First results within HydHSD hybrid model

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Contents

- The search for QGP in heavy ion collisions $\rightarrow$ it is necessary to connect observables with medium properties
- experimental data $\rightarrow$ we need to take into account collective effects

$\Rightarrow$ Simplest way is hydrodynamics.

- Hydrodynamics applicability conditions $\Rightarrow$ it cannot be applied at the initial stage of a collision $\Rightarrow$ a kinetic model – HSD/PHSD
- HSD/PHSD describes many experimental data in the energy range $E_{\mathrm{lab}} = 2 - 50\ A \cdot \mathrm{GeV}$ (NICA, FAIR)
- the final stage of an interaction – nonequilibrium $\Rightarrow$ "freeze-out" or posthydrodynamic rescattering

Hydrodynamics: equations and parameters

Equations of ideal hydrodynamics

Conservation laws of energy-momentum and baryon charge in the differential form are

$$\partial_\mu T^{\mu\nu} = 0, \quad \partial_\mu J^\mu = 0 \tag{1}$$

Ideal hydrodynamics assumes that matter is in local equilibrium!

The energy-momentum tensor, $T^{\mu\nu}$, and the vector of the baryon current, J^μ:

$$T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - P g^{\mu\nu},$$
$$J^\mu = n\, u^\mu.$$

$$u^\mu = \gamma(1, \mathbf{v}), \quad \gamma = (1 - v^2)^{-1/2}, \quad g^{\mu\nu} = \mathrm{diag}(1, -1, -1, -1)$$

The system of equations (1) is enclosed by an equation of state (EoS)

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

SHASTA (the SHarp and Smooth Transport Algorithm)

$$\mathrm{d}x = 0.2\ \text{fm}, \quad \lambda = \mathrm{d}t/\mathrm{d}x = 0.4$$

EoS of the hadron gas in a mean field [Satarov *et al.*, Phys. Atom. Nucl. **72**, 1390 (2009)] + σ-meson

The initial state

Hadron-String Dynamics

W. Cassing and E. L. Bratkovskaya, Phys. Rept. **308**, 65 (1999)

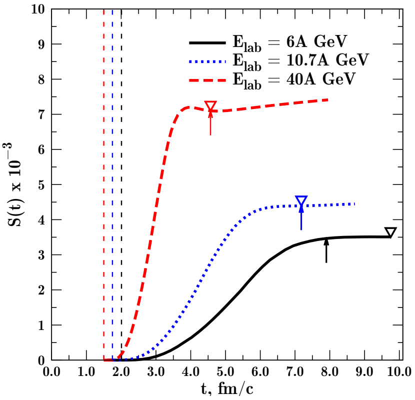
The transition from kinetic description to the hydrodynamic one occurs at some time moment $t_{\rm start}$.

$$t_{\rm start} = \frac{2R}{\gamma v} = 2R\sqrt{\frac{2m_N}{E_{\rm lab}}}$$ H. Petersen *et al.*, PRC **78**, 044901 (2008)

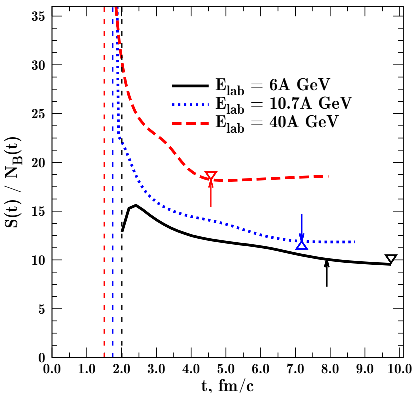
A more general approach: flattening of S and/or S/N_B

V. V. Skokov and V. D. Toneev, YaF **70**, 114 (2007)

Total entropy



Entropy-to-baryon number ratio



The short version (2 stages)
HSD + hydro + "instantaneous freeze-out"

The particle generator
H. Petersen *et al.*, PRC **78**, 044901 (2008) + N. S. Amelin *et al.*, PRC **74**, 064901 (2006) + resonance decays (AGS/SPS)

