Transport of hard probes in the Glasma

by $\int \mathcal{D}\mathcal{A}$vramescu

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University of Catania

based on PRD 107, 114021

QCD Master Class 2024

General outline

Introduction

Framework • Literature • This study

The Glasma

Color Glass Condensate • Features of the Glasma fields

Hard probes in the Glasma

Classical transport • Momentum broadening

Observables

Two particle correlations • Nuclear modification factor

Highlights

Heavy-ion collisions

Stitching together effective theories

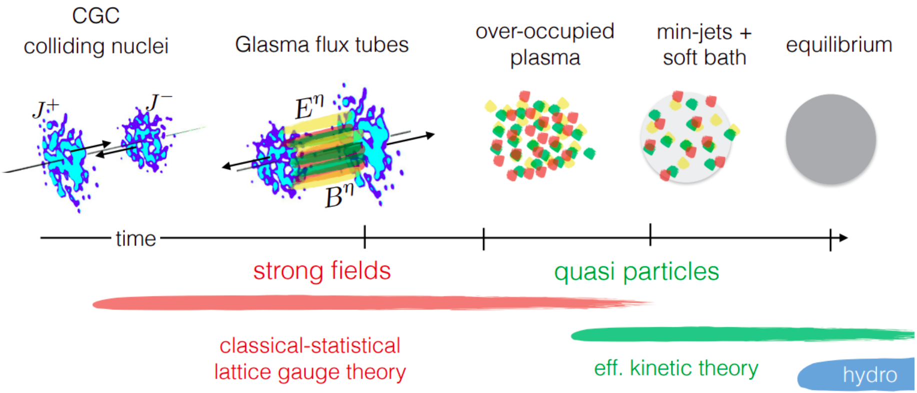


Figure credits to S. Schlichting

Heavy-ion collisions

Stitching together effective theories

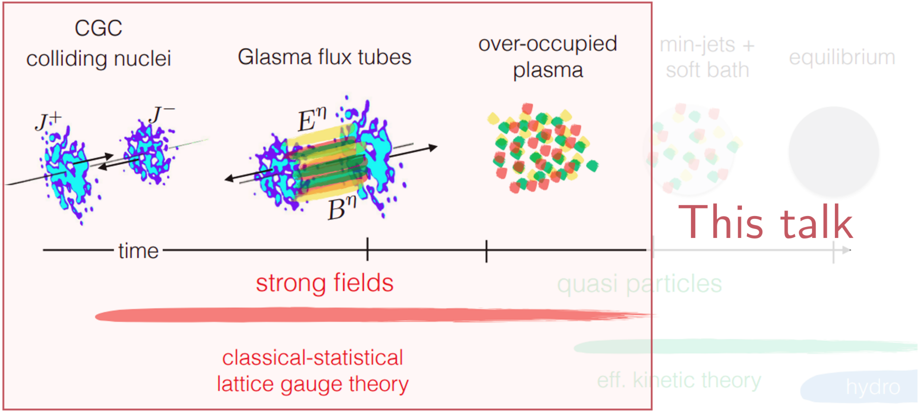


Figure credits to S. Schlichting

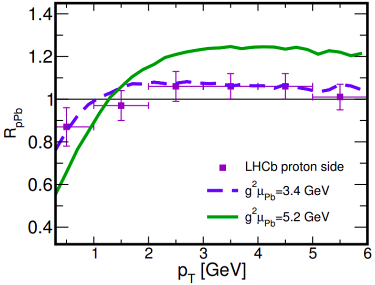
Hard probes in the pre-equilibrium stage

Literature timeline

- 2018 — Das, Ruggieri *[1805.09617]*
- 2020 — Ipp *et al.*
- 2021 — Carrington *et al.*
- 2023 — Boguslavski *et al.*
- 2024 — Barata *et al.*

Heavy quarks in Glasma

Highlights: Diffusion, R_{pA}



Hard probes in the pre-equilibrium stage

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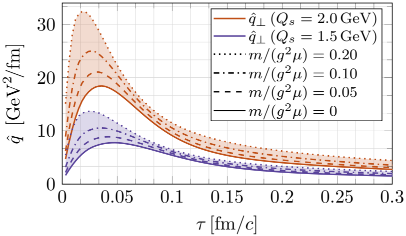
- 2018 Heavy quarks in Glasma
- 2020 Ipp, Müller, Schuh [2009.14206]
- 2021 Carrington *et al.*
- 2023 Boguslavski *et al.*
- 2024 Barata *et al.*

Eikonal jets in Glasma

Highlights: Lattice simulations

Transport coefficient $\hat{q}$



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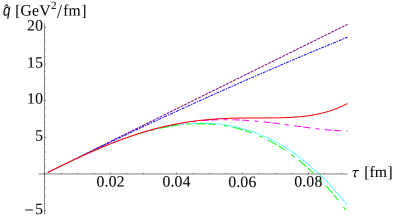
Hard probes in Glasma

Highlight: Analytical calculations

Transport coefficient $\hat{q}$



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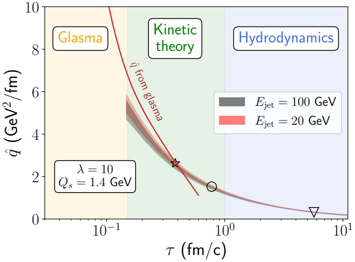
- 2020 Eikonal jets in Glasma
- 2021 Hard probes in Glasma
- 2023 Boguslavski, Kurkela, Lappi, Lindenbauer, Peuron *[2303.12595]*
- 2024 Barata *et al.*

Hard probes in kinetic theory

Highlight: Stage after Glasma

Compatible $\hat{q}$ and κ



Hard probes in the pre-equilibrium stage

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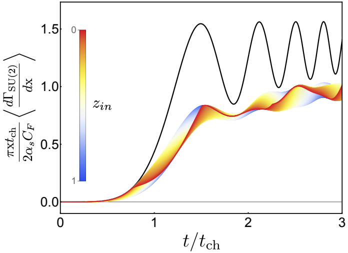
- 2020 Eikonal jets in Glasma
- 2021 Hard probes in Glasma
- 2023 Hard probes in kinetic theory
- 2024 Barata, Hauksson, López, Sadofyev *[2406.07615]*

