Photon azimuthal anizotropy and magnetic field in heavy-ion collisions

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Abstract. Recent measurements of the azimuthal anisotropy of direct photons in heavy-ion collisions at the energies of RHIC showed that it is of the same order as the hadronic one. This finding appears to contradict the expected dominance of photon production from a quark-gluon plasma at an early stage of a heavy-ion collision. A possible explanation of the strong azimuthal anisotropy of the photons, given recently, is based on the presence of a large magnetic field in the early phase of a collision. In this talk, we consider a novel photon production mechanism stemming from the conformal anomaly of QCDxQED and the existence of strong (electro)magnetic fields in heavy ion collisions. Using the hydrodynamical description of the bulk modes of QCD plasma, we show that this mechanism leads to the photon production yield that is comparable to the yield from conventional sources. The comparison of the results to the data from the PHENIX collaboration, show that this mechanism might be the most responsible for the observed azimuthal anisotropy of photons.

1. Introduction
The “direct” photons leave the fireball almost without interacting with the medium, and thus they may play an important role in unraveling the properties of hot and dense matter. According to expectations, based on the large yield of thermal photons, photon production is believed to be dominated by hot quark-gluon plasma at the early stage of a collision at the top energies in RHIC (Brookhaven) and the LHC (CERN). Indeed, measurements from the PHENIX collaboration showed that the observed temperature of photon radiation at energy $\sqrt{s} = 200$ GeV in heavy-ion collisions is about $T_{\text{ave}} \approx 220$ MeV [1]. One can argue that this value can be considered as an average over the entire evolution of the matter created in heavy-ion collisions. It is higher than the temperature of the phase transition and thus it supports the picture of photon production from the early stage in the collision. An alternative explanation of the apparent high temperature of the photon source is the formation of prethermal plasma shining photons early in a collision [2]. In both scenarios, we would expect that the photons’ azimuthal anisotropy, characterized by the second Fourier component $v_2(p_t) = \int d\phi \cos(2\phi) \frac{dN^\gamma}{dp_t d\phi}/\frac{dN}{dp_t}$, is small, because, at the early QGP stage, the evolving medium does not develop an appreciable amount of azimuthal anisotropy. Others studied this phenomenon in hydrodynamic calculations that well describe hadron production and hadron azimuthal anisotropy. The hydrodynamic calculations [3], as expected, demonstrated that the photon $v_2$ is almost an order of magnitude smaller than the one of hadrons. However, recent measurements by the PHENIX collaboration (RHIC) [4] and preliminary results by ALICE (LHC) revealed that the anisotropy of produced photons is very close to that of hadrons.
In this talk, we review a recently proposed novel mechanism which is based on the presence of a large highly anisotropic magnetic field in heavy-ion collisions that could serve as a natural source of the photons’ anisotropy. The magnetic field is maximal at the early stage of a collision, thereby allowing us to reconcile the large thermal yield of photons with significant azimuthal anisotropy.

2. Magnetic field in heavy-ion collisions

The results of Refs. [5, 6, 7] showed that in non-central heavy-ion collisions the amplitude of magnetic field can reach very high values up to a few $m^2_\pi \approx 10^{18}$ Gauss owing to a fast movement of spectators. This field is large at the time of the collision and decreases inversely proportional to the square of time. The magnetic field essentially is anisotropic and, on average, points in the direction perpendicular to the reaction plane. It is important to remember that this estimates of the magnetic field have been established without taking into account effects related to induced magnetic field in quark-gluon plasma. Depending on the magnitude of the electric conductivity, the induced magnetic field may live much longer then the one generated by spectators. Presently, we do not know neither precise values for the electric conductivity, nor we are able to perform quantitative calculations for the induced magnetic field because this requires to perform calculations in relativistic magneto-hydrodynamics. Consequently, in further estimates we will consider the magnetic field from spectators only.

Different microscopic mechanisms of the photon emission were proposed recently, including the synchrotron radiation of photons from moving charged quarks [8], and that reflecting the scale anomaly of QCD×QED [9] and owing to the axial anomaly [10]. It is important to mention that the last two mechanisms generate photons even in case of a vanishing quark number, which is expected to be rather low at the time scales of order $R/\gamma$ \(^1\), when the magnetic field is the highest and that in all the above mechanisms photons are emitted in the direction perpendicular to the magnetic field. As we show below photon production from the conformal anomaly results in a considerable contribution to $v_2$ [9] and potentially can describe the measured data.

In what follows, we neglect the spatial gradients of magnetic field and estimate the time dependence in the eikonal approximation taking into account only the (leading at large times) contribution from spectators:

$$eB_{x,y}(t) \simeq \frac{eB_{x,y}^0}{1 + (t/t_B)^2},$$

where $eB_{x,y}^0$ it the magnitude of the $i$-th component of the magnetic field at $t = 0$ and $t_B$ is the characteristic decay time. The $x$-component of magnetic field at $t = 0$, $B_{x,0}^0$, is approximately independent of the impact parameter $b$, while the $y$-component is linear in $b$. Both components $B_{x,y}^0$ are linear as a function of the collision energy, $\sqrt{s}$; the typical decay time is inversely proportional to $\sqrt{s}$.

