Emission of thermal photons and the equilibration time in heavy-ion collisions

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The emission of hard real photons from thermalized expanding hadronic matter is dominated by the initial high-temperature expansion phase. Therefore, a measurement of photon emission in ultrarelativistic heavy-ion collisions provides valuable insights into the early conditions realized in such a collision. In particular, the initial temperature of the expanding fireball or equivalently the equilibration time of the strongly interacting matter are of great interest. An accurate determination of these quantities could help to answer the question whether or not partonic matter (the quark-gluon plasma) is created in such collisions. In this work, we investigate the emission of real photons using a model that is based on the thermodynamics of QCD matter and which has been shown to reproduce a large variety of other observables. With the fireball evolution fixed beforehand, we are able to extract limits for the equilibration time by a comparison with photon emission data measured by WA98.

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I. INTRODUCTION

In the hot and dense system created in an ultrarelativistic heavy-ion collision (URHIC), the relevant momentum scales for typical processes taking place inside the strongly interacting matter drop as a function of proper time τ. Initially, the relevant scale is set by the incident beam momentum, leading to hard scattering processes that presumably can be described by perturbative quantum chromodynamics (pQCD). Secondary inelastic scattering processes subsequently lower the momentum scales due to particle production. At later times, equilibration sets in and typical momenta p are determined by the temperature T of a given volume element as $\langle p\rangle = 3T$. As the matter expands, energy stored in random motion of particles (temperature) is transferred to collective motion (flow), leading to a decrease of T with decreasing τ. Therefore, by selecting an observable associated with a given momentum scale, one simultaneously selects a time period in the evolution of the system.

For this reason, a measurement of hard real photons is an ideal tool to study the early moments of the fireball expansion. High momentum photons are not only sensitive to early proper times, but, being subject to electromagnetic interactions only, their mean free path in the fireball matter is also much larger than the spatial dimension of the system (therefore they are capable of leaving the emission region without significant rescattering). Therefore, hard photons complement a measurement of low mass, low momentum dileptons that are dominantly emitted near the kinetic freeze-out point.

Ideally, one would like to use hard photon emission as a thermometer to determine the initial temperature reached in an URHIC and use this information to verify the creation of a quark-gluon plasma (QGP). However, in reality one has to disentangle thermal contributions to the photon spectrum from contributions coming from initial hard scattering processes. The interpretation of the photon spectrum alone can therefore not be unambiguous.

In this work, we compare a model calculation of photon emission from a fireball created in an 158A GeV Pb-Pb collision at SPS with data obtained by the WA98 Collaboration [1]. In a recent paper [2], we have developed a fireball model based on information from hadronic observables and lattice QCD thermodynamics, as manifest in a quasiparticle picture of the QGP. This model has been shown to successfully describe low mass dilepton emission [2] and, within the framework of statistical hadronization, the measured abundances of hadron species [3]. In the present work, we demonstrate that the same model is also capable of describing the observed photon emission. The fixed setup of the model also enables us to establish constraints on the equilibration time τ_0, which entered the model on an *ad hoc* basis so far.

This paper is organized as follows. First, we introduce the photon emission rate used in the calculation and discuss its interpretation in the framework of the quasiparticle picture of the QGP, which has been used in the fireball evolution model. In the next section, we summarize the main properties of the evolution model and discuss constraints for the initial expansion phase. Afterwards we present the resulting photon spectrum and demonstrate that, in agreement with our expectation, hard photons originate dominantly from the early evolution phase. We investigate the possibility of using the photon data to set limits on the equilibration time of the fireball matter and conclude by comparing to the results obtained by other groups.

II. THE THERMAL PHOTON EMISSION RATE

A. The QGP contribution

As we expect the dominant contribution to the spectrum of hard photons to come from a region of high temperatures, we focus on the QGP rate. To leading order, this rate can be calculated by evaluating the four diagrams shown in Fig. 1. Here the last two diagrams are promoted to leading order because of near-collinear singularities.

