ARIZONA STATE UNIVERSITY

SHARIF U. OF TECHNOLOGY
Aug 18, 2020
REMOTE SEMINAR

Direct photons from magnetized quark-gluon plasma

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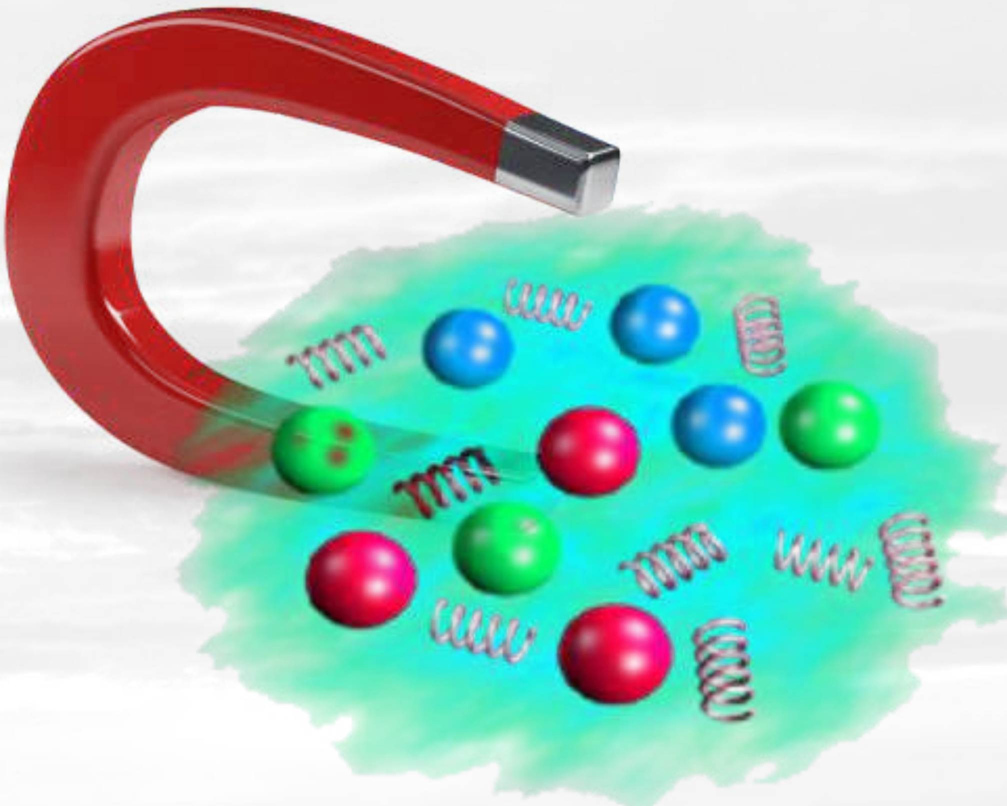
[V. Miransky, I. Shovkovy, Phys. Rep. 576, 1 (2015)]

[X. Wang, I. Shovkovy, L. Yu, M. Huang, arXiv:2006.16254]

[X. Wang, I. Shovkovy, in preparation]

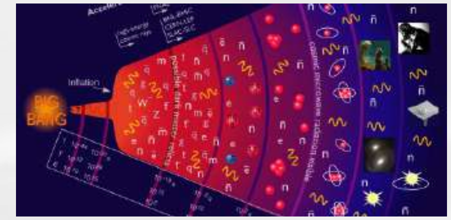


MAGNETIZED RELATIVISTIC PLASMA

Magnetized plasmas

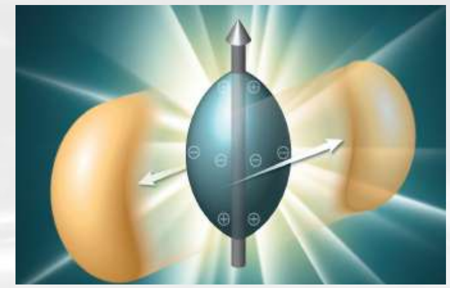
- **Early Universe**

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



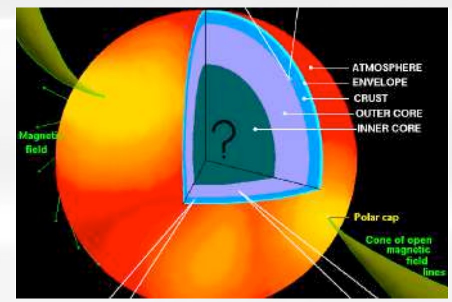
- **Heavy-ion collisions** (this talk)

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



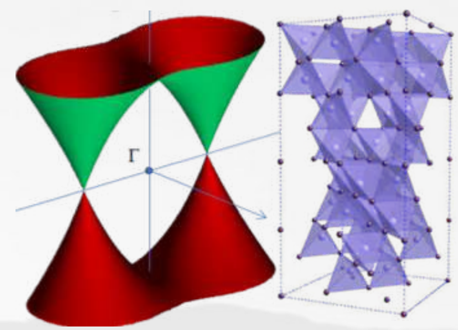
- **Super-dense matter in magnetars**

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



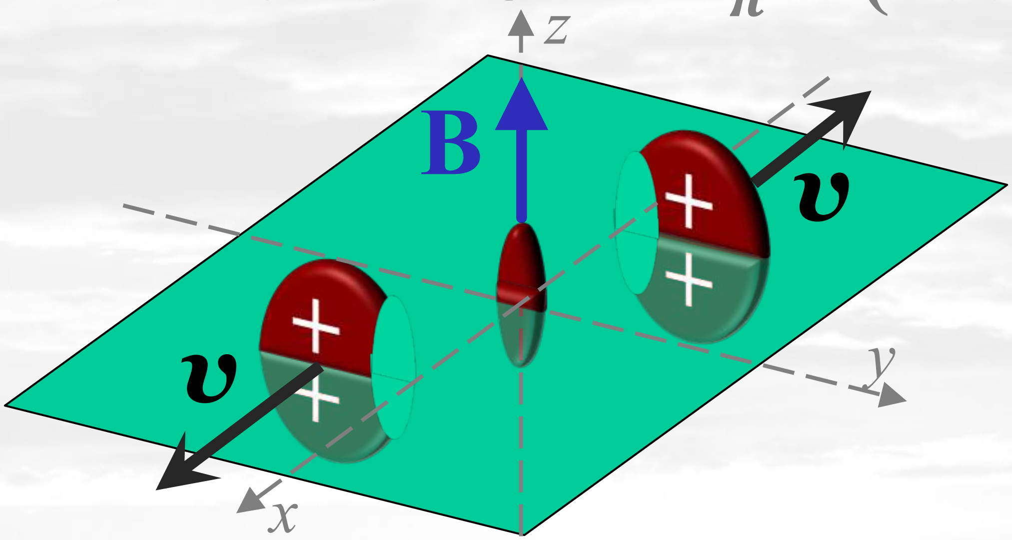
- **Electrons in Dirac/Weyl (semi-)metals**

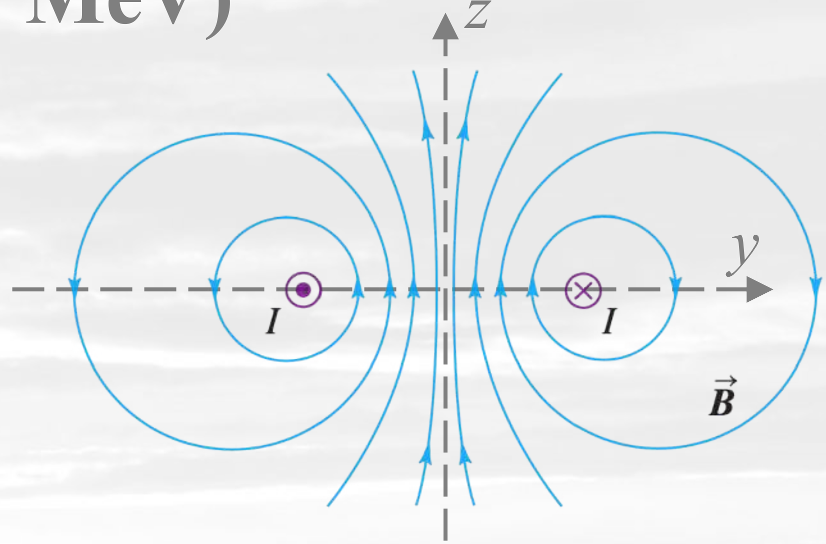
  $\lesssim 10^5$ G ~ (100 meV)^2



Heavy-ion collisions

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





- Using Lienard-Wiechert potential, one finds

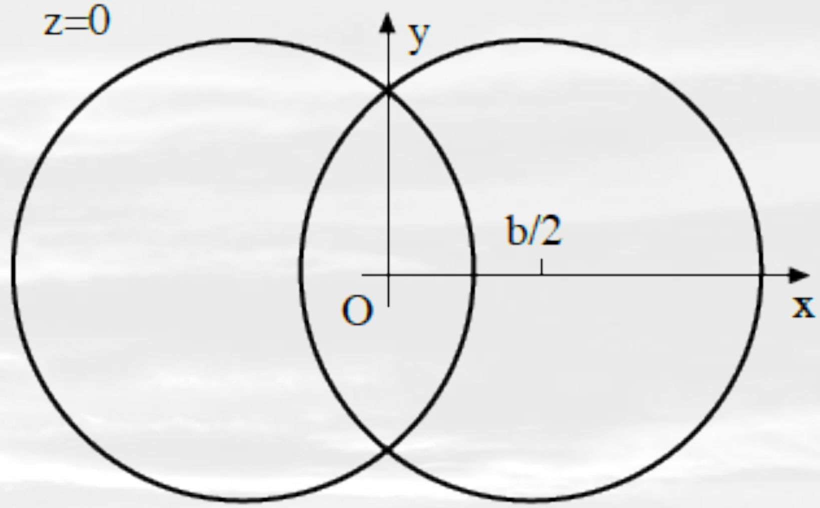
$$e\mathbf{E}(t,\mathbf{x}) = \alpha_{EM} \sum_{n\in\text{protons}} \frac{1-v_n^2}{R_n^3\left(1-[\mathbf{R}_n\times\mathbf{v}_n]^2/R_n^2\right)^{3/2}}\mathbf{R}_n$$

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

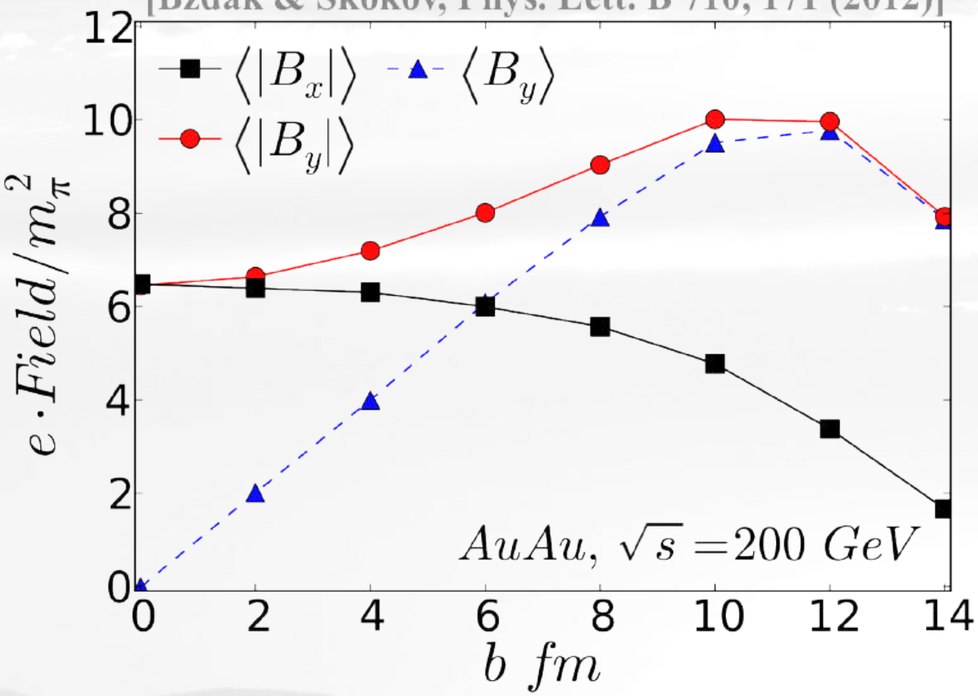
[Rafelski & Müller, PRL, 36, 517 (1976)]
[Kharzeev et al., arXiv:0711.0950]
[Skokov et al., arXiv:0907.1396]
[Voronyuk et al., arXiv:1103.4239]
[Bzdak &. Skokov, arXiv:1111.1949]
[Deng & Huang, arXiv:1201.5108]
[Bloczynski et al, arXiv:1209.6594]
…

