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# Dynamics of strongly interacting parton–hadron matter

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**Abstract**

In this study we investigate the dynamics of strongly interacting parton–hadron matter by calculating the centrality dependence of direct photons produced in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV within the Parton–Hadron-String Dynamics (PHSD) transport approach. As sources for 'direct' photons, we incorporate the interactions of quarks and gluons as well as hadronic interactions ($\pi + \pi \to \rho + \gamma$, $\rho + \pi \to \pi + \gamma$, meson–meson bremsstrahlung $m + m \to m + m + \gamma$, meson–baryon bremsstrahlung $m + B \to m + B + \gamma$), the decays of $\phi$ and $a_1$ mesons and the photons produced in the initial hard collisions ('pQCD'). Our calculations suggest that the channel decomposition of the observed spectrum changes with centrality with an increasing (dominant) contribution of hadronic sources for more peripheral reactions. Furthermore, the 'thermal' photon yield is found to scale roughly with the number of participant nucleons as $N_{part}^{\alpha}$ with $\alpha \approx 1.5$, whereas the partonic contribution scales with an exponent $\alpha_p \approx 1.75$. Additionally, we provide predictions for the centrality dependence of the direct photon elliptic flow $v_2(p_T)$. The direct photon $v_2$ is seen to be larger in peripheral collisions compared to the most central ones since the photons from the hot deconfined matter in the early stages of the collision carry a much smaller elliptic flow than those from the final hadronic interactions.



*Keywords:* Relativistic heavy-ion collisions; Inclusive production with identified leptons, photons; Quarks, gluons, and QCD in nuclear processes

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## 1. Introduction

The ‘direct photons’ from relativistic heavy-ion collisions are expected to be a valuable probe of the collision dynamics at early times and to provide information on the characteristics of the initially created parton–hadron matter once the final state hadronic decay photons are subtracted from the experimental spectra [1,2]. In the last years, the PHENIX Collaboration [3,4] has measured the spectra of the photons produced in minimal bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and found a strong elliptic flow $v_2(p_T)$ of ‘direct photons’, which is comparable to that of the produced pions. Since direct photons were expected to be essentially produced in the initial hot medium before the collective flow has developed, this observation was in contrast to the theoretical expectations and predictions [5]. Also more recent studies employing event-by-event hydrodynamical calculations [6,7] have severely underestimated the elliptic flow of direct photons and alternative sources of direct photons from the conformal anomaly have been suggested [8,9].

On the other hand, in Refs. [10,11] we have proposed that apart from the partonic production channels the direct photon yield and primarily the strong $v_2$ might be due to hadronic sources (such as meson–meson Bremsstrahlung or hadronic interactions as $\pi + \pi \to \rho + \gamma$, $\rho + \pi \to \pi + \gamma$ etc.). Indeed, the interacting hadrons carry a large $v_2$ and contribute by more than 50% to the measured ‘direct photons’ in minimum bias collisions at RHIC according to the PHSD calculations in Ref. [10] (cf. also the hydrodynamics calculations in Ref. [12]). For a quantitative understanding of the direct photon production it is important to verify the decomposition of the total photon yield according to the production sources: the late hadron decays (the cocktail), hadronic interactions beyond the cocktail (during the collision phase) and the partonic interactions in the quark–gluon plasma (QGP). Since previous transport studies have indicated that the duration of the partonic phase substantially decreases with increasing impact parameter [13] we will study here explicitly the centrality dependence of the direct photon yield together with the essential production channels and their impact on the photon $v_2$.

As in Ref. [10] we will employ the Parton–Hadron-String Dynamics (PHSD) transport approach to investigate the photon production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at various centralities thus extending the previous investigations for the case of minimum bias collisions (see also [11]). We recall that the PHSD approach has provided a consistent description of the bulk properties of heavy-ion collisions – rapidity spectra, transverse mass distributions, azimuthal asymmetries of various particle species – from low Super-Proton-Synchrotron (SPS) to top Relativistic-Heavy-Ion-Collider (RHIC) energies [13] and was successfully used for the analysis of dilepton production from hadronic and partonic sources at SPS, RHIC and Large-Hadron-Collider (LHC) energies [14]. It is therefore of interest to calculate the photon production in relativistic heavy-ion collisions from hadronic and partonic interactions within the PHSD transport approach, since its microscopic and non-equilibrium evolution of the nucleus–nucleus collision is independently controlled by a multitude of other hadronic and electromagnetic observables in a wide energy range [13–15].

## 2. Photons within PHSD

For the details on the PHSD approach we refer the reader to Refs. [15,16] and the implementation of the photon production to Refs. [10,17] (and references therein). Let us recall that the dynamical calculations within the PHSD for dileptons agree with the dilepton rate emitted by the thermalized QCD medium as calculated in lattice QCD (lQCD) [14]. We note, additionally, that