Polarization of jets in the glasma

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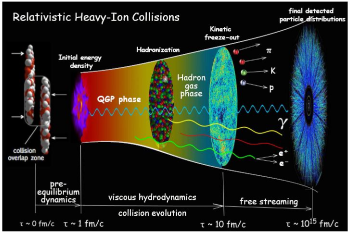
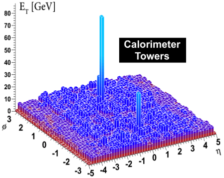
Early stages of heavy-ion collisions

- Heavy-ion collisions produce high-temperature QCD matter.
- Bulk of evolution described my 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)]

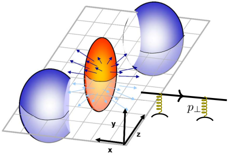


[Foka, Janik (2017)]

Jets in medium

- Transverse momentum broadening of a jet parton in medium:

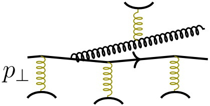
$$\widehat{q} = \frac{d\langle \mathbf{p}_\perp^2 \rangle}{dt}$$



- Allows for medium-induced gluon emission:

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

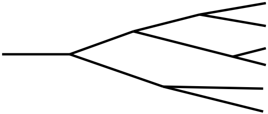
[See e.g. Qin, Wang (2015)]



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

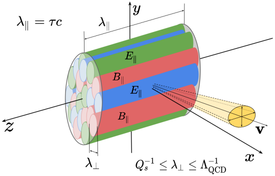
[Landau, Pomeranchuk (1953); Migdal (1955)]

- This process determines whole jet structure. [For vacuum-like emission see e.g. Majumder (2018); Wang, Guo (2001)]

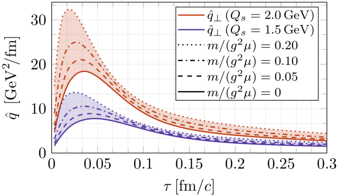


Jet broadening in glasma

- 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, $\widehat{q}_z \approx 2\,\widehat{q}_y$ where $\widehat{q}_y = \frac{d\langle p_y^2\rangle}{dt}$

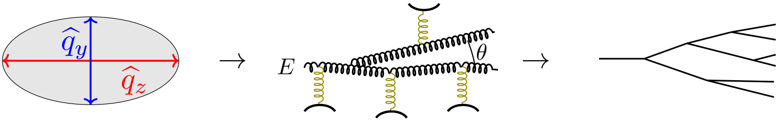


[Carrington et al. (2022)]



[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.

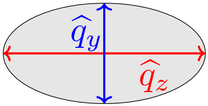
Single gluons emission in an anisotropic plasma

- Evaluate rate using AMY formalism.

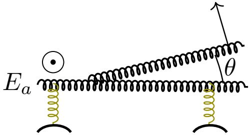
  [Arnold, Moore, Yaffe (2002); Arnold, Dogan (2008); Hauksson, Jeon, Gale (2017)]
- Total rate is still

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

  - 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.



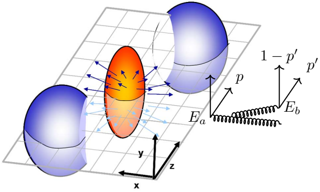
Single gluon emission in an anisotropic plasma

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

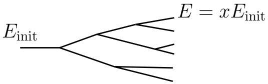
$$\boxed{p' - \tfrac{1}{2} = f(z)\left(p - \tfrac{1}{2}\right) + \tfrac{c}{4}\, g(z)\, \frac{\widehat{q}_z - \widehat{q}_y}{\widehat{q}_z + \widehat{q}_y}}$$

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

- 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 $\frac{\widehat{q}_z - \widehat{q}_y}{\widehat{q}_z + \widehat{q}_y}$.
- Use $x := E/E_{\text{init}} \ll 1$

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

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

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

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

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

Evolution of spin polarization

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

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

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

  - Polarization decays away: $\widetilde{D}\sim x^{3/2}$

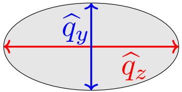
- Can also solve exactly in anisotropic medium: $\widetilde{D}\sim\frac{c}{4}\frac{\widehat{q}_x-\widehat{q}_y}{\widehat{q}_x+\widehat{q}_y}\frac{1}{\sqrt{x}}$
- Constant fraction of particles with helicity polarization at all x!

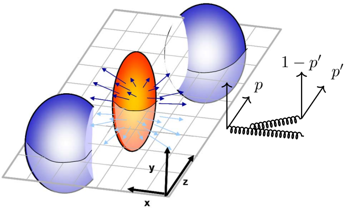
  $\widetilde{D}/D_{\rm tot}=\frac{c}{4}\frac{\widehat{q}_x-\widehat{q}_y}{\widehat{q}_x+\widehat{q}_y}.$

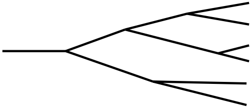
- Can this be measured?
  - Measurements of helicity difficult.
  - Hydrodynamic phase more isotropic $\rightarrow$ Can wash out polarization.

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.







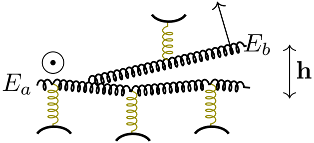
Formalism for jet splitting

- 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

$$\frac{d\Gamma_{z\to z}}{dz} \sim \alpha_s \mathrm{Re} \int d^2h\, \mathbf{h}\cdot\mathbf{F}(\mathbf{h}) \left[\cos^4\phi\, \mathcal{F}_{\mathrm{in}\to\mathrm{in,in}}(z) + \sin^4\phi\, \mathcal{F}_{\mathrm{out}\to\mathrm{out,in}}(z) + \cdots \right]$$

- Here
  $\mathbf{h} = ih^2\mathbf{F}(\mathbf{h}) - \left(\widehat{q}_z\, \partial^2_{h_z} + \widehat{q}_y\, \partial^2_{h_y}\right) \mathbf{F}(\mathbf{h})$

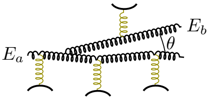


- Solve by expanding in $\frac{\widehat{q}_z - \widehat{q}_y}{\widehat{q}_z + \widehat{q}_y}$. Gives details of radiation pattern.
- Join with polarized splitting functions $\mathcal{F}(z)$, $z = E_b/E_a$.

Jets in an isotropic plasma

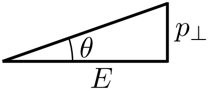
- Broadening brings parton off shell so it can radiate.

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

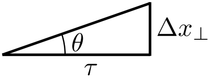


- Wavepackets overlap for a long time (LPM).

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



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

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