Strong field physics as probe into early-time dynamics of heavy-ion collisions

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  what, why, how strong, and how created?
- Vacuum birefringence of a photon
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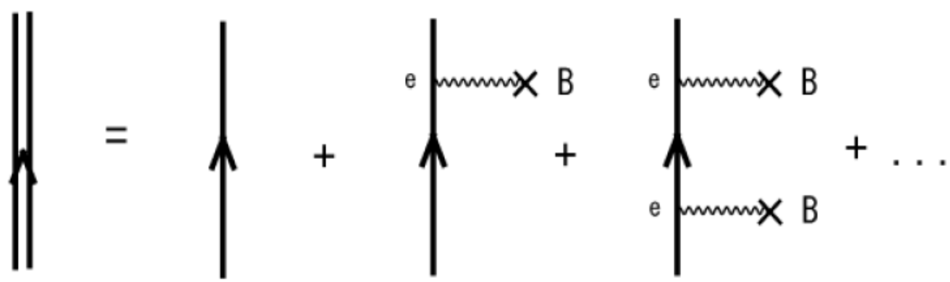
What is “strong field physics”?

- **Characteristic phenomena that occur under strong gauge fields** (EM fields and Yang-Mills fields)
- **Typically, weak-coupling but non-perturbative**

ex) electron propagator in a strong magnetic field



$$1 \;+\; O\left(\frac{eB}{m_e^2}\right) \;+\; O\left(\left(\frac{eB}{m_e^2}\right)^2\right)$$

must be resummed when $B >> B_c$

$$eB_c \equiv m_e^2$$

$$eE_c \sim m_e^2$$

Schwinger’s critical field

→ **“Nonlinear QED effects”**

Why is it important?

- **Strong EM/YM fields appear in the very early time of heavy-ion collisions. In other words, the fields are strongest in the early time stages.**

- **Indispensable for understanding the early-time dynamics in heavy-ion collisions**

  strong YM fields (glasma) → thermalization

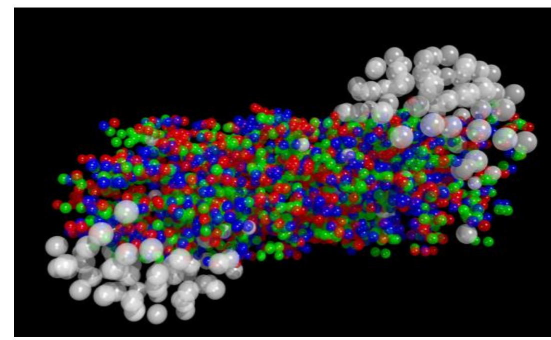
  strong EM fields → probe of early-time dynamics

  - carry the info
  - special to the early-time stages

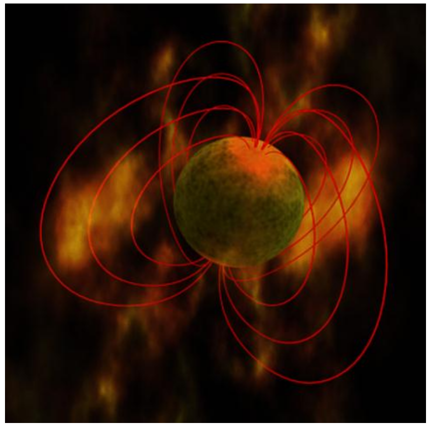
How strong?

1 Tesla = 10^4 Gauss

10^{17}—10^{18} Gauss
$\sqrt{eB} \sim 1 - 10\, m_\pi$:
Noncentral heavy-ion coll. at RHIC and LHC
Also strong Yang-Mills fields $\sqrt{gB} \sim 1$– a few GeV



10^{15}Gauss : Magnetars



$4\text{x}10^{13}$ Gauss : "Critical" magnetic field of electrons
$\sqrt{eB_c} = m_e = 0.5\text{MeV}$

