The initial state for RHIC BES modelled by three-fluid dynamics[1]

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1. Motivation

The LHC focuses on high-energy collisions in the TeV range, but studying the energy range from a few to tens of GeV is equally important, especially because the critical endpoint is assumed to be located at these energies. This energy range is being explored by the BES program at RHIC and the NA61/SHINE experiment at CERN, and two other facilities are under construction. However, hydrodynamic modelling at RHIC BES energies is more challenging due to weaker Lorentz contraction, resulting in longer interpenetration times compared to higher energies. One also cannot assume a boost-invariant longitudinal expansion or zero baryon density. A hybrid model designed for top RHIC or LHC energies would not address these challenges and would not be suitable for energies below 20 GeV.

2. Multi-Fluid Approach

One approach to handle the complexity of the initial state is called multi-fluid dynamics or three-fluid dynamics. It represents the incoming nuclei as two droplets of cold nuclear fluid, referred to as the projectile and target fluids. The collision process is then simulated as the mutual interpenetration of these fluids. Baryon stopping is modelled as friction between the projectile and target fluids, with the kinetic energy lost resulting in the creation of a third fluid representing mesons and baryon-antibaryon pairs generated in the reaction. This concept relies on a fluid dynamical description of the heavy-ion collision from the start, enabling the modelling of the compression stage and investigation of its sensitivity to the equation of state (EoS) of dense nuclear matter.

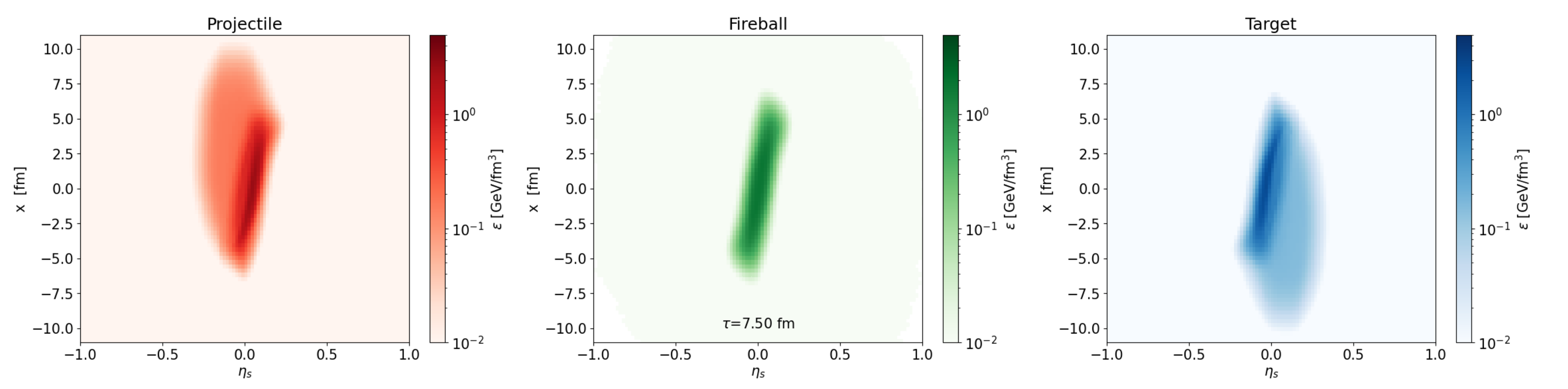

Figure 1: *Distribution of energy density of projectile (red), fireball (green) and target (blue) fluids in $x-\eta_s$ plane at $y=0$ at $\sqrt{s_{NN}}=7.7$ GeV.*

In the 1990s and 2000s, a 3-fluid hydrodynamic model was developed by Mishustin, Russkikh and Satarov [2], later enhanced by Ivanov, Russkikh and Toneev [3]. However, this model lacks viscous corrections, uses Cartesian coordinates, which is reasonable only for energies not larger than 30 GeV, has averaged initial conditions, and its EoS is hard-coded, limiting the ability to determine the most effective EoS near the critical endpoint (CEP). To address these issues, we have created MUFFIN (MUlti Fluid simulation for Fast IoN collisions): a next-generation event-by-event three-fluid dynamic model.

