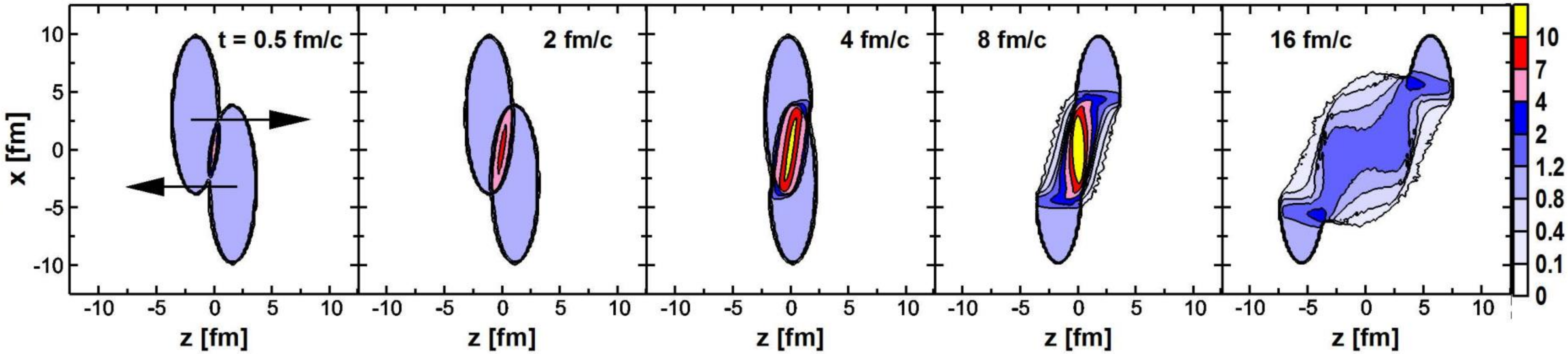
Light-nuclei production in heavy-ion collisions at $\sqrt{s_{NN}} = 6.4 - 19.6$ GeV in 3-fluid dynamics

Marina Kozhevnikova (JINR)

In collaboration with Yu. B. Ivanov



NICA 2022, Moscow, 15 December 2022

Introduction

- Light-nuclei production is related to search for critical point in QCD phase diagram.
- There are various 3D dynamical models with coalescence mechanism of the light-nuclei production.
- Microscopic approaches – PHQMD and SMASH
- The thermodynamical approach: no additional parameters needed for light-nuclei production and light nuclei are produced on the same basis as hadrons.
- THESEUS generator is based on the thermodynamical approach.

Main areas of research: study the light-nuclei production at collision energies of the BES-RHIC, SPS, NICA and FAIR.

3FD model

Target-like fluid: $\partial_\mu J_t^\mu = 0$ $\quad \partial_\mu T_t^{\mu\nu} = -F_{tp}^\nu + F_{ft}^\nu$

Leading particles carry bar. charge — exchange/emission

Projectile-like fluid: $\partial_\mu J_p^\mu = 0,$ $\quad \partial_\mu T_p^{\mu\nu} = -F_{pt}^\nu + F_{fp}^\nu$

Fireball fluid: $J_f^\mu = 0,$ $\quad \partial_\mu T_f^{\mu\nu} = F_{pt}^\nu + F_{tp}^\nu - F_{fp}^\nu - F_{ft}^\nu$

Baryon-free fluid — Source term — Exchange

The source term is delayed due to a formation time τ

Total energy-momentum conservation:

$$\partial_\mu (T_p^{\mu\nu} + T_t^{\mu\nu} + T_f^{\mu\nu}) = 0$$

The output = Lagrangian test particles (i.e. fluid droplets) for each fluid α(= p, t or f).

Fluid droplets = elements of freeze-out surface in hydrodynamic models.

Observables = numerically integrating hadron distribution functions over the set of droplets.

Physical Input:

- Equation of State
- Friction
- Freeze-out energy density ε_{frz} = 0.4 GeV/fm^3

EoS:

- hadronic EoS (no phase transition)
- hadronic+QGP EoS with 1st-order PT
- hadronic+QGP EoS with crossover

3FD: Yu.B. Ivanov, V.N. Russkikh, V.D. Toneev, PHYSICAL REVIEW C 73, 044904 (2006)

EoS: A. Khvorostukhin, V.V. Skokov, V.D. Toneev, K. Redlich, EPJ C48, 531 (2006)

THESEUS event generator

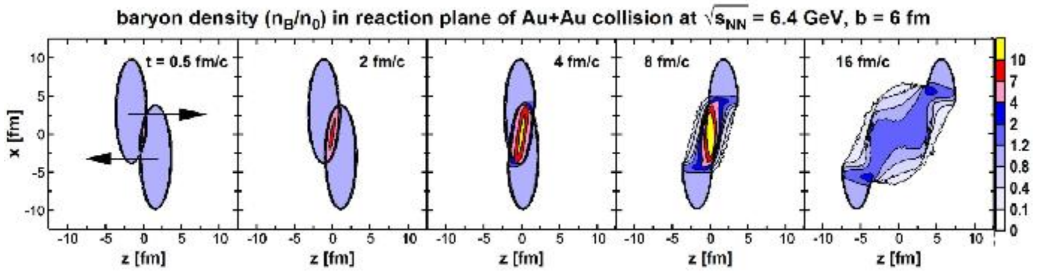
- In 2016 the THESEUS event generator was introduced.