45 Tesla : strongest steady magnetic field
(High Mag. Field. Lab. In Florida)

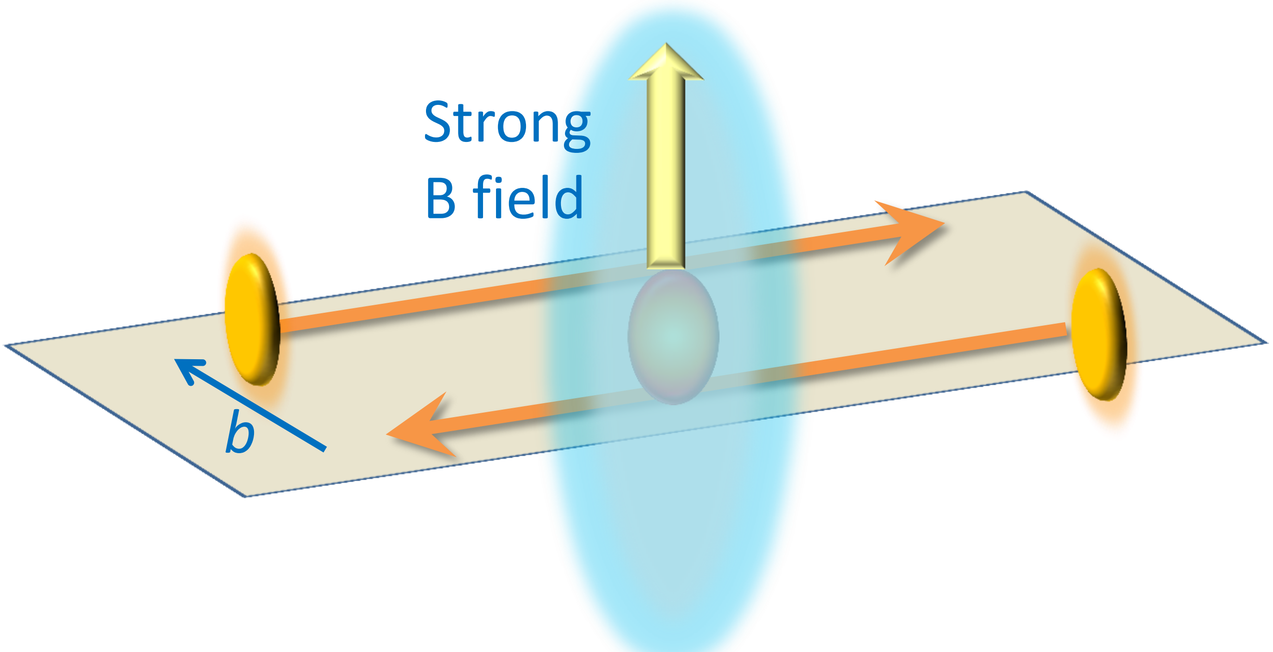
10^8Tesla=10^{12}Gauss: Typical neutron star surface

8.3 Tesla : Superconducting magnets in LHC

Super critical magnetic field may have existed in very early Universe. Maybe after EW phase transition? (cf: Vachaspati '91)

How are they created?

Strong magnetic fields are created in non-central HIC



Lorentz contracted electric field is accompanied by strong magnetic field

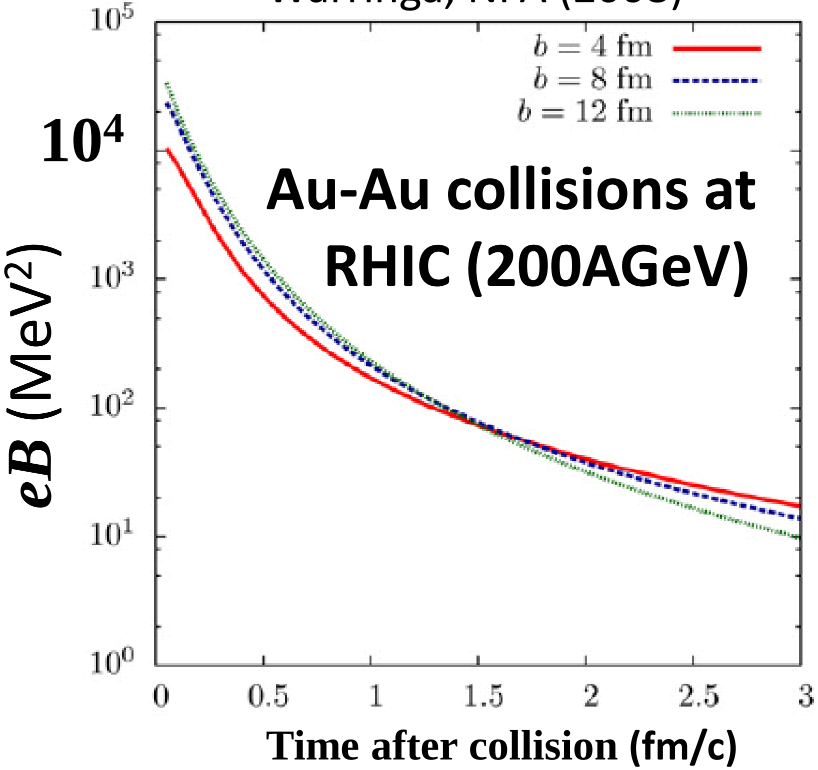
$$e\vec{B}(\vec{x}) = Z\alpha_{\mathrm{EM}}\boxed{\sinh(Y)}\frac{(\vec{x}'_\perp - \vec{x}_\perp)\times\vec{e}_z}{[(\vec{x}'_\perp - \vec{x}_\perp)^2 + (t\sinh Y - z\cosh Y)^2]^{3/2}}.$$

