Simulations of the Glasma in 2+1D and 3+1D

David I. Müller

Institute for Theoretical Physics
TU Wien, Austria

dmueller@hep.itp.tuwien.ac.at

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Overview

- Introduction
- Glasma in 2+1D
- Glasma in 3+1D
- Jets in the Glasma
- Outlook

Literature

Collisions of 3D nuclei: 3+1D Glasma

- D. Gelfand, A. Ipp, D. Müller, PRD (2016) [1605.07184]
  numerical method, proof of concept
- A. Ipp, D. Müller, PLB (2017) [1703.00017]
  rapidity profiles at RHIC
- A. Ipp, D. Müller, EPJC (2018) [1804.01995]
  numerical improvements
- D. Müller, PhD thesis (2019) [1904.04267]
  lots of technical details
- A. Ipp, D. I. Müller, EPJA (2020) [2009.02044]
  recent review

Jets in 2+1D Glasma

- A. Ipp, D. I. Müller, D. Schuh, PRD (2020) [2001.10001]
  methods, numerical checks
- A. Ipp, D. I. Müller, D. Schuh, PLB (2020) [2009.14206]
  phenomenological results, jet broadening parameter $\hat{q}(\tau)$

Introduction

Relativistic heavy ion collisions

Heavy-ion collision experiments as a means to study the properties of nuclear matter at extremely high energies

Examples:

- Au+Au at RHIC, BNL with $\sqrt{s_{\rm NN}}$ up tp $200\,\rm GeV$.
- Pb+Pb at LHC, CERN with $\sqrt{s_{\rm NN}}$ up tp $5\,\rm TeV$.

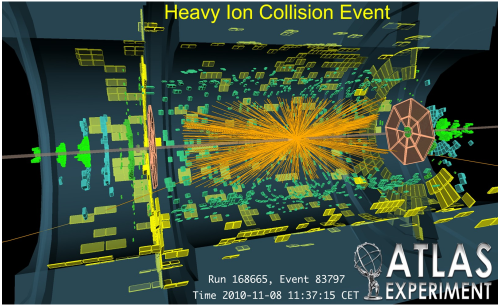


Image from ATLAS @ CERN (2010)

Relativistic heavy ion collisions

Collect experimental data:
Number of produced particles, E and $\mathbf{p}$ distributions, particle species, ...
Flow coefficients v_n, correlations, ...

All observations should be explainable using theory!

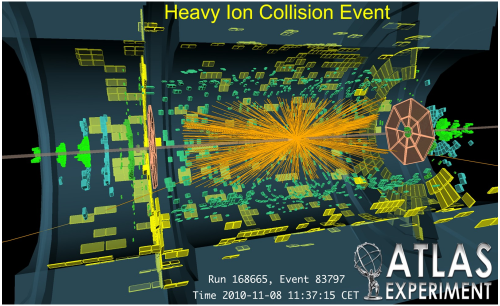
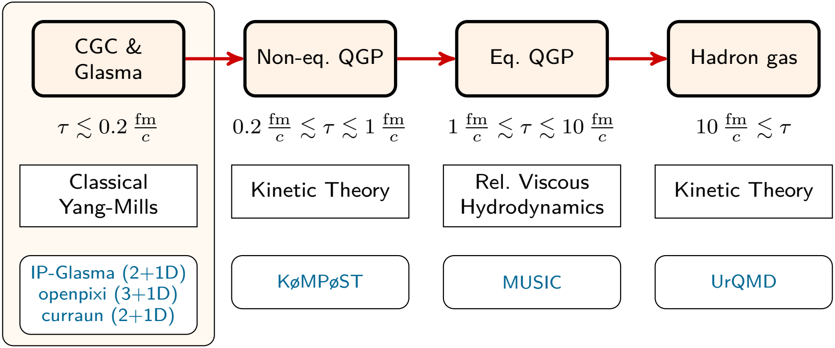


Image from ATLAS @ CERN (2010)

State of the art: a chain of simulations



Input:

- knowledge about nuclei (deep inelastic scattering, CGC models)
- properties of the QGP (collision integrals, viscosity, EOS)

Output:

- predictions for observables (multiplicities, flow coefficients, ...)

Color glass condensate

CGC is an effective theory for high energy QCD at weak coupling

Nuclei at high energies:

- Lorentz-contracted along collision axis
- Time-dilated dynamics
- hard partons: carry most of the momentum of the nucleus
- soft partons: high occupation number, (near-classical) coherent state

Split degrees of freedom:

- quarks, high momentum gluons: classical color currents J^μ
- low momentum gluons: classical color fields A_μ

$$D_\mu F^{\mu\nu} = J^\nu$$

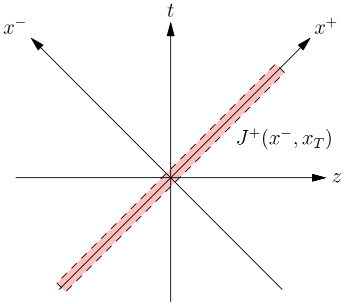
CGC allows an effectively classical treatment of high energy nuclei

