Effect of magnetic field on photon production in AA collisions

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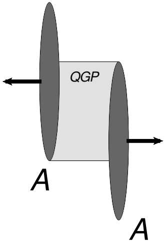
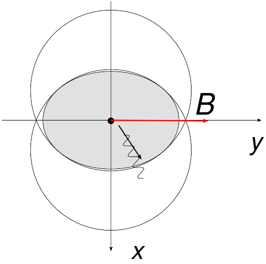
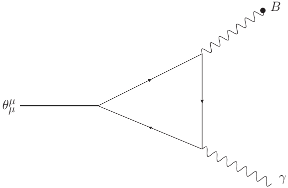
The synchrotron $q \to \gamma q$ contribution may be large [K. Tuchin, Phys.Rev. C91, 014902 (2015)]. The Lorentz force is $\propto \cos\theta \Rightarrow$ large v_2. Can the synchrotron mechanism resolve the "direct photon puzzle"? One should account for $m_q \sim gT$, $\hat{q} \neq 0$, and QGP expansion.

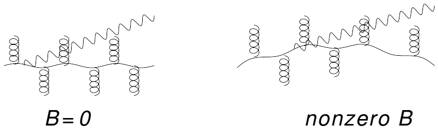




Conformal anomaly as a source of photons in AA collisions [G. Basar, D.E. Kharzeev, V. Skokov Phys.Rev.Lett. 109, 202303 (2012)]. Also gives large v_2.



The typical quark trajectories at the longitudinal scale $\sim L_f$



For $B = 0$ the typical quark scattering angle is small at $\Delta z \sim L_f$, and the collinear configurations dominate. For a QGP with magnetic field this picture will remain valid if

$$\frac{L_f}{R_L} \ll 1\,, \quad L_f \sim \min(L_1, L_2)\,, \;\; L_1 \sim \frac{2E_q(1-x)S_{LPM}}{m_q^2 x}\,, \;\; L_2 \sim \left(\frac{24E_q x(1-x)}{f^2}\right)^{1/3}$$

$f = z_q xeB$, $R_L = E_q/z_q eB$. For $eB = cm_\pi^2$ ($c \lesssim 1$) at $x \sim 0.5$ we have $L_1 < L_2$ at $E_q \lesssim 5$ GeV, and

$$\frac{L_f}{R_L} \sim z_q c \left(\frac{m_\pi}{T}\right)^{3/2} \left(\frac{m_\pi}{E_q}\right)^{1/2} \qquad (1)$$

For $c = 1$ at $E_q \gtrsim 1$ GeV for u quark $L_f/R_L \lesssim 0.25(m_\pi/T)^{3/2}$.

Photon emission rate for $q \to \gamma q$, $q\bar{q} \to \gamma$ processes

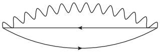
$$\frac{dN}{dtdVd\vec{k}} = \frac{dN_{br}}{dtdVd\vec{k}} + \frac{dN_{an}}{dtdVd\vec{k}} \,,$$

$$\frac{dN_{br}}{dtdVd\vec{k}} = \frac{d_{br}}{k^2(2\pi)^3} \sum_s \int_0^\infty dp p^2 n_F(p)[1 - n_F(p-k)]\theta(p-k) \frac{dP^s_{q\to\gamma q}(\vec{p},\vec{k})}{dkdL} \,,$$

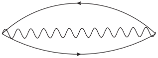
$$\frac{dN_{an}}{dtdVd\vec{k}} = \frac{d_{an}}{(2\pi)^3} \sum_s \int_0^\infty dp n_F(p) n_F(k-p)\theta(k-p) \frac{dP^s_{\gamma\to q\bar{q}}(\vec{k},\vec{p})}{dpdL} \,.$$