$x_\perp'$, Y : transverse position and rapidity (velocity) of moving charge

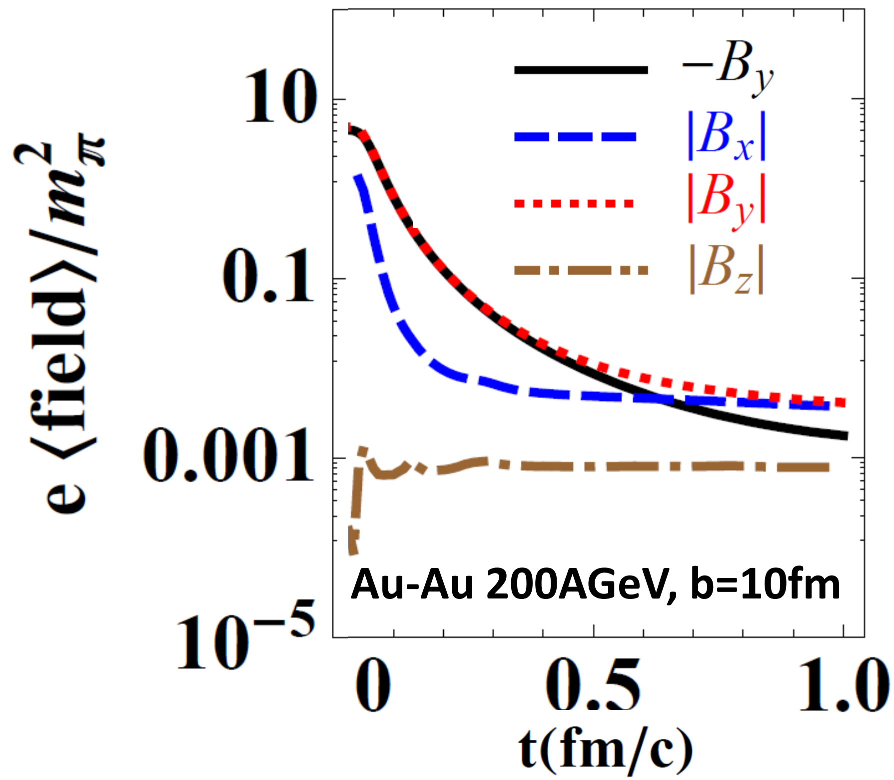
Time dependence

Simple estimate with the Lienardt-Wiechert potential

Kharzeev, McLerran, Warringa, NPA (2008)

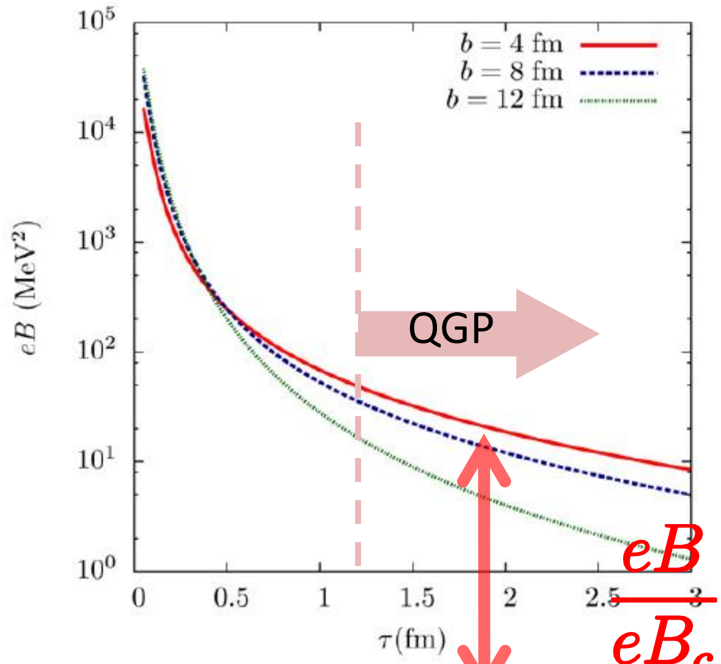


Event-by-event analysis with HIJING
Deng, Huang, PRC (2012)



