The evolution of spin polarization in jets traversing the glasma

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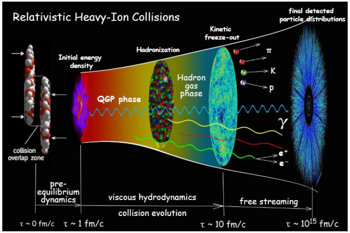
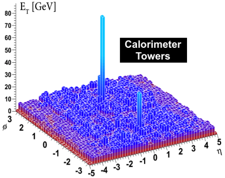
Early stages of heavy-ion collisions

- 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:

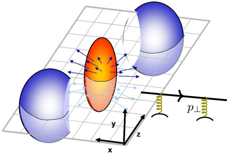
$$\Gamma \sim \frac{g^2\sqrt{\widehat{q}}}{\sqrt{E}}$$

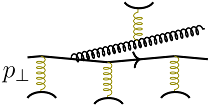
[See e.g. Qin, Wang (2015)]

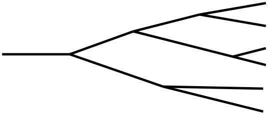
- Wavepackets of partons overlap for a long time during emission.

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

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

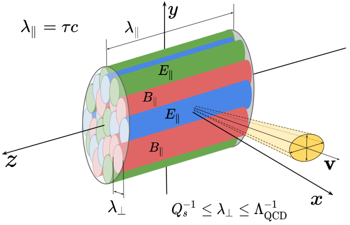




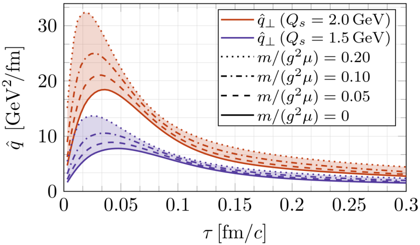


Jet broadening in glasma

- Jet partons traverse heavily occupied gluon fields.
- Deflected by chromomagnetic and chromoelectric forces.
- 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)]



[Carrington, Czajka, Mrowczynski (2022)]



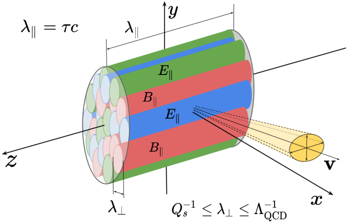
[Ipp, Muller, Schuh (2020)]

Jet broadening in glasma

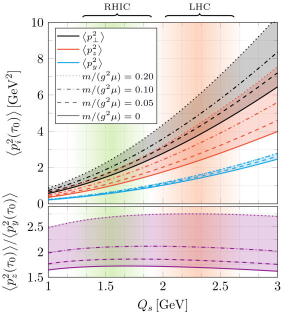
- Broadening can be anisotropic:
  - $\widehat{q}_z \neq \widehat{q}_y$ with $\widehat{q}_y = \frac{d\langle p_y^2\rangle}{dt}$

- In glasma broadening is heavily anisotropic,

$$\widehat{q}_z \approx 2\widehat{q}_y$$

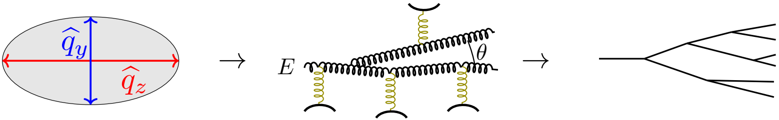


[Carrington, Czajka, Mrowczynski (2022)]



[Ipp, Muller, Schuh (2020)]

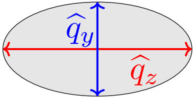
This talk

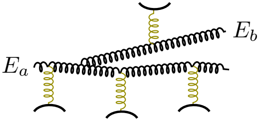


- How do jets evolve in glasma?
- How important is the glasma stage?
- How does anisotropy in broadening affect jet evolution?
    - Leads to polarization in gluon helicity.
    - The degree of polarization is constant for all energy scales in jet.

