Light-nuclei production in heavy-ion collisions at the energy range of $\sqrt{s_{NN}} = 3 - 19.6$ GeV in generator THESEUS based on 3-fluid dynamical model

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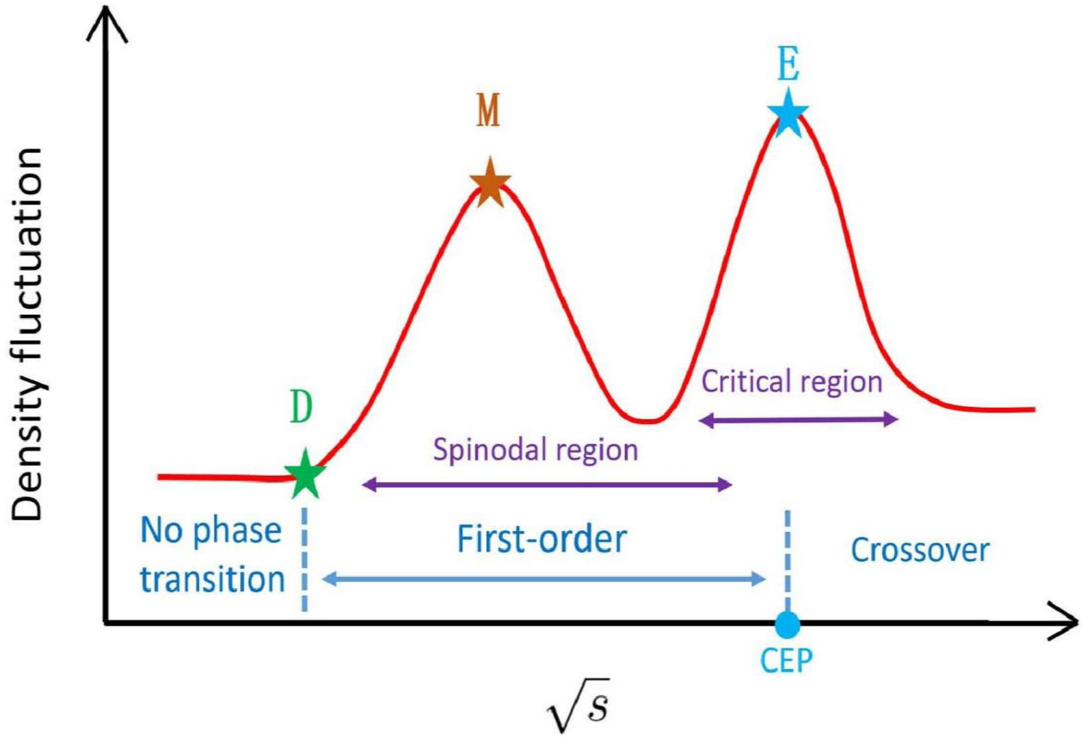
Light nuclei in heavy-ion collisions

Why are they interesting?

- Abundant production at NICA and FAIR energies
- Very scarce data at NICA and FAIR energies
- Signal of spinodal instability
- Signal of critical endpoint (CEP)
- Medium effects



Kai-Jia Sun, et al., PLB 781 (2018) 499

3FD model

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

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

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

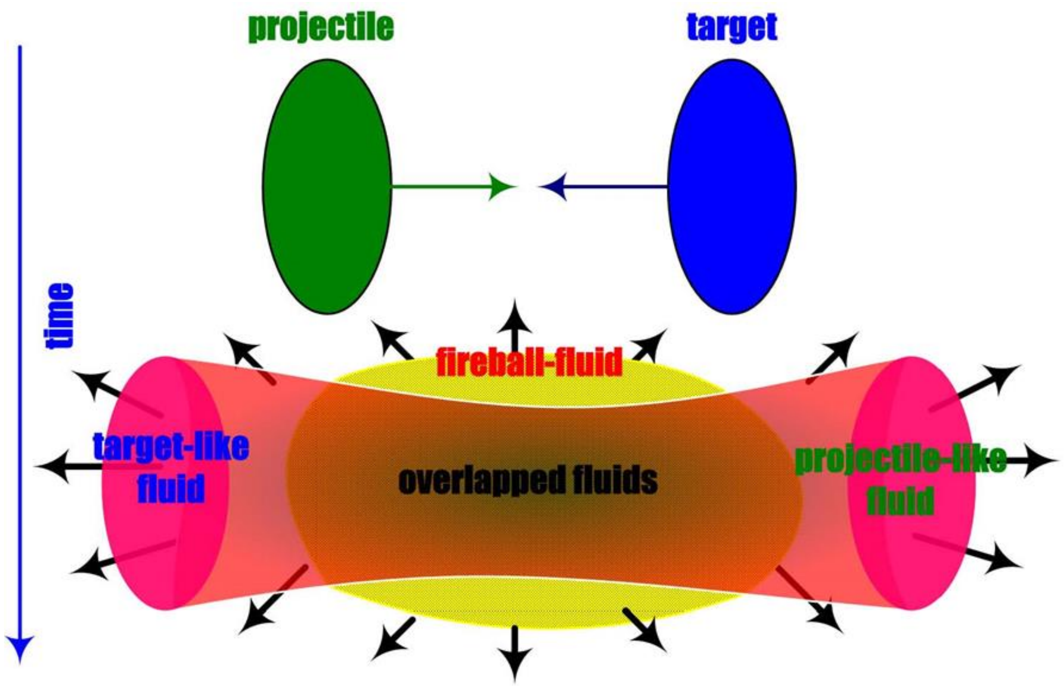
Fireball fluid: $J_f^\mu = 0$, $\qquad$ $\partial_\mu T_f^{\mu\nu} = F_{pt}^\nu + F_{tp}^\nu - F_{fp}^\nu - F_{ft}^\nu$

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

The source term is delayed due to a formation time τ

Total energy-momentum conservation:

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



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 and 3FD

3FD:

- The output = Lagrangian test particles (i.e. fluid droplets) for each fluid α(= p, t or f).
- Fluid droplet = element of freeze-out surface
- Observables = integration of hadron distribution functions over freeze-out surface

This is inconvenient for application of experimental acceptance

THESEUS:

- 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 + afterburner via UrQMD**
- THESEUS presents the 3FD output in terms of a set of observed particles.

THESEUS-v2: updates

No light-nuclei in 3FD originally.

