Virtual photon polarization and dilepton anisotropy in relativistic nucleus-nucleus collisions

Enrico Speranza

E.S., A. Jaiswal, B. Friman, PLB **782**, 395 (2018)
B. Friman, R. Rapp, E.S., J. Wambach (in preparation)

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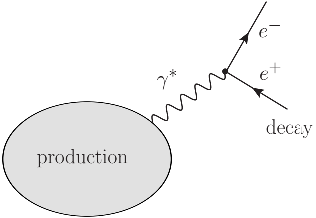
CRC-TR 211

Electromagnetic Radiation from Hot and Dense Hadronic Matter

ECT*, Trento, November 26, 2018

The goal



Angular distribution of the dilepton

$\Downarrow$

Information on the polarization states of the virtual photon

$\Downarrow$

Information on the production mechanism

- Early stages and onset of thermalization in HIC
(P. Hoyer, PLB **187**, 162; E. Shuryak, arXiv:1203.1012)
- Parton anisotropic momentum distributions in HIC
(G. Baym, T. Hatsuda, and M. Strickland, PRC **95**, 044907)
- Help disentangle different production mechanisms in elementary reactions
(E.S., M. Zétényi, and B. Friman, PLB **764**, 282)

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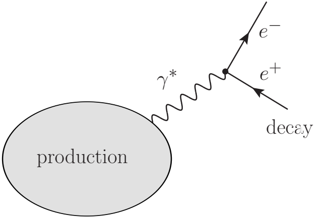

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Spin-density matrix

- **Pure state**: $|\psi\rangle = \sum_\lambda c_\lambda |\lambda\rangle$
  Expectation value of an operator $\langle O\rangle = \langle\psi|O|\psi\rangle$
- **Mixed state**: incoherent mixture of $|\psi_i\rangle$ with statistical weight a_i

$$\rho = \sum_i a_i |\psi_i\rangle\langle\psi_i| = \sum_{\lambda,\lambda'} \rho_{\lambda\lambda'} |\lambda\rangle\langle\lambda'|$$

$\rho_{\lambda\lambda'} = \sum_i a_i\, c_\lambda^{(i)} c_{\lambda'}^{(i)*}$. Expectation value: $\langle O\rangle = \mathrm{Tr}(\rho\, O)$

Example: Spin-1/2 particle (2×2 hermitian matrix):

$$\rho = \frac{1}{2}(1 + \vec{P}\cdot\vec{\sigma})$$

- Spin polarization vector: $\vec{P} = \langle\vec{\sigma}\rangle = \mathrm{Tr}(\rho\,\vec{\sigma})$

$$|\vec{P}| = 1 \quad \text{Pure state}$$
$$0 < |\vec{P}| < 1 \quad \text{Mixed state}$$
$$|\vec{P}| = 0 \quad \text{Completely unpolarized mixed state}$$

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Spin-density matrix for spin-1 particles

- Three polarization states (in rest frame)

$$\text{Transverse to } \vec{q}: \quad \epsilon(\pm 1) = \mp \frac{1}{\sqrt{2}}(0,\, 1,\, \pm i,\, 0)$$

$$\text{Longitudinal to } \vec{q}: \quad \epsilon(0) = (0,\, 0,\, 0,\, 1)$$

- **Spin-density matrix**: hermitian 3×3 matrix

$$\rho = \frac{1}{3}\left[1 + \frac{3}{2}\vec{P}\cdot\vec{S} + \sqrt{\frac{3}{2}}\sum_{i,j} T_{ij}(S_i S_j + S_j S_i)\right]$$

$\vec{S}$ are the spin-1 operators

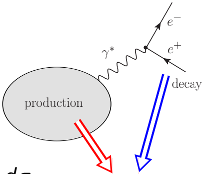
- $\mathrm{Tr}\rho = 1$ (8 parameters)
- Vector polarization: $\vec{P} = \langle \vec{S} \rangle$ (3 parameters)
- Tensor polarization: $T_{ij} = \frac{1}{2}\sqrt{\frac{3}{2}}\left(\langle S_i S_j + S_j S_i \rangle - \frac{4}{3}\delta_{ij}\right)$, $\sum_i T_{ii} = 0$
  (5 parameters)

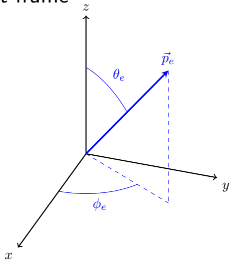
One can have tensor polarization without vector polarization

Lepton angular distribution

Photon rest frame

spin-1 $\rightarrow$ spin-$\frac{1}{2}$ + spin-$\frac{1}{2}$





$$\frac{d\sigma}{d\Omega_e} \propto \mathrm{Tr}(\,\rho\; O^{\mathrm{dec}}\,)$$

$$= \mathcal{N}\Big(1 + \lambda_\theta \cos^2\theta_e + \lambda_\phi \sin^2\theta_e \cos 2\phi_e + \lambda_{\theta\phi} \sin 2\theta_e \cos\phi_e$$

