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

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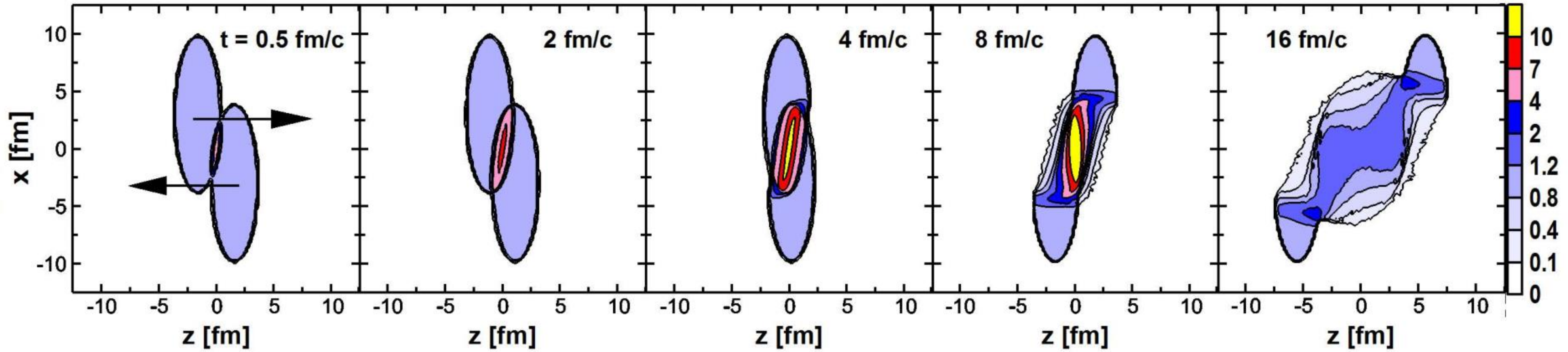

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Introduction

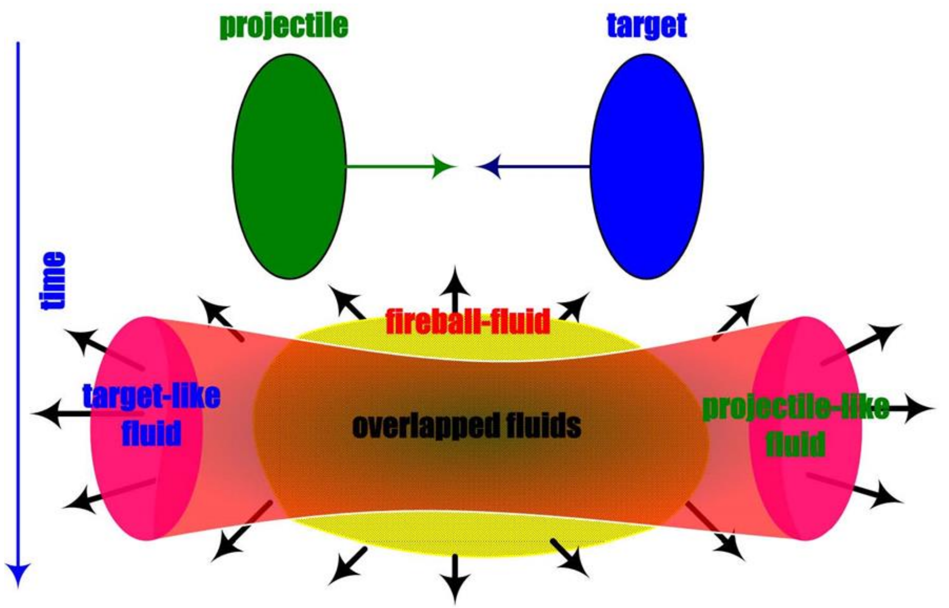
- Light-nuclei production is related to search for critical point in QCD phase diagram.
- The existing 3D dynamical models with coalescence mechanism of the light-nuclei production.
- Microscopic approaches – PHQMD and SMASH
- The thermodynamical approach: no additional parameters needed for light-nuclei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

