Single photons from relativistic collisions of lead nuclei at energies available at the CERN Super Proton Synchrotron (SPS): A reanalysis

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We present a reanalysis of single photon production from a relativistic collision of lead nuclei at CERN SPS measured by the WA98 experiment. The refinements include use of isospin and shadowing corrected NLO pQCD treatment for prompt photon production using an optimized scale for factorization, renormalization, and fragmentation and use of hydrodynamics suited for noncentral collisions along with a well tested equation of state admitting a quark-hadron phase transition. A quantitative explanation of the data requires a large initial temperature (at a small formation time of about 0.2 fm/c) and a moderate increase in the prompt yield which could perhaps be attributed to the Cronin effect in nuclei. The data can also be explained using a moderate initial temperature (at a formation time of about 1 fm/c) with a very large K-factor multiplying the prompt yield. We show that different initial times give rise to different values for the elliptic flow parameter v_2 for thermal photons. We also argue that a measurement of v_2 for thermal photons could also distinguish between the scenarios with or without a phase transition.

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I. INTRODUCTION

The first observation of single photons in a relativistic collision of lead nuclei in the WA98 experiment at CERN SPS [1] remains an important milestone in our search for the quark-hadron phase transition. The earlier experiment studying the S+Au collisions had provided only (though quite useful) an upper limit on the single photon production [2]. The importance of the single photons stems from the expectation that once produced they leave the system without any further interaction (see Ref. [3], for a recent account of nodal developments in this field). It is thus, expected that if a thermalized system of quarks and gluons or hot hadrons is produced in such collisions, its temperature could be related to the spectrum of the single photons. On the experimental front, the success of this endeavor hinges on our ability to subtract out the decay photons from the inclusive spectrum of photons, while on the theoretical front it depends on our ability to evaluate nonthermal photons in a quantitative manner.

In the present work, we re-analyze the single photon measurements reported by the WA98 experiment after incorporating several recent improvements in our understanding of the physics of relativistic heavy ion collisions. Firstly, we perform the NLO pQCD evaluation of prompt photon production using the optimized scale for factorization, renormalization, and fragmentation, $Q = p_T/2$ which has been found to describe a vast body of single photon production in pp collisions without introduction of any intrinsic k_T for protons [4,5]. We explicitly account for the isospin of the projectile target system, which affects the results at large $x_T = 2p_T/\sqrt{s}$, and include the effects of parton shadowing [6]. Next we account for the azimuthal anisotropy of the system for noncentral collisions, while performing the hydrodynamics calculations. Finally we explore the effects of varying the initial conditions to set limits on the likely initial temperature.

In the next section we briefly discuss our estimates for the prompt photon production. In Sec. III we describe the setting up of the initial conditions, and in Sec. IV we discuss the results. Finally we give our conclusions.

II. PROMPT PHOTONS

As mentioned earlier, it is quite crucial to get an accurate estimate of prompt photon production in nucleus-nucleus collisions, before we can begin to explore the initial conditions of the thermalized system. The success of the PHENIX experiment in measuring the single photon production at large p_T in Au+Au collisions at RHIC energies has brought this consideration into a sharp focus. Thus, for example, it is now realized [10] that the 'suppression' of single photons at large p_T in Au+Au collisions compared to those from pp collisions at the same nucleon-nucleon center of mass energy has its origin predominantly in the difference of isospin for protons and neutrons (or their valence quark structure).

This is often overlooked when the pp data are scaled by the nuclear thickness $T_{AA}(b)$, for the above comparison. Of course, one additionally needs to account for the effect of jet energy loss if a quark-gluon plasma is formed. The study of prompt photon production in pp collisions has reached a high degree of sophistication. All the available data have now been analyzed using NLO pQCD [4,5,12,13] and it is generally believed that choosing the factorization, renormalization, and fragmentation scales as equal to $p_T/2$ provides an excellent description to all the single photon data *except* for those from the E704 [7] and the E706 [14] experiments, without the requirement of any intrinsic k_T. Inclusion of intrinsic k_T improves the description of the these data but simultaneously destroys the good agreement with all the other data. The E704 data are at $\sqrt{s} = 19.4$ GeV, which is close to the $\sqrt{s_{NN}} \approx 17.3$ GeV relevant for the WA98 experiment. Two other experiments

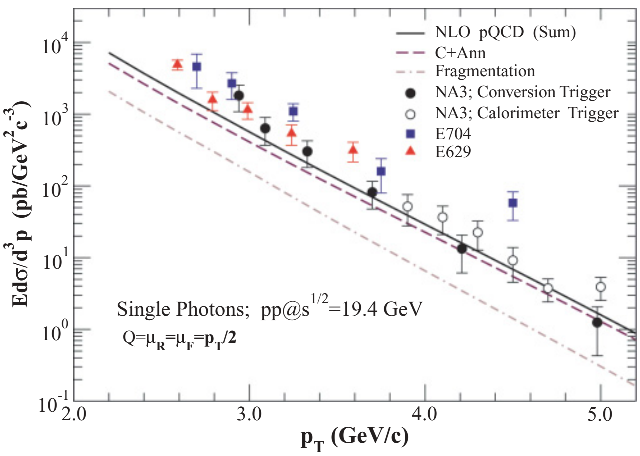

FIG. 1. (Color online) Prompt photons from pp collisions at $\sqrt{s} = 19.4$ GeV. Experimental results by E704 [7] for pp collisions and those estimated from $p + {}^{12}\mathrm{C}$ collisions by the E629 [8] and NA3 [9] experiments are also given for a comparison. The results for the NA3 experiment use two different triggers: conversion and calorimeter.

NA3 [9] and E629 [8] have measured single photon production from $p + {}^{12}\mathrm{C}$ collisions at the same energy and these data are often used with a normalization by the mass number of the target to estimate the pp data, even though half of the nucleons in the target are neutrons. We have verified that accounting for this reduces the theory values by about 2% at $p_T \approx 2$ GeV/c and by about 15% for $p_T \approx 6$ GeV/c, which is well below the other experimental uncertainties. We shall ignore this for the moment. We show our calculation for the single photon production at $\sqrt{s} = 19.4$ GeV in Fig. 1, along with the data reported by the NA3 [7,9], and E629 [8] experiments. We note that the fragmentation contribution at this energy is of the order of 30% of the Compton + annihilation term. We also see that the NLO pQCD provides a good description of the NA3 data, while it underestimates the E704 and E629 data by a factor of 2–6. This has been noted by several studies as mentioned earlier [4,13] and it is known that these data deviate also from the x_T scaling which all the other data follow [15]. We have verified that this scaling is in good agreement with the NLO pQCD results for values of p_T up to about 4.5 GeV/c, but overpredicts the results considerably at higher p_T. We are discussing this point again as several studies have tried to accommodate these data by incorporating intrinsic k_T for the partons, which is not favored by the rest of the data. We must add though these results are among the earliest measurements of single photons, which may account for the inconsistency of data between different experiments and even within the same experiment [9].

