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Heavy Ions: Theory

Carlos A. Salgado[*]
Departamento de Física de Partículas and IGFAE
Universidade de Santiago de Compostela (Galicia-Spain)
E-mail: `carlos.salgado@usc.es`

The LHC nuclear program has started with a run at $\sqrt{s}$=2.76 TeV per nucleon pair in 2010. The first data with a reduced luminosity confirms most of the trends observed in the last ten year's program at RHIC. The strong elliptic flow points to a small viscosity of the produced medium; the large jet quenching points to a large density; quarkonia is suppressed and promises to be an excellent tool for temperature measurements; finally the partonic wave function of the nuclei is subject to strong screening effects which can be understood from saturated parton densities. The theoretical approaches checked in the last ten years provide also a good understanding of these findings. At the same time, new experimental probes as reconstructed jets call for new theoretical developments. Here I present a small overview of the theoretical status of hot and dense QCD from the point of view of its application to the nuclear program at LHC and RHIC, focussing on some of the observables.

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[*] Speaker.

High energy heavy ion collisions are the experimental tools to study the structure of QCD at high temperatures and densities. After successful programs at the CERN SPS and the, still ongoing, Relativistic Heavy Ion Collider in Brookhaven, the LHC brings the nuclear collisions to the TeV scale for the first time. Some of the results presented at this conference prove the potential for discoveries which the large jump in energy from the RHIC $\sqrt{s}_{\rm NN}$=200 GeV to the LHC $\sqrt{s}_{\rm NN}$=2.76 TeV opens. From a purely qualitative point of view, the main differences of the LHC and the RHIC programs are the access to the region of much smaller values of Bjorken-x in the nuclear parton distributions and the access to processes with much larger scales involved, in particular jets and electroweak bosons.

Historically, the main goal of the experimental programs of high-energy nuclear collisions is to study the properties of a high temperature, high density QCD medium [1, 2, 3, 4, 5, 6] characterized by a deconfined phase with restored chiral symmetry. Such medium is produced in the central rapidity region of the collision where a large energy density is deposited in a macroscopic (in terms of QCD scales) region of space.

The matter produced in heavy ion collisions is studied through different indirect probes, including soft probes, especially the search for hydrodynamical behavior of the bulk particle production, and hard probes, like jet or quarkonia suppression. Our pre-LHC knowledge indicates that (i) the bulk matter can be well described by hydrodynamical models with a small viscosity [7], this points to an ideal fluid behavior: (ii) the particles produced at high transverse momentum suffer a strong suppression, pointing to a very dense created medium: (iii) screening of the small-x part of the nuclear partonic distributions is needed to understand the total multiplicities and relevant also for other observables. The data from the first run of the nuclear LHC program in 2010 have confirmed these findings and exploration into new territories have just started. The second run, with improved luminosity will start soon and, interestingly, a first proton-nucleus run could take place in 2012. Proton-nucleus collisions are recognized as an essential part of the high-energy nuclear program to provide the benchmark for some effects not related with the presence of hot matter (i.e. this information is needed for *background subtraction*) and provides interesting tools for small-x physics where high parton densities can be reached [8, 9]. In the following I will briefly summarize some of the most recent findings in the field.

1. Initial state and *cold nuclear matter* background

Hot QCD matter searches in high energy nuclear collisions involve background subtraction of those processes whose underlying dynamics is not related with the presence of a produced medium. These *cold nuclear matter effects* need to be under good control for benchmarking. In particular, a main source of uncertainty comes from the badly constrained nuclear parton distribution functions (PDFs) especially for gluons and small-x — see Fig. 1. The best way to constrain the nuclear PDFs is by experiments of lepton-nucleus deep inelastic scattering [10]. The kinematical reach of the available data (which are, in fact, more than fifteen years old) is, however, rather limited, especially for the needs of the LHC program. In Figure 1 the kinematical reach of the present DIS and Drell-Yan (DY) data with nuclear targets (the data normally used to constrain nuclear PDFs) is plotted together with the needs for both RHIC and LHC kinematics [8, 9]. The central rapidities at RHIC were placed in the lucky situation of overlap with previous DIS and DY data so

