Light cluster production in heavy-ion collisions in generator THESEUS

MARINA KOZHEVNIKOVA (JINR)

IN COLLABORATION WITH O. ROGACHEVSKY, D. BLASCHKE, YU. IVANOV, YU. KARPENKO, V. VORONYUK, G. RÖPKE

International Workshop: Light clusters in nuclei and nuclear matter:
Nuclear structure and decay, heavy ion collisions, and astrophysics
ECT* Trento, September 02-06, 2019

RSF Russian Science Foundation
Grant No. 17-12-02714

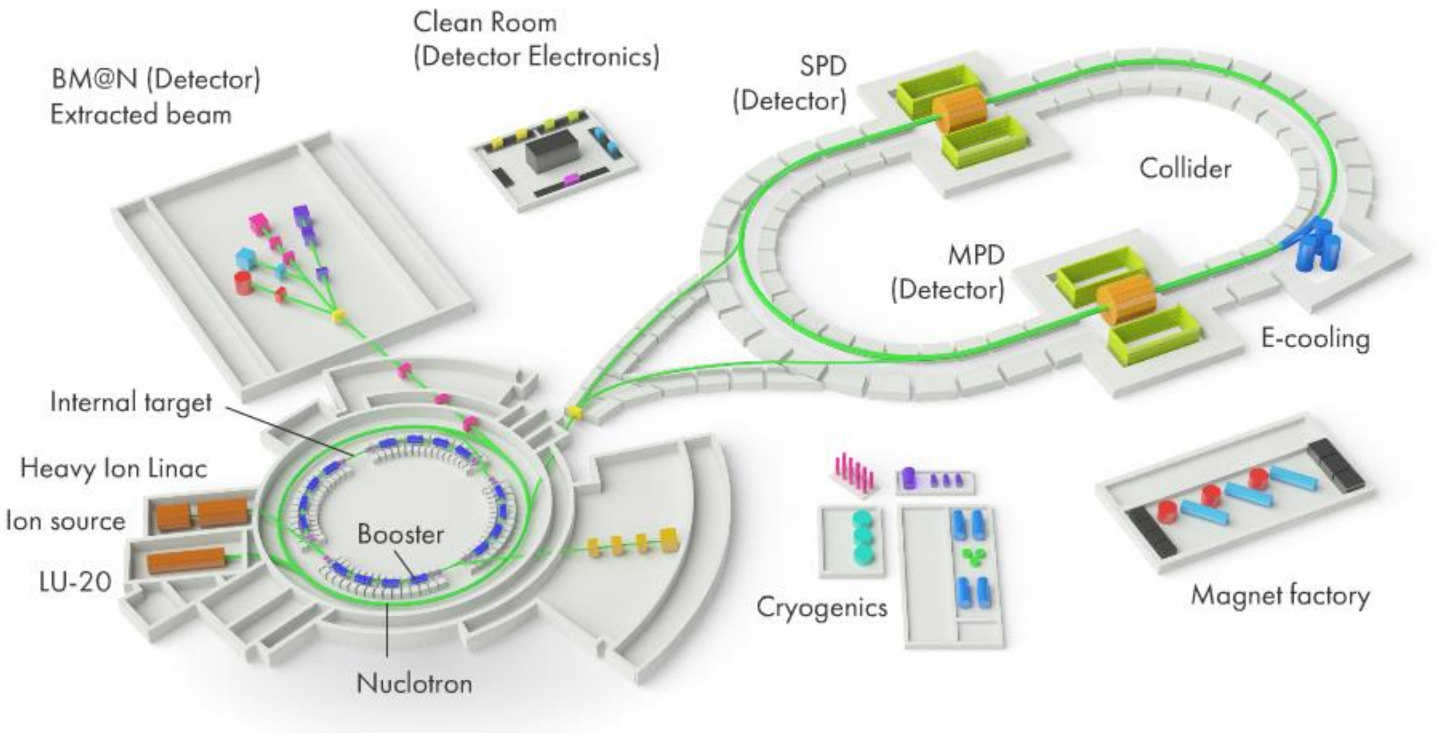
Plan of the presentation

- NICA accelerator complex
- Bound states in nuclear matter: different approaches
- Freeze-out and Mott effect: the necessity of accounting for light clusters in the formation of hadrons. QCD phase diagrams.
- Event generator THESEUS: short description
- Tests of generator: production of pions, protons in Au+Au collisions at NICA energies and comparison with 3FD-model and existing experimental data
- Light clusters production: rapidity distributions and experimental data
- Future tasks

NICA (Nuclotron-based Ion Collider fAcility)

Specific scope elements of the project NICA/MPD facility are expected to include:

- Injection complex,
- new superconducting Booster synchrotron (that will be located inside the yoke of the decommissioned Synchrophasotron),
- the existing superconducting heavy ion synchrotron Nuclotron (being developed presently to match the project specifications), collider having two new superconducting storage rings,
- new beam transfer channels.



Eur. Phys. J. A (2016) **52(8)**: 267 The NICA White Paper

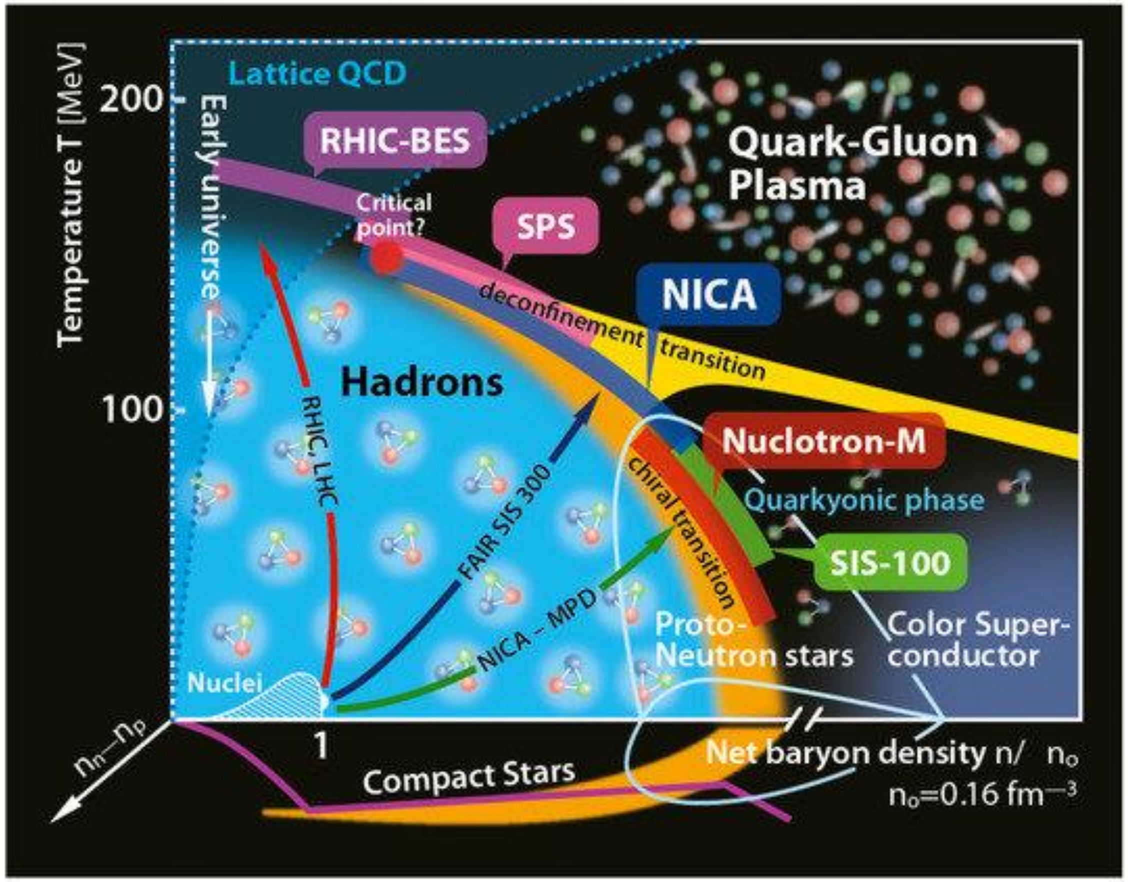
QCD phase diagram, beam energy scan programs, chemical freeze-out

Quark-hadron phase transition

- Quark deconfinement
- Chiral symmetry restoration

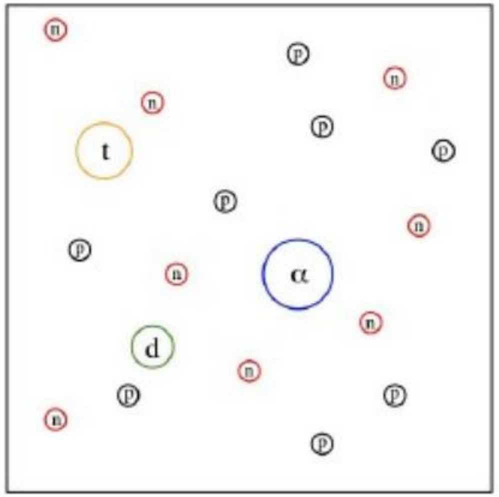
Chemical freeze-out

- Hadron species: pions, kaons, protons etc.
- Nuclear clusters: deuterons, tritons etc.