Magnetic field in HIC

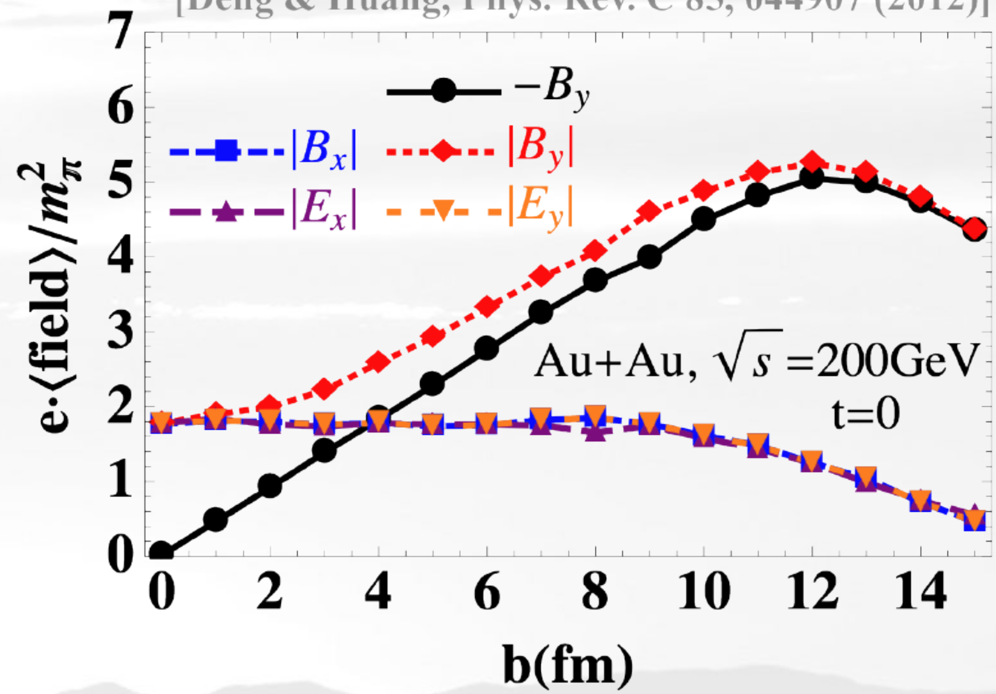
- Magnetic field
  - strong in magnitude $\sim m_\pi^2$
  - depends strongly on b
  - nonuniform
  - fluctuates from event to event



[Bzdak & Skokov, Phys. Lett. B 710, 171 (2012)]



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

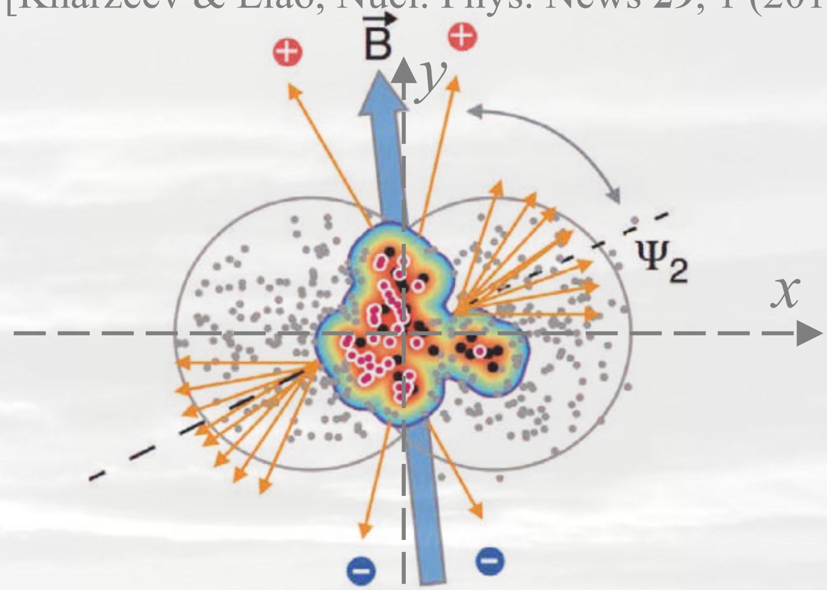


Time dependence

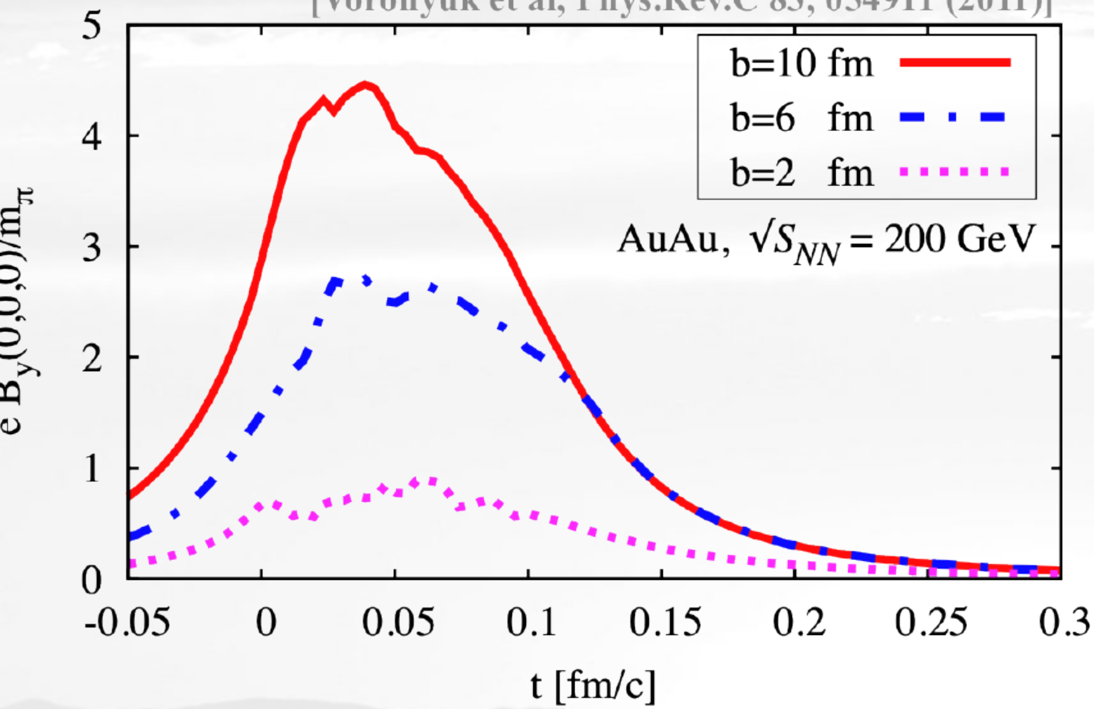
- Magnetic field
  - not always ⊥ to reaction plane
  - short-lived (≪ 1 fm/c)
  - conductivity may help a little

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

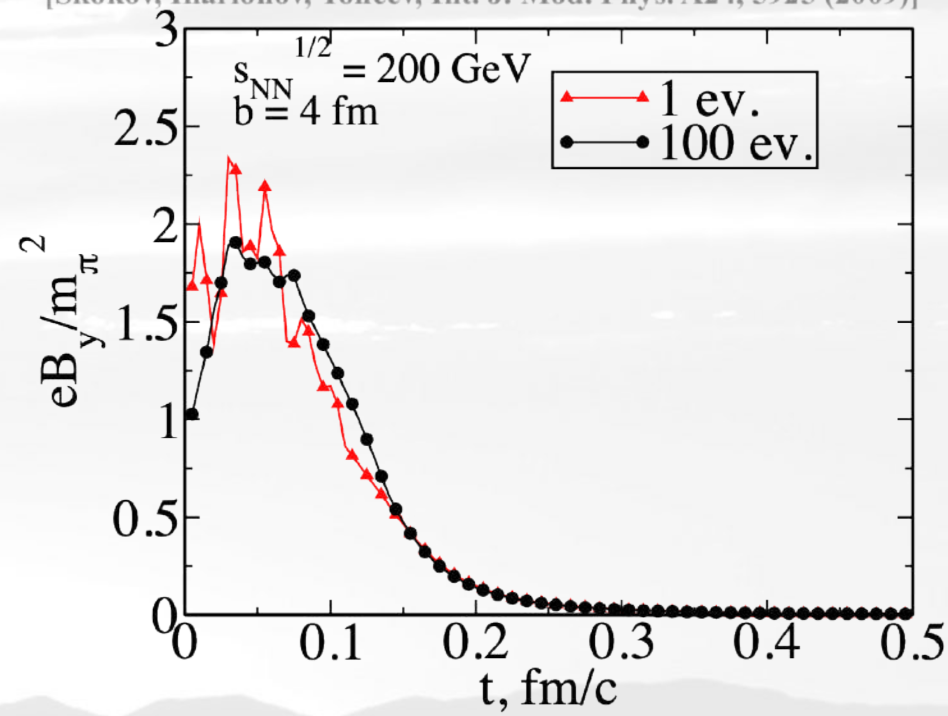
[Kharzeev & Liao, Nucl. Phys. News **29**, 1 (2019)]

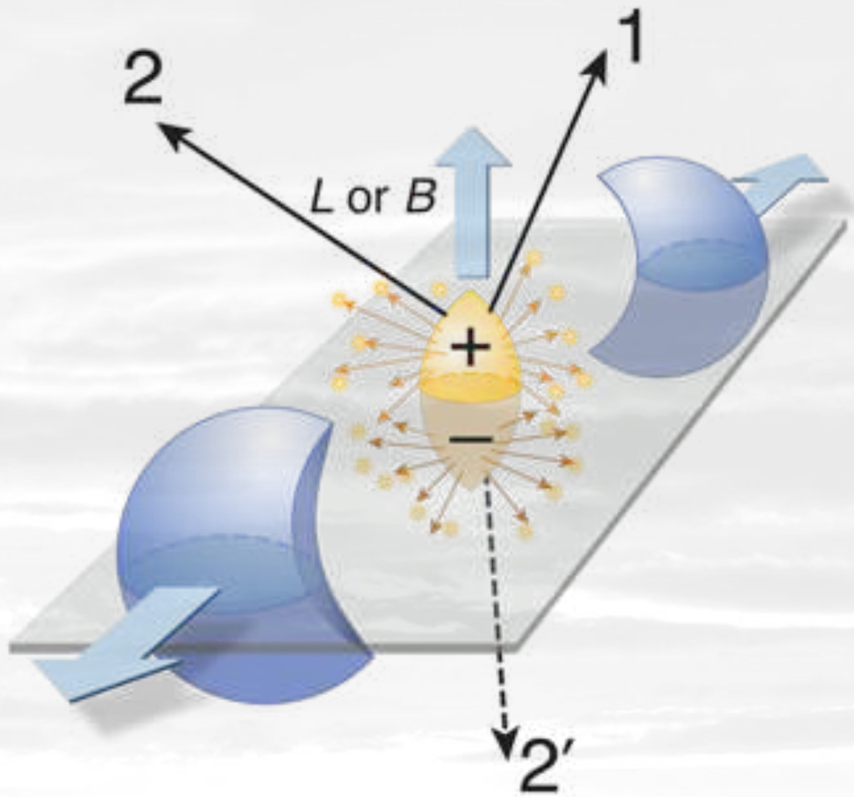


[Voronyuk et al, Phys.Rev.C 83, 054911 (2011)]



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





https://physics.aps.org/articles/v2/104

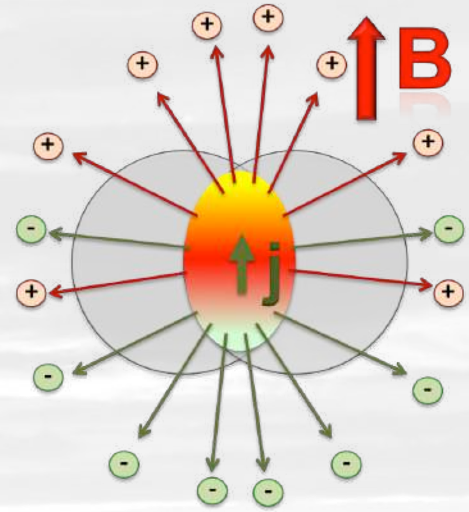
ANOMALOUS EFFECTS IN HEAVY-ION COLLISIONS

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

CME, CSE, CMW, etc.