The main update: To include light nuclei in thermodynamics we recalculate the baryon chemical potential taking into account light nuclei production, proceeding from the local baryon number conservation:

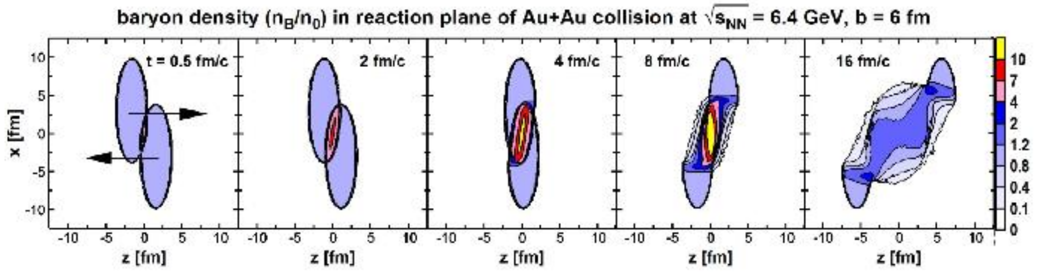
$$
\begin{aligned}
& n_{\text{primordial } N}(x;\mu_B,T) + \sum_{\text{hadrons}} n_i(x;\mu_B,\mu_S,T) \\
&= n_{\text{observable } N}(x;\mu'_B,T) + \sum_{\text{hadrons}} n_i(x;\mu'_B,\mu_S,T) \\
&\quad + \sum_{\text{nuclei}} n_c(x;\mu'_B,\mu_S,T).
\end{aligned}
$$

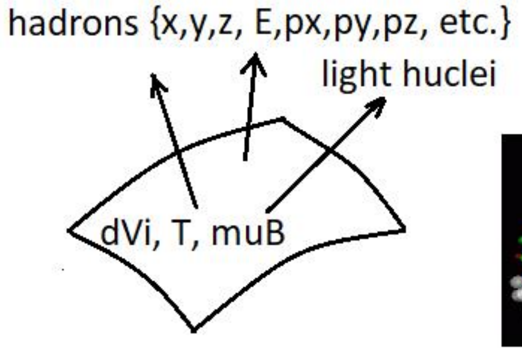
The list of light-nuclei species is shown in Table.

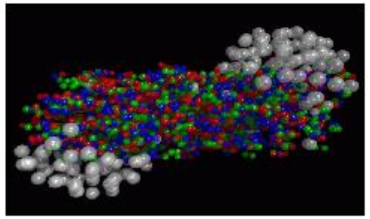
Nucleus(E[MeV])	J	decay modes, in %
d	1	Stable
t	1/2	Stable
^{3}He	1/2	Stable
^{4}He	0	Stable
^{4}He(20.21)	0	$p = 100$
^{4}He(21.01)	0	$n = 24,\ p = 76$
^{4}He(21.84)	2	$n = 37,\ p = 63$
^{4}He(23.33)	2	$n = 47,\ p = 53$
^{4}He(23.64)	1	$n = 45,\ p = 55$
^{4}He(24.25)	1	$n = 47,\ p = 50,\ d = 3$
^{4}He(25.28)	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).

Hydrodynamic modelling of nuclear collisions for NICA / FAIR







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

3-fluid hydrodynamical model (Y.Ivanov et al.) — initial state, hydrodynamic evolution

THESEUS generator — particlization

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

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

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:

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

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

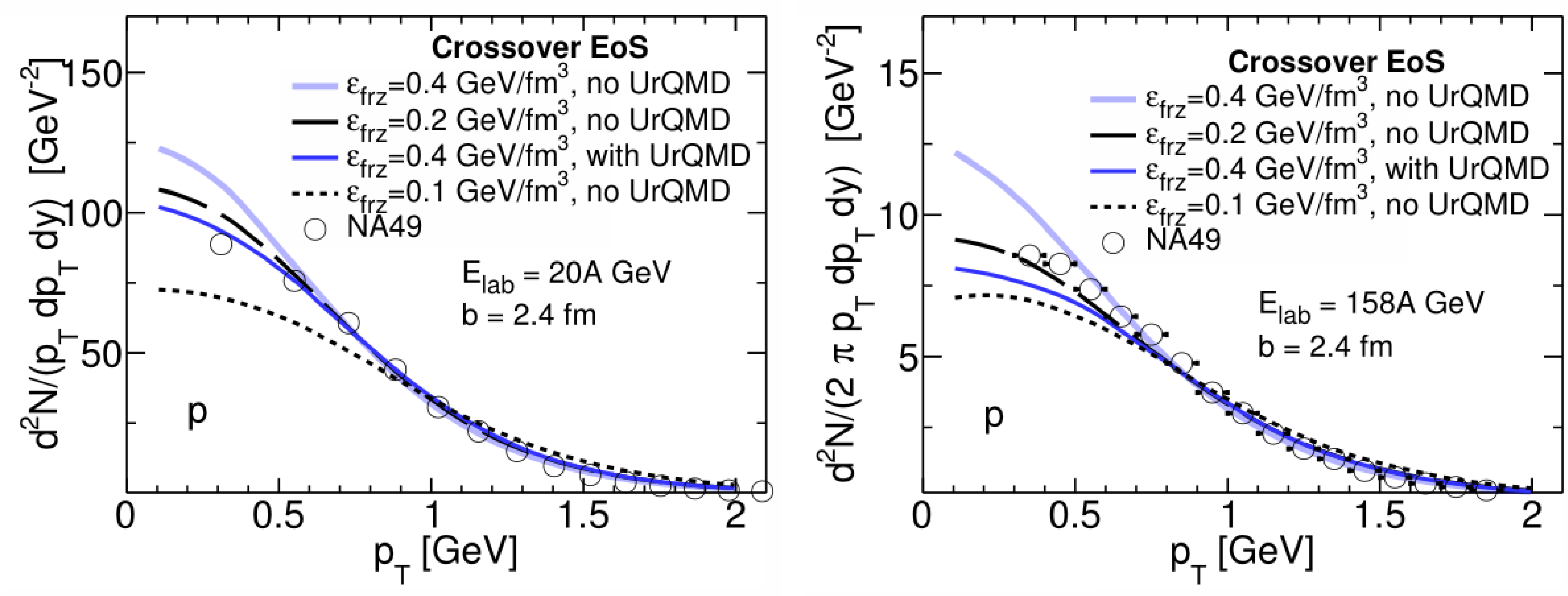
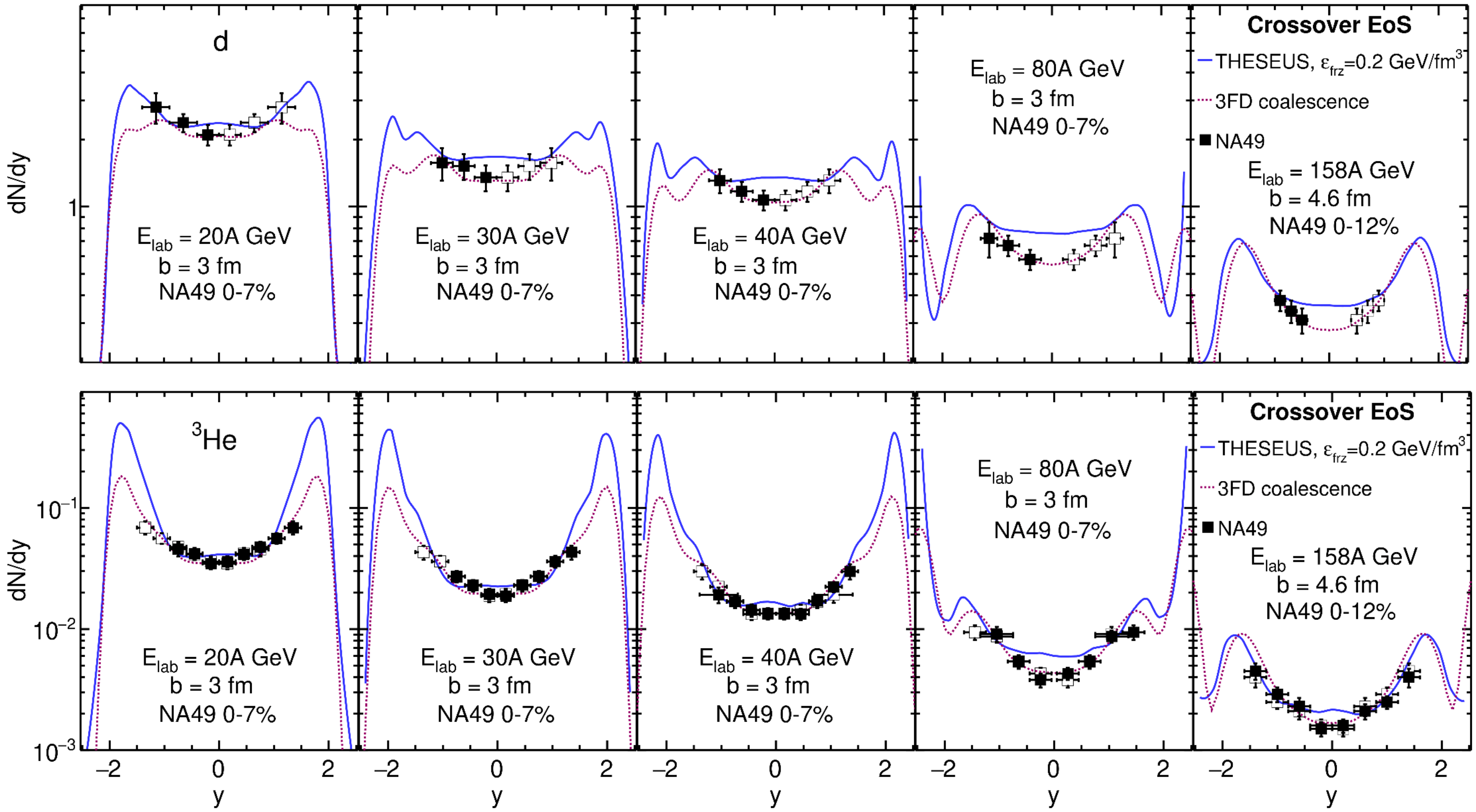


