Jet quenching in glasma

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based on:
PRC 105 (2022) 6, 064910,
PRC 106 (2022) 3, 034904,
EPJA 58 (2022) 1, 5

Jan Kochanowski University, Kielce, March 8th, 2023

Outline of the talk

1. Introduction & Motivation

   THEORY:

2. Nuclei before the collision - MV model
3. Strongly interacting matter after the collision

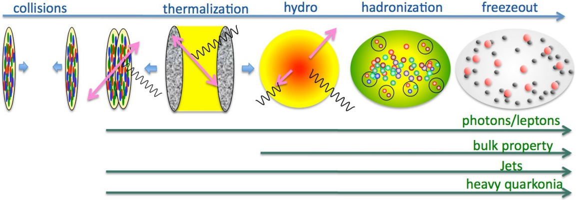
   RESULTS:

4. Characteristics of glasma
5. Energy losses of hard probes in glasma

6. Summary and conclusions

Introduction - Heavy-Ion Collisions

HEAVY-ION COLLISIONS:



Evolution of strongly interacting medium → various approaches/models needed

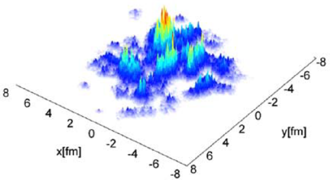
HARD PROBES:
(produced in the early phase, propagate throughout all phases of the fireball evolution)
- electroweak probes
- colour probes: quarkonia, jets with heavy quarks, jets with light quarks and gluons

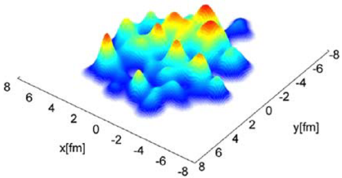
Introduction - Initial Phase

Many models to simulate the collision numerically

∗ QCD-based approach: CGC formalizm
∗ solving numerically Yang-Mills equations for gluon fields
∗ IP-glasma

∗ independent collection of nucleons
∗ Monte-Carlo simulation using geometrical properties of the system
∗ MC Glauber model

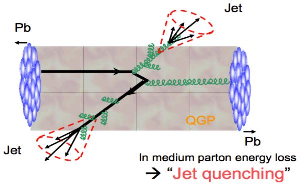


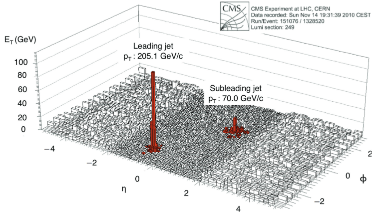


Aim: to get initial conditions for subsequent hydrodynamic evolution - energy density and pressure profiles

Introduction - Hard Probes

high-p_T probes - produced at the earliest time of the collision through hard interactions with large momentum transfer





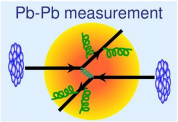
Jet quenching $\rightarrow$ energy loss of highly energetic partons because of the colour interactions

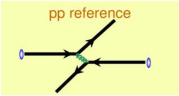
Mechanisms of the energy loss:

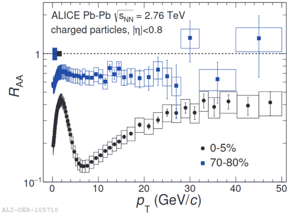
- elastic scatterings $\rightarrow$ collisional energy loss (dE/dx)
- inelastic scatterings (gluon radiation) $\rightarrow$ radiative energy loss (controlled by $\hat{q}$)
- ∗ energy loss is expected to depend on parton's colour charge and mass: hierarchy in energy loss $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$

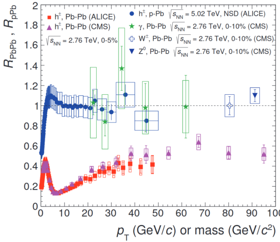
Traditional measure of energy loss - **nuclear modification factor:**

$$R^h_{AA}(p_T, \eta, \text{centrality}) = \frac{\frac{dN^{AA\to h}_{\text{medium}}}{dp_T\, d\eta}}{\langle N^{AA}_{\text{coll}}\rangle \frac{dN^{pp\to h}_{\text{vacuum}}}{dp_T\, d\eta}}$$