The complete calculation of the rate to order α_s has been a very involved task that has been finished only recently [4–10]. For the present calculation, we use the parametriza-

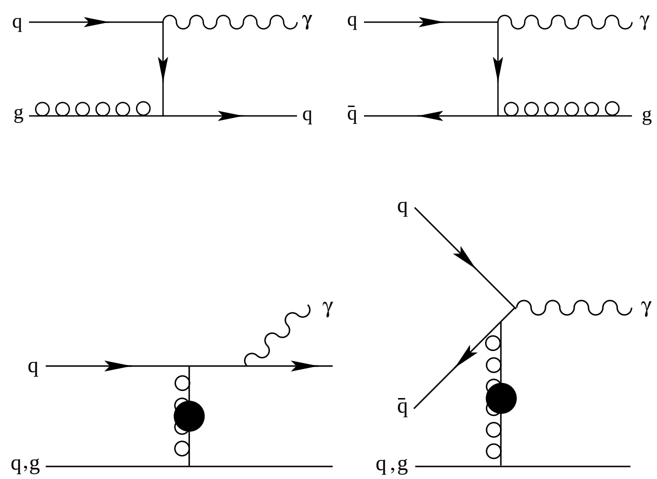

FIG. 1. (Color online) Leading order processes for photon production in the QGP (from left to right): QCD Compton scattering, $q\overline{q}$ annihilation, Bremsstrahlung, and annihilation with scattering (aws).

tion of the rate given in Ref. [10]. There, the rate for photons of momentum k is written as

$$\frac{dN}{d^4x d^3k} = \frac{1}{(2\pi)^3}\mathcal{A}(k)\left(\ln[T/m_q(T)] + \frac{1}{2}\ln(2E/T) + C_{tot}(E/T)\right) \tag{1}$$

with $E=k$ and $m_q^2(T)=4\pi\alpha_s T^2/3$ the leading order large momentum limit of the thermal quark mass. The leading log coefficient $\mathcal{A}(k)$ reads

$$\mathcal{A}(k) = 2\alpha N_C \sum_s q_s^2 \frac{m_q^2(T)}{E} f_D(E). \tag{2}$$

Here, the sum runs over active quark flavors and q_s denotes the fractional quark charges in units of elementary charge. The Fermi-Dirac distribution $f_D(E)$ dominates the momentum dependence of the rate: To a good approximation, it decreases exponentially with E. The dependence on the specific photon production process is contained in the term $C_{tot}(E/T)$,

$$C_{tot}(E/T) = C_{2\leftrightarrow 2}(E/T) + C_{brems}(E/T) + C_{aws}(E/T). \tag{3}$$

All these functions $C(E/T)$ involve nontrivial multidimensional integrals that can only be solved numerically. In Ref. [10], parametrizations for the results are given as

$$C_{2\leftrightarrow 2}(E/T) \simeq 0.041(E/T)^{-1} - 0.3615 + 1.01 \times \exp[-1.35E/T] \tag{4}$$

and

$$C_{brems}(E/T) + C_{aws}(E/T) \simeq \sqrt{1+\frac{1}{6}N_f}\left(\frac{0.548\ln[12.28+1/(E/T)]}{(E/T)^{3/2}} + \frac{0.133E/T}{\sqrt{1+(E/T)/16.27}}\right). \tag{5}$$

B. A quasiparticle interpretation

In Ref. [2], we have used a picture of massive, noninteracting quark and gluon quasiparticles to describe the QGP. Close to the phase transition these quasiparticles are subject to confinement, parametrized by a universal function $C(T)$ that reduces the number of thermodynamically active degrees of freedom as $n(T)=n_0(T)C(T)$ with $n_0(T) = \int[d^3p/(2\pi)^3]f_{B(D)}(E_p/T)$. Here, $f_{B(D)}(E_p/T)$ denotes the Bose (Fermi) distribution. In Ref. [11], it has been shown that this ansatz is capable of describing the lattice results for the QCD thermodynamics extremely well.

In the case of photon emission, we cannot strictly retain this interpretation. The process $q\overline{q}\rightarrow\gamma$ is kinematically impossible and all other emission processes would be suppressed by α_{em} for noninteracting quasiparticles. On the other hand, the fact that we want to study hard photons implies that at least one of the particles in the initial state is also hard. But such particles penetrate the screening cloud of thermal fluctuations, which is ultimately responsible for the notion of weakly interacting quasiparticles. Therefore it appears reasonable to allow for interactions of plasma particles with momenta well above the scale set by the temperature.

The remaining properties of the quasiparticle approach are encoded in the quasiparticle mass $m(T)$ and the "confinement factor" $C(T)$. In the limit of large temperatures, the quasiparticle mass in Ref. [11] is chosen so as to coincide with the result of hard thermal loop (HTL) resummed calculations for the thermal self-energy. Therefore, inserting massive quarks as degrees of freedom into the above results would amount to double counting, since those already incorporate HTL resummation, at least as long as we consider only temperatures above $1.5T_C$.

There is no equivalent of the confinement factor $C(T)$ in the calculations described in Refs. [4–10]. We can estimate the effect of introducing $C(T)$ as follows.

