Reduction and enhancement of production of linearly polarized holographic photons in a strongly coupled magnetized plasma

Daniel Ávila Hernández

March 16 2022

DOI:10.1016/j.physletb.2021.136287, arXiv:2101.08802
In collaboration with Tonantzin Monroy, Francisco Nettel and Leonardo Patiño

Holography

- Holography, or the gauge/gravity correspondence, is a **conjecture** that states that

Quantum Field Theories in d dimensions	=	**Quantum Gravity Theories in D>d dimensions**

- Different languages to describe the same physics.
- This correspondence takes the form of a **dictionary**

Strong coupling	$\rightarrow$	**Weak coupling**
Non-perturbative results	$\rightarrow$	**Computations in classical gravity**

Holography

- In principle this **tool** could be useful to study the non-perturbative properties of Quantum Chromodynamics (QCD). However

$$\textbf{QCD} \quad = \quad \text{¿?}$$

- We do know the gravitational dual to a somewhat similar theory

$$\begin{array}{ccc} \textbf{Super Yang-Mills (SYM)} & = & \textbf{IIB Supergravity} \\ \mathcal{N} = 4 \; SU(N_c) & & \textbf{in } AdS_5 \times S^5 \end{array}$$

Holography

- SYM $\mathcal{N} = 4$ $SU(N_c)$ is just a particular quantum field theory.
  - N_c number of colors.
  - The matter fields are in the adjoint representation of the gauge group and are massless.
  - It is supersymmetric.
  - Invariant under conformal transformations. It is a conformal field theory (CFT).
- At first glance different from QCD.
- However, if we consider a state at temperature T
  - Supersymmetry is broken.
  - No longer conformal invariant.

Holography

- The SYM $\mathcal{N} = 4$ plasma can be used as a toy model for the real quark gluon plasma (QGP).
- Hence we can aproximate the non-perturbative properties of the QGP using holographic methods.
- It is also possible to modify SYM $\mathcal{N} = 4$ and its gravity dual to better aproximate the real QGP.

Holography, photons and magnetized plasmas

- The QGP formed in highly energetic particle collisions, like those at RHIC and the LHC experiments, is a strongly coupled system.
- This QGP is expected to be optically thin, because of its limited extent and the small value of the electromagnetic coupling α_{EM}.
- Therefore, the emitted photons escape the plasma practically unscattered, making them very appealing probes to obtain information about the first stages of its evolution.

Holography, photons and magnetized plasmas

- It also has become increasingly accepted that an intense magnetic field is produced in non-central high energy collisions.
- Therefore understanding its effects is relevant to properly analyze experimental observation.
- This magnetic field is estimated to be in the range of $3m_\pi^2 \leq eB \leq 15m_\pi^2$, with m_π the mass of the neutral pion.

Holography, photons and magnetized plasmas

- We recently developed a new holographic model for the SYM $\mathcal{N} = 4$ plasma in the presence of a magnetic field.
- This model allows the introduction of massive flavor degrees of freedom, which are generically called quarks in this context arXiv:1809.01651.
- We found that the magnetic field induces a very interesting thermodynamic behavior on the plasma arXiv:1901.05976, arXiv:2002.02470.

Holography, photons and magnetized plasmas

- This new holographic model allows us to study how the interplay between the quarks and the magnetic field affects the produced photons.
- As a first step, we studied the emission of photons without quarks in this new model.

Photon production

- From the gauge theory side, the emitted photons are modeled by adding a $U(1)$ kinetic term to the SYM action that couples to the electromagnetic current associated to a $U(1)$ subgroup of the global $SU(4)$ R-symmetry group of the theory

$$S = S_{SYM} - \frac{1}{4}\int d^4x \left(\mathcal{F}^2 - 4e\mathcal{A}^\mu \mathcal{J}_\mu^{EM}\right)$$

Photon production

- We want to compute the differential rate of emitted photons with null wave four-vector $k^\mu = (k^0, \vec{k})$ and polarization $\epsilon^\mu_{(s)}(\vec{k})$

