Photons from the early stages of heavy ion collisions

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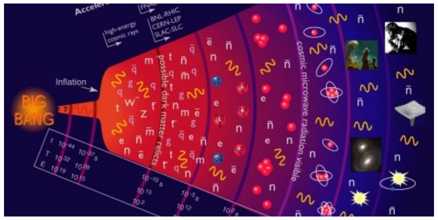
X.W, Igor Shovkovy, In preparation
X.W, Igor Shovkovy, Phys.Rev.D 109 (2024) 5, 056008
X.W, Igor Shovkovy, Phys.Rev.D 106 (2022) 3, 036014
X.W, Igor Shovkovy, Eur.Phys.J.C 81 (2021) 10, 901
X.W, Igor Shovkovy, Phys.Rev.D 104 (2021) 5, 056017
X.W, Igor Shovkovy, Lang Yu, Mei Huang, Phys.Rev.D 102 (2020) 7, 076010

Magnetized plasmas

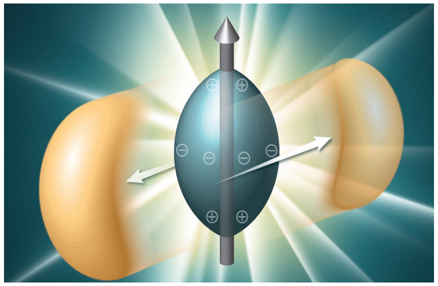
- **Early Universe**

  10^{20} to 10^{24} G ~ $(1\ \text{GeV})^2$ to $(100\ \text{GeV})^2$



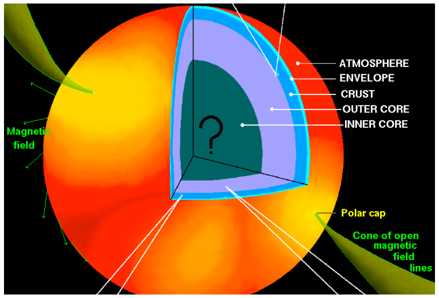
- **Heavy-ion collisions**

  10^{18} to 10^{19} G ~ $(100\ \text{MeV})^2$



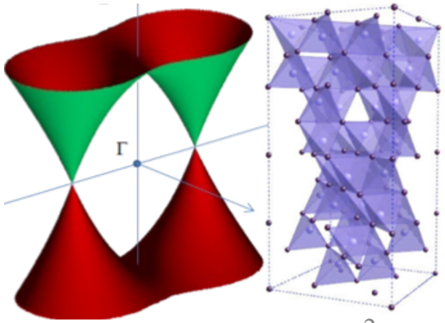
- **Super-dense matter in magnetars**

  10^{14} to 10^{16} G ~ $(1\ \text{MeV})^2$ to $(10\ \text{MeV})^2$

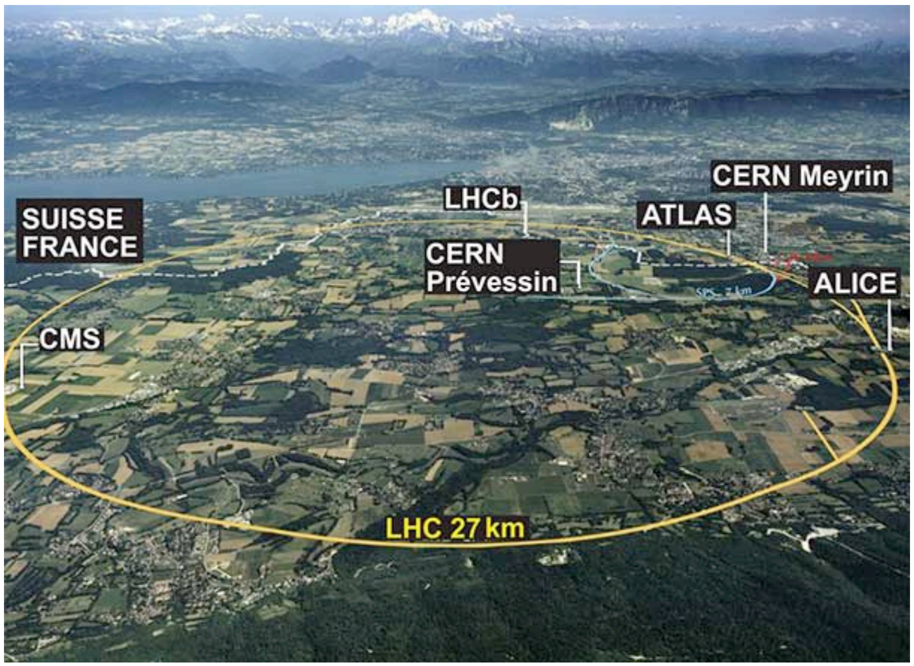


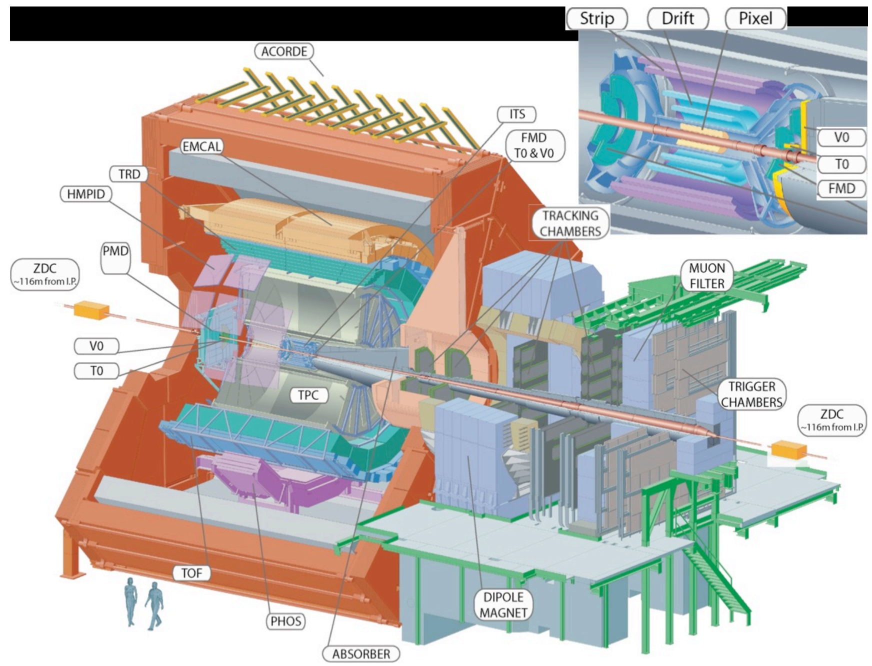
- **Electrons in Dirac/Weyl (semi-)metals**

