Measuring pressure anisotropy of the quark-gluon plasma through photon polarization

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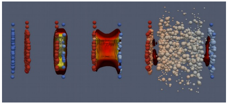
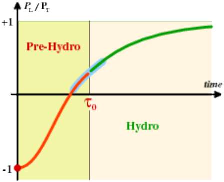
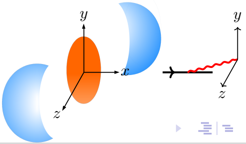
- QGP has pressure anisotropy at early and intermediate times, $P_L < P_T$.
- Due to competition between longitudinal expansion and interaction.
- Photon and dileptons emitted at this stage.
- Anisotropy of medium makes the photons and dileptons polarized.
- This polarization is a direct measure of pressure anisotropy.
- Difficult measurement.



[Bernhard et al. (2019)]



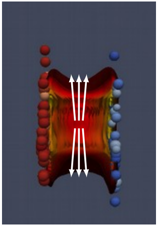
[Gelis (2015)]



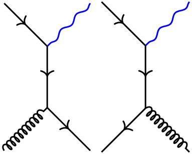
Photon and dilepton polarization

- Medium expansion leads to anisotropy in quark momentum, $\langle |p_z| \rangle < \langle |p_x| \rangle, \langle |p_y| \rangle$

$$f(\mathbf{p}) = \sqrt{1+\xi} f_{\rm eq}\left(\sqrt{\mathbf{p}^2 + \xi p_z^2}\right), \qquad \xi > 0$$



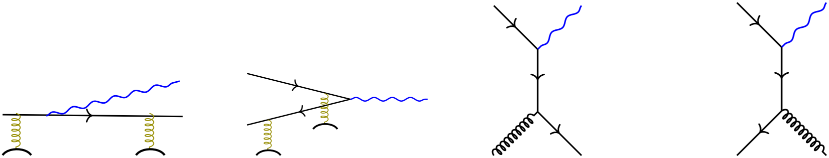
- Gives polarization to emitted photons:
    - Coupling between photon and charge current ($A^0 = 0$): $\boldsymbol{\epsilon} \cdot \mathbf{j}$
    - Anisotropy in $\mathbf{j}$ gives net polarization $\boldsymbol{\epsilon}$.
- 2-to-2 production: [Baym, Hatsuda (2015)]



- Other suggestions for sources of polarization:
    - Magnetic fields in holography: Wu, Yang (2013); Yee (2013); Avila et al. (2021)
    - Vorticity: Dong, Lin (2022)
    - Chiral magnetic effect etc: Tang, Wang (2016); Mamo, Yee (2013); Ipp et al. (2008)
- Want full LO calc. in expanding medium.

Photon and dilepton production in pQCD

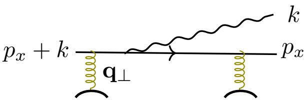
- Photon processes at leading order:



Aurenche et al. (1998) — Arnold et al. (2001) — [Baier et al. (1992)] — [Kapusta et al. (1991)]

- Here focus on bremsstrahlung and pair annihilation.
  - As important as 2-to-2 scattering for photons.
  - Want to establish sign and size of effect.
  - NLO for low-virtuality dileptons but high gluon occupancy can make more important.
    (For polarization of LO dileptons, see e.g. [Baym, Hatsuda, Strickland (2017); Shuryak (2010); Speranza, Jaiswal, Friman (2018); Coquet et al. (2021)])

Photon production through bremsstrahlung



- Transverse kicks from medium bring quark off-shell: it radiates collinearly.
- During emission of photon can have arbitrarily many medium kicks.
- In equilibrium ($\zeta = k/(p_x + k)$): Arnold, Moore, Yaffe (2001); Aurenche, Gelis, Zaraket (2002)

$$k\frac{d\Gamma_z}{d^3k} \sim \alpha_{EM} \int dp^x \; n_f(k+p^x)\left[1 - n_f(p^x)\right] \frac{k}{p_x^2(k+p_x)} P_{q\to q\gamma}(\zeta)\, \mathrm{Re} \int d^2p_\perp \; \mathbf{p}_\perp \cdot \mathbf{f},$$

$$2\mathbf{p}_\perp = i\delta E\, \mathbf{f}(\mathbf{p}_\perp) + \int \frac{d^2q_\perp}{(2\pi)^2}\, \mathcal{C}(\mathbf{q}_\perp)\left[\mathbf{f}(\mathbf{p}_\perp) - \mathbf{f}(\mathbf{p}_\perp + \mathbf{q}_\perp)\right], \qquad \delta E = \frac{k}{2p(p+k)}\left[p_\perp^2 + m_\infty^2\right]$$

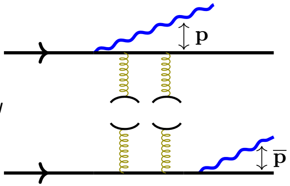
$$\mathcal{C}(\mathbf{q}_\perp) = g^2 C_F T \left(\frac{1}{q_\perp^2} - \frac{1}{q_\perp^2 + m_D^2}\right)$$

Polarization in bremsstrahlung

- Polarization comes from interplay between hard vertex and momentum broadening.

