Thermal photons and collective flow at energies available at the BNL Relativistic Heavy-Ion Collider

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We update our calculations of thermal-photon production in nuclear collisions at the BNL Relativistic Heavy-Ion Collider (RHIC). Specifically, we address the recent experimental observation of an elliptic flow of direct photons comparable in magnitude to that of pions, which is at variance with expectations based on quark-gluon plasma (QGP) dominated photon radiation. Our thermal emission rate is based on previous work, i.e., resummed leading-order QGP emission and in-medium hadronic rates in the confined phase. These rates are nearly degenerate at temperatures close to the expected QCD-phase change. The rates are convoluted over an improved elliptic-fireball expansion with transverse- and elliptic-flow fields quantitatively constrained by empirical light- and strange-hadron spectra. The resulting direct-photon spectra in central Au-Au collisions are characterized by hadron-dominated emission up to transverse momenta of $\sim$ 2-3 GeV. The associated large elliptic flow in the hadronic phase mitigates the discrepancy with the measured photon-v_2 compared to scenarios with QGP-dominated emission.

I. INTRODUCTION

Dileptons and photons are the only particles which escape the interior of the fireball created in ultrarelativistic heavy-ion collisions (URHICs) unaffected. Their production, on the other hand, is rooted in the strongly interacting medium and thus illuminates the latter's properties, see Refs. [1–3] for reviews. Recent highlights of electromagnetic observables in URHICs include "measurements" of the in-medium vector-spectral function via dilepton *invariant*-mass spectra at the Super Proton Synchrotron (SPS) [4–6] and of the medium temperature via direct photons at RHIC [7].

It is well known that the thermal component in the observed electromagnetic spectra results from a convolution of the temperature- and density-dependent emission rate over the entire space-time history of the expanding fireball in URHICs. From the interplay of decreasing temperature and increasing three-volume in the course of the fireball expansion, it can be fairly well established that photon and dilepton emission in the low-energy regime, $q_0 \lesssim 1$ GeV[1], are dominated by the hadronic phase. At energies beyond $\sim$ 1 GeV, the situation is less clear, since the competition between hadronic and QGP sources will be sensitive to additional ingredients [10], *e.g.*, the relative strength of hadronic and QGP emission rates, the phase-transition temperature (which formally demarcates the space-time dependence of the two sources) and the transverse flow (inducing a blue shift to higher q_t which is more pronounced in the later hadronic phase)[2].

In this context, recent measurements of the elliptic flow of direct photons (i.e., after the subtraction of long-lived hadron decays, mostly $\pi^0, \eta \to \gamma\gamma$) in semicentral Au-Au collisions [11] have revealed remarkable results. It has been found that the pertinent flow coefficient, $v_2^\gamma(q_t)$, is as large as that of charged pions up to momenta of $q_t \simeq 3$ GeV (albeit the photon data carry somewhat larger error bars). This result is difficult to reconcile with a dominant QGP emission source. Primordial photons from binary N-N collisions, whose emission is expected to be isotropic, will further reduce the total direct-photon v_2. Current model calculations [12–14] using a hydrodynamically expanding medium with QGP and hadronic radiation, as well as primordial photons, underpredict the experimentally measured v_2 by a factor of ~ 5 (~ 3 when accounting for the maximal systematic error in the measurement). The question thus arises what could be missing in these calculations.

[1] The energy variable, q_0, encompasses both mass (M) and transverse-momentum (q_t) dependencies, *e.g.*, $q_0 = (M^2+q_t^2)^{1/2}$ for $q_z = 0$.

[2] Note that the blue-shift distortion does not apply to dilepton *invariant*-mass spectra if a finite detector acceptance can be fully corrected for.

In the present paper we re-examine several aspects related to thermal photon emission from the hadronic medium. Since the v_2 in the hadronic phase of URHICs is large, an augmented hadronic component is a natural candidate to improve the description of thermal-photon emission at RHIC and thus reduce the discrepancy with the v_2 data. First, we note that typical hydrodynamical evolutions with first-order phase transitions tend to underestimate the radial (and possibly elliptic) flow built up in the fireball at the end of the QGP phase. This was borne out of a recent phenomenological analysis of light- and strange-hadron spectra using blast-wave parametrizations of the respective sources at thermal and chemical and freezeout (with $T_{\rm ch} \simeq 100$ MeV and $T_{\rm fo} \simeq 180$ MeV, respectively) [15]. In particular, the observed universality in kinetic-energy scaling of the v_2 of light and strange hadrons, together with an earlier decoupling of multi-strange hadrons (as inferred from their p_t spectra), suggests that most of the hadronic v_2 is indeed of partonic origin [16]. Second, for the thermal emission rates from hadronic matter we use our previous results of Ref. [9], which, in particular, include contributions from baryons which are known to be important from dilepton calculations [10], even at RHIC [17]. Finally, we take into account chemical off-equilibrium effects in the hadronic phase, i.e., effective chemical potentials for pions, kaons, etc., which can further augment the hadronic component in thermal-photon spectra (*e.g.*, typical processes like $\pi\rho \to \pi\gamma$ are enhanced by a pion fugacity to the third power).

Our paper is organized as follows. In Sec. II we briefly recall our input for the thermal-photon rates as taken from Ref. [9], as well as for the primordial contribution, which we check against *pp* data. In Sec. III we update our description of the thermal fireball evolution by constructing (a time evolution of) flow fields which is consistent with the empirical extraction at chemical and thermal freezeout. In Sec. IV we evolve the rates over the fireball evolution and discuss the resulting photon-q_t spectra, in particular the composition of the thermal yields. In Sec. V we present our results for the direct-photon v_2 in comparison to the recent PHENIX data [11] and in light of other model results. Finally, Sec. VI contains our conclusions.

