The impact of glasma on heavy quark spectra and correlations

$\int \mathcal{DA}$vramescu

T. Lappi, H. Mäntysaari
University of Jyväskylä

D. Müller
TU Wien

V. Greco
University of Catania

Based on arXiv2409.10564 and arXiv2409.10565

Centre of Excellence in Quark Matter

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

HELSINKI INSTITUTE OF PHYSICS

erc

Hard Probes 2024

Outline

Initial stage

Glasma

Color glass condensate • Features of the glasma

Heavy quarks in glasma

Transport equations • Transport coefficients

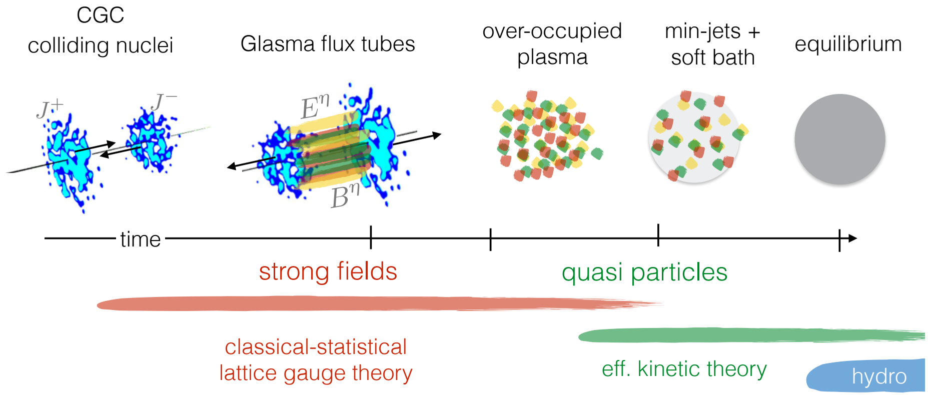
Observables

Nuclear modification factor • Two-particle correlations

Summary

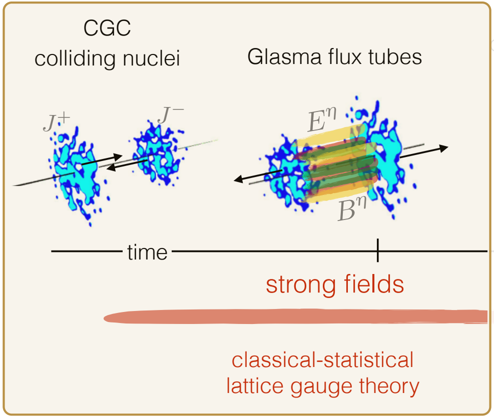
Heavy-ion collisions

Stages at weak coupling



Heavy-ion collisions

The very early stage



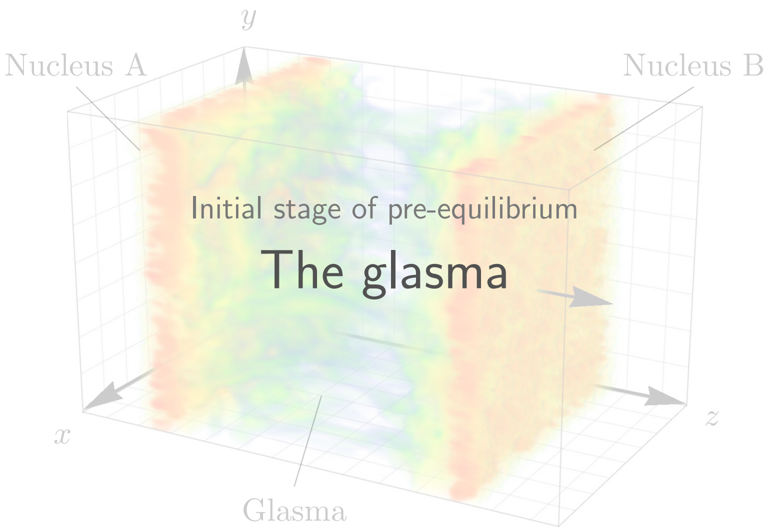
Glasma initial stage

- **Color glass condensate**
- Weakly coupled $\alpha_s \ll 1$
- **Gluon fields** with occupation number $\sim 1/\alpha_s \gg 1 \Rightarrow$ **classical**
- Real-time **lattice gauge theory**
- **Out-of-equilibrium** medium