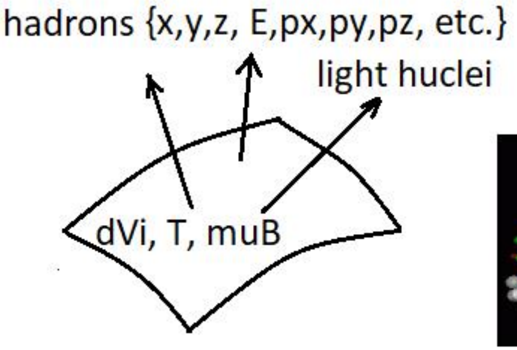
(3FD+Particlization+UrQMD): P. Batyuk et al., PHYSICAL REVIEW C 94, 044917 (2016)

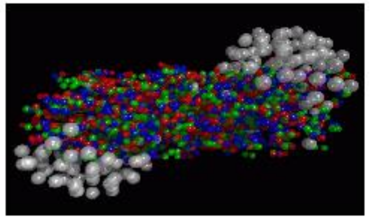
- **THESEUS = 3FD + Monte Carlo hadron sampling + rescatterings/decays via UrQMD**
- THESEUS presents the 3FD output in terms of a set of observed particles.
- There were no light nuclei included.
- Since the time THESEUS was first presented, certain updates have been made, further referred to as THESEUS-v2.

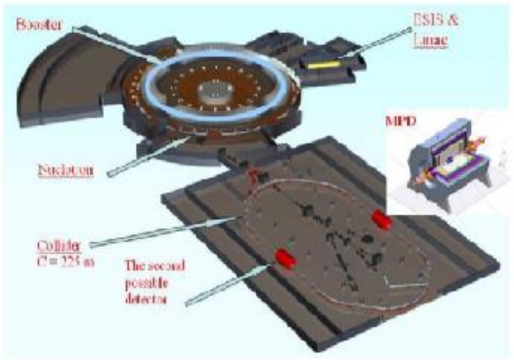
THESEUS-v2: M. Kozhevnikova, Yu. Ivanov, Yu. Karpenko, D. Blaschke, O. Rogachevsky, PRC 103 (2021) 4, 044905

Hydrodynamic modelling of nuclear collisions for NICA / FAIR









Initial state → hydrodynamic evolution → particlization → afterburner → detector response

3-fluid hydrodynamical model (Y.Ivanov et al.)

THESEUS generator

(optionally) UrQMD, etc. (Iu. Karpenko, H.Elfner)

GEANT, MPD,BM@N (O.Rogachevsky, P.Batuyk, S.Merts et al.)

THESEUS-v2: updates

No clusters in 3FD originally.

To include light nuclei in thermodynamics, baryon chemical potential should be recalculated.

The main update: recalculation of baryon chemical potential taking into account light nuclei production, proceeding from the local baryon number

$$
\begin{aligned}
& n_{\text{primordial } N}(x;\mu_B,T) + \sum_{\text{hadrons}} n_i(x;\mu_B,\mu_S,T) \\
= & \, n_{\text{observable } N}(x;\mu'_B,T) + \sum_{\text{hadrons}} n_i(x;\mu'_B,\mu_S,T) \\
& + \sum_{\text{nuclei}} n_c(x;\mu'_B,\mu_S,T).
\end{aligned}
$$

The list of light-nuclei species is shown in Table.

Nucleus(E[MeV])	J	decay modes, in %
d	1	Stable
t	1/2	Stable
^{3}He	1/2	Stable
^{4}He	0	Stable
^{4}He(20.21)	0	$p = 100$
^{4}He(21.01)	0	$n = 24,\ p = 76$
^{4}He(21.84)	2	$n = 37,\ p = 63$
^{4}He(23.33)	2	$n = 47,\ p = 53$
^{4}He(23.64)	1	$n = 45,\ p = 55$
^{4}He(24.25)	1	$n = 47,\ p = 50,\ d = 3$
^{4}He(25.28)	0	$n = 48,\ p = 52$
^{4}He(25.95)	1	$n = 48,\ p = 52$
^{4}He(27.42)	2	$n = 3,\ p = 3,\ d = 94$
^{4}He(28.31)	1	$n = 47,\ p = 48,\ d = 5$
^{4}He(28.37)	1	$n = 2,\ p = 2,\ d = 96$
^{4}He(28.39)	2	$n = 0.2,\ p = 0.2,\ d = 99.6$
^{4}He(28.64)	0	$d = 100$
^{4}He(28.67)	2	$d = 100$
^{4}He(29.89)	2	$n = 0.4,\ p = 0.4,\ d = 99.2$

Table: Stable light nuclei and low-lying resonances of the ^{4}He system (from BNL properties of nuclides).

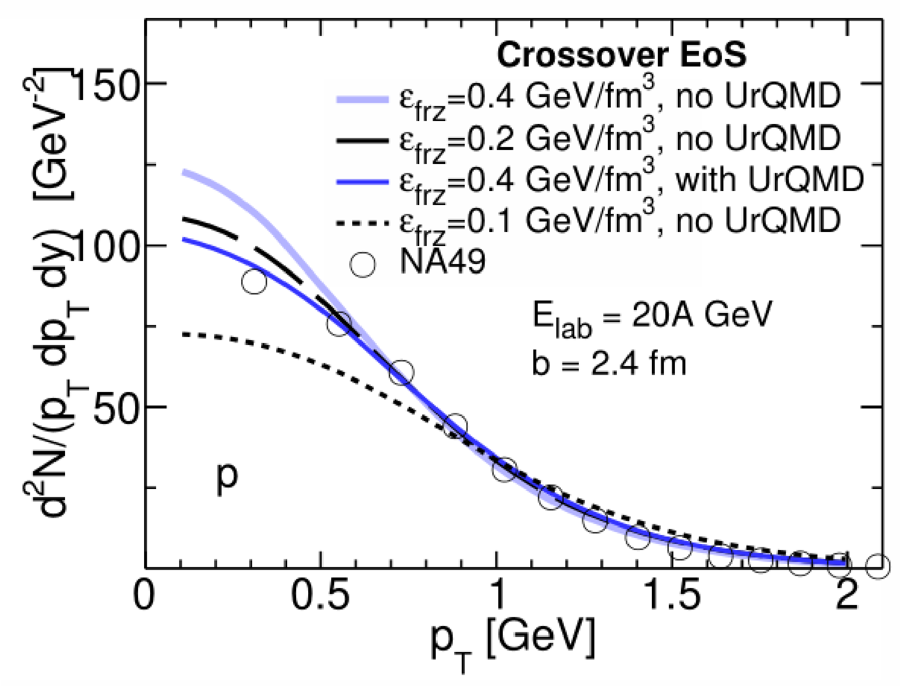
THESEUS-v2: afterburner for light nuclei