Color glass condensate

Nucleus "A" described by color current

$$J^+(x^-, x_T) = \rho_A(x^-, x_T)$$

in terms of light cone coordinates $x^\pm = (x^0 \pm x^3)/\sqrt{2}$ and transverse coordinates $x_T = (x, y)$



- YM eqs. $D_\mu F^{\mu\nu} = J^\nu$
- Use covariant gauge $\partial_\mu A^\mu = 0$
- YM eqs. reduce to 2D Poisson eq.

$$-\Delta_T A^+(x^-, x_T) = \rho_A(x^-, x_T)$$

- Solve in Fourier space with infrared regulator m

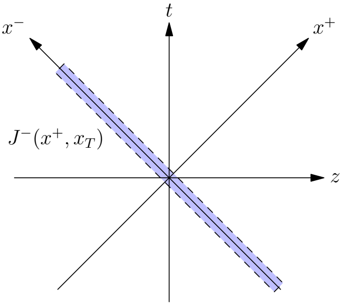
$$A^+(x^-, x_T) = \int \frac{d^2k_T}{(2\pi)^2} \frac{\widetilde{\rho_A}(x^-, k_T)}{k_T^2 + m^2} e^{-ik_T \cdot x_T}$$

Color glass condensate

Nucleus “B” described by color current

$$J^-(x^+, x_T) = \rho_B(x^+, x_T)$$

in terms of light cone coordinates $x^\pm = (x^0 \pm x^3)/\sqrt{2}$ and transverse coordinates $x_T = (x, y)$



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Color glass condensate

Classical color currents J^μ or charge densities ρ are random fields distributed according to some probability functional $W[\rho]$. This requires models.

Observables are computed as expectation values using functional integration:

$$\langle \mathcal{O}(A_\mu) \rangle = \int \mathcal{D}\rho \, \mathcal{O}(A_\mu[\rho]) \, W[\rho]$$

A simple model: McLerran-Venugopalan (MV) model

$$W[\rho] = Z^{-1} \exp \left(- \int d^2 x_T dx^- \frac{\rho^a(x^-, x_T) \rho^a(x^-, x_T)}{2 g^2 \mu^2 \lambda(x^-)} \right)$$

$$\left\langle \rho^a(x^-, x_T) \right\rangle = 0$$

$$\left\langle \rho^a(x^-, x_T) \rho^b(y^-, y_T) \right\rangle = g^2 \mu^2 \lambda(x^-) \delta^{ab} \delta(x^- - y^-) \delta^{(2)}(x_T - y_T)$$

No notion of finite radius $\Rightarrow$ suitable for central collisions of very large nuclei

Color glass condensate

Covariant gauge solutions:

$$J^+(x) = \rho_A(x) \quad \Rightarrow \quad A^+(x) = \int \frac{d^2k_T}{(2\pi)^2} \frac{\widetilde{\rho_A}(x^-, k_T)}{k_T^2 + m^2} e^{-ik_T \cdot x_T}$$
$$J^-(x) = \rho_B(x) \quad \Rightarrow \quad A^-(x) = \int \frac{d^2k_T}{(2\pi)^2} \frac{\widetilde{\rho_B}(x^+, k_T)}{k_T^2 + m^2} e^{-ik_T \cdot x_T}$$

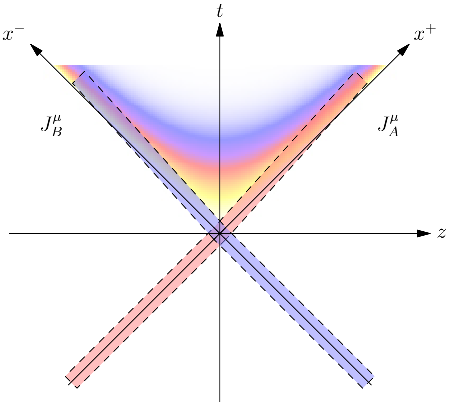
Solutions to the YM eqs. are simple for single nuclei, even though YM eqs. are non-linear.

