Thermal Photons and Collective Flow at the Relativistic Heavy-Ion Collider

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We update our calculations of thermal-photon production in nuclear collisions at the 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. [1,2] 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 SPS [3,4] and of the medium temperature via direct photons at RHIC [5].

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, 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 [6,7, 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 [8] have revealed remarkable results. It has been found that the pertinent flow coefficient, \( v_2(q_t) \), is as large as that of charged pions up to momenta \( q_t \approx 3 \) 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 [9,10] 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 \( \sim 5 (\sim 3 \) when accounting for the maximal systematic error in the measurement). The question thus arises what could be missing in these calculations.

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

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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.
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 parameterizations of the respective sources at thermal and chemical and freezeout (with $T_{ch} \approx 100$ MeV and $T_{col} \approx 180$ MeV, respectively) \cite{9}. In particular, the observed universality in kinetic-energy scaling of the $v_2$ of light and strange hadrons, together with an earlier decoupling of multistrange hadrons (as inferred from their $p_t$ spectra), suggests that most of the hadronic $v_2$ is indeed of partonic origin \cite{10}. Second, for the thermal emission rates from hadronic matter we use our previous results of Ref. \cite{9}, which, in particular, include contributions from baryons which are known to be important from dilepton calculations \cite{10}, even at RHIC \cite{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 $\pi \rho \rightarrow \pi \gamma$ 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. \cite{9}, as well as for the primordial contribution, which we check against $pp$ data. In Sec. II 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 \cite{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. \cite{9}. For QGP radiation we use the numerical parameterization of the complete leading-order in $\alpha_s$ rate as given in Ref. \cite{15}. 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, $T = 1-2T_c$, which turns out to be consistent with recent estimates from the (perturbative) Coulomb term in in-medium heavy-quark free energies \cite{22}.

The basis of the thermal emission rate in hadronic matter forms the electromagnetic correlation function computed in Refs. \cite{9, 22} using hadronic many-body theory with effective Lagrangians. It has been successfully used \cite{1} in the interpretation of dilepton data at the SPS \cite{4, 5} and has been carried to the photon point in Ref. \cite{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., $\pi$, $\omega$, and $a_1$ exchange in $\pi + p \rightarrow \pi + \gamma$ as well as strangeness-bearing reactions (e.g., $\pi + K^* \rightarrow K + \gamma$) \cite{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 $q \gtrsim 1$ GeV. We do not include here additional $\pi\pi$ Bremsstrahlung contributions ($\pi\pi \rightarrow \pi\pi\gamma$) as evaluated in Refs. \cite{24, 25}. This source is important at low momenta, $q_t \lesssim 0.5$ GeV, but plays no role in the region of interest of the present investigation ($q_t \gtrsim 1$ 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, $T_c \approx 180$ 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 \cite{14}.
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 $T_{ch} \approx 170$ MeV and kinetic freezeout at $T_0 \approx 100$ MeV. The latter is well determined by the transverse-momentum ($p_t$) spectra and elliptic flow of light hadrons ($\pi$, $K$, $p$) [20,32], while the former can be extracted from spectra and flow of multi-strange hadrons [14,51,33]. A detailed fit of these snapshots using an elliptic blast-wave source has been performed in Ref. [13], which was also shown to be compatible with the empirical constituent-quark number and transverse kinetic-energy ($K_{E_T}$) 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 ($\phi$ mesons) and light-hadron ($\pi$, $p$) 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 $cT_0 \approx 355$ MeV and $325$ MeV, and charged-hadron multiplicities of $dN_{ch}/dy \approx 610$ and 280, respectively, adjusted to recent STAR data [32].

The time evolution of the inclusive elliptic flow is shown in Fig. 3. The observed $K_{E_T}$ 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 $\sim 2.5\%$ and $\sim 5\%$ 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 $\phi$ 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 $\pi$ and $p$ curves are for direct emission only (no resonance feeddown) with absolute normalization while the $\phi$ yield is (re-) normalized to the data. Data are from Refs. [16, 43, 44].