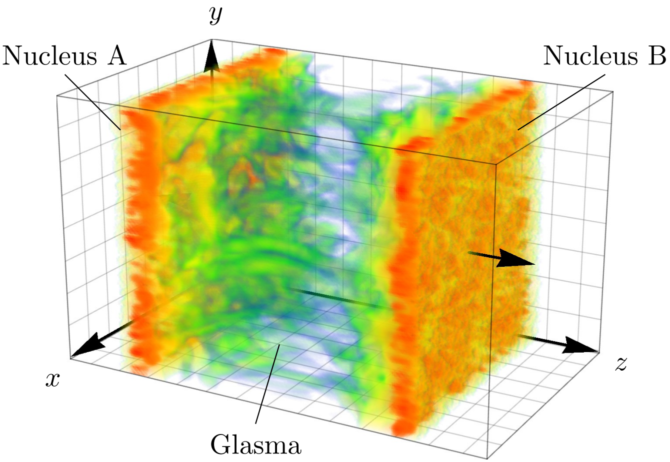
Lappi [hep-ph/0606207], Gelis [1211.3327]

Initial stage of pre-equilibrium

The glasma



Glasma color fields

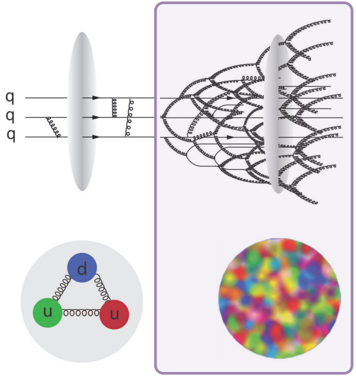


Ipp, Müller [1703.00017]

Color glass condensate

Effective field theory of QCD at high energies

- High-energy nucleus → mostly soft gluons



Color glass condensate

- Soft partons → **gauge fields A^μ**
- Hard partons → **color current J^μ**

  - Classical gluon fields → produced by color nucleus current

- Classical Yang-Mills equations

$$F^{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - ig[A_\mu, A_\nu]$$

$$\mathscr{D}_\mu F^{\mu\nu} = J^\nu \rightarrow \text{need input } J^\nu$$

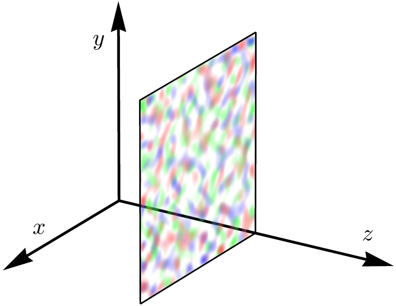
$$\mathscr{D}_\mu = \partial_\mu - igA_\mu$$

Gelis, Iancu, Jalilian-Marian, Venugopalan [1002.0333]

Color glass condensate

MV model for large nuclei

- Color charge distribution in a nucleus at high energy $\rightarrow$ thin color sheet



McLerran Venugopalan model

- **Color charge ρ** $\rightarrow$ Gaussian probability

- Color current of nucleus $\rightarrow$ generated by color charge density

- **MV model** for color charges ρ

$$\langle \rho(\vec{x}_\perp)\rho(\vec{y}_\perp)\rangle \propto g^2\mu^2\delta^{(2)}(\vec{x}_\perp - \vec{y}_\perp)$$

$g^2\mu \propto Q_s$

- **Saturation momentum Q_s**

$Q_s \approx 2\,\mathrm{GeV}$ at LHC central collisions

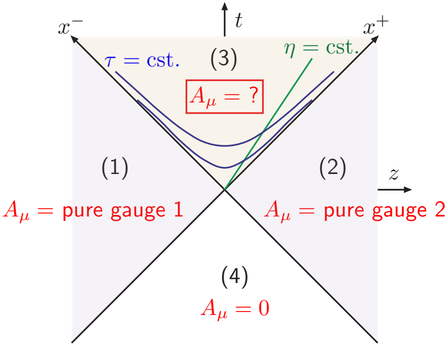
McLerran, Venugopalan [hep-ph/9309289], Müller [1904.04267]

Collision of two nuclei

How to construct the glasma fields

- Light-cone diagram of collision

  Light-cone coordinates $x^{\pm} = t \pm z$



CGC fields (regions 1, 2)

- Analytical pure gauge fields before collision

Initial condition (along light-cone)