$$\sqrt{eB} \sim 1 - 10\ m_\pi$$

Time dependence



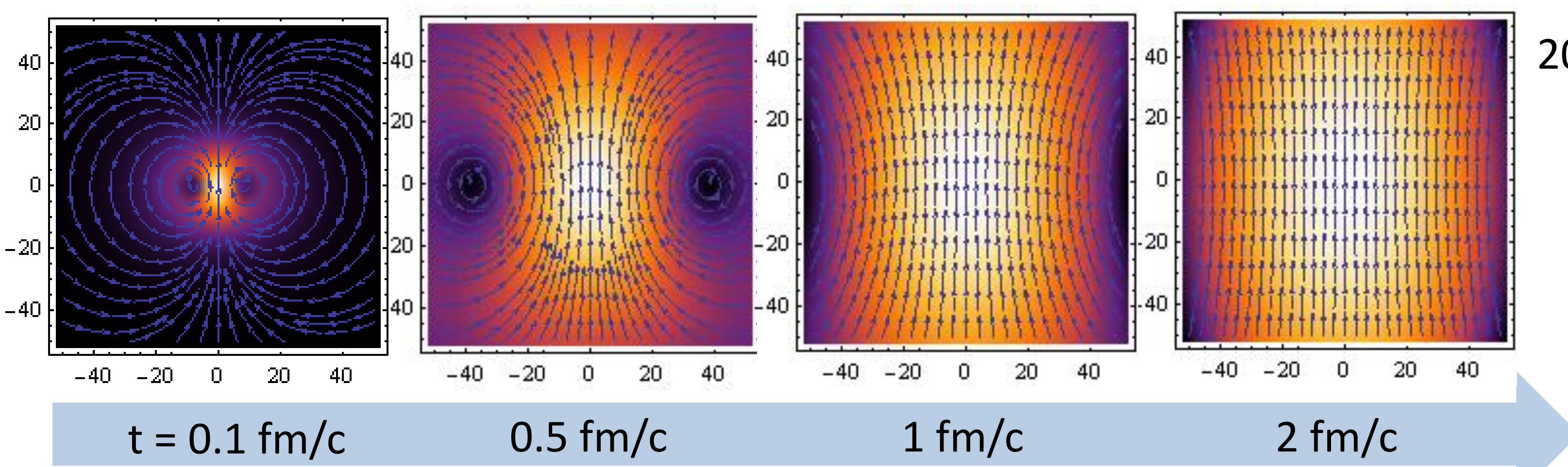
$$\frac{eB}{eB_c} \sim 10^{2\sim3}$$

$$eB_c = m_e^2 \sim 0.25 \quad \text{MeV}^2$$

Rapidly decreasing

→ Nonlinear QED effects will be prominent in pre-equilibrium region!!!

→ Still VERY STRONG even after a few fm, QGP will be formed in the magnetic background



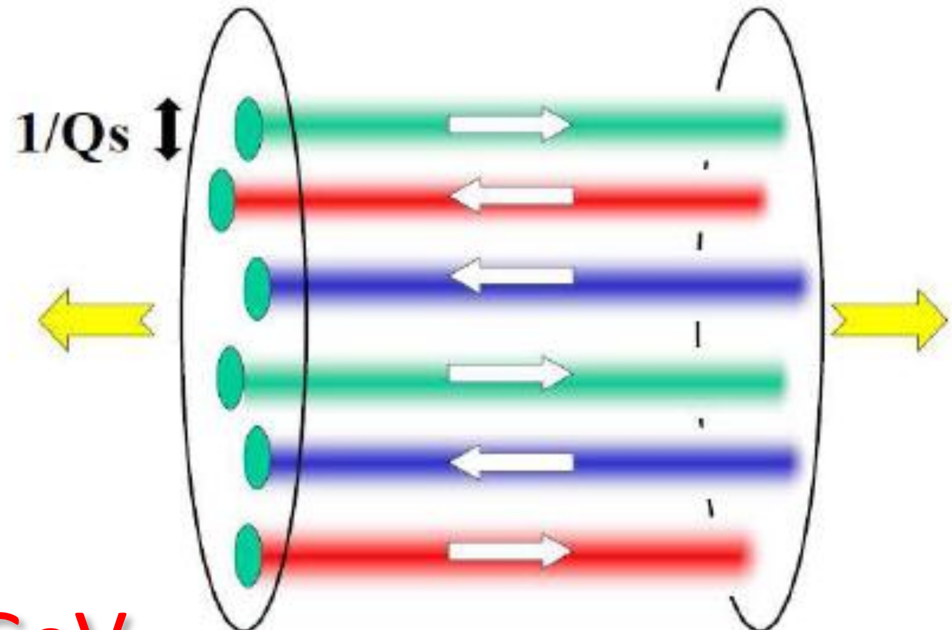
200GeV (RHIC)
Z = 79 (Au),
b = 6 fm

Plot: K.Hattori

Strong Yang-Mills fields (Glasma)

Just after the collision:
"GLASMA"

CGC gives the initial condition
→ "color flux tube" structure
with strong color fields



$$\sqrt{gB} \sim \sqrt{gE} \sim Q_s$$

~ 1 GeV – a few GeV
RHIC LHC

Nonlinear dynamics of glasma will probably lead to thermalization(?)

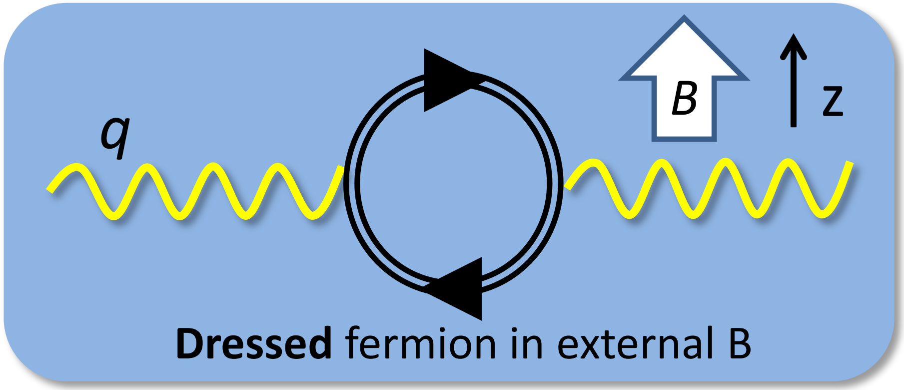
Also show various phenomena similar to the nonlinear QED effect
(but not discussed today)

An example of nonlinear QED effects

K. Hattori and KI
in preparation

"Vacuum birefringence"

Polarization tensor of a photon is modified in a magnetic field through electron one loop, so that a photon has two refractive Indices.



