Investigating virtual photon polarization via $\gamma^* \to \mu\mu$ in Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV by numerical calculation

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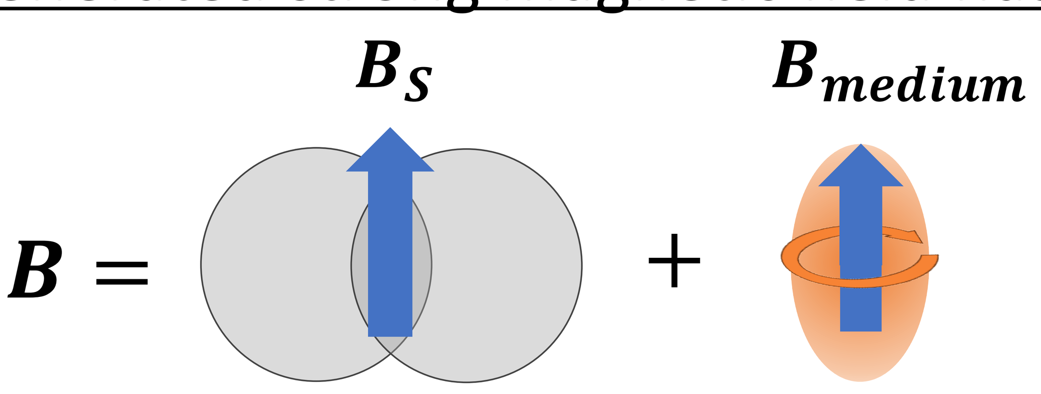
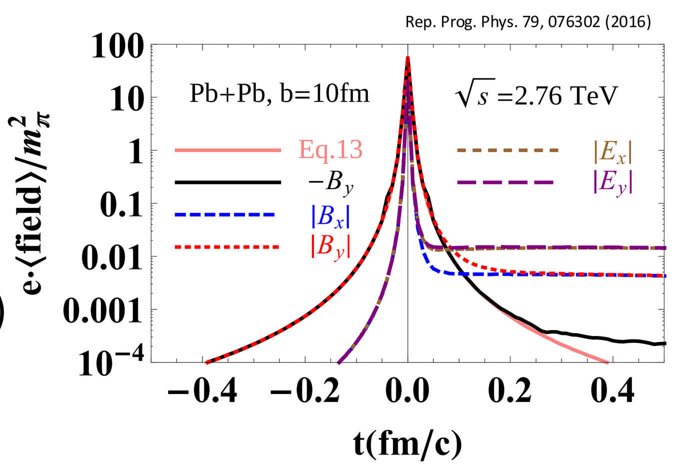
Strong magnetic field in high energy nuclear collision

Generated strong magnetic field has 2 component



B_{medium} : Generated by medium
B_s : Generated by spectator

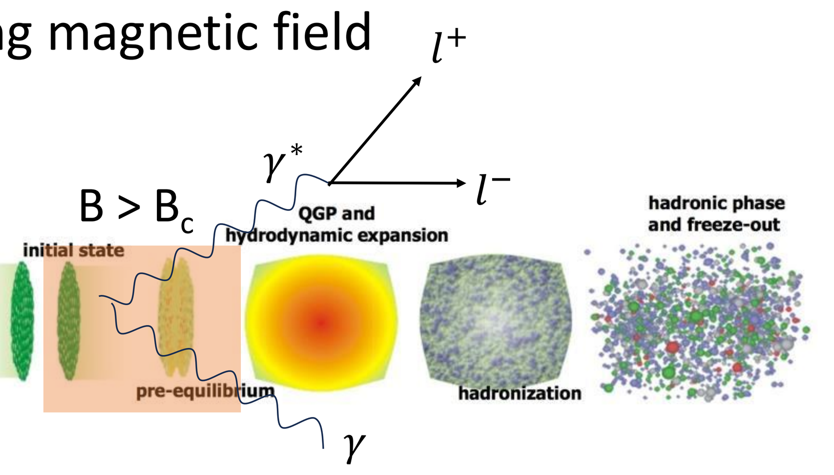
- Maximum intensity $B_s \sim 10^{15}$ T @ LHC
- lifetime of B generated by spectator ~ 0.1 fm/c
  - HIJING + Lienard-Wiechert potential
- Possibly be longer by QGP rotation
  - Observation of QGP rotation at STAR
- Predicted physics
  - Nonlinear QED (ex. vacuum birefringence, photon splitting)
  - Chiral magnetic effect
  - Quark's synchrotron radiation



