Theoretical Progress in Heavy-Ion Collisions

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I will review some recent theoretical developments on ultrarelativistic heavy-ion collisions motivated by the experimental findings at the Relativistic Heavy Ion Collider and their standard explanations. Specifically, I will discuss the recent ideas about the nuclear wave function and the initial stage of a heavy-ion collision, the collective behavior, and the suppression of high transverse momentum particles and jets.

1 Introduction

Ultrarelativistic heavy-ion collisions is an interdisciplinary field, whose ultimate goal is the understanding of confinement and chiral symmetry breaking in Quantum Chromodynamics (QCD) through the creation of deconfined chiral-symmetric matter in the laboratory. As suggested by asymptotic freedom, such state of matter can be achieved by increasing the temperature of a strongly interacting system, and it is expected to appear in high-energy collisions between heavy nuclei and to form the so-called Quark-Gluon Plasma.

This is the write-up of a plenary talk [1] at DIS 09, complementary to that on experimental aspects by David d'Enterría [2]. I will cover some selected topics on recent theoretical developments in heavy ion collisions: the nuclear wave function and the initial stage of a heavy-ion collision, the collective behavior, and high transverse momentum particle production and jets. I refer the reader to the volumes of the series *Quark-Gluon Plasma*, particularly to vol. 4 to appear this year [3] or to the recent reviews [4], for further information and references.

As a motivation, let me remember that experiments at the Relativistic Heavy Ion Collider (RHIC) at BNL claim [5] the creation of partonic matter with energy density in excess to that required in lattice QCD for the transition from confined to deconfined matter, with large coherence in soft particle production, very early behaving like a quasi-ideal fluid and extremely opaque to energetic partons traversing it. These three interpretations come from the observation of a multiplicity much lower than pre-RHIC expectations, the success of ideal hydrodynamics in describing the measured azimuthal anisotropy in particle production, and the strong suppression of the yield of high-p_T particles compared to expectations (jet quenching), respectively. The recent theoretical developments on these three aspects will be the subjects of this review.

For the sake of fixing some notation, I will talk of the *medium* as those particles with momenta around the average particle momentum (which would be the temperature if thermodynamical equilibrium were achieved), and of *hard probes* as those observables whose production in the absence of any medium (i.e. in *vacuum*) is computable using perturbative QCD techniques (pQCD) and whose medium modification characterizes it. Besides, let me note that at variance with other fields in high-energy physics, here the space-time evolution

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has to be considered, as there will be an interplay between the usual evolution (momentum) variables and the dimensions and dynamical development of the medium.

Finally, my quotation of existing work will rely heavily on a few reviews and papers, being impossible in this short space to make reference to the full existing work done on the different subjects. I apologize in advance to those whose work is insufficiently quoted.

2 Initial conditions

Nuclear modifications will be characterized by the so-called nuclear modification factor, defined as

$$R([p]) = \frac{f_A([p])}{K_{incoh} \times f_N([p])}\,, \tag{1}$$

with $[p]$ denoting the kinematical or geometric (i.e. collision centrality or impact parameter) variables characterizing the collision, f_A the measurement of a given quantity (e.g. F_2, parton density or yield of particles) in a collision involving nuclei, f_N the corresponding measurement in a hadron (nucleon) collision, and K_{incoh} the factor which scales f_N to f_A considering that the nuclear collision is a totally incoherent superposition of nucleon collisions. Thus, $R = 1$ signals the absence of nuclear effects.

2.1 Nuclear wave function

Global analysis of nuclear parton densities to DIS, Drell-Yan and hadron-nucleus data, using LO and NLO DGLAP evolution equations and including error analysis through the Hessian method exist, see the most recent one in [6]. A comparison of the nuclear modification factors for valence, sea and glue in the most recent analysis, including the error analysis using the Hessian method, is shown in Fig. 1.

As evident from this plot, the lack of experimental lepton-nucleus data at small x relevant for the LHC ($x \sim 10^{-4}$ for $Q^2 \sim 10$ GeV^2, see e.g. [9]) results in very large uncertainties for the sea and gluon parton densities at low Q^2. As expected, DGLAP evolution decreases the uncertainties with increasing Q^2.

On the other hand, at small $x < (2m_N R_A)^{-1}$, with m_N the nucleon mass and R_A the hadron radius, the interaction of photon fluctuations with the hadron occurs in the totally coherent regime. The most striking phenomenon in this region is geometric scaling, originally observed for inclusive ep scattering and then extended to diffractive scattering and for eA collisions [10]. In Fig. 2 we show the corresponding scaling curves for inclusive ep and eA. The saturation scale extracted from such studies behaves like $Q_s^2 \propto x^{-\lambda} A^{\beta}$, with $\lambda \simeq 0.2 \div 0.3$ and $\beta \simeq 1/3 \div 4/9$. While the framework in which a saturation scale appears in a natural way is saturation physics, other explanations cannot be ruled out e.g. DGLAP shows a scaling behavior for $Q^2 > 5$ GeV^2.

