Photon and dilepton production in heavy ion collisions at LHC

Patrick Aurenche

LAPTH-Conf-1164/06

PHOTON AND DILEPTON PRODUCTION IN HEAVY ION COLLISIONS AT LHC *

P. Aurenche

Laboratoire d'Annecy-le-Vieux de Physique Théorique LAPTH, †
B.P. 110, F-74941 Annecy-le-Vieux Cedex, France

Abstract

We review various production mechanisms of photons and small mass dileptons at large transverse momentum in heavy ion collisions at the LHC. Their relevance as a signal for quark-gluon plasma formation is discussed.

It is commonly accepted that direct photons, once emitted in a heavy ion collision, do not interact with the hot and dense matter produced. Photons are radiated during all stages of the collision and therefore they tell us about the history of the collision and eventually about the hot matter (quark-gluon plasma) formation. This is unlike hadrons which reflect the physics after the plasma has cooled down. However the radiative decays of hadrons provide a very large background to direct photons, specially in the lower p_T range of the spectrum. To avoid the largest such background ($\pi^0 \to \gamma\gamma$) it is interesting to look at the production of small mass lepton pairs, which involve the same dynamical processes as real photons when the ratio mass over momentum is small. In the following, I discuss the transverse momentum spectrum of real photons and small mass virtual photons. Correlation functions involving a large energy photon are also considered as they are shown to give a detailed probe of the jet energy loss mechanism.

There are several production mechanisms of real or virtual photons in heavy ion collisions [1]. In *prompt* processes photons are radiated in the interaction of quarks and gluons of the incoming nucleons: their rate involves the parton densities in the colliding ions. They lead to a power damped spectrum which should dominate at high momentum. *Thermal* photons are produced in the hot quark or hadronic matter formed during the collision: their rate is directly related to the temperature of the hot matter. Finally, *mixed* processes involve a prompt high energy quark colliding with a parton in the medium. We discuss each mechanism, commenting on the accuracy of the theoretical calculations.

Prompt processes are under good control in pp collisions where many data sets, from about 20 GeV to 2 TeV, exist (fig. 1). The underlying processes, direct and bremsstrahlung, are calculated in the next-to-leading logarithm (NLO) accuracy [2, 3]. The data cover a large range in x_T, down to 10^{-2}. All data sets but one (E706) agree, within the error bars, with the theoretical predictions using standard NLO structure [4] and fragmentation [5] functions. Extrapolating to LHC at 5.5 TeV and for p_T values of interest requires controling the theory down to $x_T \sim 10^{-3}$: in such a range predictions become uncertain because the bremsstrahlung process becomes dominant, involving the essentially

*Talk given at the 2nd International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions, June 9-16 2006, Asilomar, Pacific Grove, California

†UMR5108 du CNRS associée à l'Université de Savoie.

unconstrained gluon into photon fragmentation function. Another issue is the validity of the NLO calculation in that domain where resummed calculations of the single inclusive spectrum are called for.

In heavy ion collisions, the basic structure of prompt processes remains the same except for mod-