- Match CGC fields on the light cone
- Impose boost-invariance

  Milne coordinates $\tau = \sqrt{x^+ x^-}$ and $\eta = \ln(x^+/x^-)$

Glasma fields (region 3)

- Solve numerically YM equations
- Code gitlab.com/openpixi/curraun

Lappi [hep-ph/0602189]

Features of the glasma

- Heavy quarks and jets are sensitive to the properties of the glasma fields

Flux tubes

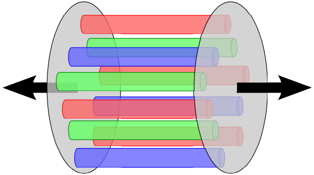
- Initially only longitudinal electric and magnetic fields

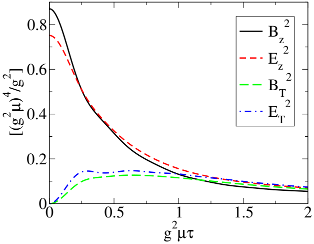
Strong fields

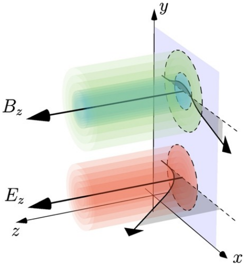
- Strong longitudinal fields, dilute after $\tau \sim 1/Q_s$

Correlation domains

- Fields correlated inside flux tubes of size $\sim 1/Q_s$



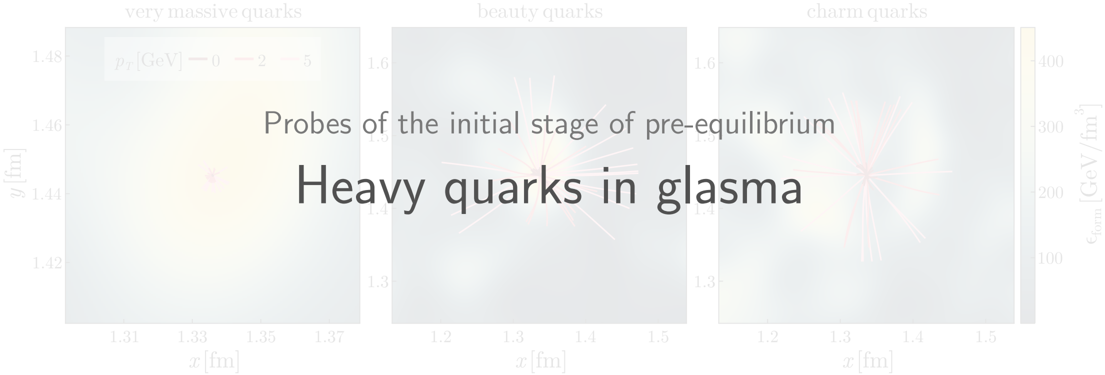




Fukushima [1603.02340], Lappi [hep-ph/0606207], Ipp, Müller, Schuh [2009.14206]
HP24 lecture by Hidetoshi Taya

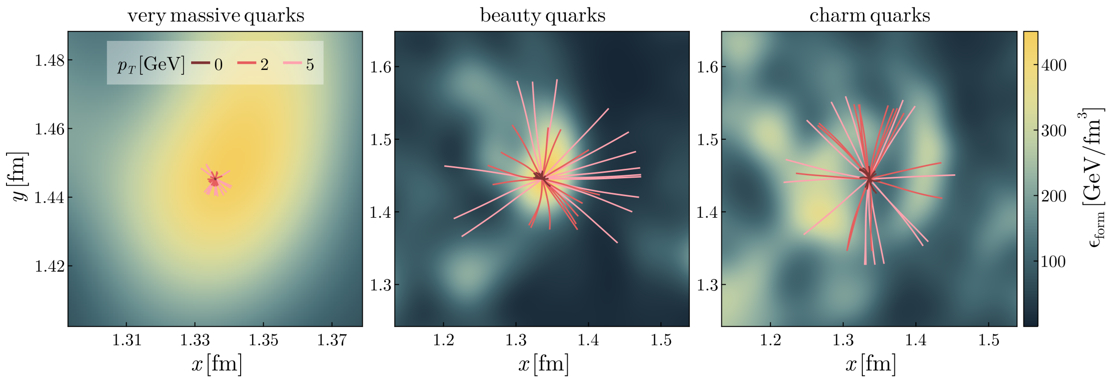
Probes of the initial stage of pre-equilibrium

