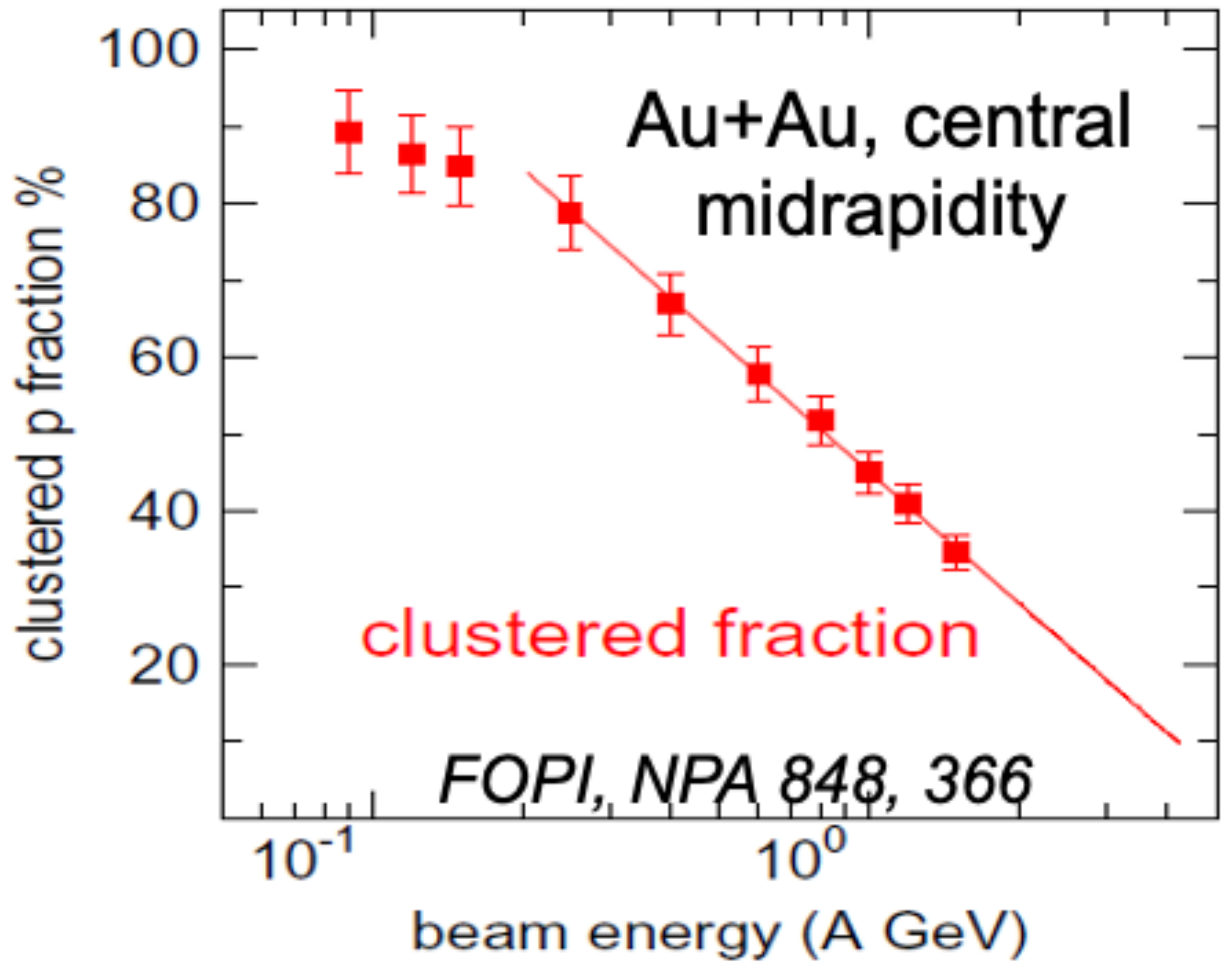
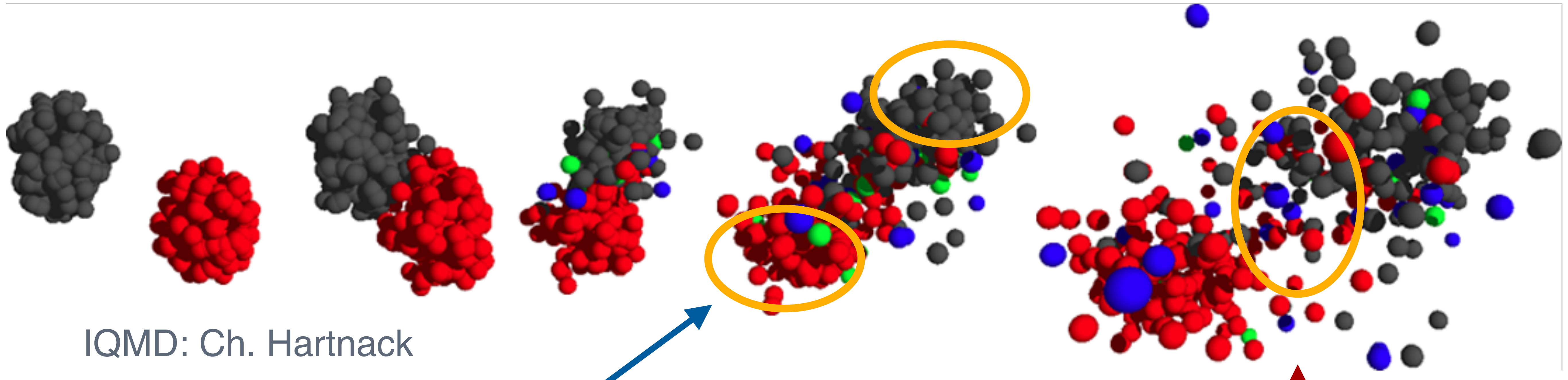
Identifying the mechanism of light nuclei production

Viktar Kireyeu for the PHQMD team and MPD collaboration

Cluster formation in heavy-ion collisions

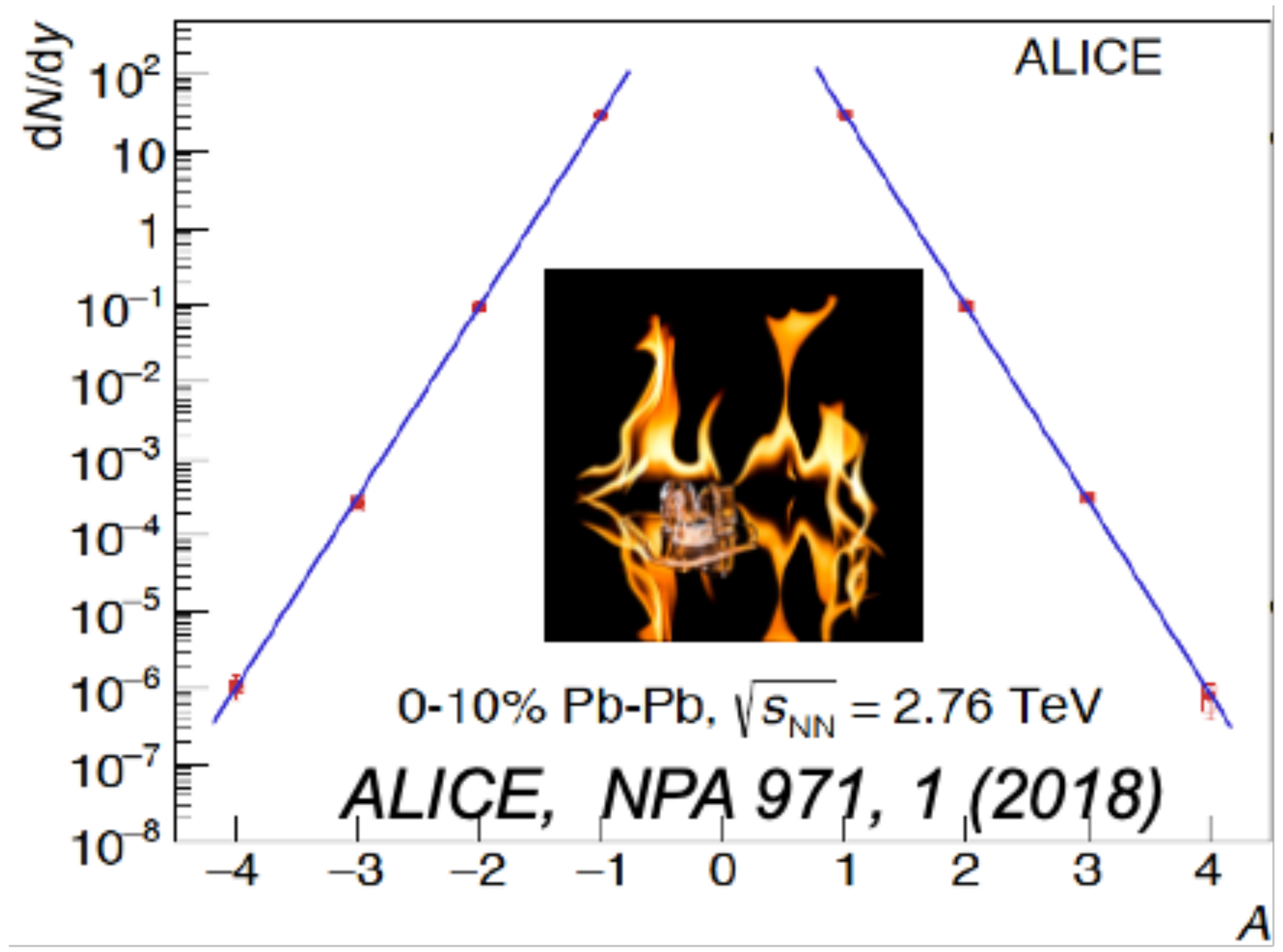


Clusters and (anti-) hypernuclei are observed experimentally at all energies



Projectile/target spectators: heavy cluster formation

Midrapidity: light clusters



(Anti)hypernuclei production:

at mid-rapidity by Λ coalescence during expansion

at projectile/target rapidity by re-scattering/absorption of Λ by spectators

«Ice in a fire» puzzle: how the weakly bound objects can be formed and survive in a hot environment?