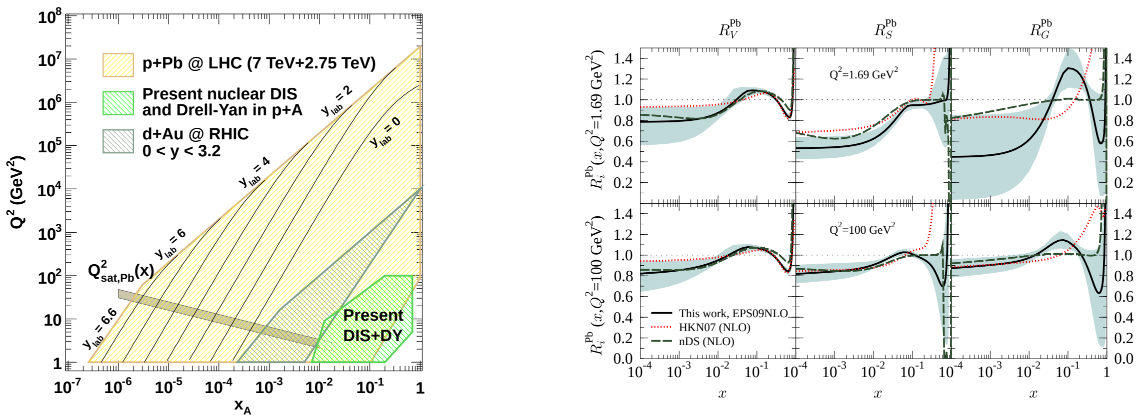

Figure 1: (Left): Total kinematical reach of p+Pb collisions at $\sqrt{s}$ =8.8 TeV at the LHC for different rapidities in the laboratory frame. Also shown are the region of phase space studied by experiments of DIS with nuclei and Drell-Yan production in proton-nucleus collisions (the two main processes used in global nPDF fits) and the total reach of RHIC for $0 < y < 3$ — Fig. from Refs. [8, 9]. (Right): Nuclear parton distribution functions ratio with respect to the free proton case for two different virtualities and three different NLO analyses — Fig. from Ref. [14].

that checks of the factorization equation and trustable subtraction of the background due to nuclear PDFs performed. The case of the forward rapidities at RHIC and basically the whole range of the LHC is, however, different. There is no experimental information which could constrain the nuclear effects in the small-x region of interest for these two machines, which results into large uncertainties in the knowledge of the nuclear PDFs — see Fig. 1 (Right). In this situation, a parallel proton-nucleus collisions program will be needed at the LHC to reduce these uncertainties [8, 9]. It is worth mentioning that in the DGLAP approach, the nuclear effects to the PDFs rapidly disappear with increasing Q^2 in the small-x region for the gluons and also for the quarks, although a bit slower. In the large-x, on the other hand, the uncertainties remain large in the whole range of Q^2.

The error bands in the nuclear PDFs from Fig. 1 translate into large uncertainties in the nuclear effects for some observables, especially those at the smaller virtualities. A recent experimental example reveals very clearly the need of constraining these uncertainties for a correct interpretation of the nucleus-nucleus data: ALICE Collaboration has measured the J/Ψ suppression in Pb+Pb collisions in the forward rapidity region [11, 12, 13]. The suppression is about a factor of two when compared with the scaled p+p cross section and within the error bands of the suppression predicted by the EPS09 global fit of nPDFs presented in Fig. 1. Taken at face value, the suppression would be compatible with cold nuclear matter effects alone. Whether this is the case or not will need of better determination of the nPDFs which, at present, is only possible with p+Pb collisions at the LHC. Checks of the factorization hypothesis for the J/Ψ-production mechanism would also be interesting, in particular in view of the difficulties to theoretically describe this production cross section even in p+p collisions.

The small values of x probed in nuclear collisions at the LHC provide also excellent conditions for studies of the saturation of partonic densities [15]. Indeed, rather general geometric arguments indicate that saturation effects are enhanced by a factor $A^{1/3}$ in the nuclear case, compared to the proton. The study of saturation is difficult in nucleus-nucleus collisions due to the presence of strong final-state effects, which lead to a thermalization of the final bulk particle production, and is expected to be best studied in proton-nucleus, or eventually in lepton-nucleus collisions. However, some of the bulk properties, as the total multiplicities or some long-range rapidity correlations, are expected to survive this thermalization. The rapid progress in saturation physics in the last ten years, especially the development of a whole formalism known as the Color Glass Condensate where the non-linear corrections to the evolution equations have been computed at NLO, make the comparison with experimental data to be meaningful and rather successful, despite the presence of still some uncertainties in the phenomenological implementation.