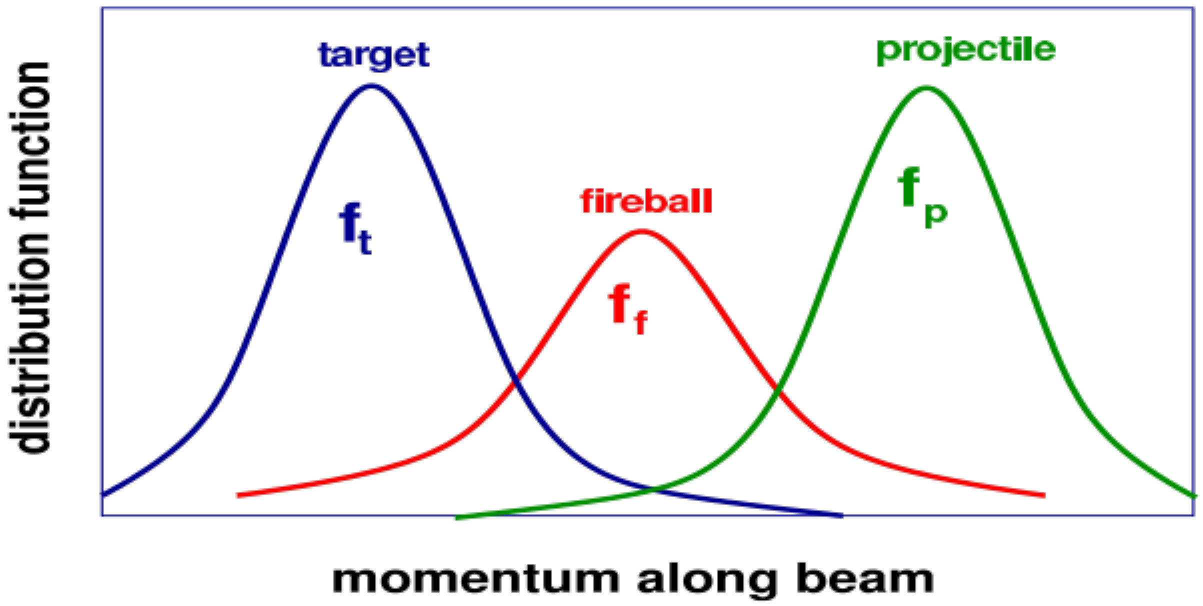
Main areas of research: study the light-nuclei production at collision energies of the BES-RHIC, SPS, NICA and FAIR.

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.





3FD model

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

Leading particles carry bar. charge exchange/emission

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

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

Baryon-free fluid Source term Exchange

The source term is delayed due to a formation time τ

EoS:

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

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 $\varepsilon_{frz} = 0.4$ GeV/fm^3

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.

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

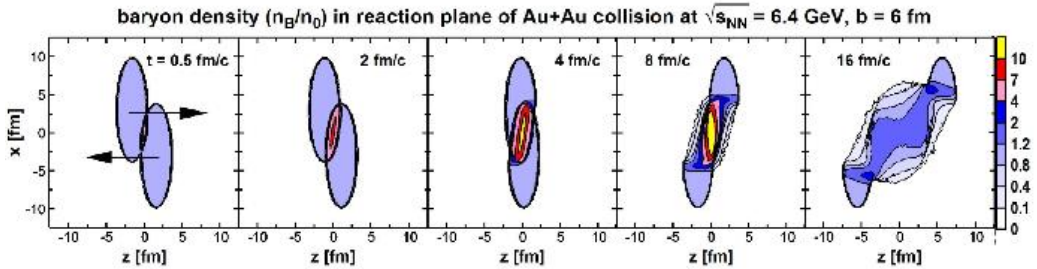
- In 2016 the THESEUS event generator was introduced.

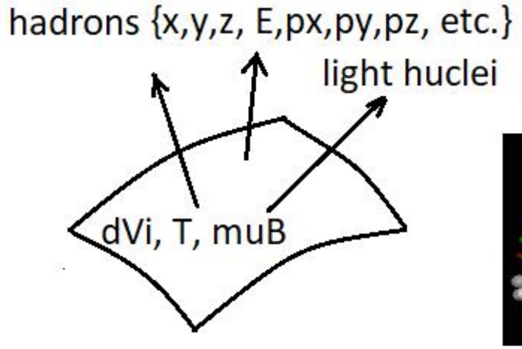
(3FD+Particlization+UrQMD): P. Batyuk et al., PHYSICAL REVIEW C 94, 044917 (2016)

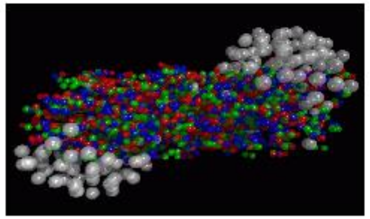
- **THESEUS = 3FD + Monte Carlo hadron sampling + rescatterings/decays via UrQMD**
- There were no light nuclei included.
- THESEUS presents the 3FD output in terms of a set of observed particles.
- Since the time THESEUS was first presented, certain updates have been made, further referred to as THESEUS-v2.

