Jet-medium interaction during the early glasma stage of heavy-ion collisions

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Jet quenching in the quark-gluon plasma, ECT*
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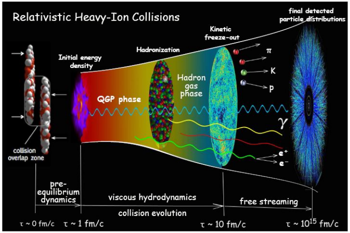
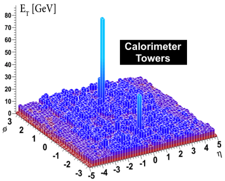
In collaboration with E. Iancu.

- Most studies of jets in heavy-ion collisions look at QGP/hydro phase.
- Far-from-equilibrium initial phase could also be important.
  - Glasma: Highly occupied, soft gluons.
    [See e.g. Berges, Heller, Mazeliauskas, Venugopalan (2020)]
    Talks by Alina Czajka, Meijian Li.
- How important is glasma for jets?
- Can we learn about glasma from jet observables?



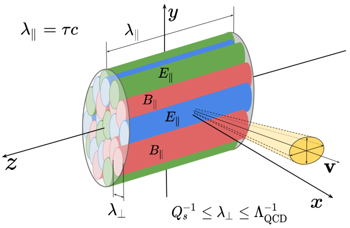
[Shen (2014)]



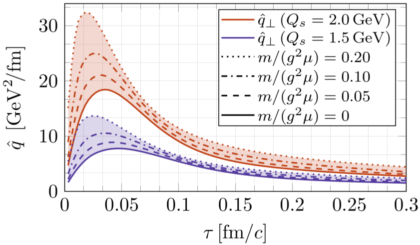
[Foka, Janik (2017)]

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)]



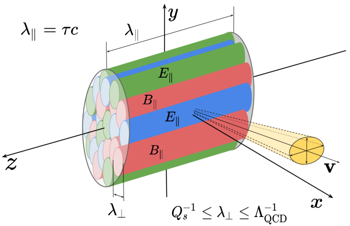
[Ipp, Muller, Schuh (2020)]

Jet broadening in glasma

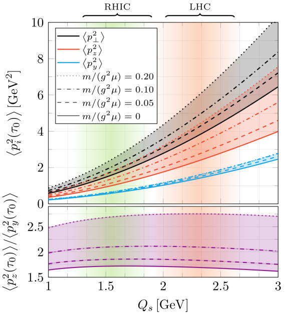
- Broadening can be anisotropic:
  - $\hat{q}_z \neq \hat{q}_y$ with $\hat{q}_y = \frac{d\langle p_y^2 \rangle}{dt}$

- In glasma broadening is heavily anisotropic,

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

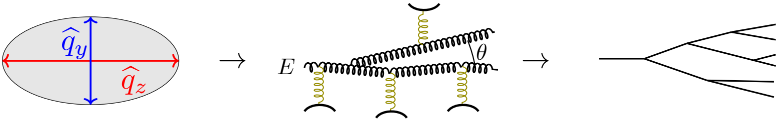


[Carrington, Czajka, Mrowczynski (2022)]



[Ipp, Muller, Schuh (2020)]

This talk



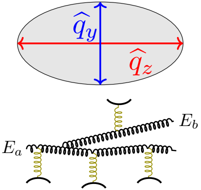
- How do jets evolve in glasma?
- How important is the glasma stage?
- How does anisotropy in broadening affect jet evolution?
  - Leads to polarization in gluon helicity.
  - The degree of polarization is constant for all energy scales in jet.

Importance of glasma phase for jets

- Need to quantify importance of glasma phase for jets:
  - Assume a jet with path-length $5\,\mathrm{fm}$.
  - Switching time $\tau_0 = 0.6\,\mathrm{fm}$ between glasma and hydro.
  - $\widehat{q}$ in hydro taken from JETSCAPE, including Bjorken expansion.
    [JETSCAPE, Phys.Rev.C (2021)]
  - $\widehat{q}$ in glasma from Vienna group.
    [Ipp, Muller, Schuh (2020)]
- Total momentum broadening:
  $\left\langle p_\perp^2 \right\rangle = \int d\tau\, \widehat{q}$: $\sim 60\,\%$ from glasma.
- Contribution to jet structure: [Rate of emission is $d\mathcal{P}/dt \sim \sqrt{\widehat{q}}$]
  $\int d\tau\, \sqrt{\widehat{q}}$: $\sim 30\,\%$ from glasma.