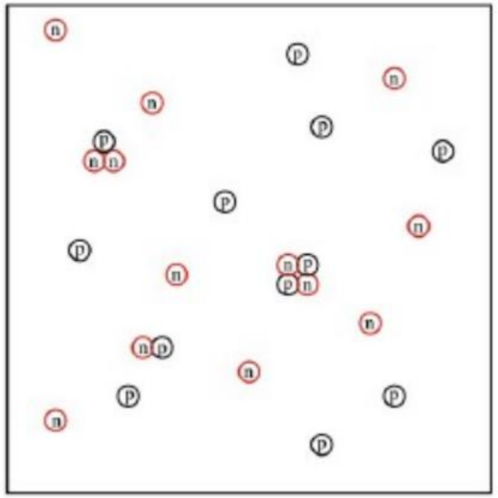
Clusters in nuclear matter

- Chemical picture: mass action law



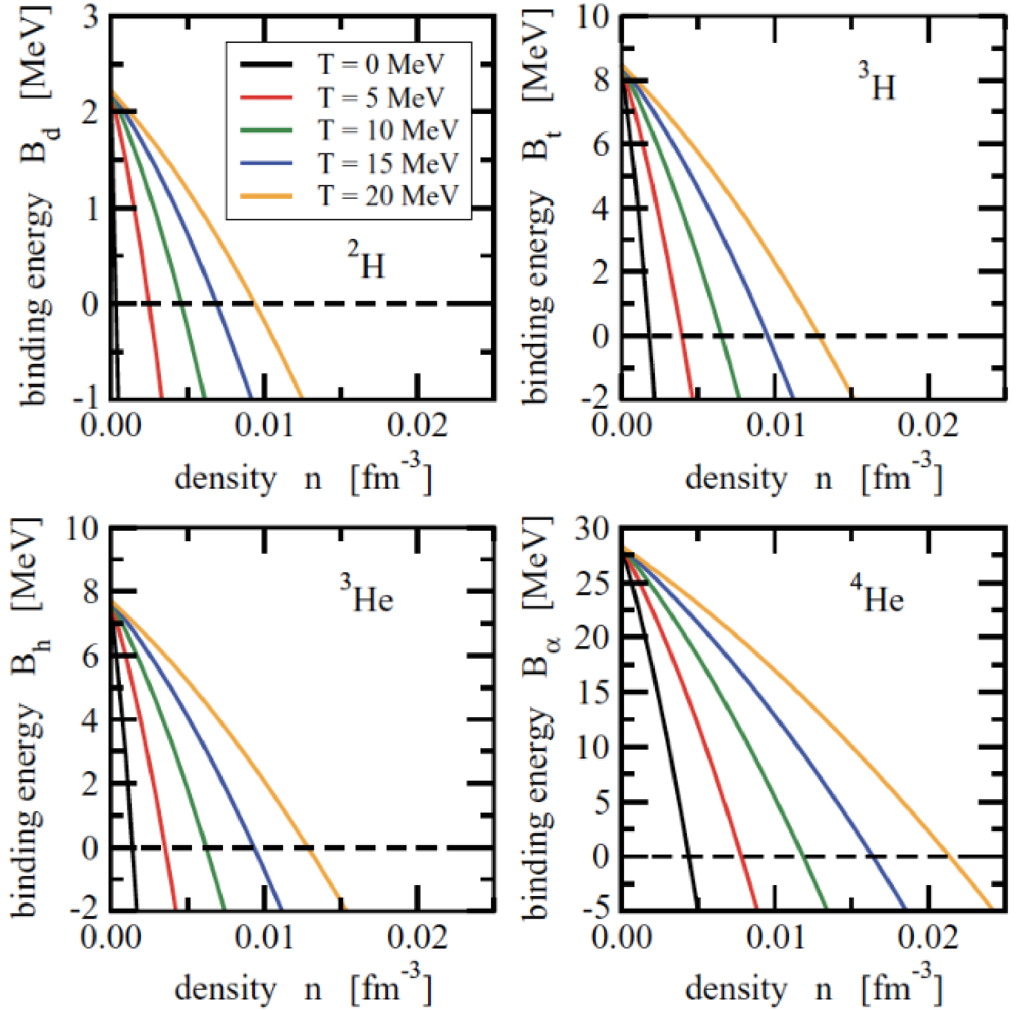
Interaction between components of nuclear matter is determined by excluded volume (Pauli blocking)

- Physical picture: interacting “elementary” constituents of nuclear matter: p and n



Interaction between components of nuclear matter is determined quantum statistics, quasiparticles approach, virial expansion

Dependence of binding energies on temperature and density

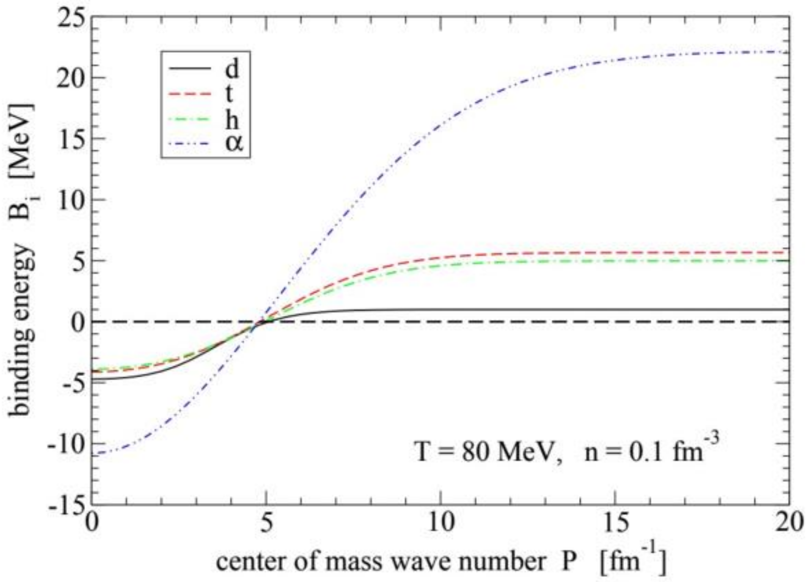


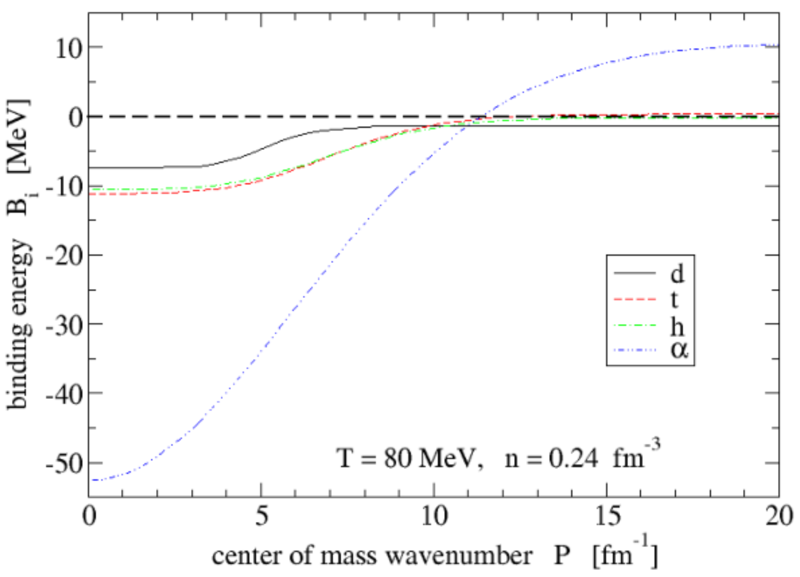
Vanishing binding energies indicate Mott effect for the light clusters!

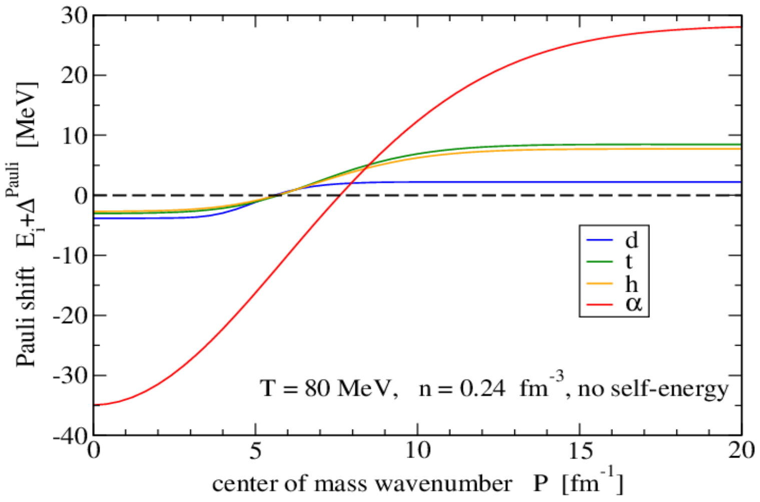
→ Mott lines in the T-μ plane (phase diagram)

S. Typel, G. Röpke, T. Klähn, D. Blaschke, H. Wolter, PRC 81, 015803 (2010)

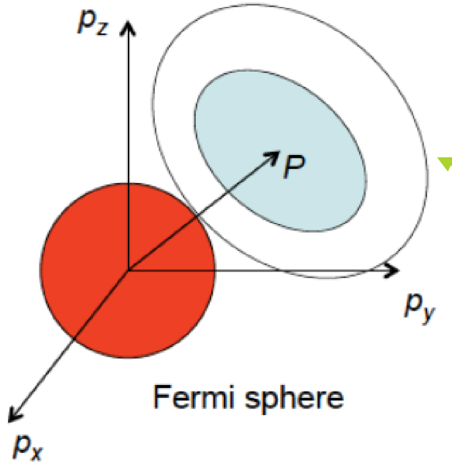
Momentum dependence of binding energies. Pauli blocking







<u>Mott dissociation at low momenta</u> – clusters do not form because of the Pauli exclusion principle.
At large momenta, beyond the Mott momentum (depending on temperature and density) binding energies become positive again, so that clusters are bound since they do not "see" the neutrons and protons of the medium (Fermi sphere; P – cluster momentum in center of mass



