Jet quenching in heavy-ion collisions: The transition era from RHIC to LHC

B. Betz

Institute for Theoretical Physics, Johann Wolfgang Goethe-University, Frankfurt am Main, Germany

Received: 29 May 2012 / Revised: 27 July 2012
Published online: 27 November 2012 – © Societ`a Italiana di Fisica / Springer-Verlag 2012
Communicated by T. B´ir´o

Abstract. A status report on the jet quenching physics in heavy-ion collisions is given as it appears after more than 10 years of collecting and analysing data at the Relativistic Heavy Ion Collider (RHIC) and ∼1.5 years of physics at the Large Hadron Collider (LHC). The (theoretical) predictions and expectations before the start of the LHC program are contrasted with the most recent experimental results, focussing on the nuclear modification factor $R_{AA}$, the elliptic flow $v_2$ of high-$p_T$ particles, and on the problem of initial conditions.

1 Introduction

In the year 2000, the physics program of the Relativistic Heavy Ion Collider (RHIC) started. For the first time, p+p, d+Au, and Au+Au collisions could be studied at identical centre-of-mass energies from 19.6 to 200 GeV using the same detectors, BRAHMS, PHENIX, PHOBOS, and STAR.

The success of the RHIC program is mainly based on the fact that the results obtained by the four experiments, summerized in a series of so-called white papers [1–4], are in remarkable agreement with each other.

The main observations include: fast thermalization (indicated by a strong elliptic flow) [5, 6], low viscosity of the medium produced (suggesting that it behaves like a “nearly ideal fluid”) [7–9], jet quenching (implying the creation of a dense and opaque system) [10,11], strong suppression of the high-$p_T$ heavy-flavour mesons (the “heavy-quark puzzle”) [12,13], and direct photon emission at high transverse momenta (confirming the scaling behaviour of hard processes) [14].

However, after more than 10 years of RHIC physics, some fundamental questions still need to be clarified. What are the initial conditions of a heavy-ion collision? Is the medium created weakly or strongly coupled? What is the process of fragmentation?

Two observables characterizing the medium are promising tools to help resolving these questions:

- The nuclear modification factor, $R_{AA}(p_T)$, parameterizes the jet suppression and is defined as the ratio of jets produced in A+A collisions to the expectation for jets created in p+p collisions

$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{N_{coll}dN_{pp}/dp_T}. \quad (1)$$

Here, $N_{coll}$ is the number of binary collisions, a theoretical parameter that depends on the centrality of the collision and has to be calculated using a model describing the initial conditions.

- The elliptic flow $v_2$, defined as the second Fourier coefficient of the azimuthal particle emission,

$$\frac{dN}{p_T dp_T dy d\phi} = \frac{1}{2\pi p_T d^2 p_T dy} \times \left[ 1 + 2 \sum_{n=1}^{\infty} v_n(p_T, y, b) \cos(n\phi) \right], \quad (2)$$

signals the creation of a medium whose expansion is determined by density gradients.

With the start of the Pb+Pb program at the Large Hadron Collider (LHC) in November 2010 a new era began in the field of heavy-ion collisions. First results offered some surprises: While the center-of-mass energy per nucleon increases by a factor of ten as compared to RHIC energies and the particle multiplicity raises by a factor of $\sim 2$ [15–17], corresponding to a 30% increase of the temperature, the magnitude of the elliptic flow is similar to the results obtained at RHIC [18–20]. Moreover, also the magnitude of jet quenching is surprisingly similar to RHIC for particles with $p_T > 10$ GeV$^1$ [21, 22].

$^1$ Throughout this paper, natural units are applied with $c = \hbar = 1$. 

---

*e-mail: betz@th.physik.uni-frankfurt.de"
In the light of these results, a status report on the jet quenching physics in heavy-ion collisions shall be given. This report is not meant to review the underlying physics processes but to contrast the (theoretical) predictions and expectations before the start of the LHC program with the most recent experimental results.

