Heavy quark dynamics in the pre-equilibrium phase

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

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in Quark Matter

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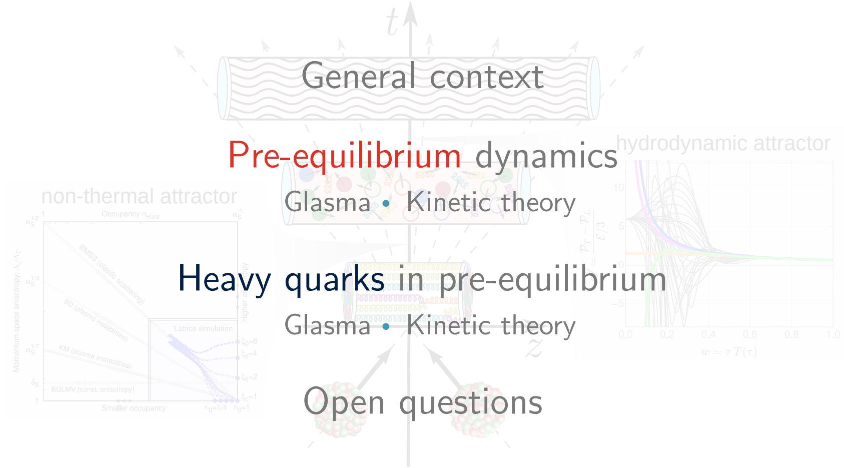
erc

QCD Challenges from pp to AA collisions 2024

Brief outline



General context

Pre-equilibrium dynamics

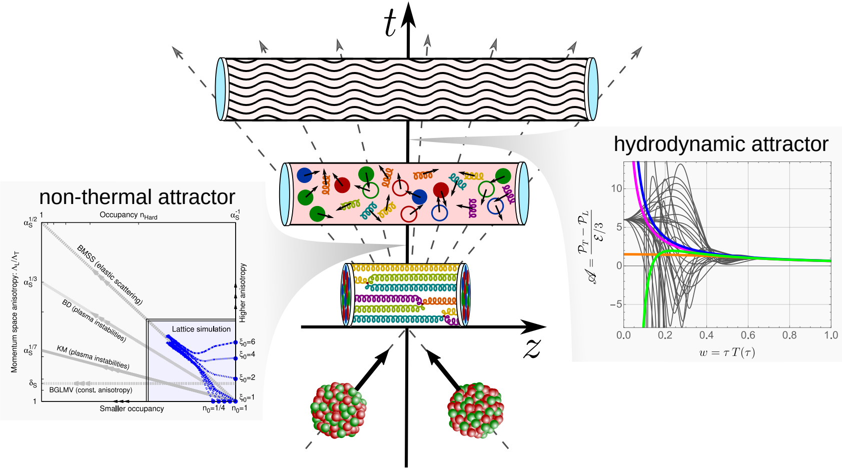
Glasma • Kinetic theory

Heavy quarks in pre-equilibrium

Glasma • Kinetic theory

Open questions

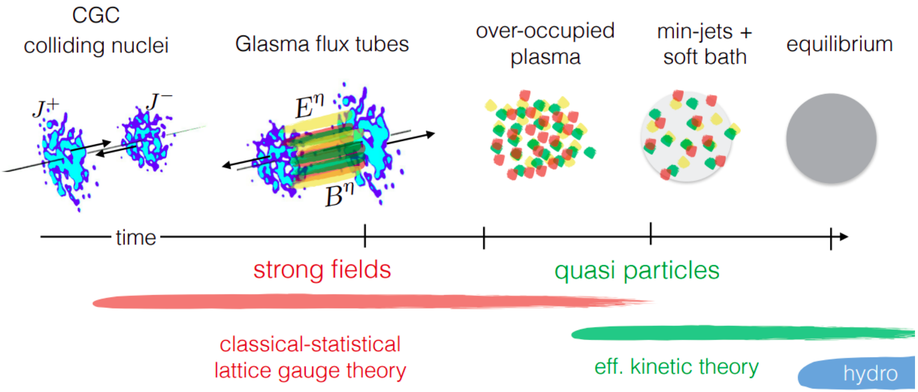
Pre-equilibrium dynamics



Berges, Heller, Mazeliauskas, Venugopalan [2005.12299]

High-energy collisions

Stitching together effective theories



CGC
colliding nuclei

Glasma flux tubes

over-occupied
plasma

min-jets +
soft bath

equilibrium

time

strong fields

quasi particles

classical-statistical
lattice gauge theory

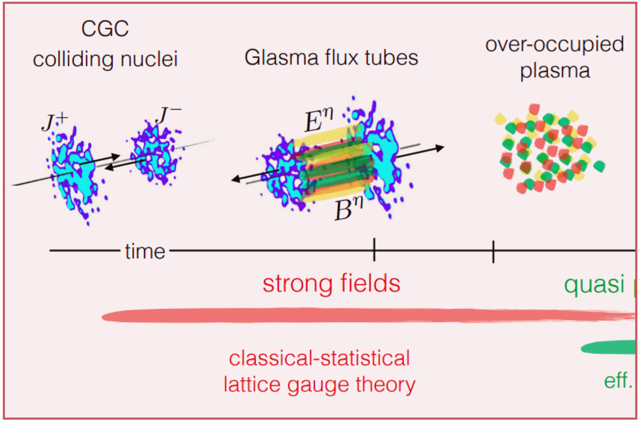
eff. kinetic theory

hydro

Schlichting [Initial Stages (2016)]

High-energy collisions

Pre-equilibrium stages



Glasma stage*

- Gluons as color fields
- Classical gauge fields
- Weak coupling regime
- Color Glass Condensate
- Real-time classical lattice gauge theory

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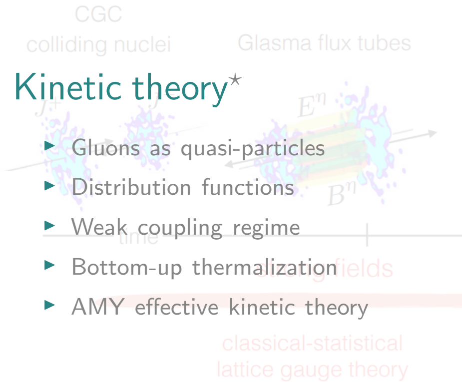
[*] Gelis [Int.J.Mod.Phys.A28(2013)]

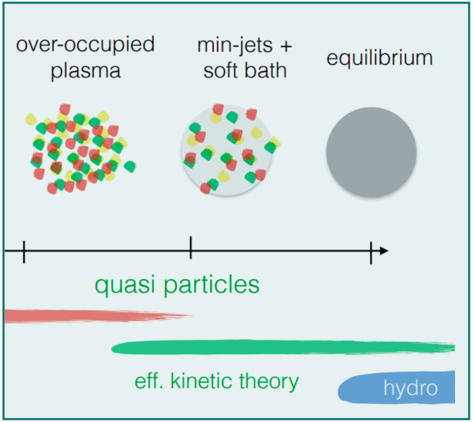
High-energy collisions

Pre-equilibrium stages

Kinetic theory*

- Gluons as quasi-particles
- Distribution functions
- Weak coupling regime
- Bottom-up thermalization
- AMY effective kinetic theory





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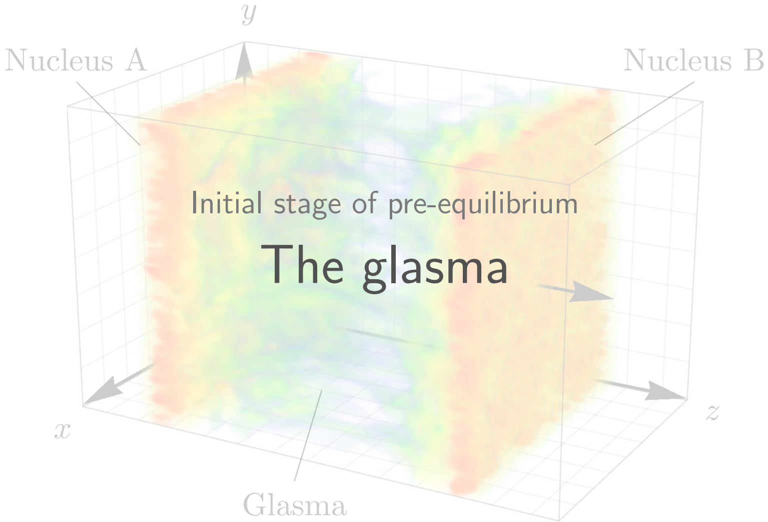
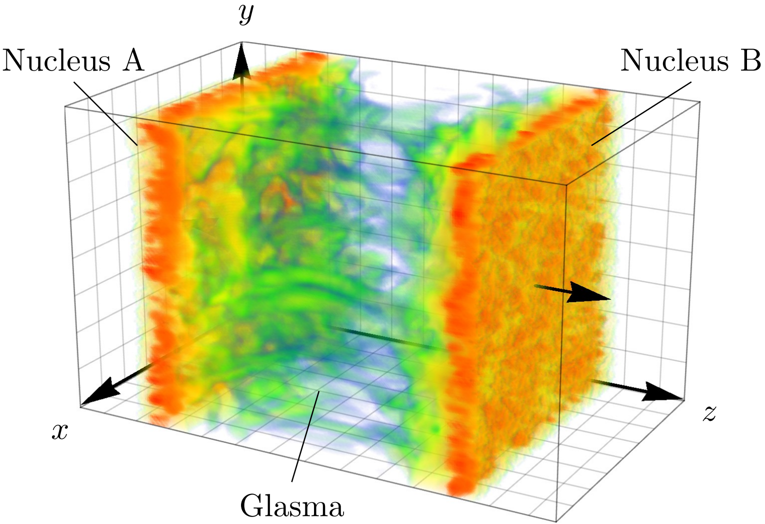
[*] Kurkela, Mazeliauskas, Paquet, Schlichting, Teaney [Phys.Rev.C99(2019)]