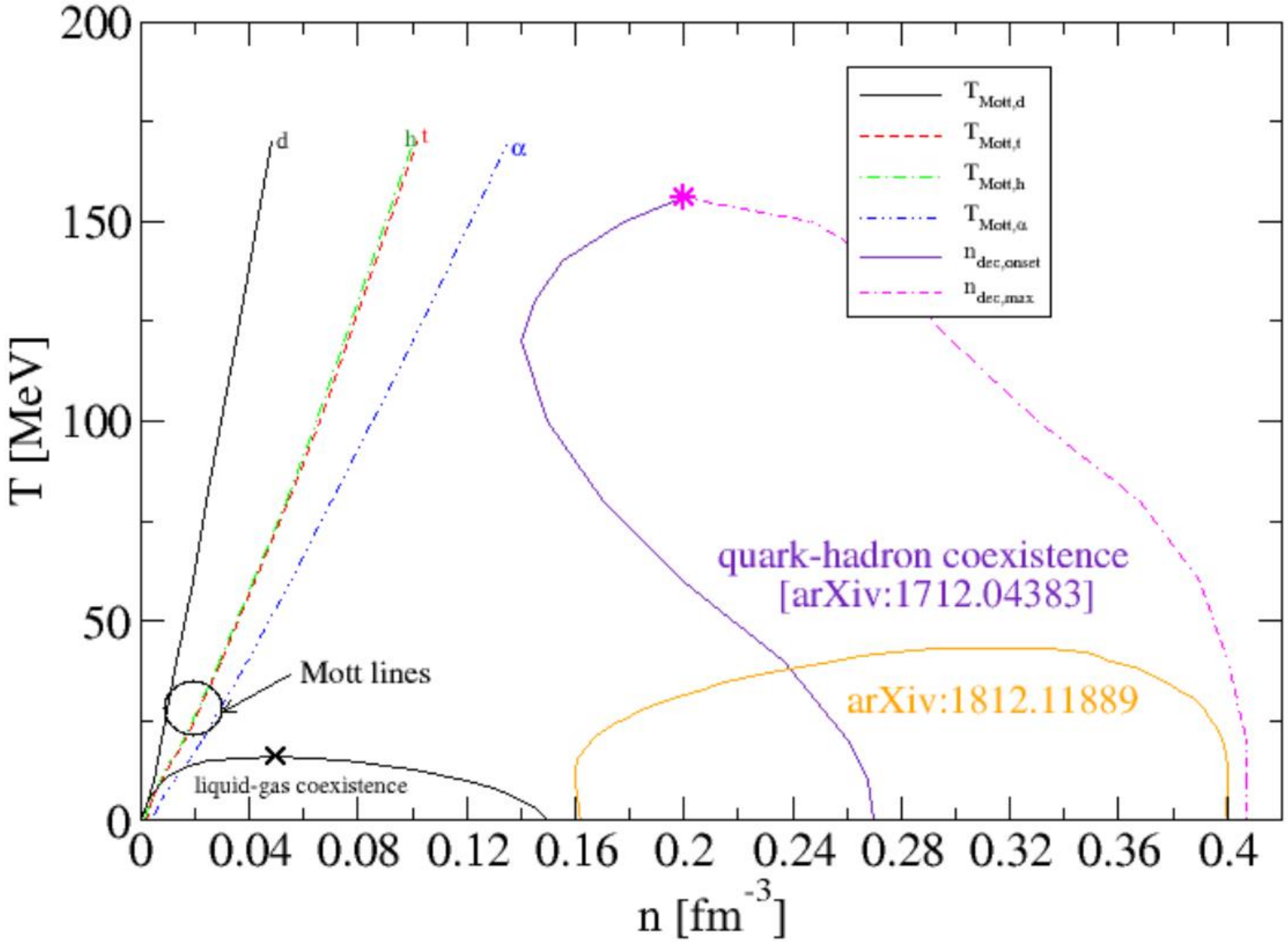
Only Pauli shift taken into account, no self-energy corrections

Cluster wave-function in momentum space

Mott lines in the QCD phase diagram

<u>Mott lines :</u>
Protons and neutrons can form clusters
(deuterons, tritons, He3, α or He4)
on the left of the lines (lower densities)
and exist separately on the right of the
Mott lines (at higher densities)

<u>Quark-hadron coexistence:</u>
different estimations: inside the violet
and orange regions there is matter of
coexisting quarks and hadrons,
at the left – hadrons,
at the right – quarks, quark-gluon plasma



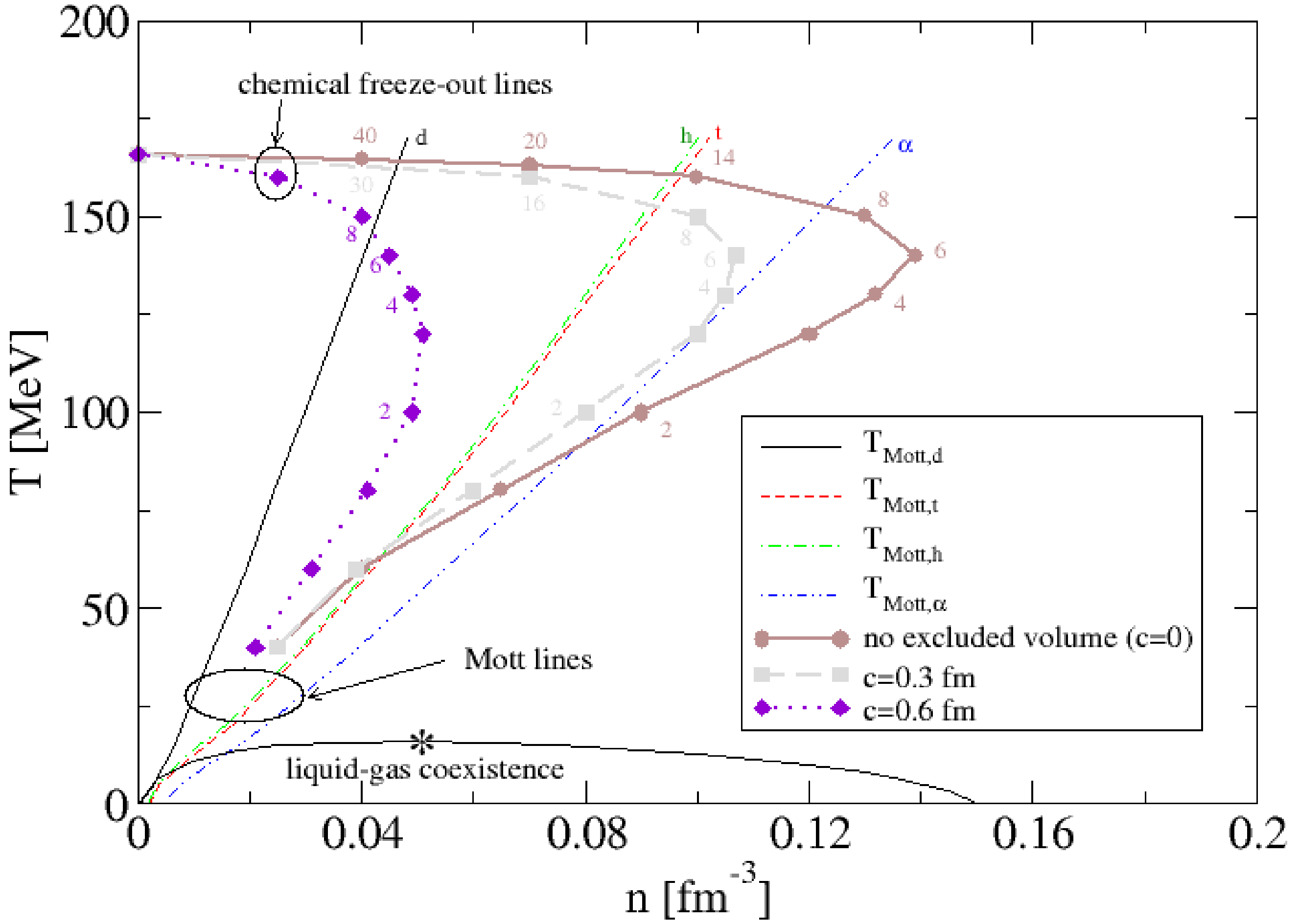
Mott lines and chemical freeze-out in the QCD phase diagram

Chemical freeze-out lines: the bounding lines of existing hadron states on parameters T and n taken into account. [Randrup & Cleymans, EPJA (2016)]

- Intersection of Mott lines with freeze-out lines – light clusters can be formed when forming hadrons

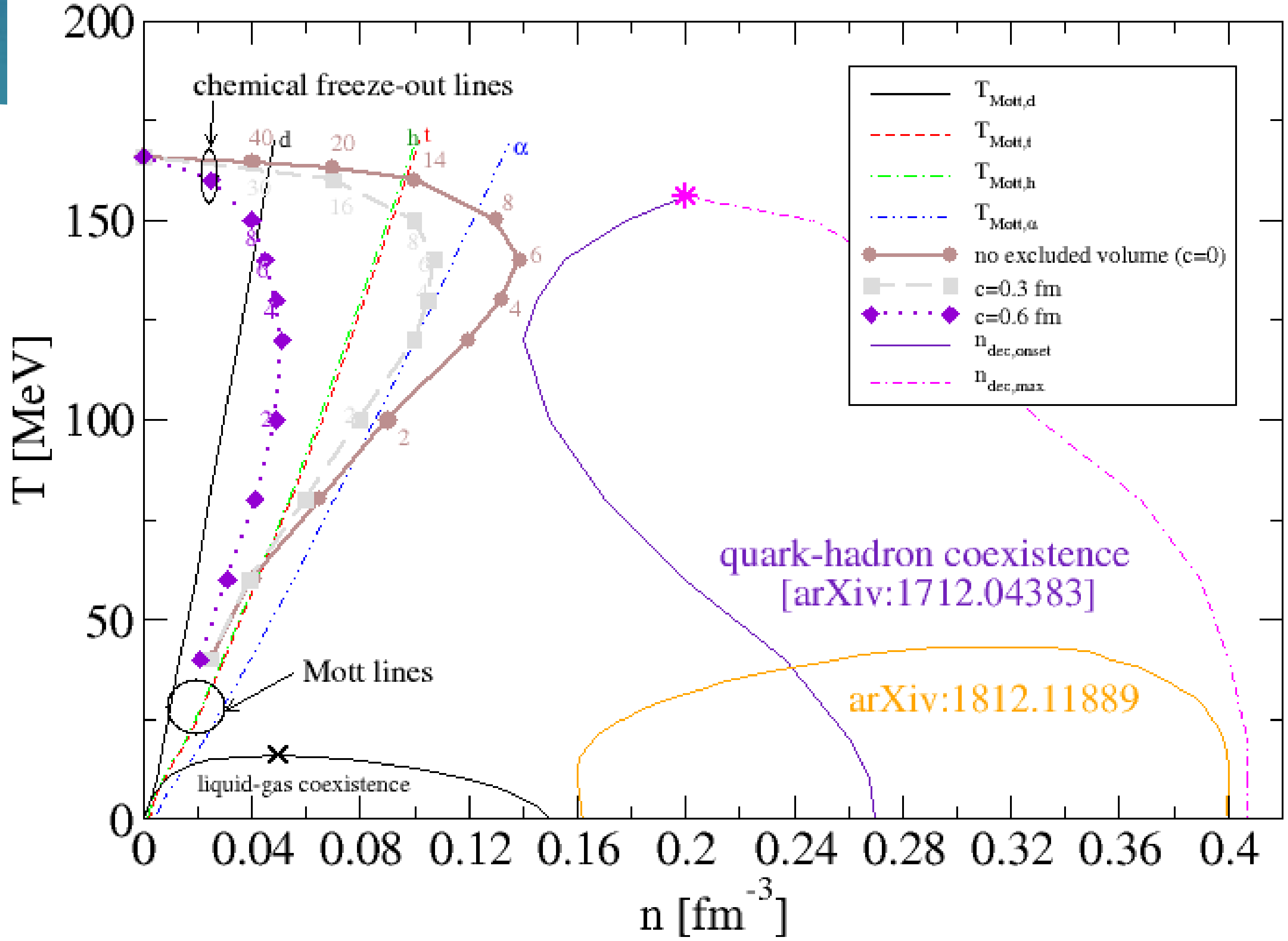
Ideal gas (point particles, radius c =0): light brown bounding line

