Jet quenching: RHIC results and phenomenology

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Abstract. I review the main experimental results on jet physics in high-energy nucleus-nucleus collisions as studied via inclusive leading hadron spectra and di-hadron correlations at high transverse momentum. In central Au+Au at RHIC ($\sqrt{s_{NN}} = 200$ GeV), the observed large suppression of high-$p_T$ hadron spectra as well as the strongly modified azimuthal dijet correlations compared to baseline p+p results in free space, provide crucial information on the thermodynamical and transport properties of QCD matter.

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INTRODUCTION

The research program of high-energy heavy-ion physics is centered on the study of the collective properties of extended quark-gluon systems. By colliding two heavy nuclei at relativistic energies one expects to form a hot and dense deconfined medium whose collective (color) dynamics can be quantitatively described by QCD thermodynamics calculations on the lattice [1]. In this context, the main goal of the RHIC experiments is the production and study under laboratory conditions of the Quark Gluon Plasma (QGP) predicted to be formed when strongly interacting matter attains energy densities above $\varepsilon \approx 1$ GeV/fm$^3$. The production of such an extremely hot and dense partonic system should manifest itself in a variety of experimental signatures [2]. One of the first proposed QGP “smoking guns” was “jet quenching” [3] i.e. the disappearance of the collimated spray of hadrons resulting from the fragmentation of a hard scattered parton due to its “absorption” in the dense medium produced in the reaction. Extensive theoretical work on high-energy parton propagation in a QCD environment [4, 5, 6, 7] has shown that the main mechanism of attenuation is of radiative nature: the traversing parton loses energy mainly by multiple gluon emission (“gluonstrahlung”). Such a medium-induced non-Abelian energy loss should result in several observable experimental consequences:

(i) depleted production of high $p_T$ leading hadrons ($dN/dp_T$) [4],
(ii) unbalanced back-to-back di-jet azimuthal correlations ($dN_{\text{pair}}/d\phi$) [8], and
(iii) modified energy flow and particle multiplicity within the final jets [9, 10].

By quantitatively comparing the jet structure modifications in A+A relative to baseline p+p collisions in free space, one can have experimental access to the properties of the produced QCD matter. In this overview, we discuss several significant experimental measurements from Au+Au reactions at RHIC which have been phenomenologically linked to key thermodynamical and transport properties which can, in some cases,
be directly computed in lattice QCD. E.g., if the observed high-$p_T$ leading hadron suppression is due to medium-induced gluon radiation off hard scattered partons, then

- the initial **gluon density** $dN^g/dy$ of the expanding plasma (with transverse area $A_\perp$ and length $L$) can be estimated from the measured energy loss via [6]:

  \[ \Delta E \propto \alpha_s^3 C_R \frac{1}{A_\perp} \frac{dN^g}{dy} L, \]

  \[ (1) \]

- and also the **transport coefficient** $\langle \hat{q} \rangle$, characterizing the squared average momentum transfer from the medium to the hard parton per unit distance, can be derived from the average energy loss according to [5, 7]:

  \[ \langle \Delta E \rangle \propto \alpha_s C_R \langle \hat{q} \rangle L^2. \]

  \[ (2) \]

Likewise, it has been argued that a fast parton propagating (and loosing energy) through the medium can generate a wake of lower energy gluons with Mach- [11, 12] or Čerenkov-like [12, 13] conical angular patterns.

- In the first case, the **speed of sound** of the traversed matter, $c_s^2 = \partial P/\partial \varepsilon$, can be determined from the characteristic angle of the emitted secondaries with respect to the (quenched) jet axis [11, 12]:

  \[ \cos(\theta_M) = c_s, \] where $\theta_M$ is the Mach shock wave angle.

- In the second scenario, the **gluon dielectric constant** in the medium $\varepsilon$ or, equivalently, its index of refraction $n = \sqrt{\varepsilon}$, can be estimated from the distinctive angular pattern of emission of the (soft) radiated gluons [12, 13]:

  \[ \cos(\theta_c) \approx \frac{1}{\sqrt{\varepsilon}} \approx \frac{1}{n}, \]

  \[ (4) \]