II. PHOTON SOURCES

The photon spectrum resulting from a heavy-ion (or *pp*) reaction is usually referred to as inclusive photons. The subtraction of long-lived final-state decays leads to the notion of direct photons, which are the ones of interest in the present context. For direct photons, we further distinguish the radiation of thermal photons (Sec. II A), characterized by an equilibrium-emission rate to be integrated over the space-time evolution of the medium, and a non-thermal component emanating from primordial interactions prior to thermalization (Sec. II B).

A. Thermal Emission

In the present work we adopt the thermal emission rates of photons as developed and compiled in Ref. [9].

For QGP radiation we use the numerical parametrization of the complete leading-order in α_s rate as given in Ref. [18]. The main input for the QGP rate is the strong coupling "constant" for which we take an expression with temperature-dependent one-loop running at the scale $\sim 2\pi T$, $\alpha_s(T) = 6\pi/27 \ln(T[\mathrm{GeV}]/0.022)$. This amounts to values of around 0.3 in the relevant temperature regime, $T = 1\text{-}2T_c$, which turns out to be consistent with recent estimates from the (perturbative) Coulomb term in in-medium heavy-quark free energies [22].

The basis of the thermal emission rate in hadronic matter forms the electromagnetic correlation function computed in Refs. [9, 23] using hadronic many-body theory with effective Lagrangians. It has been successfully used [1] in the interpretation of dilepton data at the SPS [4, 5] and has been carried to the photon point in Ref. [9]. It includes a rather extensive set of meson and baryon resonances in the interaction of the isovector current with a thermal heat bath of hadrons. It has been augmented by additional meson-exchange reactions in a meson gas which become important at photon momenta $q \gtrsim 1$ GeV, *e.g.*, π, ω, and a_1 exchange in $\pi + \rho \to \pi + \gamma$ as well as strangeness-bearing reactions (*e.g.*, $\pi + K^* \to K + \gamma$) [9]. An important element in constraining the hadronic vertices to empirical information, such as hadronic and radiative decay branchings, is the (gauge-invariant) introduction of vertex form factors. The latter lead to a substantial reduction of the hadronic emission rate with increasing photon momentum, which is essential for quantitative descriptions of hadronic emission rates at the momenta of experimental interest ($q_t \lesssim 3.5$ GeV for thermal radiation). Without vertex form factors, hadronic photon rates should not be considered reliable for momenta $q \geq 1$ GeV. We do not include here additional $\pi\pi$ Bremsstrahlung contributions ($\pi\pi \to \pi\pi\gamma$) as evaluated in Refs. [24, 25]. This source is important at low momenta, $q_t \lesssim 0.5$ GeV, put plays no role in the region of interest of the present investigation ($q_t \geq 1$ GeV).

The resulting total hadronic and QGP emission rates were found to be remarkably close to each other for temperatures around the putative transition temperature, $T_c \simeq 180$ MeV. This is appealing from a conceptual point of view in terms of a possibly continuous matching of the bottom-up and top-down extrapolated hadronic and QGP rates, respectively. It is also welcome from a practical point of view, since it much reduces the uncertainties associated with identifying the medium in the fireball as hadronic or partonic, which, in the case of a cross-over, may not even be well defined. If QGP and hadronic rates are significantly different across T_c, appreciable uncertainties in the calculated photon spectra have been found as a result of this ambiguity [14].

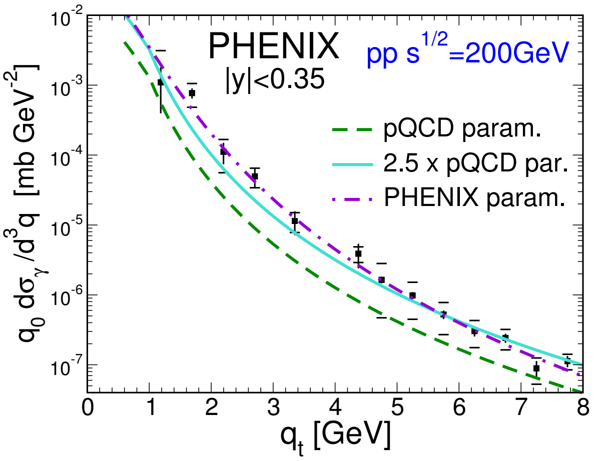

FIG. 1: (Color online) Empirical fits to the direct-photon spectrum measured by PHENIX [28] in p-p collisions at $\sqrt{s}$ = 200 GeV; dash-dotted line: power-law fit [28], solid and dashed line: x_t-scaling ansatz [29] with and without K factor, respectively.

B. Nonthermal Sources

After subtraction of final-state decays, the main source other than "thermal" radiation from the interacting medium is associated with "primordial" photons produced upon first impact of the nuclei via binary NN collisions. Primordial photon spectra are usually estimated from the direct contribution in pp collisions, where no significant reinteractions are expected. This is supported by the generally good agreement of the measured photon spectra with next-to-leading order (NLO) perturbative QCD (pQCD) calculations [26] for primordial production. In the following we will adopt a simple power-law fit performed by the PHENIX collaboration [7, 27] to their pp data [7, 28], cf. Fig. 1. Figure 4 in Ref. [7] reveals that the NLO pQCD calculations are slightly below the PHENIX parametrization in the relevant q_t range of $\sim$ 1-7 GeV. Therefore, we will alternatively estimate the primordial contribution via a x_t-scaling motivated parametrization [29], upscaled by a K-factor of 2.5 to best match the PHENIX pp data for q_t = 5-8 GeV. This fit produces a slightly smaller yield of photons with momenta q_t = 1-5 GeV compared to the PHENIX fit and is thus very similar to the NLO pQCD calculations.

In principle, photons can also be radiated off fast-moving partons (jets) interacting with the medium. The combined elliptic flow of this source is expected to be close to zero [19]. We therefore subsume this source in our primordial contribution (whose fragmentation part, *e.g.*, is expected to be reduced in the medium), which is a posteriori justified by an adequate description of the spectral yields in Au-Au collisions once thermal radiation is implemented.

