Radiation of single photons from $Pb + Pb$ collisions at the CERN SPS and quark hadron phase transition

Dinesh Kumar Srivastava[1] and Bikash Sinha[1,2]
[1] *Variable Energy Cyclotron Centre, 1/AF Bidhan Nagar, Calcutta 700 064*
[2] *Saha Institute of Nuclear Physics, 1/AF Bidhan Nagar, Calcutta 700 064*
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The production of single photons in $Pb + Pb$ collisions at the CERN SPS as measured by the WA98 experiment is analysed. A very good description of the data is obtained if a quark gluon plasma is assumed to be formed initially, which expands, cools, hadronizes, and undergoes freeze-out. A rich hadronic equation of state is used and the transverse expansion of the interacting system is taken into account. The recent estimates of photon production in quark-matter (at two loop level) along with the dominant reactions in the hadronic matter leading to photons are used. Most of the radiation of the photons is seen to arise from the quark-matter, which contributes dominantly through the mechanism of annihilation of quarks with scattering, and which in turn is possible only in a hot and dense plasma of quarks and gluons. The results thus confirm the formation of quark gluon plasma and the existence of this mechanism of the production of single photons.

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The search for quark-gluon plasma, which filled the early universe microseconds after the big bang and which may be present in the core of neutron stars, is one of the most notable collective efforts of the present day nuclear physics community. Its discovery will provide an important confirmation of the predictions of the statistical Quantum Chromodynamics (QCD) based on lattice calculations. It has been recognised for a long time [1] that electromagnetic radiations from relativistic heavy ion collisions in these experiments would be a definitive signature of the formation of a hot and dense plasma of quarks and gluons, consequent to a quark-hadron phase transition [1]. Once other signs of the quark-hadron transition, e.g., an enhanced production of strangeness, a suppression of J/ψ production, radiation of dileptons, etc., started to emerge [2], it was imperative that the more direct, yet much more difficult to isolate, signature of the hot and dense quark-gluon plasma, the single photons were identified. The WA98 experiment [3] has now reported observation of single photons in central $Pb + Pb$ collisions at the CERN SPS.

In the present work we show that these data are very well described if we assume that a quark-gluon plasma was formed in the collision.

In order to put our findings in a proper perspective, let us recall that the publication of the upper limit of the production of single photons in $S+Au$ collisions at CERN SPS [4] by the WA80 experiment was preceded and followed by several papers [5,6] exploring their connection to the quark-hadron phase transition. An early work, by the present authors [5], reported that the data were consistent with a scenario where a quark gluon plasma was formed at an initial time $\tau_0 \sim 1$ fm/c, which expanded and cooled, got into a mixed phase of quarks, gluons, and hadrons, and ultimately underwent a freeze-out from a state of hadronic gas consisting of π, ρ, ω, and η mesons. On the other hand, when the initial state was assumed to consist of (the same) hadrons, the resulting large initial temperature led to a much larger production of single photons, in gross violation of the upper limit.

A reanalysis of the WA80 data on single photons was reported recently [7] which incorporated two important developments in the field during the last few years. We recall them as they are relevant for the work to be reported here.

Firstly, it was realized that the hadronic equation of state should be generalized to include all of the hadrons [8] (limited to $M < 2.5$ GeV, in practice). This was prompted and supported by the success of the thermal models in describing particle production in these collisions. This implied that the hadrons were in chemical equilibrium [9] at least at the time of (chemical) freeze-out.

Secondly, an evaluation of the rate of single photon production from the quark matter to the order of two-loops was reported recently by Aurenche et al [10]. This had two quite important results: (i) the dominance of the bremsstrahlung ($q\,q\,(g) \rightarrow q\,q\,(g)\,\gamma$) process for all momenta over the Compton ($q\,(\overline{q})\,g \rightarrow q\,(\overline{q})\,\gamma$) plus annihilation ($q\,\overline{q} \rightarrow g\,\gamma$) contributions included in the one-loop calculations available in the literature [11,12], and (ii) a very large contribution by a new mechanism which corresponds to the annihilation of a quark (scattered from a quark or a gluon) by an anti-quark. These new rates were shown [13] to lead to a considerable enhancement of the production of single photons at SPS, RHIC, and LHC energies, if the initial state is approximated as an equilibrated plasma.