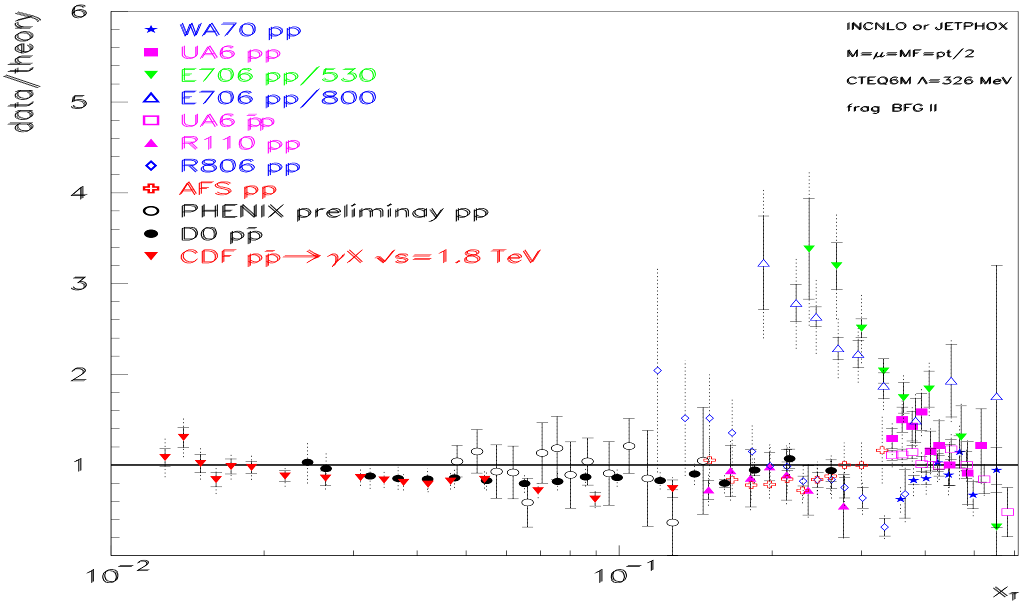

Figure 1: Prompt photon production in pp and $p\bar{p}$ collisions (from [3]).

ifications of the parton distributions due to nuclear effects, and of the fragmentation functions due to the interaction of the final hard parton with the hot medium. Several parametrisations of nuclear structure functions exist which differ in the amount of shadowing affecting the gluon at small x [6, 7, 8]. This will directly modify the photon rate which is proportional to the gluon structure function. Concerning final state effects, the mechanism of jet energy loss has been much studied [9] . It affects only photons produced by bremsstrahlung. In the first parametrisations used it was taken for granted that the same mechanism as for hadron production was at work, namely it was implicitly assumed that the photon was produced outside the plasma volume and the production rate was therefore reduced. More recently, however, it was emphasized [10] that final state interaction of the fast quark with the medium induced photon radiation: in that case the photon is emitted from within the hot plasma. Combining the jet energy loss mechanism and the enhanced photon emission will more or less compensate as shown in the model calculation in fig. 2. It should be noted that, in an *a priori* NLO calculation of the photon spectrum, thermal modifications of the fragmentation functions affect the delicate scale compensation mechanism occuring between the lowest order term and the higher order corrections, so that QCD calculations of this mechanism become of leading order accuracy only in heavy ion collisions.

The next production mechanisms we consider are purely thermal. They are usually calculated in the framework of the effective theory of Braaten and Pisarski [11] where hard thermal loops are resummed. Two classes of processes are contributing. The first one involves Compton ($Gq \to \gamma q$) and annihilation ($q\bar{q} \to \gamma G$) processes [12, 13]. The second one is of bremsstrahlung type ($Gq \to \gamma Gq$ and $qq \to \gamma qq$) together with the related crossed processes of type $Gq\bar{q} \to \gamma G$ or $qq\bar{q} \to \gamma q$ [14]. In these cases all initial partons are thermal so that the calculated rate of production of a real photon

