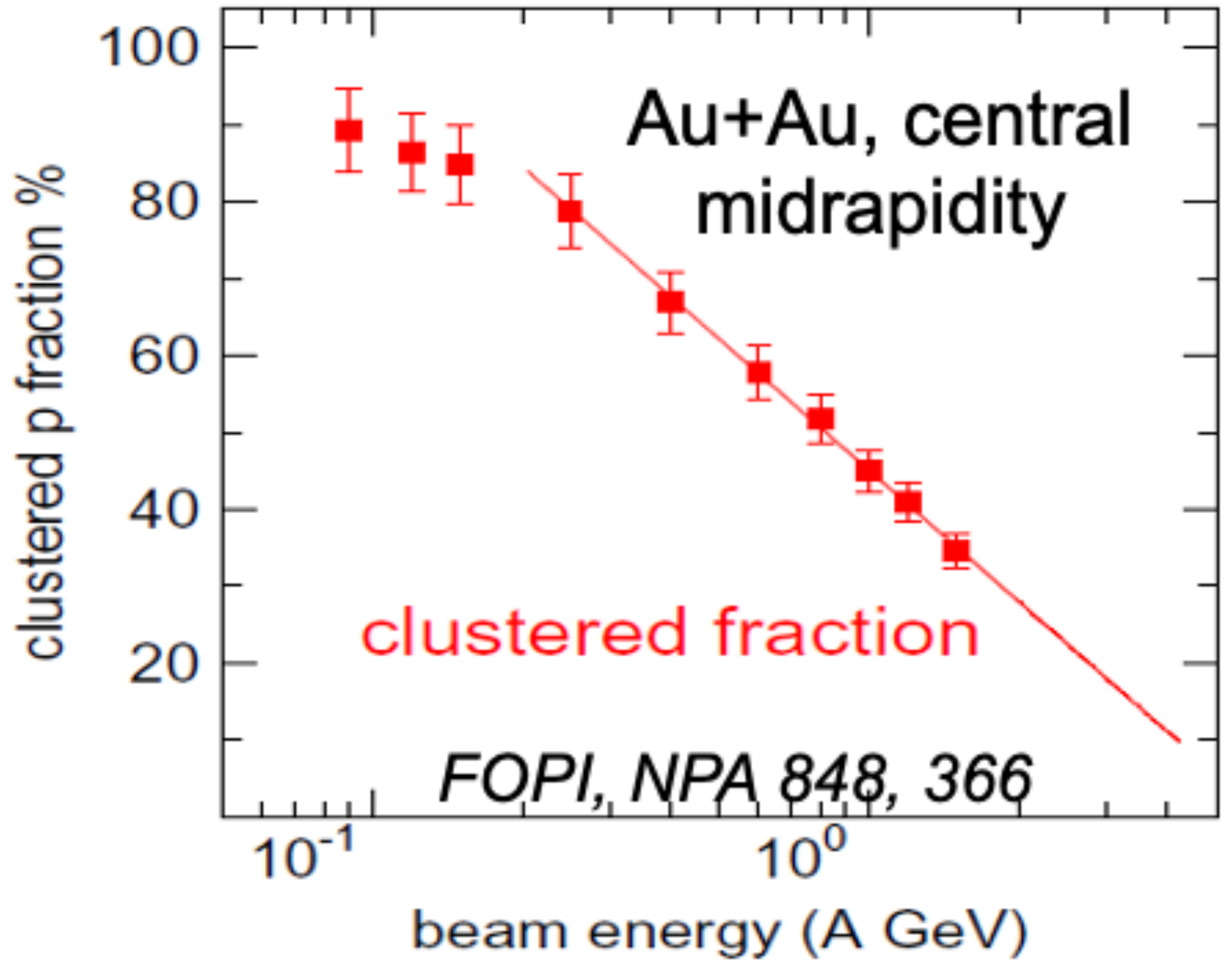
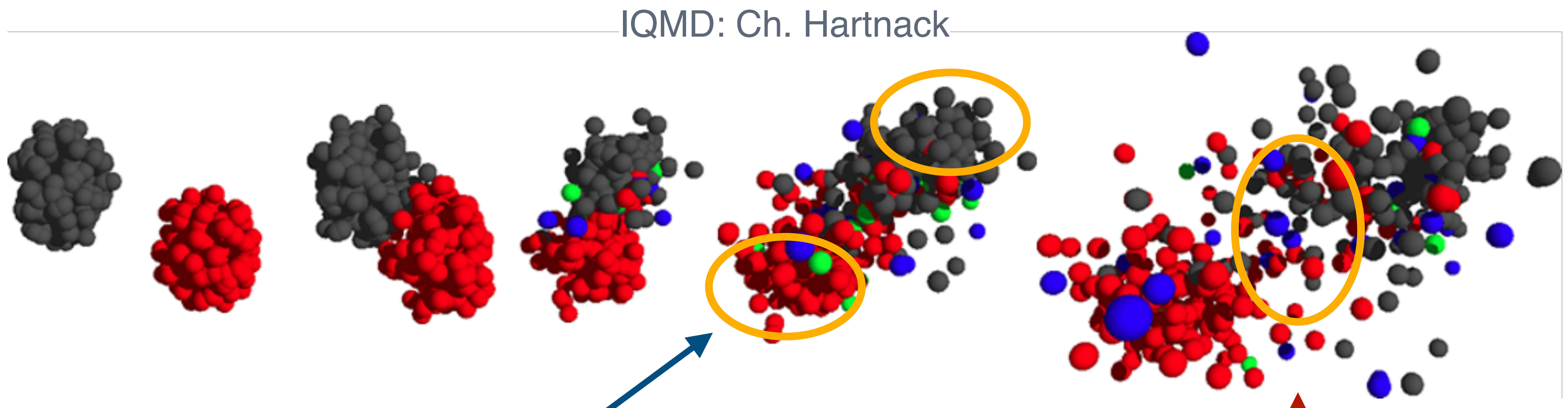
Cluster and hypernucleus production in heavy-ion collisions

Infinite and Finite Nuclear Matter — 2023

V. Kireyeu for the PHQMD team

Helmholtz Forschungsakademie Hessen für FAIR





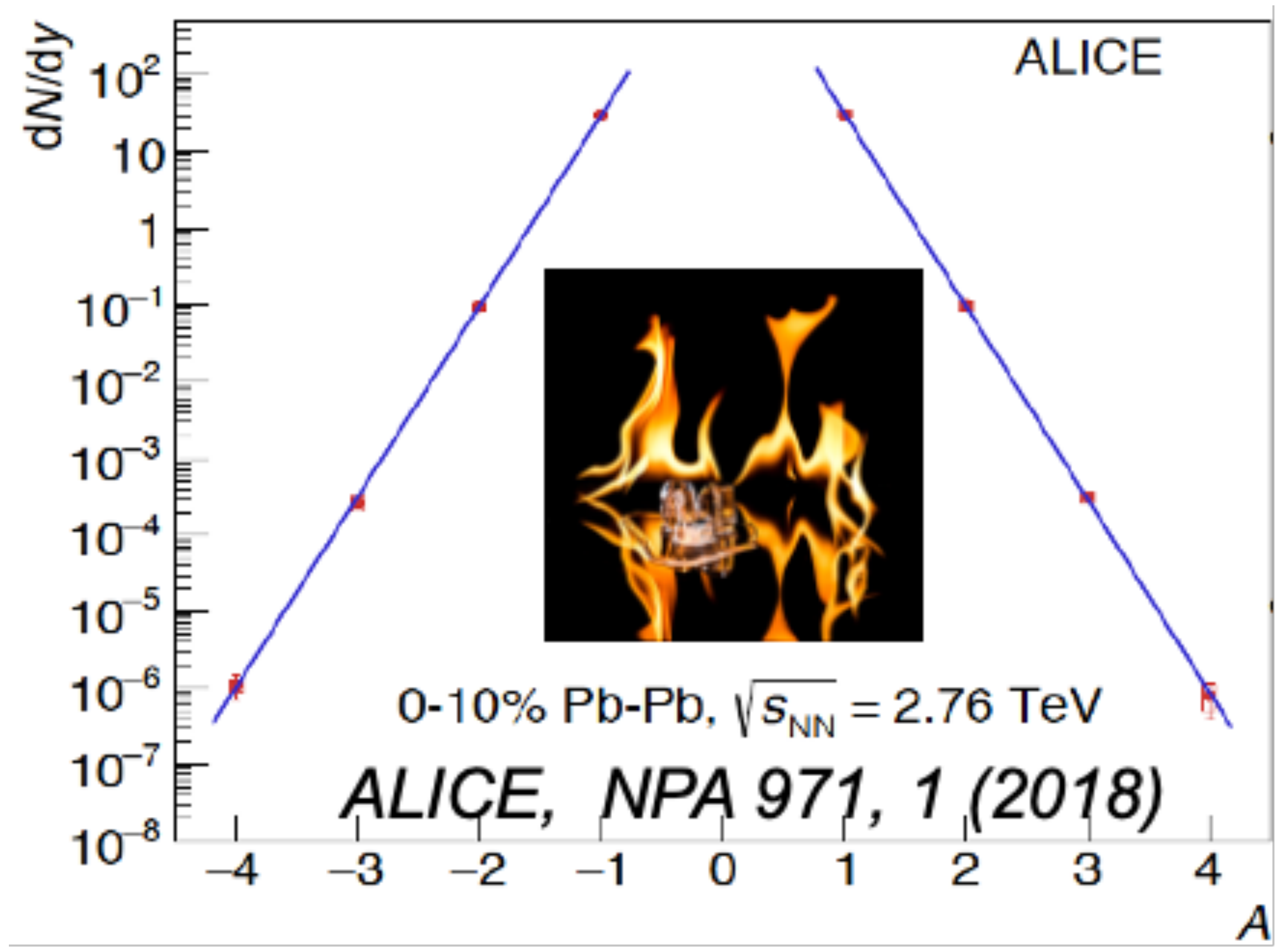
Projectile/target spectators: heavy cluster formation

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?