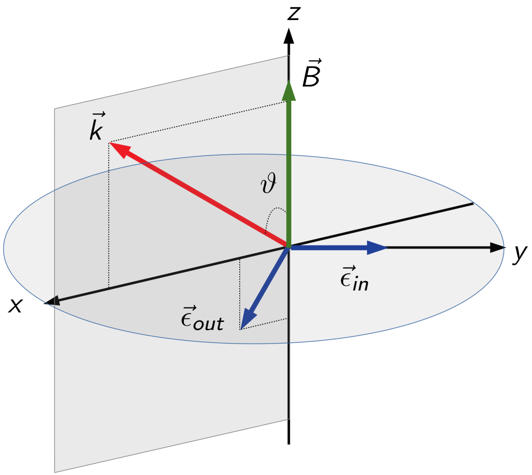
$$\frac{d\Gamma_s}{d\vec{k}} = \frac{e^2}{(2\pi)^3 2|\vec{k}|} n_B(k^0)\epsilon^\mu_{(s)}(\vec{k})\epsilon^\nu_{(s)}(\vec{k})\chi_{\mu\nu}(k)\Big|_{k=0}$$

- $\chi_{\mu\nu}(k)$ is the spectral density, and is given in terms of the two-point retarded correlation function of the electromagnetic current

$$\chi_{\mu\nu}(k) = -2\text{Im}[G^R_{\mu\nu}(k)]$$

$$G^{\rm R}_{\mu\nu}(k) = -i\int d^4x e^{-ik\cdot x}\Theta(t)\langle[\mathcal{J}^{\rm EM}_\mu(x), \mathcal{J}^{\rm EM}_\nu(0)]\rangle,$$

Photon production



Photon production

- With this choice of coordinates the differential rate of produced photons in each polarization state is given by

$$\frac{d\Gamma_{in}}{d\vec{k}} = \frac{e^2}{(2\pi)^3 2|\vec{k}|} n_B(k^0)\chi_{yy},$$

$$\frac{d\Gamma_{out}}{d\vec{k}} = \frac{e^2}{(2\pi)^3 2|\vec{k}|} n_B(k^0)(\cos^2\vartheta\chi_{xx} - 2\cos\vartheta\sin\vartheta\chi_{xz} + \sin^2\vartheta\chi_{zz})$$

Gravity dual

- Our gravity dual is a 5-dimensional consistent truncation of 10-dimensional SUGRA IIB

$$S = \frac{1}{16\pi G_5} \int d^5x\sqrt{-g}\left[R - \frac{1}{2}(\partial\varphi)^2 + V(\varphi) - e^{-\frac{2}{\sqrt{6}}\varphi}(F)^2\right]$$

$$V(\varphi) = 4\left(e^{\frac{2}{\sqrt{6}}\varphi} + 2e^{-\frac{1}{\sqrt{6}}\varphi}\right)$$

in addition to the constraint

$$F \wedge F = 0$$

Gravity dual

- The family of solutions that features a constant magnetic field and a black hole is given by

$$ds_5^2 = \frac{dr^2}{U(r)} - U(r)dt^2 + V(r)(dx^2 + dy^2) + W(r)dz^2,$$

$$F = B dx \wedge dy,$$

$$\varphi = \varphi(r).$$

Gravity dual

- All the solutions in the family have temperature $T = 3r_h/2\pi$ with $U(r_h) = 0$.
- They go to AdS_5 at the boundary, i.e. when $r \to \infty$, regardless of the value of the magnetic or scalar fields.
- For $B = 0$ and $\varphi = 0$ they reduce to the non-compact part of the D3-black brane solution.

Gravity dual

- The Maxwell field $F = B\, dx \wedge dy$ corresponds to the magnetic field B on the gauge theory.
- The scalar field φ is dual to a single trace scalar operator $\mathcal{O}_\varphi$ of scaling dimension $\Delta = 2$.
- The family of solutions is parametrized by the magnetic field intensity B and the temperature of the black hole T.

Gravity dual

- The magnetic field intensities that we can explore with our holographic model need to be below $eB/T^2 < 11.24$, which corresponds to $eB \sim 16m_\pi^2$ for $T = 170$ MeV.

Holographic photon production

- In order to model the photons we need to consider perturbations around the background (BG) solutions

$$g_{mn} = g^{BG}{}_{mn} + h_{mn},$$

$$F = F^{BG} + dA,$$

$$\varphi = \varphi^{BG} + \phi.$$

Holographic photon production

- The value that the perturbation of the gauge field takes at the boundary A^{bdry} is dual to the electromagnetic current $\mathcal{J}^{\text{EM}}$ on the gauge theory side.
- It is crucial to consider perturbations on all the fields, as all of them appear at linear order in the equations of motion.
- According to the holographic dictionary $G^R_{\mu\nu}$ is given by

$$G^{R^{\mu\nu}}(k) = \frac{\delta^2 S_{\text{on-shell}}}{\delta A_\mu^{bdry} \delta A_\nu^{bdry}}.$$

Holographic photon production

- To second order in the perturbations the on-shell action takes the schematic form

$$S_{\text{on-shell}} \propto \int d^4x(\mathcal{O}(AA') + \mathcal{O}(\phi\phi') + \mathcal{O}(h^2) + \mathcal{O}(hh')),$$

- The only terms that contribute to the second variation are

$$-\frac{1}{8\pi G_5}\int d^4x\sqrt{-\gamma^{BG}}\,U(r)^{1/2}\gamma^{BG\,\mu\nu}e^{-\frac{2}{\sqrt{6}}\varphi}A_\mu A'_\nu,$$

where γ^{BG} is the background boundary metric.