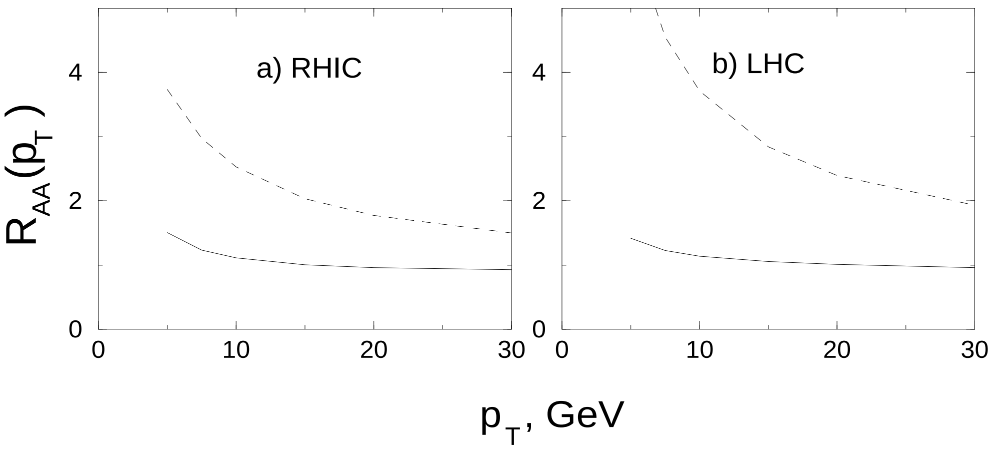

Figure 2: Ratio of direct photon production in AA collisions compared to pp collisions. Dashed line: taking into account only the induced emission by the medium. Solid line: taking into account induced emission as well as jet energy loss effects. The figure is from Zakharov [10].

is exponentially damped in the energy. For a photon of momentum $(E, \mathbf{p})$ the calculated rate is of the form $EdN/d\mathbf{p} \sim \alpha\ \alpha_s\ \exp{(-E/T)}\ T^2\ f(E/T)$ where f is a soft function of E/T. To obtain the leading order result, the second class of processes requires the resummation of ladder diagrams in the effective theory [15, 16], which is equivalent to taking into account the Landau-Pomeranchuk-Migdal effect or multiple scattering effects in the plasma. Thermal photons are also produced in the hot hadronic stage following the QGP phase [17]. In order to make predictions and compare with real data it is necessary to implement these rates in an hydrodynamical code which describes the expansion and cooling of the plasma and the transition to the hadronic phase. In the applications below we use the code of Ruuskanen *et al.* [18]. The important parameters are constrained from specified initial conditions and the predictions for various hadronic spectra were shown to agree with the measurements in $AuAu$ collisions at RHIC. In fig. 3 the thermal (dash-dotted lines) and prompt (solid line) processes discussed above are shown and compared to PHENIX data [19]. As expected, one sees the dominance of thermal processes at the smaller p_T values. The background ('decay photons') is estimated using two completely different models, the NLO + hydrodynamic model as well as the DPMJET model of Ranft *et al.* [20] involving the production and decay of hadronic strings. Both agree. It is worthwhile noting the agreement of the theoretical predictions for direct photons (prompt + thermal photons model) [1] with the published data [19, 21] within the large error bars. The model being constrained by present data, it is justified to attempt predictions for LHC (fig. 4). Thermal photons dominate over prompt photons up to rather large values of p_T, namely 6 GeV. It should stressed that thermal photons are predominantly produced in the QGP phase while at RHIC the hadronic phase is dominant. For real photons the background from hadronic decays is very large in the low p_T region. This is to be constrasted with model estimates of the dilepton spectrum ($.2 < M_{e^-e^+}$ [GeV] $< .8$) where the background becomes of the same order as the thermal rate already at 3 GeV (fig. 5). Low mass dileptons appear therefore as an important observable to directly probe the thermal effects. This has been illustrated in the case of RHIC by the recent measurement of low mass dileptons by PHENIX [21] in the low p_T region inaccessible to real photons because of the overwhelming background.

The last class of photon emission processes is the jet conversion mechanism where a hard quark (anti-quark) radiates a photon in a Compton or annihilation process with a thermal gluon or anti-quark (quark) [22]. The resulting spectrum is power behaved, reflecting the spectrum of the initial hard quark and it should contribute in the intermediate p_T region. These processes are discussed by C. Gale and S. Jeon [23, 24]. The calculation of their rate requires modeling the space time