3. Model Description

Initial state

To account for event-by-event fluctuations, we construct the initial states of the projectile and target fluids by sampling the Cartesian coordinates of individual nucleons within the incoming nuclei using the Woods-Saxon formula. We then propagate the nucleons onto $\tau=\tau_0$ hyperbola and switch to hyperbolic coordinates. Local energy, momentum, baryon and electric charge densities of the fluids are then computed by smearing the point-like energies, momenta and charges of the nucleons in coordinate space using a smearing kernel

$$K(\Delta x,\Delta y,\Delta\eta_s)=A\exp\left(-\frac{\Delta x^2+\Delta y^2+\Delta\eta_s^2\tau^2\cosh^2\eta_s\cosh^2\mathrm{y}}{2\sigma^2}\right) \quad (1)$$

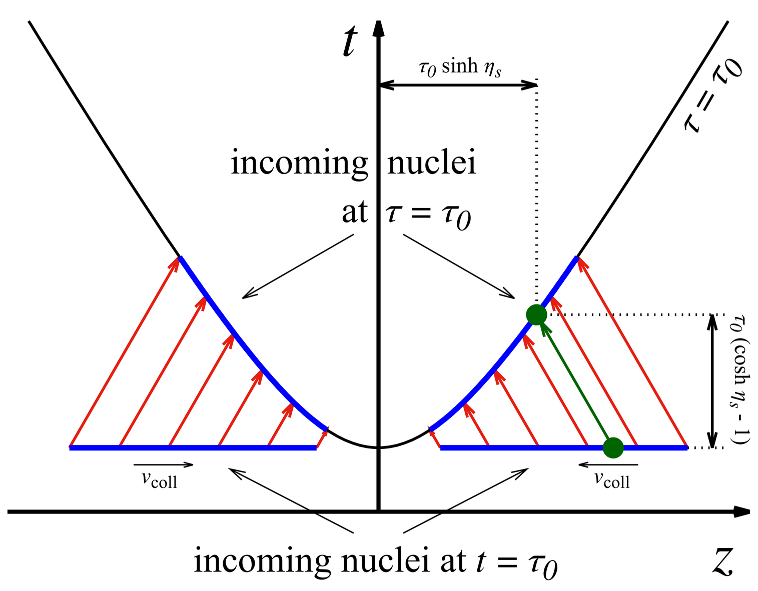

Figure 2: *Sketch of the nuclei transformation from Cartesian to hyperbolic coordinates*

Hydrodynamic evolution

The projectile, target, and fireball fluids coexist and partially overlap in the same coordinate space. We employ a modified vHLLE code [4] to compute the hydrodynamic evolution of each fluid in parallel. While vHLLE includes bulk and shear viscous corrections, we have disabled them for this study, reserving the exploration of viscous corrections in the multi-fluid context for future research.
The energy-momentum exchange between the fluids is given by friction terms

$$\partial_\mu T^{\mu\nu}_{\mathrm{p}}(x)=-F^\nu_{\mathrm{p}}(x)+F^\nu_{\mathrm{fp}}(x), \quad (2a)$$
$$\partial_\mu T^{\mu\nu}_{\mathrm{t}}(x)=-F^\nu_{\mathrm{t}}(x)+F^\nu_{\mathrm{ft}}(x), \quad (2b)$$
$$\partial_\mu T^{\mu\nu}_{\mathrm{f}}(x)=F^\nu_{\mathrm{p}}(x)+F^\nu_{\mathrm{t}}(x)-F^\nu_{\mathrm{fp}}(x)-F^\nu_{\mathrm{ft}}(x). \quad (2c)$$

There is no charge exchange between the fluids. The friction between the projectile and the target fluids is parameterized as follows:

$$F^\nu_\alpha=\vartheta^2\rho^\xi_p\rho^\xi_t m_N V^{pt}_{\mathrm{rel}}[(u^\nu_\alpha-u^\nu_{\bar\alpha})\sigma_P(s_{pt})+(u^\nu_p+u^\nu_t)\sigma_E(s_{pt})] \quad (3)$$

The friction between baryon-rich and fireball fluid is given by

$$F^\nu_{f\alpha}=\rho^b_\alpha\xi_{f\alpha}(s_{f\alpha})V^{f\alpha}_{\mathrm{rel}}\frac{T^{0\nu}_{f(eq)}}{u^0_f}\sigma^{N\pi\to R}_{tot}(s_{f\alpha}) \quad (4)$$

Equation of state

MUFFIN, like the underlying vHLLE code, offers the advantage of being able to modify the equation of state. This feature enables the investigation of how different observables are influenced by the EoS. However in these results, for the general benchmark of the model we use only one EoS based on an effective chiral hadron-quark model [5] that qualitatively matches lattice QCD results at $\mu_B=0$ and hadron-resonance gas with excluded volume corrections at low temperatures.