**HIGH $p_T$ LEADING HADRON SUPPRESSION**

The standard method to quantify the (initial- and final-state) medium effects on the production yields of a given hard probe in a nucleus-nucleus reaction is given by the **nuclear modification factor**:

\[ R_{AA}(p_T, y; b) = \frac{\text{“hot/dense QCD medium”}}{\text{“QCD vacuum”}} = \frac{d^2N_{AA}/dydp_T}{\langle T_{AA}(b) \rangle \cdot d^2\sigma_{pp}/dydp_T}, \]

\[ (5) \]

which measures the deviation of A+A at impact parameter $b$ from an incoherent superposition of nucleon-nucleon collisions ($T_{AA}(b)$ is the corresponding Glauber nuclear overlap function at $b$). Among the most exciting results from the first 5 years of operation at RHIC is the large high $p_T$ hadron suppression ($R_{AA} \ll 1$) observed in central Au+Au reactions at $\sqrt{s_{NN}} = 200$ GeV, expected in jet quenching scenarios. Most of the empirical properties of the suppression factor are in quantitative agreement with the predictions of non-Abelian parton energy loss models:

(1) **Magnitude** of the suppression: The experimental $R_{AA} \approx 0.2$ value at top RHIC energies can be well reproduced assuming the formation of a very dense system
with initial gluon rapidity density $dN^g/dy \approx 1000$ [14] (Eq. 1) or transport coefficient $\langle \hat{q} \rangle \approx 14 \text{ GeV}^2/\text{fm}$ [15] (Eq. 2), both consistent with the total charged hadron multiplicities measured in the reaction: $dN/d\eta \approx 3/2 \cdot dN_{ch}/d\eta \approx 1000$ [16].

(2) **Universal** (light) hadron suppression: Above $p_T \approx 5 \text{ GeV}/c$, $\pi^0$ [17], $\eta$ [18], and inclusive charged hadrons [19, 20] (dominated by $\pi^\pm$ [20]) show all a common factor of $\sim 5$ suppression relative to the $R_{AA} = 1$ perturbative expectation which holds for hard probes, such as direct photons, insensitive to final-state interactions [21] (Fig. 1 left). Such a “universal” hadron deficit is consistent with in-medium *partonic* energy loss of the parent quark or gluon prior to vacuum fragmentation.

(3) **Flat transverse momentum** dependence: Above $p_T \approx 5 \text{ GeV}/c$, $R_{AA}(p_T)$ remains constant up to the highest transverse momenta measured so far ($p_T \approx 14 \text{ GeV}/c$ for $\pi^0$ [18], Fig. 1 left). Such $p_T$-independence of the quenching factor is also well accommodated by parton energy loss models [14, 15, 22].

(4) **Centrality** dependence: The amount of suppression in Au+Au reactions decreases with impact parameter as expected (from Eqs. 1, 2) for the different parton production points and, hence, the different densities and lengths encountered by the traversing parton through the medium [15, 23].

(5) **Center-of-mass energy** dependence: The amount of quenching rises in the range $\sqrt{s_{NN}} \approx 20 – 200 \text{ GeV}$ as expected due to the growing initial parton densities and the increasingly longer duration of the QGP phase [16] (Fig. 1 right).

(6) **Non-Abelian nature** of the energy loss: At $y = 0$, high-$p_T$ hadroproduction is dominated by quark (gluon) scattering at large (small) fractional momentum $x_T = 2p_T/\sqrt{s_{NN}}$. In the range $\sqrt{s_{NN}} \approx 20 – 200 \text{ GeV}$ and for a fixed (high) $p_T$ value, the suppression factor increases as expected in the canonical non-Abelian scenario where there is an increasingly large relative fraction of hard scattered gluons radiating with a $C_A/C_F = 9/4$ larger probability than quarks (Fig. 2 left).

**FIGURE 1.** Left: $R_{AA}(p_T)$ measured in central Au+Au at 200 GeV for: $\pi^0$ and $\eta$ mesons [13], charged hadrons [19], and direct photons [21] compared to theoretical predictions for parton energy loss in a dense medium with $dN^g/dy = 1100$ [14]. Right: Compilation of all measured $R_{AA}(p_T)$ for high $p_T$ neutral pions in central A+A collisions in the range $\sqrt{s_{NN}} \approx 20 – 200 \text{ GeV}$ [18], compared to GLV parton energy loss calculations [14] for different initial gluon densities ($dN^g/dy = 400$, 650 and 1100).
FIGURE 2. Left: Excitation function of $R_{AA}(p_T = 4 \text{ GeV/c})$ for $\pi^0$ [16] with two different implementations of partonic energy loss [24]: (i) canonical non-Abelian (gluons loose $C_A/C_F = 9/4$ more energy than quarks; solid line) and (ii) ad hoc “non-QCD” ($q,g$ radiate with equal probability; dashed line) prescriptions. Right: $R_{AA}$ for “non-photonic” $e^\pm$ measured in central Au+Au at $\sqrt{s_{NN}} = 200 \text{ GeV}$ [30] compared to theoretical predictions of heavy-quark energy loss [31, 32].