  $\lesssim 10^5$ G ~ $(100\ \text{meV})^2$

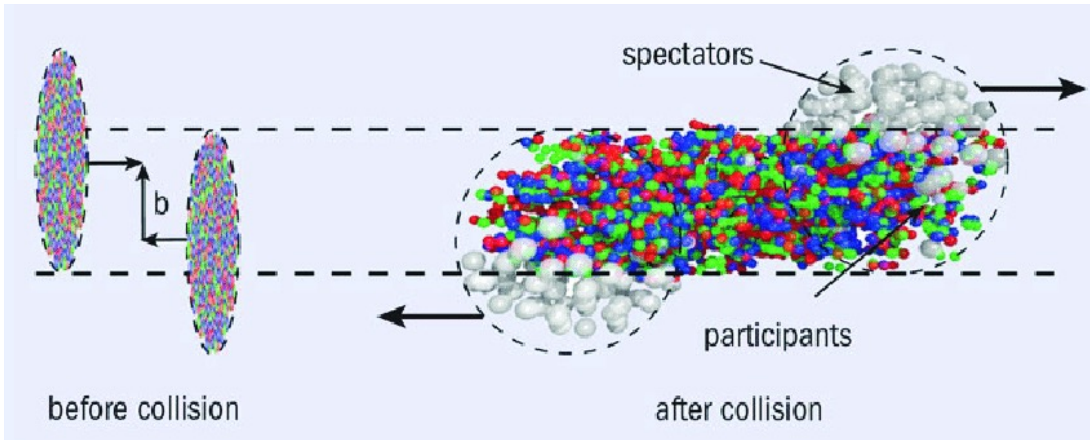


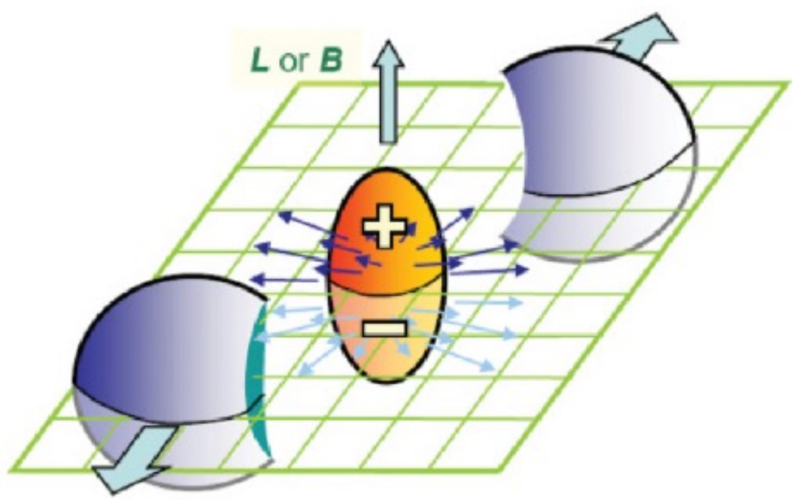
Heavy Ion collisions

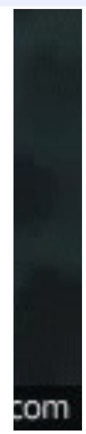




Heavy Ion collisions

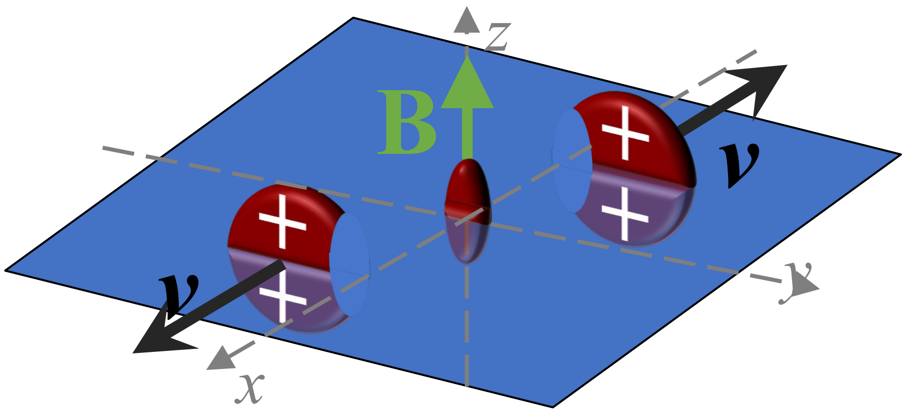


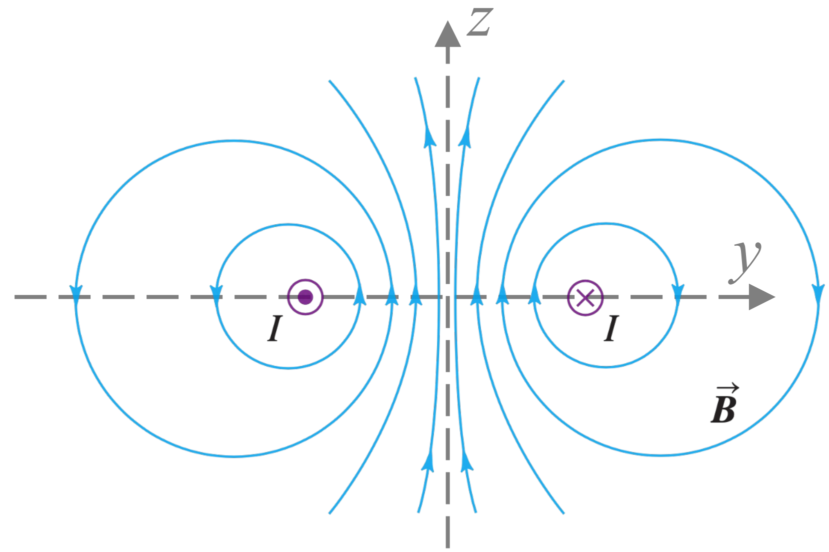




Heavy-ion collisions

- QGP produced at RHIC/LHC is magnetized





- Using Lienard-Wiechert potential, one finds

$$e\mathbf{E}(t,\mathbf{x}) = \alpha_{\rm EM} \sum_{n\in \rm protons} \frac{1-v_n^2}{R_n^3\left(1-[\mathbf{R}_n\times\mathbf{v}_n]^2/R_n^2\right)^{3/2}}\mathbf{R}_n$$

$$e\mathbf{B}(t,\mathbf{x}) = \alpha_{\rm EM} \sum_{n\in \rm protons} \frac{1-v_n^2}{R_n^3\left(1-[\mathbf{R}_n\times\mathbf{v}_n]^2/R_n^2\right)^{3/2}}\mathbf{v}_n\times\mathbf{R}_n$$

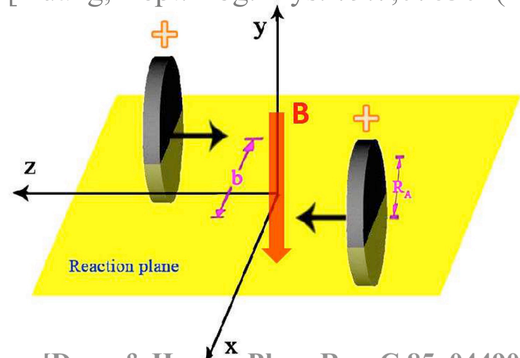
[Rafelski & Müller, PRL, 36, 517 (1976)]
[Kharzeev et al., arXiv:0711.0950]
[Skokov et al., arXiv:0907.1396]
[Voronyuk et al., arXiv:1103.4239]
[Bzdak &. Skokov, arXiv:1111.1949]
[Deng & Huang, arXiv:1201.5108]
[Bloczynski et al, arXiv:1209.6594]
…

Magnetic field in HIC

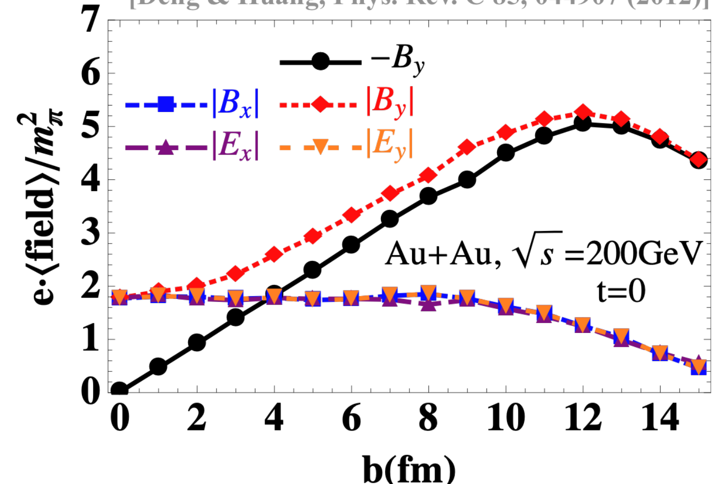
- Magnetic field
  - strong in magnitude $\sim m_\pi^2$
  - depends strongly on b
  - nonuniform
  - fluctuates from event to event
  - not always $\perp$ to reaction plane
  - short-lived ($\ll$ 1 fm/c)
  - conductivity may help a little

[McLerran, Skokov, Nucl. Phys. **A929**, 184 (2014)]

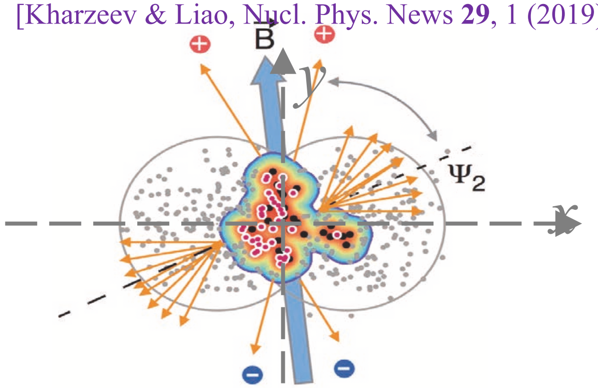
[Huang, Rept.Prog.Phys. 79.7,076302(2016)]



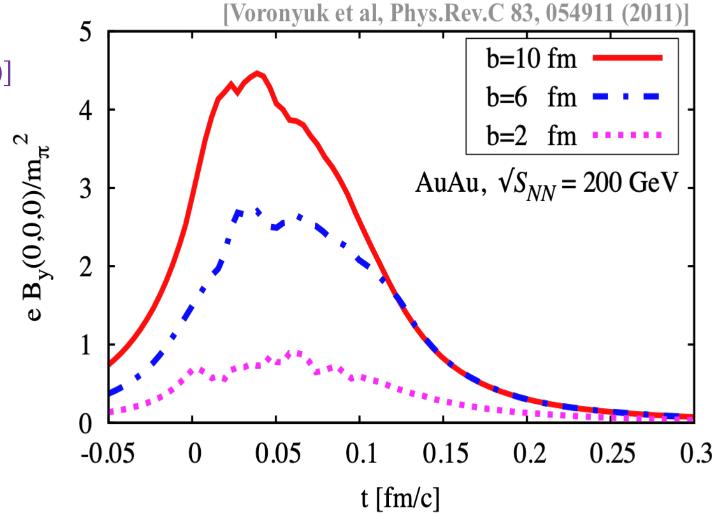
[Deng & Huang, Phys. Rev. C 85, 044907 (2012)]



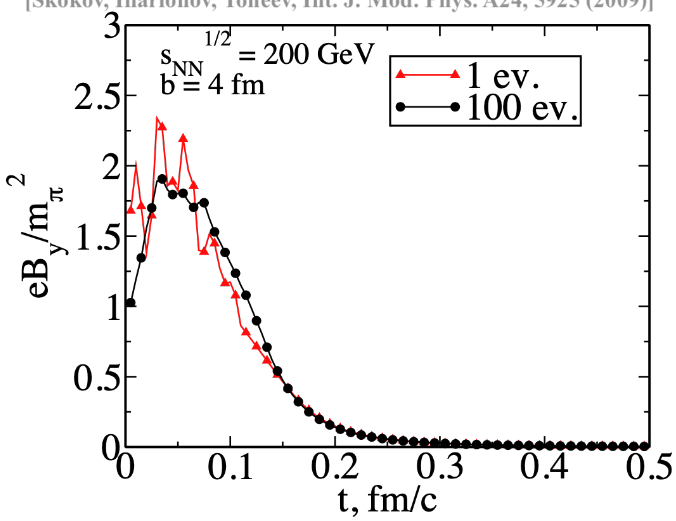
[Kharzeev & Liao, Nucl. Phys. News **29**, 1 (2019)]



[Voronyuk et al, Phys.Rev.C 83, 054911 (2011)]



[Skokov, Illarionov, Toneev, Int. J. Mod. Phys. A24, 5925 (2009)]

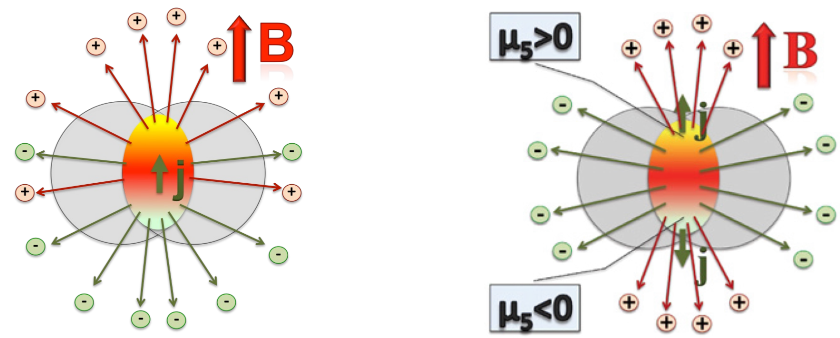


Anomalous effects in Heavy-Ion Collisions

[Miransky & Shovkovy, Phys. Rep. 576, 1 (2015)]
[Kharzeev, Liao, Voloshin, Wang, Prog. Part. Nucl. Phys. 88, 1 (2016)]

Chiral magnetic/separation effects, chiral magnetic waves

$$\langle \vec{j} \rangle = \frac{e\vec{B}}{2\pi^2}\mu_5 \quad \& \quad \langle \vec{j}_5 \rangle = \frac{e\vec{B}}{2\pi^2}\mu$$



Experiment difficulties:

Large background!

