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Doktoratskolleg
Particles and Interactions

Transverse momentum broadening in real-time lattice simulations of the glasma

for LATTICE 2021

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based on:

[1] A. Ipp D. I. Müller and D. Schuh, Phys. Rev. D **102** (2020) 074001, [hep-ph/2001.10001]

[2] A. Ipp D. I. Müller and D. Schuh, Phys. Let. B **810** (2020) 135810, [hep-ph/2009.14206]

Table of Contents

Introduction

high energy nuclei collisions → jets hit detector

jet quenching, elliptical shape of the jet → momentum broadening

seeds of jets: highly energetic partons (created by hard scatterings during collision)

→ all stages of the medium that is created by the collision may contribute to momentum broadening

consider first stage: glasma (pre-equilibrium precursor state of the quark-gluon plasma)

Glasma

high energy nuclei collisions → Color Glass Condensate framework

classical effective theory for high energy QCD; main idea: separation of scales:

- hard partons: high momentum (valence quarks, high energy gluons)

  → described by thin sheets of classical color charge (Lorentz contracted)

  → color configuration frozen with respect to QCD time scales (time dilation); specified by MV model

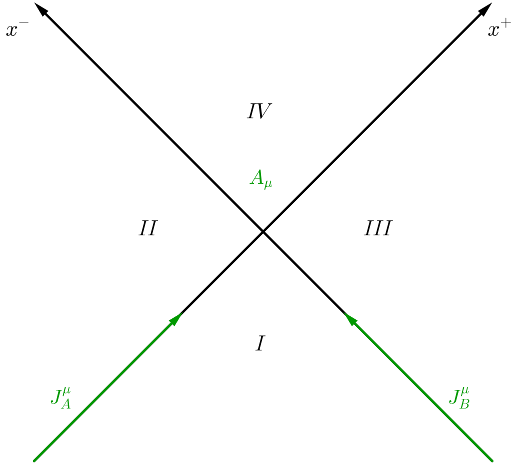
- soft partons: low momentum (low energy gluons)

  → described by a highly occupied color field

effective degrees of freedom: color currents and classical color fields

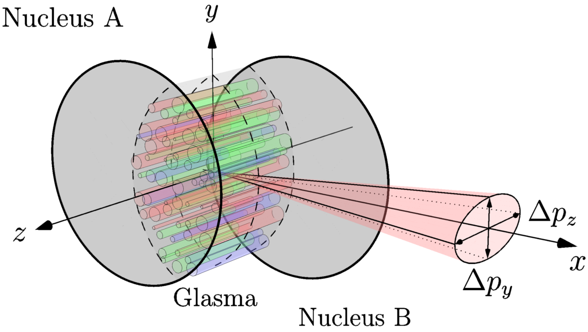
equations of motion: classical Yang-Mills equations

Glasma



consider limit of infinitely thin nuclei → 2+1D system, independent of rapidity

Momentum broadening



color fields exert Lorentz forces on the parton

no deflection in this limit, but the parton accumulates momentum

Momentum broadening

components of jet broadening parameter $\hat{q}$:

$$\hat{q}_i(\tau) = \frac{\mathrm{d}}{\mathrm{d}\tau}\langle p_i^2(\tau)\rangle_q$$

Wong equations:

$$\begin{aligned}\frac{\mathrm{d}p_\mu}{\mathrm{d}\tau} &= gQ^a(\tau)\frac{\mathrm{d}x^\nu}{\mathrm{d}\tau}F^a_{\mu\nu}(\tau)\\ \frac{\mathrm{d}Q^a}{\mathrm{d}\tau} &= g\frac{\mathrm{d}x^\mu}{\mathrm{d}\tau}f^{abc}A^b_\mu(\tau)Q^c(\tau)\end{aligned}$$

solution for a quark:

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

Momentum broadening

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

f^i is a function representing the color rotated Lorentz force:

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

lightlike Wilson line in the fundamental representation along particle trajectory:

$$U(\tau,0) = \mathcal{P}\exp\left(-ig\int_0^\tau d\tau' A_x(\tau')\right)$$

result for gluon can be found by Casimir scaling:

$$\langle p_i^2\rangle_g = \frac{C_A}{C_F}\langle p_i^2\rangle_q$$

Real-time lattice gauge theory

finite difference method to solve Yang-Mills equations numerically

transverse plane → $N_T \times N_T$ lattice with periodic boundary conditions

degrees of freedom:

- $U_{x,\hat{i}}(\tau_n)$ gauge links
- $A_{x,\eta}(\tau_n)$ vector field
- $P^i_x(\tau_{n+\frac{1}{2}})$ conjugate momenta
- $P^\eta_x(\tau_{n+\frac{1}{2}})$ conjugate momentum

