Non-thermal photons from the pre-equilibrium stages

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Abstract. I compute the invariant yield of photons from the pre-equilibrium stage of heavy-ion collision using the "bottom-up" thermalization scenario and scaling gluon distributions found in classical statistical lattice simulations. I find it to dominate the spectrum specially at higher values of the saturation scale $Q^2_s$. I constrain the system using charge hadron multiplicities from LHC and RHIC, where fair agreement with data is obtained. Finally, I present a comparison of the "bottom-up" scenario to one in which a thermal stage is achieved at an early time, $Q_s \tau \sim 1$.

1. Introduction
Direct photons are created during every stage of heavy-ion collisions (HIC), which makes them excellent probes to test the evolution of the hot medium. Because they lack final state interactions, direct photons are quite sensitive to the different stages that the expanding fireball goes through. Furthermore, photons (and dileptons) may be the only probes which are sensitive to the pre-equilibrium stage of the expanding fireball. Although this stage is normally thought to produce a negligible photon yield, recent works indicate that contributions from the pre-equilibrium stages are comparable to such of the thermal stages [1, 2, 3]. In this work I present results from a simple model for the case of a late thermalization in the bottom-up thermalization scenario [4]. For this, the system is taken to be transversally homogeneous and boost invariant system (commonly called Bjorken expansion). The information of the gluon and quark distributions is extracted from classical statistical simulations [5].

This brief paper is organized as follows. In the following section I introduce the different sources of photon production, emphasizing on the pre-equilibrium stage. In section 3 I present the results, as well as the comparison to data from ALICE and PHENIX. I present also a comparison to an early thermalization scenario, where I find that the pre-equilibrium case enhances the total spectrum, in contrast with the thermal case. Finally, I present in section 4 a summary of my findings, as well as a brief outlook.

2. Photon Contributions
Direct photons from a HIC can be produced at the initial, pre-equilibrium or thermal stages of the fireball, where the latter can be split into the thermal quark-gluon-plasma (QGP) and hadron resonance gas (HRG) stages. The total direct invariant yield is simply given by the sum of these contributions.
2.1. Prompt photons
I will start with the photons from the initial stage, which are produced by hard scattering and annihilation of the participating partons. These photons are normally referred to as prompt photons. The prompt photon invariant yield is then given by

$$\frac{dN_{\text{prompt}}}{d^2p_\perp dy} = T_{AA} \frac{d\sigma_{\text{pp}}}{d^2p_\perp dy}$$

(1)

where the $\sigma_{\text{pp}}$ label stands for prompt photon (pQCD) cross section, which will be scaled by a centrality dependent factor, $T_{AA}$, with $A = \text{Au, Pb}$. This can be calculated directly from the Glauber model. For the extension of the scaled pQCD to lower $p_\perp$ values, which is needed to add this contribution to the in-medium spectra, I have used the following functional form,

$$\frac{d\sigma_{\text{pp}}}{d^2p_\perp dy} = A_{\text{pp}} \left( 1 + \frac{p_\perp^2}{P_0^2} \right)^{-n}$$

(2)

which was used by PHENIX to fit the $p + p$ results in [6]. For ALICE at 2.76 TeV, the values obtained were $P_0 = 0.628$ GeV$^2$, $A_{\text{pp}} = 0.095$ mb GeV$^{-2}$ and $n = 2.375$.

2.2. The pre-equilibrium stage
Using the small angle approximation, one can simplify the general 2-to-2 scattering rates,

$$E \frac{dN}{d^4Xd^3p} = \frac{40}{9\pi^2} \alpha \alpha_S \mathcal{L} f_q(\tau, p) I_g,$$

(3)

where quark annihilation and Compton scattering were taken into account [1]. Here, $\alpha$ and $\alpha_S$ are the electromagnetic and strong couplings and $\mathcal{L}$ is a regulator which rises from the approximation (see ref. [2] for a discussion on this). The quark distribution, $f_q$, and the integral $I_g$ contain all phase-space information for the production of photons. I will use the hard dipole approximation, $f_q \sim \alpha_S f_g$, where I extract the gluon distribution from classical statistical simulations, which can be parametrized as

$$f_g(\tau; p_\perp, p_z) = \frac{1}{\alpha_S} (Q_s \tau)^{-2/3} f_S(p_\perp, p_z) (Q_s \tau)^{1/3}$$