=>Isobar Experiment [STAR Collaboration, 2014]

$$^{96}_{40}\mathrm{Zr} + ^{96}_{40}\mathrm{Zr} \text{ vs. } ^{96}_{44}\mathrm{Ru} + ^{96}_{44}\mathrm{Ru}$$

$$^{130}_{52}\mathrm{Te} + ^{130}_{52}\mathrm{Te} \text{ vs. } ^{130}_{56}\mathrm{Ba} + ^{130}_{56}\mathrm{Ba}$$

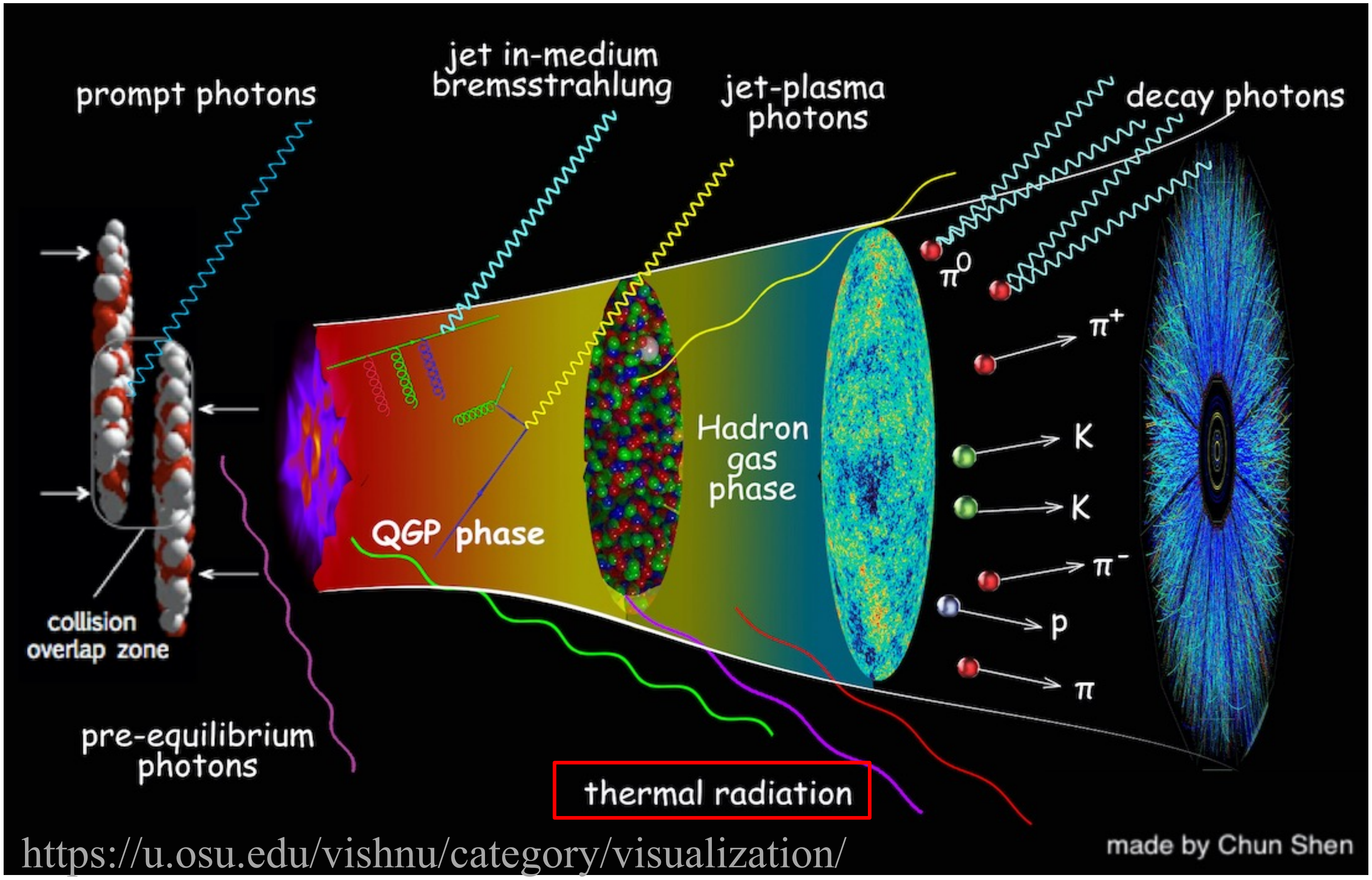
[Kharzeev&Liao, Nature Rev.Phys. 3 (2021) 1, 55-63]

Photons in heavy-ion collisions

- Photons is a Thermometer of QGP

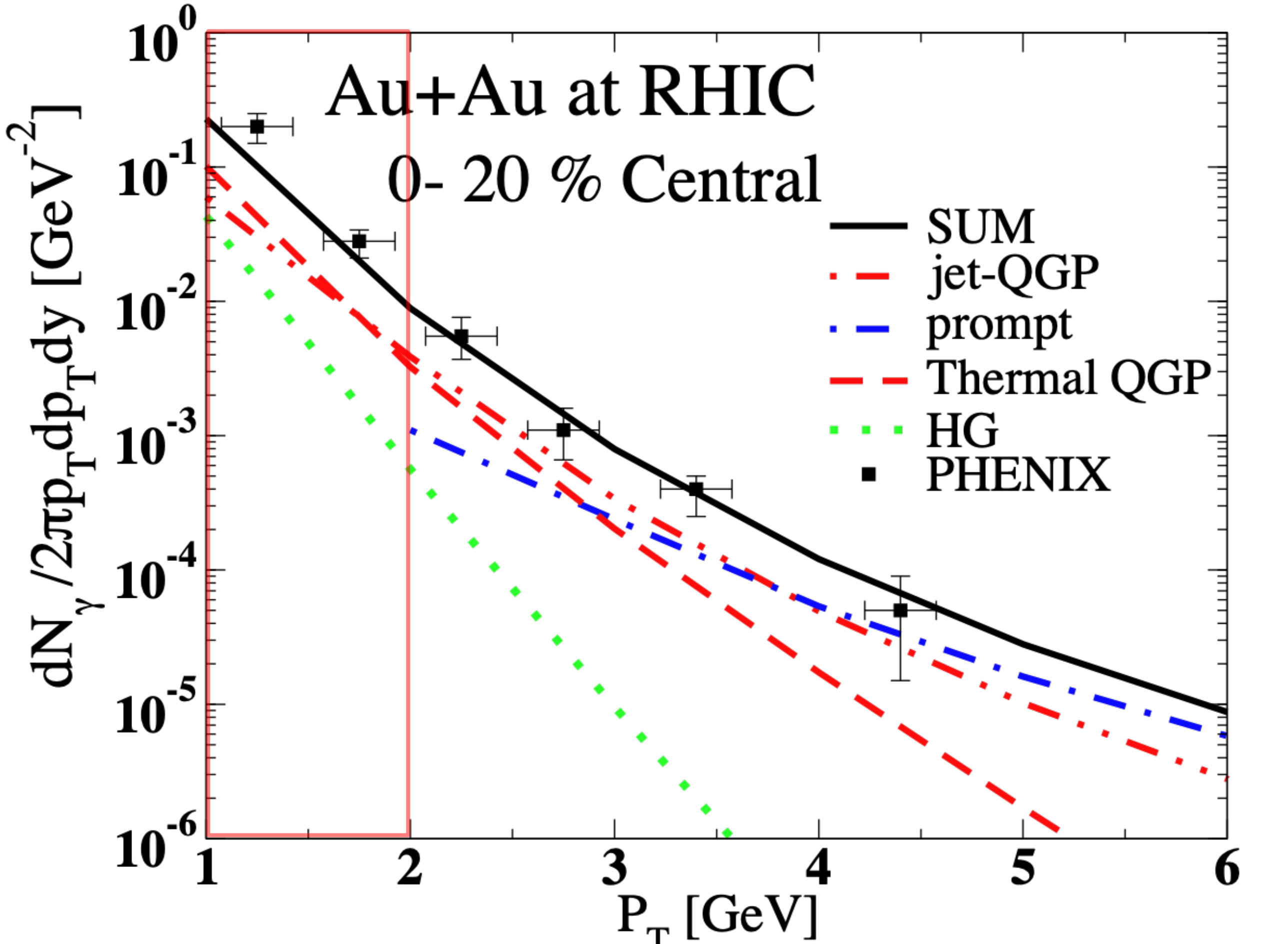
Review: [Gabor David, Rept. Prog. Phys. 83, 046301 (2020)]