Particlization and final-state interactions

With more than one fluid in the picture, determining a suitable particlization criterion becomes more challenging. If each fluid particlizes individually, space-time regions will appear with a mixture of fluid and particles, which complicates the modelling. To avoid such complications, we choose to particlize all fluids at the same hypersurface. For the particlization criterion, we choose a fixed "combined" energy density of $\varepsilon_{sw}=0.5$ GeV/fm^3, which is computed by diagonalizing the combined energy-momentum tensor of all fluids, $T^{\mu\nu}_p(x)+T^{\mu\nu}_t(x)+T^{\mu\nu}_f(x)$. With a field of combined energy density in space-time, the Cornelius subroutine [6] is used to construct the particlization hypersurface.
In conventional one-fluid calculations, most of the system at the initial time of fluid-dynamic evolution, τ_0, is hot and within the particlization hypersurface. The initial state of multi-fluid calculation consists of cold nuclear matter, and therefore no part of the system is initially within the particlization hypersurface. As a result, the constant energy density hypersurface forms an enclosed surface.
In hybrid MUFFIN-SMASH calculations, hadrons are sampled at the particlization hypersurface using the Cooper-Frye formula. The sampling process is carried out using the `SMASH-hadron-sampler` [7]. The final-state interactions are then simulated with the microscopic transport model SMASH [8], which includes resonance decays, 2-particle inelastic and elastic scatterings, and resonance excitations.