Heavy quarks in glasma



Heavy quarks in glasma

Probing the glasma correlation domains



Avramescu, Băran, Greco, Ipp, Müller, Ruggieri [2303.05599]

HP24 talk about charm quarks in IP-Glasma + next stages by Mayank Singh

Particles in Yang-Mills fields

Wong's equations of motion

Classical transport equations

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

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

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

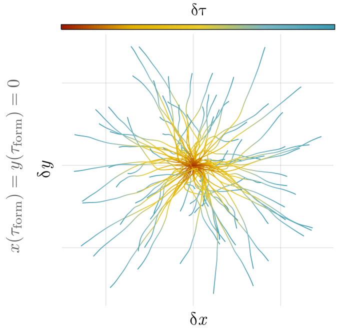
$$Q(\boldsymbol{\tau}) = \mathcal{U}(\boldsymbol{\tau}, \boldsymbol{\tau}')\, Q(\boldsymbol{\tau}')\, \mathcal{U}^\dagger(\boldsymbol{\tau}, \boldsymbol{\tau}')$$

- Solve the classical transport equations with A^μ the glasma field
- Simulation code `github.com/avramescudana/curraun/tree/wong`

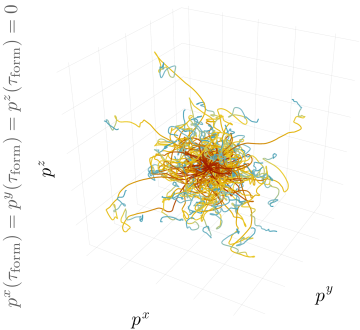
Particles in glasma fields

Visualizing the trajectories

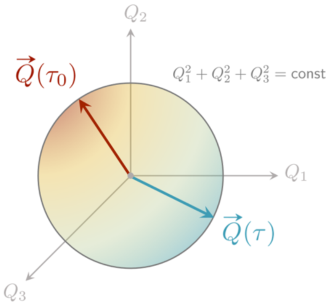
- Change in **coordinates** due to momentum kicks



- **Momentum** broadening due to color Lorentz force

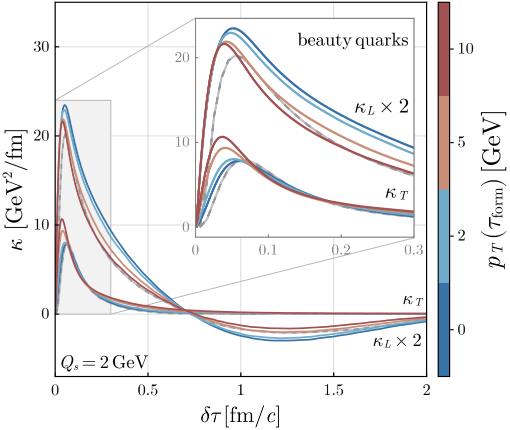


- **Color charge** rotation in SU(3) with Wilson lines



Avramescu, Băran, Greco, Ipp, Müller, Ruggieri [2303.05599]

Transport coefficient κ



Classical transport

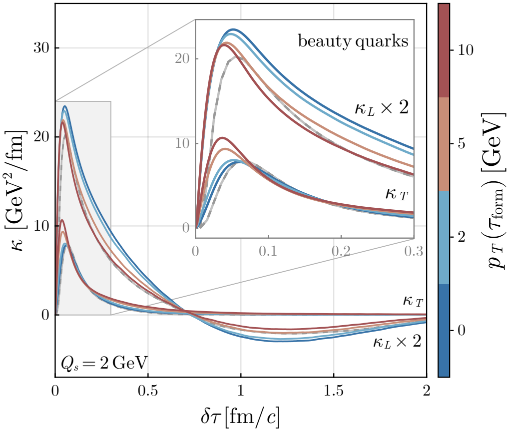
- **Momentum broadening**
  $\boldsymbol{\delta p_i^2}(\tau) = p_i^2(\tau) - p_i^2(\tau_{\mathrm{form}})$
- **Transport coefficient**
  $$\boldsymbol{\kappa_i}(\tau) = \frac{\mathrm{d}}{\mathrm{d}\tau}\langle \boldsymbol{\delta p_i^2}(\tau)\rangle$$