The hypersurface – CORNELIUS algorithm
P. Huovinen and H. Petersen, EPJA **48**, 171 (2012)

- isochronous – $\Delta t_{\mathrm{frz(tr)}} = t_{\mathrm{frz(tr)}} - t_{\mathrm{start}}$, $\mathrm{d}\sigma_\mu = \delta_{\mu,0}\mathrm{d}^3x$
- isothermal – $T \le T_{\mathrm{frz}}$
- isoenergetic – $\varepsilon \le \varepsilon_{\mathrm{frz}}$

The Cooper-Frye formulae

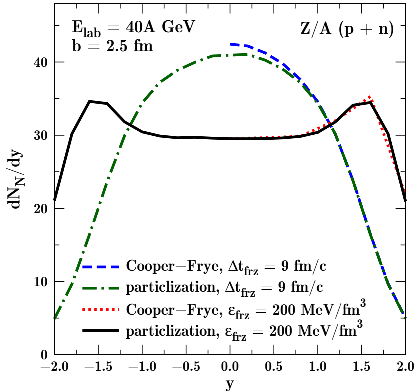
$$E\frac{\mathrm{d}^3 N_a}{\mathrm{d}p^3} = \frac{g_a}{(2\pi)^3}\int \mathrm{d}\sigma_\nu \frac{p^\nu}{e^{\beta(p^\nu u_\nu - \mu_a)} \pm 1},$$

+ resonance decays (AGS/SPS)

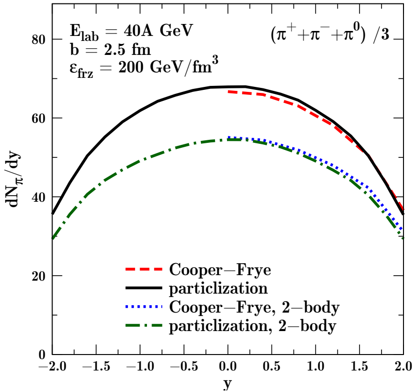
$$p^\mu = (E, \mathbf{p}), \quad \beta = 1/T, \quad \mathrm{d}\sigma_\mu = n_\mu \mathrm{d}^3\sigma$$

Particlization vs Cooper-Frye

Protons



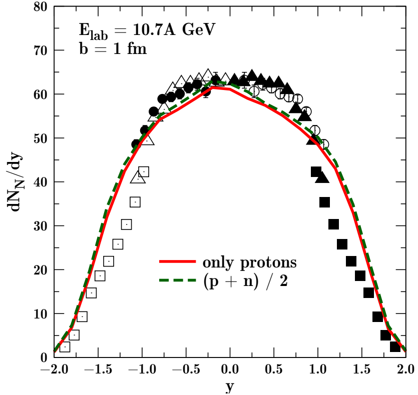
Pions

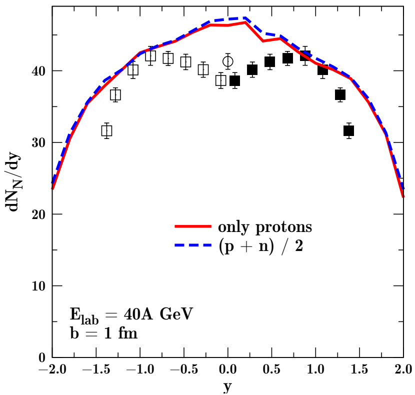


Application of the particlization procedure instead of the Cooper-Frye method gives a significant profit of numerical evaluation time.