There is no UrQMD afterburner stage for light nuclei, so we imitate the afterburner by later freeze-out for light nuclei.

- To choose suitable late freeze-out we fit protons by means of the late freeze-out:

$$\varepsilon_{\mathrm{frz}} = 0.2\ \mathrm{GeV/fm^3}.$$

- We choose protons because they are closely related to the light nuclei.



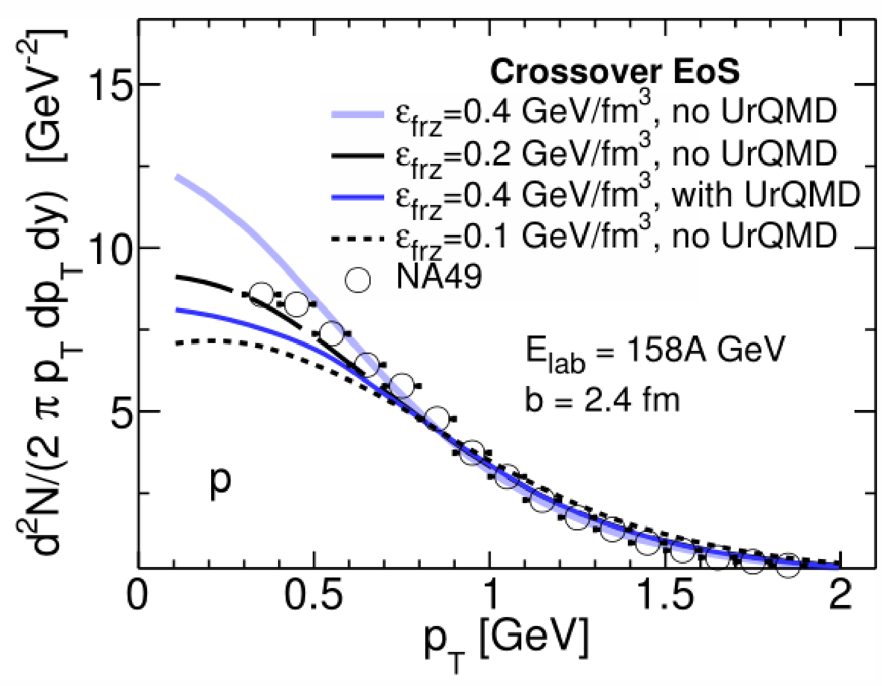
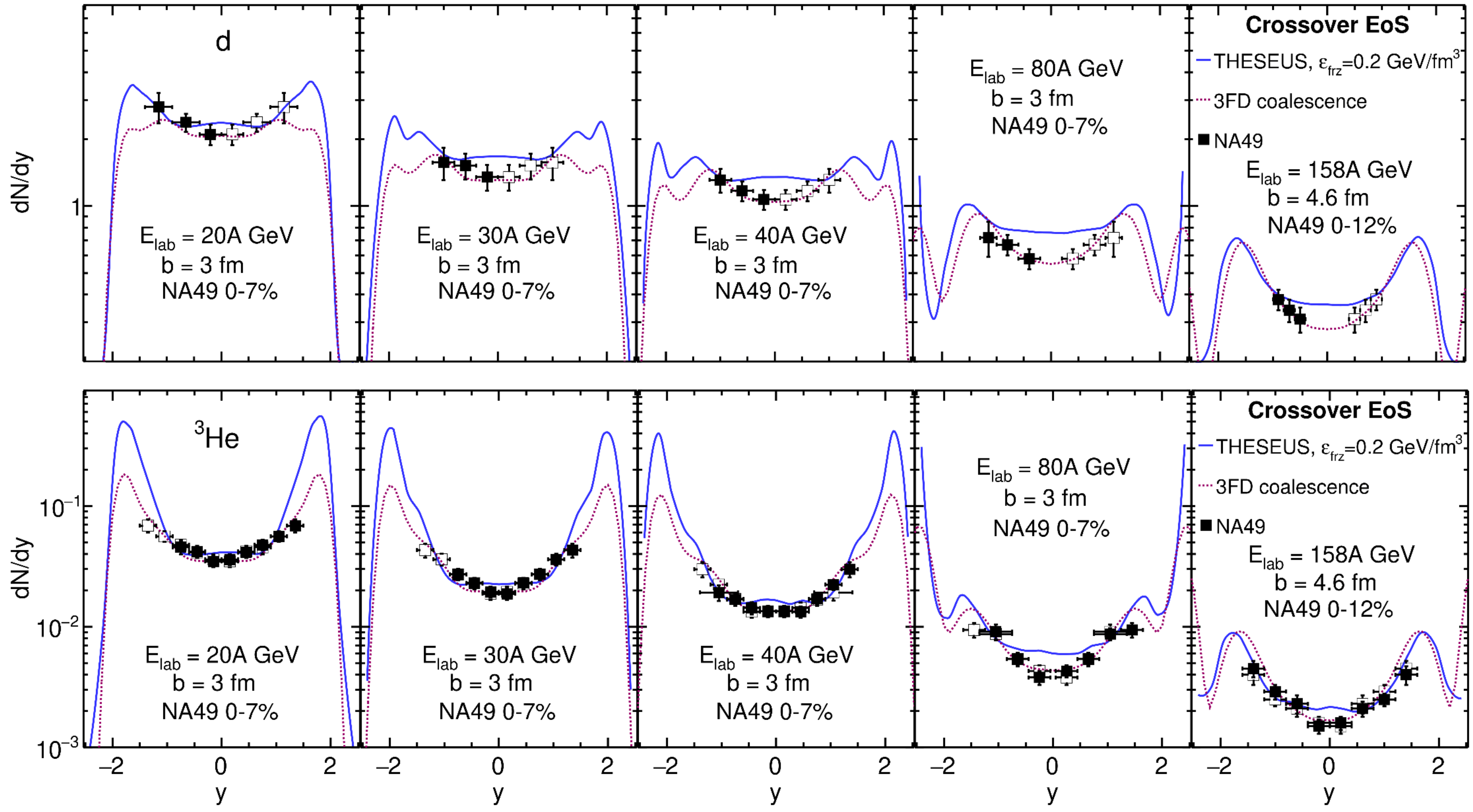