It was also reported [7] that when allowances were made for the above considerations, the WA80 upper limit was still consistent with a quark hadron phase transition, while a treatment without phase transition was untenable as it involved several hadrons/fm^3, at the initial time.

We add that there can be a large production of high momentum single photons during the pre-equilibrium phase, when treated within the parton cascade model [14], from the fragmentation of time-like quarks ($q \rightarrow q\,\gamma$) produced in (semi)hard multiple scatterings [15].

The rate for the production of hard photons evaluated to one loop order using the effective theory based on resummation of hard thermal loops is given by [11,12]:

$$E\frac{dN}{d^4x\,d^3k} = \frac{1}{2\pi^2}\,\alpha\alpha_s\,\left(\sum_f e_f^2\right)\,T^2\,e^{-E/T}\,\ln(\frac{cE}{\alpha_s T}) \quad (1)$$

where the constant $c \approx 0.23$. The summation runs over the flavours of the quarks and e_f is the electric charge of the quarks in units of charge of the electron. The rate of production of photons due to the bremsstrahlung processes evaluated by Aurenche et al is given by:

$$E\frac{dN}{d^4x\,d^3k} = \frac{8}{\pi^5}\,\alpha\alpha_s\,\left(\sum_f e_f^2\right)\,\frac{T^4}{E^2}\,\times$$
$$e^{-E/T}\,(J_T - J_L)\,I(E,T), \quad (2)$$

and the expressions for J_T, J_L, and $I(E,T)$ can be found in Ref. [10,13].

And finally the dominant contribution of the $q\bar{q}$ annihilation with scattering obtained by Aurenche et al is given by:

$$E\frac{dN}{d^4x\,d^3k} = \frac{8}{3\pi^5}\,\alpha\alpha_s\,\left(\sum_f e_f^2\right)\,ET\,e^{-E/T}\,(J_T - J_L). \quad (3)$$

Note that all the three contributions turn out to be essentially of the order $\alpha\alpha_s$ [10].

We estimate the direct photons produced from the early hard collisions of partons in the nuclei and treated under perturbative QCD as:

$$\frac{dN}{d^2k_T\,dy} = T_{AA}(b=0)\frac{d\sigma_{pp}}{d^2k_T\,dy}, \quad (4)$$

where $T_{AA}(b)$ is the nuclear thickness for the impact parameter b and the pp cross-sections (evaluated at $\sqrt{s} =$ 19.4 GeV) are taken from the calculations of Vogelsang and Whalley [16].

We assume that a chemically and thermally equilibrated quark-gluon plasma is produced in such collisions at the time τ_0 (see later), and use the isentropy condition [17];

$$\frac{2\pi^4}{45\zeta(3)}\,\frac{1}{A_T}\,\frac{dN}{dy} = 4aT_0^3\tau_0 \quad (5)$$

to estimate the initial temperature, where A_T is the transverse area.

We have taken the average particle rapidity density as 750 for the 10% most central $Pb + Pb$ collisions at the CERN SPS energy as measured in the experiment. We estimate the average number of participants for the corresponding range of impact parameters ($0 \leq b \leq 4.5$ fm) as about 380, compared to the maximum of 416 for a head-on collision. We thus use a mass number of 190 to get the radius of the transverse area of the colliding system and neglect its deviations from azimuthal symmetry, for simplicity. As this deviation, measured in terms of the number of participants, is marginal ($< 9\%$) we expect the error involved to be small. We also recall that the azimuthal flow is minimal for central collisions.