The physics of jet quenching in heavy-ion collisions has many aspects and is explored from several different angles. While both experiment and theory investigate dijet imbalance [23–28], γ-jet imbalance [29–32] and fragmentation functions [29,33,34], the focus of this report is on the initial conditions, the nuclear modification factor $R_{AA}(p_T)$, and the elliptic flow $v_2$ of high-\textit{p}_T particles since those observables already contain quite some information about the physical processes.

2 Parton energy loss and initial conditions

The jet energy loss in heavy-ion collisions can either be described as multiple scatterings of the parton [35–40], specific for a weakly coupled perturbative QCD (pQCD) medium, or using the string-theory inspired Anti-deSitter/Conformal Field Theory (AdS/CFT) correspondence [41]. For the latter, the mathematical description of a parton stopped in a thermal medium is related to a string falling$^2$ into a 5-dimensional black hole [42–46].

One of the interesting open questions is if either paradigm of a weakly or a strongly coupled medium can account for both RHIC and LHC observables. However, as shown in eq. (1), the nuclear modification factor also depends on the initial conditions via the number of binary collisions. Two models are commonly used to describe those initial conditions. The Glauber model [47] applies incoherent superpositions of p+p collisions while the “Color Glass Condensate” (CGC) [48,49], given, e.g., by the Kharzeev-Levin-Nardi (KLN) model [50–54], takes saturation effects into account. Both models were shown to reproduce RHIC results and exhibit large event-by-event fluctuations [55–58]. However, they differ by their initial temperature gradients, their initial high-\textit{p}_T parton distribution, and the distance travelled by each parton. Thus, Glauber and CGC initial conditions should lead to a different opacity estimate and different magnitudes of the nuclear modification factor, motivating a particular interest in the nuclear modification factor that might convey information about both the initial conditions and the jet-medium coupling.

One of the first results of the heavy-ion program at the LHC [15], the magnitude of the particle multiplicity, indicated that the CGC initial conditions are disfavoured. However, a more recent work on CGC initial conditions [59,60] shows that the centrality dependence of the hadron multiplicity both at RHIC and LHC is reproduced quite well if either $k_T$ factorisation is used or a formalism is applied that is based on the Balitsky-Kovchegov equations [61,62] and includes the running-coupling corrections. Moreover, it was shown in ref. [63] that quantum fluctuations of color charges in a CGC-Glasma lead to higher moments of eccentricities $[e_\eta \sim v_n \text{ in eq. } (2)]$ that are in remarkable agreement with results based on the Glauber model.

Naturally, the differences in the initial conditions should not only be given in A+A but also in p+A collisions. Since the proper description of the initial conditions is still an open problem both at RHIC and LHC, the p+Pb runs at the LHC that are scheduled for 2012 still have the potential of being a critical control experiment.

However, so far the predictions concerning the suppression in those p+Pb collisions, that are parametrised by a suppression factor $R_{p+Pb}$, differ drastically. While it was shown in ref. [64] that the $R_{p+Pb}$ might allow for a clear disentangling of Glauber vs. CGC initial conditions, ref. [59] identified a certain specification of CGC initialisation for which a disentangling between different types of initial conditions based on experimental data from the LHC will be impossible.

3 RHIC results and LHC predictions

Figure 1 displays the nuclear modification factor of direct photons, charged hadrons, pions, and $\eta$-mesons at RHIC energies. The photon $R_{AA}(p_T > 4 \text{ GeV})$ ≥ 1 is considered as proof that the direct photons measured do not interact with the medium created and can thus be used as direct

![Image](image_url)
probes of the medium. On the other hand, the hadron suppression of $R_{AA}(p_T) \sim 0.2$ indicates a rather strong jet-medium interaction that is similar for different particle species (charged hadrons, pions, and $\eta$-mesons) and stays nearly flat up to $p_T = 20$ GeV.

One of the main questions in jet physics before the start of the LHC was if this $R_{AA}(p_T)$ will stay flat or increase for larger $p_T$ and if this behaviour would allow to disentangle a weakly coupled pQCD from a strongly coupled AdS medium.