Particle system with hard core interaction, radius of hard core: c =0.3 fm (gray) and c =0.3 fm (violet)



QCD phase diagram: all states

… Including quark deconfinement (two example models)



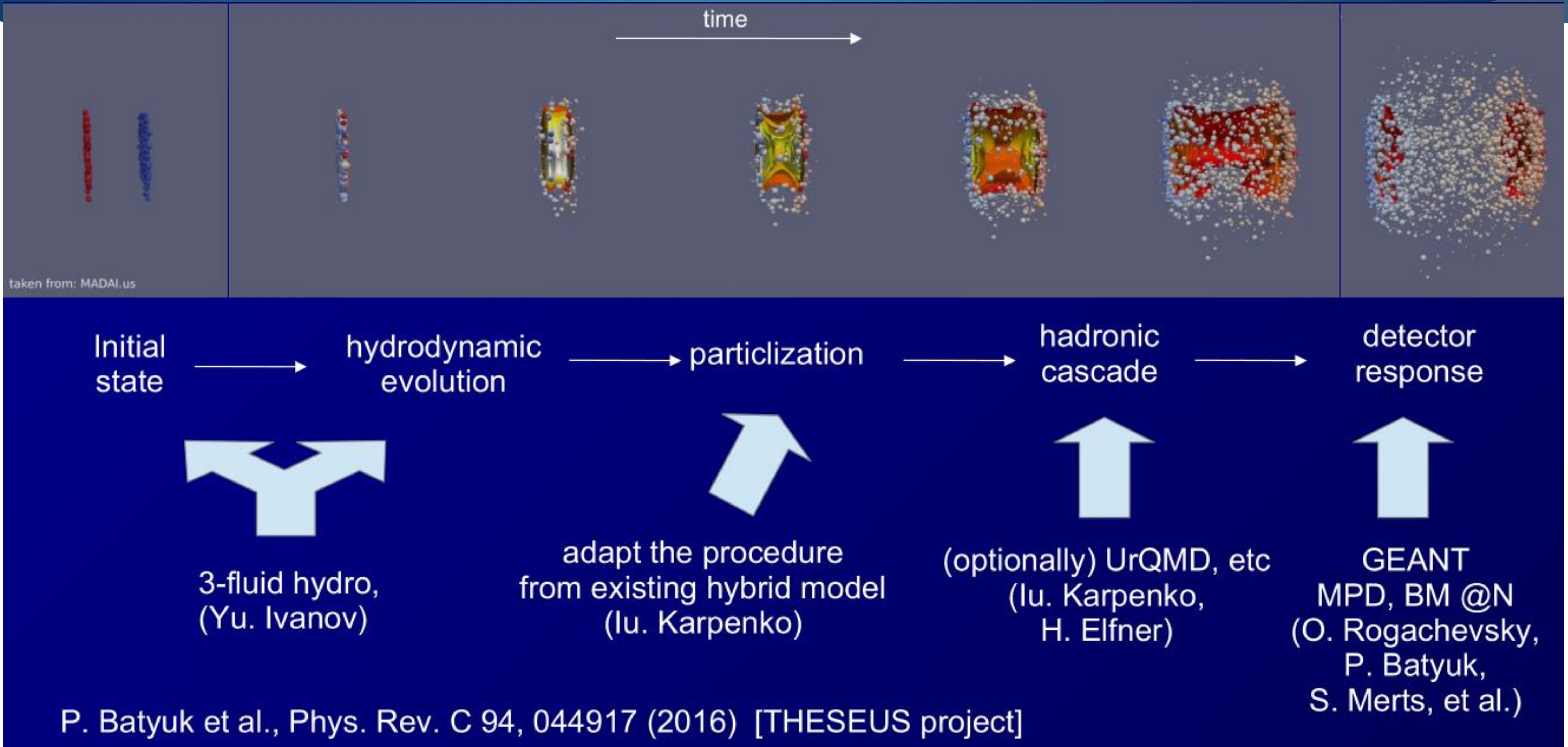
THESEUS event generator

- An event generator based on the three-fluid hydrodynamics approach (3FD) for the early stage of the collision, followed by a particlization at the hydrodynamic decoupling surface.
- Joins microscopic transport model, ultrarelativistic quantum molecular dynamics (UrQMD) to account for hadronic final-state interactions.
- Can be applied for two model equations of state, one with a first-order phase transition (1PT) and the other with a crossover-type softening at high densities.
- The new simulation program has the unique feature that it can describe a hadron-to-quark matter transition which proceeds in the baryon stopping regime that is not accessible to previous simulation programs designed for higher energies.
- One of the main goals of the generator THESEUS is to obtain final states of Au+Au collisions, at NICA energies:
- Generation of light clusters

Three-fluid hydrodynamics (3FH): Yu. B. Ivanov et al., PHYSICAL REVIEW C 73, 044904 (2006)

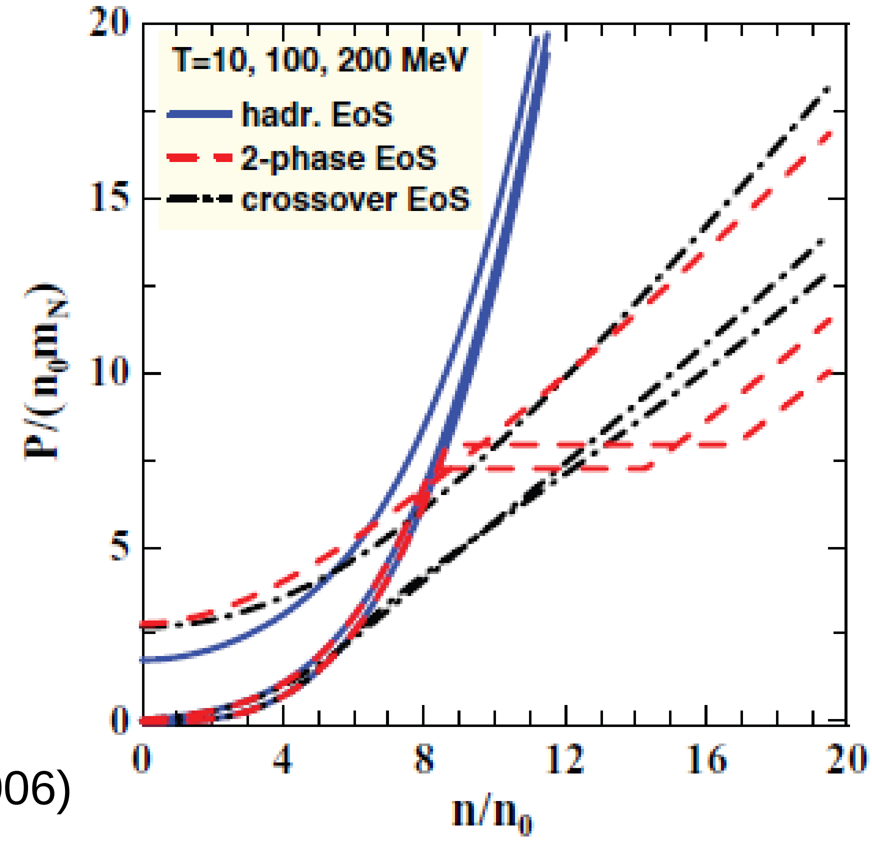
THESEUS (3FH+Particlization+UrQMD): P. Batyuk et al., PHYSICAL REVIEW C 94, 044917 (2016)