A typical diagram, say $q\overline{q}$ annihilation, which contributes R_0 to the total emission rate has the structure $R_0 \sim f_D(E/T)^2|\mathcal{M}|^2[1+f_B(E/T)]$, with the thermal quark distributions f_D in front of the squared matrix element $\mathcal{M}$ corresponding to the process in vacuum and a Bose enhancement factor for the gluon emitted into the final state. The modification of the rate R with respect to the rate R_0 in the presence of $C(T)$ will read $R\sim C(T)^2 f_D(E/T)^2|\mathcal{M}|^2[1+C(T)f_B(E/T)]$, which is always larger than $C(T)^3R_0$. In the case of quarks in the final state, $C(T)$ leads even to a reduced Pauli blocking (the final state modification becomes $[1-f_D(E/T)C(T)]$, which is larger in the presence of confinement).

On the other hand, as mentioned above, at least one of the incoming particles has to have a large momentum. Such high-momentum particles are not subject to confinement along with the bulk of the matter. One would expect them to hadronize well outside the thermalized region, leading to $C(1)=1$ at one of the incoming legs in the diagram.

Therefore, $C(T)^3$ can be taken as a conservative estimate of the effect of the confinement factor on the emission rate. If it can be shown that hard photon emission is dominated by a region where the temperature is so large that $C(T)\approx 1$, the above expression for the emission rate can be used to approximately describe photon emission from a system of quasiparticles also. This is also the region where we expect the mass of quasiparticles to be given by the HTL result. We will verify this property *a posteriori*.

Clearly, the prescription outlined here has to be regarded as an approximation till a more detailed version of a quasiparticle description of the QGP incorporating confinement is available.

C. The hadronic contribution

As the temperatures in the hadronic evolution phase of the fireball are lower than in the QGP phase, we expect the hadronic contributions to the emission of hard photons to be small. Therefore, we will not discuss this contribution in great detail.

Vector mesons play an important role for the emission of photons from a hot hadronic gas. The first calculation of such processes has been performed in Ref. [12] in the framework of an effective Lagrangian. It has been found that the dominant processes are pion annihilation, $\pi^+\pi^-\to\rho\gamma$; "Compton scattering," $\pi^\pm\rho\to\pi^\pm\gamma$; and ρ decay, $\rho\to\pi^+\pi^-\gamma$.

Several more refined approaches have been made since then (for an overview, see Ref. [13]). In the following, we will use a parametrization of the rate from a hot hadronic gas taken from Ref. [14], which is given as

$$E\frac{dN}{d^4x d^3k}[\mathrm{fm}^{-4}\ \mathrm{GeV}^{-2}] \simeq 4.8T^{2.15}\exp[-1/(1.35ET)^{0.77}]\exp[-E/T]. \quad (6)$$

D. The integrated rate

In order to compare to the experimentally measured photon spectrum [1], we have to integrate Eq. (1) over the space-time evolution of the fireball,

$$\left.\frac{dN}{d^2k_t dy}\right|_{y=0} = \frac{\pi}{\Delta y}\int d\tau R^2(\tau)\int_{z_{min}(\tau)}^{z_{max}(\tau)} dz \times \int_{k_{min}(y(z))}^{k_{max}(y(z))} dk_z \frac{dN}{d^4x d^3k}. \quad (7)$$

In this expression, $R(\tau)$ stands for the radial expansion of the fireball, Δy denotes the rapidity interval covered by the detector, $y(z)$ is the rapidity of a volume element at position z, and the limits of the k_z integration come from the fact that a photon emitted at the (boosted) edge of the fireball has to have a longitudinal momentum in a certain range in order to be detected in the rapidity window of the experiment. In this expression, we have assumed spatial homogeneity and a cylindrical fireball.

III. THE FIREBALL EVOLUTION MODEL

In this section, we briefly outline the general framework of the fireball evolution model. The model is described in greater detail in Refs. [2,15].

The underlying assumption of the model is that the strongly interacting matter produced in the initial collision reaches thermal equilibrium at a time scale $\tau_0\approx 1$ fm/c. For simplicity, we assume spatial homogeneity of all thermodynamic parameters throughout a three-volume at a given proper time. The evolution dynamics is then modeled by calculating the thermodynamic response to a volume expansion that is consistent with measured hadronic momentum spectra at freeze-out.