Initial stage of pre-equilibrium

The glasma



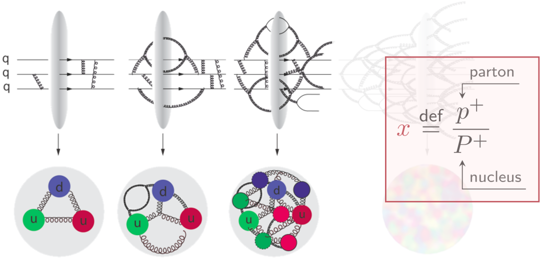


Ipp, Müller [Phys.Lett.B771(2017)]

Color Glass Condensate

An EFT for high energy QCD

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



$$x \overset{\text{def}}{=} \frac{\overset{\text{parton}}{p^+}}{\underset{\text{nucleus}}{P^+}}$$

Small-x limit of QCD ↔ evolution

Classical Yang-Mills equations

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

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[*] Gelis, Iancu, Jalilian-Marian, Venugopalan [Ann.Rev.Nucl.Part.Sci.60(2010)]
Artwork by T. Ullrich

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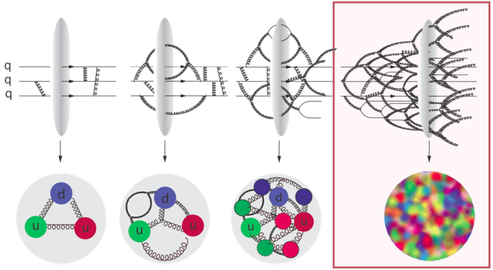

High gluon occupation numbers

cutoff

small-x | large-x → $p^+ = xP^+$

Classical Yang-Mills equations

covariant derivative

field strength tensor

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

gluons gauge field

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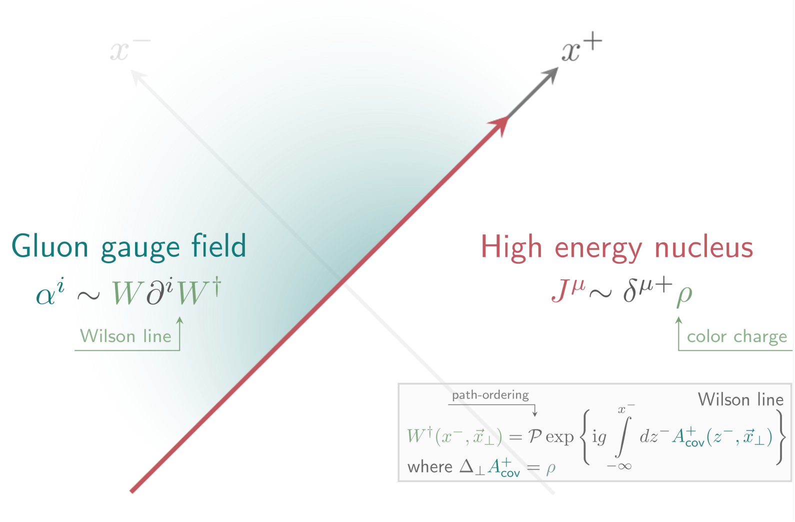
[*] Gelis, Iancu, Jalilian-Marian, Venugopalan `[Ann.Rev.Nucl.Part.Sci.60(2010)]`
Artwork by T. Ullrich

CGC fields

Analytical fields before the collision



Gluon gauge field

$\alpha^i \sim W\partial^i W^\dagger$

Wilson line

High energy nucleus

$J^\mu \sim \delta^{\mu+}\rho$

color charge

path-ordering

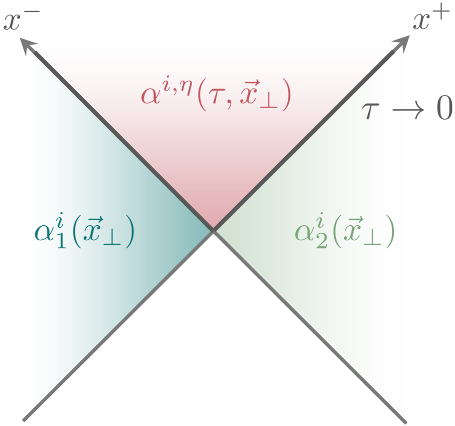
Wilson line

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

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

Glasma fields

Numerical field after the collision



- Known CGC fields at $\tau < 0$
- Boundary condition at $\tau = 0$
- Unknown Glasma fields at $\tau > 0$

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*

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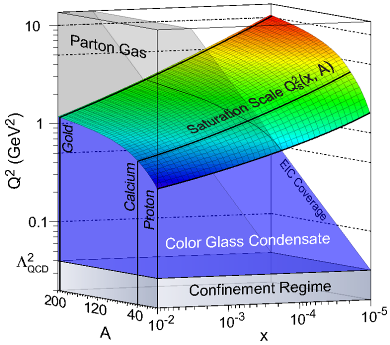
[*] Lappi, McLerran [Nucl.Phys.A772(2006)]

Features of glasma

Saturation scale, flux tubes, anisotropy



- Relevant scale saturation momentum Q_s
- Initial longitudinal color flux tubes
- Fields dilute after $\tau \simeq Q_s^{-1}$
- Fields arranged in correlation domains of $\delta x_T \simeq Q_s^{-1}$
- Longitudinal $\neq$ transverse pressures $\Rightarrow$ anisotropy

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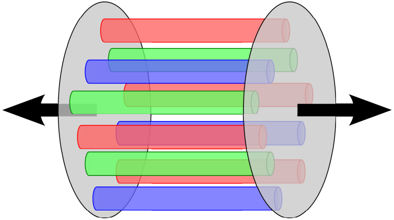
Gelis [Rept.Prog.Phys.84(2021)]

Features of glasma

Saturation scale, flux tubes, anisotropy



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Fukushima [Rept.Prog.Phys.80(2017)]

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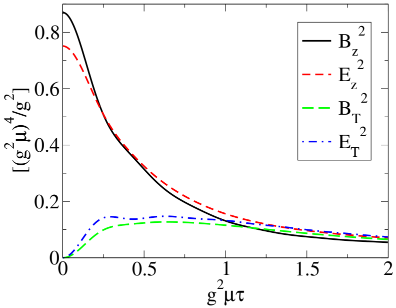
Saturation scale, flux tubes, anisotropy



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Lappi [Phys.Lett.B643(2006)]

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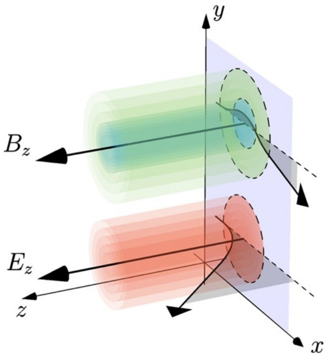

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Ipp, Müller, Schuh [Phys.Lett.B810(2020)]

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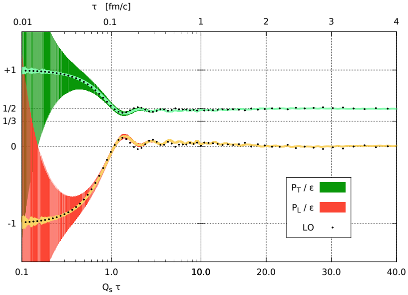

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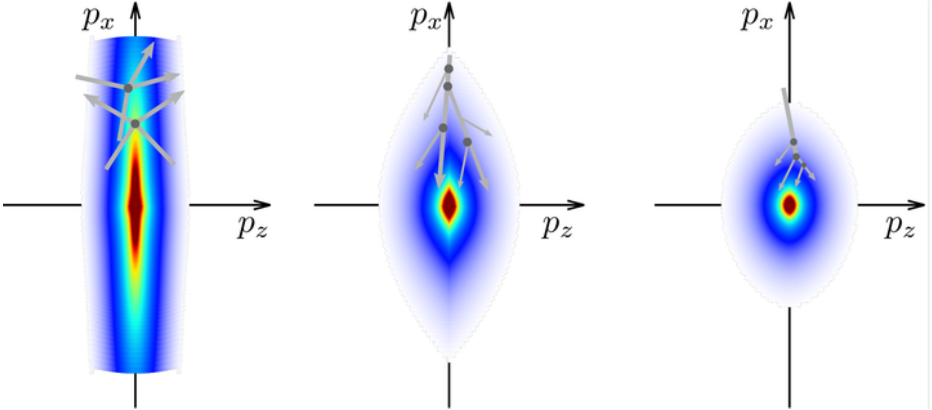
Epelbaum, Gelis `[Phys.Rev.Lett.111(2013)]`

Next stages of pre-equilibrium

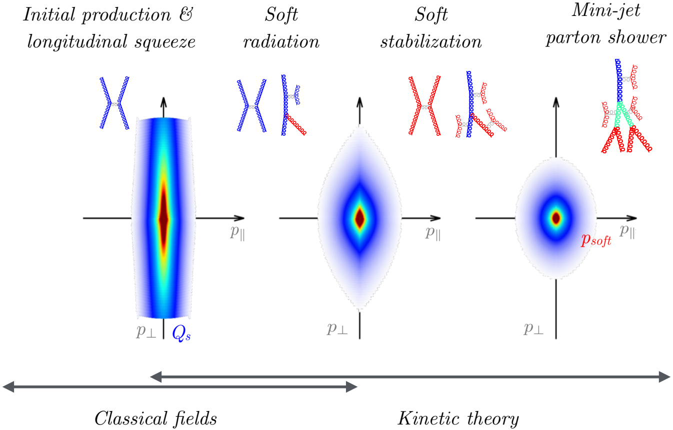
Effective kinetic theory



Kurkela, Mazeliauskas, Paquet, Schlichting, Teaney [Phys.Rev.C99(2019)]

Bottom-up thermalization

Equilibration at weak coupling

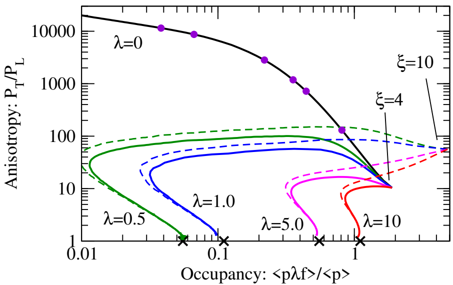


Schlichting, Teaney [Ann.Rev.Nucl.Part.Sci.69(2019)]

