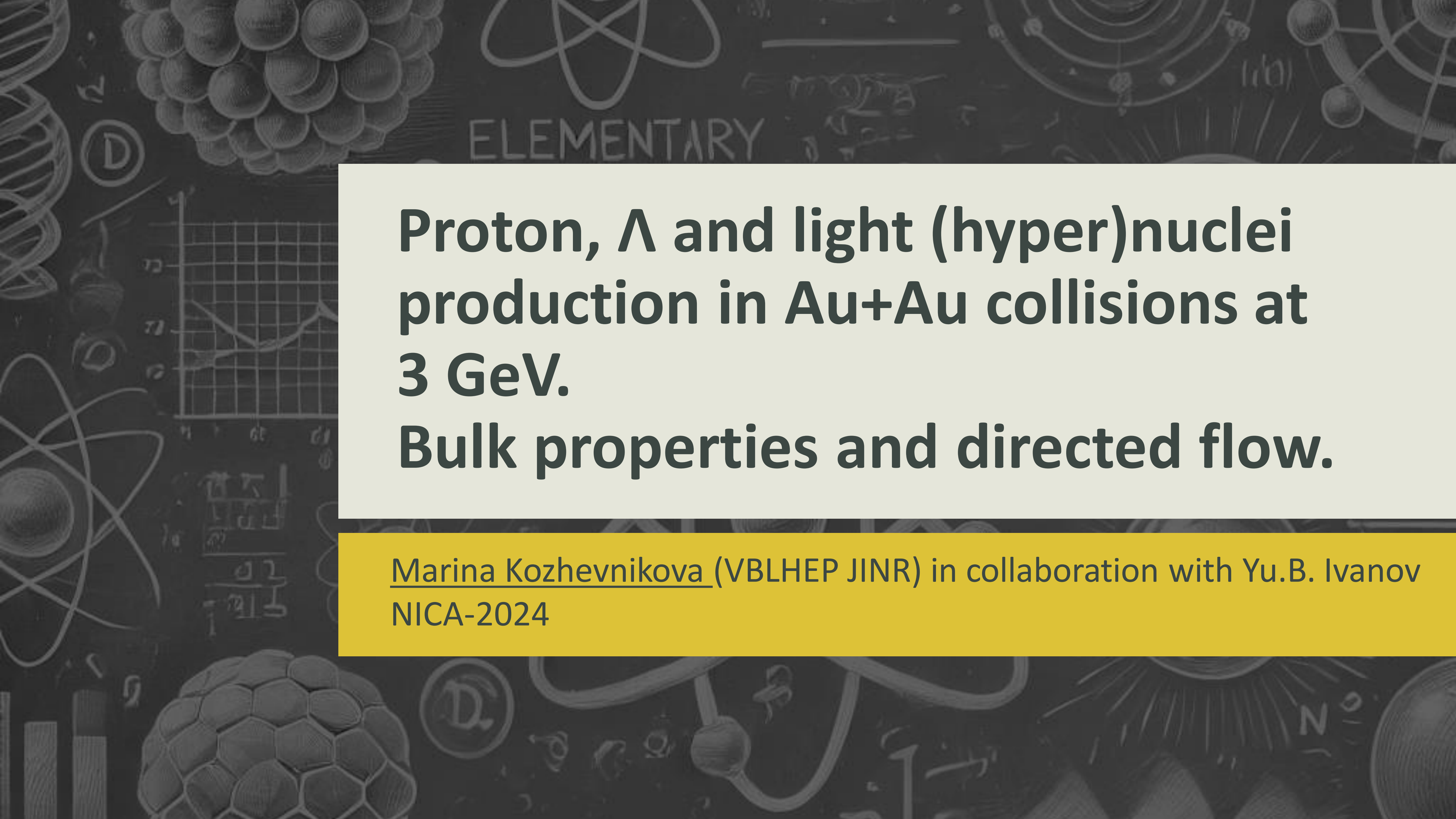


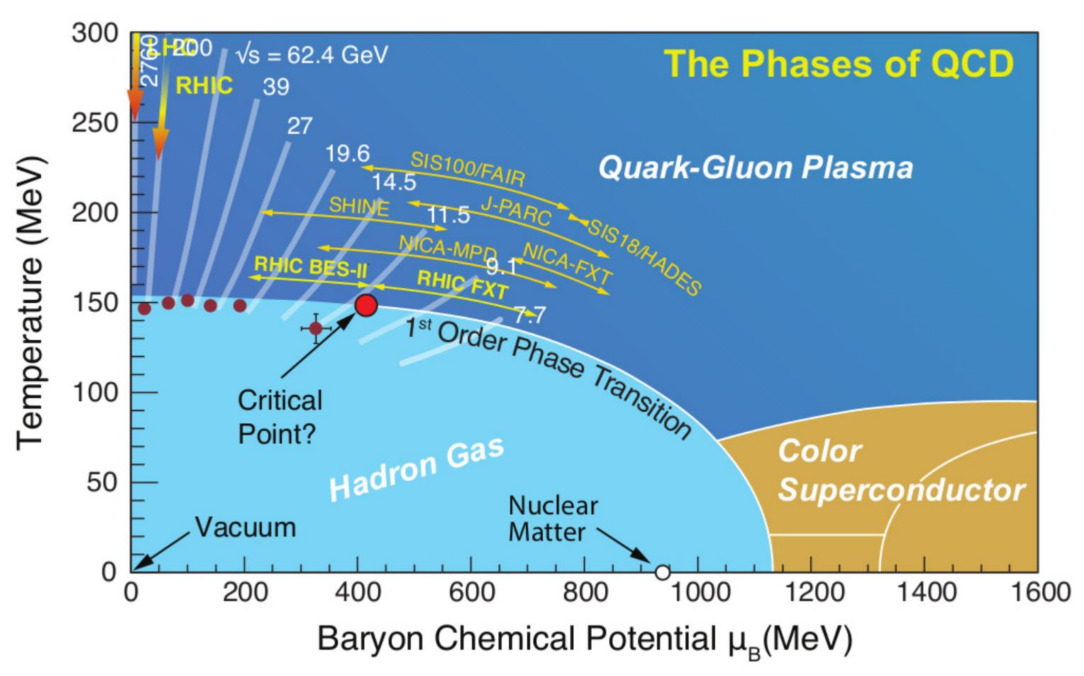
Proton, Λ and light (hyper)nuclei production in Au+Au collisions at 3 GeV.
Bulk properties and directed flow.

Marina Kozhevnikova (VBLHEP JINR) in collaboration with Yu.B. Ivanov
NICA-2024

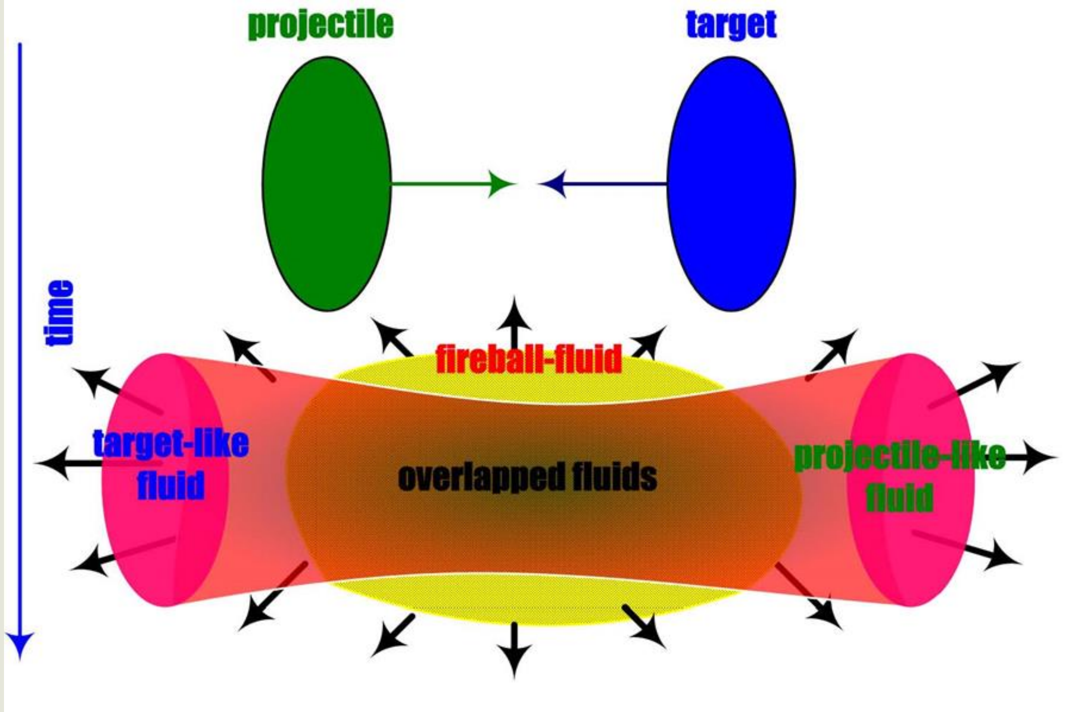
Introduction

- Light-nuclei production is related to search for critical point in QCD phase diagram and region of spinodal instability
- Most popular approaches: various 3D dynamical models with coalescence mechanism of the light-nuclei production and microscopic dynamical 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 other 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.
- Why we study of the light (hyper)nuclei at 3 GeV?

Because of abundant production of them. At low energies, a noticeable part of the baryon charge is emitted in the form of light nuclei.



