Jet quenching in QCD matter: from RHIC to LHC

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Abstract

The current experimental and theoretical status of hadron and jet production at large transverse momentum in high-energy nucleus-nucleus collisions is summarised. The most important RHIC results are compared to theoretical parton energy loss predictions providing direct information on the (thermo)dynamical properties of hot and dense QCD matter. Prospects for the LHC are also outlined.

1. Introduction

The physics programme of high-energy nucleus-nucleus (AA) collisions is focused on the study of the fundamental theory of the strong interaction – Quantum Chromo Dynamics (QCD) – in extreme conditions of temperature, density and small parton momentum fraction (low-x) – see e.g. [1] for a recent review. By colliding two heavy nuclei at ultrarelativistic energies one expects to form a hot and dense deconfined medium whose collective (colour) dynamics can be studied experimentally. Lattice QCD calculations [2] predict a new form of matter at energy densities (well) above \( \varepsilon_{\text{crit}} \approx 1 \text{ GeV/fm}^3 \) consisting of an extended volume of deconfined and chirally-symmetric (bare-mass) quarks and gluons: the Quark Gluon Plasma (QGP).

One of the first proposed “smoking guns” of QGP formation was jet quenching [3] i.e. the attenuation or disappearance of the spray of hadrons resulting from the fragmentation of a parton having suffered energy loss in the dense plasma formed in the reaction (Fig. 1, left). The energy lost by a parton provides “tomographic” information of the matter properties (temperature \( T \), interaction coupling \( \alpha \), thickness \( L \)): \( \Delta E = f(E; T, \alpha, L) \) [8]. The “scattering power” of the medium is often encoded in the transport coefficient which describes the average transverse momentum squared transferred to the traversing parton per unit path-length: \( \hat{q} \equiv m_D^2/\lambda = m_D^2 \rho \sigma \) (here \( m_D \) is the medium Debye mass, \( \rho \) its density, and \( \sigma \) the parton-matter interaction cross section). The dominant mechanism of energy loss of a fast parton in a dense QCD plasma is

\[ \hat{q} \approx 2 \text{ GeV}^2/\text{fm} \]

\[ 1 \] For an equilibrated gluon plasma at \( T = 0.4 \text{ GeV} \) with coupling \( \alpha_s \approx 0.5 \) – i.e. with density \( \rho_g = 16/\pi^2 \zeta(3) \cdot T^3 \approx 15 \text{ fm}^{-3} \), Debye mass \( m_D = (4\pi\alpha_s)^{1/2} T \approx 1 \text{ GeV} \), and cross section \( \sigma_{gg} \approx 1.5 \text{ mb} \) – one has \( \hat{q} \approx 2.2 \text{ GeV}^2/\text{fm} \).

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Fig. 1. Right: “Jet quenching” in a head-on heavy-ion collision: a fast parton traverses the dense plasma created (with transport coefficient $\hat{q}$, gluon density $dN_g/dy$ and temperature $T$), loses energy via “gluonstrahlung” and fragments into a (quenched) jet [4]. Left: Neutral pion spectrum measured by PHENIX at $\sqrt{s_{NN}} = 200$ GeV in central Au–Au (squares) [5], compared to the ($T_{AA}$-scaled) spectrum in $pp$ collisions (circles) [6] and to a NLO pQCD calculation (yellow band) [7].

of radiative nature (“gluonstrahlung”): the parton loses energy mainly by medium-induced multiple gluon emission [10,11,12,13]. Jet quenching in $AA$ reactions is characterised by various observable consequences compared to the same “QCD vacuum” measurements in proton-proton ($pp$) collisions: (i) suppressed high-$p_T$ hadron spectrum ($dN_{AA}/dp_T$), (ii) unbalanced back-to-back high-$p_T$ dihadron azimuthal correlations ($dN_{pair}/d\phi$), and (iii) modified energy-particle flow (softer hadron spectra, larger multiplicity, increased angular broadening, ...) within the final jets. A detailed review of these topics can be found in [4], of which a summary is given in the following sections.