- Chiral magnetic/separation effects, chiral magnetic waves

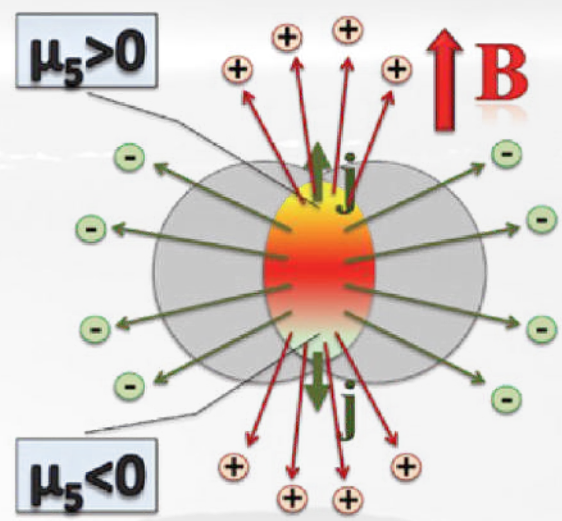
$$\left\langle \vec{j} \right\rangle = \frac{e\vec{B}}{2\pi^2}\mu_5 \quad \& \quad \left\langle \vec{j}_5 \right\rangle = \frac{e\vec{B}}{2\pi^2}\mu$$



- Signs of local P-violation?

$$\frac{d(N_R - N_L)}{dt} = -\frac{g^2 N_f}{16\pi^2}\int d^3x\, F_a^{\mu\nu}\tilde{F}_{\mu\nu}^a$$

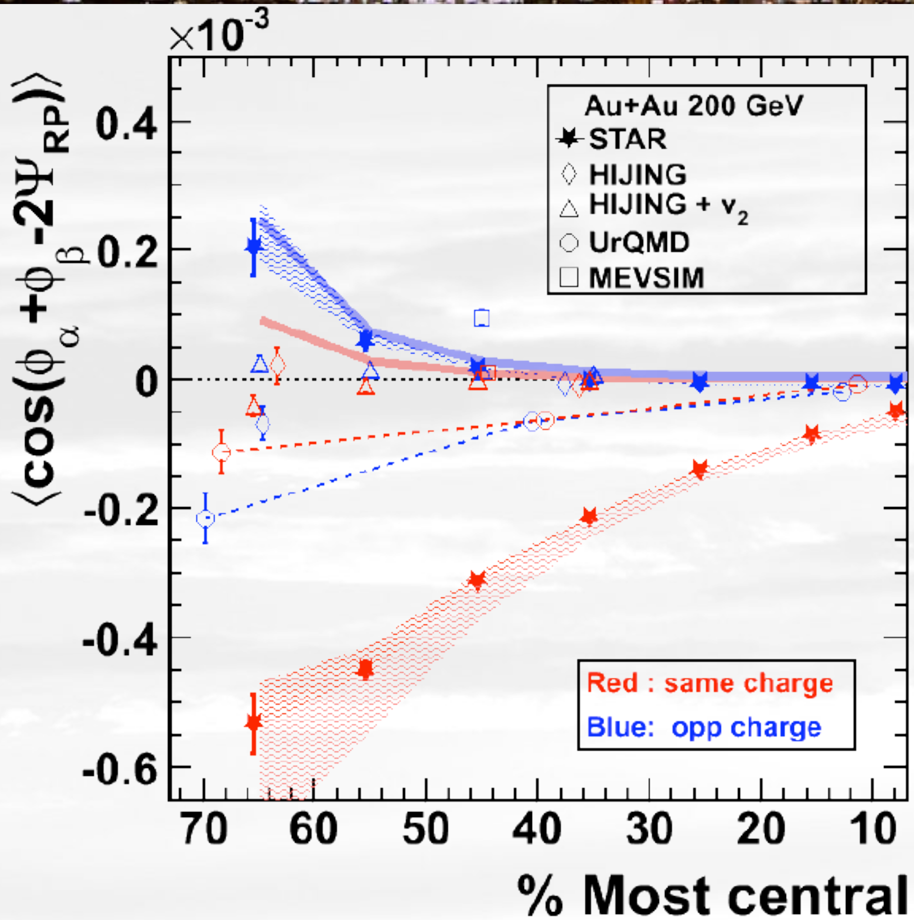
[Kharzeev, McLerran, Warringa, Nucl. Phys. A **803**, 227 (2008)]
[Fukushima, Kharzeev, Warringa, Phys. Rev. D **78**, 074033 (2008)]
[Kharzeev, Liao, Voloshin, Wang, Prog. Part. Nucl. Phys. 88, 1 (2016)]

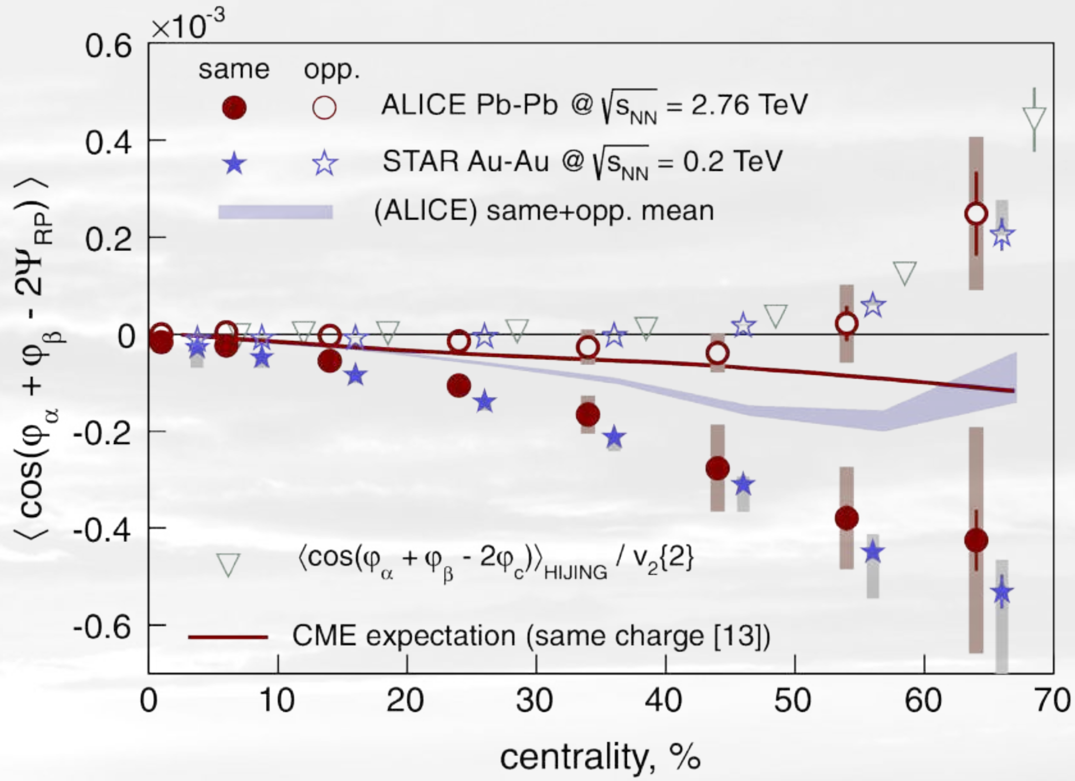


- Signs of chiral magnetic wave?

[Yee, Kharzeev, Phys. Rev. D **83**, 085007 (2011)]
[Gorbar, Miransky, Shovkovy, Phys. Rev. D **83**, 085003 (2011)]
[Burnier, Kharzeev, Liao, Yee, Phys. Rev. Lett. **107** (2011) 052303]
[Shovkovy, Rybalka, Gorbar, arXiv: 1811.10635]

CME: Experimental evidence





Correlations of same & opposite charge particles:

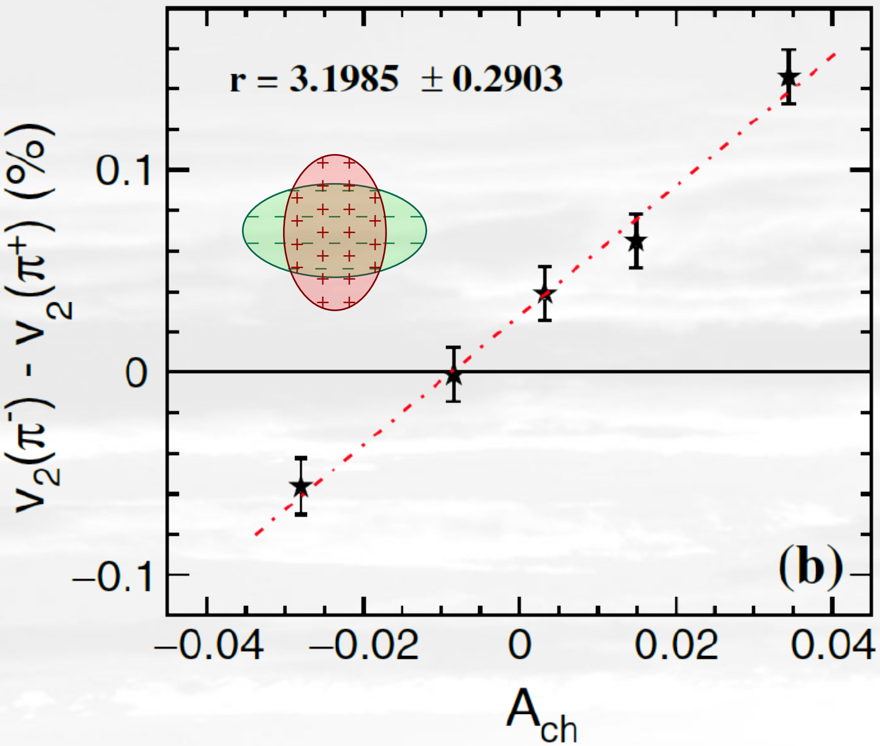
$$\begin{cases} \langle \cos(\varphi_\alpha^{\pm} + \varphi_\beta^{\mp} - 2\Psi_{RP}) \rangle \\ \langle \cos(\varphi_\alpha^{\pm} + \varphi_\beta^{\pm} - 2\Psi_{RP}) \rangle \end{cases}$$

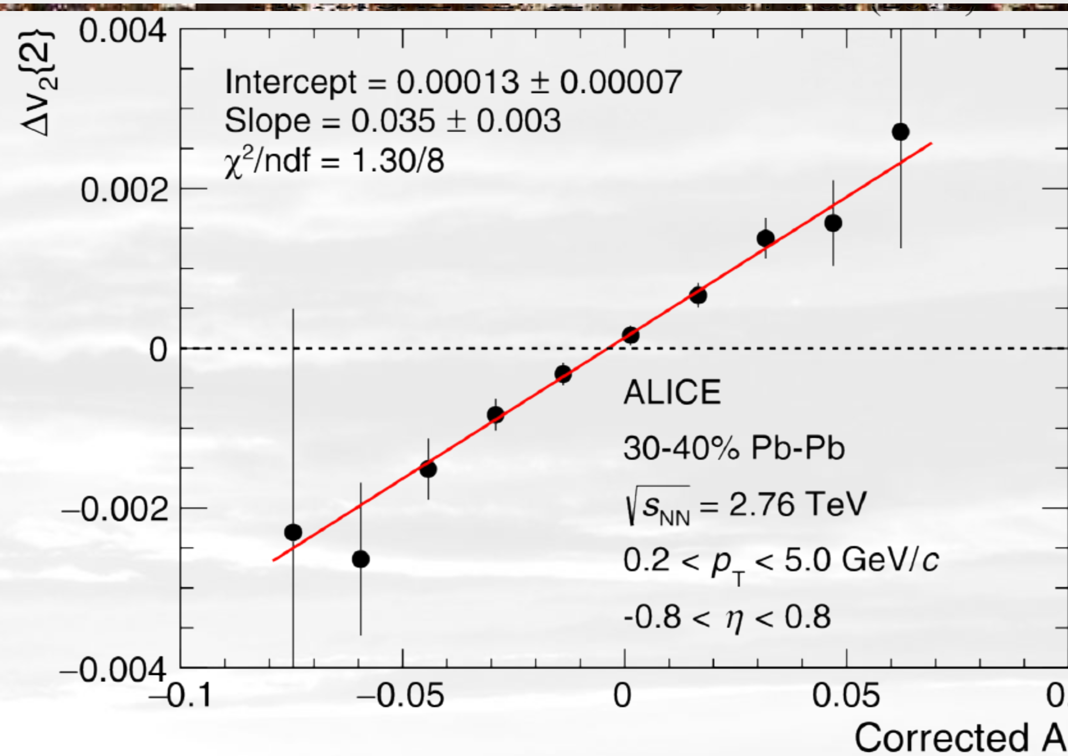
[Abelev et al. (STAR), PRL **103**, 251601 (2009)]
[Abelev et al. (STAR), PRC **81**, 054908 (2010)]
[Abelev et al. (ALICE), PRL **110**, 012301 (2013)]
[Adamczyk et al. (STAR), PRC **88**, 064911 (2013)]

Large background effects!

