Transport simulations of gluon matter in heavy–ion collisions including multi–parton scatterings

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Introduction

The matter created in the early stages of Au+Au collisions at RHIC is commonly dubbed Quark Gluon Plasma (QGP). It is now believed to be strongly coupled, exhibiting a small viscosity and showing almost perfect hydrodynamical behaviour. However, the details of the underlying mechanisms and the nature of the strong coupling are far from being fully understood.

One way of quantitatively addressing such topics is by means of transport models. We present the recent Monte Carlo parton cascade BAMPS (Boltzmann Approach of Multi–Parton Scatterings) that consistently includes inelastic $gg \leftrightarrow ggg$ processes by means of a stochastic approach. We discuss first results on observables, such as thermalization times, shear viscosity and collective behaviour in heavy ion collisions, and demonstrate the importance of inelastic processes for investigations of these quantities. Furthermore we explore the opportunities offered by the model in the sector of high–p_T phenomena, investigating for example the nuclear modification factor R_{AA}.

The Model

The transport model BAMPS [1] aims at describing the dynamics of parton–parton interactions on a pQCD basis by solving the kinetic on–shell Boltzmann equations via a stochastic collision algorithm, allowing for the consistent inclusion of inelastic $gg \leftrightarrow ggg$ processes.

From the collision terms in the Boltzmann equation one directly obtains the probability for a specific interaction to take place within a time interval Δt and a volume ΔV. For processes with two particles in the initial state this gives

$$P_{22} = v_{rel}\frac{\sigma_{22}}{N_{\text{test}}}\frac{\Delta t}{\Delta V} \qquad (1)$$

$$P_{23} = v_{rel}\frac{\sigma_{23}}{N_{\text{test}}}\frac{\Delta t}{\Delta V}. \qquad (2)$$

For annihilation processes $ggg \rightarrow gg$ the transition probability cannot be defined in terms of a cross section, but rather has to be directly computed from momentum integration over the matrix elements.

Cross sections and matrix elements used in the calculations are obtained from perturbative QCD in leading order of α_s and are infrared regularized by a Debye screening mass. For elastic gluon scattering $gg \rightarrow gg$ the differential cross section in small angle approximation, $-t \approx q_\perp^2$, is employed

$$\frac{d\sigma_{gg\rightarrow gg}}{dt} \approx \frac{9\pi\alpha_s^2}{(q_\perp^2 + m_D^2)^2} \qquad (3)$$

and the probabilities for gluon multiplication and annihilation, $gg \leftrightarrow ggg$, are calculated from the Gunion–Bertsch matrix element

$$\left|M_{gg\rightarrow ggg}\right|^2 = \left(\frac{72\pi^2\alpha_s^2\, s^2}{(\mathbf{q}_\perp^2 + m_D^2)^2}\right)\left(\frac{48\pi\alpha_s\,\mathbf{q}_\perp^2}{\mathbf{k}_\perp^2\left[(\mathbf{k}_\perp - \mathbf{q}_\perp)^2 + m_D^2\right]}\right). \qquad (4)$$

An effective Landau–Pomeranchuk–Migdal suppression is included by demanding $\lambda_g > \tau$ when integrating over the matrix element, where λ_g is the mean free path of gluons and τ denotes the formation time of the radiated gluon. See below for a more detailed discussion.