What about collisions? How can we solve

$$D_\mu F^{\mu\nu} = J_A^\nu + J_B^\nu \,?$$

The Glasma in 2+1D

General collision scenario

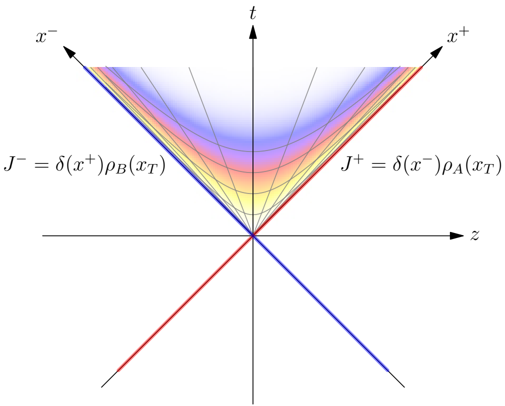


- Glasma: field produced from the collision of two CGCs
- Solution to the Yang-Mills equations

$$D_\mu F^{\mu\nu} = J_A^\nu + J_B^\nu$$

- Fields are non-perturbative
- Recoil of nuclei?
- No analytic solutions in the forward light cone
- Need approximations to make progress

Ultra-relativistic collision scenario



- Assumption 1: no recoil
- Assumption 2: infinitesimally thin along z

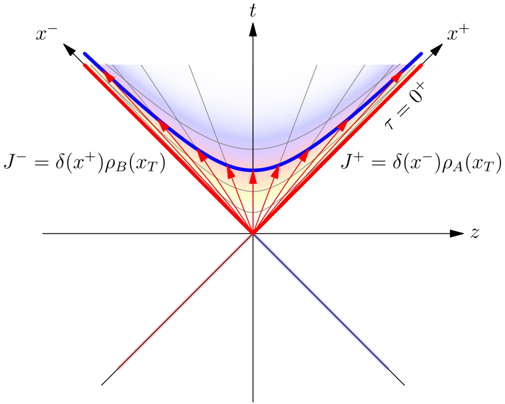
$$J^+(x) = \delta(x^-)\rho_A(x_T)$$
$$J^-(x) = \delta(x^+)\rho_B(x_T)$$

- Milne coordinates

$$\tau = \sqrt{2x^+x^-}, \quad \eta = \frac{1}{2}\ln\left(\frac{x^+}{x^-}\right)$$

- Invariance under boosts along z (rapidity η independent)
- Glasma is effectively 2+1D

Ultra-relativistic collision scenario



- Initial conditions at boundary $\tau = 0^+$ (analytic result)
- Evolution in future light cone determined by source-free Yang-Mills eqs.

$$D_\mu F^{\mu\nu} = 0$$

- In practice: real-time lattice gauge theory for time evolution along proper time τ

The boost-invariant Glasma

Initial conditions:

$$\alpha^i(\tau \to 0^+, x_T) = \alpha^i_A(x_T) + \alpha^i_B(x_T),$$
$$\alpha^\eta(\tau \to 0^+, x_T) = \frac{ig}{2}\left[\alpha^i_A(x_T), \alpha^i_B(x_T)\right],$$

with the light cone gauge solutions

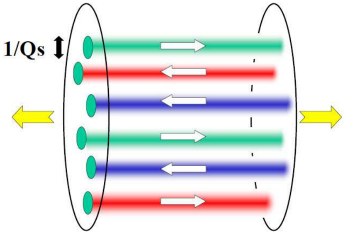
$$\alpha^i_{(A,B)}(x_T) = \frac{1}{ig} V_{(A,B)}(x_T)\partial^i V^\dagger_{(A,B)}(x_T).$$

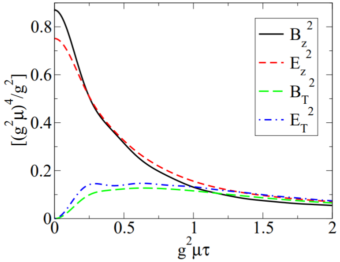
Wilson lines computed from covariant gauge solutions:

$$V^\dagger_{(A,B)}(x_T) = \mathcal{P}\exp\left(-ig\int_{-\infty}^{+\infty} dx'^{\mp} A^{\pm}(x'^{\mp}, x_T)\right)$$

The boost-invariant Glasma

Glasma at $\tau = 0^+$ consists of color-electric and -magnetic longitudinal flux tubes with typical transverse size of Q_s^{-1} (saturation momentum, $Q_s \approx g^2\mu$)





Figs. from H. Fujii, K. Itakura, Nucl. Phys. A (2008), [0803.0410]
T. Lappi, L. McLerran, Nucl. Phys. A (2006) [hep-ph/0602189]

Flux tubes expand and decay according to the YM eqs. until system reaches free streaming state

Energy-momentum tensor

One of the main observables is the energy-momentum tensor $T^{\mu\nu}$

$$T^{\mu\nu} = \frac{2}{g^2}\mathrm{Tr}\left[F^{\mu\rho}F^{\nu}{}_{\rho} - \frac{1}{4}g^{\mu\nu}F^{\rho\sigma}F_{\rho\sigma}\right].$$

Expectation value in the MV model (Glasma rest frame):

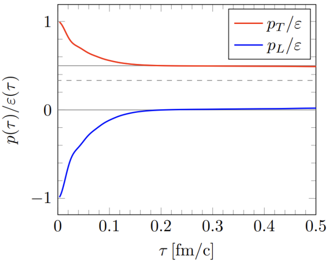
$$\left\langle T^{\mu\nu}\right\rangle = \begin{pmatrix} \left\langle \varepsilon \right\rangle & 0 & 0 & 0 \\ 0 & \left\langle p_T \right\rangle & 0 & 0 \\ 0 & 0 & \left\langle p_T \right\rangle & 0 \\ 0 & 0 & 0 & \left\langle p_L \right\rangle \end{pmatrix}$$