2. High-$p_T$ single inclusive hadron production

If a hard scattered parton suffers energy loss in a heavy-ion collision, the energy available for the hadrons issuing from its fragmentation will be reduced and their spectrum depleted compared to $pp$ collisions. The standard method to quantify the medium effects on the yield of a large-$p_T$ particle produced at rapidity $y$ in an $AA$ reaction is given by the nuclear modification factor:

$$R_{AA}(p_T,y,b) = \frac{d^2N_{AA}/dydp_T}{\langle T_{AA}(b) \rangle \times d^2\sigma_{pp}/dydp_T}$$

where $T_{AA}(b)$ being the nuclear overlap function at $b$, (1)

which measures the deviation of $AA$ at impact parameter $b$ from an incoherent superposition of nucleon-nucleon collisions ($R_{AA} = 1$). From the measured suppression factor one can determine various medium properties such as its transport parameter $\hat{q}$, via $\Delta E \propto \alpha_s(\hat{q}) L^2$ [11,13], or its initial gluon density $dN_g/dy$, via $\Delta E \propto \alpha_s^3 C_R \frac{1}{A_1} \frac{dN_g}{dy} L$ (for an expanding plasma with original transverse area $A_1 = \pi R_A^2 \approx 150$ fm$^2$ and thickness $L$) [12]. We summarise the main high-$p_T$ hadroproduction results in $pp$ and $AA$ collisions, and confront them to jet quenching predictions.
(a) Magnitude of the suppression and medium properties. Figure 1(right) shows the high-\(p_T\) \(\pi^0\) spectrum measured at \(\sqrt{s_{NN}} = 200\) GeV in central \(AuAu\) [5] compared to the \(pp\) [6] and NLO pQCD [7] spectra scaled by \(T_{AA}\). The \(AuAu\) data are suppressed by a factor of 4 – 5 with respect to the \(pp\) results. The corresponding \(R_{AA}(p_T)\), Eq. (1), is shown in Fig. 2(left). Above \(p_T\) \(\approx 5\) GeV/c, \(\pi^0\) [14], \(\eta\) [15], and charged hadrons [16][17] show all a common factor of \(\sim 5\) suppression relative to the \(R_{AA} = 1\) expectation that holds for hard probes, such as direct photons [18][19], which do no interact with the medium. The \(AuAu\) high-\(p_T\) suppression can be well reproduced by parton energy loss calculations in a very dense system with initial gluon densities \(\sigma_{gg} \approx 0.4\) GeV/fm) [25]. The consistency between the extracted \(\hat{q}\) and \(dN^g/d\gamma\) in the various models has been studied e.g. in [4][26]. Whereas the agreement between the fitted thermodynamical variables \(dN^g/d\gamma\) and \(T\) is good, the values of the transport parameter \(\hat{q}\) favoured by the data are 3 – 4 times larger than perturbative estimates [9]. An accord between the obtained \(\hat{q}\) and \(dN^g/d\gamma\) can only be achieved assuming parton-medium cross-sections much larger than the \(\sigma_{gg} \approx 1.5\) mb LO expectation. Such an observation lends support to the strongly-coupled nature of the QGP produced at RHIC [27].

(b) Centre-of-mass energy dependence. As one increases the collision energy in nucleus-nucleus collisions, the produced plasma reaches higher energy and particle densities, the system stays longer in the QGP phase, and correspondingly the traversing partons are more quenched. Figure 2(right) compiles the measured \(R_{AA}(p_T)\) for high-\(p_T\) \(\pi^0\) in central AA collisions in the range \(\sqrt{s_{NN}} \approx 20 – 200\) GeV compared to parton energy loss calculations that assume the formation of a QGP in the initial gluon densities in the range \(dN^g/d\gamma \approx 400 – 1400\) [20][28] or, equivalently, averaged transport coefficients \(\langle \hat{q}\rangle \approx 3.5 – 13\) GeV\(^2\)/fm [24]. The theoretical predictions reproduce well the magnitude and shape of the experimental data. The SPS \(R_{AA}(p_T)\) [21], though consistent with unity [22], is suppressed compared to the “Cronin enhancement” observed in peripheral PbPb and pPb collisions at the same \(\sqrt{s_{NN}}\) [29].
(c) $p_T$-dependence of the suppression. At RHIC top energies, the hadron quenching factor remains basically constant from 5 GeV/c up to the highest transverse momenta measured so far, $p_T \approx 20$ GeV/c (Fig. 2). Full calculations \cite{20,24,30,31} including the combined effect of (i) energy loss kinematics constraints, (ii) steeply falling $p_T$ spectrum of the scattered partons, and (iii) $\mathcal{O}(20\%)$ $p_T$-dependent (anti)shadowing differences between the proton and nuclear parton distribution functions (PDFs), result in an effectively flat $R_{AA}(p_T)$ as found in the data. The much larger kinematical range opened at LHC energies \cite{23} will allow one to test the $p_T$-dependence of parton energy loss over a much wider domain than at RHIC (yellow bands in Fig. 2 right).