Modelling of cluster formation in HIC

Statistical models

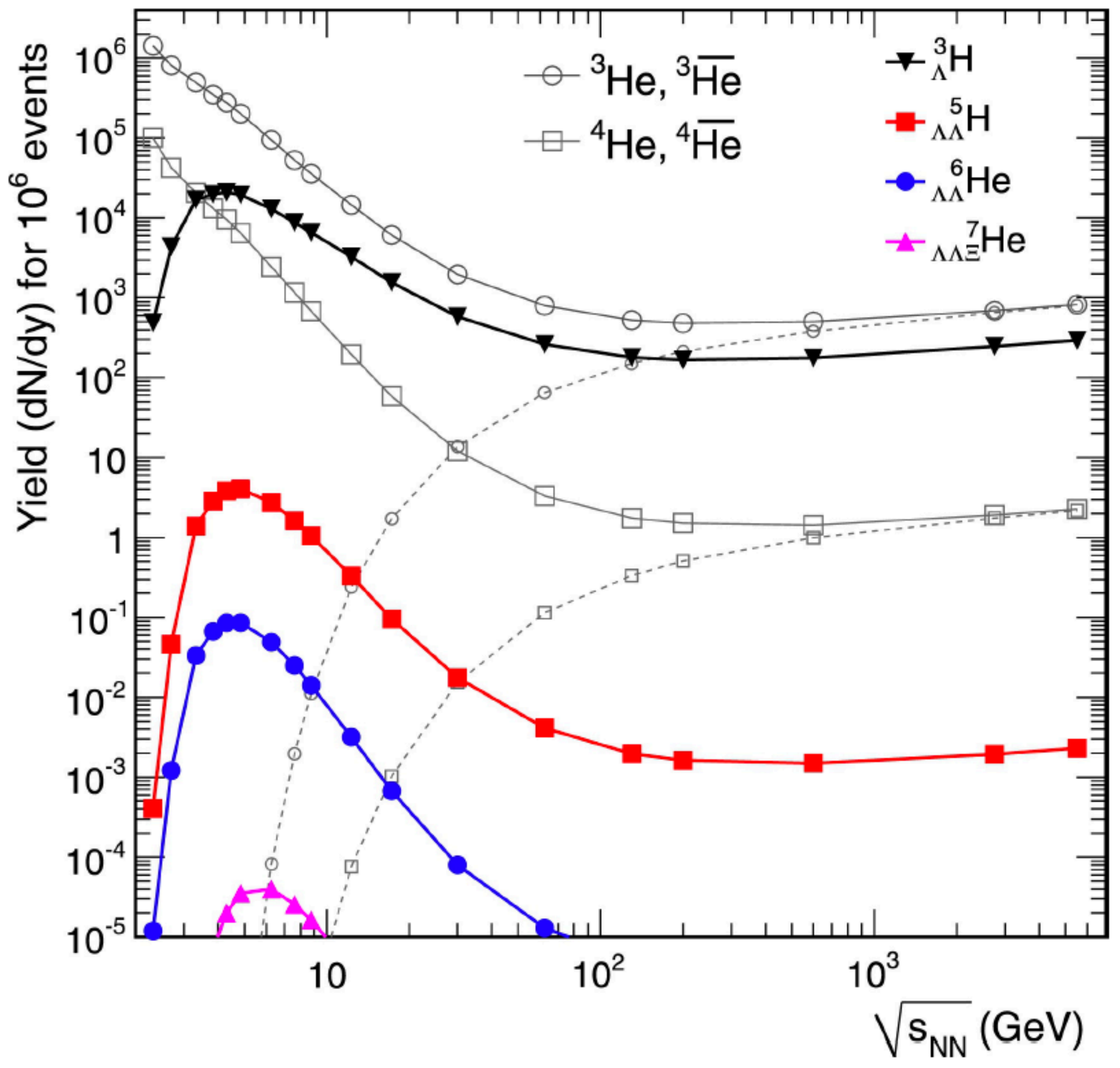
- Production of nuclei depending on T and μ_B at chemical freeze-out & particle mass

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 →

interactions of partons / interactions of hadrons — collision integral

PHSD: Primary collisions pre-hadronic states

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)

Potential mechanism for cluster production

Minimum Spanning Tree (MST)

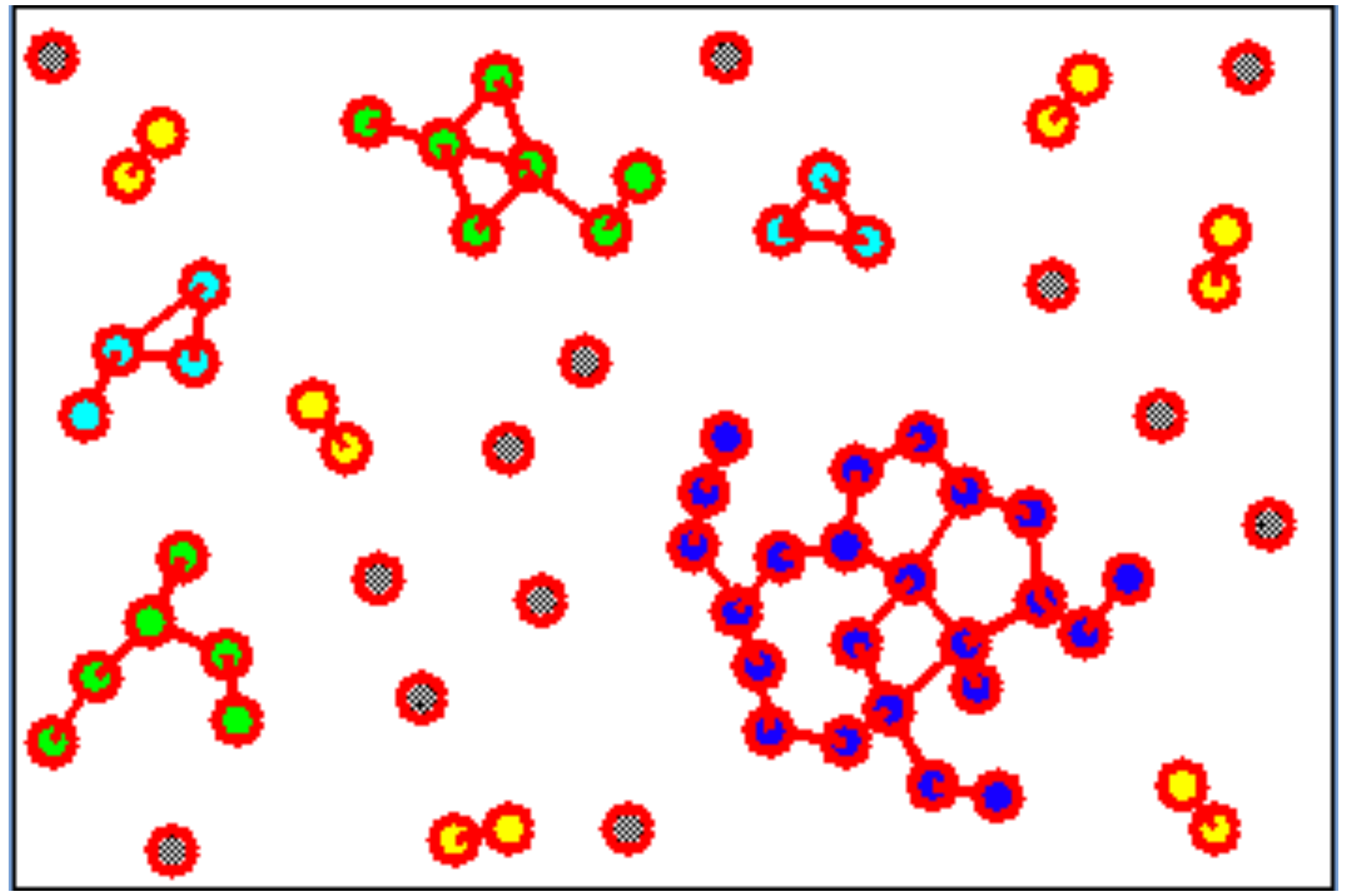
Cluster criterion: distance of nuclei

Algorithm: search for accumulations of particles in coordinate space

1. Two particles i & j are bound if:

$$|r_i - r_j| < 4.0 \text{ fm}$$

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

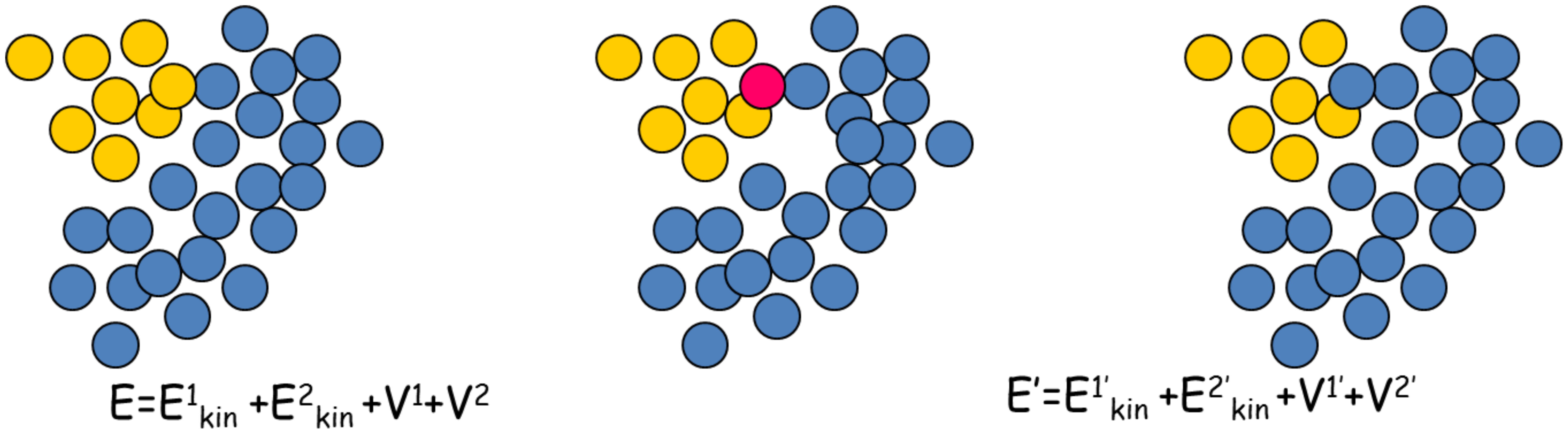


Remark: additional momentum cuts lead to a small changes: particles with large relative momentum are mostly not at the same position (V. Kireyeu, Phys.Rev.C 103 (2021) 5)

Simulated Annealing Clusterization Algorithm (SACA)

Based on ideas by Dorso and Randrup
(Phys.Lett. B301 (1993) 328)

- Take the positions and momenta of all nucleons at time t
- Combine them in all possible ways into all kinds of clusters or leave them as single nucleons
- Neglect the interaction among clusters
- Choose that configuration which has the highest binding energy:



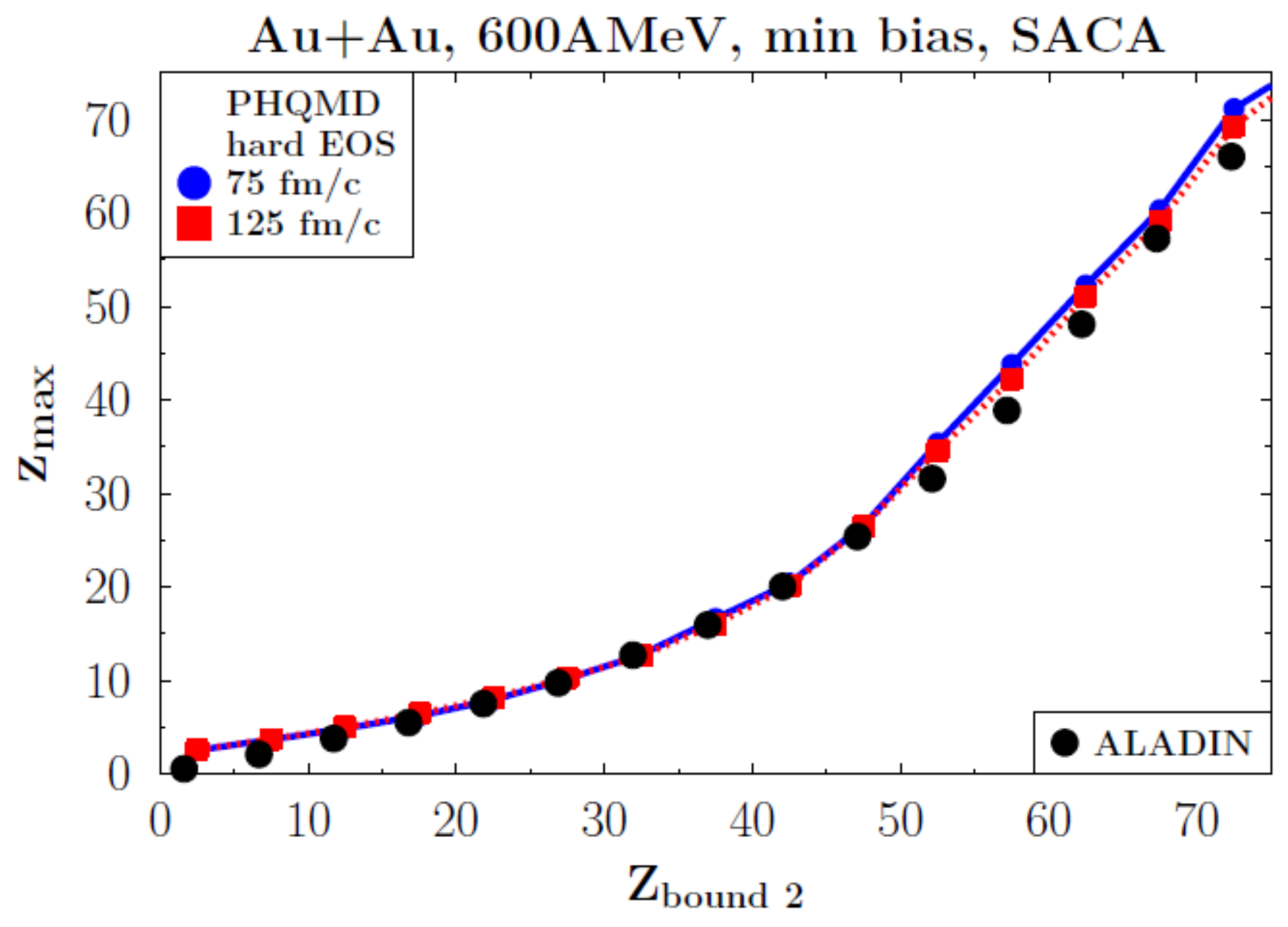
If E' < E take a new configuration
If E' > E take the old configuration with a probability depending on E'-E
Repeat this procedure many times —>   Leads automatically to finding of the most bound configurations
(realized via a Metropolis algorithm)