Single gluon emission in an anisotropic medium

- Evaluate rate using BDMPS-Z formalism.
  [E.g. Baier, Dokshitzer, Peigné, Schiff, Mueller (1996); Zakharov (1997)]
  - In path integral $\widehat{q}\,\mathbf{r}^2 \longrightarrow \widehat{q}_y r_y^2 + \widehat{q}_z r_z^2$.
- Total unpolarized rate is nearly unaffected by anisotropy ($z = E_b/E_a$; $\widehat{q} = \widehat{q}_x + \widehat{q}_y$)

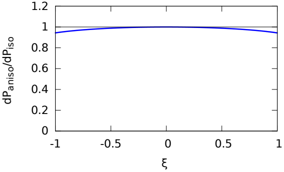




$$\frac{d\mathcal{P}}{dz\,dt} = \frac{\alpha_s}{2\pi} P_{g\to g}(z) \frac{\sqrt{1-z(1-z)}}{\sqrt{z(1-z)E_a}} \left(4\widehat{q}_x\widehat{q}_y\right)^{1/4} \times \frac{1}{2}\left[f\left(\sqrt{\frac{\widehat{q}_x}{\widehat{q}_y}}\right) + f\left(\sqrt{\frac{\widehat{q}_y}{\widehat{q}_x}}\right)\right]$$

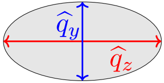
$$f(\sqrt{a}) = \int_0^\infty \left[\frac{1}{a^{1/4}y^2} - \frac{1}{\sinh^{1/2}\sqrt{a}x\,\sinh^{3/2}x}\right]$$

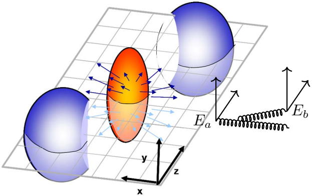
- Plot $(d\mathcal{P})_{\mathrm{aniso}}/(d\mathcal{P})_{\mathrm{iso}}$ at fixed $\widehat{q}$ with $\xi = \frac{\widehat{q}_z - \widehat{q}_y}{\widehat{q}_z + \widehat{q}_y}$

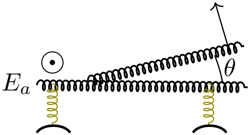


Polarized emission in anisotropic medium

- Daughter parton has net polarization:
  - Opening angle θ preferably in z direction.
  - Daughter partons are preferably polarized in plane of θ.
- Want to calculate e.g. $\frac{d\mathcal{P}_{y\to y}}{dzdt}$
- Ingredients:
  - Know polarized splitting functions given branching plane.
  - Integrate over all orientations of branching plane, weigted by medium physics.







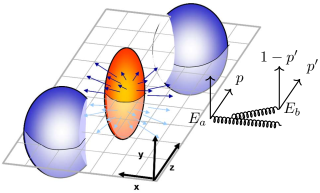
Single gluon emission in an anisotropic medium

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

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

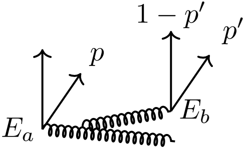
$$f(z) = \frac{z^2}{(1-z)^2 + z^2 + z^2(1-z)^2}, \quad g(z) = \frac{(1-z)^2}{(1-z)^2 + z^2(1-z)^2 + z^2}$$

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



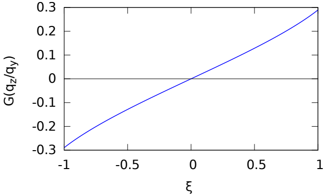
Single gluon emission in an anisotropic medium

- Two intuitive limits:
  - $z \to 0$:
    $p' - \frac{1}{2} = z^2\,(p - \frac{1}{2}) + G(\widehat{q}_z/\widehat{q}_y)$
  - $z \to 1$:
    $p' - \frac{1}{2} = (p - \frac{1}{2}) + (1-z)^2\,G(\widehat{q}_z/\widehat{q}_y)$



- Size of polarization given by $G(\widehat{q}_z/\widehat{q}_y)$.