Hydrodynamic modelling of nuclear collisions for NICA / FAIR



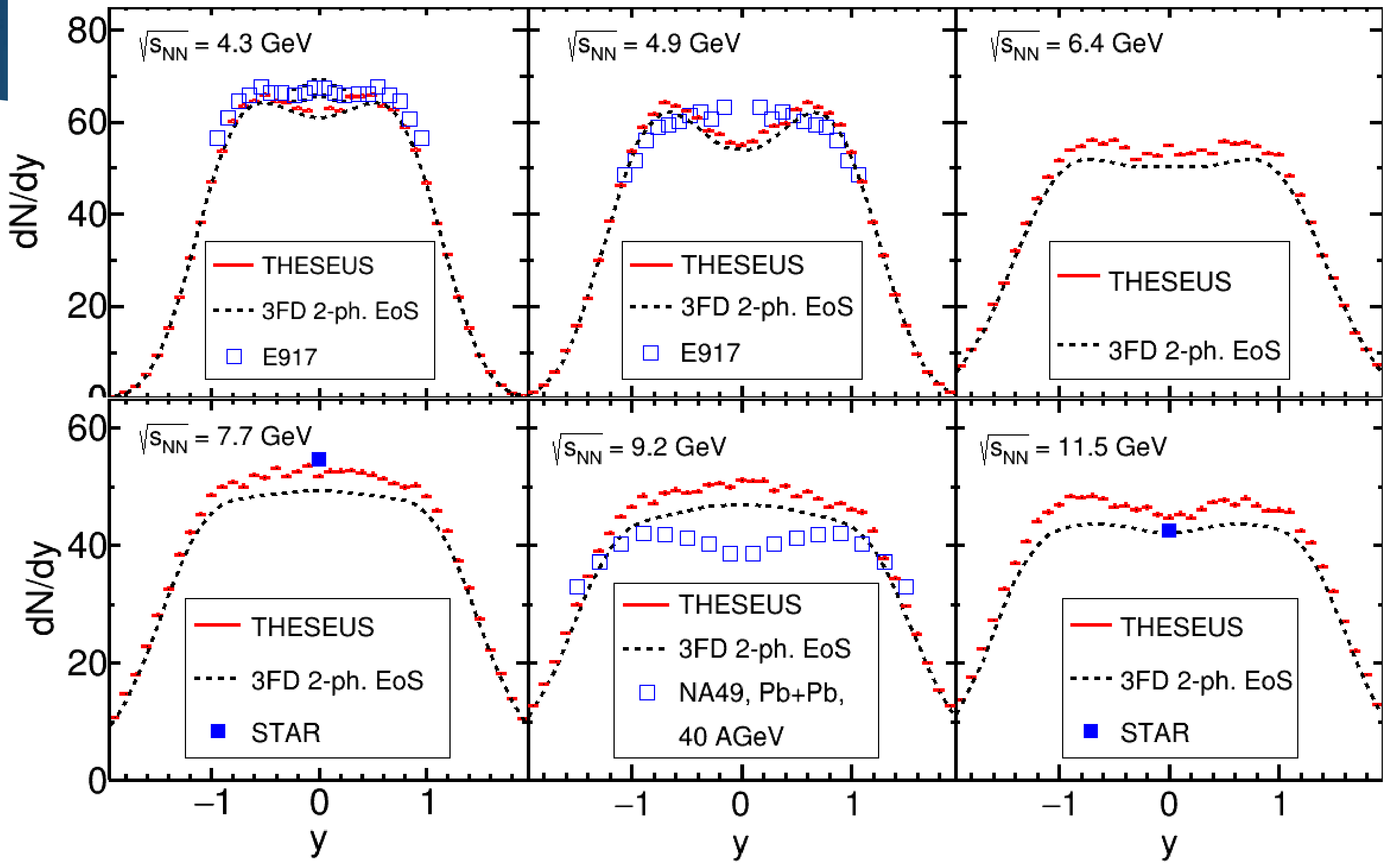
Comparison of different EoS

- Three types of EoS for the 3FH simulation:
- Hadronic EoS: Hadron resonance gas model
- 2-phase EoS: Maxwell construction with density-functional approach to quark-gluon plasma
- Crossover EoS: Smooth interpolation between HRG and QGP

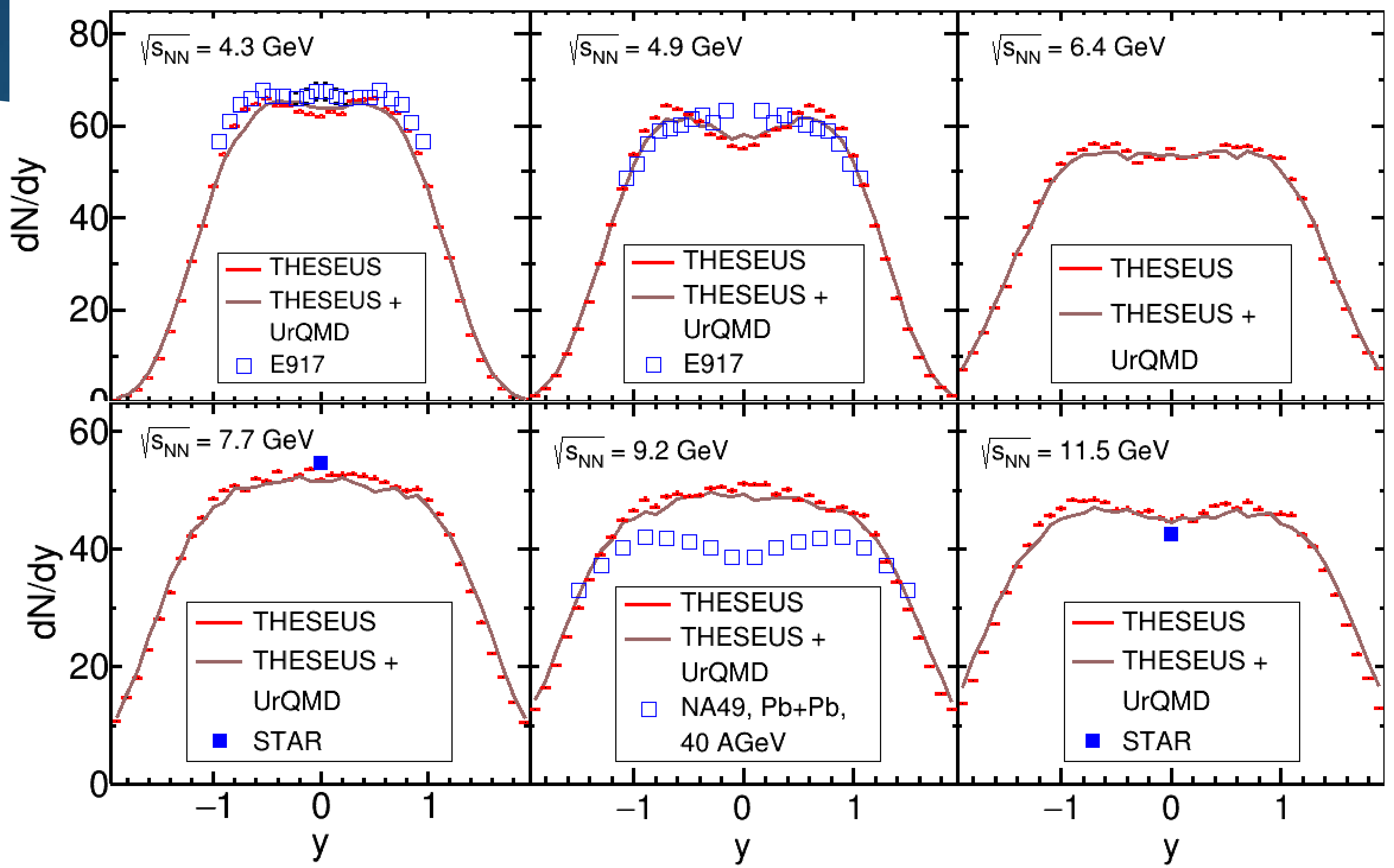


A. Khvorostukhin, V.V. Skokov, V.D. Toneev, K. Redlich, EPJ C48, 531 (2006)
Yu. B. Ivanov, D. Blaschke, PRC 92, 024916 (2015)

Tests of generator: proton rapidity distributions



Rapidity distributions of protons, with UrQMD



THESEUS and 3FD-model

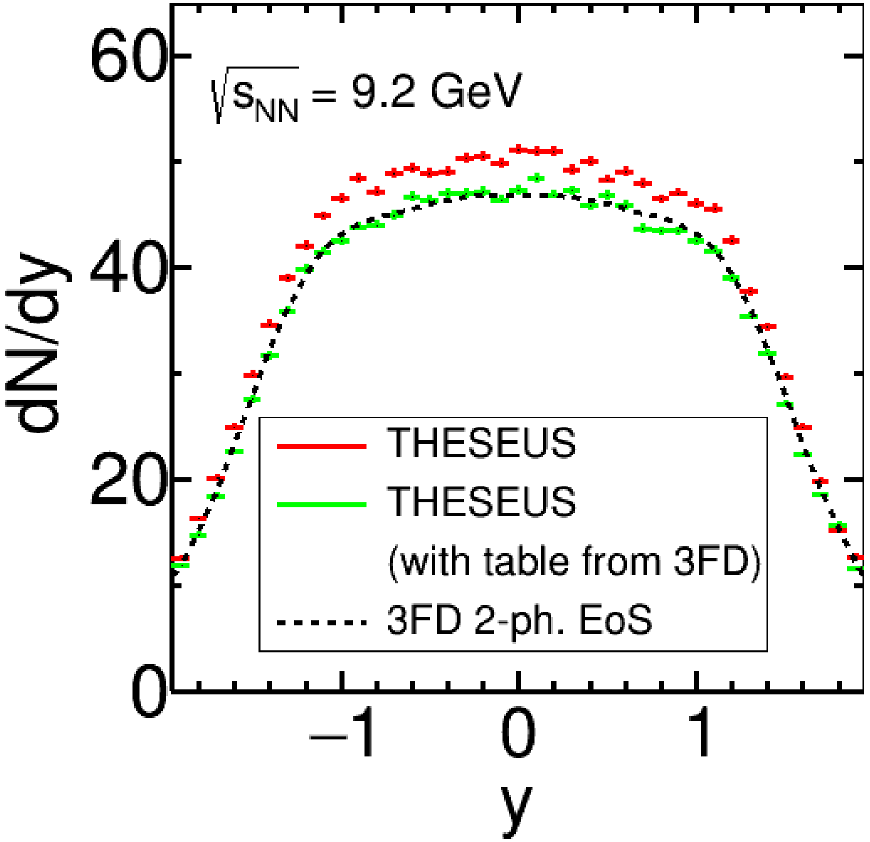
Comparison of results on rapidity of protons of THESEUS and 3FD-model.

Green dots – THESEUS with set of decaying resonances (as a table) taken from 3FD-model.

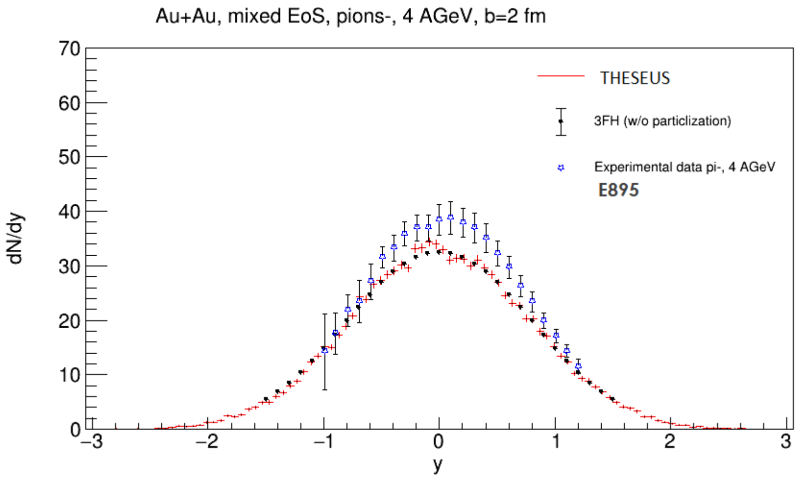
Red dots – THESEUS with its own set (table) of decaying resonances, extended in comparison of 3FD.