The Color Glass Condensate offers a perturbative realization of saturation. Its mean field approximation is the Balitsky-Kovchegov (BK) equation, a non-linear evolution equation in $\ln 1/x$ whose linear limit is BFKL. It has been shown that BK evolution leads to geometric scaling for any physically motivated initial condition, providing a dynamically generated saturation scale. It has been recently generalized to include running coupling effects [11]. With them, the BK equation provides a framework suitable for describing DIS data in the low-x region [12]. Reports on on-going work to generalize the BK equation beyond its

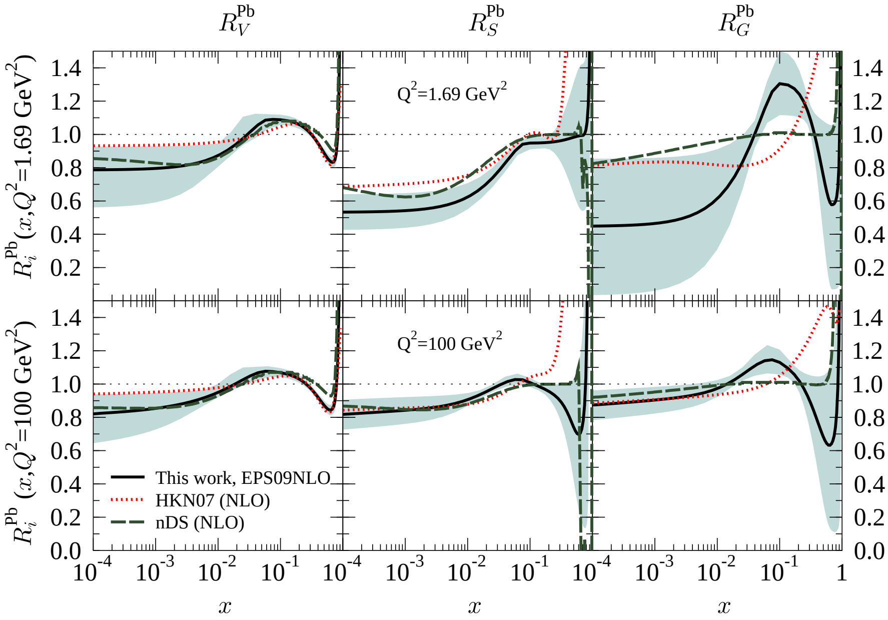

Figure 1: Comparison of the average valence and sea quark, and gluon modifications at $Q^2 = 1.69\,\mathrm{GeV}^2$ and $Q^2 = 100\,\mathrm{GeV}^2$ for Pb nucleus from the NLO global DGLAP analyses HKN07 [7], nDS [8] and EPS09NLO [6]. The shaded band corresponds to the error analysis through the Hessian method in EPS09NLO. Figure taken from [6].

original derivation of scattering of a dilute projectile on a dense target (pomeron loops) and to check the accuracy of the mean field approximation can be found in [13].

2.2 Factorization

Using k_T-factorization, implications of geometric scaling on particle production in hadron-nucleus and nucleus-nucleus have been explored (third paper in [10] and [14]) and found to be in agreement with experimental data. But the status of factorization itself is still an open question. Different groups have analyzed one-, two- and multiple parton production at high energies in different languages (see [15] and references therein): in momentum space in the BFKL language, in the dipole model, in classical gluodynamics through an expansion in projectile and target densities, in a hadron wave function language,...

The conclusion, though still subject to some debate, is that some k_T-like factorization (with unintegrated gluon distributions evolved according to BK) holds for DIS on nuclei or hadron-nucleus collisions (the dilute-dense situation) for one-gluon inclusive production, but not for two-gluon or quark production or for nucleus-nucleus (i.e. dense-dense) collisions. Factorized expressions have been obtained for many parton production, but in a functional form whose translation to formulae considering some kind of parton densities looks extremely involved.