Recently, prompt photon production in $p + {}^{12}\mathrm{C}$ and $p + {}^{208}\mathrm{Pb}$ collisions at CERN SPS energy appropriate for the WA98 experiment [16] has been measured. Only the upper limit of the single photon production could be deduced. We have verified that the upper limits are about a factor of 5–10 larger than the NLO pQCD calculations, though the slope of the data is described well by the calculations.

We also note that the inclusion of the intrinsic k_T of partons is not easy even at the lowest order of pQCD [17,18] and the results for NLO pQCD are often inferred by using a K-factor which describes the difference of results of lowest order pQCD with and without the intrinsic k_T (see also Ref. [19]). In a nuclear medium, the Cronin effect also contributes to the broadening of the transverse momentum spectrum. In Ref. [20], it was reported that this broadening by the Cronin effect can lead to an enhancement of photon production by a factor of about 2.5 for p_T of 2–4 GeV/c for the case of the WA98 experiment.

Our task of obtaining an accurate estimate of prompt photon production in Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV is further complicated. Firstly, there is no single photon production data from pp collisions at this energy. In any case there is no data for pn and nn collisions, which will also contribute to the production of prompt photons from lead nuclei. The importance of these can be seen from Fig. 2 where we show our results for the effect of isospin and shadowing for prompt photon production at this energy. We see that effects of isospin and shadowing reduce the single photon production at $p_T = 4$ GeV/c by about 30% for Pb+Pb collisions compared to naive scaling of pp data by the nuclear thickness used in most of the early studies, including those involving one of the present authors [21]. We also note that the inclusion of shadowing leads to a significant variation in the end result so that at lower transverse momenta, the single photon production goes up. The middle and the lower panels of the figure show the results for $x_T = 2p_T/\sqrt{s}$ scaling with the inclusion of isospin and parton shadowing at SPS, RHIC, and LHC energies [11]. The deviations from a scaling behavior are due to the scale dependence of the structure functions and the QCD interactions [22].

In light of the discussions above we take the following view for getting the yield of prompt photons for Pb+Pb collisions at an energy corresponding to the WA98 experiment. For a given impact parameter b, we first estimate the effective number of protons and neutrons from the number of participants:

$$N_{\mathrm{part}}(b) = \int dx dy \nu(x, y, b), \tag{1}$$

where

$$\begin{aligned}\nu(x, y, b) &= \{T_A(x+b/2, y)[1 - (1 - \sigma T_B(x-b/2, y)/B)^B] \\ &\quad + T_B(x-b/2, y)[1 - (1 - \sigma T_A(x+b/2, y)/A)^A]\}\end{aligned} \tag{2}$$

is the surface density. In the above T_A is the nuclear thickness function of the nucleus A:

$$T_A(x, y) = \int_{-\infty}^{+\infty} dz \rho_A(x, y, z), \tag{3}$$

where the nuclear density is given by a Woods-Saxon distribution,

$$\rho_A(r) = \frac{\rho_0}{1 + \exp[(r - R)/a]}, \tag{4}$$

with the normalization,

$$\int d^3r \rho_A(r) = A. \tag{5}$$

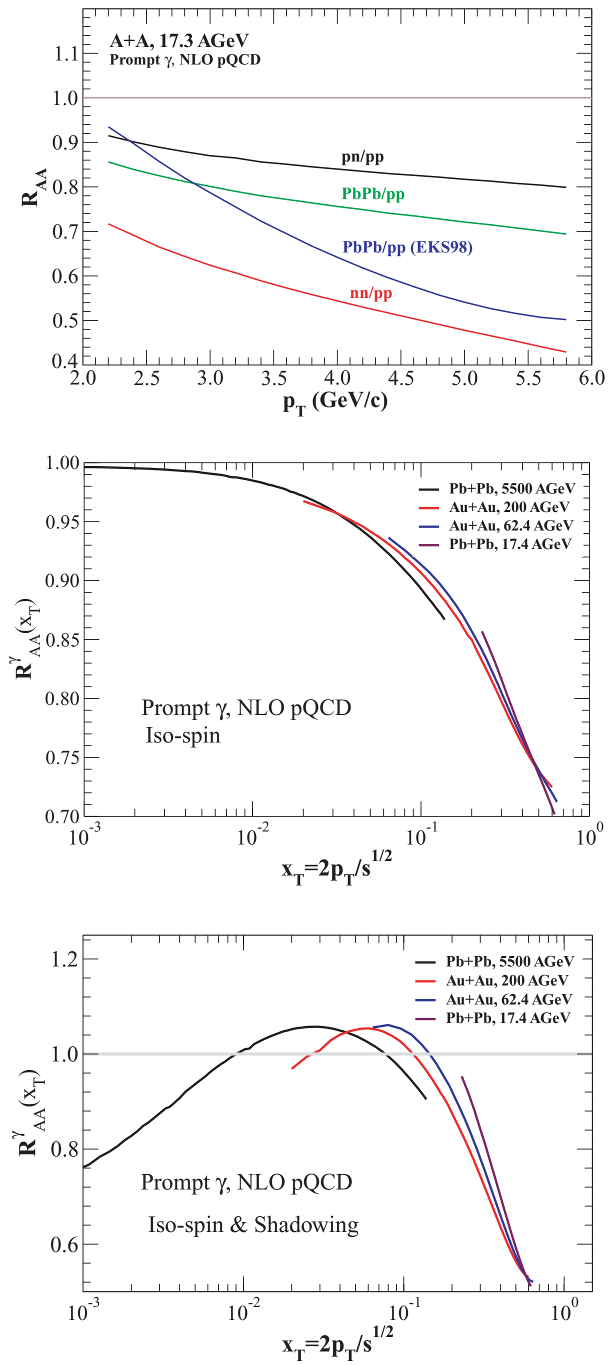

FIG. 2. (Color online) Upper panel: Effect of isospin and parton shadowing on production of prompt photons, calculated using NLO pQCD, at $\sqrt{s_{NN}} = 17.3$ GeV, which corresponds to the nucleon-nucleon center of mass energy for the WA98 [1] experiment. Results are given in terms of the nuclear modification factor R_{AA} for pn, nn, and PbPb collisions. Middle panel: Effect of isospin at SPS, RHIC, and LHC energies as a function of $x_T = 2p_T/\sqrt{s}$. Lower panel: Same as before with shadowing. (see Ref. [11]).

A similar expression holds for the nucleus B. We shall take the nuclear radius R for the Pb nucleus to be 6.5 fm and the diffuseness a to be 0.54 fm. The nucleon-nucleon inelastic cross section σ is set to 32 mb relevant for the $\sqrt{s_{NN}} = 17.3$ GeV.

