The polarization of thermal dileptons at the next-to-leading order

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Based on:

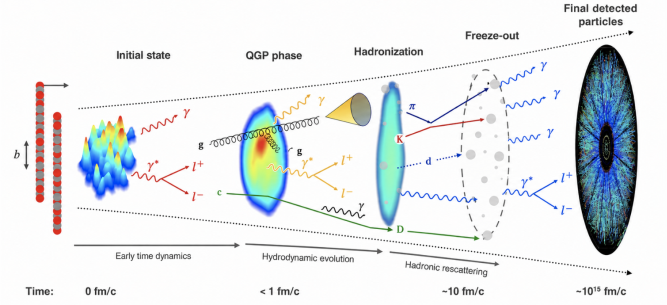
- Xiang-Yu Wu, et al, Phys. Rev. Lett., 134:242301 [2412.15052]
- Han Gao, et al [2605.30180]
- Han Gao, et al [in preparation]

Introduction

$$\frac{dN}{d^4K d\Omega_\ell} \propto 1 + \lambda_\theta \cos^2\theta_\ell + \ldots$$

EM probes of the QGP

- Real/virtual photons: produced in all stages of the fireball evolution.
  - Virtual photon = Dilepton



[ALICE, EPJC 84 (2024) 8, 813]

- $\alpha_{em} \ll \alpha_s \Rightarrow$ Penetrating probes: minimal medium interaction after created.

Dileptons and photon spectral function

- Photon spectral function: current-current correlator

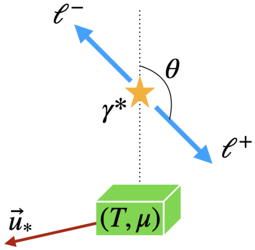
$$\rho_{\mu\nu}(\omega,\vec{k}) \equiv -\mathrm{Im}\int_0^{1/T} d\tau \int d^3\vec{x}\, e^{i\omega_n\tau - i\vec{k}\cdot\vec{x}} \langle J_\mu(\tau,\vec{x}) J_\nu(0,\vec{0})\rangle_T \Big|_{i\omega_n\to\omega+i0^+}.$$

- Dilepton production rate in the plasma rest frame: probing the trace part

$$\frac{dR_{\ell\bar{\ell}}}{d^4K} = \frac{2\alpha_{\mathrm{em}}^2}{9\pi^3}\,\frac{n_B(\omega)}{M^2}\,B\left(\frac{m_\ell^2}{M^2}\right)\rho^\mu_\mu(\omega,|\vec{k}|)$$

  - Invariant mass $M = \sqrt{K^2}$.
  - Kinematic factor $B(\xi) = (1+2\xi)\sqrt{1-4\xi}$.
  - Generalize to any frame by $\omega \to u\cdot K$ and $|\vec{k}| \to \sqrt{(u\cdot K)^2 - M^2}$.

Dilepton polarization



- The preferred direction that ℓ^+ emits into.
- Measured in the rest frame of γ^* $\Rightarrow$ Special direction set by the plasma velocity in this frame $\vec{u}_*$.
  - Even if the plasma is at rest in the lab frame.
- Quantification: polarization coefficients

$$\frac{dN}{d^4K d\Omega_\ell} = \mathcal{N}\Big(1 + \lambda_\theta \cos^2\theta_\ell + \lambda_\phi \sin^2\theta_\ell \cos 2\phi_\ell + \lambda_{\theta\phi} \sin 2\theta_\ell \cos\phi_\ell + \lambda_\phi^\perp \sin^2\theta_\ell \sin 2\phi_\ell + \lambda_{\theta\phi}^\perp \sin 2\theta_\ell \sin\phi_\ell\Big).$$

Polarization and spectral function

- $\rho^{\mu\nu}$ decomposed wrt the fluid velocity u^μ:

$$\rho_L = -\frac{K^2\, \rho_{\mu\nu} u^\mu u^\nu}{(u\cdot K)^2 - K^2}\,, \quad \rho_T = \frac{\rho^\mu_\mu - \rho_L}{2}.$$

- In complementary to rate $\propto \rho^\mu_\mu = 2\rho_T + \rho_L$, polarization measures $\rho_\Delta = \rho_T - \rho_L$.
- In HX frame where $\vec{e}_z = \hat{k}$, for a plasma at rest in the lab frame ($\vec{u} = 0$)

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

see, e.g., E. Speranza et al, PLB 2018 [1802.02479].

Polarization coefficient with flow effect

- Starting from *Kapusta & Gale*

$$E_+E_-\frac{dN}{d^3\vec{p}_+d^3\vec{p}_-} = -\frac{4e^4}{3(2\pi)^6}\frac{n_B(\omega)}{M^4}L^{\mu\nu}\rho_{\mu\nu}$$

- Generalize to any fluid velocity $u^\mu = \gamma(1, \vec{v})$.
- Integrate out irrelevant kinematics

$$\lambda_\theta = \frac{3\left(\chi_z - \frac{1}{3}\right)(1-4\xi)\,\rho_\Delta}{\frac{4}{3}(1+2\xi)\,\rho^\mu_\mu - \left(\chi_z - \frac{1}{3}\right)(1-4\xi)\,\rho_\Delta},$$

  - with $\chi_z = (u_*^z)^2/\vec{u}_*^2$, $\xi = m_\ell^2/k^2$.