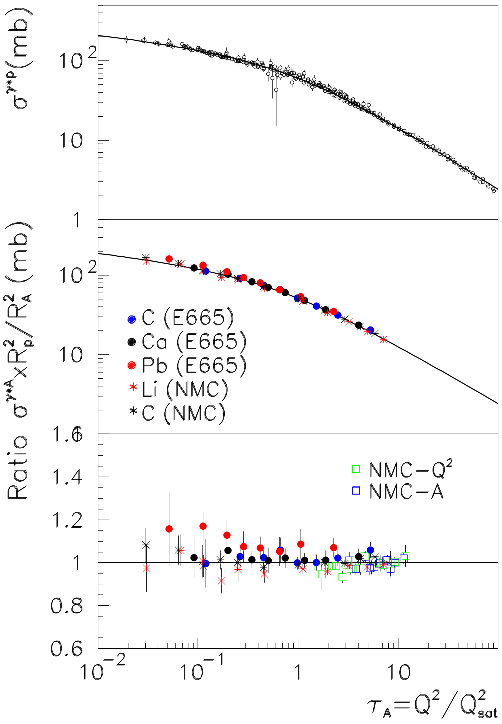

Figure 2: Geometric scaling for $\gamma^* p$ (upper panel), $\gamma^* A$ (middle panel) and the ratio of data for $\gamma^* A$ divided by the scaling curve (lower panel). (In the two upper plots, the units in the vertical axis should read μb, not mb.) Figure taken from the third paper in [10], see there the corresponding references.

3 Collective behavior

3.1 Elliptic flow

The azimuthal dependence of particle production is usually characterized through a Fourier decomposition:

$$\frac{dN_k}{dy dp_T^2 d\phi} = \frac{dN_k}{dy dp_T^2} \frac{1}{2\pi} \left[1 + 2v_1(y, p_T) \cos(\phi - \phi_R) + 2v_2(y, p_T) \cos 2(\phi - \phi_R) + \ldots \right], \quad (2)$$

with ϕ_R a reference azimuthal angle defined by the collision axis and the impact parameter vector (the so-called reaction plane). The first coefficient v_1 vanishes at mid-rapidity for symmetric collisions. The second one, v_2, called elliptic flow, is found to take large values (order 10%) for semi-central nucleus-nucleus collisions (i.e. with non-vanishing impact parameter) at RHIC [3, 5]. It shows some dependence on the particle species which can be scaled out considering the number of constituent quarks in the corresponding hadron. With soft particle production expected to be isotropic in azimuth (but for statistical fluctuations), this sizable elliptic flow is a signal of collective effects: the initial space anisotropy in a non-central collision translates into a final momentum anisotropy.

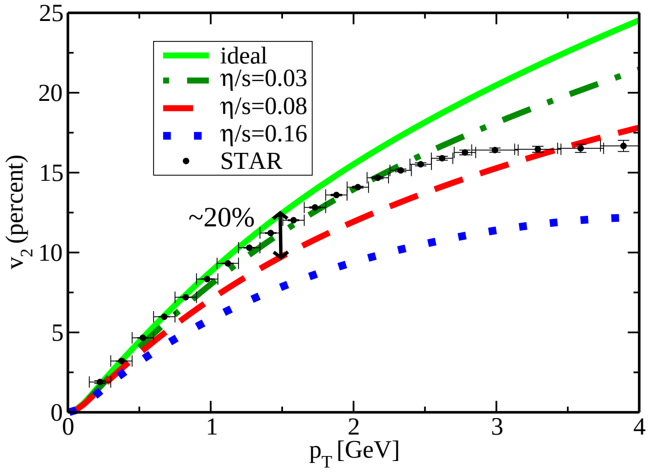

Figure 3: Reduction of elliptic flow coefficient due to shear viscosity. Figure from [16].

3.2 Hydrodynamical modeling

Data on elliptic flow are well reproduced using ideal relativistic hydrodynamics, see [3] and [16] for a recent review. Ideal relativistic hydrodynamics is the relativistic generalization of the Euler equation for fluid mechanics:

$$\partial_\mu T^{\mu\nu}_{(0)} = 0, \quad T^{\mu\nu}_{(0)} = \epsilon\, u^\mu u^\nu - p\, (g^{\mu\nu} - u^\mu u^\nu)\,, \tag{3}$$

with ϵ the energy density, p the pressure and u^μ the local fluid velocity. With M conserved quantities, we have a set of $5+M$ variables with $4+M$ equations which can be solved considering an equation of state, some initial conditions and a prescription to project the fluid onto hadrons. Ideal hydrodynamics has been very successful in describing particle spectra at low p_T and elliptic flow.

Small deviations from the perfect equilibrium that ideal hydrodynamics requires can be dealt with by including viscous corrections,

$$T^{\mu\nu} = T^{\mu\nu}_{(0)} + \Pi^{\mu\nu}, \tag{4}$$

with $\Pi^{\mu\nu}$ the viscous stress tensor that includes the contributions to $T^{\mu\nu}$ stemming from dissipation. The inclusion of viscous corrections is still an open problem. At first order in the gradients of u^μ (the relativistic counterpart of the Navier-Stokes equation), the theory contains two coefficients: bulk and shear viscosity. At second order, the theory complicates substantially and the number of coefficients grows; for a conformal field theory, its number is five (plus bulk viscosity). Numerical solutions for different approximations to second order viscous hydrodynamics indicate that only a small shear viscosity (no bulk viscosity is presently included in the numerical codes) is compatible with data, see Fig. 3.

