Next-Generation Multi-Fluid Hydrodynamics for RHIC BES

Jakub Cimerman
Iurii Karpenko, Boris Tomášik

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CTU
CZECH TECHNICAL UNIVERSITY IN PRAGUE
Motivation

- **Critical point** of the QCD phase diagram is assumed to be located at RHIC BES energy range

- Increasing number of heavy-ion experiments operating at energies from few to few tens of GeV

- Most current hydrodynamic models are not suitable for energies lower than 10 GeV
Challenges

- Non-zero baryon density
- No boost-invariant longitudinal expansion
- Weaker Lorentz contraction $\Rightarrow$ longer inter-penetration (comparable with the lifetime of the fluid stage)
Multi-fluid Approach

- The initial stage is where the nuclear compression is happening.
- Conventional hybrid models apply hydrodynamics only later, therefore there is less sensitivity to the EoS of dense baryon medium in a simulation.
- Multi-fluid addresses this issue by applying an opposite assumption that the medium is in the fluid phase from the very beginning.
- In the multi-fluid approach the initial non-equilibrium is represented as counter-flowing fluids.
Physics Assumption of 3-fluid Hydrodynamics

- Incoming nuclei are represented by two blobs of liquid.
- Third fluid is created from the friction of the incoming fluids.
- The fluids co-exist in the same coordinate space.

Au+Au
7.7 GeV
b=5 fm
Technical Description of the Model

- To account for event-by-event fluctuations, coordinates of nucleons inside the nuclei are sampled using Woods-Saxon formula
- Baryon stopping is modelled via mutual friction of the baryon fluids
- The energy-momentum from the friction is transferred to a third, net baryon-free fluid
- Hydrodynamic evolution via vHLLE
- Particlization via Cooper-Frye formula and particle sampling via smash-hadron-sampler
- Final-state interactions via transport code SMASH

\[
\rho(x, y, z) = \frac{\rho_0}{1 + \exp \left( \frac{\sqrt{x^2+y^2+z^2-R}}{a} \right)}
\]
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\[
\begin{align*}
F^\nu_\alpha &= \nabla^2 \rho_p \rho_t \xi m_N V^\nu_{\text{rel}} \left[ (u^\nu_\alpha - u^\nu) \sigma_P(s_{\text{pt}}) + (u^\nu + u^\nu) \sigma_E(s_{\text{pt}}) \right] \\
F^\nu_{1\alpha} &= \rho_s \xi (s_{f\alpha}) V^\nu_{\text{rel}} \frac{T^{0\nu}_{f(eq)}}{u_f} \sigma_{\text{tot}}^N \pi \to R(s_{f\alpha})
\end{align*}
\]

Friction in the quark-gluon phase is included!
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- **Hydrodynamic evolution via vHLLE** [Comp. Phys. Comm. 185, 3016-3027 (2014)]
- Particlization via Cooper-Frye formula and particle sampling via *smash-hadron-sampler*
- Final-state interactions via transport code *SMASH*

Evolution of 3 fluids is solved in parallel using a modified vHLLE code
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- The energy-momentum from the friction is transferred to a third, net baryon-free fluid.
- Hydrodynamic evolution via $vHLLE$.
- Particlization via Cooper-Frye formula and particle sampling via $smash$-hadron-sampler\footnote{arXiv:2112.08724}.
- Final-state interactions via transport code SMASH.

We chose to have single particlization surface to avoid issue of treating mixture of fluid and particles.

\[
N = \int \frac{d^3 p}{E_p} \int d\Sigma_{\mu}(x) p^\mu f(p, T(x), \mu_i(x))
\]
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- The energy-momentum from the friction is transferred to a third, net baryon-free fluid.
- Hydrodynamic evolution via $v\text{HLLE}$.
- Particlization via Cooper-Frye formula and particle sampling via $\text{smash-hadron-sampler}$.
- Final-state interactions via transport code $\text{SMASH}$ [Phys. Rev. C 94, 054905 (2016)].
Centrality Determination

- Based on number of charged particles within $|\eta|<0.5$ (following STAR)

- Multiplicity distribution is fitted with Glauber Monte Carlo model to estimate missing peripheral collisions
Glauber model is used as standard for extracting impact parameter in experiments, however, our model predicts quite different impact parameter intervals.
Pseudorapidity Distributions

Au+Au
19.6 GeV

Au+Au
62.4 GeV
Rapidity Distributions of Net-Protons

- Small difference due to comparison to different system and energy at 19.6GeV, otherwise good agreement with data ⇒ 3FH model yields correct baryon stopping
Although not all spectra reproduce data perfectly, the slope of the spectra is generally quite well reproduced ⇒ 3FH model yields correct strength of the transverse expansion.

Transverse Momentum Spectra

![Graphs showing transverse momentum spectra for Au+Au collisions at 7.7 GeV and 27 GeV, with different particle types and centrality bins.](image)
Elliptic Flow

- Flow is quite overestimated at the lowest energy, gets closer to data at higher energies.
- This demonstrates missing viscosity in the model, which decreases elliptic flow, and it grows towards lower energies.
Directed Flow

\[ \text{\pi}^- \quad \text{Au+Au 7.7 GeV} \]

\[ \text{\pi}^- \quad \text{Au+Au 19.6 GeV} \]

\[ \text{\pi}^- \quad \text{Au+Au 39 GeV} \]

\[ \rho \quad \text{Au+Au 7.7 GeV} \]

\[ \rho \quad \text{Au+Au 19.6 GeV} \]

\[ \rho \quad \text{Au+Au 39 GeV} \]
Directed Flow before Hadronic Rescatterings

\[ v_1(y) \]

- \( \pi^- \) Au+Au 7.7 GeV
- \( \pi^- \) Au+Au 19.6 GeV
- \( \pi^- \) Au+Au 39 GeV
- \( p \) Au+Au 7.7 GeV
- \( p \) Au+Au 19.6 GeV
- \( p \) Au+Au 39 GeV
Summary

- We developed a novel hybrid model designed for BES energies with:
  - 3-fluid hydrodynamics (in Milne coordinates)
  - fluctuating initial state
  - final-state hadronic cascade: SMASH
- Tuning parameters do not depend on collision energies
- Rapidity distributions and momentum spectra are well reproduced
- Flow is overestimated, indicating that the model lacks viscosity
- Future plans:
  - adding viscous corrections to the model
  - studying various equations of state within the model

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Backup slides
Transverse Momentum Spectra
Transverse Momentum Spectra

Au+Au 39 GeV

\( \pi^+ \)

\( \bar{p} \)

\( p \)

\( \bar{p} \)

Au+Au 62.4 GeV

\( \pi^+ \)

\( \bar{p} \)

\( p \)

\( \bar{p} \)
Elliptic Flow

![Graph showing elliptic flow for different energies]