HQS JETS HARD PROBES IN THE GLASMA

by Dana Avramescu
University of Jyväskylä, Center of Excellence in Quark Matter

based on [2303.05599]

Supervisors: T. Lappi, H. Mäntysaari (Uni Jyväskylä)
Collaborators: A. Ipp, D. Müller (TU Wien), V. Greco, M. Ruggieri (Uni Catania), V. Băran (Uni Bucharest)

Hard Probes in Aschaffenburg, March 2023

General outline

1. Introduction
   Framework • Literature • This study
2. Hard probes in Glasma
   Glasma • Probes in Glasma • Numerics
3. Key results
   Heavy quarks • Jets
4. Highlights

Heavy-ion collisions

Heavy-ion collision $\leftrightarrow$ multi-stage process with each stage $\mapsto$ effective theory

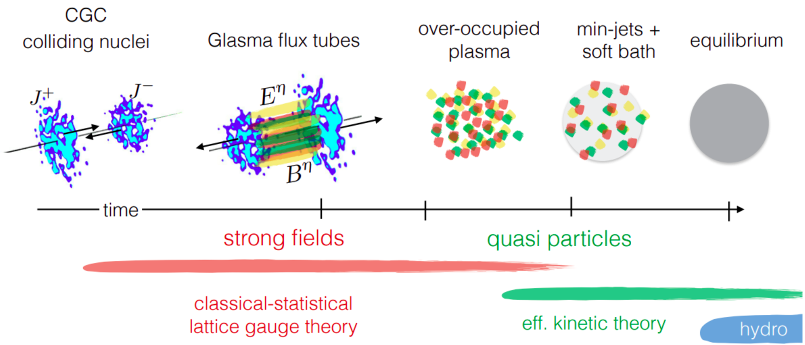


Figure from S. Schlichting's talk [1]

Initial stage

Initial stage using Color Glass Condensate $\leftrightarrow$ EFT for high energy QCD
High energy nucleus $\rightsquigarrow$ many gluons $\Rightarrow$ classical colored fields $\equiv$ Glasma

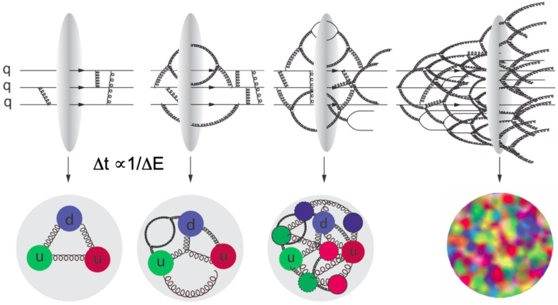
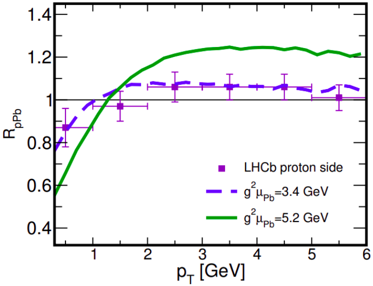


Figure from F. Salazar's talk [2]

Literature timeline

- 2018 — Coci, Das, Greco, Ruggieri, Plumari, Sun
  [1805.09617], [1902.06254]
- 2020 — Ipp, Müller, Schuh
- 2020 — Boguslavski, Kurkela, Lappi, Peuron
- 2021 — Carrington, Czajka, Mrowczynski
- 2023 — Avramescu, Băran, Greco, Ipp, Müller, Ruggieri

Heavy quarks in Glasma
Highlights: Diffusion, v_2, R_{AA}



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  [2001.10001], [2009.14206]
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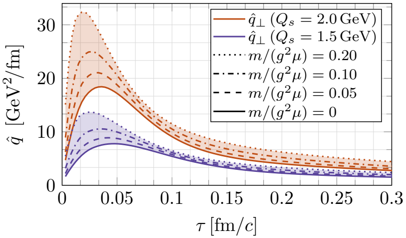
- 2023 Avramescu, Băran, Greco, Ipp, Müller, Ruggieri

Lightlike jets in Glasma
Highlight: Large $\hat{q}$ at small τ



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[2005.02418], [2001.11863]

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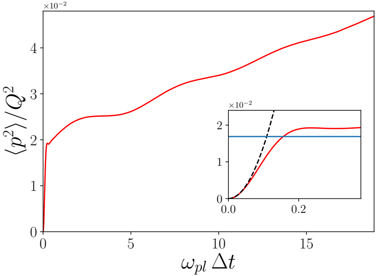
2023 Avramescu, Băran, Greco, Ipp, Müller, Ruggieri

Static quarks in gluon plasma

Highlight: Rapid increase in $\langle p^2 \rangle$



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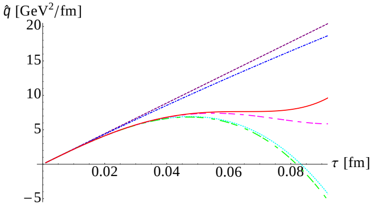
- 2023 — Avramescu, Băran, Greco, Ipp, Müller, Ruggieri

Analytical hard probes in Glasma
Highlight: Significant $\hat{q}$ in early τ



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This talk. No spoilers.