2. Hydrodynamical description of the bulk

A powerful way of looking at the degree of collectivity reached in a heavy ion collision is by studying the azimuthal distribution of particles produced at a given transverse momentum p_T: if the collisions were all independent, the particles would be uniformly distributed (within statistical fluctuations) while the presence of azimuthal anisotropies would indicate that non-trivial phenomena are taking place. The hydrodynamic modeling of the heavy ion collisions provides the most successful phenomenological tool to study the data

In those dynamical situations in which the mean free path of the particles in the medium is very small, medium properties as energy density, pressure or temperature can be described in a hydrodynamical approach. The basic equation corresponds to the conservation of the energy-momentum tensor $\partial_\mu T^{\mu\nu}=0$. Neglecting viscosity, the energy momentum tensor can be written as

$$T^{\mu\nu}=(\varepsilon+p)u^\mu u^\nu-pg^{\mu\nu} \tag{2.1}$$

where ε, p and u^μ are the (local) energy density, pressure and four-velocity of a fluid element. This last one is normalized as $u^\mu u_\mu=1$. See e.g. Ref [16] for a recent review.

If the matter formed in a high-energy nuclear collision is locally thermalized, the corresponding hydrodynamic behavior should be reflected in the spectra of the produced particles and visible away of the region dominated by hard QCD scatterings. The most useful observables are those in which strong anisotropies in the transverse momentum azimuthal distributions are identified. In a hydrodynamical approach, these anisotropies are the reflection of the initial geometrical anisotropy of the system which produces different pressure gradients and, hence, azimuthal angle dependent transverse flows. An intuitive picture can be found when considering the Euler equation

$$\frac{d\beta}{dt}=-\frac{c^2}{\varepsilon+p}\nabla p\,. \tag{2.2}$$

Assuming an ideal equation of state $p=\varepsilon/3$, the gradients of energy density — present if the initial state of the system is anisotropic as in the case of non-central collisions — Eq. (2.2) implies a different acceleration, $d\beta/dt$, for fluid elements in different directions.

A Fourier decomposition is normally performed for the azimuthal angle spectrum ϕ — see e.g. [7]

$$\frac{2\pi}{N}\frac{dN}{d\phi}=1+\sum_{n=1}^{\infty}2v_n\cos n(\phi-\Psi_n) \tag{2.3}$$

In the last ten years, the study of the second harmonic coefficient v_2 in the expansion, sometimes also known as elliptic flow, lead to a rapid development of the theory and the phenomenology of hydrodynamical approaches, which eventually lead to an estimate of the viscosity of the produced matter. This viscosity is very low, consistent with the bound proposed by some implementations of the AdS/CFT correspondence [17]. Such a small values of the viscosity indicate that the produced medium is a perfect liquid. In the last couple of years, the main efforts have been devoted to a better implementation of the viscosity effects and to the implications of fluctuations in the initial conditions, reflected in the presence of the odd terms in the series, which could be zero in the absence of these fluctuations. For two recent references on these topics see [18] and [7] respectively.

3. Quarkonia suppression

Quarkonia suppression is a conceptually simple and potentially powerful tool to characterize the properties of the produced QCD matter. An intuitive idea can be formulated in terms of the potential between a quark and an antiquark which, in the case of a hot deconfined medium is screened: if such a medium is created in a nuclear collision bound states are disfavored during the plasma phase and the production of charmonia or bottomonia states suppressed [19]. The interpretation of the corresponding data has been confusing, however, in the last twenty years. The suppression has indeed been observed already in the pioneering experiments at the CERN-SPS of fixed-target S+U [20] and Pb+Pb [21] or In+In collisions [22], it was also observed at RHIC in Au+Au [23, 24] and Cu+Cu collisions [25] and recently also at the LHC not only for the J/Ψ [11, 12, 13] but also for excited quarkonia states [26]. One of the main problems for the interpretation of the data is the subtraction of the cold nuclear matter background. The suppression of both the J/Ψ, the Υ and other excited states has also been observed in proton-nucleus (or deuteron-gold) collisions in magnitude similar to the one in nucleus-nucleus collisions [27, 28, 29, 30, 31]. The theoretical description of this cold nuclear matter effects is not under good theoretical control and several mechanisms of J/Ψ-suppression are proposed. The most canonical one assumes a modification of the J/Ψ yield due to nuclear PDFs and a modification of the hadronization modeled by a probabilistic Glauber model — see e.g. [32, 33]. This factorization is not proved but used as a working hypothesis.

In this situation, the long-standing problem of the suppression of quarkonia states in nuclear collisions needs of a systematic study of the production in different systems (p+p, p+A, A+A) and energies as well as a systematic study of the different quarkonia states. Indeed, the excited states are predicted [34] to be more easily destroyed in hot matter than the ground states J/Ψ and Υ — a fact which is in qualitative agreement with the findings in [26] but whose quantitative understanding would need a better control over the cold nuclear matter effects. With the data accumulated in the last 20 years and the new data from both RHIC and, especially, the LHC a more clear picture of this interesting observable should emerge in the near future.