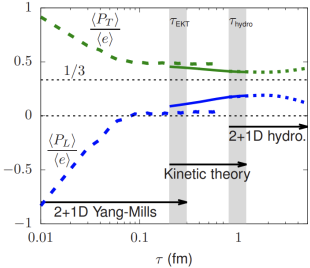
Event-by-event: all components of $T^{\mu\nu}$ relevant

Energy-momentum tensor

One of the main observables is the energy-momentum tensor $T^{\mu\nu}$

- Problem 1: pressure anisotropy
  (solved by KøMPøST)
- Problem 2: boost invariance
- $T^{\mu\nu}$ input for hydrodynamics/kinetic theory





Figs. from: D. Müller, PhD thesis (2019) [1904.04267]

A. Kurkela, A. Mazeliauskas, JF Paquet, S. Schlichting, D. Teaney, PRL (2019) [1805.01604]

Energy-momentum tensor

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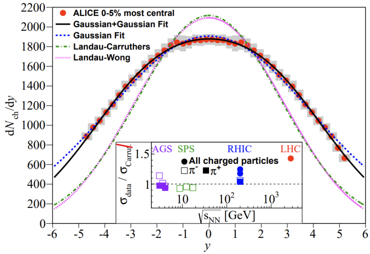
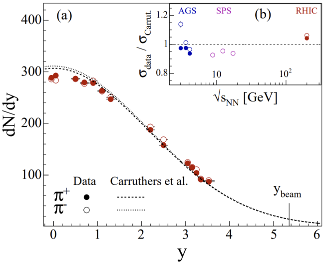
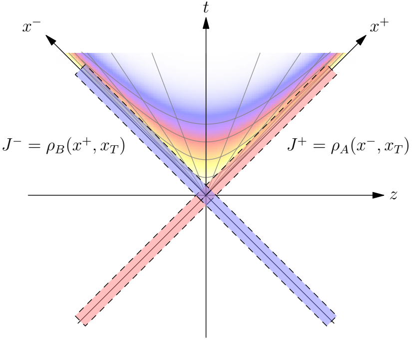




Figs. from ALICE, PLB (2013) [1304.0347] and BRAHMS, PRL (2005) [nucl-ex/0403050]

The Glasma in 3+1D

Relativistic collision scenario with finite widths

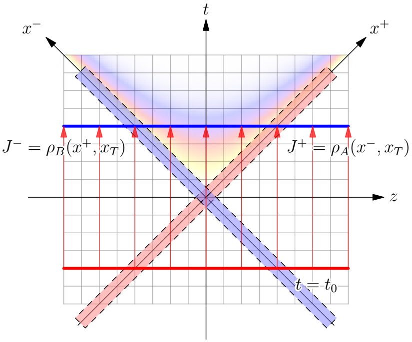


- Assumption: no recoil
- Keep width along z finite

$$J^+(x) = \rho_A(x^-, x_T)$$
$$J^-(x) = \rho_B(x^+, x_T)$$

- Finite interaction time
- No boost invariance
- Glasma is 3+1D
- Problem: rapidity dependent initial conditions in Milne coordinates?

Relativistic collision scenario with finite widths



- Give up description in Milne coordinates (τ, η)
- Describe collision in laboratory frame (t, z)
- Full 3+1D Yang-Mills eqs. with current

$$D_\mu F^{\mu\nu} = J_A^\nu + J_B^\nu$$

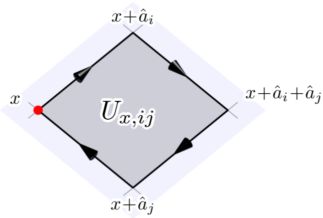
- Initial conditions at $t = t_0$ (analytic result)
- Simulate full collision with real-time lattice gauge theory and colored particle-in-cell

Real-time lattice gauge theory

Lattice gauge theory is a gauge covariant discretizion of Yang-Mills theory on a lattice with lattice spacings a^μ

Degrees of freedom: gauge links

$$U_{x,\mu} = \bar{\mathcal{P}} \exp\left(ig \int_x^{x+\hat{a}^\mu} dx'^\nu A_\nu(x') \right)$$
$$\approx \exp\left(iga^\mu A_\mu(x + \frac{1}{2}\hat{a}^\mu) \right)$$



Plaquettes to approximate field strength tensor

$$U_{x,\mu\nu} = U_{x,\mu} U_{x+\mu,\nu} U^\dagger_{x+\nu,\mu} U^\dagger_{x,\nu}$$
$$\approx \exp\left(iga^\mu a^\nu F_{\mu\nu}(x + \frac{1}{2}\hat{a}^\mu + \frac{1}{2}\hat{a}^\nu) \right)$$