Now we assume that the effective number of protons from the projectile or the target which constitute the participants at a given impact parameter b is given by

$$Z^{\rm eff}_{\rm Proj} = Z^{\rm eff}_{\rm Targ} = \frac{Z}{A}\frac{N_{\rm part}(b)}{2}, \tag{6}$$

with a similar expression for the effective number of neutrons. These numbers then decide the shadowing functions $R_{A_{\rm eff}}(x, Q^2)$ as well as the effective structure functions,

$$f_{A_{\rm eff}}(x) = \frac{Z_{\rm eff}}{A_{\rm eff}} f_p(x) + \frac{N_{\rm eff}}{A_{\rm eff}} f_n(x) \tag{7}$$

for the prompt photon calculations. We multiply the cross sections for the production of photons from the "effective" nucleon-nucleon collisions using NLO pQCD, with the nuclear overlap function:

$$T_{AB}(b) = \int dx dy T_A\left(x + \frac{b}{2}, y\right) T_B\left(x - \frac{b}{2}, y\right) \tag{8}$$

to get the yield of prompt photons. Finally the yield is averaged over the impact-parameter range covered by the centrality of the collision.

III. THERMAL PHOTONS

A. Initial conditions

We have already noted that the importance of thermal photons lies in their sensitivity to initial conditions. The simplest and most widely used initial conditions assume the formation of a hot, thermalized, and chemically equilibrated quark gluon plasma at some initial time τ_0, beyond which the system expands isentropically ignoring the viscosity effect. This makes the powerful methods of hydrodynamics available to us. One may also use a parametrized fireball to describe the evolution of the system.

For this study, we employ a boost invariant hydrodynamics [23] as our model of the underlying bulk evolution, especially for the purpose of obtaining the initial energy and temperature distributions. This model has been used extensively to explore and hadron production and elliptic flow of hadrons as well as photons [24] and dileptons [25]. For the SPS energies under consideration, the initial conditions are estimated by assuming [23,26–28] that the deposited energy in the transverse plane is proportional to the number of wounded nucleons [29] (or participants):

$$\epsilon(x, y, b, \tau_0) = K\,\nu(x, y, b), \tag{9}$$

where K is a constant and $\nu(x, y, b)$ is given in Eq. (2). We further assume, as in Ref. [23] that the initial transverse density profile of net baryon number is proportional to the participant profile as well

$$n(x, y, b, \tau_0) = L\epsilon(x, y, b, \tau_0). \tag{10}$$

The authors of Ref. [23] have shown that taking $\tau_0 = 0.8$ fm/c along with $K = 2.04$ GeV/fm and $L = 0.122$ GeV^{-1} provides a remarkably quantitative description of the particle spectra measured for the Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV, using the equation of state Q, which provides that the thermally and chemically equilibrated QGP undergoes a first order phase transition to hadrons at $T_c \approx 164$ MeV. We have checked that these values give a quantitative description of the deposited transverse energy measured by the WA98 experiment [30] for central collisions.

In the present work we use these values for K, L, and τ_0. We additionally explore the consequences of varying τ_0 such that the rapidity density of total entropy, dS/dy, and net baryons, $dN_{B\overline{B}}/dy$, remains fixed (see Refs. [28,34] for a similar approach). This is attained by taking the entropy density $\propto \epsilon^{3/4}$ and then using $s_0\tau_0$ and $n_0\tau_0$ as constants, where $s_0 = s(x = 0, y = 0, b = 0)$ and $n_0 = n(x = 0, y = 0, b = 0)$. This corresponds to an isentropic expansion. Note that the shape of the these distributions are taken as independent of τ_0. Thus we have used $\tau_0 = 0.2, 0.4, 0.6, 0.8$, and 1.0 fm/$c$. These then correspond to the peak temperature, $T_0(x = 0, y = 0, b = 0)$ of 420, 330, 284, 257, and 238 MeV, respectively, while the average temperatures are 380, 295, 257, 233, and 215 MeV, respectively.

B. The flow patterns

As a first step we determine the time-evolution of the average energy density, average temperature, and the average transverse velocity of the expanding system obtained from the hydrodynamic calculations for a central collision. We take the average by defining

$$\langle f \rangle = \frac{\int dxdy f(x, y)\epsilon(x, y, \tau)}{\int dxdy \epsilon(x, y, \tau)}. \tag{11}$$

We note (see Fig. 3) that in the overlapping time-span, the variations of these quantities are quite similar, though an earlier start leads to a slightly larger build-up of the flow velocity and a faster cooling of the system. In the final stages the temperatures and the velocities do not differ beyond about 10% for different initial times, though the energy density varies by about 40% (as it varies as T^4).

Photons are sensitive to the initial temperature. Therefore, an earlier initial time with higher initial temperature will lead to a considerably enhanced production of photons at higher transverse momenta. On the other hand, this should not affect the spectra of hadrons since they are emitted at a much later freeze-out stage when the effect of having different initial times is mostly washed out.

In Fig. 4 we have shown the time-evolution of the average effective temperature (or the blue-shifted temperature) to see the combined effect of the cooling and expansion (velocity). We define the effective temperature as

$$T_{\text{eff}} = T\sqrt{\frac{1 + v_T}{1 - v_T}}. \tag{12}$$

We note that as in Fig. 3, the results differ only marginally beyond the time of about 1 fm/c, confirming once again our surmise that the difference in the production of thermal photons should mostly arise from contributions before this time.

C. Thermal photons

We calculate the production of thermal photons by folding the history of the evolution of the system with the rate

