Event-by-event pre-equilibrium dynamics with conserved charges

Travis Dore[1], Xiaojian Du[2,1], Sören Schlichting[1]
[1]*Universität Bielefeld, Germany*
[2]*Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Spain*

Introduction

We use QCD effective kinetic theory to calculate far-from-equilibrium dynamics in the presence of quarks on an event-by-event basis within the KoMPoST framework. We present non-equilibrium response functions and dynamical evolution pertinent to the early time dynamics of heavy-ion collisions at the highest energies. The KoMPoST framework with conserved baryon, strangeness, and electric charges can then be readily implemented into a multistage model allowing for the initialization of a non-equilibrium charge current in hydrodynamic simulations. In the precision era of high energy heavy-ion collisions, it is imperative for models to capture first principles physics as faithfully as possible. The work presented here opens the door for new charge related observables which can further our understanding of the plasma produced in heavy-ion collisions, from a first principles perspective.

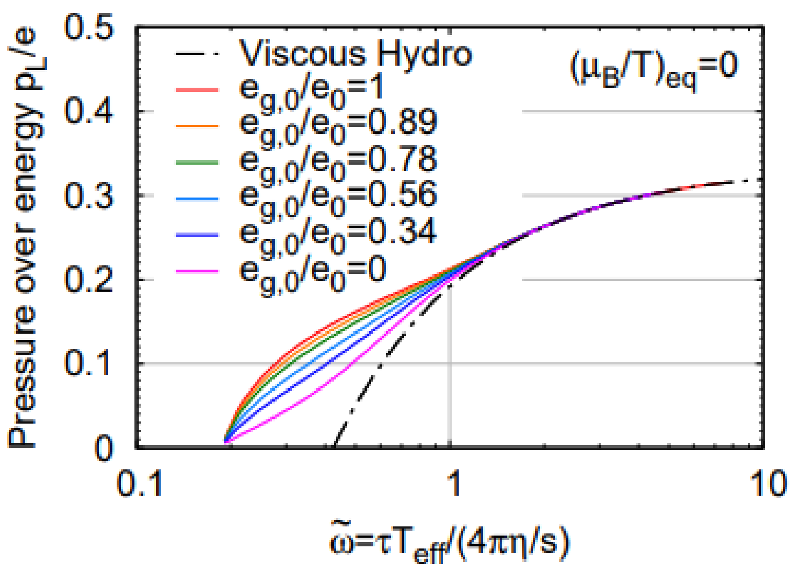
Event-by-event description of pre-hydro QGP

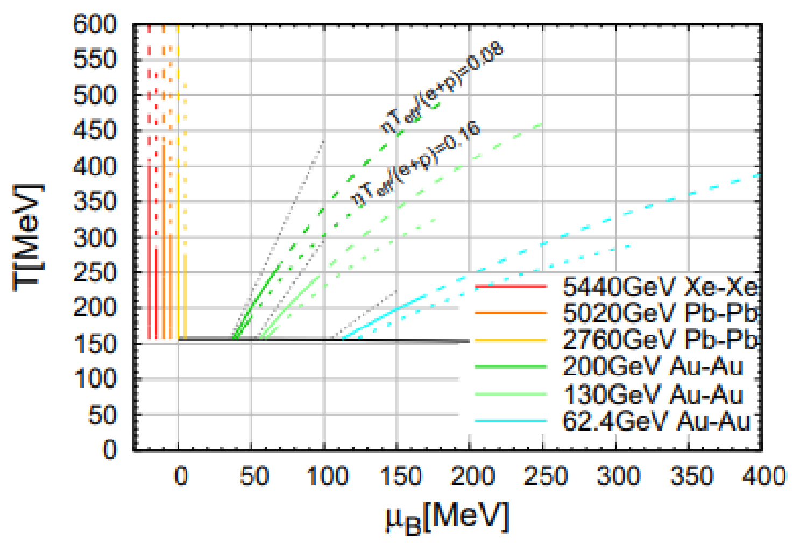
The dynamical evolution of the non-equilibrium quark-gluon plasma (QGP) in the pre-hydrodynamic stage of heavy-ion collisions can be described by a QCD effective kinetic theory including both gluon and quark degrees of freedom, with a set of coupled Boltzmann equations, in a Bjorken expansion background

$$\left(\frac{\partial}{\partial\tau}+\vec{v}\cdot\nabla-\frac{p_z}{\tau}\nabla_{p_z}\right)f_a(\tau,x,p)=-C_a^{LO\ 2\leftrightarrow2,1\leftrightarrow2}[f](\tau,x,p)$$

where partons in the QGP: a=gluon, quark, anti-quark, are coupled together in the collision integral $C_a\,[f](t,x,p)$.
Two main processes need to be encoded in the collision integral, the $2\leftrightarrow2$ collisional scattering and the $1\leftrightarrow2$ radiation with resumed soft scatterings.