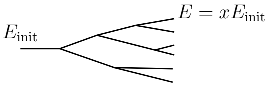
$$G(\widehat{q}_z/\widehat{q}_y) = \frac{f\left(\sqrt{\widehat{q}_y/\widehat{q}_z}\right) - f\left(\sqrt{\widehat{q}_z/\widehat{q}_y}\right)}{f\left(\sqrt{\widehat{q}_y/\widehat{q}_z}\right) + f\left(\sqrt{\widehat{q}_z/\widehat{q}_y}\right)}; \quad \xi = \frac{\widehat{q}_z - \widehat{q}_y}{\widehat{q}_z - \widehat{q}_y}$$



  - For glasma $G \sim 0.08 - 0.15$

- Expected branching is democratic $(z \sim \frac{1}{2})$.
  - Not clear which wins out in the end.
  - Need evolution of jet as a whole

Evolution of polarization



- Consider total evolution of jet in glasma brick with constant $G(\widehat{q}_z/\widehat{q}_y)$.
  - $\tau = \frac{\alpha_s N_c}{\pi}\sqrt{\frac{\widehat{q}}{E}}t$
- $$\frac{dD_{\rm tot}(x,\tau)}{d\tau} = \int_x^1 dz\, \mathcal{K}_0(z)\sqrt{\frac{z}{x}}\, D_{\rm tot}\left(\frac{x}{z},\tau\right) - \int_0^1 dz\, \mathcal{K}_0(z)\, \frac{z}{\sqrt{x}}\, D_{\rm tot}(x,\tau)$$
  $$\frac{d\widetilde{D}(x,\tau)}{d\tau} = \int_x^1 dz\, \mathcal{M}_0(z)\sqrt{\frac{z}{x}}\, \widetilde{D}\left(\frac{x}{z},\tau\right) - \int_0^1 dz\, \mathcal{K}_0(z)\, \frac{z}{\sqrt{x}}\, \widetilde{D}(x,\tau) + \int_x^1 dz\, \mathcal{L}_0(z)\sqrt{\frac{z}{x}}\, D_{\rm tot}\left(\frac{x}{z},\tau\right).$$

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

- $D_{\rm tot} = x\frac{d(N_z+N_y)}{dx}$ is energy spectrum, $\widetilde{D} = x\frac{d(N_z-N_y)}{dx}$ is polarization.
  [Equation for $D_{\rm tot}$: Blaizot, Iancu, Mehtar-Tani (2013); Blaizot, Mehtar-Tani (2015); Fister, Iancu (2014); Iancu, Wu (2015); Escobedo, Iancu (2016). See also Mehtar-Tani, Schlichting (2018)]

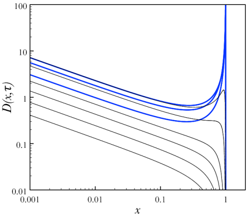
Evolution of polarization

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

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

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

Blaizot, Mehtar-Tani (2015)]



- Can solve exactly for helicity spectrum at $x \ll 1$:
  - Use method of Green's functions [Fister, Iancu (2014)].

$\widetilde{D} = \frac{1}{3} G(\widehat{q}_z/\widehat{q}_y) \frac{\tau e^{-\pi\tau^2}}{\sqrt{x}}$

- Constant fraction of particles with helicity polarization at all x!

$$\widetilde{D}/D_{\text{tot}} = \frac{1}{3} G(\widehat{q}_z/\widehat{q}_y) \sim 0.05.$$

Measurements

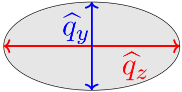
- Our estimates suggest that after glasma stage, constant $\sim 5\,\%$ polarization of gluons.
    - Larger than $\sim 2\,\%$ polarization of Λ hyperons at RHIC.
- Hydro phase reduces polarization:
    - Eventually,

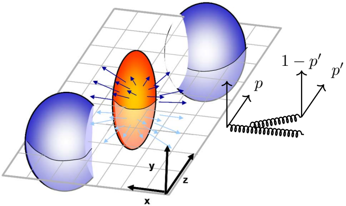
$$\widetilde{D} \sim G(\widehat{q}_z/\widehat{q}_y)\, x^{3/2}\, \frac{e^{-\pi(\tau-\tau_c)^2}}{(\tau-\tau_c)^2}$$

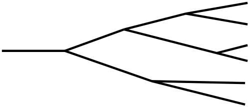
- What happens at hadronization?

Conclusions

- Early glasma stage important for jets in heavy-ion collisions.
- Anisotropy in momentum broadening leads to $\sim 5\,\%$ gluon polarization.
- Calculated rate of polarized gluon emission and solved evol. eqs.
    - Polarization constant at all energy scales.
- Need to study fate of polarization in experiments further.