We take $a = 42.25\pi^2/90$ for a plasma of massless quarks (u, d, and s) and gluons, where we have put the number of flavours as ≈ 2.5 to account for the mass of the strange quarks. We now use Eq.(5) to estimate the (average) initial temperature, with the additional assumption of a rapid thermalization [18] so that the formation time is decided by the uncertainty relation and $\tau_0 = 1/3T_0$. This T_0 is then used to get the (average) initial energy density.

The initial energy density profile is now assumed to follow the so-called 'wounded-nucleon' distribution, which for central collision of identical nuclei leads to:

$$\epsilon(\tau_0, r) \propto \int_{-\infty}^{\infty} \rho(\sqrt{r^2+z^2})\,dz \quad (6)$$

where ρ is the (Woods-Saxon) distribution of nucleons in a nucleus having a mass number of 190 and r is the transverse distance. This is prompted by the experimental observation that transverse energy deposited in these collisions scales with the number of participants. The normalization in the above is determined from a numerical integration so that:

$$A_T\,\epsilon_0 = \int\,2\pi\,r\,\epsilon(r)\;dr. \quad (7)$$

Note that this leads to a temperature varying with r, as indeed it should.

We further assume that the phase transition takes place at $T = 180$ MeV and the freeze-out takes place at 100 MeV. This value of the critical temperature is motivated by the recent lattice QCD results which give values of about $170 - 190$ MeV [19], and the thermal model analyses of hadronic ratios which suggest that the chemical freeze-out in such collisions takes place at about 170 MeV. (A recent analysis by Becattini et al yields a value of 181.3 ± 10.3 MeV [9] for the chemical freeze-out temperature.) The phase transition should necessarily take place at a higher temperature. The freeze-out temperature is fixed at 100 MeV.

As already indicated we use a hadronic equation of state consisting of *all* hadrons and resonances from the particle data table which have a mass less then 2.5 GeV [8]. The rates for the hadronic matter have been obtained [11] from a two loop approximation of the photon self energy using a model where $\pi - \rho$ interactions have been included. The contribution of the A_1 resonance is also included according to the suggestions of Xiong et al [20]. The relevant hydrodynamic equations are solved using the procedure [21] discussed earlier and an integration over history of evolution is performed [8].

In Fig. 1 we show our results. The dashed curve gives the contribution of the quark-matter and the solid curve gives the sum of the contributions of the quark matter and the hadronic matter. We have also given the (NLO) pQCD estimate of the direct photons. A very good description of the data is obtained.

How sensitive are the results to the choice of our parameters? In Fig. 2, we show our results where we vary the transition temperature by ± 20 MeV. It is seen that the results at higher k_T (which have their origin in earlier times) remain unaltered. However, in a surprising finding we see that as the critical temperature is increased the production of photons having lower transverse momenta is reduced.

This interesting result has its origin in the rich hadronic equation of state employed in the present work. When the critical temperature is raised, many more hadronic resonances are populated, the number of "effective" degrees of freedom of the hadronic matter during the mixed phase increases, and the phase transition is completed quickly. Thus the temperature is held at T_C for a shorter duration and the photon production drops. A lower critical temperature, on the other hand, leads to a smaller number of the effective degrees of freedom for the hadronic matter, a slower conversion of the plasma to the hadronic matter and a longer duration of hot phase, and a larger production of photons. An equation of state with a fixed number of degrees of freedom for the hadronic matter would *not* have revealed this richness of the dynamics of the quark-hadron phase transition. We also note that the upper limit of the data rules out a critical temperature which is much lower than 180 MeV.

The initial time τ_0 affects the results much more strongly, as increasing it lowers the initial temperature (Eq.5). In Fig. 3 we show our results for $\tau_0 = 0.20$, 0.40, 0.60, and 1 fm/c, corresponding to $T_0 = 335$, 265, 232, and 196 MeV. We see that the data clearly favour a large initial temperature (and early thermalization).