[Belmont & Nagle, PRC **96**, 024901 (2017)], [ALICE Collaboration, Phys. Lett. B777, 151 (2018)]

CMW: Experimental evidence





[Ke (for STAR) J. Phys. Conf. Series **389**, 012035 (2012)]

[Adamczyk et al. (STAR), Phys. Rev. Lett. **114**, 252302 (2015)]

[Adam et al. (ALICE), Phys. Rev. C **93**, 044903 (2016)]

Background effects may dominate over the signal!

[CMS Collaboration, arXiv:1708.08901]

- On the theoretical side: CMW is likely to be overdamped (unless magnetic field is very strong) [Shovkovy, Rybalka, Gorbar, arXiv:1811.10635]

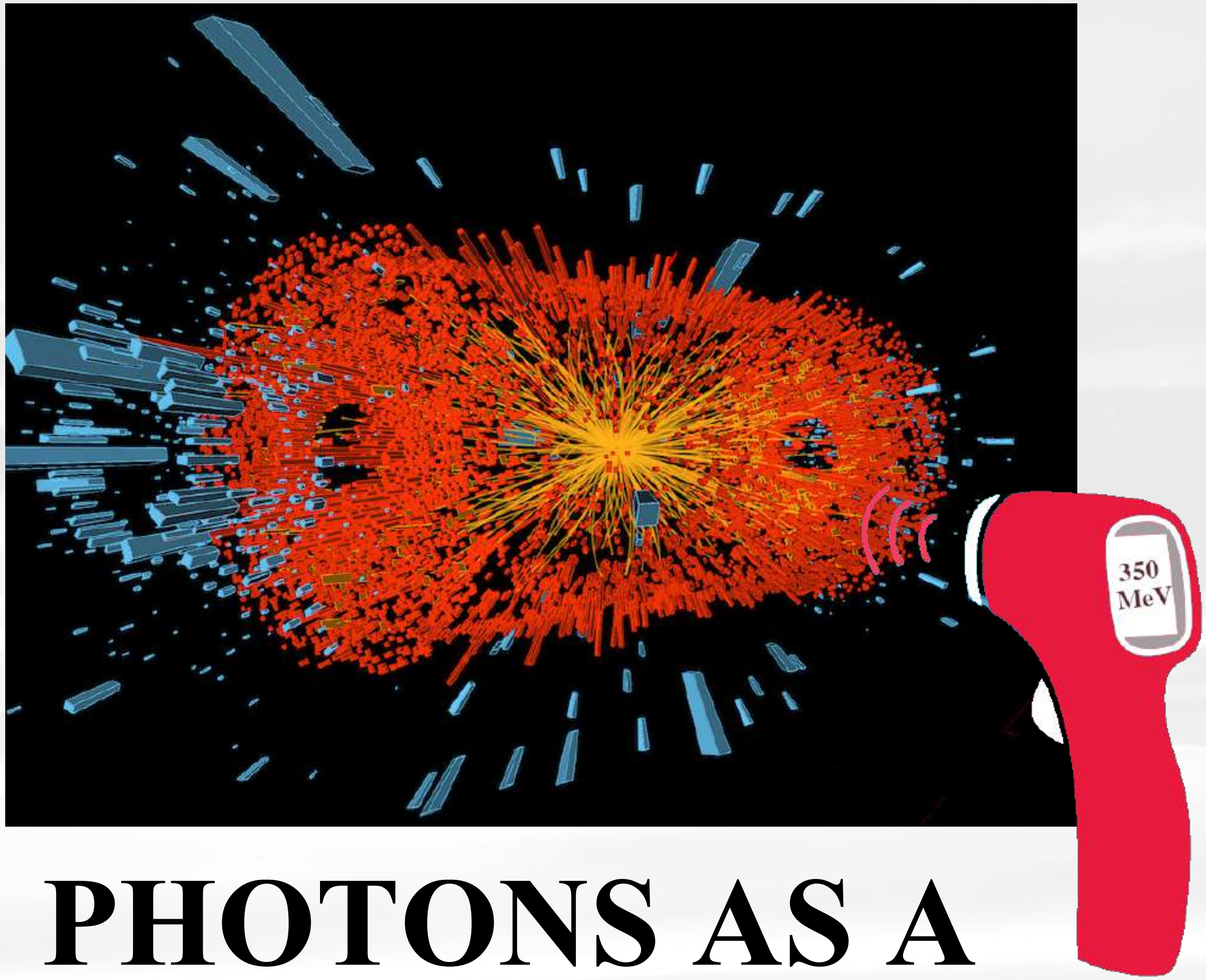
How to measure $\vec{B}$?

- One of the ideas [STAR Collaboration, 2014]
  - "measure" the relative strengths of the effects in isobar collisions, e.g., [Koch, Schlichting, Skokov et al., arXiv:1608.00982]

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

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

- Any chance of measuring $\vec{B}$ directly?
- Perhaps an electromagnetic probe?
- Current proposal:
  - thermal photons
  - dilepton rates

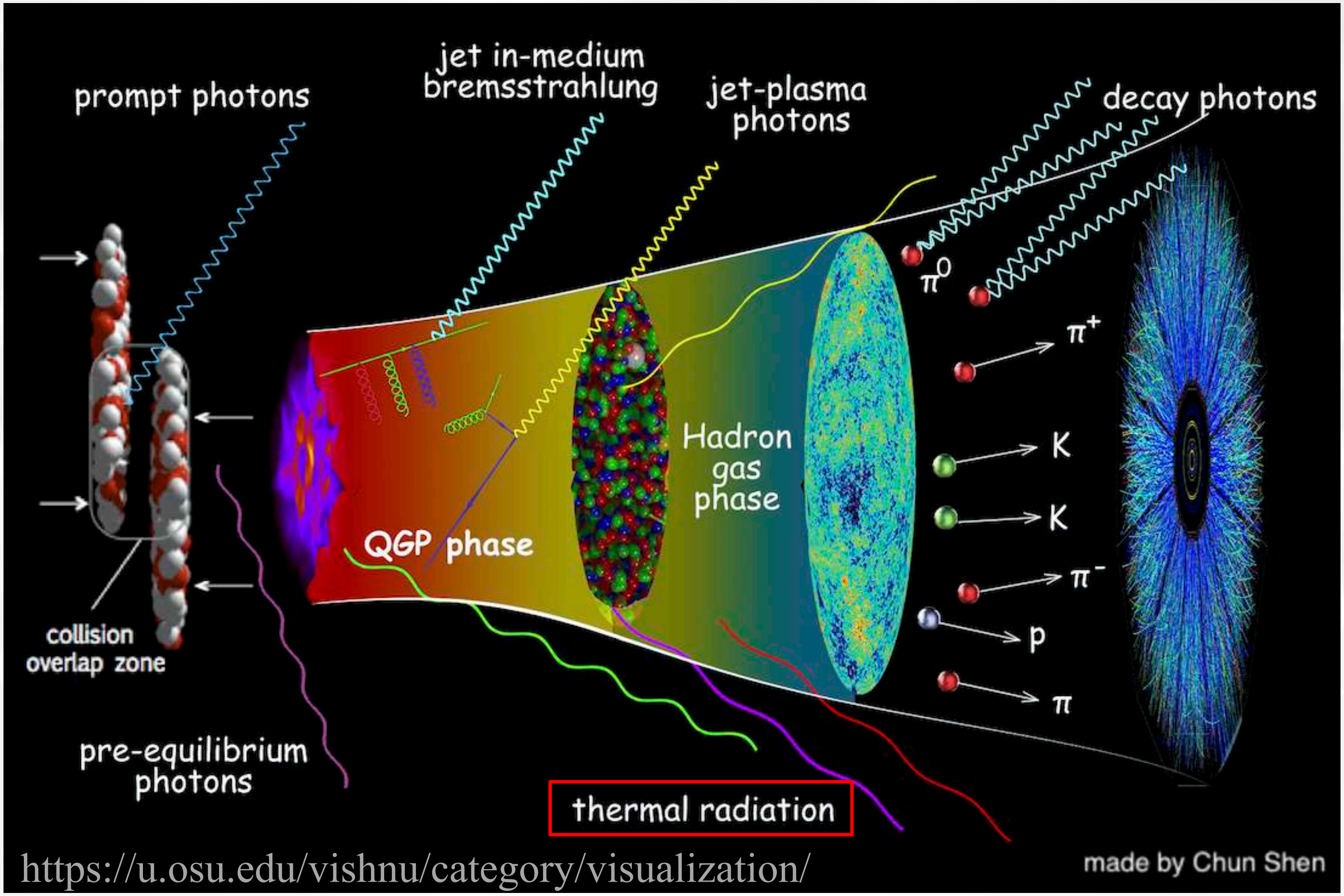


PHOTONS AS A THERMOMETER OF QGP

[Kapusta, Lichard, & Seibert, Phys. Rev. D44, 2774 (1991)]
[Paquet et al., Phys. Rev. C93, 044906 (2016); arXiv:1509.06738]
Review: [Gabor David, Rept. Prog. Phys. 83, 046301 (2020); arXiv:1907.08893]
…

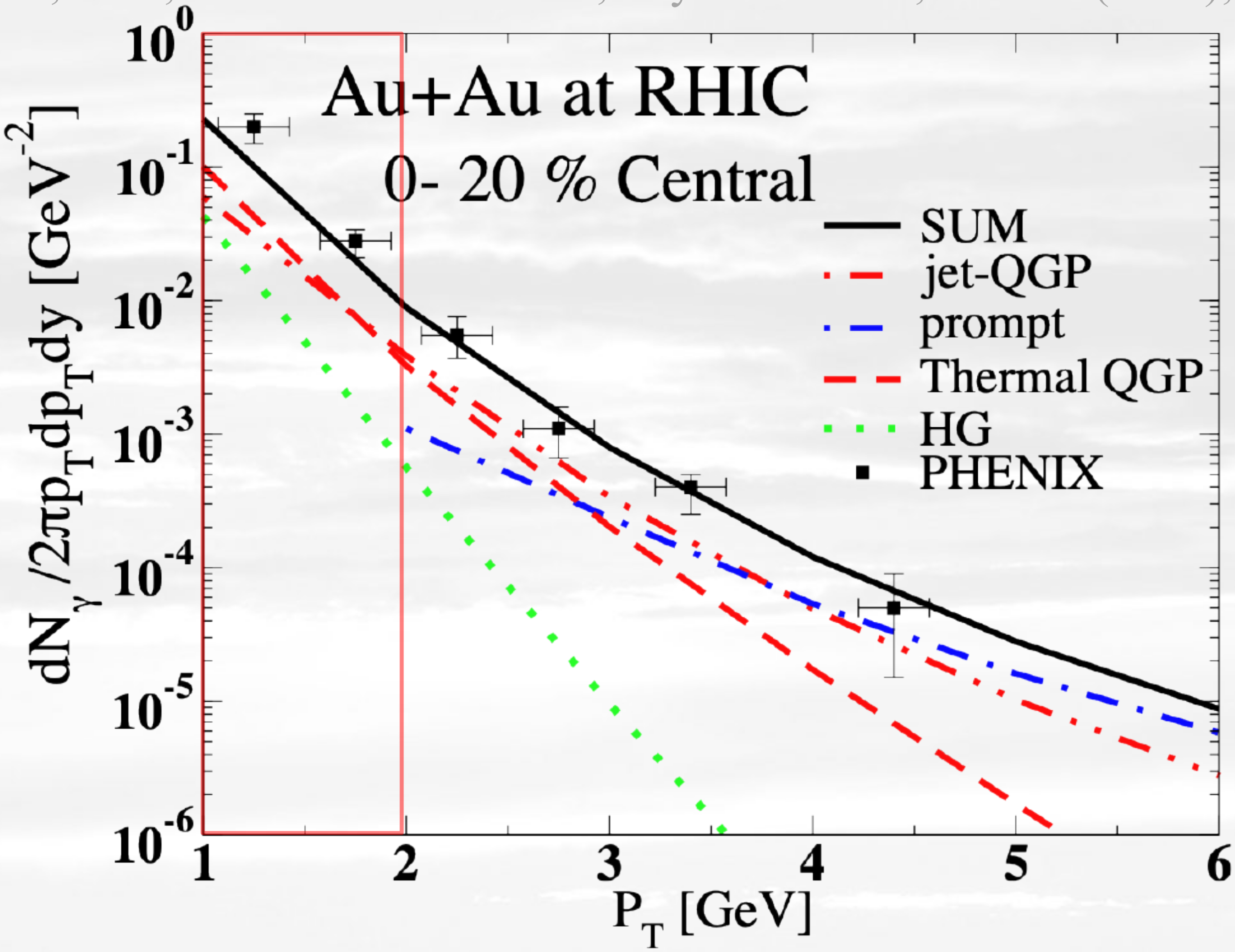
Photons in heavy-ion collisions

- 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
- $2 \text{ GeV} \lesssim p_T \lesssim 4$ GeV: the jet-plasma contribution dominates