Thermalization

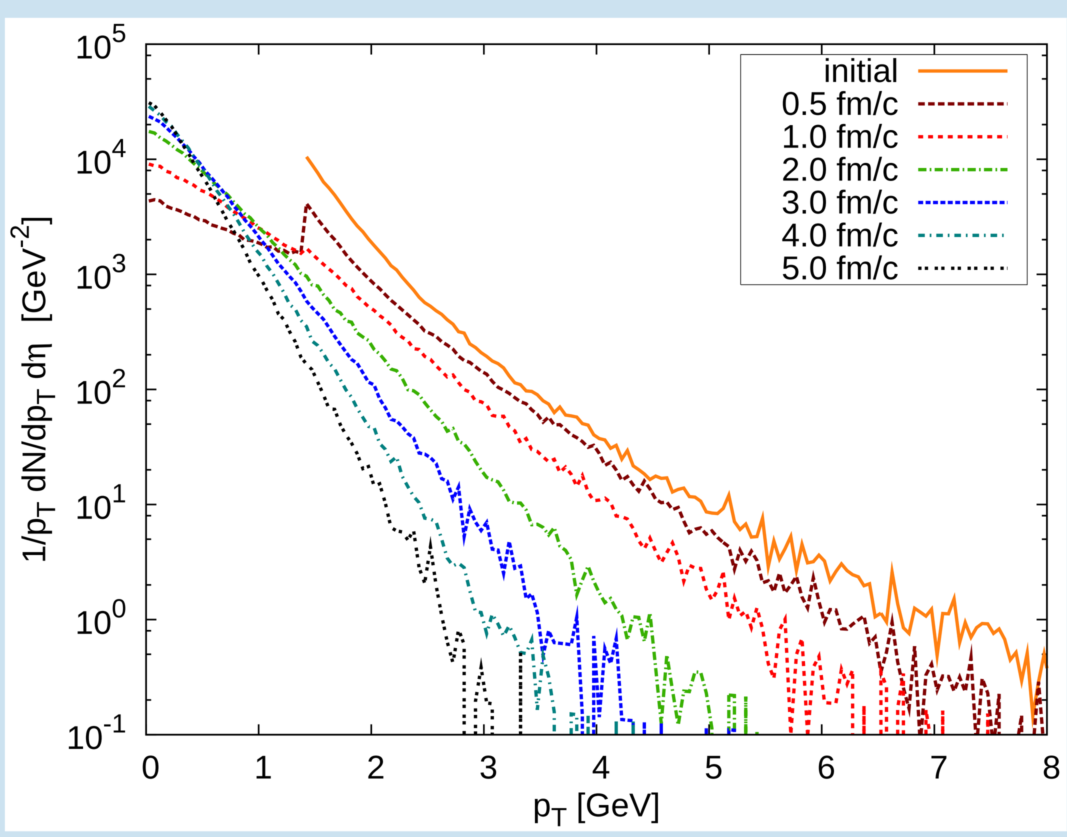

Figure 1: Time evolution of the p_T–spectrum in the innermost region ($|\eta| \leq 0.5$, $x_T < 1.5\,\text{fm}$) of a central ($b = 0$) Au+Au collision at 200 AGeV. The initial (uppermost) spectrum directly reflects the initial mini–jet distribution. Results are obtained from an average over 50 runs.

The transport model is employed to simulate the early stages of heavy–ion collisions at RHIC energies of 200 AGeV on a partonic level with quasi–particle degrees of freedom. As an initial condition the superposition of mini–jets with a lower momentum cut–off $p_0 = 1.4\,\text{GeV}$ is chosen. This value for the phenomenological cut–off p_0 leads to a final transverse energy density of roughly $dE_T/dy|_{y=0} = 625\,\text{GeV}$ being in agreement with experimental data.

Additionally each mini–jet is given a formation time $\Delta t_f = \cosh y / p_T$ that models an off–shell propagation of the partons produced in the initial nucleon–nucleon interactions.

Figure 1 shows the evolution of the p_T–spectrum in the innermost region ($|\eta| \leq 0.5$, $x_T < 1.5\,\text{fm}$) of a simulated central ($b = 0$) Au+Au collision at 200 AGeV. A swift transition from the non–equilibrium power law distribution of the initial mini–jets towards a thermal spectrum is clearly visible. Kinetic equilibrium is reached at a scale of about 1–2 fm/c. Chemical equilibration also happens within a few fm/c, but is slightly more dependend on the choice of p_0.

Calculations of gluon matter in Bjorken geometries with color glass initial conditions, as well as static calculations, confirm the finding of fast thermalization. There it can be demonstrated that it are the inelastic processes, especially $gg \rightarrow ggg$, who are responsible for the rapid equilibriation. Indeed, thorough analyses and computations show that inelastic processes dominate the total transport collision rate and increase the efficiency of momentum isotropization roughly by a factor of five [2].

