RESULTS FROM A CGC AND PROPER TIME EXPANDED CALCULATION OF GLASMA PROPERTIES*

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We present some results that describe the properties of the glasma phase that exists at very early times after a relativistic heavy-ion collision. We discuss the isotropization of the glasma, the Fourier coefficients of the momentum flow, and the momentum broadening of a hard probe traversing the glasma.

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1. Introduction

We use a Colour Glass Condensate (CGC) approach and a proper time expansion to calculate correlators of glasma chromodynamic electric and magnetic fields. More details on our method and a complete discussion of our results can be found in [1–5]. Correlators of chromodynamic fields can be used to study a number of observables. In these proceedings we present some of our main results, including the first three Fourier coefficients of the momentum flow, and the momentum broadening coefficient for a hard probe passing through a glasma. It is usually assumed that these quantities develop almost exclusively during the hydrodynamic phase of the evolution of the system. Our calculation shows that the contribution of the glasma phase is much larger than anticipated.

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The CGC method was introduced in [6–8] and has been developed over a period of 20 years by many authors. The proper time expansion was first proposed in [9] and has been used in several calculations since its introduction. Our work represents the first serious attempt to study the radius of convergence of the expansion.

2. Results

The glasma is produced in a highly anisotropic initial state. A key question is if the effect of the interactions is such that the glasma moves towards isotropy before it transforms into a quark–gluon plasma. To study this, we look at the quantity [10] $A_{\rm TL} \equiv 3(p_{\rm T} - p_{\rm L})/(2p_{\rm T} + p_{\rm L})$, where $p_{\rm T}$ and $p_{\rm L}$ are the transverse and longitudinal pressures, which would be zero in an equilibrated isotropic plasma. Figure 1 shows $A_{\rm TL}$ at three different orders in the proper time expansion. The independent variable is the dimensionless parameter $\tilde{\tau} = \tau Q_{\rm s}$, where τ is the proper time and $Q_{\rm s}$ is the saturation scale, which is set to 2.0 GeV. The figure shows that the radius of convergence of the proper time expansion is approximately $\tilde{\tau} \approx 0.5$, which corresponds to $\tau \approx 0.05$ fm, and that over the range where the expansion can be trusted, the value of $A_{\rm TL}$ moves monotonically toward the isotropic value of zero.

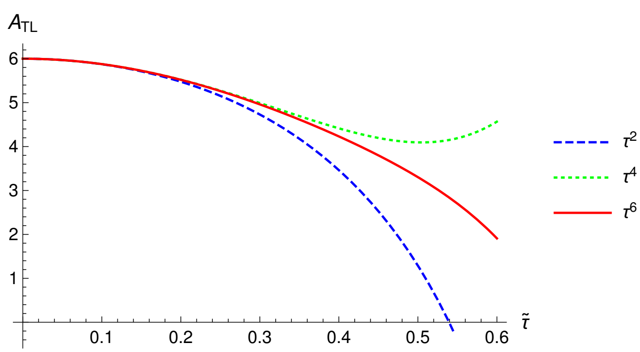

Fig. 1. $A_{\rm TL}$ at $R = 5$ fm and $\eta = 0$ for three different orders in the τ expansion.

We can also use our results for the glasma field correlators to calculate the Fourier coefficients of the momentum flow. Flow vectors are used as input in hydrodynamic codes, and the Fourier coefficients are related to experimental observables. In figure 2, we look at the first three Fourier coefficients as functions of space-time rapidity and impact parameter, at $\tau = 0.04$ fm. The left panel shows v_1, v_2 and v_3 at $\tau = 0.04$ fm with $b = 2$ fm as a function of rapidity; in the right panel $\eta = 0.1$ and the independent variable is the impact parameter. Our results for the second and third Fourier coefficients are of the same order as experimental values [11, 12], and our result for $|v_1|$ is much bigger than expected [13]. We note