Although uncertainties remain on the initial conditions for hydrodynamical evolution and on the implementation of viscous corrections, the common conclusion of hydrodynamical studies is that the collective behavior of the medium created at RHIC can be reproduced by quasi-ideal hydrodynamics which has to be initialized very early (at times < 1 fm/c) for the initial space anisotropy to generate the observed momentum anisotropy: the medium at RHIC behaves like a quasi-ideal fluid which has nearly equilibrated extremely fast.

3.3 Strong coupling calculations

The need of strong coupling calculations to describe some aspects of ultrarelativistic heavy ion collisions is suggested by: The success of ideal hydrodynamics, which requires a mean free path $\lambda = (\rho\sigma)^{-1} \ll R$ with R the size of the system, ρ its density and σ the typical cross section of the particles in the medium; The early thermalization or isotropization required for the development of the collective behavior, which is very difficult to explain within pQCD (see e.g. [17] and references therein); The strong quenching of energetic particles in the medium, see the next Section.

Nowadays the most popular technique to deal with strongly coupled field theories is the AdS/CFT correspondence [18], see the reviews [3, 4, 19]. The correspondence allows to compute the dynamics of $\mathcal{N} = 4$ super-symmetric QCD for $N_c, \lambda = g^2 N_c \to \infty$ using classical gravity in a ten-dimensional space with an $\text{AdS}^5 \times \text{S}_5$ metric. One of the coordinates of the AdS^5 acts as an holographic coordinate and the Minkowski, field theory space lies at the boundary of the AdS^5. A precise recipe exists for computing expectation values of operators on the super-symmetric QCD side by knowing the partition function on the string theory side in ten dimensions, which in the limits indicated before amounts to classical gravity calculations in AdS^5. Temperature can be included introducing a back hole metric.

Though $\mathcal{N} = 4$ super-symmetric QCD is not QCD (no running coupling, no confinement, no fundamental matter, no chiral symmetry breaking,. . .), none of these features is expected to be present in QCD at temperatures a few times above the deconfinement temperature, and extensions of the correspondence are under development to consider field theories closer to QCD. In any case, the correspondence allows for a laboratory in which many problems, non-tractable by lattice techniques, can be attacked from first principles. For example, it has been used to explain the energy loss of fast and slow partons, the energy deposition from a fast parton in the medium, DIS at strong coupling [20] and the initial conditions for a heavy ion collision: the early thermalization or isotropization, and the hydrodynamical behavior [16, 21].

4 Hard probes: high-p_T particles and jets

The observation at RHIC that the nuclear modification factor for hadrons was much smaller than one in central AuAu collisions, and that there was a strong suppression (or even disappearance, compared to pp) of the yield of particles with opposite azimuth to a high-p_T one, constituted one of the strongest evidences of high-density partonic matter created in the collisions [5]. This phenomena are commonly referred to as jet quenching, and its explanation given in terms of energy loss of the partons traveling through the medium. At large parton energies, radiative energy loss (i.e. medium-induced gluon radiation) is expected to be the dominant energy loss mechanism. I will comment in the rest of this Section about its successes, failures and limitations, and how to overcome them [3, 4].

4.1 Successes and problems in radiative energy loss

The change in the radiation pattern off a parton in a medium is determined by the interplay between emission and rescattering of both the parent parton and its descendants, see Fig.

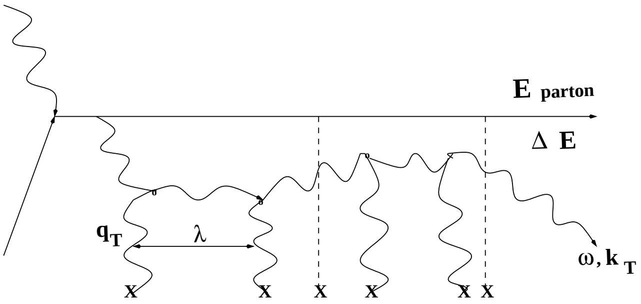

Figure 4: Mechanism of medium-induced gluon radiation, with the crosses representing scattering with medium constituents. Figure taken from the first paper in [4].

4. When squaring this amplitude, terms for emission in the vacuum both in amplitude and in its complex conjugate which correspond to the standard DGLAP splitting functions, and medium-medium and interference vacuum-medium terms, appear. All information about the medium comes through two pieces of information: the cross section for rescattering times the density of the medium, usually encoded in the transport coefficient $\hat{q}$ (squared transverse momentum transferred from the medium to the parton per mean free path), and the medium geometry (length, dynamical expansion,. . .), see the reviews [3, 4].

Radiative energy loss has been very successful in describing the suppression of one-particle inclusive distributions and the modifications in the backward peak for light hadrons, see [4] and [22] and references therein. This success is illustrated in Fig. 5.