Though most of the experimental results on high $p_T$ hadron suppression in A+A reactions are in agreement with the non-Abelian energy loss “paradigm”, it is worth to stress that there are a few aspects of the data which are less well reproduced:

1. The pronounced path-length $L$ dependence of the energy loss, – as determined by the $\pi^0$ suppression factor along different azimuthal angles $\phi$ with respect to the Au+Au reaction plane [25] –, does not support the theoretical $\propto L$ or $L^2$ behaviour given by Eqs. 1, 2. Such a failure of the jet-quenching models points to an extra source of azimuthal anisotropy that enhances the in-plane $\pi^0$ production even in a kinematic domain beyond $p_T \approx 4.5 \text{ GeV/c}$ where non-perturbative effects should play a minor role [16].

2. The unsuppressed baryon ($p, \bar{p}$ [26] and $\Lambda, \bar{\Lambda}$ [27]) spectra within $p_T \approx 2 – 5 \text{ GeV/c}$ have been explained in terms of an extra mechanism of baryon production based on in-medium quark coalescence [28] which compensates for the energy loss suffered by the fragmenting parent partons. Though such a mechanism successfully describes many aspects of the data, it cannot explain (in its simplest “thermal recombination” form) the similar (“jet-like”) azimuthally-correlated hadron yields measured for trigger baryons and mesons at intermediate $p_T$ [29].

3. The large amount of heavy-quark quenching indicated by the suppressed high-$p_T$ spectra of electrons from semi-leptonic $D$ and $B$ meson decays measured by PHENIX in central Au+Au [30] (Fig. 2, right) is in apparent conflict with the robust $\Delta E_Q < \Delta E_q < \Delta E_g$ prediction of parton energy loss models. State-of-the-art theoretical predictions [31, 32] require much larger gluon densities to reproduce the high $p_T$ open charm/bottom results at RHIC, than they needed to describe the quenched light hadron spectra.
MODIFIED HIGH $P_T$ DI-HADRON $\phi, \eta$ CORRELATIONS

Full jet reconstruction in A+A collisions with standard jet algorithms \[33\] is unpractical at RHIC energies due to the overwhelming background of soft particles in the underlying event. Thus, beyond the leading hadron spectra measurements discussed in the previous section, more detailed studies of the modifications of the jet structure in a dense QCD environment have been addressed via the study of high-$P_T$ two-particle $\phi, \eta$ correlations. Jet-like correlations are measured on a statistical basis by selecting high-$P_T$ trigger particles and measuring the azimuthal ($\Delta \phi = \phi - \phi_{\text{trig}}$) and rapidity ($\Delta \eta = \eta - \eta_{\text{trig}}$) distributions of associated hadrons ($P_{T,\text{assoc}} < P_{T,\text{trig}}$) relative to the trigger:

$$C(\Delta \phi, \Delta \eta) = \frac{1}{N_{\text{trig}} d\Delta \phi d\Delta \eta} \frac{d^2 N_{\text{pair}}}{N_{\text{pair}} d\Delta \phi d\Delta \eta}.$$  \(6\)

Combinatorial background contributions, corrections for finite pair acceptance, and the superimposed effects of collective azimuthal modulations (elliptic flow) are then taken care of with different techniques \[34, 35, 36\]. If no initial- or final- state interactions affect the parton-parton scattering process, a dijet signal should appear to first order as two distinct back-to-back Gaussian peaks at $\Delta \phi \approx 0, \Delta \eta \approx 0$ (near-side) and at $\Delta \phi \approx \pi$ (away-side). At variance with this standard dijet topology in the QCD vacuum, the dihadron correlations in Au+Au reactions at RHIC show several striking features:

1. The gradual disappearance of the away-side azimuthal peak with centrality (observed at $\Delta \phi \approx \pi$ in the $dN_{\text{pair}}/d\Delta \phi$ distributions for hadrons with $2 < P_{T,\text{assoc}} < 4 < P_{T,\text{trig}} < 6 \text{ GeV/c}$), consistent with strong suppression of the leading fragments of the recoiling jet traversing the medium \[34\].

2. The broadening of the nearside pseudo-rapidity correlations $dN_{\text{pair}}/d\Delta \eta$ (“stretching” of the jet cone along $\eta$), reminiscent of the coupling of the induced radiation with the longitudinal expansion of the system \[35\].