Yet to be experimentally observed

Electromagnetic probe

- Prompt real/virtual photon is sensitive to strong magnetic field
  - Generated in the initial stage
    - Compton scattering and annihilation
  - Not to interact with strong interaction



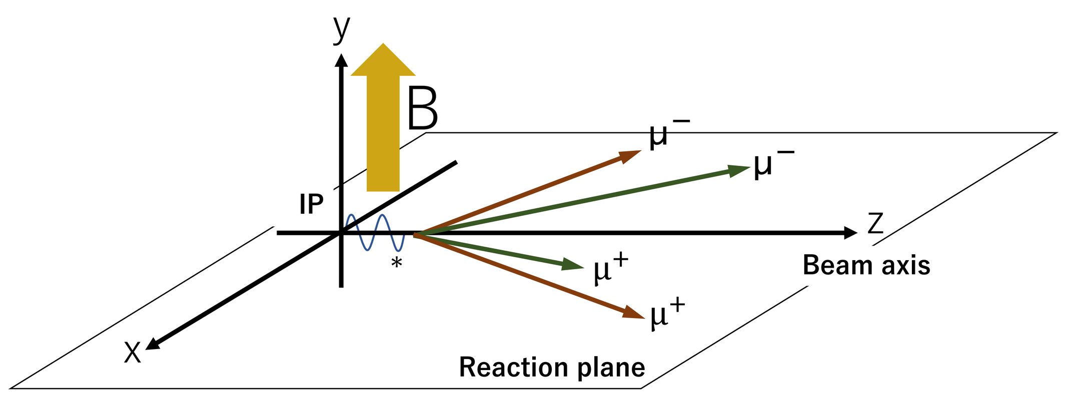
Virtual photon polarization

- Virtual photons decay anisotropically into lepton pairs due to the strong magnetic field
  - Contribute up to $(eB/m^2)^n$ $(n \to \infty)$ to virtual fermion pairs in one-loop

$$P = \frac{\langle N_\perp \rangle - \langle N_\parallel \rangle}{\langle N_\perp \rangle + \langle N_\parallel \rangle} \neq 0$$

$\langle N_\perp \rangle$: #($\gamma^* \to l^+l^-$) perpendicular to B

$\langle N_\parallel \rangle$: #($\gamma^* \to l^+l^-$) parallel to B



Purpose

We numerically calculate virtual photon polarization as input the time evolution of the magnetic field with RRMHD to evaluate polarization measurability in Pb-Pb at $\sqrt{s_{NN}} = 5.36$ TeV

Time evolution

Calculate time evolution of the magnetic field in Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV with Relativistic resistive Magneto-HydroDynamics (RRMHD) Nakamura, K., Miyoshi, T., Nonaka, C. *et al.* *Eur. Phys. J. C* 83, 229 (2023).

RRMHD

Hydrodynamics
$$\nabla_\mu N^\mu = 0$$
$$\nabla_\mu T^{\mu\nu} = 0$$
$$\nabla_\mu S^\mu \geq 0$$

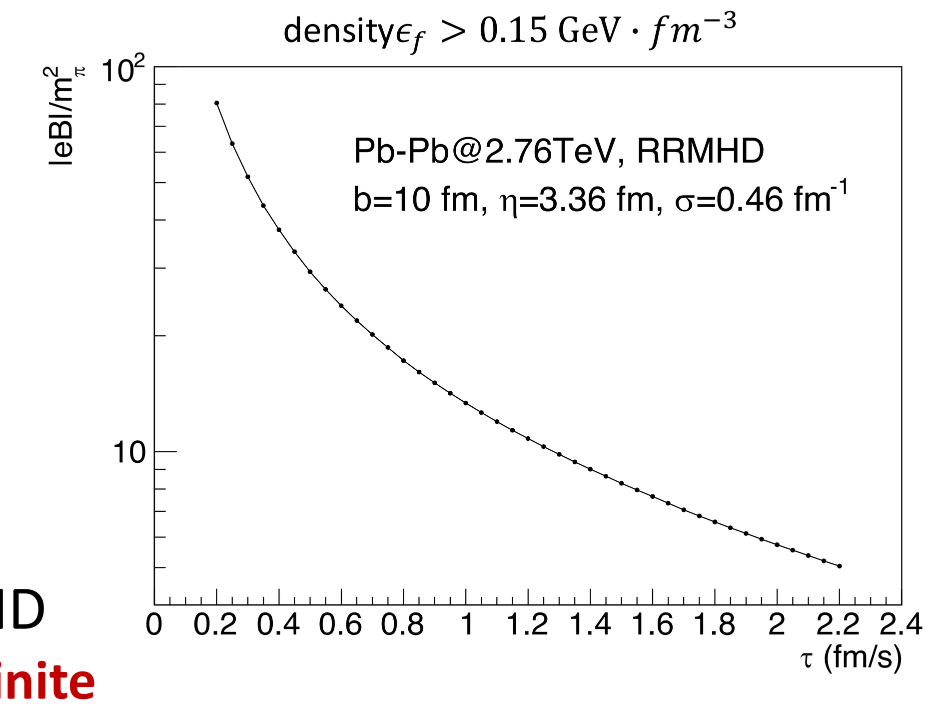
Maxwell's formula
$$\nabla_\mu F^{\mu\nu} = -J^\nu$$
$$\nabla_\mu {}^\star F^{\mu\nu} = 0$$

