

Polarization of jets in the glasma

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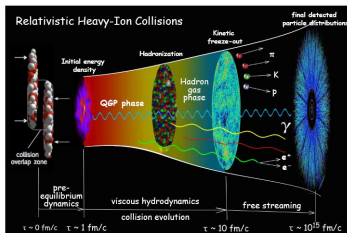
Assemblée Générale du GDR QCD

May 23th 2022

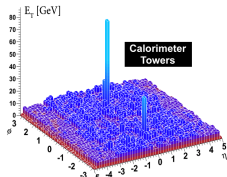
In collaboration with E. Iancu.

Early stages of heavy-ion collisions

- Heavy-ion collisions produce high-temperature QCD matter.
- Bulk of evolution described by hydrodynamics.
- Want to understand early-time evolution before hydro.
- Characterized by highly occupied gluonic fields (glasma).
[See e.g. Berges, Heller, Mazeliauskas, Venugopalan (2020)]
- Want experimental probes of the glasma, e.g. jets.



[Shen (2014)]



[Foka, Janik (2017)]

Jets in medium

- Transverse momentum broadening of a jet parton in medium:

$$\widehat{q} = \frac{d\langle \mathbf{p}_\perp^2 \rangle}{dt}$$

- Allows for medium-induced gluon emission:

$$\Gamma \propto \frac{g^2 \sqrt{\widehat{q}}}{E}$$

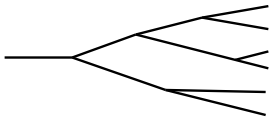
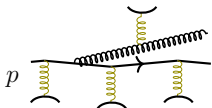
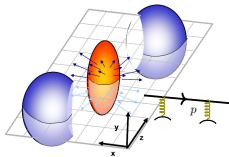
[See e.g. Qin, Wang (2015)]

- Wavepackets of partons overlap for a long time during emission.

[Landau, Pomeranchuk (1953); Migdal (1955)]

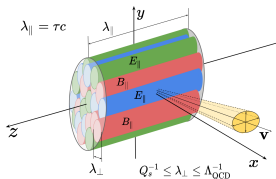
- This process determines whole jet structure. [For vacuum-like emission see e.g.

Majumder (2018); Wang, Guo (2001)]

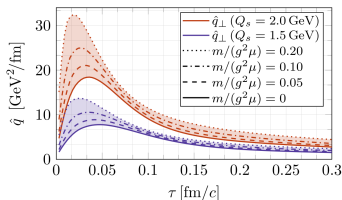


Jet broadening in glasma

- At early times, jet partons traverse heavily occupied gluon fields.
- As much broadening as during hydro stage!
 - $\Delta p_{\perp}^2 \big|_{\text{glasma}} / \Delta p_{\perp}^2 \big|_{\text{hydro}} \approx 0.9$
[Carrington, Czajka, Mrowczynski (2022)]
- Broadening is anisotropic, $\hat{q}_z \approx 2 \hat{q}_y$ where $\hat{q}_y = \frac{dhp_y^2}{dt}$

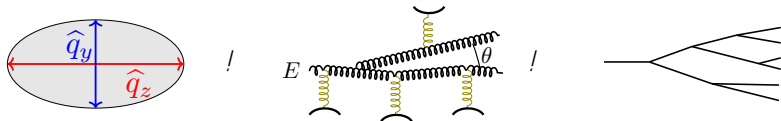


[Carrington et al. (2022)]



[Ipp, Muller, Schuh (2020)]

This talk



- How do jets evolve in glasma?
- How does anisotropy in broadening affect jet evolution?
- Anisotropy leads to polarization in gluon helicity.
- The degree of polarization is constant for all energy scales in jet.

Single gluons emission in an anisotropic plasma

- Evaluate rate using AMY formalism.

[Arnold, Moore, Yaffe (2002); Arnold, Dogan (2008); Hauksson, Jeon, Gale (2017)]

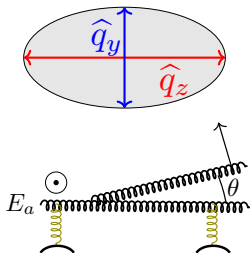
- Total rate is still

$$\Gamma \sim \alpha_s P(z) \frac{\sqrt{\hat{q}_y + \hat{q}_z}}{E} \left[1 + \mathcal{O} \left(\left(\frac{\hat{q}_z - \hat{q}_y}{\hat{q}_z + \hat{q}_y} \right)^2 \right) \right]$$

- Much splitting in glasma phase.

- Daughter parton has net polarization:

- Opening angle θ preferably in z direction.
- Daughter partons are preferably polarized in plane of θ .



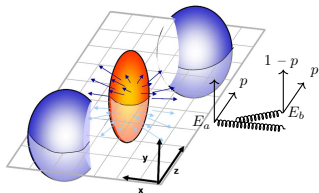
Single gluon emission in an anisotropic plasma

- Ensemble of gluons: Probability p of polarization in beam direction.
- Daughter parton has ($z = E_b/E_a$)

$$p^\ell \frac{1}{2} = f(z) \left(p \frac{1}{2} \right) + \frac{c}{4} g(z) \frac{\hat{q}_z \hat{q}_y}{\hat{q}_z + \hat{q}_y}$$

$$f(z) = \frac{z^2}{(1-z)^2 + z^2 + z^2(1-z)^2}, \quad g(z) = \frac{(1-z)^2}{(1-z)^2 + z^2(1-z)^2 + z^2}$$

- Isotropic:
Polarization reduced at each splitting.
- Anisotropic:
Unpolarized mother radiates polarized daughter!
- Two competing effects.



