Three-fluid Hydrodynamics-based Event Simulator Extended by UrQMD final State interactions (THESEUS) for FAIR-NICA-SPS-BES/RHIC energies

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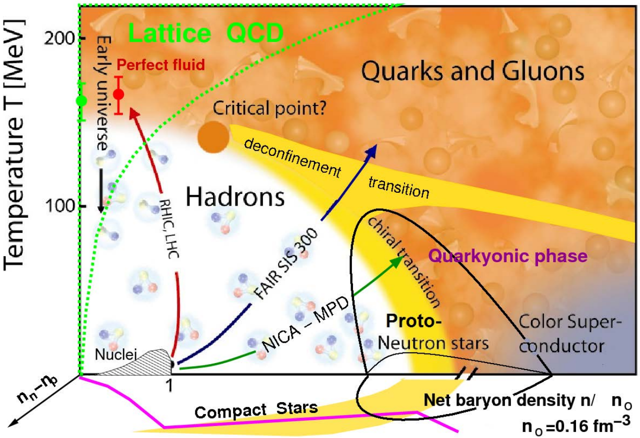
Exploring Nuclear Phase Diagram



http://theor0.jinr.ru/twiki-cgi/view/NICA/WebHome

At which incident energy does onset of deconfinement happen?

What is the order of the deconfinement transition at high baryon densities?

Is there a critical end point in the phase diagram?

Hydrodynamics versus Kinetics

Why we are not satisfied with kinetics or hybrid models?

- Only crossover transition into QGP is accessible in kinetics

  A Multi-Phase Transport (AMPT) model [Lin, Ko and Pal, PRL 89, 152301 (2002)]
  Parton-Hadron-String Dynamics [Cassing, Bratkovskaya, arXiv:0907.5331 (2009)]

- In hybrid models (Kinetics-Hydro-Kinetics), transition into QGP is inaccessible at the early (nonequilibrium) stage of the collision

3-Fluid Hydrodynamics

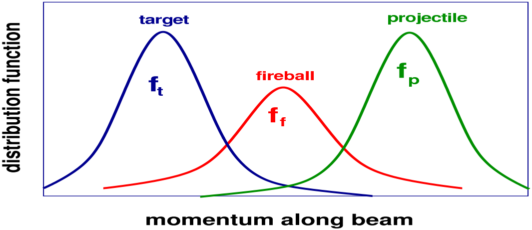
- directly addresses **Equation of State (EoS)**!
- 1st-order phase transition into QGP is accessible through EoS
- Transition into QGP is accessible also at the early (nonequilibrium) stage of the collision
- However, all this requires certain approximations

3FH Assumption

- Distributions are separated in momentum space
  ⇒ different fluids
- Leading particles carry baryon charge
  ⇒ 2 baryon-rich fluids: **projectile-like** and **target-like**

At high incident energies ($E_{lab} \gtrsim 10A$ GeV)

- Produced particles populate mid-rapidity ⇒ **fireball fluid**



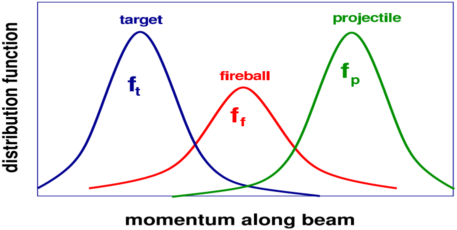
This a minimal extension of hydrodynamics required by heavy-ion dynamics

History

- Kurchatov Inst. 1988–1991:
  2-fluid hydro with free-streaming radiation of pions
  Mishustin, Russkikh, and Satarov
- Frankfurt University 1993–2000:
  3-fluid hydrodynamics with instant formation of fireball
  Brachmann, Katscher, Dumitru, Rischke, Maruhn, Stöcker, Greiner, Mishustin, Satarov, *et al.*
- GSI 2003–now:
  3-fluid hydrodynamics with delayed formation of fireball
  Ivanov, Russkikh, Toneev

3FH Equations of Motion

Produced particles populate mid-rapidity $\Rightarrow$ fireball fluid



Target-like fluid: $\partial_\mu J^\mu_t = 0$ $\qquad \partial_\mu T^{\mu\nu}_t = -F^\nu_{tp} + F^\nu_{ft}$

