ARIZONA STATE UNIVERSITY

FUNQCD
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ONLINE

Anisotropic photon emission from magnetized QGP

Igor Shovkovy

Arizona State University

[X. Wang, I. Shovkovy, L. Yu, M. Huang, Phys. Rev. D 102, 076010 (2020)]

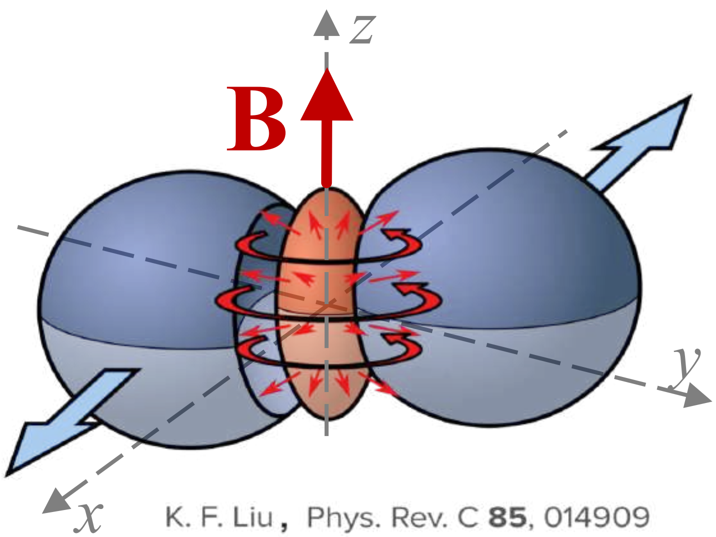
[X. Wang, I. Shovkovy, arXiv:2103.01967]

FUNQCD FunQCD: from first principles to effective theories

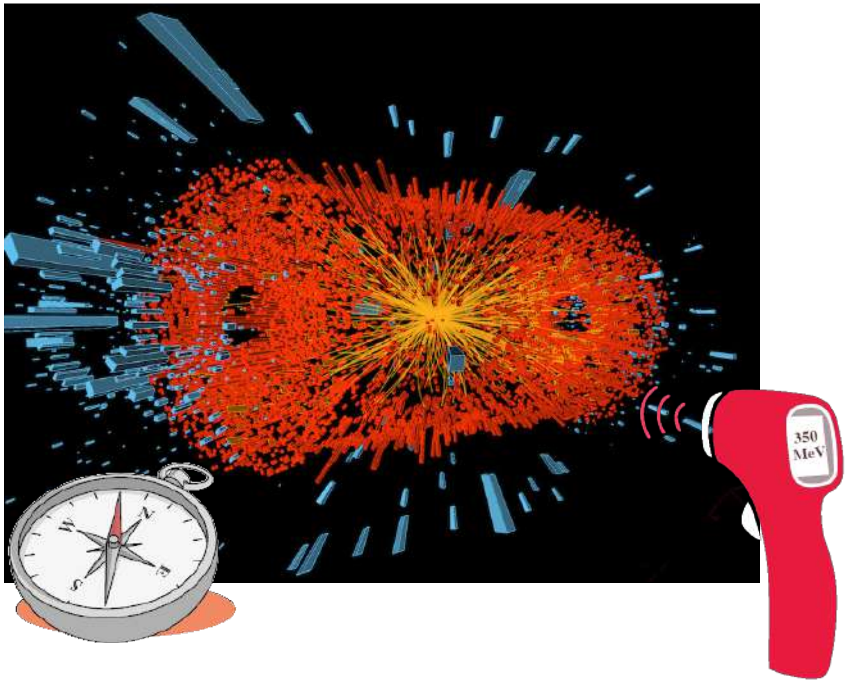
29 March 2021 to 1 April 2021

Magnetic field in HICs

- QGP produced at RHIC/LHC is **magnetized**
  - **10^{18} to 10^{19} G** $\sim m_\pi^2 \sim (100\ \text{MeV})^2$



K. F. Liu, Phys. Rev. C **85**, 014909



Main idea

- Photon emission is not only a **thermo**meter but also **magneto**meter of QGP

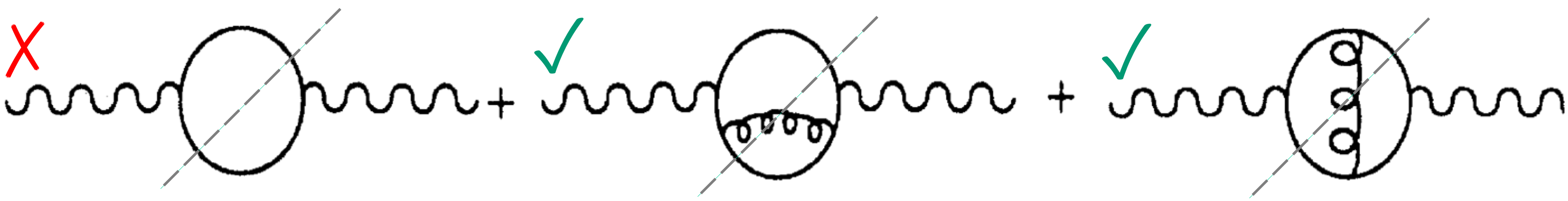
Thermal photons ($B = 0$)