Introduction - Hard Probes

hard probes in (near) equilibrium QGP - very broad area, various approaches and techniques used, complex structure of jet structure and propagation

hard probes in pre-equilibium phase - relatively new idea

* glasma
* out-of-equilibrium system made of quasiparticles

- transport coefficients studied via Fokker-Planck equation
  Mrówczyński, Eur. Phys. J, A54 no 3, 43 (2018)
- solving Wong equations numerically within CGC
  Ruggieri, Das et al, Phys. Rev. D 98, 094024 (2018)
- HQ momentum diffusion in far-from-equilibrium overoccupied plasma
  Boguslavski, Kurkela, Lappi, Peuron, JHEP 09, 077 (2020)
- jet momentum broadening in pre-equilibrium glasma
  Ipp, Müller, Schuh, Phys. Lett. B 810, 135810 (2020)

Motivation

- properties of the initial stage
  - the least understood phase of the collision
  - lack of a direct experimental access to it
  - initial conditions for subsequent hydrodynamic evolution
  - transition between early-time dynamics and hydrodynamics

- impact of pre-equilibrium phase on hard probes
  - expected hierarchy of energy loss not confirmed
  - influence of initial dynamics on hard probes ignored for a long time

- limitations, consistency and reliability of the method

  expansion of glasma fields in the proper time:
  $\rightarrow$ analytical approach to study the initial state
  $\rightarrow$ purely classical

  - allows for control over different approximations and sources of errors
  - can be systematically extended
  - no fluctuations of positions of nucleons $\rightarrow$ less detailed when compared, for example, to IP-glasma

Initial dynamics

Nuclei before the collision

MV model - a specific realization of CGC:

- large x partons: valence quarks, color sources for gluon fields represented by the color density ρ: $J^\mu(x^-, \vec{x}_\perp) = \delta^{\mu +}\rho(x^-, \vec{x}_\perp)$
- small x partons: due to large occupation numbers effectively represented by soft gluon fields $\beta^\mu(x)$: $F^{\mu\nu} = \frac{i}{g}[D^\mu, D^\nu]$ with $D^\mu = \partial^\mu - ig\beta^\mu$
- gluons are in the saturation regime controlled by the saturation scale Q_s
- separation scale between small-x and large-x partons is fixed
- alternatively: $\mathbf{E}(x)$ and $\mathbf{B}(x)$ fields

Yang-Mills equations: $[D_\mu, F^{\mu\nu}] = J^\nu$

Solution: $\beta^-(x^-, \vec{x}_\perp) = 0 \qquad \beta^i(x^-, \vec{x}_\perp) = \theta(x^-)\frac{i}{g}U(\vec{x}_\perp)\partial^i U^\dagger(\vec{x}_\perp)$

$$U(\vec{x}_\perp) - \text{Wilson line}$$

Glasma

Glasma:

* highly energetic and anisotropic medium made of mostly gluon fields
* glasma fields $\alpha(\tau, \vec{x}_\perp)$ and $\alpha^i_\perp(\tau, \vec{x}_\perp)$ develop in the forward light-cone region:

$$\alpha^+(x) = x^+\alpha(\tau, \vec{x}_\perp) \qquad \alpha^-(x) = -x^-\alpha(\tau, \vec{x}_\perp) \qquad \alpha^i(x) = \alpha^i_\perp(\tau, \vec{x}_\perp)$$

* evolve in time parametrized by $\tau = \sqrt{t^2 - z^2} = \sqrt{2x^+x^-}$
* are boost-independent
* gluon fields obtained as solutions to classical source-less Yang-Mills equations
* current dependence enters through boundary conditions, which connect different light-cone sectors

$$\alpha^i_\perp(\tau = 0, \vec{x}_\perp) = \beta^i_1(\vec{x}_\perp) + \beta^i_2(\vec{x}_\perp) \qquad \alpha(\tau = 0, \vec{x}_\perp) = -\frac{ig}{2}[\beta^i_1(\vec{x}_\perp), \beta^i_2(\vec{x}_\perp)]$$