Real-time lattice gauge theory

Approximate Yang-Mills action with plaquettes: Wilson action

$$S = -\frac{1}{2}\int d^4x\,\mathrm{Tr}\left[F_{\mu\nu}F^{\mu\nu}\right]$$
$$\approx a^4 \sum_x \sum_i \frac{1}{(g a^\mu a^\nu)^2}\mathrm{Tr}\left[\mathbf{1} - \frac{1}{2}U_{x,\mu\nu} - \frac{1}{2}U^\dagger_{x,\mu\nu}\right]$$

- Discretization is correct up to $\mathcal{O}(a^2)$
- Wilson action is symmetric under (space-)time reversal
- Wilson action is gauge invariant under lattice gauge transformations

$$U_{x,\mu} \to \Omega_x U_{x,\mu} \Omega^\dagger_{x+\mu}$$
$$U_{x,\mu\nu} \to \Omega_x U_{x,\mu\nu} \Omega^\dagger_x$$

- Variation yields gauge covariant equations of motion

Real-time lattice gauge theory

Discrete Yang-Mills equations (continuous time t)

$$\dot{E}_i(t,\mathbf{x}) = -\sum_j \frac{1}{ga^i(a^j)^2}\left[U_{i,j}(t,\mathbf{x}) + U_{i,-j}(t,\mathbf{x})\right]_{\mathrm{ah}} + J_i(t,\mathbf{x})$$

$$\dot{U}_i(t,\mathbf{x}) = iga^i E_i(t,\mathbf{x})U_i(t,\mathbf{x})$$

- Time evolution can be performed numerically
- External color current $J_\mu(t,\mathbf{x})$
- Gauge covariant conservation

$$\dot{\rho}(t,\mathbf{x}) + \sum_i \frac{J_i(t,\mathbf{x}) - U_{x,-i}(t)J_i(t,\mathbf{x}-\hat{a}^i)U^\dagger_{x,-i}(t)}{a^i} = 0$$

- Gauss constraint

$$\sum_i \frac{E_i(t,\mathbf{x}) - U_{x,-i}(t)E_i(t,\mathbf{x}-\hat{a}^i)U^\dagger_{x,-i}(t)}{a^i} = \rho(t,\mathbf{x})$$

Colored particle-in-cell method

- Particle-in-cell (PIC): numerical method to simulate systems with large number of charged particles (plasma theory)
- Main concept: approximate continuous charge density with large number of charged particles

$$\rho(t, \mathbf{x}) \approx \sum_n Q_n \, \delta^{(3)}(\mathbf{x} - \mathbf{x}(t))$$

- Colored particle-in-cell (CPIC): non-Abelian generalization

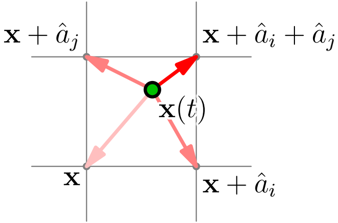
$$\rho(t, \mathbf{x}) \approx \sum_n \mathbf{Q}_n(t) \, \delta^{(3)}(\mathbf{x} - \mathbf{x}(t))$$

with time-dependent color charge $\mathbf{Q}_n(t)$

- Allows gauge covariant treatment of color currents on the lattice

Colored particle-in-cell method

- How to couple charged particles with continuous positions $\mathbf{x}(t)$ with fields on a lattice? $\Rightarrow$ Interpolation methods



- We use nearest grid point (NGP) interpolation
- Particles contribute to lattice charge density at NGP
- Particle movement generates current whenever NGP changes

Color rotation: particle moves from $\mathbf{x}$ to $\mathbf{y}$

$$\mathbf{Q}(t + \Delta t) = U_{\mathbf{x}\to\mathbf{y}}(t)\mathbf{Q}(t)U^{\dagger}_{\mathbf{x}\to\mathbf{y}}(t)$$

McLerran-Venugopalan model in 3+1D

Relax ultrarelativistic approximation by allowing for finite width along z

$$J^+_A(x^-, x_T) = \delta(x^-)\rho_A(x_T) \quad \Rightarrow \quad J^+_A(x^-, x_T) = f(x^-)\rho_A(x_T)$$

- Longitudinal profile $f(x^-)$ or simply $f(z)$
- Use Gaussian profile with longitudinal extent $L \propto R_A/\gamma$

$$f(z) = \frac{1}{\sqrt{2\pi}L} \exp\left(-\frac{z^2}{2L^2}\right)$$

- Trivial color longitudinal structure (no fluctuations along z)