- The rate of the thermal emission of photons (more precisely, the energy loss rate) is

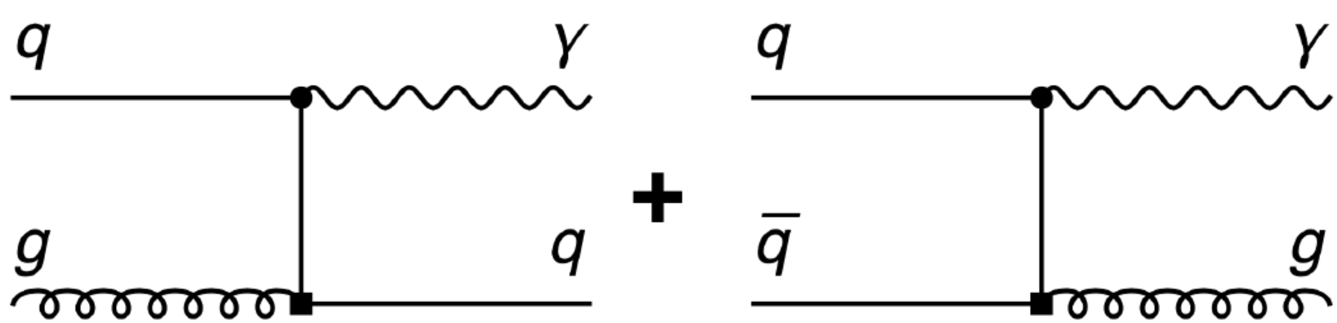
$$k^0 \frac{d^3 R}{dk_x dk_y dk_z} = -\frac{1}{(2\pi)^3} \frac{\mathrm{Im}\left[\Pi^\mu_\mu(k)\right]}{\exp\left(\frac{k_0}{T}\right) - 1}$$

[Kapusta, Lichard, Seibert, Phys. Rev. D 44, 2774 (1991)]
[Baier, Nakkagawa, Niegawa, Redlich, Z. Physik C 53 (1992) 433]

- In the case of hot QCD plasma,



- Processes:



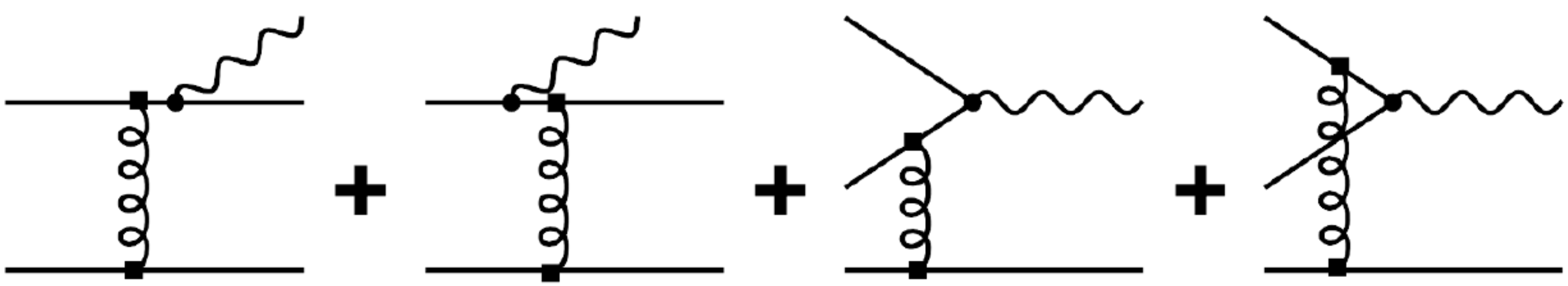
Thermal photons ($B = 0$)

- The approximate result is given by

$$E\frac{dR}{d^3p} = \frac{5}{9}\frac{\alpha\alpha_s}{2\pi^2}T^2 e^{-E/T}\ln\left(\frac{2.912}{g^2}\frac{E}{T}\right)$$

[Kapusta, Lichard, Seibert, Phys. Rev. D 44, 2774 (1991)]

- There are important corrections from **bremsstrahlung** and **inelastic pair annihilation**