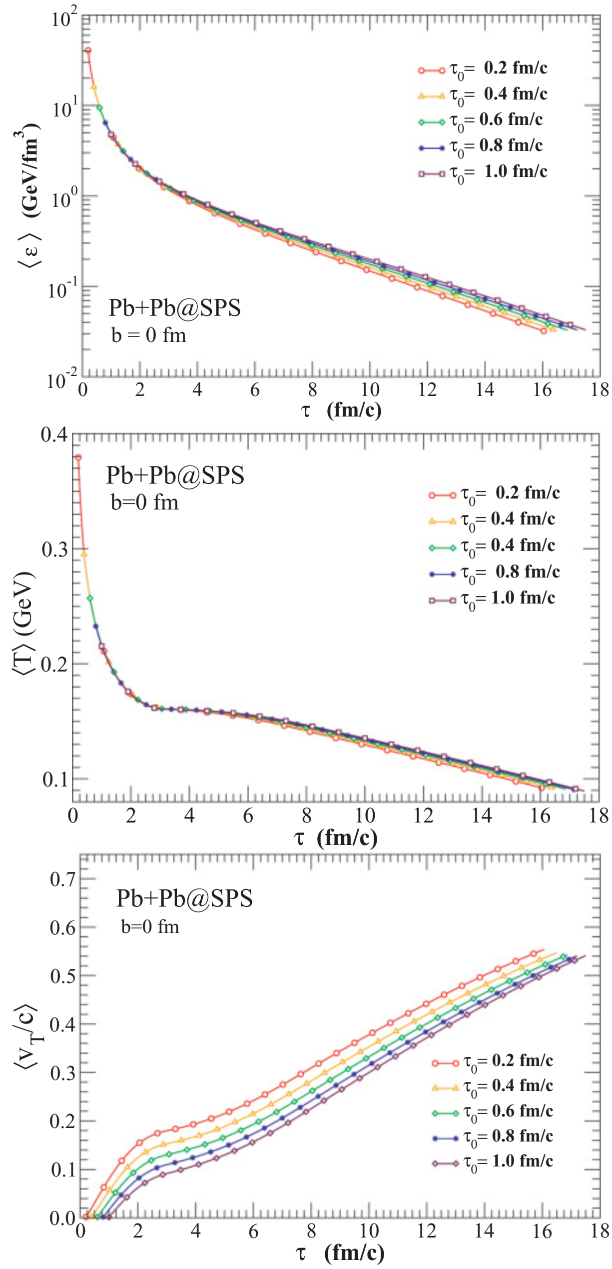

FIG. 3. (Color online) Evolution of average energy density (upper panel), temperature (middle panel), and radial flow velocity (lower panel) with time for different initial times τ_0 but identical rapidity density for total entropy and net baryons for a central collision of two lead nuclei at SPS energies.

for the production of photons from the quark matter and the hadronic matter. We use the complete leading-order results for the production of photons from the QGP from Arnold, Moore, and Yaffe [31] and the latest results for the radiation of photons from a hot hadronic gas obtained by Turbide, Rapp, and Gale [20]. As mentioned earlier, the equation of state (EOS Q [23]) incorporating a phase transition to quark gluon plasma at $T \approx 164$ MeV, and resonance gas for the hadronic phase below the energy density of 0.45 GeV/fm^{-3} is used to describe the evolution. The mixed

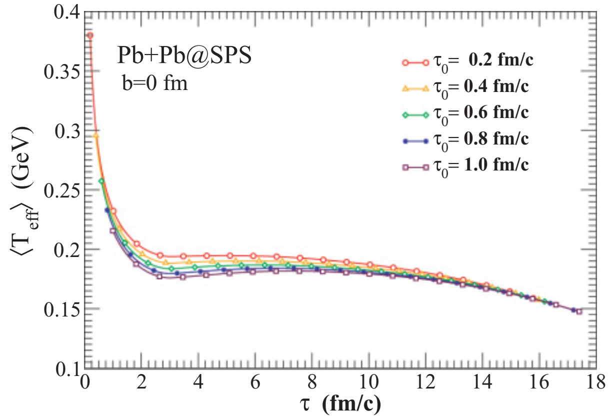

FIG. 4. (Color online) Evolution of average effective temperature with time for different initial times τ_0 but identical rapidity density for total entropy and net baryons for a central collision of two lead nuclei at SPS energies.

phase is described using Maxwell's construction. The freeze-out is assumed to take place at $\epsilon = 0.075$ GeV/fm^3. Final results are obtained by taking an average of the results over the range of impact parameters b between 0 and 4.6 fm corresponding to 0–10% of most central collisions, considered by the WA98 experiment.

We summarize our results for the case of $\tau_0 = 0.2, 0.4, 0.6, 0.8$, and 1.0 fm/$c$ in Figs. 5–9. As expected from the discussion earlier, we find that the hadronic matter contribution to the single photons is only marginally altered as we increase the initial time or decrease the initial temperature. The quark matter contribution at large p_T however drops as the initial time is increased (the initial temperature increased).

We note that the prompt photon production is about 17% of the total yield. Noting that these are NLO results, the lowest order prompt photon production is perhaps only of the order of 10% of the total single photon production measured in the experiment. We also note that the thermal production of photons is almost identical to the prompt photon production when $\tau_0 = 0.4$fm/c.

We have also shown the results for the "Thermal+κ × Prompt" photon contribution, with κ adjusted to reproduce the experimental results at $p_T = 2.55$ GeV/c. It is good to see that the same normalization provides a good description to the entire p_T range in every case (see middle panels). We find that scaling the prompt photon results by factors of 2.7, 4.9, 5.4, 5.7, and 5.9, respectively, are necessary in order to provide a *quantitative* description of experimental results.

We can perhaps argue that κ accounts for the Cronin effect in case of nucleus-nucleus collisions as well as pre-equilibrium contributions which must surely be accounted for when τ_0 is large. We do know that the pre-equilibrium electromagnetic radiations look thermal in nature [32], and we have noted that in the present case, the prompt and the thermal contributions have similar slopes, for large initial temperatures

Even though a value of $\tau_0 = 0.2$ fm/c may be considered too small, let us not forget that in this notation the nuclei would start interacting at $\tau = -R/\gamma$ or at about $\tau \approx -0.6$ fm/c, and thus a hot and dense system can be considered to be formed soon after the complete overlap, which occurs at $\tau = 0$ fm/c.