Glasma in 3+1D

3D density plot of energy density $\varepsilon(x)$

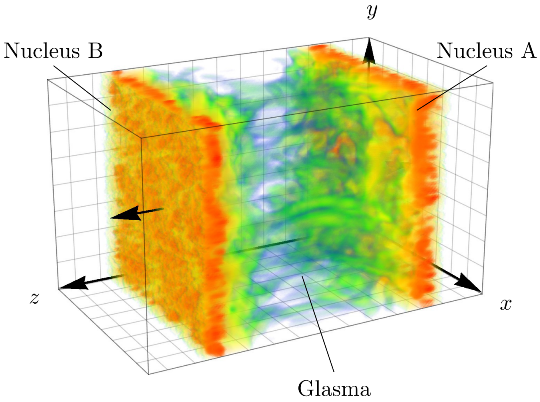


Fig. adapted from A. Ipp, D. Müller, PLB (2017) [1703.00017]

Energy-momentum tensor

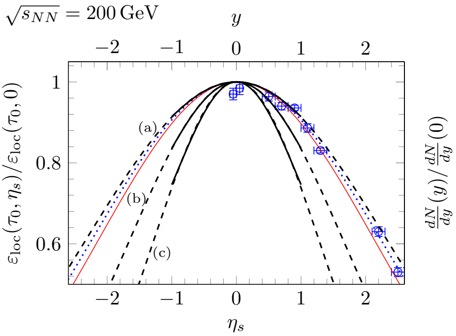
Expectation value in the 3+1D MV model (laboratory frame):

$$\langle T^{\mu\nu} \rangle = \begin{pmatrix} \langle \varepsilon \rangle & 0 & 0 & \langle S_L \rangle \\ 0 & \langle p_T \rangle & 0 & 0 \\ 0 & 0 & \langle p_T \rangle & 0 \\ \langle S_L \rangle & 0 & 0 & \langle p_L \rangle \end{pmatrix}$$

- Longitudinal energy flux (Poynting vector) $\langle S_L \rangle$
- What is the rapidity dependence of the produced Glasma?
- Observable of interest: local rest frame energy density $\langle \varepsilon_{\mathrm{loc}} \rangle$
- Choose local frame s.t. $\langle S_L \rangle$ vanishes and obtain diagonal $\langle T^{\mu\nu} \rangle$
- Use Milne coordinates to obtain $\langle \varepsilon_{\mathrm{loc}} \rangle(\tau, \eta)$

Rapidity profiles

Comparison of space-time rapidity η dependence of $\langle \varepsilon_{\mathrm{loc}} \rangle$ at $\tau = 1\,\mathrm{fm}/c$ to charged particle multiplicity as a function of momentum rapidity y from BRAHMS experiment at RHIC



IR regulator m dependence: (a) $m = 0.2\,\mathrm{GeV}$, (b) $m = 0.4\,\mathrm{GeV}$, (c) $m = 0.8\,\mathrm{GeV}$

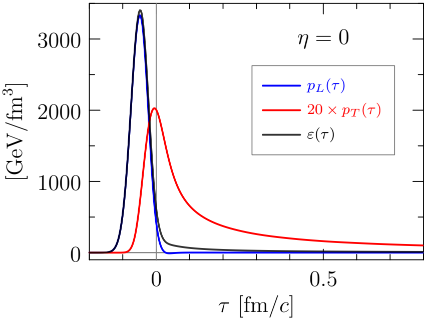
Red line: Landau model

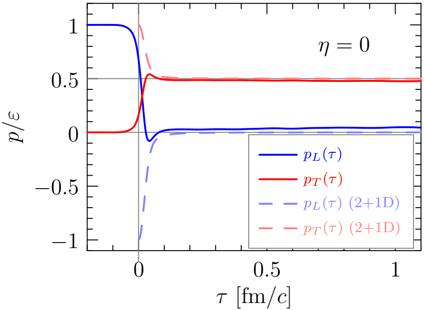
Fig. from A. Ipp, D. Müller, PLB (2017) [1703.00017]

Data from BRAHMS, PRL (2005) [nucl-ex/0403050]

Pressure anisotropy

- At early times: color fields of the nucleus dominate over Glasma
- At late times: free-streaming limit $\langle p_L \rangle \approx 0$
- Same anisotropy issue as in 2+1D Glasma
- Full space-time distribution of e.g. transverse pressure p_T





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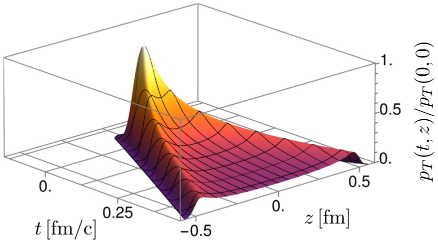

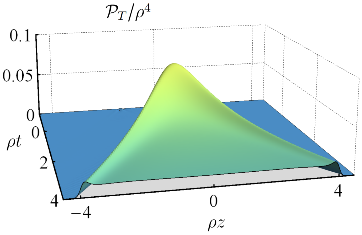

Figs. from A. Ipp, D. Müller, PLB (2017) [1703.00017]