Polarized emission in anisotropic medium

- Is BDMPS-Z justified in this context?
  - Formation time $\sqrt{\frac{\omega}{\hat{q}}} \gg 1/Q_s$ gives $\omega \gg g^2 Q_s$ for $\hat{q} \sim g^2 Q_s^3$.
  - Ignore any net drift, i.e. assume $\langle \mathbf{p}_\perp \rangle = 0$.
- Rate given by

$$\frac{dP_{i\to jk}}{dzdt} \sim \mathrm{Re} \int_0^\infty d\Delta t \int_{\mathbf{P_1},\mathbf{P_2}} \Gamma^{ijk}(\mathbf{P_1}, z)\, \Gamma^{ijk}(\mathbf{P_2}, z)\, \tilde{S}^{(3)}(\Delta t, \mathbf{P}_1, \mathbf{P}_2).$$

where

$$\widetilde{S}^{(3)}(\Delta t, \mathbf{P}_1, \mathbf{P}_2) = \frac{2\pi(1+i)}{k_x k_y \sqrt{\sinh \Omega_x \Delta t}\sqrt{\sinh \Omega_y \Delta t}}$$
$$\times \exp\left[-\frac{(1+i)}{4k_x^2 \tanh \frac{\Omega_x \Delta t}{2}} (P_{1\,x} - P_{2\,x})^2 - \frac{(1+i)}{4k_x^2 \coth \frac{\Omega_x \Delta t}{2}} (P_{1\,x} + P_{2\,x})^2\right]$$
$$\times \exp\left[(x \leftrightarrow y)\right]$$

- E.g. $\Gamma^{y\to yy}(\mathbf{P}_1, z) \sim \widehat{P}_{1y} \frac{1-z(1-z)}{z(1-z)}$

What happens in hydro phase?

- Hydrodynamic phase more isotropic.
  - Hydro:
    $\widehat{q} \sim g^4 T^3 \int d^2 p_\perp p_\perp^2 \left(\frac{1}{p_\perp^2}\right)^2 \sim g^4 \Lambda^3 \log E/m_D$
    [Hauksson, Jeon, Gale (2021)]
  - Glasma: Saturation scale is the cutoff.
    $\widehat{q} \sim g^2 Q_s^3 + g^4 Q_s^3 \log E/Q_s$
- Hydro phase reduces polarization:
  - If switch to isotropic at time τ_c, start to see decay at $\tau - \tau_c \sim \sqrt{x}$.
  - Eventually,

$$\widetilde{D} \sim G(\widehat{q}_z/\widehat{q}_y)\, x^{3/2} \, \frac{e^{-\pi(\tau-\tau_c)^2}}{(\tau-\tau_c)^2}$$

Measurements?

- Our estimates suggest that after glasma stage, constant $\sim 5\,\%$ polarization of gluons.
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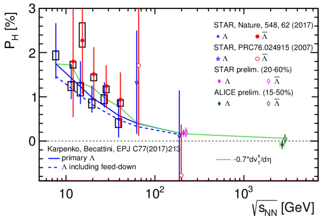


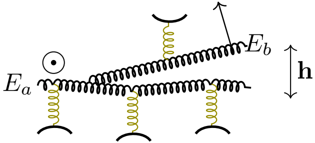
- Hydro phase reduces polarization. [Voloshin (2017)]
- What happens at hadronization?
  [See e.g. Kerbizi, Artru, Belghobsi, Martin (2019); Kerbizi, Lönnblad (2020)]
- Measurements of polarization difficult.
- Other ways: Photon emitted by quarks in jets?

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

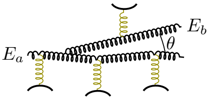


- Solve by expanding in $\frac{\widehat{q}_z - \widehat{q}_y}{\widehat{q}_z + \widehat{q}_y}$. Gives details of radiation pattern.
- Join with polarized splitting functions $\mathcal{F}(z)$, $z = E_b/E_a$.

Jets in an isotropic plasma

- Broadening brings parton off shell so it can radiate.

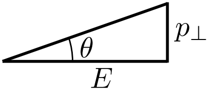
  [See e.g. review: Qin, Wang (2015)]

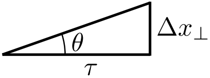


- Wavepackets overlap for a long time (LPM).

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

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