Effective kinetic theory

À la AMY[†] and KZ[⋆]

Trajectories for different initial conditions[⋆]



- Boltzmann equation

collision terms

$$-\frac{\mathrm{d}}{\mathrm{d}\tau}\, f_{\boldsymbol{p}} = \left(\mathcal{C}_{1\leftrightarrow 2} + \mathcal{C}_{2\leftrightarrow 2} + \mathcal{C}_{\mathrm{exp}} \right)(f_{\boldsymbol{p}})$$

longitudinal expansion

distribution function

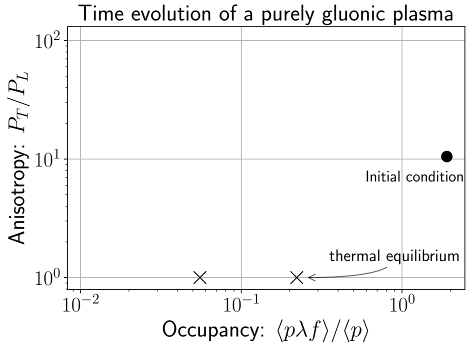
- Soft scale m_D ≪ hard scale Q_s
- Overoccupied $f \sim 1/\alpha_s$ at $Q_s\tau \sim 1$
- Boost-invariance $p_z \ll p_T$

[†] Arnold, Moore, Yaffe [JHEP01(2003)]

[⋆] Kurkela, Zhu [Phys.Rev.Lett.115(2015)]

Stages of bottom-up

Classical fields, soft particles, energy loss

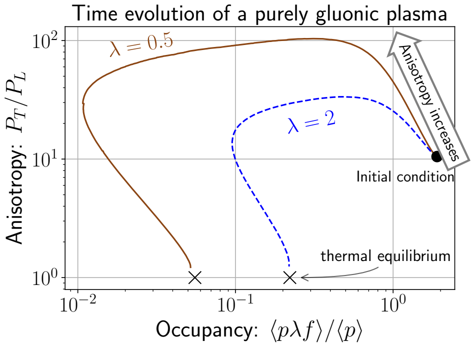


- Stage ○
  Overoccupied gluon fields
  Anisotropy ξ, coupling $\lambda = 4\pi N_c\alpha_s$
- Stage ⋆
  Maximum anisotropy, hard modes
- Stage •
  Minimum occupancy, bath of soft modes
- Stage ▾
  Almost isotropic, hard modes radiated
  Thermalization $\tau_{\text{BMSS}} \sim \alpha_s^{-13/5} Q_s^{-1}$

Figures courtesy of F. Lindenbauer

Stages of bottom-up

Classical fields, soft particles, energy loss



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- Stage ★
  Maximum anisotropy, hard modes
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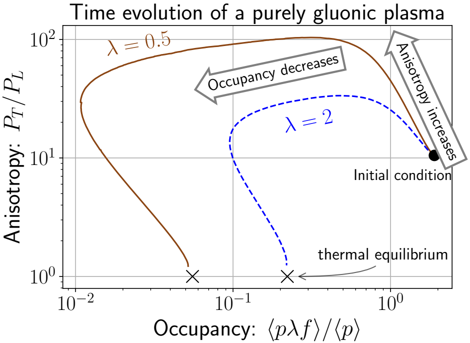

Time evolution of a purely gluonic plasma

- Stage ○

  Overoccupied gluon fields

  Anisotropy ξ, coupling $\lambda = 4\pi N_c\alpha_s$
- Stage ★

  Maximum anisotropy, hard modes
- Stage ●

  Minimum occupancy, bath of soft modes
- Stage ▾

  Almost isotropic, hard modes radiated

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Stages of bottom-up

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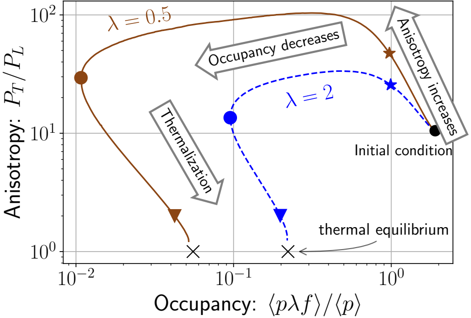

- Stage ○
  Overoccupied gluon fields
  Anisotropy ξ, coupling $\lambda = 4\pi N_c \alpha_s$
- Stage ★
  Maximum anisotropy, hard modes
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Stages of bottom-up

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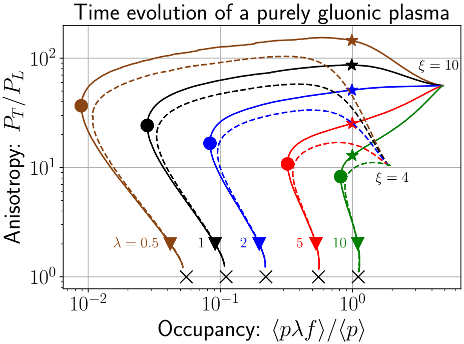

- Stage ∘

  Overoccupied gluon fields

  Anisotropy ξ, coupling $\lambda = 4\pi N_c \alpha_s$
- Stage ★

  Maximum anisotropy, hard modes
- Stage ●

  Minimum occupancy, bath of soft modes
- Stage ▼

  Almost isotropic, hard modes radiated

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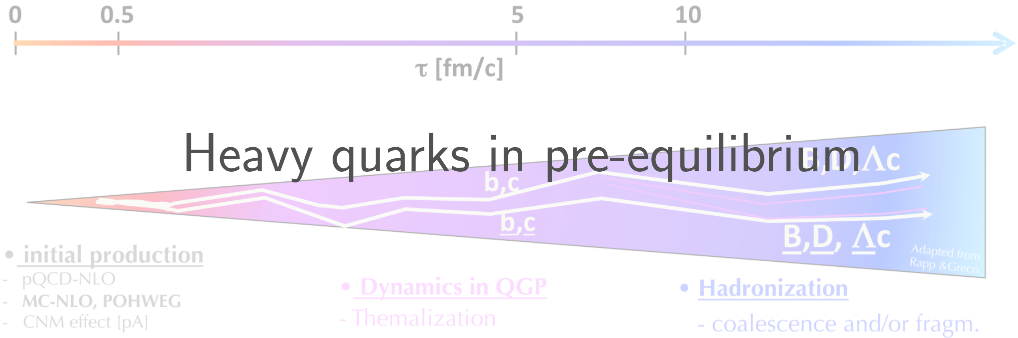
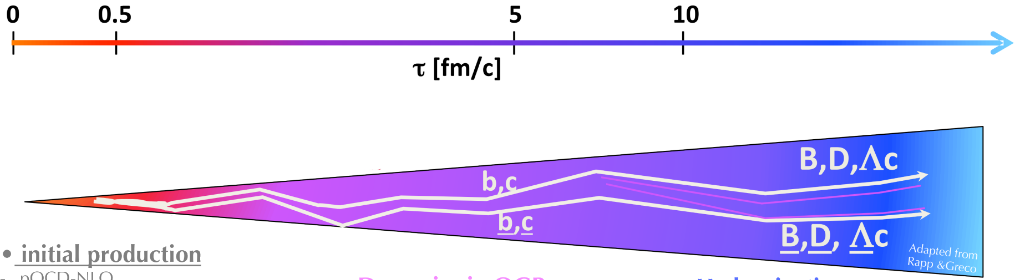
Figures courtesy of F. Lindenbauer

Heavy quarks in pre-equilibrium



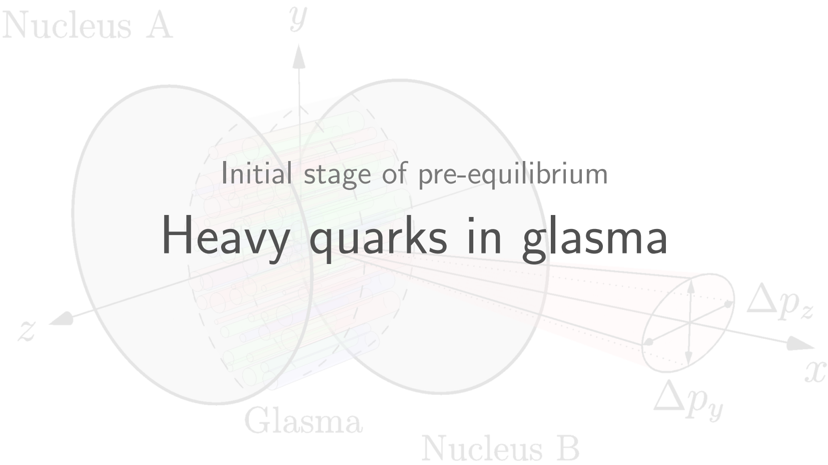


- **initial production**
  - pQCD-NLO
  - **MC-NLO, POHWEG**
  - CNM effect [pA]

- **Dynamics in QGP**
  - Themalization

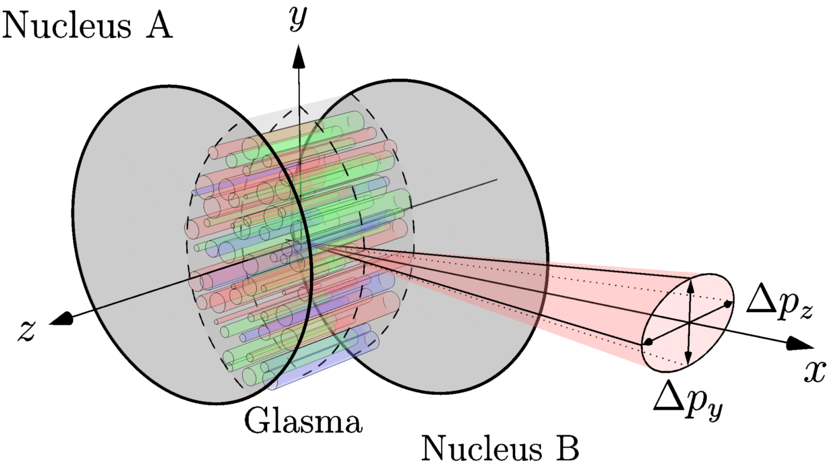
- **Hadronization**
  - coalescence and/or fragm.