Evolution of spin polarization



- Consider total evolution of jet in medium with constant $\frac{\hat{q}_z}{\hat{q}_z + \hat{q}_y}$.
- Use $x := E/E_{\text{init}} \quad 1$

$$\frac{dD_{\text{tot}}(x, \tau)}{d\tau} = \int_x^1 dz K_0(z) \sqrt{\frac{z}{x}} D_{\text{tot}}\left(\frac{x}{z}, \tau\right) - \int_0^1 dz K_0(z) \frac{z}{x} D_{\text{tot}}(x, \tau)$$

$$\begin{aligned} \frac{d\tilde{D}(x, \tau)}{d\tau} &= \int_x^1 dz M_0(z) \sqrt{\frac{z}{x}} \tilde{D}\left(\frac{x}{z}, \tau\right) - \int_0^1 dz K_0(z) \frac{z}{x} \tilde{D}(x, \tau) \\ &+ \int_x^1 dz L_0(z) \sqrt{\frac{z}{x}} D_{\text{tot}}\left(\frac{x}{z}, \tau\right). \end{aligned}$$

$$K_0(z) = \frac{1}{z^{3/2}(1-z)^{3/2}}, \quad M_0(z) = z^2 K_0(z), \quad L_0(z) = \frac{c}{2} \frac{\hat{q}_x}{\hat{q}_x + \hat{q}_y} (1-z)^2 K_0(z)$$

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

[Equation for D_{tot} : Blaizot, Iancu, Mehtar-Tani (2013); Blaizot, Mehtar-Tani (2015); Fister, Iancu (2014); Iancu, Wu (2015); Escobedo, Iancu (2016)]

Evolution of spin polarization

- Isotropic medium, $D_{\text{tot}}(x, \tau = 0) = \delta(1 - x)$:

$$D_{\text{tot}}(x, \tau) = \frac{1}{x(1-x)^{3/2}} e^{-\pi\tau^2/(1-x)} \frac{1}{x}$$

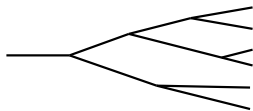
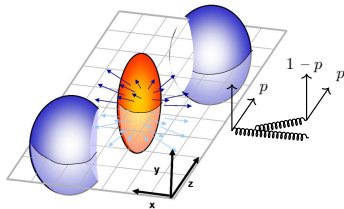
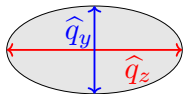
[Blaizot, Iancu, Mehtar-Tani (2013)]

- Polarization decays away: $\tilde{D} \sim x^{3/2}$
- Can also solve exactly in anisotropic medium: $\tilde{D} = \frac{c}{4} \frac{\hat{q}_x \hat{q}_y}{\hat{q}_x + \hat{q}_y} \frac{1}{x}$
- Constant fraction of particles with helicity polarization at all x !

$$\tilde{D}/D_{\text{tot}} = \frac{c}{4} \frac{\hat{q}_x \hat{q}_y}{\hat{q}_x + \hat{q}_y}.$$
- Can this be measured?
 - Measurements of helicity difficult.
 - Hydrodynamic phase more isotropic ! Can wash out polarization.

Conclusions

- Early glasma stage important for jets in heavy-ion collisions.
- Anisotropy in momentum broadening leads to gluon polarization.
- Polarization constant at all energy scales.
- Need to study fate of polarization in experiments further.
- Similar effects in photon production.



Formalism for jet splitting

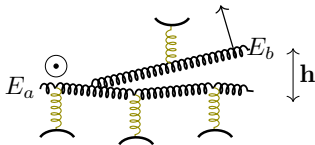
- Isotropic case has been analyzed widely:
[E.g. Baier, Dokshitzer, Peigné, Schiff, Mueller (1996); Zakharov (1997)
Arnold, Moore, Yaffe (2002); Hauksson, Jeon, Gale (2018)]

- Rate of branching is

$$\frac{d}{dz} \alpha_s \text{Re} \int d^2 \mathbf{h} \mathbf{F}(\mathbf{h}) \left[\cos^4 \phi F_{\text{in}/\text{in},\text{in}}(z) + \sin^4 \phi F_{\text{out}/\text{out},\text{in}}(z) + \dots \right]$$

- Here

$$\mathbf{h} = i h^2 \mathbf{F}(\mathbf{h}) \left(\hat{q}_z \partial_{h_z}^2 + \hat{q}_y \partial_{h_y}^2 \right) \mathbf{F}(\mathbf{h})$$



- Solve by expanding in $\frac{\hat{q}_z}{\hat{q}_z + \hat{q}_y}$. Gives details of radiation pattern.
- Join with polarized splitting functions $F(z)$, $z = E_b/E_a$.

Jets in an isotropic plasma

- Broadening brings parton off shell so it can radiate.

[See e.g. review: Qin, Wang (2015)]

- Wavepackets overlap for a long time (LPM).

[Landau, Pomeranchuk (1953); Migdal (1955)]

- Schematic estimate:

- $\theta \sim \frac{p_{\perp}}{E} \sim \frac{\Delta x_{\perp}}{\tau}$

- Uncertainty principle: $p_{\perp} \Delta x_{\perp} \sim 1$

so $\tau \sim \frac{E}{p_{\perp}^2} \sim \frac{E}{\hat{q} \theta^2}$

- Get rate $\Gamma \sim \alpha_s P(z) / \tau \sim \alpha_s P(z) \theta^2 \frac{\hat{q}}{E}$

- $P_{\text{hard}}(z) = \frac{1+z^4+(1-z)^4}{z(1-z)}$ is splitting function;
 $z = E_b/E_a$.