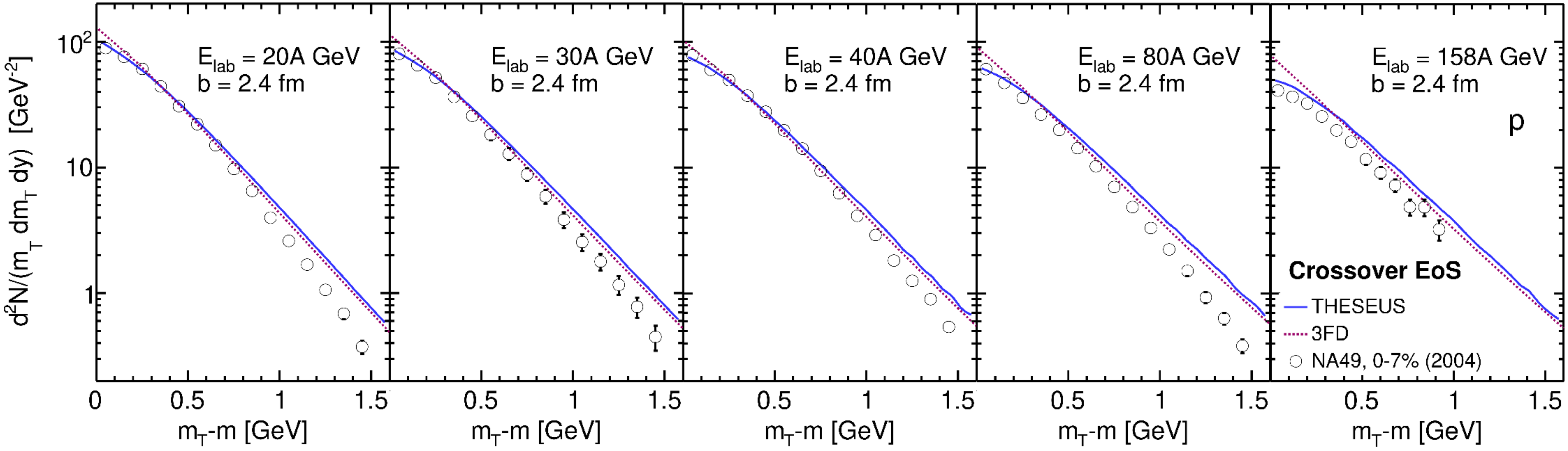
Fig.: Transverse-momentum spectra of protons in central Au+Au collisions.

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



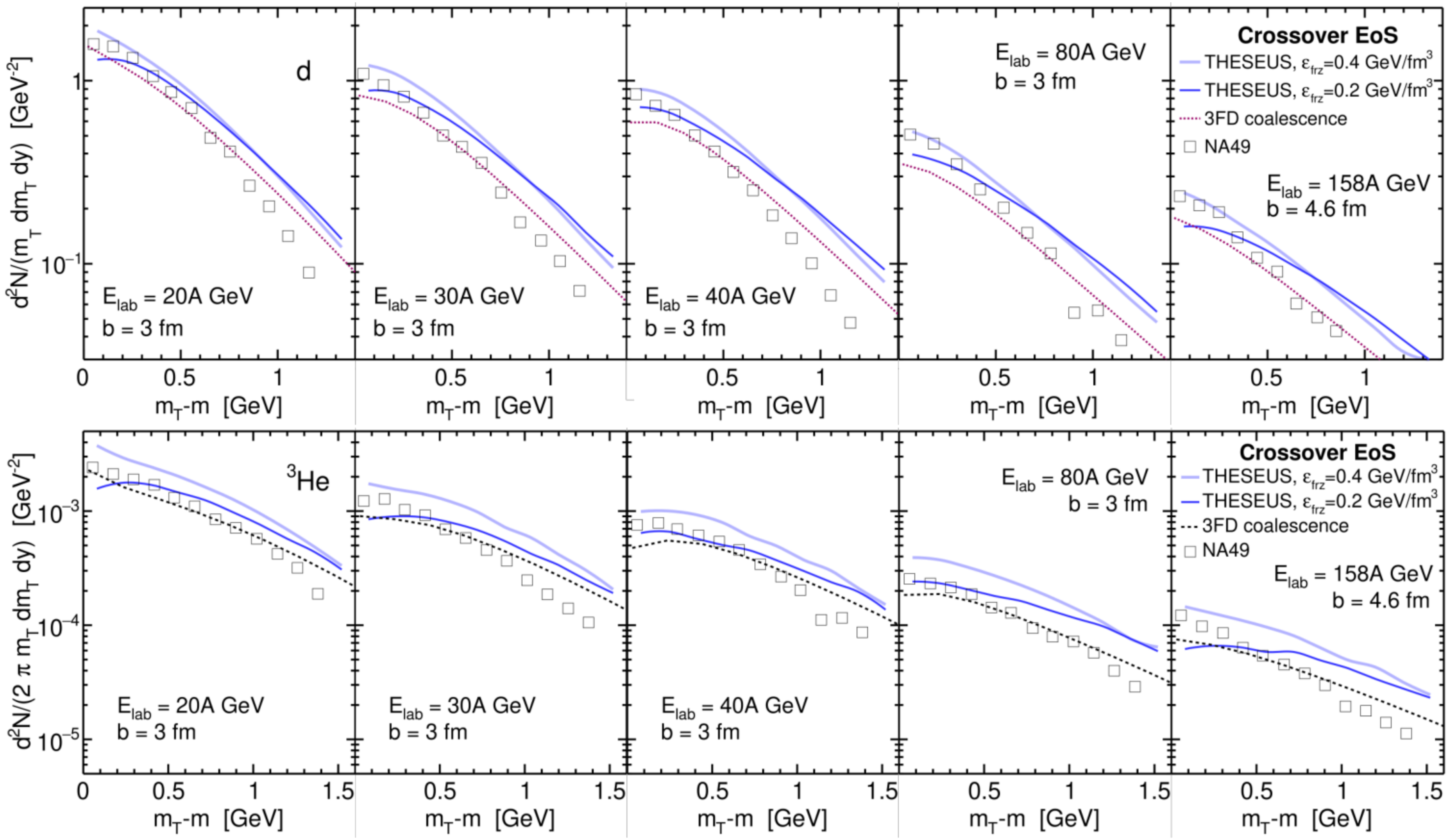
Puzzle: reproduction of the ^3He data is better than that of deuterons, in spite of that ^3He heavier.