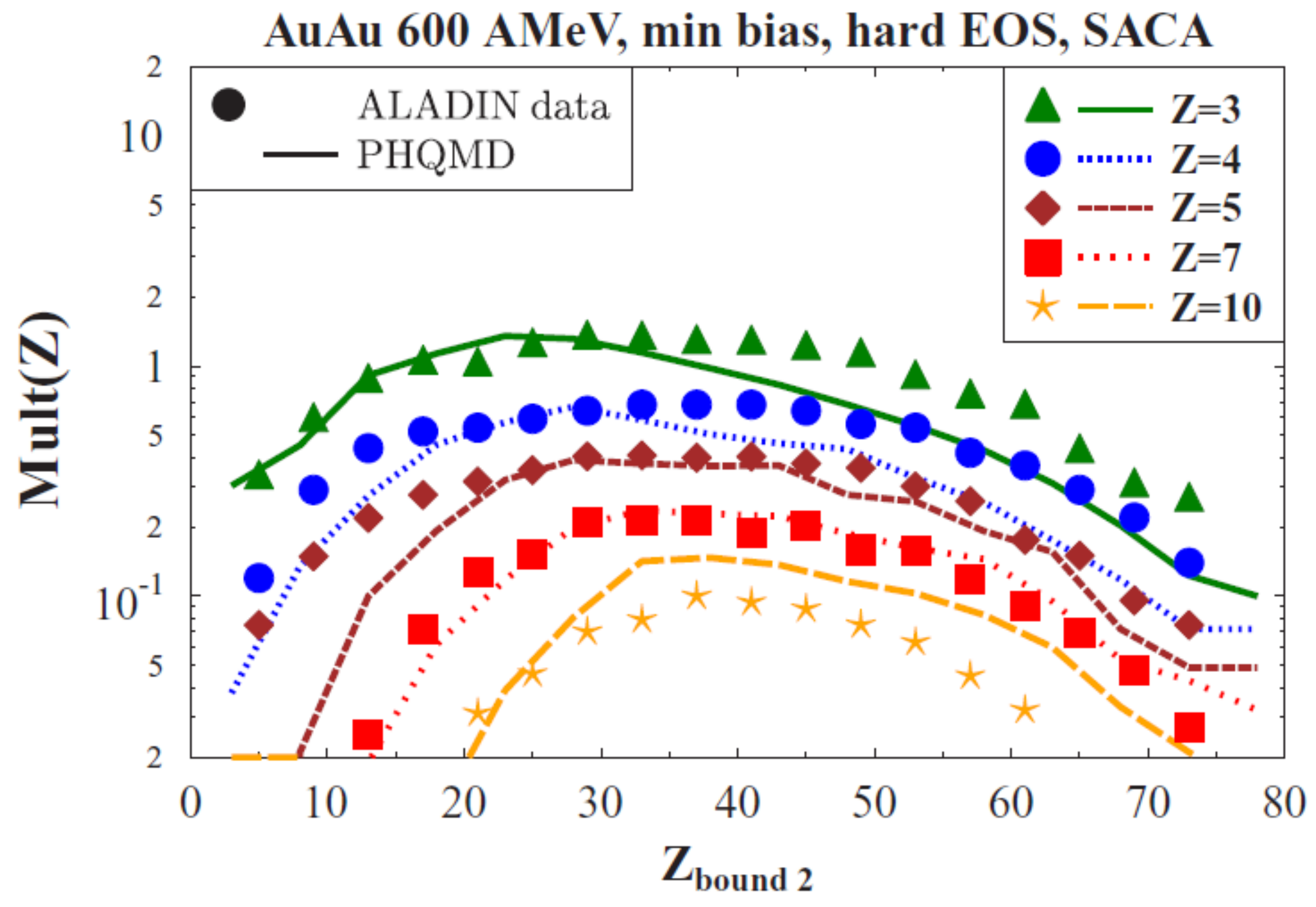
R. K. Puri, J. Aichelin, PLB301 (1993) 328, J.Comput.Phys. 162 (2000) 245-266;
P.B. Gossiaux, R. Puri, Ch. Hartnack, J. Aichelin, Nuclear Physics A 619 (1997) 379-390

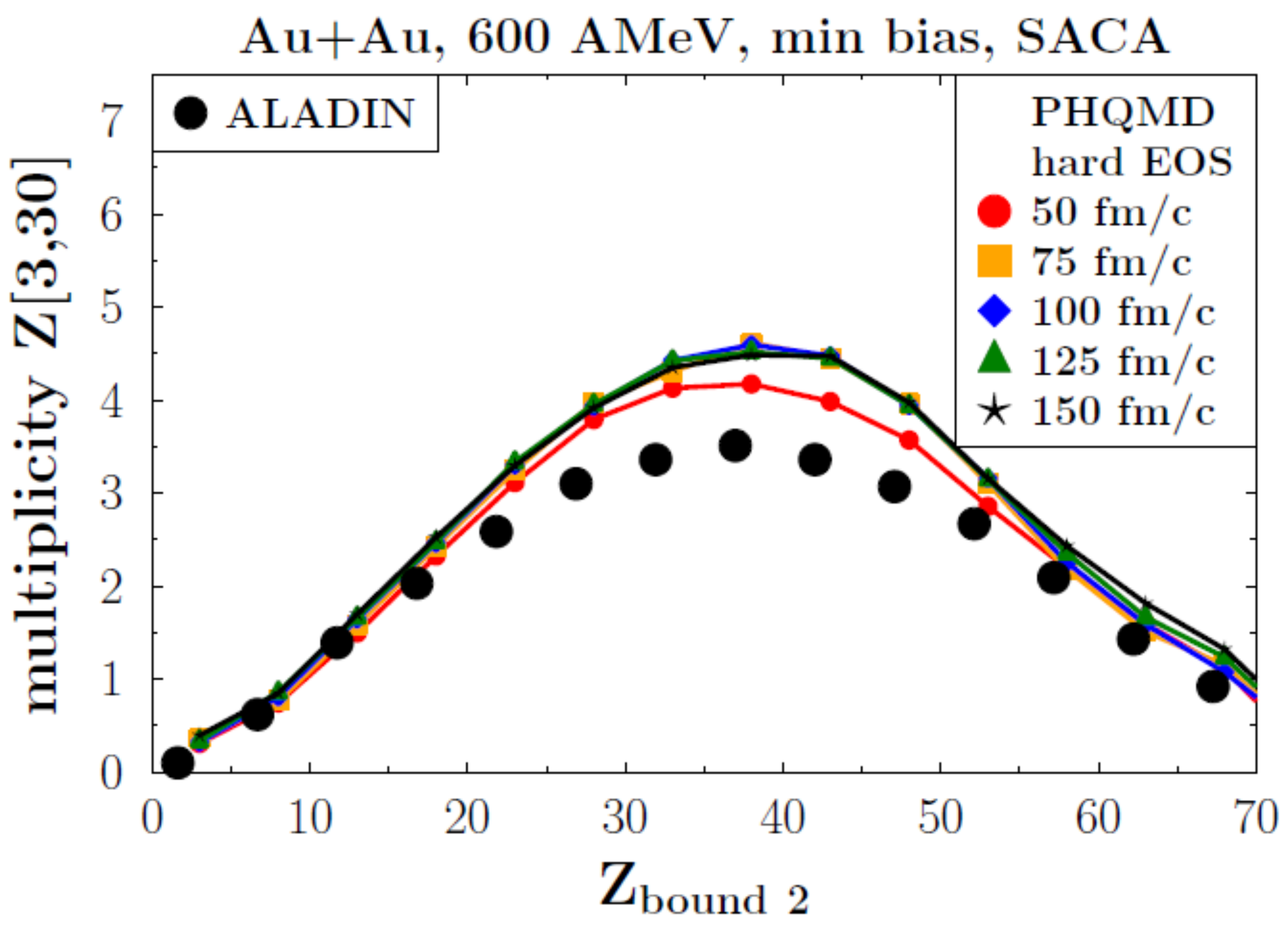
Heavy clusters in PHQMD

PHQMD with SACA shows an agreement with ALADIN data for very complex cluster observables as

- Largest clusters (Zbound)
- Multiplicity (Zbound)
- Energy independent 'rise and fall'