Figure 2 displays a synopsis of the $R_{AA}(p_T)$ at different energies [36, 72] applying the GLV formalism, ranging from the Super Proton Synchrotron (SPS) to the LHC, basically summarizing the results and predictions for the nuclear modification factor of pions based on pQCD calculations [37, 38, 72–90]. While the Cronin enhancement [91] dominates at SPS, shadowing and jet quenching cause a flat suppression pattern out to the largest $p_T$ at RHIC. For LHC energies however, the $R_{AA}(p_T \sim 10$ GeV) is smaller than the one at RHIC but rises for larger $p_T$. At those large transverse momenta ($p_T \gtrsim 10$ GeV) the nuclear modification factor is completely dominated by the jet energy loss that depends on the particle multiplicity produced at LHC.

While the nuclear modification factor at RHIC for light particles (e.g., pions) is in remarkable quantitative agreement with the measured data (see figs. 1, 2, and refs. [72, 73, 77, 78, 80–85, 87]), the quenching of heavy quarks is significantly underpredicted [92–94], an effect closely connected to the “heavy-quark puzzle”. In contrast to theoretical predictions, the nuclear modification factor measured for heavy quarks suggests that the magnitude of the energy loss for heavy quarks is similar to that of light quarks.

However, such a heavy-quark energy loss can be determined using the AdS/CFT correspondence [95–104] which also allows to explain the small viscosity to entropy ratio $\eta/s$ of the “nearly perfect fluid” [105] at RHIC. This success motivated the application of string theory inspired models to the nuclear collision phenomenology, even though the AdS/CFT correspondence between string theory, conformal Supersymmetric Yang-Mills (SYM) gauge theory, and non-conformal QCD is still debated. Unfortunately, the AdS/CFT-based approaches for light-quark energy loss are much more complicated than for heavy quarks [46, 106], limiting their application to heavy-ion phenomenology.

Using those AdS/CFT-based models to calculate the heavy-quark energy loss, the $R_{AA}(p_T)$ flattens at LHC energies as compared to RHIC energies (see fig. 3). Thus, it was assumed that the slope of the nuclear modification factor as a function of $p_T$ could be an indicator for a pQCD weakly coupled vs. an AdS/CFT-like strongly coupled energy loss prescription.

It should be stressed here that a recent work on falling string energy loss [46] has identified important corrections to the original works [42, 43] and indicates that also an AdS/CFT-like strongly coupled energy loss prescription could lead to an increasing $R_{AA}(p_T)$.

One model that allows to test a weakly vs. a strongly coupled jet-medium interaction is the analytic geometric absorption model introduced in refs. [107–109] that can also be used to investigate Glauber vs. CGC initial conditions. For this model, the energy loss per unit length, $dE/dx = dP/d\tau$

$$\frac{dP}{d\tau}(x_0, \phi, \tau) = -\kappa \rho(\phi)\tau^z \tau^{c-(z-a)+2}|x_+|^{\tau},$$  

(3)

given is as a function of proper time $\tau$ for a fixed jet rapidity $y$. The energy loss per unit length is characterized by the three exponents ($a, z, c$) that determine the jet momentum dependence $P_\perp$, the path-length dependence $\tau^z$, and the local temperature power dependence $\tau^{c-(z-a)+2}$ in terms of the t’Hooft coupling at large $N_c$ in case of gravity-dual holography which allows to quantify the magnitude of the jet-medium coupling at RHIC vs. LHC [109]. $T(x, \tau)$ is the local temperature field of the QGP.

In the Bethe-Heitler limit $a = 1$ and $z = 0$, while in the heavy-Lundau-Pomeranchuk-Migdal (LPM) [110, 111] pQCD limit $a \sim 0$ and $z \sim 1$, if $a = 1$ and $z = 2$, eq. (3) coincides with the model referred to as “AdS/CFT” in ref. [112] while the heavy-quark string drag energy loss of conformal AdS holography [42, 43] is depicted by $a = 1, z = 0$.

The scenario with $a = 1/3$ and $z = 1$ describes approximately both the pQCD and the AdS/CFT falling
The ratio of a charm to a bottom nuclear modification factor as a function of $p_T$ for RHIC (left panel) and LHC energies (right panel), comparing a pQCD vs. an AdS/CFT-inspired model fixing either the t’Hooft coupling $\lambda$ or the momentum diffusion coefficient $D = 2/\sqrt{\lambda \pi T}$ [103]. The (yellow and orange) bands display the cumulative uncertainties. The additional lines on the right-hand side correspond to different implementations of the initialization and the energy loss. For details, see ref. [103].