Greco [ECT* 2020]



Initial stage of pre-equilibrium

Heavy quarks in glasma



Ipp, Müller, Schuh [Phys.Lett.B810(2020)]

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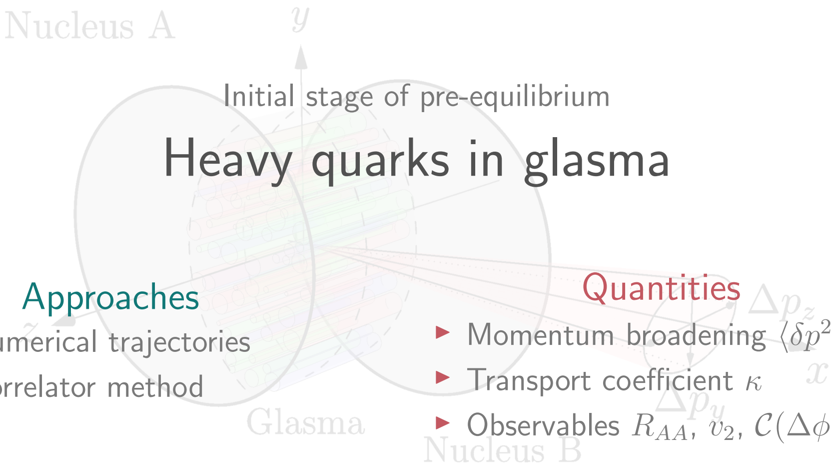


Approaches

- Numerical trajectories
- Correlator method

Quantities

- Momentum broadening $\langle \delta p^2 \rangle$
- Transport coefficient κ
- Observables R_{AA}, v_2, $\mathcal{C}(\Delta\phi)$

Figure from A. Ipp, D. Müller, D. Schuh [2009.14206]

Particles in Yang-Mills fields

Wong's equations of motion

- Approach: numerical trajectories of classical particles in glasma fields

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

coordinate

$$\frac{\mathrm{d}}{\mathrm{d}\boldsymbol{\tau}} x^\mu = \frac{p^\mu}{m},$$

proper time

mass

momentum

gauge field

$$\frac{\mathrm{D}}{\mathrm{d}\boldsymbol{\tau}} p^\mu = 2g\,\mathrm{Tr}\left\{Q F^{\mu\nu}[A^\mu]\right\}\frac{p_\nu}{m},$$

coupling constant

covariant derivative

color charge

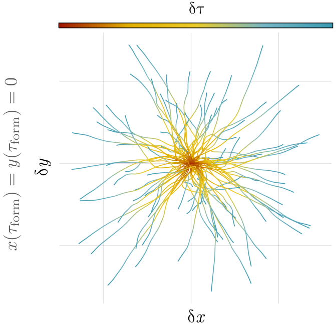
$$\underbrace{\frac{\mathrm{d}}{\mathrm{d}\boldsymbol{\tau}} Q = -ig[A_\mu, Q]\frac{p^\mu}{m}}_{\text{color rotation} \to \mathcal{U} \in \mathrm{SU}(3)}$$

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

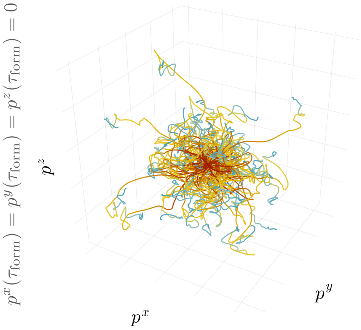
Particles in Yang-Mills fields

Vizualizing the trajectories⋆

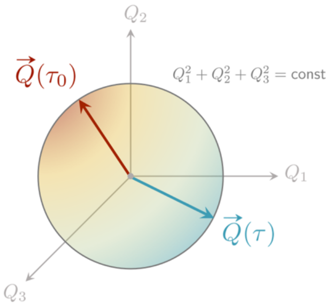
Change of coordinates



Color Lorentz force



Color rotation



⋆Avramescu, Băran, Greco, Ipp, Müller, Ruggieri [Phys.Rev.D107(2023)]

Particles in Yang-Mills fields

- Quantities: averaged over particle trajectories and glasma events
  - Momentum broadening $\langle \delta p_i^2 \rangle(\tau) = \langle p_i^2(\tau) - p_i^2(\tau_{\text{form}}) \rangle$
  - Transport coefficient[⋆] $\kappa_i = \dfrac{\mathrm{d}}{\mathrm{d}\tau} \langle \delta p_i^2(\tau) \rangle$

theoretical

  - Transverse momentum spectra $\dfrac{\mathrm{d}N}{\mathrm{d}p_T}(\tau)$ using FONLL input $\dfrac{\mathrm{d}N}{\mathrm{d}p_T}(\tau_{\text{form}})$
  - Nuclear modification factor $R_{AA} = \dfrac{\mathrm{d}N^{AA}/\mathrm{d}p_T}{A^2 \mathrm{d}N^{pp}/\mathrm{d}p_T}$
  - Azimuthal correlation $\mathcal{C}(\Delta\phi) = \dfrac{1}{N_{\text{pairs}}} \dfrac{\mathrm{d}N}{\mathrm{d}\Delta\phi}$ for $Q\overline{Q}$ pairs

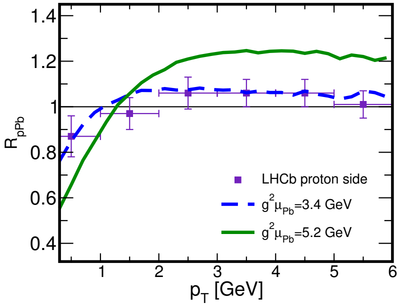
observables[†]

[⋆] More on transport coefficients in QGP from Maria-Lucia and Salvatore

[†] More on HF observables from Mattia

Numerical trajectories results

2018 2019 2021 2022 2024



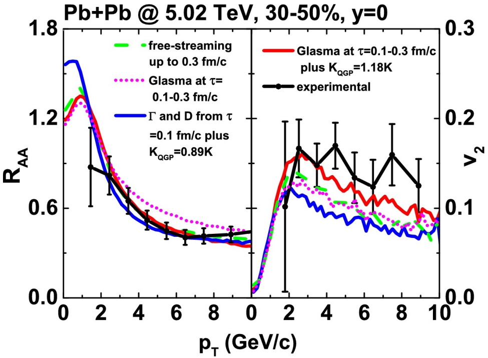
R_{pA} for D-mesons

- First study of HQs in glasma
- SU(2) glasma, static box
- Proton Q_s from hot spot model
- FONLL input + fragmentation

Ruggieri, Das `[Phys.Rev.D98(2018)]`

Numerical trajectories results

2018 2019 2021 2022 2024



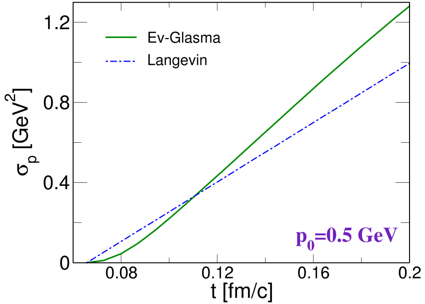
Hybrid R_{AA} and v_2

- SU(2) glasma, static box
- Compared with Fokker-Planck
- Including glasma increases v_2

Sun, Coci, Das, Plumari, Ruggieri, Greco [Phys.Lett.B798(2019)]

Numerical trajectories results

2018 2019 2021 2022 2024



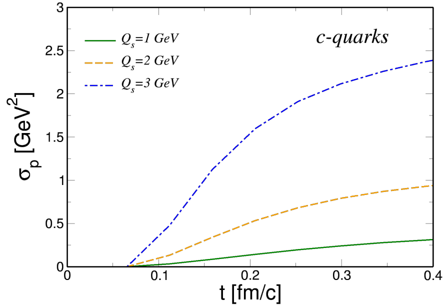
Momentum variance σ_p

- SU(2) glasma, static box
- Compared with Langevin
- Glasma correlation domains

Liu, Das, Greco, Ruggieri [Phys.Rev.D103(2021)]

Numerical trajectories results

2018 2019 2021 2022 2024

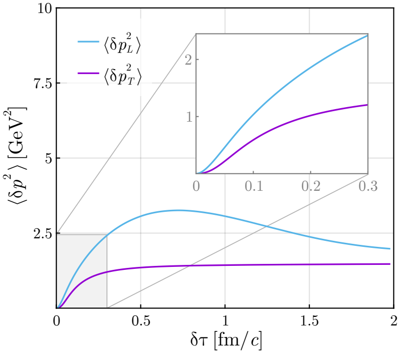


Momentum variance σ_p

- SU(2) glasma, longitudinal expansion
- Compared with Langevin
- Glasma correlation domains

Khowal, Das, Oliva, Ruggieri [Eur.Phys.J.Plus137(2022)]

Numerical trajectories results



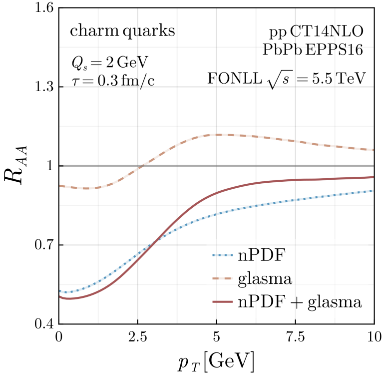
Momentum broadening $\langle \delta p^2 \rangle$
Transport coefficient κ

- SU(3) glasma, longitudinal expansion
- Colored-particle-in-cell solver
- Compared with correlator method