* general solutions not known

Expansion in the proper time

An analytical approach to solve Yang-Mills equations proposed in:

Fries, Kapusta, Li, arXiv:0604054
Chen, Fries, Kapusta, Li, Phys. Rev. C 92, 064912 (2015)

- glasma is a short-lived phase and decays before the system reaches equilibrium ($\tau < 1$ fm/c)
- proper time can be treated as an expansion parameter of glasma fields:

$$\alpha^i_\perp(\tau,\vec{x}_\perp) = \sum_{n=0}^{\infty} \tau^n \alpha^i_{\perp(n)}(\vec{x}_\perp), \qquad \alpha(\tau,\vec{x}_\perp) = \sum_{n=0}^{\infty} \tau^n \alpha_{(n)}(\vec{x}_\perp)$$

- the system of coupled Yang-Mills equations can be solved recursively to any order in τ
- 0th-rder coefficients are identified with boundary conditions
- solutions are written in terms of precollision potentials
- effective dimensionless parameter is $\tilde{\tau} = \tau Q_s$

Summary of the method:

$$\rho(x^-,\vec{x}_\perp) \;\rightarrow\; \beta(x^-,\vec{x}_\perp) \;\rightarrow\; \alpha(0,\vec{x}_\perp) \;\rightarrow\; \alpha(\tau,\vec{x}_\perp) \;\rightarrow\; E(\tau,\eta,\vec{x}_\perp),\, B(\tau,\eta,\vec{x}_\perp)$$

Correlators of gauge potentials

- colour charge distributions are not known → average over colour sources assuming a Gaussian distribution within each nucleus

$$\langle \rho_a(x^-, \vec{x}_\perp)\rho_b(y^-, \vec{y}_\perp)\rangle = g^2\delta_{ab}\lambda(x^-, \vec{x}_\perp)\delta(x^- - y^-)\delta^2(\vec{x}_\perp - \vec{y}_\perp)$$

$\lambda(x^-, \vec{x}_\perp)$ - volume density of sources

- potentials of different nuclei are uncorrelated: $\langle \beta^i_{1a}\beta^j_{2b}\rangle = 0$

Basic building block: 2-point correlator

$$\langle \beta^i_a(\vec{x}_\perp)\beta^j_b(\vec{y}_\perp)\rangle = \frac{2\delta_{ab}}{g^2 N_c \tilde{\Gamma}(\vec{x}_\perp, \vec{y}_\perp)} \left(\exp\left[\frac{g^4 N_c}{2}\,\tilde{\Gamma}(\vec{x}_\perp, \vec{y}_\perp)\right] - 1\right)\partial^i_x\partial^j_y\tilde{\gamma}(\vec{x}_\perp, \vec{y}_\perp)$$

$\tilde{\Gamma}$ and $\tilde{\gamma}$ - given by Bessel functions and the charge density density

$$\langle \rho_a\rho_b\rangle \to \langle \beta_a\beta_b\rangle \to \cdots \to \langle E_a E_b\rangle, \langle B_a B_b\rangle$$

Correlators of gauge potentials

- **Wick's theorem:**
  - $\langle\beta_1^i\beta_1^j\,\beta_2^l\beta_2^m\beta_2^k\beta_2^r\rangle = \langle\beta_1^i\beta_1^j\rangle\left(\langle\beta_2^l\beta_2^m\rangle\langle\beta_2^k\beta_2^r\rangle+\langle\beta_2^l\beta_2^k\rangle\langle\beta_2^m\beta_2^r\rangle+\langle\beta_2^l\beta_2^r\rangle\langle\beta_2^k\beta_2^m\rangle\right)$
  - correlators of odd number of gauge fields vanish

- **charge density per unit transverse area:**
  - $\bar{\mu} = g^{-4}Q_s^2$, where Q_s is the saturation scale (uniform nuclei)
  - Woods-Saxon distribution (internal structure of nuclei)