THESEUS-v2: m_T-spectra of protons.



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

m_T-spectra: deuterons and Helium 3



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

Preliminary rapidity distributions for protons and light nuclei

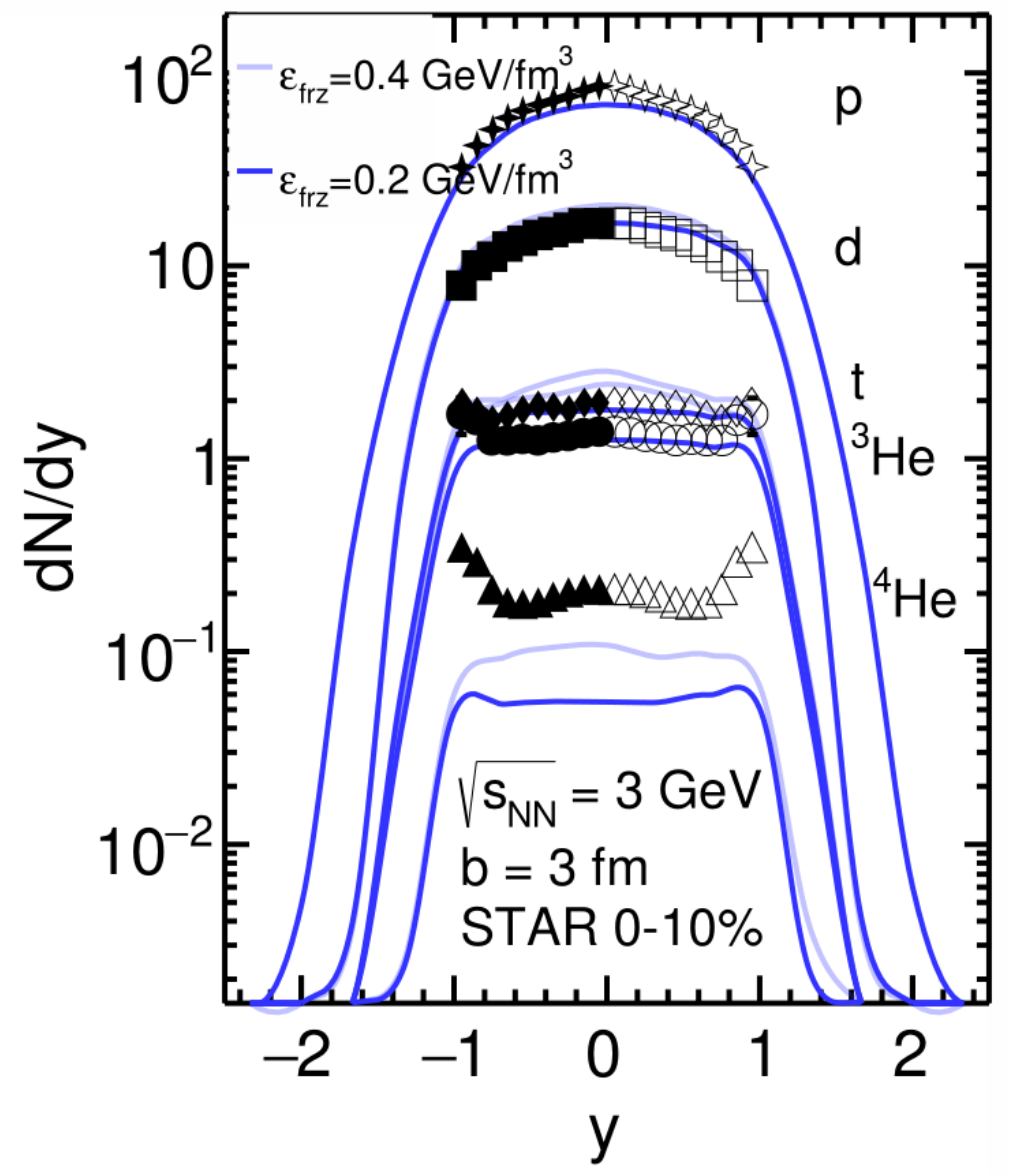


Fig.: Rapidity distributions of **protons** and **light nuclei** as function of rapidity in Au+Au central (b = 3 fm) collisions at $\sqrt{s_{NN}} = 3$GeV.