Describing the cluster formation in HIC

Statistical models

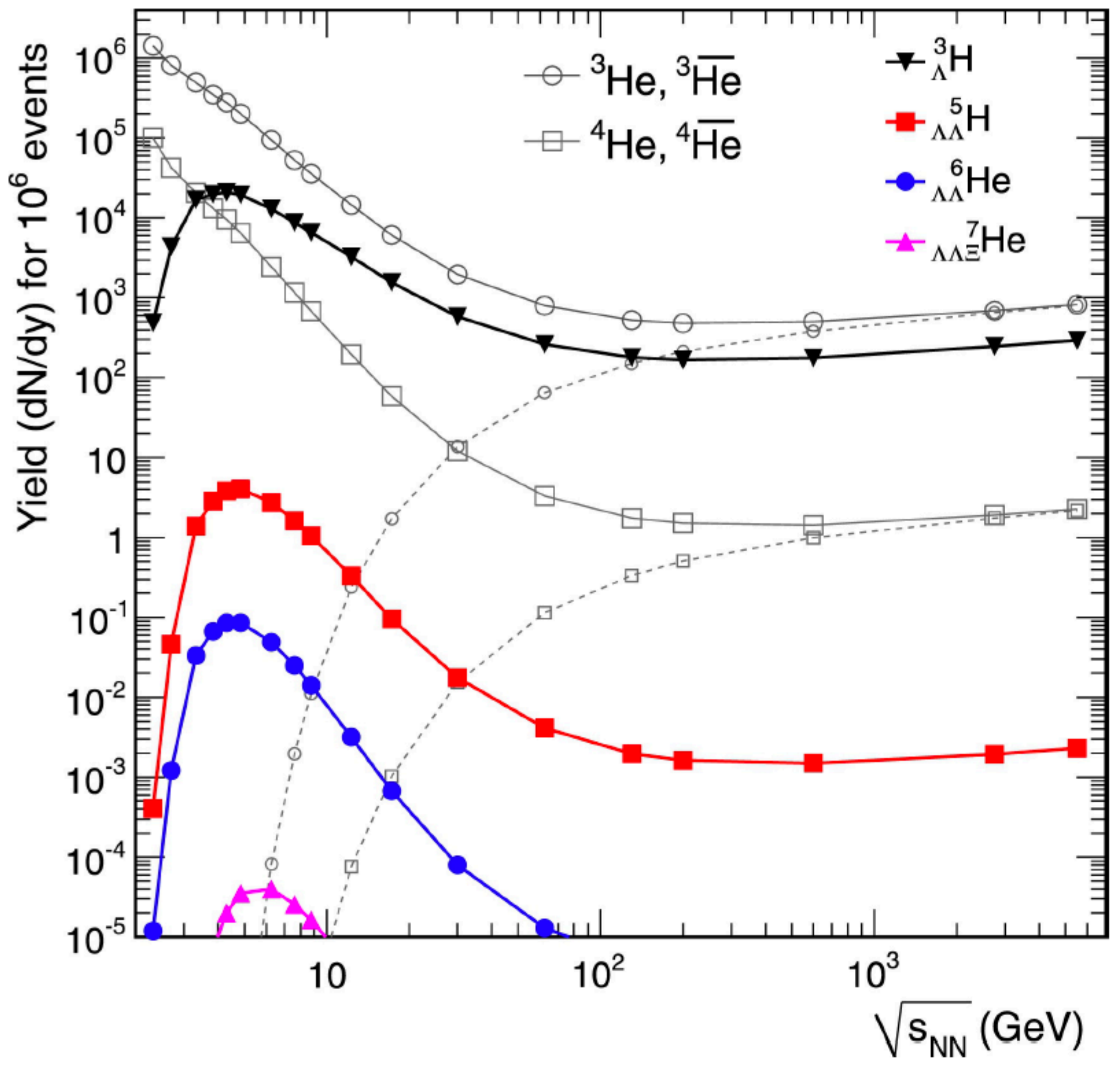
- Production of nuclei depending on T and μ_B at chemical freeze-out & particle mass

Coalescence models

- Formation of nuclei by nucleons & hyperons that are close in coordinate and momentum spaces at freeze-out time

=> no dynamical cluster formation during time evolution

=> no information on the dynamics of clusters formation & microscopic origin



A. Andronic et al., Phys. Lett. B697 (2011) 203-207.

In order to understand the microscopic **origin of cluster formation** one needs a realistic model for the **dynamical time evolution** of the HIC

Transport models — dynamical modelling of cluster formation based on interactions:
via potential interaction – **'potential' mechanism**
by scattering – **'kinetic' mechanism**

Parton-Hadron-Quantum-Molecular Dynamics

= n-body microscopic transport approach for the description of heavy-ion dynamics with dynamical cluster formation from low to ultra-relativistic energies

Relativistic considerations + Correlations between nucleons + Cluster recognition

Initial A+A collisions → Formation of QGP → Partonic phase → Hadronization → Hadronic phase

QMD: Initialization nuclei; propagation of baryons →

local $\varepsilon > \varepsilon_c$ dissolution of pre-hadrons →

propagation of partons →

PHSD: Primary collisions pre-hadronic states

interactions of partons / interactions of hadrons — collision integral

propagation of mesons →

Cluster recognition: MST or SACA

J. Aichelinet al., PRC 101 (2020) 044905

PHSD: W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168(2009)

Minimum Spanning Tree (MST)

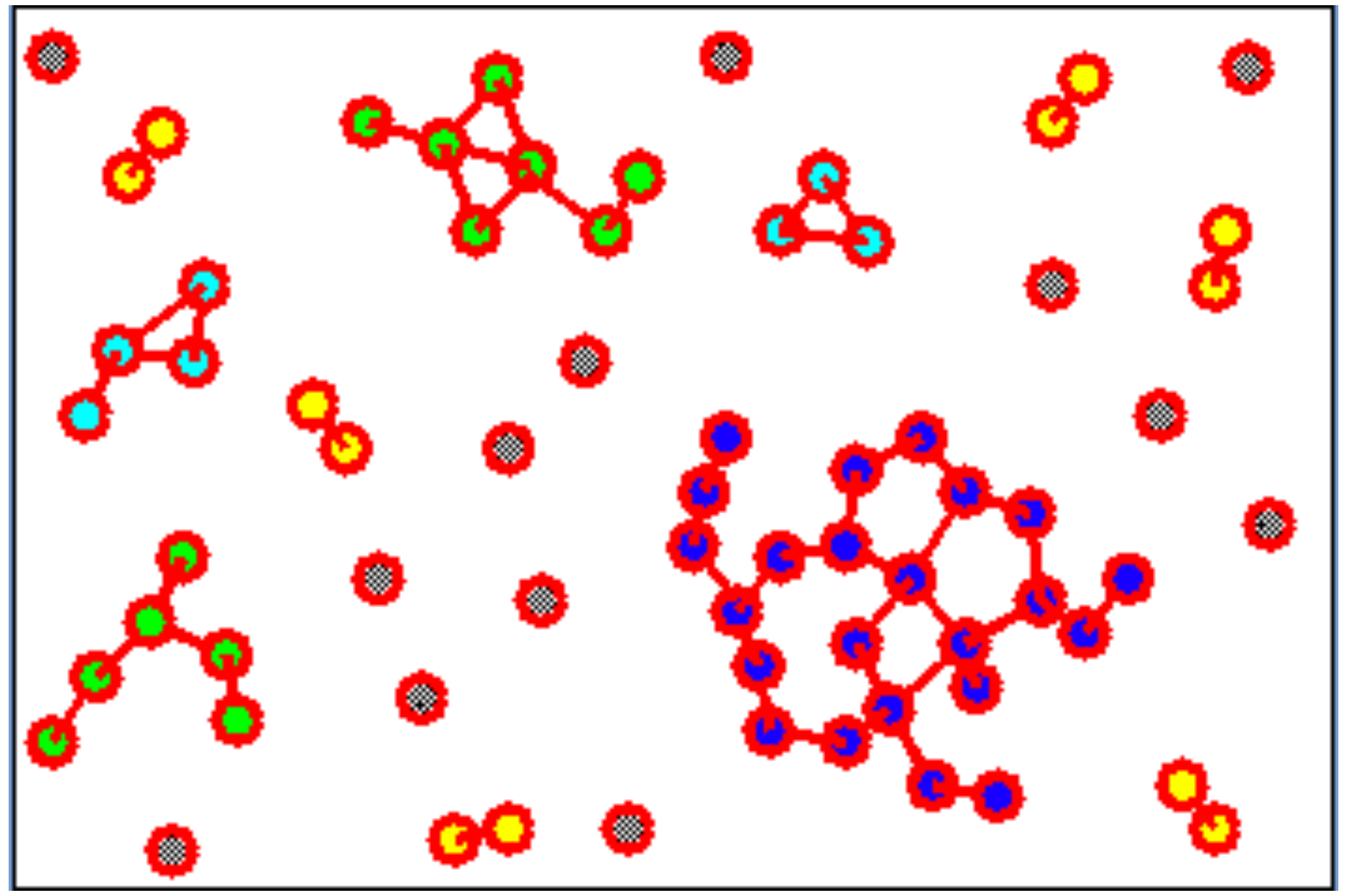
Cluster criterion: distance of nuclei

Algorithm: search for accumulations of particles in coordinate space

1. Two particles i & j are bound if:

   $|r_i - r_j| < 4.0$ fm

2. Particle is bound to cluster if bound with at least one particle of cluster



Remark: additional momentum cuts lead to a small changes: particles with large relative momentum are mostly not at the same position (**V. Kireyeu, Phys.Rev.C 103 (2021) 5, 054905**).