4. Jet quenching

A quark or gluon produced at high transverse momentum in an elementary QCD collision is associated with a large phase space available for extra radiation. This extra radiation is emitted at small angles and can be experimentally identified in the form of jets. The theoretical control on the jet production and evolution is very good in the absence of a medium, this is, in fact, an essential requirement in the searches for new physics at the LHC. In a parton shower approach, the large virtuality of the original quark or gluon is reduced during evolution by radiating (mainly) gluons with a probability controlled by the Altarelli-Parisi splitting functions. The corresponding evolution equations of the fragmentation functions are known in different approximations.

The case of the medium is not as well understood. Assuming that the evolution of the final state jet can be factorized from the initial state in a way similar to the vacuum, several different effect could appear: (1) *collisional energy loss*, due to elastic scatterings of the fast partons with the medium; (2) medium-induced gluon radiation also known as *radiative energy loss*; (3) a modification of the color flow within the jet due to exchanges with the medium [35]; (4) a modification of the ordering variable, or, in general, the evolution equations; etc..

RHIC phenomenology has been dominated by the energy loss mechanisms, this is because the corresponding jet quenching measurements were performed with inclusive particle measurements (one- or two-particle correlations) which measures the effects on the most energetic (leading) particle in the jet. A rather successful formalism (see e.g. Refs. [36, 37, 38, 39] for recent reviews) based on the medium-induced gluon radiation is able to reproduce the corresponding data with two main unsolved issues

1. *Heavy flavor suppression*: Basically all formalisms predict that heavy quarks will lose less energy than light quarks [40, 41, 42, 43]. The exact difference depend on the details of the formalism but experimental data on the suppression of non-photonic electrons point to a stronger suppression [44, 45]

2. *Sizable discrepancies between theoretical implementations*: The underlying physical hypothesis in the computations of the medium-induced gluon radiation are basically common to all formalisms but the actual approximations made translate into sizable differences in the output medium parameters [46].

4.1 Jet quenching with inclusive particles

The simplest jet-related observable in nuclear collisions is the measurement of the one-particle inclusive production at high transverse momentum. The effect of the surrounding matter can be identified by the suppression of the signal, with respect to the proton-proton collisions, due to energy loss. The nuclear modification ratio

$$R_{AA}=\frac{d\sigma^{AA}/dydk_T}{N_{\rm coll}d\sigma^{AA}/dydk_T} \tag{4.1}$$

is normally employed to single-out the medium effects, where $N_{\rm coll}$ is a normalization factor computed in the Glauber model to allow the comparison with the proton-proton cross section. The suppression of high-p_T hadrons is one of the first, and also one of the main, observations at RHIC [47, 48, 49, 50]. Several theoretical approaches have been used to reproduce the data, the most successful ones being those based on radiative energy loss as explained above. In Fig. 2 we plot the description of the data in one of this approaches [51] for both the one- and two-particle inclusive distributions (back-to-back signals for the second). The description of the data is good.

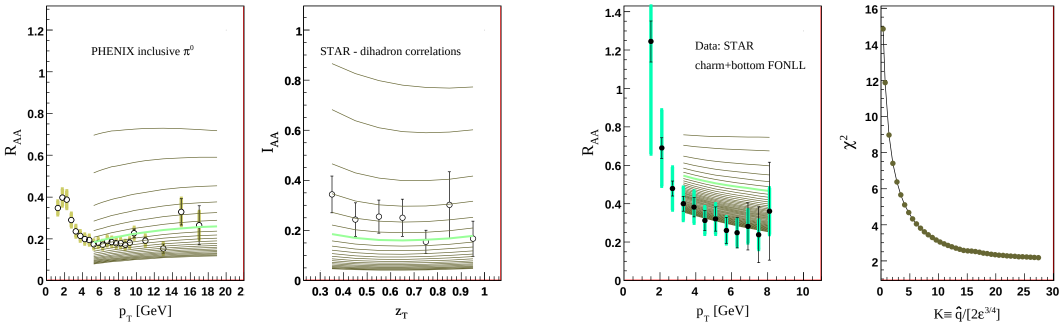

Figure 2: Nuclear modification factors R_{AA} for single inclusive distributions and I_{AA} for double inclusive distributions for pions (first panel from the left) charged hadrons (second panel) and non-photonic electrons (third panel). The different lines correspond to K=0.5, 1, 2, ... 20. The last panel shows the values of χ^2 computed for different K for the case of the non-photonic electrons. Fig. from Ref. [14].

A quality analysis returns a value $K = 4.1 \pm 0.6$ when the transport coefficient is parametrized as $\hat{q} = 2K\varepsilon^{3/4}$, ε being the local energy density of the medium in a hydrodynamical approach. In the case of an ideal quark-gluon plasma, a free gas of quarks and gluons, $K \sim 1$ — see e.g. [52] — indicating that the properties of the medium do not naively correspond to this simplified scenario. As mentioned above, however, despite the successful description of the data two main open issues need to be solved for which LHC data will be most helpful.