$d_{br} = 4N_c$, $d_{an} = 2$, $n_F(p) = 1/[\exp(p/T)+1]$, $dP^s_{q\to\gamma q}(\vec{p},\vec{k})/dkdL$ is the probability distribution for $q_s \to \gamma q_s$, $dP^s_{\gamma\to q\bar{q}}(\vec{k},\vec{p})/dpdL$ is the probability distribution for $\gamma \to q_s \bar{q}_s$ transition. In the small angle approximation $\vec{p} \parallel \vec{k}$.
In AMY [P.B. Arnold, G.D. Moore, and L.G. Yaffe, JHEP **0112**, 009 (2001)] approach $dP/dkdL$ in the QGP without magnetic field is expressed via solution of the integral equation

The formulas of the AMY approach have been reproduced [P. Aurenche and BGZ, JETP Lett. **85**, 149 (2007)] in the light-cone path integral (LCPI) approach [BGZ, JETP Lett. **63**, 952 (1996)]. In the LCPI formalism $dP/dxdL$ for $q \to \gamma q$ and $\gamma \to q\hat{q}$ are described by the diagrams



$q \to \gamma q$



$\gamma \to q\bar{q}$

$$\frac{dP_{q\to\gamma q}}{dxdL} = 2\mathrm{Re}\int\limits_0^\infty dz \exp\left(-i\frac{z}{\lambda_f}\right)\hat{g}(x)\left[\mathcal{K}(\vec{\rho}_2, z|\vec{\rho}_1, 0) - \mathcal{K}_{vac}(\vec{\rho}_2, z|\vec{\rho}_1, 0)\right]\Big|_{\vec{\rho}_{1,2}=0},$$

$\lambda_f = 2M(x)/\epsilon^2$ with $M(x) = E_q x(1-x)$, $\epsilon^2 = m_q^2 x^2 + m_\gamma^2(1-x)$,

$\hat{g}(x) = \frac{V(x)}{M^2(x)}\frac{\partial}{\partial\vec{\rho}_1}\cdot\frac{\partial}{\partial\vec{\rho}_2}$, $V(x) = z_q^2\alpha_{em}(1 - x + x^2/2)/x$.

$\mathcal{K}$ is the Green function of a Schrödinger equation with the Hamiltonian

$$\hat{\mathcal{H}} = -\frac{1}{2M(x)}\left(\frac{\partial}{\partial\vec{\rho}}\right)^2 + v(\vec{\rho}),$$

The potential v can be written as

$$v = v_f + v_m,$$

where v_f is due to the fluctuating gluon fields of the QGP, and v_m is related to the mean electromagnetic field

$$v_m = -\vec{f}\vec{\rho}$$

with $\vec{f} = xz_q\vec{F}$, $\vec{F}$ is transverse component (to the parton momentum) of the Lorentz force for a particle with charge e. The component v_f reads

$$v_f = -iP(x\rho).$$

$$P(\vec{\rho}) = g^2 C_F \int\limits_{-\infty}^{\infty} dz[G(z,0_\perp,z) - G(z,\vec{\rho},z)], \quad G(x-y) = u_\mu u_\nu \langle\langle A^\mu(x)A^\nu(y)\rangle\rangle$$

$u^\mu = (1, 0_\perp, 1)$ is the light-like four vector along the z axis.

In the HTL resummation scheme

$$P(\vec{\rho}) = \frac{g^2 C_F T}{(2\pi)^2} \int d\vec{q}[1 - \exp(i\vec{\rho}\vec{q})]C(\vec{q}), \quad C(\vec{q}) = \frac{m_D^2}{\vec{q}^2(\vec{q}^2 + m_D^2)}$$