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.
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 $a_T = 0.053 c^2$ has been assumed, which, together with a fireball lifetime of 15 fm/c, leads to a surface velocity of $\beta_s \approx 0.62$ and a freezeout temperature of $T_{fo} = 108$ MeV for Au-Au collisions in the 0-20% centrality bin ($N_{part} = 280$ and $N_{coll} = 765$). The pertinent photon spectra, displayed in the upper panel of Fig. 14, closely resemble the results of Fig. 12 in Ref. [9]. A window of QGP-radiation dominance is present for $q_t \approx 1.5$-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 $a_T = 0.085 c^2$ 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 $\tau \approx 15$ fm/c results in a freezeout temperature of $T_{fo} = 98$ MeV with a surface transverse flow of $\beta_s = 0.77$. 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 radiation spectrum becomes noticeably harder, thus shifting the crossing with the QGP part up to $q_t \approx 1.8$ 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 $q_t \approx 2.1$ GeV.

Finally, recent systematic analyses of light-hadron spectra by the STAR collaboration [32] requires an even...
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 \cite{7,11} in 0-20\% (upper panels) and 20-40\% (lower panels) central Au-Au ($\sqrt{s} = 200\,\text{AGeV}$) collisions. Models (a) and (b) in the right panels refer to the use of the pQCD parameterization and the PHENIX fit for primordial production, respectively (in the left panels, only model (a) is displayed).

harder expansion, to reach a thermal freezeout configuration at $T_{fo} \simeq 90-95\,\text{MeV}$ 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 $a_T = 0.12\,c^2/\text{fm}$ at a slightly reduced lifetime of $\tau \simeq 14\,\text{fm}/c$. 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 $q_t \simeq 2.4\,\text{GeV}$, 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 $N_{\text{coll}}$-scaled primordial contribution, are compared to PHENIX data in the 0-20\% and 20-40\% centrality classes of Au-Au ($\sqrt{s} = 200\,\text{AGeV}$) 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 $q_t \simeq 1.2\,\text{GeV}$. 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 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 $T_\tau$ 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 more severe, hinting at a missing relatively soft source.

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. 4. 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, $q_t \geq 2$ 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 $p\bar{p}$-scaled primordial emission), we evaluate the effective slope parameters, $T_{\text{eff}}$, of our thermal spectra. We recall that PHENIX extracted the effective slope of the excess radiation in their data as $T_{\text{eff}} = 221 \pm 19^{\text{stat}} \pm 19^{\text{syst}}$ MeV [19]. In Fig. 6 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,

$$T_{\text{eff}} \simeq T \sqrt{\frac{1 + \langle \beta \rangle}{1 - \langle \beta \rangle}},$$

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. VII 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 $T_{\text{eff}} \simeq 240$-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, $\langle \beta \rangle = 0.7 \beta_s$, in Eq. (1), tends to underestimate the actual slopes, especially at high $q_t$ and $\beta_s$; 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. 6). 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 are significantly larger than in previous studies, our hadronic phase includes meson-chemical potentials and lasts longer (both due to a smaller $T_{th}$ dictated by data and a slightly larger $T_{ch}$ as used in our previous calculations [4, 17, 33]), 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 KET-scaling properties of multi-strange and light hadrons [13]; 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 $T \leq T_c$. For the reduced thermalization time of $\tau_0 = 0.17 \text{fm}/c$ the maximal $v_2$ drops by ca. 15% to $v_2^{\text{max}} \simeq 6.3\%$, cf. right panel in Fig. 6.

In the present work, we have assumed a critical temperature of $T_c \simeq 180 \text{ MeV}$, 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 $\pm 15 \text{ MeV}$ around the default value of $T_c = 175 \text{ MeV}$, the QGP emission spectra in the intermediate-mass region ($M \gtrsim 1 \text{ GeV}$) 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 freeze out 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 $q_t \simeq 2 \text{ GeV}$ 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 $\sim 3$ 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 $T_{\text{stag}} \approx 220$ MeV in the (flowing) hadronic phase. Initial QGP temperatures of above $T_0 \approx 400$ 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. [18]). 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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