Leading particles carry bar. charge $\qquad$ exchange/emission

Projectile-like fluid: $\partial_\mu J^\mu_p = 0,$ $\qquad \partial_\mu T^{\mu\nu}_p = -F^\nu_{pt} + F^\nu_{fp}$

Fireball fluid: $J^\mu_f = 0,$ $\qquad \partial_\mu T^{\mu\nu}_f = F^\nu_{pt} + F^\nu_{tp} - F^\nu_{fp} - F^\nu_{ft}$

Baryon-free fluid $\qquad$ Source term $\qquad$ Exchange

The source term is delayed due to a formation time τ

Total energy-momentum conservation:

$$\partial_\mu (T^{\mu\nu}_p + T^{\mu\nu}_t + T^{\mu\nu}_f) = 0$$

Hydrodymanic densities

Baryon current:

$J^{\mu}_{\alpha} = n_{\alpha} u^{\mu}_{\alpha}$

n_{α} = baryon density of α-fluid

u^{μ}_{α} = 4-velocity of α-fluid

Energy-momentum tensor:

$T^{\mu\nu}_{\alpha} = (\varepsilon_{\alpha} + P_{\alpha}) u^{\mu}_{\alpha} u^{\nu}_{\alpha} - g_{\mu\nu} P_{\alpha}$

ε_{α} = energy density

P_{α} = pressure

+ Equation of state:

$$P = P(n, \varepsilon)$$

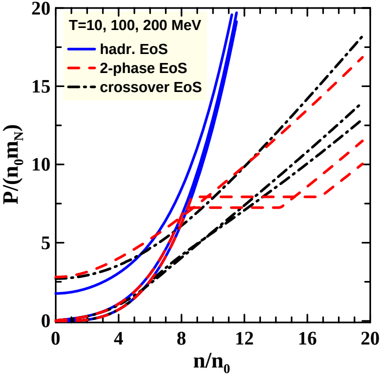
Final Aim: To find a proper EoS, which reproduces all data

Physical Input I

I. Equation of State

- **Hadronic EoS**
  Galitsky&Mishustin (1979)
- 1st-order transition to QGP **(2-phase EoS*)**
- **crossover EoS***

*[Khvorostukhin, Skokov, Redlich, Toneev, (2006)]



Phase transition $\Longrightarrow$ EoS softening

Physical Input II and III

II. Friction was fitted to reproduce the baryon stopping

- **Hadronic EoS**

  Friction in hadronic phase was estimated by Satarov (SJNP 1990)

  This friction had to be enhanced.

- **2-phase EoS and crossover EoS**

  Phenomenological friction in QGP phase.

  Advantage of deconfinement scenarios:

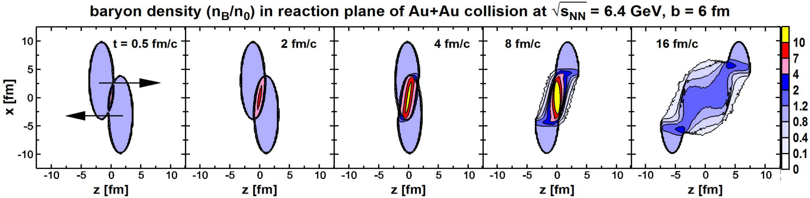
  Satarov's friction in hadronic phase needs no modification

III. Freeze-out

When system becomes dilute, hydro has to be stopped

Freeze-out energy density $\varepsilon_{frz} = 0.4$ GeV/fm^3

3FH Output



baryon density (n_B/n_0) in reaction plane of Au+Au collision at $\sqrt{s_{NN}}$ = 6.4 GeV, b = 6 fm

Output at the freeze-out stage

All fluids are frozen out in small droplets characterized by

- proper volume V^{pr},
- temperature T,
- baryon, μ_{B}, and strange, μ_{S}, chemical potentials
- collective flow velocity u^{μ},

T, μ_{B} and μ_{S}
are determined from
baryon ρ_{B}, strangeness ρ_{S} and energy ε densities
using hadronic-gas EoS.

3FH observables

Hadron phase space distributions,

$$p^{*0}\frac{d^3N_i}{d^3\mathbf{p}^*} = \sum_\alpha \frac{g_i V_\alpha^{\mathrm{pr}}}{(2\pi)^3} \frac{p^{*0}}{\exp\left[(p^{*0}-\mu_{\alpha i})/T_\alpha\right] \pm 1}$$

$\mu_{\alpha i} = B_i \cdot \mu_{\alpha \mathrm{B}} + S_i \cdot \mu_{\alpha \mathrm{S}}$ is the chemical potential of hadron i with baryon number B_i and strangeness S_i,
α summation runs over droplets from all (p, t and f) fluids,
* denotes momentum in the droplet rest frame.