J. Aichelin et al., PRC 101 (2020) 044905

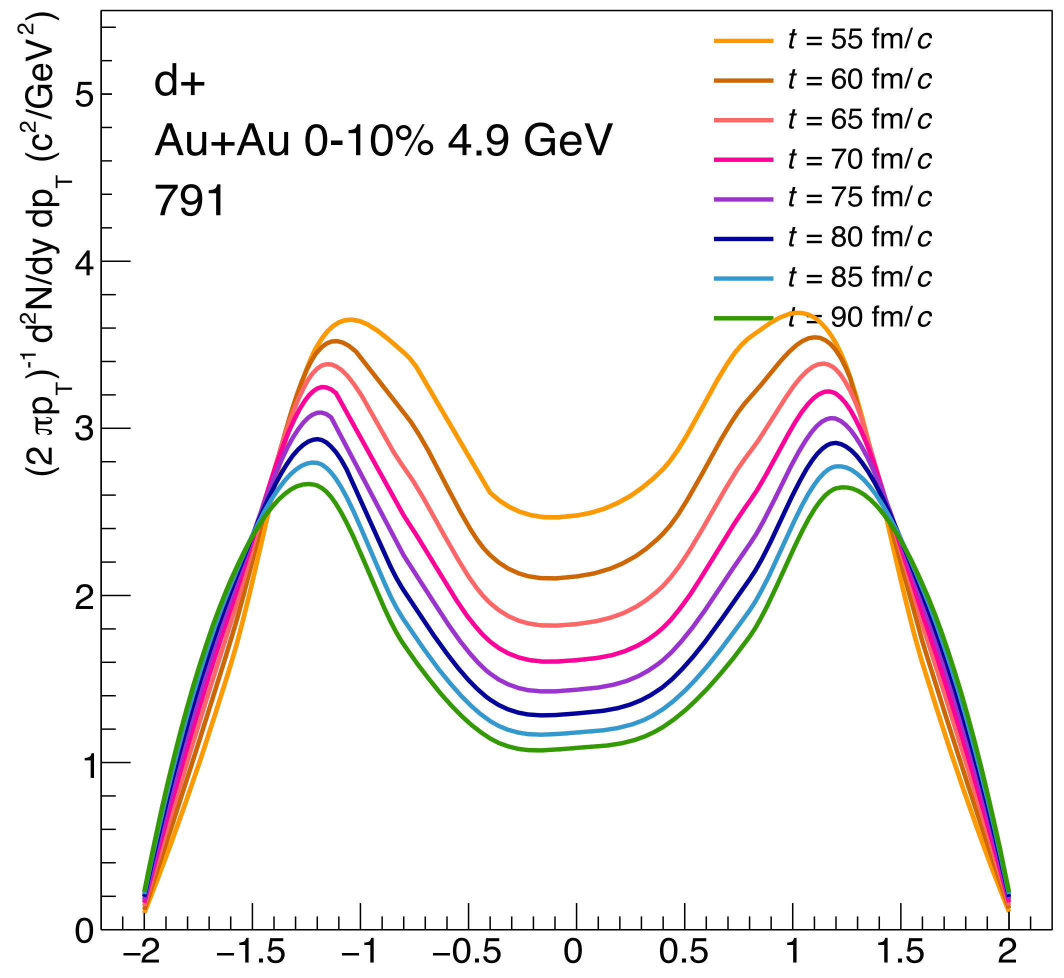
Cluster stability over time

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, pT distribution and ratio of particles do not change with time

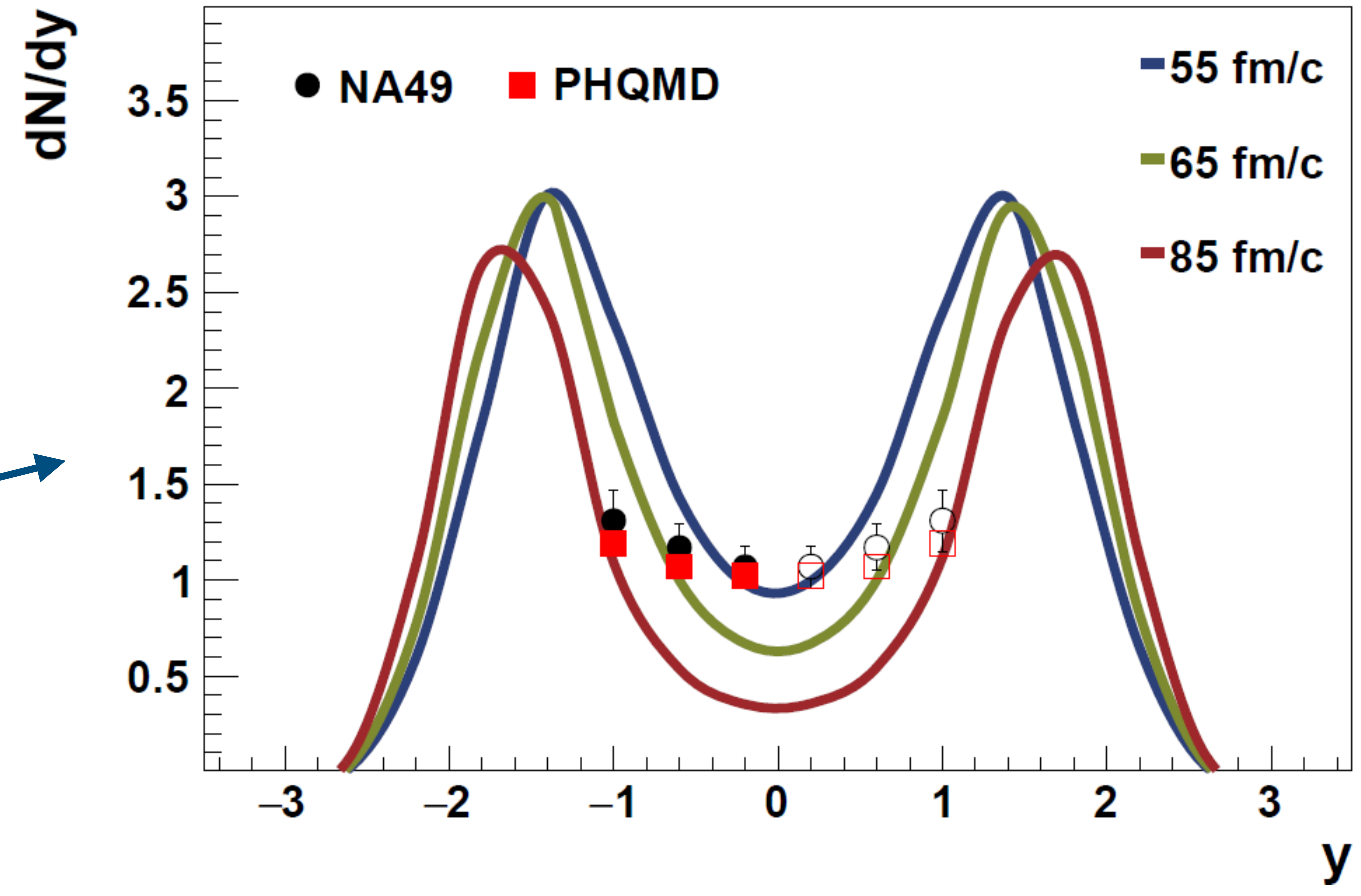
How to stabilize QMD clusters?

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

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

Scenario 2:
G. Coci et al., in preparation

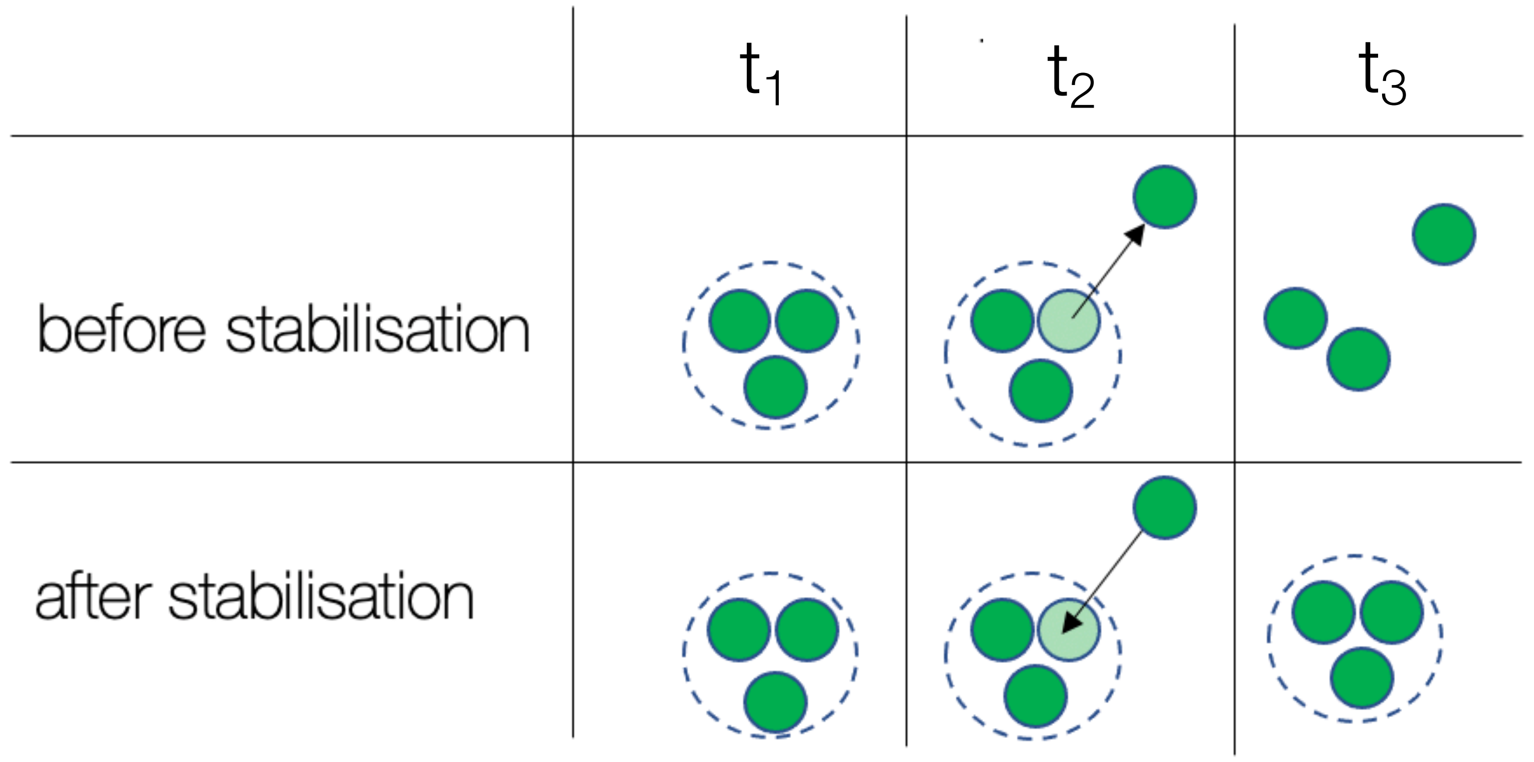
Stabilisation Procedure:

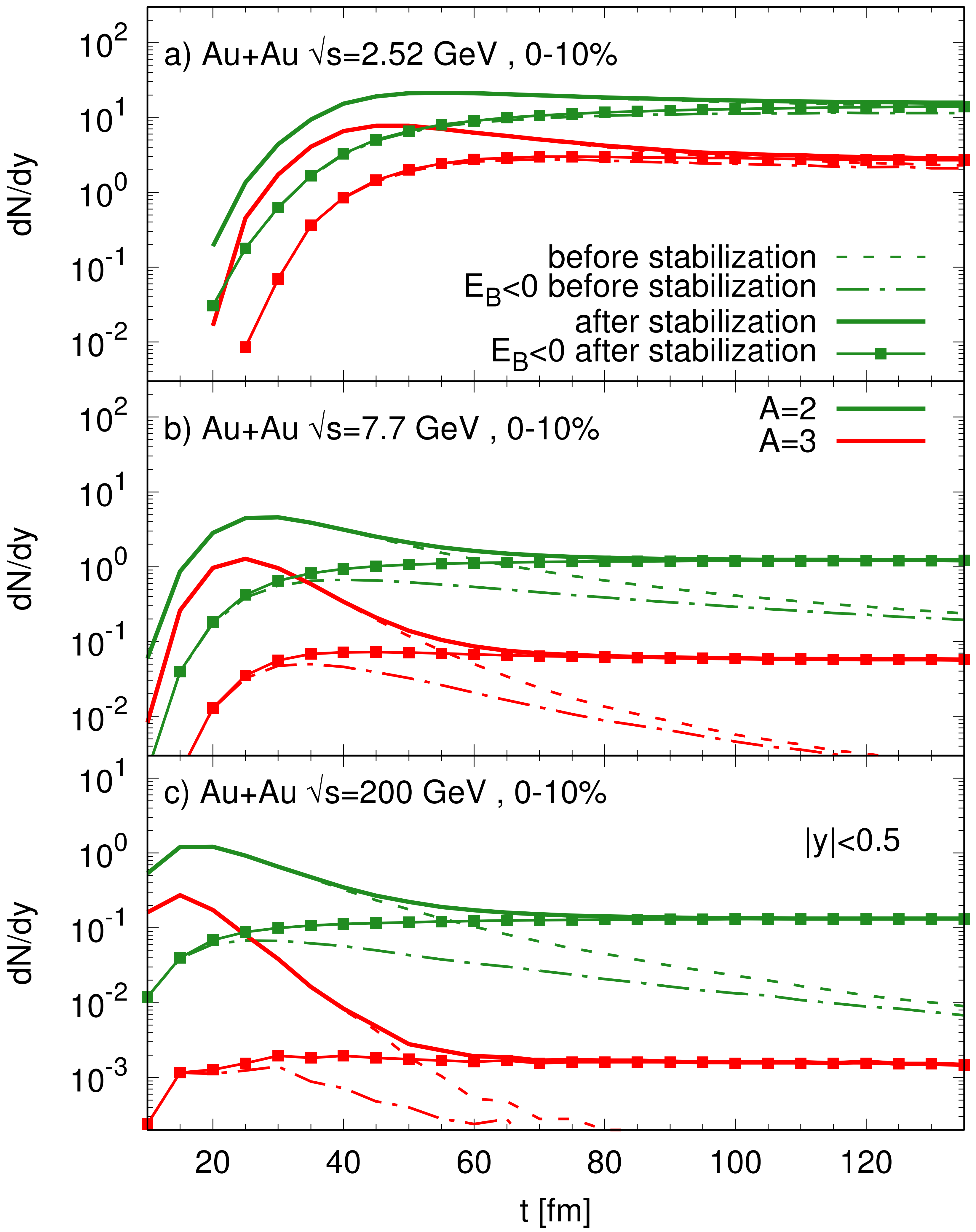
- consider asymptotic state: clusters and free nucleons

- 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

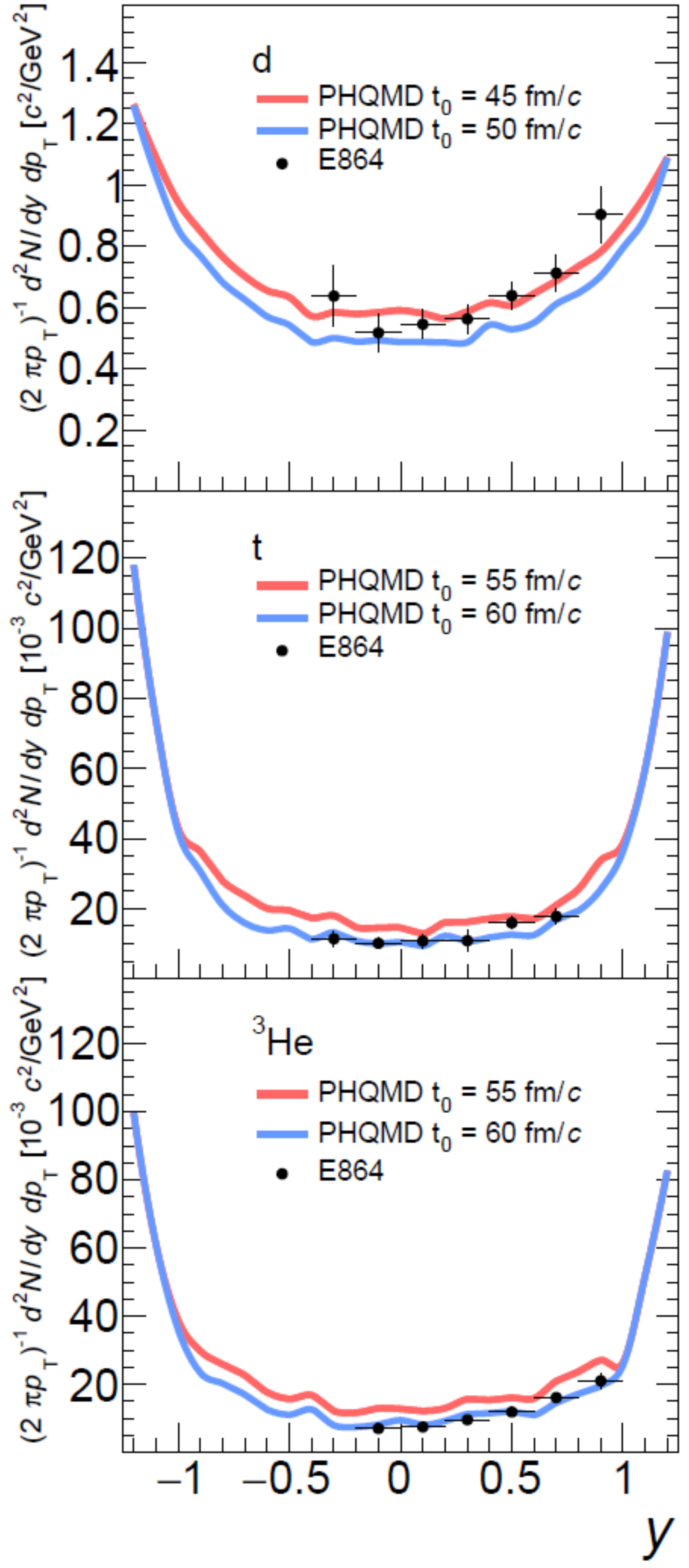
Allows to recover most of “lost” clusters