Ohm's law
$$J^\mu = \sigma F^{\mu\nu} u_\nu + q u^\mu$$

Initial value

relativistic column potential

Average of B_y in the energy density $\epsilon_f > 0.15\ \mathrm{GeV} \cdot fm^{-3}$

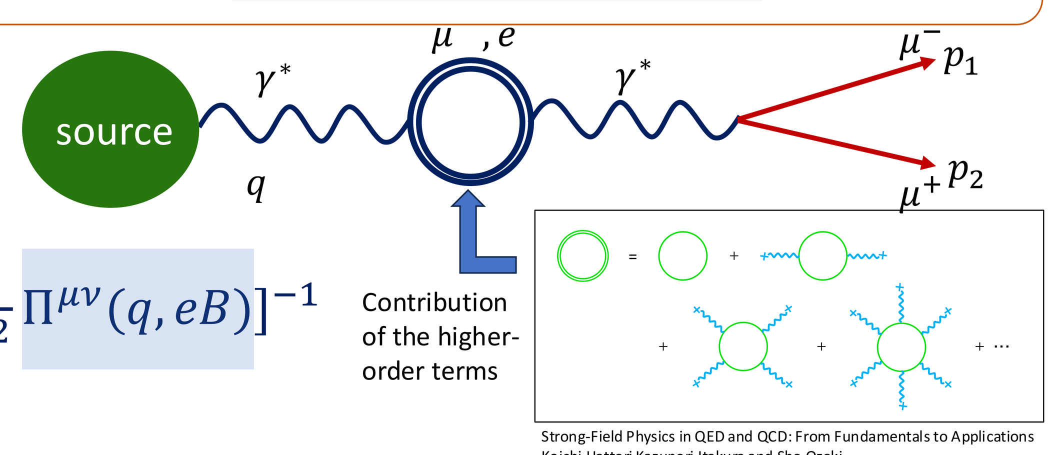


RRMHD is more realistic than RMHD
- electric conductivity: Infinity → **Finite**

Dimuon Production rate

K-I.Ishikawa *et al.*, Int. J. Mod. Phys. A 28, 1350100 (2013)

$$R_{\mu^+\mu^-} = \frac{\alpha^2}{2\pi^4}\left(\left(-g^{\alpha\beta}q^2 + q^\alpha q^\beta\right)C\right) D_{\mu\alpha}(q,eB) D^*_{\nu\beta}(q,eB)\, L^{\mu\nu}(p_1,p_2)$$



Photon propagator

$$D_{\mu\nu}(q,eB) = -\frac{i}{q^2}\left[g^{\mu\nu} - \frac{1}{q^2}\Pi^{\mu\nu}(q,eB)\right]^{-1}$$

◆ Vacuum polarization tensor

$$\Pi^{\mu\nu}(k) = \left(P^{\mu\nu} - P_\parallel^{\mu\nu} - P_\perp^{\mu\nu}\right)N_0(k) + P_\parallel^{\mu\nu}N_1(k) + P_\perp^{\mu\nu}N_2(k)$$

$$N_i = -\frac{\alpha}{4\pi}\sum_{n=0}^{\infty} C_n \sum_{l=0}^{\infty} \Omega_{i,l}^n(r,\eta,\mu) - \frac{\alpha}{4\pi}\int_{-1}^{1} dv \int_0^\infty dz\left[(\bar{N}_i(z,v)e^{i\bar{\psi}(z,v)\eta} - \frac{1-v^2}{z})e^{-i\frac{z}{\mu}}\right]$$