Avramescu, Băran, Greco, Ipp, Müller, Ruggieri `[Phys.Rev.D107(2023)]`

Numerical trajectories results

2018 2019 2021 2022 2024



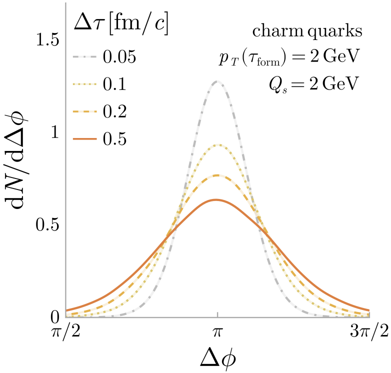
R_{AA} with nPDF effects

- SU(3) glasma, longitudinal expansion
- Colored-particle-in-cell solver
- FONLL + EPPS16 input calculation

Avramescu, Greco, Lappi, Mäntysaari, Müller `[in preparation]`

Numerical trajectories results

2018 2019 2021 2022 2024



Azimuthal decorrelation $\mathcal{C}(\Delta\phi)$

- First study of $Q\overline{Q}$ correlations in glasma
- SU(3) glasma, longitudinal expansion
- Colored-particle-in-cell solver
- Extraction of decorrelation widths $\sigma_{\Delta\phi}$

Avramescu, Greco, Lappi, Mäntysaari, Müller `[in preparation]`

Particles in Yang-Mills fields

Correlator method

- **Approach**: infer particle dynamics from background **field correlators**

$$\langle \delta p_i^2(\tau) \rangle = g^2 \int\limits_{\tau_0}^{\tau} \mathrm{d}\tau' \int\limits_{\tau_0}^{\tau} \mathrm{d}\tau'' \left\langle \mathrm{Tr}\left[\widetilde{\mathcal{F}}_i(\tau') \widetilde{\mathcal{F}}_i(\tau'') \right] \right\rangle$$

gauge invariant force correlator

Lorentz force $\mathcal{F}_i = F_{i\mu} \frac{p^\mu}{p^\tau} \xrightarrow{\text{gauge invariant}}$ parallel transport on lattice $\widetilde{\mathcal{F}}_i$

$$\sum_x \left\langle E_{i,x}(\tau') \times E_{i,x}(\tau'') \right\rangle$$

- **Static heavy quarks** on lattice*

$$\langle \delta p_i^2(\tau) \rangle \big|_{m\to\infty} \propto \int_{\tau_0}^{\tau} \mathrm{d}\tau' \int_{\tau_0}^{\tau} \mathrm{d}\tau'' \left\langle \mathrm{Tr}\left[E_i(\tau') E_i(\tau'') \right] \right\rangle$$

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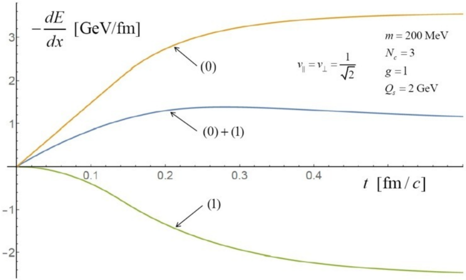
*Electric field correlators also used by Vijami and Tom

Field correlators results

2020

2023

2024



Transport coefficient κ
Collisional energy loss $\mathrm{d}E/\mathrm{d}x$

- Analytical glasma fields in τ expansion
- Glasma $\langle EE \rangle$ and $\langle BB \rangle$ correlators
- Fokker-Planck equation for heavy quarks

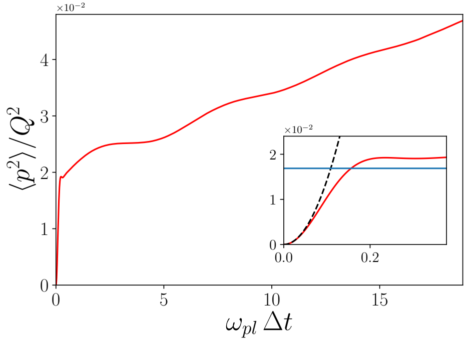
Carrington, Czajka, Mrowczynski `[Nucl.Phys.A1001(2020)]`

Field correlators results

2020

2023

2024



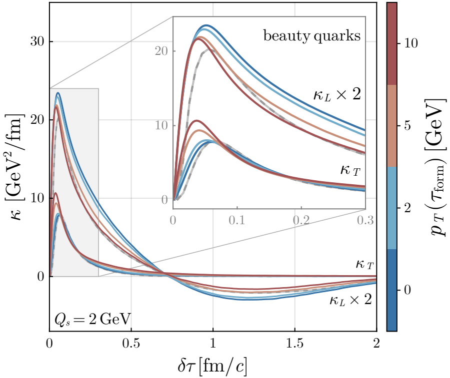
Momentum broadening $\langle \delta p^2 \rangle$
Transport coefficient κ

- Over-occupied classical Yang-Mills
- Numerical lattice $\langle EE \rangle$ correlator
- Large peak in $\langle \delta p^2 \rangle$
- Oscillations of κ with plasmon frequency

Boguslavski, Kurkela, Lappi, Peuron [JHEP09(2020)]

Field correlators results

2020 2023 2024

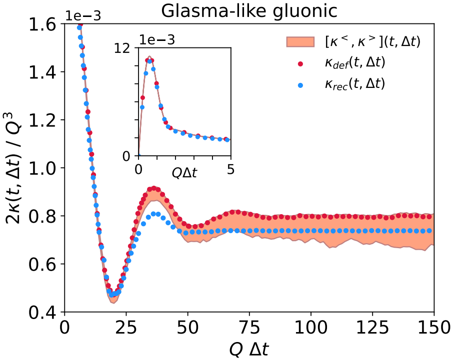


Momentum broadening $\langle \delta p^2 \rangle$
Transport coefficient κ

- SU(3) glasma, longitudinal expansion
- Numerical lattice $\langle EE \rangle$ correlator
- Comparison with numerical trajectories
- Ordering $\langle \delta p_L^2 \rangle > \langle \delta p_T^2 \rangle$, negative $\kappa_L < 0$

Avramescu, Băran, Greco, Ipp, Müller, Ruggieri [PoSHardProbes2023(2024)]

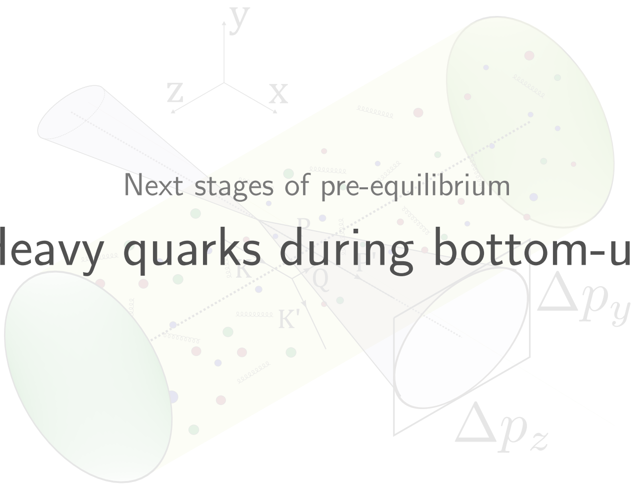
Field correlators results



Transport coefficient κ

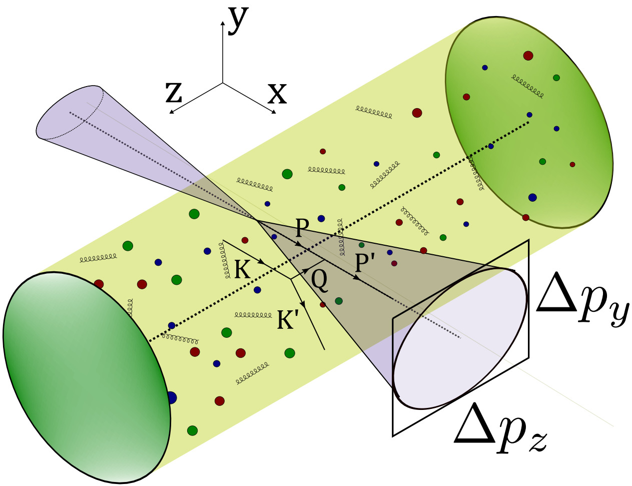
- Glasma-like classical fields
- Numerical lattice $\langle EE \rangle$ correlator
- Non-perturbative gluonic excitations
- Explain the peak in κ

Backfried, Boguslavski, Hotzy `[arXiv2408.12646]`



Next stages of pre-equilibrium

Heavy quarks during bottom-up



Boguslavski, Kurkela, Lappi, Lindenbauer, Peuron [Phys.Rev.D110(2024)]

Next stages of pre-equilibrium

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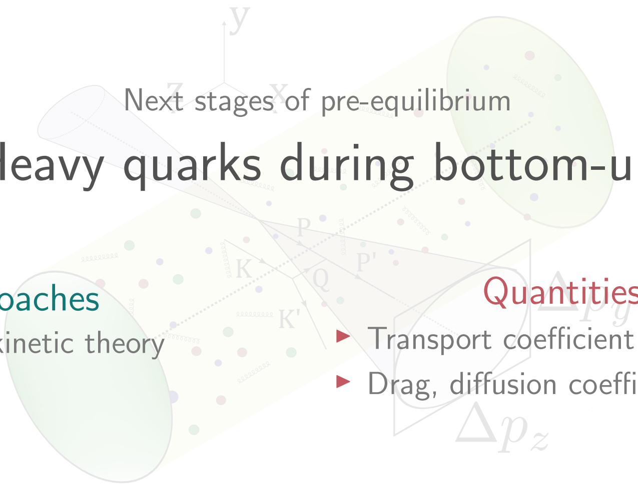


Approaches

- Effective kinetic theory

Quantities

- Transport coefficient κ
- Drag, diffusion coefficients A_i, B_{ij}

Heavy quarks in EKT

Extracting transport coefficients

- Approach: effective kinetic theory to study the gluon distribution function $f(\boldsymbol{k})$
  - Quantities: various transport coefficients κ, A_i, B_{ij} extracted from $f(\boldsymbol{k})$