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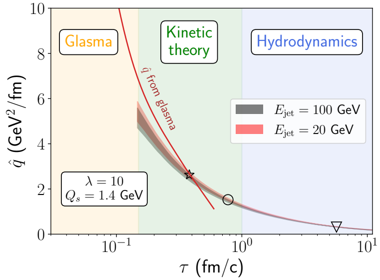
2023 Boguslavski, Kurkela, Lappi, Lindenbauer, Peuron
[2303.12520], [2303.12595]

Hard probes with kinetic theory
Highlight: Fill gap Glasma $\mapsto$ hydro



Motivation

Glasma fields → initial stage

hard probes → early-produced partons

Effect of the initial stage on the early-produced partons

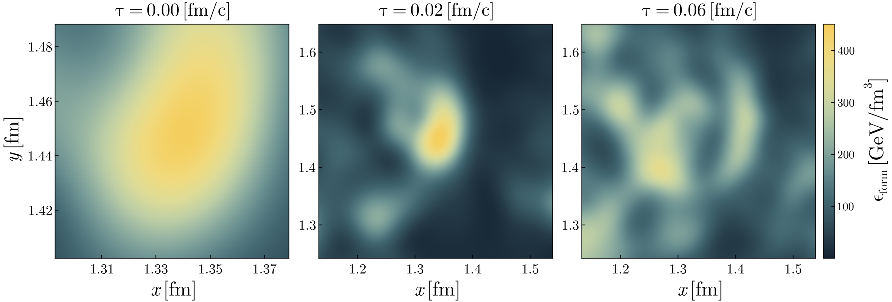
Literature $\Rightarrow$ qualitatively significant impact

This study: How much? $\Leftrightarrow$ refinements: $\begin{cases} \text{fields} \mapsto \text{SU(3) lattice} \\ \text{particles} \mapsto \text{full dynamics} \end{cases}$ $\Rightarrow$ GPU solver

Approach

Prerequisite: Classical lattice gauge theory $\xrightarrow{\text{solver}}$ Glasma fields

Task: Glasma fields $\xleftrightarrow{\text{background}}$ ensemble of particles $\xleftarrow{\text{solver}}$ colored particle-in-cell method



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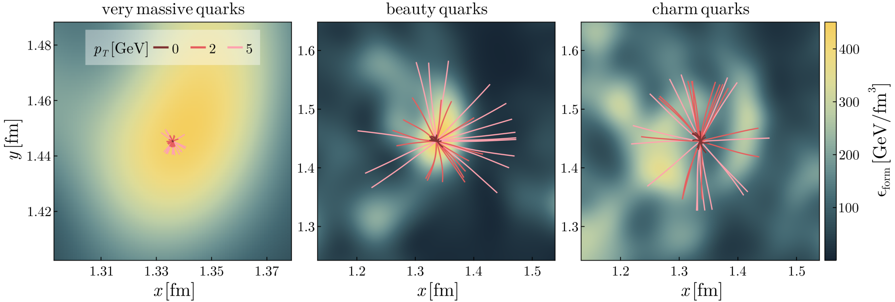
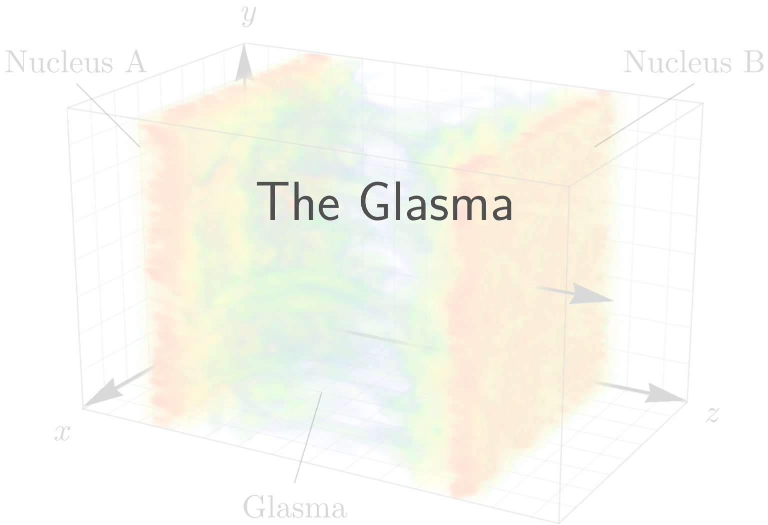


The Glasma



CGC basics *(technicalities)*

Separation of scales between small-x and large-$\mathcal{X}$ degrees of freedom

Small-x $\Leftrightarrow$ classical gluon fields $\mapsto$ Yang-Mills equations with sources $\Leftrightarrow$ large-$\mathcal{X}$

covariant derivative — field strength tensor

$$\left(\mathcal{D}_\mu \; F^{\mu\nu}\right)\left[A^\mu\right] = J^\nu$$

gluons gauge field — color current of nucleus

McLerran-Venugopalan model $\mapsto J^{\mu,a}(x) \propto \delta^{\mu+}\,\rho^a(x^-, x_\perp)$

large nuclei — stochastic variable

Two-point function $\langle \rho^a \rho^a \rangle \propto Q_s^2$ saturation momentum