Energy loss in Glasma

Highlight: Analytical calculations
Medium-induced gluon radiation

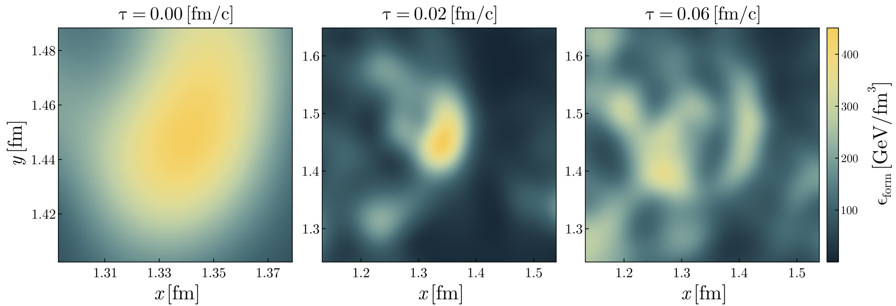


Hard probes in Glasma

Classical transport in the very-early stage

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

This work: Glasma fields $\xleftrightarrow{\text{background}}$ test particles $\xleftarrow{\text{solver}}$ colored particle-in-cell



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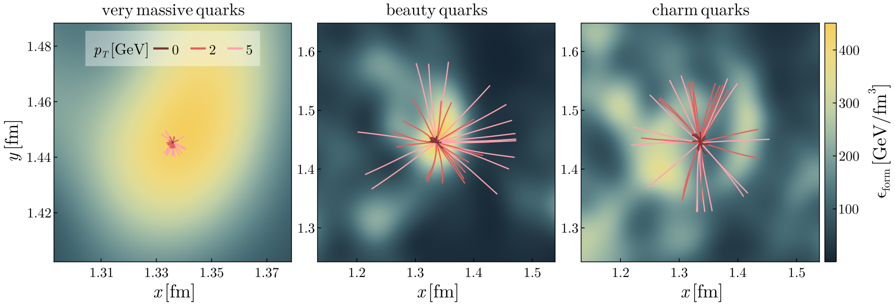
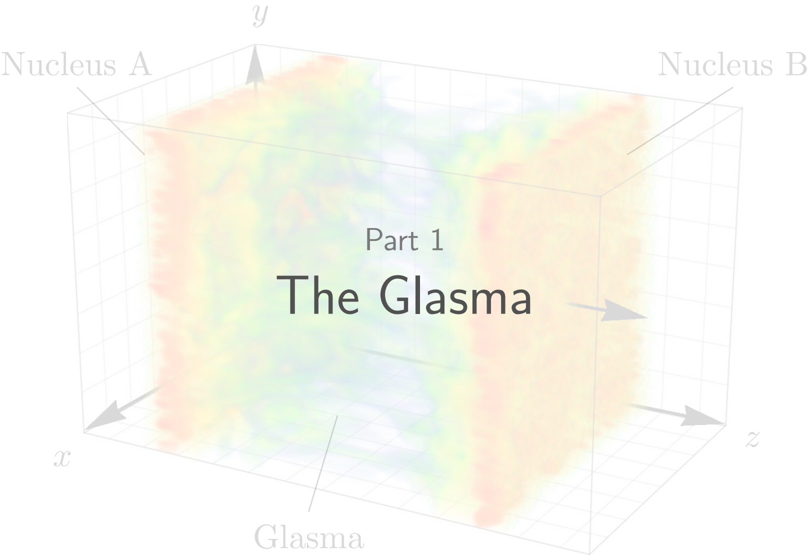


Part 1

The Glasma



High energy QCD

Glons as main degrees of freedom

parton

$$x \stackrel{\text{def}}{=} \frac{p^+}{P^+}$$

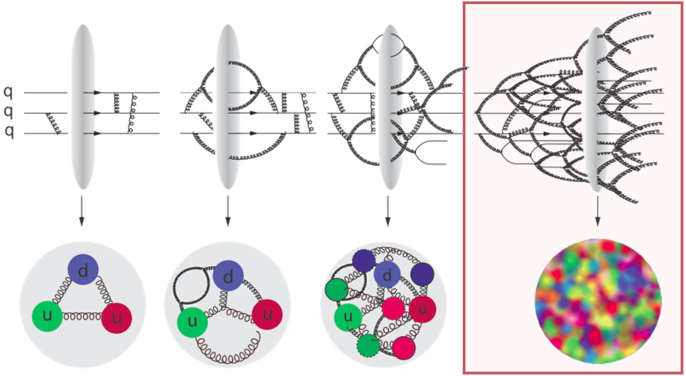
nucleus

Small-x limit of QCD $\leftrightarrow$ evolution

Figure credits to T. Ullrich

High energy QCD

Glons as main degrees of freedom



High gluon occupation numbers

Figure credits to T. Ullrich

CGC as an EFT for high energy QCD

Classical Yang-Mills fields

Separation of scales between
small-x and large-x degrees of freedom

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

- $\mathcal{D}_\mu$: covariant derivative
- $F^{\mu\nu}$: field strength tensor
- A^μ: gluons gauge field
- J^ν: color current of nucleus

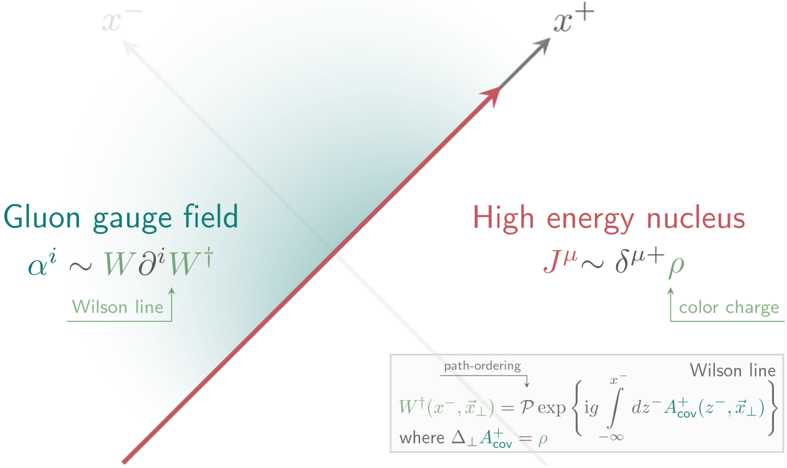
MV model and LC kinematics $\Rightarrow J^{\mu,a}(x) \propto \delta^{\mu +} \rho^a \left(x^-, \boldsymbol{x}_\perp \right)$