Transport properties

Exploring the transport properties of the simulated medium is of great interest. In itself as well as for the interpretation of the results of BAMPS. Of particular interest in the field of heavy–ion physics is the question how ideal, in a hydrodynamical sense, the created medium really is, i.e. what viscosity it possesses. The viscosity, or rather the ratio of shear viscosity to entropy, of the simulated medium is investigated in a Bjorken scenario with color glass like initial conditions, $f(p)|_{z=0} \propto \frac{1}{\alpha_s N_C}\frac{1}{\tau_f}\delta(p_z)\Theta(Q_s^2 - p_T^2)$. Shear viscosity η and entropy s within the simulation are computed from standard dissipative hydrodynamics, with $\eta = \frac{\tau}{4}\left(T_{xx} + T_{yy} - 2T_{zz}\right)$ and $s = 4n - \ln(\lambda)$, where λ denotes the gluon fugacity.

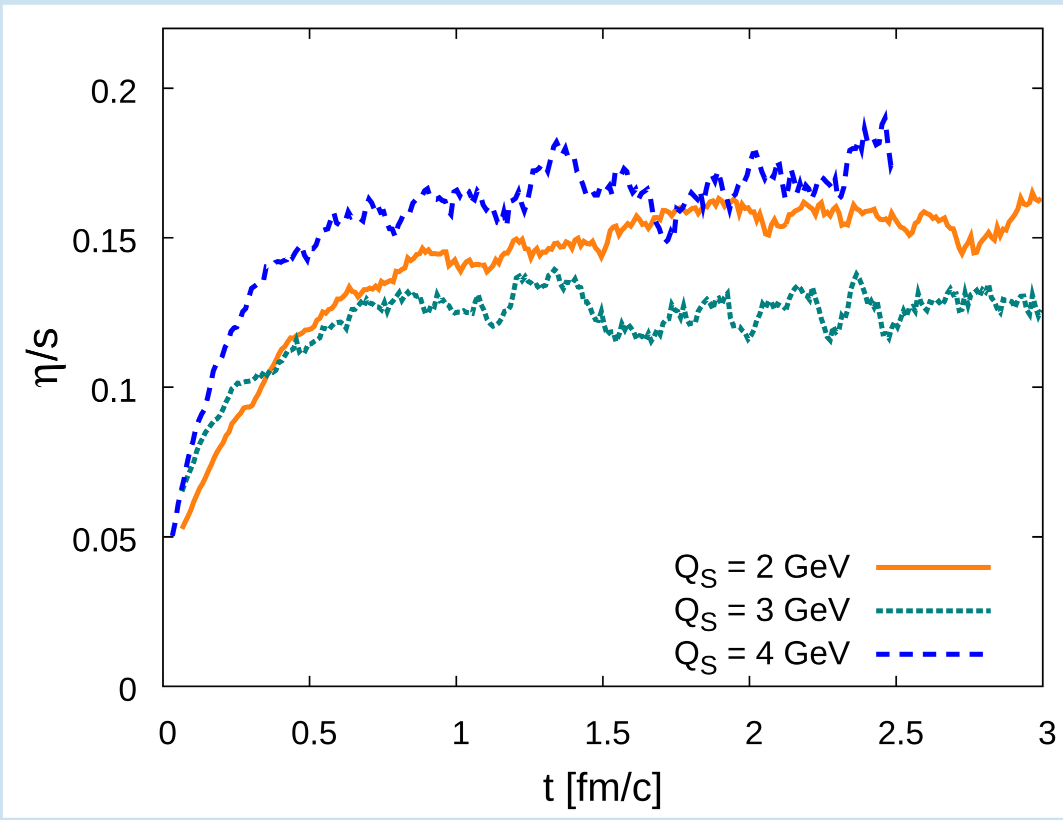

Figure 2: Ratio of the shear viscosity η to the entropy s as obtained from simulations of gluon matter in a Bjorken geometry. For the initial conditions simple CGC gluon distributions with different Q_s are chosen, the coupling constant is taken to be $\alpha_s = 0.3$.

As can be seen in figure 2 the ratio η/s proves to be virtually independent of the parameter Q_s, but rather is an univeral number within the BAMPS framework. Furthermore the value is found to be astonishingly small, $\frac{\eta}{s} \approx 0.15$ [4]. A finding that is also in accordance with first results from full 3–dimensional simulations.