The volume itself is taken to be cylindrically symmetric around the beam (z) axis. In order to account for collective flow, we boost individual volume elements inside the fireball volume with velocities depending on their position. As flow velocities in longitudinal direction turn out to be close to the speed of light, we have to include the effects of time dilatation. On the other hand, we can neglect the additional time dilatation caused by transverse motion, since typically $v_\perp \ll v_z$. The thermodynamically relevant volume is then given by the collection of volume elements corresponding to the same proper time τ. In order to characterize the volume expansion within the given framework, we need first of all the expansion velocity in longitudinal direction as it appears in the center of mass frame. For the position of the front of the cylinder, we make the ansatz

$$z(t)=v_0 t + c_z\int_{t_0}^{t} dt'\int_{t_0}^{t'} dt''\frac{p(t'')}{\epsilon(t'')}, \quad (8)$$

where c_z is a free parameter. The time t starts running at t_0 such that $z_0=v_0 t_0$ is the initial longitudinal extension with v_0 the initial longitudinal expansion velocity. The longitudinal position $z(t)$ and t itself define a proper time curve $\tau=\sqrt{t^2-z^2(t)}$. Solving for $\tilde{t}=t(\tau)$, one can construct $\tilde{z}(\tau)=z(\tilde{t})$. Then the position of the fireball front $z(t)$ in the center of mass frame can be translated into the longitudinal extension $L(\tau)$ of the cylinder on the curve of constant proper time τ. One obtains

$$L(\tau)=2\int_0^{\tilde{z}(\tau)} ds\sqrt{1+\frac{s}{\sqrt{s^2+\tau^2}}}. \quad (9)$$

At the same proper time we can define the transverse flow velocity and construct the transverse extension of the cylinder as a circle of radius

$$R(\tau)=R_0 + c_\perp\int_{\tau_0}^{\tau} d\tau'\int_{\tau_0}^{\tau'} d\tau''\frac{p(\tau'')}{\epsilon(\tau'')}, \quad (10)$$

where R_0 corresponds to the initial overlap radius, and $c_\perp$ is a free parameter. With the values of L and R obtained at a given proper time, we can parametrize the three-dimensional volume as

$$V(\tau)=\pi R^2(\tau)L(\tau). \tag{11}$$

In principle, the model is fully constrained by fixing the freeze-out time t_f (at the fireball front), the proper time τ_f, and the two constants $c_\perp$ and c_z, such that the measured hadronic observables are reproduced. In practice, this is achieved only at SPS energy, where the freeze-out analysis [16] allows a complete characterization on the basis of hadronic dN/dy and m_t spectra and HBT radii. For the 5% most central Pb-Pb collisions one requires

$$R(\tau_f)=R_f,\quad v_\perp(\tau_f)=v_\perp^f,\quad v_z(\tau_f)=v_z^f,\quad \text{and}$$
$$T(\tau_f)=T_f, \tag{12}$$

while making a trial ansatz for the ratio p/ϵ. Note that the proportionality of the acceleration to this ratio (which is reminiscent of the behavior of the speed of sound) allows a soft point in the EoS to influence and delay the volume expansion.

Assuming entropy conservation during the expansion phase, we fix the entropy per baryon from the number of produced particles per unit rapidity. Calculating the number of participant baryons as

$$\begin{aligned}N_p(b)&=\int d^2s\,n_p(\mathbf{b},\mathbf{s})\\&=\int d^2s\,T_A(s)\{1-\exp[-\sigma_{NN}^{in}T_B(|\mathbf{b}-\mathbf{s}|)]\}\\&\quad+(T_A\leftrightarrow T_B),\end{aligned} \tag{13}$$

we find the total entropy S_0. The entropy density at a given proper time is then determined by $s=S_0/V(\tau)$. Using the EoS given by the quasiparticle approach [11], thereby providing the link with lattice QCD, we find $T(s(\tau))$ and also $p(\tau)$ and $\epsilon(\tau)$, which in the next iteration replace the trial ansatz in the volume parametrization. Finally, we arrive at a thermodynamically self-consistent model for the fireball which is, by construction, able to describe the hadronic momentum spectra at freeze-out.

In order to find the fireball evolution relevant for the photon emission measured for the 10% most central collisions, we follow the procedure outlined in Ref. [2]. In brief, we consider an effective system that starts out with a reduced number of participants and hence reduced total entropy content. Neglecting azimuthal asymmetries, we keep parametrizing the expanding system as a cylinder with reduced initial radius. Assuming that the freeze-out temperature is approximately unchanged for more peripheral collisions, we determine a reduced proper evolution time and modify the geometrical freeze-out radius and the transverse flow velocity accordingly. However, going from the 5% to the 10% most central collisions, we find differences in the early evolution phases on the level of a few percent only.