Kozhevnikova, Ivanov, Karpenko, Blaschke, 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.

Recalculation of 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	$n = 0.4,\ p = 0.4,\ d = 99.2$

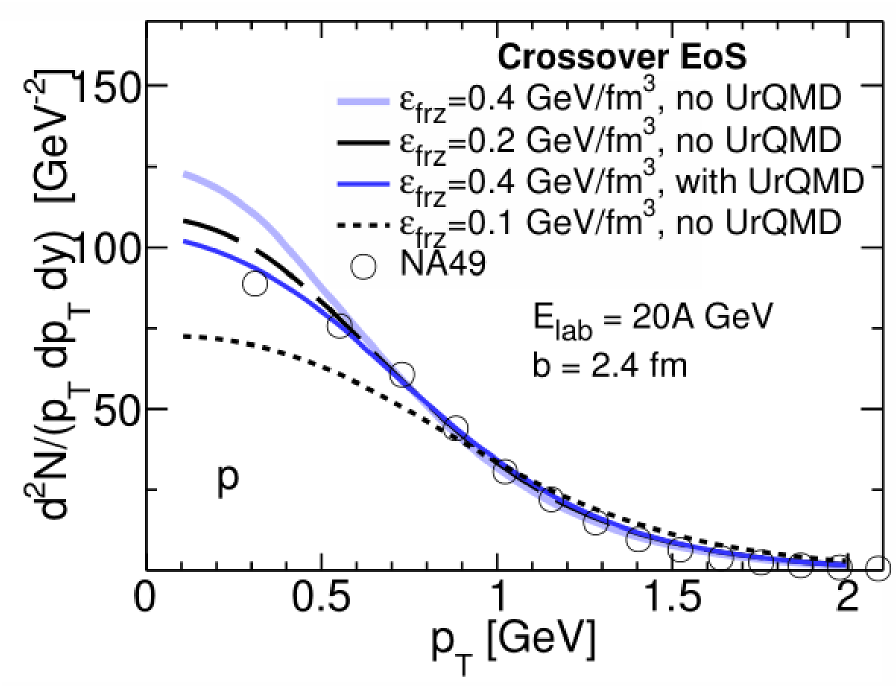
Table: Stable light nuclei and low-lying resonances of the ^{4}He system (from BNL properties of nuclides).

