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Photonic measurements of the longitudinal expansion dynamics in relativistic heavy-ion collisions

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Owing to the smallness of the electromagnetic coupling, photons escape from the hot and dense matter created in a heavy-ion collision at all times, in contrast to hadrons, which are predominantly emitted in the final freeze-out phase of the evolving system. Thus, the thermal photon yield carries an imprint from the early evolution. We suggest how this fact can be used to gain information on where the actual evolution can be found between the two limiting cases of Bjørken (boost-invariant expansion) and Landau (complete initial stopping and re-expansion) hydrodynamics. We argue that both the rapidity dependence of the photon yield and photonic two-particle correlation radii are capable of answering this question.

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I. INTRODUCTION

The boost-invariant hydrodynamic model proposed by Bjørken [1] for the description of ultrarelativistic heavy-ion collisions is frequently used at Relativistic Heavy Ion Collider (RHIC) energies for estimates of the initial energy density in heavy-ion collisions or the lifetime from the measured Hanbury-Brown Twiss (HBT) correlation radius R_{long} [2] as well as in hydrodynamical descriptions of the evolving system (see, e.g. [3]).

Although the original notion of boost invariance is an asymptotic concept, its application to RHIC energies usually implies two assumptions: 1. the distribution of matter in some finite interval around midrapidity being (almost) independent of rapidity and 2. the longitudinal dynamics being unaccelerated expansion, which in turn means that momentum rapidity $y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$ always equals spacetime rapidity $\eta_s = \frac{1}{2}\ln\frac{t+z}{t-z}$ (which is not true in the presence of longitudinal acceleration).

In contrast, charged meson rapidity distributions as obtained by the BRAHMS collaboration [4] do not show a flat plateau around midrapidity even at top RHIC energy. The distributions are, however, well described by Landau hydrodynamics [5] as argued in [6]. Likewise there is no boost invariance seen in the rapidity dependence of elliptic flow as measured by the PHOBOS collaboration [7].

In a model framework adjusted to reproduce the full set of observables characterizing the hadronic freeze-out (i.e., single-particle transverse mass spectra and rapidity distributions and two-particle HBT correlation radii [8]) it was found that simultaneous agreement with all data sets can only be achieved if the assumption of a boost-invariant expansion is dropped. In fact, a sizable difference of $\Delta y = 2 \times 1.8$ between initial and final widths of the source in momentum space rapidity is required.

This, however, is rather indirect evidence since it rests on a backward extrapolation of the observed final state. In contrast, thermal photons would offer the opportunity to test the longitudinal evolution directly [9]. The essential idea is as follows: In a Landau scenario, the source is initially very narrow around midrapidity. Since the hard photon emission rate is strongly temperature dependent, the dominant contribution to the photon yield arises from early times. Thus, we expect that the hard photon yield as a function of rapidity shows a thermal smearing of the initial (narrow) source extension in rapidity. In contrast, in a boost-invariant expansion we expect a much broader distribution, reflecting the initial distribution of matter across a large rapidity interval.

There is an additional factor that needs to be taken into account: Owing to its large initial extension in rapidity, a Bjørken scenario leads to much more rapid cooling than does a Landau one. Hence, whereas in a Landau scenario the hot, early phase will be dominant, this is not so in a Bjørken framework. The different weights of the contributions of early times and late times are expected to leave a characteristic imprint on HBT correlation radii measured even at midrapidity.

In this work, we discuss both ideas and demonstrate what predictions for the photonic observables can be made using either the scenario determined from a fit to spectra and HBT in [8] or a Bjørken or a Landau one. This is conceptually very different from various attempts to use soft photon Bremsstrahlung resulting from the deceleration of (charged) nuclear matter to measure the expansion dynamics [10–12].

II. THE MODEL FRAMEWORK

Several calculations studying photon emission based on a hydrodynamical fireball evolution model have been made so far for different collision systems and energies [13–16]. In the present study investigating 200*A* GeV AuAu collisions, we will instead use a parametrized evolution model that allows for a complete description of hadronic transverse mass spectra as well as HBT correlation parameters [8] and that can easily be tuned to interpolate between Bjørken and Landau dynamics.

The model for the evolution of hot matter is described in detail in [8,17]. Here we only present the essential outline and focus on (almost) central collisions.