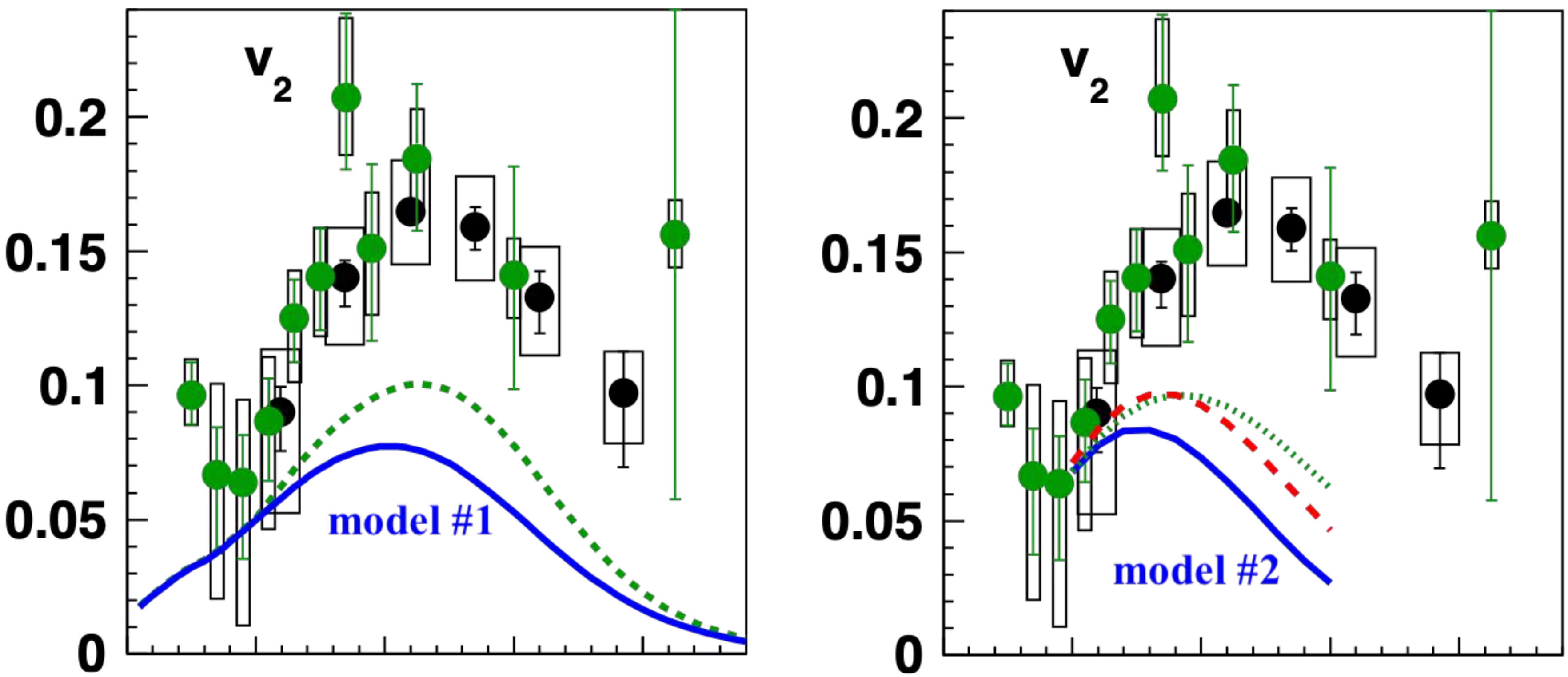
[Arnold, Moore,Yaffe, JHEP 12 (2001) 009; hep-ph/0111107]

- Next to leading order corrections are ~ 100%

[Arnold, Moore,Yaffe, JHEP 12 (2001) 009; hep-ph/0111107]
[Ghiglieri et al., JHEP 05 (2013) 010; arXiv:1302.5970]

Photon v_2 puzzle

- Most photons are produced early (before flow develops)
- Thus, v_2 for photons should be very small

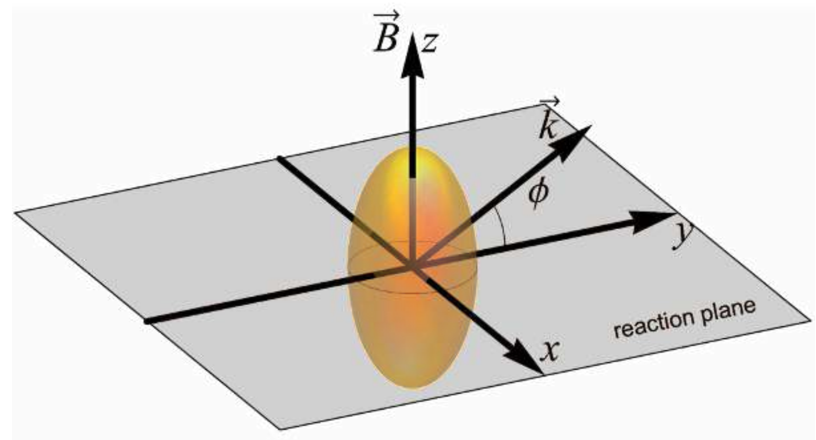


[Adare et al., Phys. Rev. C 94, 064901 (2016)]

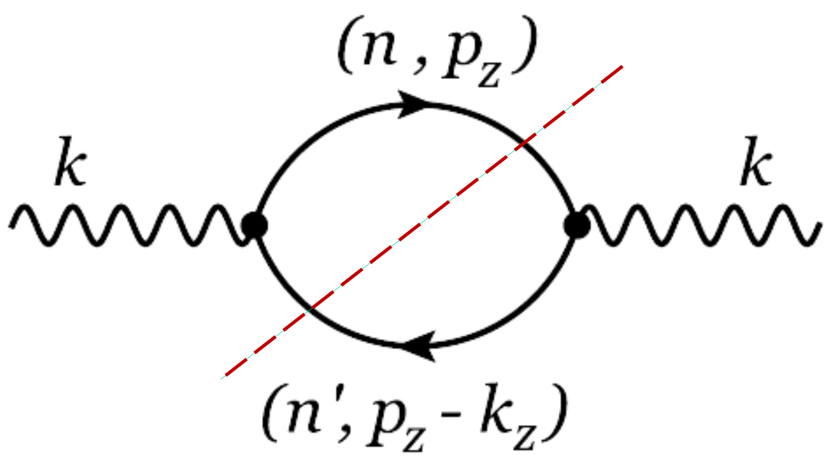
Photon emission ($B \neq 0$)