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

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



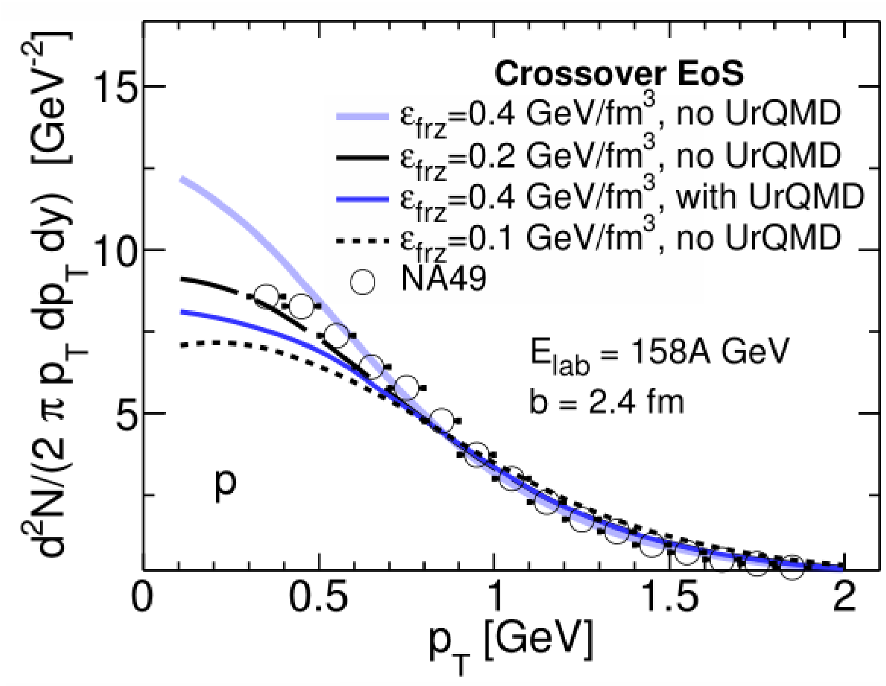
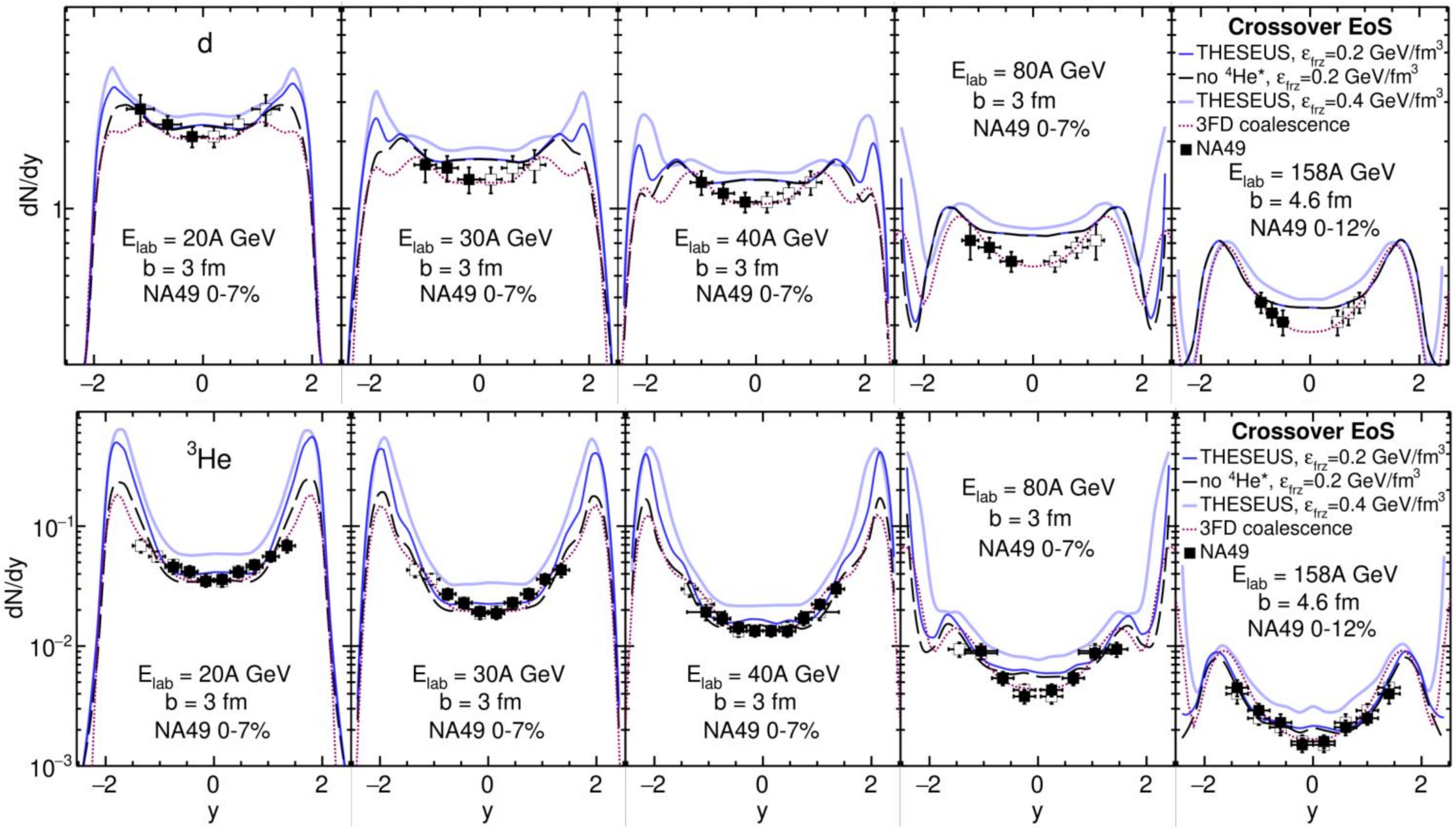


Fig. : Transverse-momentum spectra of protons in central Au+Au collisions.