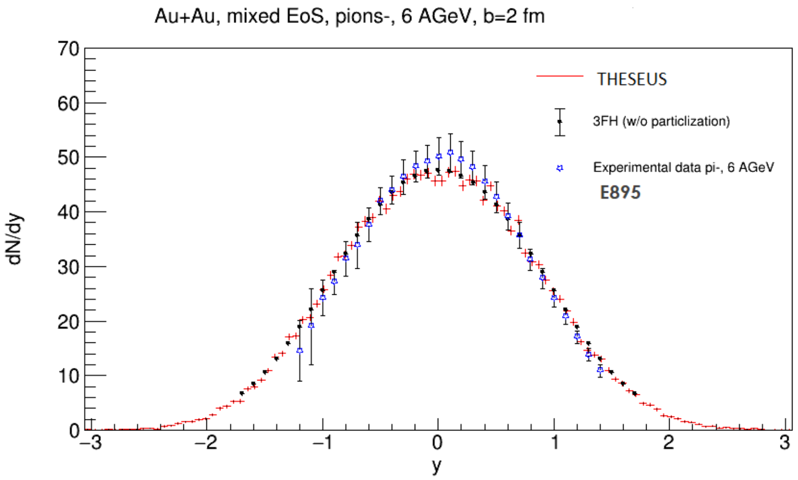
Black dashed curve – 3FD-model.

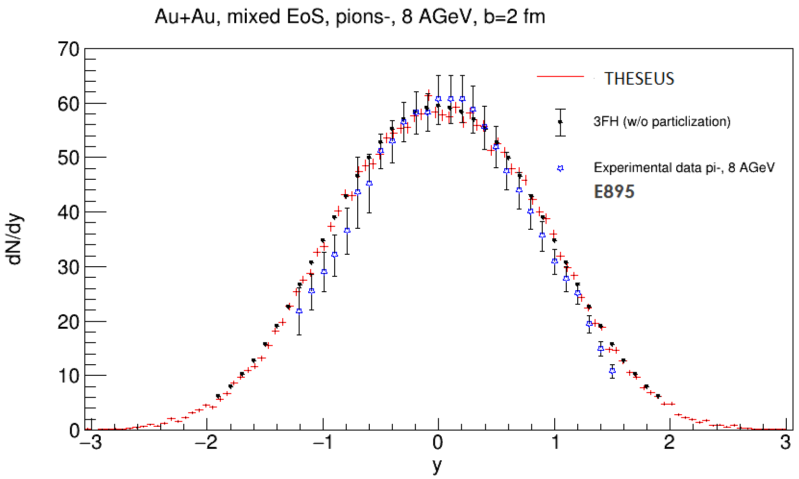
3FD and THESEUS give very similar results with a single set of decaying resonances!



Rapidity distributions of pions (π^-), Au+Au

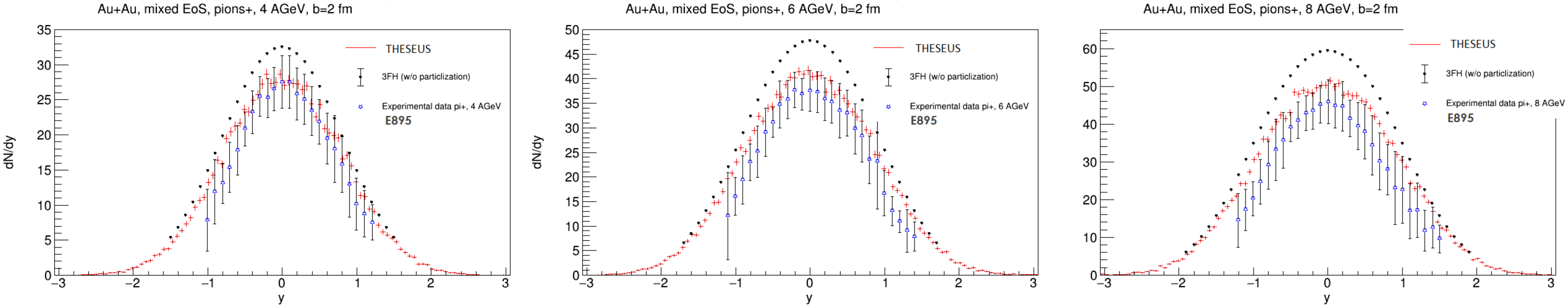






$E_{\rm lab}$ = 4, 6, 8 AGeV $\rightarrow$ = 3.319, 3.843, 4.303 GeV:
Experimental data: J. L. Klay et al. (**E895 Collaboration**), Phys. Rev. C 68, 054905 (2003).

Rapidity distributions of pions (π^+), Au+Au

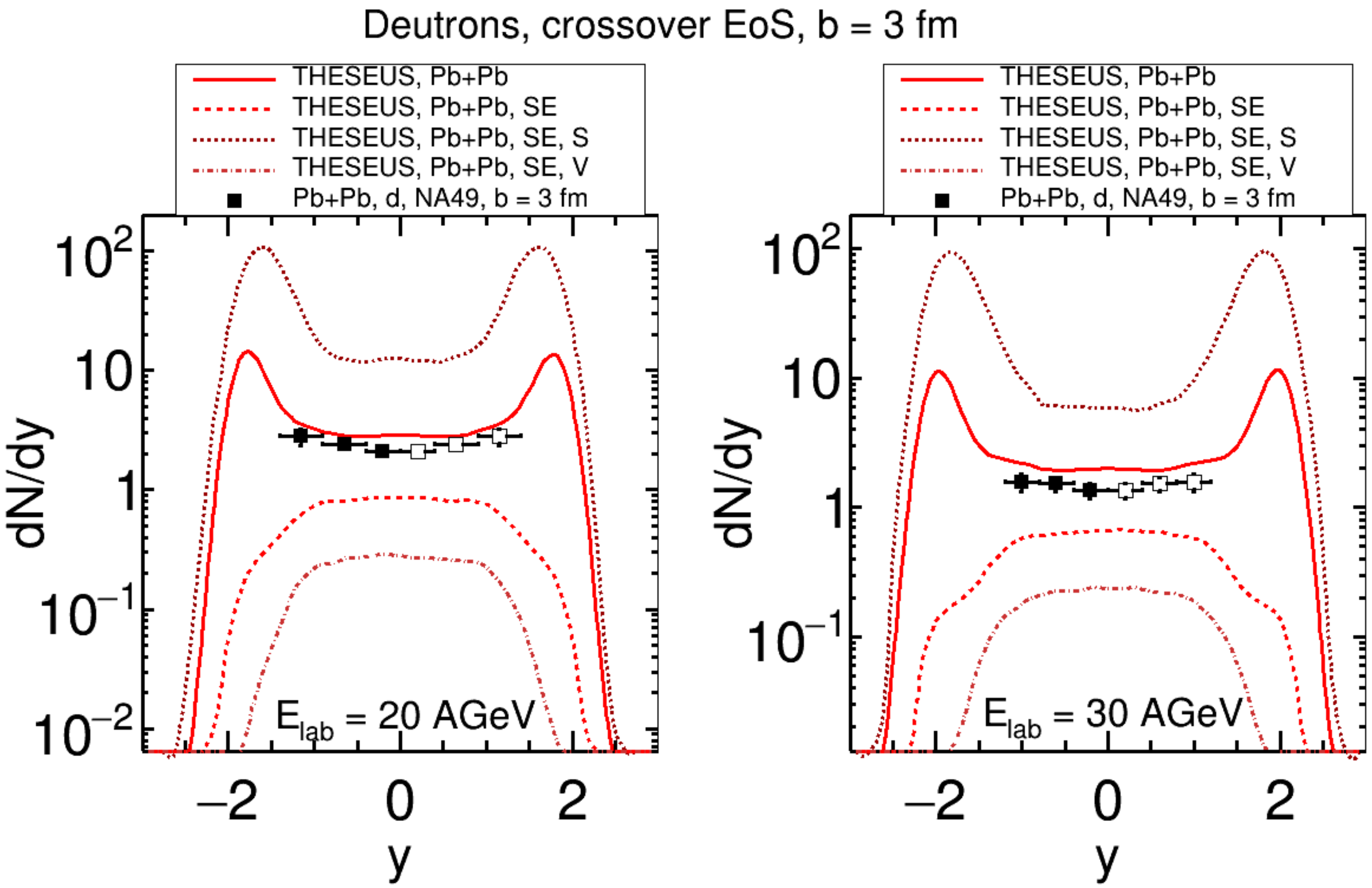


- E_{lab}= 4, 6, 8 AGeV $\rightarrow \sqrt{s_{NN}}$ = 3.319, 3.843, 4.303 GeV:
  Experimental data: J. L. Klay et al. (**E895 Collaboration**), Phys. Rev. C 68, 054905 (2003).