- The expression for the rate is

$$k^0 \frac{d^3R}{dk_x dk_y dk_z} = -\frac{1}{(2\pi)^3} \frac{\mathrm{Im}\left[\Pi^{\mu}_{\mu}(k)\right]}{\exp\left(\frac{k_0}{T}\right) - 1}$$



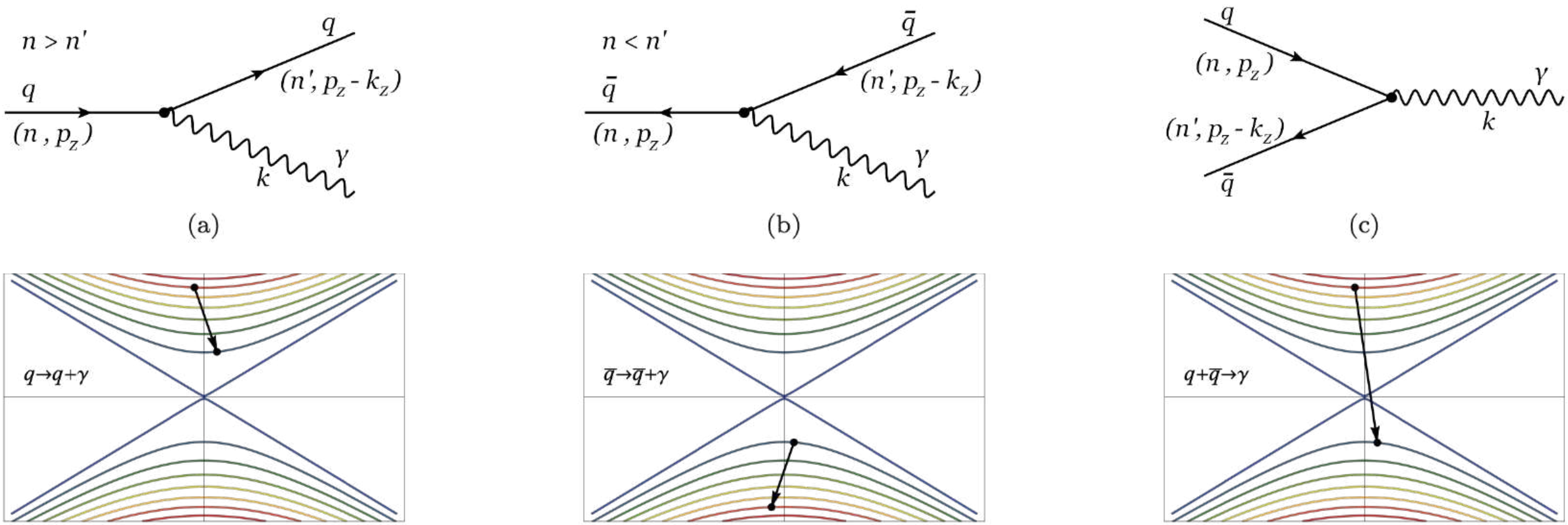
- At $\vec{B} \neq 0$, the imaginary part of the leading-order polarization tensor



leads to a nonzero result!

[Wang, Shovkovy, Yu, Huang, arXiv:2006.16254]

- Relevant physics processes (0th order in α_s):



The energy momentum conservation

$$E_{n,p_z,f} - \lambda E_{n',p_z-k_z,f} + \eta\Omega = 0$$

is satisfied for these 1 → 2 and 2 → 1 processes

[Wang, Shovkovy, Yu, Huang, arXiv:2006.16254]

Photon emission rate

The explicit expression for $\mathrm{Im}\left[\Pi^{\mu}_{R,\mu}(\Omega,\mathbf{k})\right]$ is

$$\mathrm{Im}\left[\Pi^{\mu}_{R,\mu}\right] = \sum_{f=u,d} \frac{N_c \alpha_f}{2\pi l_f^4} \sum_{n>n'}^{\infty} \frac{g(n,n')\left[\theta\left(k_-^f - |k_y|\right) - \theta\left(|k_y| - k_+^f\right)\right]}{\sqrt{[(k_-^f)^2 - k_y^2][(k_+^f)^2 - k_y^2]}} \left(\mathcal{F}_1^f + \mathcal{F}_4^f\right)$$

$$- \sum_{f=u,d} \frac{N_c \alpha_f}{4\pi l_f^4} \sum_{n=0}^{\infty} \frac{g_0(n)\theta\left(|k_y| - k_+^f\right)}{\sqrt{k_y^2[k_y^2 - (k_+^f)^2]}} \left(\mathcal{F}_1^f + \mathcal{F}_4^f\right),$$

where $g(n,n')$ and $g_0(n)$ are combinations of the Fermi-Dirac distribution functions.

