quad (3)
\]

The assumption of incoherent scattering at high \( p_T \) entails also that \( f_{a=A} = A \cdot f_N \), i.e. that the density of partons in a nucleus \( A \) should be equivalent to the superposition of \( A \) independent nucleons. Thus,

\[
E \frac{d^{\text{hard}}}{d^3p} = A \cdot B \cdot f_p (x; \mu^2) \cdot f_{\text{pp}} (x; \mu^2) \cdot E \frac{d^{\text{abl}}}{d^3p} \cdot D_{c=1} (z; \mu^2); \quad (4)
\]

and minimum bias hard cross-sections in A+B are expected to scale simply as

\[
E \frac{d^{\text{hard}}}{d^3p} = A \cdot B ; \quad (5)
\]

In the general case, for a given A+B reaction with impact parameter \( \rho \)

\[
E \frac{d^{\text{hard}}}{d^3p} = T_{AB} (\rho) f(\rho) \cdot I \cdot E \frac{d^{\text{abl}}}{d^3p}; \quad (6)
\]

where \( T_{AB} (\rho) = \rho^2 T_A (\rho) T_B (\rho) \) (normalized to \( A \cdot B \)) is the nuclear overlap function\(^4\) at \( \rho \). Since \( T_{AB} \) is proportional to the number of nucleon-nucleon (N N ) collisions: \( T_{AB} (\rho) = N_{\text{coll}} (\rho) \cdot \frac{\text{inel}_{\text{AB}}}{\text{inel}_{pp}} \), one alternatively quotes Eq. (6) in the form of “(binary) collision scaling” of invariant yields:

\[
E \frac{d^{\text{hard}}}{d^3p} = h N_{\text{coll}} (\rho) I \cdot E \frac{d^{\text{inp}}}{d^3p}; \quad (7)
\]

From (5) and (7), it is easy to see that\(^5\) \( h N_{\text{coll}} (\rho) I = A \cdot B \cdot \frac{\text{inel}_{\text{pp}}}{\text{inel}_{\text{AB}}} \).

Following Eqs. (2) and (5), since \( \frac{\text{inel}_{\text{pp}}}{\text{inel}_{\text{AA}}} \cdot A^2 / A^{2-3} \), the atomic number dependence of soft processes in symmetric A+A reactions is of the type

\[
E \frac{d^{\text{soft}}}{d^3p} = A \cdot B \cdot \frac{\text{inel}_{\text{pp}}}{\text{inel}_{\text{AA}}} \quad \text{and} \quad E \frac{d^{\text{soft}}}{d^3p} = \frac{\text{inel}_{\text{pp}}}{\text{inel}_{\text{AA}}}; \quad (8)
\]

whereas the A dependence of hard processes is of the form:

\[
E \frac{d^{\text{hard}}}{d^3p} = A^{4-3} \cdot \frac{\text{inel}_{\text{pp}}}{\text{inel}_{\text{AA}}} \quad \text{and} \quad E \frac{d^{\text{hard}}}{d^3p} = A_2 \cdot \frac{\text{inel}_{\text{pp}}}{\text{inel}_{\text{AA}}}; \quad (9)
\]

\(^4\)The “natural” magnitudes of \( T_A (\rho) \) and \( T_{AB} (\rho) \) are \( A = R_A^2 \) and \( A \cdot B = (R_A + R_B)^2 \) respectively [10].

\(^5\)Also, for min. bias A+A collisions: \( h N_{\text{coll}} (\rho) I = A^2 \cdot \frac{\text{inel}_{\text{pp}}}{\text{inel}_{\text{AA}}} \cdot A^2 \cdot \frac{\text{inel}_{\text{pp}}}{\text{inel}_{\text{AA}}} \cdot (\Omega A)^2 \cdot A^{4-3} = 4.\)
4. High $p_T$ production: Au+Au vs. p+p

One of the most interesting experimental results at RHIC so far is the breakdown of the expected incoherent parton scattering assumption for high $p_T$ production in non-peripheral Au+Au collisions. Fig. 1 shows the comparison of the measured $p+p$ spectrum [11] to peripheral (left) and central (right) Au+Au spectra [12], and to standard NLO pQCD calculations [13]. Whereas peripheral data is consistent with a simple superposition of individual $NN$ collisions, central data shows a suppression factor of 4 – 5 with respect to this expectation.

![Figure 1](image)

**Figure 1.** Invariant $^0$ yields measured by PHENIX in peripheral (left) and in central (right) Au+Au collisions (stars) [12], compared to the $T_{AA}$ scaled $p+p$ $^0$ cross-section (circles) [11] and to a NLO pQCD calculation (gray line) [13]. The yellow band around the scaled $p+p$ points represents the overall normalization uncertainties.