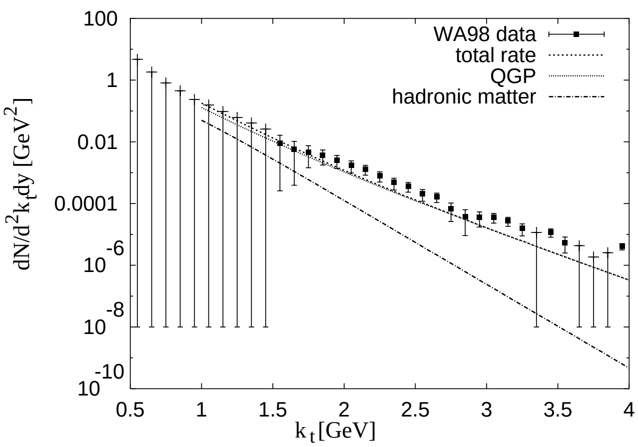

FIG. 2. (Color online) Thermal photon spectrum for 10% most central Pb-Pb collisions at SPS, 158A GeV Pb-Pb collisions, shown are calculated rate (total, contribution from QGP and hadronic gas) and experimental data [1].

Thus, the fireball evolution is completely constrained by hadronic observables. In Ref. [2], it has been shown that this scenario is able to describe the measured spectrum of low mass dileptons, and in Ref. [3] it has been demonstrated that under the assumption of statistical hadronization at the phase transition temperature T_C, the measured multiplicities of hadron species can be reproduced. None of these quantities is, however, sensitive to the detailed choice of the equilibration time τ_0. Therefore, we have only considered the "canonical" choice $\tau_0=1$ fm/c so far. The calculation of photon emission within the present framework provides the opportunity to test this assumption and to limit the choice of τ_0.

IV. RESULTS

The result of the evaluation of Eq. (7) with the fireball evolution model described in the preceding section is shown in Fig. 2. The overall agreement with the data is remarkably good. Above 2 GeV, the calculation underestimates the data somewhat, leaving room for a contribution of prompt photons from initial hard processes of about the same magnitude as the thermal yield. Note that the spectrum is almost completely saturated by the QGP contribution—for $k_t>3$ GeV, the hadronic contribution is almost two orders of magnitude down. This can, in essence, be traced back to the strong temperature dependence of the emission rate normalization and justifies the approximate treatment of the hadronic contribution *a posteriori*.

In order to study the importance of the initial, high temperature phase in more detail, we present the time evolution of the spectrum in Fig. 3. One observes that the large k_t region is almost exclusively dominated by the first fm/c of evolution proper time, whereas the yield in the low k_t region is not yet saturated after 2 fm/c. However, the temperature associated with these evolution times is always larger than 250 MeV, leading to $C(T)>0.9$ [11] and $C(T)^3\approx 0.7$. This justifies neglecting the effect of quasiparticle properties on the rate *a posteriori*. There is a 30% uncertainty introduced into the calculation, but this is comparable with other intrin-

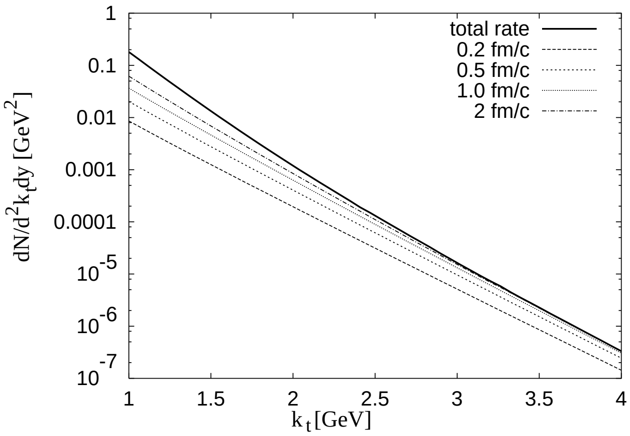

FIG. 3. (Color online) The total photon emission spectrum and the integrated rate at proper times $\tau = 0.2$, 0.5, 1.0, and 2 fm/c of the fireball evolution.

sic uncertainties, such as the detailed choice of the numerical value of $\alpha_S(T)$ in this temperature regime.

The high k_t tail of the spectrum is potentially capable of providing information about the initial temperature reached immediately after equilibration. This capability is seriously limited in practice, however, by the need to assess an unknown contribution of prompt photons, which may be large in this region. Bearing this uncertainty in mind, we can, nevertheless, pursue this idea further in Fig. 4, where we investigate the sensitivity of the result to the equilibration time τ_0 of the fireball.