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Collision of CGC nuclei

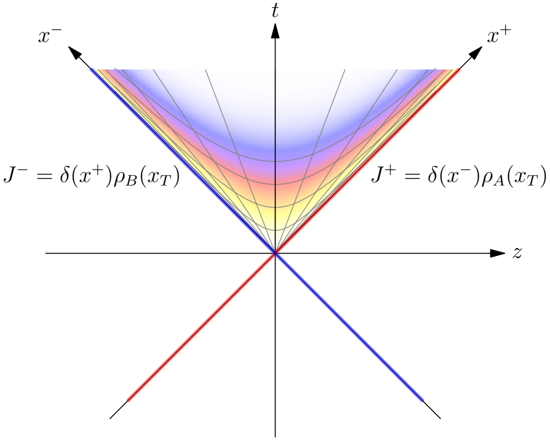


Figure credits to D. Müller

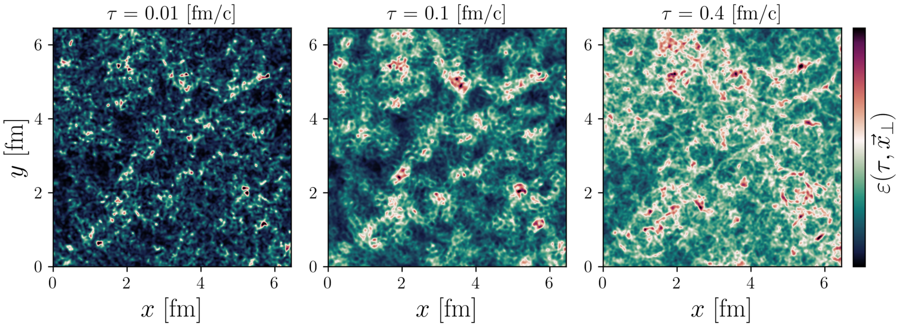
- Thin nuclei along light-cone
- Glasma fields in the forward light-cone

Milne coordinates (τ, η)
$\tau = \sqrt{2x^+x^-}$, $\eta = \ln(x^+/x^-)/2$

Boost-invariant approximation
$\text{fields} = \text{indep}(\eta)$

Numerical solution of Yang-Mills equations $\Rightarrow$ Glasma

Glasma fields

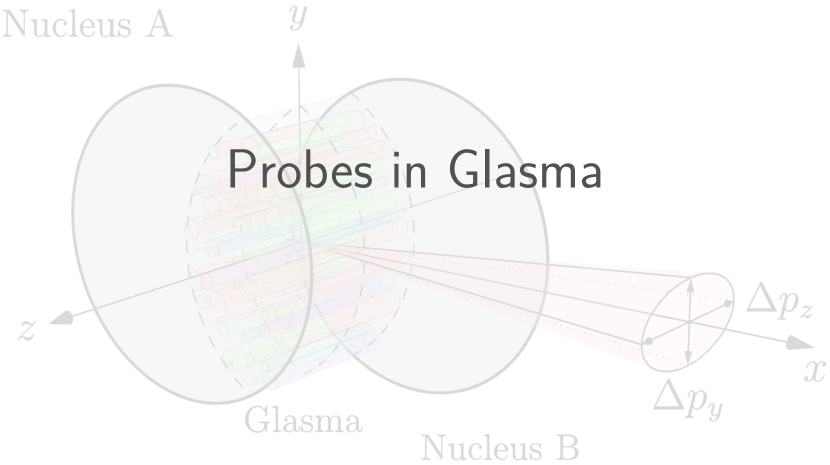


Relevant scale Q_s

*Fields **dilute** after $\delta\tau \simeq Q_s^{-1}$, arrange themselves in **correlation domains** of $\delta x_T \simeq Q_s^{-1}$*

Boost-invariant, highly anisotropic

Probes in Glasma



Particles in YM fields *(technicalities)*

Wong's equations $\leftrightarrow$ classical equations of motion for particles (x^μ, p^μ, Q)
evolving in Yang-Mills fields A^μ

$$\frac{\mathrm{d}}{\mathrm{d}\boldsymbol{\tau}} x^\mu = \frac{p^\mu}{m}, \qquad \frac{\mathrm{D}}{\mathrm{d}\boldsymbol{\tau}} p^\mu = 2g\mathrm{Tr}\left\{ Q F^{\mu\nu}[A^\mu] \right\} \frac{p_\nu}{m}, \qquad \underbrace{\frac{\mathrm{d}}{\mathrm{d}\boldsymbol{\tau}} Q = -\mathrm{i}g[A_\mu, Q]\frac{p^\mu}{m}}_{\text{color rotation} \rightarrow \mathcal{U} \in \mathrm{SU}(3)}$$

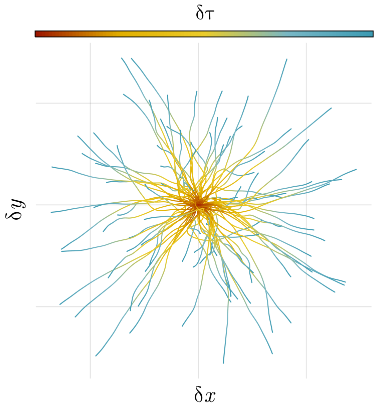
coordinate (x^μ), momentum (p^μ), gauge field (A^μ), color charge (Q); proper time ($\boldsymbol{\tau}$), mass (m), covariant derivative ($\mathrm{D}/\mathrm{d}\boldsymbol{\tau}$), coupling constant ($g$)

$$Q(\boldsymbol{\tau}) = \mathcal{U}(\boldsymbol{\tau},\boldsymbol{\tau}')\, Q(\boldsymbol{\tau}')\, \mathcal{U}^\dagger(\boldsymbol{\tau},\boldsymbol{\tau}')$$

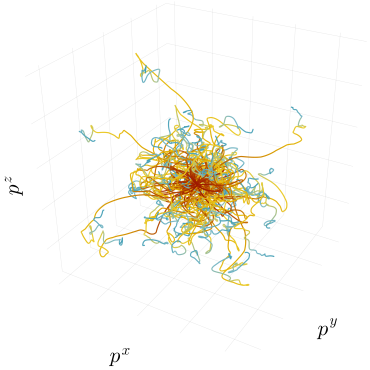
CPIC solver $\xrightarrow{\text{assures}}$ $Q \in \mathrm{SU}(3)$, conservation of Casimir invariants