This dynamical description catches the main feature of the pre-hydrodynamic QGP evolution, including thermalization/isotropization and chemical equilibration even at finite-net baryon density





Due to difficulty in simulating highly non-equilibrium QGP in both position and momentum with different initial conditions, one may consider calculating the universal linear response function instead. In case of small fluctuation in position space, one may decompose the parton distribution with a spatially homogeneous background and inhomogeneous perturbation

$$f_a(\tau,x,p)=f_a(\tau,p)+\delta f_a(\tau,x,p)$$

One arrive at a linearized QCD effective kinetic theory

$$\left(\frac{\partial}{\partial\tau}+i\vec{v}\cdot\nabla-\frac{p_z}{\tau}\nabla_{p_z}\right)\delta f_a(\tau,x,p)=-\delta C_a^{LO\ 2\leftrightarrow2,1\leftrightarrow2}[f](\tau,x,p)$$

The evolution of the linearized component represents the propagation of the fluctuation in position space, which provides an opportunity to achieve an event-by-event description of the pre-hydrodynamic QGP, in terms of energy-momentum tensor and charge-currents $\delta T^{\mu\nu}(\tau,x)$, $\delta J^{\mu}(\tau,x)$ and provide an initial condition for the following hydrodynamic evolution.

Propagation of the energy-momentum fluctuation and char-current fluctuation is achieved by a convolution of the initial condition over response function calculated from the QCD kinetic theory until Hydrodynamization time in a light-cone to preserve causality.

The convolution is performed mainly in the transverse plane

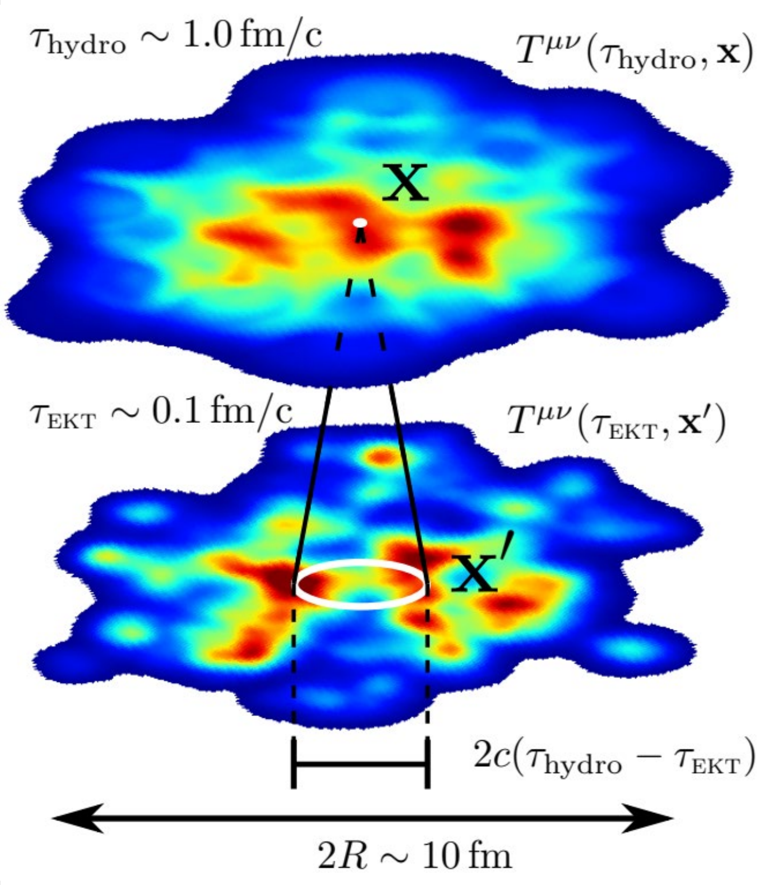


Fig. 1 Propagation of the fluctuation in a light-cone from initial state to hydrodynamic state

Propagation of the energy-momentum fluctuation:

$$\delta T^{\mu\nu}(\tau,\boldsymbol{x})=\int d^2\boldsymbol{x}'\,G^{\mu\nu}_{\alpha\beta}(\tau-\tau',\boldsymbol{x}-\boldsymbol{x}')\delta T^{\alpha\beta}(\tau',\boldsymbol{x}')\frac{T^{\tau\tau}(\tau)}{T^{\tau\tau}(\tau')}$$

Propagation of the charge-current fluctuation:

$$\delta J^{\mu}(\tau,\boldsymbol{x})=\int d^2\boldsymbol{x}'\,F^{\mu}_{\alpha}(\tau-\tau',\boldsymbol{x}-\boldsymbol{x}')\delta J^{\alpha}(\tau',\boldsymbol{x}')\frac{J^{\tau}(\tau)}{J^{\tau}(\tau')}$$

Response functions from the QCD kinetic theory

In order to propagate the energy-momentum fluctuation and charge-current fluctuation, one needs to calculate the response functions from the QCD kinetic theory.