Yang-Mills equations → leapfrog scheme

initial conditions → discretized

lattice expressions for E_i and $B_i \rightarrow f^i$, replace integrals by sums:

$$\langle p^2_{(y,z)}(t_n)\rangle_q \approx \frac{g^2 a_T^2}{N_c} \langle \mathrm{Tr}\left[\Big(\sum_{i=0}^{n} f^{(y,z)}(t_n)\Big)^2\right]\rangle$$

Results

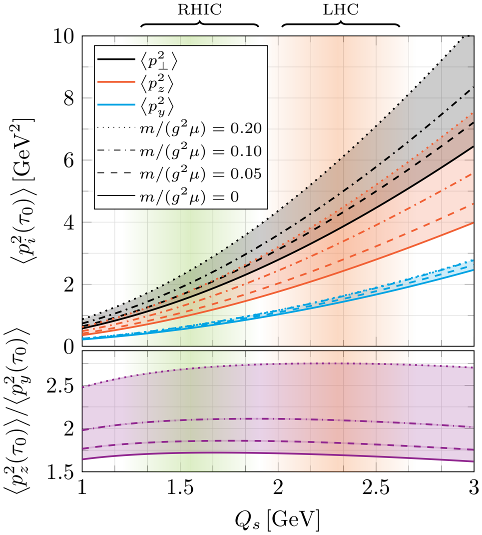


Figure: Accumulated transverse momentum (top) and momentum broadening anisotropy (bottom) at $\tau_0 = 0.6\,\mathrm{fm/c}$

Results

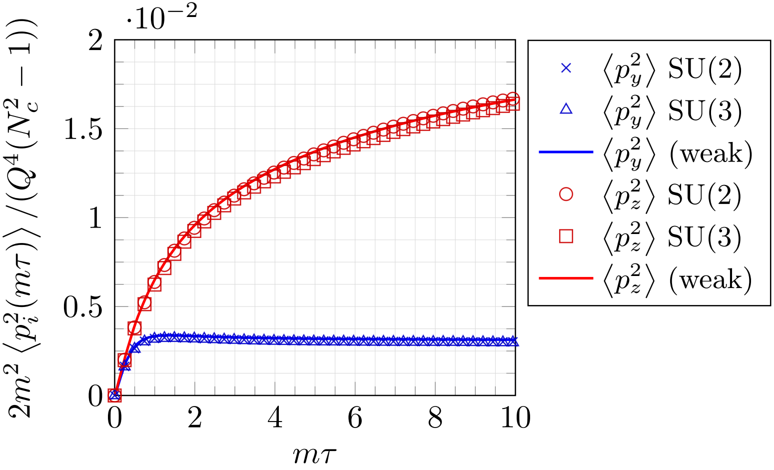
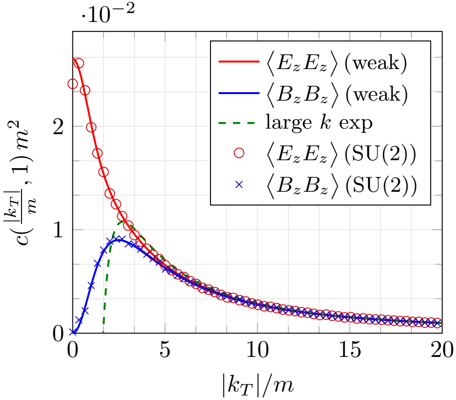


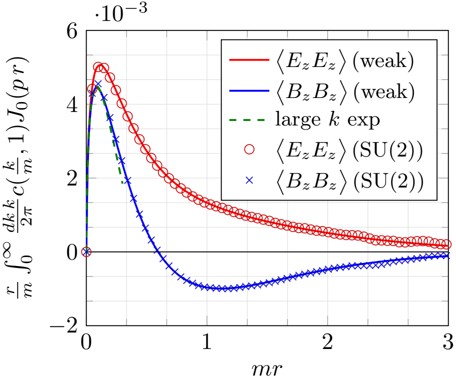
Figure: Accumulated transverse momentum in the dilute glasma: weak field approximation and lattice approximation

Results

$$\langle p^2_{(y,z)}(\tau)\rangle = \int_0^\infty dk\, g(\tau,k)\, c_{(B,E)}(k)$$



(a) Initial correlators in momentum space



(b) Initial correlators in coordinate space multiplied by the dimensionless distance *mr*

Conclusions & Outlook

this talk:

- momentum broadening in the very early stages of heavy ion collisions
- amount, anisotropy and its origin
- weak field approximation and lattice approximation

future work:

- relax approximations (nuclei moving at the speed of light, test parton moving at the speed of light, no backreaction of the parton in the glasma)
- energy loss
- improve understanding of physics behind the form of the initial correlators

open source code: gitlab.com/openpixi/curraun