- MV model: large nuclei
- ρ^a: stochastic variable

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

CGC as an EFT for high energy QCD

Gauge fields before the collision



path-ordering

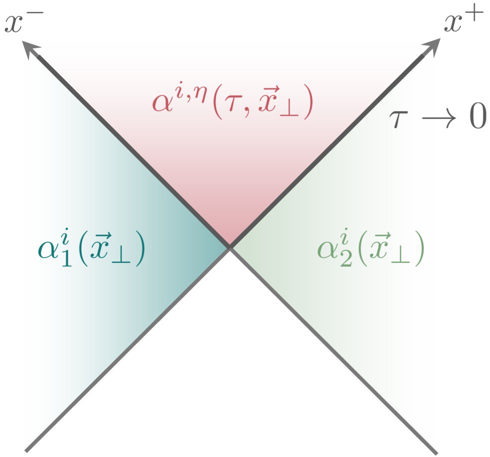
Wilson line

$$W^\dagger(x^-, \vec{x}_\perp) = \mathcal{P} \exp \left\{ ig \int_{-\infty}^{x^-} dz^- A^+_{\mathrm{cov}}(z^-, \vec{x}_\perp) \right\}$$

where $\Delta_\perp A^+_{\mathrm{cov}} = \rho$

Collision of CGC nuclei

Light-cone diagram of the collision



- Known CGC fields before the collision
- Unknown Glasma fields in the forward light-cone

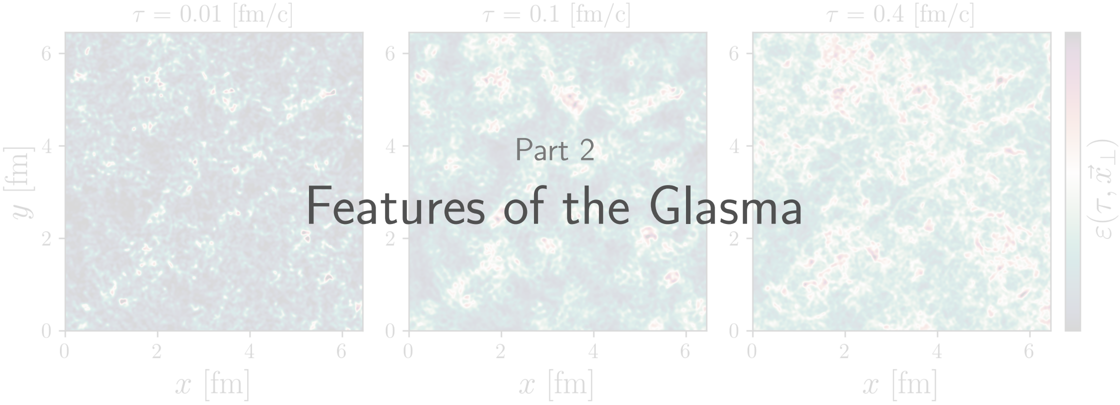
Milne coordinates (τ, η)
$\tau = \sqrt{2x^+x^-}$, $\eta = \ln(x^+/x^-)/2$

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

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

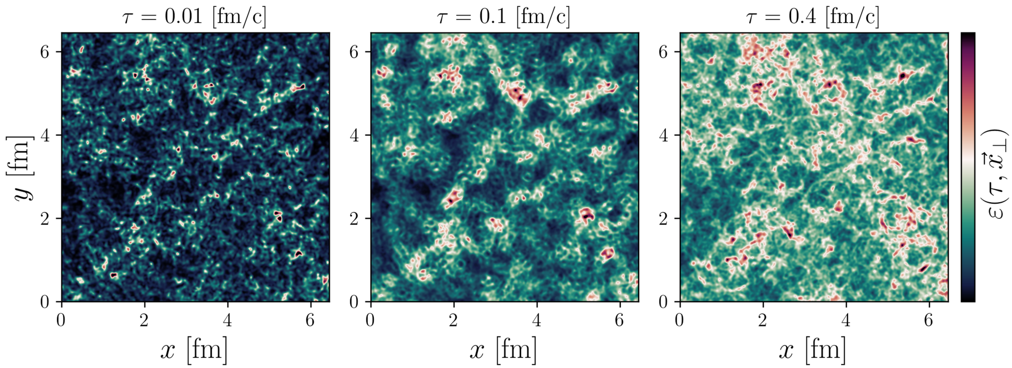
Part 2

Features of the Glasma



The Glasma fields

General features



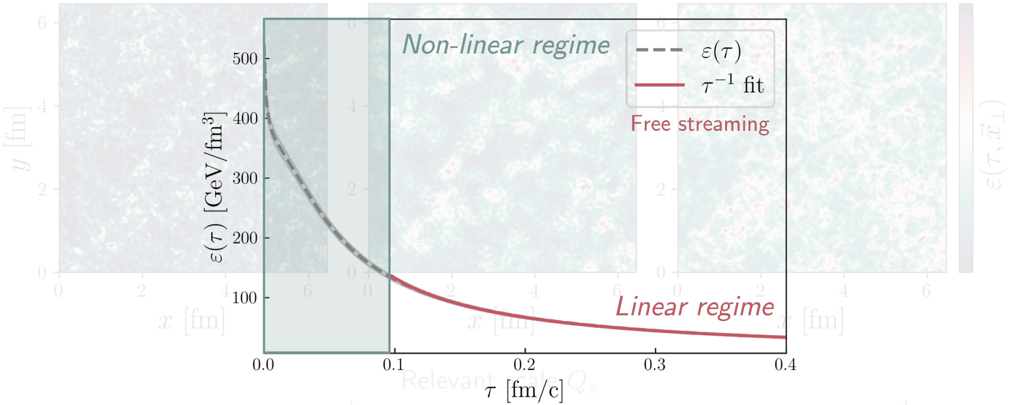
Relevant scale Q_s

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

The Glasma fields

Bjorken expansion

The fields become dilute after $\delta\tau \simeq Q_s^{-1}$



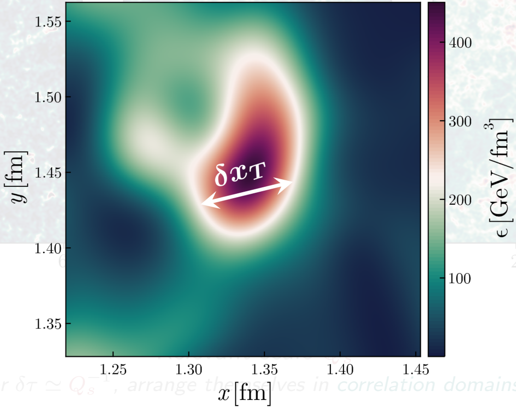
Relevant scale Q_s

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

The Glasma fields

Flux tubes

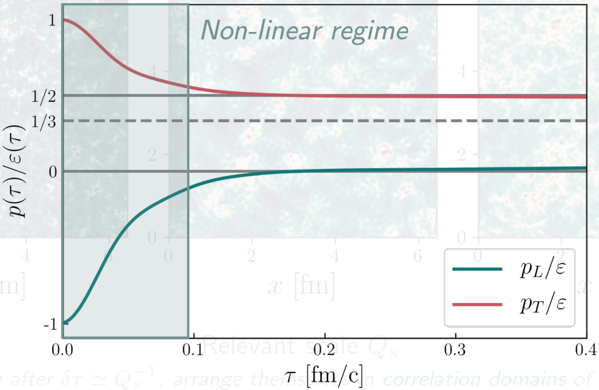
The fields arrange themselves in correlation domains of $\delta x_T \simeq Q_s^{-1}$