Glasma plate *(just before lunch...)*

Spaghetti coordinate trajectories



Noodles momentum trajectories



Quantifying the effect of Glasma

Momentum broadening

$$\delta p_\mu^2(\tau) \equiv p_\mu^2(\tau) - p_\mu^2(\tau_{\mathrm{form}})$$

Instantaneous transport coefficient

$$\frac{\mathrm{d}}{\mathrm{d}\tau}\langle \delta p_i^2(\tau)\rangle \equiv \begin{cases} \kappa_i(\tau), & \text{heavy quarks} \\ \hat{q}_i(\tau), & \text{jets} \end{cases}$$

Anisotropy $\equiv \langle \delta p_L^2\rangle / \langle \delta p_T^2\rangle$

Toy model particle setup

- Uniformly distributed in (x, y)
- Formed at $\tau_{\mathrm{form}} \propto 1/m$
- Fixed initial $p_T(\tau_{\mathrm{form}})$

Glasma setup

- Large nuclei, central collisions
- Saturation scale $Q_s = 2\,\mathrm{GeV}$

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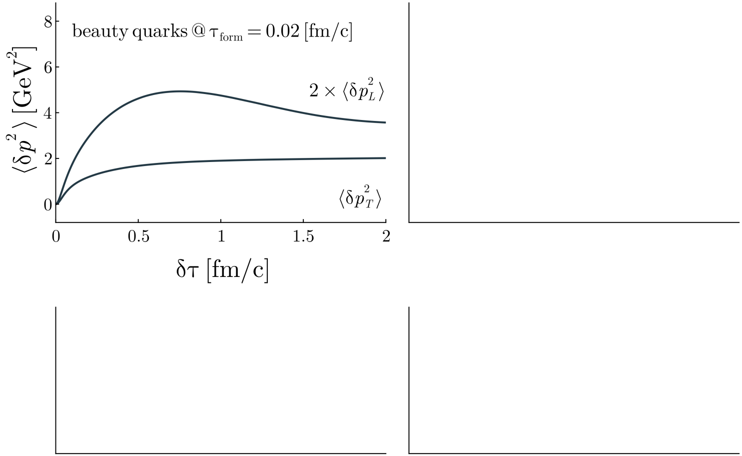

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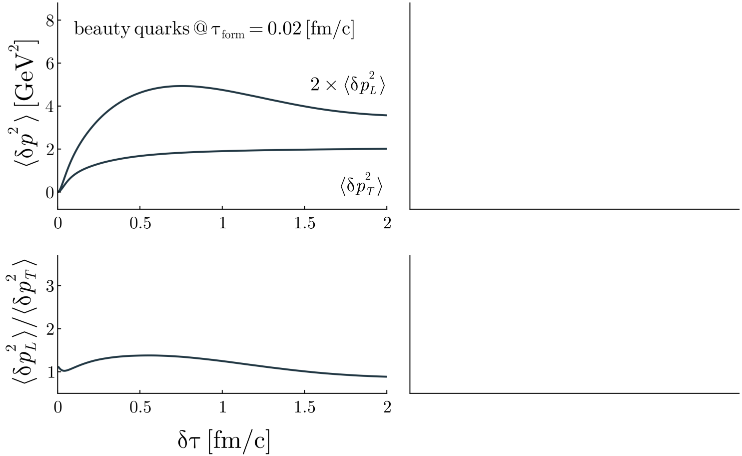

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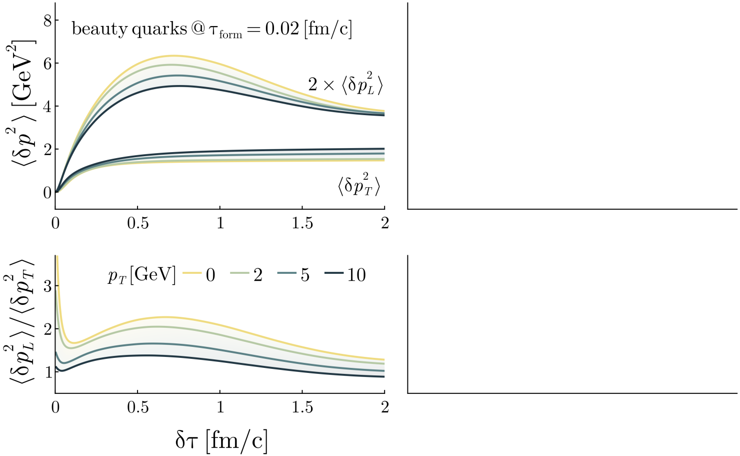

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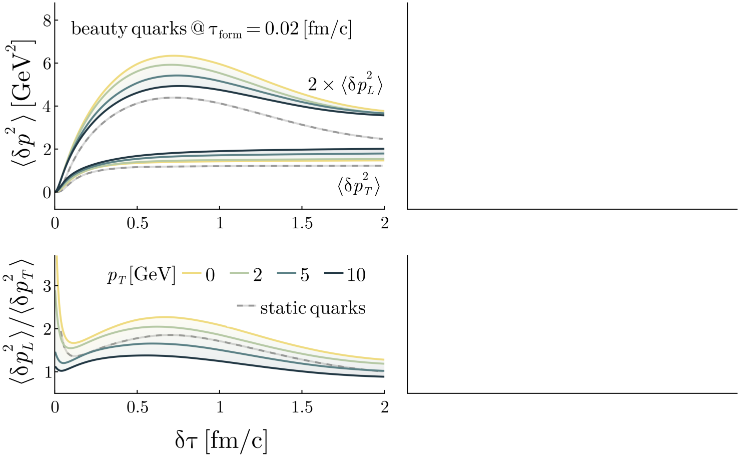