- Photons are emitted at all stages of evolution



Photon sources in HIC

Turbide, Gale, Frodermann & Heinz, Phys. Rev. C77, 024909 (2008); arXiv:0712.0732



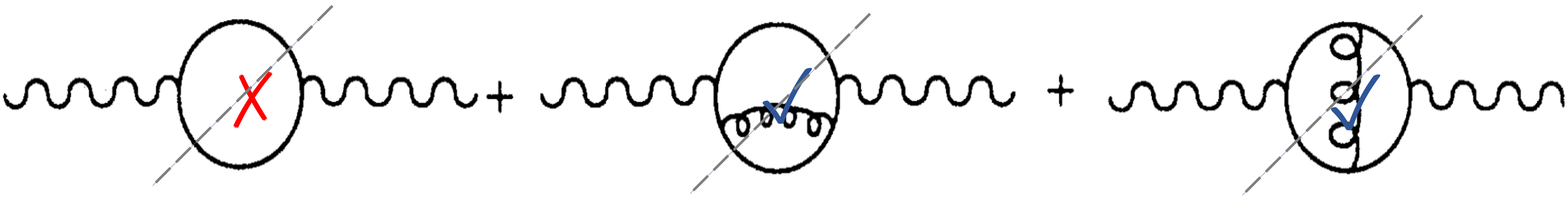
- $p_T \lesssim 2$ GeV: thermal emission dominates
- 2 GeV $\lesssim p_T \lesssim$ 4 GeV: the jet-plasma contribution dominates

Thermal photons

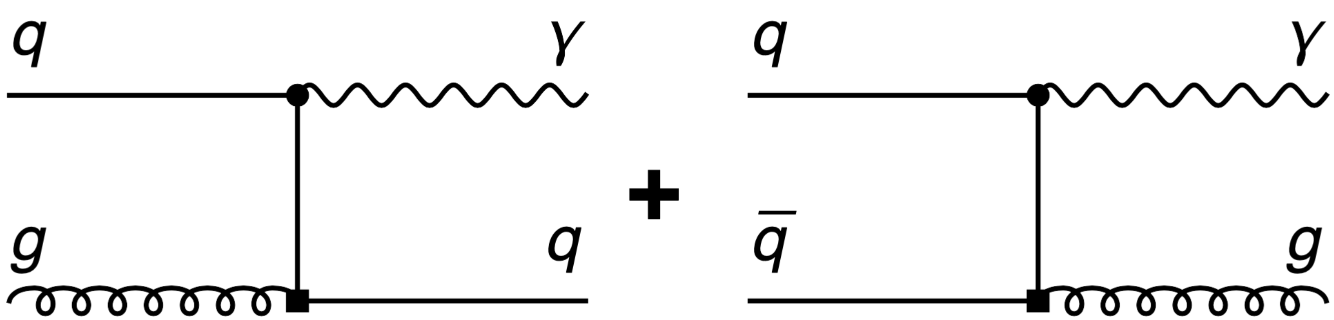
- The rate of the thermal emission of photons (the energy loss rate) is

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

- In the case of hot QCD plasma,



- Processes:

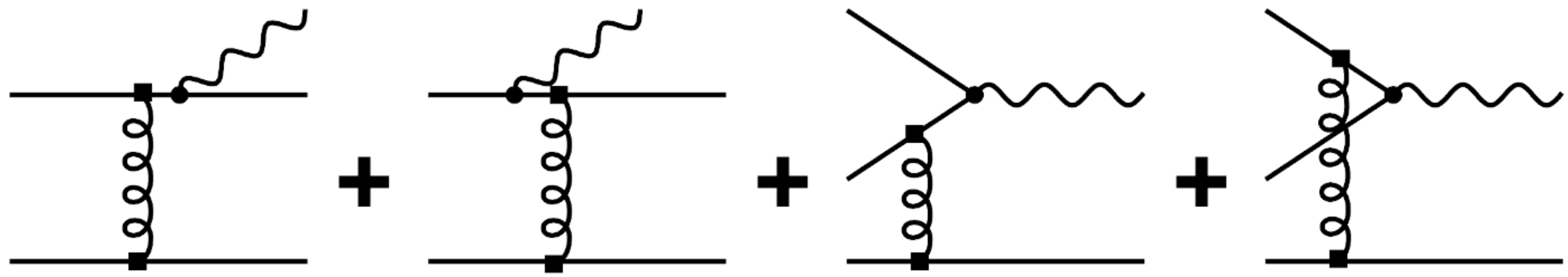


[Kapusta, Lichard, Seibert, Phys. Rev. D 44, 2774 (1991)]
[Baier, Nakkagawa, Niegawa, Redlich, Z. Physik C 53 (1992) 433]

- The approximate result is given by

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

- There are important corrections from bremsstrahlung and inelastic pair annihilation



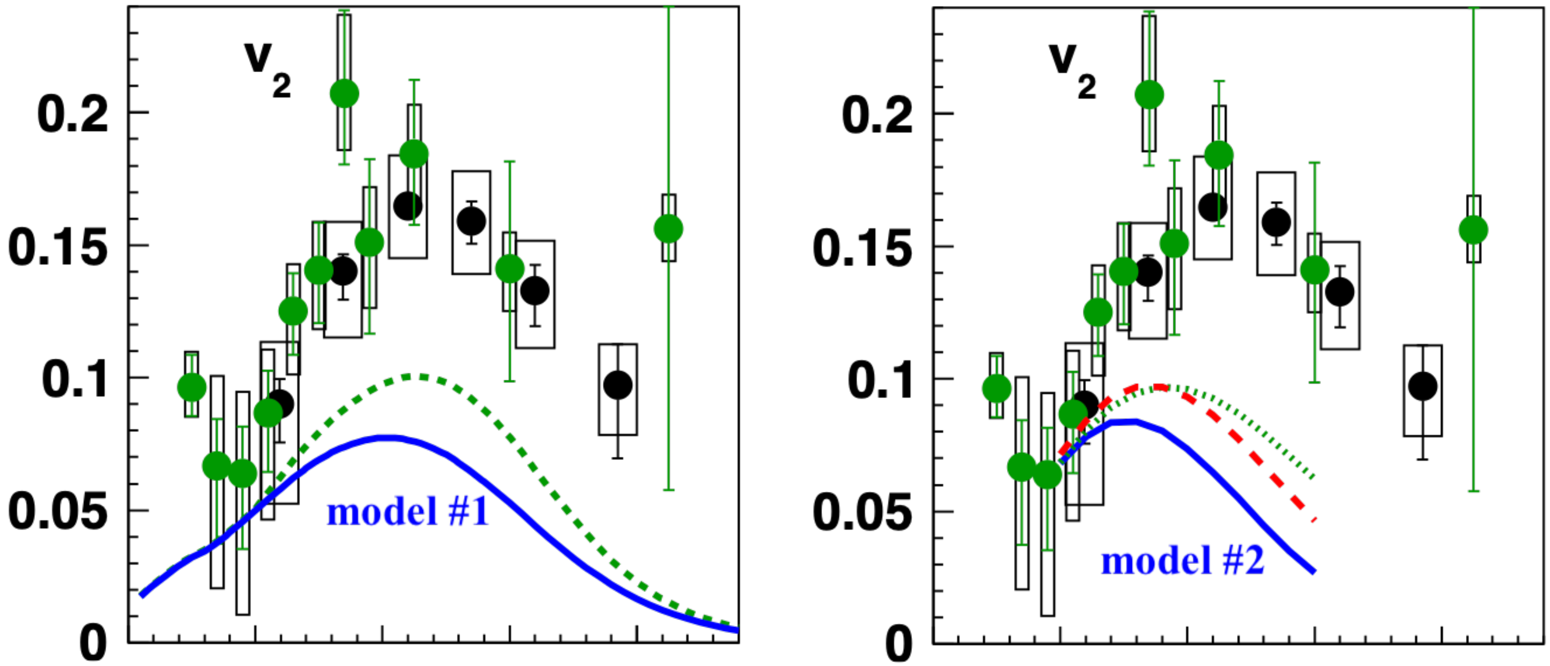
Corrections are ~ 100%

[Arnold, Moore,Yaffe, JHEP 12 (2001) 009]
[Ghiglieri et al., JHEP 05 (2013) 010]

Photon v_2 puzzle

$$E\frac{d^3N}{d^3\mathbf{p}} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \Psi_{RP})]\right)$$

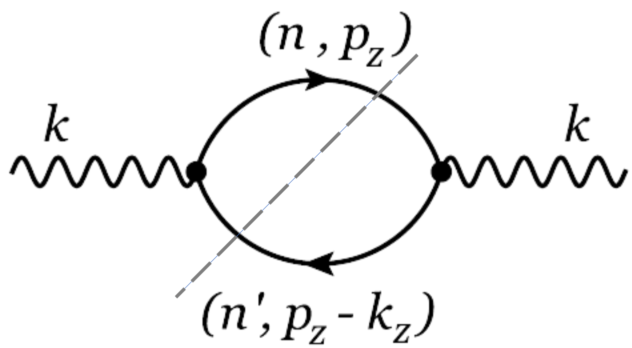
- Most photons are produced early (before flow develops)
- Thus, v_2 for photons should be very small



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

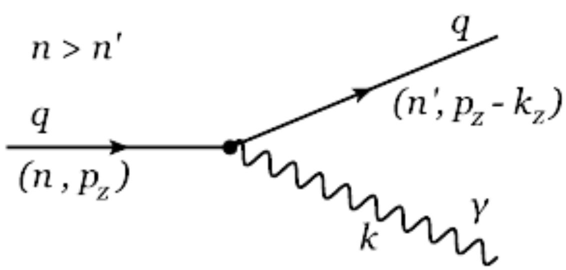
Photons from magnetized plasma

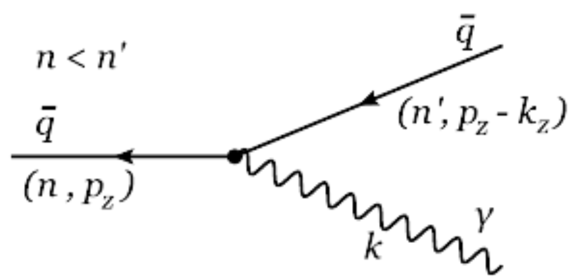
- At $\vec{B} \neq 0$, the leading-order polarization tensor

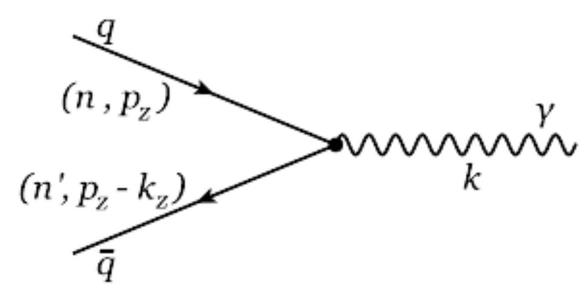


leads to a nonzero result!