Holographic photon production

- The equations for the perturbations decouple into two independent groups, corresponding to the two independent polarization states.

Out-plane polarization state

- The equations for the out-plane polarization state impose that

$$A'_t = A'_x = A'_z = 0$$

- Hence the only contribution to the 2-point function is

$$-\frac{1}{8\pi G_5}\int d^4x U\sqrt{W}e^{-\frac{2}{\sqrt{6}}\varphi}A_yA'_y,$$

Out-plane polarization state

- This means that

$$G^{R^{xx}}(k) = \frac{\delta^2 S_{\text{on-shell}}}{\delta A_x^{bdry} \delta A_x^{bdry}} = 0$$

$$G^{R^{xz}}(k) = \frac{\delta^2 S_{\text{on-shell}}}{\delta A_x^{bdry} \delta A_z^{bdry}} = 0$$

$$G^{R^{zz}}(k) = \frac{\delta^2 S_{\text{on-shell}}}{\delta A_z^{bdry} \delta A_z^{bdry}} = 0$$

Out-plane polarization state

- Hence

$$\chi_{xx} = \chi_{xz} = \chi_{zz} = 0$$

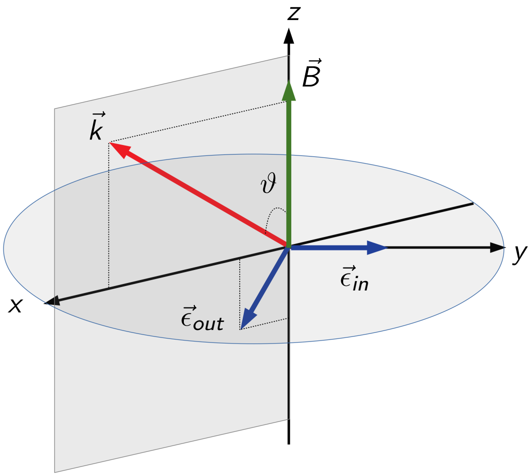
$$\frac{d\Gamma_{out}}{d\vec{k}} = \frac{e^2}{(2\pi)^3 2|\vec{k}|} n_B(k^0)(\cos^2\vartheta\chi_{xx} - 2\cos\vartheta\sin\vartheta\chi_{xz} + \sin^2\vartheta\chi_{zz})$$

Out-plane polarization state

$$\frac{d\Gamma_{out}}{d\vec{k}} = 0$$

- No photons are produced in the ϵ_{out} polarization state, that is, the state that is not parallel to the reaction plane.

Out-plane polarization state



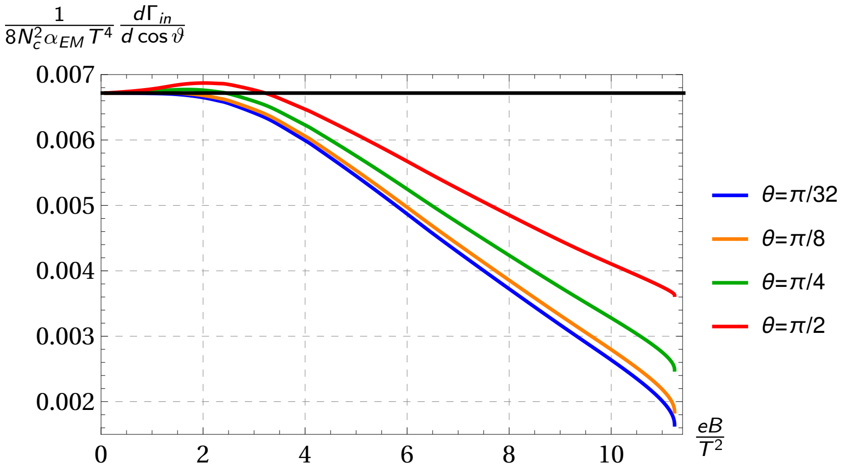
In-plane polarization state

- The production of photons in the in-plane polarization state can be computed by solving the remaining equations. This gives the differential photon production