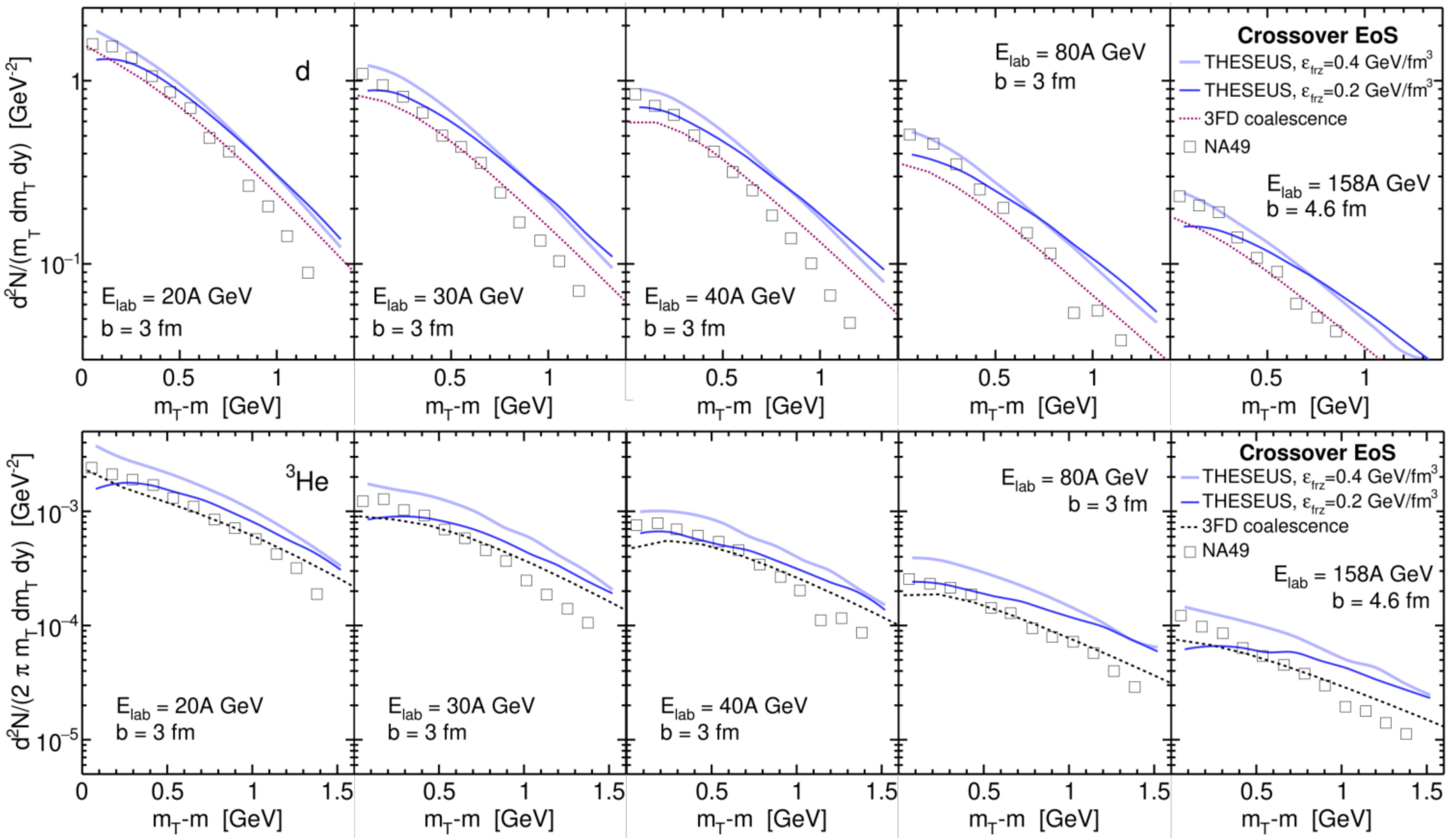
Fig.: Transverse-momentum spectra of protons in central Au+Au collisions.