The Glasma fields

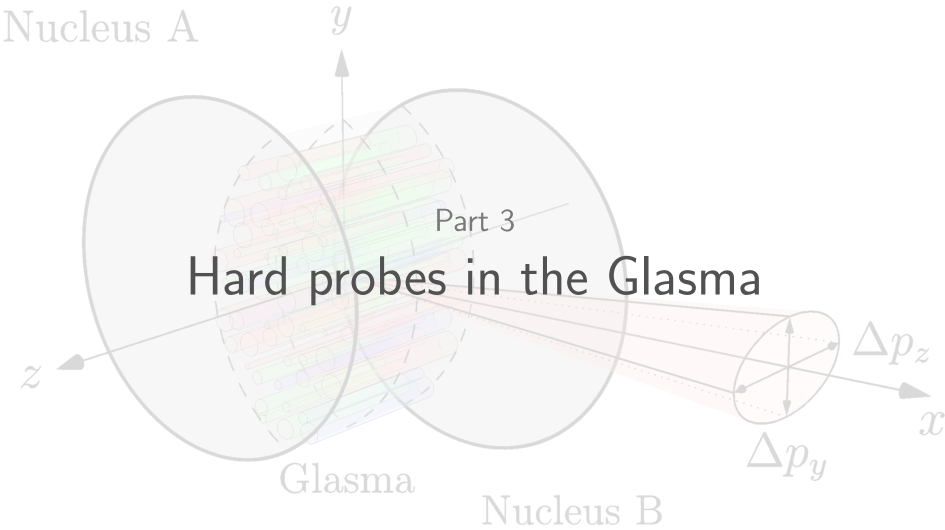
Anisotropy

Longitudinal $\neq$ transverse $\Rightarrow$ anisotropy



Part 3

Hard probes in the Glasma



Particles in Yang-Mills fields

Wong's equations of motion

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

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

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

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

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

Particles in Yang-Mills fields

Wong's equations of motion

Boltzmann-Vlasov collisionless non-Abelian plasma

$$p^\mu[\partial_\mu + gQ^a F^{\mu\nu}(x^\mu)\partial^\nu_{p^\mu} + g f^{abc} A^b_\mu(x^\mu) Q^c \partial_{Q^a}] \boldsymbol{f}(x^\mu, p^\mu, Q^a) = 0$$

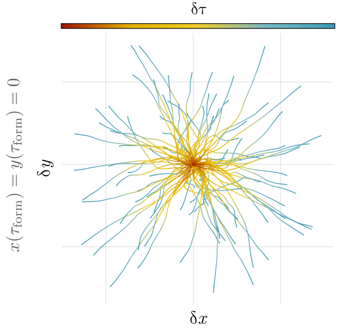
$$\boldsymbol{f}(x^\mu, p^\mu, Q^a) \xrightarrow{\text{sample}} \text{test particles } (x^\mu, p^\mu, Q^a)$$

