Virtual photon polarization and dilepton anisotropy in nucleus-nucleus collisions

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Introduction

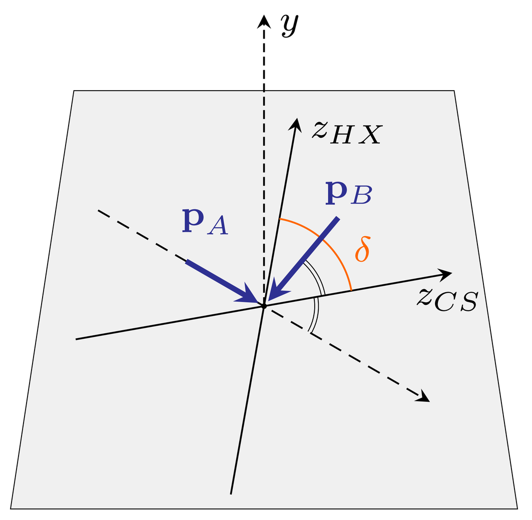
The polarization of virtual photons produced in relativistic nucleus-nucleus collisions provides information on the conditions in the emitting medium. In a hydrodynamic framework, the resulting angular anisotropy of the dilepton final state depends on the flow as well as on the transverse momentum and invariant mass of the photon. We illustrate these effects in dilepton production from quark-antiquark annihilation in the QGP phase and $\pi^+\pi^-$ annihilation in the hadronic phase for a static medium in global equilibrium and for a longitudinally expanding system [1].

Anisotropy coefficients

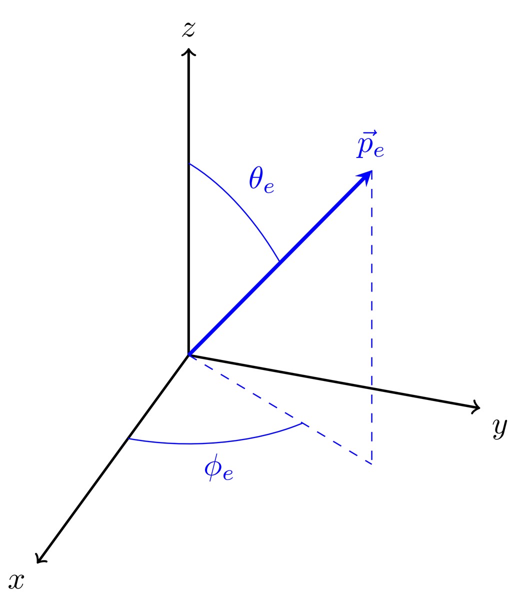
Angular distribution for $\gamma^* \to e^+e^-$ [2]:

$$\frac{d\Gamma}{d^4q d\Omega_e} = \mathcal{N}\Big(1 + \lambda_\theta \cos^2\theta_e + \lambda_\phi \sin^2\theta_e \cos 2\phi_e + \lambda_{\theta\phi} \sin 2\theta_e \cos\phi_e + \lambda_\phi^\perp \sin^2\theta_e \sin 2\phi_e + \lambda_{\theta\phi}^\perp \sin 2\theta_e \sin\phi_e\Big)$$

γ^* rest frame



The production plane, indicated in gray, is spanned by the three momenta of the initial ions ($\mathbf{p}_A$ and $\mathbf{p}_B$) in the γ^* rest frame



Polar and azimuthal angle of lepton momentum, the xz-plane is the production plane

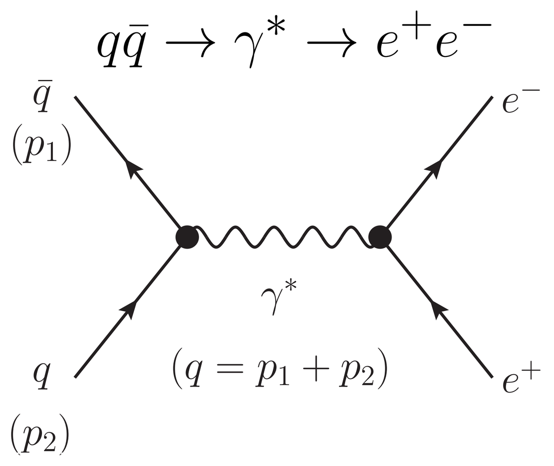
$$\lambda_\theta = \frac{\Sigma_\perp - \Sigma_\parallel}{\Sigma_\perp + \Sigma_\parallel}$$