THESEUS-v2: rapidity distributions, $\varepsilon_{\text{frz}} = 0.2\ \text{GeV/fm}^3$.



Puzzle: reproduction of the ^{3}He data is better than that of deuterons, in spite of that ^{3}He heavier.

m_T-spectra: deuterons and Helium 3



The slopes change. The curves become in better agreement with data at low m_T.

Particle ratios

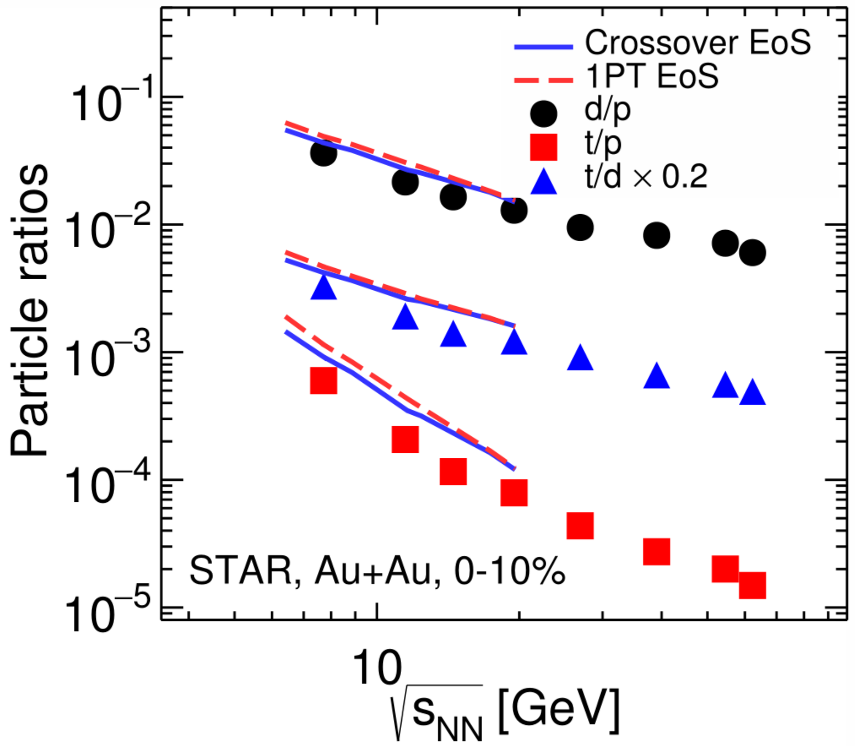


Fig.: Energy dependence of d/p, t/p, and t/d midrapidity ratios for central (0-10%) Au+Au collisions. Simulations were performed at b = 4 fm for Au+Au and at b = 3 fm for Pb+Pb in rapidity bin |y| < 0.5.

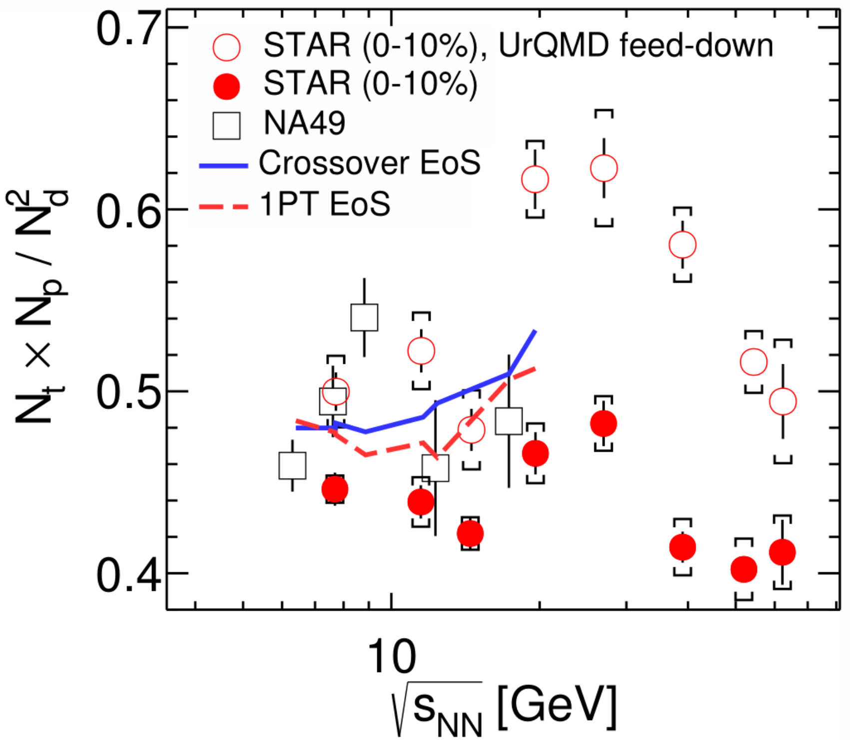


Fig.: Energy dependence of the midrapidity ratio $N(t) \times N(p)/N^2(d)$ in central Au+Au and Pb+Pb collisions. Simulations at b = 4 fm for Au+Au, at b = 3 fm ($\sqrt{s_{NN}} < 17.4$ GeV) and b = 4.6 fm ($\sqrt{s_{NN}} = 17.4$ GeV) for Pb+Pb in rapidity bin |y| < 0.5. N(p) is related to protons without feed-down from weak decays.

Growth near 20 GeV resembles preliminary STAR data, where feed-down from weak decays was subtracted by means of UrQMD.