(d) Centrality (system-size) dependence. The volume of the produced plasma in a heavy-ion collision can be “dialed” by modifying the overlap area between the colliding nuclei either by selecting a given impact-parameter $b$ – i.e. by choosing more central or peripheral reactions – or by colliding larger or smaller nuclei, e.g. Au ($A = 197$) versus Cu ($A = 63$). The relative energy loss depends on the effective mass number $A_{eff}$ or, equivalently, on the number of participant nucleons in the collision $N_{part}$, as: $\Delta E/E \propto A_{eff}^{2/3} \propto N_{part}^{2/3}$ \cite{24,32}. The measured $R_{AA}(p_T)$ in central CuCu at 22.4, 62.4, and 200 GeV \cite{33} is a factor of $(A_{Au}/A_{Cu})^{2/3} \approx 2$ lower than in central AuAu at the same energies. Yet, for a comparable $N_{part}$ value, the suppression in AuAu and CuCu is very similar. Fitting the $N_{part}$ dependence to $R_{AA} = (1 - \kappa N_{part}^\alpha) n^{2/3}$ yields $\alpha = 0.56 \pm 0.10$ \cite{5}, consistent with parton energy loss calculations.

(e) Path-length dependence. Experimentally, one can test the dependence of parton suppression on the plasma thickness ($L$) by exploiting the spatial asymmetry of the system produced in non-central nuclear collisions. Partons produced “in plane” (“out-of-plane”) i.e. along the short (long) direction of the ellipsoid matter with eccentricity $\varepsilon$ will comparatively traverse a shorter (longer) thickness. PHENIX has measured the high-$p_T$ neutral pion suppression as a function of the angle with respect to the reaction plane, $R_{AA}(p_T, \phi)$ \cite{34}. Each azimuthal angle $\phi$ can be associated with an average medium path-length $L_\varepsilon$ via a Glauber model. The energy loss is found to satisfy the expected $\Delta E \propto L$ dependence \cite{12} above a “threshold” length of $L \approx 2$ fm.

![Fig. 3. Left: $R_{AA}(p_T = 4$ GeV/c) for $\pi^0$ in central AA collisions as function of collision energy compared to non-Abelian (solid) and “non-QCD” (dotted) energy loss curves \cite{35,36}. Right: $R_{AA}(p_T)$ for decay electrons from D and B mesons in central AuAu at $\sqrt{s_{NN}} = 200$ GeV \cite{37,38,39} compared to a model of D and B meson dissociation in the plasma \cite{40}.](image)
(f) Non-Abelian (colour factor) dependence. The amount of energy lost by a parton in a medium is proportional to its colour Casimir factor: \( C_A = 3 \) for gluons, \( C_F = 4/3 \) for quarks. Asymptotically, the probability for a gluon to radiate another gluon is \( C_A/C_F = 9/4 \) times larger than for a quark and thus \( g \)-jets are expected to be more quenched than \( q \)-jets in a QGP. One can test such a genuine non-Abelian property of QCD energy loss by measuring hadron suppression at a fixed \( p_T \) for increasing \( \sqrt{s_{NN}} \) [35,36]. At large (small) \( x \), the PDFs are dominated by valence-quarks (“wee” gluons) and consequently hadroproduction is dominated by quark (gluon) fragmentation. Figure 3 (left) shows the \( R_{AA} \) for 4-GeV/c pions measured at SPS and RHIC compared to two parton energy loss curves [36]. The lower (upper) curve shows the expected \( R_{AA} \) assuming a normal (arbitrary) behaviour with \( \Delta E_g/\Delta E_q = 9/4 \) (\( \Delta E_g = \Delta E_q \)). The experimental high-\( p_T \) \( \pi^0 \) data support the expected colour-factor dependence of \( R_{AA}(\sqrt{s_{NN}}) \) [35].

(g) Heavy-quark mass dependence. Due to the “dead cone” effect [42], the radiative energy loss for a charm (bottom) quark is a factor \( 1-(m_Q/m_D) \approx 25\% \) (75\%) smaller than for a light-quark. Yet, RHIC measurements [37,38,39] of high-\( p_T \) electrons from the semi-leptonic decays of \( D \) and \( B \)-mesons (Fig. 3, right) indicate the same suppression for light and heavy mesons: \( R_{AA}(Q) \sim R_{AA}(q,g) \approx 0.2 \), in contradiction with parton energy loss predictions [43,44]. Various explanations have been proposed to solve the ‘heavy flavor puzzle’ [4]. Among them is the observation that the hypothesis of vacuum hadronisation (after in-medium radiation) implicit in all formalisms may well not hold in the case of heavy quarks. The formation time of \( D \)- and \( B \)-mesons is of order \( \tau_{form} \approx 0.4 – 1 \) fm/c respectively and, thus, one needs to account for the energy loss of the heavy-quark as well as the possible dissociation of the heavy-quark meson inside the QGP [40]. The expected amount of suppression in that case is larger and consistent with the data (Fig. 3, right).