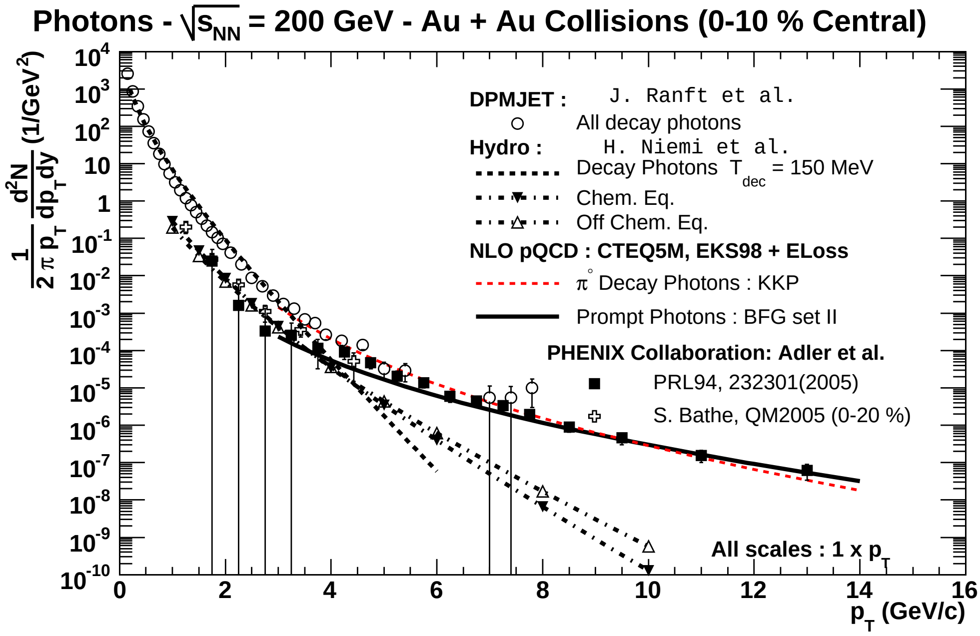

Figure 3: Single photon spectrum in $AuAu$ collisions at RHIC (from [1]). Data based on real photon [19] (black squares) and lepton pair [21] (open crosses) measurements are added for comparison with the predictions (*courtesy H. Delagrange*).

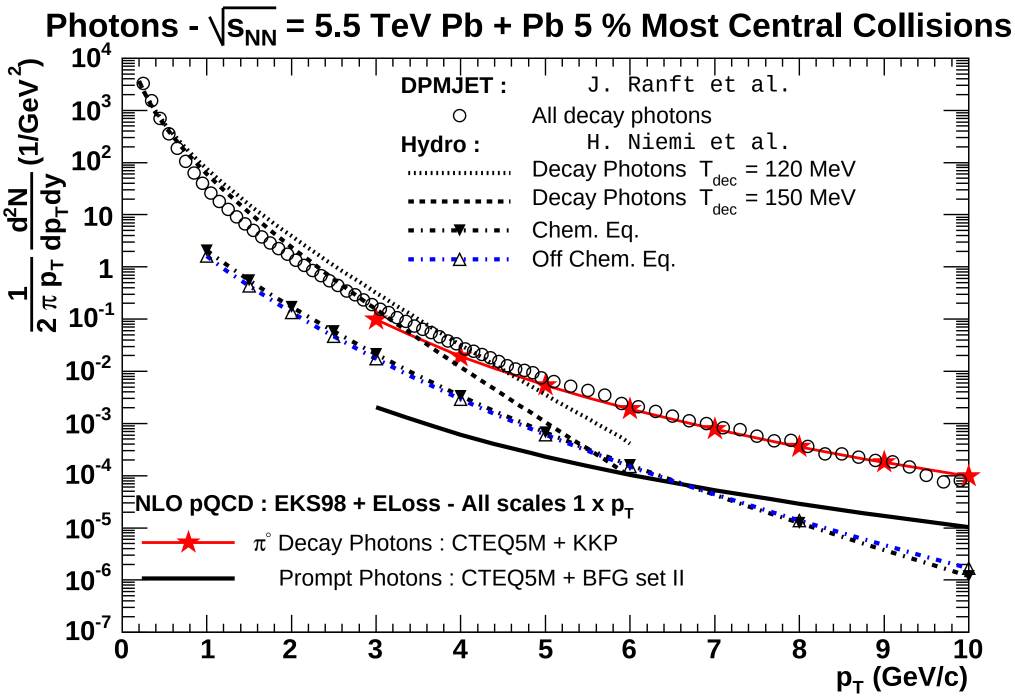

Figure 4: The various components of the single photon p_T spectrum in $PbPb$ collisions at LHC.