(4)

where $Q_s$ is the characteristic scale of the system, which can be associated to the saturation scale [11]. This scaling solution, $f_S$, was found in numerical studies for Bjorken expanding lattices [5], and it is given by the form

$$f_S(p_\perp, p_z) = f_0 \frac{Q_s}{p_\perp} \exp \left( -\frac{p_\perp^2}{2 \sigma_0^2} \right) \left\{ \theta(Q_s - p_\perp) + \theta(p_\perp - Q_s) \exp \left[ -\frac{1}{2} \left( \frac{p_\perp - Q_s}{r Q_s} \right)^2 \right] \right\},$$

(5)

where $f_0$ is fixed to find the results for total yield in ref.[1]. This scaling solution is compatible to the bottom-up prediction of scaling exponents, which I will use to determine the space-time dependence of $I_g$ in eq. (3), which is related directly to the Debye mass of the gluons. Using this scenario, the pre-equilibrium epoch is divided in three stages: first, hard scatterings dominate, then there is a rise in soft gluons and finally the soft bath thermalizes the system. During the first stage, $1 < \tau Q_s < \alpha^{-3/2}$, hard gluons dominate the system. These gluons are created during the earlier times via the production of instabilities, arising from the strong interaction of the

1 The $I_g$ integral is related to an effective screening. Int thermal equilibrium, where $m_D^2 = 16\pi\alpha_S(N_c I_g + N_f I_g)$. Here, $N_c$ and $N_f$ are the number of colors and flavors, respectively
Figure 1. Upper panels: Fraction for each contribution to the total direct photon multiplicity in Au-Au collisions at √s = 200 GeV, for the 0 − 20% centrality class, and a saturation scale of Q_s^2 = 1.67 GeV^2 and comparison to RHIC data [6]. Lower panels: Fraction in Pb-Pb collisions at √s = 2.76 TeV, for 0 − 20% centrality class, and a saturation scale of Q_s^2 = 2.8 GeV^2 and comparison to data [10].

macroscopic gluon fields [8], and are described by the scaling solution of eq. (4). The Debye mass is dominated by hard gluons, with m_D ∼ α_S n_{hard}/Q_s ∼ 1/(Q_s τ). Using this, it can be found that for the first two stages

\[ I_g(\tau) = \frac{Q_s^2}{4\pi^2 \alpha_S (Q_s \tau)^\lambda}, \quad \text{with} \quad \kappa_g = \frac{c}{2N_c}. \]  

(6)

Here, c = 1.1 corresponds to the gluon liberation factor from ref. [9], and λ = 1 during the first stage. During the second stage, α^{−3/2} < τ Q_s < α^{−5/2}, the number of soft gluons increases, dominating the Debye mass. Now the exponent in eq.(6) is λ = 1/2. In the third stage, α^{−5/2} < τ Q_s < α^{−13/5}, hard gluons lose quickly energy to a bath of thermal soft gluons. In this stage, I use thermal rates to compute this contributions. Finally, the system arrives to a thermalization temperature of T_{th} ∼ c_T c_{eq} α^{2/5} Q_s at a time τ_{th} ∼ c_{eq} α^{-13/5} Q_s^{-1}. The parameters c_T and c_{eq} are dimensionless proportionality constants, use to fix the thermalization time and temperature. While c_T = 0.18, is known to logarithmic accuracy, c_{eq} can be fixed by using experimental data on dN_{ch}/dy, the yield of charged hadrons. For information on the fixing procedure, see refs. [1, 2]. The saturation scale is found using the IP-Glasma model [11]. The remaining parameters are taken here to be free, and fixed to describe the data, with σ_0/Q_s = 0.15 and r = 0.35.

The total contribution of the pre-equilibrium stage is then found by integrating these three rates throughout the evolution, for a boost invariant, transversely homogeneous cylinder, for which the area is found using the Glauber model [12].