- All three processes i.e.,







are allowed by the energy conservation.

Photon polarization tensor

Fermion propagator in a mixed coordinate-momentum space representation under a magnetic field:

$$G(t-t';\mathbf{r},\mathbf{r}') = e^{i\Phi(\mathbf{r}_\perp,\mathbf{r}'_\perp)}\bar{G}(t-t';\mathbf{r}-\mathbf{r}')$$

$$\bar{G}(t;\mathbf{r}) = \int \frac{d\omega dp_z}{(2\pi)^2} e^{-i\omega t + ip_z z}\bar{G}(\omega;p_z;\mathbf{r}_\perp)$$

$$\bar{G}(\omega,p_z;\mathbf{r}_\perp) = i\frac{e^{-\mathbf{r}_\perp^2/(4\ell^2)}}{2\pi\ell^2}\sum_{n=0}^{\infty}\frac{\tilde{D}_n(\omega,p_z;\mathbf{r}_\perp)}{\omega^2-p_z^2-m^2-2n|qB|}$$

$$\tilde{D}_n(\omega,p_z;\mathbf{r}_\perp) = (\omega\gamma^0 - p_z\gamma^3 + m)\left[\mathcal{P}_+ L_n\left(\frac{\mathbf{r}_\perp^2}{2\ell^2}\right) + \mathcal{P}_- L_{n-1}\left(\frac{\mathbf{r}_\perp^2}{2\ell^2}\right)\right] - \frac{i}{\ell^2}(\mathbf{r}_\perp\cdot\boldsymbol{\gamma}_\perp)L_{n-1}^1\left(\frac{\mathbf{r}_\perp^2}{2\ell^2}\right)$$

$$\mathcal{P}_\pm \equiv \frac{1}{2}\left(1 \pm is_\perp\gamma^1\gamma^2\right) \qquad \ell = 1/\sqrt{|qB|} \qquad s_\perp = \mathrm{sign}(qB)$$

[Phys. Rep. 576, 1 (2015)]]

The polarization tensor by using Fermion propagator in a mixed coordinate-momentum space representation :

$$\Pi^{\mu\nu}(i\Omega_m;\mathbf{k}) = 4\pi N_c \sum_{f=u,d} \alpha_f T \sum_{k=-\infty}^{\infty} \int \frac{dp_z}{2\pi} \int d^2\mathbf{r}_\perp e^{-i\mathbf{r}_\perp\cdot\mathbf{k}_\perp} \mathrm{tr}\left[\gamma^\mu \bar{G}_f(i\omega_k, p_z; \mathbf{r}_\perp)\gamma^\nu \bar{G}_f(i\omega_k - i\Omega_m, p_z - k_z; -\mathbf{r}_\perp)\right]$$

$$\Pi^{\mu\nu}(i\Omega_m;\mathbf{k}) = -\sum_{f=u,d} \frac{\alpha_f N_c}{\pi \ell_f^2} \sum_{n,n'=0}^{\infty} \int \frac{dp_z}{2\pi} \sum_{\lambda=\pm1} \frac{(E_{n,p_z} - \lambda E_{n',p_z-k_z,f})\left[n_F(E_{n,p_z,f}) - n_F(\lambda E_{n',p_z-k_z,f})\right]}{2\lambda E_{n,p_z,f} E_{n',p_z-k_z,f}\left[(E_{n,p_z,f} - \lambda E_{n',p_z-k_z,f})^2 + \Omega_m^2\right]} \sum_{i=1}^{4} I_{i,f}^{\mu\nu}$$

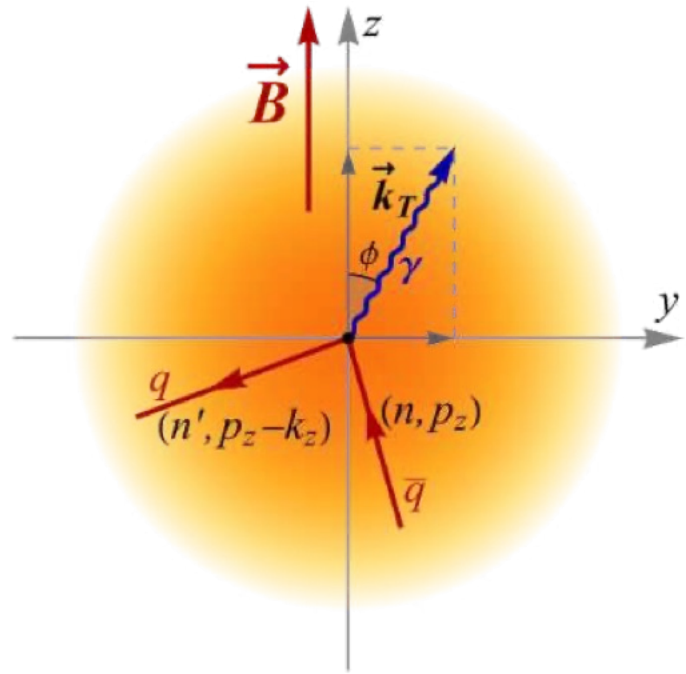
$$E_{n,p_z,f} = \sqrt{m^2 + p_z^2 + 2n|e_f B|} \qquad\qquad i\Omega_m \to \Omega + i\epsilon$$

$$\mathrm{Im}\left[\Pi_R^{\mu\nu}(\Omega;\mathbf{k})\right] = \sum_{f=u,d} \frac{\alpha_f N_c}{2\ell_f^4} \sum_{n,n'=0}^{\infty} \int \frac{dp_z}{2\pi} \sum_{\lambda,\eta=\pm1} \frac{n_F(E_{n,p_z,f}) - n_F(\lambda E_{n',p_z-k_z,f})}{2\eta\lambda E_{n,p_z,f} E_{n',p_z-k_z,f}} \sum_{i=1}^{4} I_{i,f}^{\mu\nu} \delta\left(E_{n,p_z,f} - \lambda E_{n',p_z-k_z,f} + \eta\Omega\right)$$

$$\begin{aligned}
\Pi_R^{\mu\nu}(\Omega;\mathbf{k}) &= \left(\frac{k_\parallel^\mu k_\parallel^\nu}{k_\parallel^2} - g_\parallel^{\mu\nu}\right)\Pi_1 + \left(g_\perp^{\mu\nu} + \frac{k_\perp^\mu k_\perp^\nu}{k_\perp^2}\right)\Pi_2 + \frac{\tilde{k}_\parallel^\mu \tilde{k}_\parallel^\nu}{k_\parallel^2}\Pi_3 \\
&+ \left(\frac{k_\parallel^\mu \tilde{k}_\parallel^\nu + \tilde{k}_\parallel^\mu k_\parallel^\nu}{k_\parallel^2} + \frac{\tilde{k}_\parallel^\mu k_\perp^\nu + k_\perp^\mu \tilde{k}_\parallel^\nu}{k_\perp^2}\right)\Pi_4 + \left(\frac{k_\parallel^\mu k_\perp^\nu + k_\perp^\mu k_\parallel^\nu}{k_\parallel^2} + \frac{k_\perp^2}{k_\parallel^2} g_\parallel^{\mu\nu} - g_\perp^{\mu\nu}\right)\Pi_5 \\
&+ \left(\frac{F^{\mu\nu}}{B} + \frac{k_\parallel^\mu \tilde{k}_\perp^\nu - \tilde{k}_\perp^\mu k_\parallel^\nu}{k_\parallel^2}\right)\tilde{\Pi}_6 + \frac{\tilde{k}_\parallel^\mu \tilde{k}_\perp^\nu - \tilde{k}_\perp^\mu \tilde{k}_\parallel^\nu}{k_\parallel^2}\tilde{\Pi}_7,
\end{aligned}$$

$$\begin{aligned}
g_\parallel^{\mu\nu} &= \mathrm{diag}(1,0,0,-1), & k_\parallel^\mu &= g_\parallel^{\mu\nu} k_\nu = k_0\delta_0^\mu + k_z\delta_3^\mu, & \tilde{k}_\parallel^\mu &= -\varepsilon^{\mu 12\nu} k_\nu = k_z\delta_0^\mu + k_0\delta_3^\mu, \\
g_\perp^{\mu\nu} &= \mathrm{diag}(0,-1,-1,0), & k_\perp^\mu &= g_\perp^{\mu\nu} k_\nu = k_x\delta_1^\mu + k_y\delta_2^\mu, & \tilde{k}_\perp^\mu &= \varepsilon^{0\mu\nu 3} k_\nu = k_y\delta_1^\mu - k_x\delta_2^\mu.
\end{aligned}$$