Collective behaviour

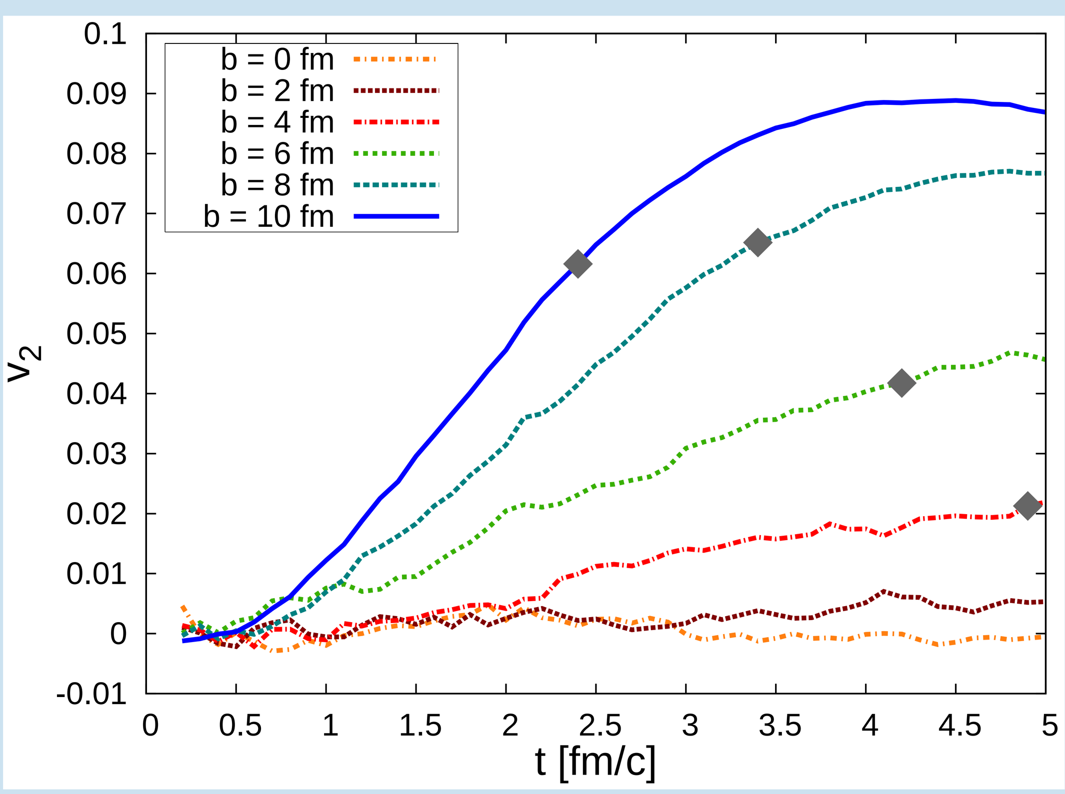

Figure 3: Time evolution of the elliptic flow parameter v_2 at midrapidity for different impact parameters in simulated Au+Au collisions at a center of mass energy of 200 AGeV. The diamonds indicate the time at which the energy density in the innermost region drops below 1 GeV. Figure taken from [3]

A major result of the heavy–ion program at RHIC is that the created matter exhibits a large degree of collectivity, measured by the elliptic flow parameter v_2. It is therefore most interesting to investigate this observable within the simulation framework. Figure 3 shows the time evolution of the elliptic flow for different impact parameters. The diamonds mark the points in the evolution of the system where the energy density drops below $1\,\text{GeV}/\text{fm}^3$ in the innermost region, i.e. where the a description in terms of partonic degrees of freedom becomes inadequate and the system should hadronize. The values for v_2 at these points are in fair agreement with experimental data.

High–p_T observables

Particles with high transverse momentum provide good probes of the quark–gluon plasma, as their initial production is expected to be describable by an appropriate scaling of results from proton–proton collisions. For that reason it is highly interesting to study high–p_T probes also within the framework of BAMPS. Within the simulations the evolution of observables can be investigated throughout the expansion of the system. Of special interest is also the interplay between the degree of collective behaviour and the strength of jet quenching, which can both be investigated within the same framework.

