Heavy Quark Diffusion in Glasma and Gluonic Plasma

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Introduction

The research of the pre-equilibrium stage produced in the ultrarelativistic heavy-ion collisions and its evolution to quark-gluon plasma (QGP) is of great interest as it provides insights into the Quantum Chromodynamics (QCD) matter under extreme conditions. The collision of high-energy nucleons can be described within the framework of color-glass condensate (CGC) effective theory. The non-abelian interaction of two CGC sheets produces a set of longitudinal colored electric and magnetic fields, commonly known as Glasma [1]. Glasma fields evolve, and the lifetime of these strong fields is of the order of the formation and thermalization time of the QGP, typically a short fraction of fm/c.

Heavy quarks [2, 3], namely charm and beauty quarks, form very early in Large Hadron Collider (LHC) and Relativistic Heavy Ion Collider (RHIC) experiments due to their large masses. They are good probes to study the early stages of high-energy collisions. We perform a systematic comparison of the diffusion of heavy quarks in the evolving Glasma (EvGlasma) fields with that of the Markovian-Brownian motion in a thermalized medium of gluons. Hence, we compute the transverse momentum broadening of heavy quarks, defined as

$$\sigma_p = \frac{1}{2}\langle (p_x(t) - p_{0x})^2 + (p_y(t) - p_{0y})^2 \rangle. \quad (1)$$

where p_{0x} and p_{0y} are the initial x and y components of transverse momentum, p_T; and p_x and p_y are the x and y components of p_T at time t.

Formalism

The gluon fields are treated classically due to their high occupation number, hence, their dynamics is governed by the classical Yang-Mills (CYM) equations [3]. The diffusion of heavy quarks in the hot thermalized medium is studied by the standard Langevin equation with uncorrelated noise [4], while Wong equations [5] are used for heavy quarks propagating in dense gluon fields:

$$\frac{dx^i}{dt} = \frac{p^i}{E}, \quad (2)$$

$$\frac{dp^i}{dt} = \frac{g}{E} Q_a F_a^{i\nu} p_\nu, \quad (3)$$

$$\frac{dQ_a}{dt} = -\frac{g}{E} f_{abc} A_b^\nu p_\nu Q_c. \quad (4)$$

Results

We have fixed the saturation scale, Q_s, and the QCD coupling [6], g in our calculations.

In Fig. 1, we plot the transverse momentum broadening of charm quarks as a function of time for three different values of Q_s. We observe that, regardless of any Q_s, during the very early time, σ_p evolves non-linearly with time which later on connects smoothly to a linear evolution. Hence, we observe the superdiffusion of heavy quarks in the EvGlasma fields during initial times. This early non-linear behavior of the σ_p is explained as the diffusion of heavy quarks due to correlated Lorentz force, which can be comprehended as the memory [7] of the gluon fields. The later linear behavior represents the standard Brownian motion of heavy quarks with no energy loss.

We prepare a bath of gluons at temperature T, with the same energy density ε of the

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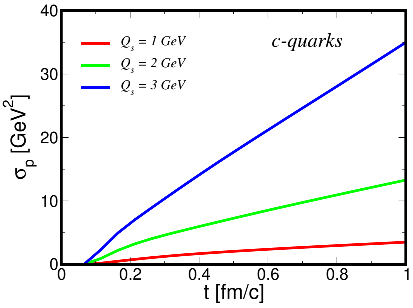

FIG. 1: σ_p versus proper time for charm quarks, for the initial $p_T = 0.5$ GeV. The calculations correspond to evolving Glasma fields in a static box.

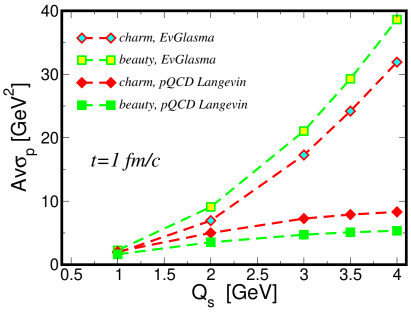

FIG. 2: Time-averaged σ_p versus Q_s for charm and beauty quarks, for EvGlasma and pQCD Langevin dynamics. The calculations correspond to the static box geometry.

EvGlasma using the relation

$$\varepsilon = 2(N_c^2-1)\int \frac{d^3p}{(2\pi)^3}\frac{p}{e^{p/T}-1} = \frac{(N_c^2-1)\pi^2 T^4}{15}, \tag{5}$$

to study the diffusion of heavy quarks in this fictional bath with the Langevin equation.

In Fig. 2, we plot the time-averaged transverse momentum broadening, Avσ_p versus Q_s for charm and beauty quarks. We observe that the Avσ_p is fairly same as long as the saturation scale Q_s is small. It is justified because Glasma fields are dilute for smaller Q_s, hence its dynamics is similar to pure collisional Langevin dynamics. However, for the larger Q_s, in EvGlasma, the colored fields are no more dilute, hence, heavy quarks feel strong coherent gluonic fields, while the dynamics still remain the same as collisional for pQCD Langevin. Therefore, we get a substantial difference in the two calculations.

Conclusions and Outlook

The early pre-equilibrium stage of high energy nuclear collisions can be described as a set of dense, colored fields called Glasma which affects the heavy quarks dynamics significantly. We observe the superdiffusion of heavy quarks in the early stage of high energy collisions due to the strong, coherent gluon fields and memory effects become influential there. The average momentum broadening of heavy quarks in the EvGlasma is in agreement with the standard pQCD-Langevin for smaller values of Q_s, while Langevin dynamics underestimates the σ_p, for larger values of Q_s.

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References

[1] T. Lappi, L. McLerran, Nucl. Phys. A **772**, 200-212 (2006).
[2] S. K. Das, F. Scardina, S. Plumari, V. Greco, Phys. Rev. C **90**, 044901 (2014).
[3] M. Ruggieri, S. K. Das, Phys. Rev. D **98**, 094024 (2018).
[4] M. Ruggieri, Pooja, J. Prakash and S. K. Das, Phys. Rev. D **106**, 034032 (2022).
[5] S. K. Wong, Nuovo Cim. A **65**, 689-694 (1970).
[6] P. Khowal, S. K. Das, L. Oliva, M. Ruggieri, Eur. Phys. J. Plus **137**, 307 (2022).
[7] J. H. Liu, S. K. Das, V. Greco, M. Ruggieri, Phys. Rev. D **103**, 034029 (2021).