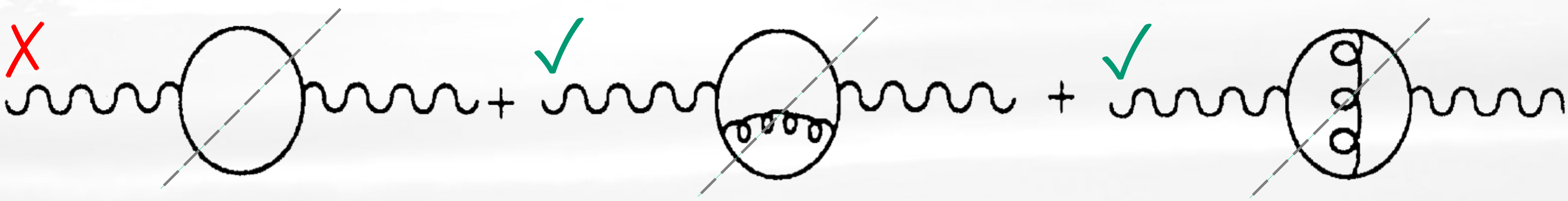
Thermal photons (1)

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

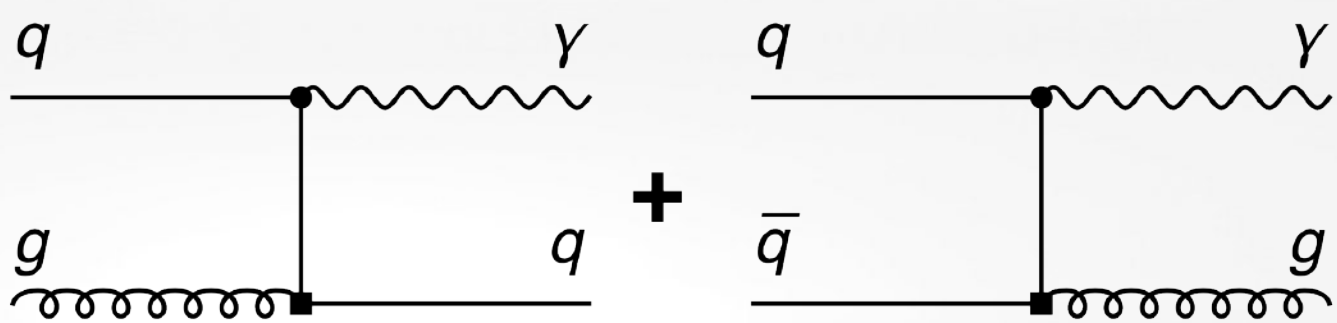
$$k^0 \frac{d^3 R}{dk_x dk_y dk_z} = -\frac{1}{(2\pi)^3} \frac{\mathrm{Im}\left[\Pi^{\mu}_{\mu}(k)\right]}{\exp\left(\frac{k_0}{T}\right) - 1}$$

[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:



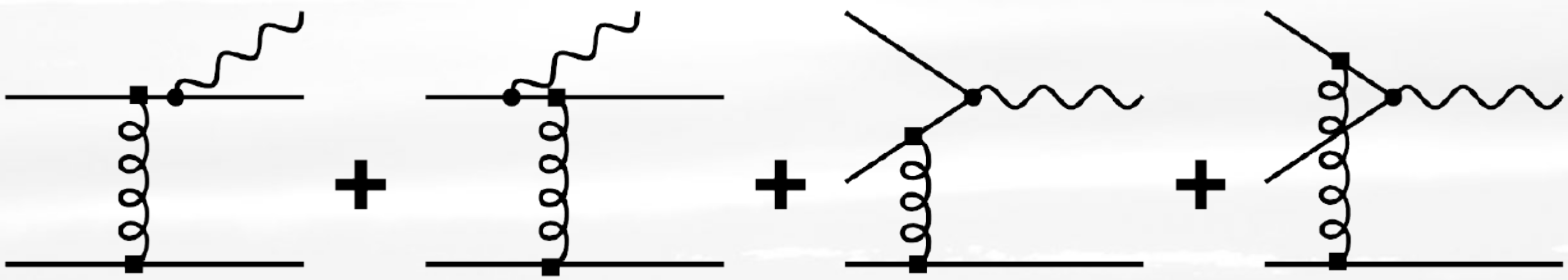
Thermal photons (2)

- 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**



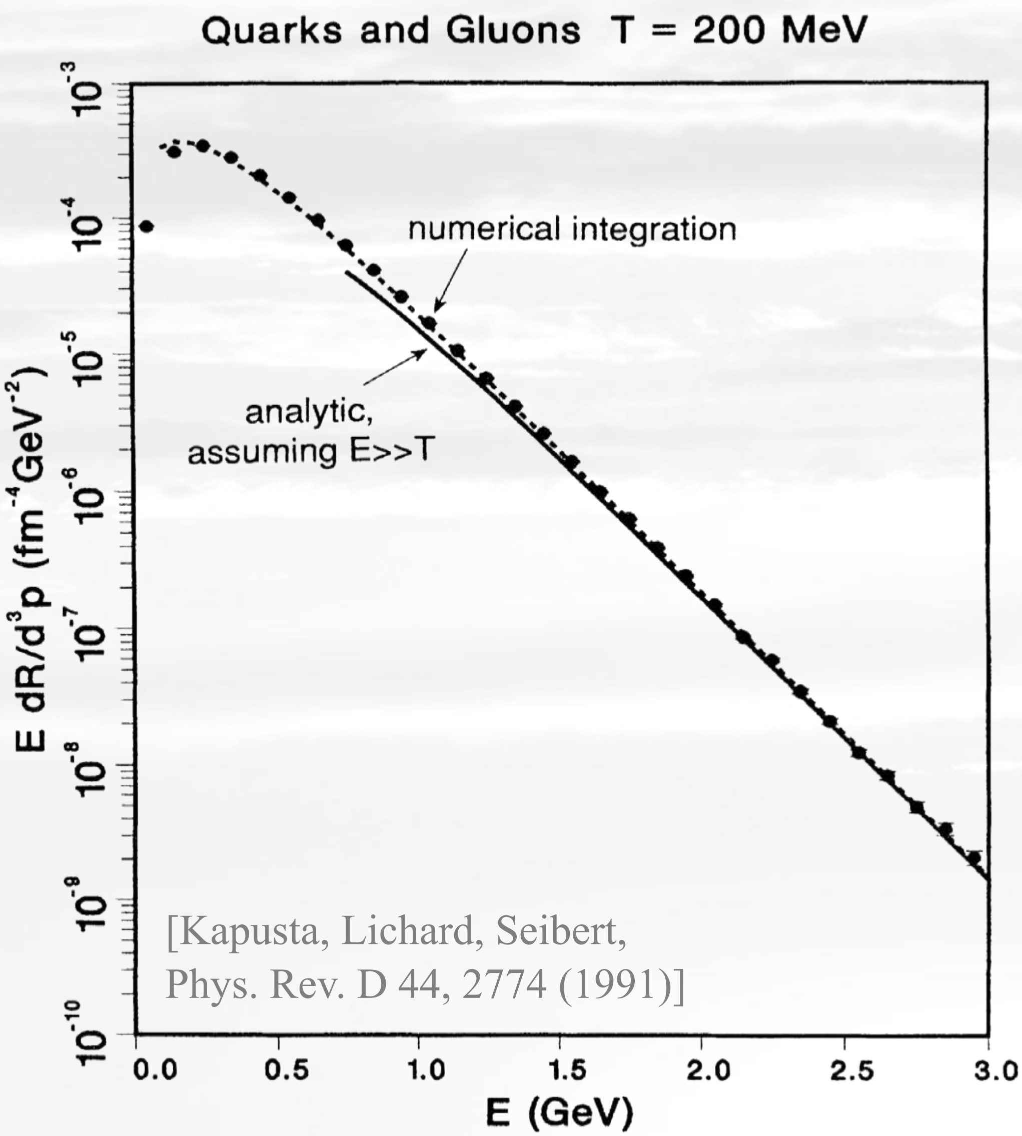
[Arnold, Moore,Yaffe, JHEP 12 (2001) 009; hep-ph/0111107]

- 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]

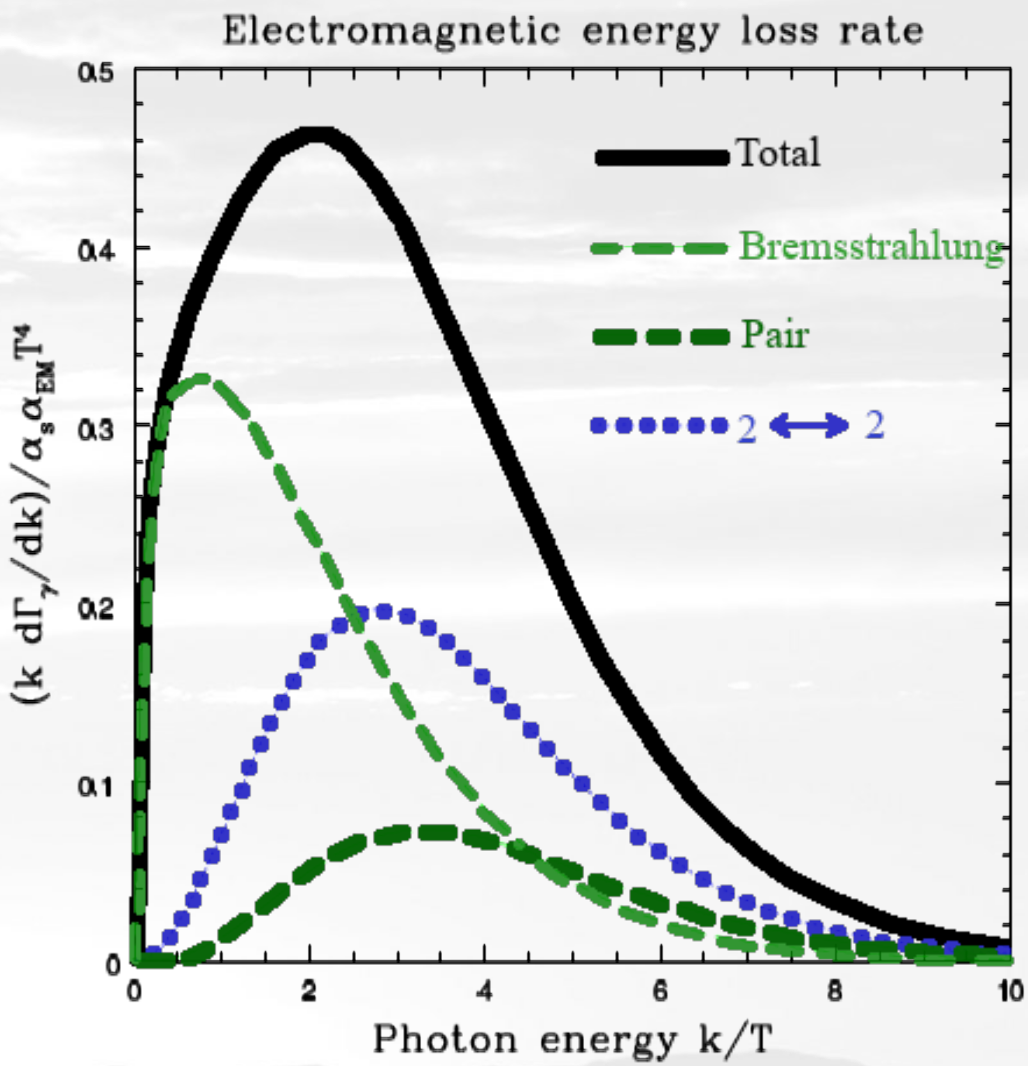
Thermal photons (3)