$\Rightarrow$ Wong's equations

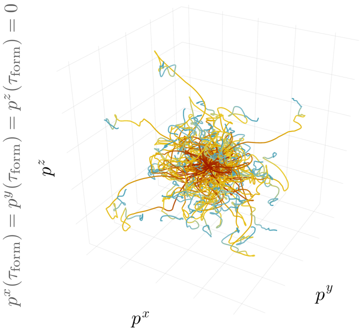
Particles in Yang-Mills fields

Vizualizing the trajectories

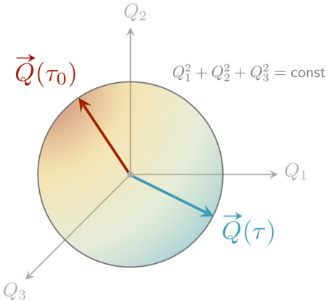
Change of coordinates



Color Lorentz force

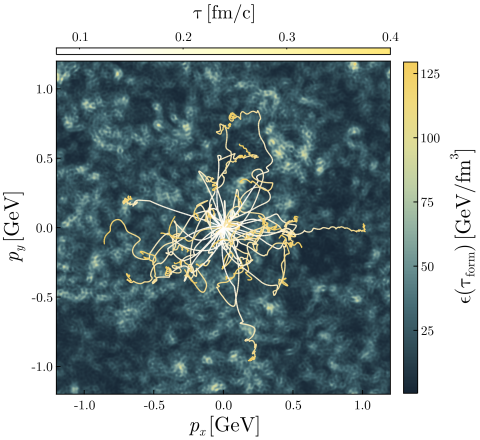


Color rotation



Quantifying the effect of Glasma

Momentum broadening



Momentum broadening

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

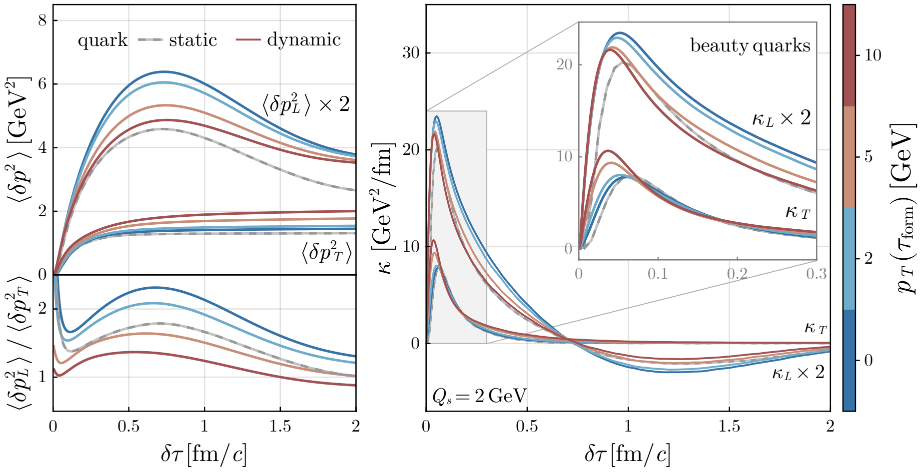
Instantaneous transport coefficient

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

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

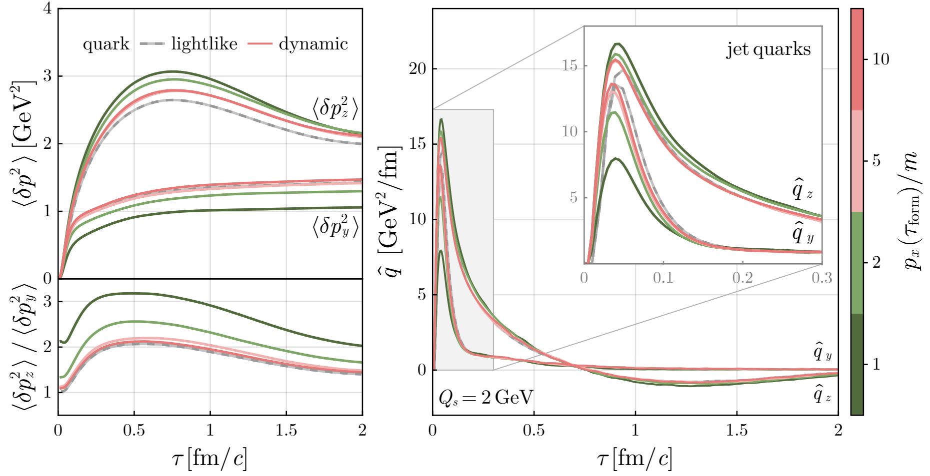
Heavy quarks in Glasma

Momentum broadening and κ



Jets in Glasma

Momentum broadening and $\hat{q}$



Large transport coefficients

Plausible in an EKT framework

Schematic evolution of $\hat{q}$

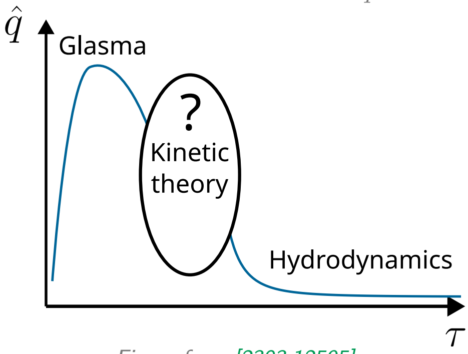
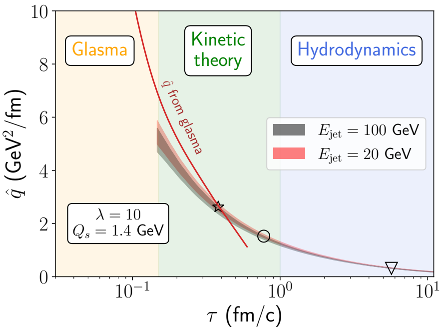


Figure from [2303.12595]

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



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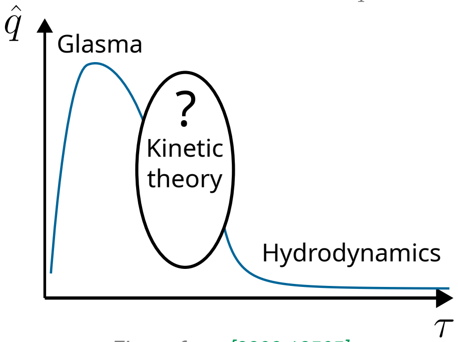

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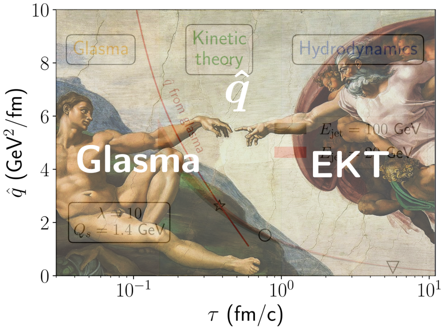
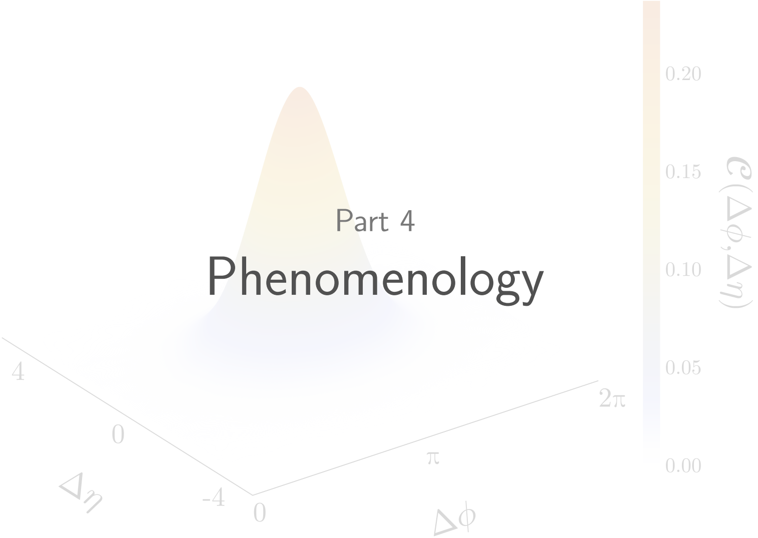


Part 4

Phenomenology

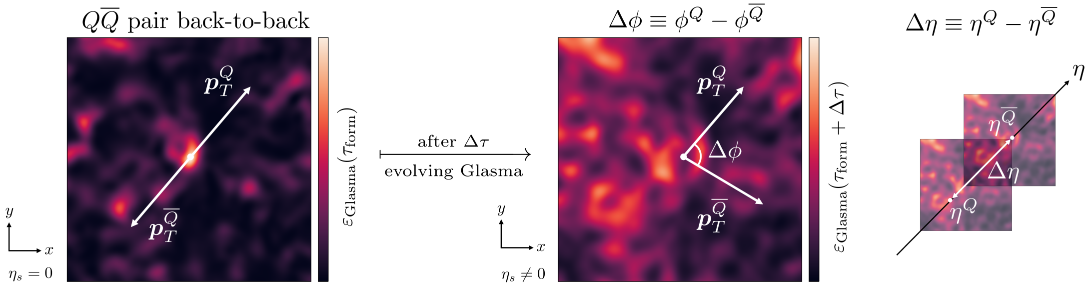


Two particle correlations

Sketch of $Q\overline{Q}$ pairs in the Glasma

Glasma fields → saturation momentum Q_s; heavy quarks → initial p_T

Control parameters: saturation momentum Q_s and initial p_T with $\tau_{\text{form}} = 1/(2m_T)$