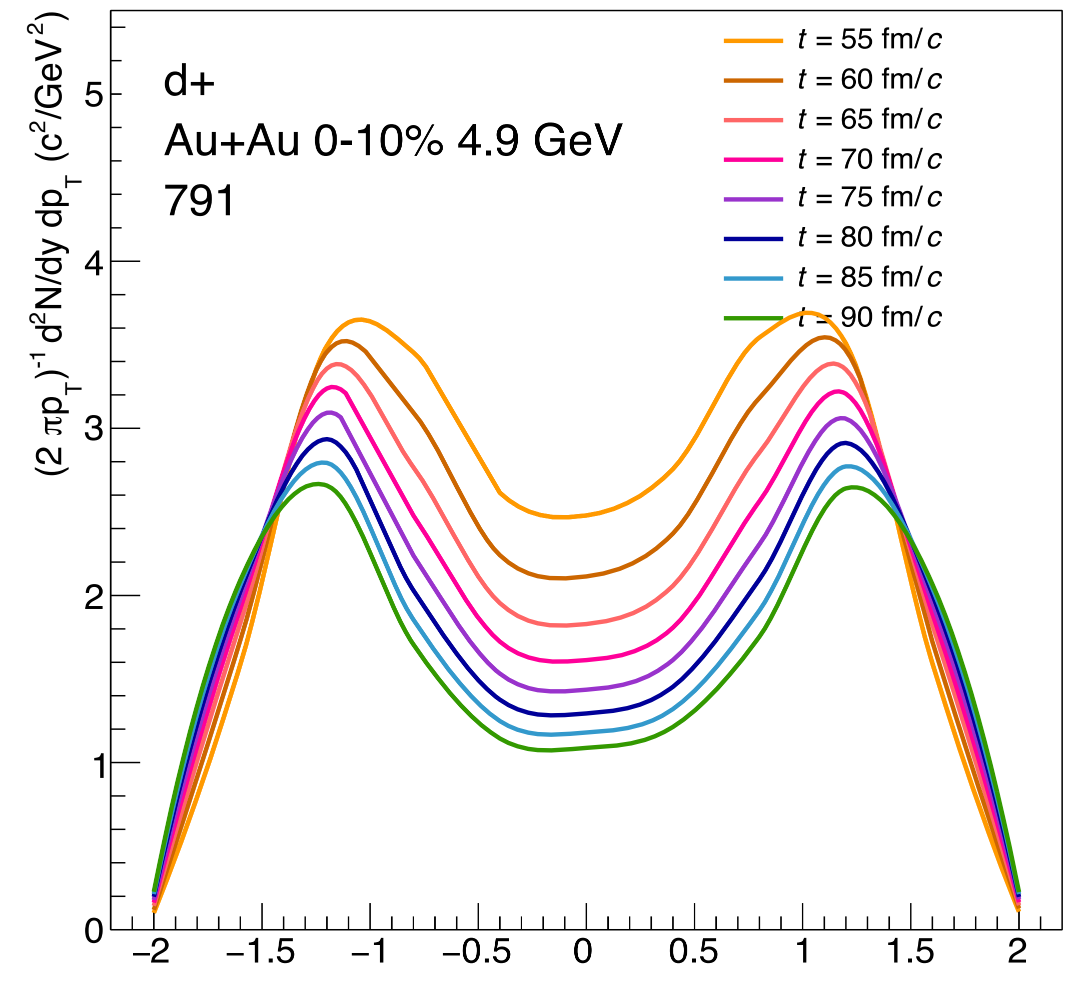
Cluster stability over time

QMD can not describe clusters as ‘quantum objects’

the cluster **quantum ground state** has to respect a minimal average kinetic energy of the nucleons while **the semi-classical** (QMD) ground state - not!

nucleons may still be emitted from the QMD clusters while in the corresponding quantum system this is not possible

thus, a cluster which is “bound” at time t can **spontaneously** dissolve at t + Δt



= **QMD clusters are not fully stable over time**:

the multiplicity of clusters is time dependent

the form of the final rapidity, p_T distribution and ratio of particles do not change with time

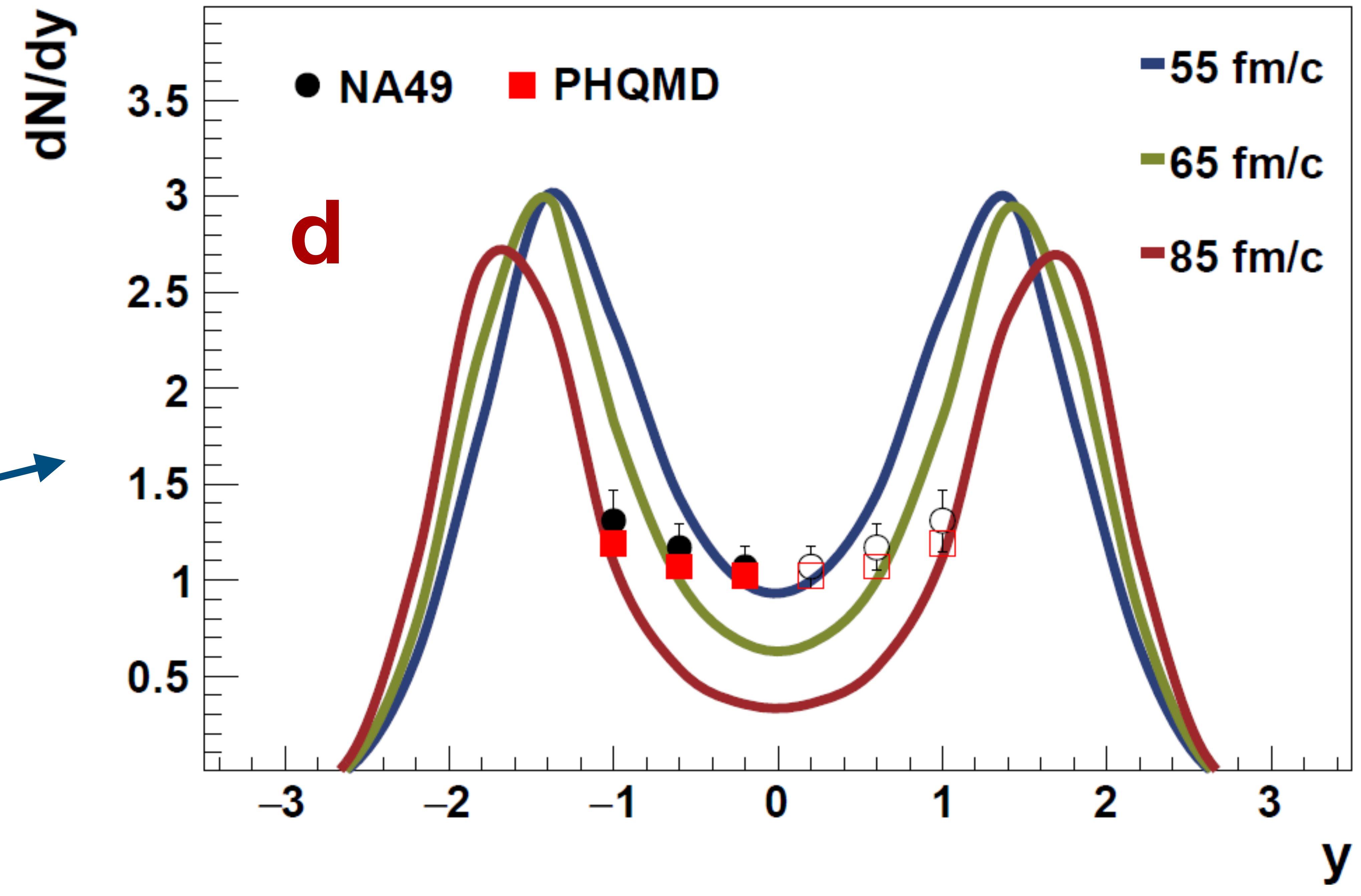
How to stabilize QMD clusters?