$$\Pi^{\mu\nu}_{\rm ex}(q) = \chi_0(q^2\eta^{\mu\nu} - q^\mu q^\nu) + \underline{\chi_1(q_\parallel^2\eta_\parallel^{\mu\nu} - q_\parallel^\mu q_\parallel^\nu) + \chi_2(q_\perp^2\eta_\perp^{\mu\nu} - q_\perp^\mu q_\perp^\nu)}$$

present only in external fields

$$\eta_\parallel^{\mu\nu} = diag(1,0,0,-1)$$
$$\eta_\perp^{\mu\nu} = diag(0,-1,-1,0)$$

$$\begin{aligned} q^\mu &= (q^0, q_\perp, 0, q^3) \\ q_\parallel^\mu &= (q^0, 0, 0, \ q^3) \\ q_\perp^\mu &= (0, q_\perp, 0, 0) \end{aligned}$$

II parallel to B
⊥ transverse to B

Vacuum Birefringence

- **Maxwell eq. with the polarization tensor :**

$$\left(q^2\eta^{\mu\nu} - q^\mu q^\nu + \hat{\Pi}^{\mu\nu}_{\rm ex}\right) A_\nu(q) = 0$$

$$\Pi^{\mu\nu}_{\rm ex}(q) = \chi_0(q^2\eta^{\mu\nu} - q^\mu q^\nu) + \chi_1(q_\parallel^2\eta_\parallel^{\mu\nu} - q_\parallel^\mu q_\parallel^\nu) + \chi_2(q_\perp^2\eta_\perp^{\mu\nu} - q_\perp^\mu q_\perp^\nu)$$

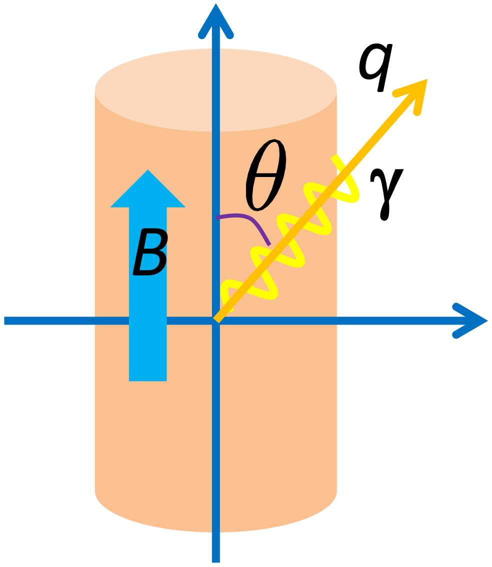
- **Dispersion relation of two physical modes gets modified**

→ Two refractive indices : "Birefringence"

$$n^2 \equiv \frac{|\boldsymbol{q}|^2}{\omega^2}$$

$$\begin{cases} n_1^2 = \dfrac{1+\chi_0+\chi_1}{1+\chi_0+\chi_1\cos^2\theta} \\ n_2^2 = \dfrac{1+\chi_0}{1+\chi_0+\chi_2\sin^2\theta} \end{cases}$$

Need to know χ_0, χ_1 , χ_2



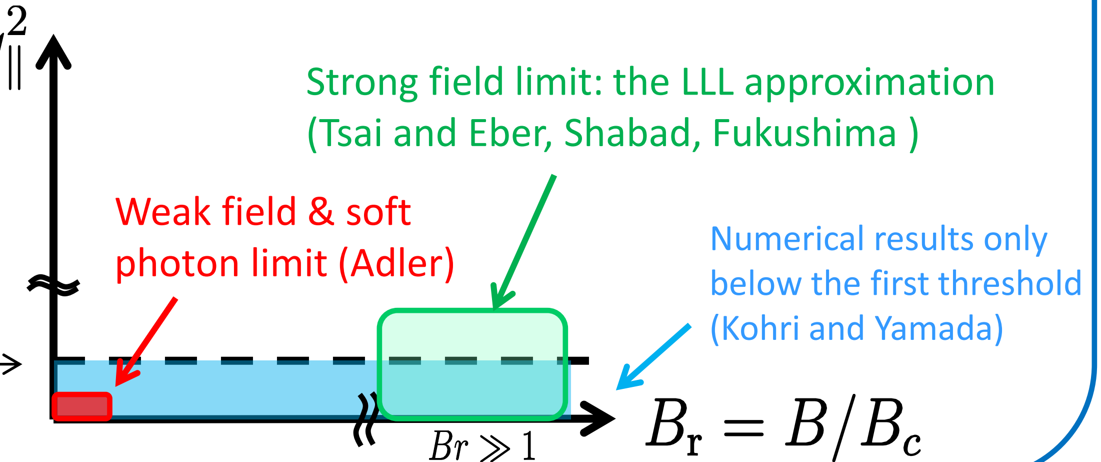
Recent achievements

K.Hattori and KI
in preparation

Obtained analytic expressions for χ_0, χ_1, χ_2 at any value of *B* and any value of photon momentum *q*.