III. FIREBALL AND TRANSVERSE-FLOW FIELD

The continuous emission of photons throughout the evolution of a heavy-ion reaction causes their elliptic-flow signal to be more sensitive to its time evolution than that of hadronic final states. Therefore, a calculation of the photon-v_2 requires special care in constructing a realistic time evolution of both radial and elliptic flow (the former affects the spectral weight of photon emission at a given time snapshot). In principle, hydrodynamic models are believed to be able to accomplish such a task; however, current uncertainties including initial conditions (*e.g.*, fluctuations and initial flow fields), viscosity corrections and the coupling to hadronic cascades in the dilute stages render this a challenging task, which has not been completed (yet). In the present paper we take a more pragmatic (and simple) approach which nevertheless accurately captures two experimentally established snapshots of the fireball evolution, namely the flow fields at chemical freezeout at $T_{\rm ch} \simeq 170$ MeV and kinetic freezeout at $T_{\rm fo} \simeq 100$ MeV. The latter is well determined by the transverse-momentum (p_t) spectra and elliptic flow of light hadrons (π, K, p) [30–32], while the former can be extracted from spectra and flow of multi-strange hadrons[16, 31, 33]. A detailed fit of these snapshots using an elliptic blast-wave source has been performed in Ref. [15], which was also shown to be compatible with the empirical constituent-quark number and transverse kinetic-energy (KE$_T$) scaling of the elliptic flow of light and strange hadrons. We use these results to improve a previously constructed expanding elliptic fireball [34] so that its evolution passes through these benchmarks at the end of the mixed phase and at thermal freezeout. Representative examples of the resulting multi-strange (ϕ mesons) and light-hadron (π, p) spectra and v_2 at chemical and thermal freezeout, respectively, are illustrated in Fig. 2.

Concerning initial conditions, we assume an initial longitudinal fireball size of z_0 = 0.6 fm corresponding to $c\tau_0 \simeq z_0/\Delta y \simeq 0.33$ fm ($\Delta y \simeq 1.8$) as our default value for both 0-20% and 20-40% centrality classes. With total entropies of S = 7900 and 3600 (assumed to be conserved), this translates into (average) initial temperatures of $T_0 \simeq 355$ MeV and 325 MeV, and charged-hadron multiplicities of $\mathrm{d}N_{\rm ch}/\mathrm{d}y \simeq 610$ and 280, respectively, adjusted to recent STAR data [32].

The time evolution of the inclusive elliptic flow is shown in Fig. 3. The observed KE$_T$ scaling of light and multi-strange hadrons is the main constraint which requires a rather rapid increase of the bulk v_2, and a subsequent leveling off shortly after chemical freezeout. The final values of ~2.5% and ~5% for the pion-v_2 are adjusted to experimental data [31].

Another important aspect in our medium evolution is the implementation of chemical freezeout, i.e., the use of effective meson (and baryon) chemical potentials to preserve the observed hadron ratios in the fireball expan-