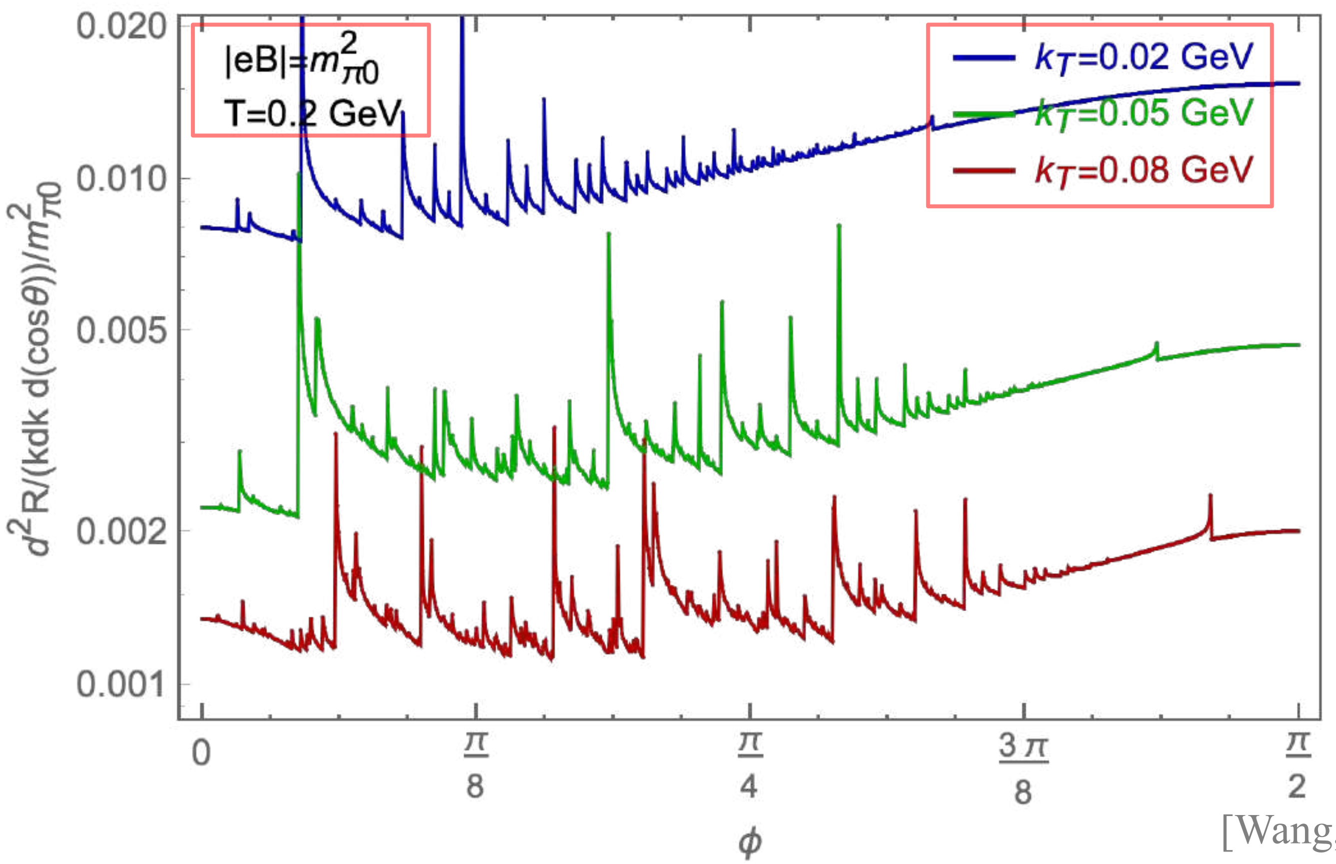
The momentum *thresholds* are determined by

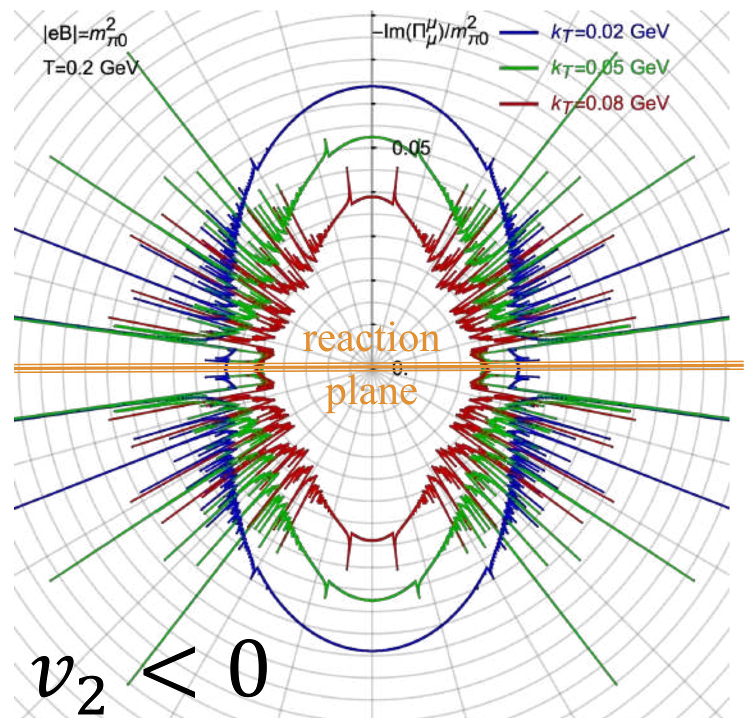
$$k_\pm^f = \left|\sqrt{m^2 + 2n|e_f B|} \pm \sqrt{m^2 + 2n'|e_f B|}\right|$$