UrHIC
$\sim 100^2 - 300^2$ MeV^2 (thermal)
$\sim$ GeV^2 (prompt)

The first threshold:
$q_\parallel^2 = 4m^2 = 1$ MeV^2



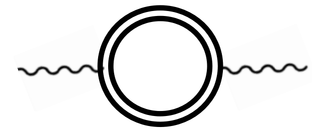
Obtained self-consistent solutions to the refractive indices including imaginary parts (within the LLL approx)

$$\begin{cases} n_1^2 = \dfrac{1+\chi_0+\chi_1}{1+\chi_0+\chi_1\cos^2\theta} \\ n_2^2 = \dfrac{1+\chi_0}{1+\chi_0+\chi_2\sin^2\theta} \end{cases}$$

χ_i contain refractive indices through photon momentum

Properties of coefficients χ_i

- **Given by the sum over two series of Landau levels**



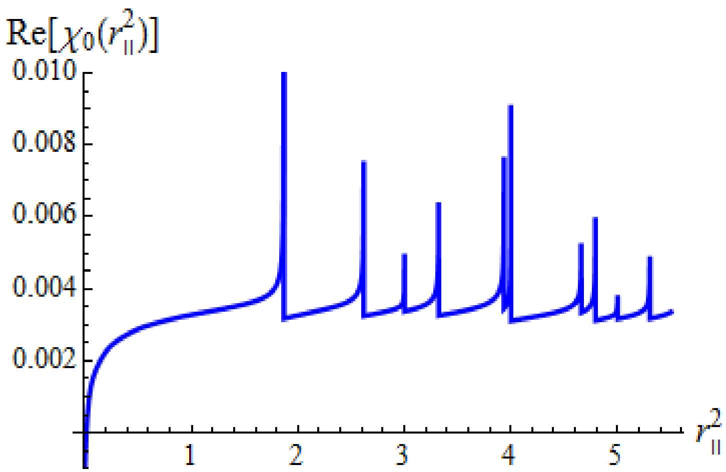
- **Imaginary parts appear at the thresholds**

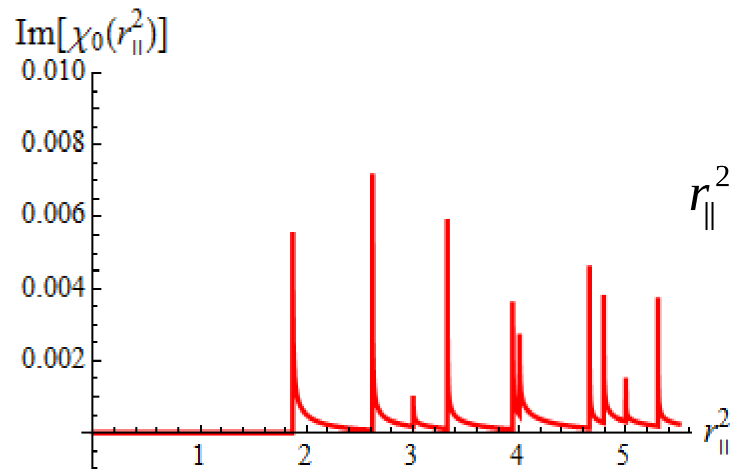
$$q_{\parallel}^2 = \left[\sqrt{m^2 + 2\ell eB} + \sqrt{m^2 + 2(\ell + n)eB} \right]^2$$

invariant masses of an e+e- pair in the Landau levels

corresponding to the "decay" of a (real) photon into an e+e- pair

- **Refractive indices are finite while there are divergences at each thresholds**





$$r_{\parallel}^2 = \frac{q_{\parallel}^2}{4m^2}$$

Self-consistent solutions

(in the LLL approximation $\chi_0 = \chi_2 = 0, \chi_1 \neq 0$)

Dielectric constants
$$\begin{cases} \epsilon_{\parallel} = \dfrac{1+\chi_1}{1+\chi_1 \cos^2\theta} \ (= n_{\parallel}^2) \\ \epsilon_{\perp} = 1 \end{cases}$$

$\chi_1(q_{\parallel}^2, q_{\perp}^2; B_{\mathrm{r}})$

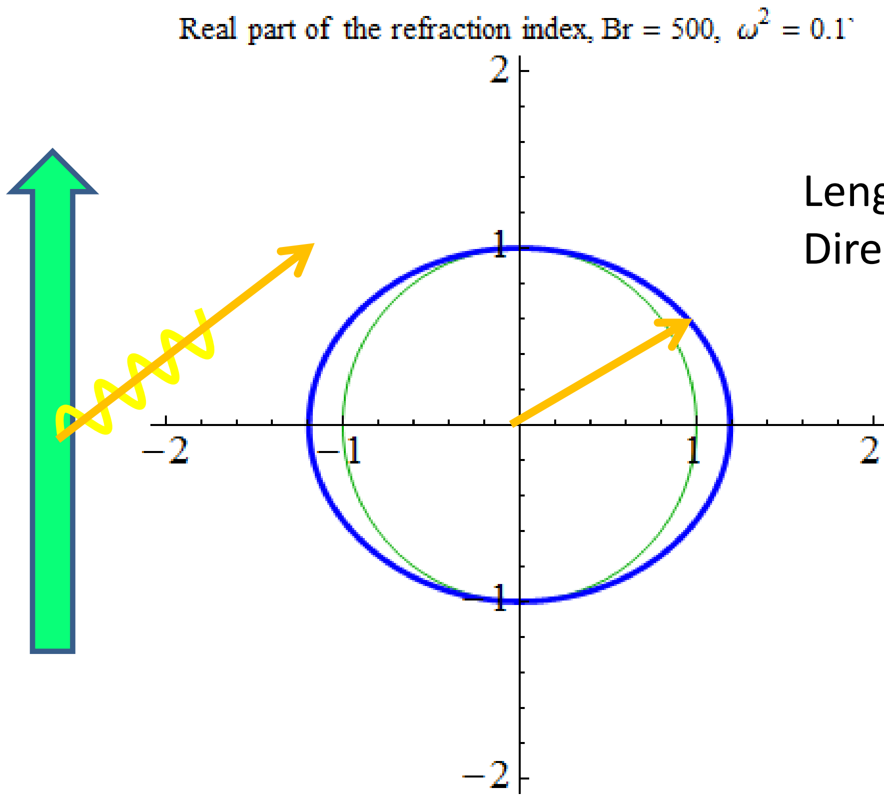
$$q_{\parallel}^2 = \omega^2 - q_z^2 = \omega^2(1 - \epsilon \cos^2\theta)$$
$$q_{\perp}^2 = -|\boldsymbol{q}_{\perp}|^2 = -\epsilon\, \omega^2 \sin^2\theta$$