For the entropy density at a given proper time we make the ansatz

$$s(\tau, \eta_s, r) = N R(r, \tau) H(\eta_s, \tau), \tag{1}$$

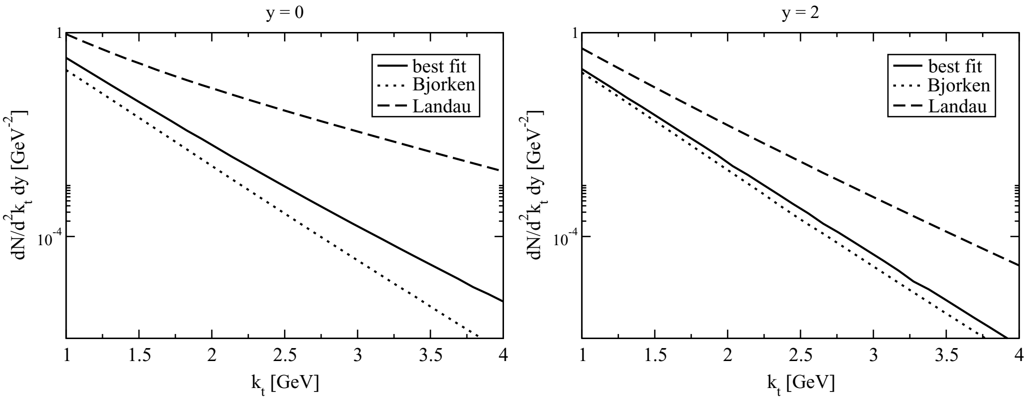

FIG. 1. The hard thermal photon spectrum at midrapidity ($y = 0$, left panel) and forward rapidity ($y = 2$, right panel) for the best-fit scenario described in [8], a Bjørken scenario and a Landau scenario.

where τ is the proper time measured in a frame comoving with a given volume element, $R(r,\tau)$ and $H(\eta_s,\tau)$ are two functions describing the shape of the distribution, and N is a normalization factor. We use Woods-Saxon distributions

$$\begin{aligned} R(r,\tau) &= 1\Big/\left\{1+\exp\left[\frac{r-R_c(\tau)}{d_{\mathrm{ws}}}\right]\right\}, \\ H(\eta_s,\tau) &= 1\Big/\left\{1+\exp\left[\frac{\eta_s-H_c(\tau)}{\eta_{\mathrm{ws}}}\right]\right\} \end{aligned} \tag{2}$$

for the shapes. Thus, the ingredients of the model are the skin thickness parameters d_{ws} and η_{ws} and the parametrizations of the expansion of the spatial extensions $R_c(\tau)$, $H_c(\tau)$ as a function of proper time. From the distribution of entropy density, the thermodynamics can be inferred via the equation of state and particle emission is then calculated using the Cooper-Frye formula. For simplicity, we assume that the flow is built up by a constant acceleration $a_\perp$, hence $R_c(\tau) = R_c^0 + \frac{a_\perp}{2}\tau^2$ with R_c^0 an initial radial extension as found in overlap calculations. The rapidity distribution is assumed to grow from some initial width $2y_0$ to a final width $2y_F$. This determines the extension of the emitting source in spacetime rapidity η_s [8,17].

In [8], the model parameters have been adjusted such that the model gives a good description of the data. This implies an initial rapidity width of $y_0 = 1.7$. To compute a Bjørken scenario, we set the initial width of the rapidity distribution equal to the final distribution width $y_0 = y_F$. For a Landau scenario we choose $y_0 = 0$. In both cases we readjust the model parameters such that the single-particle spectra are reproduced (which implies losing agreement with the HBT data).

The spectrum of emitted photons can be found by folding the photon emission rates for the quark-gluon plasma (QGP) phase [18] and for a hot hadronic gas [19] with the fireball evolution. To account for flow, the energy of a photon emitted with momentum $k^\mu = (k_t, \mathbf{k_t}, 0)$ has to be evaluated in the local rest frame of matter, giving rise to a product $k^\mu u_\mu$ with $u_\mu(\eta_s, r, \tau)$ the local flow profile. Following the results in [8] we assume for the spatial dependence of the flow field the relations $y = f(\tau)\eta_s$ and $y_\perp = g(\tau)r$ with $y_\perp$ the transverse rapidity and f, g two functions determined by the evolution. The distribution of entropy density is manifest in the dependence of the temperature $T = T(\eta_s, r, \tau)$ on the spacetime position. To account for the breakup of the system once a temperature T_F is reached, a factor $\theta(T - T_F)$ has to be included into the folding integral.