Observables are integrals of distribution functions

$$\text{directed flow} = v_1(y) \quad = \quad \int d^2p_T\,(p_x/p_T)\,(p^{*0}\,d^3N/d^3p^*)/(d^3N/dy)$$

$$\text{rapidity distribution} \quad = \quad dN/dy = \int d^2p_T\;p^{*0}\;d^3N/d^3p^*$$

Particlization

In order to use the 3FH as an event generator, the output should be in terms of observed particles.

Monte Carlo sampling procedure:

Hadrons are sampled according to their phase space distributions,

$$p^{*0}\frac{d^3N_i}{d^3\mathbf{p}^*} = \sum_\alpha \frac{g_i V_\alpha^{\rm pr}}{(2\pi)^3} \frac{p^{*0}}{\exp\left[(p^{*0}-\mu_{\alpha i})/T_\alpha\right] \pm 1}$$

* denotes momentum in the droplet rest frame

$\mu_{\alpha i} = B_i \cdot \mu_{\alpha \rm B} + S_i \cdot \mu_{\alpha \rm S}$ is the chemical potential of hadron i with baryon number B_i and strangeness S_i,

α summation runs over droplets from all (p, t and f) fluids.

Sampling

The sampling is runs as a loop over all droplets:

- average multiplicities of all hadron species are calculated according to
$$\Delta N_{i,\alpha} = V_\alpha^{\mathrm{pr}} n_{i,\mathrm{th}}(T, \mu_i),$$
together with their sum $\Delta N_{\mathrm{tot},\alpha} = \sum_i \Delta N_{i,\alpha}$;
- total (integer) number of hadrons from each droplet is sampled according to Poisson distribution with mean $\Delta N_{\mathrm{tot},\alpha}$.
If the number is greater than zero, sort of hadron is randomly chosen based on probabilities $\Delta N_{i,\alpha}/\Delta N_{\mathrm{tot},\alpha}$;
- hadron's momentum p^* is sampled according to its phase space distribution, which is isotropic in momentum space;
- momentum is Lorentz boosted to the global frame of the collision.

Particle multiplicities fluctuate from event to event according to the composition of grand canonical ensembles.

UrQMD simulation of final state interactions

Afterburner:

The Ultra-relativistic Quantum Molecular Dynamics (UrQMD)
is used to treat the interactions during the late non-equilibrium
hadronic stage of heavy ion reactions,
i.e. after particlization.

3FH + Particlization + Afterburner
Three-fluid Hydrodynamics-based Event Simulator Extended by UrQMD final State interactions (THESEUS)

p_T spectrum

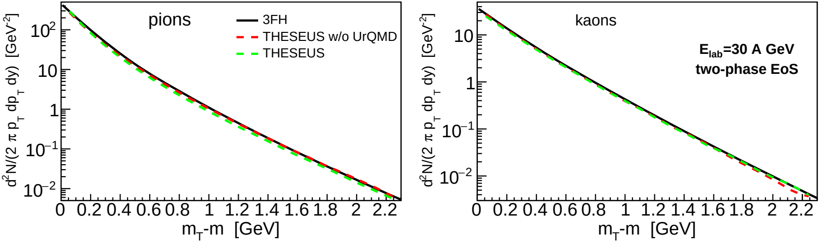


Figure: Transverse momentum spectrum for pions (left panel) and kaons (right panel) for central Au+Au collisions ($b = 2$ fm) at $E_{\rm lab} = 30$ A GeV for the 2-phase EoS.

3FH and THESEUS without UrQMD show excellent agreement.

UrQMD leads to a slight steepening of the pion p_T spectrum.