2.3. Thermal stages

As stated above, photons can be radiated in both the QGP and HRG stages. In the quark gluon plasma stage, electromagnetic probes are radiated directly from the deconfined medium
of quarks and gluons. To compute this contribution I use the full leading order (LO) results as parametrized in ref. [7]. This rate contains the LL terms from 2-to-2 scattering contributions, as well as near-collinear radiation, which dominates at lower photon energies. At a critical temperature, \( T_c = 154 \) MeV, I switch to the HRG stage, where hadron bremsstrahlung rates are used. This contribution includes meson and baryon rates, as well as \( \pi\pi \rightarrow \pi\pi\gamma \) scattering rate. I have included, as in ref. [13], the reactions of the \( \pi\rho\omega \) meson system [14, 15, 16] The thermal contribution is the computed on a Bjorken expanding cylinder, initialized at the thermalization time and temperature.

3. Results

In fig. 1, I present the computation for the case of direct photons from the bottom-up scenario and thermal stages. To compute it, I sum over the sources presented above, with a small caveat. To account for the uncertainties which may arise for normalization discrepancies, e.g. volume and evolution uncertainties, I rescale the pre-equilibrium and thermal stages by a factor of \( K_{\gamma} = 2.8 \). This factor accounts also for sensitivities of the spatial energy density profile, which is neglected in this calculation. Error bands are presented by varying the parameters \( \sigma \) and \( c_T \) by 50%. The pre-equilibrium rates are mildly sensitive also to order \( O(1) \) coefficients which precisely give the initial and ending times of the stages. Nevertheless, such fine tuning of the epochs is not the scope of the calculation. For a full discussion on the source of errors from the parameters, see ref. [2].

I find in fig. 1 (left) that the low-\( p_{\perp} \) part of the spectrum is dominated by pre-equilibrium photons, for both energies studied. This is in high contrast to what is commonly expected for the pre-equilibrium. I can explain this discrepancy by noting that given the late thermalization time found in this study, \( \tau_{th} \sim 2 \) fm, it is possible that this study serves as a best case-scenario for pre-equilibrium photons. Nonetheless, this work serves to establish that the contribution of the pre-equilibrium stage is considerable. Further studies should focus on better distinguishing the relevance of the pre-equilibrium stages of direct photon production.

Since the thermalization time found in this study is so large in comparison to what is commonly used to initialize simulation, \( \tau_{hydro} \sim 0.4 \) fm, I perform a comparison to scenario which I call early hydro (see fig. 2). This scenario consists of a thermal stage initialized at \( Q_s\tau = 1 \). I fix the system to have the same energy density as the bottom-up case at \( \tau_{th} \), for a fair comparison. I find that for both LHC and RHIC energies, at high centralities, the pre-

![Figure 2. Comparison of the bottom-up case to an early thermalization scenario for \( \sqrt{s} = 200 \) GeV, for 0 – 20% centrality class (left) and \( \sqrt{s} = 2.76 \) TeV, for 0 – 20% centrality class (right). I can see that for higher energies, the pre-equilibrium stage becomes more relevant.](image-url)
equilibrium contribution is larger than the thermal case by about a factor of two. This is a promising result, as it is hinting that the inclusion of pre-equilibrium photons to the standard hydrodynamical simulations may be key to solving the so-called direct photon puzzle [17].

4. Summary and Outlook
I present a calculation for the complete spectrum of direct photons, where the contribution added in this work is the pre-equilibrium stage. To model the latter, I use the bottom-up scenario. This contribution dominates the total photon spectrum for $p_\perp < Q_s$ and realistic parameters at LHC and RHIC energies. Taking all contributions together, and the inclusion of an overall normalization factor, I find fair agreement with ALICE and PHENIX data. This simplified model serves then as a proof-of-concept to challenge the idea of the volume suppression of photon production from the pre-equilibrium stage. In fact, these results, as well as previous works [3, 18] seem to suggest that the direct photon puzzle’s solution may be achievable with the inclusion of pre-equilibrium photons.

In future work, two avenues can be taken to better understand the relevance of the pre-equilibrium stage. First, the inclusion of anisotropies in the form of a dynamical, transverse resolved profile for the non-equilibrium energy density will enhance the photon spectrum, creating a blue-shift in the spectrum, and accounting for the correct initial conditions (temperature and velocity) of the thermal stage. On the other hand, photon correlations, in the form of Hanbury-Brown-Twiss functions [19] are more sensitive to the space-time evolution than the invariant yield. Studying these is a valuable tool to distinguishing between different scenarios of photon production [20].

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