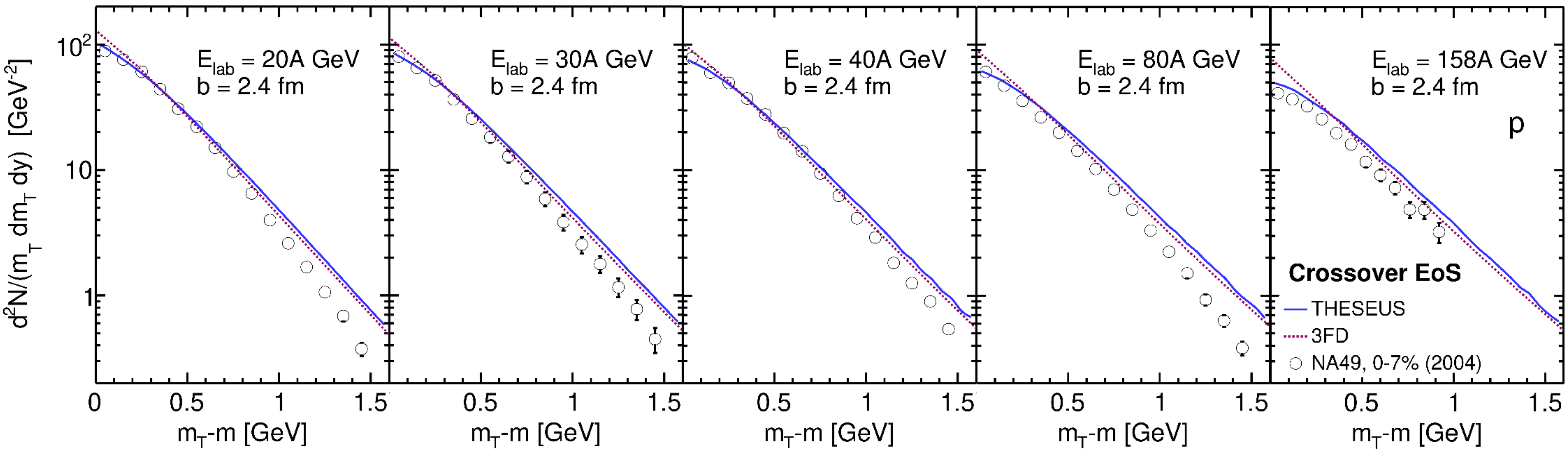
THESEUS-v2: rapidity distributions, $\varepsilon_{\text{frz}} = 0.2\ \text{GeV/fm}^3$.