J. Casalderrey-Solana, M. P. Heller, D. Mateos, W. van der Schee, PRL (2013) [1305.4919]

Extensions

Model for charge density $\rho(x)$ is too simple:

- No finite radius
- No longitudinal color fluctuations

$$J_A^+(x^-, x_T) = f(x^-)\rho_A(x_T) \quad \Rightarrow \quad J_A^+(x^-, x_T) = \rho_A(x^-, x_T)$$

Numerical issues:

- 3+1D simulations are computationally expensive!
- High lattice resolution for numerical stability
- Large simulation volumes for realistic results
- Semi-implicit methods as an alternative to standard leapfrog approach
  For details, see: A. Ipp, D. Müller, EPJC (2018) [1804.01995]

Other works on 3+1D Glasma

S. Schlichting, B. Schenke, PRC (2016) [1605.07158]

- Rapidity dependence from JIMWLK
- No full 3+1D dynamics, "stitched together" 2+1D
- LHC energies

S. McDonald, S. Jeon, C. Gale, QM 2018 & 2019 [1807.05409], [2001.08636]

- Rapidity dependence from JIMWLK
- 3+1D dynamics in (τ, η) + hydrodynamics
- LHC energies
- No rigorous derivation of the initial conditions

3+1D CPIC approach (this talk)

- Rapidity dependence from finite width, no JIMWLK
- 3+1D dynamics in (t, z)
- RHIC energies
- Rigorous initial conditions, but no longitudinal fluctuations (yet)

Jets in the Glasma

Jets in the Glasma

- $T^{\mu\nu}$ is not everything!
- Jets: highly energetic, focused particle "sprays" that originate from hard scatterings of partons during the collision at $\tau \approx 0$
- Interactions with the medium
  - momentum broadening (opening angle)
  - energy loss (quenching)
- Jets interact with all stages of the medium
- Strong color fields of the Glasma might affect jets even before the hydrodynamical stage

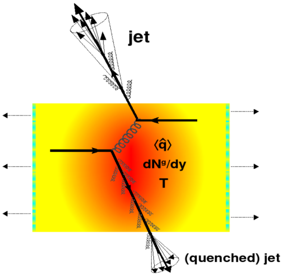

Fig. from D. d'Enterria, *Jet quenching*, Landolt-Bornstein (2010) [0902.2011]

Jets in the Glasma

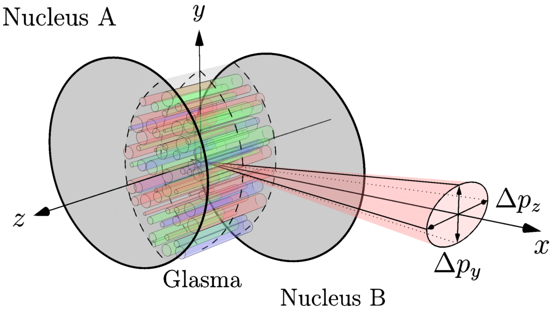

Fig. from A. Ipp, D. I. Müller, D. Schuh, PRD (2020) [2001.10001]

Jets in the Glasma

- Model early-time jet as single quark (or gluon)
- Very high initial momentum, no deflection
- Interaction with the Glasma via the non-Abelian Lorentz force
- Accumulation of transverse momentum $p_\perp$ over time
- 2+1D Glasma for simplicity

Wong equations

$$\frac{dp_\mu}{dt} = g\, Q^a \frac{dx^\nu}{dt} F^a_{\mu\nu}(x(t))$$
$$\frac{dQ^a}{dt} = g \frac{dx^\mu}{dt} f^{abc} A^b_\mu(x(t)) Q^c$$

$$\frac{dp_\mu}{dt} = q \frac{dx^\nu}{dt} F_{\mu\nu}(x(t))$$
$$\frac{dq}{dt} = 0$$

Background field A_μ from 2+1D Glasma simulation

Jet momentum broadening in the Glasma

- Integrate Wong's equations
- Average over color charges of the jet and background field

Main result for a quark moving along x-axis ($i = y, z$):

$$\left\langle p_i^2(\tau) \right\rangle_q = \frac{g^2}{N_c} \int_0^\tau d\tau' \int_0^\tau d\tau'' \left\langle \mathrm{Tr}\left[f^i(\tau') f^i(\tau'') \right] \right\rangle$$

$$f^y(\tau) = U(\tau) \left(E_y(\tau) - B_z(\tau) \right) U^\dagger(\tau)$$

$$f^z(\tau) = U(\tau) \left(E_z(\tau) + B_y(\tau) \right) U^\dagger(\tau)$$

Color rotation matrix in temporal gauge $A^\tau = 0$:

$$U(\tau) = \mathcal{P} \exp\left(-ig \int_0^\tau d\tau' A_x(\tau') \right)$$

Jet momentum broadening in the Glasma

Simplified jet broadening picture in terms of Glasma flux tubes:

- Electric flux tubes:
  Δp_z (or rapidity) broadening
- Magnetic flux tubes:
  Δp_y (or azimuthal) broadening
- Electric and magnetic flux tubes are not created equally
- Momentum broadening is anisotropic

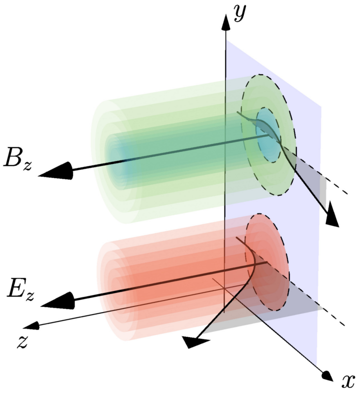

Fig. from A. Ipp, D. I. Müller, D. Schuh, PLB (2020) [2009.14206]

Jet momentum broadening in the Glasma

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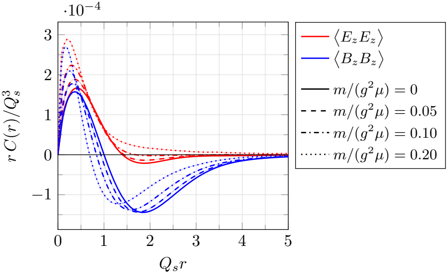


Plot: initial correlation functions for E_z and B_z

Fig. from A. Ipp, D. I. Müller, D. Schuh, PRD (2020) [2001.10001]

Accumulated momenta at $\tau = 0.6\,\mathrm{fm}/c$

- Accumulated momenta at transition time $\tau_0 = 0.6\,\mathrm{fm}/c$ for various Q_s

$$\langle p_\perp^2 \rangle \approx Q_s^2$$

- Broadening is anisotropic

$$\frac{\langle p_z^2 \rangle}{\langle p_y^2 \rangle} \approx 2$$

- Infrared dependence m
- Gluonic jets

$$\frac{\langle p_\perp^2 \rangle_g}{\langle p_\perp^2 \rangle_q} = \frac{C_A}{C_F} = \frac{2N_c^2}{N_c^2 - 1}$$

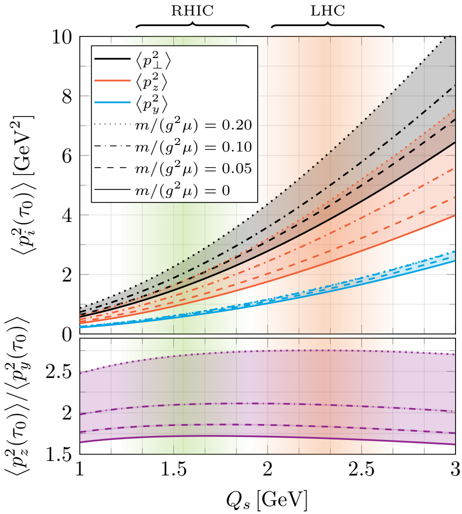
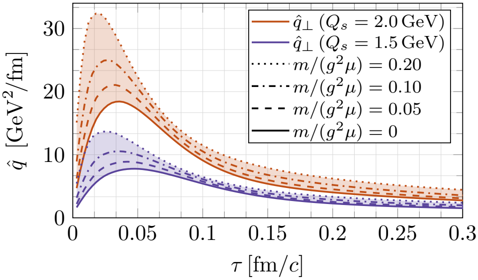


Fig. from A. Ipp, D. I. Müller, D. Schuh, PLB (2020) [2009.14206]

Jet momentum broadening in the Glasma

Jet broadening parameter $\hat{q}$: accumulated (squared) momentum per unit time

$$\hat{q}_\perp(\tau) = \frac{d\langle p_\perp^2 \rangle}{d\tau}$$



Most momentum is accumulated in the earliest stages of the Glasma!

Fig. from A. Ipp, D. I. Müller, D. Schuh, PLB (2020) [2009.14206]

Outlook

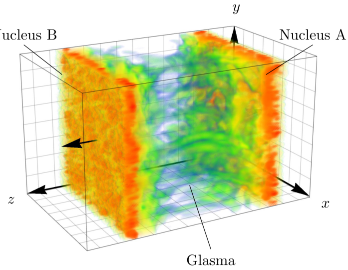
3+1D Glasma

- Collisions at higher energies (LHC)
- Include longitudinal structure

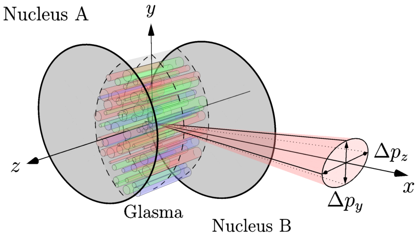
Jets in the Glasma

- Energy loss
- CPIC simulations for jets
- Jets in 3+1D Glasma

Thank you!



y
Nucleus B
Nucleus A
z
x
Glasma



Nucleus A
y
z
Δp_z
x
Δp_y
Glasma
Nucleus B