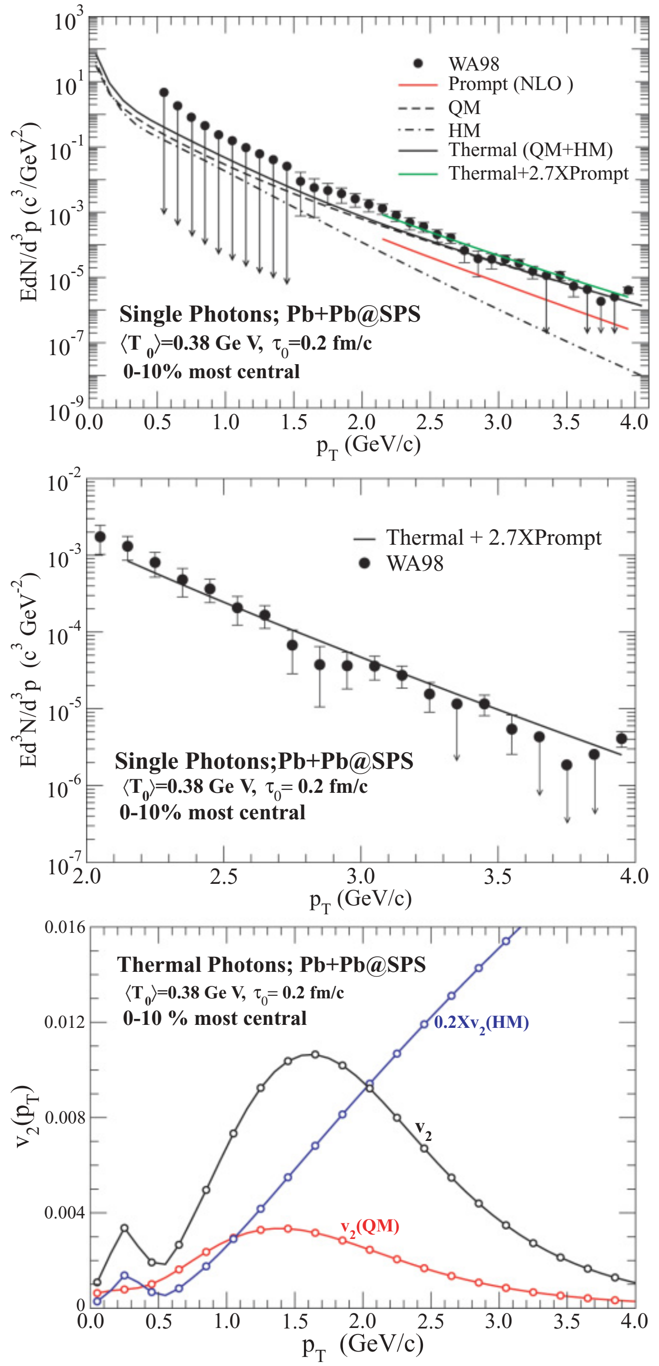

FIG. 5. (Color online) Upper Panel: Fit to single photon spectra from Pb(158A GeV) + Pb collisions measured by the WA98 [1] experiment for $\tau_0 = 0.2$ fm/c The prompt photon contribution, is scaled by a factor of 2.7 to normalize the theoretical results to the experimental data at $p_T = 2.55$ GeV/c. Middle panel: Details. Lower panel: Elliptical flow coefficients for the thermal photons. QM and HM stand for photons from quark matter and hadronic matter.

Let us try to see if some additional experimental result could actually distinguish between the different values for τ_0, and thus in a potentially interesting observation, we note (see lower

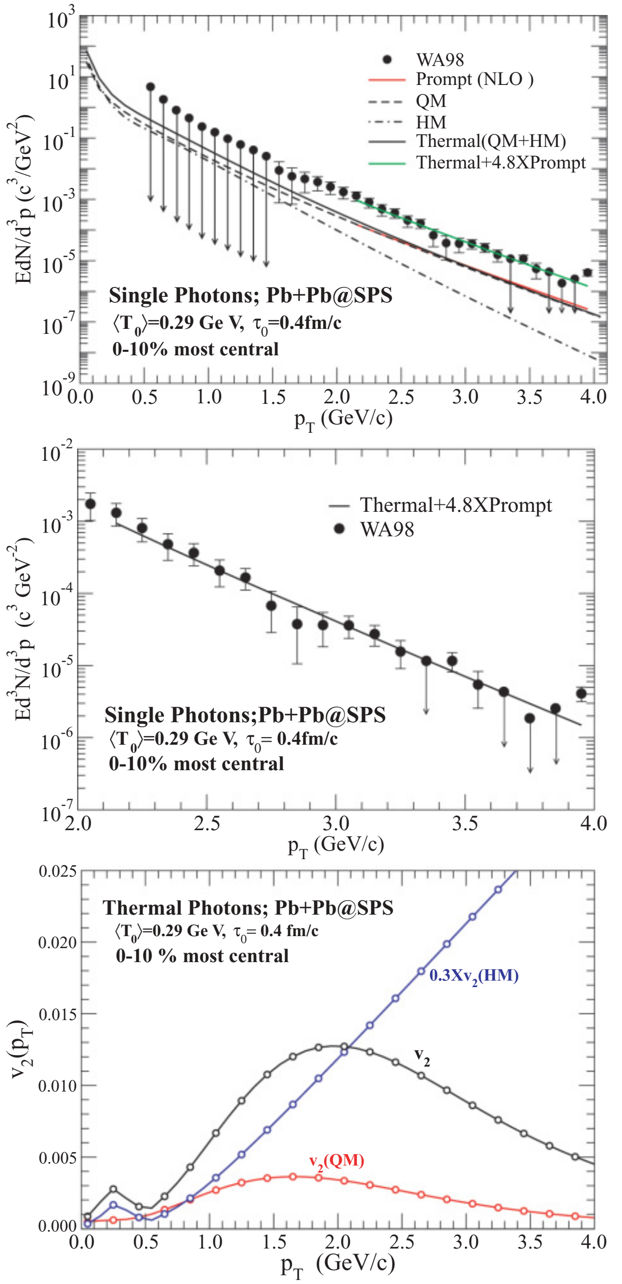

FIG. 6. (Color online) Same as Fig. 5 for $\tau_0 = 0.4$ fm/c. Note that the NLO pQCD results have to be scaled up by 4.8 for describing the data.