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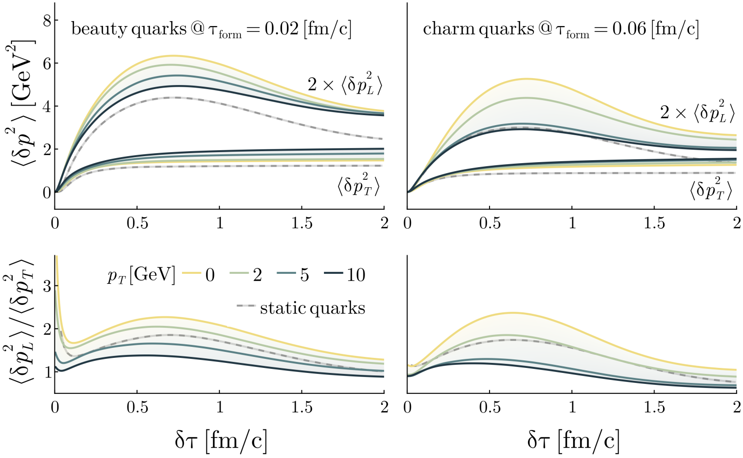
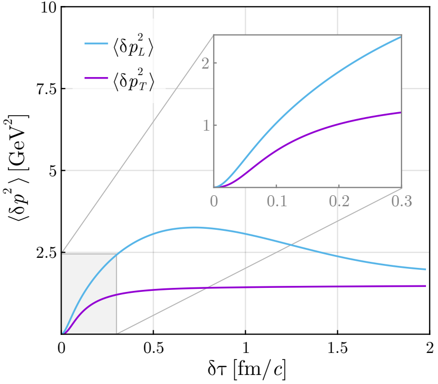


Transport in Glasma *(study case: beauty quarks)*

Rapid increase in $\langle p^2 \rangle$



$\Rightarrow$ Early peak* in κ

*$\kappa_{\text{peak}} \approx 15\,\text{GeV}^2/\text{fm}$ *but peak value depends on particle* (m, τ_{form}, *initial* p_T) *and Glasma* (Q_s)

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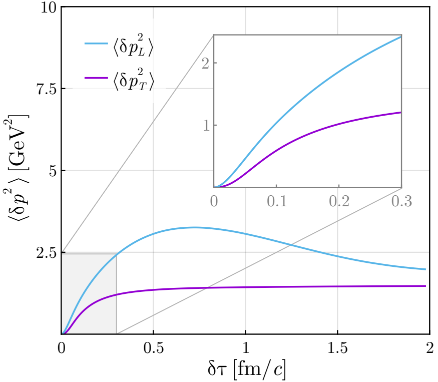

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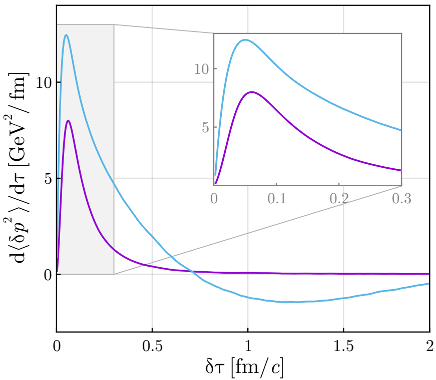

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Jet momentum broadening

Schematic geometry of jets in Glasma

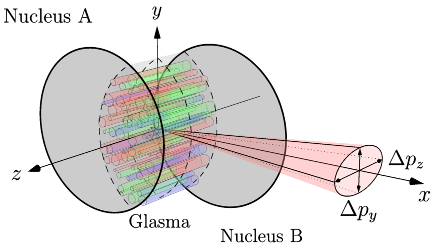

Figure from [2009.14206]

Early larger peak* in $\hat{q}$

* $\hat{q}_{\text{peak}} \approx 25\,\text{GeV}^2/\text{fm}$ *with weak dependence on particle (m or initial p^x) but affected by Glasma (Q_s)*

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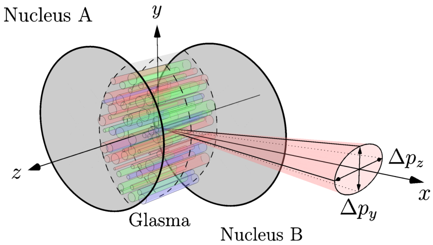

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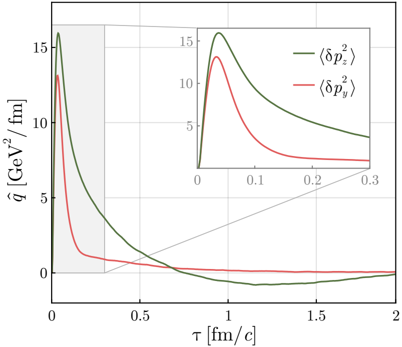


$^*\,\hat{q}_{\text{peak}} \approx 25\,\text{GeV}^2/\text{fm}$ *with weak dependence on particle* (m *or initial* p^x) *but affected by Glasma* (Q_s)

This is plausible!