We find that the low k_t region of the spectrum is hardly affected by different choices for the equilibration time, while for larger k_t one is increasingly sensitive to short evolution time scales. An equilibration time of 0.5 fm/c corresponding to an initial temperature of 370 MeV leads to a good description of the data without the inclusion of any prompt photon contribution. On the other hand, a rather slow equilibration corresponding to $\tau_0 = 2$ fm/c and an initial temperature of 260 MeV requires a sizeable contribution from prompt photons.

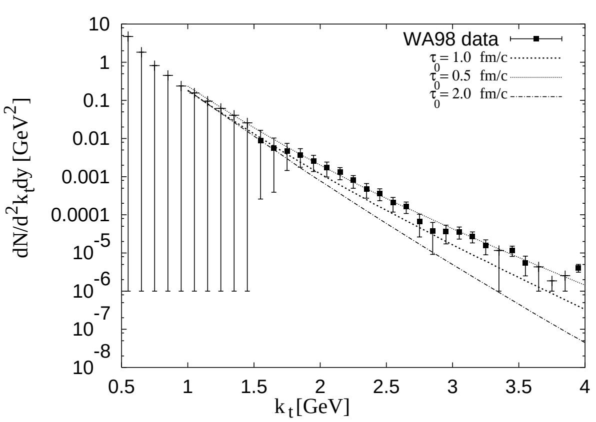

FIG. 4. (Color online) The thermal photon emission spectrum for different choices of the equilibration time τ_0 as compared to experimental data [1].

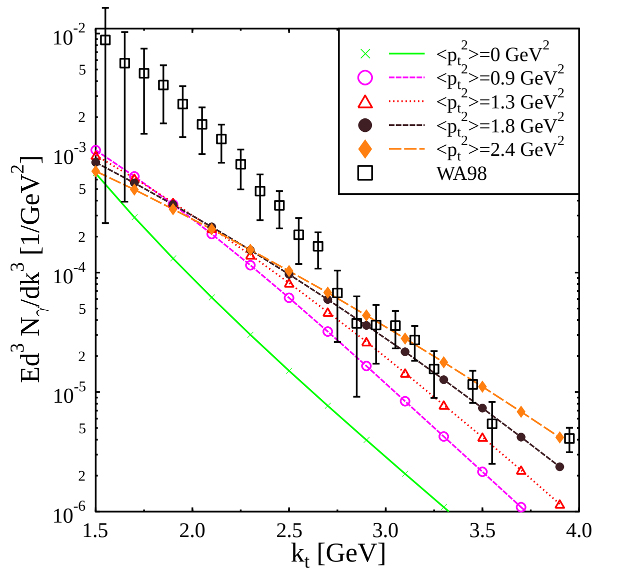

FIG. 5. (Color online) Prompt photon production in Pb-Pb collisions as a function of the photon transverse momentum k_t for different values of average parton intrinsic transverse momentum $\langle p_t^2\rangle$ [17], as compared to experimental data [1] (figure adapted from Ref. [17]).

Without any reference to prompt photons, we are therefore able to fix $\tau = 0.5$ fm/c as the lower bound for the equilibration time. Shorter time scales would lead to thermal photon emission overshooting the data.

If we want to find an upper limit for the equilibration time, we have to address the issue of prompt photon emission. For this purpose, we use the results of two different works [17,18] to illustrate the possible range of predictions dependent on the average value of p_t, an "intrinsic" transverse momentum scale that is introduced as a phenomenological parameter to account for nonperturbative effects. (Fig. 5).

One observes that prompt photon production is able to explain the data above 3 GeV for $\langle p_t^2\rangle \sim 1.8$ GeV^2, but no choice of $\langle p_t^2\rangle$ leads to a description of the data below 3 GeV. Thus, there is a momentum region between 2 and 2.5 GeV where the data are only weakly affected by a prompt photon contribution.

On the other hand, the present calculation of thermal photon emission indicates sensitivity to the equilibration time in this region (see Fig. 4). One finds that an equilibration time of 2 fm/c is unable to describe the data even in the presence of a sizable prompt photon contribution, hence we may regard this as the upper limit for the equilibration time, given the results of Ref. [17].