Numerical results of real and imaginary parts of dielectric constant was shown here as functions of photon energy omega propagating in the direction of 45 degree for Br=500.

- **Dielectric constant (refractive index) deviates from 1**
- **There are two branches when the photon energy is larger than the threshold**
- **New branch is accompanied by an imaginary part indicating decay**

Effects on heavy-ion events

- **Refractive indices depend on the angle btw the photon momentum q and the magnetic field B.**

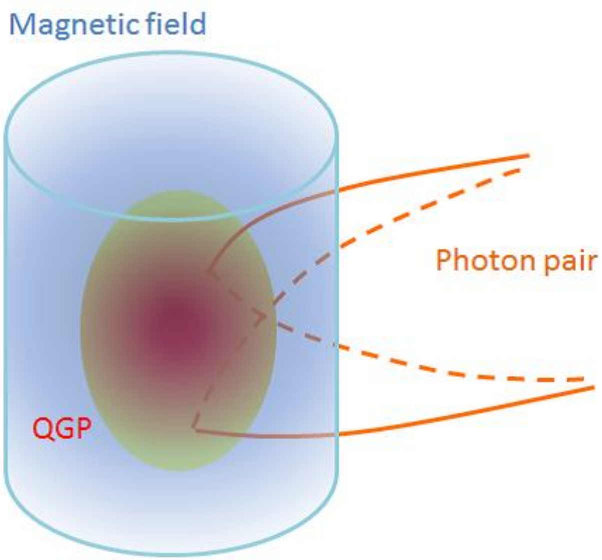


Length: magnitude of n
Direction: propagating direction

Angle dependence of the refractive indices yields anisotropic spectrum of photons

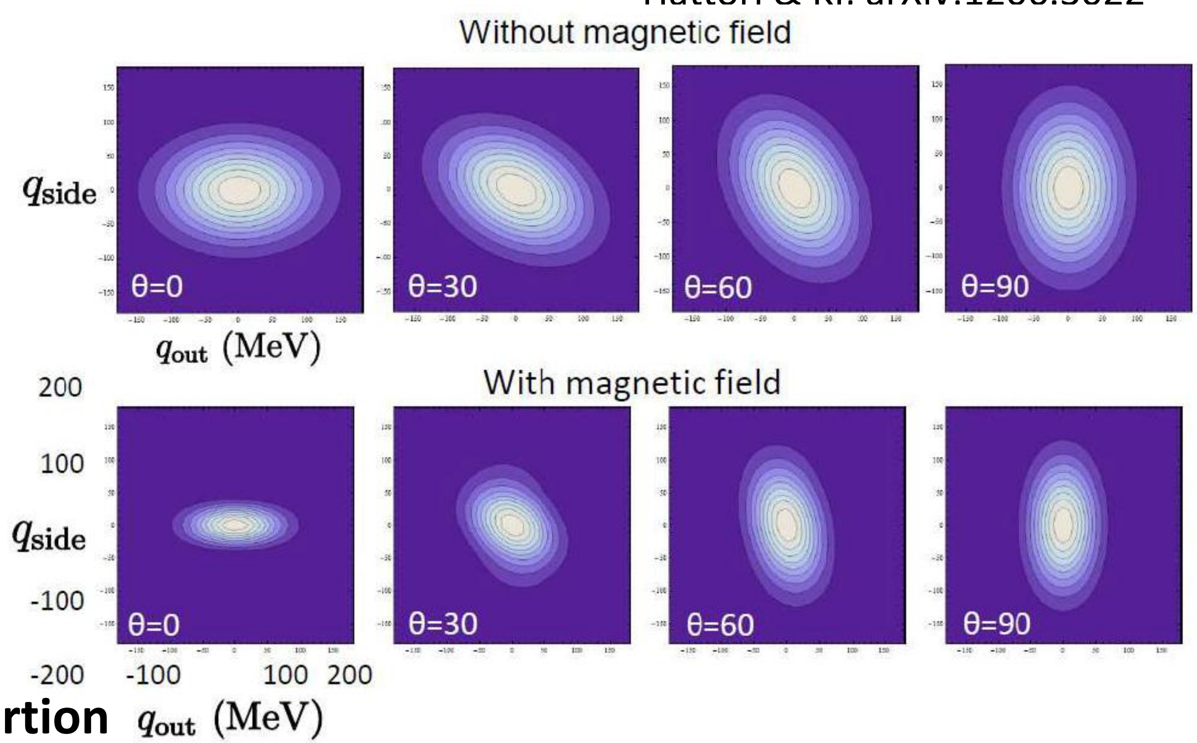
Consequences in HIC?