Cluster production in HICs at AGS energies

Au+Pb@10.6 AGeV



Scenario 1

The PHQMD results for the y-distribution are taken at **'equal physical time'**

$$t = t_0 \cosh(y),$$

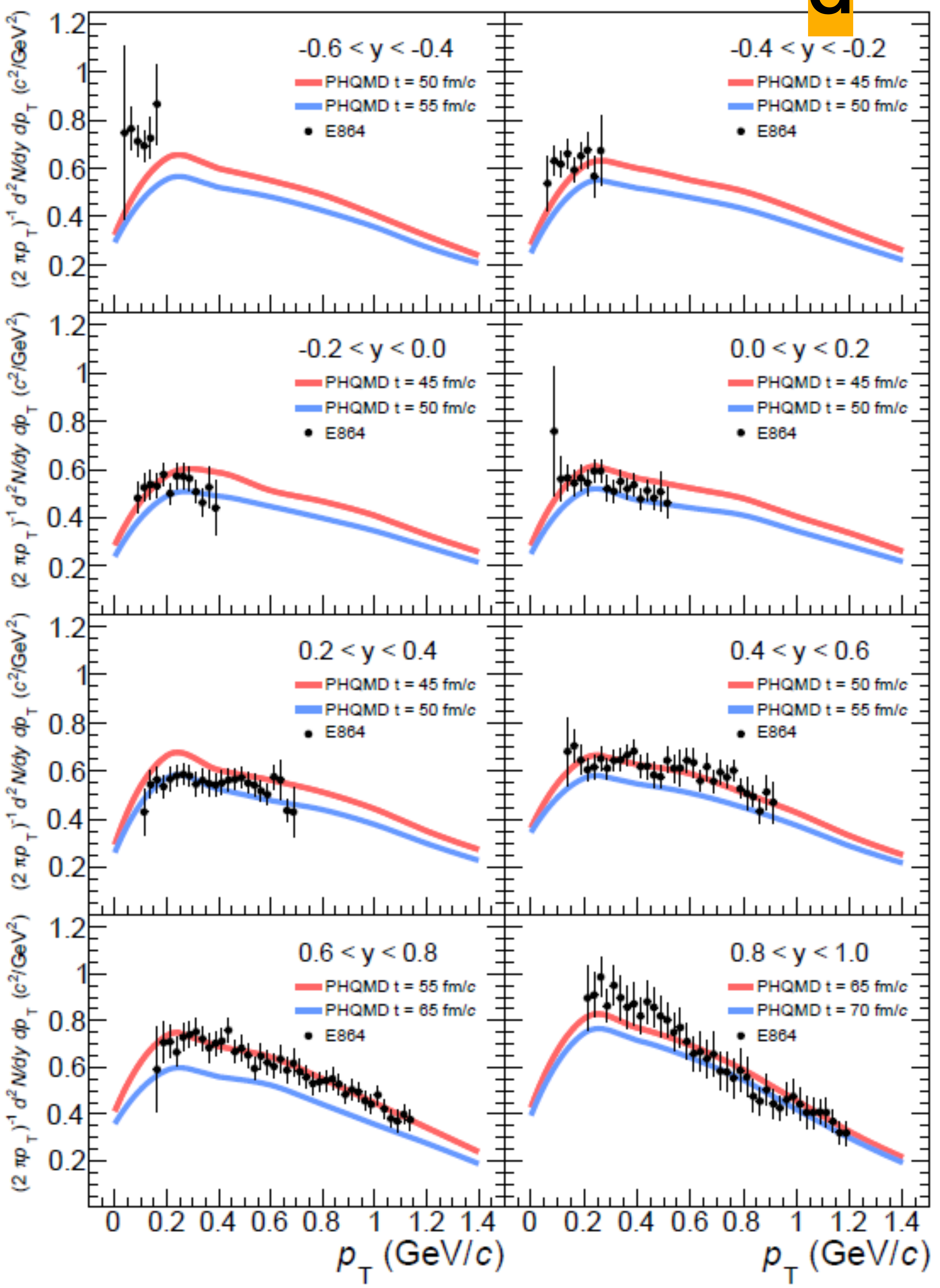
where t_0 is the time at y=0

Consider t_0 =45 and 50 fm/c

S. Gläßel et al., PRC 105 (2022) 1

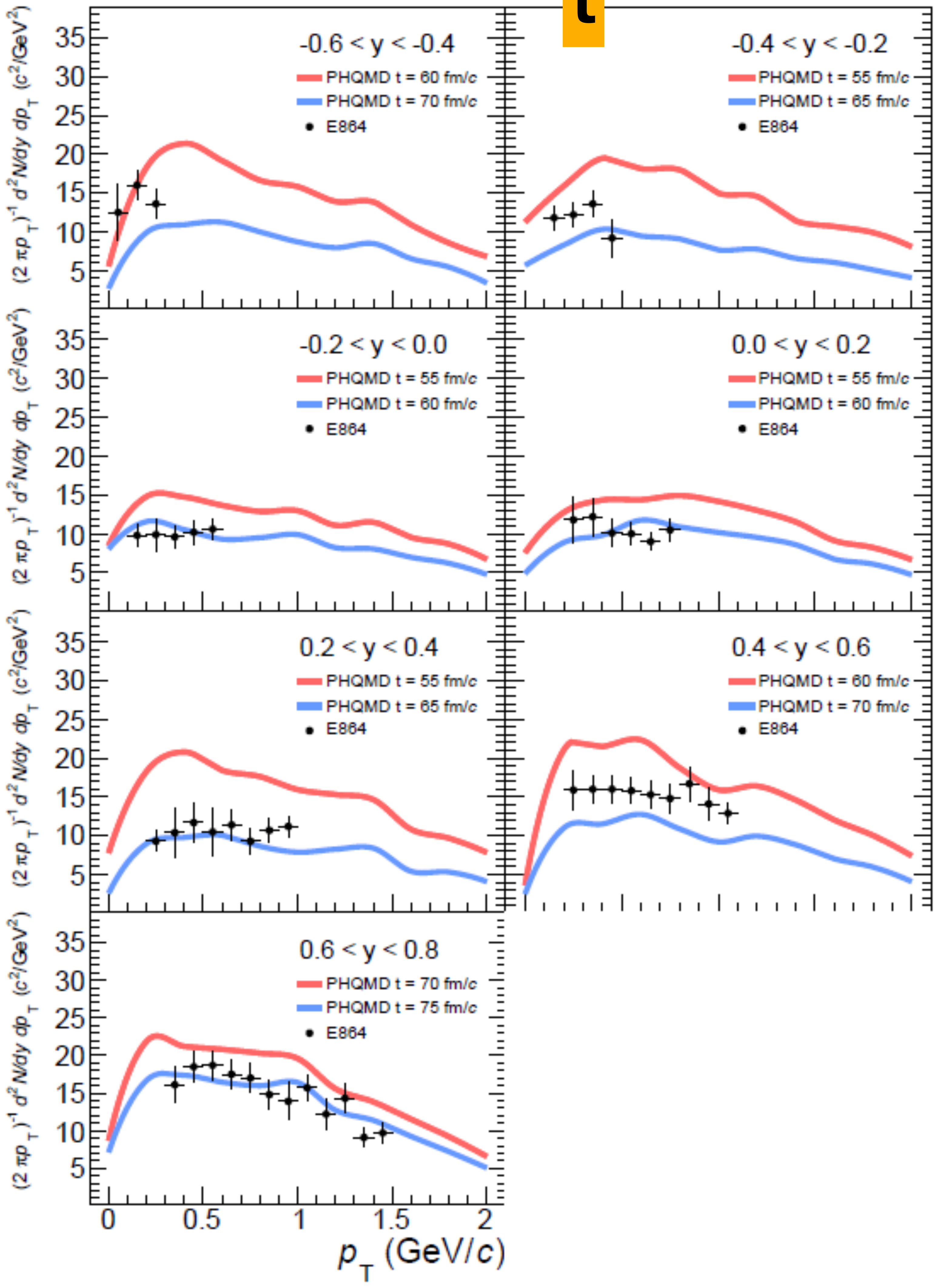
Au+Pb@10.6 AGeV

d



Cluster production in HICs at AGS energies

Au+Pb@10.6 AGeV **t**



Scenario 1

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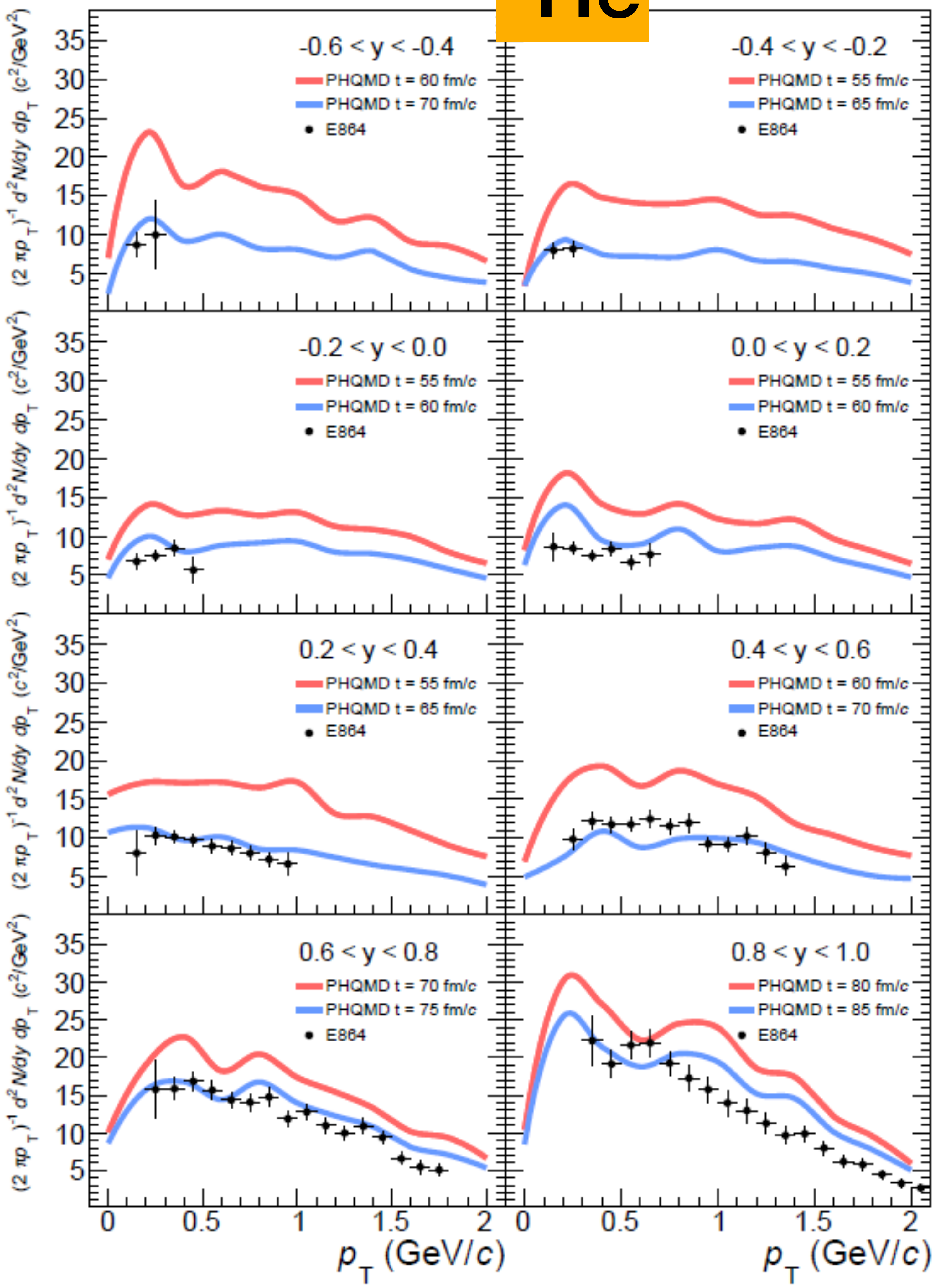
Au+Pb@10.6 AGeV **^{3}He**