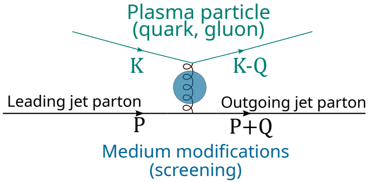


Figure credits to F. Lindenbauer

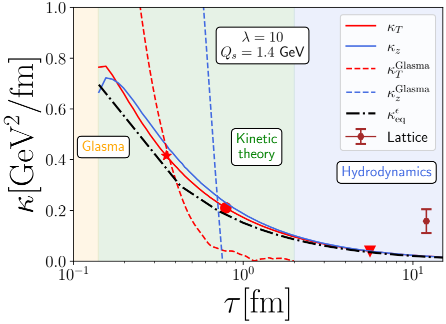
$$\kappa \propto \int \overbrace{\mathrm{d}\Gamma_{\mathrm{PS}}}^{\text{phase space measure}}\, \underbrace{\boldsymbol{q}^2}_{\text{momentum exchange}} \Big|\overbrace{\mathcal{M}}^{\text{matrix element}}\Big|^2 \underbrace{f(\boldsymbol{k})}_{\text{incoming}}[1+\underbrace{f(\boldsymbol{k}')}_{\text{outgoing}}]$$

Drag $A_i \propto \int \mathrm{d}\Gamma_{\mathrm{PS}}\, \boldsymbol{q}_i \left|\mathcal{M}\right|^2 f(\boldsymbol{k})[1 \pm f(\boldsymbol{k}')]$

Diffusion $B_{ij} \propto \int \mathrm{d}\Gamma_{\mathrm{PS}}\, \boldsymbol{q}_i \boldsymbol{q}_j \left|\mathcal{M}\right|^2 f(\boldsymbol{k})[1 \pm f(\boldsymbol{k}')]$

EKT results

2024

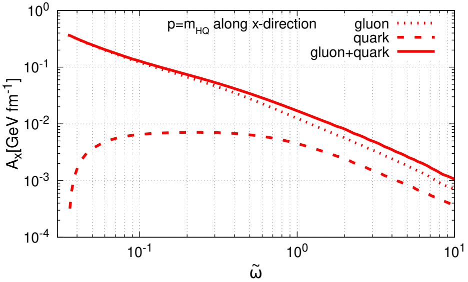


Transport coefficient κ

- Energy density ε matched to glasma
- Compare to κ in glasma
- Compare with equilibrium κ_{eq}
- Match for the same m_D, $T_\star$ and ε

Boguslavski, Kurkela, Lappi, Lindenbauer, Peuron [Phys.Rev.D109(2024)]

EKT results



Drag, diffusion A_i, B_{ij}

- Contributions from $g, q, g + q$
- Angular dependence
- Rescaled coefficients, attractor behavior

Du [Phys.Rev.C109(2024)]

My questions

- Theoretical improvements
  - First stage of bottom-up thermalization

    How to connect κ from glasma to EKT? Match using gluon distribution function
  - Heavy quark energy loss in glasma

    Only recently: jet energy loss in glasma from synchrotron radiation[*]
- Experimental observables
  - Observables sensitive to pre-equilibrium

    What to extract? The most sensitive is the azimuthal correlation
  - Large initial anisotropy

    How to measure anisotropy? Many studies in anisotropic systems[†]
- Compare theory to experiment
  - How sensitive is data to pre-equilibrium? Simulations of all stages for HQ transport

---

[*] Barata, Hauksson, López, Sadofyev [2406.07615]

[†] Hauksson, Jeon [Phys.Rev.C105(2022)]; Barata, Sadofyev, Salgado [Phys.Rev.D105(2022)]

Thank you!

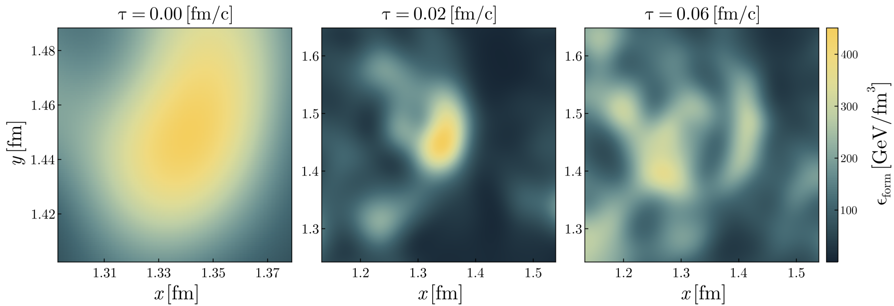
Back-up

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



Hard probes in Glasma

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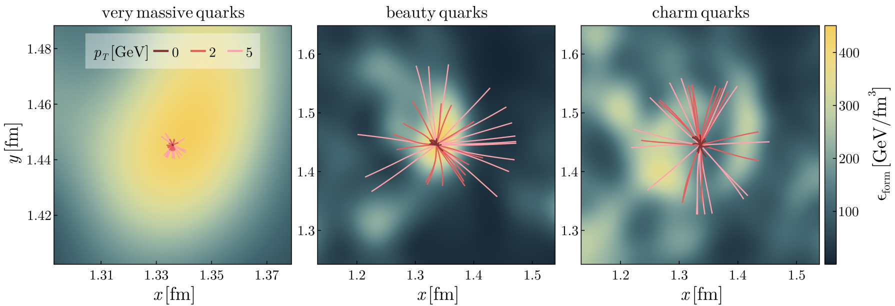
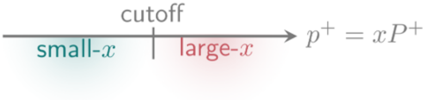


CGC as an EFT for high energy QCD

Classical Yang-Mills fields



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

covariant derivative

field strength tensor

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

gluons gauge field

color current of nucleus

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

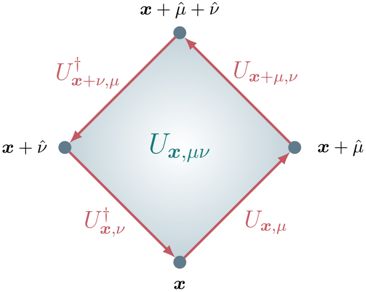
large nuclei

stochastic variable

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

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 ↦ gauge invariant

Wilson lines on the lattice ↔ gauge links

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

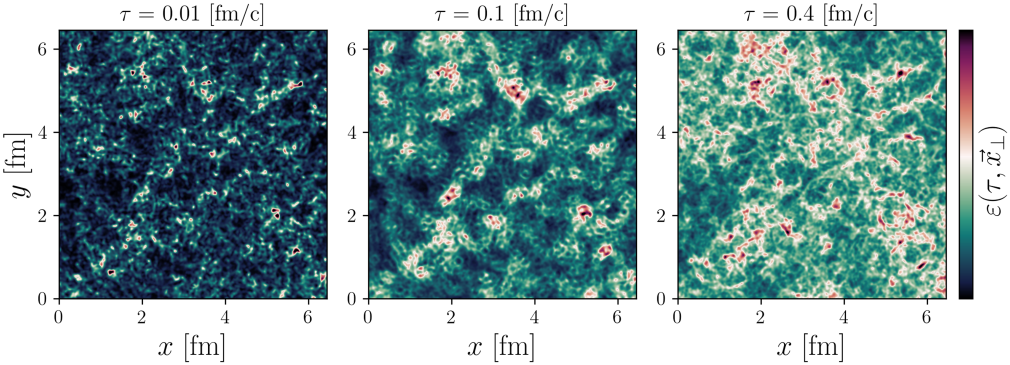
Wilson loops on lattice ↔ plaquettes

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

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

The Glasma fields

General features



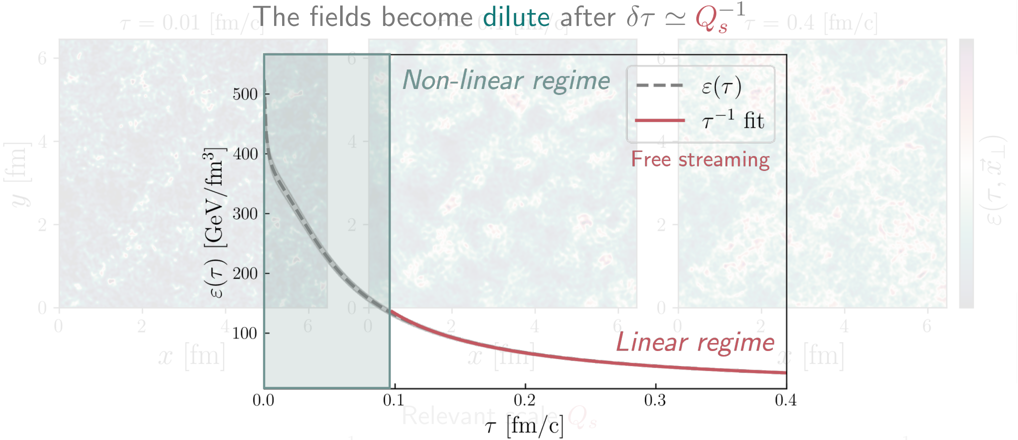
Relevant scale Q_s

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 $\delta\tau \simeq Q_s^{-1}$



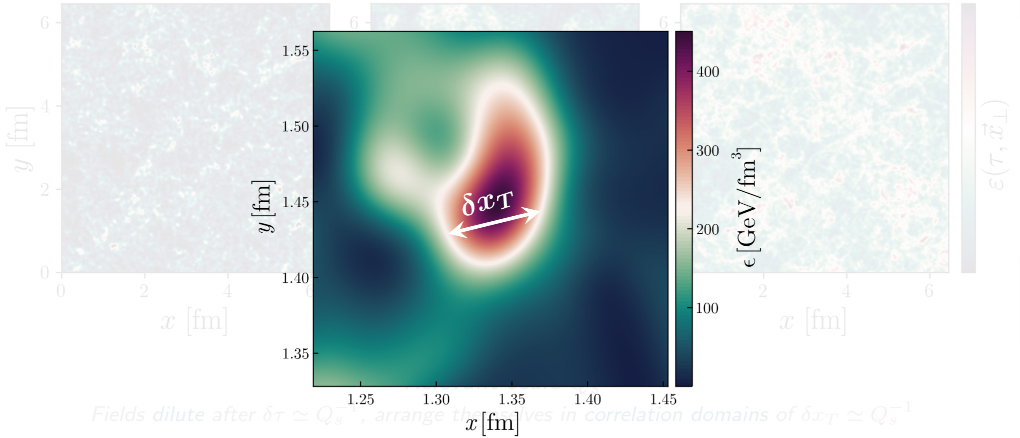
Relevant scale Q_s

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 $\delta x_T \simeq Q_s^{-1}$