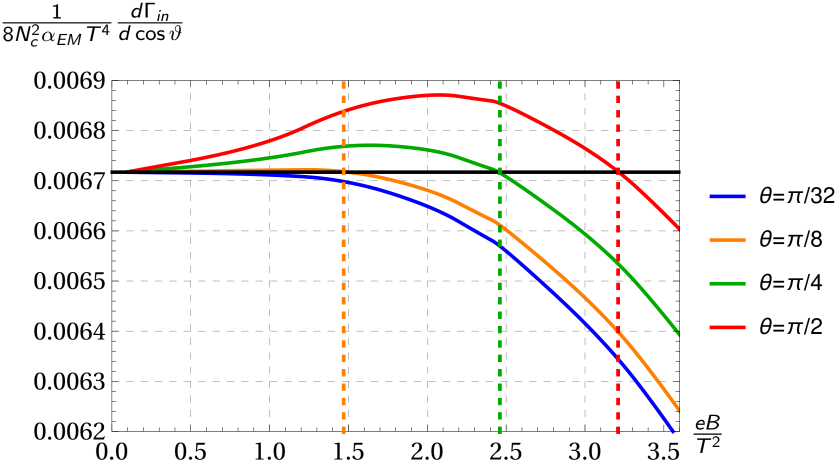
$$\frac{d\Gamma}{d\vec{k}} = \frac{d\Gamma_{in}}{d\vec{k}}$$

- The total energy emitted at a given direction and fixed magnetic field and temperature can be computed by integrating this expression.

In-plane polarization state



In-plane polarization state



In-plane polarization state

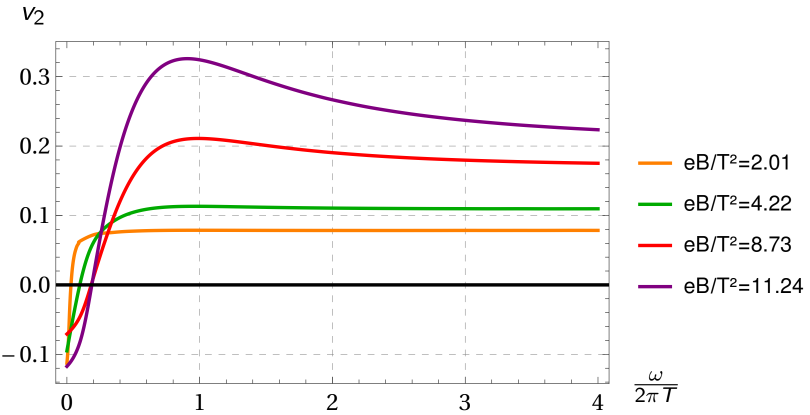
- For any fixed ϑ, there exists a magnetic field intensity B_ϑ such as if $B > B_\vartheta$ less photons are produced when compared to the b $= 0$ case.
- For magnetic field intensities above $eB_{\pi/2}/T^2 \sim 3.21$ the production is always less than for $B = 0$ (for perspective $eB_{\pi/2} \sim 4.7m_\pi^2$ if $T = 170$ MeV).
- However, if $0 < B < B_\vartheta$ the magnetic field enhances the production of photons.

Elliptic Flow

- The elliptic flow v_2 gives a measure of the degree of the momentum anisotropy of the particles generated in the collision.
- It is given by the the second harmonic coefficient of the Fourier expansion in the azimuthal photon distribution. For central rapidity

$$v_2 = -\frac{\int_0^{\frac{\pi}{2}} d\vartheta \cos(2\vartheta) \frac{d\Gamma}{d\vec{k}}}{\int_0^{\frac{\pi}{2}} d\vartheta \frac{d\Gamma}{d\vec{k}}}.$$

Elliptic Flow



Conclusions

- The photons emitted by the SYM $\mathcal{N} = 4$ magnetized plasma presented here are in its polarization state parallel to the reaction plane.
- While previous holographic models have reported that the presence of spatial anisotropies can cause an increase in the production of photons in one polarization state over the other, the strict polarization effect is a novelty of our model.

Conclusions

- For any given direction of propagation, the production of photons is increased with respect to the $B = 0$ value if the magnetic field intensity lies in the interval $0 < B < B_\vartheta$, while it decreases for any $B > B_\vartheta$.

Conclusions

- The magnetic field has the general effect of increasing the value of v_2 except for very small frequencies.
- This is consistent with the excess observed in heavy-ion experiments in RHIC and LHC.
- While there are plenty of evidence that the magnetic field can be the cause of this excess by means of perturbation theory, here we provide a non-perturbative confirmation.

Thank you for your attention!