On the contrary [23], data on the nuclear suppression factor of non-photonic electrons (i.e. electrons whose origin is attributed to the semileptonic decay of heavy flavors) are overestimated by scenarios of radiative energy loss. It is an unambiguous prediction of radiative energy loss that gluons will lose, due to their color representation, more energy than light quarks which in turn will lose more energy than massive quarks (the latter fact parallels the dead cone effect in standard parton cascades from massive quarks). This is not seen in data which show a suppression for non-photonic electrons roughly as large as that measured for light hadrons, see Fig. 6. While many alternative explanations have been proposed, see e.g. [3, 25], the crucial point here is the need of a theoretical model to separate the contributions from c and b quarks. Uncertainties in the pQCD calculations [22] and discrepancies between pQCD predictions and pp data on non-photonic electrons, demand real data on identified D and B mesons for clear conclusions to be extracted.

Beyond the comparison with data, present formalisms for radiative energy loss [26] suffer from several limitations which make them inadequate for dealing with observables beyond single inclusive quantities:

- The medium characteristics extracted from the comparison of the results in the models and experimental data depend strongly on the medium model with which the energy loss realization is interfaced [4, 22]. This caveat has motivated collaborative efforts for the implementation of realistic medium modeling [27].

- Calculations have been done in the high-energy approximation, with energy-momentum constraints imposed a posteriori. The usual way to overcome this limitation is by

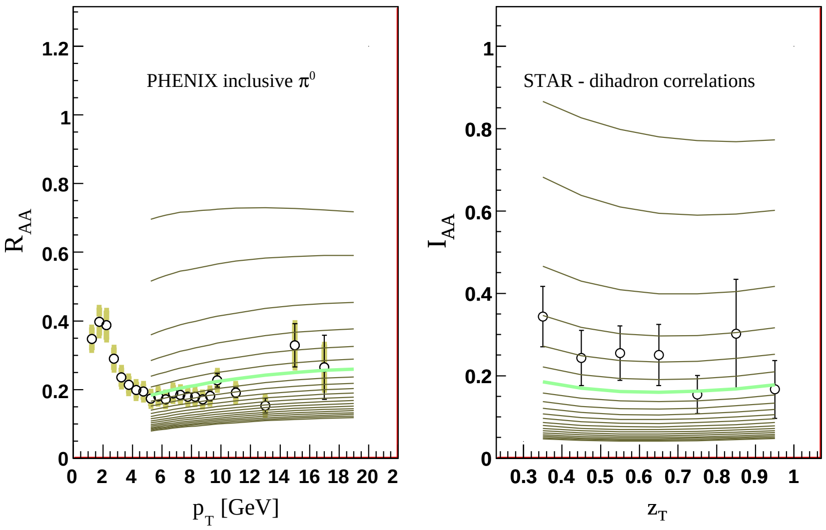

Figure 5: Nuclear modification factors R_{AA} for single-inclusive (left) and I_{AA} for hadron-triggered fragmentation functions (right) for different values of the transport coefficient, with the green line showing the best simultaneous fit to both data sets. Figure taken from [22].

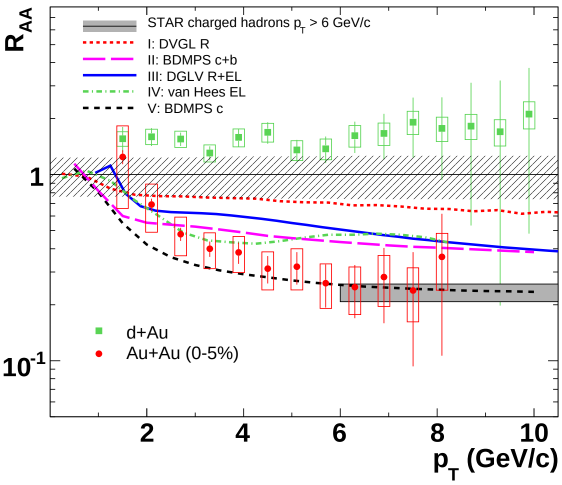

Figure 6: The nuclear modification factor, R_{AA}, for non-photonic electrons in dAu and AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV. Figure taken from [24].

Monte Carlo implementations which I will discuss in the next Subsection.

- Multiple gluon emissions are computed through an iteration, within a Poissonian ansatz, of the single inclusive radiation spectrum. This assumption has to be overcome, again, by the use of Monte Carlo techniques.
- Hadronization is assumed to happen in the vacuum for high-enough parent parton energy (i.e. the projection of partons onto hadrons assumed to be given by standard fragmentation functions at the end of the parton cascade). Medium and vacuum emissions are treated differently and no role is played in medium emission by any evolution variable. Both this point and the previous one demand further theoretical work.