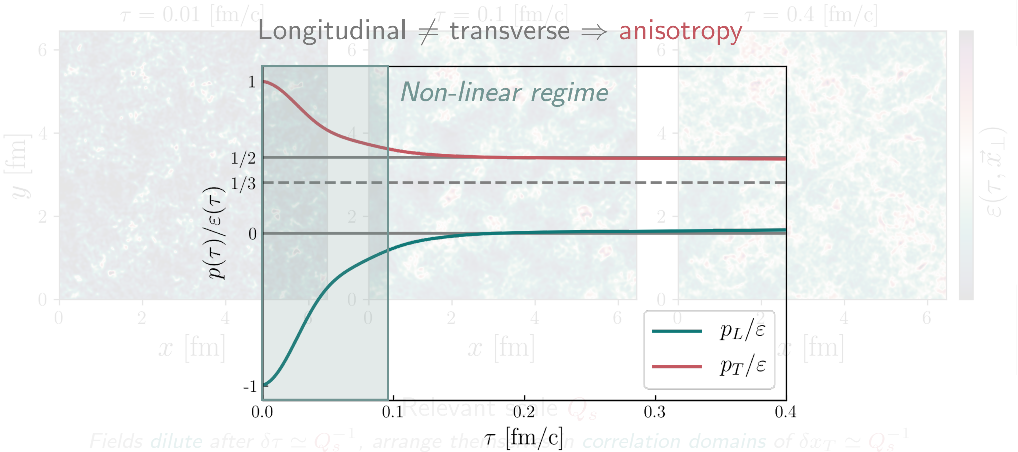


Fields dilute after $\delta\tau \simeq Q_s^{-1}$, arrange themselves in correlation domains of $\delta x_T \simeq Q_s^{-1}$

The Glasma fields

Anisotropy

Longitudinal $\neq$ transverse $\Rightarrow$ anisotropy



Relevant scale Q_s

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

Particles in Yang-Mills fields

Wong's equations of motion

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

Boltzmann-Vlasov collisionless non-Abelian plasma

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

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

$$\Rightarrow \text{Wong's equations}$$

coordinate

momentum

gauge field

color charge

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

proper time

mass

covariant derivative

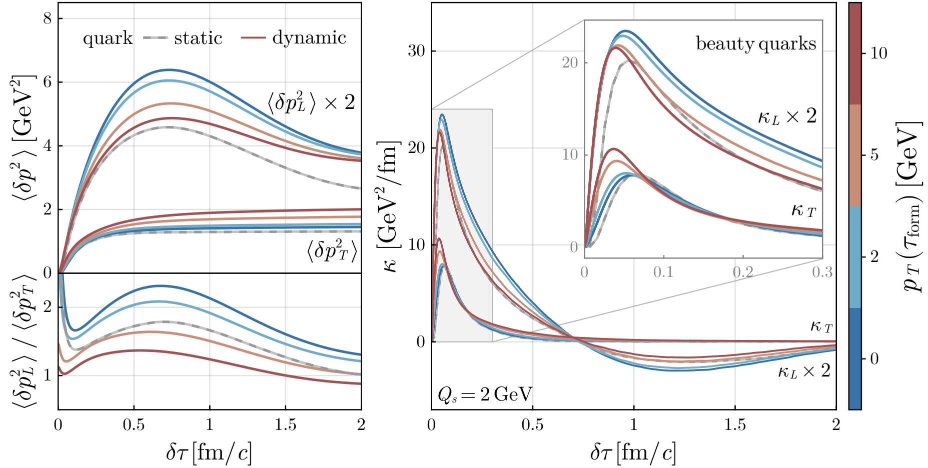
coupling constant

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

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

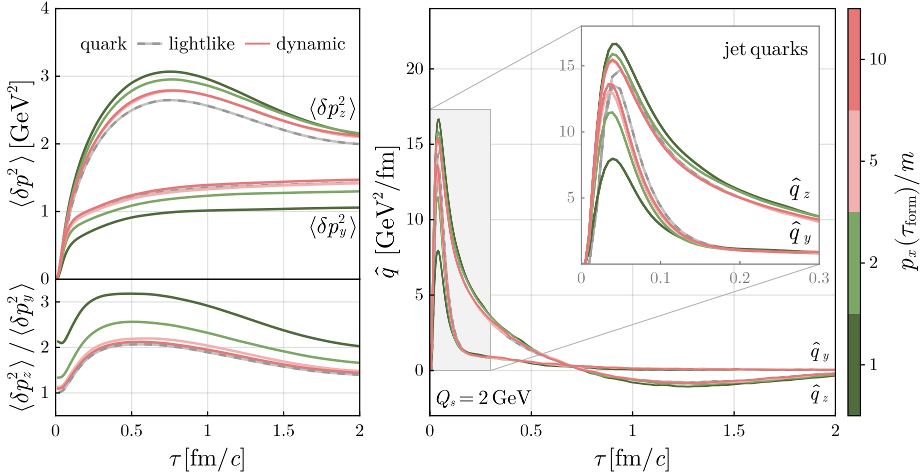
Heavy quarks in Glasma

Momentum broadening and κ



Jets in Glasma

Momentum broadening and $\hat{q}$



Large transport coefficients

Plausible in an EKT framework

Schematic evolution of $\hat{q}$

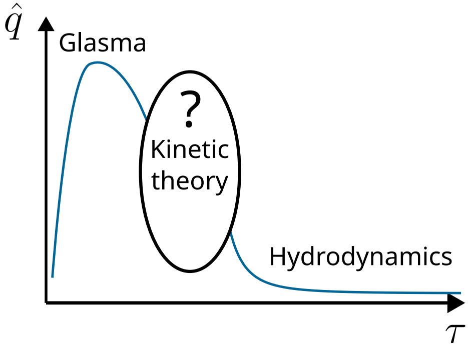
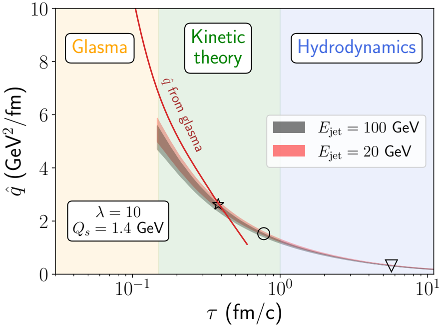


Figure from [2303.12595]

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



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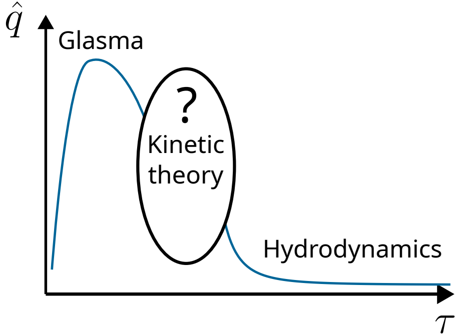

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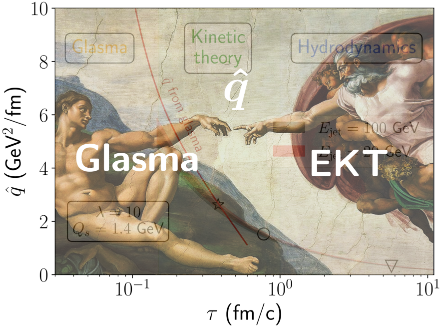
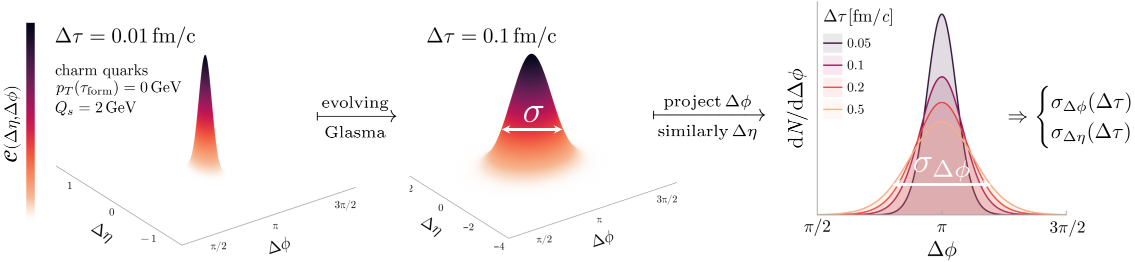


Two particle correlations

Quantifying the decorrelation

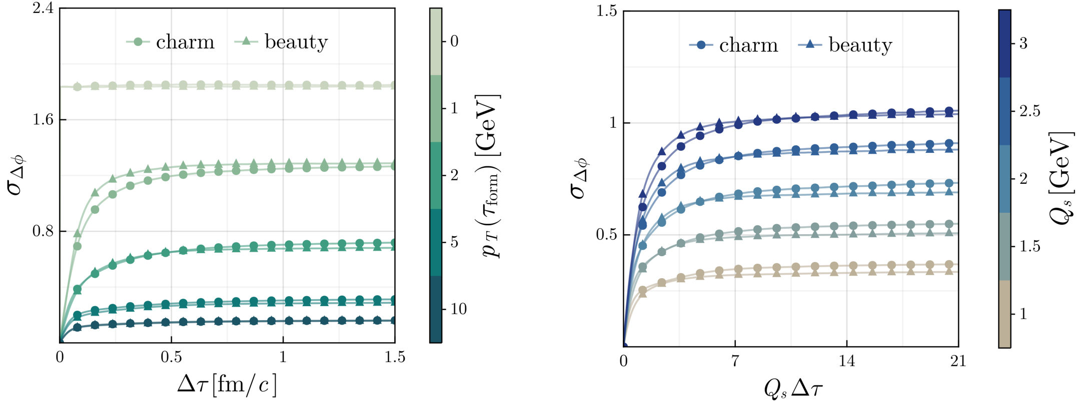
Rapidity and azimuthal correlations $\mathcal{C}(\Delta\eta, \Delta\phi) \equiv \frac{1}{N_{\text{pairs}}} \frac{\mathrm{d}^2 N}{\mathrm{d}\Delta\eta \mathrm{d}\Delta\phi}$