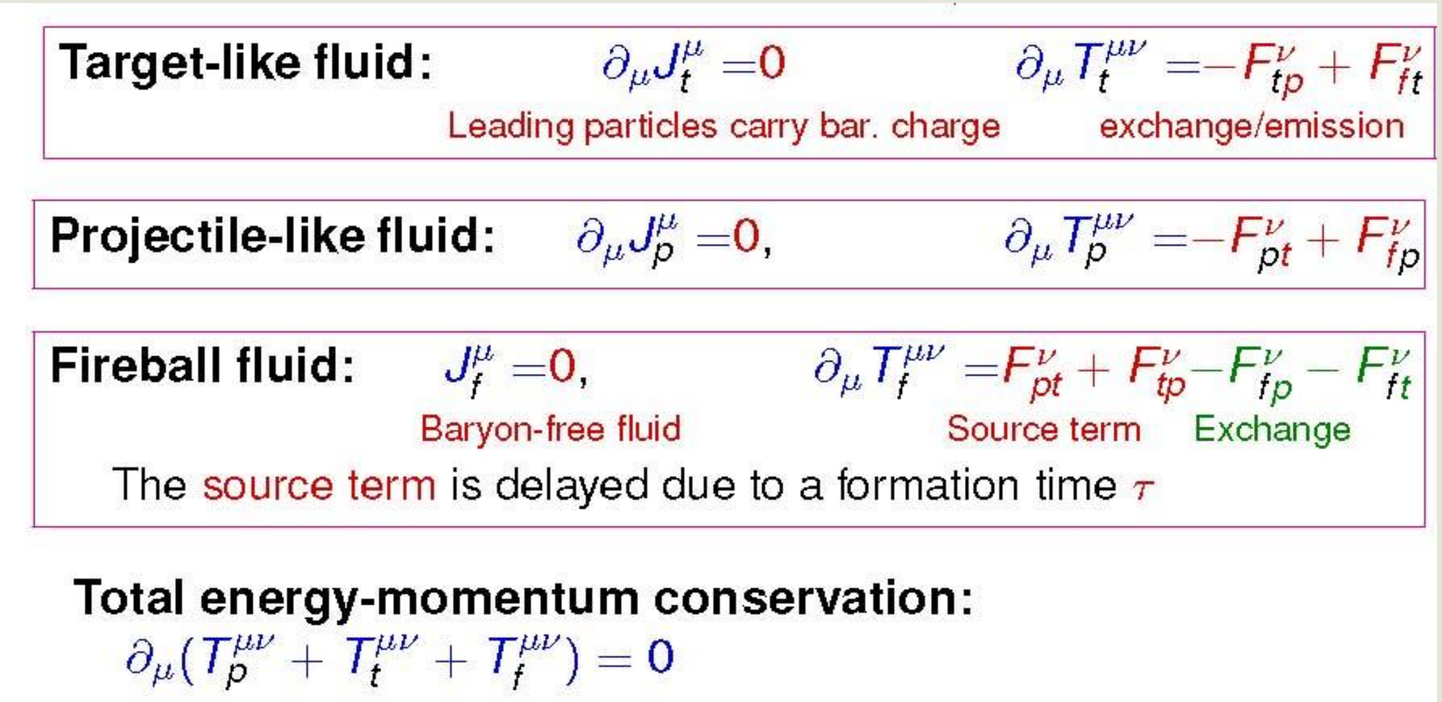
3FD model



The 3FD approximation simulate the early, nonequilibrium stage of the strongly-interacting matter until the freeze-out.

- 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 during the evolution process.

3FD model



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

Leading particles carry bar. charge exchange/emission

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

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

Baryon-free fluid Source term Exchange

The source term is delayed due to a formation time τ

Total energy-momentum conservation:

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

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

Physical Input:

- Initial conditions: two spherical nuclei with sharp edges and initial density $n_B = 0.15 \mathrm{fm}^{-3}$ without fluctuatuions
- the finite stopping power of nuclear matter
- Equation of State
- Hydrodynamical equations with friction terms to modelling of the interaction between fluids
- Freeze-out with standard energy density $\varepsilon_{\mathrm{frz}} = 0.4\ \mathrm{GeV/fm^3}$.

3FD model

Equation of state (EoS):

- hadronic EoS in which only hadronic states (hadron gas) are considered and there is no phase transition; → Mishustin I. N., Russkikh V. N., Satarov L. M., Sov. J. Nucl. Phys. Vol. 54. P. 260–314 (1991).

- 1PT EoS: hadronic states+QGP with 1st-order phase transition;
- EoS with crossover: hadronic states+QGP with a smooth transition (crossover) between phases, the coexistence of the hadronic phase and the QGP in a wide range of temperatures and baryon densities

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

THESEUS

- In 2016 the THESEUS event generator (Three-fluid Hydrodynamics-based Event Simulator Extended by UrQMD final State interactions) was introduced: P. Batyuk et al., PHYSICAL REVIEW C 94, 044917 (2016);
- The generator is based on the 3FD model;
- Performs the procedure of particlization: allows to move from the description of a liquid to a kinetic description;
- The kinetic stage is modeled using the UrQMD model, which describes hadronic rescattering (or afterburning) processes.

THESEUS vs 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

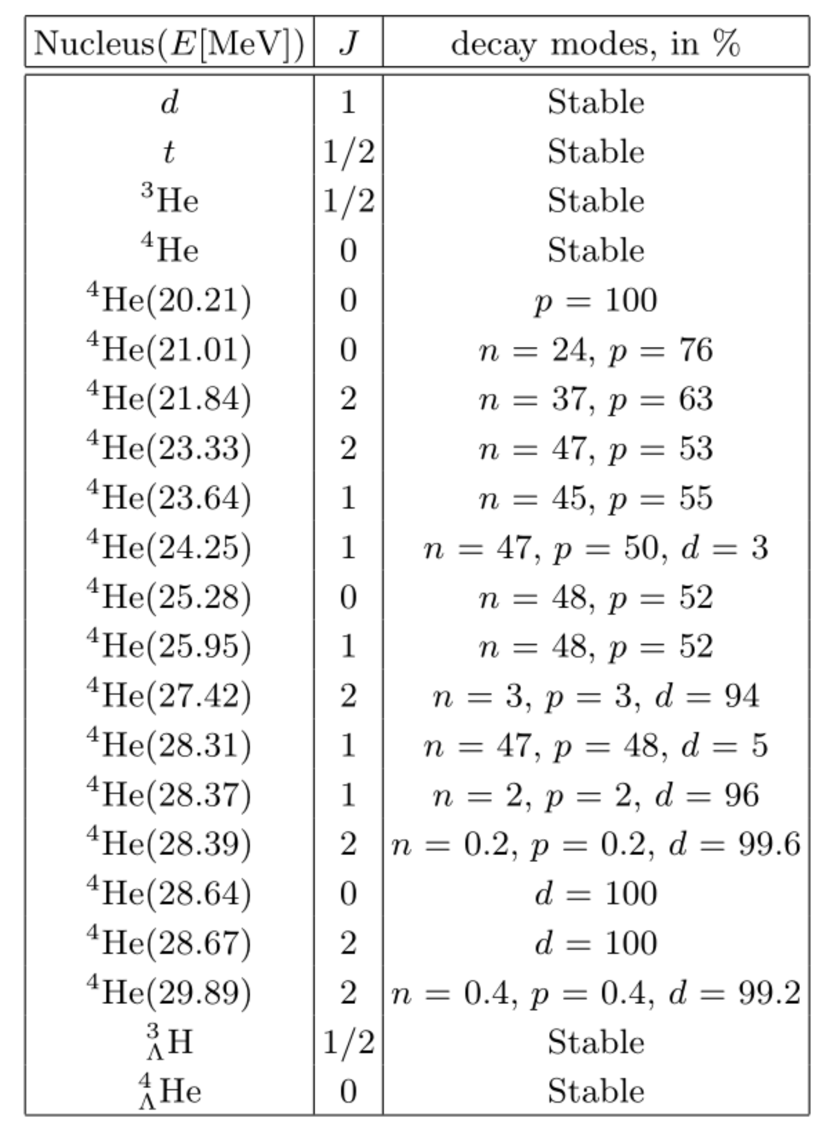
- THESEUS = 3FD + Monte Carlo hadron sampling + afterburner via UrQMD ;
- THESEUS uses 3FD hydrodynamical frozen-out hypersurfaces (T, μ_B, μ_S) to generate particles from them $(x, y, z, p_x, p_y, p_z, E, \ldots)$;
- It presents the output in terms of a set of observed particles.

Experimental cuts are possible.