[P. Aurenche, F. Gelis, and H. Zaraket, Phys. Rev. D**61**, 116001 (2000)].
Approximately $P(\rho) \propto \rho^2$ at $\rho \ll 1/m_D$. We work in the oscillator approximation

$$P(\rho) = C_p \rho^2, \quad C_p = \hat{q} C_F / 4 C_A$$

We use $\hat{q} \propto T^3$ and set $\hat{q} = 0.2$ GeV^3 at $T = 250$ MeV. It agrees with the qualitative pQCD calculations $\hat{q} \sim 2\varepsilon^{3/4} \approx 14 T^3$ [R. Baier, Nucl. Phys. A**715**, 209 (2003)], and with the relation $\hat{q} \sim 1.25 T^3 s/\eta$ [A. Majumder, B. Muller, and X.-N. Wang, Phys. Rev. Lett. **99**, 192301 (2007)] if one takes $\eta/s = 1/4\pi$.

$$\hat{\mathcal{H}} = -\frac{1}{2M}\left(\frac{\partial}{\partial\vec{\rho}}\right)^2 + \frac{M\Omega^2\vec{\rho}^2}{2} - \vec{f}\vec{\rho}, \quad \Omega = \sqrt{-iC_p x^2/M}\,.$$

$$\mathcal{K}(\vec{\rho}_2, z_2|\vec{\rho}_1, z_1) = \frac{M\Omega}{2\pi i \sin(\Omega z)} \exp\left[iS_{cl}(\vec{\rho}_2, z_2|\vec{\rho}_1, z_1)\right],$$

$dP/dxdL$ depends on two dimensionless parameters $\kappa = \lambda_f|\Omega|$, $\phi = \vec{f}^2/M|\Omega|^3$

$$\frac{dP}{dxdL} = \frac{2V(x)\pi}{|\Omega|}[I_{osc}(\kappa) + I_1^s(\kappa,\phi) + I_2^s(\kappa,\phi)]\,,$$

$$I_{osc}(\kappa) = \mathrm{Re}\int_0^\infty \frac{d\tau\exp(i\pi/4)}{\tau^2}\left(1 - \frac{\tau^2}{\sinh^2\tau}\right)\exp\left(-\frac{(1+i)\tau}{\sqrt{2}\kappa}\right)\,,$$

$$I_1^s(\kappa,\phi) = \mathrm{Re}\int_0^\infty \frac{d\tau\exp(i\pi/4)}{\sinh^2\tau}\left[1-\exp(-U)\right]\exp\left(-\frac{(1+i)\tau}{\sqrt{2}\kappa}\right)\,,$$

$$I_2^s(\kappa,\phi) = \frac{\phi}{2}\mathrm{Re}\int_0^\infty d\tau\frac{(1-\cosh\tau)^2}{\sinh^3\tau}\exp\left(-\frac{(1+i)\tau}{\sqrt{2}\kappa} - U\right)\,,$$

$$U = \frac{(1-i)\phi}{2\sqrt{2}}\left[\tau - 2\tanh(\tau/2)\right]\,.$$

For $\gamma \to q\bar{q}$ $M(x) = E_\gamma x(1-x)$ $\epsilon^2 = m_q^2 - m_\gamma^2 x(1-x)$, $\vec{f} = z_q\vec{F}$, and

$$V(x) = z_q^2\alpha_{em}N_c[x^2 + (1-x)^2]/2\,,\;\; \Omega = \sqrt{-iC_p/M}\,.$$

We will use extremely optimistic magnetic field $eB = m_\pi^2$ in the QGP. However even $eB \sim 0.1m_\pi^2$ is too optimistic.

Model of the fireball

Even for a very fast thermalization of the glasma color fields at $\tau \sim 1/Q_s$ one can apply the formulas obtained for the equilibrium QGP only at $\tau \gtrsim 0.2 - 0.5$ fm. We describe the QGP fireball at $\tau > \tau_0$ in the Bjorken model with $s \propto 1/\tau$, and take $s \propto \tau$ at $\tau < \tau_0 = 0.5$ fm. We take Gaussian rapidity distribution that gives at $\tau > \tau_0$