- Virtual photon completely **transverse** polarized: $\lambda_\theta = +1$
  Virtual photon completely **longitudinal** polarized: $\lambda_\theta = -1$
- Photon polarization reflected in lepton angular distribution
- Anisotropy coefficients depend on the choice of the quantization axis
  - Helicity (HX): z-axis along photon momentum
  - Collins-Soper (CS): z-axis along bisector between beam and target
  - Different frames are related by rotation through angle δ about y-axis

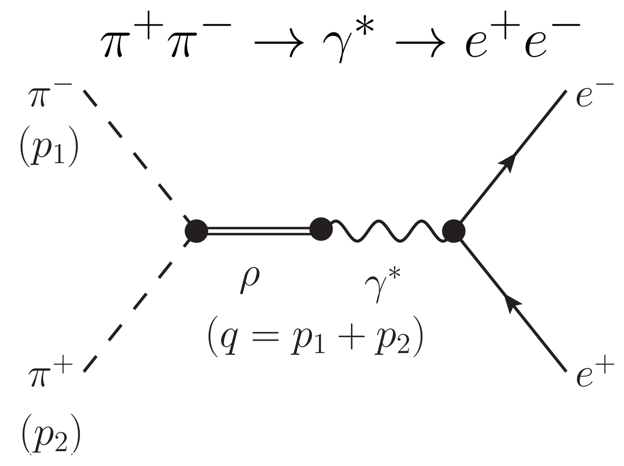
Virtual photon polarization from a thermal bath

In this work we considered two examples:

$q\bar{q} \to \gamma^* \to e^+e^-$



$\pi^+\pi^- \to \gamma^* \to e^+e^-$



- Thermal average of initial particles momenta p (Fermi or Bose distribution)

$$f(p) = \frac{1}{e^{(u\cdot p)/T} \pm 1}$$

- Fluid rest frame $u^\mu = (1,0,0,0)$

  $\Rightarrow$ Distribution is spherically symmetric. Photon momentum $\vec{q}$ breaks spherical symmetry (but not azimuthal symmetry)

  $\Rightarrow$ Virtual photons are tensor polarized (not vector polarized)
- $|\vec{q}| \to 0 \Rightarrow$ Spherical symmetry restored $\Rightarrow$ No virtual photon polarization
- Boltzmann limit $|\vec{q}| \to \infty$