4.2 In-medium parton showers.

A large effort is being devoted to elaborate Monte Carlo codes adequate to deal with the problem of parton branching in a colored medium, see e.g. [4, 28] and references therein. Those efforts range from theoretical investigations on the interplay between medium dimensions and evolution variables, to the practical implementation of medium effects in standard Monte Carlo simulators [29] for final state radiation. Several codes exist at present [30, 31]: PYQUEN, JEWELL, YaJem and Q-PYTHIA.

Presently, the way to treat the medium emission consists in assuming that some evolution variable (either virtuality, transverse momentum or emission angle [29]) exists both for vacuum and medium emissions, and in supplementing the usual DGLAP splitting functions by some additional pieces corresponding to medium effects, both at the level of no-emission (Sudakov) probabilities and at the level of splitting kernels. This is done either effectively or, in a more involved way, through the analogy of the DGLAP splitting functions with radiation spectra in the collinear limit [28]. Besides radiative energy loss, some models include collisional contributions.

The generic expectations of radiative energy loss are: a softening of parton spectra (the jet quenching itself); an increase in the emission angles (jet broadening); and an increase in intra-jet multiplicities. Monte Carlo models are tested against these generic predictions. As an example, in Fig. 7 I show the results of the model Q-PYTHIA [31] at parton level on the hump-backed plateau, and the transverse momentum and angular distributions with respect to the parent parton. All the generic expectations are reproduced. But strong energy-momentum conservation effects are seen e.g. in the fact that the large transverse momentum region is depleted in the medium while the generic expectation is that radiated partons will be pushed to larger transverse momenta by medium interactions.

Ongoing work is under development within the Monte Carlo groups to include elastic energy losses, color reconnections with the medium which may alter the standard color flow in a parton cascade in the vacuum and thus hadronization, momentum exchanges with the medium (which are absent e.g. in Q-PYTHIA and may modify the results about the transverse momentum distributions previously discussed),... Also much effort is being devoted to the identification of jet observables [2] which may allow to characterize the medium in heavy ion collisions. While measurements of jets at RHIC suffer from strong limitations [32], the LHC [33] will be the ideal place for such studies due to both the high yields and the detector capabilities. Still, severe problems of jet definition and background subtraction, and of energy determination and calibration, have to be overcome [2].

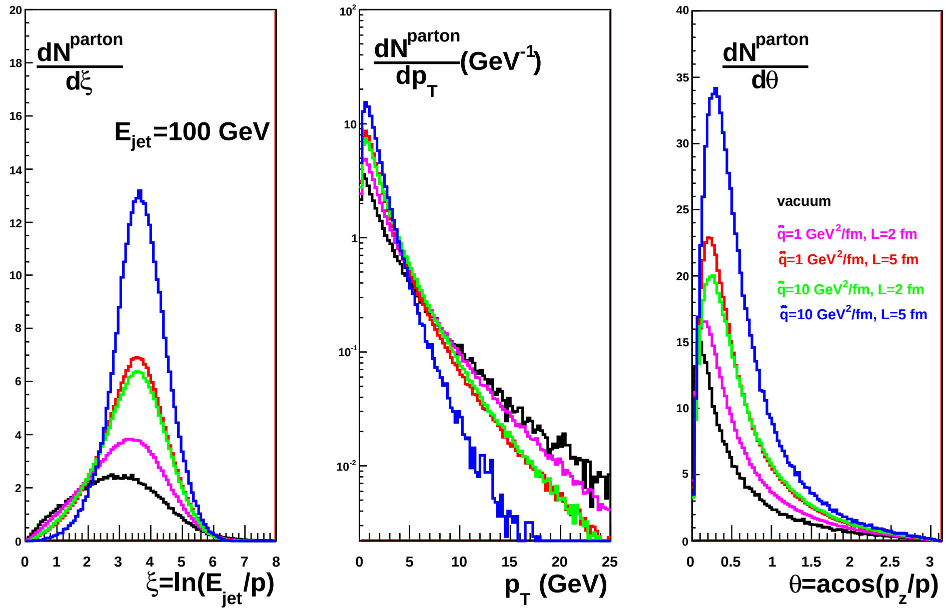

Figure 7: Q-PYTHIA results for the intra-jet parton distributions in ξ (left), p_T (middle) and θ (right) for a gluon of initial energy $E_{jet} = 100$ GeV in a medium of length $L = 2$ and 5 fm and for different transport coefficients $\hat{q} = 0$, 1 and 10 GeV^2/fm, see the legend on the plot. Figure from [31].

