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Photons production from the early stages of relativistic heavy ion collisions

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Abstract

We present preliminary results about photons production in relativistic heavy ion collisions. The main novelty of our study is the calculation of the contribution of the pre-equilibrium stage to the photon spectrum. The initial stage is modeled by an ensemble of classical gluon fields which decay to a quark-gluon plasma via the Schwinger mechanism, and the evolution of the system is studied by coupling classical field equations to relativistic kinetic theory; photons production is then computed by adding collision processes into the collision integral. We find that the contribution of early stage photons to the direct photon spectrum is substantial in the transverse momentum region $p_T \gtrsim 1.5$ GeV.

Keywords: Relativistic heavy ion collisions, Glasma, Photons, Relativistic transport theory

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1. Photons sources in heavy ion collisions

Photons are important probes of the quark-gluon plasma (QGP) produced in relativistic heavy ion collisions. In fact, they are radiated during the whole lifetime of the system produced by the collisions, and because their mean free path is much larger than the collision volume, they leave the system undisturbed. It is common to distinguish among direct photons, namely those arising from collision processes, and decay photons that are instead produced by hadron decays. Direct photons are mainly split into prompt photons, produced by primordial scatterings among the nucleons, and thermal photons, that instead are produced by a thermalized QGP and hadron gas. This conventional splitting of the contributions to the direct photons produced in nuclear collisions misses a potentially important contribution, namely the photons produced by quark-gluon scatterings in the pre-equilibrium stage. While thermal and prompt photons have been already studied [1, 2, 3, 4], a study of photon emission in the out-of-equilibrium stage of heavy ion collisions is still missing.

We aim to fill this gap here, by presenting preliminary results about photon production considering pre-equilibrium photons on the same footing of themal photons. Although the initial state is gluon dominated (in fact, it is represented by a classical field given the large gluon occupation number) the decay of the initial field produces quickly quarks and gluons that scatter and create photons even when the system is not a thermalized QGP. We implement photons production by means of a collision integral, therefore we do not follow the common strategy used in previous calculations [1] in which one has to assume local thermalization and integrate the rates over the spacetime volume of the fireball. This is the advantage of using relativistic transport theory, which allows to study photons production also in the early stages where hydro certainly cannot be applied. Nonetheless, we will see that in thermal QGP phase the two approaches gives nearly identical results.

2. Model and dynamics

In this section we explain the model that we use for the initial stage, as well as the theoretical scheme that we use to describe the dynamical evolution of the

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system, see [5] for further details. We implement the Abelian Flux Tube (AFT) model [6] with an initial condition made of a longitudinal color-electric field, neglecting for simplicity color-magnetic fields which should be considered in a more appropriate description of the Glasma. We also assume the initial field is boost-invariant along the longitudinal direction, ignoring initial transverse fields as well as quantum fluctuations in rapidity. The initial field then decays into QGP by the Schwinger mechanism [7].

The dynamics of the many-particle system produced by the decay of the color-electric field is described by the relativistic Boltzmann transport equation:

$$\left(p^\mu \partial_\mu + gQ_{jc}F^{\mu\nu} p_\nu \partial^p_\mu\right) f_{jc}(x,p) = \frac{dN_{jc}}{d\Gamma} + C_{jc}\left[f\right], \quad (1)$$

where $f_{jc}(x,p)$ is the distribution function for flavor j and color c and $F^{\mu\nu}$ is the field strength tensor. On the right hand side of the above equation, $dN/d\Gamma$ is the invariant source term which accounts for the creation of pairs due to the Schwinger effect. Finally $C\left[f\right]$ represents the collision integral, which describes how f changes due to collision processes.