- **IR regulator:**

$m \sim \Lambda_{\rm QCD}$ - chosen so that because of confinement the effect of valence sources dies off at transverse length scales larger than $1/\Lambda_{\rm QCD}$

- **UV regulator:**

Q_s - saturation scale

Energy-momentum tensor

Correlators of gauge fields and the proper time expansion determine the structure of the energy-momentum tensor:

$$T^{\mu\nu} = 2\mathrm{Tr}\big[F^{\mu\lambda}F_{\lambda}{}^{\nu} + \frac{1}{4}g^{\mu\nu}F^{\alpha\beta}F_{\alpha\beta}\big]$$

$$F_{\mu\nu} = \frac{i}{g}[D_\mu, D_\nu]$$

- the result is complicated and long and given in powers of τ up to τ^6 order

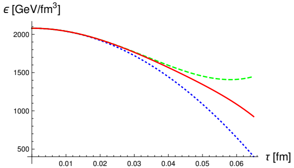
$$\mathcal{O}(T_{\mathrm{milne}}) = \begin{pmatrix} (0,2,4,6) & (1,3,5) & (1,3,5) & (1,3,5) \\ (1,3,5) & (-2,0,2,4) & (0,2,4) & (0,2,4) \\ (1,3,5) & (0,2,4) & (0,2,4,6) & (2,4,6) \\ (1,3,5) & (0,2,4) & (2,4,6) & (0,2,4,6) \end{pmatrix}.$$

- the energy-momentum tensor is gauge-invariant, divergence-less, traceless and symmetric
- due to symmetries only 6 components are independent

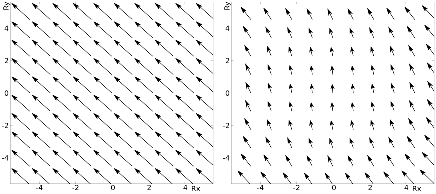
Energy density and pressure

$$\mathcal{E} = T^{00} \qquad \frac{p_L}{\mathcal{E}} = \frac{T^{11}}{T^{00}} \qquad \frac{p_T}{\mathcal{E}} = \frac{1}{2}\frac{(T^{22}+T^{33})}{T^{00}}$$

- $T^{\mu\nu}$ was found in powers of τ up to τ^6 order
- various profiles of $\mathcal{E}$, p_T, and p_L for different geometries of the collision and different charge densities were studied



($\eta = 0$ and uniform $\bar{\mu}$)



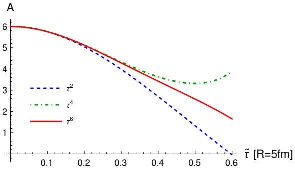
$(p_L/\epsilon, p_T/\epsilon)$ at $\tau = 0$ and $\tau = 0.05$ fm

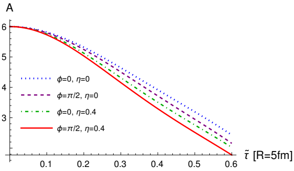
* $\mathcal{E}$, p_T (and p_L) are smooth functions in time and space
* proper time expansion works reasonably well for times $\tilde{\tau} \sim 0.5$ (or $\tau \sim 0.05$ fm)

Anisotropy of p_L and p_T

- anisotropy of the transverse and longitudinal pressure ($A_{TL} = 6$ at $\tau = 0$ and $A_{TL} = 0$ in equilibrated plasma)

$$A_{TL} \equiv \frac{3(p_T - p_L)}{2p_T + p_L}$$





* approach to isotropy faster at space points perpendicular to the reaction plane than in it
* approach to isotropy faster for larger rapidities

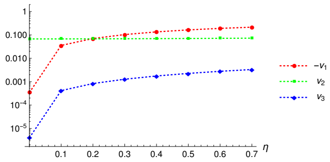
Azimuthal flow

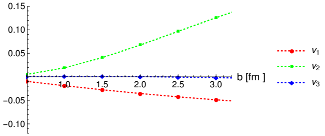
- Fourier coefficients of the momentum azimuthal flow

$$v_n = \int_0^{2\pi} d\phi \, \cos(n\phi) \, P(\phi)$$

$P(\phi) \equiv \frac{1}{\Omega} \int d^2\vec{x}_\perp \, \delta(\phi - \varphi(\vec{x}_\perp)) \, W(\vec{x}_\perp), \quad W \equiv \sqrt{(T^{0x})^2 + (T^{0y})^2},$
$\varphi = \cos^{-1}\left(\frac{T^{0x}}{W}\right)$

