Bulk observables within hybrid approach for heavy ion collisions with SMASH afterburner

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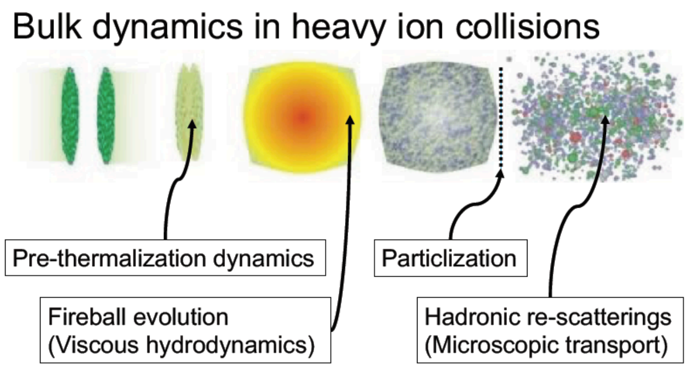
Introduction

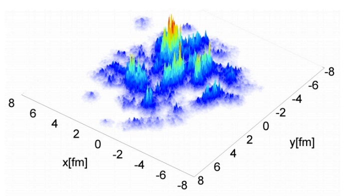
Our goal is to understand QCD matter :
how it looks like (e.g. **equation of state**) and how it behaves (e.g. **transport coefficients**).



Q : How to validate our understanding of QCD matter?
A : We need to have dynamical modelling, which is as close to real experiments as possible.

IP-Glasma pre-thermalization dynamics

Nucleon + partonic fluctuations



In the IP-Glasma picture [1], partons with high x provide color sources for classical Yang-Mills fields. The color gauge field in terms of the path-orderd Wilson line is given by

$$A^i(\mathbf{x}_\perp) = \frac{i}{g} V(\mathbf{x}_\perp) \partial_i V^\dagger(\mathbf{x}_\perp) \quad (1)$$

$$V(\mathbf{x}_\perp) = P \exp\left[-ig \int dx^- \frac{\rho(x^-, \mathbf{x}_\perp)}{\nabla_T^2 - m^2} \right] \quad (2)$$

The fluctuation of color charges carried by high-x partons in nuclei are described as

$$\langle \rho^a(x^-, \mathbf{x}_\perp) \rho^b(y^-, \mathbf{y}_\perp) \rangle = g^2 \mu_A^2(\mathbf{x}_\perp) \delta^{ab} \delta(x^- - y^-) \delta^{(2)}(\mathbf{x}_\perp - \mathbf{y}_\perp) \quad (3)$$

where $g^2\mu$ depends on the transverse position inside the nucleus. These fluctuations are not present in the MC-Glauber model.

MUSIC Hydrodynamics

Second-order viscous hydrodynamics

MUSIC [2] solves $3+1$D hydrodynamic conservation equations $\partial_\mu T^{\mu\nu}(t, \mathbf{x}) = 0$, along with the equations for the dissipative currents

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta \theta - \delta_{\Pi\Pi} \Pi \theta + \lambda_{\Pi\pi} \pi^{\mu\nu} \sigma_{\mu\nu} \quad (4)$$

$$\tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta \sigma^{\mu\nu} - \delta_{\pi\pi} \pi^{\mu\nu} \theta + \varphi_7 \pi_\alpha^{\langle\mu} \pi^{\nu\rangle\alpha} - \tau_{\pi\pi} \pi_\alpha^{\langle\mu} \sigma^{\nu\rangle\alpha} + \lambda_{\pi\Pi} \Pi \sigma^{\mu\nu}. \quad (5)$$

The transport coefficients are determined using the relaxation time and 14-moment approximation [3].

Cooper-Frye particlization

Switching from hydro to particles

Hadrons are sampled on the freeze-out hypersurface Σ according to the Cooper-Frye formula [4].

$$\left. \frac{dN}{d^3\mathbf{p}} \right|_{\text{1-cell}} = \begin{cases} \frac{d}{(2\pi)^3} \left[f_0(x, \mathbf{p}) + \delta f_{\text{shear}}(x, \mathbf{p}) + \delta f_{\text{bulk}}(x, \mathbf{p}) \right] \frac{p^\mu \Delta\Sigma_\mu}{E_\mathbf{p}} \\ \quad \text{if} \quad f_0 + \delta f_{\text{shear}} + \delta f_{\text{bulk}} > 0 \quad \text{and} \quad p^\mu \Delta\Sigma_\mu > 0 \\ 0 \quad \text{otherwise} \end{cases} \quad (6)$$

where f_0 is the local equilibrium distribution function and the bulk [5] and shear [6] viscous corrections are given by

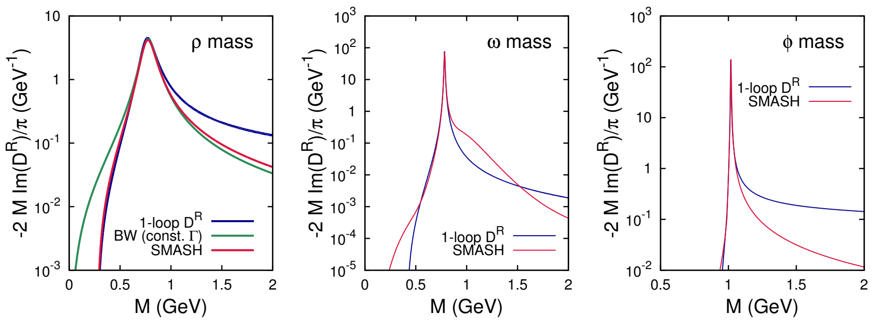
$$\delta f_{\text{shear}} = f_0(1 \pm f_0) \frac{\pi_{\mu\nu} p^\mu p^\nu}{2(\epsilon_0 + P_0) T^2} \quad (7)$$

$$\delta f_{\text{bulk}} = -f_0(1 \pm f_0) \frac{C_{\text{bulk}}}{T} \left[\frac{m^2}{3(p \cdot u)} - \left(\frac{1}{3} - c_s^2 \right) (p \cdot u) \right] \Pi \quad (8)$$

We assume a grand canonical ensemble where particles on each fluid cell are sampled independently.