If we use alternatively the results of Ref. [18] to estimate the contribution of prompt photons, the situation is somewhat less clear, though the main conclusions remain valid. In the momentum region near 2 GeV, the result obtained for the prompt photon contribution in Ref. [18] is about 50% of the thermal emission spectrum obtained with $\tau_0 = 1$ fm/c in the present calculation, which in turn is already on the lower end of the error bars of the data. Therefore, the prompt photon contribution alone is unable to explain the spectrum in this momentum region, and a thermal contribution with $\tau_0 \approx 2$ fm/c is needed to describe the data near $k_t = 2$ GeV. (In Ref. [18], it is stated that the prompt photon contribution is of the same size as the thermal emission spectrum corresponding to a fireball with initial temperature of 300 MeV, which is not true in the present calculation. However, this statement is derived using Bjorken hydrodynamics, whereas the present model incorporates longitudinal acceleration of the fireball matter, which leads to less cooling initially and hence to a prolonged QGP phase.)

However, there are several uncertainties in the calculation. We have already discussed the complications introduced by the quasiparticle picture and the detailed choice of α_S. An additional potential problem in the calculation is that the rate has been calculated to order α_S, but α_S is not a small quantity in the relevant temperature region, so there might be sizable higher order corrections. In view of these uncertainties and the less urgent need for an additional contribution to prompt photons if the results of Ref. [18] are taken, it is possibly better to estimate 0.5 fm/$c < \tau_0 < 3$ fm/c for the equilibration time.

In principle, one might try to construct a scenario with a large equilibration time, using the most optimistic estimate for the prompt photon contribution. Below temperatures ~ 200 MeV, the approximations made to calculate the photon emission from the QGP phase break down; however, qualitatively we expect the confinement factor $C(T)$ to strongly reduce the emission rate. Likely candidates for photon yield between 2 and 2.5 GeV are therefore only the hadronic evolution phase and the preequilibrium phase.

In order for the hadronic phase to contribute significantly, either the emission rate or the four-volume of emitting matter needs to be increased significantly. The four-volume of fireball matter in the hadronic phase, however, is tightly constrained by the measured amount of dilepton radiation, which has been discussed in the present framework in Ref. [2]. An increase of the emissivity of a hadronic gas, on the other hand, would very likely be accompanied by a change in the number of active degrees of freedom, which presumably are driven by in-medium mass reductions of resonances as argued in Ref. [19]. A strong increase of active degrees of freedom, however, is not in agreement with a statistical hadronization analysis done in Ref. [3]. Even an overall mass reduction of 10% (excluding the pseudoscalars) is not compatible with the observed hadron ratios. Therefore, within the present framework, the hadronic phase is not likely to give a large contribution to the photon spectrum.

There remains the question of the yield from the preequilibrium phase. No rigorous scenario leading to thermal equilibrium for SPS conditions has been developed so far, however, several aspects of the preequilibrium dynamics have already been investigated.

In Ref. [20], the kinetic equilibration of different quark flavors was investigated under the assumption that gluons come to an early equilibrium and constitute a heat bath in which quark motion takes place. An early nonequilibrium distribution of quarks would of course directly influence the photon emission spectrum. Somewhat related is the question of chemical equilibration of quarks. Here, the hot-glue scenario [21] has been suggested where an initial undersaturation of the quark densities with respect to the thermal equilibrium densities is assumed, i.e., almost all of the entropy of the system is carried by the gluons, leading to a drastically increased initial temperature.

The findings of Ref. [20] suggest, albeit for relativistic heavy-ion collider conditions, that the typical time scale for the kinetic equilibration of light quark flavors is of order ~ 1 fm/c. This time scale is roughly in line with the assumptions made in the present work. However, it leaves the question if the photon emission signal is affected if one starts with a suitable out-of-equilibrium initial quark distribution.

Regarding the hot-glue scenario, note that the drastically increased temperature of the partonic matter would mostly affect the high momentum tail of observed photons and therefore leave the momentum region below 2.5 GeV less affected. This is especially true since also the overall normalization of the emission rate is reduced with respect to equilibrium conditions due to the undersaturation of the quark densities.

A different approach to preequilibrium dynamics has been taken in Ref. [22]. Here, transverse momentum dependence of dilepton emission has been calculated in a kinetic framework and calculations for different initital parton distributions have been tested. While the approach is very interesting, it is hard to directly estimate its possible influence on photon emission within the present framework.

In Ref. [23], an investigation of nonequilibrium photon emission has been carried out using a parton-cascade model (PCM). Here, the essential findings were that only a very dilute partonic medium is created in the collision. Photon emission from this medium was shown to explain the data above 3 GeV when integrated up to the hadronization point, but below 3 GeV, the photon spectrum from the partonic phase falls below the data. It is difficult to relate these findings directly to the present approach, since no equilibrium phase in either partonic or hadronic phase is described in the PCM. However, we may take this as an indication that preequilibrium dynamics is most likely to strongly affect the high momentum region of the photon spectrum only where we find considerable uncertainties with regard to the question of intrinsic p_t anyway.