Using the folding integral of the rate with the fireball evolution as emission function $S(x, K)$ (describing the amount of photons with momentum K^μ emitted at spacetime point x^μ) we calculate the HBT parameters as [20,21]

$$R^2_{\mathrm{side}} = \langle\tilde{y}^2\rangle, \quad R^2_{\mathrm{out}} = \langle(\tilde{x} - \beta_\perp\tilde{t})^2\rangle, \quad R_{\mathrm{long}} = \langle\tilde{z}^2\rangle \tag{3}$$

with $\tilde{x}_\mu = x_\mu - \langle x_\mu\rangle$ and

$$\langle f(x)\rangle(K) = \frac{\int d^4x f(x) S(x,K)}{\int d^4x S(x,K)}. \tag{4}$$

III. RAPIDITY DEPENDENCE OF HARD THERMAL PHOTON EMISSION

We show the resulting spectra of hard thermal photons in the momentum range between 1 and 4 GeV in Fig. 1 at two different rapidities.

It is instructive to observe that both slope and absolute yield change strongly as a function of y for the Landau scenario. This reflects the fact that the initial high-temperature phase (leading to a relatively flat slope) never radiates out into the $y = 2$ slice—only in the later stages when hot matter expands across $y = 2$ is there a significant contribution, albeit from matter with a much lower temperature, leading to a steeper spectral slope and reduced yield.

In contrast, the photon yield from a Bjørken scenario is practically unchanged as a function of rapidity, reflecting the approximate boost invariance.

To highlight the differences more clearly we show in Fig. 2 the k_T-integrated yield (1 GeV $< k_T <$ 4 GeV) at rapidity y_0 divided by the integrated yield at midrapidity. This choice has the additional advantage that model dependences such as the precise normalization of the emission rates tend to cancel out.

The different longitudinal source structure is now directly apparent. The Landau scenario is characterized by thermal smearing of about 1 unit of rapidity of a source at midrapidity (without any longitudinal flow) whereas the Bjørken scenario

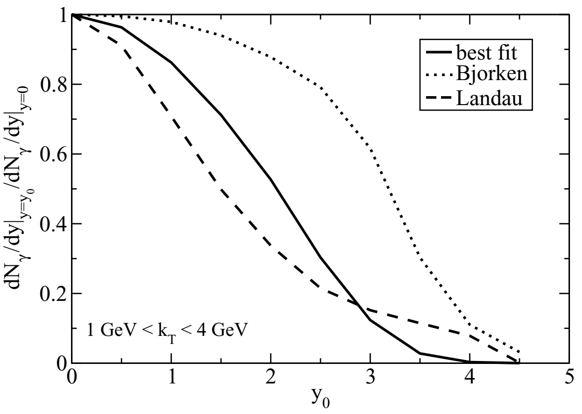

FIG. 2. Integrated yield (1.0 GeV $< k_T <$ 4 GeV) of thermal photons as a function of rapidity y_0.

shows the broad distribution of matter across ∼3 units of rapidity at all times. A measurement of the thermal photon yield at midrapidity and at $y_0 = 2$ would easily distinguish among the three scenarios.

IV. HARD THERMAL PHOTON HBT AT MIDRAPIDITY

HBT correlation measurements do not measure the true geometrical size of the source but rather a region of homogeneity [20,21] that is only identical with the geometry for vanishing flow gradients in the source. For finite flow gradients, the measured correlation radii show a characteristic falloff with the correlated pair momentum k_T. The precise shape of the correlation radii as a function of transverse momentum results from a complex interplay between temperature and flow during the whole evolution.

Nevertheless, we can formulate some basic expectations. Because of the high initial compression, the hard photon yield from a Landau scenario is expected to be dominated by the initial phase of the expansion. In this phase, however, there is no significant transverse flow (which builds up gradually and is driven by transverse pressure) and the geometrical size of the source in the longitudinal direction is very small (for complete stopping it is given by the Lorentz-contracted size of the overlapping nuclei). Thus, we would expect only a weak falloff of R_{side} with k_T and R_{long} to be determined primarily by the spatial resolution scale of photons with a given momentum.

In contrast, a Bjørken expansion may well receive significant relative contributions to the yield from later stages owing to the shorter duration of the inital hot phase. This would imply a slightly larger R_{side} for vanishing k_T but a stronger falloff with k_T and an increased value of R_{long} as compared to the initial size at equilibration time. The relevant underlying scale for R_{side} is in all cases the nuclear overlap radius.

The result of the calculation can be seen in Fig. 3. To a good degree, the expected behavior is indeed seen. In particular, the different falloff of R_{side} for $k_T > 2.5$ GeV appears to be a good indicator of the longitudinal dynamics. R_{long}, in contrast, is presumably only capable of identifying a scenario very similar to a Landau one; otherwise, the qualititive behavior of the different curves is too similar. Note that the observed R_{long} for the Landau scenario could not be as small as shown in the plot because of constraints posed by the uncertainty relation, which does not allow us to narrow down the photon emission region to arbitrary small size.

