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 $\varepsilon_{crit} \approx 1$ 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 α, 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, ρ its density, and σ the parton-matter interaction cross section) [1]. The dominant mechanism of energy loss of a fast parton in a dense QCD plasma is

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[1] For an equilibrated *gluon* plasma at $T = 0.4$ GeV with coupling $\alpha_s \approx 0.5$ – i.e. with density $\rho_g = 16/\pi^2\,\zeta(3)\cdot T^3 \approx$ 15 fm^{-3}, Debye mass $m_D = (4\pi\alpha_s)^{1/2}T \approx 1$ GeV, and cross section $\sigma_{gg} \approx 1.5$ mb – one has $\hat{q} \simeq 2.2$ GeV^2/fm [9].

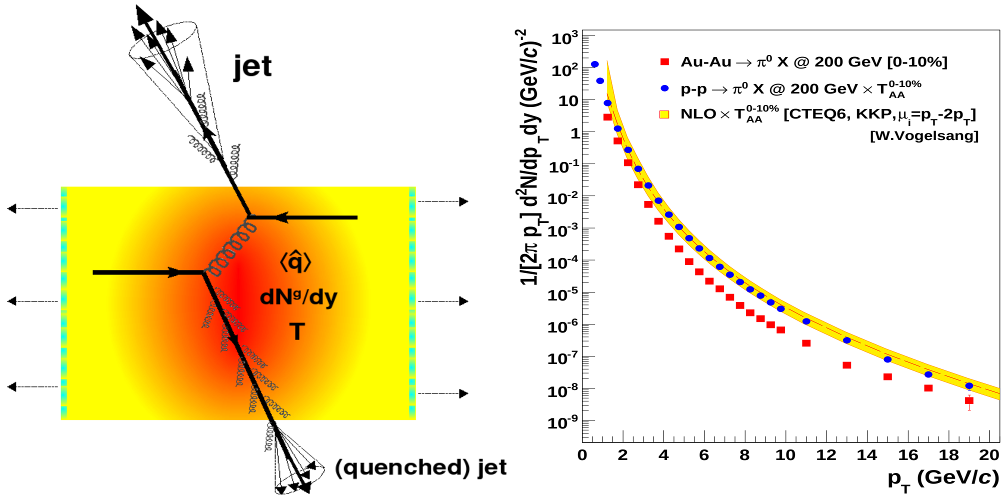

Fig. 1. Right: "Jet quenching" in a head-on heavy-ion collision: a fast parton traverses the dense plasma created (with transport coefficient $\hat{q}$, gluon density dN^g/dy and temperature T), loses energy via "gluonstrahlung" and fragments into a (quenched) jet [4]. Left: Neutral pion spectrum measured by PHENIX at $\sqrt{s_{NN}}$ = 200 GeV in central *AuAu* (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 a *AA* reaction is given by the *nuclear modification factor*:

$$R_{AA}(p_T,y;b) = \frac{d^2N_{AA}/dydp_T}{\langle T_{AA}(b)\rangle \times d^2\sigma_{pp}/dydp_T}\ ,\ T_{AA}(b) \text{ being the nuclear overlap function at } b, \quad (1)$$

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 $\langle \Delta E\rangle \propto \alpha_s \langle \hat{q}\rangle L^2$ [11,13], or its initial gluon density dN^g/dy, via $\Delta E \propto \alpha_s^3 C_R \frac{1}{A_\perp}\frac{dN^g}{dy} L$ (for an *expanding* plasma with *original* transverse area $A_\perp = \pi R_A^2 \approx 150$ 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 π^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, π^0 [14], η [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