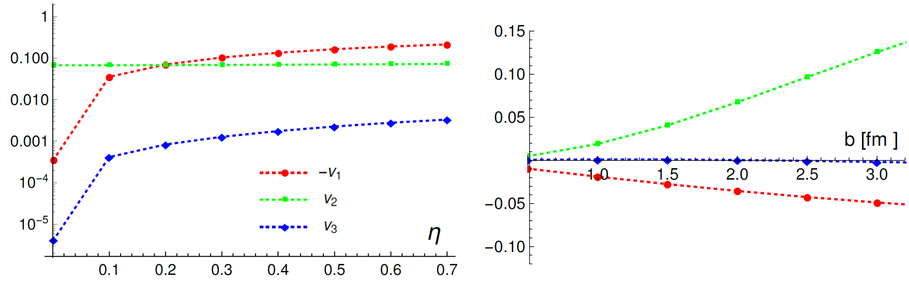

Fig. 2. The Fourier coefficients v_1, v_2, and v_3 at $\tau = 0.04$ fm. The left panel is for fixed $b = 2$ fm and the right panel is for fixed $\eta = 0.1$.

however that it is usually assumed that anisotropy develops mostly during the hydrodynamic evolution that follows the glasma phase, and from this perspective, our results are surprisingly large for all three Fourier coefficients.

One of the most important physical observables in the study of QGP physics is jet broadening, which is generally taken to be a signal of the formation of a deconfined state of matter. Theoretically, one usually studies the momentum broadening of a hard probe. A Fokker–Planck approach can be used to determine the momentum broadening coefficient, $\hat{q}$, of a hard probe traversing a glasma [1, 4, 14]. Figure 3 shows $\hat{q}$ *versus* τ at different orders in the proper time expansion. The figure shows that the order τ^5 results are reliable to about $\tau = 0.07$ fm, and the momentum broadening coefficient saturates before the expansion breaks down.

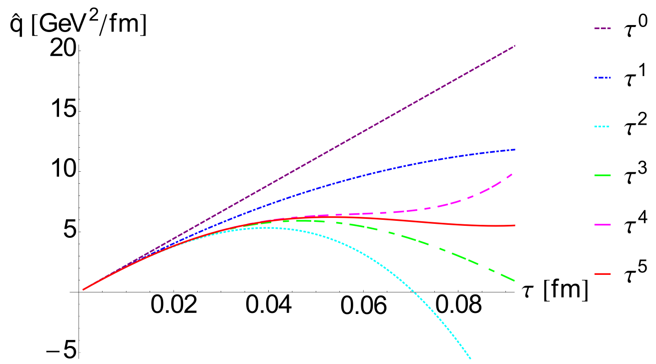

Fig. 3. The transport coefficient $\hat{q}$ of an ultra-relativistic quark with velocity perpendicular to the beam axis at different orders in the proper time expansion.

Our calculation does not describe the decrease of $\hat{q}$ from the value of ≈ 6 GeV^2/fm at $\tau \approx 0.06$ fm which is seen in figure 3 to the much smaller value that is characteristic of the hydrodynamic phase. However, assuming a simple linear decrease until the start of hydrodynamic evolution at $\tau \approx 0.6$ fm, one can estimate that the contributions of the glasma phase and the hydrodynamic phase are approximately equal [5], which contradicts the common assumption that the contribution from the glasma phase can be neglected.

3. Conclusions

We have used a CGC approach and an expansion in proper time to derive analytic results for all correlators of chromodynamic electric and magnetic field components to sixth order in the proper time. These results can be used to obtain the energy-momentum tensor, from which many physical quantities can be derived. In these proceedings, we have discussed the evolution of the transverse and longitudinal pressures towards isotropy, and the Fourier coefficients of the momentum flow. We can also use the field correlators we have calculated to determine transport coefficients, using a Fokker–Planck method. We have presented our results for the momentum broadening coefficient and argued that the contribution to this quantity from the glasma phase is much larger than expected.

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