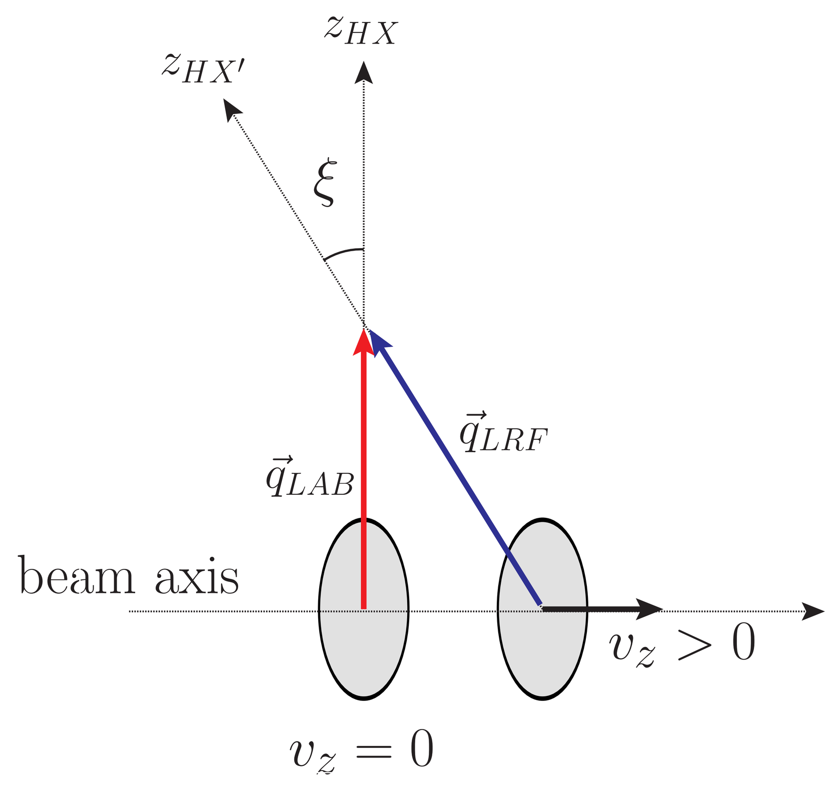
$$\int \frac{d^3p_1}{E_1}\frac{d^3p_2}{E_2}\frac{1}{e^{(u\cdot p_1)/T} \pm 1}\frac{1}{e^{(u\cdot p_2)/T} \pm 1} \sim e^{-(u\cdot q)/T} \int \frac{d^3p_1}{E_1}\frac{d^3p_2}{E_2}$$