4. Results

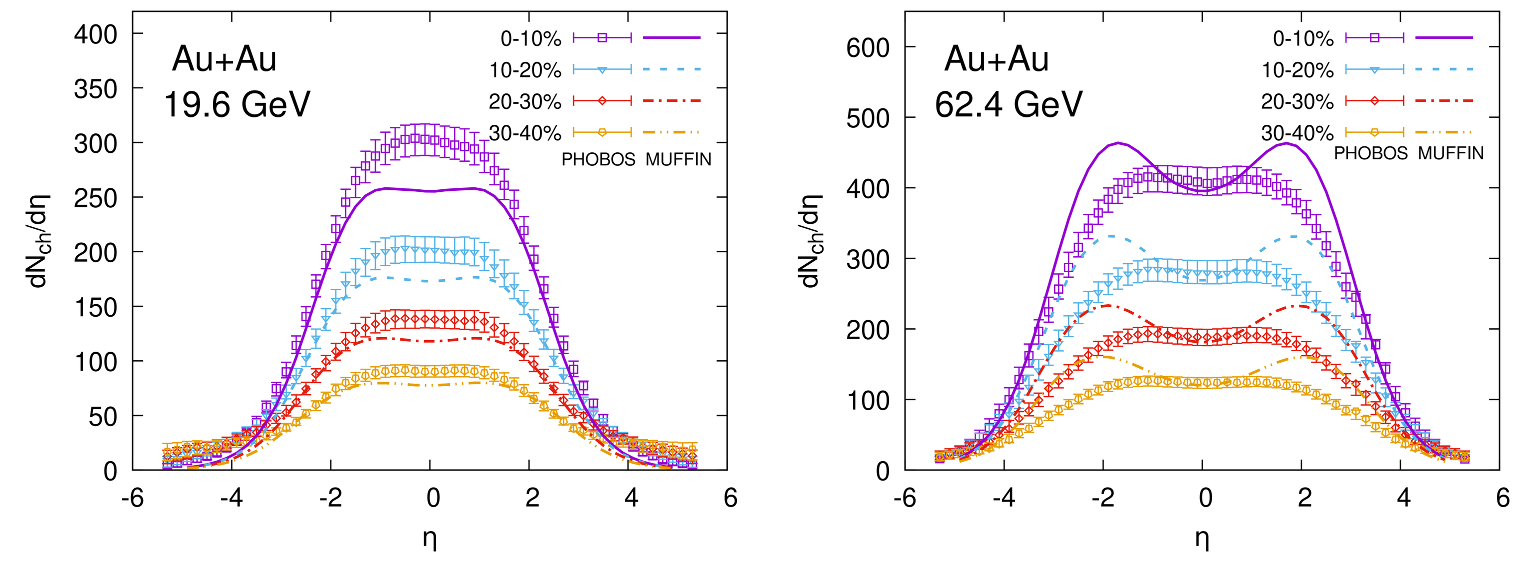

Figure 3: *Pseudorapidity distributions of charged hadrons compared to the experimental data from PHOBOS [9]*

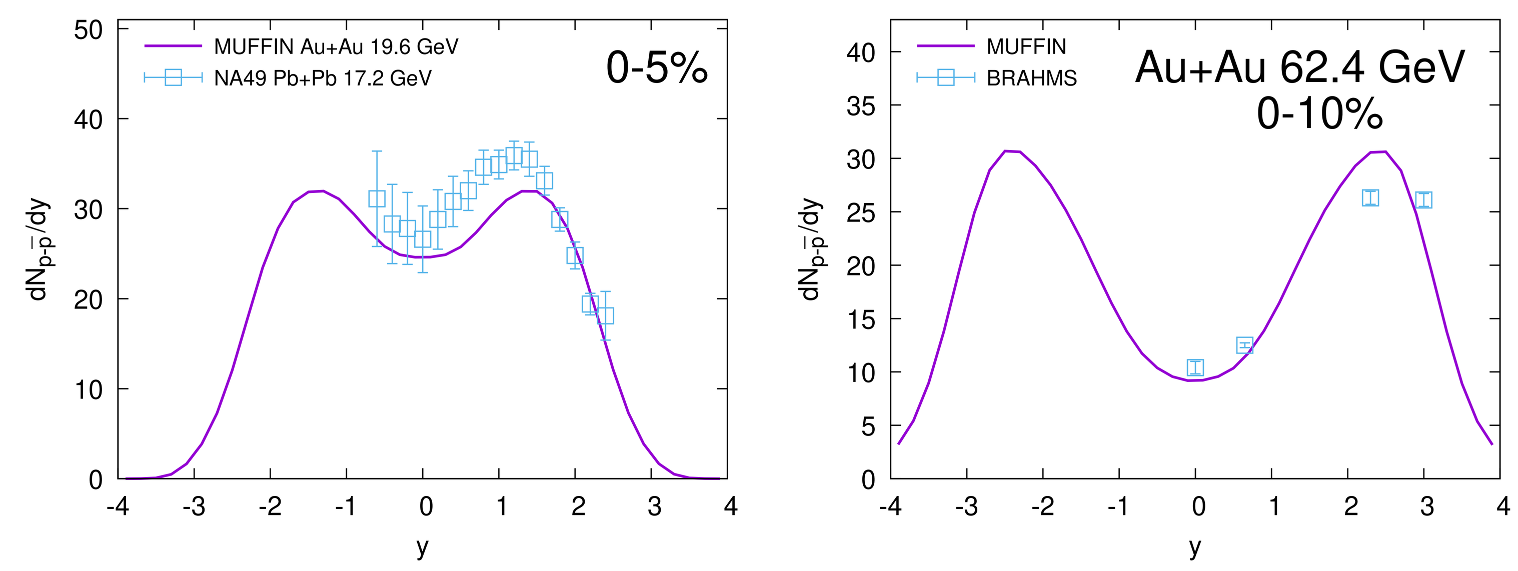

Figure 4: *Rapidity distributions of net-protons compared to the experimental data from NA49 [10] and BRAHMS [11]*