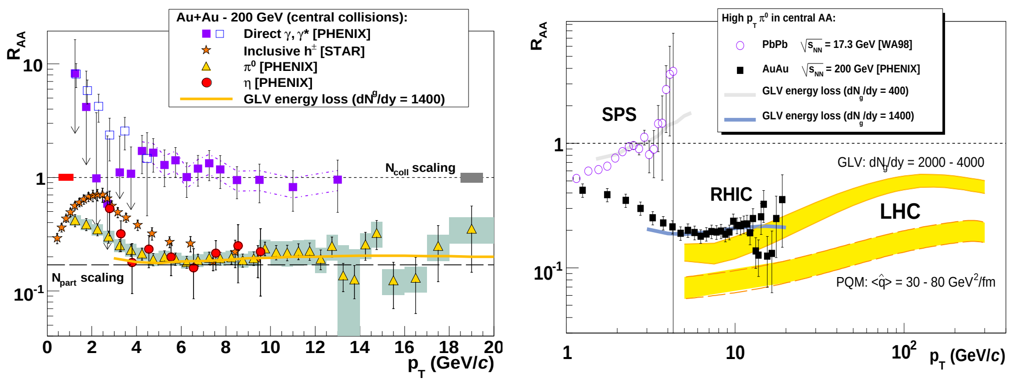

Fig. 2. Left: $R_{AA}(p_T)$ in central *AuAu* at 200 GeV for π^0 [5], η [15], charged hadrons [16], and direct γ [18,19] compared to the GLV model ($dN^g/dy = 1400$, yellow curve) [20]. Right: $R_{AA}(p_T)$ for π^0's at SPS [21,22] and RHIC [5] compared to GLV calculations (dN^g/dy = 400, 1400) and to predictions for central *PbPb* at $\sqrt{s_{NN}}$ = 5.5 TeV (yellow bands) [23]: GLV (dN^g/dy = 2000 – 4000) and PQM ($\langle\hat{q}\rangle \approx 30 - 80$ GeV^2/fm).

reproduced by parton energy loss calculations in a very dense system with initial gluon rapidity densities $dN^g/dy \approx 1400$ (Gyulassy-Lévai-Vitev curve in Fig. 2, left) [20], transport coefficients $\hat{q} \approx 13$ GeV^2/fm [5,24], or plasma temperatures $T \approx 0.4$ GeV [25]. The consistency between the extracted $\hat{q}$, dN^g/dy and T values in the various models has been studied e.g. in [4,26]. Whereas the agreement between the fitted *thermodynamical* variables dN^g/dy 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/dy 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 π^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 with initial gluon densities in the range $dN^g/dy \approx 400 - 1400$ [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 [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 [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 $A_{\rm eff}$ or, equivalently, on the number of participant nucleons in the collision $N_{\rm part}$, as: $\Delta E/E \propto A_{\rm eff}^{2/3} \propto N_{\rm part}^{2/3}$ [24,32]. The measured $R_{AA}(p_T)$ in *central CuCu* at 22.4, 62.4, and 200 GeV [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 $R_{AA} = (1 - \kappa\, N_{part}^{\alpha})^{n-2}$ yields $\alpha = 0.56 \pm 0.10$ [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 ε 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, $R_{AA}(p_T, \phi)$ [34]. Each azimuthal angle ϕ can be associated with an average medium path-length L_ε via a Glauber model. The energy loss is found to satisfy the expected $\Delta E \propto L$ dependence [12] above a "threshold" length of $L \approx 2$ fm.

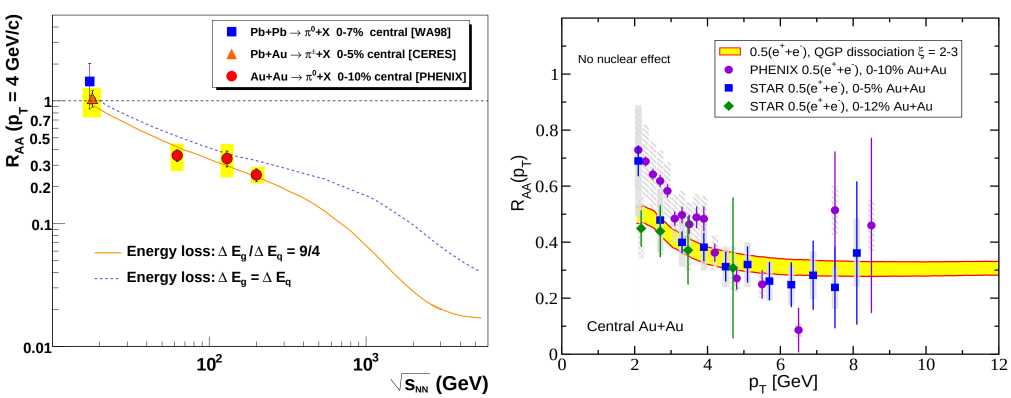

Fig. 3. Left: $R_{AA}(p_T = 4$ GeV/c) for π^0 in central *AA* collisions as function of collision energy compared to non-Abelian (solid) and "non-QCD" (dotted) energy loss curves [35,36]. Right: $R_{AA}(p_T)$ for decay electrons from *D* and *B* mesons in central *AuAu* at $\sqrt{s_{NN}} = 200$ GeV [37,38,39] compared to a model of *D* and *B* meson dissociation in the plasma [40].