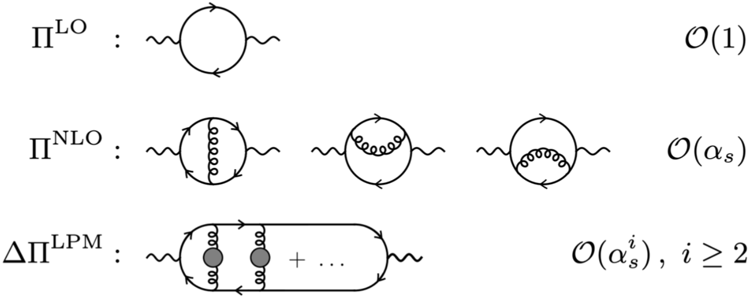
- Includes flow info $\vec{u}_* = \vec{u} + \left(\frac{\omega}{M} - 1\right)(\vec{u}\cdot\hat{k})\hat{k} - \frac{u_0\vec{k}}{M}$ $\Rightarrow$ Embedded in hydro simulation.

NLO dilepton polarization

As $M \to 0$, the LO process $q\bar{q} \to \ell^+\ell^-$ becomes kinematically forbidden.

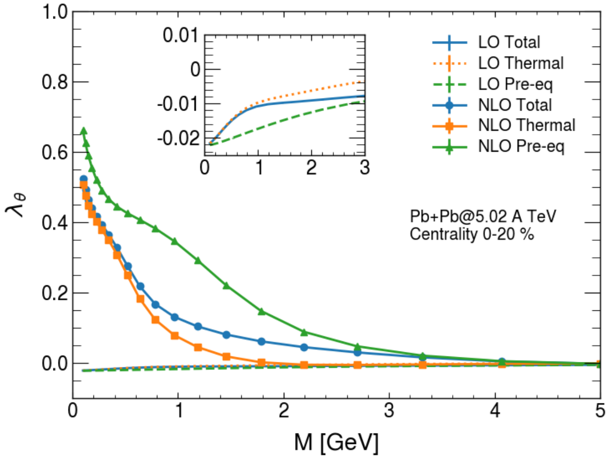
Spectral function at LO and NLO

- Leading order $\rho_{\mu\nu}$: a single fermion loop for $q\bar{q}$ annilation
  - Phase space vanishes as $M \to 0$.
- Next-to-leading order + Landau-Pomeranchuck-Migdal: gluon mediated processes [J. Churchill, et al, PRC 2024, 2311.06675]



  - "NLO" = NLO + LPM hereon.

Comparing LO and NLO polarization



- Gluonic processes such as $gq \to \gamma^* q$ open up new phase space $\Rightarrow$ allowing "almost real" photons.
- Real photons have only T polarization $\Rightarrow$ For $M \lesssim 3$ GeV, adding NLO changes λ_θ significantly.

Phenomenological approach to pre-eq

Fireball side:

- KøMPøST: evolves $T_K^{\mu\nu}(\tau, \vec{x})$ by QCD kinetic theory.
- Landau matching $T^\mu_\nu u^\nu = \mathcal{E} u^\mu \Rightarrow T_\text{eff}$ extracted from QCD EoS.

Dilepton side:

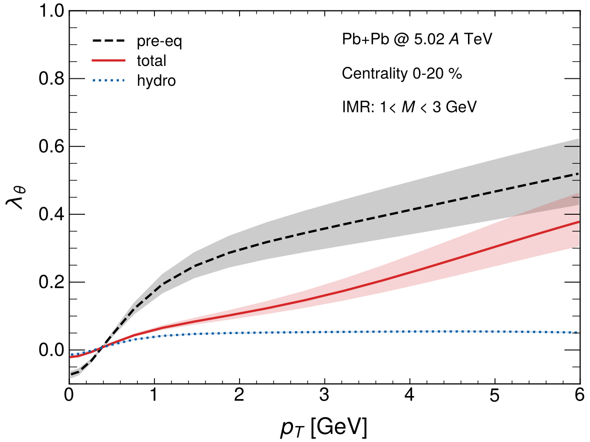
- Differential rate with $T \to T_\text{eff}$.
- Less quarks than chemical eq. $\Rightarrow$ suppression factor $f^\text{pre-eq}_{q/\bar{q}} = \text{SF}(T, \tau) f^\text{eq}_{q/\bar{q}}$.
- To rate: LO channel $q\bar{q} \to \gamma^*$ has two quarks; NLO channels involve 1 or 2 quarks $\Rightarrow$ less suppressed

$$dR^\text{pre-eq} = \mathrm{SF}^2 \cdot dR^\mathrm{eq}_\mathrm{LO} + \mathrm{SF}^\alpha \cdot dR^\mathrm{eq}_\mathrm{NLO}.$$

- Suppression index $\alpha \in (1, 2)$.