Formation time $\tau_{\mathrm{form}} = 1/2m$
Relative time $\delta\tau = \tau - \tau_{\mathrm{form}}$
Longitudinal $i = L$, transverse $i = T$

- **Anisotropic** $\kappa_L \neq \kappa_T$
- Rapid increase in κ at early times
- Negative κ_L at late times
- **Large κ peak in glasma**
- **Compatible to κ in EKT**

Avramescu, Băran, Greco, Ipp, Müller, Ruggieri [2307.07999]
Boguslavski, Kurkela, Lappi, Lindenbauer, Peuron [2303.12520]

Transport coefficient κ



Classical transport

- **Momentum broadening**
  $\boldsymbol{\delta p_i^2}(\tau) = p_i^2(\tau) - p_i^2(\tau_{\mathrm{form}})$
- **Transport coefficient**
  $$\boldsymbol{\kappa_i}(\tau) = \frac{\mathrm{d}}{\mathrm{d}\tau}\langle \boldsymbol{\delta p_i^2}(\tau)\rangle$$

Formation time $\tau_{\mathrm{form}} = 1/2m$
Relative time $\delta\tau = \tau - \tau_{\mathrm{form}}$
Longitudinal $i = L$, transverse $i = T$

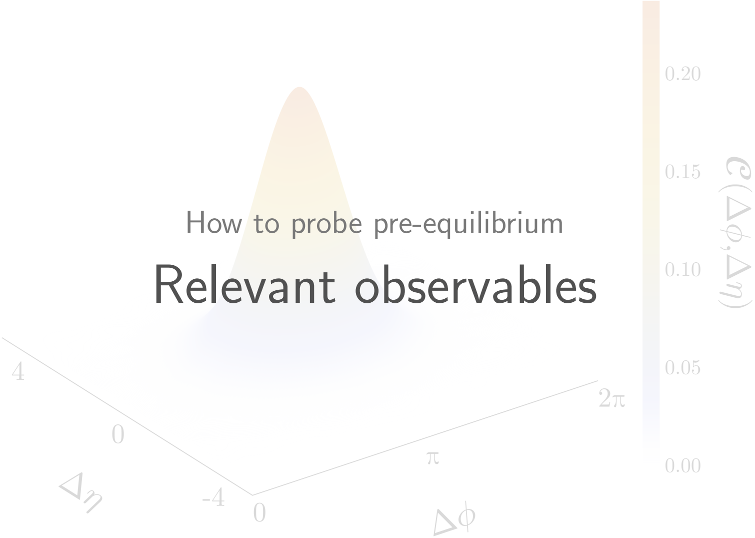
Limitation

- Transport coefficients $\neq$ **measurable** quantities

Avramescu, Băran, Greco, Ipp, Müller, Ruggieri [2307.07999]

How to probe pre-equilibrium

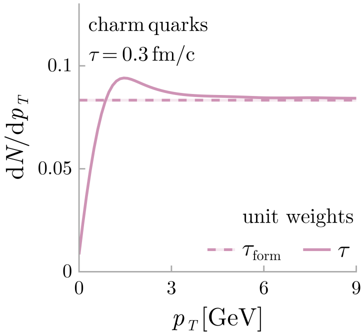
Relevant observables



Effect of glasma on spectra

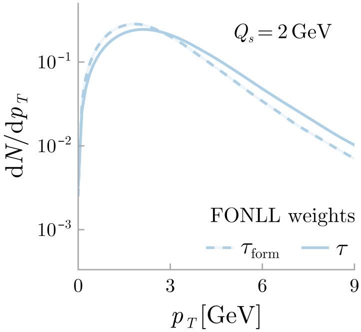
Effect of glasma

- Initial flat p_T distribution
- p_T migration from small to large p_T



Effect of initial spectrum

- Initial pQCD FONLL p_T spectrum
  Fixed-Order+Next-to-Leading Logarithm



Cacciari, Greco, Nason [hep-ph/9803400], [FONLL web form]

Nuclear modification factor

Extraction of R_{AA} in glasma

R_{AA} in glasma

- Ratio of AA to pp normalized spectra

- AA evolved in **glasma**, pp from **FONLL**
- Glasma spectrum initialized with FONLL