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

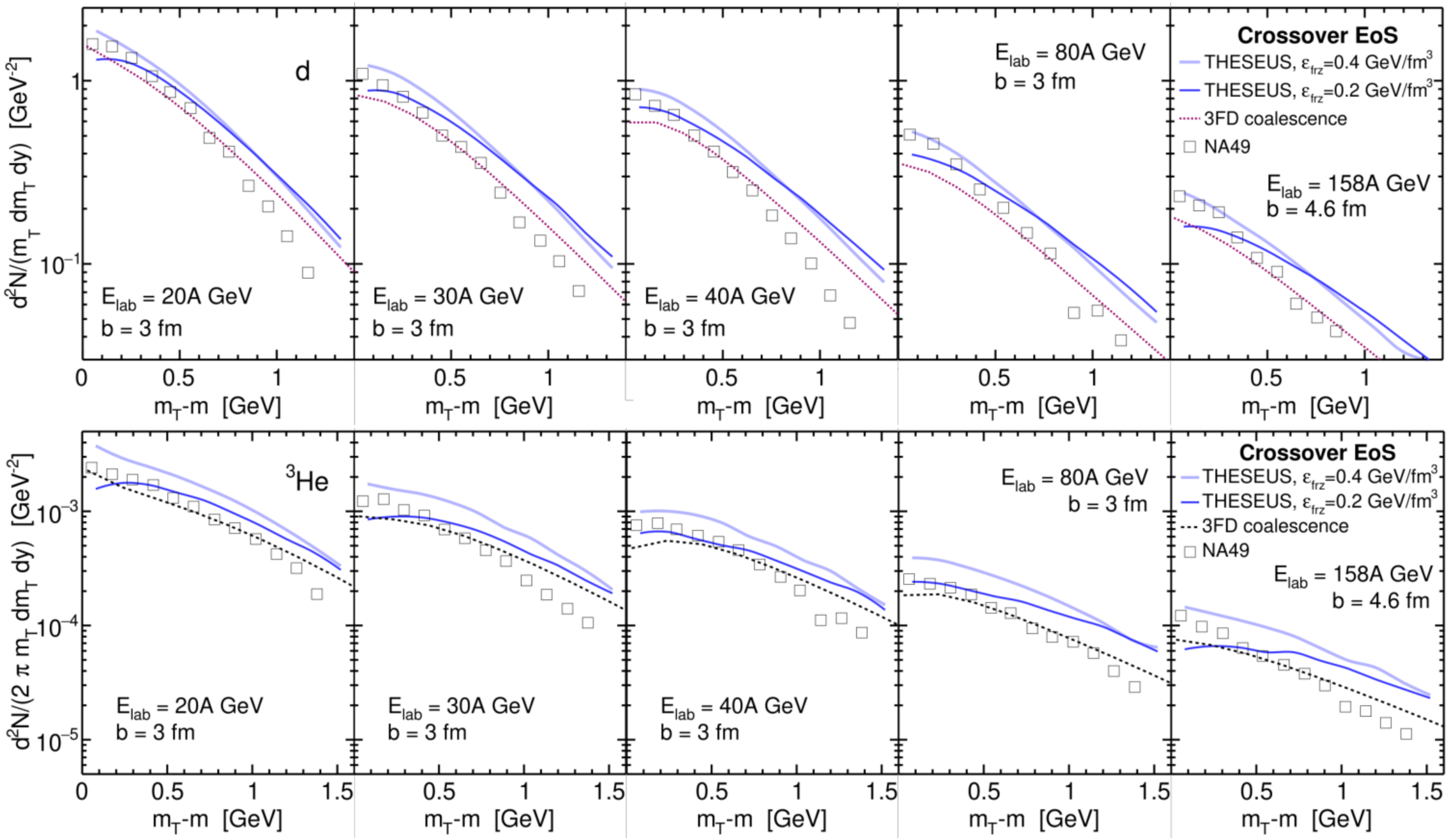
Puzzle: reproduction of the 3He data is better than that of deuterons, in spite of that 3He heavier.

THESEUS-v2: m_T spectra of protons.



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

mT-spectra: deuterons and Helium 3



Small disagreement with proton m_T data transforms into a large disagreement with data on light nuclei.