Light cluster production: deutrons

Rapidity distributions for deuterons in Pb+Pb collisions at energies 20 AGeV and 30 AGeV, b = 3 fm

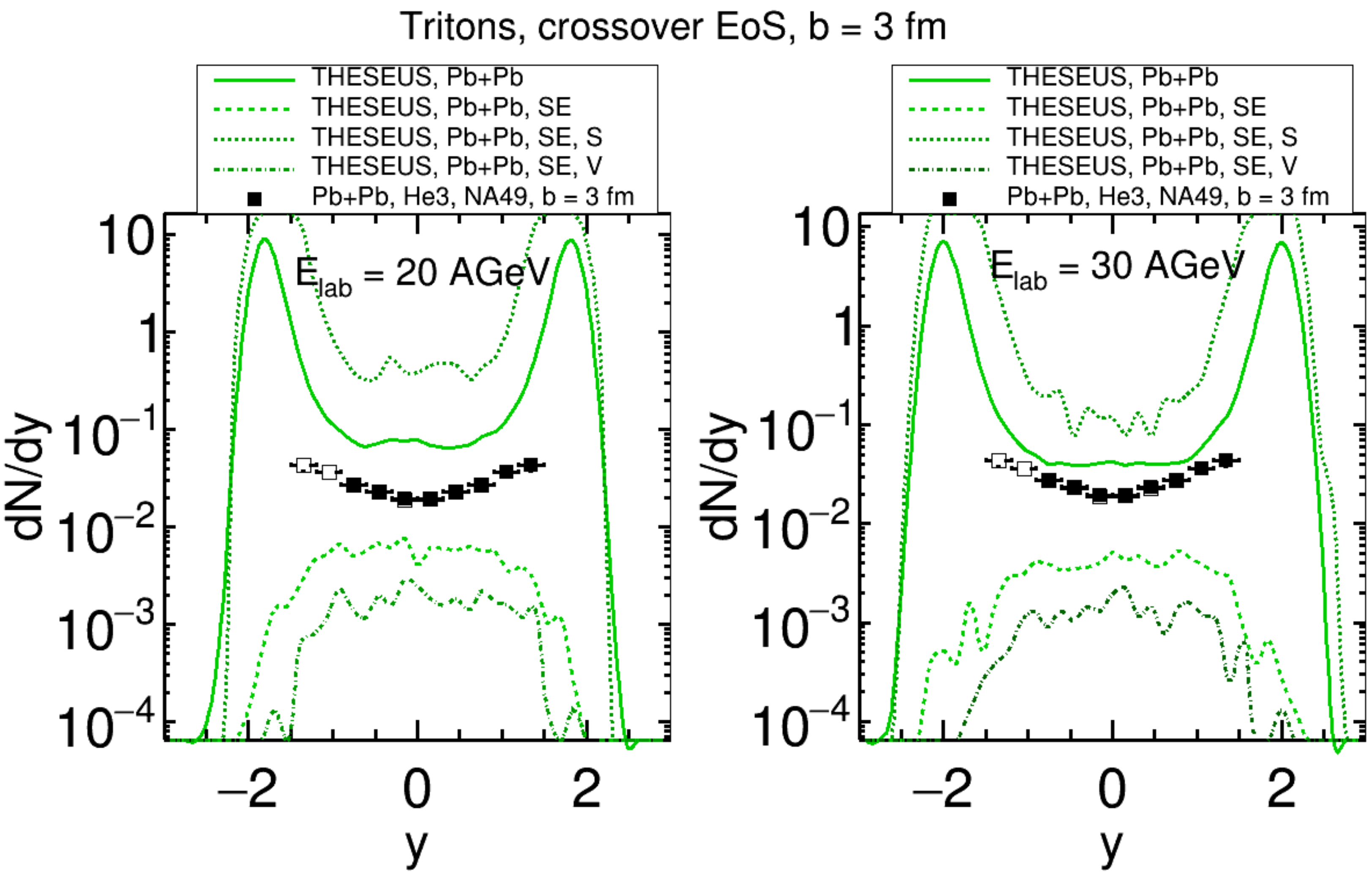
- The scalar (S) and vector (V) self energies (SE) corrections to the mass and chemical potential are included as rough estimations.
- S-correction is positive and increases the clusters production, V is negative and reduces clusters production
- Comparison with experimental data: NA49



Light clusters: tritons

Rapidity distributions for tritons in Pb+Pb collisions at energies 20 AGeV and 30 AGeV, b = 3 fm

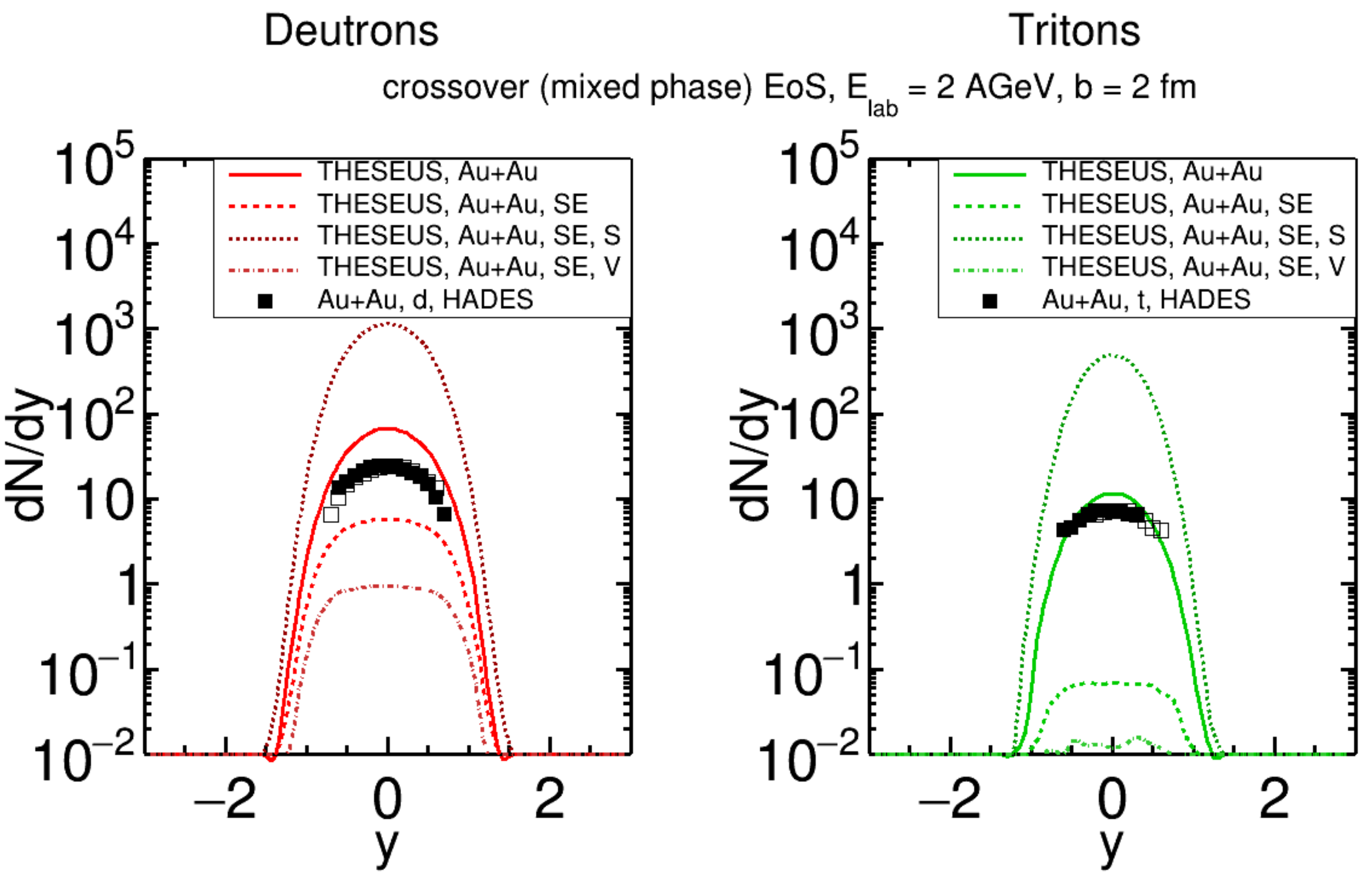
- The scalar (S) and vector (V) self energies (SE) corrections to the mass and chemical potential are included as rough estimations.
- S-correction is positive and increases the clusters production, V is negative and reduces clusters production
- Comparison with experimental data for He3: NA49



Light clusters at low energies, HADES data

Comparison of THESEUS results with preliminary HADES data,

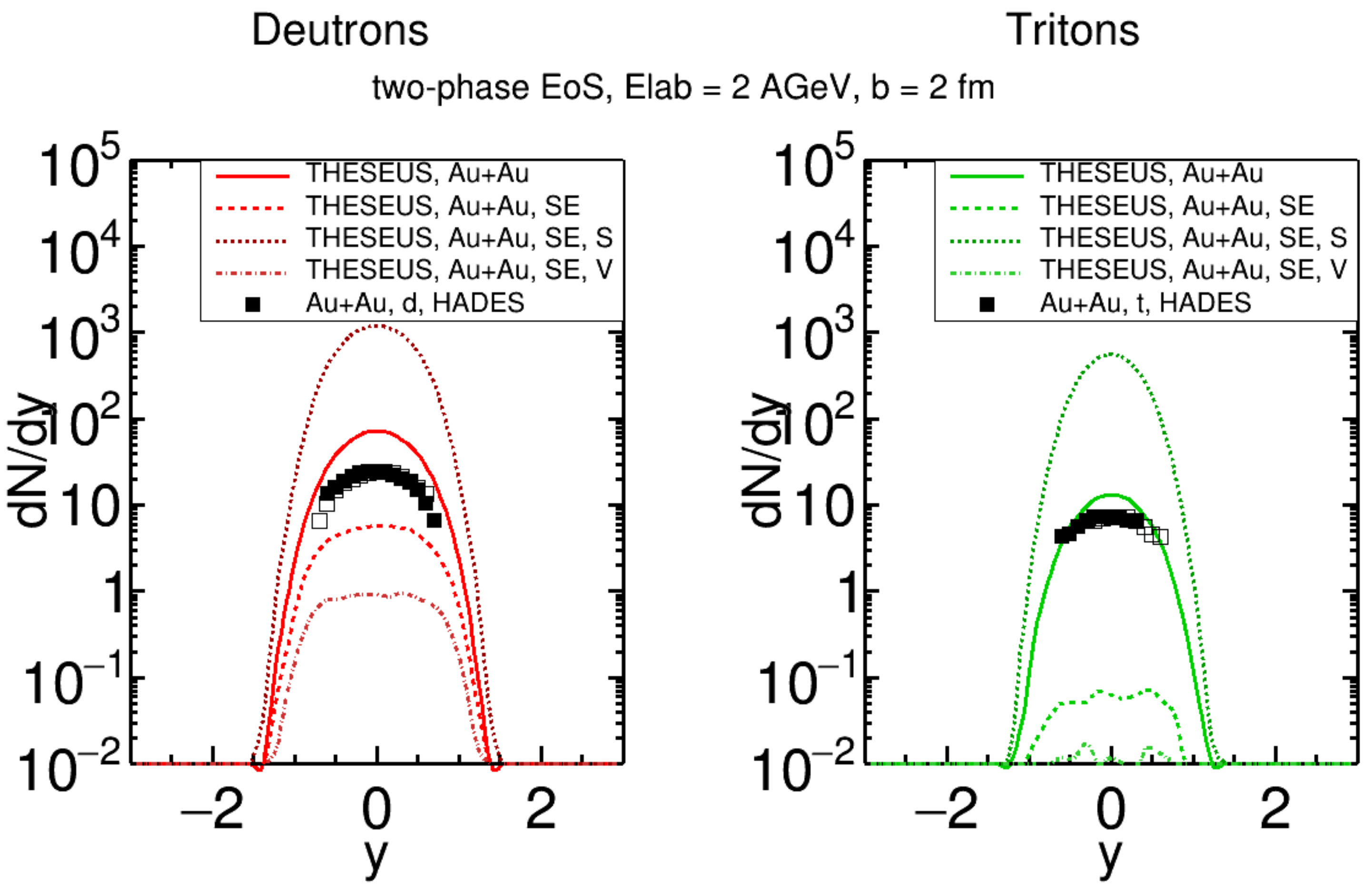
- THESEUS: 2 AGeV, b = 2 fm, mixed phase EoS
- HADES: 2.4 GeV, b = 5 fm