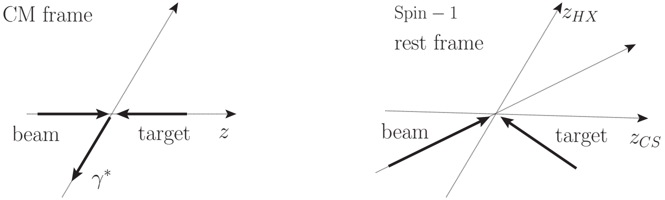
$$+ \lambda_\phi^\perp \sin^2\theta_e \sin 2\phi_e + \lambda_{\theta\phi}^\perp \sin 2\theta_e \sin\phi_e + \text{parity violating terms}\Big)$$

$$\lambda_\theta = \frac{\rho_T - \rho_L}{\rho_T + \rho_L}$$

- Transverse: $\rho_T = \rho_{-1-1} + \rho_{+1+1}$
  Longitudinal: $\rho_L = 2\rho_{00}$
  $(\rho = \sum_{\lambda,\lambda'} \rho_{\lambda\lambda'} |\lambda\rangle\langle\lambda'|)$
- Completely **transverse** polarized: $\lambda_\theta = +1$
  Completely **longitudinal** polarized: $\lambda_\theta = -1$
- Photon polarization reflected in angular distribution

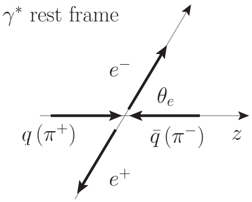
Reference frames

Anisotropy coefficients depend on the reference frame



- Helicity (HX): z-axis along photon momentum
- Collins-Soper (CS): z-axis along bisector between beam and target
- Different frames are related by rotation

Examples



- Drell-Yan process: $q\bar{q} \to \gamma^* \to e^+e^-$

$$\frac{d\sigma}{d\Omega_e} \sim 1 + \cos^2\theta_e$$

$\lambda_\theta = +1$. Virtual photon is completely transverse polarized along beam axis

- Pion annihilation process: $\pi^+\pi^- \to \gamma^* \to e^+e^-$

$$\frac{d\sigma}{d\Omega_e} \sim 1 - \cos^2\theta_e$$

$\lambda_\theta = -1$. Virtual photon is completely longitudinal polarized along beam axis

Virtual photon emission from a thermal medium

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

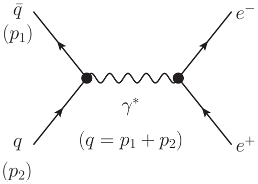
- Thermal average of initial particles momenta p through Fermi or Bose distribution
$$f(p) = \frac{1}{e^{(u\cdot p)/T} \pm 1}$$
- Fluid rest frame $u^\mu = (1, 0, 0, 0)$ ⇒ Distribution is spherical symmetric

> Photon momentum $\vec{q}$ breaks spherical symmetry,
> but not azimuthal symmetry

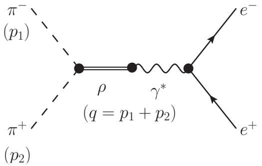
- Photons are only tensor polarized
- $|\vec{q}| \to 0$ ⇒ No anisotropy ⇒ No photon polarization

Boltzmann limit

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



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

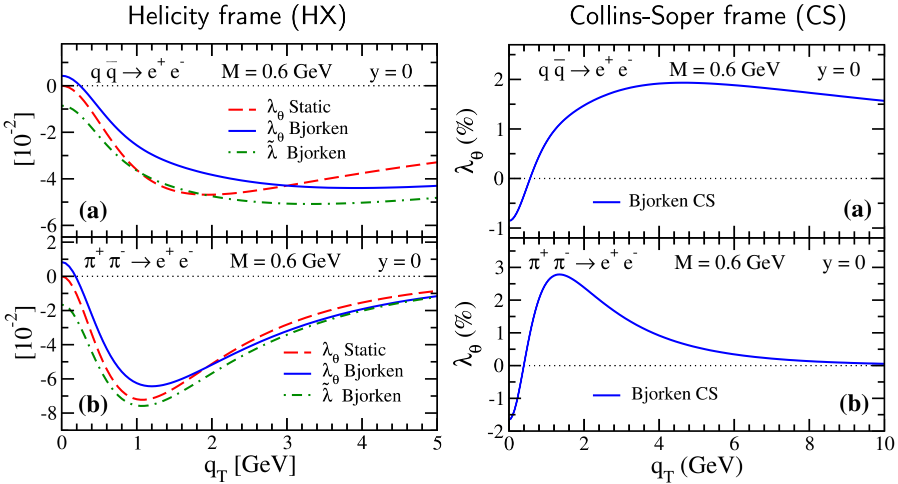


$$\int \frac{d^3 p_1}{E_1} \frac{d^3 p_2}{E_2} \frac{1}{e^{(u \cdot p_1)/T} \pm 1} \frac{1}{e^{(u \cdot p_2)/T} \pm 1} \sim e^{-(u \cdot q)/T} \int \frac{d^3 p_1}{E_1} \frac{d^3 p_2}{E_2}$$

- No photon polarization independently of photon momentum

Photon polarization is due to quantum statistics!