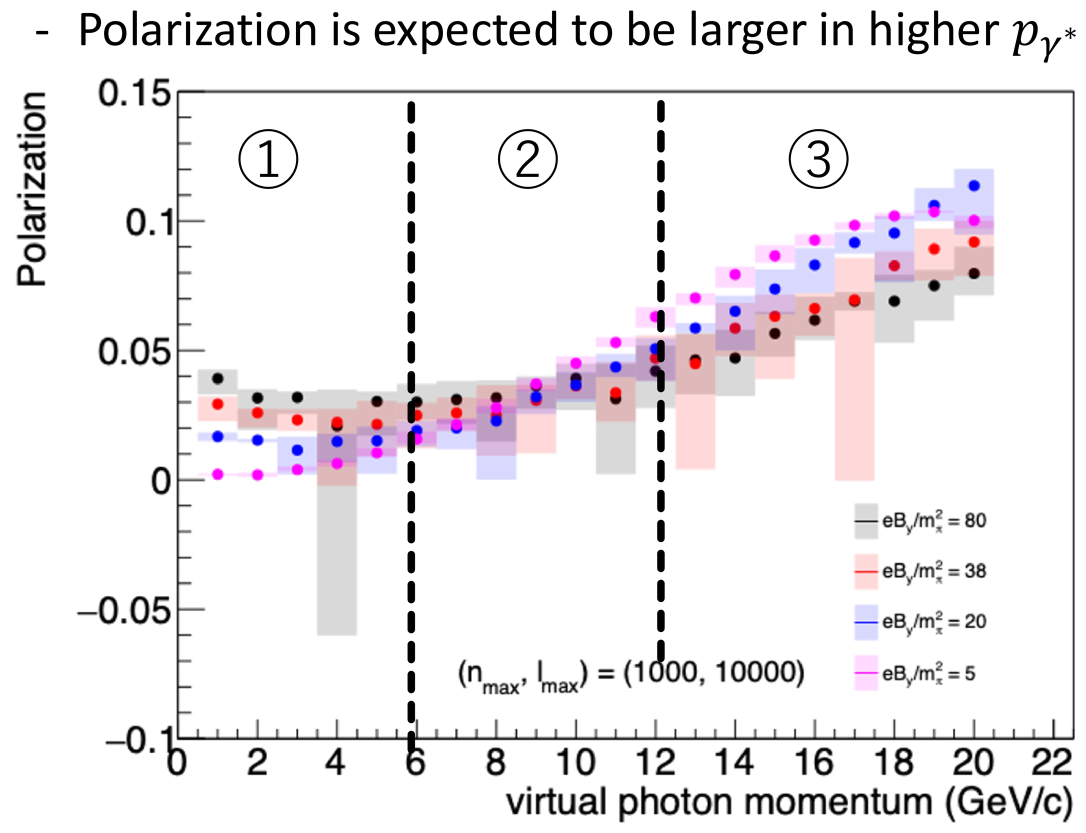
where $\mu = \frac{eB}{m^2}, r = \frac{k_\parallel^2}{4m^2}, \eta = \frac{2q}{\mu}, q = \frac{k_\perp^2}{4m^2}$

Double summation of landau level of virtual fermion pair in one-loop
- Set upper limit of landau level $(n_{max}, l_{max}) = (1000, 10000)$