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



Azimuthal decorrelation width

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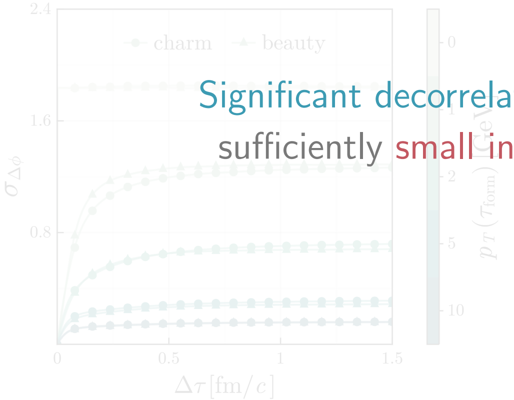
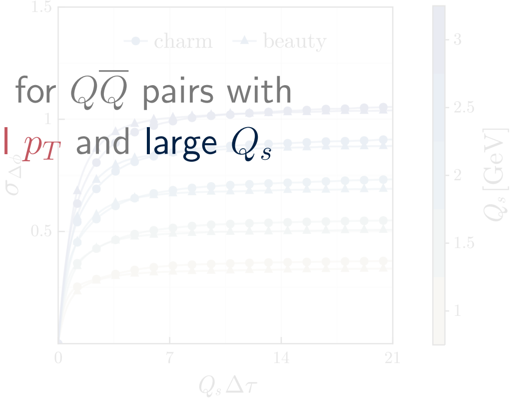


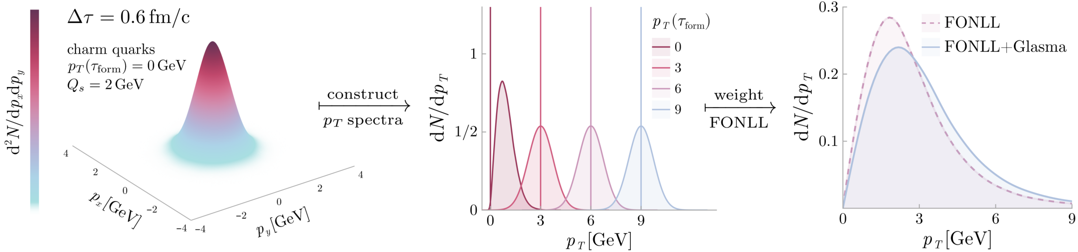


Significant decorrelaton for $Q\overline{Q}$ pairs with sufficiently small initial p_T and large Q_s

Nuclear modification factor

Sketch of p_T spectra in the Glasma

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



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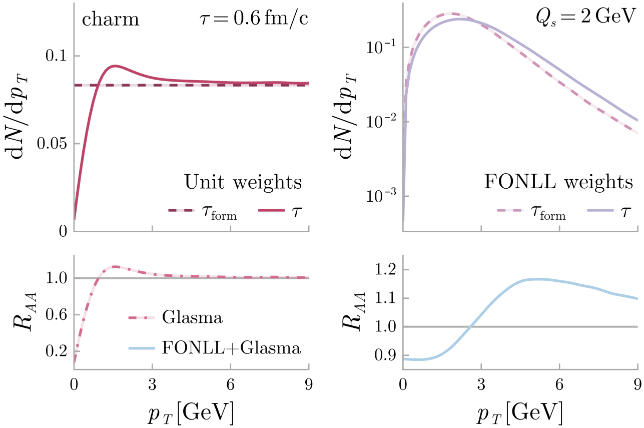
* *Fixed Order + Next-to-Leading Logarithms*, state-of-the-art resummed heavy quark production

Nuclear modification factor

Extraction of R_{AA} in Glasma



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

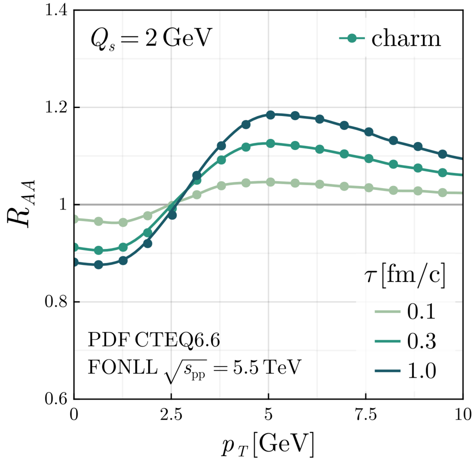
Initialized with FONLL in pp/AA

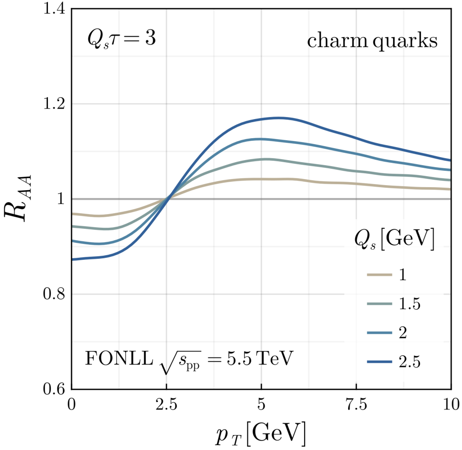
Nuclear modification factor at τ

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

R_{AA} in the Glasma

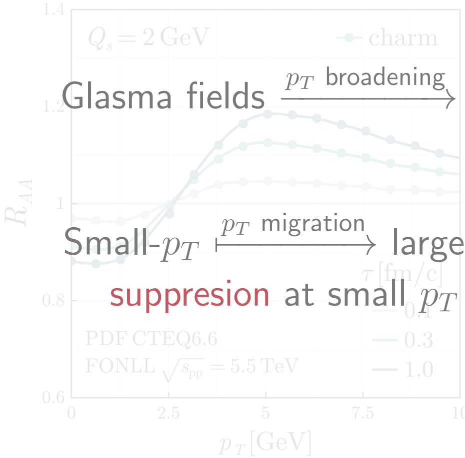
Temporal evolution and Q_s dependence

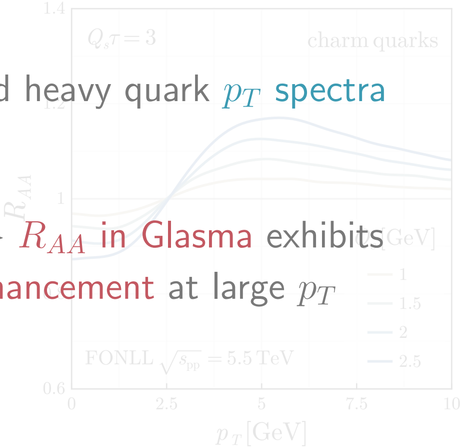




R_{AA} in the Glasma

Temporal evolution and Q_s dependence



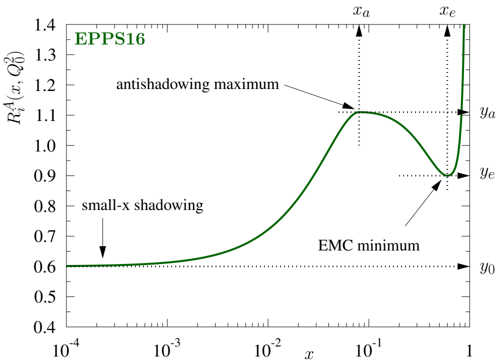


Glasma fields $\xrightarrow{p_T \text{ broadening}}$ shifted heavy quark p_T spectra

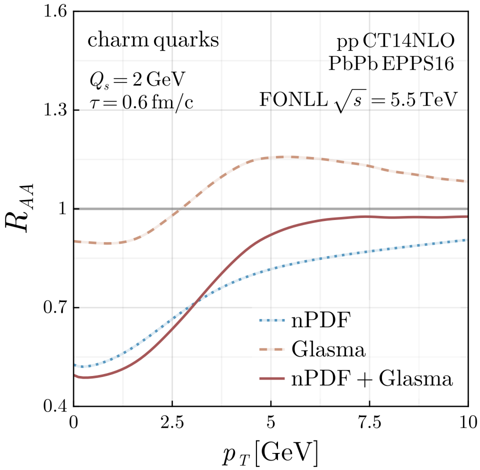
Small-p_T $\xmapsto{p_T \text{ migration}}$ large-p_T $\Rightarrow$ R_{AA} in Glasma exhibits suppresion at small p_T $+$ enhancement at large p_T

R_{AA} in the Glasma with nPDFs

Cold nuclear matter effects



EPPS16 nuclear PDF from [1612.05741]



R_{AA} in the Glasma with nPDFs

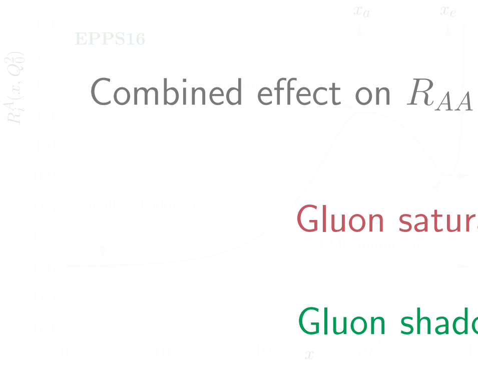
Cold nuclear matter effects

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

Gluon saturation from Glasma

$+$

Gluon shadowing from nPDFs



EPPS16 nuclear PDF from [1612.05741]