Schematic evolution of $\hat{q}$

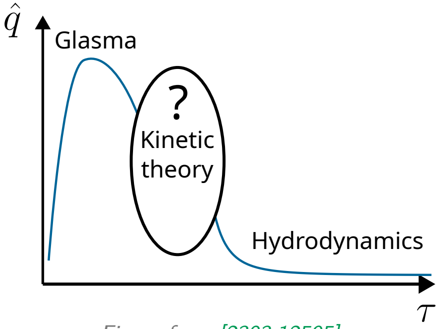
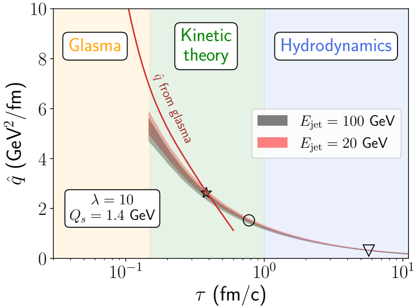


Figure from [2303.12595]

Kinetic theory* connects large $\hat{q}$ in Glasma to subsequent hydrodynamics



* *Bottom-up thermalization scenario*

Recall Kirill Boguslavski's plenary @ Monday, see Jarkko Peuron's talk @ Wednesday
Moreover, see Marcos González Martínez's talk @ Wednesday

Highlights

This work:

Numerical solver for hard probes in Glasma

$\langle \delta p^2 \rangle \Rightarrow \mathrm{d}\langle \delta p^2 \rangle / \mathrm{d}\tau \mapsto \boldsymbol{\kappa}$ or $\hat{\boldsymbol{q}}$ **large** and **peaked**, $\langle \delta p_L^2 \rangle / \langle \delta p_T^2 \rangle$

Effect of τ_{form}, m and $p_T(\tau_{\mathrm{form}})$

Work in progress:

Behavior of $\langle \delta p^2 \rangle \rightsquigarrow$ Glasma field correlators

$Q\overline{Q}$ angular correlations in Glasma

Improvements:

Jet energy loss

Hard probes in 3+1D Glasma

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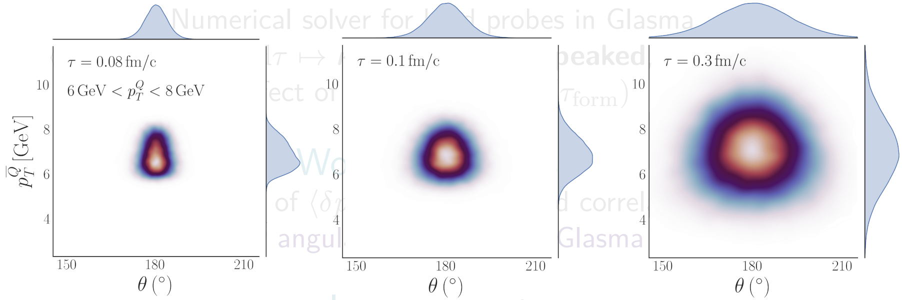

$c\bar{c}$ pairs initially produced back-to-back, measure θ pair angle in Glasma, FONLL initial p_T

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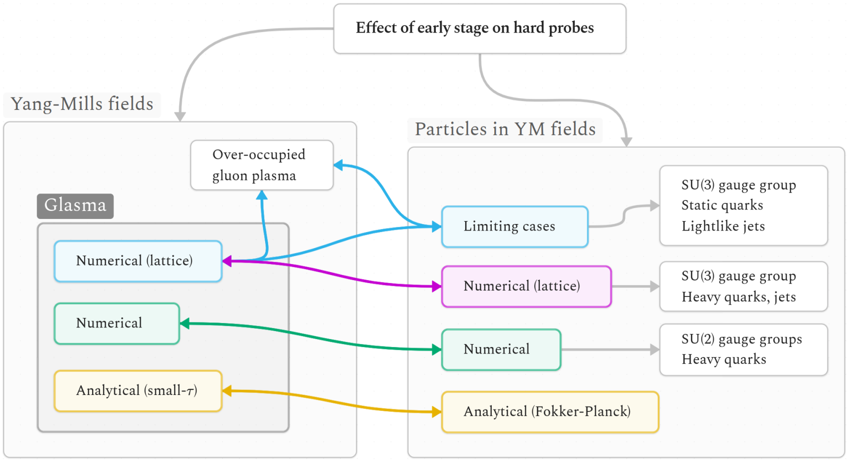
Thank you!

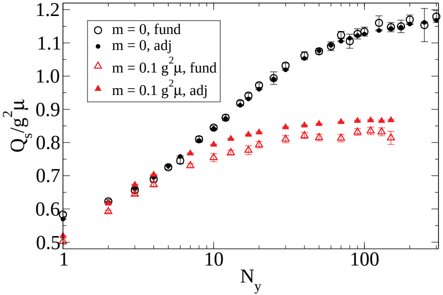
Back-up

Synthesis of hard probes in initial stages



Features of the Glasma fields

- Relevant scale → saturation momentum Q_s from DIS ⇒ $Q_s/g^2\mu$ [7]
- Fields ⇝ dilute after $\delta\tau \simeq Q_s^{-1}$
- Fields ⇝ correlation domains of transverse size $\delta x_T \simeq Q_s^{-1}$
- Anisotropic field configurations



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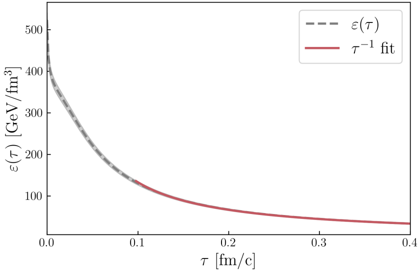