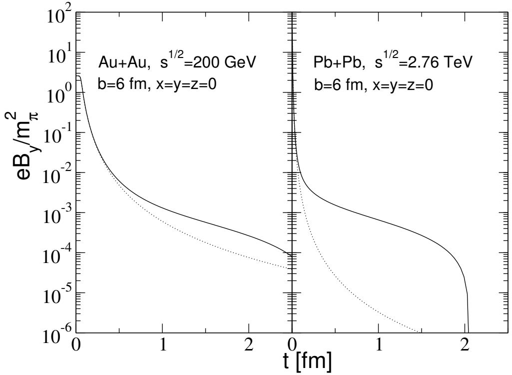
$$s(\tau, \vec{\rho}, Y, \vec{b}) = \frac{1}{\tau} \frac{dS(\vec{\rho}, Y = 0, \vec{b})}{d\vec{\rho} dY} \exp\left(-Y^2/2\sigma_Y^2\right)$$

with $\sigma_Y = 2.63$ for Au+Au collisions at $\sqrt{s} = 0.2$ TeV. We take $dS/d\vec{\rho}dY = CdN_{ch}/d\vec{\rho}d\eta$ with $C = 7.67$ [B. Müller and K. Rajagopal, Eur. Phys. J. C**43**, 15 (2005)]. We use the two component wounded nucleon Glauber model (with $\alpha = 0.135$ for Au+Au collisions at $\sqrt{s} = 0.2$ TeV)

$$\frac{dN_{ch}(\vec{\rho}, \vec{b})}{d\eta d\vec{\rho}} = \frac{dN_{ch}^{pp}}{d\eta} \left[\frac{(1-\alpha)}{2} \frac{dN_{part}(\vec{\rho}, \vec{b})}{d\vec{\rho}} + \alpha \frac{dN_{coll}(\vec{\rho}, \vec{b})}{d\vec{\rho}} \right],$$

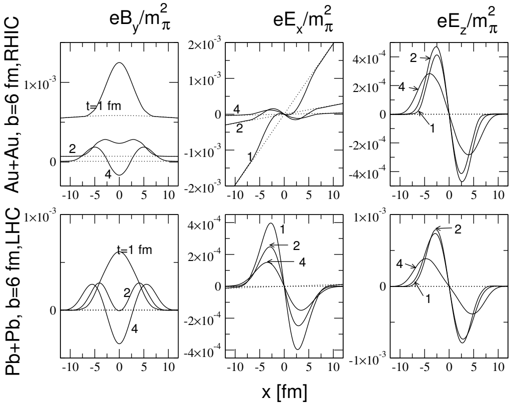
To determine T we use $s(T)$ from the lattice calculations [S. Borsanyi *et al.*, JHEP **1011**, 077 (2010)].
Presently, there is no consensus on the magnitude of the electromagnetic fields in the QGP. Our calculations [BGZ, 2014] show that the induced currents cannot generate the classical field at all.

eB_y/m_π^2 vs t at the center of the fireball for AA collisions



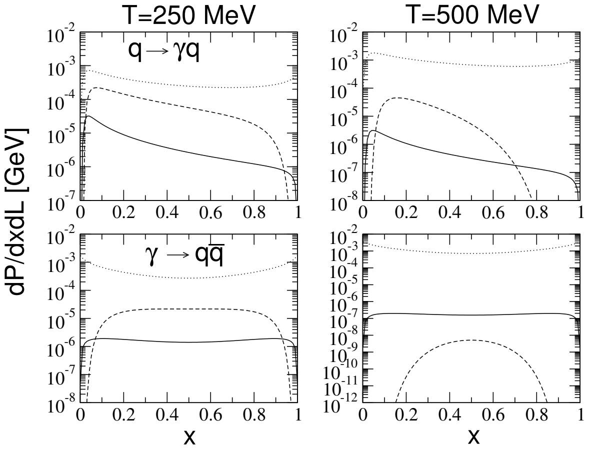
Magnetic field with (solid) and without (dotted) account for the induced currents [BGZ, Phys. Lett. B737 (2014) 262]. Results obtained by solving Maxwell's equations with the initial condition $F^{\mu\nu}_{in} = 0$ at $\tau = R_A/\gamma$. The conductivity is from the lattice calculations for $N_f = 3$ [A. Amato *et al.*, arXiv:1310.7466] that give $\sigma/(e^2 \sum z_q^2)T$ which rises smoothly from ~ 0.07 at $T = 150$ MeV to ~ 0.32 at $T = 350$ MeV.