Particle ratios

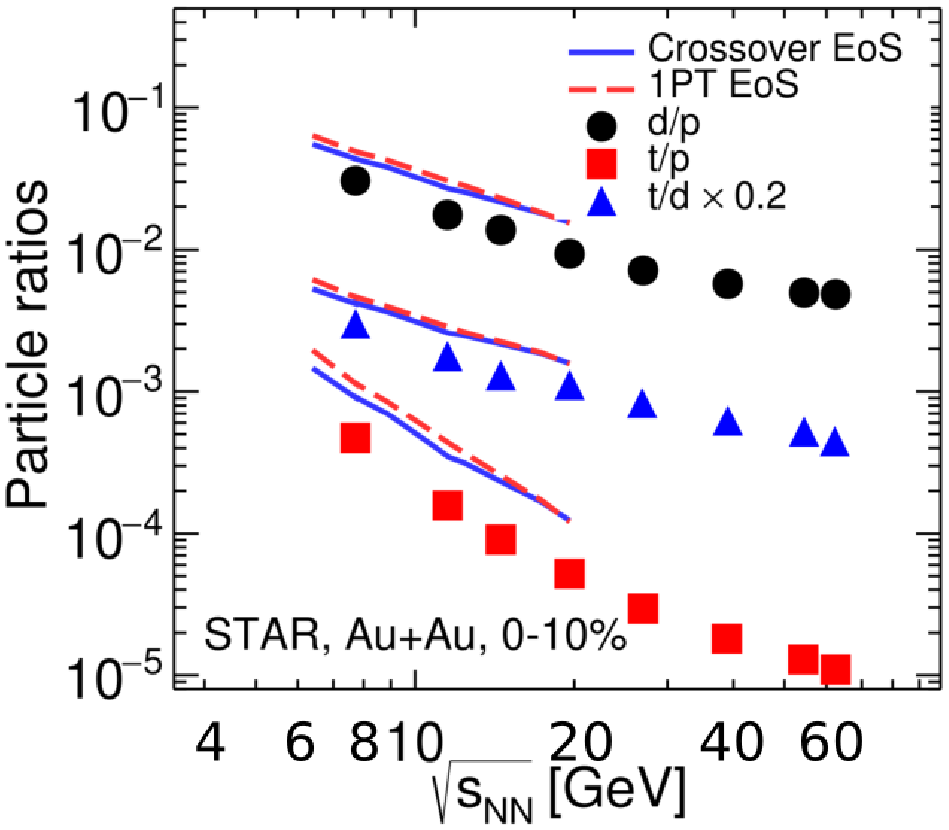


Fig.: Energy dependence of d/p, t/p, and t/d midrapidity ratios for central (0-10%) Au+Au collisions. Simulations were performed at b = 4 fm for Au+Au and at b = 3 fm for Pb+Pb in rapidity bin |y| < 0.3.

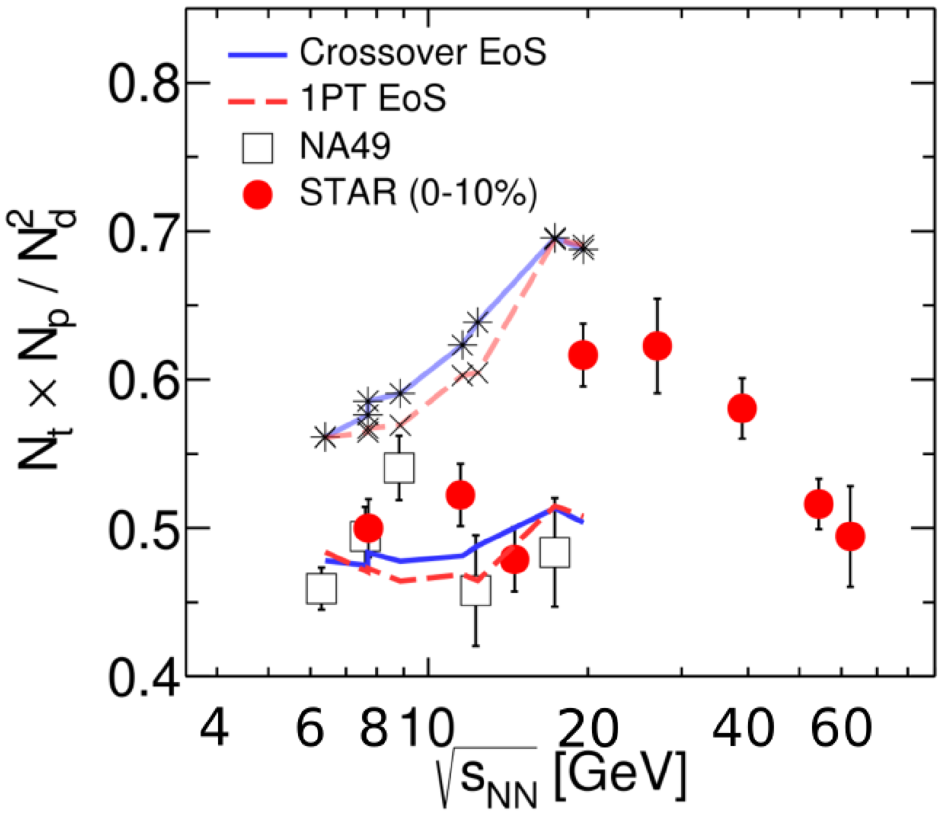


Fig.: Results are presented for ratios with N(p) related to protons with (two upper lines marked by crosses) and without (two lower lines) feed-down from weak decays.

Observed peak around 20 GeV resembles the result of feed-down from weak decays into proton yield.

