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Impact of the initial high gluon density on the prompt photon yield and v_2 in heavy-ion collisions with magnetic fields

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We compute prompt photon production from gluon fusion in the presence of a magnetic field in semi-central relativistic heavy-ion collisions. The main ingredient is the treatment of the high gluon density at early stages of the collision where intense magnetic fields are also present. The magnetic field opens new channels for photon production that are forbidden otherwise. The elliptic flow coefficient v_2 is also computed. The calculation takes into account the saturation scale and phenomenological factors. Overall, the treatment gives a good description of the excess photon yield and v_2, particularly at low values of photon transverse momentum.

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1. Introduction

Recent results from experiments in heavy-ion collisions carried out at the CERN Large Hadron Collider [1, 2, 3] and at the BNL Relativistic Heavy-Ion Collider [4, 5, 6, 7] have shown that photon production deviates from what is measured in proton-proton collisions [8, 9, 10, 11]. Hydrodynamical and transport calculations [9, 12, 13] obtain a better but still incomplete agreement with ALICE and PHENIX measurements, which motivates to explore new sources of photons in the different stages of the collision. At early stages, where a magnetic field can be generated in peripheral collisions, even new channels such as synchrotron radiation, bremsstrahlung and pair annihilation [14, 15] are not enough to explain the measured photon excess.

In previous works [16, 17], we have shown that the presence of an intense magnetic field combined with a medium with high gluon occupation number [18] can be a significant source of photons. These fields are found in the very early stages of the reaction and reach magnitudes ranging from one to several times the pion mass squared, for peripheral and semi-central collisions [19, 20]. The presence of a magnetic field breaks rotational invariance which can be translated also into a contribution to the elliptic flow coefficient v_2.

This work summarizes a calculation of the spectrum and of the v_2 harmonic coefficient for prompt photons produced during the early stages of a semi-central collision. The process we consider is gluon fusion in pQCD at leading order. In our approximation, the quarks in the internal loops are assumed to be in the Lowest Landau Level (LLL) and the first Landau Level (1LL), and the magnetic field is taken as the dominant energy scale. The theoretical results are compared with the excess yield of experimental data from PHENIX over state-of-the-art calculations [9], and show a good agreement when the parameters take reasonable phenomenological values. Details can be found in Ref. [17].

2. Photon production by gluon fusion in magnetic fields

Figure 1 shows the processes computed in the present work. It can be shown that the three quark lines in the loop cannot be all in the LLL and that for the description of the leading order contribution, one of them has to be in the 1LL. By considering two quarks in the LLL and one in the 1LL for each diagram, and by assuming that the external magnetic field is the dominant scale ($|q_fB| >> r_\parallel^2, s_\parallel^2, t_\parallel^2,$), in the limit of massless quarks, the sum of amplitudes is given by

$$\begin{aligned} \tilde{\mathscr{M}} \; &= \; -i(2\pi)^4\delta^{(4)}(q-k-p)\frac{|q_f|g^2\delta^{cd}e^{f(p_\perp,k_\perp)}}{32\pi(2\pi)^8}\varepsilon_\mu(\lambda_p)\varepsilon_\nu(\lambda_k)\varepsilon_\alpha(\lambda_q) \\ &\times \left\{ \left(g_\parallel^{\mu\alpha}-\frac{p_\parallel^\mu p_\parallel^\alpha}{p_\parallel^2}\right)h^\nu(a) - \left(g_\parallel^{\mu\nu}-\frac{p_\parallel^\mu p_\parallel^\nu}{p_\parallel^2}\right)h^\alpha(a) + \left(g_\parallel^{\mu\nu}-\frac{k_\parallel^\mu k_\parallel^\nu}{k_\parallel^2}\right)h^\alpha(b) \right. \\ &- \left. \left(g_\parallel^{\alpha\nu}-\frac{k_\parallel^\alpha k_\parallel^\nu}{k_\parallel^2}\right)h^\mu(b) + \left(g_\parallel^{\alpha\nu}-\frac{q_\parallel^\alpha q_\parallel^\nu}{q_\parallel^2}\right)h^\mu(c) - \left(g_\parallel^{\mu\alpha}-\frac{q_\parallel^\mu q_\parallel^\alpha}{q_\parallel^2}\right)h^\nu(c) \right\} \end{aligned} \tag{2.1}$$

with $h^\mu(x) = (i/\pi)\varepsilon_{ij}a^i g_\perp^{j\mu}$, $a_i = p_i + 2k_i + i\varepsilon_{im}p_m$; $b_i = 2p_i + k_i - i\varepsilon_{im}k_m$, $c_i = k_i - p_i + i\varepsilon_{im}(p_m +$

k_m) and

$$f(p_\perp, k_\perp) = \frac{1}{8|q_f B|}\left(p_m - k_m + i\varepsilon_{mj}(p_j + k_j)\right)^2 - \frac{1}{2|q_f B|}\left(p_m^2 + k_m^2 + 2i\varepsilon_{jm} p_m k_j\right). \quad (2.2)$$