Particle ratios

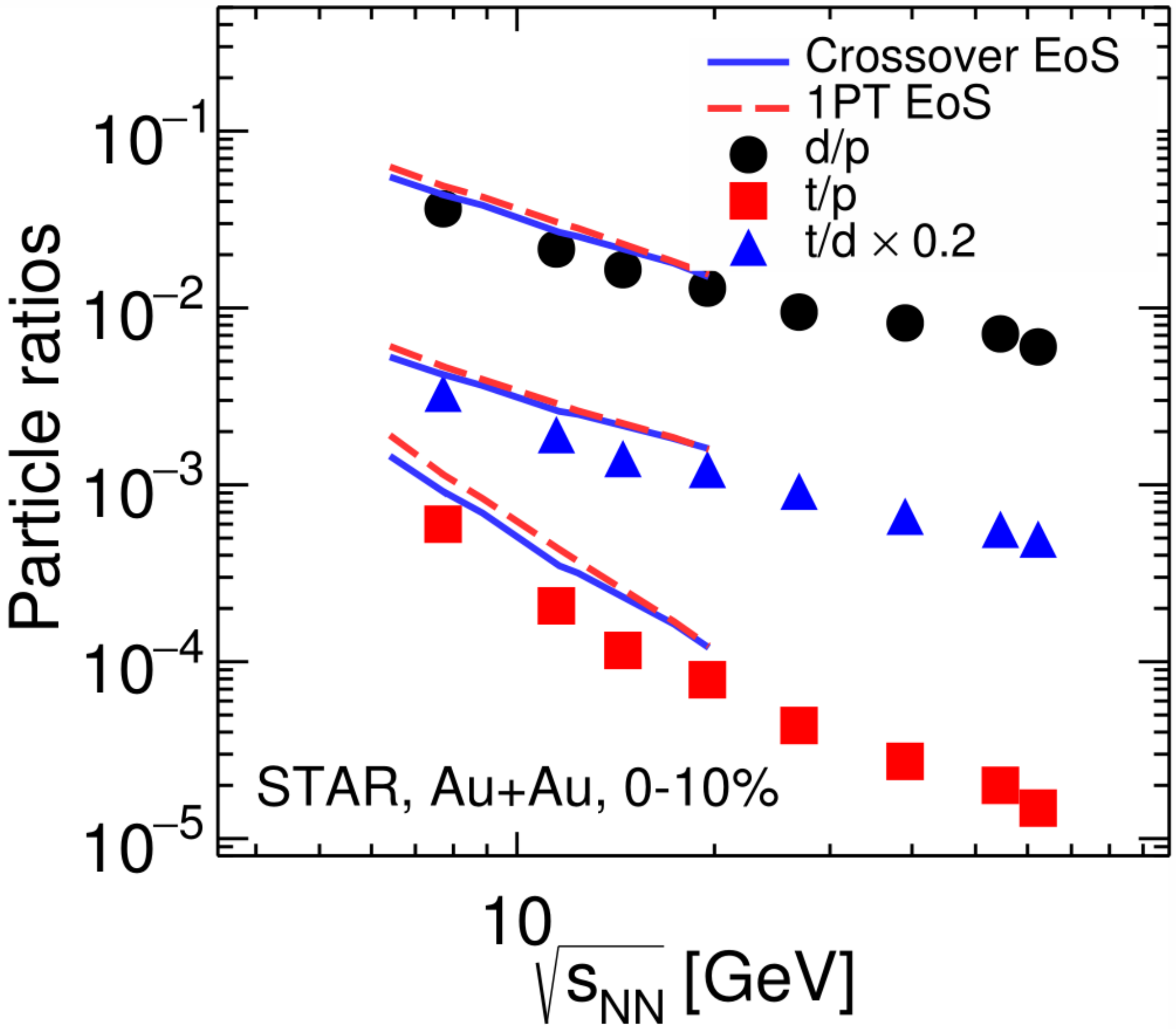


Fig.: Energy dependence of d/p, t/p, and t/d midrapidity ratios for central (0-10%) Au+Au collisions. Simulations were performed at b = 4 fm for Au+Au and at b = 3 fm for Pb+Pb in rapidity bin |y| < 0.5.

M. Kozhevnikova, Yu. B. Ivanov, PRC 107, 024903 (2023)

$N(t) \times N(p)/N^2(d)$ ratio

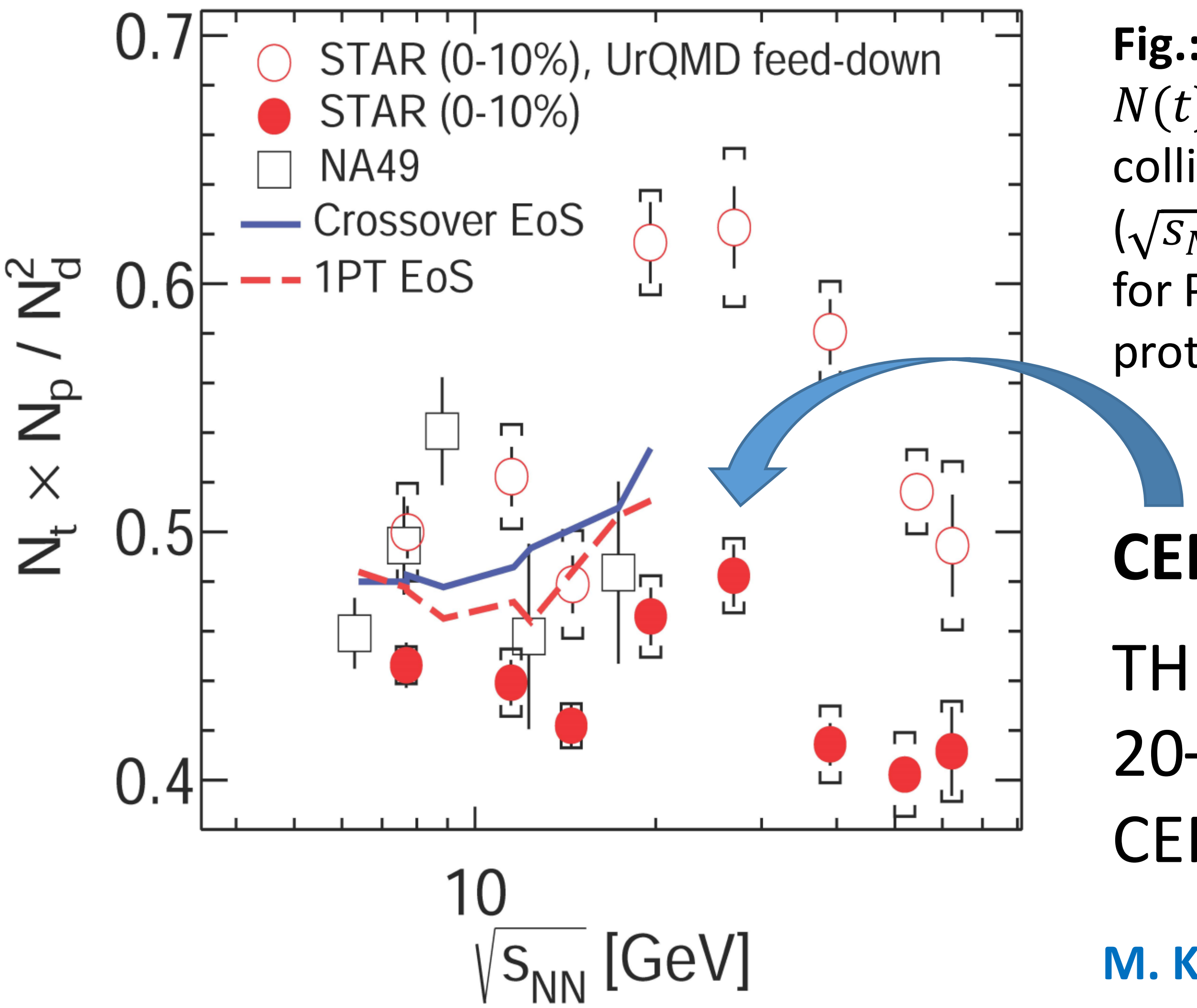


Fig.: Energy dependence of the midrapidity ratio $N(t) \times N(p)/N^2(d)$ in central Au+Au and Pb+Pb collisions. Simulations at b = 4 fm for Au+Au, at b = 3 fm ($\sqrt{s_{NN}} < 17.4$ GeV) and b = 4.6 fm ($\sqrt{s_{NN}} = 17.4$ GeV) for Pb+Pb in rapidity bin |y| < 0.5. N(p) is related to protons without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

CEP? Spinodal instability?

THESEUS models growth to energies of 20–30 GeV, although there is neither CEP nor spinodial instability?