- Fourier coefficients v_1, v_2 and v_3 calculated as a function of rapidity (at fixed $b = 2$ fm) and as a function of impact parameter (at fixed $\eta = 0.1$)





∗ **symmetries: n-odd coefficients are rapidity odd and n-even coefficients are rapidity even** (we know the reaction plane and we do not include fluctuations in the positions of participants)

∗ v_2 **and** v_3 **are of the same order as experimental values**

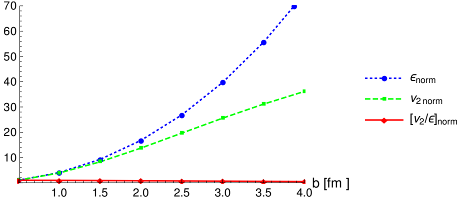
∗ $|v_1|$ **is bigger than expected**

Eccentricity and elliptic flow coefficient

- eccentricity - spatial deviations from azimuthal symmetry

$$\varepsilon_n = -\frac{\int d^2\vec{R}|\vec{R}|\cos(n\phi)\mathcal{E}(\vec{R})}{\int d^2\vec{R}|\vec{R}|\mathcal{E}(\vec{R})} \qquad \phi = \tan^{-1}(R_y/R_x)$$

- calculated as a function of the impact parameter at $\tau = 0.04$ fm and $\eta = 0$



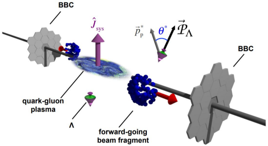
→ **correlation of eccentricity ϵ_2 and v_2 is treated as a indication of onset of hydrodynamic behaviour**

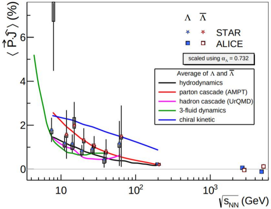
The expected role of angular momentum in HIC

- large angular momentum generated in non-central collisions

STAR Collaboration,
Nature 548, 62 (2017)

Becattini and Lisa,
Ann.Rev.Nucl.Part.Sci. 70 (2020) 395-423





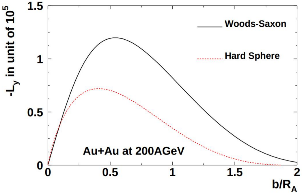
- consequences:
  - spin-orbit coupling leads to alignment of spins to the direction of the angular momentum → polarization of hyperons and vector mesons
  - QGP is rapidly-rotating (vortical) system
- many attempts to formulate hydrodynamics with spin

Experimental observations:

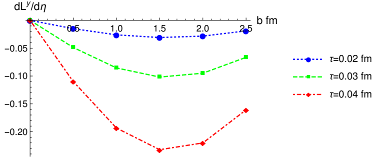
* at RHIC energies polarization of a few percent is seen in non-central AA collisions
* at LHC energies polarization is not observed at all

Angular momentum

- angular momentum at RHIC energies
  Gao et al, Phys. Rev C 77, 044902 (2008)



- angular momentum of the glasma as a function of the impact parameter



∗ the shape and the position of the peak similar
∗ the result at RHIC energies $\sim 10^5$ bigger than our results
∗ most of the momentum of the incoming nuclei is NOT transmitted to the glasma
∗ small angular momentum of the glasma $\rightarrow$ no polarization effect at highest collision energies

Hard probes in glasma

Fokker-Planck equation

Evolution equation on the distribution function of heavy quarks:
Mrówczyński, Eur. Phys. J, A54 no 3, 43 (2018)

$$\Big(D - \nabla_p^\alpha X^{\alpha\beta}(\mathbf{v})\nabla_p^\beta - \nabla_p^\alpha Y^\alpha(\mathbf{v})\Big)n(t,\mathbf{x},\mathbf{p}) = 0$$