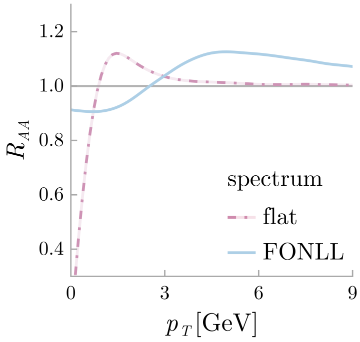
glasma

$$R_{AA}(\tau) = \frac{1}{A^2}\frac{\sigma_{\text{tot}}^{AA}}{\sigma_{\text{tot}}^{pp}}\frac{\mathrm{d}N/\mathrm{d}p_T\,(\tau)}{\mathrm{d}N^{pp}/\mathrm{d}p_T}$$

normalization FONLL

R_{AA} in glasma explained

- Small p_T particles only migrate to larger p_T
- Depletion at small p_T, enhancement at large p_T



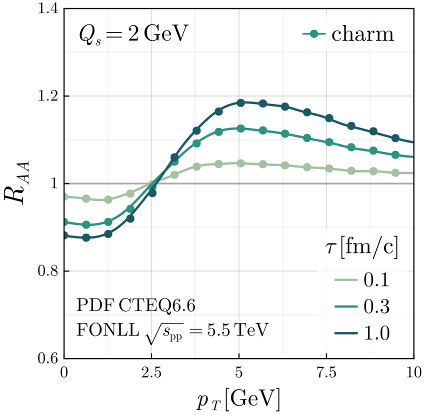
R_{AA} in glasma

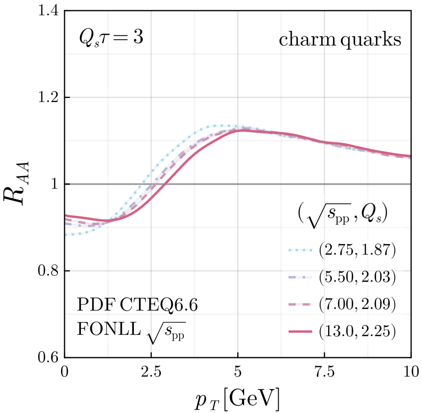
Time τ evolution

- More enhancement in R_{AA} at later τ

Effect of energy scales

- Weak dependence on $\sqrt{s_{\rm pp}}$ and glasma Q_s



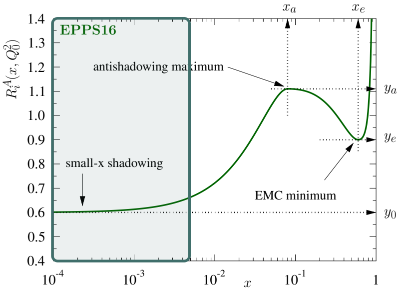


R_{AA} in glasma with nPDFs

Previous studies

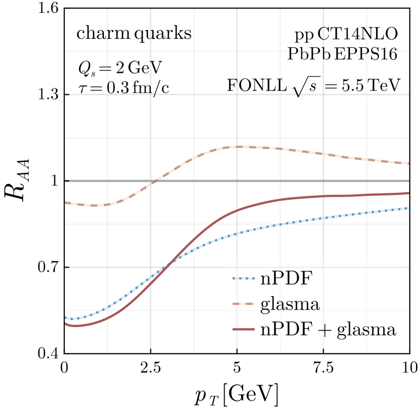
- AA glasma spectrum initialized with FONLL in pp, no nPDF effect

This study: FONLL + EPPS16



nPDF + glasma

- Glasma effect modest compared to nPDF



Sun, Coci, Das, Plumari, Ruggieri, Greco [1902.06254], Eskola, Paakkinen, Paukkunen, Salgado [1612.05741]

Effect of glasma on correlations

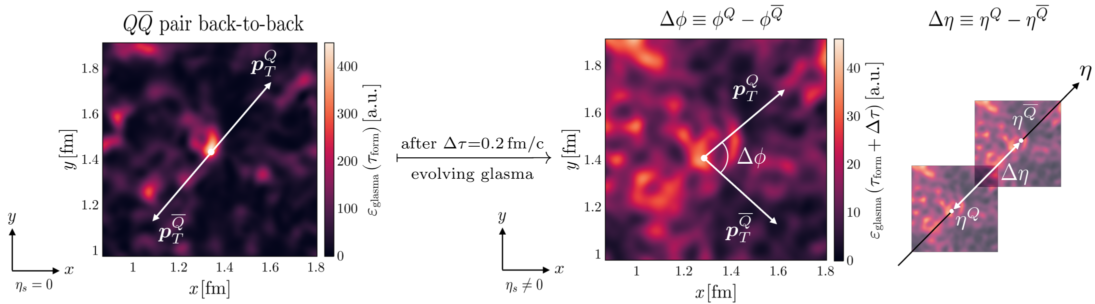
Two-particle correlations of $Q\overline{Q}$ pairs