[Wang, Shovkovy, Yu, Huang, arXiv:2006.16254]

Angular dependence (1)

- At small k_T, the emission rate is maximal at $\phi = \frac{\pi}{2}$ (i.e., **perpendicular** to the reaction plane)
- Effectively, this gives photon "flow" with $v_2 < 0$
- Note: $k_x = 0$, $k_y = k_T \cos\phi$ and $k_z = k_T \sin\phi$

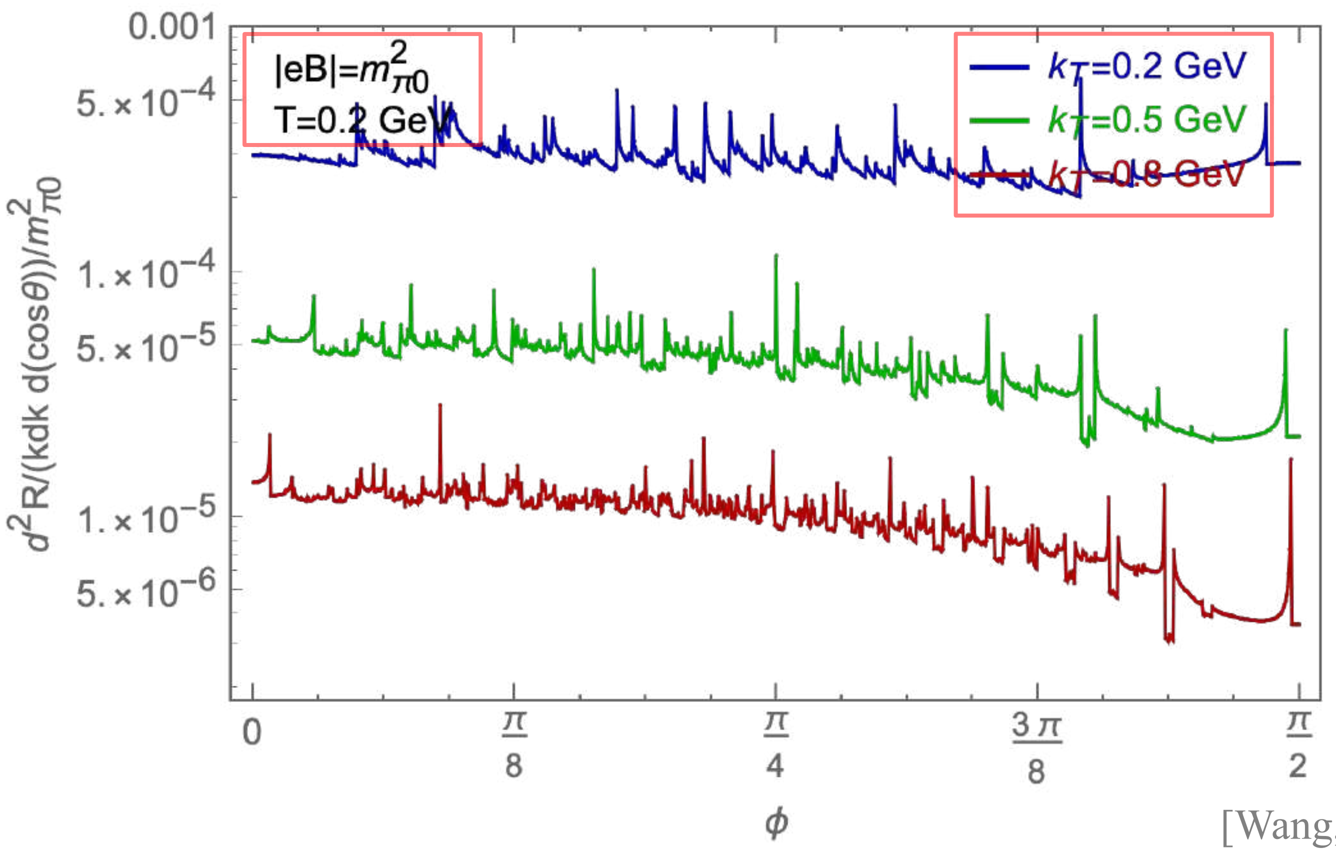