There are several types of fluctuations and response functions one needs to consider, including scalar, vector and tensor types. As a preliminary result, we present here scalar, vector and tensor responses to a scalar-type energy-momentum fluctuation

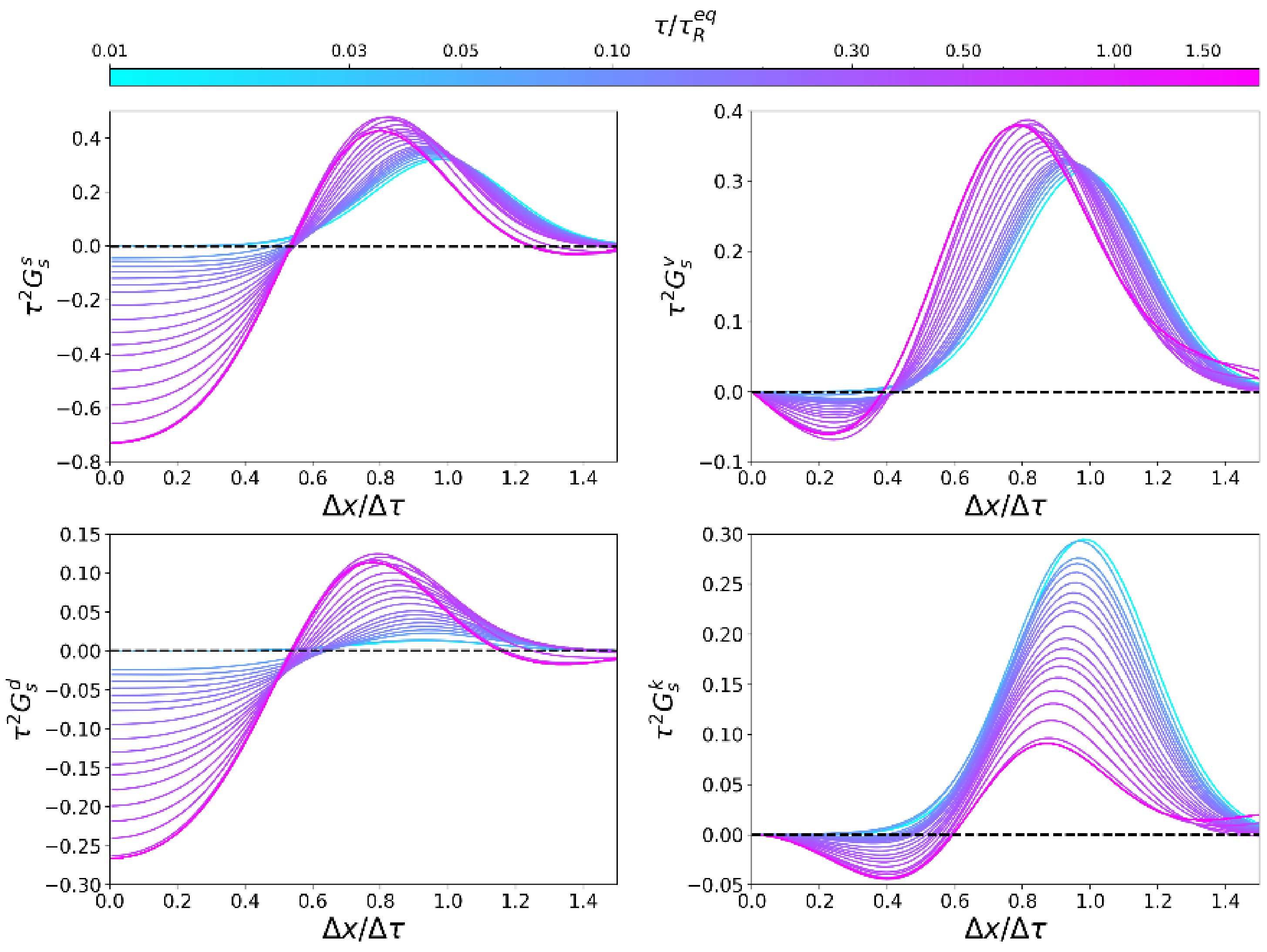


Fig. 2 Scalar, vector and tensor responses to scalar-type energy perturbation in energy-momentum tensor

Specifically for the QCD plasma, we present the charge-current response to a charge perturbation.