LHC collaborations have also measured R_{AA} for inclusive particles at high-p_T both for light hadrons [53, 54] and, interestingly, for charmed mesons [55]. The suppression for light hadrons turns out to be similar, though slightly larger, than the one at RHIC for moderate values of p_T. Models tested at RHIC can reproduce the data reasonably well, including the positive slope which indicates $R_{AA} \to 1$ for large transverse momenta. Concerning the D-meson suppression, with large error bars it also indicates a similar, although slightly smaller, suppression than the corresponding one for light hadrons. This was expected from calculations of medium-induced gluon radiation [56]. So, there seems to be a compatibility of the well-tested approaches used in RHIC phenomenology with the new data from the LHC. More quantitative analyses should be performed now, with all available data, also when the medium density distributions from hydrodynamical analyses become available as input.

4.2 Reconstructed jets in nuclear collisions

Although the results from the previous section are extremely interesting for the characterization of the medium properties, the use of inclusive quantities present also limitations which are difficult to overcome. In particular, in a scenario of very dense medium, surface effects could affect the extraction of the medium parameters and different approaches are difficult to distinguish. A powerful tool to overcome this limitations is the reconstruction of jets in nuclear collisions. In the ideal situation, if the whole energy of the jet can be reconstructed, the modifications that the medium induce in its structure gives a direct information about the splitting process as well as other mechanisms which could be present.

Jet reconstruction is one of the main issues in hadronic colliders, and essential for physics searches. In the case of the nuclear collisions, the size of the underlying event, with a very large multiplicity, makes the identification of the jets more difficult. The first data on identified jets has been performed at RHIC [57, 58] and the first published data appeared very recently from the LHC [59, 60]. The analysis of the ATLAS and CMS collaborations present some surprising results. They can be summarized as follows:

1. Reconstructed jets from ATLAS are suppressed from central to peripheral collisions ($R_{CP} \sim 0.5$ and basically flat). This indicates that the sample of studied jets are still biased to some extent.

2. When the back-to-back jet signals are studied, the energy imbalance from the most energetic jet to the one in the opposite direction is larger in central Pb+Pb than in p+p collisions. This indicates a large energy loss of jets in the produced matter.

3. CMS data indicate that this lost energy is dominantly carried away by soft particles (less than 2 GeV) at large angles. This contrasts with the vacuum where the particles are harder at large angles due to angular ordering.

4. The di-jet azimuthal asymmetry is very similar in Pb+Pb collisions and in p+p collisions. So, no strong change with respect to the vacuum jets is observed: the effect is not dominantly driven by e.g. emission of hard particles which would change the direction of the jets.

5. The fragmentation functions of the leading and the subleading jets do not present any change from Pb+Pb or p+p collisions. So, the fragmentation function is vacuum-like[1].

Some of these properties were not, a priori, expected from theoretical estimates. In particular, the usual, and quite generic, relation between broadening and energy loss, $\Delta E \sim \langle k_T^2 \rangle L/\alpha_s$, seems difficult to reconcile with those observations at least naively. However, a note of caution needs to be made in here as a complete picture of the underlying mechanism of jet quenching needs of a controlled analysis of several factors as, e.g. the amount of jets which are lost; the effect of the background subtraction [61]; the actual theoretical implementations which are compared with the data, etc. One can imagine, for example, a simplified scenario in which two different jet quenching mechanisms are at work and one of them is removed from the sample because it produces e.g. a too hard spectrum. With all these cautions, we can still try to extract some consequences, and the properties above indicate that the effects in the measured jets are not compatible with a hard radiation at large angles, which would modify, in particular, the di-jet azimuthal asymmetry or with a strong modification of the radiation pattern inside the cone, which would modify the fragmentation functions. A naive interpretation of the data would then indicate that mechanisms in which the jet broadening and the energy loss do not follow the traditional relation $\Delta E \sim \langle k_T^2 \rangle L/\alpha_s$ are favored in the particular sample of jets measured.

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[1] Notice that the experimental fragmentation function (FF) is built by dividing the particles' transverse momentum by the jet's total energy, while the theoretical predictions before the data appeared typically dividing the transverse momentum of the particle by the energy *of the parton* originating the jet. In the second case (not possible in experimental conditions unless the whole energy of the jet is reconstructed) a suppression of the FF is predicted, in agreement with the suppression found in inclusive particle measurements as the ones in Fig. 2.