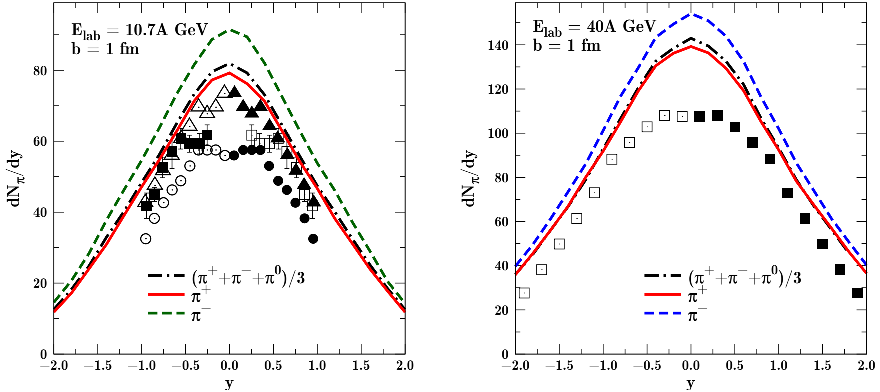
Z/A for isochronous freeze-out

HSD: (p+n)/2 for iso-T, ϵ





Isospin factor: pions



Comparision of freeze-out scenarios (the 2-stage model)

Some remarks

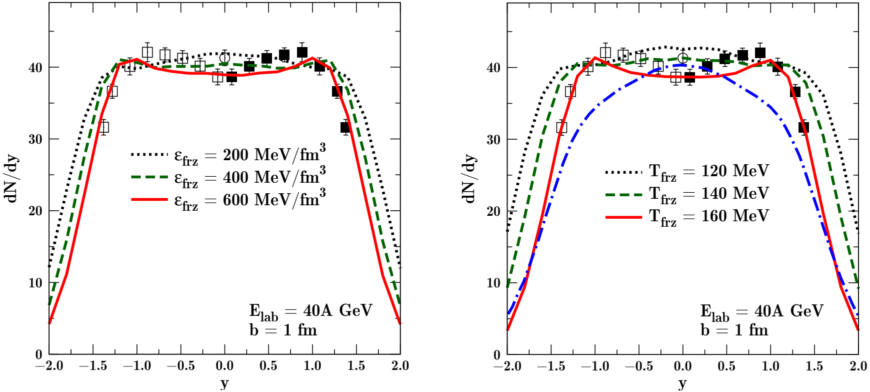
The assumption of isochronous freeze-out is manifestly not realistic!

The impact parameter $b = 1$ fm for all considering energies.

Only particles that have suffered interactions are included for obtaining the initial state since the hydro-stage of our model describes produced fireball expansion.

$E_{\mathrm{lab}} = 40\ A \cdot \mathrm{GeV}$

iso-ε iso-T



Satarov L.M., private communication

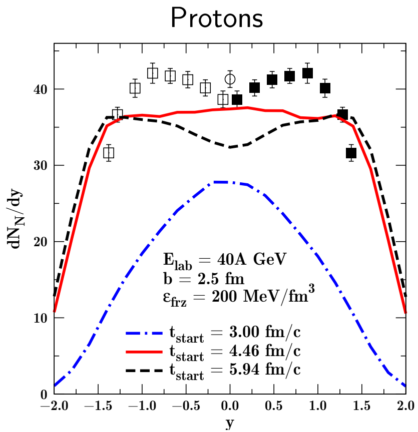
Properties of our model

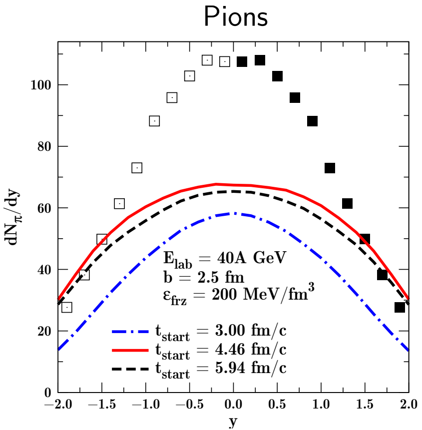
To reproduce the two-hump structure of the proton rapidity distribution, one needs to take rather large values of the parameters.

A 2-phase EoS is not necessary!