A very important outcome of these results (Fig. 1) is that a very large component of the single photons is seen to have its origin in the quark-matter itself! If the rates obtained by Aurenche et al [10] are not used, then the major contribution would come from the hadronic matter [13] and will be obviously inadequate to explain the results. (We have verified that with the same initial conditions the yield with the rates for quark matter from Ref. [11] is a factor of 3–4 lower than the data). Recall that the new mechanism of the annihilation of quarks with scattering, suggested by Aurenche et al., is operative *only* if a hot and dense plasma is formed (see the detailed discussion in the Appendix in Ref. [10]). Thus these results confirm the existence of this mechanism and the formation of quark gluon plasma in such collisions.

Even though we realize that the creation of a hot (confined) hadronic matter in thermal and chemical equilibrium within $\tau_0 \approx 0.20$ fm/c, consequent to nuclear collision is highly unlikely [22], we estimate the initial temperature for such a system from Eq.(5) for the hadronic equation of state used here, as more than 260 MeV, when the hadronic density would be ≈ 10 hadrons/fm^3 [8]. We consider this very unphysical and unlikely. A larger formation time will give a much lower initial temperature and fail to explain the data.

How are we to understand the use of $\tau_0 = 1/3T_0 \approx 0.20$ fm/c here against the canonical value of 1 fm/c, employed often? Firstly, within the model used, this value is *favoured* by the data (Fig. 3). Secondly, if a larger value of τ_0 is used, then an allowance should be made to supplement the predictions with an appropriate pre-equilibrium contribution [23]. Finally, we note that the matter at $z = 0$ starts interacting by $t = -R/\gamma \approx -0.7$ fm/c in the present case, when the two nuclei start touching. Thus by the lapse of $\tau = 0.2$ fm/c, the matter there has been under interaction for a time which may be enough for the formation of the plasma. We do realize, however, that the two nuclei will not have fully disengaged by then and a more detailed microscopic analysis is needed to fully understand this evolution. If these estimates are considered reliable, then it may be tempting to imagine a scenario where the plasma is formed by the time $\tau = 0.2$ fm/c and the hadronic matter passing through it at later times converts into a plasma. Such a scheme was discussed in a different context by Svetitsky and Uziel [24].

Are we justified in making the assumption of a chemically equilibrated plasma, considering that indeed the predictions at the lower transverse momenta are close to the upper limits given by the experiment? This needs to be investigated (see Neumann et al [6]) as also the effect of (likely) medium modification of hadron properties. The neglect of the baryo-chemical potential for the QGP is perhaps justified as the net-baryon to hadron ratio is quite small [25], especially in the region of the central rapidity.

Summarizing, we find that the single photons measured in the WA98 experiment seem to confirm the formation of quark gluon plasma in the collision and that most of the radiation seems to come from the annihilation of quarks with scattering, which operates only if a plasma is formed.

As expected, the slope of the spectrum provides a very good measure of the initial temperature reached in the collision, while the upper limit of the data at smaller transverse momenta rule out a value much lower than 180 MeV for the critical temperature.

This holds out the hope of a rich display of radiation of photons from the quark matter at RHIC and LHC energies in collisions involving heavy nuclei, as much larger temperatures are likely to be attained there. The long life of the QGP phase at LHC energies will make it sensitive to such details like the transverse flow (within the

QGP phase itself!), which will be of immense help in deciphering the properties of the quark-matter.

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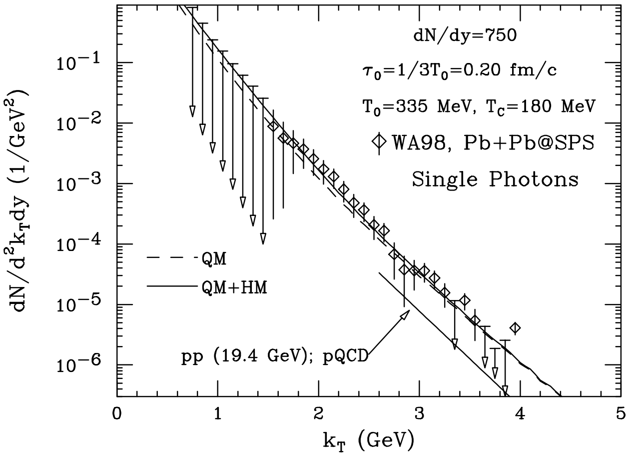