Photon thermal rate



- 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 is

$$\mathrm{Im}\left[\Pi^\mu_{R,\mu}(\Omega;\mathbf{k})\right] = \sum_{f=u,d} \frac{N_c \alpha_f}{2 l_f^4} \sum_{n,n'=0}^{\infty} \int \frac{dp_z}{2\pi} \sum_{\lambda,\eta=\pm 1} \frac{n_F(E_{n,p_z,f}) - n_F(\lambda E_{n',p_z-k_z,f})}{2\eta\lambda E_{n,p_z,f} E_{n',p_z-k_z,f}} \sum_{i=1}^{4} \mathcal{F}_i^f \times \boxed{\delta\left(E_{n,p_z,f} - \lambda E_{n',p_z-k_z,f} + \eta\Omega\right)}.$$

where the Landau level energies are

$$E_{n,p_z,f} = \sqrt{m^2 + p_z^2 + 2n|e_f B|}$$

Photon thermal rate

- After integrating over p_z, the final expression reads

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

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

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

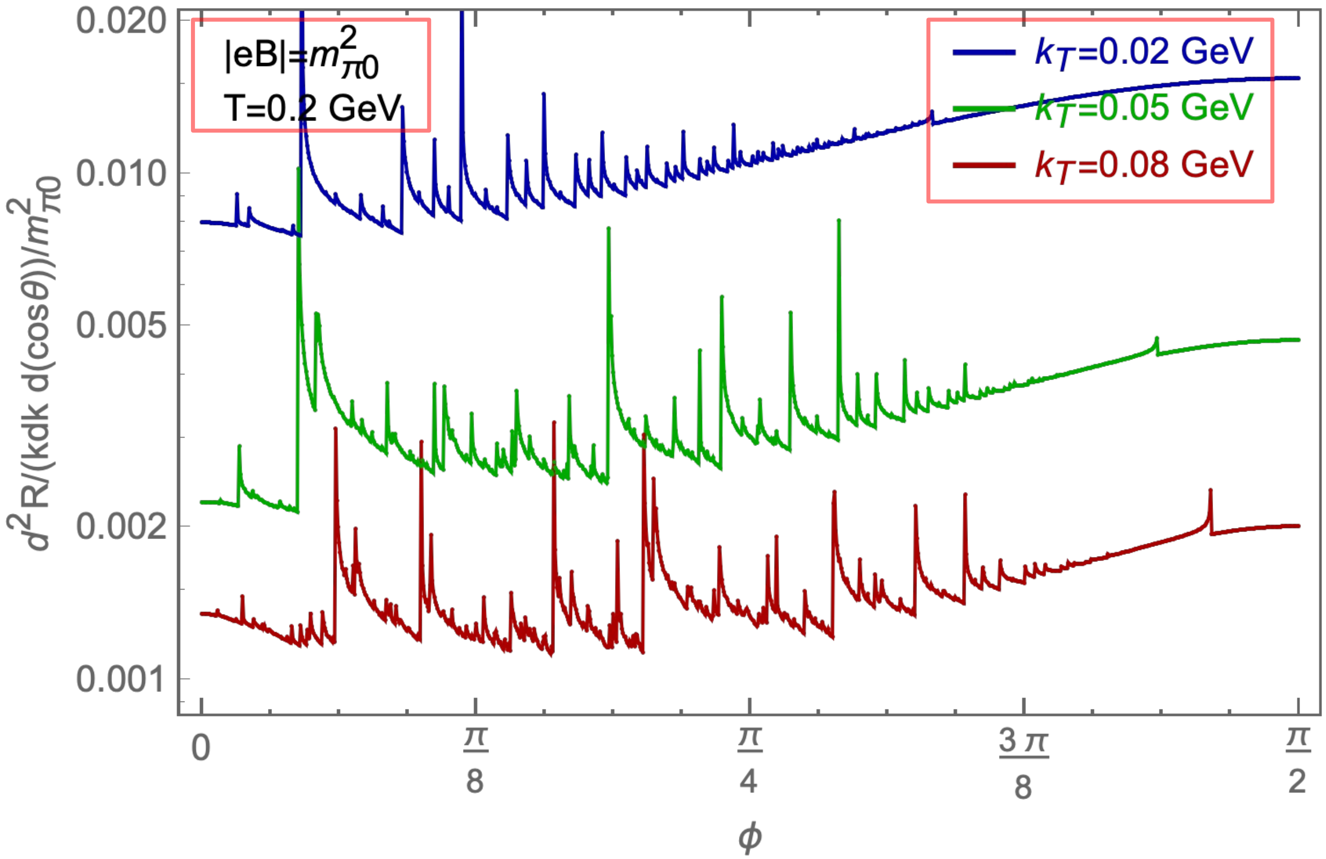
The momentum thresholds are determined by

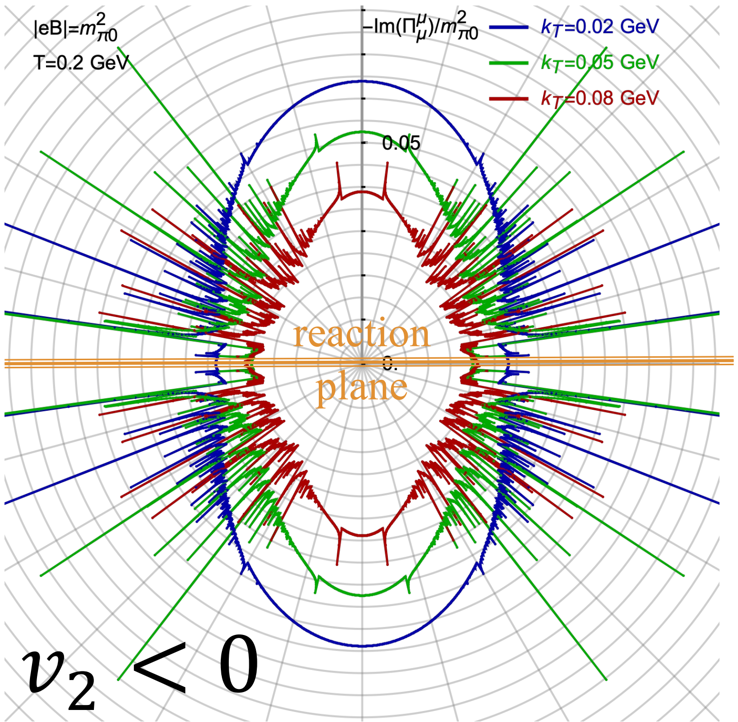
$$k_\pm^f = \left|\sqrt{m^2 + 2n|e_f B|} \pm \sqrt{m^2 + 2n'|e_f B|}\right|$$

[Phys.Rev.D 102 (2020) 7, 076010]

Angular dependence: small k_T

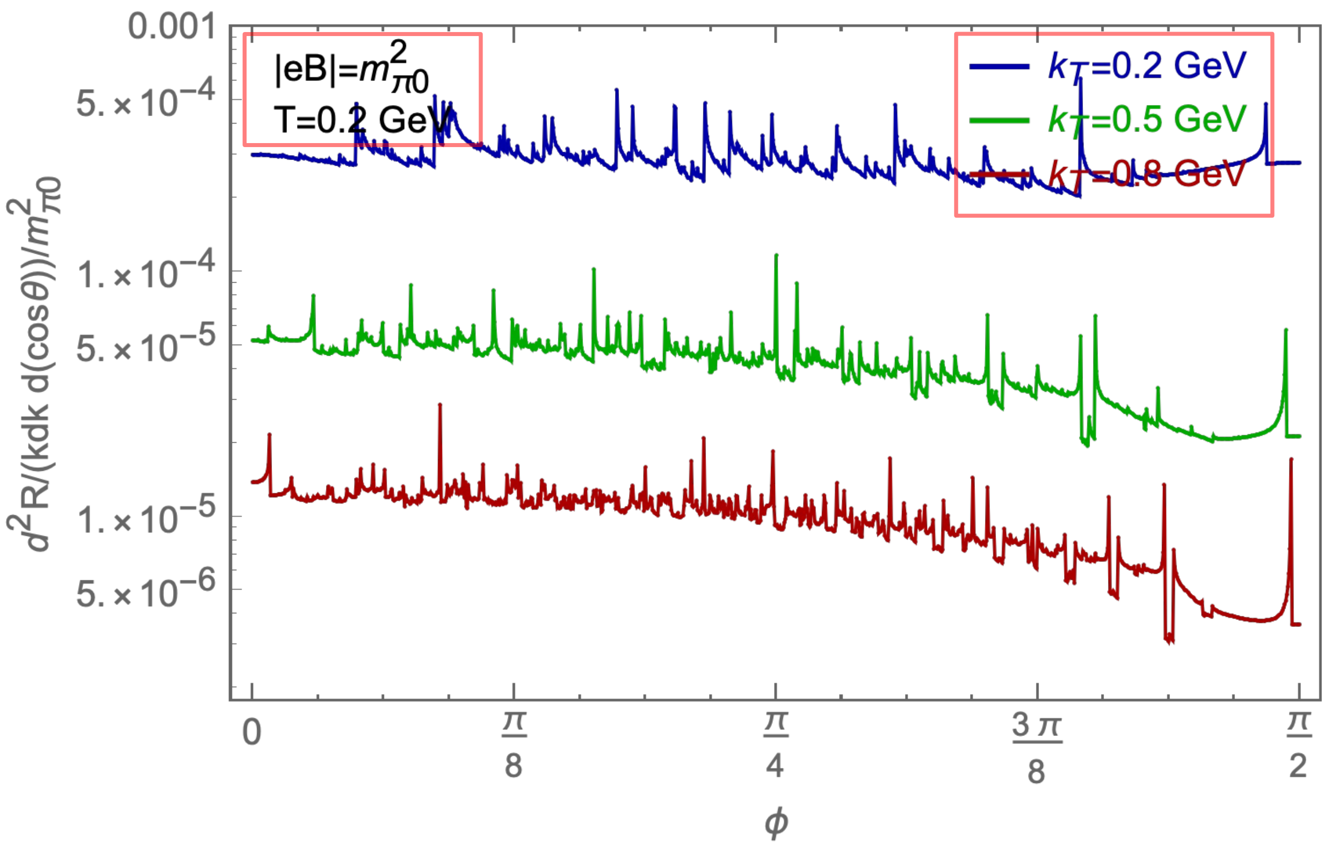
- Non-smooth dependence on ϕ (due to many thresholds)
  Parametrization: $k_x = 0$, $k_y = k_T \cos\phi$ and $k_z = k_T \sin\phi$
- Average rate is maximal at $\phi = \frac{\pi}{2}$ (i.e., $\perp$ to the reaction plane)