The 3+1 dimensional dynamics of the QGP is coupled to that of the classical gluon field, the latter being governed by the abelian Maxwell equations:

$$\nabla \cdot \mathbf{E} = \rho, \qquad \frac{\partial \mathbf{E}}{\partial t} = -\mathbf{J}, \quad (2)$$

where t is the time in the laboratory frame. The initial field is only longitudinal, whereas transverse components of $\mathbf{E}$ will be generated by transverse currents according to Eq. 2. The total current is $\mathbf{J} = \mathbf{J}_D + \mathbf{J}_M$; while $\mathbf{J}_M$ represents the standard color current due to charge movements, $\mathbf{J}_D$ corresponds to the displacement current, namely describes the variation of the local dipole moment in the system induced by the pair creation. Since color charges and currents depend on parton distribution functions, we solve field and particles equations self-consistently, taking into account the back-reaction of the QGP on the field. We notice that, even if the equation of motion of the classical field is abelian, there is a sign of the non-abelian nature of QCD because the background field interacts with gluon quanta via $\mathbf{J}_D$.

We solve numerically the Boltzmann equation and the field equations simultaneously on a tridimensional lattice by means the test particle method to sample $f(x,p)$; the collision integral is computed by means of a stochastic algorithm [8, 9, 10, 11, 12, 13, 14]. Within this theoretical approach one can follow the entire dynamical evolution of the system produced in relativistic heavy ion collisions.

In our calculation we add, to the collision integral of Eq. 1, the processes with one photon in the final state. In this preliminary work we focus on the $2 \to 2$ scatterings, *i.e.* the QCD Compton scattering $q/\bar{q}+g \to q/\bar{q}+\gamma$ and the quark-antiquark annihilation $q+\bar{q} \to g+\gamma$, leaving the inclusion of $2 \to 3$ processes and of the Landau-Pomeranchuk-Migdal effect [2] to future works. Once again we remark that within our calculation it is not necessary to integrate a collision rate over a spacetime volume, as it is done in hydro calculations, because photon production is considered consistently by means of microscopic processes in the collision integral; moreover, photons are produced by quark-gluon scatterings as soon as QGP is produced by the decay of the color field, therefore photon radiation starts as soon as the conversion from the initial field to QGP takes place.

Next we turn to describe the initializations that we use in our calculations. We consider a Glauber model with the standard mixture $0.85N_{part} + 0.15N_{coll}$ and a thermalized spectrum in the transverse plane at a time $\tau_0 = 0.6\,\mathrm{fm}/c$ with a maximum initial temperature $T_0 = 340\,\mathrm{MeV}$. Following Ref. [13] we call the latter case the Th-Glauber initialization. For the AFT model initialization, although an ensemble of flux tubes in the transverse plane would be more appropriate to mimic the Glasma [15], we assume for the sake of simplicity that the initial chromo-electric field is given by smooth distribution in the transverse plane, that is

$$E^0_z(\boldsymbol{x}_T) = E_0\left[c\rho_{coll}(\boldsymbol{x}_T) + (1-c)\rho_{part}(\boldsymbol{x}_T)\right], \quad (3)$$

with $\boldsymbol{x}_T$ standing for a coordinate in the transverse plane. The two free parameters E_0 and c are fixed in order to match at $t_0 = 0.6\,\mathrm{fm}/c$ particle multiplicity and eccentricity with those of the Th-Glauber case at initial time. In this talk we focus on RHIC collisions with an impact parameter $b = 7.5\,\mathrm{fm}$, although we have checked that simulations at LHC energies as well as with other impact parameters do not give qualitatively different results from the one presented here. For RHIC collision at $b = 7.5\,\mathrm{fm}$ we obtain, for the parameters in Eq. (3), $E_0 = 3.3\,\mathrm{GeV}^2$ and $c = 0.6$.

3. Results

In the upper panel of Fig. 1 we plot the evolution of the color-electric field, averaged at midrapidity $|y| \le 0.5$ and over a central region of the transverse plane, $|\boldsymbol{x}_T| \le 3$ fm. In the inset of the upper panel we plot the averaged transverse components of the color field. In the middle panel we plot the number of gluons (indigo solid line) and quarks+antiquarks (orange dashed line)