3. The vanishing away-side peak, observed in the $dN_{\text{pair}}/d\Delta \phi$ distribution for recoiling hadrons with $P_{T,\text{assoc}} = 2 – 4 \text{ GeV/c}$, is accompanied with an enhanced production of lower $P_T$ hadrons ($P_{T,\text{assoc}} = 1 – 2.5 \text{ GeV/c}$ \[36\] or $0.15 – 4 \text{ GeV/c}$ \[35\]) with a characteristic “double-peak” structure at $\Delta \phi \approx \pi \pm 1.3$ or $\pi \pm 1.1$ (Fig. 3).

Figure 3 shows the double-peak structure appearing in the away-side azimuthal correlations of central Au+Au (top left-plot, and star symbols in the right-plot), compared to the standard back-to-back dijet topology seen in peripheral Au+Au (bottom, left) and in d+Au and p+p collisions (right). Such a non-Gaussian “volcano”-like shape seen in the away-side hemisphere has attracted much theoretical attention because it suggests conical patterns induced by Mach-shock \[11, 12\] or Čerenkov-like \[12, 13\] emissions.

In the “Mach cone” scenario \[11, 12\], the local maxima (red arrows in the plots) in central Au+Au at an angle $\Delta \phi \approx \pi \pm 1.2$ relative to the high-$P_T$ trigger are caused by the Mach shock of the supersonic recoiling (quenched) parton through the medium. The resulting preferential emission of secondary partons from the plasma at an angle $\theta_M \approx 1.2$, yields (Eq. 5) a value of the speed sound $c_s \approx 0.36$, close to that of an ideal QGP ($c_s = 1/\sqrt{3}$). In the Čerenkov gluonstrahlung picture \[12\], developed at a more quantitative level \[13\] after this conference, it is argued that the combination of the
Landau-Pomeranchuk-Migdal interference characteristic of gluon bremsstrahlung and a medium with a large dielectric constant ($n \approx 2.75$) is needed to reproduce the location of the experimental peaks using Eq. 4. It should also result in the two-peak shape observed in the data. At variance with the cone angle of the “sonic boom” mechanism (which is constant in the fluid but effectively increases with $p_{T, assoc}$ at the spectra level [11]), the Čerenkov angle decreases with the momentum of the radiated gluon. Such a trend, however, seemingly in disagreement with the fact that PHENIX (STAR) measures a larger (lower) $\theta_c \approx 1.3 (1.1)$ for higher (lower) average values of $p_{T, assoc}$.

**SUMMARY**

Experimental results on single inclusive spectra and dihadron correlations measured at high transverse momentum in Au+Au at RHIC collider energies ($\sqrt{s_{NN}} = 200$ GeV) have been reviewed as a means to learn about jet production and fragmentation in hot and dense QCD matter. The analysis of jet structure modifications in A+A collisions provides quantitative information on the thermodynamical and transport properties of the strongly interacting medium produced in the reactions. Two notable experimental results have been discussed: (i) the observed factor $\sim 5$ suppression of high $p_T$ leading hadrons in central Au+Au relative to p+p collisions in free space; and (ii) the conical-like shape of the azimuthal distributions of secondary hadrons emitted in the away-side hemisphere of a high-$p_T$ trigger hadron. Most of the properties of the observed high $p_T$ suppression (such as its magnitude, light flavor “universality”, $p_T$, reaction centrality, and $\sqrt{s_{NN}}$ dependences) are in quantitative agreement with predictions of non-Abelian energy loss models. The confrontation of these models to the data permits to derive the
initial gluon density $dN^g/dy \approx 1000$ and transport coefficient $\langle q \rangle \approx 14$ GeV$^2$/fm of the produced medium. The second striking observation of a softer and broadened angular distribution of secondary hadrons peaking at a finite angle away from the (quenched) jet axis has been attributed to Mach conical flow caused by the propagation of a supersonic parton through the dense system. If such a phenomenon is confirmed, the speed of sound of the medium could be extracted. The same angular pattern could also be the result of Čerenkov gluon radiation and provide, in that case, information on the gluon dielectric constant in hot and dense QCD matter.