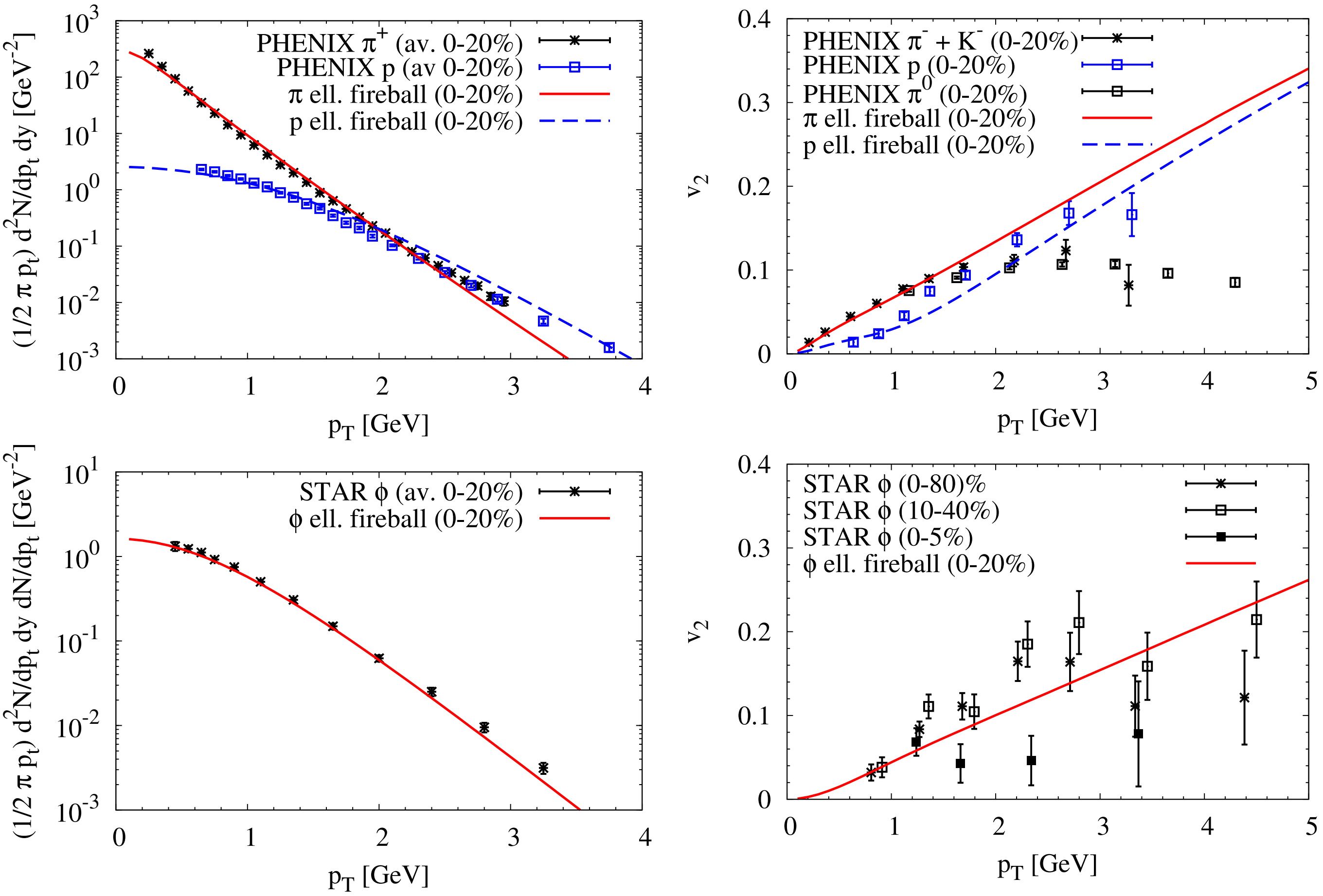

FIG. 2: (Color online) Snapshots of p_t spectra and v_2 for pions and protons (upper panels), as well as ϕ mesons (lower panels), following from our fireball evolution in 0-20% Au-Au($\sqrt{s}$ = 200 AGeV) collisions at thermal and chemical freezeout, respectively. The π and p curves are for direct emission only (no resonance feeddown) with absolute normalization while the ϕ yield is (re-) normalized to the data. Data are from Refs. [16, 43, 44].

sion at temperatures between $T_{\rm ch}$ and $T_{\rm fo}$. We do this as described in Ref. [35], which was adopted in our previous work [9]. Most of the hydrodynamic evolutions used for photon calculations at RHIC to date assume chemical equilibrium throughout the hadronic phase. This assumption likely leads to an appreciable underestimate of the thermal hadronic component in the observed photon spectra, and thus of its contribution to the direct-photon elliptic flow. For example, typical meson annihilation processes such as $\pi + \rho \to \pi + \gamma$ (proceeding through t- and s-channel π, ω and a_1 exchanges), are augmented by an initial pion fugacity, $z_\pi^3 = \exp(3\mu_\pi/T)$ (in Boltzmann approximation), where $\mu_\pi \simeq 100$ MeV in the vicinity of thermal freezeout, $T_{\rm fo} \simeq 100$ MeV. This implies a significantly larger enhancement in photon production in the later hadronic stages relative to the conservation of the hadron ratios for which the chemical potentials are introduced. In other words, the faster cooling of the fireball in chemical off-equilibrium relative to the equilibrium evolution is overcompensated in the leading photon-production channels due to a "high" power of pion densities.

IV. DIRECT-PHOTON SPECTRA

We start the comparison of our theoretical calculations of direct photons to data at RHIC with the absolute yields in the transverse-momentum (q_t spectra). Let us first illustrate the quantitative effect of updating the radial expansion starting from our original predictions in Ref. [9].[3] In the latter, a transverse acceleration of the fireball surface of $a_T = 0.053c^2$/fm had been assumed, which, together with a fireball lifetime of 15 fm/c, leads to a surface velocity of $\beta_s \simeq 0.62$ and a freezeout tem-

[3] For simplicity we will use for this purpose a cylindrically symmetric fireball (no v_2) and apply an average boost of 70% of the fireball surface flow to the photon spectra in the rest frame, $\langle\beta\rangle = 0.7\beta_s$.

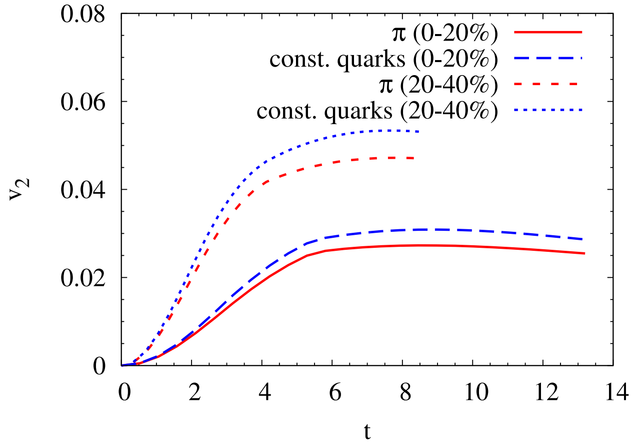

FIG. 3: (Color online) Time evolution of the inclusive elliptic flow for 0-20% and 20-40% Au-Au($\sqrt{s}$=200 AGeV) collisions within our fireball model, evaluated with either constituent-quark or pion content of the medium.

perature of $T_{\rm fo}$ = 108 MeV for Au-Au collisions in the 0-20% centrality bin ($N_{\rm part}$ = 280 and $N_{\rm coll}$ = 765). The pertinent photon spectra, displayed in the upper panel of Fig. 4, closely resemble the results of Fig. 12 in Ref. [9].[4] A window of QGP-radiation dominance is present for $q_t \simeq$ 1.5-3 GeV.

The situation changes somewhat with an update performed in 2007 triggered by the analysis of NA60 dileptons at the SPS, specifically in the context of their q_t-spectra. The fireball acceleration was increased to a_T = 0.08-0.1c^2/fm to better reproduce hadron spectra, which also allowed for a significantly improved description of the slope parameters in the dilepton q_t spectra [10]. It was also checked that the agreement with the WA98 direct-photon spectra at SPS [36], as found in Ref. [9], was not distorted (see, *e.g.*, Fig. 23 in Ref. [1]). At RHIC, the pertinent fireball of lifetime $\tau \simeq$ 15 fm/c results in a freezeout temperature of $T_{\rm fo}$ = 98 MeV with a surface transverse flow of β_s = 0.77. The consequences for the direct-photon spectra, using the same thermal emission rates and fireball chemistry as before, are illustrated in the middle panel of Fig. 4: while the spectral distribution of the QGP radiation is barely affected, the hadronic ra-