$n(t,\mathbf{x},\mathbf{p})$ - distribution of hard probes $\qquad D \equiv \frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla$

Collision terms:

$$X^{\alpha\beta}(\mathbf{v}) = \frac{1}{2N_c}\int_0^t dt' \langle F_a^\alpha(t,\mathbf{x})F_a^\beta(t',\mathbf{x}-\mathbf{v}(t-t'))\rangle$$

$$Y^\alpha(\mathbf{v}) = X^{\alpha\beta}\frac{v^\beta}{T}$$

T - temperature of a plasma that has the same energy density as in equilibrium
$\mathbf{F}(t,\mathbf{r}) = g(\mathbf{E}(t,\mathbf{r}) + \mathbf{v}\times\mathbf{B}(t,\mathbf{r}))$ - color Lorentz force
g - constant coupling
$\mathbf{E}(t,\mathbf{r}), \mathbf{B}(t,\mathbf{r})$ - chromoelectric and chromomagnetic fields
$\mathbf{v} = \frac{\mathbf{p}}{E_\mathbf{p}}$ - velocity of the probe:

$\mathbf{v} \simeq 1$ - light quarks and gluons $\qquad \mathbf{v} \leq 1$ - heavy quarks

Energy losses

Physical meaning of the collision terms:

$$\frac{\langle \Delta p^\alpha \rangle}{\Delta t} = -Y^\alpha(\mathbf{v}) \qquad \frac{\langle \Delta p^\alpha \Delta p^\beta \rangle}{\Delta t} = X^{\alpha\beta}(\mathbf{v}) + X^{\beta\alpha}(\mathbf{v})$$

Energy losses are defined by:

$$\frac{dE}{dx} = \frac{v^\alpha}{v} \frac{\langle \Delta p^\alpha \rangle}{\Delta t} \qquad \hat{q} = \frac{1}{v}\Big(\delta^{\alpha\beta} - \frac{v^\alpha v^\beta}{v^2}\Big)\frac{\langle \Delta p^\alpha \Delta p^\beta \rangle}{\Delta t}$$

Collisional energy loss and transverse momentum broadening

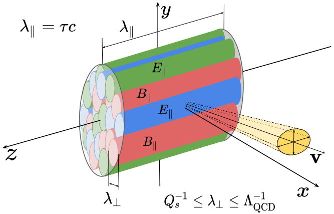
$$-\frac{dE}{dx} = \frac{v}{T}\frac{v^\alpha v^\beta}{v^2} X^{\alpha\beta}(\mathbf{v})$$

$$\hat{q} = \frac{2}{v}\Big(\delta^{\alpha\beta} - \frac{v^\alpha v^\beta}{v^2}\Big) X^{\alpha\beta}(\mathbf{v})$$

$$X^{\alpha\beta}(\mathbf{v}) = \frac{g^2}{2N_c}\int_0^t dt' \Big[\big\langle E_a^\alpha(t,\mathbf{x}) E_a^\beta(t-t',\mathbf{y})\big\rangle + \epsilon^{\beta\gamma\gamma'} v^\gamma \big\langle E_a^\alpha(t,\mathbf{x}) B_a^{\gamma'}(t-t',\mathbf{y})\big\rangle$$
$$+ \epsilon^{\alpha\gamma\gamma'} v^\gamma \big\langle B_a^{\gamma'}(t,\mathbf{x}) E_a^\beta(t-t',\mathbf{y})\big\rangle + \epsilon^{\alpha\gamma\gamma'}\epsilon^{\beta\delta\delta'} v^\gamma v^\delta \big\langle B_a^{\gamma'}(t,\mathbf{x}) B_a^{\delta'}(t-t',\mathbf{y})\big\rangle\Big]$$

Schematic picture

Hard probe traversing glasma at $\tau = 0$ $(\lambda_{\|}, \lambda_{\perp}$ - correlation lengths)