Rapidity distribution

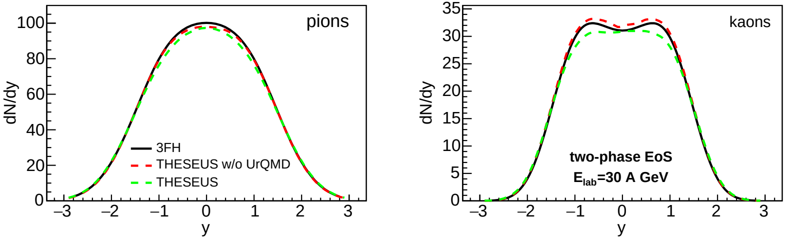


Figure: Rapidity distribution for pions (left panel) and kaons (right panel) for central Au+Au collisions ($b = 2$ fm) at $E_{\text{lab}} = 30$ A GeV for the 2-phase EoS.

3FH and THESEUS without UrQMD show excellent agreement. UrQMD hadronic rescattering smeares out the double-peak structure in the kaon rapidity spectrum.

Directed-Flow Slope for semicentral Au+Au

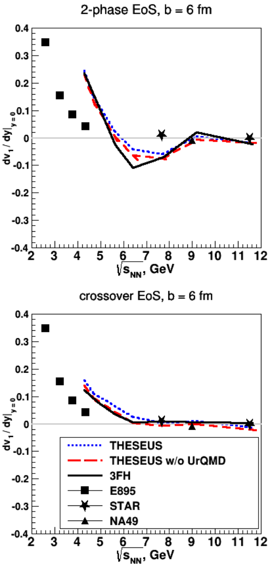


Figure: dv_1/dy of protons

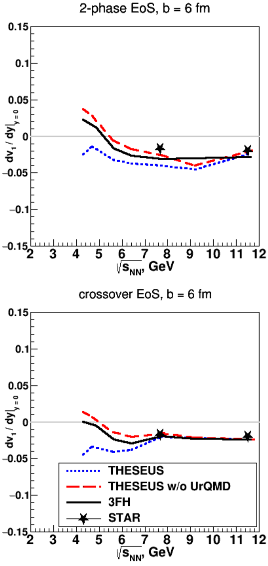
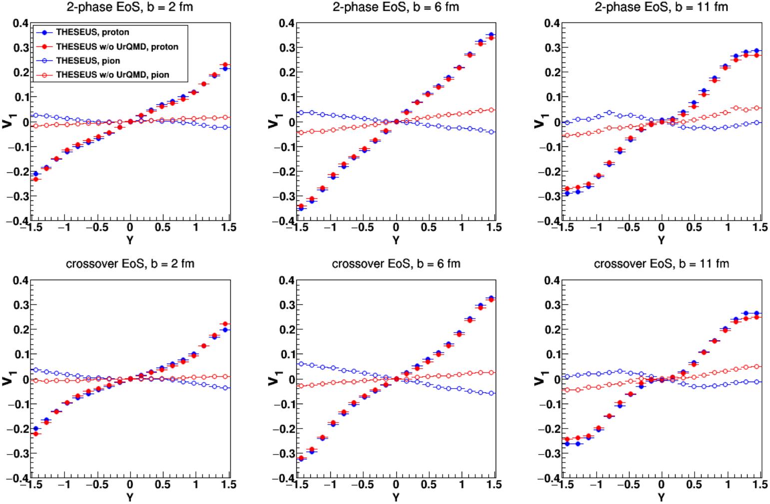


Figure: dv_1/dy of pions

Directed Flow for Au+Au collisions



Afterburner: Shadowing of pion by baryonic matter.

S. A. Bass, et al., Phys. Lett. B **302**, 381 (1993).

Femtoscopy

Bose-Einstein correlations of identical pions

$$C(\mathbf{q}) \propto 1 + \lambda\, exp(-R^2_{out}\, q^2_{out} - R^2_{side}\, q^2_{side} - R^2_{long}\, q^2_{long})$$

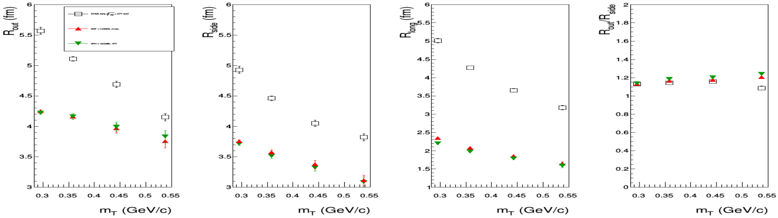
the “long” axis is directed along the beam,
“out”, along the pair transverse momentum and
“side”, perpendicular to the latter one in the transverse plane.