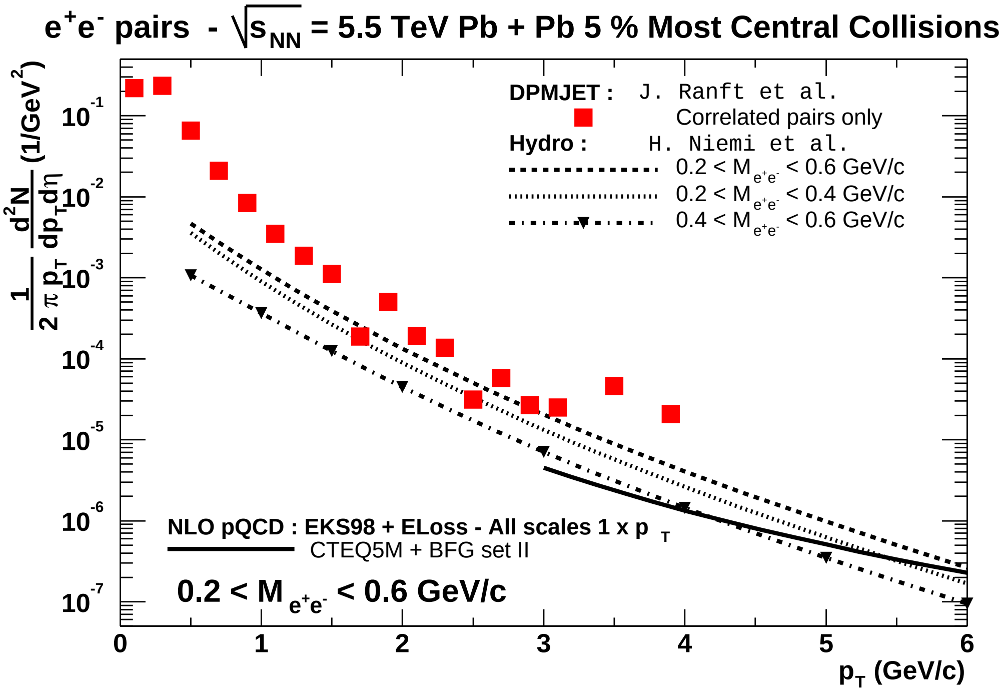

Figure 5: The various components of the single dilepton p_T spectrum in $PbPb$ collisions at LHC, for small dilepton masses. The squares are an estimate of the background.

evolution of the hard quark in the medium and therefore the model dependence is expected to be rather large. The fact that present data are consistent with models without jet conversion [1] or with jet conversion [23, 24] gives an indication on the theoretical uncertainties.

In conclusion, the single real or virtual photon spectra in a heavy ion collision receive contributions from several mechanisms: at the lowest p_T, thermal effects dominate the signal; at medium p_T jet conversion may play a role while, at the upper end of the spectrum, the medium modified bremsstrahlung and direct processes dominate. Turning to RHIC data, it is not yet possible to constrain experimentally the relative normalisation of each class of processes. Other observables should be considered to distinguish the various mechanisms.

One such class of observables concerns correlation functions involving a photon. One selects a large p_T photon, to insure that it is produced in a prompt process (the largest the transverse momentum, the smallest the bremsstrahlung component) and one can construct various measures involving this photon and hadrons or photons found in the decay of the recoiling jet [25]. Comparing these measures in pp and AA collisions should give a direct information on the medium modifications to the jet fragmentation function. Of particular interest is the variable $z = -\mathbf{p}_T^\gamma \cdot \mathbf{p}_T^a / \mathbf{p}_T^{\gamma 2}$ where $\mathbf{p}_T^a$ is the transverse momentum of a hadron or a photon recoiling from the large p_T photon. In a leading order calculation, if the hard photon is directly produced, one has simply $z \sim z_{\rm frag}$. An illustration is shown in fig. 6 with the z distribution for a photon pair: the curve labeled $\omega_c = 0$ GeV makes use of the parton into photon fragmentation function as in the vacuum, while the curve $\omega_c = 50$ GeV is for a model energy loss mechanism appropriate for LHC. Superimposed on the correlation curves are the input fragmentation functions. The z distributions appear to follow closely the input functions and therefore provide a way to probe in detail the jet energy loss mechanism. The same measure involving a pion (photon-pion correlation) would have a larger rate but leads to a more complex picture because of the convolution with the production processes [25]. At small z the dominant process is direct photon