Simulation setup

- $Q\overline{Q}$ pairs produced **back-to-back** (LO) in ϕ

Control parameters

- Glasma field $\boldsymbol{Q_s}$ + heavy quark initial $\boldsymbol{p_T}$



Decorrelation of $Q\overline{Q}$ pairs

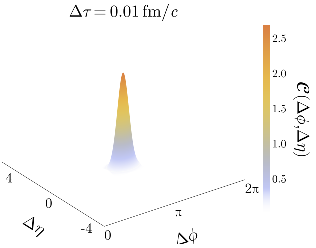
Quantifying the decorrelation in glasma

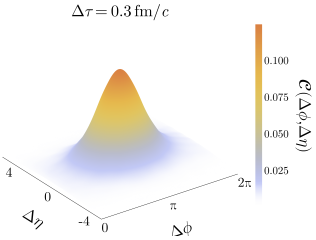
Decorrelation in glasma

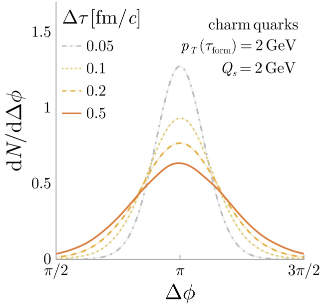
- Two-particle correlations $\mathcal{C}(\Delta\phi, \Delta\eta)$ at $\Delta\tau = \tau - \tau_{\text{form}}$
- Initial peak $\delta(\Delta\phi - \pi)\delta(\Delta\eta)$ gets broadened by glasma

Azimuthal decorrelation

- $D\overline{D}$ **angular correlations**
- Decorrelation width $\sigma_{\Delta\phi}(\Delta\tau)$







HP24 talks about $Q\overline{Q}$ correlations by Soumya Mohapatra and Pol-Bernard Gossiaux

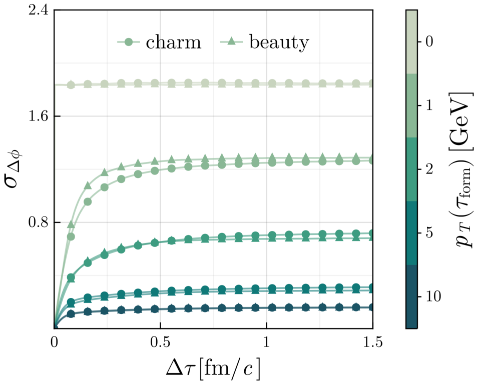
Azimuthal decorrelation

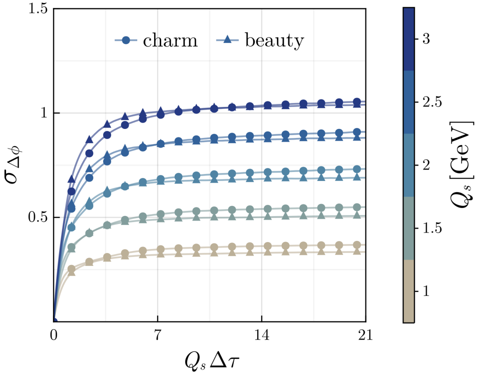
Effect of heavy quark p_T

- Small p_T pairs decorrelate immediately

Effect of glasma Q_s

- Large Q_s glasma decorrelates pairs faster





Summary

Framework

- Classical transport of heavy quarks in glasma
- **Large** transport coefficient κ

Main results

- Impact of glasma on R_{AA} weaker than **nPDF** effect
- Large **azimuthal decorrelation** of $Q\overline{Q}$ pairs in glasma
  Relevant for upcoming $D\overline{D}$ **measurements** in AA

Improvements

- **Energy loss** mechanism in glasma
- Couple glasma to effective kinetic theory (**EKT**)

HP24 talks about jet energy loss in glasma by Andrey Sadofyev and Carlos Lamas
HP24 talks about jets in EKT by Florian Lindenbauer and Sergio Barrera Cabodevila

Thank you!