M. Kozhevnikova, Yu. B. Ivanov, PRC 107, 024903 (2023)

Accurate subtraction of weak-decays feed-down from proton yield is important

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.

Preliminary directed flow $v_1(y)$: protons and light nuclei

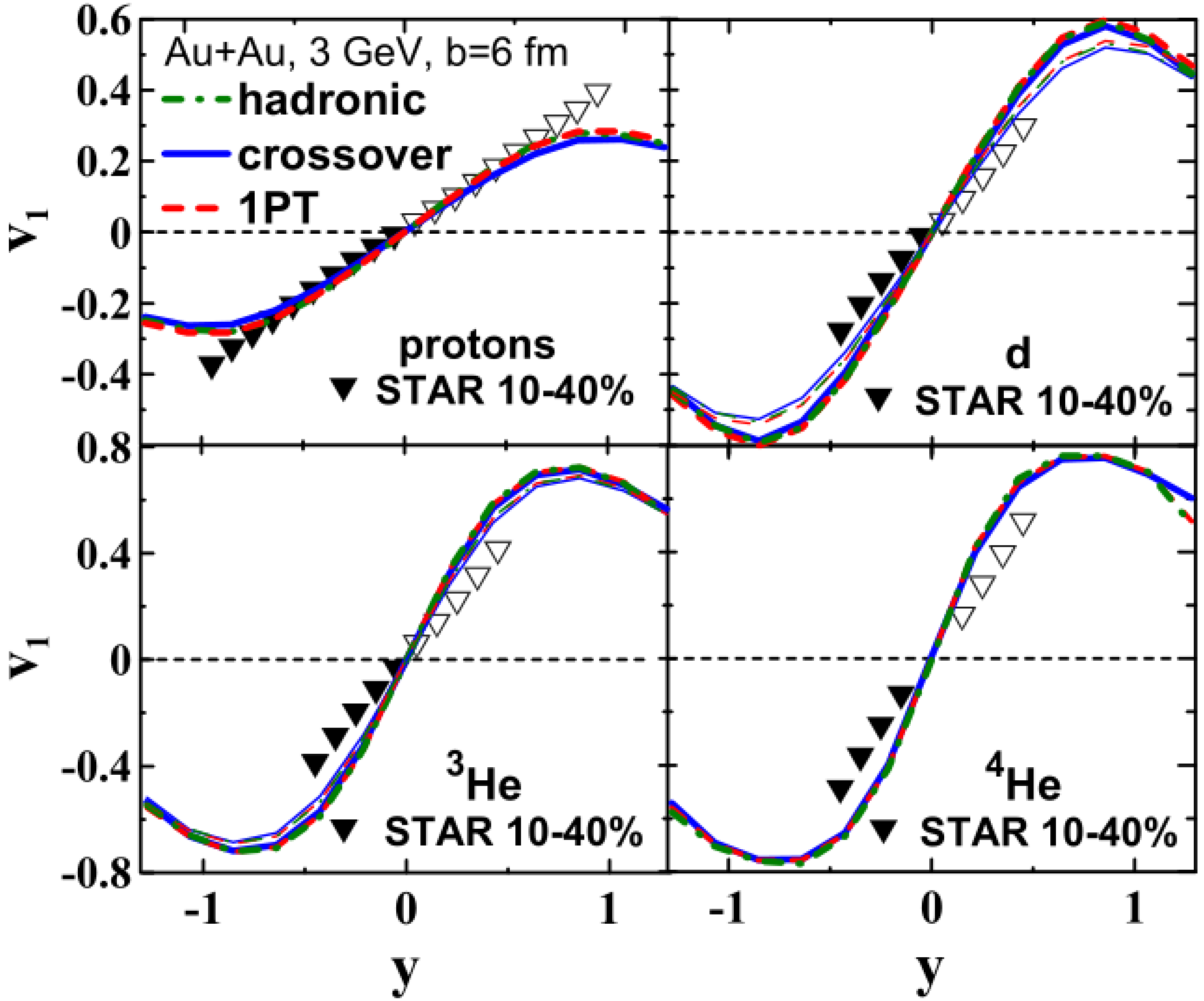


Fig.: Directed flow of **protons** and **light nuclei** as function of rapidity in semicentral (b = 6 fm) Au+Au collisions.

Thin lines – **without decays of He4*.**

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.
- Medium effects are currently studied