Fig. 3.

string cases [42, 43]. An $(E/T)^{1/3}$ energy dependence is numerically similar to the $\log(E/T)$ dependence predicted by fixed coupling pQCD energy loss in the range $10 < E/T < 600$ relevant both at RHIC and LHC energies. This power law is also predicted to be the lower bound of the power $a$ in the falling-string scenario in an AdS/CFT conformal holography [46].

While it has widely been assumed that varying $z = 1$ to $z = 2$ allows to interpolate between the weakly and strongly coupled dynamical limits [42–45, 108, 109, 112–114], the recent work of ref. [46] indicates that the necessary corrections to refs. [42, 43] reduce the path-length power law dependence from $z = 2$ back to $z \approx 1$. Parametrically, this would make pQCD and AdS/CFT descriptions virtually indistinguishable for light jets.

Applying ideal boost-invariant Bjorken hydrodynamics [115] and a uniform static plasma brick of thickness $L$, the nuclear modification factor for a final momentum $p_f$ is given by [107]

$$R_{AA}(p_f) \approx 1 + \kappa \frac{(dN/dy)^{2-\alpha+3/3}}{(L p_f)^{2-\alpha}} \frac{n(n(p_f))}{n} ,$$

which allows to directly access the spectral index $n(p_f)$. The only parameter $\kappa$ needs to be determined by a fit to a reference point usually chosen to be $R_{AA}(p_T \sim 10 \text{ GeV})$ [107,109].

Considering an energy loss with $a = 1/3$ and $(z \in [1,3])$, the generic absorption model of eq. (4) leads to an increase in the slope of the $R_{AA}(p_T)$ for LHC as compared to RHIC energies (see fig. 4) [107], in line with the early pQCD calculations [72], if a reduced spectral index $n(p_f)$ is assumed at the LHC. Moreover, fig. 4 shows that an increasing opacity (i.e. a larger value for the path-length dependence $z$) as well as a larger density at the LHC cause a lowering of the nuclear modification factor that actually falls below the $R_{AA}^{RHIC}(10 \lesssim p_T \lesssim 20 \text{ GeV})$.

Fig. 4.

4 First results from the LHC

First experimental results on the nuclear modification factor at LHC energies showed (see fig. 5) that the $R_{AA}$ increases with $p_T$, as originally proposed by pQCD [72, 86–89, 103] and recently also suggested for a revised AdS/CFT-inspired string model [46]. Moreover, the $R_{AA}(p_T)$ decreases with centrality and has a minimum at $p_T \sim 6–7 \text{ GeV}$.

However, while the nuclear modification factor at LHC energies for $p_T < 10 \text{ GeV}$ is significantly below the values at RHIC energies [21,22] (cf., e.g., the right panel of fig. 5), RHIC and LHC results for the $R_{AA}(p_T)$ are in remarkable agreement for $p_T > 10 \text{ GeV}$ [22].

This “surprising transparency” [107] contradicts LHC predictions based on density-dependent energy loss models [107–109, 116, 117], including GLV [36], ASW [95], PQM [118], and YaJEM [87,119]. Those models under-
Fig. 5. The nuclear modification factor at LHC energies as a function of $p_T$ for different centralities (left panel) [21] and compared to earlier results for lower energies at SPS and RHIC (right panel) [22].

Fig. 6. The nuclear modification factor as a function of $p_T$ at LHC energies as measured by the ALICE Collaboration compared to different theoretical models [21].

predict the measured data as seen in the right panel of figs. 5 as well as in fig. 6.

To solve this puzzle, different approaches are chosen, considering, e.g., different densities for RHIC and LHC [88,117], or adding an escape probability of a parton without any medium interaction (YaJEM-D) [87]. Other recent studies [109, 120, 121], including one based on the generic energy loss introduced in eq. (3) for $\alpha = 1/3$ and $z = 1$, showed that a plausible moderate reduction of the pQCD coupling ($\kappa \propto \alpha_s$ in eq. (3)) due to slow running (creeping) of the coupling above the deconfinement temperature at LHC leads to a better description of the data as shown in fig. 7.