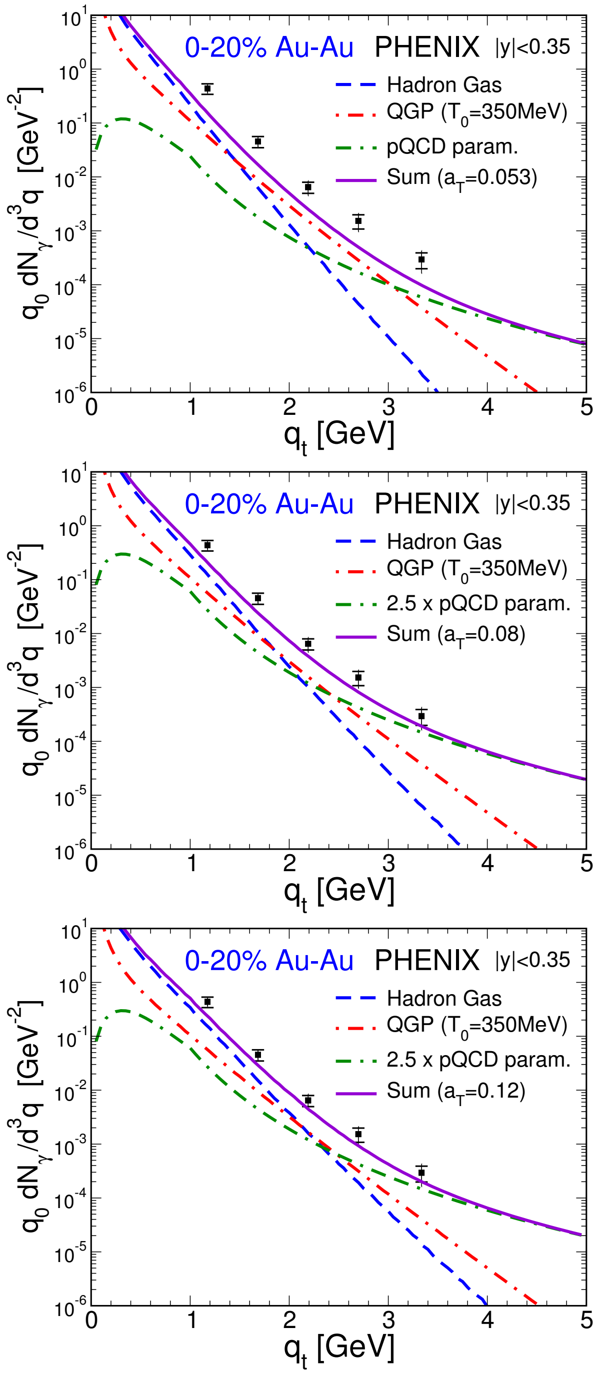

FIG. 4: (Color online) The impact of an increasingly strong radial flow in an expanding fireball model on direct-photon spectra in 0-20% central Au-Au collisions at RHIC. The transverse fireball acceleration increases from 0.053/fm (upper panel, corresponding to Ref. [9]) via 0.08 (middle panel; see Refs. [1, 10]) to 0.12/fm (lower panel). The same QGP and hadronic emission rates have been used in all cases, while the primordial contribution has been upscaled in the middle and lower panel. As a benchmark, we also show the pertinent PHENIX data [7].

diation spectrum becomes noticeably harder, thus shift-

[4] We note that in Figs. 12 and 13 of Ref. [9] the contribution labeled "Hadron Gas" only includes the in-medium ρ spectral function part, not the meson-gas contributions also calculated in there. Unfortunately, we recently realized that the spectral function part in the photon spectra at RHIC and LHC (Figs. 12 and 13 in Ref. [9]) was computed with the spin-averaged ρ propagator, $D_\rho = (2D_\rho^T + D_\rho^L)/3$, which, at the photon point (where the transverse part, D_ρ^T, should be used), is by a factor of 2/3 too small. It was done correctly in the rate plots and for the SPS calculations shown in Ref. [9]. In the present work we refer to the "Hadron Gas" emission as the sum of spectral-function and meson-gas contributions.