  [For vacuum-like emission see e.g. Majumder (2018); Wang, Guo (2001)]
- Does the glasma impart a specific signature to jets?
  - Anisotropy in momentum broadening.

Single gluon emission in an anisotropic medium



- Evaluate rate using BDMPS-Z formalism.

  [E.g. Baier, Dokshitzer, Peigné, Schiff, Mueller (1996); Zakharov (1997)]

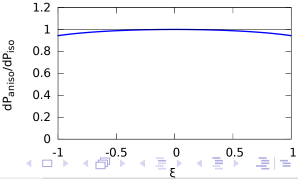
  - In path integral $\widehat{q}\,\mathbf{r}^2 \longrightarrow \widehat{q}_y r_y^2 + \widehat{q}_z r_z^2$, $\widehat{q} = \widehat{q}_x + \widehat{q}_y$

- Total unpolarized rate is $(z = E_b/E_a)$

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

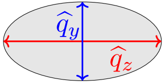
$$f(\sqrt{a}) = \int_0^\infty \left[\frac{1}{a^{1/4}y^2} - \frac{1}{\sinh^{1/2}\sqrt{a}x\,\sinh^{3/2}x}\right]$$

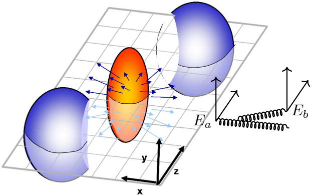
- Total rate only slightly decreased by anisotropy.
  - Plot $(d\mathcal{P})_{\text{aniso}}/(d\mathcal{P})_{\text{iso}}$ at fixed $\widehat{q}$ with $\xi = \frac{\widehat{q}_z - \widehat{q}_y}{\widehat{q}_z + \widehat{q}_y}$

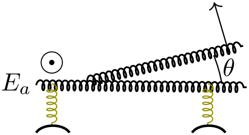


Polarized emission in anisotropic medium

- 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.







Polarized emission in anisotropic medium

- Is BDMPS-Z justified in this context?
  - Formation time $\sqrt{\frac{\omega}{\widehat{q}}} \gg 1/Q_s$ gives $\omega \gg g^2 Q_s$ for $\widehat{q} \sim g^2 Q_s^3$.
  - 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

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

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

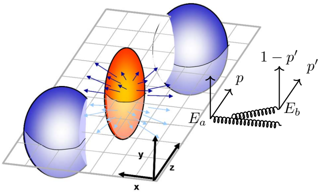
Single gluon emission in an anisotropic medium

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

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

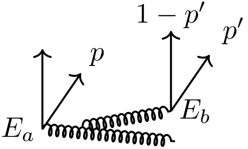
$$f(z) = \frac{z^2}{(1-z)^2 + z^2 + z^2(1-z)^2}, \quad g(z) = \frac{(1-z)^2}{(1-z)^2 + z^2(1-z)^2 + z^2}$$

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



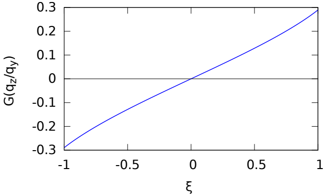
Single gluon emission in an anisotropic medium

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



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

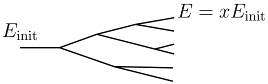
$$G(\widehat{q}_z/\widehat{q}_y) = \frac{f\left(\sqrt{\widehat{q}_y/\widehat{q}_z}\right) - f\left(\sqrt{\widehat{q}_z/\widehat{q}_y}\right)}{f\left(\sqrt{\widehat{q}_y/\widehat{q}_z}\right) + f\left(\sqrt{\widehat{q}_z/\widehat{q}_y}\right)}; \quad \xi = \frac{\widehat{q}_z - \widehat{q}_y}{\widehat{q}_z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