Scenario 1: **S. Gläßel et al., PRC 105 (2022) 1, 014908**

PHQMD results are taken at **‘physical time’** :

$$t = t_0 cosh(y)$$

where t_0 is the time selected as a best description of the cluster multiplicity at y=0

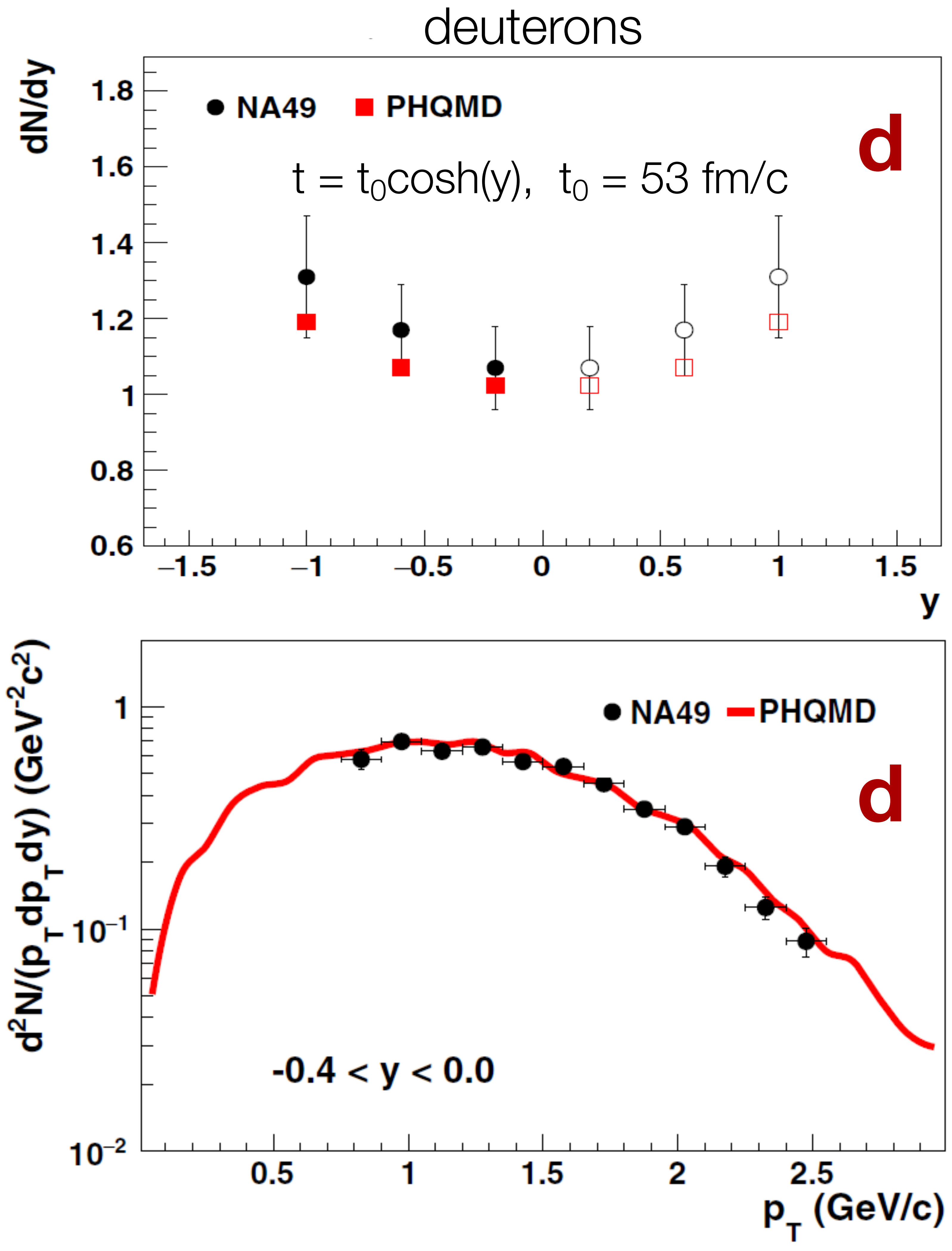


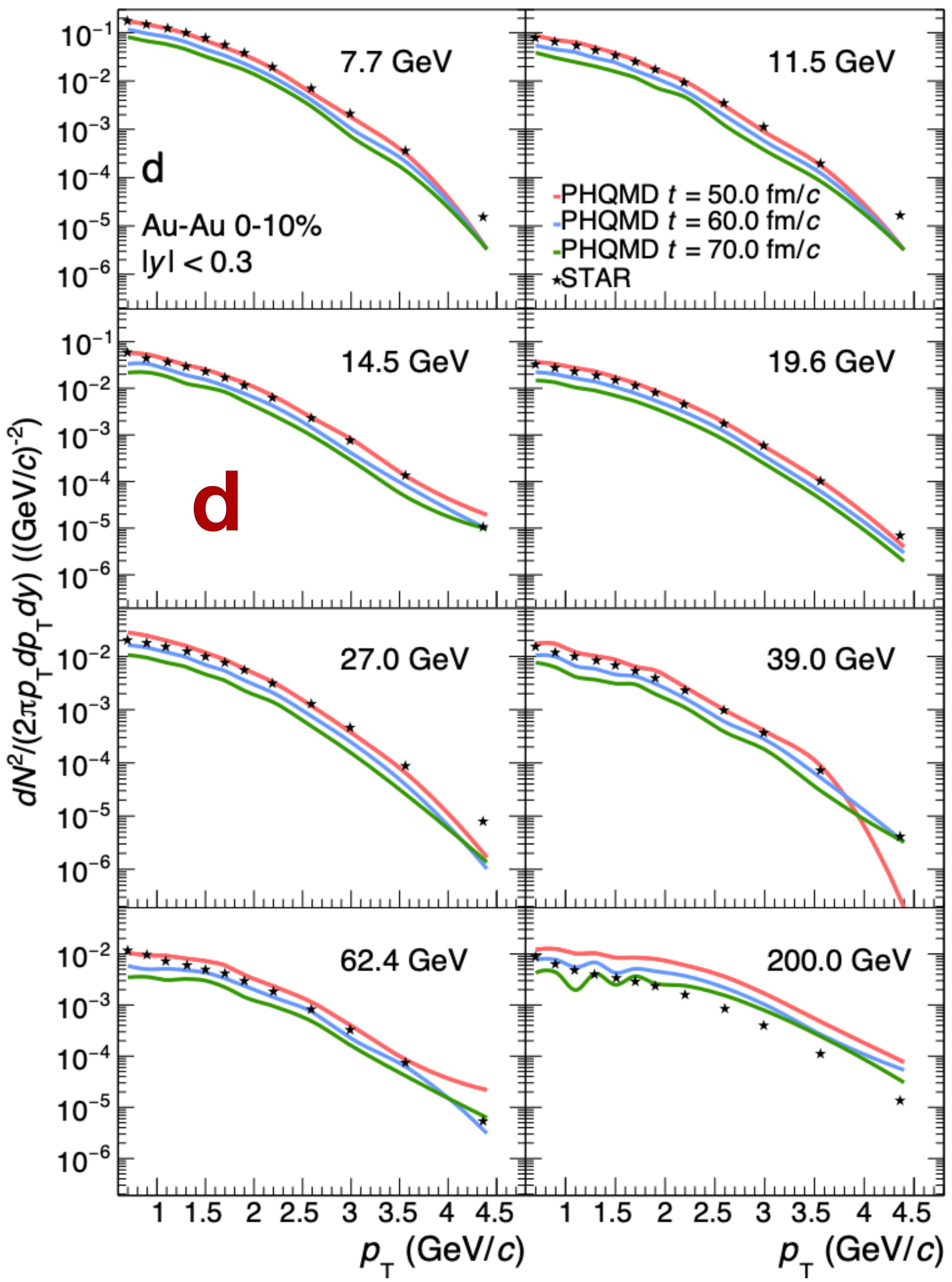
Cluster stability over time

STAR: J. Adam et al., Phys. Rev. C 99, 064905

NA49 $\sqrt{s_{NN}}$ = 8.8 GeV

STAR $\sqrt{s_{NN}}$ = 7.7 GeV – 200 GeV





=> The PHQMD results for d and ^{3}He agree with NA49 and STAR data.