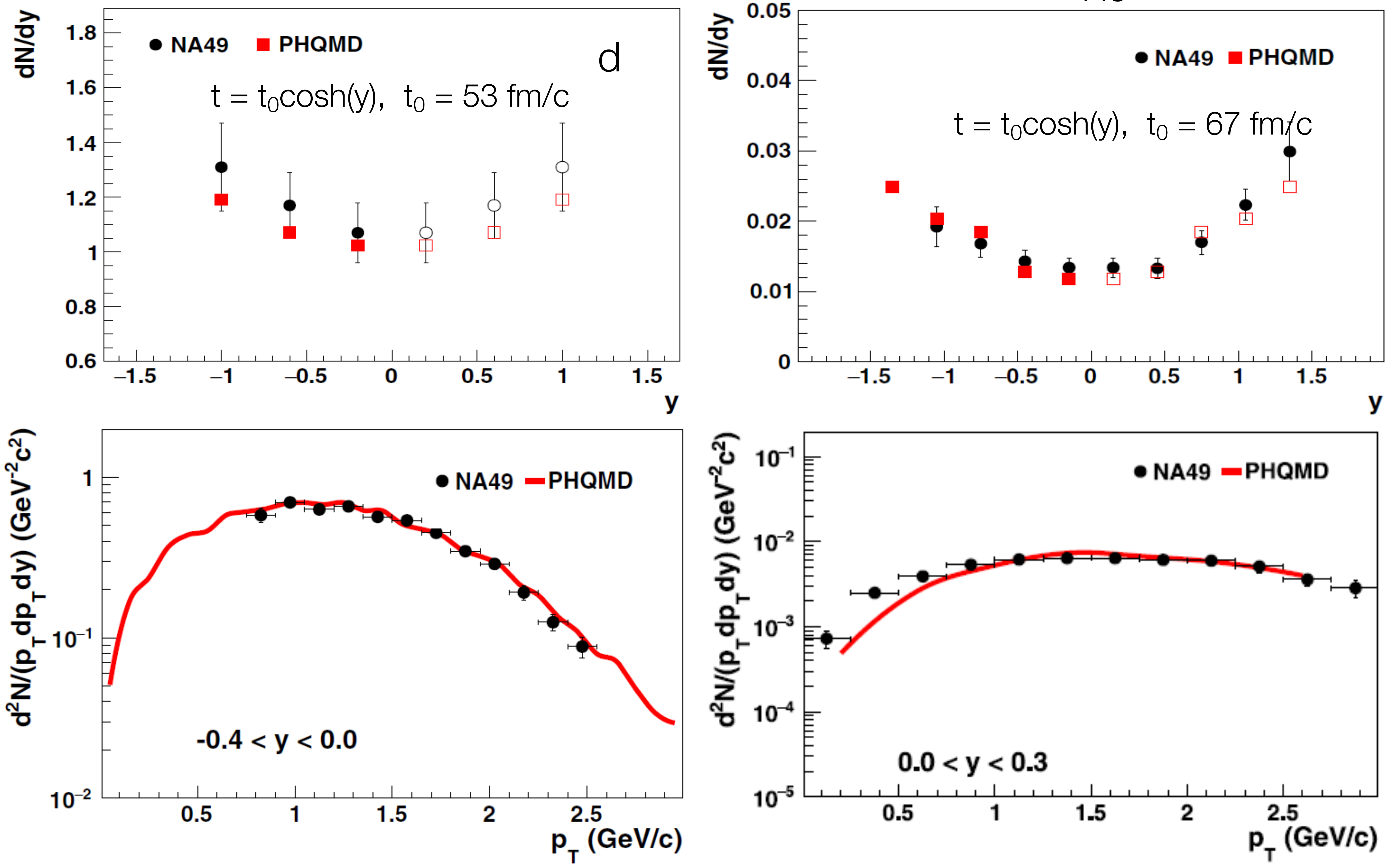


S. Gläßel et al., PRC 105 (2022) 1

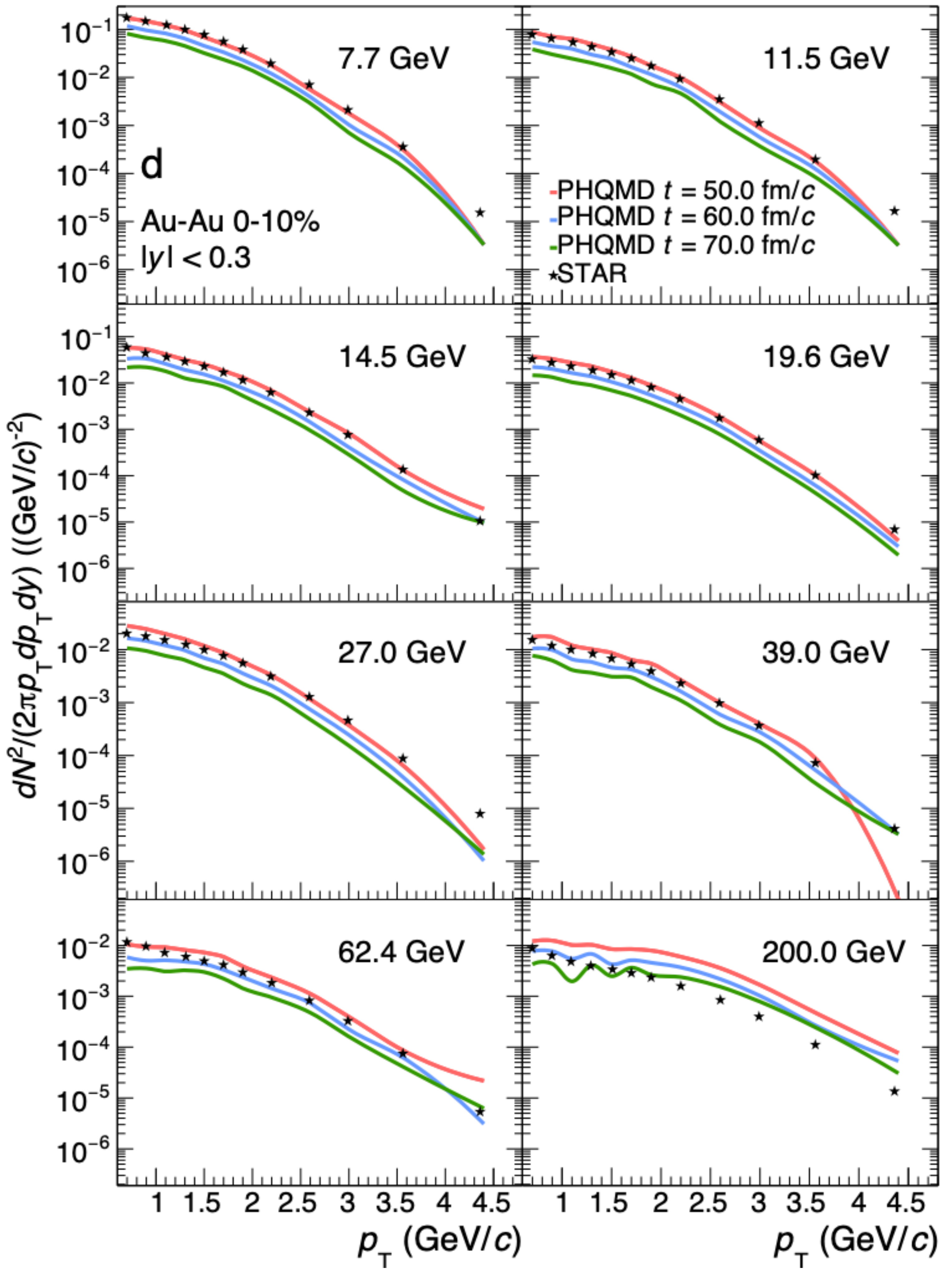
Cluster production in HICs at SPS and RHIC energies

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

deuterons $\quad$ ^{3}He



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

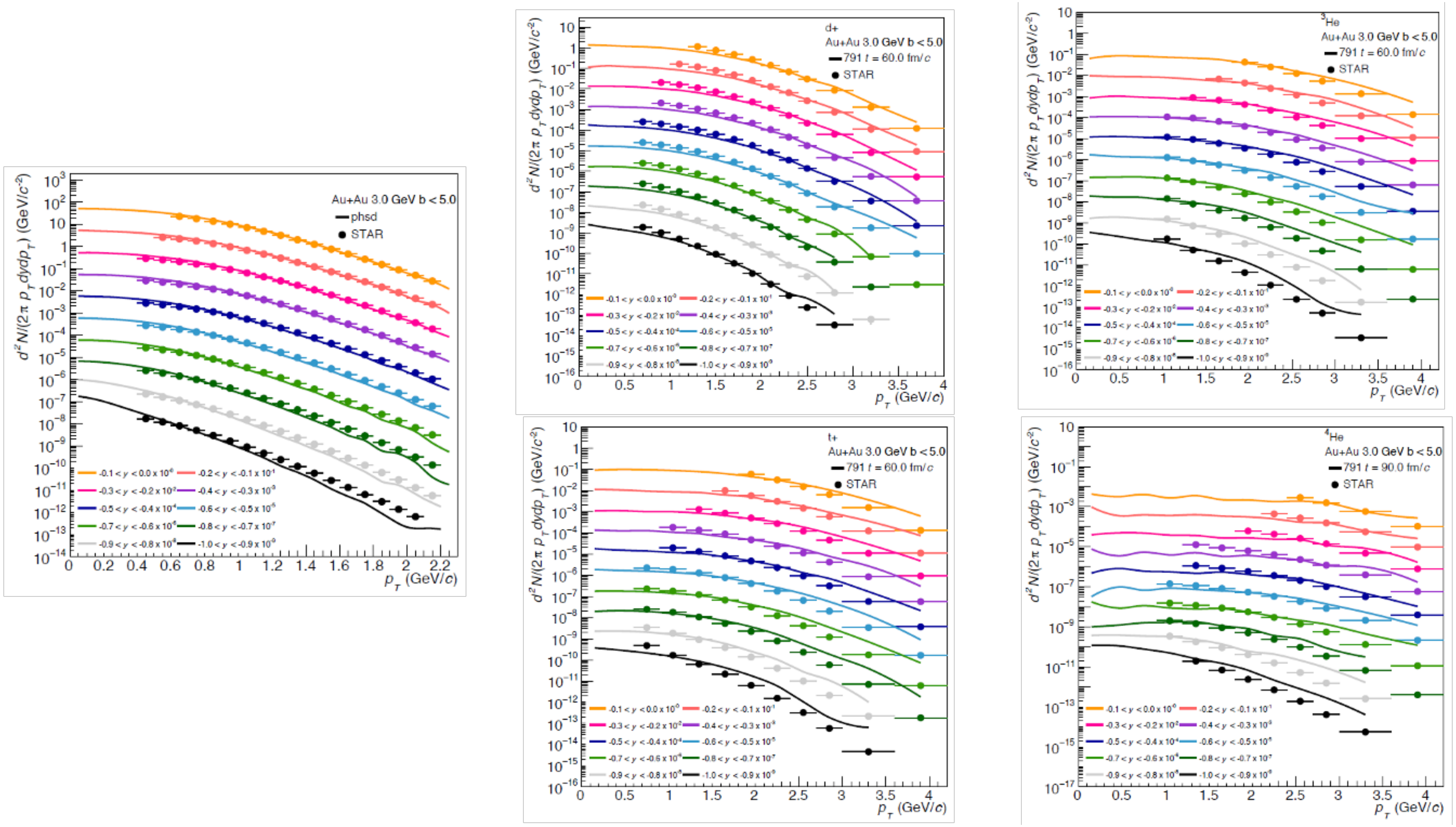


=> The PHQMD results for d and ^{3}He agree with NA49 and STAR data.