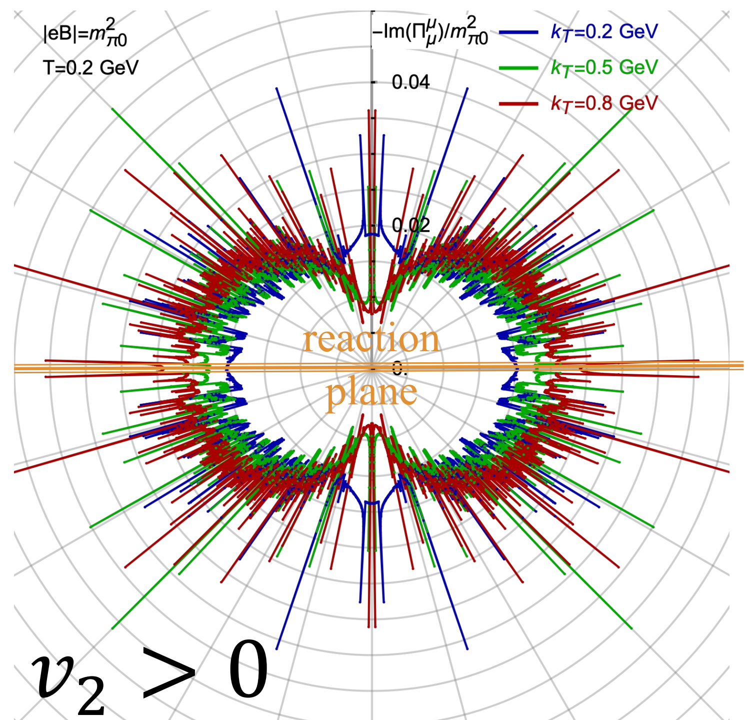




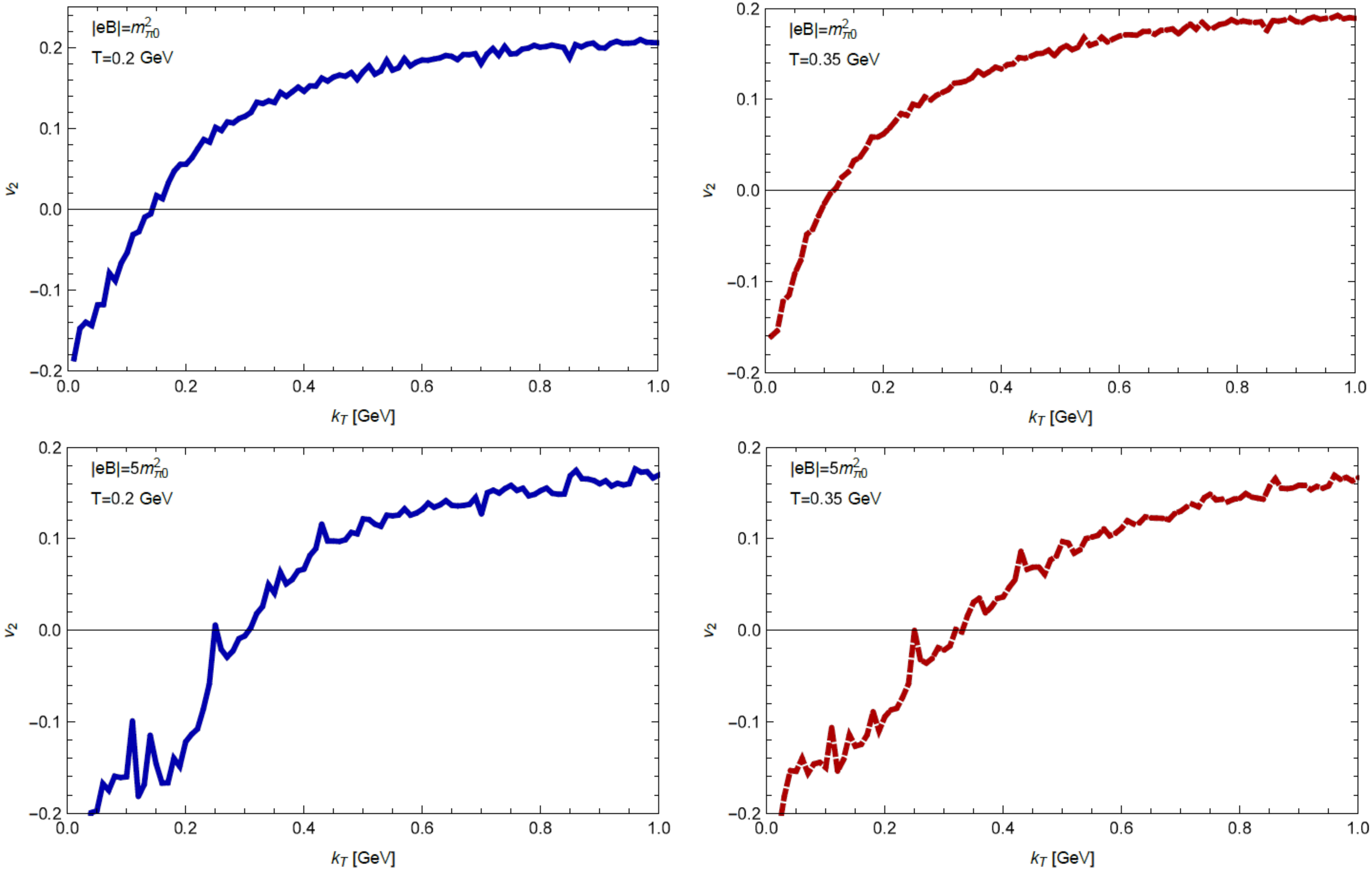
Angular dependence: large k_T

- Rate quickly decreases with k_T
- Average rate is maximal at $\phi = 0$ (i.e., ∥ to the reaction plane)



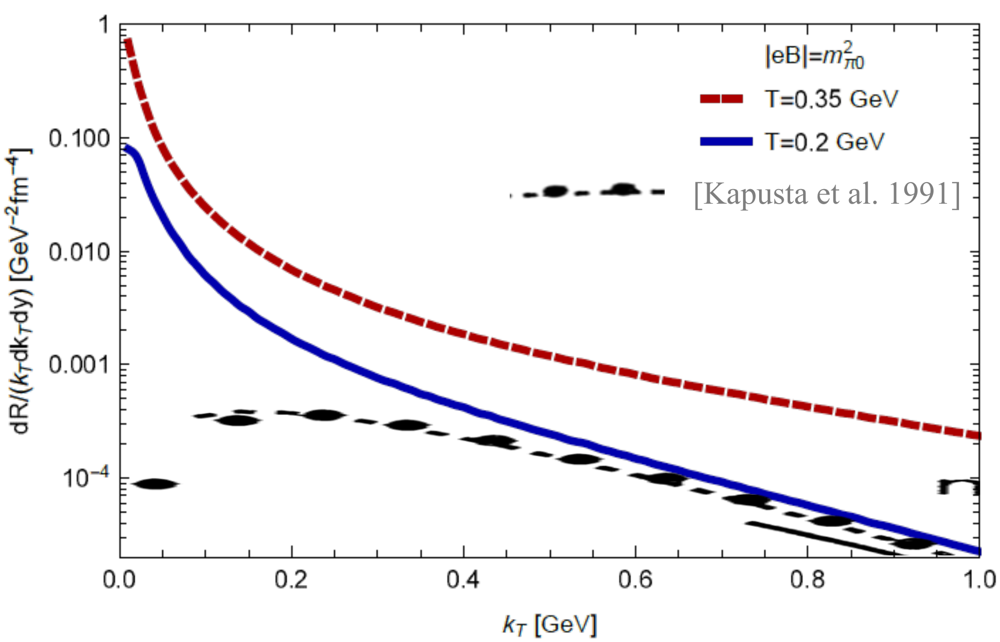


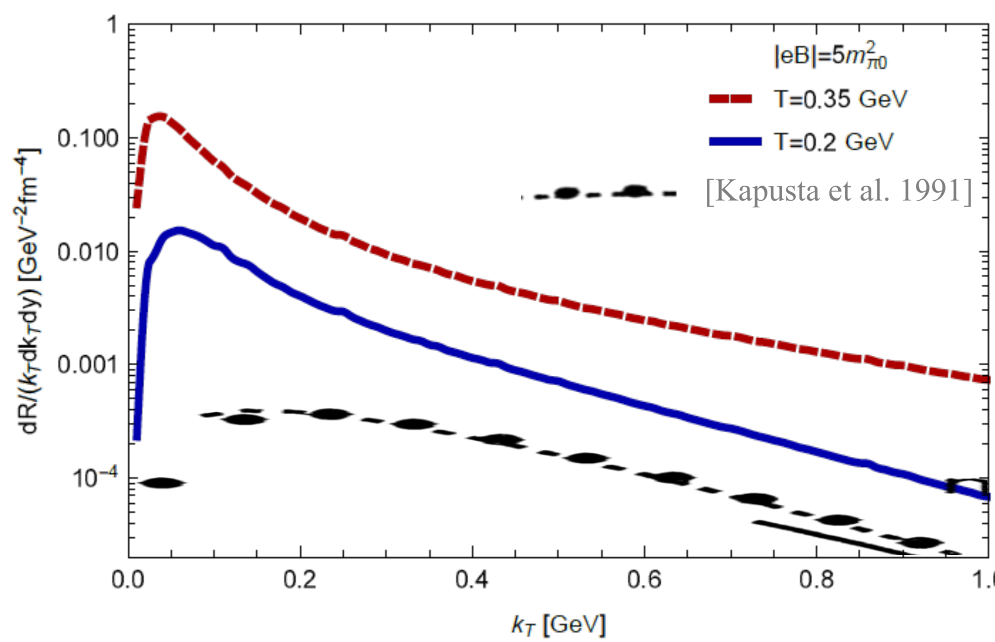
Nonzero elliptic "flow" (v_2)