- Numerically,



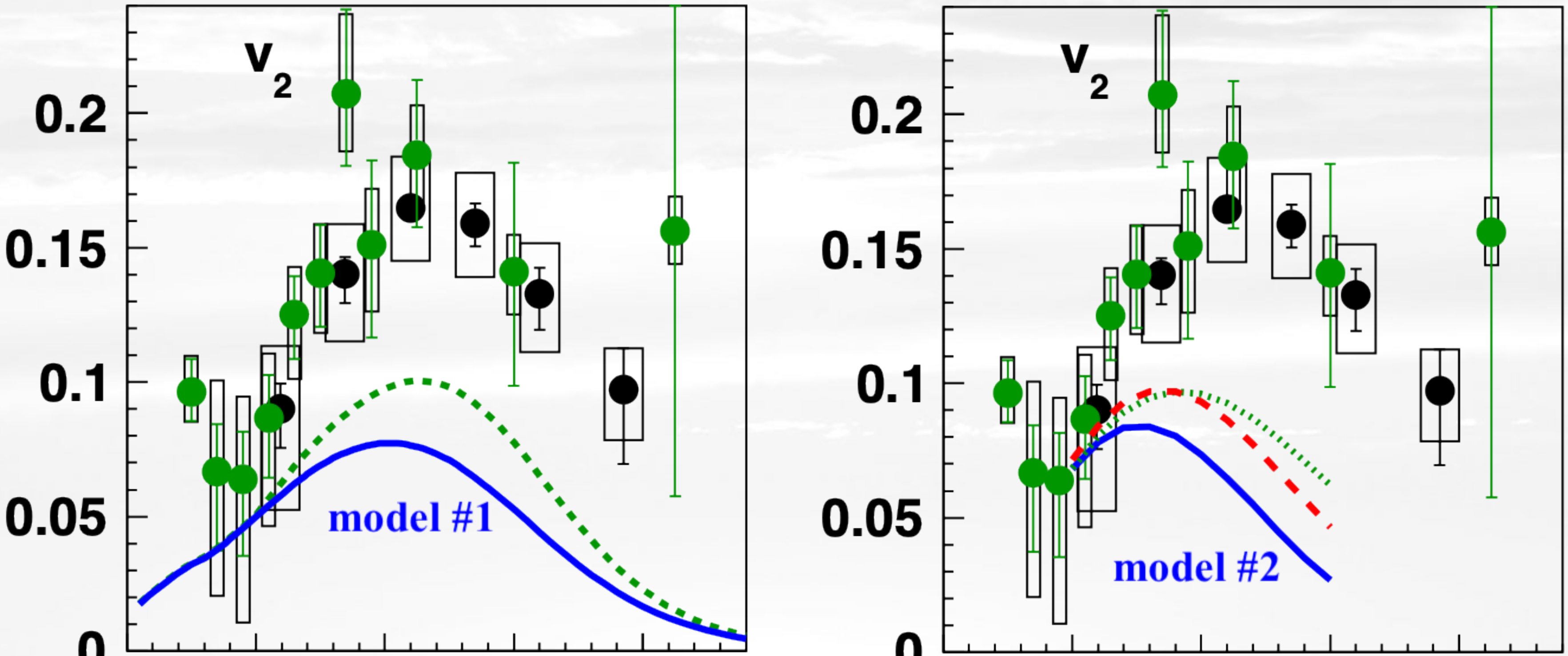
[Kapusta, Lichard, Seibert, Phys. Rev. D 44, 2774 (1991)]

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

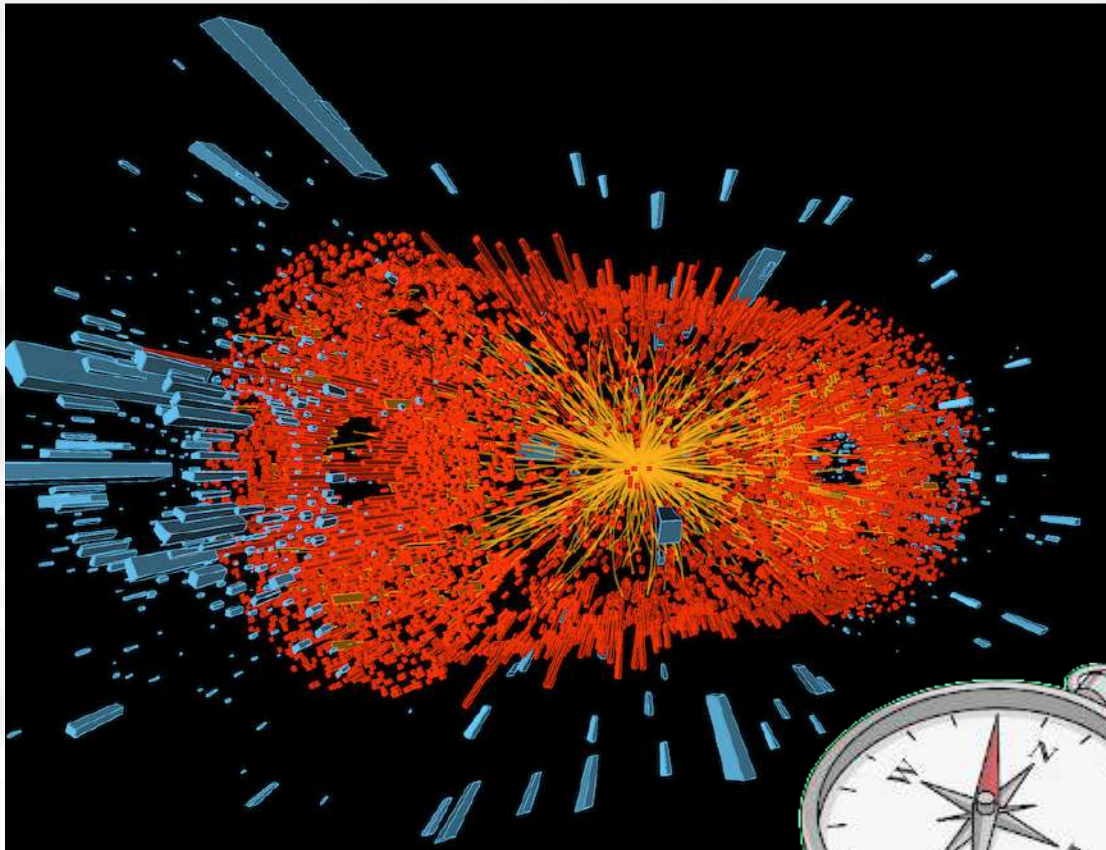


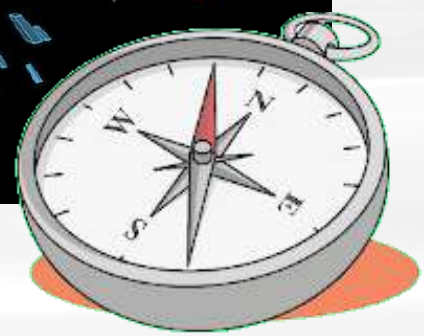
Photon v_2 puzzle

- 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)]

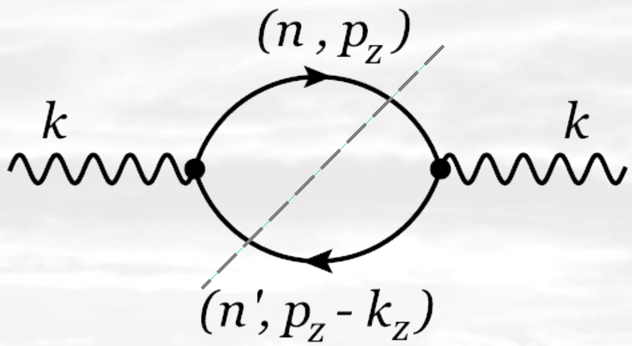


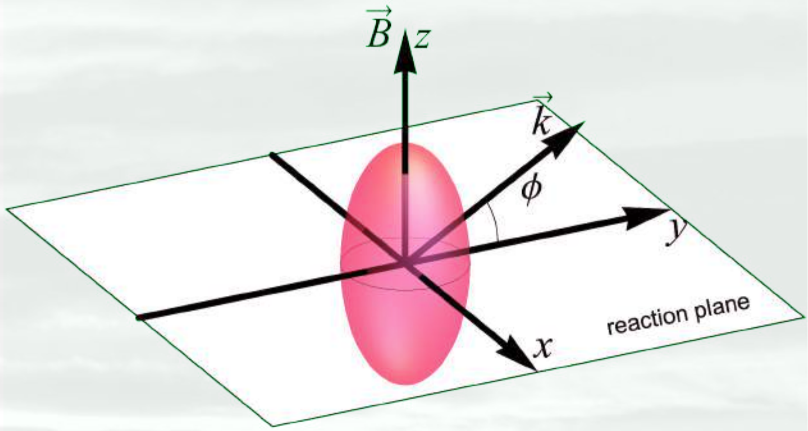


DIRECT PHOTONS AS A MAGNETOMETER OF QGP

Photons from magnetized plasma

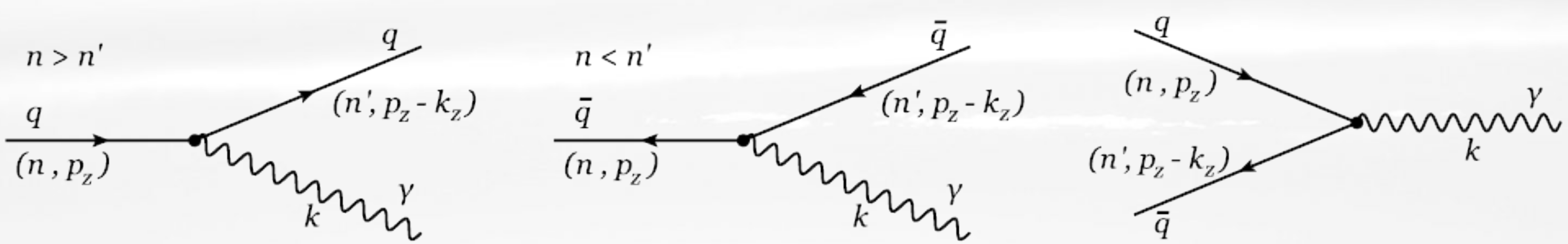
- At $\vec{B} \neq 0$, the leading-order polarization tensor





leads to a nonzero result!

- All three processes (without the gluon mediation), i.e.,

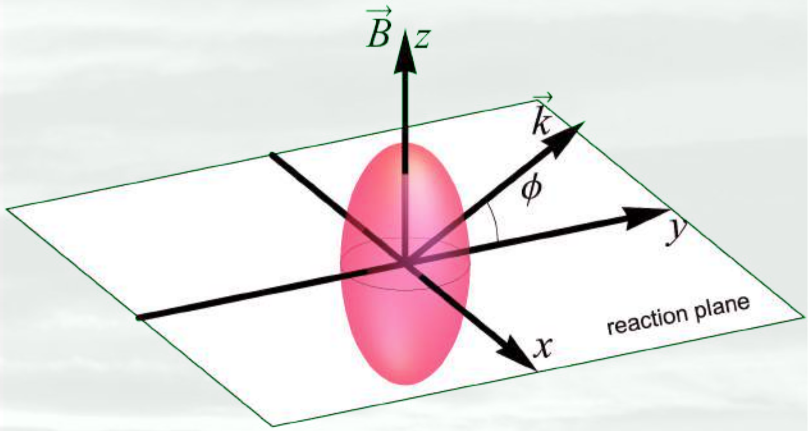


are allowed by the energy conservation

Photon thermal rate

- The expression for the rate is

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



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

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

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

Photon thermal rate

- After integrating over p_z, the final expression reads

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

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

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

The momentum *thresholds* are determined by

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

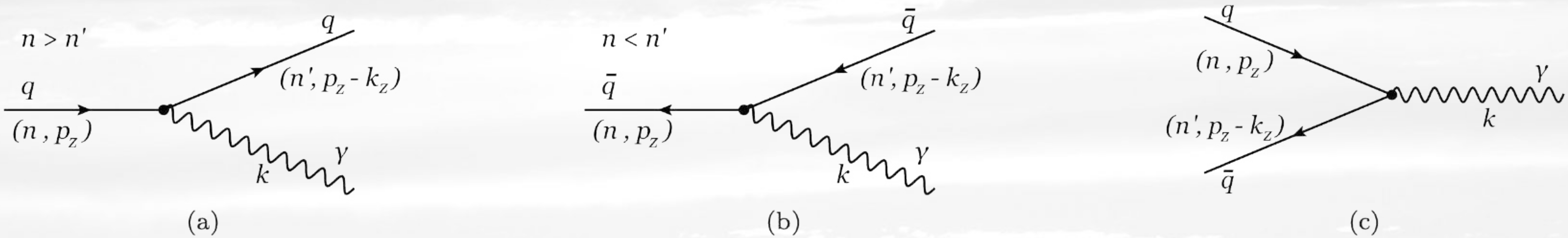
Physics processes

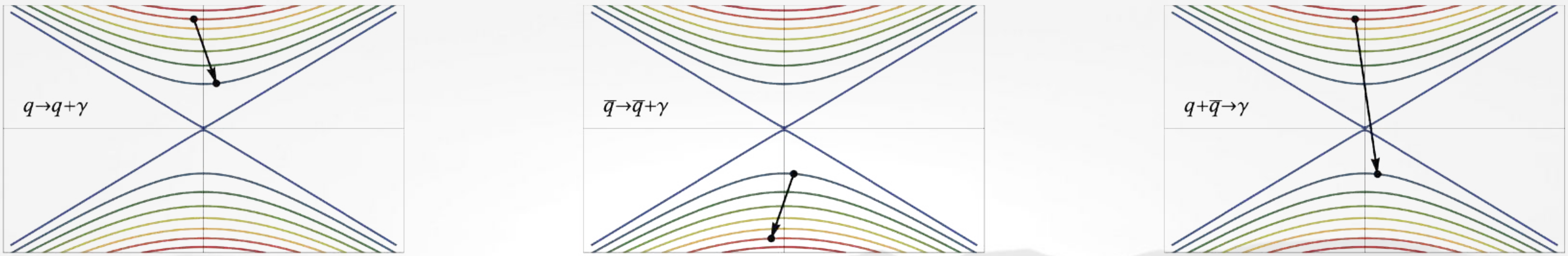
- Real solutions to the energy conservation equation