We have ambiguity between the choice of a proper initial state or EoS
J. Sollfrank *et al.*, PRC **55**, 392 (1997)

$E_{\text{lab}} = 40\ A \cdot \text{GeV}$, iso-$\varepsilon$

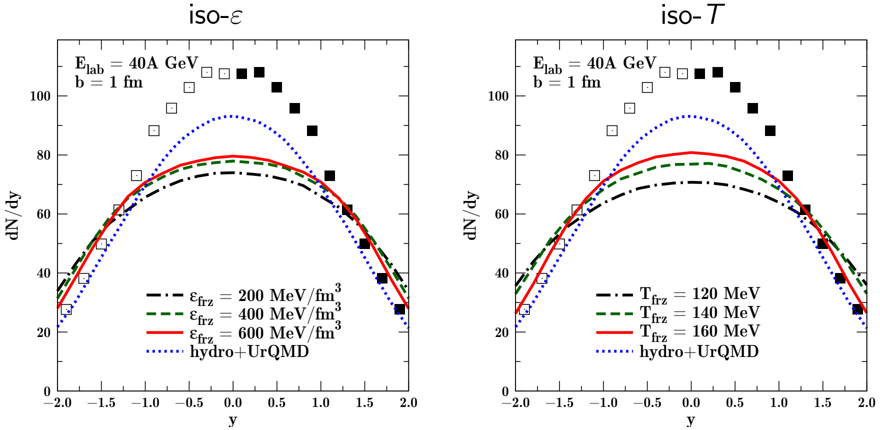




The two-hump structure also appears for a later transition time to hydrodynamics.

The distribution height at midrapidity, $y \approx 0$, depends on the choice of the transition time.

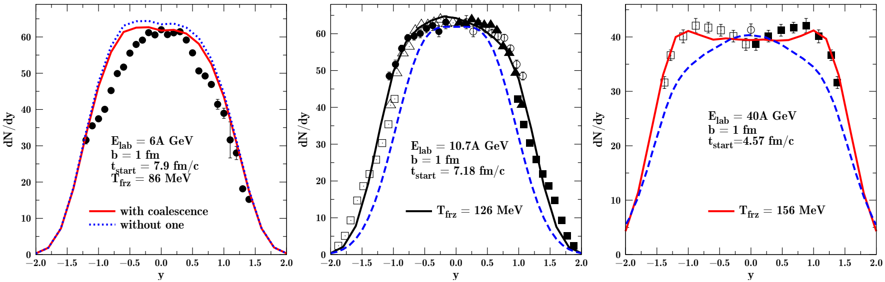
$E_{\rm lab} = 40\ A \cdot \text{GeV}$



One did not succeed in reproducing experimental pion spectra in a hybrid model with ideal hydrodynamics

Iu. A. Karpenko *et al.*, PRC **91**, 064901 (2015)

The statistical model: $T_{\mathrm{frz}}(E_{\mathrm{lab}})$
A. Andronic *et al.*, NPA **772**, 167 (2006)

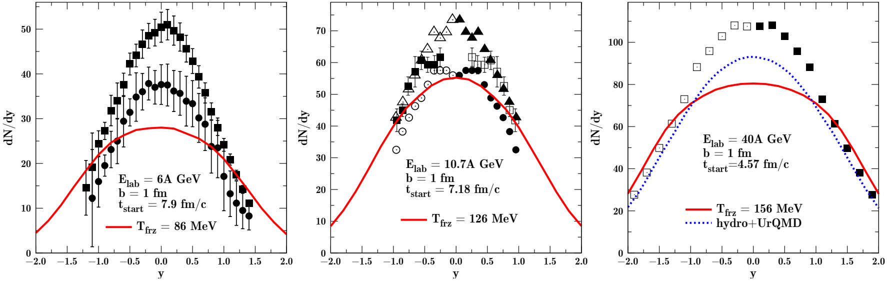


The nucleon coalescence effect is small for $E_{\mathrm{lab}} = 6\ A \cdot \mathrm{GeV}$ but it has to increase for lower energies.

Dashed lines are results for isochronous freeze-out [A. V. Merdeev, L. M. Satarov]:

appropriate initial conditions + the fit of t_{frz}.

The two-stage model for pions



The lack of pions is due to the absence in our model of dissipative effects which increase the entropy.