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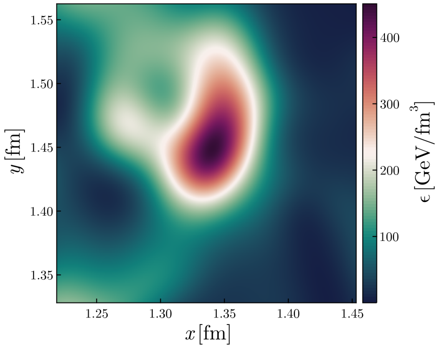

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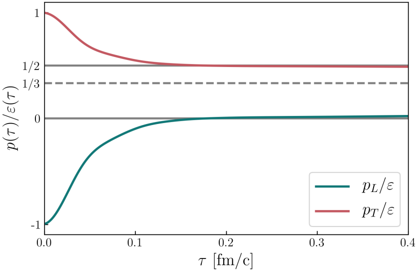
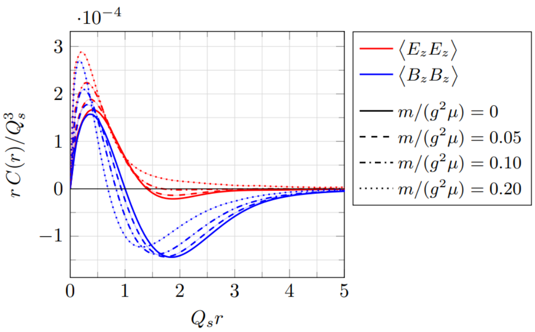
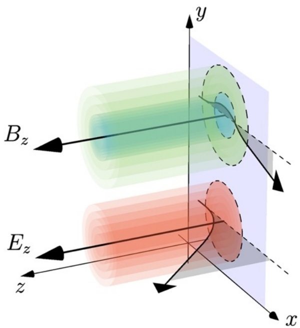


Glasma electromagnetic fields





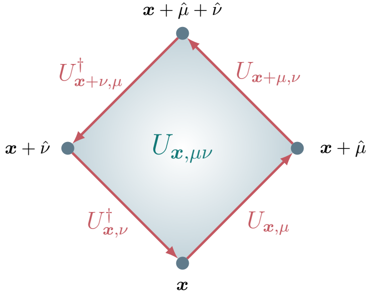
Correlation domains of typical size $1/Q_s$

Longitudinal electric fields correlated, magnetic fields exhibit anti-correlation

Figures from [2001.10001], [2009.14206]

Numerical implementation *(technicalities)*

Boost-invariant Yang-Mills equations for $A_i(\tau, \vec{x}_\perp, \cancel{\eta})$ and $A_\eta(\tau, \vec{x}_\perp, \cancel{\eta})$



Trace of a plaquette $\mapsto$ gauge invariant

Wilson lines on the lattice $\leftrightarrow$ gauge links

$$U_{x,\mu} = \exp\{igaA_\mu(x)\}$$

Wilson loops on lattice $\leftrightarrow$ plaquettes

$$U_{x,\mu\nu} \equiv U_{x,\mu}\, U_{x+\mu,\nu}\, U^\dagger_{x+\mu,\mu}\, U^\dagger_{x,\nu}$$

Glasma $\xrightarrow{\text{boost invariance}}$ transverse gauge links $U_i(\tau, \vec{x}_\perp)$, while $A_\eta(\tau, \vec{x}_\perp)$

Color rotation on the lattice *(oversimplified)*

Color charge $\xrightarrow{\text{evolved by}}$ color lattice rotation $Q(\tau) = \mathcal{U}(\tau, \tau_0)\, Q(\tau_0)\, \mathcal{U}^\dagger(\tau, \tau_0)$
particle Wilson line $\mathcal{U} \in \mathrm{SU}(3) \leftrightarrow$ path-ordered exponential from Glasma gauge fields

Initial color charge $Q_0 = Q_0^a T^a$ constructed with fixed quadratic q_2 and cubic q_3 Casimirs

$$q_2(R) = Q_0^a Q_0^a, \quad q_3(R) = d_{abc} Q_0^a Q_0^b Q_0^c, \quad R \mapsto \text{representation}$$

Particle temporal Wilson line $\mathcal{U}(\tau, \tau_0) = \mathscr{P} \exp\left\{ ig \int_{\tau_0}^{\tau} \mathrm{d}\tau' \frac{\mathrm{d}x^\mu}{\mathrm{d}\tau'} A_\mu(x^\mu) \right\}$

Color rotation on the lattice *(details)*

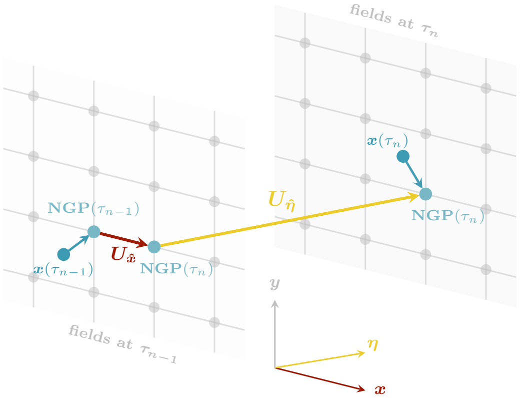
In the Glasma, it simplifies to:

$$\mathcal{U}(\tau_0,\tau) = \mathscr{P}\exp\left\{ \mathrm{i}g\int_{\tau_0}^{\tau}\mathrm{d}\tau' \cancelto{0}{A_\tau} + \mathrm{i}g\int_{\vec{x}_\perp(\tau_0)}^{\vec{x}_\perp(\tau)}\mathrm{d}x'^{\,i} A_i\left(\vec{x}'_\perp(\tau)\right) + \mathrm{i}g\underbrace{\int_{\eta(\tau_0)}^{\eta(\tau)}\mathrm{d}\eta'}_{\eta(\tau)-\eta(\tau_0)}\ \underbrace{A_\eta\left(\vec{x}_\perp(\tau)\right)}_{\mathrm{indep}(\eta')} \right\}$$