3. High-\( p_T \) di-hadron correlations

Jet-like correlations in heavy-ion collisions can be measured on a statistical basis by selecting a high-\( p_T \) trigger particle and measuring the azimuthal (\( \Delta \phi = \phi - \phi_{trig} \)) and pseudorapidity (\( \Delta \eta = \eta - \eta_{trig} \)) distributions of its associated hadrons (\( p_{assoc}^{<p_T^{trig}} \)); \( C(\Delta \phi, \Delta \eta) = 1/\mathcal{N}_{trig} \int d\Delta \phi d\Delta \eta N_{assoc}^{<p_T^{trig}} \). In \( pp \) collisions, a dijet signal appears as two distinct back-to-back Gaussian-like peaks at \( \Delta \phi \approx 0 \), \( \Delta \eta \approx 0 \) (near-side) and at \( \Delta \phi \approx \pi \) (away-side). At variance with such a topology, Fig. 4 shows the increasingly distorted back-to-back azimuthal correlations in high-\( p_T \) triggered central AuAu events as one decreases the \( p_T \) of the associated hadrons (right to left). Whereas, the \( AuAu \) and \( pp \) near-side peaks are similar for all \( p_T \)'s, the away-side peak is only present for the highest partner \( p_T \)'s but progressively disappears for less energetic partners [45,46]. Early STAR results [47] showed a monojet-like topology with a complete disappearance of the opposite-side peak for \( p_{T^{assoc}}^{<2-4 \text{ GeV/c}} \). The correlation strength over an azimuthal range \( \Delta \phi \) between a trigger hadron \( h_t \) and a partner hadron \( h_a \) in the opposite azimuthal direction can be constructed as a function of the momentum fraction \( \varepsilon_T = p_{T^{assoc}}^{<2-4 \text{ GeV/c}}/p_T^{trig} \) via a “pseudo-fragmentation function”:

\[ f \] The use of high-\( p_T \) (anti)protons (mostly coming from gluon fragmentation) as an alternative test of the colour charge dependence of the quenching [43] is, unfortunately, distorted by the presence of extra non-perturbative mechanisms of baryon production (see discussion in [4]).
Fig. 4. Comparison of the azimuthal di-hadron correlation $dN_{pair}/d\Delta\phi d\eta$ for $pp$ (open symbols) and central AuAu (histograms) at $\sqrt{s_{NN}} = 200$ GeV for $p_T^{trig} = 5–10$ GeV/c and increasingly smaller (right to left) values of $p_T^{assoc}$ [45].

$$D_{AA}^{away}(z_T) = \int d\phi_T^{trig} \int d\phi_T^{assoc} \int_{\Delta\phi^{away} > 130^0} d\Delta\phi dN_{trig}^{ha}/d\phi_T^{trig} dN_{assoc}^{ha}/d\phi_T^{assoc}.$$ (2)

shown in Fig. 5 (top-left) compared to predictions of the HT model for various values of the $\varepsilon_0$ parameter quantifying the amount of energy loss [48]. Similarly to $R_{AA}$, the magnitude of the suppression of back-to-back jet-like two-particle correlations can be quantified with the ratio $I_{AA}^{away} = D_{AA}^{away}/D_{pp}^{away}$. $I_{AA}^{away}$ is found to decrease with increasing centrality, down to about 0.2 – 0.3 for the most central events (Fig. 5 bottom-left) [47,49]. The right plot of Fig. 5 shows the best $\varepsilon_0 \approx 1.9$ GeV/fm value that fits the measured $R_{AA}(p_T)$ and $I_{AA}(z_T)$ factors. Due to the irreducible presence of (unquenched) partons emitted from the surface of the plasma, the single-hadron quenching factor $R_{AA}(p_T)$ is in general less sensitive to the value of $\varepsilon_0$ than the dihadron modification ratio $I_{AA}(z_T)$. 

Fig. 5. Left: $D_{AA}^{away}(z_T)$ distributions for $dAu$ and $AuAu$ and $I_{AA}(z_T)$ ratio for central $AuAu$ at 200 GeV [49], compared to HT calculations for varying $\varepsilon_0$ energy losses [48]. Right: Data vs. theory $\chi^2$ values for the fitted $\varepsilon_0$ parameter [48].
4. Jet observables

The measurements in AA collisions of fully reconstructed (di)jets or of jets tagged by an away-side photon or Z-boson allow one to investigate – in much more detail than with single- or double-hadron observables – the mechanisms of in-medium parton radiation as well as to characterise the matter properties through modified jet profiles [50,51] and fragmentation functions [52].