3. Conformal anomaly as a source of photons

In this talk, we investigate photon production mechanism stemming from the conformal SVV anomaly that involves a dilatation current $S_\mu$ and two vector currents $V_\mu$ and reflects the violation of conformal invariance of QCD by quantum effects. The conformal anomaly results from the running of the coupling constant in QCD and expresses the non-conservation of the dilatation current $S^\mu$, so that the trace of the energy-momentum tensor $\theta^\mu_\mu$ does not vanish even in the chiral limit of massless quarks: $\partial_\mu S_\mu = \theta^\mu_\mu = \frac{2\alpha}{2\pi} G^{\mu\nu} G_{\mu\nu} + \sum_q m_q [1 + \gamma_m(g)] \bar{q}q$.

The quarks carry both color and electric charges, so when QCD is coupled to electromagnetism, the quark triangle diagram induces an anomalous coupling of the trace of the

\(^1\) Here, $R$ is the radius of colliding nuclei and $\gamma$ is the Lorentz factor.
energy-momentum tensor to photons [11, 12, 13]. The trace of the energy-momentum tensor in hydrodynamics excites the bulk modes of the fluid that are abundant in (non-conformal) quark-gluon plasma [14, 15, 16, 17]. As a result, the conformal anomaly coupled to the magnetic field acts as a source of photon production that is powered by the energy of the bulk hydrodynamical modes in the plasma (see Fig. 1, left panel). This is the mechanism of photon production that will be discussed in detail in Ref. [9]. Note that while in what follows the hydrodynamics will be used to describe the bulk modes in the plasma, the deviation from equilibrium in general need not be small for this mechanism to operate. For example, the non-equilibrated Bose-Einstein condensate of gluons [18] may be even more effective in producing photons, see right panel in Fig. 1. Note that unlike in the conventional scenario, the quarks in this case appear only in the triangle loop that receives contributions from the virtual UV modes – so the production of real on-shell quarks is not required, and the mechanism can operate even at very early times.

In vacuum, the coupling of QCD scale anomaly to electromagnetism can be defined by the coupling of the scalar meson to photons. This coupling is described by the triangle quark diagram, see Figure 1, and leads to the following effective interaction [11, 12, 13]:

$$L_{\sigma\gamma\gamma} = g_{\sigma\gamma\gamma} \sigma F_{\mu\nu} F^{\mu\nu},$$

where numerical value of the coupling $g_{\sigma\gamma\gamma}$ can be fixed using the parameter of the lightest scalar meson. We obtain $g_{\sigma\gamma\gamma} \simeq 0.02 \text{ GeV}^{-1}$ (see Ref. [9] for details).

To compute the photon production rate from the diagram of Fig. 1, we evaluate the imaginary part for the photon self-energy, see [19, 20]. A straightforward calculation yields for the production rate at mid-rapidity ($q_z = 0$) the following expression:

$$q_0 \frac{d\Gamma_B}{dq} = C \frac{(B_y^2 - B_z^2)q_0^2 + q^2q_0^2 B_z^2}{\exp(3q_0) - 1} \rho_\theta(q_0 = |q|),$$

(2)

where the proportionality factor $C$ is defined by the properties of the lowest mass scalar meson and the coupling $g_{\sigma\gamma\gamma}$; $\rho_\theta$ is the spectral function for the operator $\theta$. Since we consider production of photons in the QCD plasma, it is appropriate to use the hydrodynamic spectral function of the bulk mode $\theta$ [21, 22]: $\rho_\theta(q_0, \vec{q}) = 9q_0^2/2 + \rho_{\text{sound}}$, where $\zeta$ is the bulk viscosity. The second term describes the sound peak at $q_0 = c_s q$. The sound mode does not contribute to the production of real photons since the width of the sound peak is not large enough to reach the null dispersion of photons. Therefore the photon production is dominated by the bulk viscosity $\zeta$.

In deriving Eq. (2) we neglected the $z$-component of the magnetic field, because it is expected to be an order of magnitude smaller than $B_x$ and $B_y$ ($B_z \sim B_{x,y}/\gamma$); we also neglect the contribution of the electric field.