However, considering a falling-string scenario the effective reduced jet-medium coupling $\kappa \propto \sqrt{\lambda}$ would imply a rather large reduction of $\lambda_{\text{LHC}}$ by a factor $\sim 2–4$ relative to RHIC [109]. It is not yet clear if current non-conformal holographic models are consistent with such a strong variation (see, for example, refs. [104, 122]), suggesting that pQCD-based models might be favoured. Complementary to those results, the analysis for jet asymmetry and energy imbalance [23,26], as done, e.g., using MARTINI [27], will provide further constraints on the jet-medium coupling.

The advantage of the above-mentioned generic absorption model (dE/dx = $-\kappa E^ax^zT^c$) [109] introduced in sect. 3 is that it can not only analytically interpolate between weakly coupled tomographic and strongly coupled...
holographic jet energy loss models but also easily mimic different prescriptions for the energy dependence. An important result is that the class of geometric optics models with $a = 1$, that had been very successful in describing the RHIC data [112,114], has to be excluded at the LHC since it does not reproduce the $p_T$-dependence of the nuclear modification factor at LHC [109].

5 Open questions

While LHC data seem to suggest that pQCD tomography is either favoured over AdS/CFT holography for $p_T > 10$GeV or might even be indistinguishable from string inspired models for light quarks [46,109], there are still open puzzles for both pQCD tomography and AdS/CFT holography, including the intermediate to high-$p_T$ elliptic flow [109,127] and the heavy-quark jet quenching [12,13,94,123,124].

Reference [123] shows that leading-order AdS/CFT holography with a common large t’Hooft coupling of $\lambda \sim 20$–30 may simultaneously describe the elliptic flow of bulk hadrons as well as the nuclear modification factor of heavy-quark jet fragments. But it also predicts a much stronger suppression for charm particles. However, including dynamical multi-scattering in the pQCD-based GLV model [117], this oversuppression is compensated. This might help solve the heavy-quark puzzle. It should be stressed that among the models computing both, the three holovraphy is either favoured over AdS/CFT holography for $p_T > 10$GeV as well as with the upcoming analyses of already collected experimental data. A crucial test for all present theoretical models of jet energy loss will be the release of data with $p_T > 60$GeV.

The author acknowledges support from the Alexander von Humboldt foundation and thanks M. Gyulassy, G. Torrieri, J. Noronha, A. Buzzatti, A. Ficnar, W. Horowitz, J. Jia, J. Liao, and G. Roland for fruitful discussions.