FIG. 1. Single photon production in $Pb + Pb$ collision at the CERN SPS. An equilibrated (chemically and thernally) quark-gluon plasma is assumed to be formed at $\tau_0 = 1/3T_0$ which expands, cools, enters into a mixed phase and undergoes freeze-out from a hadronic phase. QM stands for radiations from the quark matter in the QGP phase and the mixed phase. HM, likewise denotes the radiation from the hadronic matter in the mixed phase and the hadronic phase. The curve marked pQCD denotes the direct photons estimated using (NLO) perturbative quantum chromodynamics (at *pp* cm energy of 19.4 GeV). The (tail) ends of the arrows denote the upper limit of the production at 90% confidence limit.

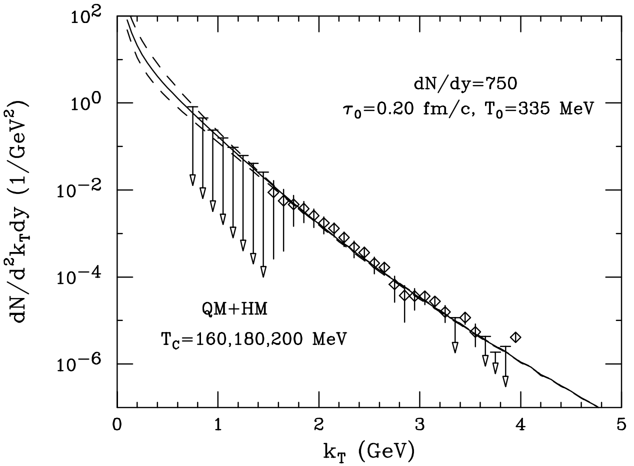


FIG. 2. The sensitivity of single photon spectrum to critical temperature. The solid curve is for $T_C = 180$ MeV, while the upper (lower) dashed curve is for 160 (200) MeV.