Experimental reconstruction of jets in nuclear reactions is an involved three-steps exercise [4]:

(i) **Clustering algorithm:** The measured hadrons are clustered together, according to relative distances in momentum and/or space, following an infrared- and collinear-safe procedure which is also fast enough to be run over events with very high multiplicities. The $k_T$ and SISCone algorithms implemented in the FASTJET package [53] fulfill all such conditions.

(ii) **Background subtraction:** Jets are produced on top of a large “underlying event” (UE) of hadrons coming from other (softer) parton-parton collisions in the same interaction. In central PbPb collisions at the LHC one expects $E_{T}^{UE} \approx 80$ GeV (with large fluctuations) in a cone of radius $R = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.4$. Various UE subtraction techniques are available in combination with the $k_T$ [54], UA1-cone [55] or iterative-cone [56] algorithms.

(iii) **Jet energy corrections:** Data-driven methods are needed to experimentally control the jet energy-scale which is the single most important source of systematic uncertainties in the jet yield. The non-perturbative effects introduced by the UE and hadronisation can be gauged by comparing the sensitivity of the jet spectrum obtained with different Monte Carlo’s [4].

STAR [57] has a preliminary measurement of jets in AuAu at 200 GeV (Fig. 6, left) using a cone algorithm with $R = 0.4$, and estimating the UE background from the average energy in cones without seeds. Control of the jet energy corrections is still work in progress. Jet physics will definitely benefit from the highest energies (and therefore statistics) available at the LHC. The expected $p_T$ reach in PbPb at 5.5 TeV is as large as $p_T \approx 500$ GeV/c (Fig. 6, right).

The $\gamma$-jet (and Z-jet) channel provides a very clean means to determine medium-modified parton fragmentation functions (FFs) [59,60]. Since the prompt $\gamma$ is not affected by final-state interactions, its transverse energy ($E_{T}^{\gamma}$) can be used as a proxy of the away-side parton energy ($E_{T}^{jet} \approx E_{T}^{\gamma}$) before any jet quenching. The FF, defined as the normalised distribution of hadron momenta $1/N_{jets} dN/dz$ relative to that of the parent parton $E_{T}^{jet}$, can then be constructed using

Fig. 6. Left: Preliminary STAR jet $E_T$ spectra in central AuAu (triangles) and $pp$ (squares, scaled by $T_{AA}$) at 200 GeV [57].
Right: Jet spectra for various PbPb centralities expected at 5.5 TeV in CMS ($/\not{E}_T = 0.5$ nb$^{-1}$) [58].
\[ z_p = p_T/E_{\text{jet}} \] or, similarly, \[ \xi = \log(E_{\text{jet}}/p_T) = -\log(z), \] for all particles with momentum \( p_T \) associated with a jet. In a QCD medium, energy loss shifts parton energy from high-\( z \) to low-\( z \) hadrons [61], resulting in a higher “hump-back plateau” in the FFs at intermediate \( \xi \approx 3 – 4 \) values (Fig. 7 left). Full simulation studies of the \( \gamma \)-jet channel in central Pb-Pb (Fig. 7 right) indicate that medium modified FFs are measurable with small uncertainties in the ranges \( z < 0.7 \) and \( 0.2 < \xi < 6 \) [62].

5. Summary

The analysis of jet structure modifications in heavy-ion collisions provides quantitative “tomographic” information on the thermodynamical and transport properties of the strongly interacting medium produced in the reactions. At RHIC energies (up to \( \sqrt{s_{NN}} = 200 \) GeV), strong suppression of the yields of high-\( p_T \) single hadrons and of dihadron azimuthal correlations, have been observed in central \( AuAu \) collisions. Most of the properties of the observed suppression are in quantitative agreement with the predictions of parton energy loss models in a very dense QCD plasma. The confrontation of these models to the data permits to derive the initial gluon density \( dN_g/dy \approx 1400 \) and transport coefficient \( \hat{q} = \mathcal{O}(10 \text{ GeV}^2/\text{fm}) \) of the produced medium at RHIC. At the upcoming LHC energies, the detailed analysis of jet spectra, jet shapes and the extraction of medium-modified parton-to-hadron fragmentation functions promise to fully unravel the mechanisms of parton energy loss in QCD matter. The study of jet quenching phenomena proves an excellent tool to expand our knowledge of the dynamics of the strong interaction at extreme conditions of temperature and density.

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