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)
  - and, thus, has a peak at small nonzero k_T
- The thermal rate at $\vec{B} \neq 0$ is relatively large

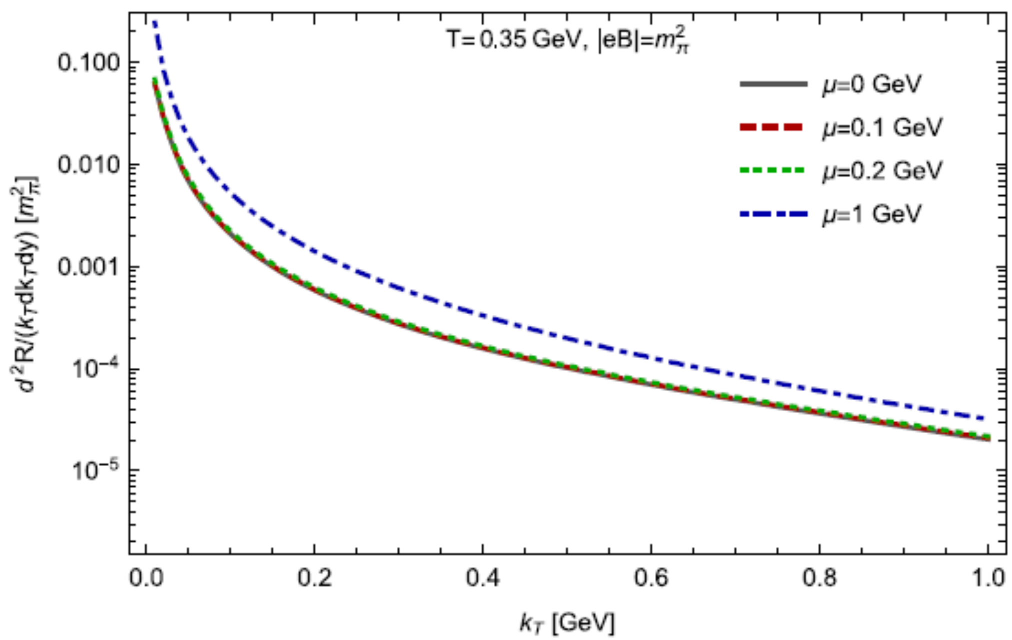


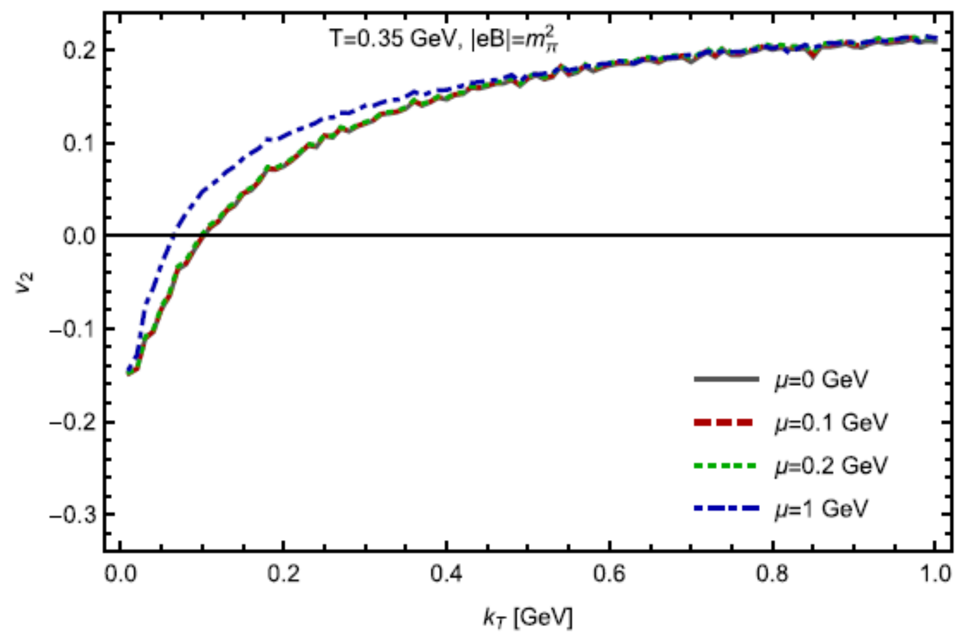


Finite Chemical potential

$$\bar{G}_f(\omega, p_z; \mathbf{r}_\perp) = i\frac{e^{-\mathbf{r}_\perp^2/(4\ell_f^2)}}{2\pi l_f^2}\sum_{n=0}^{\infty}\frac{\tilde{D}_n^f(\omega, p_z; \mathbf{r}_\perp)}{(\omega+\mu)^2 - p_z^2 - m^2 - 2n|e_f B|}$$

$$\tilde{D}_n^f(\omega, p_z; \mathbf{r}_\perp) = \left[(\omega+\mu)\gamma^0 - p^3\gamma^3 + m\right]\left[\mathcal{P}_+^f L_n\left(\frac{\mathbf{r}_\perp^2}{2\ell_f^2}\right) + \mathcal{P}_-^f L_{n-1}\left(\frac{\mathbf{r}_\perp^2}{2\ell_f^2}\right)\right] - \frac{i}{l_f^2}(\mathbf{r}_\perp \cdot \boldsymbol{\gamma}_\perp) L_{n-1}^1\left(\frac{\mathbf{r}_\perp^2}{2l_f^2}\right)$$





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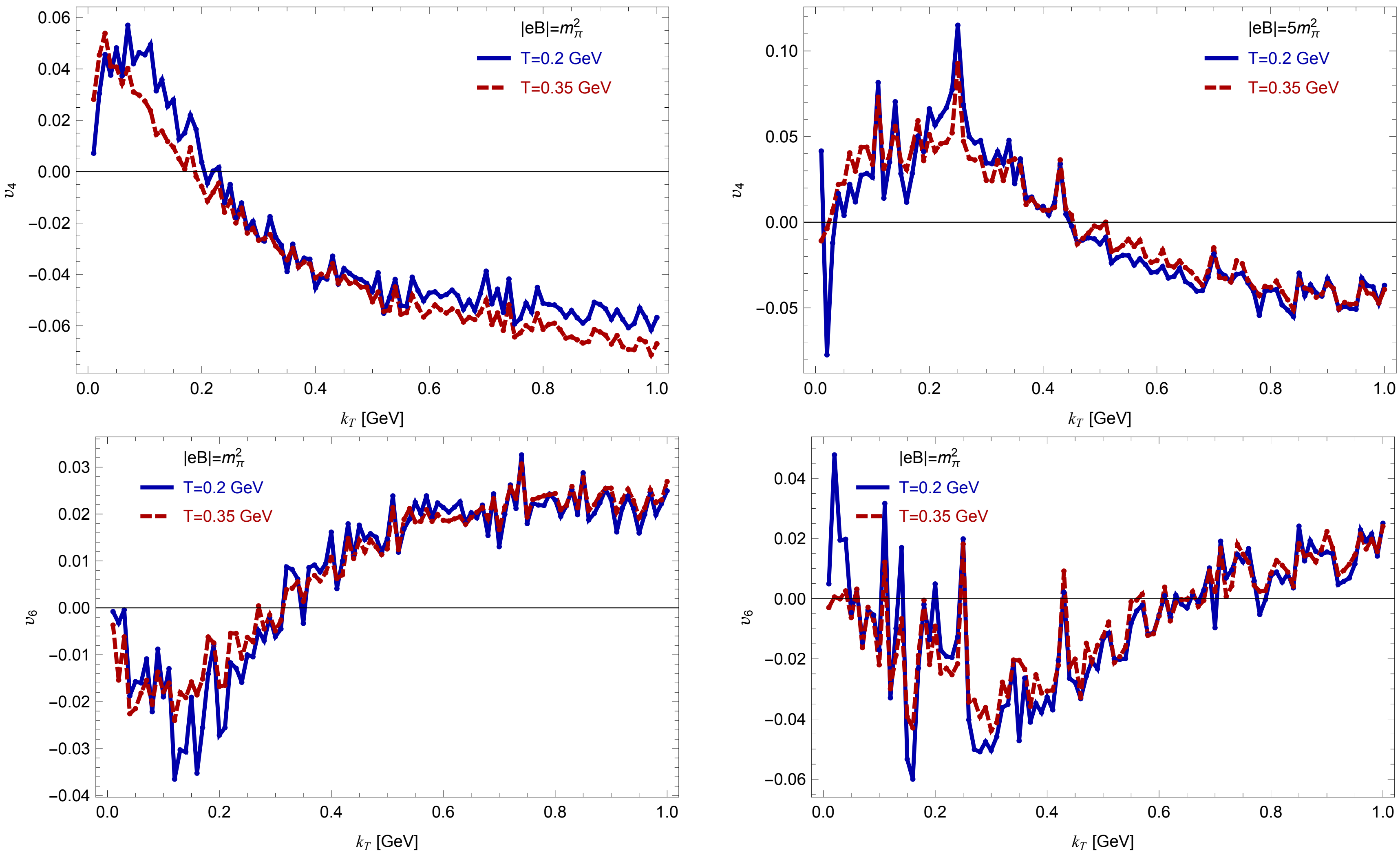
Photon v_4 and v_6



[Phys.Rev.D 109 (2024) 5, 056008]

Thank you!