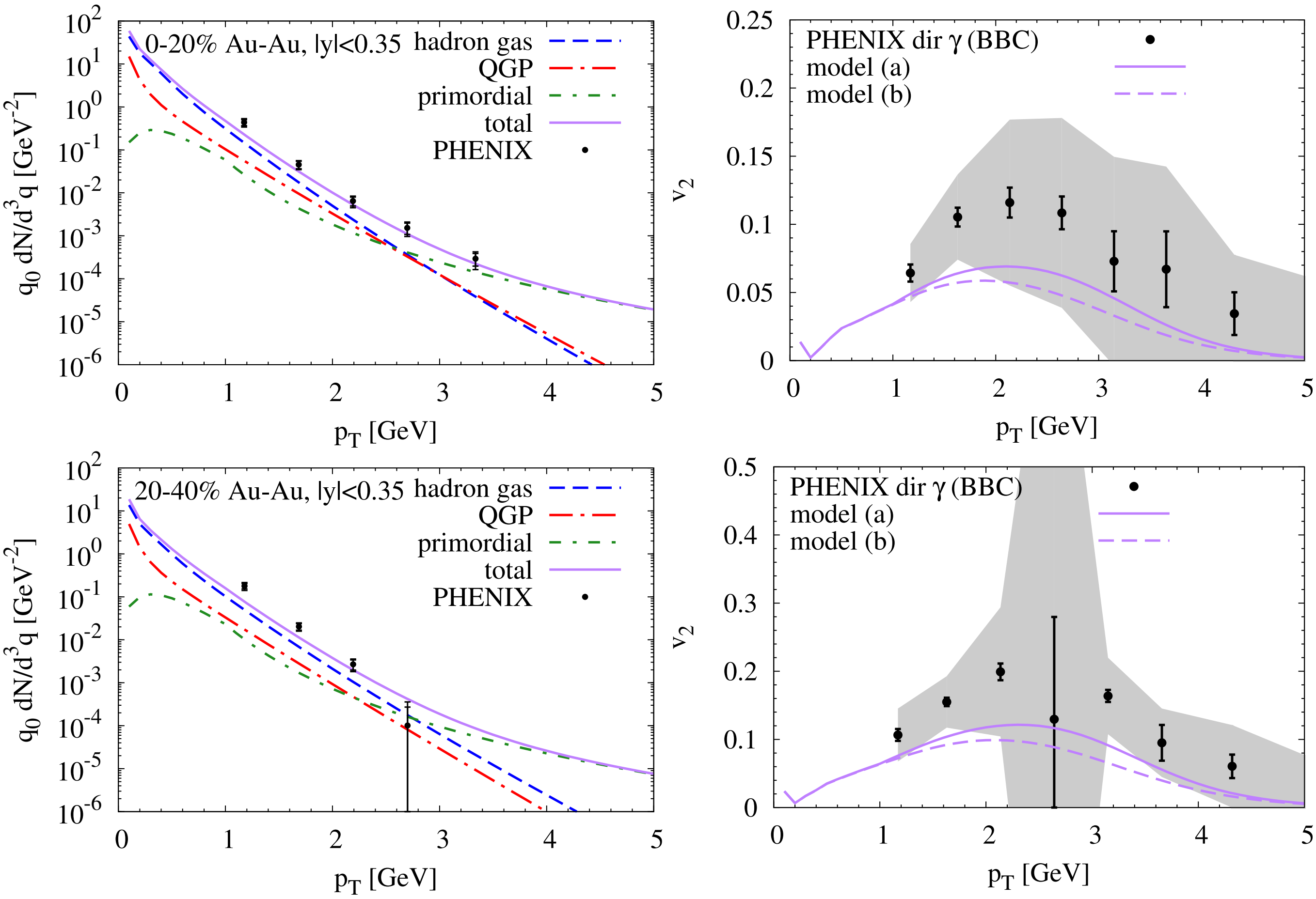

FIG. 5: (Color online) Comparison of our calculated direct-photon spectra (left panels) and their elliptic-flow coefficient (right panels) from an elliptically expanding fireball model with QGP and hadronic radiation, supplemented with primordial emission, to PHENIX data [7, 11] in 0-20% (upper panels) and 20-40% (lower panels) central Au-Au($\sqrt{s}$ = 200 AGeV) collisions. The error bars indicate the statistical and the gray band the systematical errors. Models (a) and (b) in the right panels refer to the use of the pQCD parametrization and the PHENIX fit for primordial production, respectively (in the left panels, only model (a) is displayed).

ing the crossing with the QGP part up to $q_t \simeq 1.8$ GeV. In combination with an improved estimate of the primordial emission, adjusted to then available PHENIX pp data, the QGP window shrinks appreciably, with a maximum fraction of ca. 42% of the total at $q_t \simeq 2.1$ GeV.

Finally, recent systematic analyses of light-hadron spectra by the STAR collaboration [32] requires an even harder expansion, to reach a thermal freezeout configuration at $T_{\rm fo} \simeq$ 90-95 MeV and $\langle\beta\rangle \simeq 0.59$ for central Au-Au collisions. This can be achieved in the fireball model by a further increase of the acceleration to $a_T = 0.12\ c^2$/fm at a slightly reduced lifetime of $\tau \simeq 14$ fm/c. As expected, for the direct-photon spectra this implies a further hardening of the hadronic emission and thus an additional squeezing of the QGP window to a small region around $q_t \simeq 2.4$ GeV, cf. lower panel of Fig. 4. The increasing transverse flow of the three fireballs also seems to improve the description of the PHENIX direct-photon spectra, although that was not the objective of this exercise.

The final (third) fireball setup has been refined by implementing realistic ellipticities and an explicit linearly increasing flow profile in the transverse boost of the photon emission rate. The corresponding comparisons to hadronic data have been discussed in the previous section. The resulting direct-photon q_t spectra from thermal QGP and hadronic sources, supplemented with an $N_{\rm coll}$-scaled primordial contribution, are compared to PHENIX data in the 0-20% and 20-40% centrality classes of Au-Au($\sqrt{s}$ = 200AGeV) in the two left panels of Fig. 5. The more central data set is fairly well reproduced, even though there appears to be a slight underestimation of the datum at the lowest $q_t \simeq 1.2$ GeV. The inclusion of the full transverse-flow profile leads to a further hardening of the hadronic component relative to the lower panel in Fig. 4, while the QGP component is essentially unaffected, even at the highest q_t (continuing the constant trend of the three panels in Fig. 4). This means

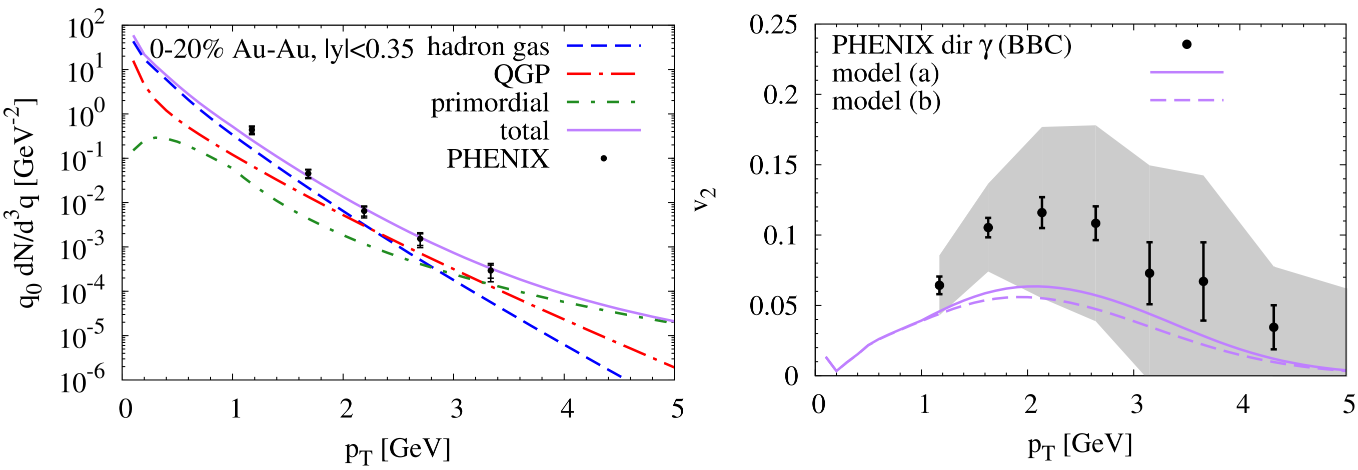

FIG. 6: (Color online) Same as Fig. 5 for 0-20% Au-Au collisions, but with a QGP contribution evaluated for a reduced thermalization time of $\tau_0 \simeq 0.17$ fm/c translating into an average initial temperature of $T_0 \simeq 445$ MeV.