Hybrid model vs 3-fluid one [Yu. B. Ivanov et al., PRC 73, 044904 (2006)]

Parameter	Hybrid approach	3-fluid model
impact parameter, b	+	+
isotopic factor	freeze-out scenario dependent	Z/A
freeze-out parameter	$T_{\rm frz}(E_{\rm lab})$ or $\varepsilon_{\rm frz}(E_{\rm lab})$ or $t_{frz}(E_{\rm lab})$	$\varepsilon_{\rm frz} = 200$ MeV/fm^3
time	hydrodynamics start time, $t_{start}(E_{\rm lab})$	the formation time of the fireball fluid, $\tau = 2$ fm/c
non-equilibrium	$\eta(E_{\rm lab})$	$\xi_h(E_{\rm lab})$

So, a hybrid model with viscous hydro and 3-fluid model have, generally, the same number and kinds of parameters.

Non-equilibrium effects play a very important role in description of heavy-ion collisions in the AGS-SPS-NICA energy range.

Conclusions

- The two-stage hybrid model,
  HSD (the initial stage) + ideal hydro (the expansion) + freeze-out
  is proposed for describing heavy-ion collisions in NICA energy range
- The model is in qualitative satisfactory agreement with experiments on hadron spectral distributions. It allows to describe the proton spectra reasonably and even quantitatively.
- It is shown that 2-phase EoS doesn't needed to explain the two-hump structure in the proton rapidity distributions.
- The model including the ideal hydrodynamic stage is not able to describe pion rapidity spectra simultaneously with those for protons. It is necessary to take into account hadron matter viscosity within hydrodynamics!

Thank you for attention!

The full hybrid model (with an isochronous transition to particles)

Posthydrodynamic rescattering: motivation and the transition condition

the mean free path of particles > the system size

Hydrodynamics breaks to work!

$\Rightarrow$ It is needed to switch to the kinetic description

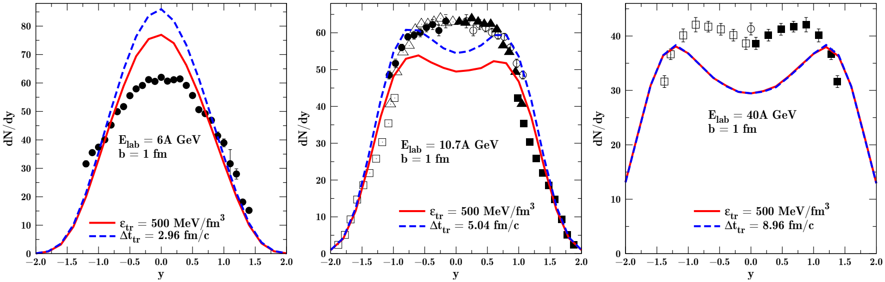
The transition to particles is similar to freeze-out, just the evolution is not finished

the isochronous transition when $\varepsilon < \varepsilon_{\mathrm{tr}}$ for all cells

$\varepsilon_{\mathrm{tr}} = 500$ MeV/fm^3

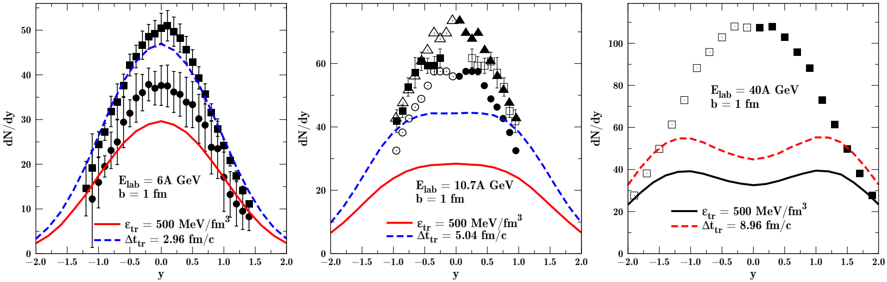
Iu. A. Karpenko *et al.*, J. Phys.: Conf. Ser. **509**, 012067 (2014)

Posthydrodynamic rescattering effect for protons



Taking rescattering into account at the final stage results in decreasing rapidity distributions

Posthydrodynamic rescattering effect for pions



The results are worse than for the 2-stage version.
The reason is the isochronous particlization.