From Eq. (6), it is customary to quantify the medium effects at high $p_T$ using the nuclear modification factor given by the ratio of the A+A invariant yields to the p+p cross-sections scaled by the nuclear overlap at impact parameter $b$

$$R_{AA}(p_T; b) = \frac{\frac{d^2N_{AA}^0}{dydp_T}(b)}{\frac{d^2N_{pp}^0}{dydp_T}} : \quad (10)$$

$R_{AA}(p_T)$ measures the deviation of A+A from an incoherent superposition of $NN$ collisions in terms of suppression ($R_{AA} < 1$) or enhancement ($R_{AA} > 1$). Figure 2 shows $R_{AA}$ as a function of $p_T$ for several $^0$ measurements in high-energy A+A collisions. Much of the excitement at RHIC comes from the fact that the PHENIX $R_{AA}$ values for central collisions at 200 GeV (circles) and 130 GeV (triangles) are noticeably below unity in contrast to the enhanced production ($R_{AA} > 1$) observed at CERN-ISR [14] (stars) and CERN-SPS [15] (squares) energies. This enhanced production, observed first in p+A fixed-
target experiments [16] (“Cronin effect”), 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 itself.

![Graph showing the nuclear modification factor, $R_{AA}(p_T)$, for $^0\pi$ measured in central ion-ion reactions at CERN-SPS [15], CERN-ISR [14], and BNL-RHIC [17, 12] energies. The dashed (dotted) line is the expectation of “$N_{coll}/N_{part}$ scaling” for “hard” (“soft”) particle production.]

Figure 2. Nuclear modification factor, $R_{AA}(p_T)$, for $^0\pi$ measured in central ion-ion reactions at CERN-SPS [15], CERN-ISR [14], and BNL-RHIC [17, 12] energies. The dashed (dotted) line is the expectation of “$N_{coll}/N_{part}$ scaling” for “hard” (“soft”) particle production.

The breakdown of the expectations from collinear factorization for high $p_T$ production in central A+A collisions at RHIC by such a large factor, has been interpreted as due to one (or more) of the following facts:

1. Breakdown of leading-twist QCD collinear factorization itself: The incoherence between long- and short-distance effects in which the factorized product Eq. (3) relies upon, does not hold for A+A collisions.

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

3. 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.

Explanations 1. and 2. are usually invoked in the context of the “Color-Glass-Condensate” picture [4] which assumes that the kinematical conditions prevailing in the initial-state of an atomic nucleus boosted to RHIC energies (moderate $Q^2$ $Q^2 \approx 1–2$ GeV$^2$c$^{-2}$, and small parton fractional momenta $x \approx 10^{-2}$) 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 strong saturation of the parton (mostly gluon) densities in the nuclei. In this scenario, one expects $N_{\text{part}}$ (instead of $N_{\text{coll}}$) scaling at moderately high $p_T$\’s [18], as approximately observed in the data (dotted line in Fig. 2). Explanation 3., on the other hand, relies on the expectations of “jet quenching” in a Quark Gluon Plasma [19] 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 $\phi^0$ suppression assuming the formation of a hot and dense partonic system characterized by different, but closely related, properties: i) large initial gluon densities $\int dy \int dy' 10^{10}$ [20], ii) large “transport coefficients” $\hat{q}$ 3.5 GeV/fm$^2$ [21], iii) high opacities $\hat{L} = 3.5$ [22], iv) effective parton energy losses of the order of $dE/dx = 14$ GeV/fm [23], or v) plasma temperatures of $T = 0.4$ GeV [24].

5. High $p_T$ production: d+Au vs p+p

In order to disentangle between the two different (QGP and CGC) QCD scenarios, it was of paramount interest to determine experimentally the modification, if any, of high $p_T$ hadron production due to initial-state nuclear effects alone, i.e. for a system in which a hot and dense medium is not produced in the final state. The results of high $p_T$ $\phi^0$ production at midrapidity in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [25] do not show any indication of suppression (Fig. 3). On the contrary, $\phi^0$ production seems to be slightly enhanced ($R_{dAu}$ = 1.1) compared to the expectations of collinear factorization.

![Nuclear modification factor](image_url)
This result, reminiscent of the “Cronin enhancement”, indicates that the observed suppression in Au+Au central collisions at mid-rapidity is not an initial-state effect arising from strong modifications of the gluon distribution functions in nuclei at moderately small values of parton fractional momenta $x$, but more likely a final-state effect of the produced dense medium.

6. Summary

PHENIX has measured $^0_\pi$ at mid-rapidity up to $p_T = 10$ GeV$c$ in p+p, d+Au and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The spectral shape and invariant yields in peripheral Au+Au reactions are consistent with those of p+p reactions scaled by the number of inelastic NN collisions, in agreement with pQCD collinear factorization expectations. In central Au+Au reactions, the $^0_\pi$ are suppressed by a factor 4–5 with respect to the same expectations. The magnitude of this deficit can be reproduced by pQCD-based parton final-state energy loss calculations in an opaque medium, as well as by initial-state gluon saturation models. The unquenched high $p_T$ $^0_\pi$ production in minimum bias d+Au collisions, however, seems to rule out any significant “cold” nuclear matter effect as responsible for the observed suppression in Au+Au central reactions.

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