S. Gläßel et al., PRC 105 (2022) 1, 014908

NA49: T. Anticic et al., Phys. Rev. C 94, 044906

Cluster stability over time

Scenario 2:
G. Coci et al., PRC 108 (2023) 1, 014902

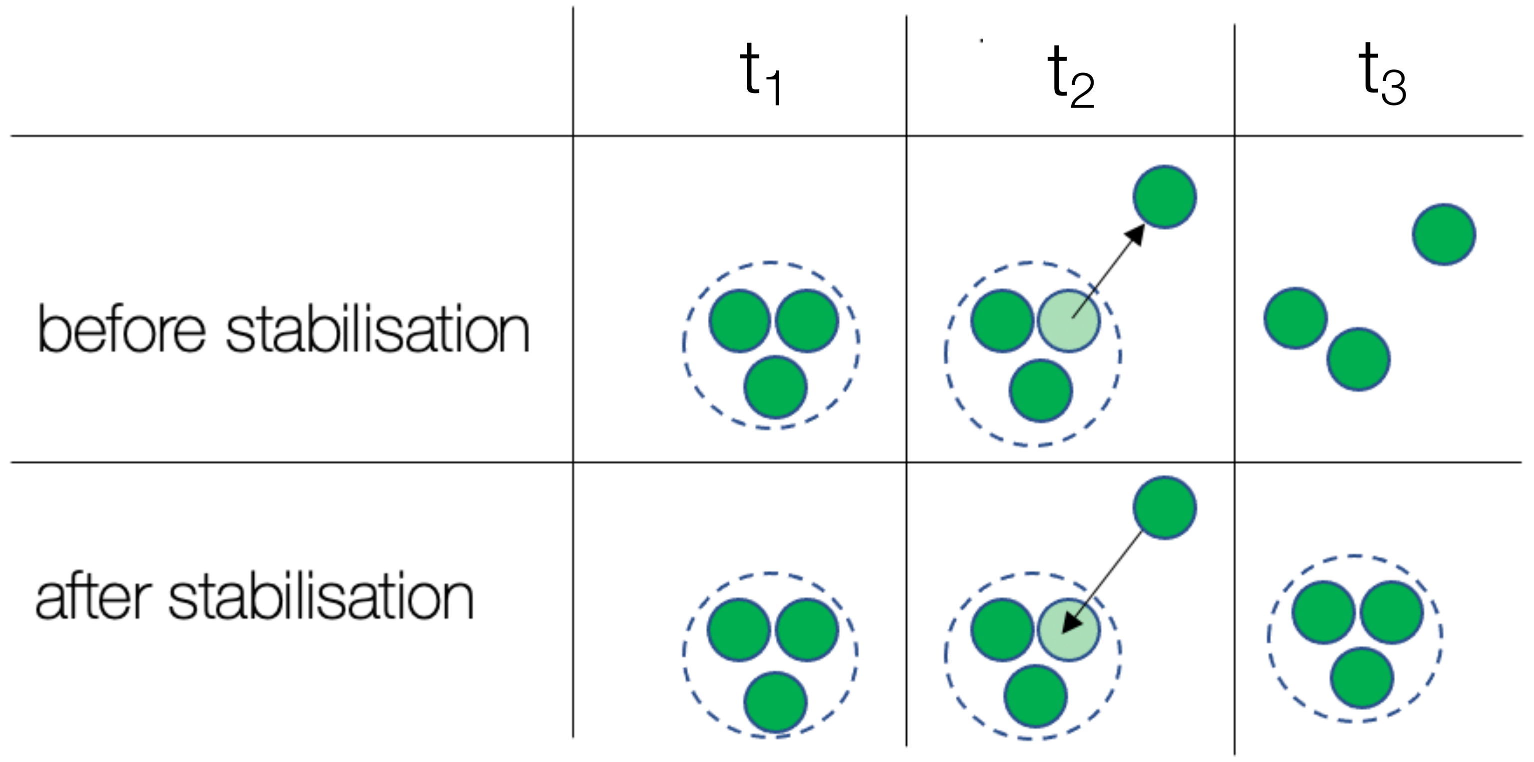
Stabilisation Procedure:

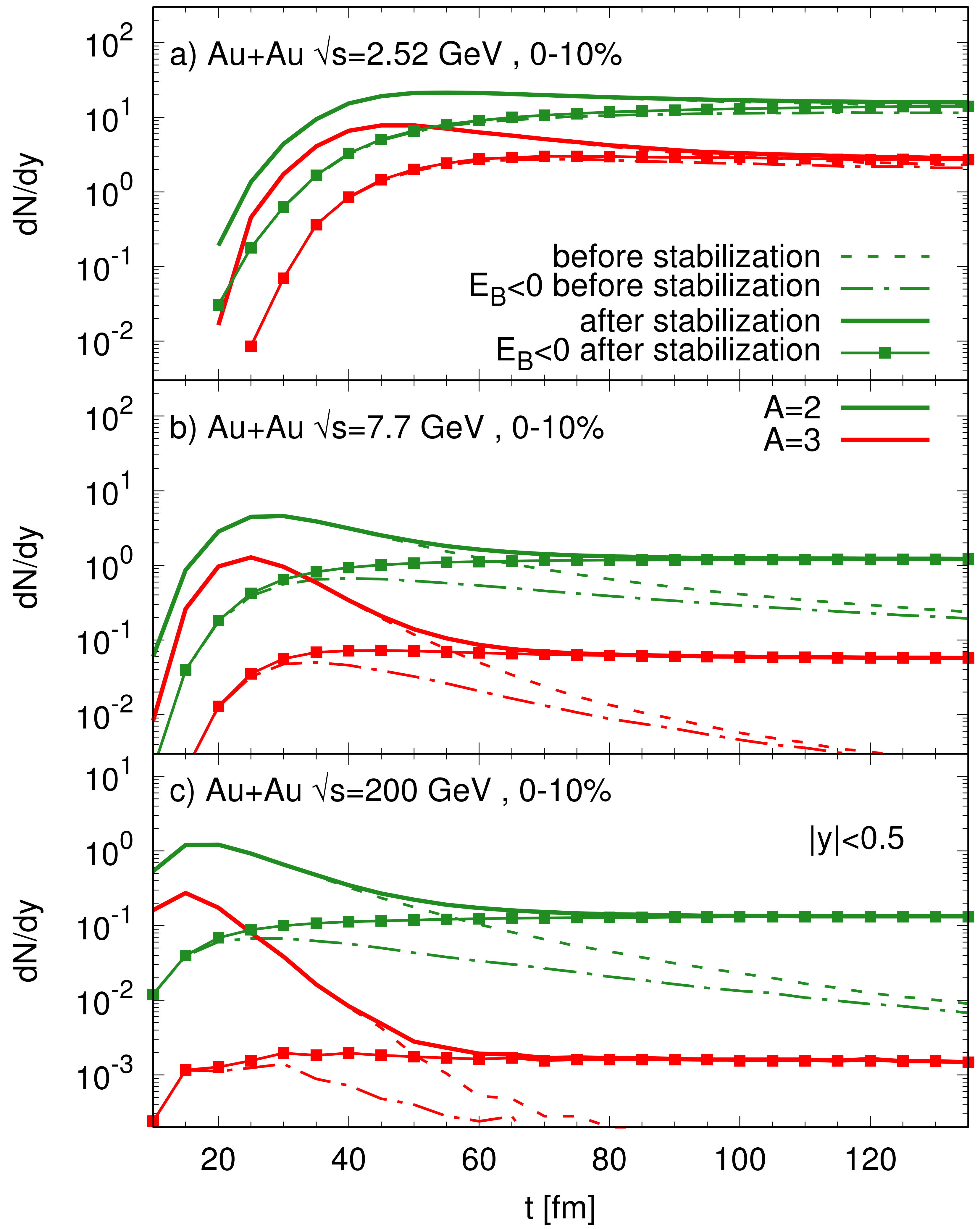
- consider asymptotic state: clusters and free nucleons

- For each nucleon in MST track the **freezout-time** = time at which the last collision occurred

- Recombine nucleons into clusters with **$E_B < 0$** if time of cluster disintegration is larger than nucleon freeze-out time

Allows to recover most of “lost” clusters





Kinetic mechanism for deuteron formation

G. Coci et al., PRC 108 (2023) 1, 014902

$$\pi^{\pm,0} + p + n \leftrightarrow \pi^{\pm,0} + d$$
$$\pi^- + p + p \leftrightarrow \pi^0 + d$$
$$\pi^+ + n + n \leftrightarrow \pi^0 + d$$
$$\pi^0 + p + p \leftrightarrow \pi^+ + d$$
$$\pi^0 + n + n \leftrightarrow \pi^- + d$$

N+N+π inclusion of all possible channels allowed by total isospin T conservation:

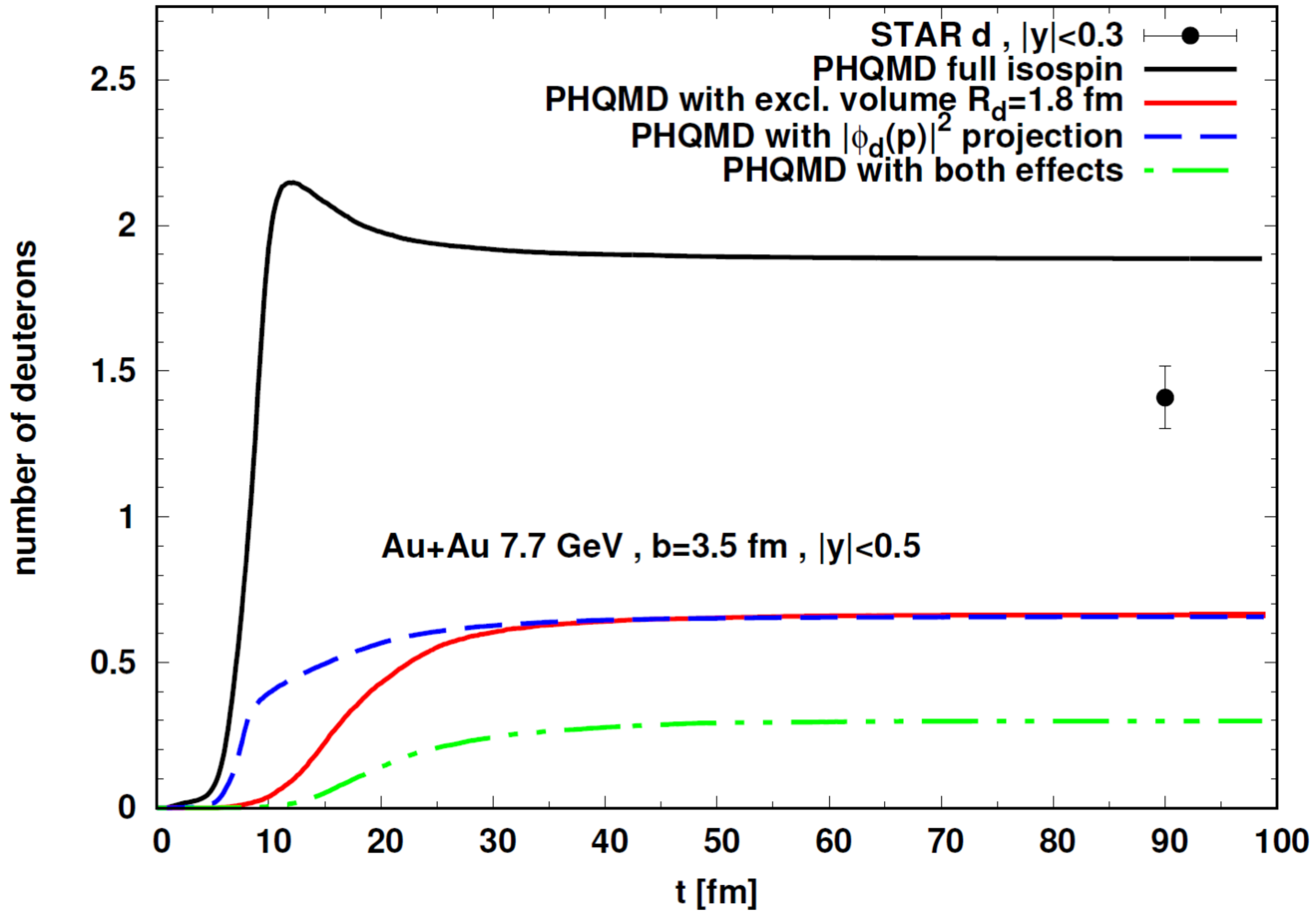
↓

Enhance deuteron production

↓

Modelling of the d quantum properties lead to a strong reduction of d production:

1) The finite-size of *d* in the **coordinate space** (Excluded volume condition): $|\vec{r}(i)^* - \vec{r}(d)^*| < R_d$
2) The momentum correlations of *p* and *n* inside *d* by the projection of the relative momentum of *p*+*n* pair on the *d* wave-function.



Kinetic mechanism for deuteron formation

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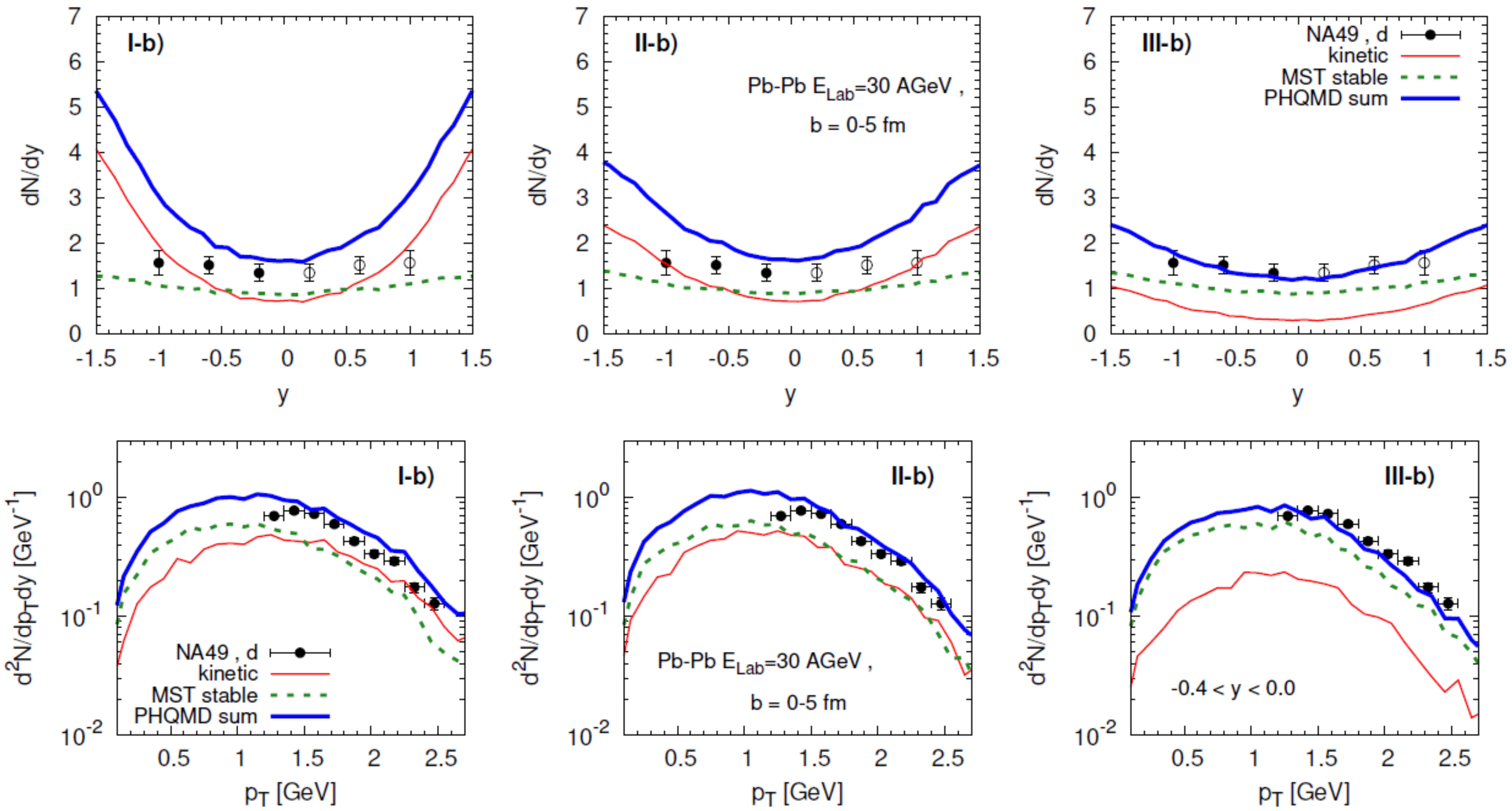
Total deuteron production = **Kinetic mechanism with finite-size effects**
+ **MST (with stabilization)** identification of deuterons ("stable" bound (E_B<0) A=2, Z=1 clusters)

Finite-size effects for kinetic deuterons:

1) excluded-volume 2) Momentum projection 3) both effects



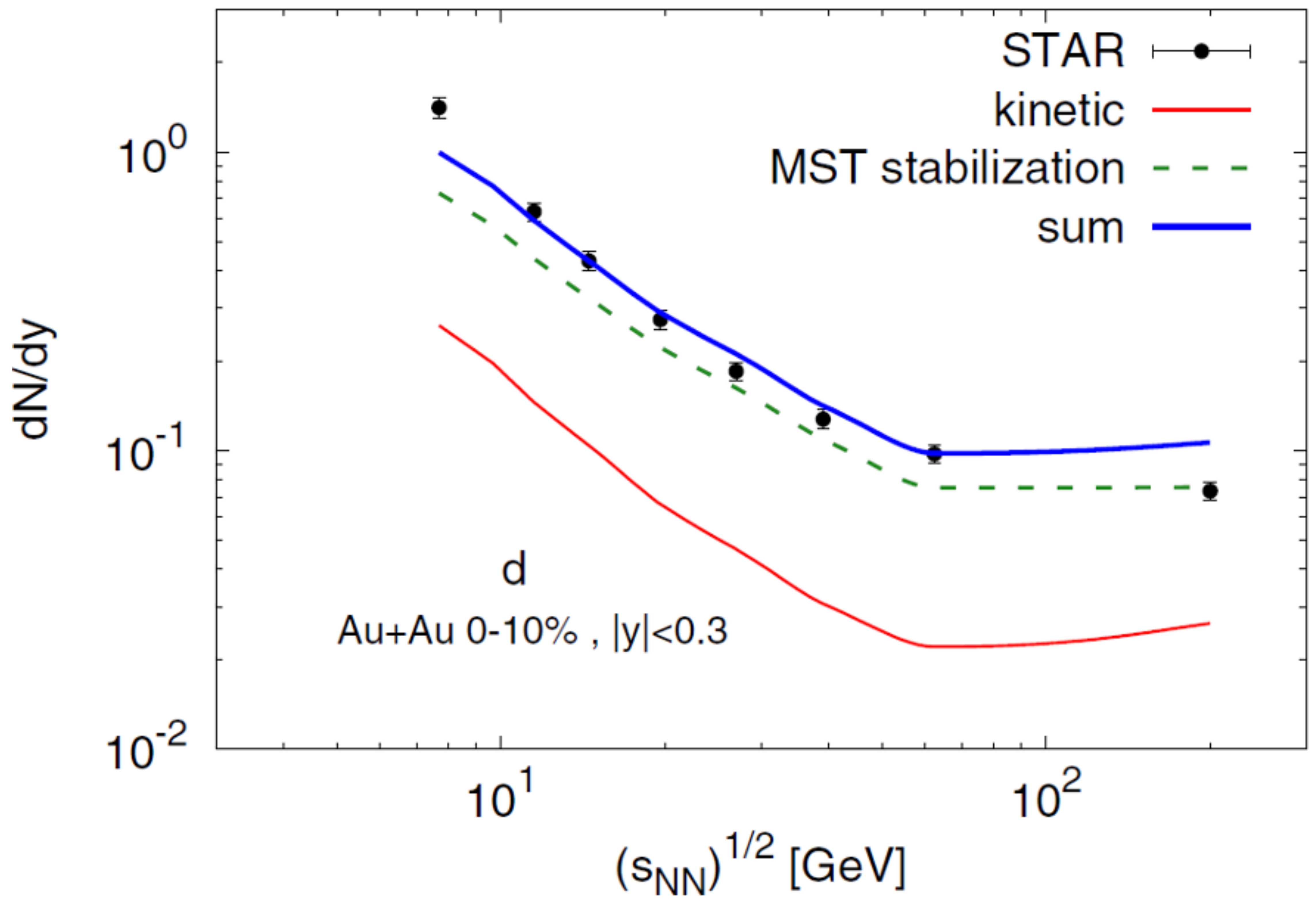
NA49 data [PRC 94 (2016) 04490699]