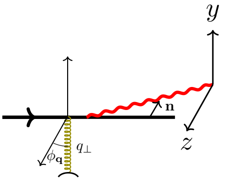
- Hard vertex:

$$\begin{array}{lccc} \text{z-polarized} & \frac{(2-\zeta)^2}{\zeta} p_z \overline{p}_z & + & \zeta\, p_y \overline{p}_y \\ \text{y-polarized} & \zeta\, p_z \overline{p}_z & + & \frac{(2-\zeta)^2}{\zeta} p_y \overline{p}_y \end{array}$$



- Kicks from medium needed to bring $\mathbf{p}$ to $\overline{\mathbf{p}}$.

- If more momentum broadening in z-direction get net z-polarization.



Momentum broadening

- Strong anisotropy at early times, $\widehat{q}_z > \widehat{q}_y$.

  $\widehat{q}_z := d\langle p_z^2\rangle/dt$

- For photons need microscopic collision kernel,

$$\color{red}{\mathcal{C}(\mathbf{q}_\perp)} = g^2 C_F \int \frac{dq^0 dq_x}{(2\pi)^2} \ \langle \{ \color{red}{A^\mu, A^\nu} \} \rangle (Q) v_\mu v_\nu \, \delta(v \cdot Q)$$

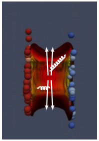
  [See e.g.: Aurenche, Gelis, Zaraket (2002); Caron-Huot (2008); Panero, Rummukainen, Schaefer (2014)]

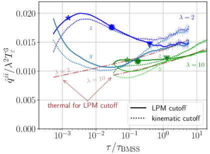
- Difficult to evaluate out of equilibrium due to instabilities. [E.g. Hauksson et al. (2021)]

- Will use model

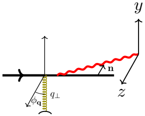
$$\color{red}{\mathcal{C}(\mathbf{q}_\perp)} = g^2 C_F T \left(\frac{1}{q_\perp^2} - \frac{1}{q_\perp^2 + \color{blue}{m_D^2(\phi_\mathbf{q})}} \right)$$

$$\color{blue}{m_D^2(\phi_\mathbf{q})} = \left(1 - \frac{2\xi}{3}\right) m_{D0}^2 + \xi m_{D0}^2 \color{blue}{\cos^2 \phi_\mathbf{q}}$$





[Boguslavski, Kurkela, Lappi, Lindenbauer, Peuron (2023)]



Numerical solution

- Rate for e.g. z polarization is [Hauksson, Jeon, Gale (2017)]

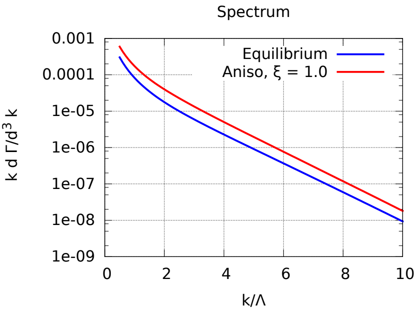
$$k\frac{d\Gamma_z}{d^3k} \sim \alpha_{EM} \int dp^x \; n_f(k+p^x)\left[1-n_f(k+p^x)\right] \frac{k}{p_x^2(k+p_x)}$$
$$\times \left[\frac{(2-\zeta)^2}{\zeta} \,\mathrm{Re} \int d^2p_\perp \; p_z \mathbf{f}_z + \zeta \,\mathrm{Re} \int d^2p_\perp \; p_y \mathbf{f}_y\right],$$

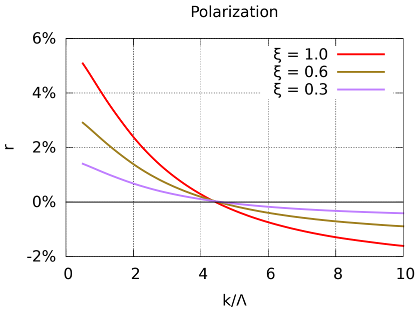
$$2\mathbf{p}_\perp = i\delta E \, \mathbf{f}(\mathbf{p}_\perp) + \int \frac{d^2q_\perp}{(2\pi)^2} \, \mathcal{C}(\mathbf{q}_\perp) \left[\mathbf{f}(\mathbf{p}_\perp) - \mathbf{f}(\mathbf{p}_\perp + \mathbf{q}_\perp)\right]$$

- Developed new algorithm to solve 2D integral equation.
  - Earlier 1D methods: [E.g. Aurenche, Gelis, Zaraket (2002)]
- Transform to impact parameter space, do multipole expansion and solve as boundary value problem.