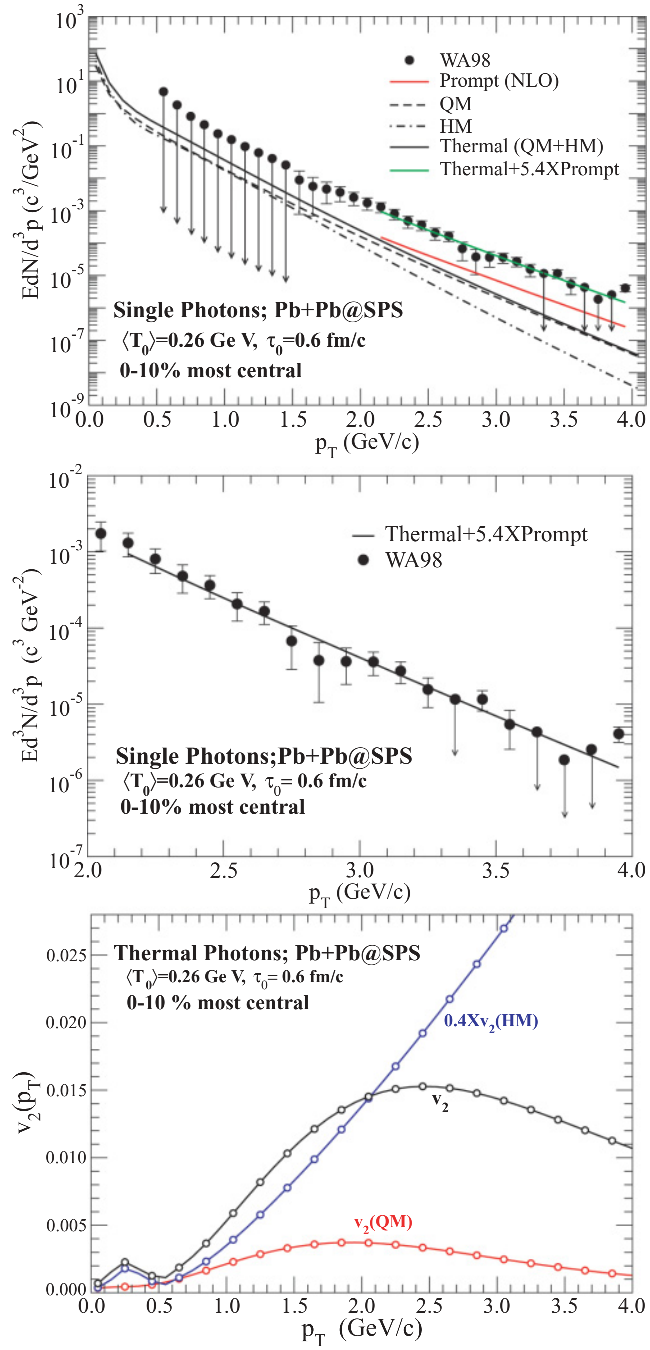

FIG. 7. (Color online) Same as Fig. 5 for $\tau_0 = 0.6$ fm/c. Note that the NLO pQCD results have to be scaled up by 5.4 for describing the data.

panels of Figs. 5–9), that the elliptic flow parameter v_2 for the thermal photons [24] is quite sensitive to the formation time τ_0 [33]. We also note the peak at low p_T in the $v_2(p_T)$, first noted by the authors of Ref. [24] and interpreted as a consequence of competition of $\pi\pi \rightarrow \rho\gamma$ and $\pi\rho \rightarrow \pi\gamma$ reactions. We note that as we decrease τ_0, the contribution of the quark matter increases. As this contribution arises from earlier times, where the momentum anisotropies are smaller, decreasing τ_0 thus leads to an overall reduction in v_2 for thermal photons. Even though the azimuthal anisotropies for these fairly central collisions are small, they reveal an important sensitivity to the formation time (see Fig. 10). Note also the inversion of the order of the results for v_2 with increasing τ_0 with and without accounting for the nonthermal component).

Let us pause here to consider a question which has troubled the analysis of single photons from the WA98 experiment, from the very beginning. In the present work, we have started with the assumption of a formation of QGP at time τ_0. However, several studies have also [34,35] presented a reasonable description of the data by assuming only the formation of a hot hadronic gas in the collision without ever forming a QGP.

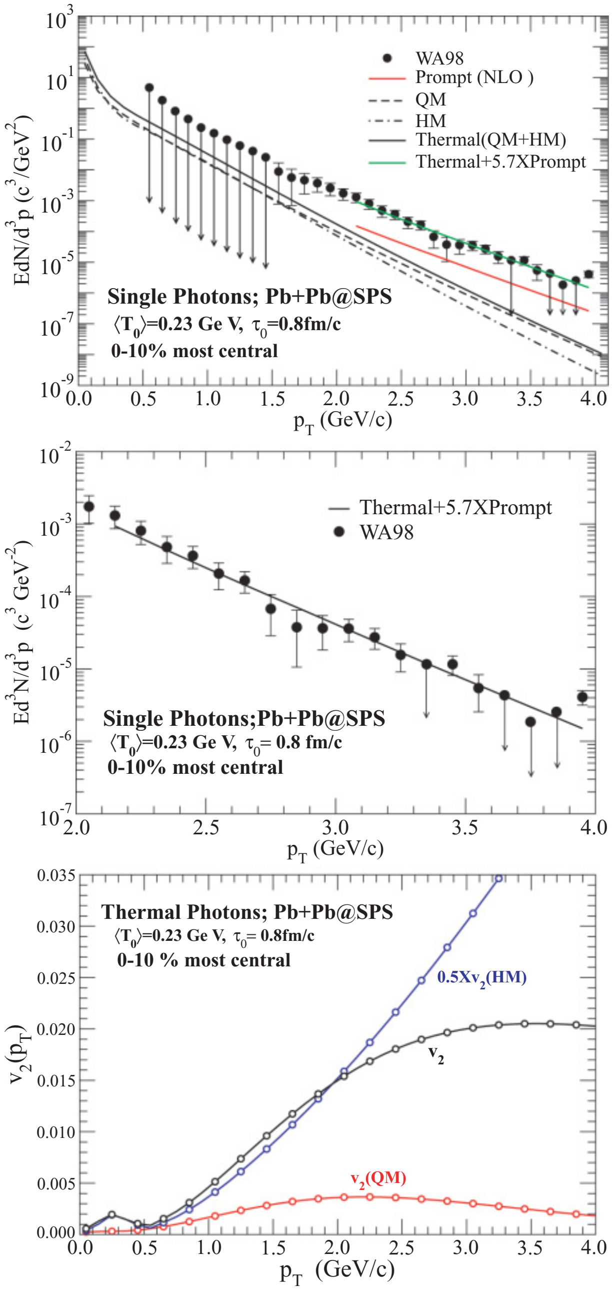

FIG. 8. (Color online) Same as Fig. 5 for $\tau_0 = 0.8$ fm/c. Note that the NLO pQCD results have to be scaled up by 5.7 for describing the data.

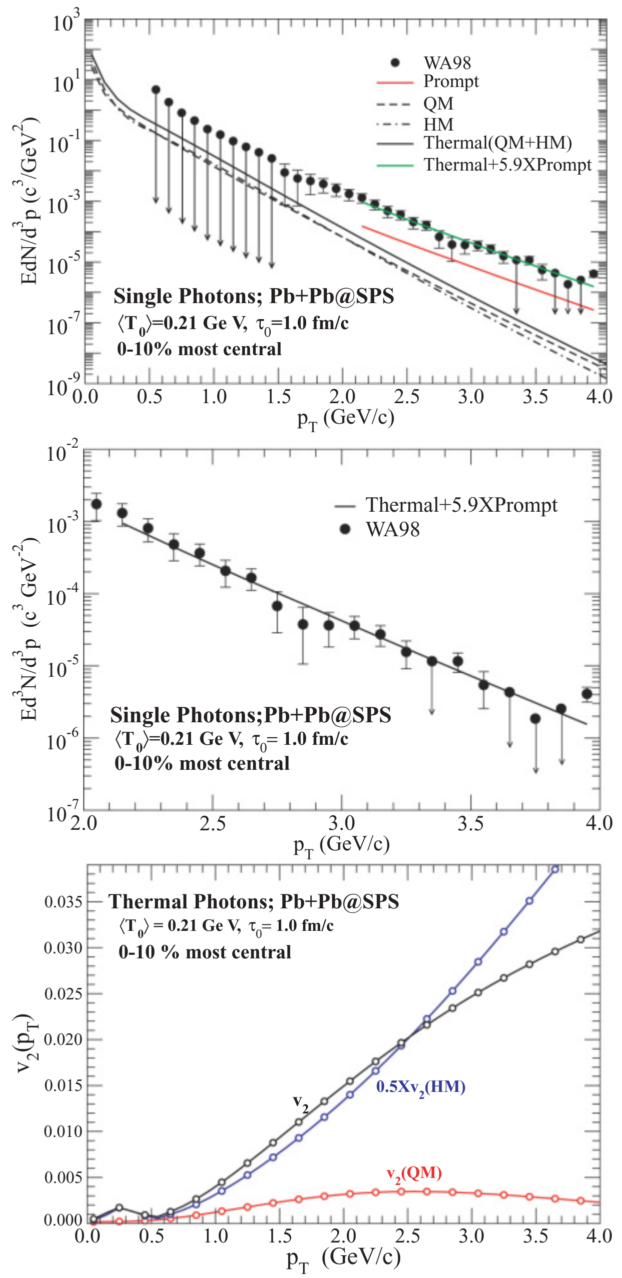

FIG. 9. (Color online) Same as Fig. 5 for $\tau_0 = 1.0$ fm/c. Note that the NLO pQCD results have to be scaled up by 5.9 for describing the data.