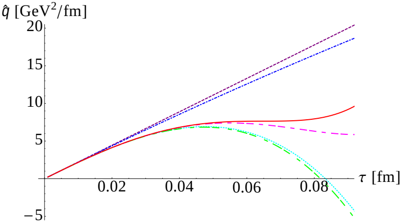


$*$ experiments focus on the region of the momentum-space rapidity $y \in (-1, 1) \rightarrow v_{\|} \in (-0.76, 0.76)$
$*$ transport coefficients built up during the time that the probe spends within the domain of correlated field
$*$ this time determined by $\lambda_{\perp}$ and $\mathbf{v}$
$*$ transport coefficients saturate when the probe leaves the region of correlated fields
$*$ at higher order in τ $\rightarrow$ calculations needed

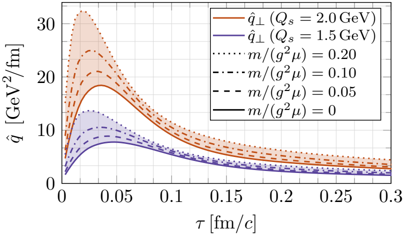
Consistency and reliability of the approach are fixed by convergence of the proper time expansion and saturation of the results.

Time dependence of $\hat{q}$

- $\hat{q}$ calculated up to τ^5 order
- parameters $m = 0.2$ GeV, $Q_s = 2$ GeV, $N_c = 3$, $g = 1$, $v = v_\perp = 1$



Carrington, Czajka, Mrówczyński
PRC 105, 064910 (2022)

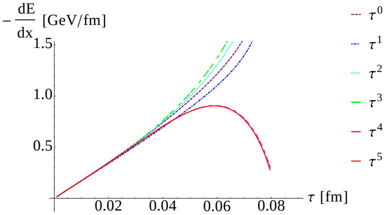


Ipp, Müller, Schuh
PLB 810, 135810 (2020)

- saturation of $\hat{q}$ observed before the τ expansion breaks down,
- $\hat{q} \simeq 6$ GeV^2/fm - maximal value

Time dependence of dE/dx

- dE/dx and $\hat{q}$ calculated up to τ^5 order
- temperature T obtained by matching:
  $\varepsilon_{\mathrm{QGP}} = \frac{\pi^2}{60}\big(4(N_c^2-1)+7N_f N_c\big)T^4$
  $\varepsilon_{\mathrm{QGP}} = 130.17\big(15.9773 - 29.6759\,\tilde{\tau}^2 + 42.6822\,\tilde{\tau}^4 - 49.2686\,\tilde{\tau}^6\big)$

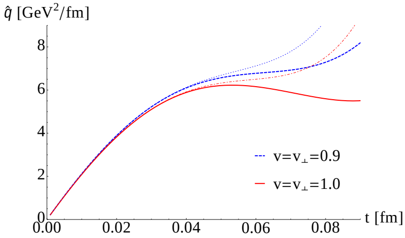


$$v = 1, v_{\|} = v_{\perp} = 1/\sqrt{2}$$

- dE/dx reaches a maximal value 0.9 GeV/fm, no saturation $\rightarrow$ order of magnitude estimate only

Velocity dependence of $\hat{q}$

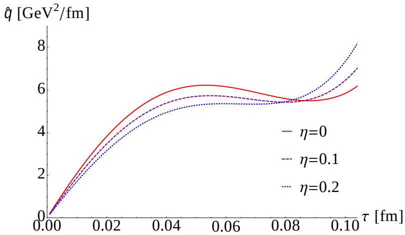
Purely transverse motion of hard probes through the glasma ($v_{\|} = 0$)



- the results at orders τ^4 and τ^5 agree quite well up to about $\tau \sim 0.07 - 0.08$ fm
- the probe spends less time in the region of correlated fields $\rightarrow$reduction of the coefficient for ultra-relativistic quarks

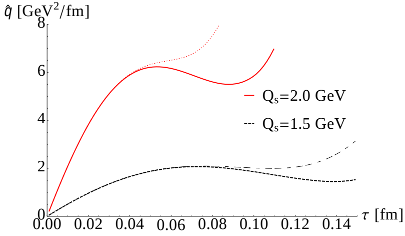
Space-time rapidity dependence of $\hat{q}$

dependence on spatial rapidity $\eta \to$ dependence on the initial position of the probe in the glasma