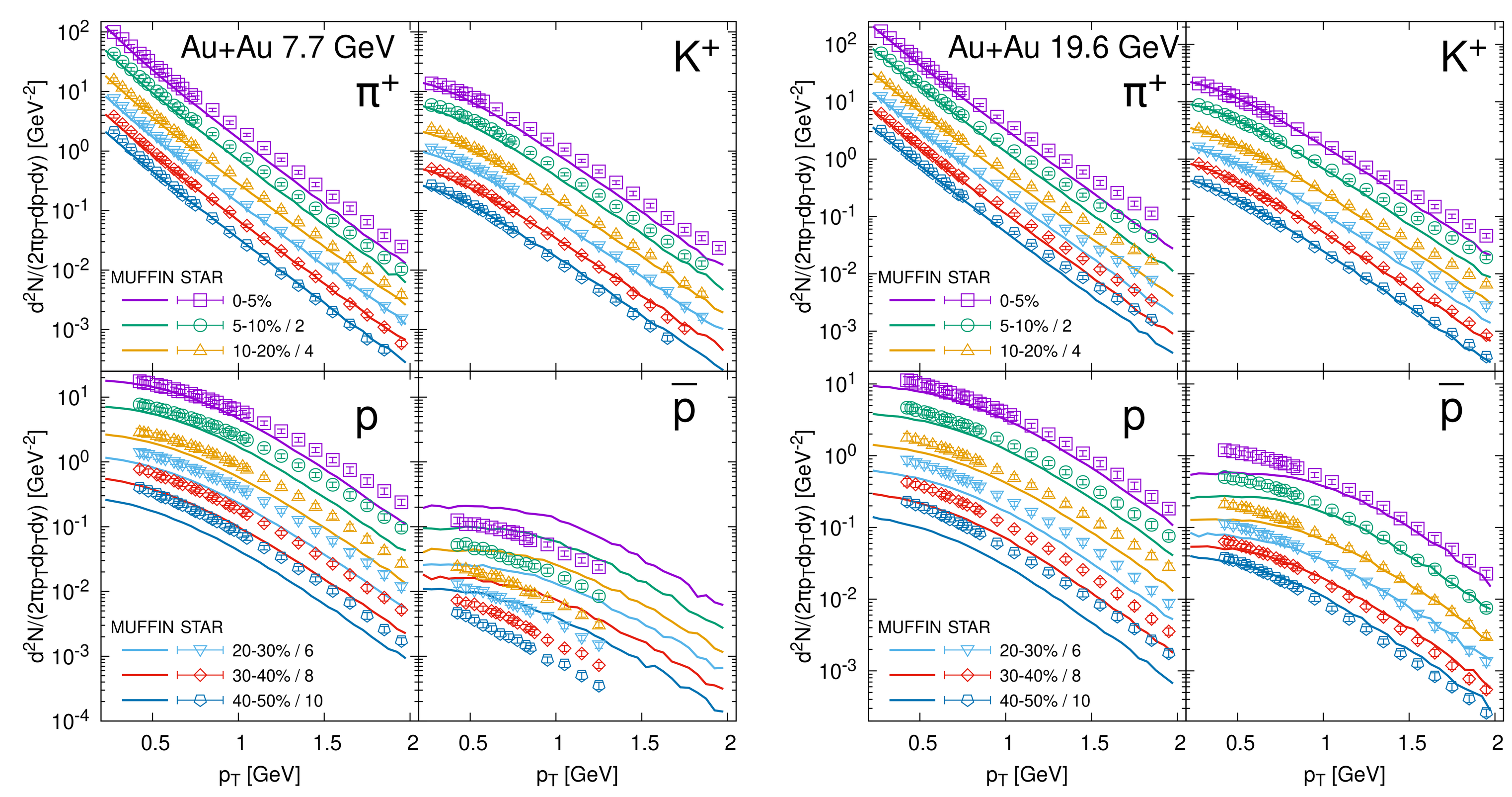

Figure 5: *Transverse momentum spectra of π^+, K^+, protons and antiprotons compared to the experimental data from STAR [12]*

5. Conclusions

We developed a next-generation hybrid three-fluid model for simulating heavy-ion collisions at energies from a few to a few tens of GeV. This model is aimed for phenomenological studies of heavy-ion collisions at BES energies at RHIC, NA61/SHINE at CERN and FAIR at GSI. The main features of the model are fluctuating initial conditions, a hyperbolic coordinate system, Monte Carlo hadron sampling at particlization, SMASH for hadronic rescatterings and the possibility to easily change the EoS.

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