4.3 Towards a new theory of jets in a medium

The limitations in the theoretical implementation of jet quenching as well as the quality of the new data becoming available, especially from LHC, calls for a new theory of jets in a medium. An essential ingredient that any description of the jet development should contain is a correct treatment of the multi-parton emissions. The traditional way of assuming an independent gluon emission approximation is probably good enough to estimate the energy loss and, hence, for the phenomenology of inclusive particle suppression. The description of a final state with a large number of gluons emitted needs, on the other hand, the inclusion of quantum interferences among different emitters which are known to be essential in the vacuum. As a first step towards this goal, recent developments consider the emission out of a quark-antiquark antenna [62, 63, 64, 65, 66, 67]. The setup captures the main physical ingredients in the vacuum, in particular, the presence of angular ordering due to color coherence effects. In the case of a medium the situation is radically changed. Several regimes have been identified, and interestingly, a new contribution emerges in which a vacuum-like radiation, but *antiangular ordered* [62] can be identified. This new contribution is especially interesting because its features are completely different from all known medium-induced gluon radiation presented in the previous sections. This becomes more clear in the soft limit where the sum of the vacuum plus the medium-induced gluon radiation off a $q\bar{q}$ antenna with opening angle $\theta_{q\bar{q}}$ in a singlet state is simply

$$dN^{\text{tot}}_{q,\gamma^*} = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{\sin\theta\; d\theta}{1-\cos\theta}\left[\Theta(\cos\theta-\cos\theta_{q\bar{q}})-\Delta_{\text{med}}\,\Theta(\cos\theta_{q\bar{q}}-\cos\theta)\right] . \tag{4.2}$$

Here the first term is just the vacuum angular-ordered contribution and the second term is the new medium contribution which has been called *antiangular ordering* [62]. In particular, and in contrast to previous results, a soft divergence appears also for the medium-induced part due to the vacuum-like spectrum. The parameter of the medium controlling the amount of *antiangular ordering* is the dipole scattering amplitude

$$\Delta_{\text{med}} = 1-\frac{1}{N_c^2-1}\langle \mathbf{Tr}\, U_p(L,0)U_p^\dagger(L,0)\rangle\,, \tag{4.3}$$

which, by unitarity, is bounded by 1. In the case of an opaque medium, $\Delta_{\text{med}}\to 1$, a *total decoherence* is then achieved in which the total spectrum is [63]

$$dN^{\text{tot}}_{q,\gamma^*}\Big|_{\text{opaque}} = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{\sin\theta\; d\theta}{1-\cos\theta} = dN^{\text{tot}}_{q,g^*}\Big|_{\text{opaque}} \tag{4.4}$$

The last equality means that another property of the spectrum is the *memory loss*: the radiated gluons do not keep information about the original pair being in a singlet or an octect state. Interestingly, these new properties survive the soft limit and the spectrum retains a form similar to (4.2) for sizable values of the gluon energy.

These new results indicate that the medium-induced gluon radiation off a single emitter, considered up to now in all phenomenological approaches and also implemented in some Monte Carlo codes [68, 69, 70, 72, 71], would not be enough for a correct interpretation of the experimental data. Non-trivial structures appear when considering more than one emitter, the realistic situation in a jet shower, as already known from the vacuum.

The features of the radiation are, on the other hand, in good qualitative agreement with the experimental data on jets presented in the previous sections: The spectrum (4.2) presents vacuum-like radiation outside the cone delimited by the pair angle, in particular with a soft divergency, so, soft, vacuum-like, radiation is expected at relatively large angles while the radiation inside remains unchanged and just as in vacuum. These are qualitative behaviors which should be contrasted with data in a more quantitative analysis once the correct implementation of the multigluon emission is known.

Acknowledgments

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References

[1] N. Cabibbo and G. Parisi, Phys. Lett. B **59** (1975) 67.

[2] J. C. Collins and M. J. Perry, Phys. Rev. Lett. **34** (1975) 1353.

[3] B. A. Freedman and L. D. McLerran, Phys. Rev. D **16** (1977) 1169.

[4] E. V. Shuryak, Phys. Lett. B **78** (1978) 150 [Sov. J. Nucl. Phys. **28** (1978) 408] [Yad. Fiz. **28** (1978) 796].

[5] N. Itoh, Prog. Theor. Phys. **44** (1970) 291.

[6] D. D. Ivanenko and D. F. Kurdgelaidze, Astrophysics **1** (1965) 251 [Astrofiz. **1** (1965) 479].

[7] M. Luzum, J. Phys. G **38** (2011) 124026 [arXiv:1107.0592 [nucl-th]].

[8] C. A. Salgado *et al.*, arXiv:1105.3919 [hep-ph].