Which is the right scenario, then? We note here that the photon v_2 provides a possible resolution to this question. If no QGP is formed, then the v_2 for thermal photons will closely follow the $v_2(p_T)$ for ρ mesons at larger p_T. Hence, it will be considerably larger than our prediction and also will rise monotonically [24] as p_T increases. This suggests that a measurement of the v_2 of thermal photons along with their spectra could very firmly distinguish between the two scenarios.

Coming back to our present discussion, we note that the results for v_2 for direct photons will be modified from the values for the thermal photons due to the presence of prompt photons (see Fig. 10, lower panel). However, the *prompt photons as well as the pre-equilibrium photons* will not contribute to the azimuthal anisotropy of the photon distribution, as they are not subjected to any collectivity. We can safely neglect the small effect of azimuthal dependence of jet-quenching which may affect the fragmentation photons (which is less than about 30% of the prompt contribution in the present case) or those of jet-induced photons [36], which measure the anisotropy of the initial state [37]. This is because the QGP, if formed at the SPS, is very short lived and not very hot, as indicated by a small jet-quenching (not exceeding about 25–30%) for such collisions [38]. We show the results for final

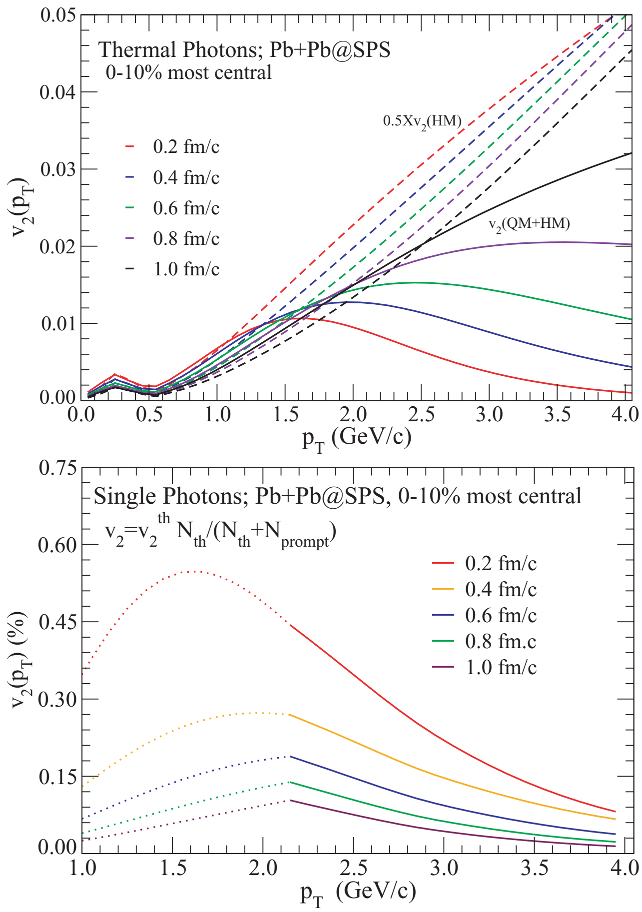

FIG. 10. (Color online) Upper panel: v_2 for thermal photons for different τ_0. The results for photons from hadronic matter alone are also given. Lower panel: v_2 for single photons. Results below $p_T = 2.15$ GeV/c (shown as dotted curve) are obtained by arbitrarily using the normalizing factor at $p_T = 2.15$ GeV/c. It is assumed that the difference of experimental data and the thermal production can be attributed to prompt and pre-equilibrium contributions.

v_2 for single photons for the case of the WA98 experiment in Fig. 10.

We finally recall a completely different calculation using the parton cascade model [39,40] for this case, where the scattering and radiating partons produced a not-so-dense partonic system, but it was enough to reproduce the single photon production seen by the WA98 experiment beyond about 3 GeV/c, *if* the partonic distributions are given an intrinsic $\langle k_T \rangle$ of about 0.44 GeV/c. In absence of the intrinsic $\langle k_T \rangle$ the production is smaller by a factor of about 2. These photons can be considered as due to prompt and the pre-equilibrium contributions.

We have so far assumed that the prompt and pre-equilibrium photons and their enhanced production due to intrinsic k_T can be estimated by using a multiplicative factor κ to the NLO pQCD results. Within this approach, we have ascertained that the photon observables, especially the v_2, are sensitive measures of the initial condition. Admittedly, there are some uncertainties in our approach such as the NLO contribution to the thermal photon production and the effect of the viscous hydrodynamic evolution. At present, their effects are unknown although the effect of the finite viscosity on photons may soon be calculated [41].

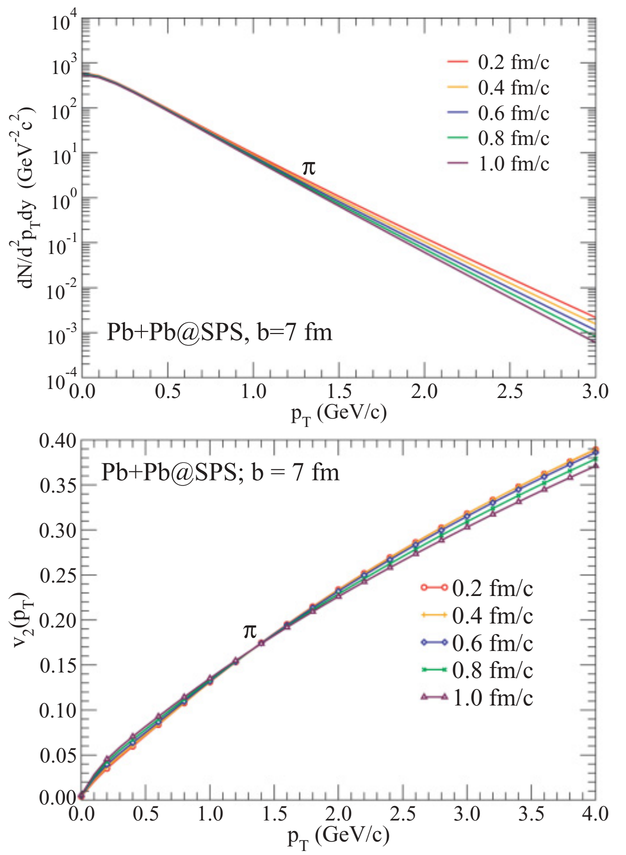

FIG. 11. (Color online) Spectra (upper panel) and $v_2(p_T)$ (lower panel) for primary pions from Pb+Pb collisions having $b = 7$ fm at SPS energy, for different initial times.