In the present work, no attempt has been made to calculate a contribution to the photon spectrum from preequilibrium matter. It is, however, unlikely that a long-lasting preequilibrium phase is characterized by a strong photon emission rate, since strong photon emission indicates frequent interaction processes in the medium, which in turn would lead to fast equilibration. Furthermore, it is plausible that a preequilibrium contribution mainly affects the (uncertain) high momentum region of the spectrum, as it is characterized by hard momentum scales. Nevertheless, all results discussed in this paper are subject to some uncertainties resulting from the poor knowledge of preequilibrium dynamics.

V. COMPARISON TO OTHER WORKS

Several other scenarios have been investigated by different authors in order to explain the photon spectrum measured by WA98. In Ref. [24], a hydrodynamical evolution model has been used. The favored scenario found in this work uses a very short equilibration time of 0.2 fm/c, corresponding to an (average) initial temperature of 335 MeV. The contribution of thermal photons is about 50% of the total yield, the rest is prompt photon contribution.

While the result for the equilibration time is clearly very different from the findings of the present work, several other results are similar, among them are the weak sensitivity to the phase transition temperature T_C (indicating the dominance of early emission phases), the favored large initial temperature, and the dominance of the QGP over the hadronic signal. It remains to explain the remarkable difference in the conclusions about the equilibration time.

Note that both in Ref. [24] and the present work large initial temperatures $T_i \gtrsim 300$ MeV are needed to give a sizable thermal photon emission in the momentum range in question. The choice of $\tau_0 = 0.2$ fm/c seems mainly driven by the need to create such large T_i. There are, however, two important differences between our model and the one in Ref. [24], which lead naturally to large initial temperatures for equilibration times above 0.5 fm/c in our approach.

First, we employ an EoS as based on lattice results, which leads to a temperature increase of about 30% for a given entropy density as compared to a bag model EoS. Second, the temperatures quoted in Ref. [24] are obtained using the Bjorken estimate [25]. Our fireball evolution, however, incorporates significant longitudinal acceleration of matter, which in essence leads to a peaked initial distribution of energy density at central rapidities and hence to significantly larger initial temperatures.

In Ref. [26], a number of scenarios with different EoS and initial state have been investigated within a hydrodynamical description. The reference scenario described there uses a bag model EoS for the QGP phase with a transition temperature of 180 MeV and an initial state that leads to a peak initial temperature of $T_i^{max} = 325$ MeV and an average initial temperature of $\overline{T}(z=0) = 255$ MeV. There is clearly a discrepancy between the average initial temperature in Ref. [26] and the present work. Due to the different space-time expansion patterns of the hot matter in the (averaged) present calculation and a hydrodynamics evolution, this issue could possibly best be clarified by comparing the amount of four-volume corresponding to a given temperature instead of comparing the average at a given τ. At the moment, however, this has to be regarded as an open question.

In addition, there is a larger contribution to the photon spectrum of matter with temperatures below 200 MeV observed in Ref. [26] (about 40% of the total yield) as compared to our model. This is presumably caused by the different choice of the EoS, which in the bag model case leads to faster cooling and to a long-lasting mixed phase, in essence reducing the weight of contributions from high temperatures and enhancing the low-temperature yield.

VI. SUMMARY

A measurement of hard real photon emission provides a good opportunity to study the early evolution of a fireball. Due to the temperature dependence of the photon emission rate, the QGP phase is expected to dominate over the contribution from the hadronic phase. We have used the leading order photon emission rate from the QGP, along with estimates of the impact of our phenomenological quasiparticle picture on this rate, in a simple model for the fireball evolution to calculate the resulting photon spectrum. As this model was fixed beforehand, we have not introduced any new free parameters.

For the ‘‘standard choice’’ of the equilibration time τ_0, the model has been able to give a good description of the data. Nevertheless, we have tried variations of this quantity in order to work out constraints. With the help of an estimate for the contribution of photons from initial, hard processes, we found for the equilibration time 0.5 fm/$c < \tau_0 < 3$ fm/c. This would imply that a QGP phase must be present in the evolution, at least within the present model.

Overall, our picture of the space-time evolution of the fireball finds now support from both the low momentum (late time) and the high momentum (early time) region of the evolution. More precise future measurements and calculations can be expected to tighten the constraints on the equilibration time.

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