$C(\mathbf{q})$ also depends on m_T (= transverse mass of the pair)

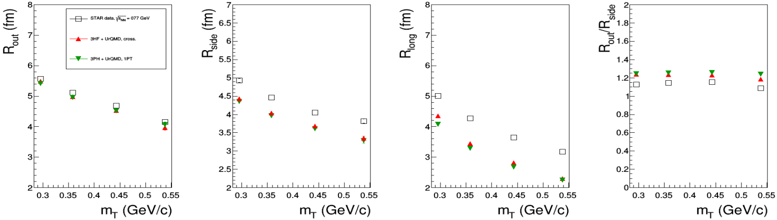
Femtoscopy (Batyuk&Malinina, preliminary)

Au+Au (b = 2 fm) at Elab = 30 A GeV vs STAR data

without UrQMD afterburner



with UrQMD afterburner

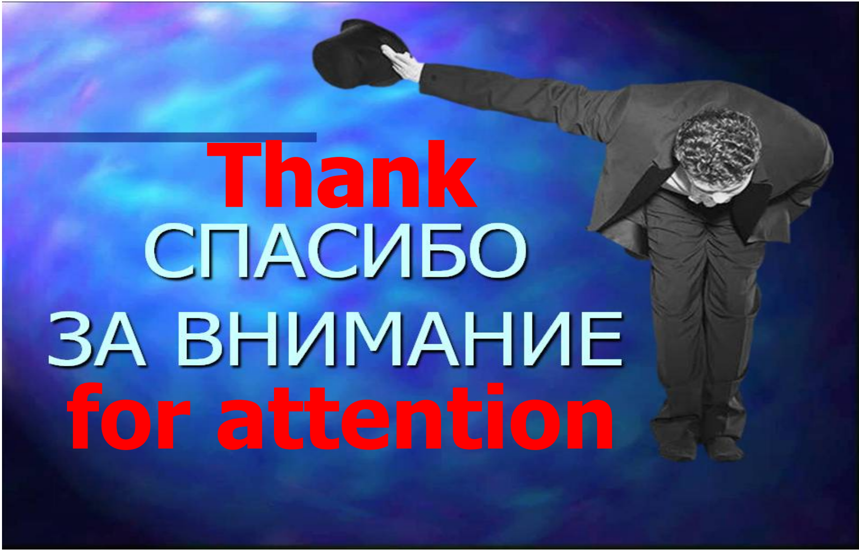


Afterburner is of prime importance!

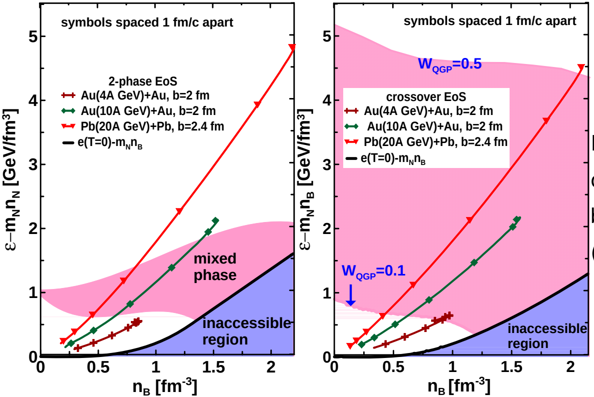
Summary

A new
Three-fluid Hydrodynamics-based Event Simulator Extended by UrQMD final State interactions (THESEUS)
is developed
3FH + Particlization + Afterburner(UrQMD)

- **it can be used for simulations of experimental events at FAIR-NICA-SPS-BES/RHIC**
- THESEUS without UrQMD well reproduces 3FH results
- **afterburner results in a qualitative change of the pion emission pattern: from flow to antiflow**
- **afterburner is of prime importance in femtoscopy**


Thank
СПАСИБО
ЗА ВНИМАНИЕ
for attention

Phase Evolution



Dynamical trajectories of matter in the central box of colliding nuclei (4fm×4fm×γ_{cm} 4fm)

Crossover transition by *Khvorostukhin et al.* is too smooth

Lattice QCD predicts a fast crossover.

Therefore, a true EoS is somewhere in between the *”Khvorostukhin et al.”*-crossover and *”Khvorostukhin et al.”*-2-phase EoS’s.

Onset of deconfinement happens at top-AGS–low-SPS energies.