Pre-equilibrium dileptons: results

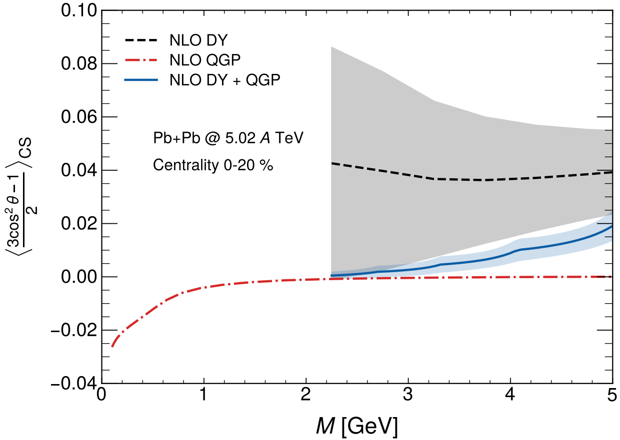
- Pre-eq dileptons are the major contributor of the polarization in IMR $1\text{ GeV} \lesssim M \lesssim 3\text{ GeV}$.
  - Chemically: richer in gluon $\Rightarrow$ larger λ_θ.
  - Thermodynamically: higher "temperature" $\Rightarrow$ stronger medium effect $\Rightarrow$ larger λ_θ.



*uncertainties from all possible α values.

Drell-Yan dileptons

- DY dileptons: hard partonic reactions at the first instant.
- pQCD processes, NLO calculation by DY Turbo [S. Camarda, et al, EPJC 2020, 1910.07049].
- Dominate polarization signals for $M \gtrsim 3$ GeV.



*uncertainties from renormalization scale in DY Turbo.

Off-equilibrium effects

For a more complex $\rho^{\mu\nu}$

More than a single decomposition

- Vector/tensor elements other than u^μ
  - EM field $F^{\mu\nu}$, vorticity $\omega^{\mu\nu}$, shear tensor $\pi^{\mu\nu}$, diffusion n^μ ...

$\Rightarrow$ more complex tensor structure in $\rho^{\mu\nu}$

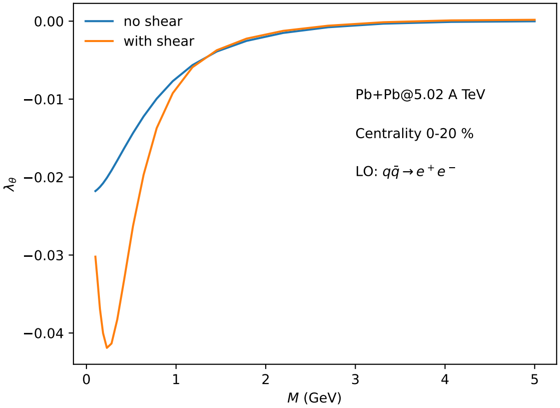
- T & L decomposition of $\rho^{\mu\nu}$ no longer holds.
- Obtain an equation for λ_θ for $\rho_{\mu\nu} = \rho^{(0)}_{\mu\nu} + \delta\rho_{\mu\nu}$.
- In $m_\ell = 0$ limit

$$\delta\lambda_\theta = \left(3 + \lambda_\theta^{(0)}\right) \frac{2\left(1 + \lambda_\theta^{(0)}\right)\delta\rho_Z^* - \left(1 - \lambda_\theta^{(0)}\right)\left(\delta\rho_X^* + \delta\rho_Y^*\right)}{4(1 + 2\xi)\rho_V}$$

  - where $\delta\rho_I^* = \delta\rho^*_{\mu\nu} e_I^\mu e_I^\nu$.

Shear induced polarization

- Shear correction $\delta\rho^{\mu\nu}$ obtained by kinetic theory $\Rightarrow$ limited in LO.
- Enhancement observed in low M region.
- See also dilepton polarization induced by plasma anisotropy: M. Coquet, et al, PRL 2024 [2309.00555].



Summary

- Dilepton polarizations provide a direct window to measure the in-medium photon spectral function, especially for $\rho_\Delta = \rho_T - \rho_L$.
- NLO correction in $\rho^{\mu\nu}$ changes polarization signal significantly.
- Pre-eq dileptons are the main contributor to polarization in IMR; DY dileptons HMR.

Outlook

- Potential of probing vector/tensor elements of the QGP.
- Higher order in α_s, lattice inputs.
- Including hadronic gas $\rho^{\mu\nu}$ $\Rightarrow$ a complete description.

Backup: the frames