x-dependence of B_y, $E_{x,z}$ in Au+Au collisions at $\sqrt{s} = 0.2$ TeV and in Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV at $b = 6$ fm



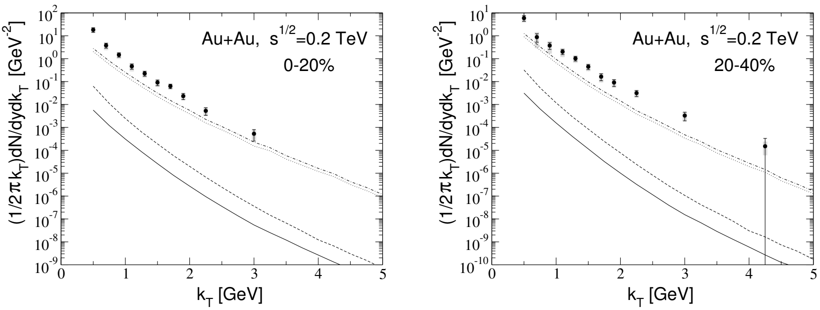
$\int dV(E^2 + B^2)/2 \ll \langle k \rangle \Rightarrow N_k \ll 1$, i.e. induced fields are in a deep quantum regime.

$dP/dxdL$ for $q \to \gamma q$ and $\gamma \to q\bar{q}$ at $E_{q,\gamma} = 2$ GeV



$dP/dxdL$ for $q \to \gamma q$ (upper) and $\gamma \to q\bar{q}$ (lower) for u quark at $eB = m_\pi^2$.
Solid: the synchrotron contribution with account for multiple scattering ($\hat{q} \neq 0$),
dashed: the pure synchrotron contribution ($\hat{q} = 0$),
dotted: the contribution of multiple scattering.

Photon spectrum in Au+Au collisions at $\sqrt{s} = 200$ GeV



Solid: the sum of the synchrotron contributions from $q \to \gamma q$ and $q\bar{q} \to \gamma$ processes calculated with $\hat{q} \neq 0$,
dashed: the same as solid but for $\hat{q} = 0$,
dotted: the contribution from $q \to \gamma q$ and $q\bar{q} \to \gamma$ processes due to quark multiple scattering alone,
dot-dashed: the sum of the contributions from $q \to \gamma q$ and $q\bar{q} \to \gamma$ processes due to quark multiple scattering and the contribution of the LO $2 \to 2$ processes.
The data are from PHENIX.

Summary

- We have developed a formalism for evaluation of the photon emission from the QGP with external electromagnetic field due to the collinear processes $q \to \gamma q$ and $q\bar{q} \to \gamma$. Within this formalism we have studied the effect of magnetic field on the photon emission rate from the QGP in AA collisions for a realistic model of the plasma fireball.
- We showed that that multiple scattering reduces considerably the effect of magnetic field.
- We found that even for an extremely optimistic assumption on the magnitude of magnetic field ($eB \sim m_\pi^2$) the effect of magnetic field on the photon emission in AA collisions is very small. For more realistic fields ($eB \sim 0.1 m_\pi^2$) the effect is practically negligible.
  $\Rightarrow$The synchrotron mechanism cannot lead to a considerable azimuthal asymmetry in the photon emission rate in AA collisions, and cannot resolve the direct photon puzzle.