Results

- Calculate up to $\xi = 1.0$, i.e. $P_L/P_T \sim 0.3$.
- Polarization quantified with $r = \frac{R_z - R_y}{R_z + R_y}$, $R_z = k d\Gamma_z / d^3 k$.

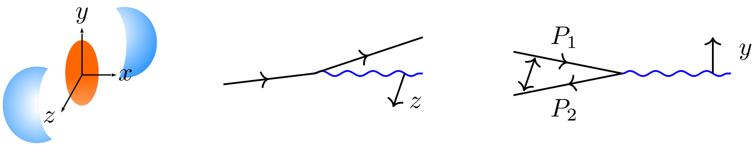




- Increase in spectrum due to $f(\mathbf{p}) = \sqrt{1+\xi}\, f_{\rm eq}(\sqrt{p^2 + \xi p_z^2})$
- Polarization changes signs around $k \sim 4.5\Lambda$.

Results

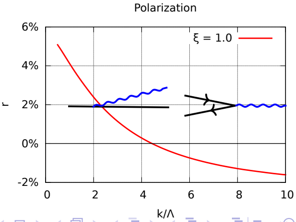
- Pair annihilation and bremsstrahlung give opposite polarization.



- Pair annihilation: $\overline{u}(P_1)\not{P}_1 u(P_2) = \overline{u}(P_1)\not{P}_2 u(P_2) = 0$ so $(P_1 - P_2)_\mu \overline{u}(P_1)\gamma^\mu u(P_2) = 0$ and no contribution in z-direction.

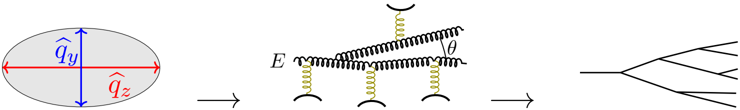
- z-polarization $(r > 0)$ wins out as more photons there.

- Same polarization as from 2-to-2 scattering.



Similar effects for jets

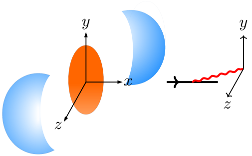
- Similarly, get polarization of jet gluons in anisotropic medium.
  [Hauksson, Iancu (2023)]



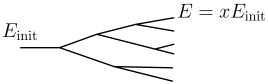
- Have studied how polarization is transmitted at each vertex.
- Net polarization tracks anisotropy of medium.
- Might give elliptical shape of jets after hadronization.

Conclusions

- Longitudinal expansion of plasma gives rise to photon polarization.
- Photon polarization thus works as a measure of pressure anisotropy in medium.
- Have for first time evaluated all LO diagrams in expanding medium.
- Get net polarization along beam axis.
- Some cancellation takes place but get polarization of a few percent.



Evolution of polarization



- Consider total evolution of jet in glasma brick with constant $G(\widehat{q}_z/\widehat{q}_y)$.
    - $\tau = \frac{\alpha_s N_c}{\pi}\sqrt{\frac{\widehat{q}}{E}}t$
-

$$\frac{dD_{\text{tot}}(x,\tau)}{d\tau} = \int_x^1 dz\ \mathcal{K}_0(z)\sqrt{\frac{z}{x}}\, D_{\text{tot}}\left(\frac{x}{z},\tau\right) - \int_0^1 dz\ \mathcal{K}_0(z)\ \frac{z}{\sqrt{x}}\, D_{\text{tot}}(x,\tau)$$

$$\frac{d\widetilde{D}(x,\tau)}{d\tau} = \int_x^1 dz\ \mathcal{M}_0(z)\sqrt{\frac{z}{x}}\, \widetilde{D}\left(\frac{x}{z},\tau\right) - \int_0^1 dz\ \mathcal{K}_0(z)\ \frac{z}{\sqrt{x}}\, \widetilde{D}(x,\tau) + \int_x^1 dz\ \mathcal{L}_0(z)\sqrt{\frac{z}{x}}\, D_{\text{tot}}\left(\frac{x}{z},\tau\right).$$

$$\mathcal{K}_0(z) \approx \frac{1}{z^{3/2}(1-z)^{3/2}}, \qquad \mathcal{M}_0(z) \approx z^2\mathcal{K}_0(z), \qquad \mathcal{L}_0(z) \approx G(\widehat{q}_z/\widehat{q}_y)(1-z)^2\,\mathcal{K}_0(z)$$

- $D_{\text{tot}} = x\frac{d(N_z+N_y)}{dx}$ is energy spectrum, $\widetilde{D} = x\frac{d(N_z-N_y)}{dx}$ is polarization.

  [Equation for D_{tot}: Blaizot, Iancu, Mehtar-Tani (2013); Blaizot, Mehtar-Tani (2015); Fister, Iancu (2014); Iancu, Wu (2015); Escobedo, Iancu (2016). See also e.g. Mehtar-Tani, Schlichting (2018), Adhya, Salgado, Spousta, Tywoniuk (2021)]