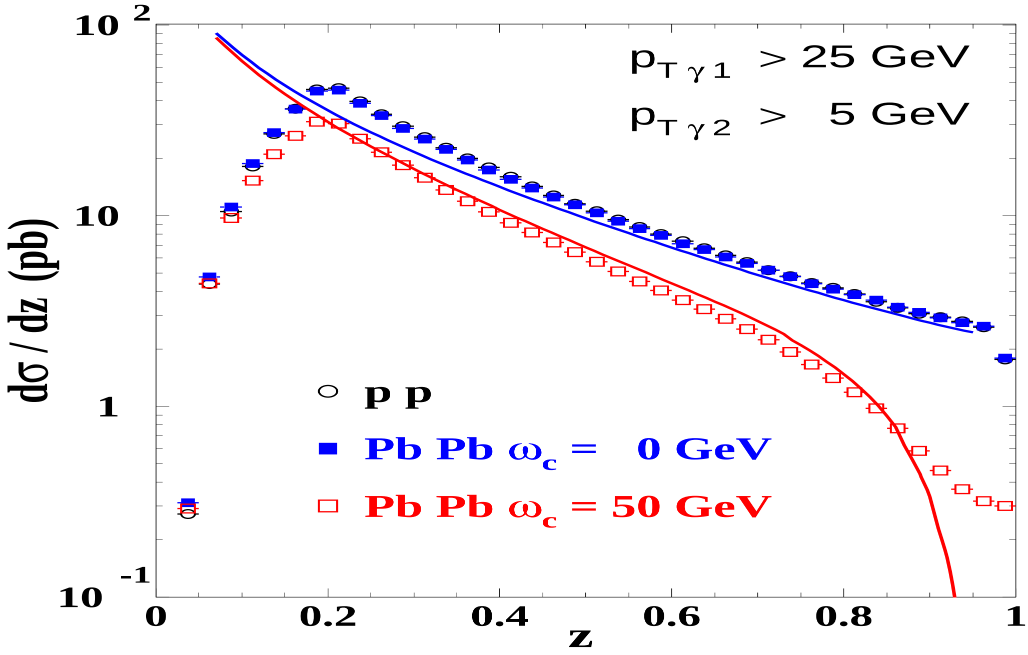

Figure 6: Exemple of a photon-photon correlation function at LHC (*courtesy F. Arleo*).

while at large z it is bremsstrahlung production where the relation $z \sim z_{\rm frag}$ does not hold. The simple relation between the fragmentation function and the observable is lost. However, comparing the pp and AA cases gives important information on the fragmentation process.

In conclusion, observables involving photons provide promising signals for thermal effects. Due to the variety of emission mechanisms single spectra do not allow to disentangle between the various channels. Correlation observables such as that presented above provide detailed information on the hard parton interaction in the hot medium.

I thank F. Arleo for discussions and H. Delagrange for discussions and providing many figures. I also thank the organizers of the meeting for financial support.

References

[1] For a review on photon and dilepton production at the LHC, see F. Arleo *et al.*, *Photon physics in heavy ion collisions at the LHC*, hep-ph/0311131, in CERN Yellow Report *Hard probes in heavy ion collisions at the LHC*.

[2] P. Aurenche, R. Baier, M. Fontannaz and D. Schiff, Nucl. Phys. **B297**, 661 (1988); P. Aurenche, P. Chiappetta, M. Fontannaz, J.Ph. Guillet and E. Pilon, Nuc. Phys. **B399**, 34 (1993).