(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* $\sqrt{s}$ [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 π^0 data supports [2] 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 ($p_T^{assoc} < p_T^{trig}$): $C(\Delta\phi, \Delta\eta) = \frac{1}{N_{trig}} \frac{d^2N_{pair}}{d\Delta\phi d\Delta\eta}$. 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 [46,45]. Early STAR results [47] showed a monojet-like topology with a complete disappearance of the opposite-side peak for $p_T^{assoc} \approx$ 2 – 4 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 $z_T = p_T^{assoc}/p_T^{trig}$ via a "pseudo-fragmentation function":

[2] 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 [41] is, unfortunately, distorted by the presence of extra non-perturbative mechanisms of baryon production (see discussion in [4]).

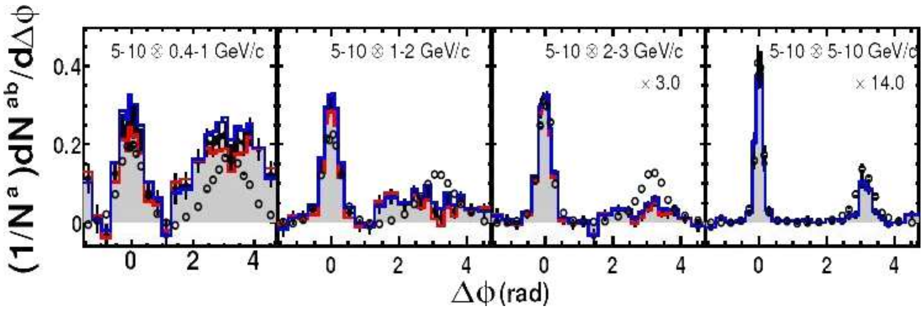

Fig. 4. Comparison of the azimuthal di-hadron correlation $dN_{pair}/d\Delta\phi d\eta$ for pp (open symbols) and central $AuAu$ (histograms) at $\sqrt{s_{NN}}$ = 200 GeV for p_T^{trig} = 5–10 GeV/c and increasingly smaller (right to left) values of p_T^{assoc} [45].

$$D_{AA}^{away}(z_T) = \int dp_T^{trig} \int dp_T^{assoc} \int_{\Delta\phi_{away}>130^o} d\Delta\phi \, \frac{d^3\sigma_{AA}^{h_t h_a}/dp_T^{trig} dp_T^{assoc} d\Delta\phi}{d\sigma_{AA}^{h_t}/dp_T^{trig}} . \tag{2}$$

shown in Fig. 5 (top-left) compared to predictions of the HT model for various values of the ε_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

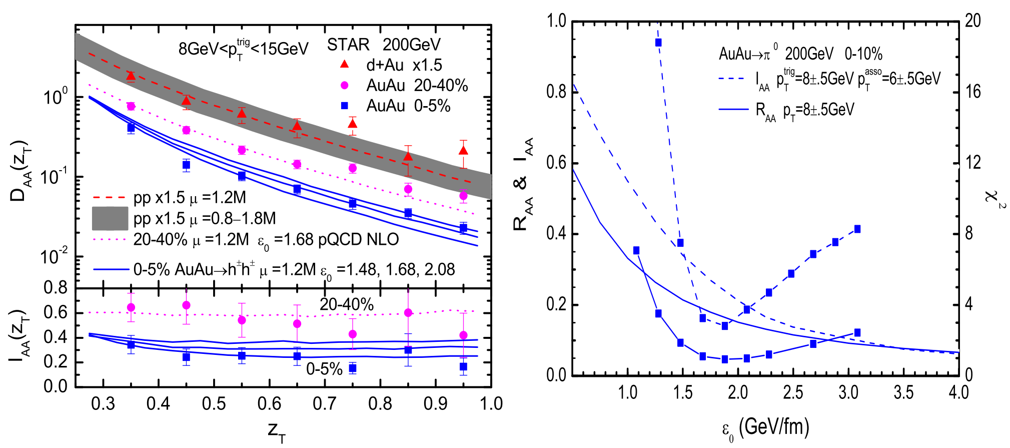

Fig. 5. Left: $D_{AA}^{away}(z_T)$ distributions for dAu and $AuAu$ and $I_{AA}(z_T)$ ratio for central $AuAu$ at 200 GeV [49], compared to HT calculations for varying ε_0 energy losses [48]. Right: Data vs. theory χ^2 values for the fitted ε_0 parameter [48].