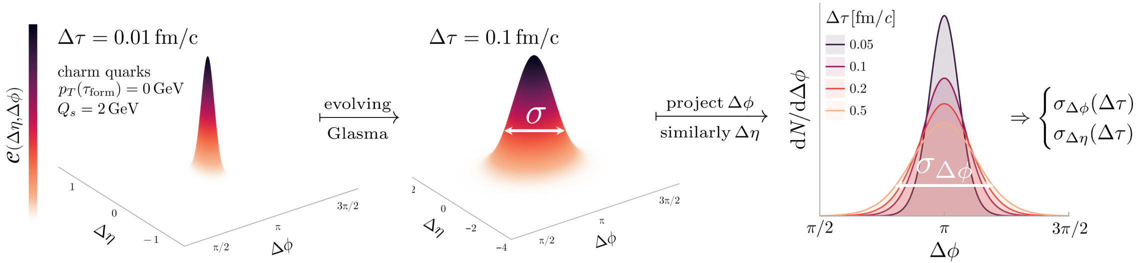


Two particle correlations

Quantifying the decorrelation

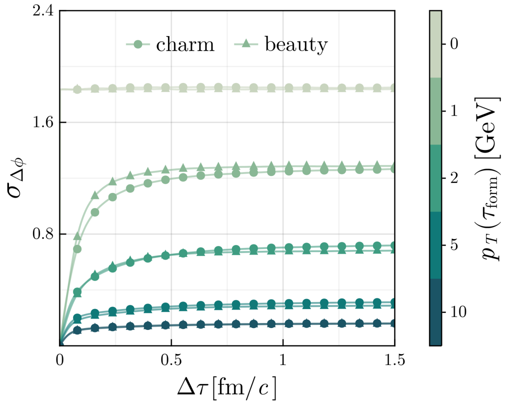
Rapidity and azimuthal correlations $\mathcal{C}(\Delta\eta, \Delta\phi) \equiv \frac{1}{N_{\text{pairs}}} \frac{\mathrm{d}^2 N}{\mathrm{d}\Delta\eta \mathrm{d}\Delta\phi}$

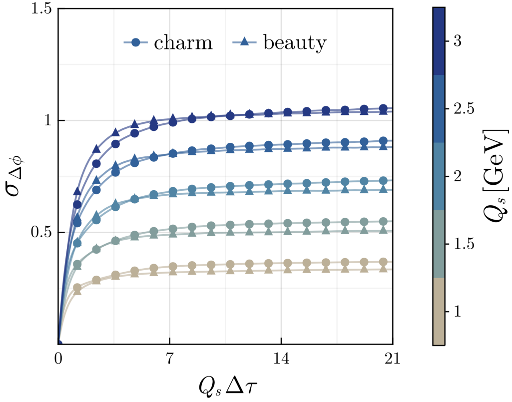
Initial $\mathcal{C}(\tau_{\text{form}}) \propto \delta(\Delta\phi - \pi)\delta(\Delta\eta) \xmapsto{\Delta\tau \text{ in Glasma}} \mathcal{C}(\tau_{\text{form}} + \Delta\tau) \xRightarrow{\text{extract}} \sigma_{\Delta\phi}(\Delta\tau), \sigma_{\Delta\eta}(\Delta\tau)$



Azimuthal decorrelation width

Effect of heavy quark p_T and Glasma Q_s





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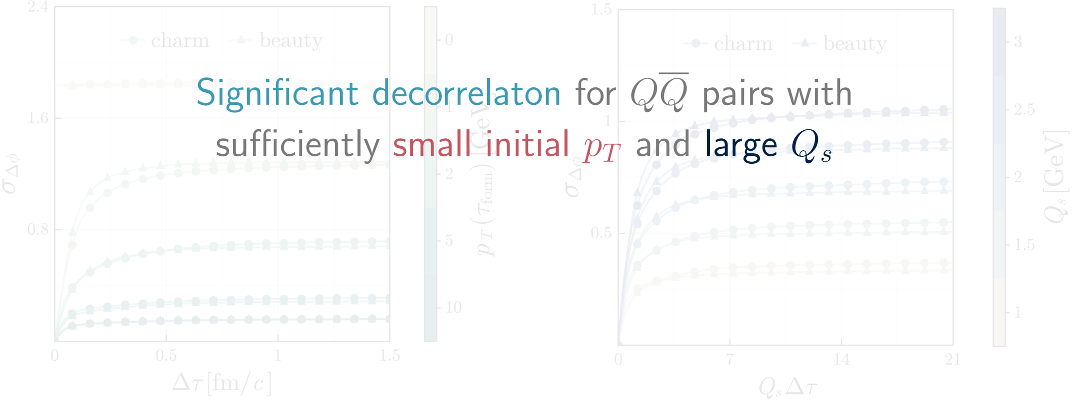
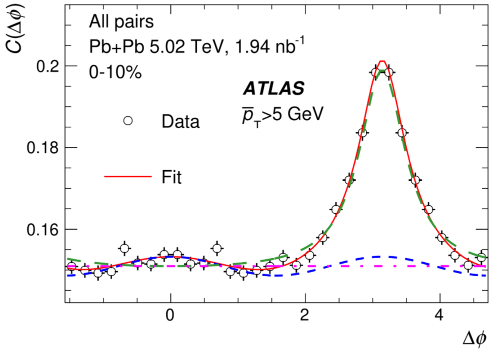


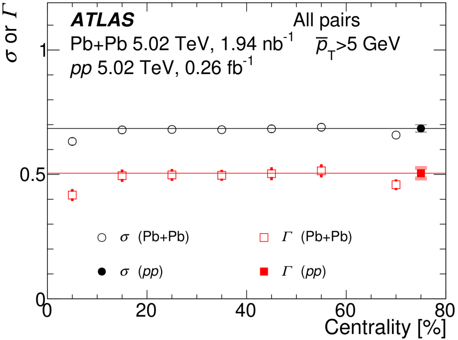
Significant decorrelaton for $Q\overline{Q}$ pairs with sufficiently small initial p_T and large Q_s

Phenomenology implications

Azimuthal angle correlations

First measurement of azimuthal correlations in PbPb from [ATLAS 2308.16652]





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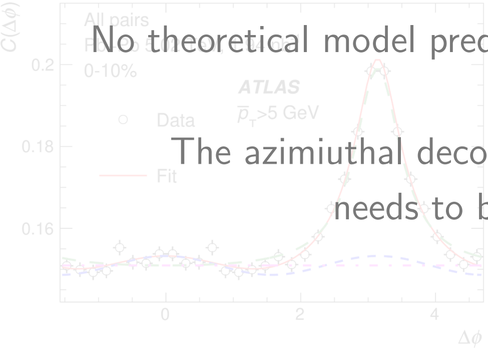
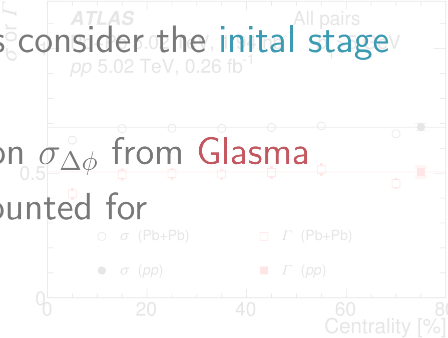