[9] C. A. Salgado, J. Phys. G **38**, 124036 (2011) [arXiv:1108.5438 [hep-ph]].

[10] P. Newman, these proceedings.

[11] G. Aad *et al.* [Atlas Collaboration], Phys. Lett. B **697** (2011) 294 [arXiv:1012.5419 [hep-ex]].

[12] P. Pillot [ALICE Collaboration], J. Phys. G **38** (2011) 124111 [arXiv:1108.3795 [hep-ex]].

[13] G. Martinez Garcia [ALICE Collaboration], J. Phys. G **38** (2011) 124034 [arXiv:1106.5889 [nucl-ex]].

[14] K. J. Eskola, H. Paukkunen and C. A. Salgado, JHEP **0904** (2009) 065 [arXiv:0902.4154 [hep-ph]].

[15] J. L. Albacete, these proceedings.

[16] T. Hirano, N. van der Kolk and A. Bilandzic, Lect. Notes Phys. **785** (2010) 139 [arXiv:0808.2684 [nucl-th]].

[17] P. Kovtun, D. T. Son and A. O. Starinets, Phys. Rev. Lett. **94** (2005) 111601 [hep-th/0405231].

[18] B. Schenke, S. Jeon and C. Gale, Phys. Rev. Lett. **106** (2011) 042301 [arXiv:1009.3244 [hep-ph]].

[19] T. Matsui and H. Satz, Phys. Lett. B **178** (1986) 416.

[20] M. C. Abreu *et al.* [NA38 Collaboration], Phys. Lett. B **449** (1999) 128.

[21] M. C. Abreu *et al.* [NA50 Collaboration], Phys. Lett. B **477** (2000) 28.

[22] R. Arnaldi *et al.* [NA60 Collaboration], Phys. Rev. Lett. **99** (2007) 132302.

[23] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **98** (2007) 232301 [arXiv:nucl-ex/0611020].

[24] R. Reed [STAR Collaboration], J. Phys. Conf. Ser. **270** (2011) 012026 [Nucl. Phys. A **855**, 440 (2011)].

[25] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **101** (2008) 122301 [arXiv:0801.0220 [nucl-ex]].

[26] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Rev. Lett. **107** (2011) 052302 [arXiv:1105.4894 [nucl-ex]].

[27] D. M. Alde *et al.*, Phys. Rev. Lett. **66** (1991) 133.

[28] D. M. Alde *et al.*, Phys. Rev. Lett. **66** (1991) 2285.

[29] M. C. Abreu *et al.* [NA38 Collaboration], Phys. Lett. B **444** (1998) 516.

[30] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. C **77** (2008) 024912 [Erratum-ibid. C **79** (2009) 059901] [arXiv:0711.3917 [nucl-ex]].

[31] R. Arnaldi *et al.* [NA60 Collaboration], arXiv:1004.5523 [nucl-ex].

[32] R. Vogt, Phys. Rev. C **71** (2005) 054902 [arXiv:hep-ph/0411378].

[33] E. G. Ferreiro, F. Fleuret, J. P. Lansberg and A. Rakotozafindrabe, Phys. Lett. B **680** (2009) 50 [arXiv:0809.4684 [hep-ph]].

[34] S. Digal, P. Petreczky and H. Satz, Phys. Rev. D **64** (2001) 094015 [arXiv:hep-ph/0106017].

[35] A. Beraudo, J. G. Milhano and U. A. Wiedemann, arXiv:1109.5025 [hep-ph].

[36] J. Casalderrey-Solana and C. A. Salgado, Acta Phys. Polon. B **38** (2007) 3731 [arXiv:0712.3443 [hep-ph]].

[37] D. d'Enterria, arXiv:0902.2011 [nucl-ex].

[38] U. A. Wiedemann, arXiv:0908.2306 [hep-ph].

[39] A. Majumder and M. Van Leeuwen, Prog. Part. Nucl. Phys. A **66** (2011) 41 [arXiv:1002.2206 [hep-ph]].

[40] Y. L. Dokshitzer and D. E. Kharzeev, Phys. Lett. B **519** (2001) 199 [arXiv:hep-ph/0106202].

[41] M. Djordjevic and M. Gyulassy, Phys. Lett. B **560** (2003) 37 [arXiv:nucl-th/0302069].

[42] N. Armesto, C. A. Salgado and U. A. Wiedemann, Phys. Rev. D **69** (2004) 114003 [arXiv:hep-ph/0312106].

[43] S. Wicks, W. Horowitz, M. Djordjevic and M. Gyulassy, Nucl. Phys. A **784** (2007) 426 [arXiv:nucl-th/0512076].