References

1. BRAHMS Collaboration (I. Arsene et al.), Nucl. Phys. A 757, 1 (2005).
2. PHENIX Collaboration (K. Adcox et al.), Nucl. Phys. A 757, 184 (2005).
3. B.B. Back et al., Nucl. Phys. A 757, 28 (2005).
4. STAR Collaboration (J. Adams et al.), Nucl. Phys. A 757, 102 (2005).
5. J.-Y. Ollitrault, Phys. Rev. D 46, 229 (1992).
6. P.F. Kolb, J. Sollfrank, U.W. Heinz, Phys. Lett. B 459, 607 (1999).
7. M. Gyulassy, L. McLerran, Nucl. Phys. A 750, 30 (2005).
8. E. Shuryak, Prog. Part. Nucl. Phys. 53, 273 (2004).
9. P. Romatschke, U. Romatschke, Phys. Rev. Lett. 99, 172301 (2007).
10. M. Gyulassy, M. Plumer, Phys. Lett. B 243, 432 (1990).
11. X.N. Wang, M. Gyulassy, Phys. Rev. Lett. 68, 1480 (1992).
12. PHENIX Collaboration (S.S. Adler et al.), Phys. Rev. Lett. 96, 032301 (2006).
13. STAR Collaboration (J. Biedcik), Nucl. Phys. A 774, 697 (2006).
14. PHENIX Collaboration (S.S. Adler et al.), Phys. Rev. Lett. 94, 232301 (2005).
15. ALICE Collaboration (B. Abelev et al.), Phys. Rev. Lett. 105, 252301 (2010).
16. ATLAS Collaboration (G. Aad et al.), Phys. Lett. B 710, 363 (2012).
17. CMS Collaboration (S. Chatrchyan et al.), JHEP 08, 141 (2011).
18. The ALICE Collaboration (K. Aamodt et al.), Phys. Rev. Lett. 105, 252302 (2010).
19. ATLAS Collaboration (G. Aad et al.), Phys. Lett. B 707, 330 (2012).
20. CMS Collaboration (S. Chatrchyan et al.), arXiv:1204.1409 [nucl-ex].
21. ALICE Collaboration (J. Otwinowski), J. Phys. G 38, 124112 (2011).
22. CMS Collaboration (S. Chatrchyan et al.), Eur. Phys. J. C 72, 1945 (2012).
23. Atlas Collaboration (G. Aad et al.), Phys. Rev. Lett. 105, 252303 (2010).
24. CMS Collaboration (S. Chatrchyan et al.), Phys. Rev. C 84, 024906 (2011).
25. CMS Collaboration (S. Chatrchyan et al.), Phys. Lett. B 712, 176 (2012).
26. G.-Y. Qin, B. Muller, Phys. Rev. Lett. 106, 162302 (2011).
27. C. Young, B. Schenke, S. Jeon, C. Gale, Phys. Rev. C 84, 024907 (2011).
28. T. Renk, arXiv:1204.5572 [hep-ph].
29. ALICE Collaboration (A. Morsch), J. Phys. G 38, 104167 (2011).
30. H. Zhang, J.F. Owens, E. Wang, X.-N. Wang, Nucl. Phys. A 830, 443C (2009).
31. ATLAS Collaboration, ATLAS-CONF-2011-031.
32. CMS Collaboration (S. Chatrchyan et al.), arXiv:1205.0206 [nucl-ex].
33. ATLAS Collaboration (G. Aad et al.), Eur. Phys. J. C 71, 1795 (2011).
34. CMS Collaboration (Y. Yilmaz), J. Phys. G 38, 124157 (2011).
110. L.D. Landau, I. Pomeranchuk, Dokl. Akad. Nauk Ser. Fiz. 92, 535 (1953).
111. R. Baier, Y.L. Dokshitzer, S. Peigne, D. Schiff, Phys. Lett. B 345, 277 (1995).
112. J. Jia, R. Wei, Phys. Rev. C 82, 024902 (2010).
113. J. Jia, W.A. Horowitz, J. Liao, Phys. Rev. C 84, 034904 (2011).
114. PHENIX Collaboration (A. Adare et al.), Phys. Rev. Lett. 105, 142301 (2010).
115. J.D. Bjorken, Phys. Rev. D 27, 140 (1983).
116. B.G. Zakharov, JETP Lett. 93, 683 (2011).
117. A. Buzzatti, M. Gyulassy, Phys. Rev. Lett. 108, 022301 (2012).
118. A. Dainese, C. Loizides, G. Paic, Eur. Phys. J. C 38, 461 (2005).
119. T. Renk, Int. J. Mod. Phys. E 20, 1594 (2011).
120. S. Pal, M. Bleicher, Phys. Lett. B 709, 82 (2012).
121. A. Buzzatti, M. Gyulassy, arXiv:1207.6020 [hep-ph].
122. M. Mia, K. Dasgupta, C. Gale, S. Jeon, J. Phys. G 39, 054004 (2012).
123. J. Noronha, M. Gyulassy, G. Torrieri, Phys. Rev. C 82, 054903 (2010).
124. M. Djordjevic, J. Phys. G 32, S333 (2006).
125. ALICE Collaboration, arXiv:1203.2160 [nucl-ex].
126. R. Sharma, I. Vitev, B.-W. Zhang, Phys. Rev. C 80, 054902 (2009).
127. W.A. Horowitz, M. Gyulassy, J. Phys. G 38, 124114 (2011).