Results (static and Bjorken expansion)

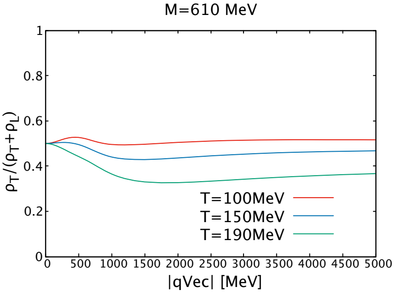


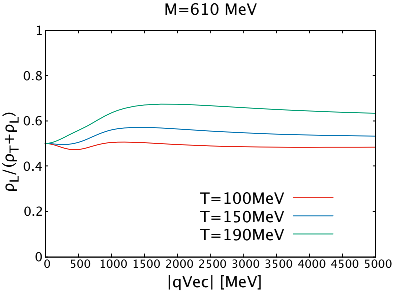
- Static case: $\lambda_\theta \to 0$ for $q_T \to 0$, and for $q_T \to \infty$ (Boltzmann limit)
- λ_θ changes sign from the Helicity to Collins-Soper frame
- Frame invariant combination: $\tilde{\lambda}_\theta = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$
- Experiments: sum over q_T

Realistic models (Preliminary)

$$\frac{d\sigma}{d\Omega_e} \propto \rho^{\mu\nu} L_{\mu\nu}$$

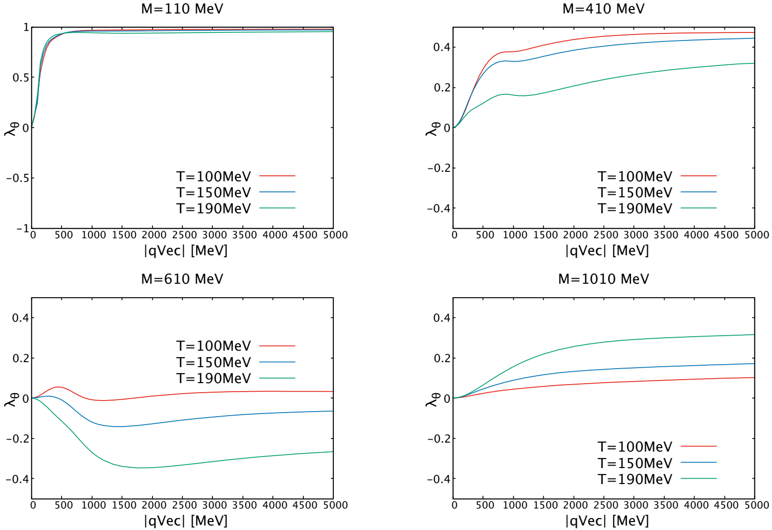
$$\rho^{\mu\nu} = \rho_T P_T^{\mu\nu} + \rho_L P_L^{\mu\nu}$$





- ρ_T, ρ_L taken from: Rapp, Chanfray, Wambach, NPA **617**, 472; Rapp, Wambach EPJA **6**, 415; Urban, Buballa, Rapp, Wambach, NPA **673**, 357

Polarization with realistic models (Preliminary)

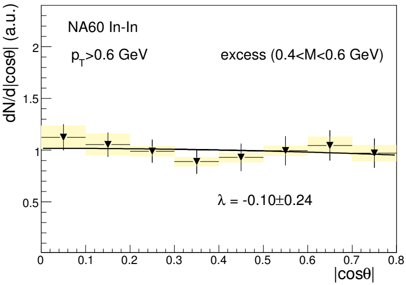


$\lambda_\theta = \frac{\rho_T - \rho_L}{\rho_T + \rho_L}$

Large polarization!