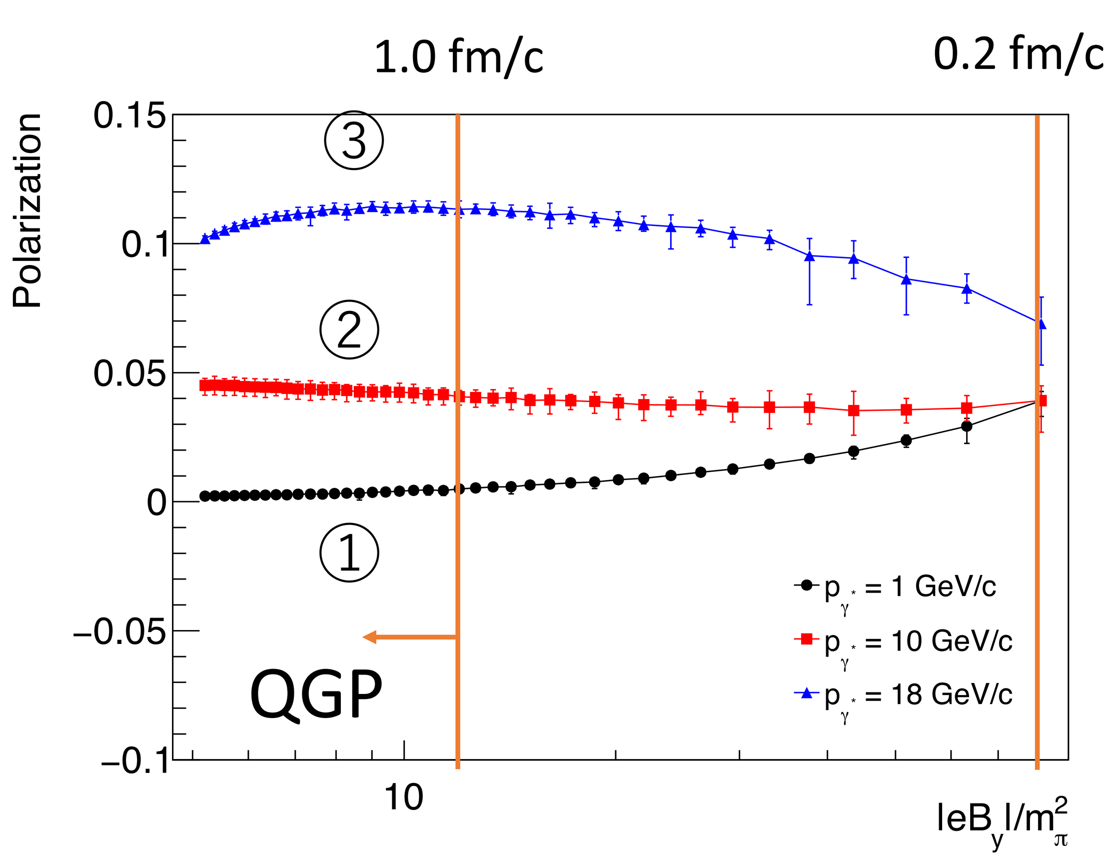
Calculation results of polarization in Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV

Calculation condition
- Virtual photon decay into dimuon parallel (perpendicular) to the magnetic field
- $M_{\gamma^*} = 300$ MeV
- $p_{\gamma^*} = (0, 0, p_{\gamma^*})$, $0 < p_{\gamma^*} < 20\ \mathrm{GeV}/c$

Polarization increases monotonically with p_{γ^*}
- At $p_{\gamma^*} = 20\ \mathrm{GeV}/c$, P is around 0.07
- Polarization is expected to be larger in higher p_{γ^*}



It is promising that different p_{γ^*} regions being measured could be sensitive to different times.
- In $\tau > 1.0$ fm/c, virtual thermal photons are expected to polarize
  - $p_{\gamma^* T}$ < 4 GeV/c, thermal photon is dominant



Expected Polarization at ALICE

◆Muon detector
- Acceptance : $2.45 < |\eta| < 4.0$
  - $p_T \approx 0.1 p_{\gamma^*}$

◆Yield of prompt virtual photon
- Estimate #(prompt real photon) in Pb-Pb at $\sqrt{s_{NN}} = 2.76\ TeV$ by pQCD
- Estimate #(promt virtual photon) by Kroll-Wada formula

◆For $0.5 < p_T < 2\ \mathrm{GeV}/c$, $\mathbf{P \approx 0.05}$
- Lower limit in the momentum region dominated by prompt photon

◆When $P_{cal} = 0.05$ and $p_T > 4\ \mathrm{GeV}/c$, $\boldsymbol{P_{meas} \neq 0}$ **at $\boldsymbol{\sigma = 1.8}$** at ALICE Run3
- Combinatorial background generated by PYTHIA8 PbPb

Prospect

- Need technical improvement on the numerical calculation in the higher photon moment
- Calculate time evolution in Pb-Pb at $\sqrt{s_{NN}} = 5.36$ TeV with RRMHD
- Measure virtual photon polarization with ALICE
- Need cut optimization to improve S/N