For our purposes, we ignore the dispersive properties of the magnetized medium and therefore the gluons' three-momenta turn out to be parallel to that of the photon. Note that from Eq. (2.1) only one polarization needs to be taken into account, given that the tensor structure of the diagrams is given only in terms of a parallel (to the magnetic field) polarization. The photon spectrum is computed by means of

$$\omega_q \frac{dN^{\rm mag}}{d^3q} = \frac{\chi \mathscr{V} \Delta\tau_s}{2(2\pi)^3} \int \frac{d^3p}{(2\pi)^3 2\omega_p} \int \frac{d^3k}{(2\pi)^3 2\omega_k} n(\omega_p) n(\omega_k) (2\pi)^4 \delta^{(4)}(q - k - p) \sum_{{\rm pol}, f} |\mathscr{M}|^2, \quad (2.3)$$

where occupation number $n(\omega)$ is given as in Refs. [21, 22]. Finally, we sum over the three light flavors and the result is shifted by the expansion factor $\omega_{p,k} \to (p,k)\cdot u$. For simplicity we allow for a constant flow velocity $u^\mu = \gamma(1,\beta)$, with $\gamma = 1/\sqrt{1-\beta^2}$. The harmonic coefficient v_2 is given by a Fourier decomposition of the Eq. (2.3) and it is added to the calculations of Ref. [9] in terms of a weighed average

$$v_2(\omega_q) = \frac{\frac{dN^{\rm mag}}{d\omega_q}(\omega_q)\, v_2^{\rm mag}(\omega_q) + \frac{dN^{\rm direct}}{d\omega_q}(\omega_q)\, v_2^{\rm direct}(\omega_q)}{\frac{dN^{\rm mag}}{d\omega_q}(\omega_q) + \frac{dN^{\rm direct}}{d\omega_q}(\omega_q)}. \quad (2.4)$$

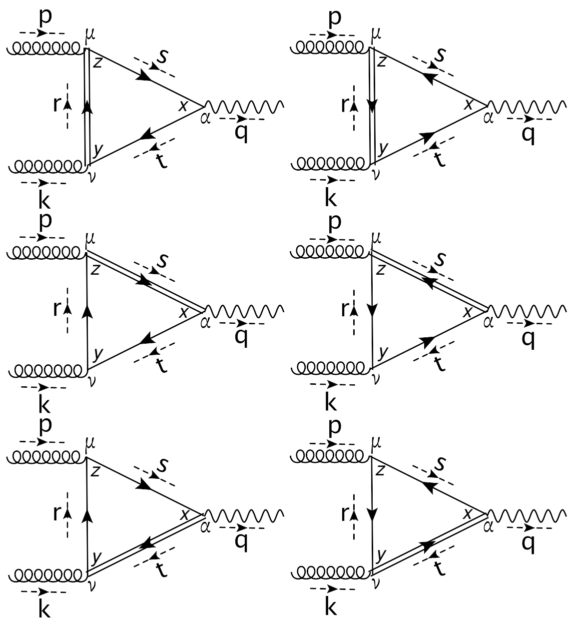

Figure 1: Leading order contribution for photon production from gluon fusion in the presence of a magnetic field. The double lines represent that the corresponding propagator is in the first Landau Level. The single lines represent the propagator in the lowest Landau Level. The arrows in the propagators represent the direction of the flow of charge. The arrows on the sides of the propagator lines represent the momentum direction.

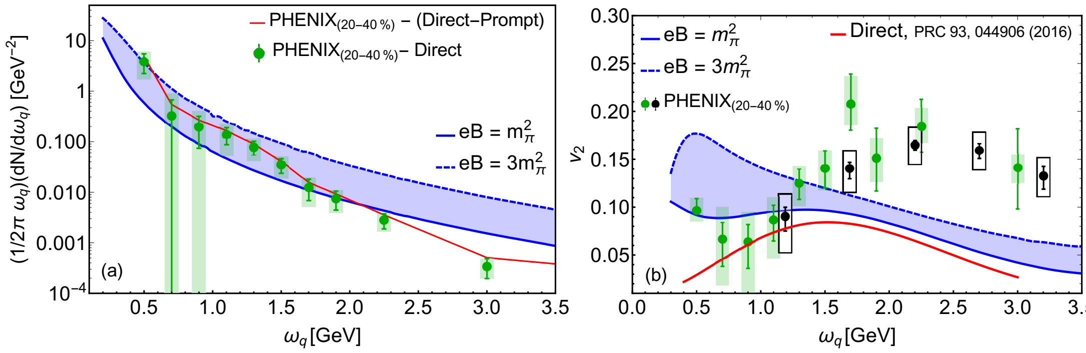

Figure 2: (Left) Difference between PHENIX photon invariant momentum distribution [6] and direct (points) or direct minus prompt (zigzag) photons from Ref. [9] compared to the yield from the Eq. (2.3). (Right) Harmonic coefficient v_2 from Eq. (2.4) compared to PHENIX data [7]. The direct photons are taken from the calculation of Ref. [9]. Curves are shown as functions of the photon energy for central rapidity and the centrality range 20-40%. Only the experimental error bars are shown. The bands show variations of the parameter eB within the indicated ranges, computed with parameter settings listed in Ref. [17].

3. Results and Discussion

Our goal is to determine the *photon excess* over the reported models and to compare this excess to experimental data. Figure 2-left represents the excess yield (bands) compared to the difference between PHENIX data [6] and the hydrodynamical calculations of Ref. [9] (points). We note that there is a good agreement with the experimental data. Figure 2-right shows the coefficient v_2 from Eq. (2.4) compared to PHENIX data [7]. The curves are shown as functions of the photon energy for central rapidity and the centrality range 20% - 40%.

We notice that the photon excess from gluon fusion helps to better describe the experimental data, particularly at the lowest end of the spectrum, and highlights the importance of including the effects of magnetic fields in the early stages of the collision and its impact on the final state observables. A systematic study on centrality dependence of the impact of this analysis using simulated values of the magnetic field is in process.

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