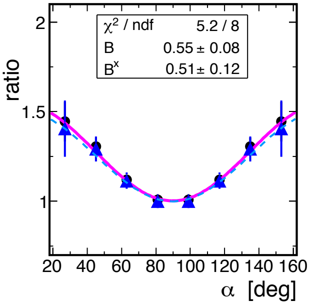
Experimental results (NA60 and HADES)

Collins-Soper frame



In-In at 158*A* GeV
(NA60 Collaboration), PRL **96**, 222301 (2009)

Helicity frame

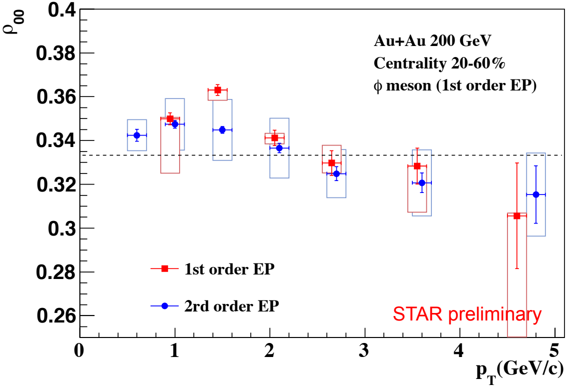


Ar-KCl at 1.76*A* GeV
(HADES Collaboration), PRC **84**, 014902 (2011)

- NA60: $\lambda_\theta \simeq 0$, but large error bars
- HADES: large polarization $\lambda_\theta \simeq 0.5$

ϕ meson polarization (STAR)

$$\lambda_\theta = \frac{3\rho_{00} - 1}{1 - \rho_{00}}, \qquad \rho_{00} = \rho_L$$



A. Tang, Chirality Workshop, Florence 2018; C. Zhou QM2018

- Noncentral collisions: large global angular momentum
  $\Rightarrow$ Vorticity $\Rightarrow$ Particle polarization
- Vorticity or just thermalized medium?

Conclusions

Summary

- Anisotropy coefficients as a tool to understand heavy-ion collisions
- Virtual photons from (unpolarized) thermal sources are polarized
- Collective flow affects shape of anisotropy coefficients
- Realistic models give large polarization

Outlook

- Analyze different elementary reactions
- Anisotropic momentum distributions $\Rightarrow$ nonequilibrium
- Effect of vorticity and magnetic field (polarized medium)

BACKUP

Diagonal form of the spin-density matrix

$$\rho = \frac{1}{3}\begin{pmatrix} 1+\frac{3}{2}P_z+\sqrt{\frac{3}{2}}T_{zz} & 0 & 0 \\ 0 & 1-\sqrt{6}T_{zz} & 0 \\ 0 & 0 & 1-\frac{3}{2}P_z+\sqrt{\frac{3}{2}}T_{zz} \end{pmatrix}$$

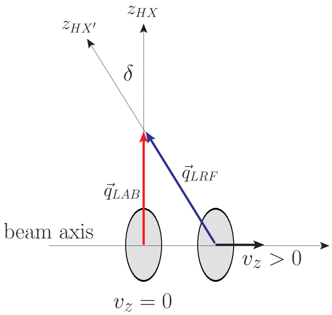
- In unpolarized system $P_z = 0$, but often $T_{zz} \neq 0$,
  i.e., no vector but tensor polarization!
- In general vector and tensor polarization axes can be different

Medium and flow

Static uniform medium

- Photon rest frame: fluid velocity $\vec{v}$ opposite to photon "direction"
- Only $\lambda_\theta \neq 0$

Longitudinal Bjorken expansion



- $v_z = z/t$ along beam axis
- Photon polarized along $z_{HX'}$ defined by its momentum in local rest frame
- Rotation δ between $z_{HX'}$ and z_{HX} (Wick helicity rotation) $\Rightarrow \lambda_\theta, \lambda_\phi, \lambda_{\theta\phi} \neq 0$
- Frame invariant combination:

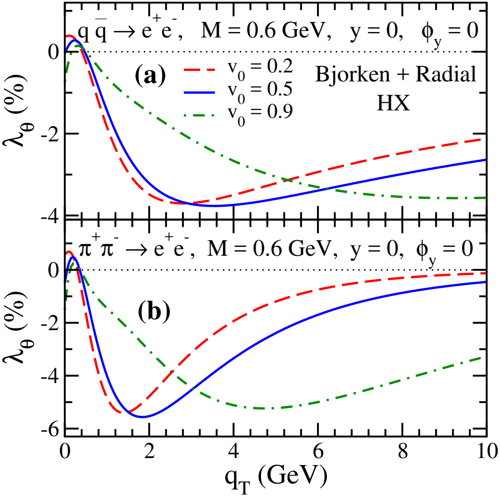
$$\tilde{\lambda}_\theta = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$$

Longitudinal Bjorken + Radial expansion

- All coefficients $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}, \lambda_\phi^\perp, \lambda_{\theta\phi}^\perp \neq 0$

Results (Bjorken + radial expansion)

Helicity frame (HX)



- $v_\perp = v_0 r_\perp / R_0$ (Transverse to beam axis)
- The position of the minimum shifts towards higher q_T as v_0 increases