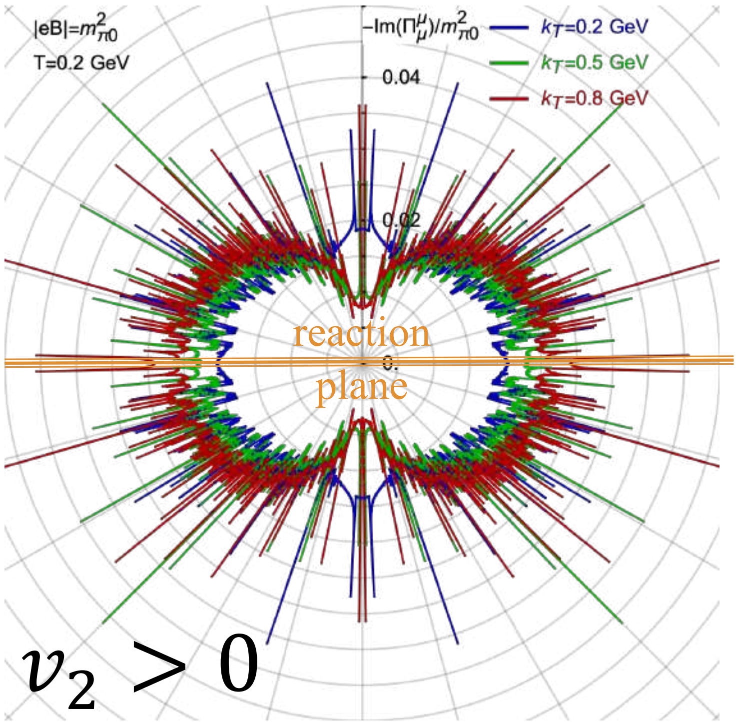


[Wang, Shovkovy, Yu, Huang, arXiv:2006.16254]

Angular dependence (2)

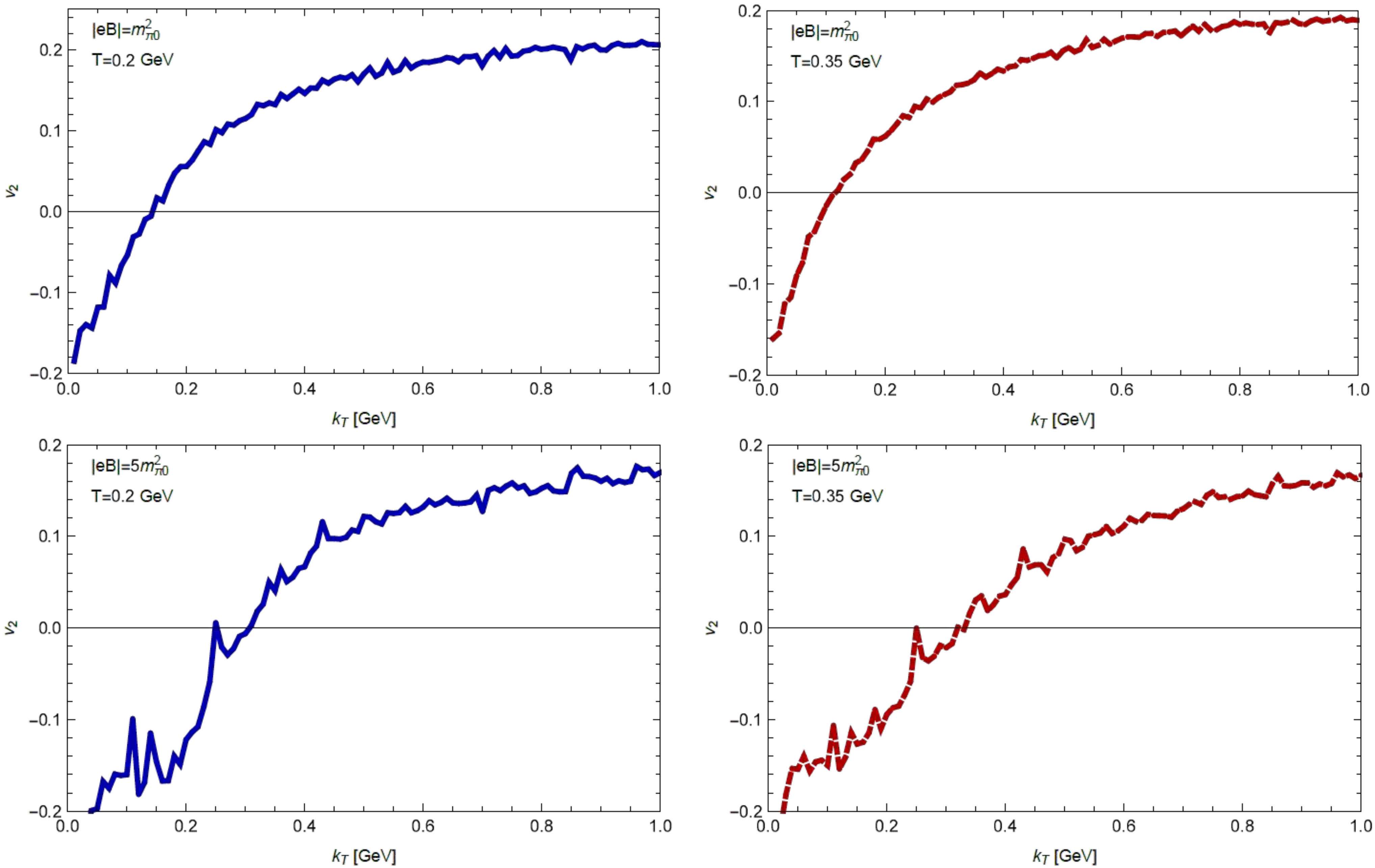
- At large k_T, the emission rate is maximal at $\phi = 0$ (i.e., **parallel** to the reaction plane)
- Effectively, this gives photon "flow" with $v_2 > 0$