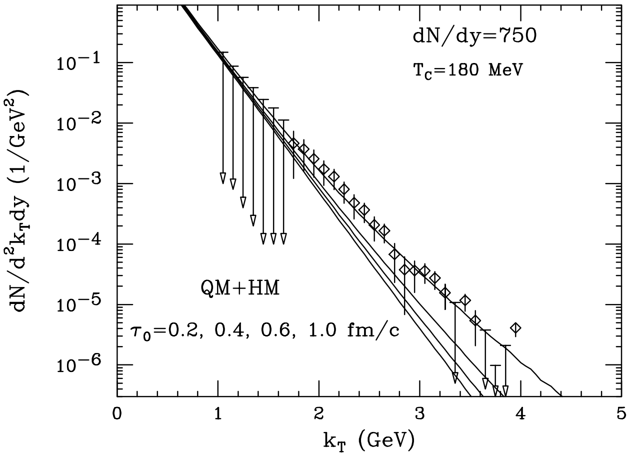
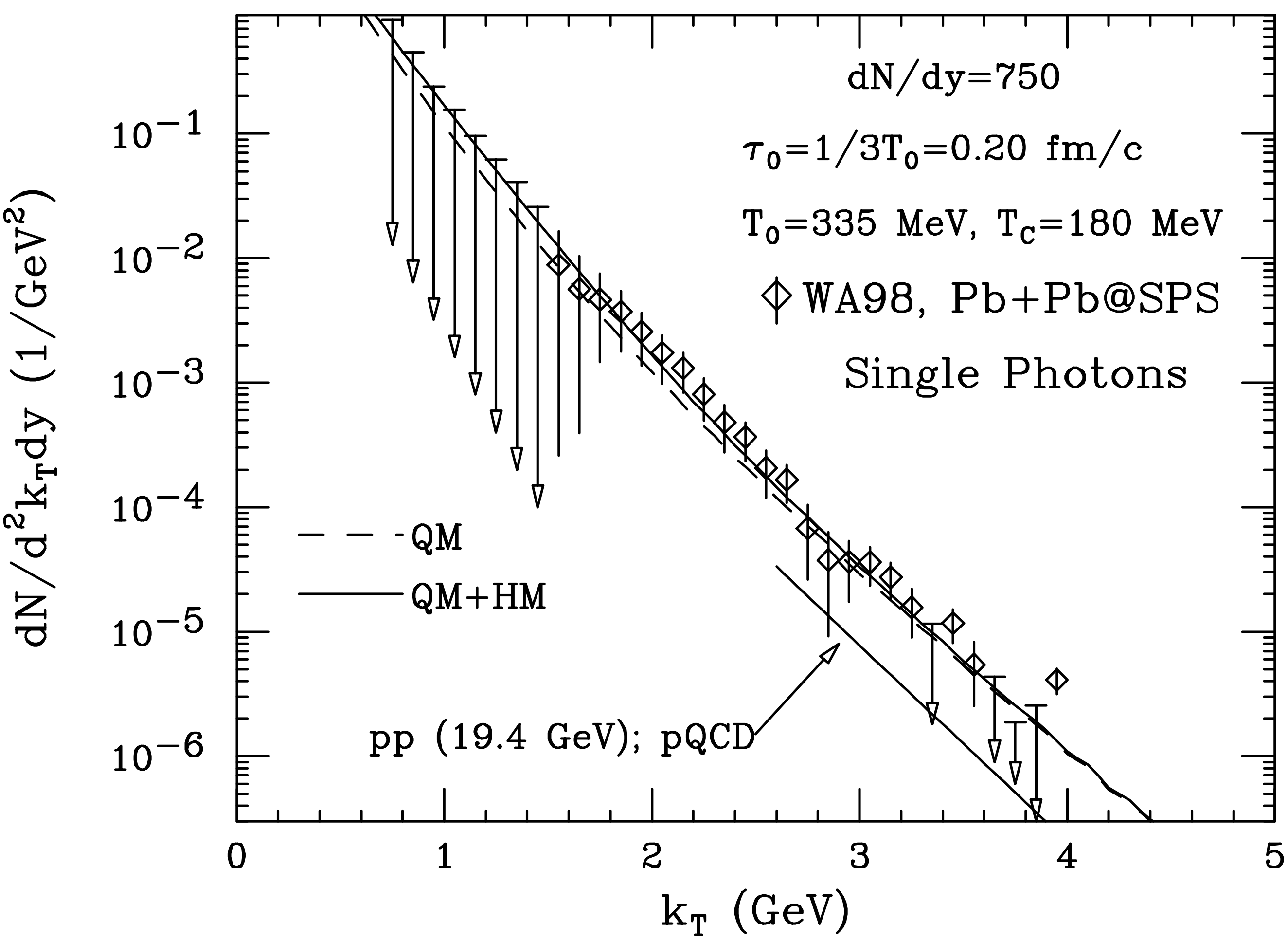
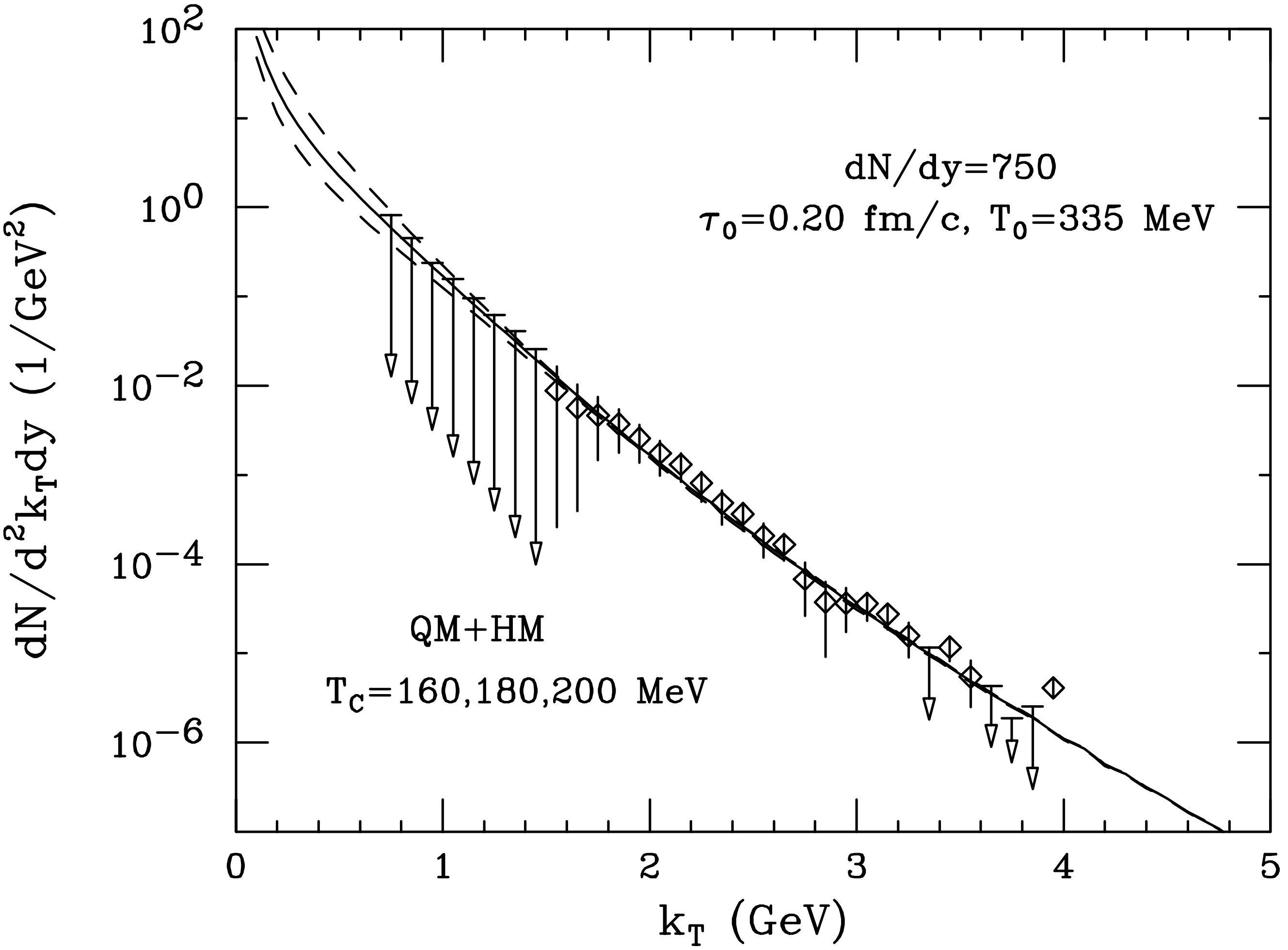
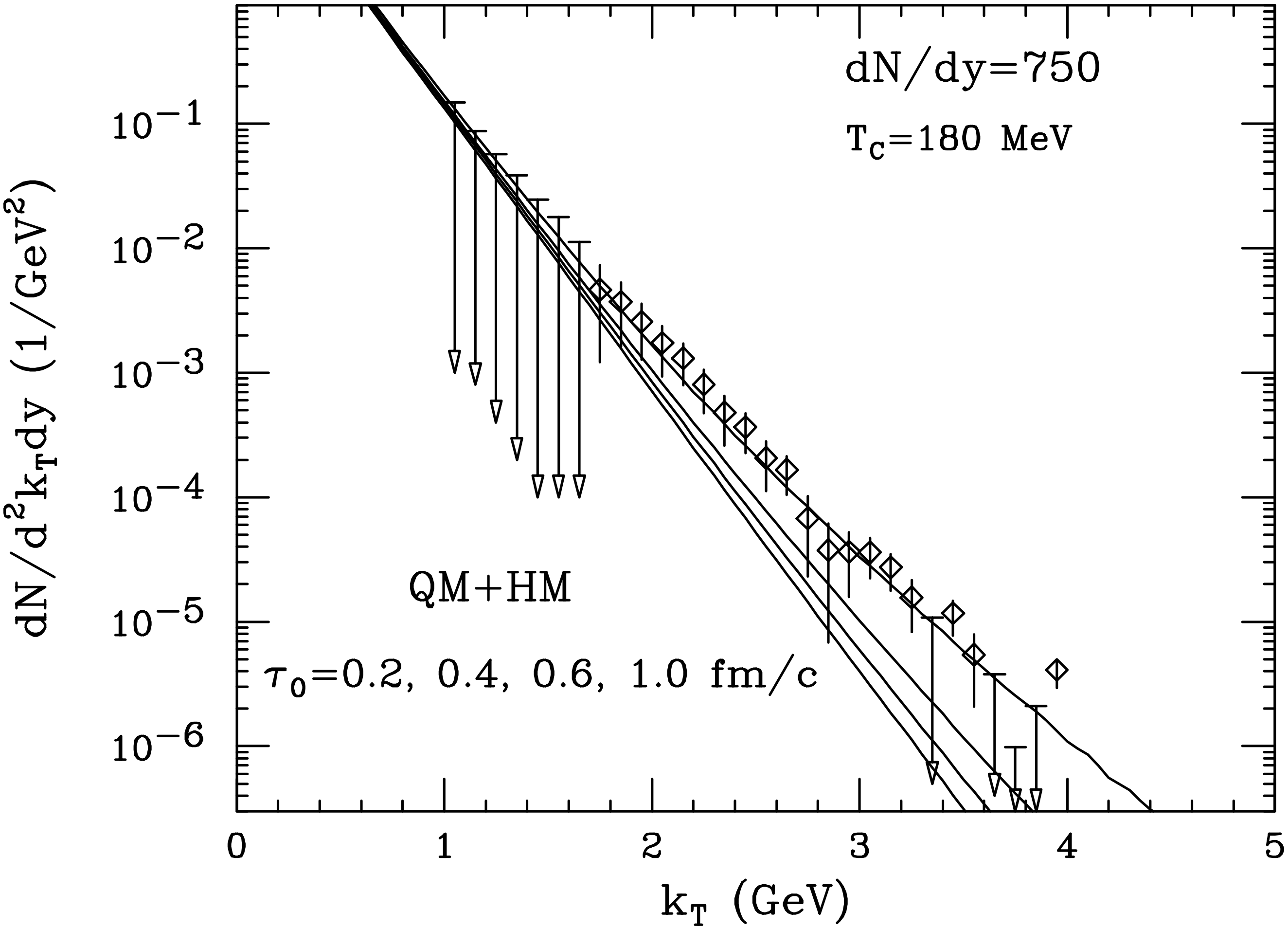


FIG. 3. The sensitivity of single photon spectrum to initial time (temperature). The curves, from top to bottom, correspond to initial times of 0.20, 0.40, 0.60, and 1.0 fm/c (see text).


dN/dy=750
$\tau_0=1/3T_0=0.20$ fm/c
$T_0=335$ MeV, $T_C=180$ MeV
WA98, Pb+Pb@SPS
Single Photons
QM
QM+HM
pp (19.4 GeV); pQCD
dN/d^2k_Tdy (1/GeV^2)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
1
2
3
4
5
k_T (GeV)


dN/dy=750
τ_0=0.20 fm/c, T_0=335 MeV
QM+HM
T_C=160,180,200 MeV
dN/d^2k_Tdy (1/GeV^2)
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
0
1
2
3
4
5
k_T (GeV)


dN/dy=750
T_c=180 MeV
QM+HM
τ_0=0.2, 0.4, 0.6, 1.0 fm/c
dN/d^2k_Tdy (1/GeV^2)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
1
2
3
4
5
k_T (GeV)