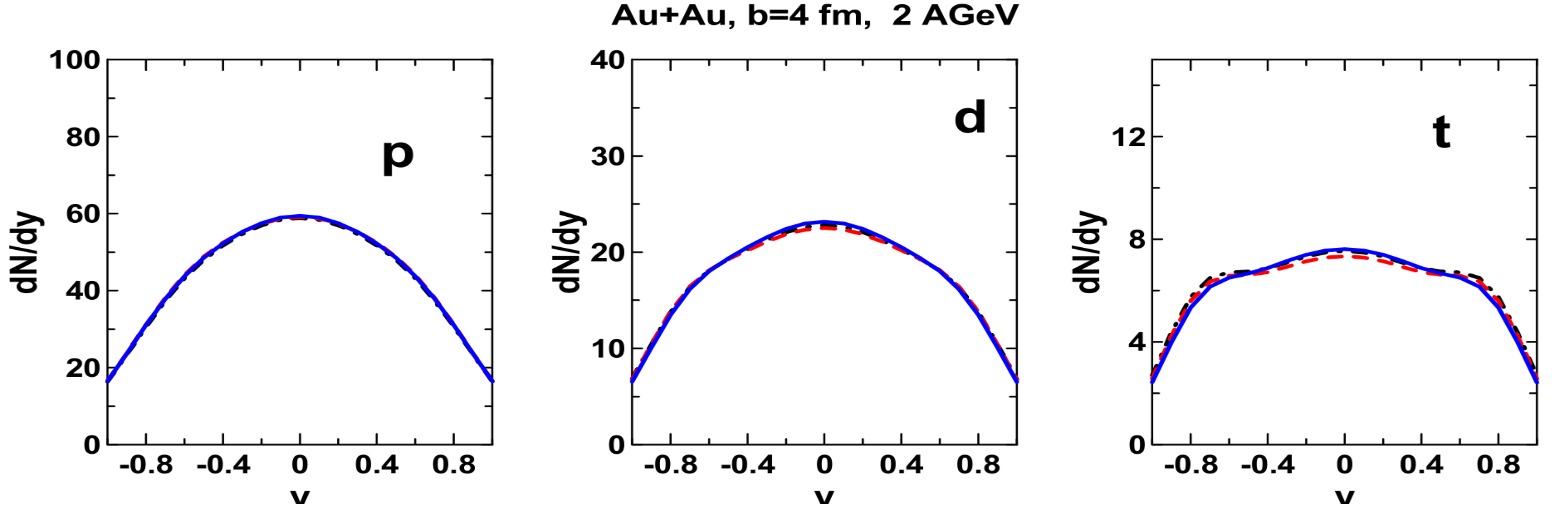
Light clusters at low energies, HADES data

Comparison of THESEUS results with preliminary HADES data,

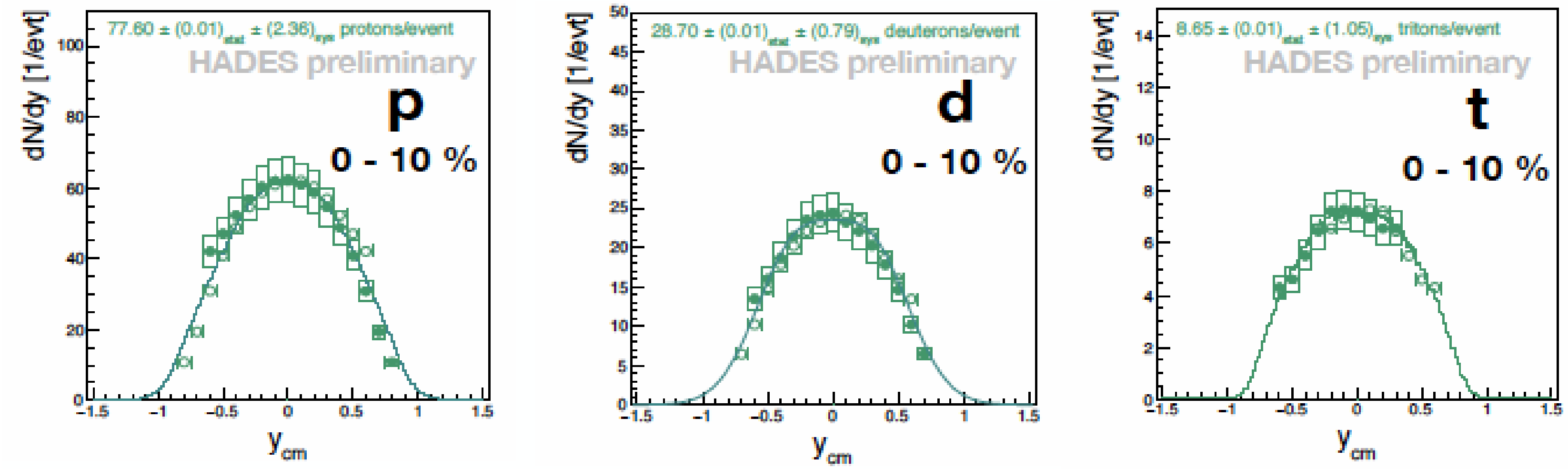
- THESEUS: 2 AGeV, b = 2 fm, two-phase EoS
- HADES: 2.4 GeV, b = 5 fm



Coalescence of clusters in 3FD-model



Yu. Ivanov,
private
communication
(old calculation)



M. Szala,
Talk at SQM 2019 (Bari)

Light clusters: future tasks

- Pauli corrections and rapidity distributions with them
- B_2 of deuterons: why there is minimum?

$$E_A \frac{d^3 N_A}{d\boldsymbol{p}_A^3} = B_A \left(E_p \frac{d^3 N_p}{d\boldsymbol{p}_p^3} \right)^Z \left(E_n \frac{d^3 N_n}{d\boldsymbol{p}_n^3} \right)^{A-Z}$$

$$\approx B_A \left(E_p \frac{d^3 N_p}{d\boldsymbol{p}_p^3} \right)^A ,$$

- Distributions on transverse momentum mT and comparison with experiments
- Flow of clusters at early stage of evolution

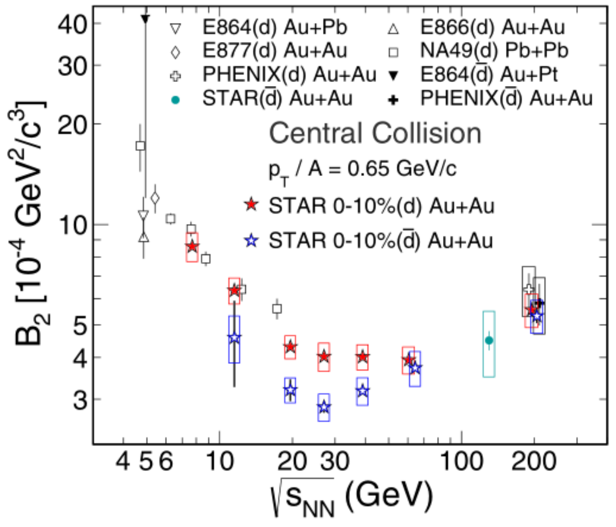


FIG. 13. Energy dependence of the coalescence parameter for $B_2(d)$ and $B_2(\bar{d})$ at $p_T/A = 0.65$ GeV/c from Au+Au collisions at RHIC. For comparison, results from AGS [31,33,34], SPS [35,39,62] (0%–7% and 0%–12% collision centralities), RHIC [25,36] (0%–18% and 0%–20% collision centrality for $\sqrt{s_{NN}} = 130$ GeV and 200 GeV) are also shown.

J. ADAM et al.,
PHYSICAL REVIEW C 99, 064905 (2019)

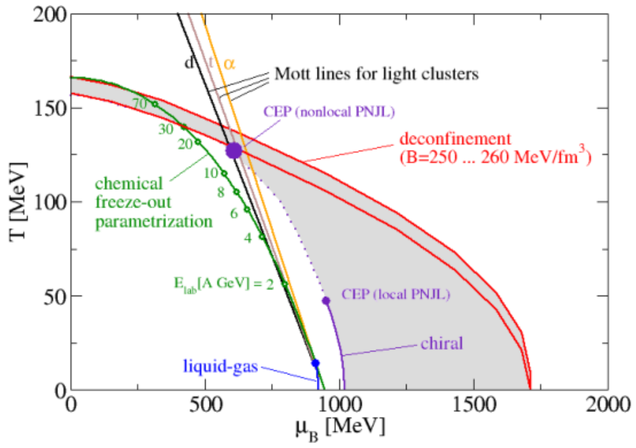


Fig. 1. Phase diagram of dense nuclear matter in the plane of temperature T and baryochemical potential μ_B. The diagram includes Mott-lines for the dissociation of light nuclear clusters, extrapolated also to the deconfinement region. For details, see text.

N.-U. Bastian et al.,
arXiv:1608.02851v1

Thank you

for your attention!

NICA (additionally)

Physics tasks of the NICA heavy-ion program
(to be studied for different ions (from p to Au) by scanning in b and energy (in the range from 3 to 11A GeV)

- event-by-event fluctuation in hadron productions (multiplicity, Pt etc.);
- femtoscopic correlation;
- directed and elliptic flows for various hadrons;
- multi-strange hyperon production (including hypernuclei): yield and spectra (the probes of nuclear media phases);
- photon and electron probes
- charge asymmetry