In what follows we will compare our result with the baseline provided by the conventional thermal photon production rate. Note that this conventional mechanism is expected to be the dominant one for low transverse momentum, $p_\perp$, photons. For photons with $p_\perp \sim 2$ GeV and above there will be additional contributions to the rate which can be calculated perturbatively. However we did not include these additional contributions as we are mainly interested in low $p_\perp$ photons.
Figure 2. Left panel: The azimuthal anisotropy \( v_2 \) of the direct photons for different values of bulk viscosity corresponding to \( C_\zeta \) in the range of \( 2.5 \div 5 \) calculated for minimum bias Au-Au collisions. The dashed line represents the results with \( C_\zeta = 4 \). The black dots are the data from the PHENIX collaboration [4] for minimum bias Au-Au collisions at \( \sqrt{s} = 200 \) GeV. Right panel: The transverse momentum spectra of the produced direct photons for \( C_\zeta = 2.5 \) calculated for minimum bias Au-Au collisions, see text for details.

The spectral function for \( \theta \) and the bulk viscosity was calculated in lattice QCD [16, 22]. However the extraction of bulk viscosity from the lattice data is notoriously difficult. To get an independent estimate of the bulk viscosity we thus follow [23, 24] and assume that \( \frac{\zeta}{\eta} = C_\zeta \left( \frac{1}{3} - c_s^2 \right)^2 \). Thus the bulk viscosity vanishes in the conformal limit, \( c_s^2 = 1/3 \). In the relaxation time approximation, this expression is obtained in the kinetic theory with \( C_\zeta = 15 \) (see e.g. [25]). The paper [25] contains also a phenomenological estimate of the value of bulk viscosity inferred from the comparison of viscous hydrodynamical computations with the data on the elliptic flow of mesons and baryons. The resulting estimate is \( \zeta/s = 0.005 \) [25]. Using the lattice data for the speed of sound in the freeze-out temperature range from Ref. [26], \( c_s^2 = 0.175 \pm 0.221 \), we infer for the bulk viscosity \( C_\zeta = 2.5 \div 5 \). The leading log calculations in SU(3) Yang Mills theory results in a much larger value \( C_\zeta \simeq 48 \), see Ref. [25]. In our calculations, we choose the lowest value available in the literature, \( C_\zeta = 2.5 \div 5 \), with an assumption \( \eta/s = 1/4\pi \).

Here we neglect the transverse expansion of the fireball and approximate the time evolution of the temperature at early times using the Bjorken hydrodynamics \( T/T_0 = (\tau_0/\tau)^{1/3} \), where \( T_0 \) is the initial temperature and \( \tau_0 \) is the initial time (given by the characteristic thermalization time of the gluons) that can be estimated in terms of the saturation scale, \( Q_s \), and the coupling constant, \( \alpha_s \), see e.g. Ref. [18]. For Au-Au collisions at \( \sqrt{s} = 200 \) GeV we use \( \tau_0 = 0.1 \) fm/c.

The results for the azimuthal anisotropy of photons calculated using both conventional production mechanism and the one from the conformal anomaly are shown in Fig. 2 for the minimum bias Au-Au collisions at \( \sqrt{s} = 200 \) GeV. In our approximation (no transverse flow), the conventional mechanism does not give any contribution to the azimuthal anisotropy. The comparison with the experimental data from PHENIX [4] indicates that conformal anomaly could account for a large fraction of the observed photon anisotropy.

In Fig. 2 we show our result for the transverse momentum spectrum of direct photons. Due to the factor of \( q^2 \) in the production rate (2), the spectrum of photons produced due to conformal anomaly is enhanced in comparison to the conventional one at transverse momenta \( k_\perp > 1 \) GeV. The factor of \( q^2 \) in the rate hardens the transverse momentum spectrum, and magnetic field grows with the impact parameter of the collision; these two effects thus conspire in mimicking
both the elliptic and radial flow of photons in non-central collisions.

4. Experimental signatures

In this section we discuss the experimental signatures of the photon produced in a magnetic field. Firstly, because the anisotropic contribution to the photon production rate is proportional to \(q^2\), the fourth harmonics \(v_4^{\gamma}\) will be significantly suppressed, violating the established scaling for hadrons \(v_4^{\text{hadr}}/v_2^{\text{hadr}} \sim 1\). Secondly, by properly selecting specific system geometries, we could diminish either the magnetic field, or the hadronic elliptic flow. The former possibility can be experimentally realized by performing central collisions with deformed nuclei, e.g. U-U collisions. The magnetic field is defined by the centrality, while the hadronic flow by the initial eccentricity. Consequently, if our mechanism gives dominant contribution to the photon azimuthal anisotropy, the central U-U collisions would show small photon \(v_2^{\gamma}\) compared to the hadronic one. The later possibility can be achieved in non-central Au-Au collision of a given centrality class. Since the initial eccentricity and, consequently, the hadronic \(v_2^{\text{hadr}}\) fluctuates at given centrality, it is possible to select non-central events with zero \(v_2^{\text{hadr}}\). Again if the proposed mechanism gives the dominant contribution to the photon production, \(v_2^{\gamma}\) will be much larger then \(v_2^{\text{hadr}}\).

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