No theoretical model predictions consider the inital stage

The azimiuthal decorrelation $\sigma_{\Delta\phi}$ from Glasma needs to be accounted for

Highlights

Framework:

Numerical solver for hard probes in Glasma

Anisotropic momentum broadening

Large transport coefficients $\boldsymbol{\kappa}$ and $\hat{\boldsymbol{q}}$

Phenomenology:

Azimuthal decorrelation of $Q\overline{Q}$ pairs

Nuclear modification factor R_{AA} with **nPDFs**

Improvements:

Energy loss

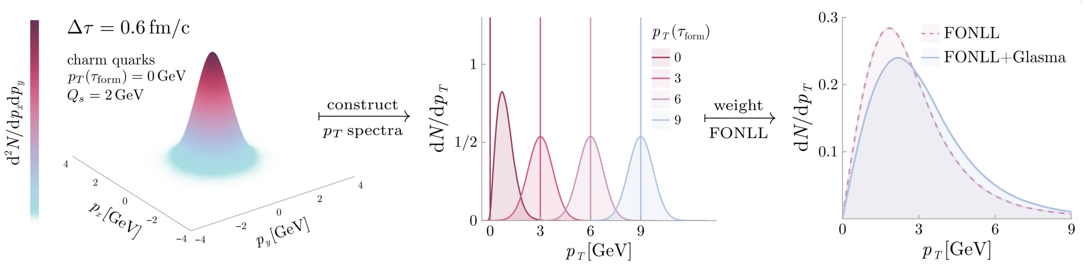
Thank you!

Back-up

Nuclear modification factor

Sketch of p_T spectra in the Glasma

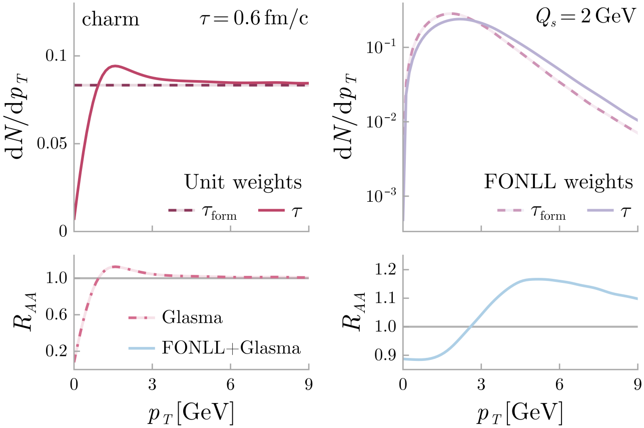
Heavy quarks $\xrightarrow{\text{FONLL}^*}$ initial p_T distribution $\propto \mathrm{d}\sigma^{pp/AA}/\mathrm{d}p_T(\sqrt{s}, \mathrm{PDF}/\mathrm{nPDF})$



* *Fixed Order + Next-to-Leading Logarithms*, state-of-the-art resummed heavy quark production

Nuclear modification factor

Extraction of R_{AA} in Glasma



Glasma p_T broadening $\Rightarrow \frac{\mathrm{d}N}{\mathrm{d}p_T}(\tau)$

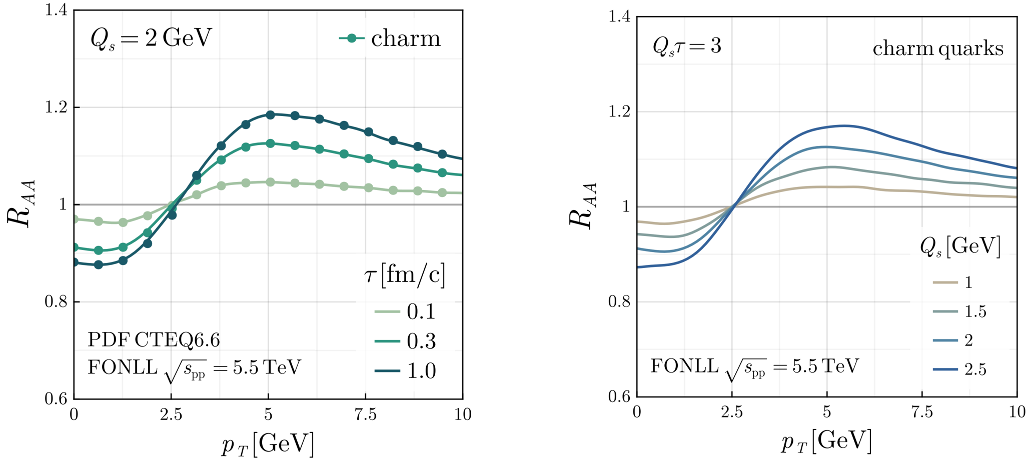
Initialized with FONLL in pp/AA

Nuclear modification factor at τ

$$R_{AA} = \frac{\sigma^{AA}_\mathrm{tot}}{A^2\sigma^{pp}_\mathrm{tot}} \frac{\frac{\mathrm{d}N}{\mathrm{d}p_T}(\tau; pp/AA)}{\frac{\mathrm{d}N^{pp}}{\mathrm{d}p_T}(\tau_\mathrm{form})}$$

