Progress Report for Project B02

Collective Dynamics in Nuclear Collisions

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CRC-TR 211 Strong-interaction matter under extreme conditions

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What the Project Promised

Establish a comprehensive theoretical description of the space-time dynamics of nuclear collision based on

- (Non-equilibrium) transport of conserved quantities
- Sensitivity to initial conditions, early-time dynamics and transport coefficients
- Investigating the range of applicability of fluid dynamics

Transport of Conserved Quantities: Goals and Timeline I

Goals: Understand the transport of conserved quantities through all stages of nuclear collisions

- Pre-equilibrium charge transport
- Hydrodynamic charge transport
- Hadronic charge transport

Timeline:

2021
- Calculate non-equilibrium Green's functions for conserved charges and implement them into KoMPoST (done for baryon number, strangeness, electric charge [2312.14081])
- Implement equations of motion of multi-component fluid dynamics (✓HYDRA)

2022
- Compare KoMPoST initial state to SMASH for spatial profiles of B, S, and Q densities and investigate their evolution in fluid dynamics (Charge profiles ready, comparison to be done)
- Introduce tabulated lattice equation of states for multiple conserved charges (Work in progress (WIP))

Transport of Conserved Quantities: Goals and Timeline II

- Implement temperature- and density-dependent diffusion matrix matched to the hadronic stage (Needs to be calculated reliably and compared)

2023

- Develop particlization interface including proper δf corrections and couple it to hadronic transport for diffusive hybrid approach conserving all currents (not done yet, but planned)
- Examine baryon-stopping at low-energy collisions and compare fluid dynamics to BAMPS to find links to quark-gluon coupling (WIP with initial conditions from McDipper into HYDRA)

2024

- Perform full hybrid-approach calculations for coupled conserved charges (All ingredients are there, runs have to be done)
- Identify (hadronic) observables sensitive to coupled-charge transport (see above)

2025

- Examine interplay of bulk viscous pressure and diffusion

Sensitivity to Initial Conditions, Early-Time Dynamics and Transport Coefficients: Goals and Timelines I

Goals: Explore sensitivity to each stage of the collision and transport coefficients to disentangle different effects

- Dynamics of longitudinal fluctuations
- Electromagnetic probes
- T and μ dependence of transport coefficients

Timeline:

2021
- Include photon and di-lepton production in QCD kinetic solver (✓Including universal scaling functions [2403.04846][2308.09747])
- Collect constraints on T and μ_B dependence of transport coefficients and devise functional form for parametrization (✓[2207.05778])

2022
- Extend QCD Kinetic Solver to include longitudinal fluctuations (not done)
- Develop CGC-inspired 3-dimensional initial state and compare it to dynamical SMASH initial state ✓(MCDipper developed [2308.11713], comparison WIP)
- Classify and calculate longitudinal Green's functions in QCD kinetic theory and viscous hydrodynamics (not done)

Sensitivity to Initial Conditions, Early-Time Dynamics and Transport Coefficients: Goals and Timelines II

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- Calculate pre-equilibrium photon and di-lepton production in QCD kinetic theory (✓Including universal scaling functions [2403.04846][2308.09747])
- Parametrize net baryon chemical potential dependence of shear viscosity in hybrid approach (✓[2207.05778])

2023

- Calculate longitudinal Green's functions in QCD kinetic theory and viscous hydrodynamics (continued) and implement them into KoMPoST (not done)
- Include finite bulk viscosity as a function of net baryon chemical potential and explore sensitivities of observables (Early WIP)

2024

- Implement longitudinal Green's functions into KoMPoST (continued) and compare longitudinal dynamics in 3+1-dimensional KoMPoST, BAMPS, and SMASH (not clear if it will be done)
- Compare pre-equilibrium photon and di-lepton production to initial-state and final-state emission in hybrid approach (✓)
- Investigate interplay of initial state and temperature- and density-dependent shear and bulk viscosity (Will be done with Bayesian analysis)

Sensitivity to Initial Conditions, Early-Time Dynamics and Transport Coefficients: Goals and Timelines III

2025

- Compute excitation function of bulk observables within SMASH hybrid approach with temperature- and density-dependent transport coefficients (Will be done with Bayesian analysis)

Investigating the Range of Applicability of Fluid Dynamics: Goals and Timelines I

Goals: Examine the range of validity of viscous fluid dynamics in small systems, and investigate the structure and relevance of collective excitations beyond hydrodynamics

- Attractor solutions, system size, and flow
- Non-hydrodynamic excitations

Timeline:

2021
- Implement rotationally symmetric anisotropic initializations in kinetic and hydrodynamic boost-invariant solvers (✓[2109.03290])
- Include spatial and momentum anisotropies into linearized QCD kinetic description (✓[2109.03290])

2022
- Compare kinetic and hydrodynamic calculations with rotationally symmetric initializations (✓[2211.14379][2211.14356])
- Calculate spectrum of non-hydrodynamic excitations in leading-order QCD kinetic theory (Done in ϕ^4 [2308.04491] and WIP in Yang-Mills / Effective approach in QCD [2306.09094])

Investigating the Range of Applicability of Fluid Dynamics: Goals and Timelines II

2023
- Implement radially asymmetric initializations in kinetic and hydrodynamic boost-invariant solvers (✓[2109.03290])
- Explore relevant parameter ranges and compare kinetic and hydrodynamic calculations (✓Applicability of Hydrodynamics [2211.14356])
- Include non-perturbative $C(b_T)$ into linearized QCD kinetic description (WIP in Yang-Mills)

2024
- Perform semi-perturbative calculation of shear viscosity and spectrum of non-hydrodynamic excitations (WIP in Yang-Mills)

Additional Opportunities and Directions

- Stochastic transport of conserved charges
  - Inclusion of linearized stochastic B,Q,S charge transport in MUSIC (WIP)
  - Impact on the freeze-out and calculation of cumulants of charges (planned)
- Characterization of the initial state in heavy-ion collisions using an average state and fluctuation modes
  - Develop decomposition of initial state profiles into basis of modes (✓[2209.01176])
  - Comparison of event-by-event fluctuations in initial state between Glauber and saturation physics models (✓[2209.01176])
  - Study centrality dependence (WIP)
  - Study influence of nuclear deformation (WIP)
  - Extension to conserved charges and 3D profiles (planned)

B02: Outlook

- Transport of conserved quantities
  - Overall on time: projects maybe not finished but all the groundwork is there to finish in time
  - Additional research direction of stochastic transport of conserved charges
  - There was no major shift in direction
- Sensitivity to initial conditions, early-time dynamics and transport coefficients
  - Overall on time: most timeline goals finished and rest in near future
  - No progress on longitudinal dynamics, not clear about future
  - Additional research direction of initial state mode decomposition
  - There was no major shift in direction
- Investigating the range of applicability of fluid dynamics
  - We are on time except non-hydrodynamic spectrum
  - Additional spectrum calculations in ϕ^4 and Yang-Mills
  - There was no major shift in direction

Appendix