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

can be found under the following conditions:

$$q \to q + \gamma \ (\lambda = +1,\ \eta = -1): \qquad \sqrt{\Omega^2 - k_z^2} \le k_-^f \text{ and } n > n',$$
$$\bar{q} \to \bar{q} + \gamma \ (\lambda = +1,\ \eta = +1): \qquad \sqrt{\Omega^2 - k_z^2} \le k_-^f \text{ and } n < n',$$
$$q + \bar{q} \to \gamma \ (\lambda = -1,\ \eta = -1): \qquad \sqrt{\Omega^2 - k_z^2} \ge k_+^f,$$



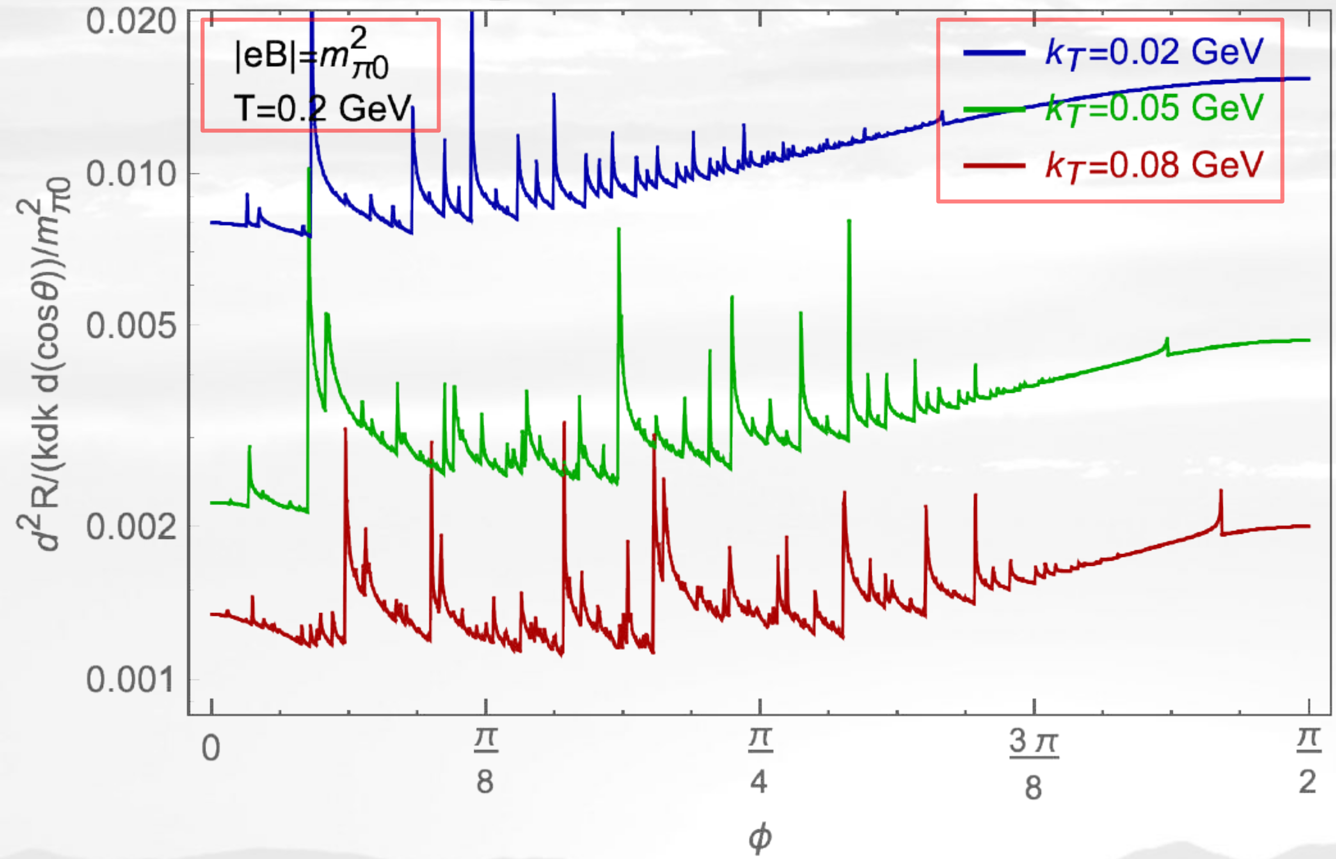


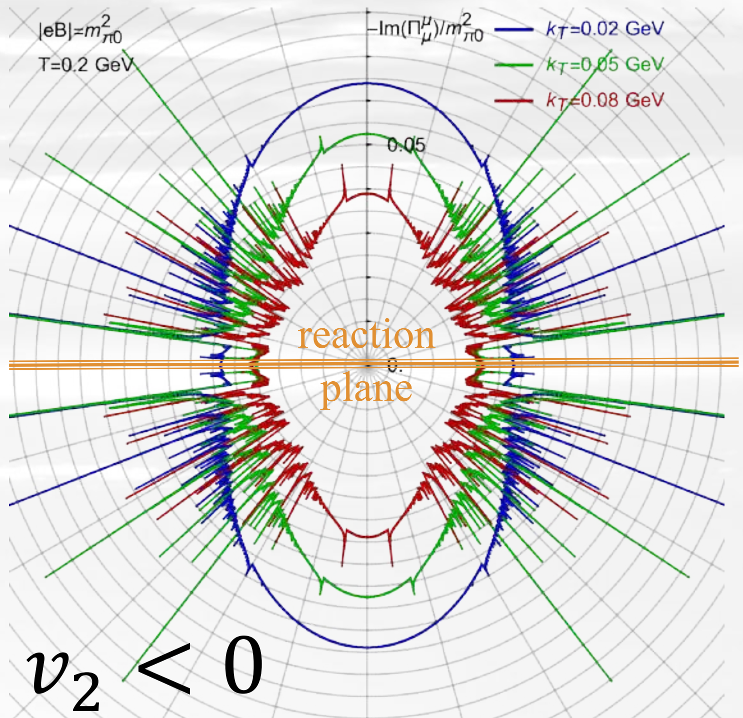
Angular dependence: small k_T

- Non-smooth dependence on ϕ (due to many thresholds)

  Paramertization: $k_x = 0$, $k_y = k_T \cos\phi$ and $k_z = k_T \sin\phi$

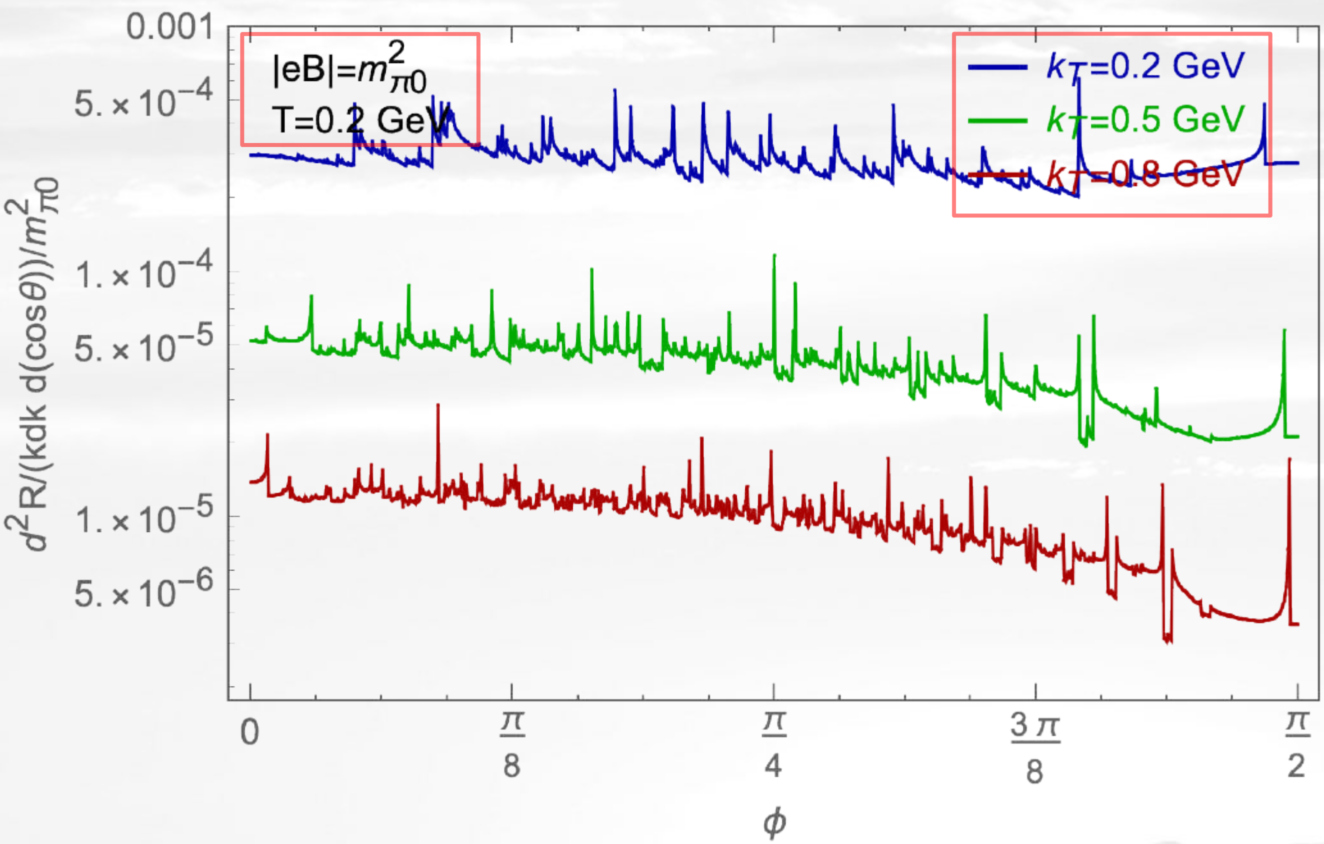
- Average rate is maximal at $\phi = \frac{\pi}{2}$ (i.e., ⊥ to the reaction plane)