THESEUS-v2

- In the initial version of THESEUS no light nuclei were included. In the present one (THESEUS-v2) light nuclei and hypernuclei are produces at the same basis as other particles – thermodynamically without fitting;
- 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:

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

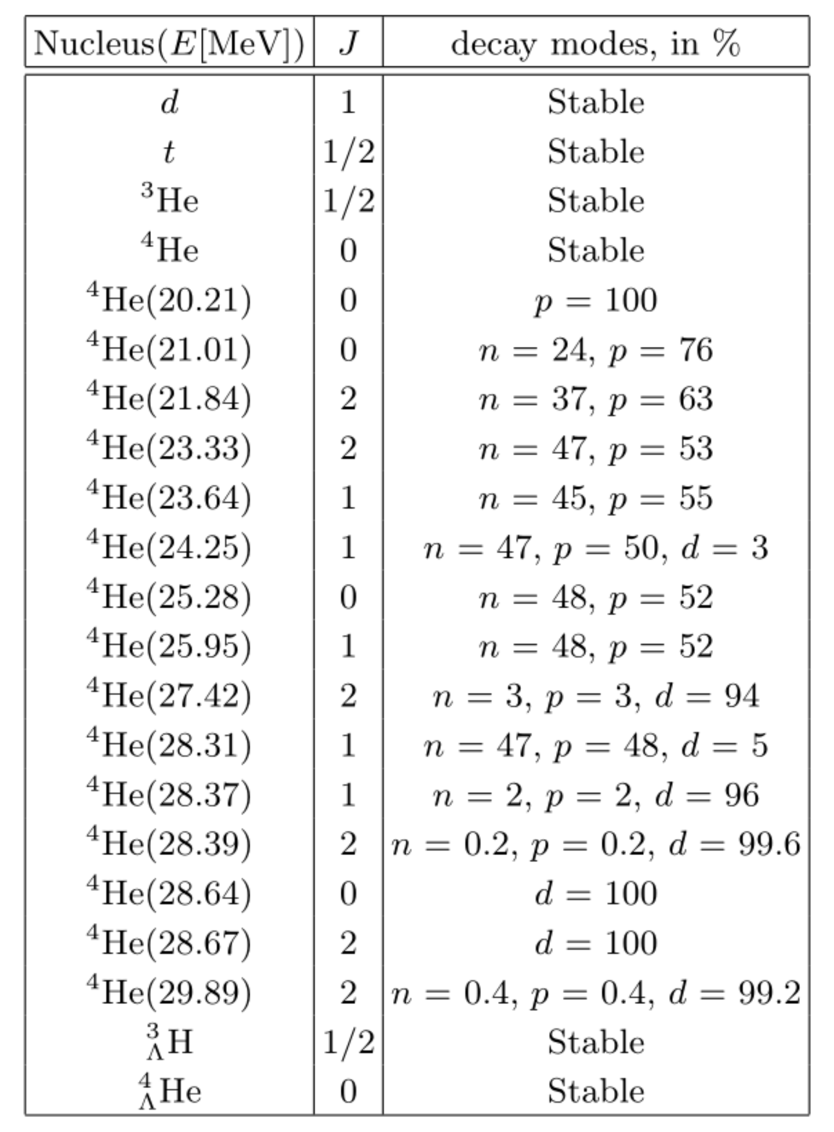


Nucleus(E[MeV])	J	decay modes, in %
d	1	Stable
t	1/2	Stable
^{3}He	1/2	Stable
^{4}He	0	Stable
^{4}He(20.21)	0	$p = 100$
^{4}He(21.01)	0	$n = 24,\ p = 76$
^{4}He(21.84)	2	$n = 37,\ p = 63$
^{4}He(23.33)	2	$n = 47,\ p = 53$
^{4}He(23.64)	1	$n = 45,\ p = 55$
^{4}He(24.25)	1	$n = 47,\ p = 50,\ d = 3$
^{4}He(25.28)	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	$n = 0.4,\ p = 0.4,\ d = 99.2$
$^3_\Lambda$H	1/2	Stable
$^4_\Lambda$He	0	Stable

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

THESEUS-v2

- Unstable species decay and contribute to the distributions of stable light nuclei.
- No afterburner for light nuclei, because UrQMD does not process them. We simulate afterburner stage by the late freeze-out with $\varepsilon_{\mathrm{frz}} = 0.2\ \mathrm{GeV/fm}^3$, which is suitable for many species of light nuclei, which is the same for all collision energies, centralities and combinations of colliding nuclei, see: M. Kozhevnikova, Yu.B. Ivanov Phys.Rev.C 107 (2023) 2, 024903



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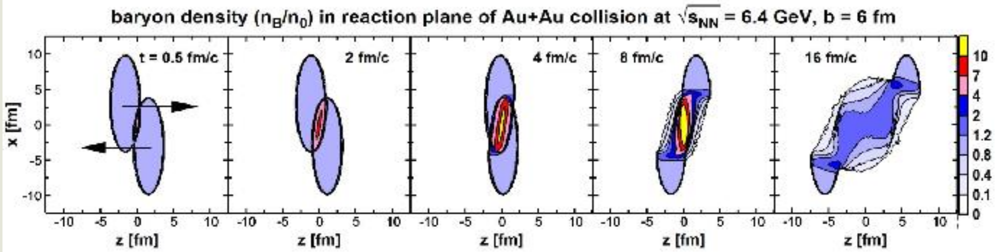
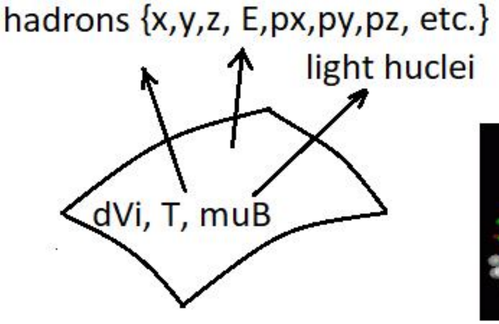
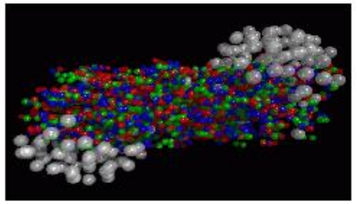
$^3_\Lambda$H	1/2	Stable
$^4_\Lambda$He	0	Stable

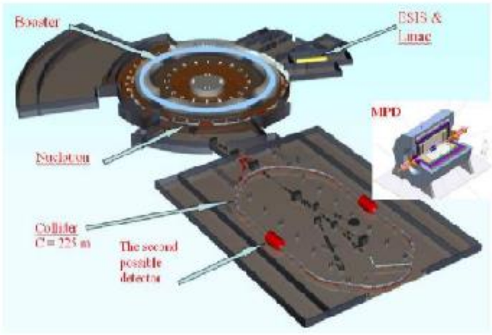
Table: Stable light nuclei, hypernuclei and low-lying resonances of the ^{4}He system (from BNL properties of nuclides).

Hydrodynamic modelling of nuclear collisions for NICA / FAIR









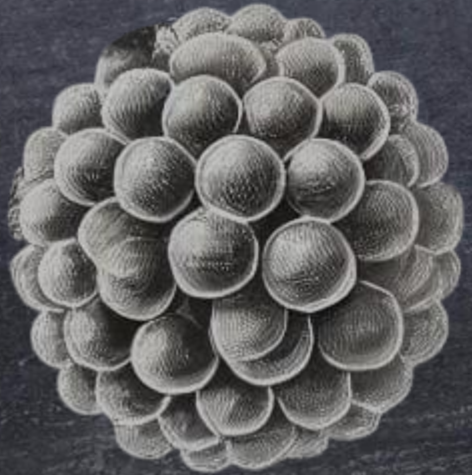
Initial state → hydrodynamic evolution → particlization → afterburner → detector response

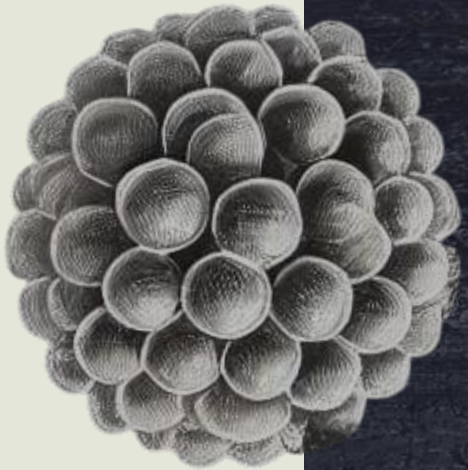
3-fluid hydrodynamical model
(Y.Ivanov et al.)