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 ε_0 than the dihadron modification ratio $I_{AA}(z_T)$.

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).

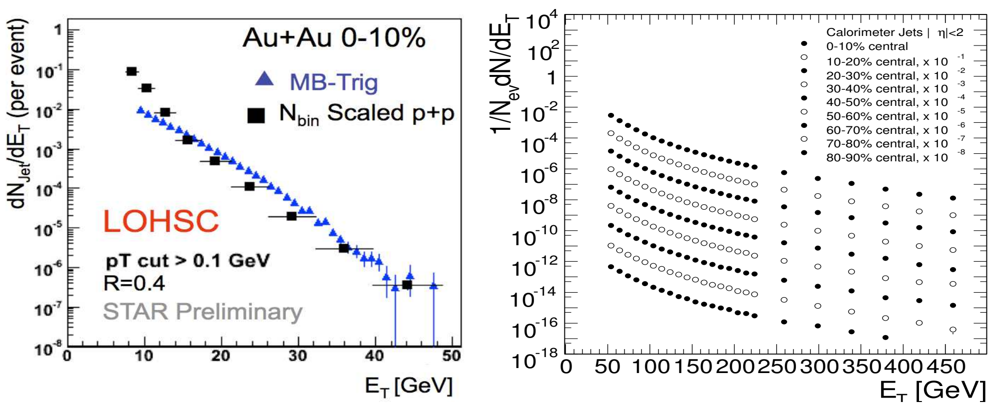

Fig. 6. Left: Preliminary STAR jet E_T spectra in central *AuAu* (triangles) and pp (squares, scaled by T_{AA}) at 200 GeV [57]. Right: Jet spectra for various *PbPb* centralities expected at 5.5 TeV in CMS ($\int \mathscr{L}\, dt$ = 0.5 nb^{-1}) [58].

The γ-jet (and *Z*-jet) channel provides a very clean means to determine medium-modified parton fragmentation functions (FFs) [59,60]. Since the prompt γ is not affected by final-state interactions, its transverse energy (E_T^{γ}) 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

$z_{\gamma h} = p_T / E_T^{jet}$ or, similarly, $\xi = \log(E_T^{jet}/p_T) = -\log(z)$, 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 γ-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].

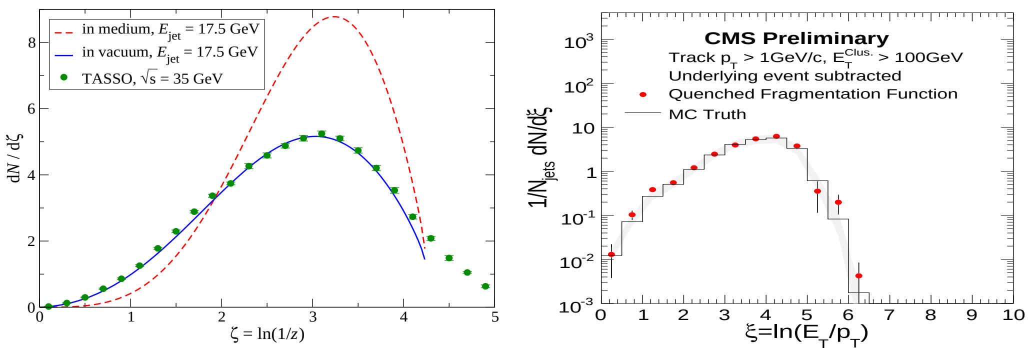

Fig. 7. Left: Single inclusive distribution of hadrons vs. $\xi = \ln(E_{jet}/p)$ for a 17.5-GeV jet in e^+e^- collisions (TASSO data) compared to QCD radiation predictions in the vacuum (solid curve) and in-medium (dashed curve) [61]. Right: FFs as a function of ξ for quenched partons obtained in CMS γ-jet simulations for central Pb-Pb at 5.5 TeV (0.5 nb^{-1}) [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 $\hat{q} = \mathscr{O}(10\ \mathrm{GeV}^2/\mathrm{fm})$ 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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