REFERENCES

1. F. Karsch, Lect. Notes Phys. 583, 209 (2002).
2. J. W. Harris and B. Muller, Ann. Rev. Nucl. Part. Sci. 46, 71 (1996).
3. J. D. Bjorken, FERMILAB-PUB-82-059-THY.
4. M. Gyulassy, M. Plümer, Phys. Lett. B243, 432 (1990); X.N. Wang, M. Gyulassy, Phys. Rev. Lett. 68, 1480 (1992).
5. R. Baier, Y. L. Dokshitzer, A. H. Mueller, S. Peigné and D. Schiff, Nucl. Phys. B484, 265 (1997); R. Baier, D. Schiff, B.G. Zakharov, Ann. Rev. Nucl. Part. Sci. 50, 37 (2000).
6. M. Gyulassy, P. Levai and I. Vitev, Phys. Rev. Lett. 85, 5535 (2000); Nucl. Phys. B594, 371 (2001).
7. U. A. Wiedemann, Nucl. Phys. B588, 30 (2000); C. A. Salgado and U. A. Wiedemann, Phys. Rev. D68, 014008 (2003).
8. D. A. Appel, Phys. Rev. D 33, 717 (1986); J. P. Blaizot, L. D. McLerran, Phys. Rev. D 34, 2739 (1986).
9. C. A. Salgado and U. A. Wiedemann, Phys. Rev. Lett. 93, 042301 (2004).
10. N. Borghini and U. A. Wiedemann, hep-ph/0506218.
11. H. Stoecker, Nucl. Phys. A750, 121 (2005); J. Casalderrey, E. Shuryak, D. Teaney, hep-ph/0411315.
12. J. Ruppert and B. Muller, Phys. Lett. B618, 123 (2005).
13. A. Majumder and X. N. Wang, nucl-th/0507062; V. Koch, A. Majumder and X. N. Wang, nucl-th/0507063; I. M. Dremin, hep-ph/0507167.
14. I. Vitev and M. Gyulassy, Phys. Rev. Lett. 89, 252301 (2002); I. Vitev, J. Phys. G 30, S791 (2004).
15. A. Dainese, C. Loizides and G. Paic, Eur. Phys. J. C38, 461 (2005).
16. D. d’Enterria, Eur. Phys. J. C43, 295 (2005).
17. S.S. Adler et al. [PHENIX Collaboration], Phys. Rev. Lett. 91, 072301 (2003).
18. H. Busching [PHENIX Collaboration], Eur. Phys. J. C43, 303 (2005).
19. J. Adams et al. [STAR Collaboration], Phys. Rev. Lett. 91, 172302 (2003).
20. S. S. Adler et al. [PHENIX Collaboration], Phys. Rev. C69, 034910 (2004).
21. S.S. Adler et al. [PHENIX Collaboration], nucl-ex/0503003.
22. S. Jeon and G. D. Moore, Phys. Rev. C 71, 034901 (2005).
23. X.N. Wang, Phys. Rev. C70, 031901 (2004).
24. Q. Wang and X.N. Wang, Phys. Rev. C71, 014903 (2005).
25. B. Cole [PHENIX Collaboration], Eur. Phys. J. C43, 271 (2005).
26. S. S. Adler et al. [PHENIX Collaboration], Phys. Rev. Lett. 91, 172301 (2003).
27. J. Adams et al. [STAR Collaboration], Phys. Rev. Lett. 92, 052302 (2004).
28. R. C. Hwa, C. B. Yang, Phys. Rev. C67, 034902 (2003); R. J. Fries, B. Muller, C. Nonaka, S. A. Bass, Phys. Rev. C68, 044902 (2003); V. Greco, C. M. Ko, P. Levai, Phys. Rev. Lett. 90, 202302 (2003).
29. S. S. Adler et al. [PHENIX Collaboration], Phys. Rev. C71, 051902 (2005).
30. B. Jacak [PHENIX Collaboration], Proceeds. ICPAQGP 2005, India, Feb 2005; nucl-ex/0508036.
31. M. Djordjevic, M. Gyulassy and S. Wicks, Phys. Rev. Lett. 94, 112301 (2005).
32. N. Armesto, A. Dainese, C. A. Salgado and U. A. Wiedemann, Phys. Rev. D71, 054027 (2005).
33. See e.g G. C. Blazey et al., hep-ex/0005012.
34. C. Adler et al. [STAR Collaboration], Phys. Rev. Lett. 90, 082302 (2003).
35. J. Adams et al. [STAR Collaboration], Phys. Rev. Lett. 95, 152301 (2005); F. Wang [STAR Collaboration] in RIKEN/BNL Workshop on Jet Correlations at RHIC, March 2005.
36. S. S. Adler et al. [PHENIX Collaboration], nucl-ex/0507004.