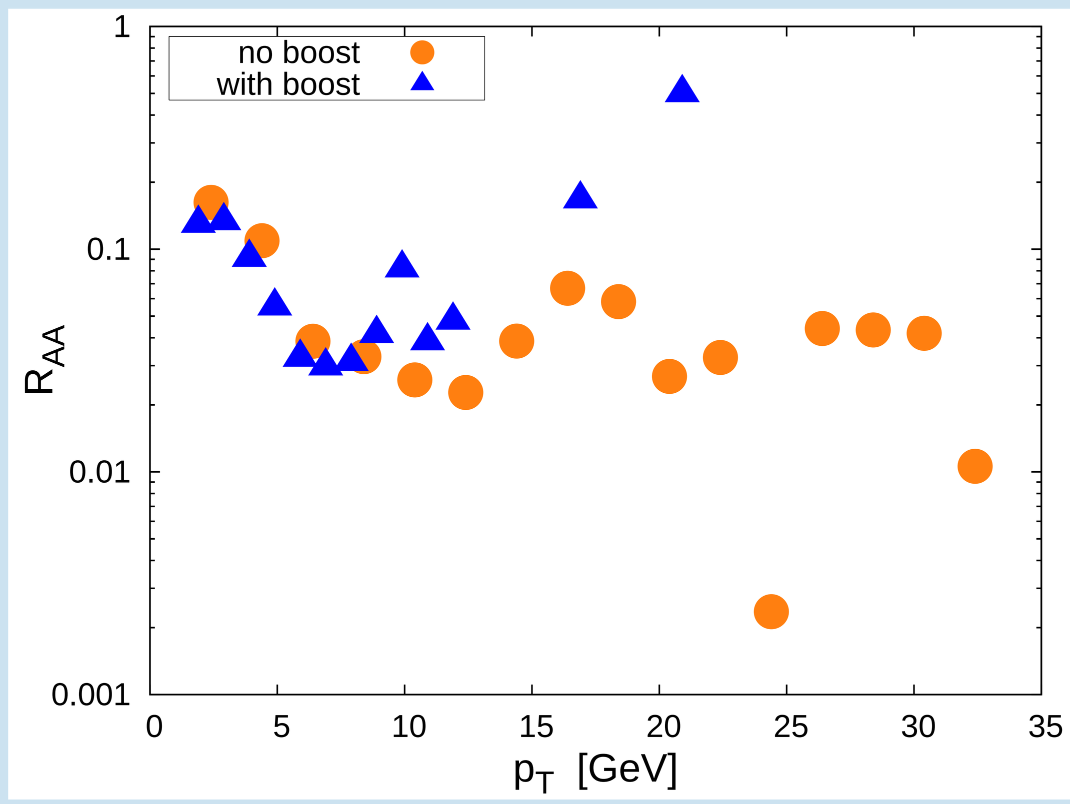

Figure 4: Nuclear modification factor, R_{AA}, of gluons as obtained from simulations of central Au+Au collisions at a center of mass energy of 200 AGeV. Data is shown with and without an implemented Lorentz boost of the mean free path λ_g in the LPM cut–off for the integration of the Matrix element M_{23}.

A basic and still very important jet observable is the nuclear modification factor, R_{AA}. Figure 4 shows our results of the jet quenching in central Au+Au collisions at 200 AGeV within the BAMPS framework. A clear and strong suppression of high–p_T jets is visible that is about a factor of 4 stronger than experimentally observed for pions. Note however, that our results exclusively show the gluonic contribution, which is expected to be below the pion value. Furthermore a more careful implementation of the LPM cut–off might affect the nuclear modification factor, when the mean free path entering the theta function in the momentum integrals is Lorentz boosted to the appropriate center of mass frame. First results are indicated by the blue symbols in fig. 4.

Summary

The partonic transport model BAMPS provides a framework for the investigation of the early stage of a heavy–ion collision in terms of a quasi–particle picture. It is shown that the consistent inclusion of multi–particle interactions provides means of reaching thermalization within a purely pQCD framework. The ratio of the shear viscosity to the entropy, η/s, is found to be distinctly smaller than unity.

Furthermore, the model provides means of investigating collective behaviour and high–p_T phenomena, such as jet quenching, within the same framework. The elliptic flow parameter v_2 is found to be compatible with experimental data, while the suppression of jets is rather strong. Future works will extend these studies and investigate the influence of the effective LPM cut–off on the results.

Future studies will also address the inclusion of quarks into the model and the implementation of a hadronization scheme.

References

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