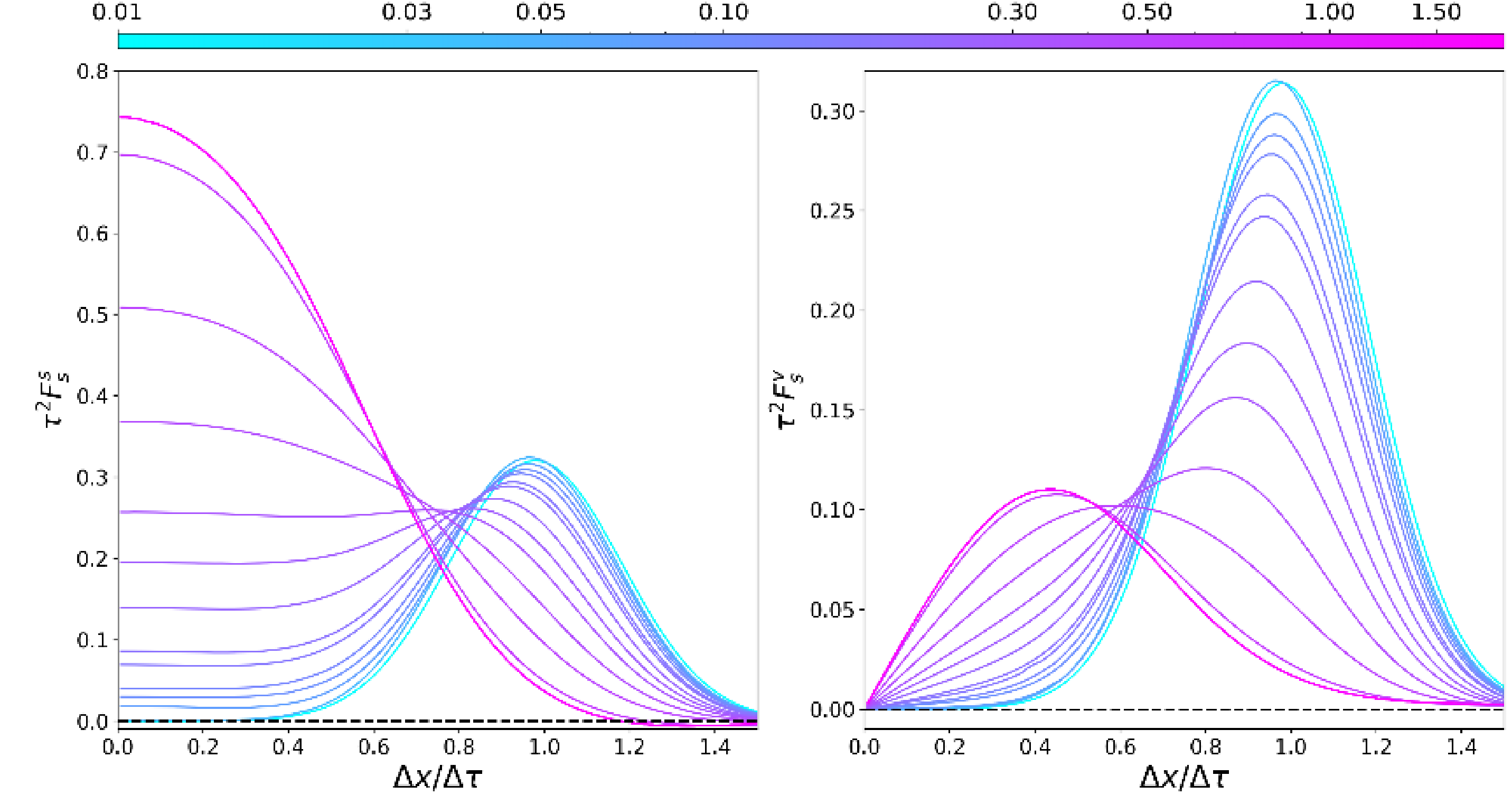


Fig. 3 Charge, current responses to scalar-type charge perturbation in charge-current vector

Conclusions

We present the framework to provide the event-by-event simulation of the pre-hydrodynamic QGP with both energy-momentum and charge-current perturbation with linear response functions from the QCD kinetic solver. This is an extension to the KoMPoST framework to include charge. This framework will provide a complete picture of the pre-hydrodynamic QGP and realistic event-by-event initial conditions for relativistic hydrodynamic simulations.

References

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