[3] P. Aurenche, M. Fontannaz, J.Ph. Guillet, E. Pilon and M. Werlen, Phys. Rev. **D73**, 094007 (2006).

[4] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. Nadolsky, W. K. Tung, JHEP **0207**, 012 (2002); A.D. Martin, R.G. Roberts,W.J. Stirling, R.S. Thorne, Phys. Lett. **B604**, 61 (2004)

[5] L. Bourhis, M. Fontannaz and J. P. Guillet, Eur. Phys. J. **C2**, 529 (1998).

[6] K.J. Eskola, V.J. Kolhinen, C.A. Salgado, Eur. Phys. J. **C9**, 61 (1999).

[7] M. Hirai, S. Kumano, M. Miyama, Phys. Rev. **D64**, 034003 (2001).

[8] D. de Florian, R. Sassot, Phys. Rev. **D69**, 074028 (2004).

[9] R. Baier, D. Schiff and B.G. Zakharov, Ann. Rev. Nucl. Part. Sci. **50**, 37 (2000)

[10] B.G. Zakharov, JETP Lett. **80**, 1 (2004), hep-ph/0405101.

[11] E. Braaten, R.D. Pisarski, Nucl. Phys. **B337**, 569 (1990); **B339**, 310 (1990); J. Frenkel, J.C. Taylor, Nucl. Phys. **B334**, 199 (1990); **B374**, 156 (1992).

[12] J.I. Kapusta, P. Lichard, D. Seibert, Phys. Rev. **D44** 2774 (1991) 2774; R. Baier, H. Nakkagawa, A. Niegawa, K. Redlich, Z. Phys. **C53**, 433. (1992).

[13] T. Altherr, P.V. Ruuskanen, Nucl. Phys. **B380**, 377 (1992); M.H. Thoma, C.T. Traxler, Phys. Rev. **D56**, 198 (1997).

[14] P. Aurenche, F. Gelis, R. Kobes, H. Zaraket, Phys. Rev. **D58**, 085003 (1998); P. Aurenche, F. Gelis, H. Zaraket, JHEP **0207**, 063 (2002).

[15] P. Aurenche, F. Gelis, H. Zaraket, Phys. Rev. **D61**, 116001 (2000); **D62**, 096012 (2000) ; P. Arnold, G.D. Moore, L.G. Yaffe, JHEP **0111**, 057 (2001); *JHEP* **0112**, 009 (2001); *JHEP* **0206**, 030 (2002).

[16] P. Aurenche, F. Gelis, G.D. Moore, H. Zaraket, JHEP **0212**, 006 (2002).

[17] R. Rapp and J. Wambach, Eur. Phys. J. **A6**, 415 (1999).

[18] K.J. Eskola, K. Kajantie, P.V. Ruuskanen, Eur. Phys. J. **C1**, 627 (1998); P. Huovinen, P.V. Ruuskanen, nucl-th/0605008.

[19] PHENIX Collaboration, S.S. Adler *et al.*, Phys. Rev. Lett. **94**, 232301 (2005).

[20] R. Engel and J. Ranft, Phys. Rev. **D54**, 4244 (1996); S. Roesler, R. Engel and J. Ranft, hep-ph/0012252; J. Ranft, hep-ph/9911213, hep-ph/9911232.

[21] Y. Akiba, Nucl. Phys. **A774**, 403 (2006); S. Bathe, *ibid.* 731 (2006).

[22] R. J. Fries, B. Müller and D. K. Srivastava, Phys. Rev. Lett. **90**, 132301 (2003).

[23] S. Turbide, C. Gale, Sangyong Jeon, G. D. Moore, Phys. Rev. **C72**, 014906 (2005); S. Turbide, C. Gale, D. K. Srivastava, R. J. Fries, *ibid.* **C74**, 014903 (2006).

[24] Talks by C. Gale and S. Jeon in these proceedings.

[25] F. Arleo, P. Aurenche, Z. Belghobsi and J. Ph. Guillet, JHEP **11**, 009 (2004); for RHIC, see F. Arleo hep-ph/0601075.