# Early time dynamics of gluon fields in high energy nuclear collisions

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The initial interactions of nuclei colliding at very high energies have been investigated for the last two decades, in order to understand the initial conditions from which quark gluon plasma (QGP) is formed. From experimental data collected at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) we have found that QGP is indeed created and that it is near local kinetic equilibrium very early in the collision (< 1 fm/c). This can be induced from simulations using ideal or viscous relativistic hydrodynamics that are applicable once the system is close to equilibrium. However, the precise initial conditions are still poorly known.

Although direct experimental evidence is still scarce there are very good theoretical arguments that the very first stage of the collision is dominated by a phase of quantum chromodynamics (QCD) called color glass condensate (CGC) in which gluons reach a saturation density ($\sim Q_s^2$) in hadrons or nuclei moving close to the light cone. $Q_s$ is called the saturation scale. Before the collision, and up to a time scale $\sim 1/Q_s$ after the collision color glass should be effectively described by the classical Yang Mills equations coupled to suitably defined color currents on the light cone. After the time $\sim 1/Q_s$ the classical approximation breaks down as fields decohere, and the system is driven towards chemical and kinetic equilibrium. The latter part is still under investigation, but with our work we have effectively solved the first part of the puzzle of the initial phase.

The classical Yang Mills problem immediately after the collision has been solved numerically by several groups in recent years. Our work presents a systematic *analytic* solution based on an expansion of the fields as power series in proper time [1]. A recursion for the coefficients of these series has been found. A resummation into known functions is possible in simple cases, but even in the most general case one can get results for the initial fields and the initial energy momentum tensor order-by-order in time. This method delivers reliable results up to times $\sim 1/Q_s$ at which point the entire classical approximation to CGC loses validity. Results for the initial gluon field strength and the energy momentum tensor are calculated as functions of the color charges in the initial nuclei. For a given collision they are unknown but reasonable models for their statistical distributions exist. We follow the McLerran-Venugopalan model of independent Gaussian fluctuations of charges around a color-neutral mean and calculate expectation values for the components of the energy momentum tensor.

We highlight a few results. It is straight forward in our approach to derive results for the time evolution of initial energy density, transverse pressure and longitudinal pressure in the system after the collision. For example for the ratio of longitudinal to transverse pressure up to second order in time, τ, we find the pocket formula (neglecting some logs),

$$\frac{p_L}{p_T} \approx -\frac{2-3Q_s\tau}{2-2Q_s\tau}.$$

Fig. 1 gives a more detailed account of initial pressures (normalized to energy density) up to fourth order in time. We show a well-established numerical results in comparison [2]. Note that our analytic approach fails around $\tau \sim 1/Q_s$ as expected.

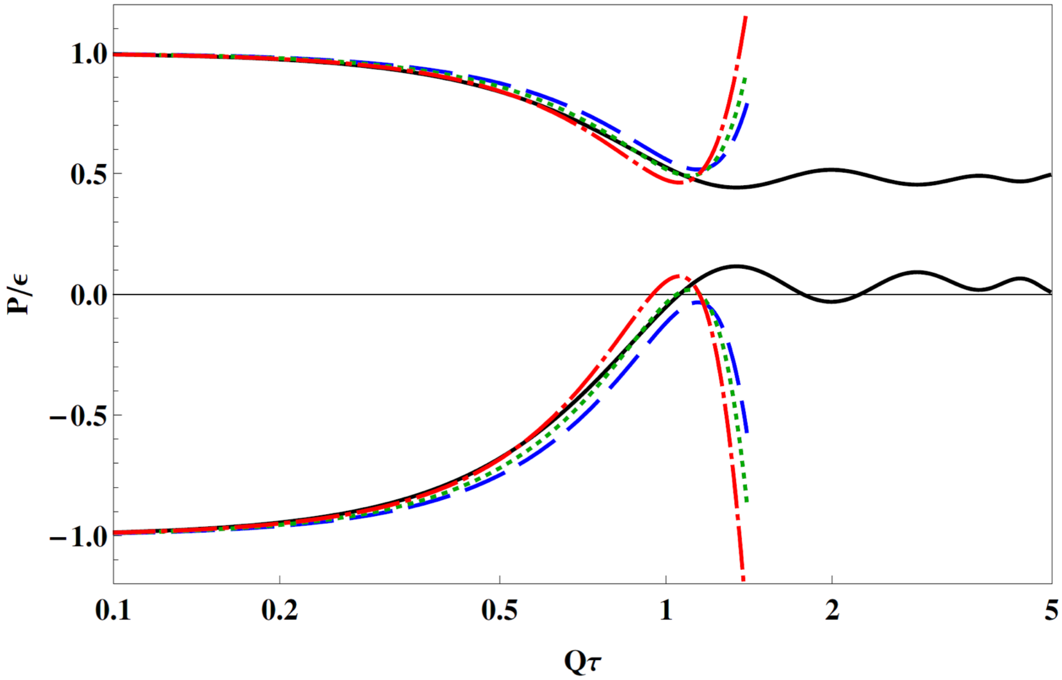

**FIG. 1.** The ratio of transverse pressure to energy density (upper curves) and longitudinal pressure to energy density (lower curves) calculated analytically from our approach for three different numerical treatments of ultraviolet and infrared cutoffs (red dashed-dotted, blue dashed and green dotted lines). For comparison we show the numerical solution of Epelbaum and Gelis [2] (black solid line).

Our approach also yields some interesting insights into early flow phenomena. In particular it established a mechanism how rapidity-odd flow (like directed flow) and angular momentum can be built up in the system. Some of those results have been discussed already in a previous publication [3]. In summary, we found a viable analytic solution to the problem of calculating the very initial time evolution of key quantities in high energy nuclear collisions.

[1] Guangyao Chen, Rainer J. Fries, and Joseph I. Kapusta, Yang, Phys. Rev. C **92**, 064912 (2015).
[2] T. Epelbaum and F. Gelis, Phys. Rev. Lett. **111**, 232301 (2013).
[3] Guangyao Chen and Rainer J. Fries, Phys.Lett. B **723**, 417 (2013).