- **Generates elliptic flow (v_2) and higher harmonics (v_n)**
  (at low momentum region)
- **Distorted photon HBT image due to vacuum birefringence**



Based on a simple toy model with moderate modification

Hattori & KI. arXiv:1206.3022



Magnification and distortion

← can determine the profile of photon source if spatial distribution of magnetic field is known.

Other possible phenomena

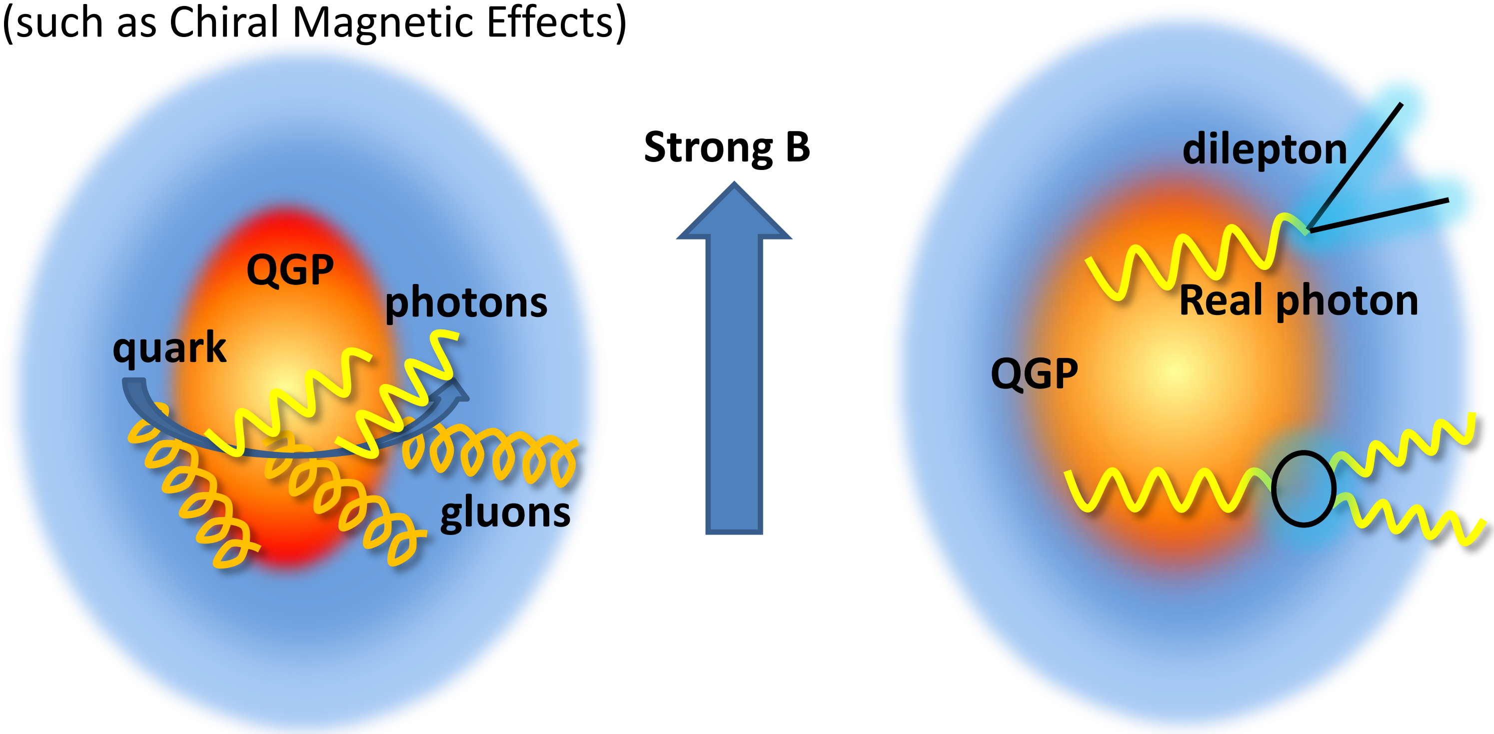
- **Synchrotron radiation of photons/gluons**

  → enhanced v_2 of photons or pions (scaling)

  photon v_2 will be further modified by birefringence

- **Photon splitting** → anomalous enhancement of soft photons
- **Interplay with color Yang-Mills fields/glasma**

  (such as Chiral Magnetic Effects)



Summary

- Strong-field physics of EM and YM fields is an indispensable aspect in understanding the early-time dynamics of HIC events.
- One can, in principle, extract the information of early-time dynamics by using the strong-field physics as probe.
- An example is “vacuum birefringence” of a photon which occurs in the presence of strong magnetic fields. It yields nontrivial v2 and higher harmonics, and distorted HBT images.
- A systematic analysis on the strong field physics will be necessary to better understand the early-time dynamics of HIC.