D. Particle spectra

How will the reported good description of particle spectra [23] obtained using $\tau_0 = 0.8$ fm/c, be affected, if a different value is used for τ_0? Instead of discussing a complete calculation (with resonance decay accounted for), we show the primary spectra of pions, rho mesons, and protons for a typical impact parameter $b = 7$ fm, for different values of τ_0, but keeping the entropy fixed as in the calculations discussed above (see Figs. 11–13). We note that as the inverse slope for all the cases rises with decrease in τ_0 as the radial flow sets in earlier. We have checked that the increase in the inverse slope for pions is about 11%, about 15% rho mesons and protons as the initial time is decreased from 1 fm/c to 0.2 fm/c. We also note that the change in the spectra for the primary particles is quite marginal for p_T below 1.5 GeV/c, even though it varies by a factor of about 3 at $p_T = 3$ GeV/c. What is most interesting is that the differential elliptic flow parameter v_2 for hadrons is almost independent of the initial time.

We conclude then, that the good description of hadronic spectra for low transverse momenta at SPS energies will

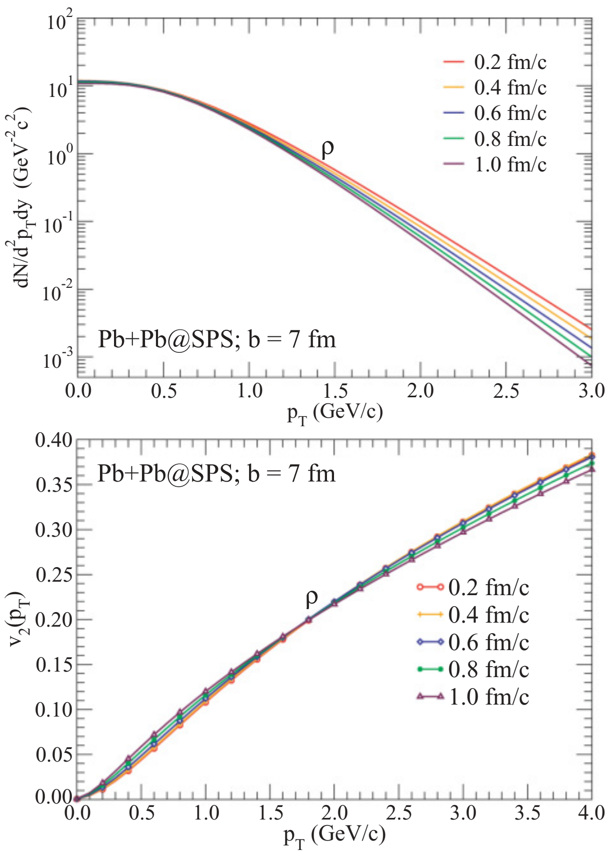

FIG. 12. (Color online) Spectra (upper panel) and $v_2(p_T)$ (lower panel) for primary rho-mesons from Pb+Pb collisions having $b = 7$ fm at SPS energy, for different initial times.

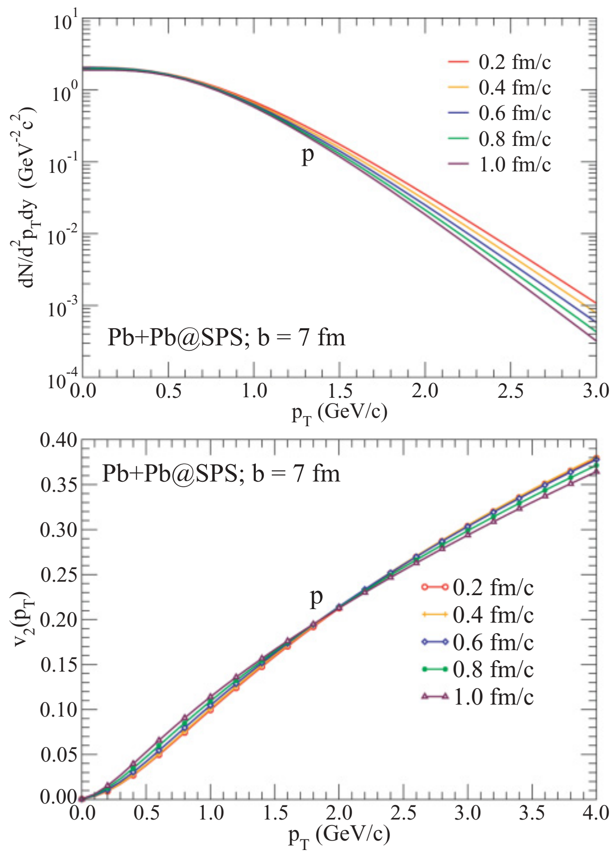

FIG. 13. (Color online) Spectra (upper panel) and $v_2(p_T)$ (lower panel) for primary protons from Pb+Pb collisions having $b = 7$ fm at SPS energy, for different initial times.

remain unaffected by the reduction of initial time from 1 fm/c to 0.2 fm/c. This is in contrast to what we saw earlier for thermal photons.

IV. SUMMARY AND CONCLUSIONS

We have re-analyzed the single photon production in Pb+Pb collisions at the CERN SPS energies for 10% most central collisions. Several improvements have been incorporated. The isospin, shadowing, and impact parameter dependence of the prompt photon production are explicitly included. NLO pQCD calculations are performed with the factorization, fragmentation, and renormalization scales fixed at $p_T/2$ based on a global description of the available data for pp collisions. For the thermal photons calculations the initial conditions are taken as those which provided a good description to hadronic spectra, with a $\tau_0 = 0.8$ fm/c. We explored the consequences of using smaller initial times, keeping the entropy and the net-baryon number fixed.

We find that the data can be explained using a small formation τ_0 of the order of 0.2 fm/c when supplemented with prompt photons evaluated at NLO pQCD with a κ factor ≈ 2.7 to account for the Cronin effect. Larger initial times require much larger values for κ, which may be mimicking the pre-equilibrium contribution. A unique sensitivity to the formation time is seen in the photon elliptic flow, which could be useful in ascertaining whether a QGP was formed at the SPS energy.

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