Kinetic mechanism for deuteron formation

G. Coci et al., PRC 108 (2023) 1, 014902

Total deuteron production = **Kinetic mechanism with finite-size effects**
+ **MST (with stabilization)** identification of deuterons (“stable” bound (E_B<0) A=2, Z=1 clusters)

Excitation function dN/dy of deuterons at midrapidity

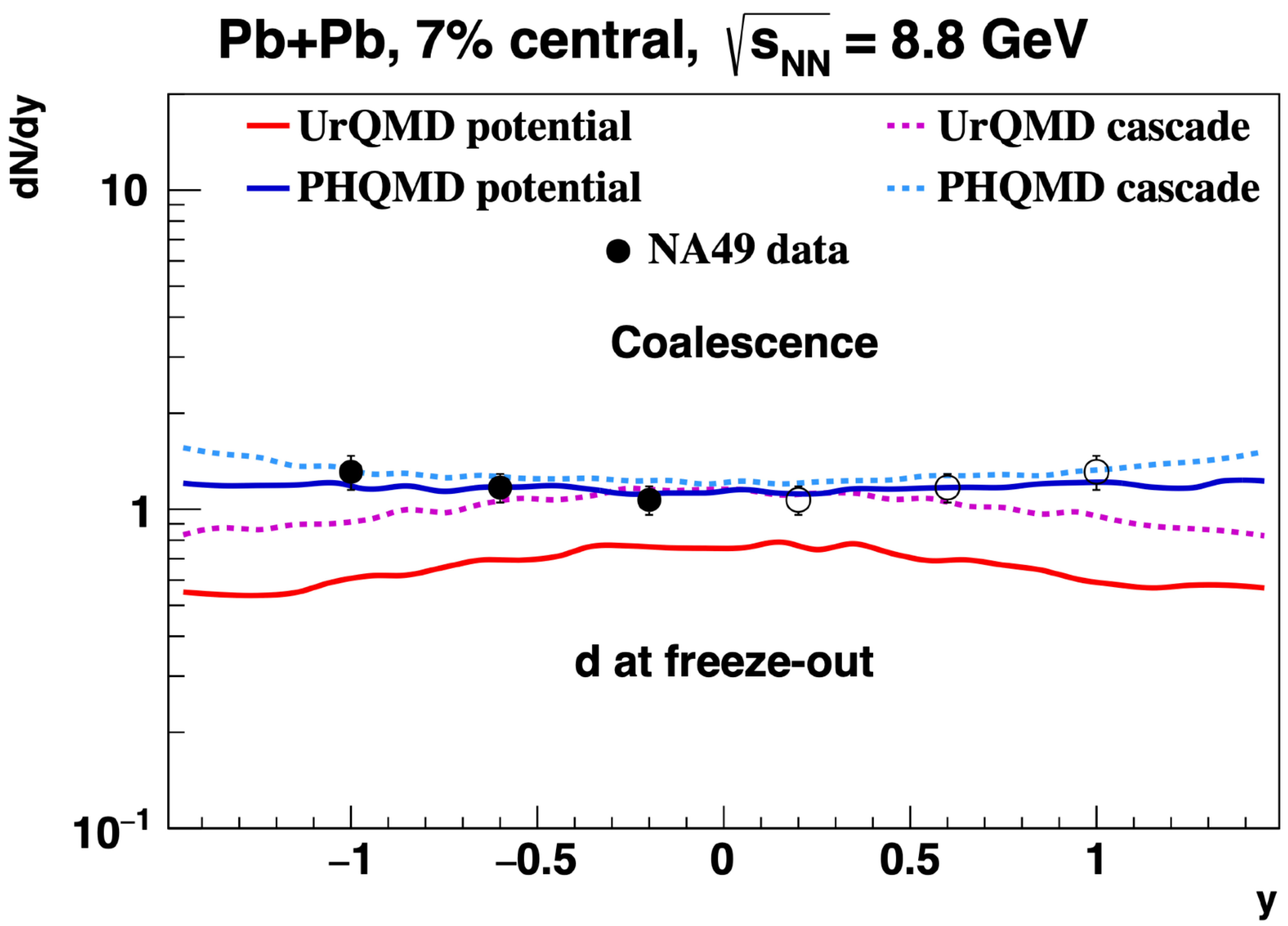


- **PHQMD provides a good description of STAR data**
- **The potential mechanism is dominant for the deuterons production at all energies!**

Coalescence for deuterons

Statistical description of cluster production, based on proximity in momentum and coordinate space.

- Calculations are performed at the **«freeze-out»**.
- The relative momentum ΔP and distance ΔR between the proton and the neutron are calculated in the p-n CM frame.
- If ΔP < 0.285 GeV and ΔR < 3.575 fm, a deuteron may be formed with the probability Pd = 3/8 (the spin-isospin combinatorial factor).

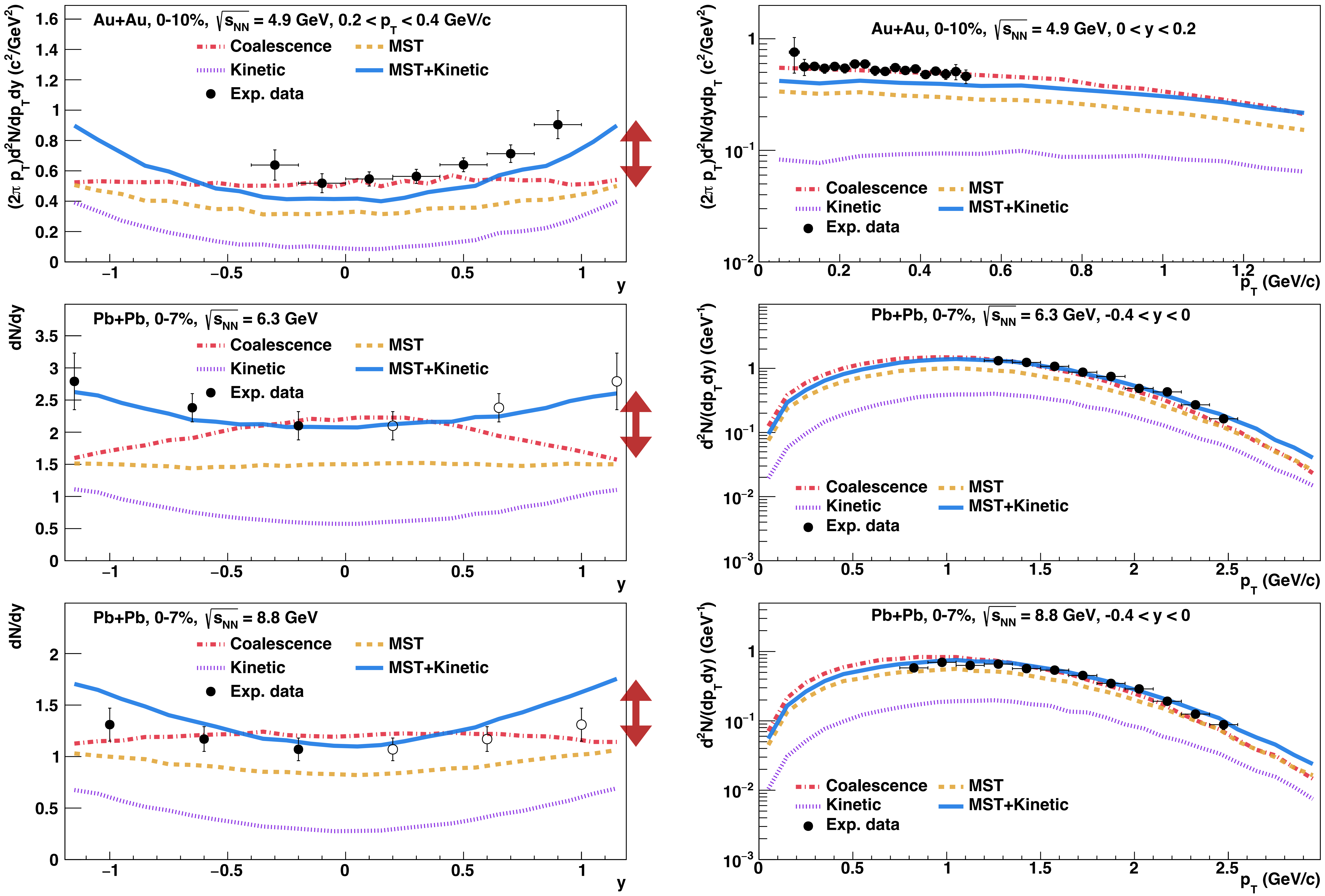


«psMST» library: **MST and coalescence** for any model

V. Kireyeu, Phys.Rev.C 103 (2021) 5, 054905
V. Kireyeu et al., PRC 105 (2022) 044909

Which mechanism: potential, kinetic or coalescence?