Summary

- The thermodynamical approach approximately reproduces data on light nuclei with a single parameter, $\varepsilon_{\mathrm{frz}} = 0.2\ \mathrm{GeV/fm^3}$.
- The functional dependencies (on y, p_T, centrality, mass of light nuclei) qualitatively are reproduced.
- Imperfect reproduction of the light-nuclei data leaves room for medium effects.

Acknowledgments

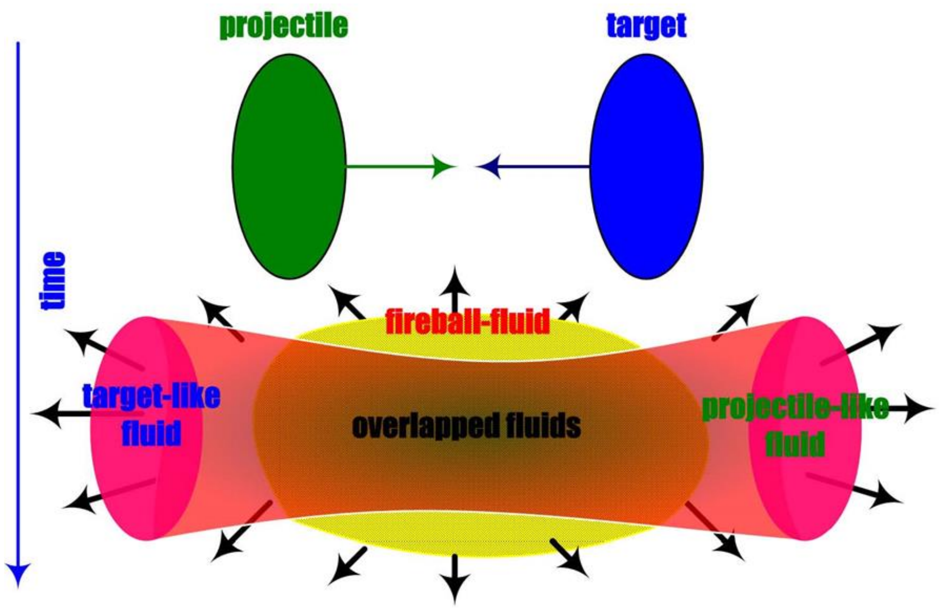
- We are grateful to **David Blaschke** for convincing us to apply the thermodynamic approach to modeling the light-nuclei production in heavy-ion collisions.
- We are especially grateful to **Iu. Karpenko** for the expertise, interesting suggestions and discussions.

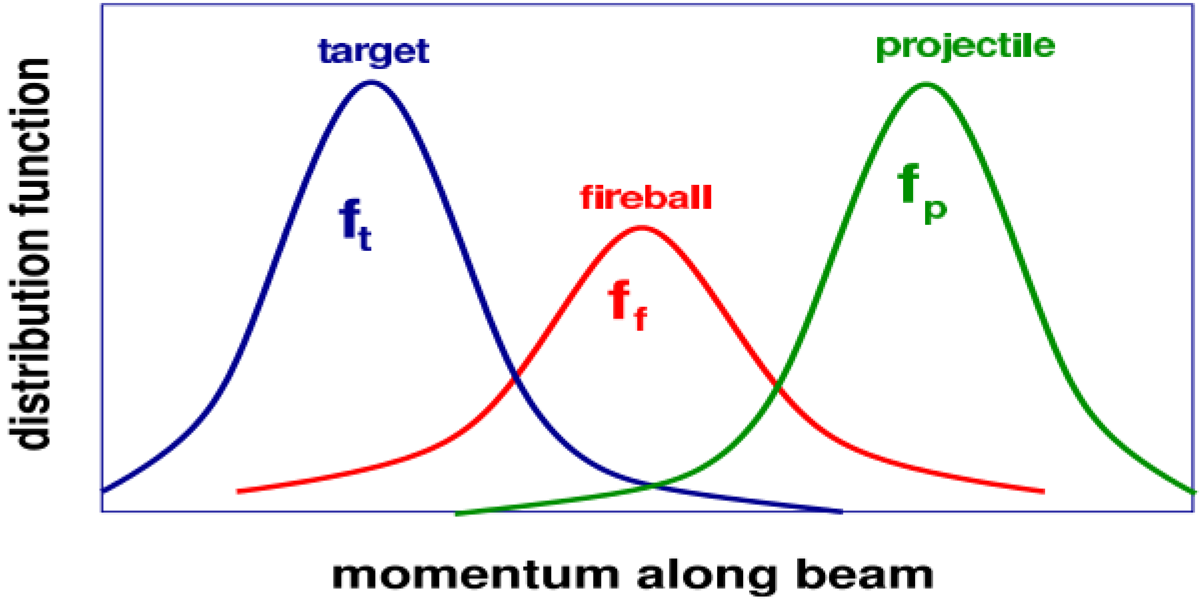
Thank you
for your attention!