[Wang, Shovkovy, Yu, Huang, arXiv:2006.16254]

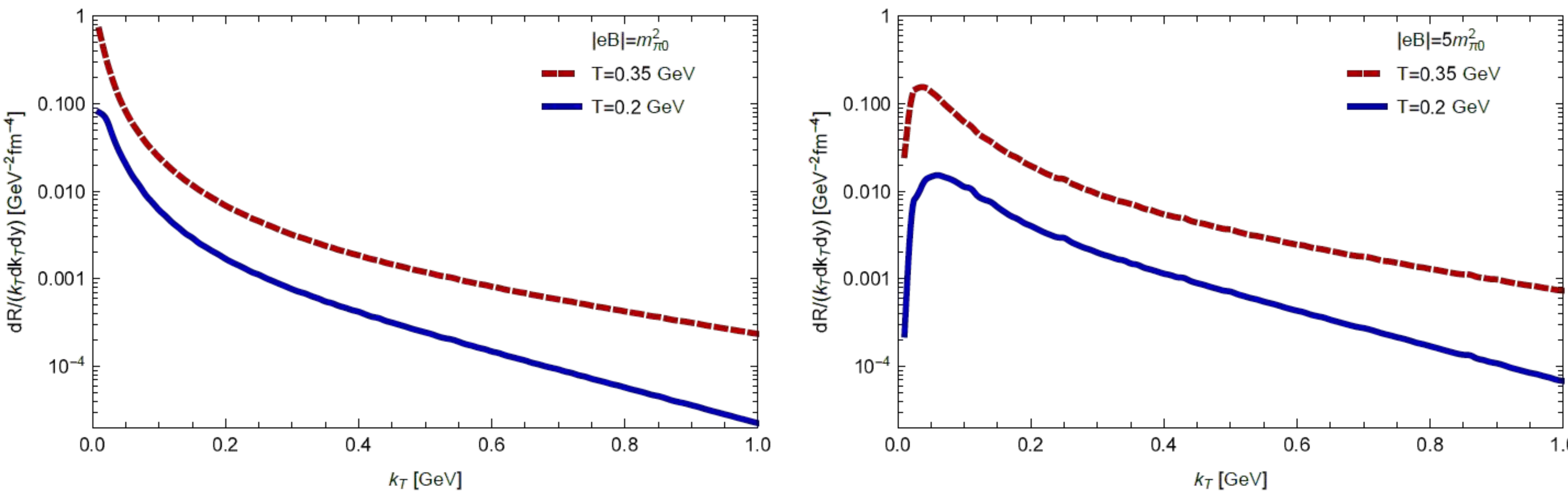
Nonzero elliptic "flow" (v_2)



[Wang, Shovkovy, Yu, Huang, arXiv:2006.16254]

Thermal rate at $\vec{B} \neq 0$

- The photon production rate
  - decreases with energy (k_T) at large k_T
  - increases with temperature
  - goes to zero when $k_T \to 0$ (quantization effects)
  - has a peak at a small nonzero k_T



[Wang, Shovkovy, Yu, Huang, arXiv:2006.16254]

Magnetic enhancement of v_2

- Estimate of v_2 in a hot magnetized QGP

$$\mathcal{R}_{\substack{2\to1\\1\to2}}: \quad v_2 \sim 20\%$$

- Noting that

$$\mathcal{R}_{\substack{2\to1\\1\to2}} \gtrsim \mathcal{R}_{2\to2} \gtrsim \mathcal{R}_{\substack{2\to3\\3\to2}}$$

- Naïve estimate at $p_T \sim 1$ GeV gives

$$6.7\% \lesssim v_2 \lesssim 20\%$$

- A more realistic estimate should consider non-isotropic expansion & non-thermal processes

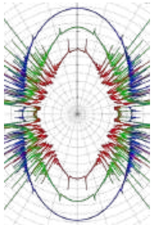
Summary

- $\vec{B} \neq 0$: photons are produced at 0^{th} order in α_s

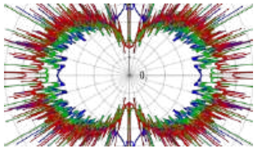
  (i) $q \to q + \gamma$, (ii) $\bar{q} \to \bar{q} + \gamma$, (iii) $q + \bar{q} \to \gamma$

- Photon emission has pronounced ellipticity

  – $v_2 < 0$ at small k_T ($k_T \lesssim \sqrt{|eB|}$)



  – $v_2 > 0$ at large k_T ($k_T \gtrsim \sqrt{|eB|}$)



- Nonzero ellipticity of thermal emission could be used to "measure" the magnetic field