that the high-q_t QGP radiation is entirely determined by the earliest radiation, where no flow has built up yet; the subsequent QGP flow cannot overcome the softening due to the decreasing temperature. This further implies a significant dependence of the high-q_t QGP yield on the thermalization time (a quantitative example will be discussed at the end of Sec. V). On the other hand, hadronic emission only sets in at T_c when there is already substantial flow in the system, and thus even at high momenta the hadronic spectra are sensitive to the fireball flow field.

In the 20-40% centrality bin, the discrepancy between the theoretical yields and the data becomes somewhat more severe, hinting at a missing relatively soft source (and therefore suggestive for the later hadronic phase). One speculation at this point could be related to $\omega \to \pi^0\gamma$ decays. These have been subtracted by the PHENIX collaboration employing m_t scaling of the ω spectra with π^0's [27], assuming $\omega/\pi^0 = 1$, as found in pp measurements [37, 38], as well as in 0-92% Au-Au collisions for $p_t > 4$ GeV [38]. *If*, however, ω mesons at lower p_t become part of the chemically equilibrated medium in heavy-ion collisions, one expects their multiplicity at given m_t to be up to 3 times larger, due their spin degeneracy. In this case there might be a direct-photon component in the Au-Au data at low $q_t \leq 2$ GeV due to some fraction of final-state $\omega \to \pi^0\gamma$ decays which have not been subtracted (and which would carry large v_2). This possibility may be worth further experimental and theoretical study.

It is quite remarkable that the hadronic yield dominates over the QGP one over the entire plotted range. This will have obvious ramifications for the v_2 of the direct photons, which is larger in the hadronic phase. The sub-leading role of the (early) QGP component further implies that the effects of initial-state fluctuations on thermal-photon production [20, 21] are diminished.

To examine the dependence of the QGP yield on the thermalization time, we have conducted calculations with a factor-2 reduced initial longitudinal size, $z_0 = 0.3$ fm, corresponding to $\tau_0 \simeq 0.17$ fm/c as used, *e.g.*, in Ref. [14], cf. Fig. 6. The QGP spectra in 0-20% Au-Au collisions increase over the $z_0 = 0.6$ fm calculation by a factor of 1.6, 2.7 and 4.8 at $q_t = 2$, 3 and 4 GeV, respectively, and turn out to be in fair agreement (within ca. 30%) with the hydrodynamic calculations reported in Ref. [14] (using smooth initial conditions). The significance of this increase mostly pertains to momenta, $q_t > 2$ GeV, where a small "QGP window" reopens, but it does not significantly affect the description of the experimental yields.

To further characterize the nature of the direct-photon excess (i.e., beyond the pp-scaled primordial emission), we evaluate the effective slope parameters, $T_{\rm eff}$, of our thermal spectra. We recall that PHENIX extracted the effective slope of the excess radiation in their data as $T_{\rm eff} = 221 \pm 19^{\rm stat} \pm 19^{\rm syst}$ MeV [7]. In Fig. 7 we compare this range with the temperature evolution, $T(\tau)$, of our fireball; they only overlap inside the QGP phase. However, when accounting for the flow-induced blue shift, as estimated by the schematic expression for a massless particle,

$$T_{\rm eff} \simeq T\sqrt{\frac{1+\langle\beta\rangle}{1-\langle\beta\rangle}} \ , \qquad (1)$$

the overlap with the experimental window is shifted to significantly later in the evolution, mostly for a flowing hadronic source with a restframe temperature of $T \simeq$ 100-150 MeV. This suggests a reinterpretation of the experimental slope as mainly hadronic in origin, which, as we will see in Sec. V below, is further supported by the v_2 data. An explicit fit of the slope to our total thermal spectrum from the elliptic fireball (with $T_0 = 355$ MeV) in the range $q_t \simeq 1-3$ GeV yields $T_{\rm eff} \simeq$ 240-250 MeV, which is at the upper end of the data (consistent with the slight underestimate of the lowest-q_t datum; also note that the use of the average, $\langle\beta\rangle = 0.7\beta_s$

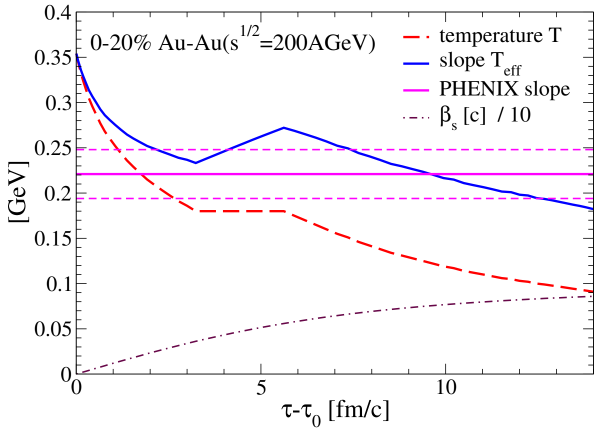

FIG. 7: (Color online) Time dependence of the effective slope parameter of thermal-photon radiation emitted from our fireball for 0-20% Au-Au collisions (solid (blue) line, given by QGP and hadronic sources for $\tau - \tau_0 \lesssim 3$ fm/c and $\gtrsim$ 6fm/c, respectively), using Eq. (1) with $\langle\beta\rangle = 0.7\beta_s$. For comparison, we plot the effective slope extracted by PHENIX from their data (horizontal line with dashed lines indicating the experimental error) [7], and the "true" temperature in the thermal restframe (long-dashed line). Also shown is the surface flow velocity of the fireball (dash-dotted line).

in Eq. (1), tends to underestimate the actual slopes, especially at high q_t and β_s; we noted that already when going from the spectra in the lower panel of Fig. 4 to the full results in the upper left panel of Fig. 5). Higher initial temperatures are less favorable, since they result in a further increase of the slope, *e.g.*, by 10-15 MeV for $T_0 = 445$ MeV.