THESEUS generator

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

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





Studying of the light nuclei, protons and Λ-hyperons

Bulk properties
Directed flow

Protons and light nuclei: p_T-spectra

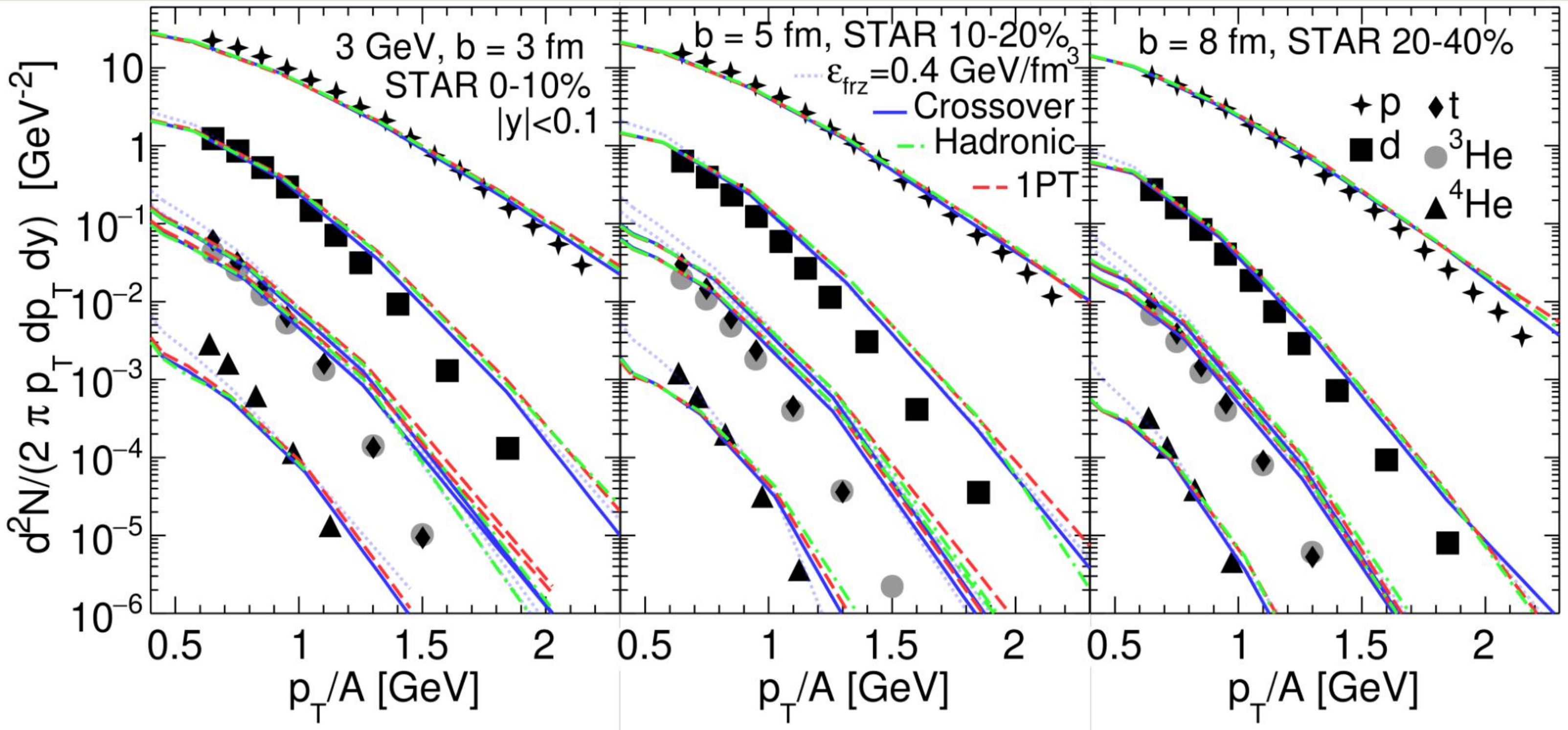


Figure: THESEUS results on transverse-momentum spectra of protons and light nuclei (deuterons, tritons, $^3\mathrm{He}$, $^4\mathrm{He}$) in midrapidity bin ($|y| < 0.1$) in comparison with STAR data calculated for three different EoS and with late freeze-out ($\varepsilon_{\mathrm{frz}} = 0.2\ \mathrm{GeV/fm^3}$). For comparison, the result with standard freeze-out ($\varepsilon_{\mathrm{frz}} = 0.4\ \mathrm{GeV/fm^3}$) for crossover EoS is shown.

Light nuclei: rapidity distributions

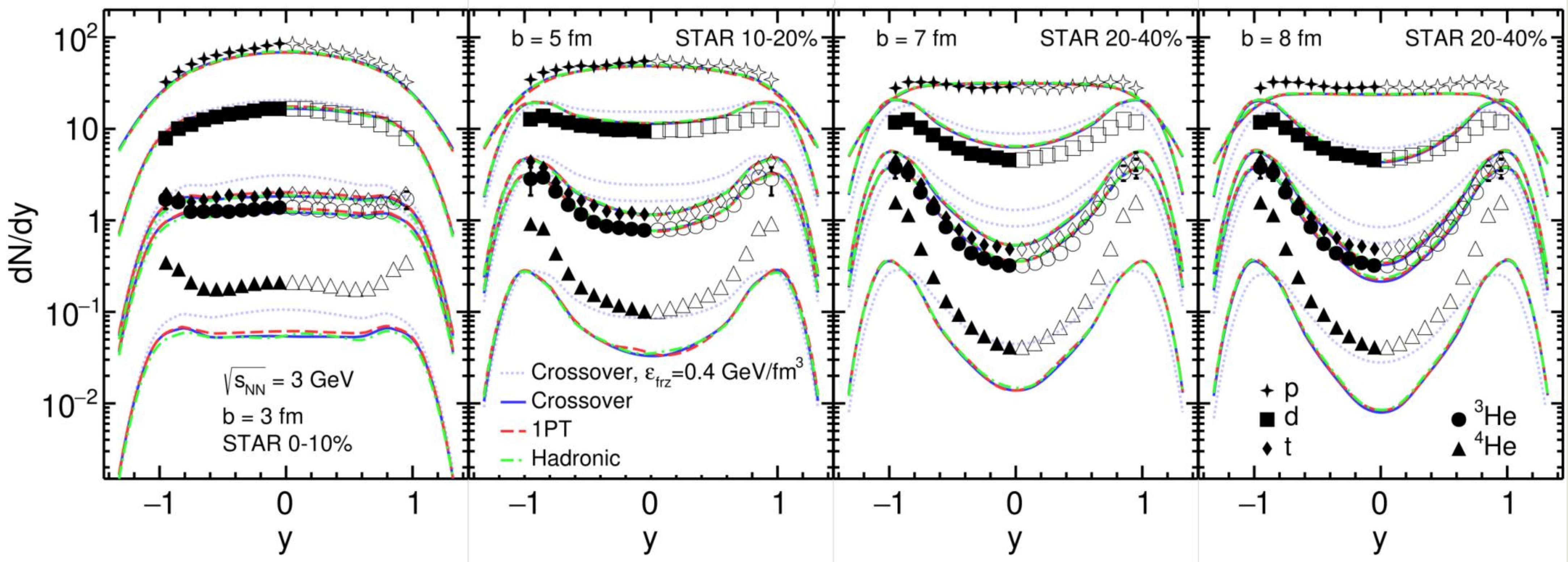


Figure: THESEUS results on rapidity distributions of protons and light nuclei (deuterons, tritons, $^3\mathrm{He}$, $^4\mathrm{He}$) in comparison with STAR data calculated for three different EoS and with late freeze-out ($\varepsilon_{\mathrm{frz}} = 0.2\ \mathrm{GeV/fm^3}$). For comparison, the result with standard freeze-out ($\varepsilon_{\mathrm{frz}} = 0.4\ \mathrm{GeV/fm^3}$) for crossover EoS is shown.

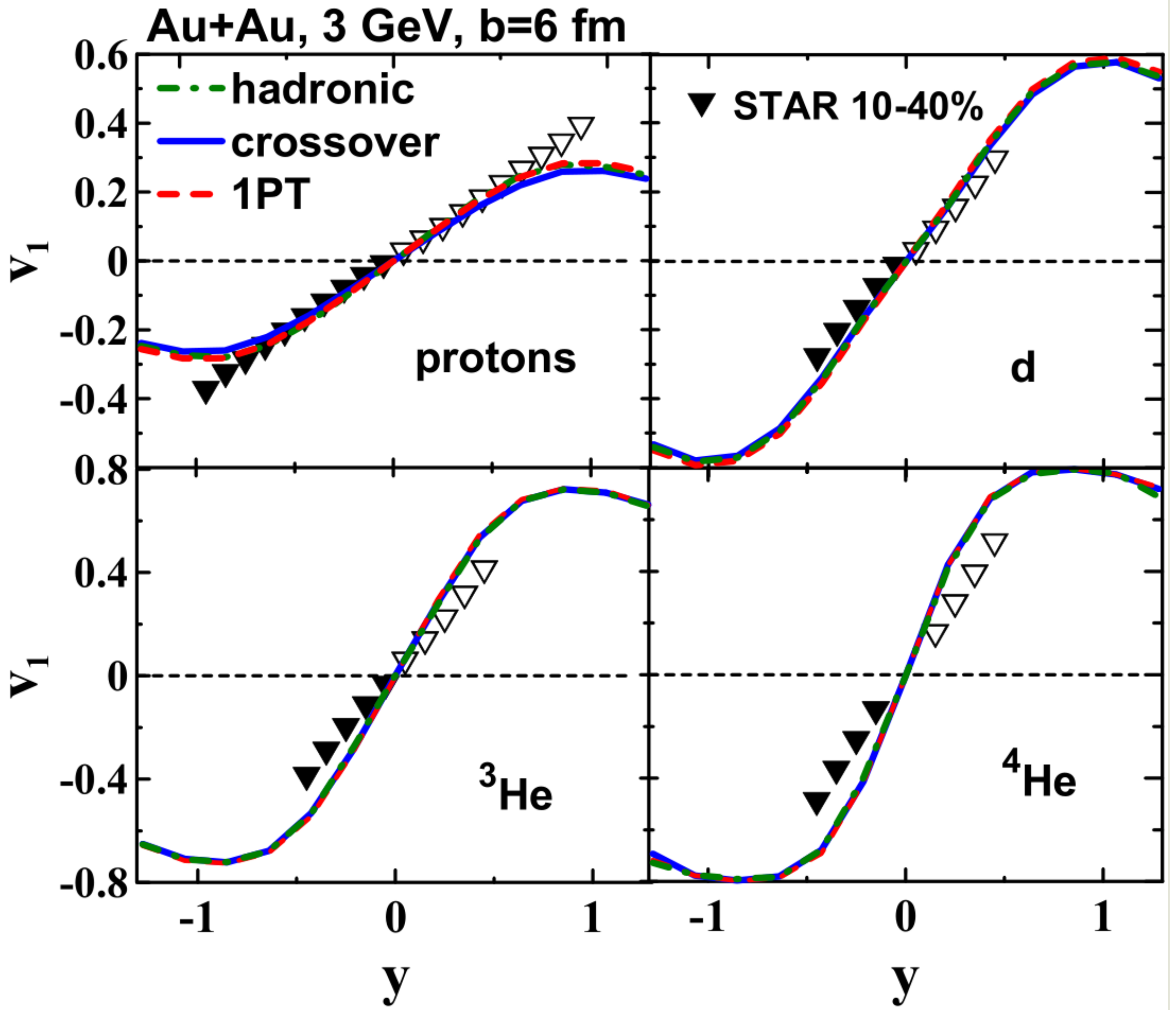
Light nuclei: rapidity distributions

- The THESEUS simulations well describe difference in the form of proton and light-nuclei distributions and its dependence on the centrality.
- Results for $b = 7\ \mathrm{fm}$ and $b = 8\ \mathrm{fm}$ show uncertainty of choice of impact parameter to reproduce the centrality of 20-40%. In general $b = 7\ \mathrm{fm}$ gives better results.
- the choice of EoS does not affect on the rapidity distributions: the evolution of the system at collision energy $\sqrt{s_{NN}} = 3\ \mathrm{GeV}$ is realized in hadronic phase.
- For d, t and $^3\mathrm{He}$ the late freeze-out characterized by energy density $\varepsilon_{\mathrm{frz}} = 0.2\ \mathrm{GeV/fm^3}$ is more suitable, while for $^4\mathrm{He}$ the standard one ($\varepsilon_{\mathrm{frz}} = 0.4\ \mathrm{GeV/fm^3}$) gives better results. This suggests that the $^4\mathrm{He}$ nuclei better survive in the afterburner stage because they are more spatially compact and tightly bound objects.