Three-fluid dynamics (3FD) model

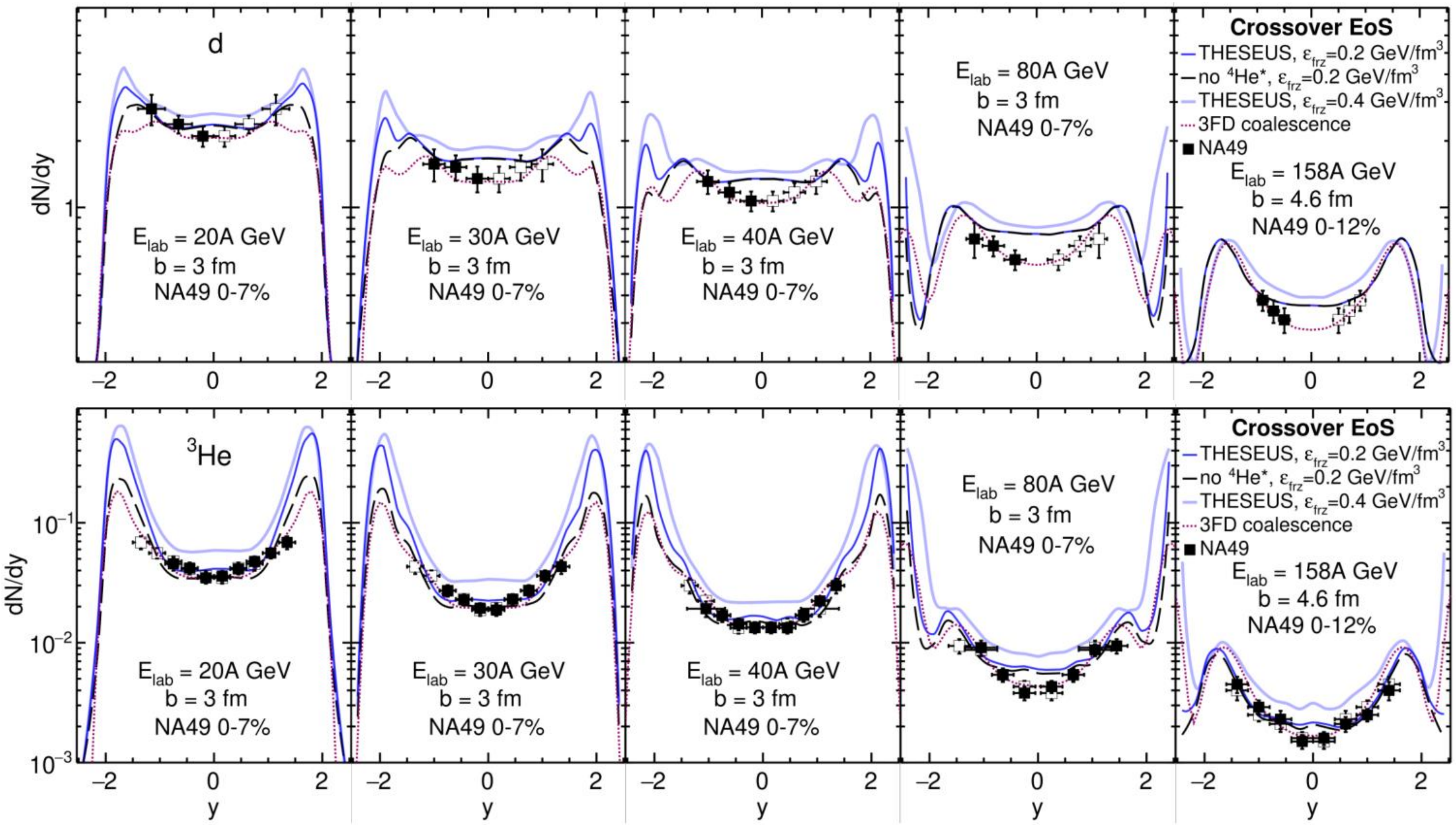
The 3FD approximation simulate the early, nonequilibrium stage of the strongly-interacting matter:

- baryon-rich fluids: nucleons of the projectile (p) and the target (t) nuclei;
- fireball (f) fluid: newly produced particles which dominantly populate the midrapidity region.





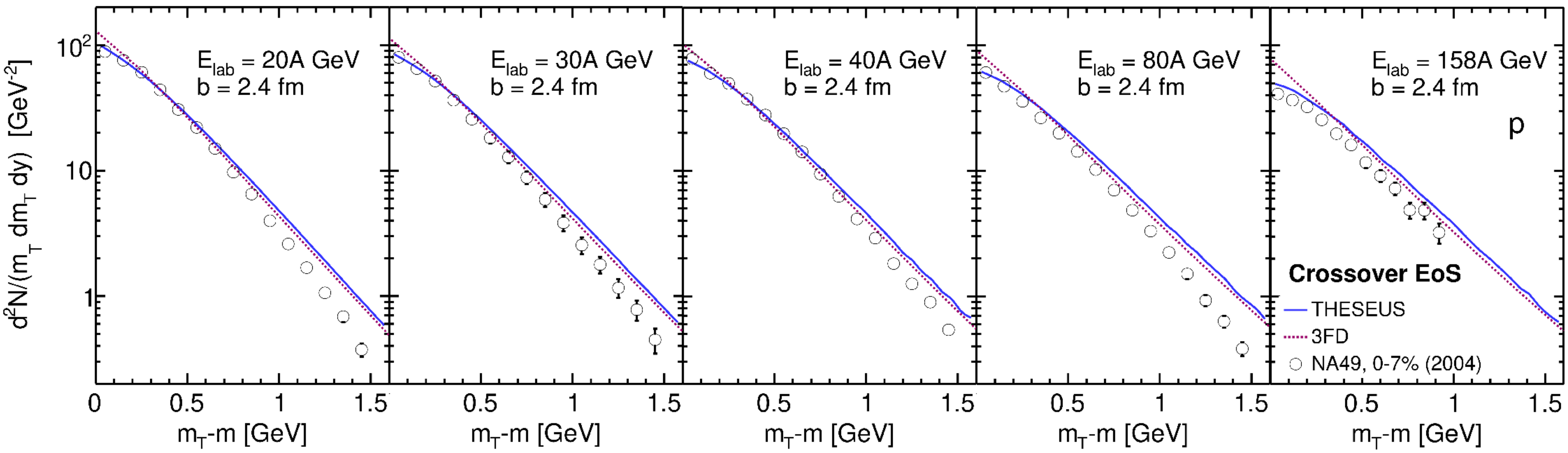
THESEUS-v2: rapidity distributions, $\varepsilon_{\rm frz} = 0.2\ {\rm GeV/fm^3}$.