[44] B. I. Abelev *et al.* [STAR Collaboration], Phys. Rev. Lett. **98** (2007) 192301 [Erratum-ibid. **106** (2011) 159902] [arXiv:nucl-ex/0607012].

[45] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. C **84** (2011) 044905 [arXiv:1005.1627 [nucl-ex]].

[46] N. Armesto *et al.*, arXiv:1106.1106 [hep-ph].

[47] K. Adcox *et al.* [PHENIX Collaboration], Nucl. Phys. A **757**, 184 (2005) [arXiv:nucl-ex/0410003].

[48] B. B. Back *et al.*, Nucl. Phys. A **757**, 28 (2005) [arXiv:nucl-ex/0410022].

[49] I. Arsene *et al.* [BRAHMS Collaboration], Nucl. Phys. A **757**, 1 (2005) [arXiv:nucl-ex/0410020].

[50] J. Adams *et al.* [STAR Collaboration], Nucl. Phys. A **757**, 102 (2005) [arXiv:nucl-ex/0501009].

[51] N. Armesto, M. Cacciari, T. Hirano, J. L. Nagle and C. A. Salgado, J. Phys. G **37**, 025104 (2010) [arXiv:0907.0667 [hep-ph]].

[52] R. Baier and Y. Mehtar-Tani, Phys. Rev. C **78**, 064906 (2008) [arXiv:0806.0954 [hep-ph]].

[53] K. Aamodt [ALICE Collaboration], Phys. Lett. B **696**, 30 (2011) [arXiv:1012.1004 [nucl-ex]].

[54] Y. J. Lee, J. Phys. G **38**, 124015 (2011) [arXiv:1107.2131 [hep-ex]].

[55] A. Dainese and f. t. A. Collaboration, J. Phys. G **38**, 124032 (2011) [arXiv:1106.4042 [nucl-ex]].

[56] N. Armesto, A. Dainese, C. A. Salgado and U. A. Wiedemann, Phys. Rev. D **71**, 054027 (2005) [arXiv:hep-ph/0501225].

[57] J. Putschke [STAR Collaboration], Eur. Phys. J. C **61**, 629 (2009) [arXiv:0809.1419 [nucl-ex]].

[58] S. Salur [STAR Collaboration], Eur. Phys. J. C **61**, 761 (2009) [arXiv:0809.1609 [nucl-ex]].

[59] G. Aad *et al.* [Atlas Collaboration], Phys. Rev. Lett. **105**, 252303 (2010) [arXiv:1011.6182 [hep-ex]].

[60] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Rev. C **84**, 024906 (2011) [arXiv:1102.1957 [nucl-ex]].

[61] M. Cacciari, G. P. Salam and G. Soyez, Eur. Phys. J. C **71**, 1692 (2011) [arXiv:1101.2878 [hep-ph]].

[62] Y. Mehtar-Tani, C. A. Salgado and K. Tywoniuk, Phys. Rev. Lett. **106**, 122002 (2011) [arXiv:1009.2965 [hep-ph]].

[63] Y. Mehtar-Tani, C. A. Salgado and K. Tywoniuk, arXiv:1102.4317 [hep-ph].

[64] Y. Mehtar-Tani and K. Tywoniuk, arXiv:1105.1346 [hep-ph].

[65] J. Casalderrey-Solana and E. Iancu, JHEP **1108**, 015 (2011) [arXiv:1105.1760 [hep-ph]].

[66] N. Armesto, H. Ma, Y. Mehtar-Tani, C. A. Salgado and K. Tywoniuk, arXiv:1108.5298 [hep-ph].

[67] N. Armesto, H. Ma, Y. Mehtar-Tani, C. A. Salgado and K. Tywoniuk, arXiv:1110.4343 [hep-ph].

[68] K. Zapp, G. Ingelman, J. Rathsman, J. Stachel and U. A. Wiedemann, Eur. Phys. J. C **60**, 617 (2009) [arXiv:0804.3568 [hep-ph]].

[69] I. P. Lokhtin, L. V. Malinina, S. V. Petrushanko, A. M. Snigirev, I. Arsene and K. Tywoniuk, Comput. Phys. Commun. **180**, 779 (2009) [arXiv:0809.2708 [hep-ph]].

[70] N. Armesto, L. Cunqueiro and C. A. Salgado, Eur. Phys. J. C **63**, 679 (2009) [arXiv:0907.1014 [hep-ph]].

[71] B. Schenke, C. Gale and S. Jeon, Phys. Rev. C **80**, 054913 (2009) [arXiv:0909.2037 [hep-ph]].

[72] N. Armesto, G. Corcella, L. Cunqueiro and C. A. Salgado, JHEP **0911**, 122 (2009) [arXiv:0909.5118 [hep-ph]].