Protons and light nuclei: directed flow v_1

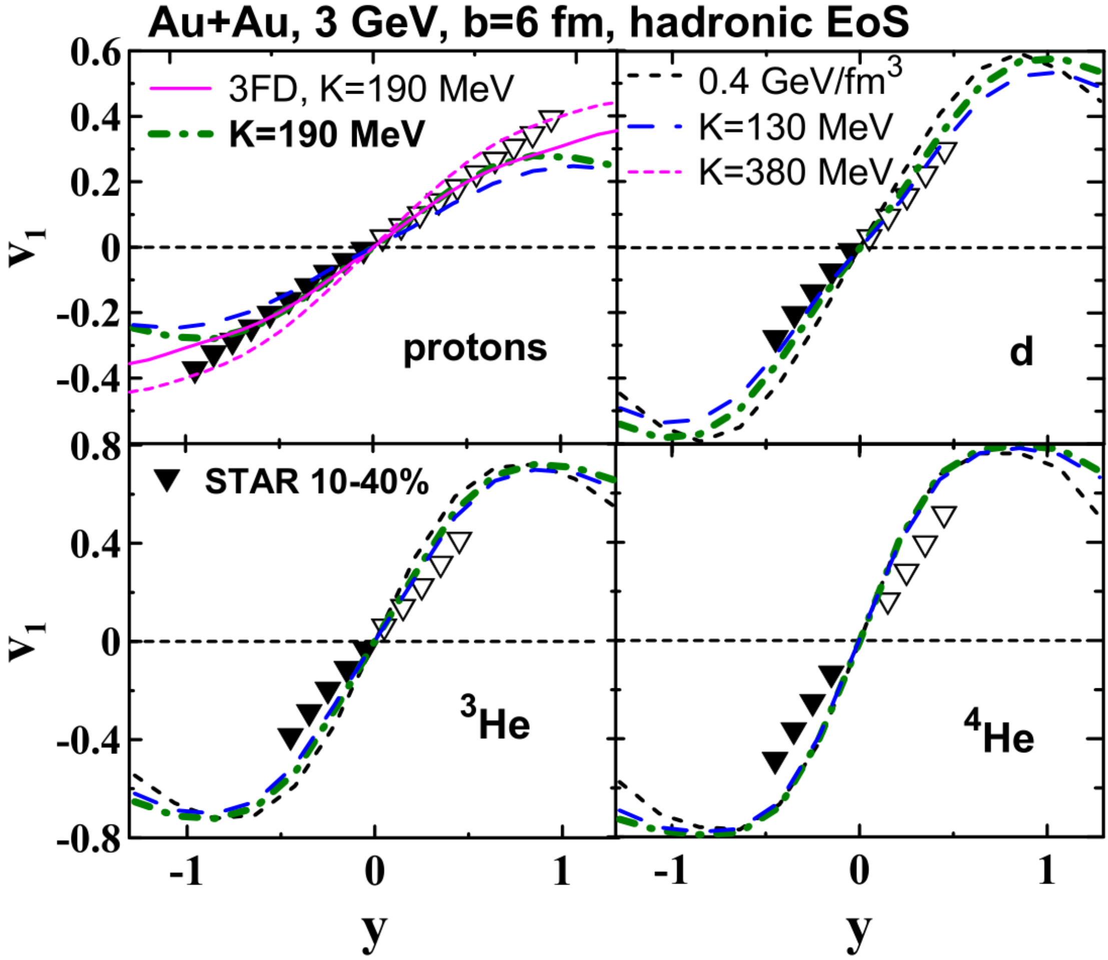
Figure: THESEUS results on directed flow v_1 of protons and light nuclei (d, $^3\mathrm{He}$, $^4\mathrm{He}$) in comparison with STAR data calculated for three different EoS.

- almost perfect agreement or protons with STAR data except for very forward/backward rapidities
- Agreement with the STAR data is getting worse with increase of atomic number of light nucleus
- the choice of EoS has no significant effect -> the dynamics is dominated by the hadronic phase



Protons and light nuclei: directed flow v_1

Figure: THESEUS results on directed flow v_1 of protons and light nuclei (d, ^{3}He, ^{4}He) for various versions of hadronic EoS: the standard (K = 190 MeV), very soft EoS (K = 130 MeV) and hard. Late freeze-out ($\varepsilon_{\rm frz} = 0.2$ GeV/fm^3) and conventional 3FD freeze-out ($\varepsilon_{\rm frz} = 0.4$ GeV/fm^3) used for light nuclei. v_1 of protons in 3FD model (without afterburner), is for the standard EoS (K = 190 MeV, thin solid line) and stiff EoS (K = 380 MeV, thin short-dashed line). Therefore, the conventionally used soft hadronic EoS with K = 190 MeV seems to be the optimal choice.



- Stiffness is characterized by incompressibility of nuclear matter that is defined as

$$K = 9n_0^2 \frac{d^2}{dn^2}\left(\frac{\varepsilon(n, T=0)}{n}\right)_{n=n_0}$$

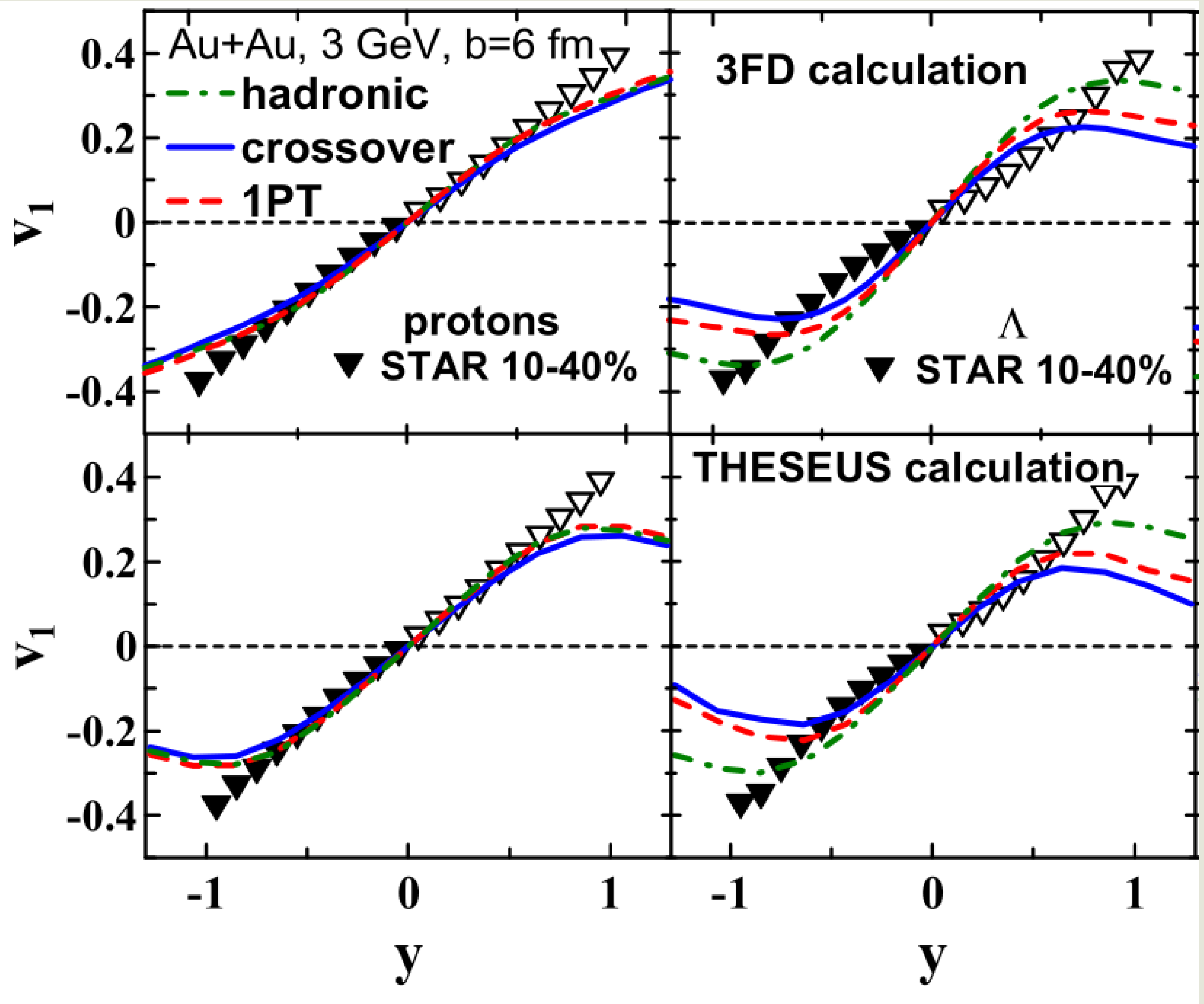
where $\varepsilon(n, T=0)$ is the energy density of the nuclear matter at $T = 0, n_0$ is the normal nuclear density. The conventionally used hadronic EoS is characterized by K = 190 MeV (quite soft).