V. Kireyeu et. al, Phys. Rev. C 109, 044906

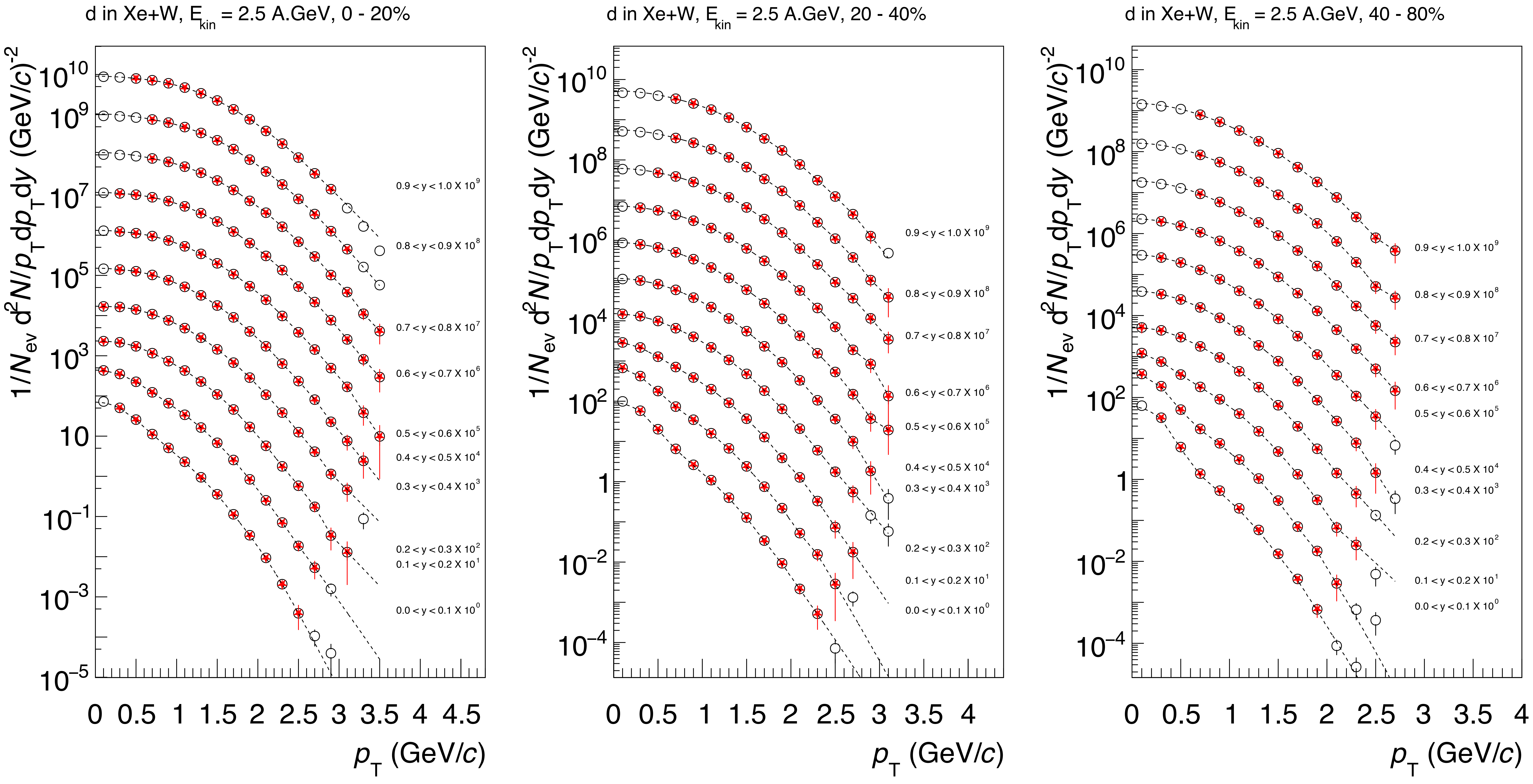


The analysis of the presently available data points tentatively to the potential (MST) + kinetic scenario.

However, due to large interpolations (lack of the low p_T experimental data point) **further studies are necessary** to establish this mechanism.

NICA/MPD — new data soon!

NICA/MPD: possible advancing for the future studies



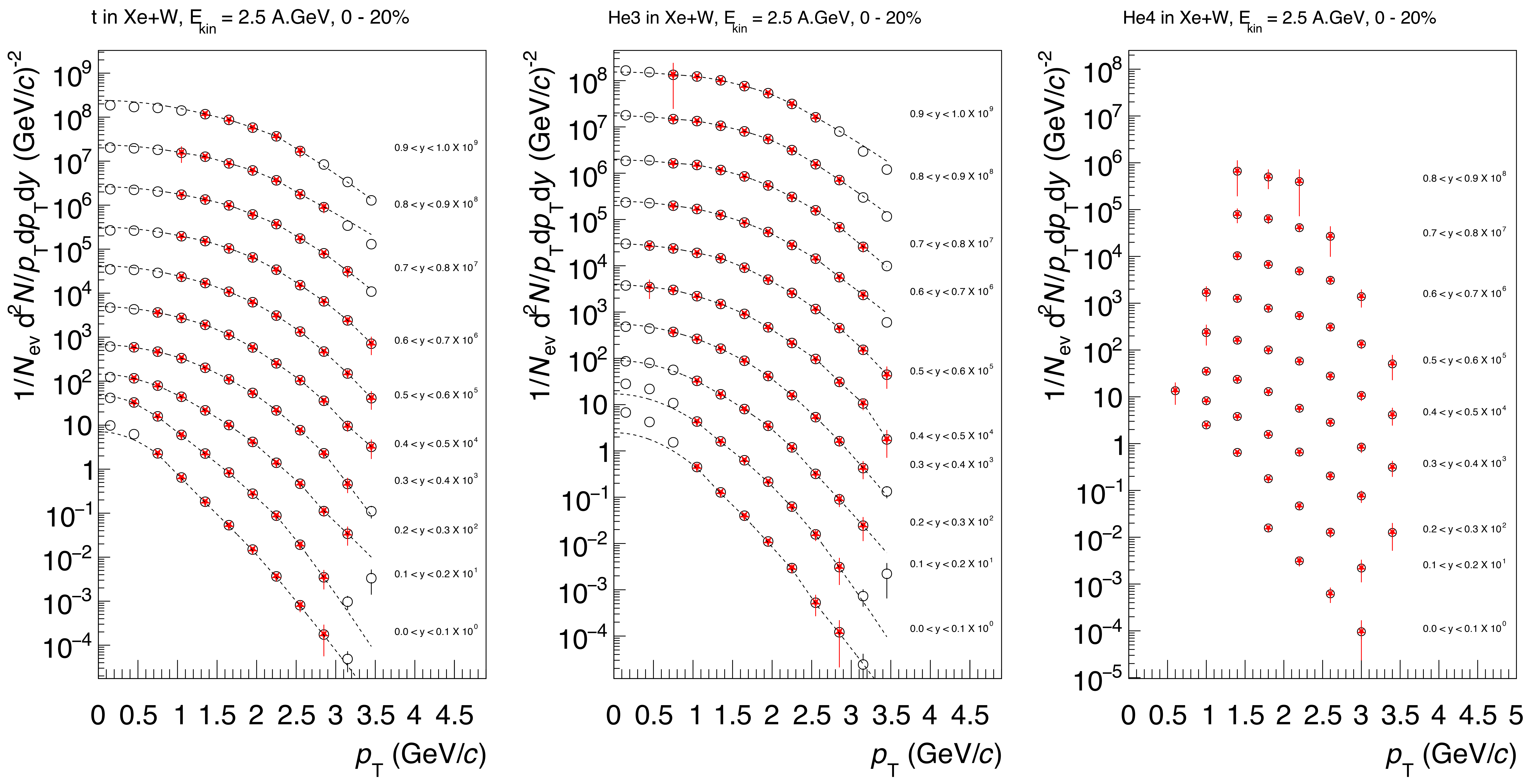
Dashed lines — data driven fit: the slope is extracted at last points of the low and high p_T spectra parts and then passed to the thermal functions.

Only reconstructed points used for fit.

Procedure under development.

The low p_T performance of the MPD may shed a light on the light nuclei production mechanism.

NICA/MPD: possible advancing for the future studies



Dashed lines — data driven fit: the slope is extracted at last points of the low and high p_T spectra parts and then passed to the thermal functions.

Only reconstructed points used for fit.

Procedure under development.

Limited statistics used for these plots does not allow to make unambiguous conclusions concerning a bit heavier nuclei: $t, {}^3He, {}^4He$

Summary

- **The PHQMD** is a microscopic n-body transport approach for the description of heavy-ion dynamics and cluster and hypernuclei formation.
- Clusters can be formed:
  - by **potential interactions** among nucleons and hyperons,
  - by **kinetic mechanism** for deuterons production,
  - by the **coalescence**.
- Current experimental data favours the **dynamical cluster production + kinetic** production mechanism for deuterons.
- The low transverse momentum capabilities of the **NICA/MPD** matches the theoretical interest in the light nuclei studies and can shed a light on the nuclei production mechanism.

Thank you for your attention!