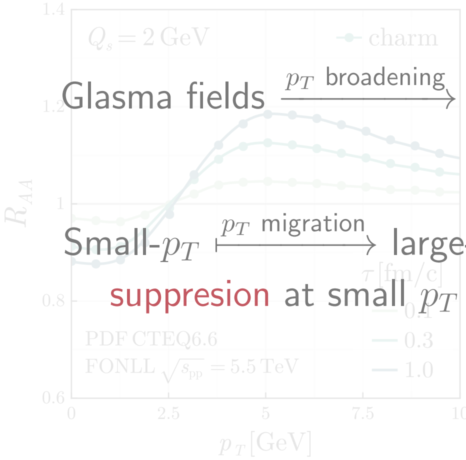
R_{AA} in the Glasma

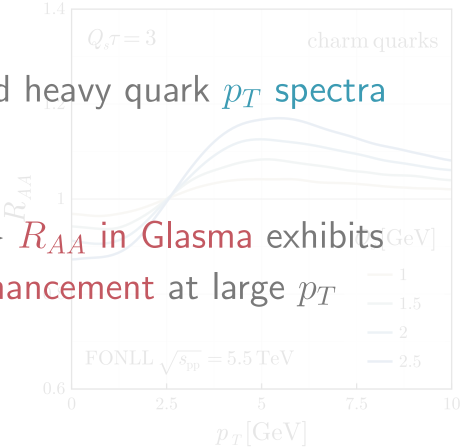
Temporal evolution and Q_s dependence



R_{AA} in the Glasma

Temporal evolution and Q_s dependence



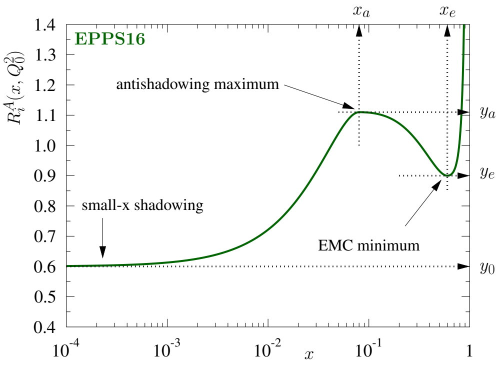


Glasma fields $\xrightarrow{p_T \text{ broadening}}$ shifted heavy quark p_T spectra

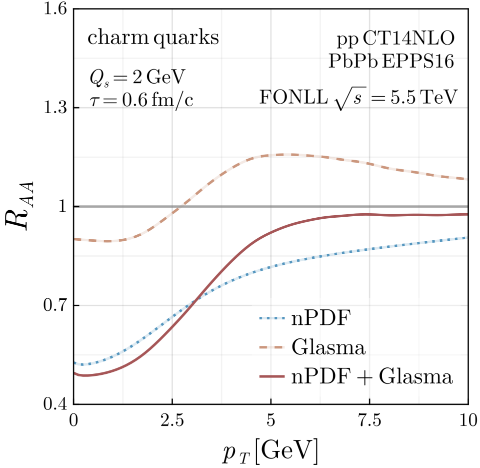
Small-p_T $\xmapsto{p_T \text{ migration}}$ large-p_T $\Rightarrow$ R_{AA} in Glasma exhibits suppresion at small p_T + enhancement at large p_T

R_{AA} in the Glasma with nPDFs

Cold nuclear matter effects

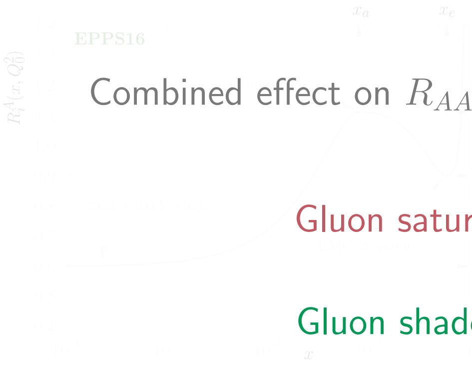


EPPS16 nuclear PDF from [1612.05741]

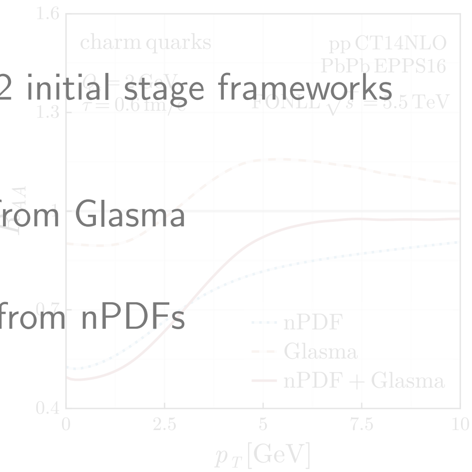


R_{AA} in the Glasma with nPDFs

Cold nuclear matter effects



EPPS16 nuclear PDF from [1612.05741]



Combined effect on R_{AA} from 2 initial stage frameworks

Gluon saturation from Glasma

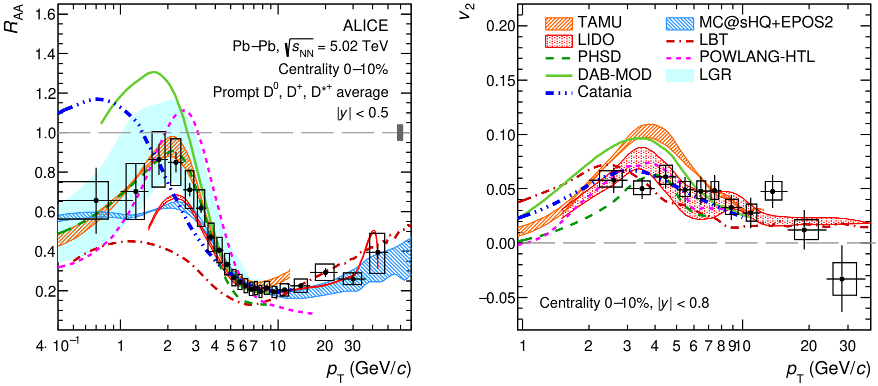
$+$

Gluon shadowing from nPDFs

Phenomenology implications

R_{AA} and v_2 puzzle

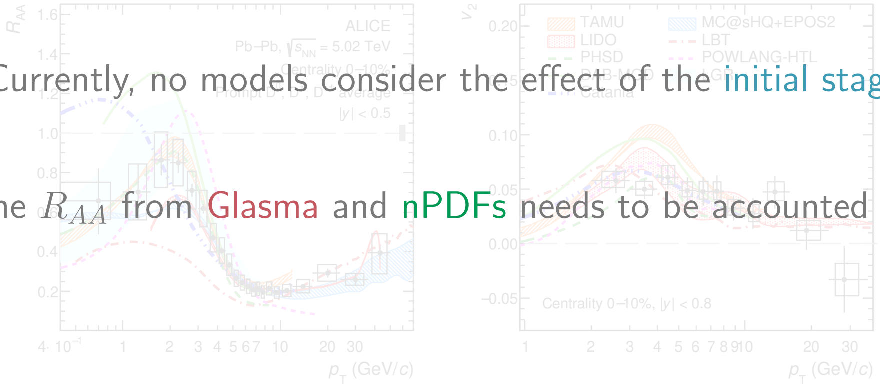
D mesons R_{AA} and v_2 from [ALICE 2110.09420] compared to various transport models



Phenomenology implications

R_{AA} and v_2 puzzle

D mesons R_{AA} and v_2 from [ALICE 2110.09420] compared to various transport models



Currently, no models consider the effect of the initial stage

The R_{AA} from Glasma and nPDFs needs to be accounted for