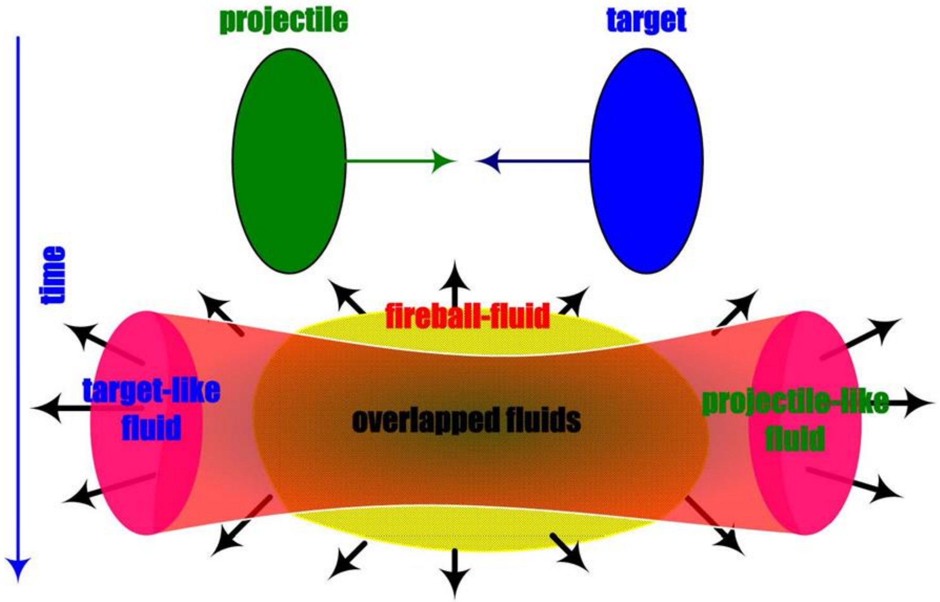
Thank you

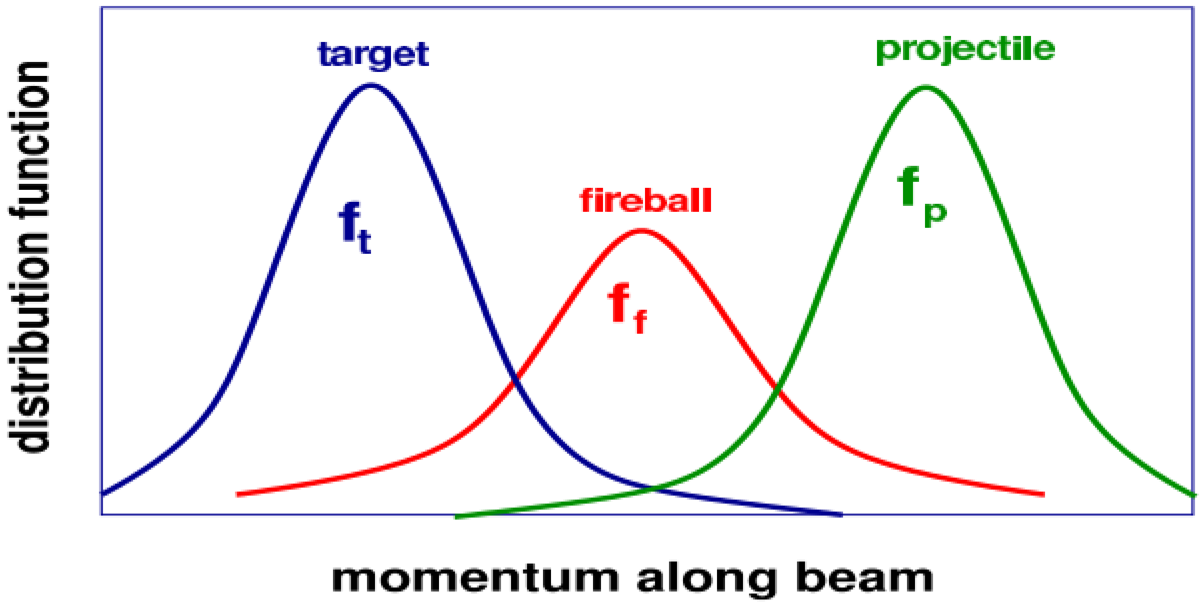
for your attention!

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.





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

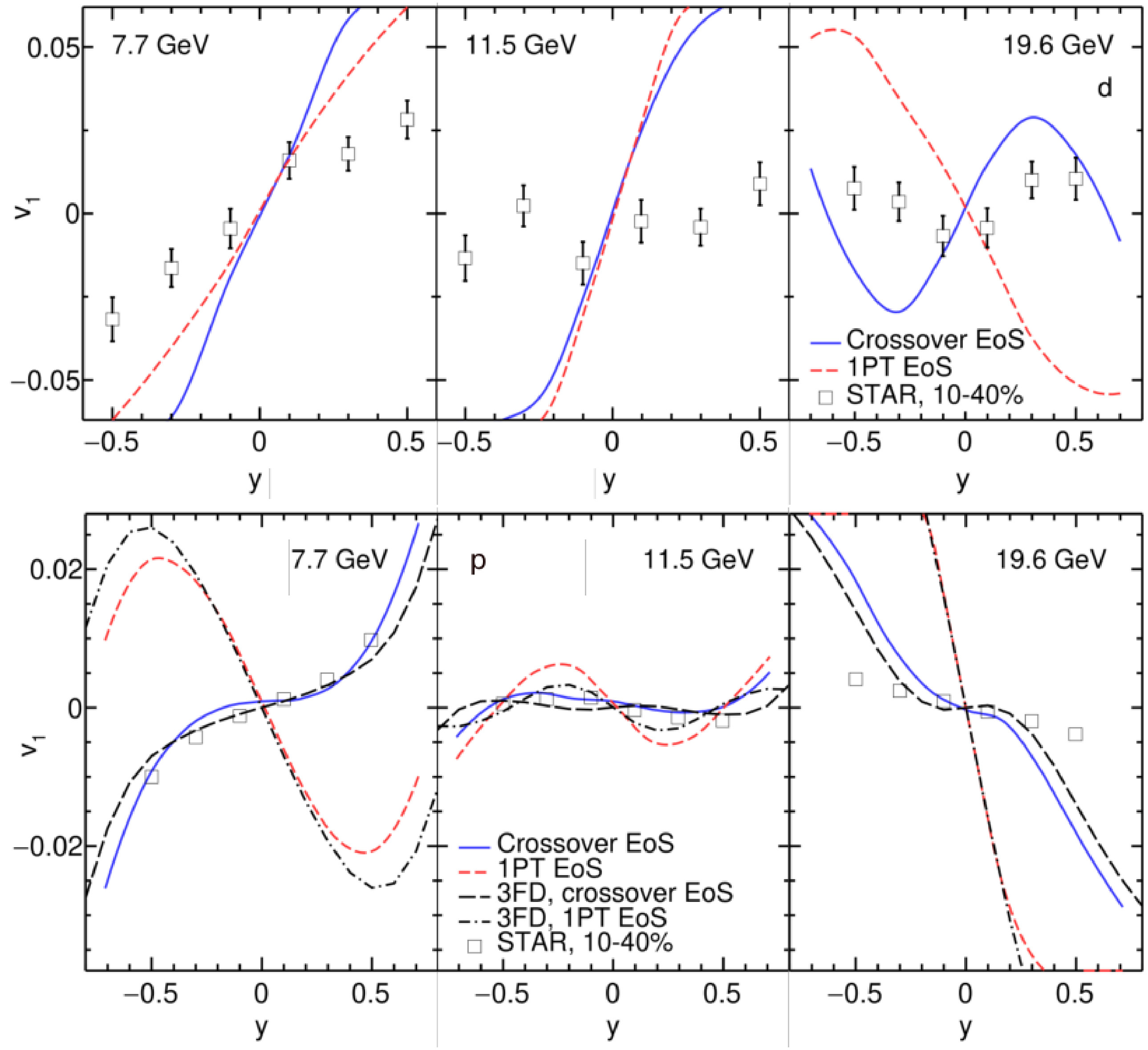
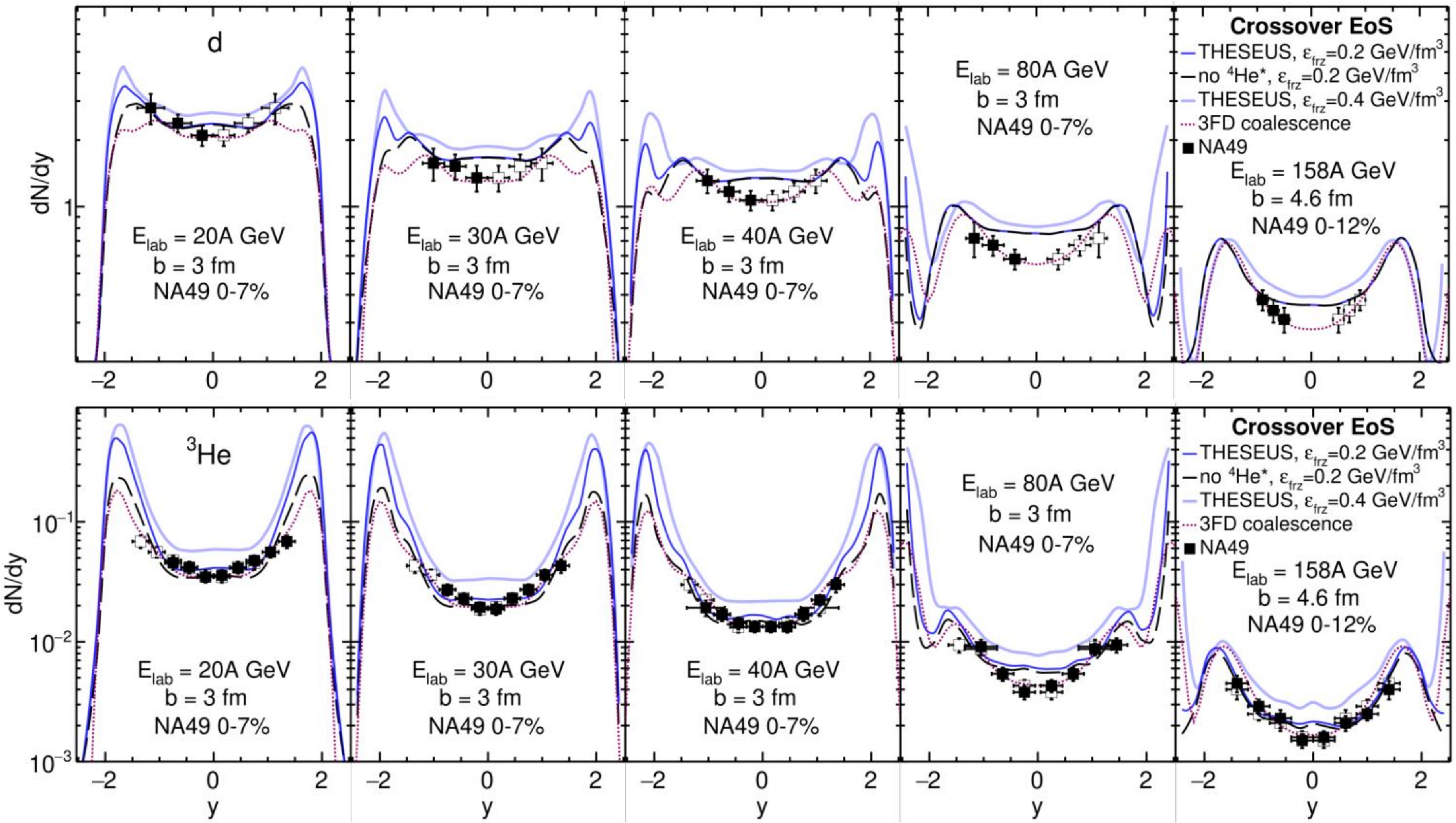