No virtual photon polarization independently of virtual photon momentum

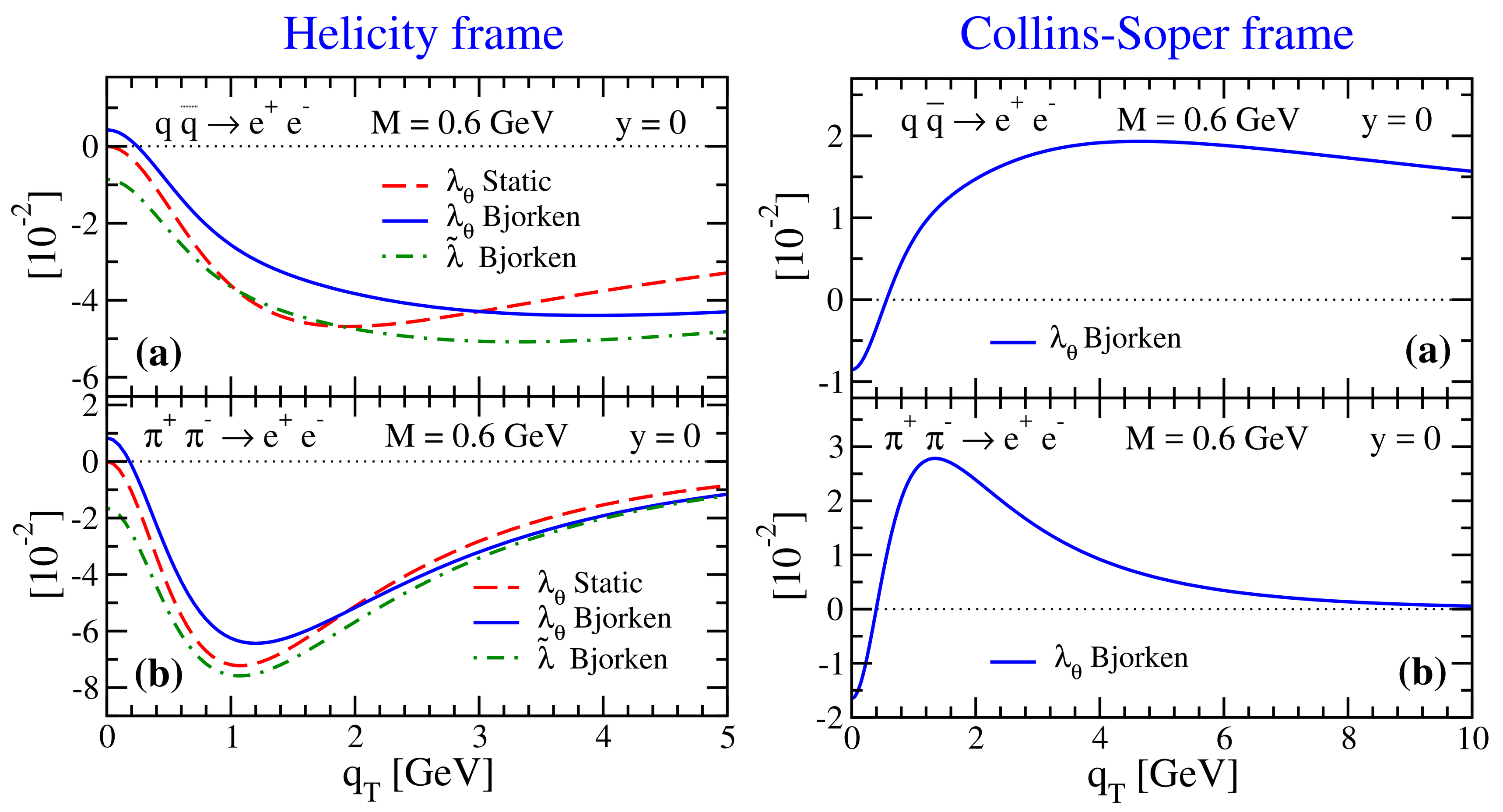
Medium and flow

- **Static uniform medium**
  - γ^* rest frame: fluid velocity $\vec{v}$ opposite to photon "direction"
    $\Rightarrow$ Only $\lambda_\theta \neq 0$
- **Longitudinal Bjorken expansion**
  - $v_z = z/t$ along beam axis
  - Virtual photon polarized along $z_{HX'}$ defined by its momentum in local rest frame
  - Rotation ξ between $z_{HX'}$ and z_{HX} (Wick helicity rotation)
    $\Rightarrow \lambda_\theta, \lambda_\phi, \lambda_{\theta\phi} \neq 0$
  - Frame invariant combination

$$\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$$



Results



Anisotropy coefficients as functions of the virtual photon transverse momentum q_T at an invariant mass $M = 0.6$ GeV and rapidity $y = 0$ for (a) the Drell-Yan process, and (b) pion annihilation. Left: HX frame, right: CS frame

- Static case: $\lambda_\theta \to 0$ for $q_T \to 0$
- Anisotropy coefficients $\to 0$ for $q_T \to \infty$ (Boltzmann limit)
- λ_θ changes sign from the Helicity to Collins-Soper frame
- Integration over γ^* kinematics (0.4 GeV $< M <$ 0.9 GeV, 0.6 GeV $< q_T <$ 2 GeV and $0.3 < y < 1.3$)
  - $q\bar{q}$ annihilation: $\lambda_\theta^{HX} \simeq -0.008$, $\lambda_\theta^{CS} \simeq 0.002$, $\tilde{\lambda} \simeq -0.034$
  - $\pi^+\pi^-$ annihilation: $\lambda_\theta^{HX} \simeq -0.014$, $\lambda_\theta^{CS} \simeq 0.007$, $\tilde{\lambda} \simeq -0.061$
- **Comparison with experimental results**
  - NA60 (In-In $158A$ GeV): $\lambda_\theta \simeq 0$ within error bars [3]
    $\Rightarrow$ Higher statistics $\Rightarrow$ unambiguous signal of virtual photon polarization
  - HADES (Ar-KCl at $1.76A$ GeV): $\lambda_\theta \simeq 0.5$, large polarization [4]
    $\Rightarrow$ Not consistent with annihilation processes in local thermal equilibrium (non equilibrium effects, Δ Dalitz decay)

Outlook

- Study different elementary reactions
- Anisotropic momentum distributions $\Rightarrow$ nonequilibrium [5, 6]
- Effect of vorticity and magnetic field (polarized medium)

References

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