V. DIRECT-PHOTON ELLIPTIC FLOW

With a fair description of the photon q_t spectra at hand, we proceed to the calculation of the direct-photon elliptic flow as a function of transverse momentum, $v_2(q_t)$. The results for the 0-20% and 20-40% centrality classes of Au-Au collisions at RHIC are again compared to PHENIX data, see upper- and lower-right panel of Fig. 5, respectively. The shape of our calculated $v_2(q_t)$ matches the measurements rather well, but our maximum value of ca. 7.5% (12%) is below the central values of the 0-20% (20-40%) data. Our results are a factor of 3-4 larger than existing calculations using hydrodynamic expansions, and reach into the lower end of the (mostly systematic) experimental uncertainties. The main differences compared to the hydro calculations are the following: our equilibrium hadronic rates [9] are significantly larger than in previous studies, our hadronic phase includes meson-chemical potentials and lasts longer (both due to a smaller $T_{\rm fo}$ as dictated by data and a slightly larger $T_{\rm ch}$ as used in our previous calculations [9, 17, 35]), and our bulk elliptic flow is built up faster than in standard (ideal) hydro calculations (recall that only a small increase of the v_2 during the hadronic phase facilitates its KE$_T$-scaling properties of multi-strange and light hadrons [15]; also note that a more rapid expansion in the QGP and transition region has been identified as an important ingredient to solve the "HBT puzzle"[39]). The combined effect of these four points is a thermal source which is dominated by hadronic emission carrying most of the finally observed elliptic flow from its beginning on, i.e., for $T \le T_c$. For the reduced thermalization time of $\tau_0 = 0.17$ fm/c the maximal v_2 drops by ca. 15% to $v_2^{\rm max} \simeq 6.3\%$, cf. right panel in Fig. 6.

In the present work, we have assumed a critical temperature of $T_c \simeq 180$ MeV, which is in line with $N_f = 2+1$ flavor lattice calculations reported, *e.g.*, in Ref. [40]. However, very recent lattice data [41] (as well as earlier ones [42]) indicate that T_c could be as low as 155-160 MeV and therefore one should ask what impact this could have on our results. A pertinent study has been done in the context of dilepton production at SPS energies [10]. When varying the critical temperature by ± 15 MeV around the default value of $T_c = 175$ MeV, the QGP emission spectra in the intermediate-mass region ($M \gtrsim 1$ GeV) vary by up to $\pm 50\%$ (less at higher masses where the contribution from earlier phases increases). At the same time, the hadronic emission part varies by approximately the same amount in the opposite direction, so that the total yield roughly stays the same while the relative QGP and hadronic partition varies appreciably. We expect similar effects for the photon q_t spectra. If one still requires the multi-strange hadron spectra to freezeout at T_c, we expect that the v_2 in the hadronic phase does not significantly change with T_c. However, since for smaller T_c the hadronic contribution to the direct photon yields is reduced, so should be the total (weighted) v_2. For example, if for the 0-20% centrality class the QGP$-$hadronic partition of $1/3-2/3$ at $q_t \simeq 2$ GeV changes to $1/2-1/2$, we estimate that $v_2(q_t)$ is lowered from 7% to 6%.

VI. CONCLUSIONS

We have updated and extended our calculations of thermal-photon spectra at RHIC by constructing an improved elliptic fireball expansion which is quantitatively constrained by bulk-hadron data. In particular, we have implemented the notion of sequential freezeout by reproducing an empirical extraction of radial and elliptic flow from multi-strange and light-hadron data at chemical and kinetic decoupling, respectively. The fireball evolution has been combined with existing photon emission rates in the hadronic and QGP phases to obtain thermal-photon spectra in Au-Au collisions at RHIC. Supplemented with a primordial component estimated from *pp* collisions, we have compared our calculations to spectra and v_2 of direct photons as recently measured by the PHENIX collaboration. Due to a large medium flow (as required by hadron data), relatively large hadronic photon rates (approximately degenerate with QGP rates around T_c), and effective chemical potentials to conserve the observed hadron ratios, we have found that the hadronic medium outshines the QGP for most of the momenta where thermal radiation is relevant. This, in turn, leads to a maximal elliptic flow coefficient of $v_2 \simeq 10\%$ in semicentral Au-Au, which is a factor of ~ 3 increased over previous estimates based on QGP-dominated emission. Consequently, the discrepancy with the PHENIX v_2 data is reduced appreciably. Our results are corroborated by evaluating the effective slope parameters of the radiation from the thermal source, which have the largest overlap with the experimental value of $T_{\rm eff} \simeq 220$ MeV in the (flowing) hadronic phase. Initial QGP temperatures of above $T_0 \simeq 400$ MeV are increasingly disfavored by both the slope and v_2 data. Further scrutiny is needed whether these results can be confirmed in dynamical space-time models, i.e., in hydrodynamical and transport simulations, and what the quantitative impact of the transition temperature is (using, *e.g.*, the (3+1)D viscous hydrodynamics of Ref. [45]). The prevalence of the hadronic emission in our calculations reiterates the necessity of a good understanding of the strongly coupled hadronic phase in heavy-ion collisions. With these considerations, a satisfactory explanation of the (surprisingly?) strong direct-photon v_2 signal at RHIC might be possible. The extension of the v_2 studies to virtual photons (aka dileptons) would also be illuminating. First phenomenological studies of this observable have been initiated [46, 47] and are also planned within our framework.

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