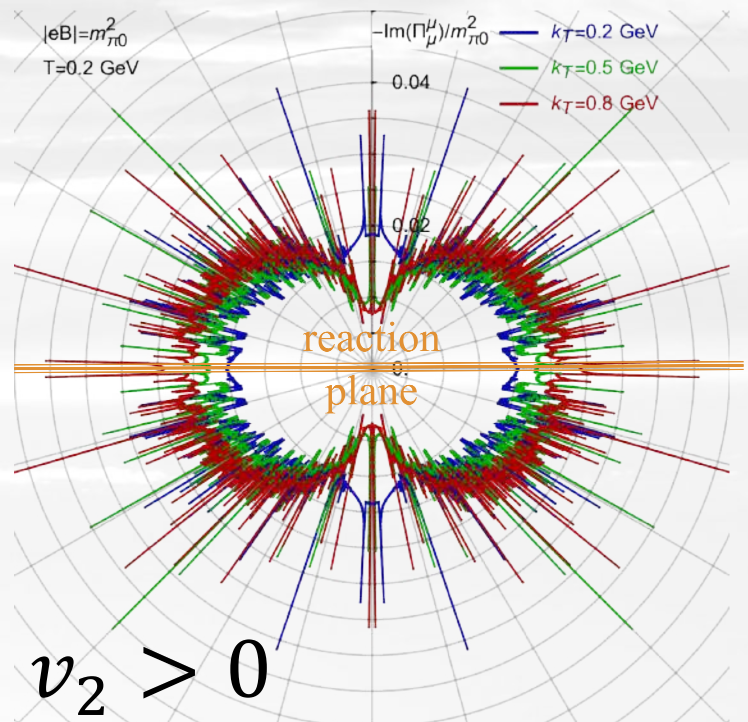




Angular dependence: large k_T

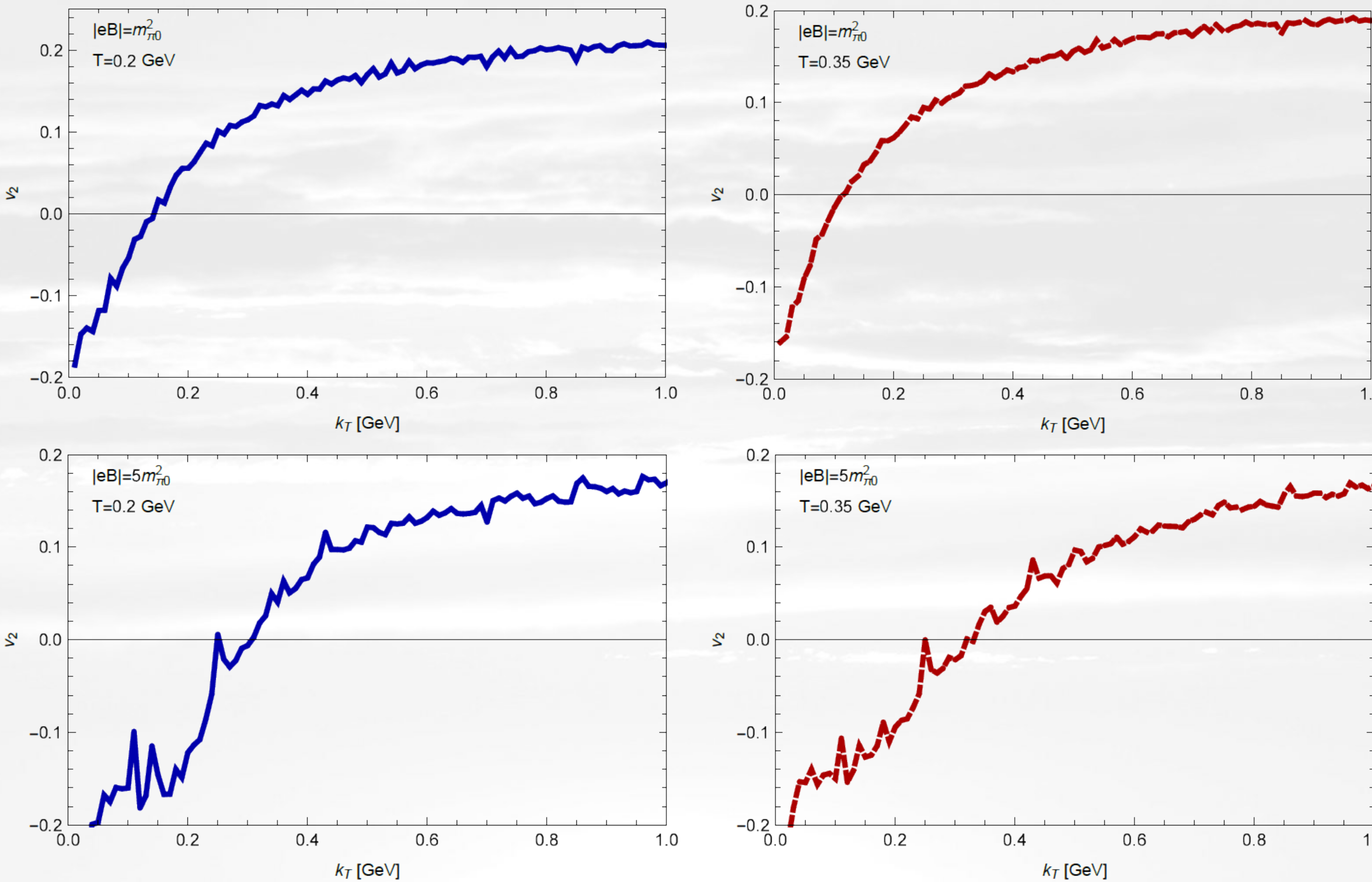
- Rate quickly decreases with k_T
- Average rate is maximal at $\phi = 0$ (i.e., ∥ to the reaction plane)





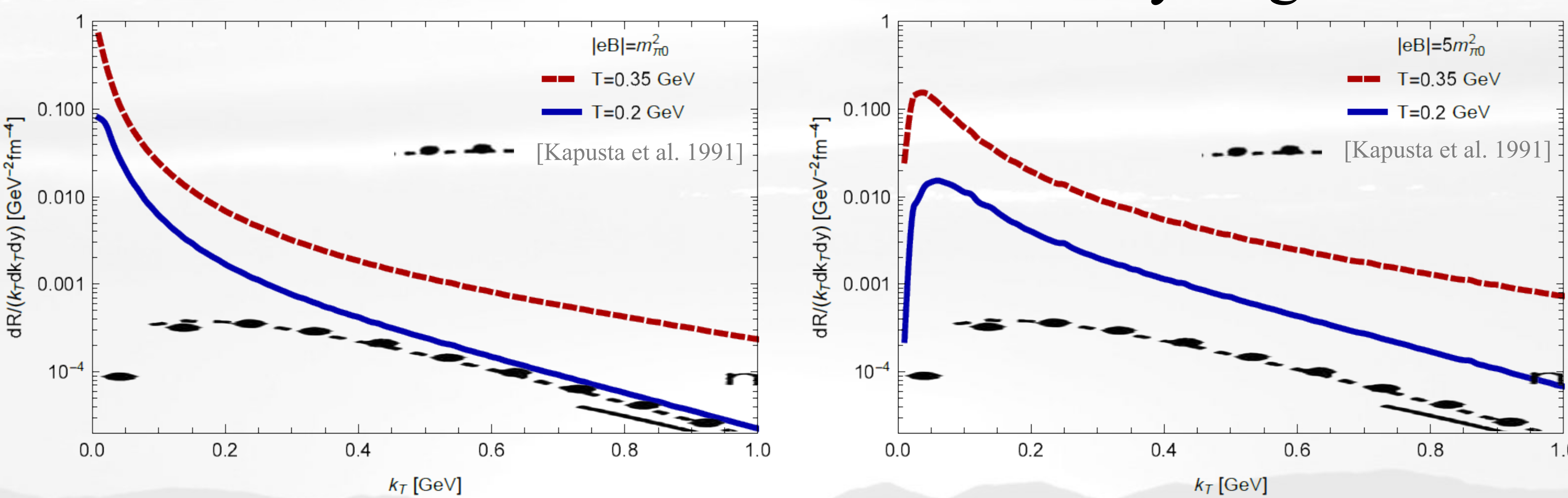
$v_2 > 0$

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

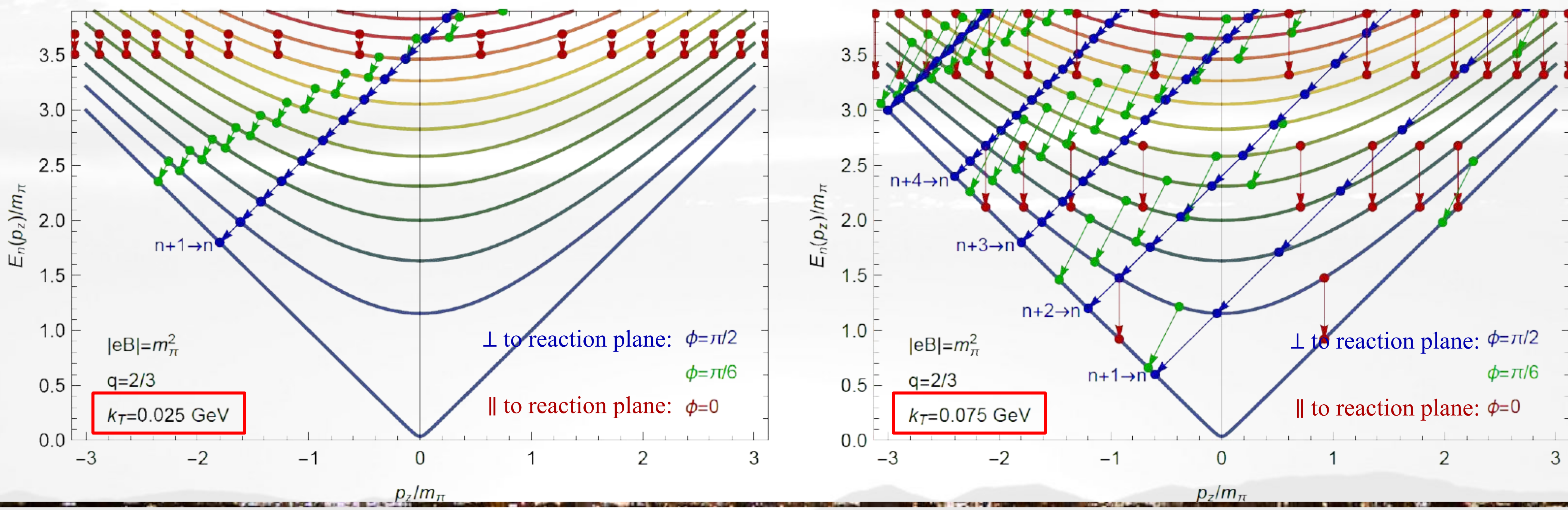


Quantization @ small k_T

- Quantization is important when $k_T \lesssim \sqrt{|eB|}$
  - Transitions are possible only at large p_z

$$|p_z| \sim |e_f B| / \left[k_T (1 + |\sin\phi|) \right]$$

  - This explains why $\mathrm{Im}(\Pi^{\mu}_{\mu}) \to 0$ when $k_T \to 0$
  - Dependence on ϕ also explains the negative v_2!

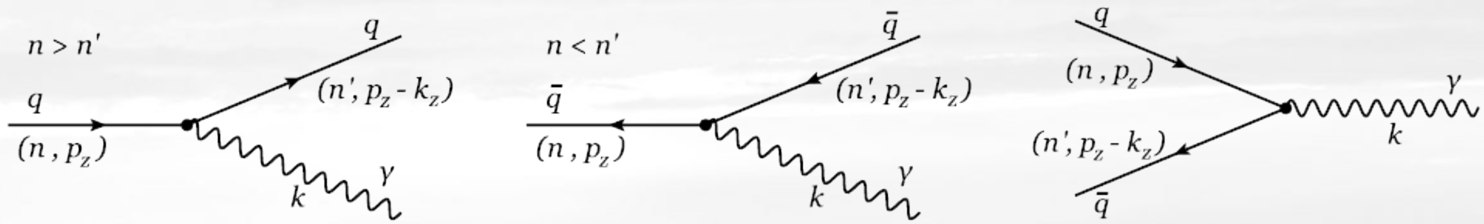


Anisotropy of photon emission

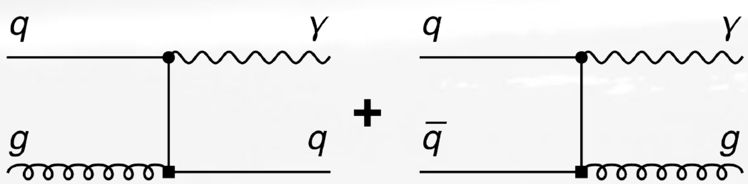
- The total rate is

$$\frac{k^0 d^3 R}{dk_x dk_y dk_z} = \underbrace{\mathcal{R}_{\substack{1\to 2\\ 2\to 1}}}_{\text{only at } \vec{B}\neq 0} + \underbrace{\mathcal{R}_{2\to 2} + \mathcal{R}_{\substack{2\to 3\\ 3\to 2}}}_{\text{even at } \vec{B}=0} + \cdots$$

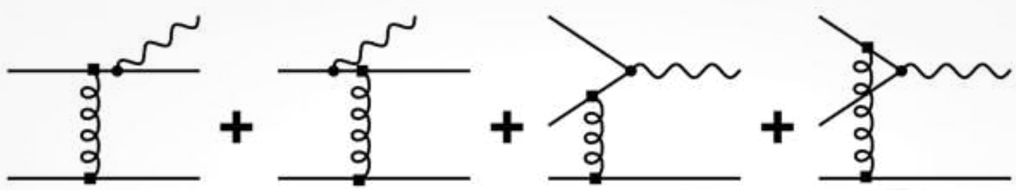
$\mathcal{R}_{\substack{2\to 1\\ 1\to 2}}$:



$\mathcal{R}_{2\to 2}$:



$\mathcal{R}_{\substack{2\to 3\\ 3\to 2}}$:



Magnetic enhancement of v_2

- Estimate of v_2 in a hot magnetized QGP

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

- Noting that

$$\mathcal{R}_{\substack{2\to 1\\1\to 2}} \gtrsim \mathcal{R}_{2\to 2} \gtrsim \mathcal{R}_{\substack{2\to 3\\3\to 2}}$$

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

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

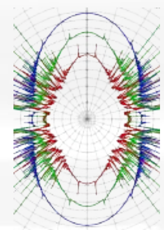
- A more realistic estimate should consider non-isotropic expansion & non-thermal processes

Summary

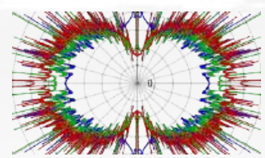
- At $\vec{B} \neq 0$, photons are produced at 0th order in α_s

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

- The annihilation contribution grows with k_T
- Quantization effects are important for $k_T \lesssim \sqrt{|eB|}$
- 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