  - 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 $G(\widehat{q}_z/\widehat{q}_y)$.
  - $\tau = \frac{\alpha_s N_c}{\pi}\sqrt{\frac{\widehat{q}}{E}}t$
-
$$\frac{dD_{\text{tot}}(x,\tau)}{d\tau} = \int_x^1 dz\ \mathcal{K}_0(z)\sqrt{\frac{z}{x}}\,D_{\text{tot}}\left(\frac{x}{z},\tau\right) - \int_0^1 dz\ \mathcal{K}_0(z)\ \frac{z}{\sqrt{x}}\,D_{\text{tot}}(x,\tau)$$
$$\frac{d\widetilde{D}(x,\tau)}{d\tau} = \int_x^1 dz\ \mathcal{M}_0(z)\sqrt{\frac{z}{x}}\,\widetilde{D}\left(\frac{x}{z},\tau\right) - \int_0^1 dz\ \mathcal{K}_0(z)\ \frac{z}{\sqrt{x}}\,\widetilde{D}(x,\tau)$$
$$+\int_x^1 dz\ \mathcal{L}_0(z)\sqrt{\frac{z}{x}}\,D_{\text{tot}}\left(\frac{x}{z},\tau\right).$$

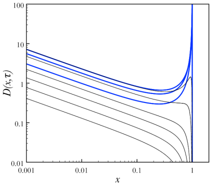
$$\mathcal{K}_0(z) \approx \frac{1}{z^{3/2}(1-z)^{3/2}}, \qquad \mathcal{M}_0(z) \approx z^2\mathcal{K}_0(z), \qquad \mathcal{L}_0(z) \approx G(\widehat{q}_z/\widehat{q}_y)(1-z)^2\,\mathcal{K}_0(z)$$

- $D_{\text{tot}} = x\frac{d(N_z+N_y)}{dx}$ 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 Mehtar-Tani, Schlichting (2018)]

See also talk by Souvik Adhya

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!

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

- Follows from demanding that both polarizations described by wave turbulence.

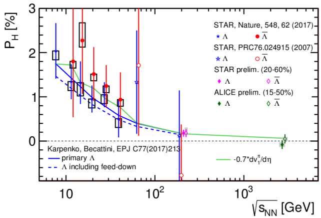
What happens in hydro phase?

- 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.
  - Bigger than $\sim 2\,\%$ polarization of Λ hyperons at RHIC.



- Hydro phase reduces polarization. [Voloshin (2017)]

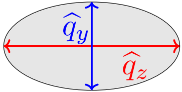
- What happens at hadronization?
  [See e.g. Kerbizi, Artru, Belghobsi, Martin (2019); Kerbizi, Lönnblad (2020)]

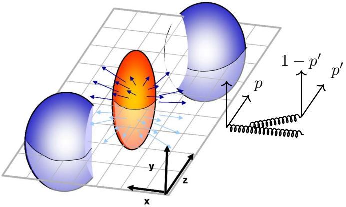
- Measurements of polarization difficult.

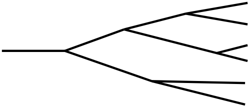
- Other ways: Photon emitted by quarks in jets?

Conclusions

- Early glasma stage important for jets in heavy-ion collisions ($\sim 30\,\%$ of structure?)
- 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.







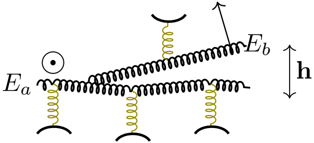
Formalism for jet splitting

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

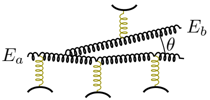


- Solve by expanding in $\frac{\widehat{q}_z - \widehat{q}_y}{\widehat{q}_z + \widehat{q}_y}$. Gives details of radiation pattern.
- Join with polarized splitting functions $\mathcal{F}(z)$, $z = E_b/E_a$.

Jets in an isotropic plasma

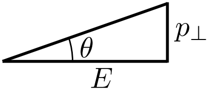
- Broadening brings parton off shell so it can radiate.

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

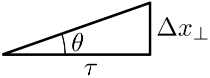


- Wavepackets overlap for a long time (LPM).

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

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