Directed flow v1(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:

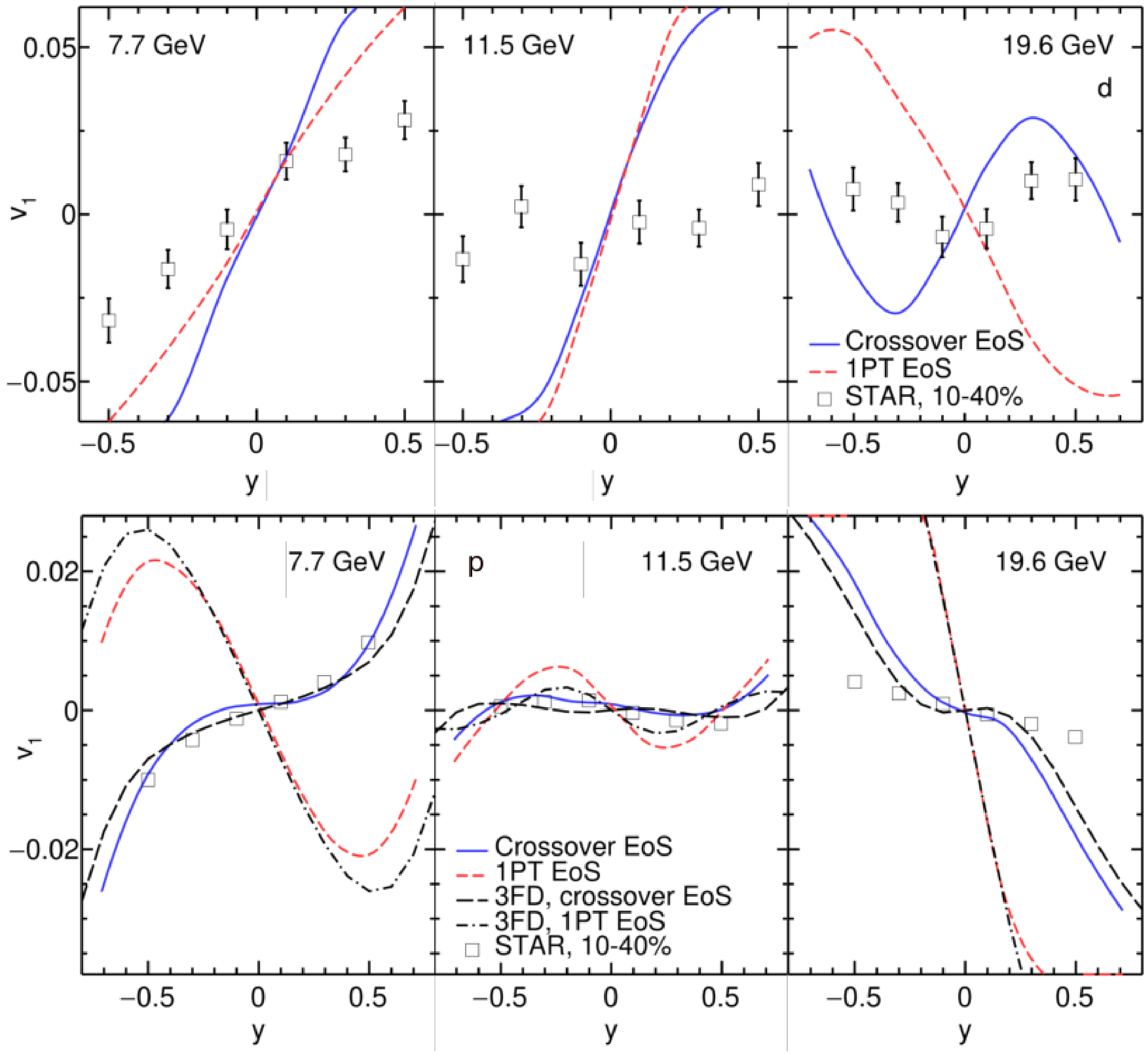
$$v_1^{(a)}(y) = \frac{\int d^2p_T\,(p_x/p_T)\,E\;dN_a/d^3p}{\int d^2p_T E\;dN_a/d^3p}.$$

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

THESEUS: v1 is in terms of sums over hadrons rather than integrals over momenta

Directed flow v1(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.



Discussion:

- Puzzle: different v1 slopes for p and d within 1PT EoS at 7.7 GeV and within crossover EoS at 19.6 GeV

Summary

- The thermodynamical approach approximately reproduces data on light nuclei with a single parameters, $\varepsilon_{\mathrm{frz}} = 0.2\ \mathrm{GeV/fm}^3$.
- The functional dependencies (on y, pT, centrality, mass of light nuclei) qualitatively are reproduced
- Still there is a puzzle with v1 of deuterons.
- Imperfect reproduction of the light-nuclei data leaves room for medium effects

Nearest plans

- Study of v1 puzzle for deuterons: pT-differential v1(pT);
- 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, without his help expertise this work would hardly have been possible.

Thank you

for your attention!