5 Summary

I have summarized the most recent theoretical developments on ultrarelativistic heavy ion collisions. They have been motivated by the standard claims at RHIC on the creation of dense partonic matter which nearly equilibrates very early and behaves collectively like a quasi-ideal fluid, shows strong coherence in particle production and is extremely opaque to energetic partons traversing it. Just to mentioned a few which I have briefly discussed in this manuscript:

1. The strong coherence in particle production has triggered efforts on the understanding the nuclear wave function at very small x, and the mechanism (factorization) for particle production in nucleus-nucleus collisions, see Section 2.

2. The early thermalization mechanism and the small dissipation effects have triggered developments on viscous hydrodynamics and on strong coupling methods (i.e. applications of the AdS/CFT correspondence), see Section 3.

3. The observed jet quenching has triggered activities on new formalisms for energy loss which, besides, are required for future jet quenching studies at the LHC [33], see Section 4.

The future experimental programs at RHIC-II and at the LHC offer new possibilities to verify or falsify the picture of the medium created in ultrarelativistic heavy-ion collisions which has arisen from RHIC. There will be new observables like jets, identified heavy flavors, electro-weak boson production,. . . which demand new methods which are under development. Obviously, some of the points mentioned above, more specifically points 1 and 3, have clear connections with pp and lepton-hadron collisions. Therefore there will be an interplay between the physics in ultrarelativistic heavy-ion collisions and that in pp collisions at the LHC, and in future lepton- proton and ion colliders, all these studies sharing the ultimate goal of the complete understanding of the strong interaction.

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References

[1] Slides:
`http://indico.cern.ch/contributionDisplay.py?contribId=14&sessionId=9&confId=53294`

[2] D. d'Enterria,
`http://indico.cern.ch/contributionDisplay.py?contribId=13&sessionId=9&confId=53294`

[3] R. Hwa (ed.), *Quark-Gluon Plasma*, Vol. 1 (World Scientific, Singapore, 1990);
R. Hwa (ed.), *Quark-Gluon Plasma*, Vol. 2 (World Scientific, Singapore, 1995);
R. Hwa and X. N. Wang (eds.), *Quark-Gluon Plasma*, Vol. 3 (World Scientific, Singapore, 2004);
D. A. Teaney, arXiv:0905.2433 [nucl-th];
P. Sorensen, arXiv:0905.0174 [nucl-ex];
R. C. Hwa, arXiv:0904.2159 [nucl-th];
N. Armesto, arXiv:0903.1330 [hep-ph];
R. Rapp and H. van Hees, arXiv:0903.1096 [hep-ph];
S. S. Gubser, S. S. Pufu, F. D. Rocha and A. Yarom, arXiv:0902.4041 [hep-th].

[4] D. d'Enterria, arXiv:0902.2011 [nucl-ex];
J. Casalderrey-Solana and C. A. Salgado, Acta Phys. Polon. B **38** (2007) 3731;
C. A. Salgado, arXiv:0907.1219 [hep-ph].

[5] K. Adcox *et al.* [PHENIX Collaboration], Nucl. Phys. A **757** (2005) 184;
B. B. Back *et al.* [PHOBOS Collaboration], Nucl. Phys. A **757** (2005) 28;
I. Arsene *et al.* [BRAHMS Collaboration], Nucl. Phys. A **757** (2005) 1;
J. Adams *et al.* [STAR Collaboration], Nucl. Phys. A **757** (2005) 102.

[6] K. J. Eskola, H. Paukkunen and C. A. Salgado, JHEP **0904** (2009) 065.

[7] M. Hirai, S. Kumano and T. H. Nagai, arXiv:0709.3038 [hep-ph].

[8] D. de Florian and R. Sassot, Phys. Rev. D **69** (2004) 074028.

[9] A. Accardi *et al.*, arXiv:hep-ph/0308248.

[10] A. M. Stasto, K. J. Golec-Biernat and J. Kwiecinski, Phys. Rev. Lett. **86** (2001) 596;
C. Marquet and L. Schoeffel, Phys. Lett. B **639** (2006) 471;
N. Armesto, C. A. Salgado and U. A. Wiedemann, Phys. Rev. Lett. **94** (2005) 022002.

[11] I. Balitsky,
`http://indico.cern.ch/contributionDisplay.py?contribId=85&sessionId=0&confId=53294`

[12] J. L. Albacete, N. Armesto, J. G. Milhano and C. A. Salgado, arXiv:0902.1112 [hep-ph].

[13] A. Kovner, Acta Phys. Polon. B **36** (2005) 3551;
D. N. Triantafyllopoulos, Acta Phys. Polon. B **36** (2005) 3593;
T. Altinoluk, A. Kovner, M. Lublinsky and J. Peressutti, JHEP **0903** (2009) 109;
Y. V. Kovchegov, J. Kuokkanen, K. Rummukainen and H. Weigert, Nucl. Phys. A **823** (2009) 47.