- The conventionally used soft hadronic EoS with K = 190 MeV seems to be the optimal choice.

Protons and Λ-hyperons: directed flow v_1

Figure: directed flow v_1 of protons and Λ-hyperons in comparison with STAR data calculated for three different EoS. 3FD results are shown on upper panels, THESEUS results – on lower panels.

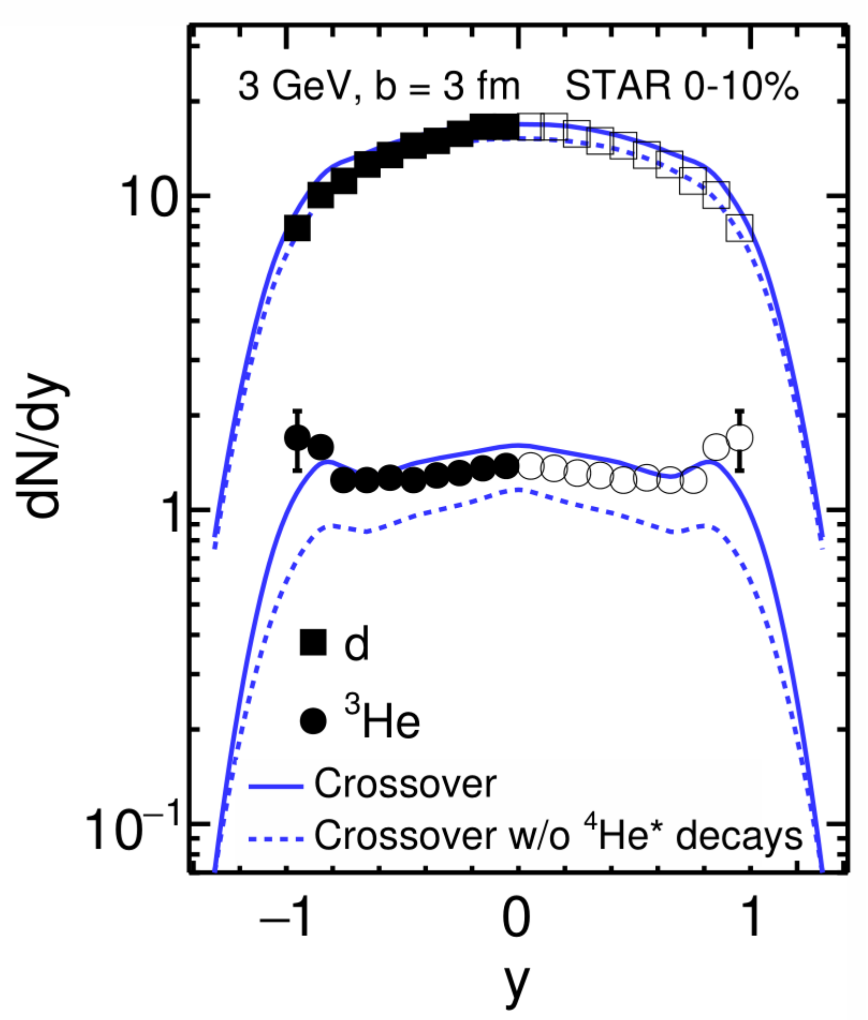
- good agreement with STAR data except forward/backward rapidities
- Afterburner (in THESEUS) slightly improves results of Λ.
- the choice of EoS has no significant effect on protons, but crossover EoS describes better the v_1 of Λ.



Light nuclei: contribution of ^{4}He* decays

Figure: Rapidity distributions of light nuclei (deuterons and ^{3}He) in central Au+Au collisions in crossover scenario with and without (w/o ^{4}He* decays) the feed-down contributions. STAR data are for comparison.

- As found in our works (Phys. Rev. C 107, no.2, 024903 (2023), Particles 6, no.1, 440-450), the feed-down contributions from unstable ^{4}He* to deuterons are negligibly small, but essential to tritons and ^{3}He $\sqrt{s_{NN}} > 6$ GeV in the midrapidity.
- At $\sqrt{s_{NN}} = 3$ GeV it was predicted in article V. Vovchenko, et al., Phys. Lett. B, 135746 (2020), that contributions are about 60% for tritons and ^{3}He even in midrapidity. We are in agreement : the feed-down contribution is~20% for deuterons and 50–100% (depending on the rapidity) for ^{3}He.
- contribution into the deuteron yield is inessential, but important for ^{3}He. Without this feed-down the ^{3}He yield is visibly underestimated
- The v1 flow of deuterons, tritons and ^{3}He turns out to be insensitive to the feed-down contributions from unstable ^{4}He* .



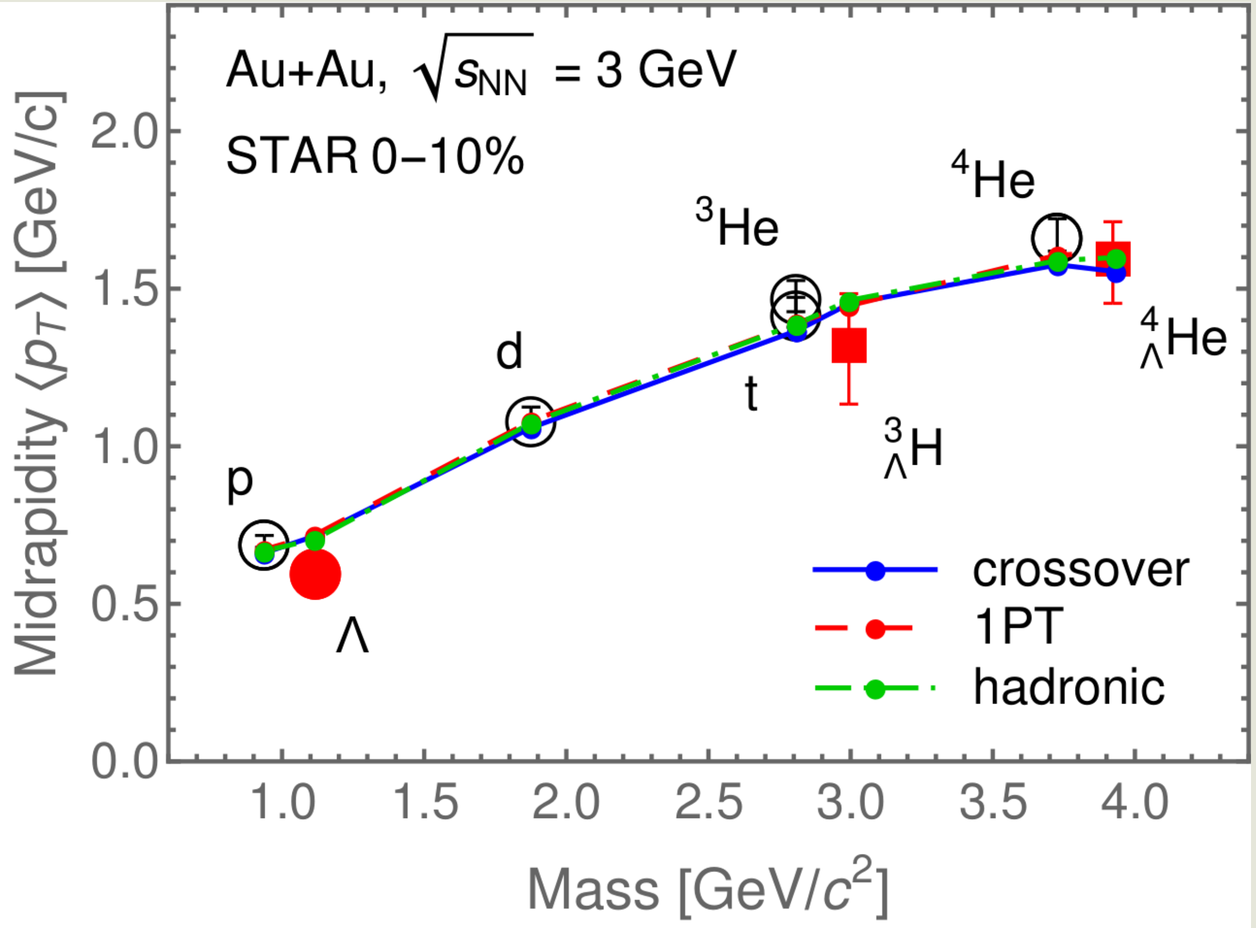
Studying of the hypernuclei

Protons, Λ and (hyper)nuclei: average p_T at midrapidity

Figure: average p_T at midrapidity for p, Λ and different species of light nuclei and hypernuclei in comparison with STAR data. Calculations are done with three different EoS.

- For p and Λ the standard freeze-out with $\varepsilon_{\mathrm{frz}} = 0.4\ \mathrm{GeV/fm^3}$ is used with consequent UrQMD afterburner;
- For d, t and $^3\mathrm{He}$ the late freeze-out with $\varepsilon_{\mathrm{frz}} = 0.2\ \mathrm{GeV/fm^3}$ is used
- For ^{4}He and $^4_\Lambda\mathrm{He}$ the standard one is used with $\varepsilon_{\mathrm{frz}} = 0.4\ \mathrm{GeV/fm^3}$.

Results well agree with the data. Even slight deviation of these curves from straight lines is reproduced.