Fig.: Directed flow of **deuterons** (upper raw of panels) and **protons** (lower raw of panels) as function of rapidity in semicentral (b = 6 fm) Au+Au collisions.

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



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.

Directed flow $v_1(y)$: hadrons

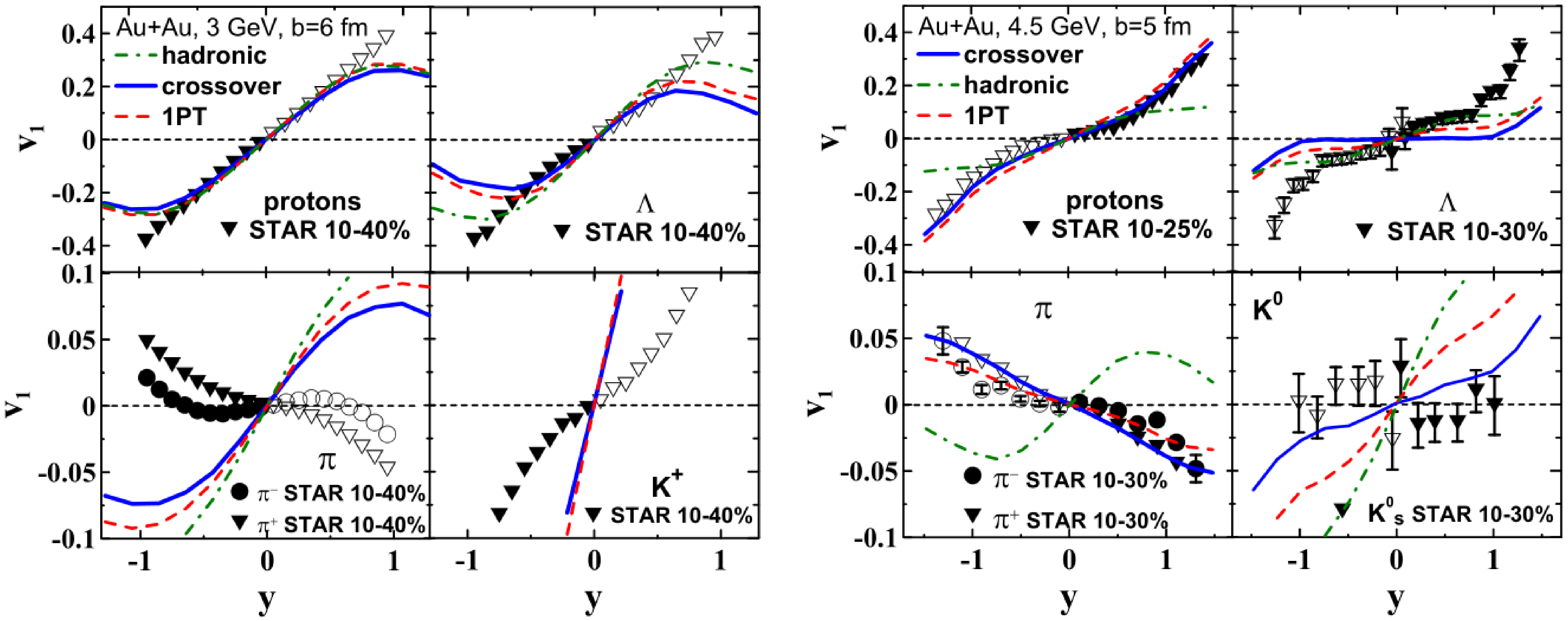


Fig.: Directed as function of different hadrons as function of rapidity in semicentral (b = 6 fm) Au+Au collisions.

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.

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.

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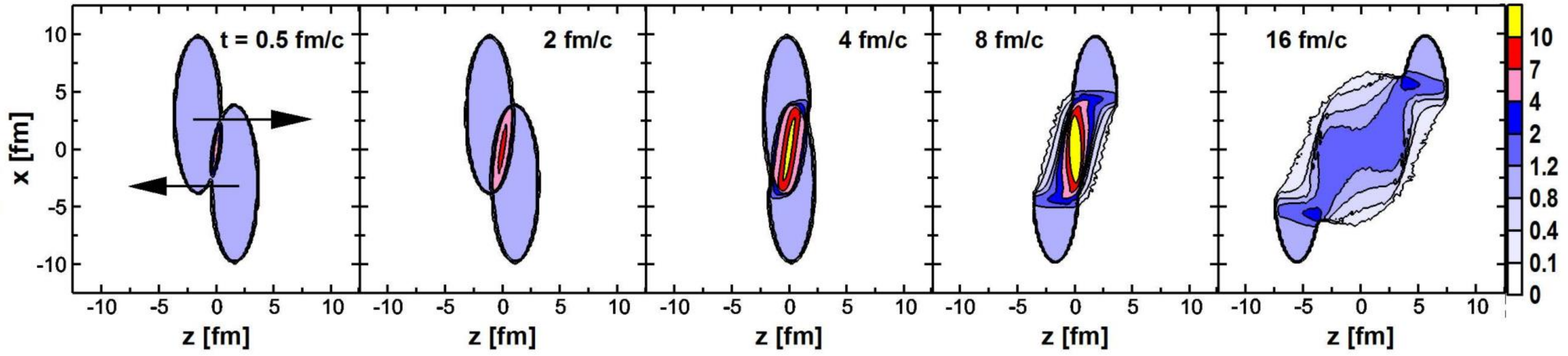

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