V. THE ROLE OF PRE-EQUILIBRIUM PHOTONS

It is well known that in addition to thermal photons prompt photons (calculable in perturbative QCD) are expected to significantly contribute to the hard photon yield, and various attempts have been made to calculate the magnitude of this contribution (see, e.g. [22–24]), which might well outshine the signals proposed here and change the conclusions.

To address this question carefully, we have to take into account not only the primary hard scattering processes as a potential source of photons but also hard rescattering processes as the system approaches equilibrium. Therefore we use here the VNI/BMS parton cascade model (PCM) to estimate the role of pre-equilibrium hard photon production [25,26].

There remains the caveat that the rescattering described by the PCM does not lead to a Landau-like stopping of the incoming matter; nevertheless, we use the results to gain some intuition about the orders of magnitude involved.

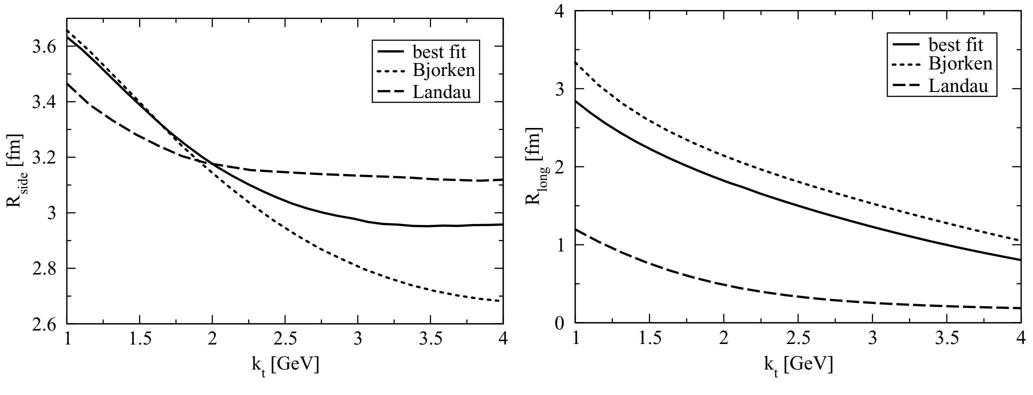

FIG. 3. Hard photon HBT correlation radii R_{side} (left panel) and R_{long} (right panel) for the best-fit scenario described in [8], a Bjørken scenario and a Landau scenario.

Including the Landau-Pomeranchuk-Migdal suppression in the PCM, we find that thermal photons may dominate the yield below 2–2.5 GeV for the best-fit and the Bjørken scenarios whereas they would dominate the yield in the whole momentum range for a pure Landau evolution [27].

Since the photon yield drops (almost) exponentially with k_t, this implies that the rapidity dependence of the integrated yield would still be a reliable signal (being dominated by the low-k_T yield).

However, the behavior of the HBT correlation radii in the interesting region above 2 GeV is likely to be distorted by pre-equilibrium photons (which would incidentially resemble Landau dynamics as they are characterized by small transverse flow).

Turning the argument around, we see that a simultaneous measurement of the HBT correlations at midrapidity and of the integrated yield at forward rapidity could still provide valuable insight into the magnitude of the pre-equilibrium contribution at different momenta. A detailed investigation of this question is however beyond the scope of this work.

VI. SUMMARY

We have argued that photons provide a direct measurement of the early longitudinal dynamics of a heavy-ion collision that can otherwise only be inferred indirectly from hadronic probes. The underlying reason for this is that the smallness of the electromagnetic coupling means that the measured photon yield represents an integral over the whole fireball evolution rather than a snapshot at breakup.

In particular, we have argued that the rapidity dependence of the hard photon yield is a good probe to distinguish between Landau-like and Bjørken-like dynamics since it directly reveals the rapidity extension of the emission source. Since we compare the rapidity dependence of a ratio of integrated yields many uncertainties associated with the calculation of emission rates drop out and the result mainly reflects kinematic properties of the source.

In addition, we have investigated the potential of using HBT correlation measurements at midrapidity to investigate the longitudinal evolution. HBT correlations show what part of the evolution dominates the photon yield rather than directly reflecting longitudinal dynamics. We found that the falloff of R_{side} with k_t above 2.5 GeV would indeed give a good indication if the photon emission is dominated by matter without significant transverse flow or not; however, this signal is easily obscured by pre-equilibrium photon emission, which would never show significant transverse flow.

Nevertheless, measurements of both the rapidity dependence of the hard photon yield and the HBT correlation parameters at midrapidity are capable of revealing interesting details of the early fireball evolution that cannot easily be studied otherwise.

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