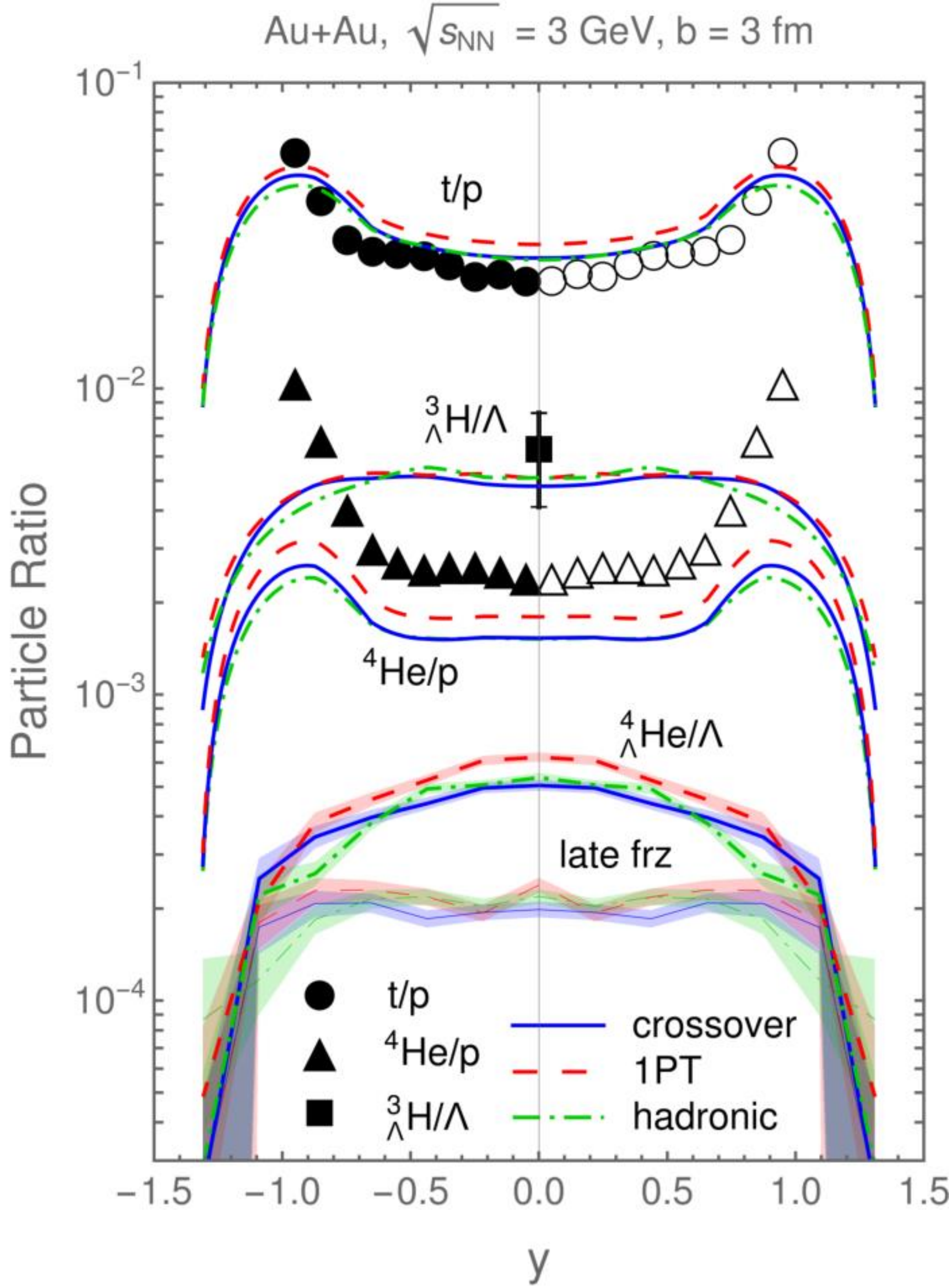


Hypernuclei: particle ratios

Figure: particle ratios in dependence of rapidity for t/p, $^3\mathrm{He}/p$, $^3_\Lambda\mathrm{H}/\Lambda$ $^4_\Lambda\mathrm{He}/\Lambda$ in comparison with STAR data. Calculations are done with three different EoS.

- For p and Λ the standard freeze-out with $\varepsilon_{\mathrm{frz}} = 0.4\ \mathrm{GeV/fm^3}$ is used with consequent UrQMD afterburner;
- For t and $^3_\Lambda\mathrm{He}$ the late freeze-out $\varepsilon_{\mathrm{frz}} = 0.2\ \mathrm{GeV/fm^3}$ is used
- For ^{4}He and $^4_\Lambda\mathrm{He}$ the standard one is used $\varepsilon_{\mathrm{frz}} = 0.4\ \mathrm{GeV/fm^3}$.
- predictions for $^4_\Lambda\mathrm{He}$ with use of standard and late freeze-out.

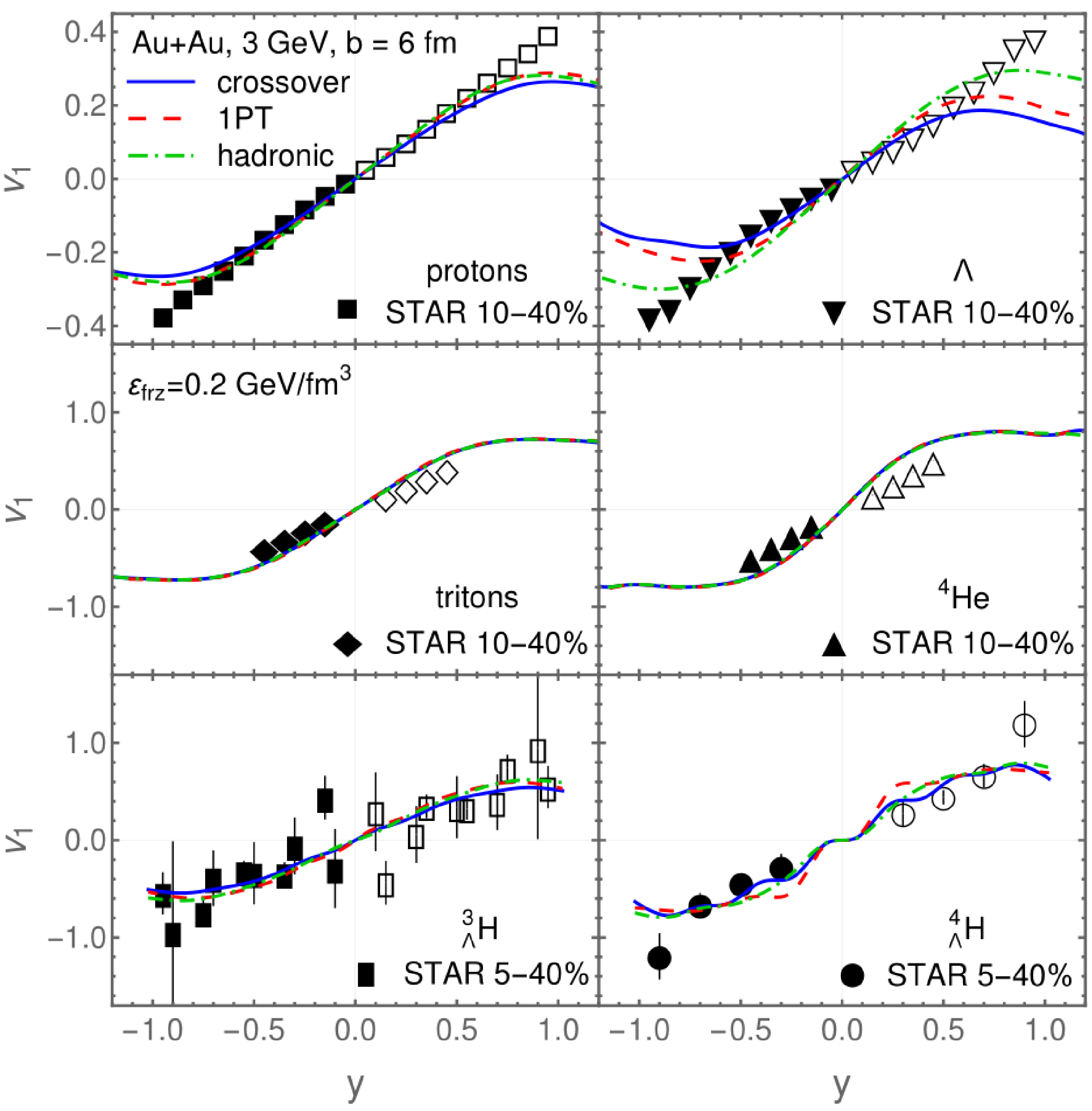
The slight overestimation of the t/p ratio is because of underestimation of the proton yield (see Kozhevnikova, Ivanov, Phys. Rev. C 109, no.1, 014913 (2024)). Almost without difference of EoS -> collision process develops in the hadronic phase.



Hypernuclei: directed flow v_1

Figure: directed flow v_1 for p, Λ and different species of light nuclei and hypernuclei in comparison with STAR data. Calculations are done with three different EoS.

- For p and Λ the standard freeze-out $\varepsilon_{\mathrm{frz}} = 0.4\ \mathrm{GeV/fm^3}$ is used with consequent UrQMD afterburner;
- For t, ^{4}He $^3_\Lambda$H and $^4_\Lambda$H the late freeze-out with $\varepsilon_{\mathrm{frz}} = 0.2\ \mathrm{GeV/fm^3}$ is used.
- Good agreement of p and Λ especially in midrapidity region;
- No dependence on EoS for (hyper)nuclei;
- For hypernuclei results are in agreement with experiment within statistical uncertainties.