Numerically: $$\mathcal{U}(\tau_{n-1},\tau_n) \approx \underbrace{\exp\left\{\mathrm{i}g\int_{\boldsymbol{x}_{n-1}}^{\boldsymbol{x}_n}\mathrm{d}x'^{\,i}A_i\left(\boldsymbol{x}'_n\right)\right\}}_{U_{\boldsymbol{x}_{n-1},\hat{i}}(\tau_n)} \times \underbrace{\exp\left\{\mathrm{i}g\delta\eta_n A_\eta(\boldsymbol{x}_n)\right\}}_{\equiv\, U_{\boldsymbol{x}_n,\hat{\eta}}(\tau_n)}$$

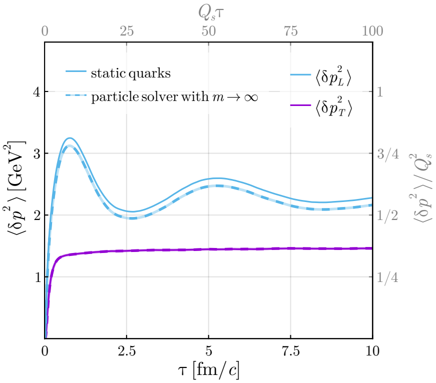
Color rotation on the lattice *(vizualization)*

$$Q(\tau_n) = \mathcal{U}(\tau_{n-1}, \tau_n)\, Q(\tau_{n-1})\, \mathcal{U}^\dagger(\tau_{n-1}, \tau_n) \text{ with } \mathcal{U}(\tau_{n-1}, \tau_n) = U_{x_{n-1},\hat{x}} \cdot U_{x_{n-1},\hat{\eta}}$$

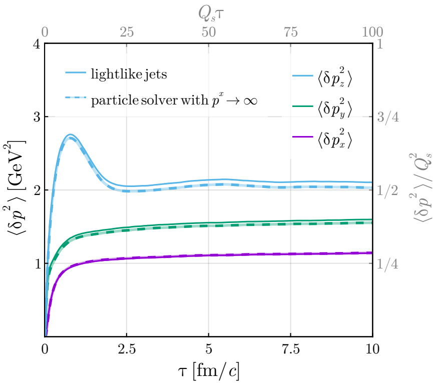


Limiting cases

Static quarks $\langle \delta p^2 \rangle_{m\to\infty} \propto \langle EE \rangle_{\text{Glasma}}$



Lightlike quarks $\langle \delta p^2 \rangle_{p^x\to\infty} \propto \langle \widetilde{F}\widetilde{F} \rangle_{\text{Glasma}}$



$\langle p^2 \rangle$ in limiting cases

Static heavy quark limit $m \to \infty \Rightarrow$ electric field correlators

$$\left\langle \delta p_i^2(\tau) \right\rangle_{m\to\infty} = g^2 \int_0^\tau \mathrm{d}\tau' \int_0^\tau \mathrm{d}\tau'' \left\langle \mathrm{Tr}\left\{ E_i(\tau') E_i(\tau'') \right\} \right\rangle$$

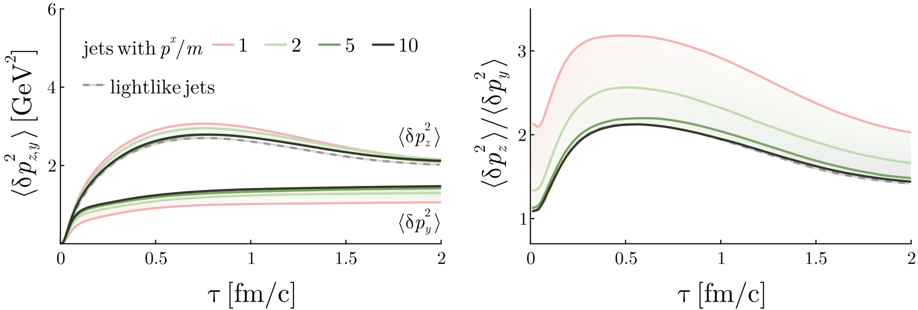
Fast light-like jet quark limit $p^x \to \infty \Rightarrow$ electromagnetic field correlators

$$\left\langle \delta p_i^2(\tau) \right\rangle_{p^x\to\infty} = g^2 \int_0^\tau \mathrm{d}\tau' \int_0^\tau \mathrm{d}\tau'' \left\langle \mathrm{Tr}\left\{ \widetilde{F}_i(\tau') \widetilde{F}_i(\tau'') \right\} \right\rangle$$

Color force components $F_x \equiv E_x$, $F_y \equiv E_y - B_z$, $F_z \equiv E_z + B_y$, parallel transported

$\widetilde{F}_i(\tau) \equiv \mathcal{U}_x{}^\dagger(\tau,\tau_0) F_i(\tau) \mathcal{U}_x(\tau,\tau_0)$ with Wilson lines $\mathcal{U}_x(\tau,\tau_0) = \mathscr{P} \exp\left(-ig \int_0^\tau \mathrm{d}\tau' A_x(\tau') \right)$

Jet momentum broadening



Dependence on Q_s