[14] J. L. Albacete,
`http://indico.cern.ch/contributionDisplay.py?contribId=103&sessionId=26&confId=53294`

[15] M. A. Braun, Eur. Phys. J. C **55** (2008) 377;
J. Bartels, M. Salvadore and G. P. Vacca, JHEP **0806** (2008) 032;
Y. V. Kovchegov and K. Tuchin, Phys. Rev. D **65** (2002) 074026
F. Gelis, T. Lappi and R. Venugopalan, Phys. Rev. D **78** (2008) 054019;
I. Balitsky, Phys. Rev. D **72** (2005) 074027;
C. Marquet, Nucl. Phys. A **796** (2007) 41;
K. Fukushima and Y. Hidaka, Nucl. Phys. A **813** (2008) 171;
N. N. Nikolaev and W. Schafer, Phys. Rev. D **71** (2005) 014023;
T. Altinoluk, A. Kovner and M. Lublinsky, JHEP **0903** (2009) 110.

[16] P. Romatschke, arXiv:0902.3663 [hep-ph].

[17] A. Rebhan, P. Romatschke and M. Strickland, Phys. Rev. Lett. **94** (2005) 102303;
A. El, Z. Xu and C. Greiner, Nucl. Phys. A **806** (2008) 287.

[18] J. M. Maldacena, Adv. Theor. Math. Phys. **2** (1998) 231 [Int. J. Theor. Phys. **38** (1999) 1113];
S. S. Gubser, I. R. Klebanov and A. M. Polyakov, Phys. Lett. B **428** (1998) 105;
E. Witten, Adv. Theor. Math. Phys. **2** (1998) 253;
E. Witten, Adv. Theor. Math. Phys. **2** (1998) 505.

[19] J. D. Edelstein and C. A. Salgado, AIP Conf. Proc. **1031** (2008) 207.

[20] J. Polchinski and M. J. Strassler, JHEP **0305** (2003) 012;
Y. Hatta, E. Iancu and A. H. Mueller, JHEP **0801** (2008) 026;
J. L. Albacete, Y. V. Kovchegov and A. Taliotis, JHEP **0807** (2008) 074.

[21] R. A. Janik and R. B. Peschanski, Phys. Rev. D **74** (2006) 046007;
J. L. Albacete, Y. V. Kovchegov and A. Taliotis, JHEP **0807** (2008) 100.

[22] N. Armesto, M. Cacciari, T. Hirano, J. L. Nagle and C. A. Salgado, arXiv:0907.0667 [hep-ph].

[23] N. Armesto, M. Cacciari, A. Dainese, C. A. Salgado and U. A. Wiedemann, Phys. Lett. B **637** (2006) 362.

[24] B. I. Abelev *et al.* [STAR Collaboration], Phys. Rev. Lett. **98** (2007) 192301.

[25] M. G. Mustafa, Phys. Rev. C **72** (2005) 014905;
A. Adil, M. Gyulassy, W. A. Horowitz and S. Wicks, Phys. Rev. C **75** (2007) 044906.

[26] A. Majumder, J. Phys. G **34** (2007) S377.

[27] Theoretical and Experimental Collaboration for Hot QCD Matter,
`https://wiki.bnl.gov/TECHQM/index.php/Main_Page`

[28] A. D. Polosa and C. A. Salgado, Phys. Rev. C **75** (2007) 041901;
N. Armesto, L. Cunqueiro, C. A. Salgado and W. C. Xiang, JHEP **0802** (2008) 048;
X. N. Wang and X. f. Guo, Nucl. Phys. A **696** (2001) 788.

[29] S. Frixione,
`http://indico.cern.ch/contributionDisplay.py?contribId=10&sessionId=8&confId=53294`

[30] I. P. Lokhtin and A. M. Snigirev, Eur. Phys. J. C **45** (2006) 211;
K. Zapp, G. Ingelman, J. Rathsman, J. Stachel and U. A. Wiedemann, Eur. Phys. J. C **60** (2009) 617;
T. Renk, Phys. Rev. C **78** (2008) 034908;
K. Zapp, J. Stachel and U. A. Wiedemann, arXiv:0812.3888 [hep-ph].

[31] N. Armesto, L. Cunqueiro and C. A. Salgado, arXiv:0907.1014 [hep-ph].

[32] S. Salur [for the STAR Collaboration], arXiv:0809.1609 [nucl-ex];
J. Putschke [for the STAR Collaboration], arXiv:0809.1419 [nucl-ex];
S. Salur, arXiv:0905.1917 [nucl-ex].

[33] F. Carminati *et al.* [ALICE Collaboration], J. Phys. G **30** (2004) 1517;
B. Alessandro *et al.* [ALICE Collaboration], J. Phys. G **32** (2006) 1295;
D. G. d'Enterria *et al.* [CMS Collaboration], J. Phys. G **34** (2007) 2307;
P. Steinberg [ATLAS Collaboration], J. Phys. G **34** (2007) S527.