Hypernuclei: directed flow v_1

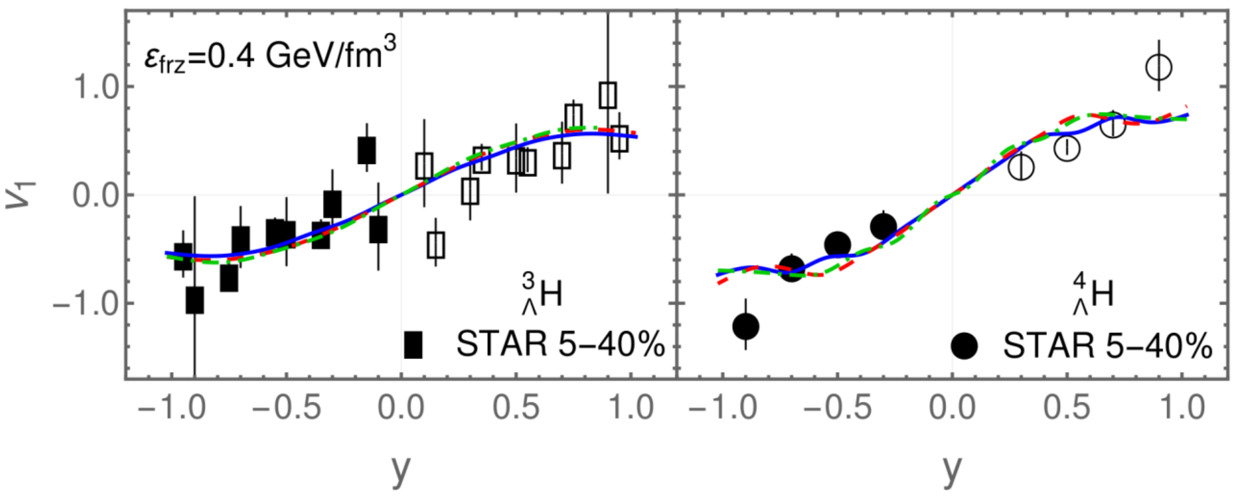


Figure: directed flow v_1 for hypernuclei in comparison with STAR data. Calculations are done with three different EoS.

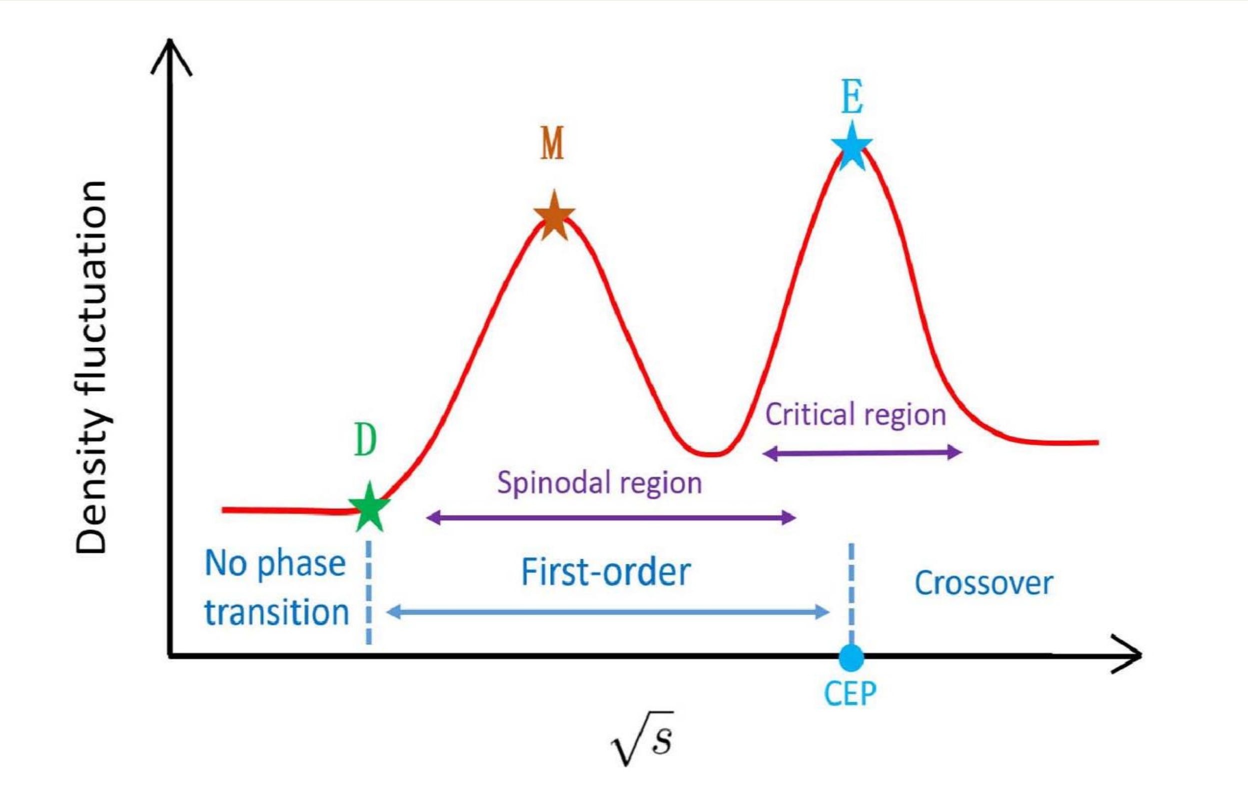
- The standard freeze-out with $\varepsilon_{\mathrm{frz}} = 0.4\ \mathrm{GeV/fm^3}$ is used;
- No significant difference with the results calculated with the late freeze-out → the baryon directed flow is formed at the early stage of the evolution.

Summary

- At the collision energy $\sqrt{s_{NN}} = 3\ \mathrm{GeV}$ results do not depend on choice of EoS, so it indicates to that evolution of the system performs in hadronic phase. However, crossover EoS gives better result for Λ-hyperons.
- Bulk observables and directed flow generally are in good agreement with data. THESEUS simulations give reasonable results even for hypernuclei at the collision energy $\sqrt{s_{NN}} = 3\ \mathrm{GeV}$.
- For treatment of almost all studied (hyper)nuclei we need late freeze-out, so afterburner plays significant role in their production. An exception is $^4\mathrm{He}$ which requires standard freeze-out.
- It is important to take into account contributions of unstable $^4\mathrm{He}^*$ to $^3\mathrm{He}$ yields and not so much for deuterons.
- We need contributions from unstable species of light nuclei with A=5 to ^4He (work in process).
- Predictions for argon-nucleus collisions at NICA energy $3.2A\ \mathrm{GeV}$ (in the nearest plans).

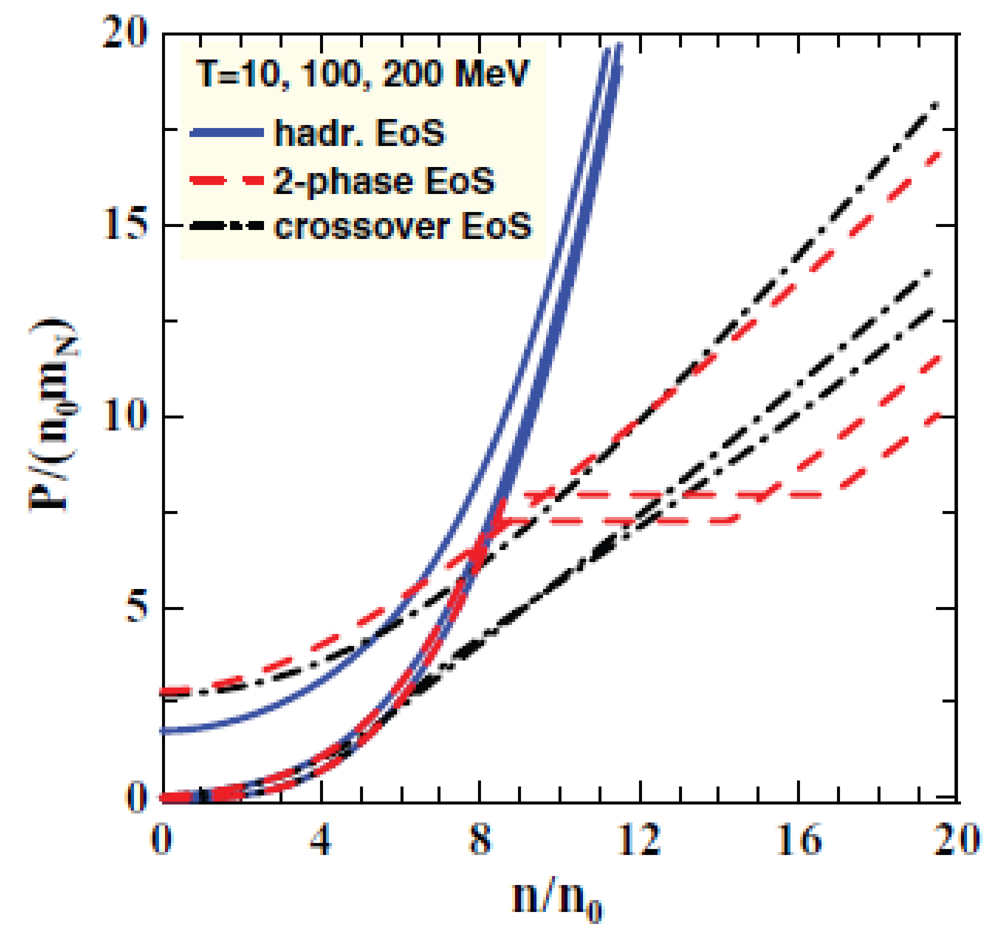
Thank you for your attention!

Spinodal region



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

Different EoS



Directed flow

The single particle distribution function:

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

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.