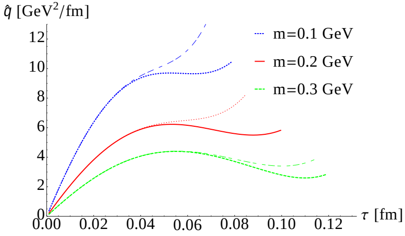


- $\hat{q}$ at orders τ^4 and τ^5 agree well up to $\tau \simeq 0.07$ fm
- $\hat{q}$ is weakly dependent on η fo small values of η (CGC is expected to work best in the region of mid-spatial-rapidity region)

Dependence on UV and IR energy scales



fixed $m = 0.2$ GeV



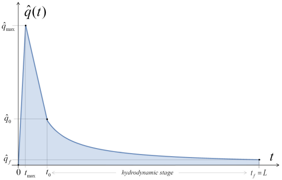
fixed $Q_s = 2$ GeV

$\rightarrow$ $\hat{q}$ sensitive to the choice of m and Q_s
$\rightarrow$ decreasing m increases the value of $\hat{q}$
$\rightarrow$ decreasing Q_s decreases the maximal value of $\hat{q}$ but extends the validity region of τ
$\rightarrow$ Q_s is smaller at smaller collision energies $\rightarrow$ $\hat{q}$ is smaller at smaller collision energies (RHIC vs LHC collision energies)

$\rightarrow$ reduction in $\hat{q}$ at $\tau = 0.6$ fm for high-p_T hadron at the RHIC energies compared to LHC energies observed by the JET Collaboration
K. M. Burke et al (JET Collaboration), Phys. Rev. C 90, 014909 (2014)

Glasma impact on jet quenching

Total accumulated transverse momentum: $\Delta p_T^2 = \int_0^L dt\, \hat{q}(t)$



- non-equilibrium case: $\Delta p_T^2\Big|^{\rm non-eq} = \frac{1}{2}\hat{q}_{\rm max} t_0 + \frac{1}{2}\hat{q}_0(t_0 - t_{\rm max})$
- equilibrium case: $\Delta p_T^2\Big|^{\rm eq} = 3T_0^3\, t_0\, \ln\frac{L}{t_0}$

  where we used $\hat{q}(t) = 3T^3$ and $T = T_0\left(\frac{t_0}{t}\right)^{1/3}$
- parameters:
  $\hat{q}_{\rm max} \approx 6$ GeV^2/fm, $t_{\rm max} \approx 0.06$ fm, $L = 10$ fm, $\hat{q}_0 \approx 1.4$ GeV^2/fm, $t_0 \approx 0.6$ fm, $T_0 = 0.45$ GeV
  JETSCAPE, Phys. Rev. C 104, 024905 (2021), C. Shen et al, Phys. Rev. C 84, 044903 (2011)

$$\frac{\Delta p_T^2\Big|^{\rm non-eq}}{\Delta p_T^2\Big|^{\rm eq}} = 0.93$$

Non-equilibrium phase gives comparable contribution to the radiative energy loss as the equilibrium phase.

Summary and conclusions

* Glasma dynamics and transport of hard probes through it studied in the proper time expansion
* Many physical characteristics of glasma dynamics calculated
* Impact of the glasma on hard probes quantified
* Convergence of the proper time expansion tested

- Hydrodynamic-like behaviour in the glasma phase
  - Fourier coefficients of the azimuthal flow relatively large
  - Sizeable correlation of the eccentricity and elliptic flow coefficient
- Small angular momentum of the glasma
  - Glasma is not a rapidly rotating system, no polarization effect (in agreement with experimental observations for LHC energies)
- Significant impact of the glasma phase on transport of hard probes
  - Both $\hat{q}$ and dE/dx are found to be relatively large
  - Our approach most reliable for probes moving transversally (this is experimentally relevant domain)