Resonance mass sampling

Resonance masses are sampled according to the spectral functions at the point of particlization.



Spectral functions from the retarded propagator [7] are used for vector mesons (ρ, ω and ϕ), while Breit-Wigner (with constant width) is used for others.

Global conservations

SPREW (Single Particle Rejection with Exponential Weight) sampling [8] is implemented for the global conservation of baryon number, strangeness, electric charge and energy.

1. If the newly sampled particle is deviating total quantum number X from their average, it is rejected with probability

$$P_{\text{reject}} = 1 - e^{-|X_{\text{sample}} - X_{\text{surface}}|} \quad (9)$$

2. In addition, the energy conservation is achieved by rescaling 3-momenta of particles

$$E_{\text{surface}} = \sum_i \left((1+a)^2 \mathbf{p}_i^2 + m_i^2 \right)^{1/2} \quad (10)$$

Multiparticle correlations (e.g. correlations among particles with opposite charges) might be affected by conservation.

SMASH Cascade

Transport approach for dilute hadronic matter

SMASH (Simulating Many Accelerated Strongly-interacting Hadrons) [9] is a transport model dealing with the Boltzmann transport equation

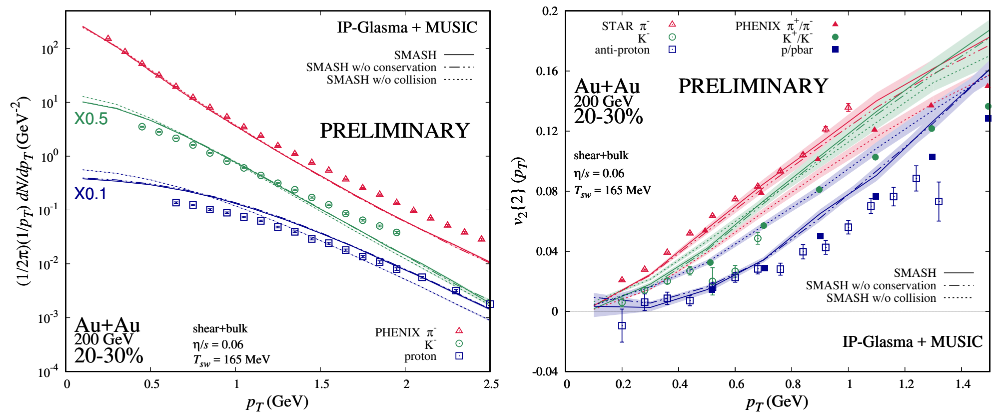
$$p^\mu \frac{\partial f_i}{\partial x^\mu} + F^\mu \frac{\partial f_i}{\partial p^\mu} = \mathcal{C}_i[f] \quad (11)$$

It performs wide range of hadronic and electromagnetic interactions.

- resonance excitations and decays
- $2 \to 2$ inelastic collisions (e.g. $NN \to NN^*$)
- dilepton and photon production (perturbative)
- string excitation processes
- baryon-antibaryon annihilations (work in progress)
- additive quark model (work in progress)

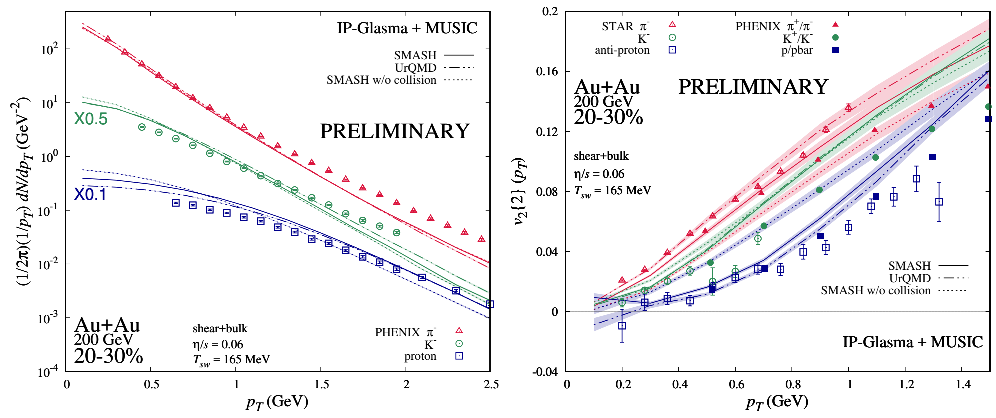
Results

Effects of re-scattering and conservation



- Protons are accelerated by pions as they flow outward with different velocities.
- Global conservation does not alter the single particle distribution.

Comparison with MUSIC+UrQMD



- Due to the absence of baryon-antibaryon annihilation in this work, `MUSIC+SMASH` overestimates the proton spectrum compared to the `MUSIC+UrQMD` calculation [10].
- `SMASH` has less splitting in the elliptic flow.

Conclusion

1. Improvement of hybrid approach by the optional global conservation (of B, S, Q and E) and broad spectral function in the particlization procedure.
2. SMASH shows the same tendency as previous approaches, but results are sensitive to annihilation and scattering of exotic particles.

Outlook / Future works

1. Additive quark model (AQM), string excitation/fragmentation and $B\overline{B}$ annihilation will be included.
2. Investigation of impact of hadronic rescattering on CME (chiral magnetic effects) observables is in progress.

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