Resonances of ^{4}He are unimportant in midrapidity at the considered collision energies.

Puzzle: reproduction of the ^{3}He data is better than that of deuterons, in spite of that ^{3}He heavier.

THESEUS-v2: m_T-spectra of protons.



m_T-spectra of protons: thermodynamics works good with soft particles and with hard particles not perfect.

Directed flow $v_1(y)$

The single particle distribution function:

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_{RP}))\right)$$

The first coefficient of Fourier expansion, i.e. **directed flow**:

$$v_1^{(a)}(y) = \frac{\int d^2p_T\,(p_x/p_T)\,E\;dN_a/d^3p}{\int d^2p_T E\;dN_a/d^3p}.$$

$v_1 = \langle \cos\phi \rangle$, where ϕ – azimuthal angle.

In THESEUS: $v_1(y)$ is calculated in terms of sums over hadrons rather than integrals over momenta.

Directed flow $v_1(y)$: protons and deuterons

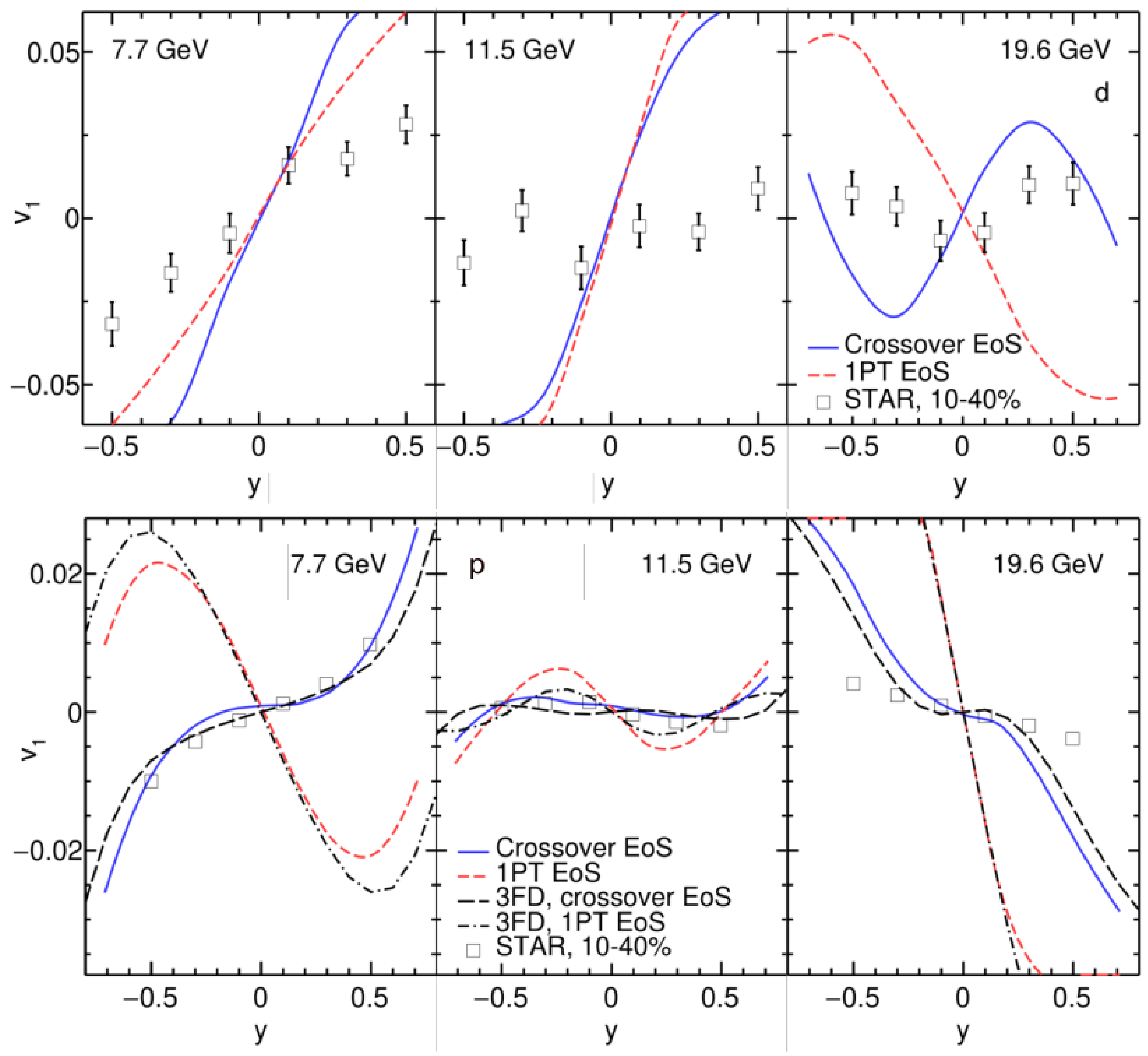


Fig.: Directed flow of **deuterons** (upper raw of panels) and **protons** (lower raw of panels) as function of rapidity in semicentral (b = 6 fm) Au+Au collisions.

Nearest plans

- Study of v_1 puzzle for deuterons: p_T-differential $v_1(p_T)$;
- Including medium effects;
- Predictions for NICA energies;
- HADES and AGS data;
- Hyper-(anti)nuclei.