S. Gläßel et al., PRC 105 (2022) 1

T. Anticic et al. (NA49), Phys. Rev. C 94, 044906 (2016) $\quad$ J. Adam et al. (STAR), Phys. Rev. C 99, 064905 (2019)

Cluster production in HICs at SPS and RHIC energies



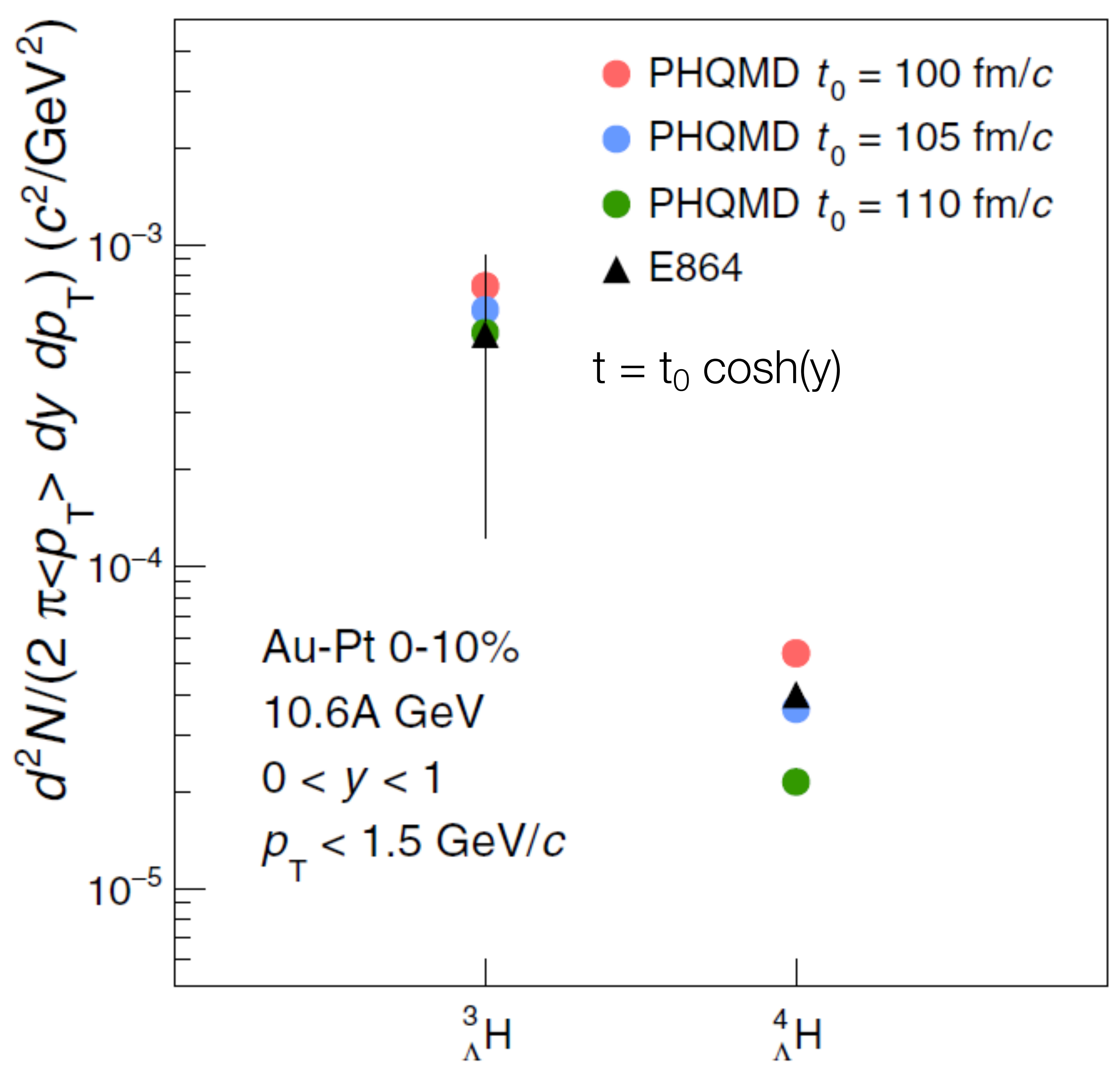
Good description of cluster production

S. Gläßel et al., PRC 105 (2022) 1

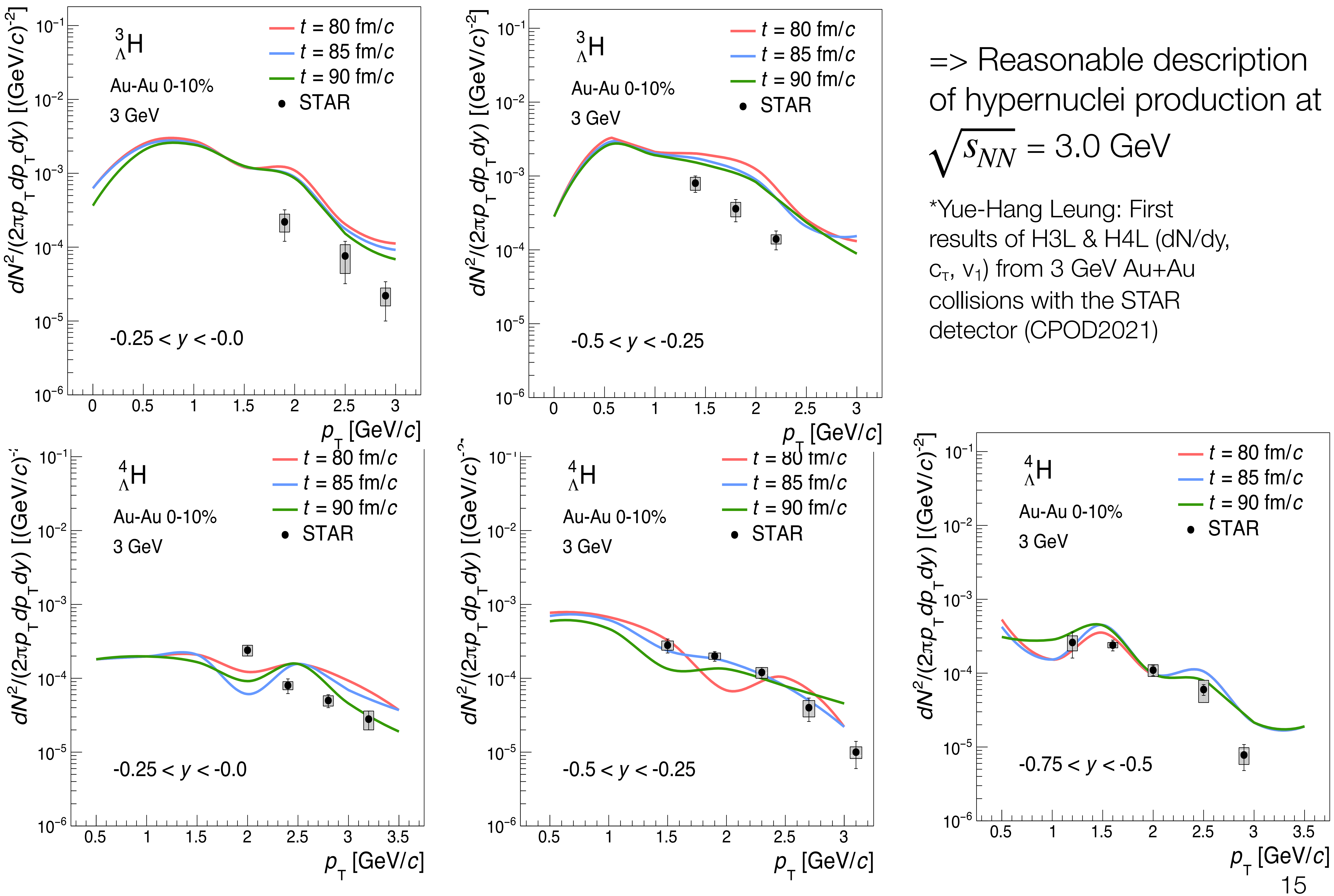
Hypernuclei production at $\sqrt{s_{NN}}$ = 3.0 and 4.9 GeV

S. Gläßel et al., PRC 105 (2022) 1

E864 $\sqrt{s_{NN}}$ = 4.9 GeV



STAR $\sqrt{s_{NN}}$ = 3.0 GeV



=> Reasonable description of hypernuclei production at $\sqrt{s_{NN}}$ = 3.0 GeV

*Yue-Hang Leung: First results of H3L & H4L (dN/dy, c_T, v_1) from 3 GeV Au+Au collisions with the STAR detector (CPOD2021)

Assumption for nucleon-hyperon potential: V_{NL} = 2/3 V_{NN}

=> trend of the experimental STAR* & p_T-spectra at $\sqrt{s_{NN}}$ =3 is produced well

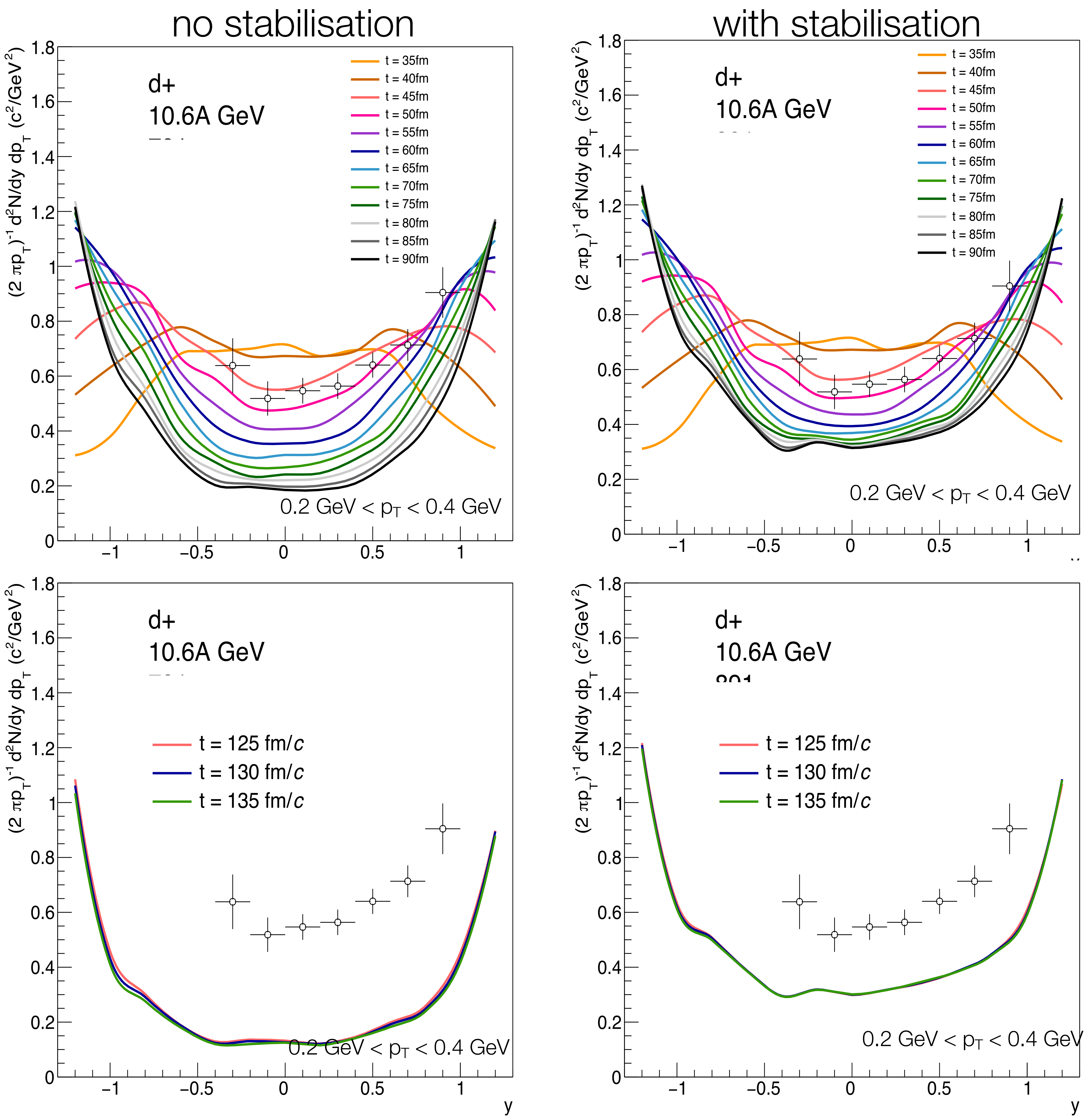
=> yields are slightly overpredicted

dN/dy time evolution for deuteron at $\sqrt{s_{NN}}$ = 4.9 GeV

Scenario 2: «Advanced MST»

35 fm < t < 90 fm

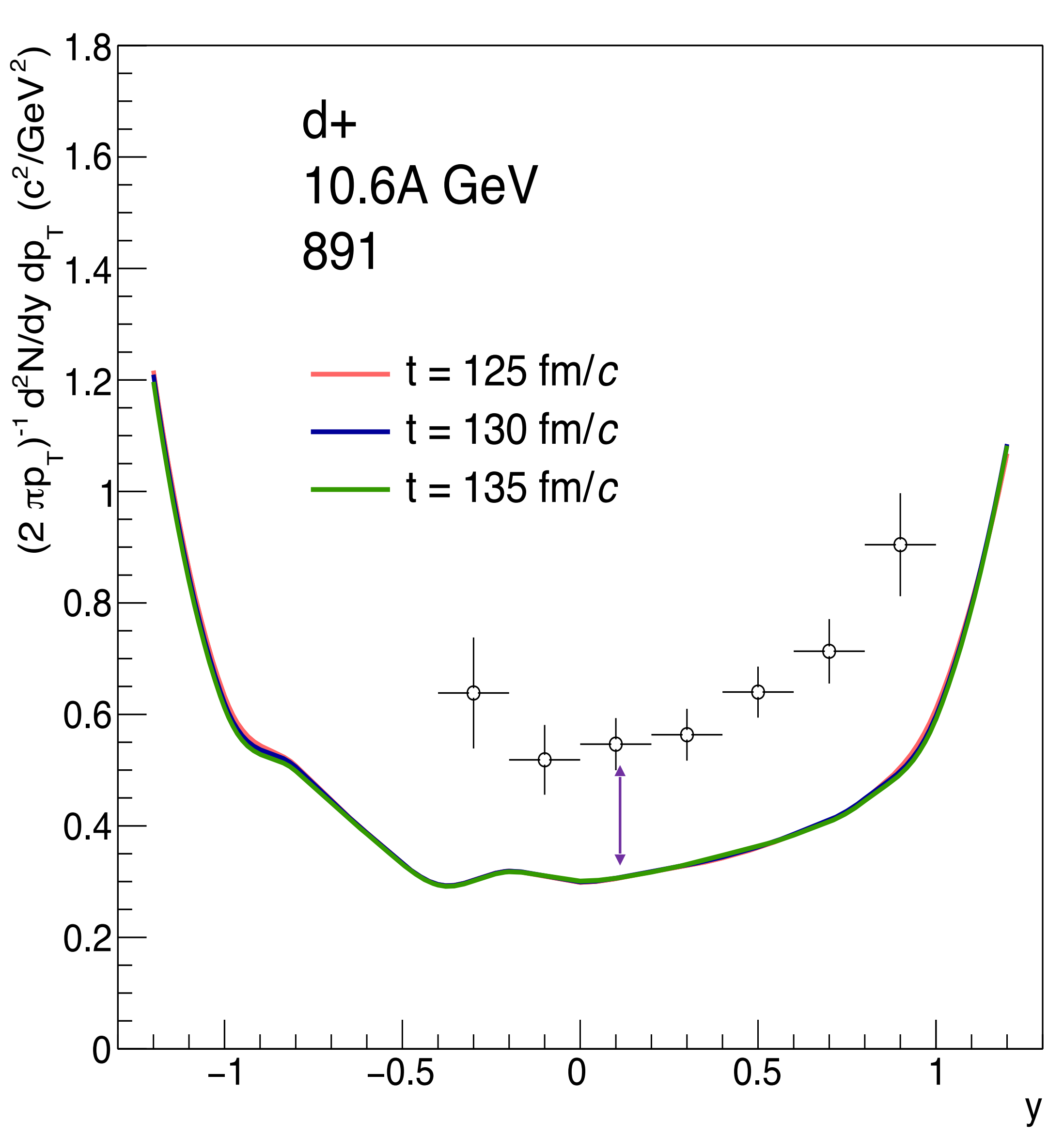
125 fm < t < 135 fm

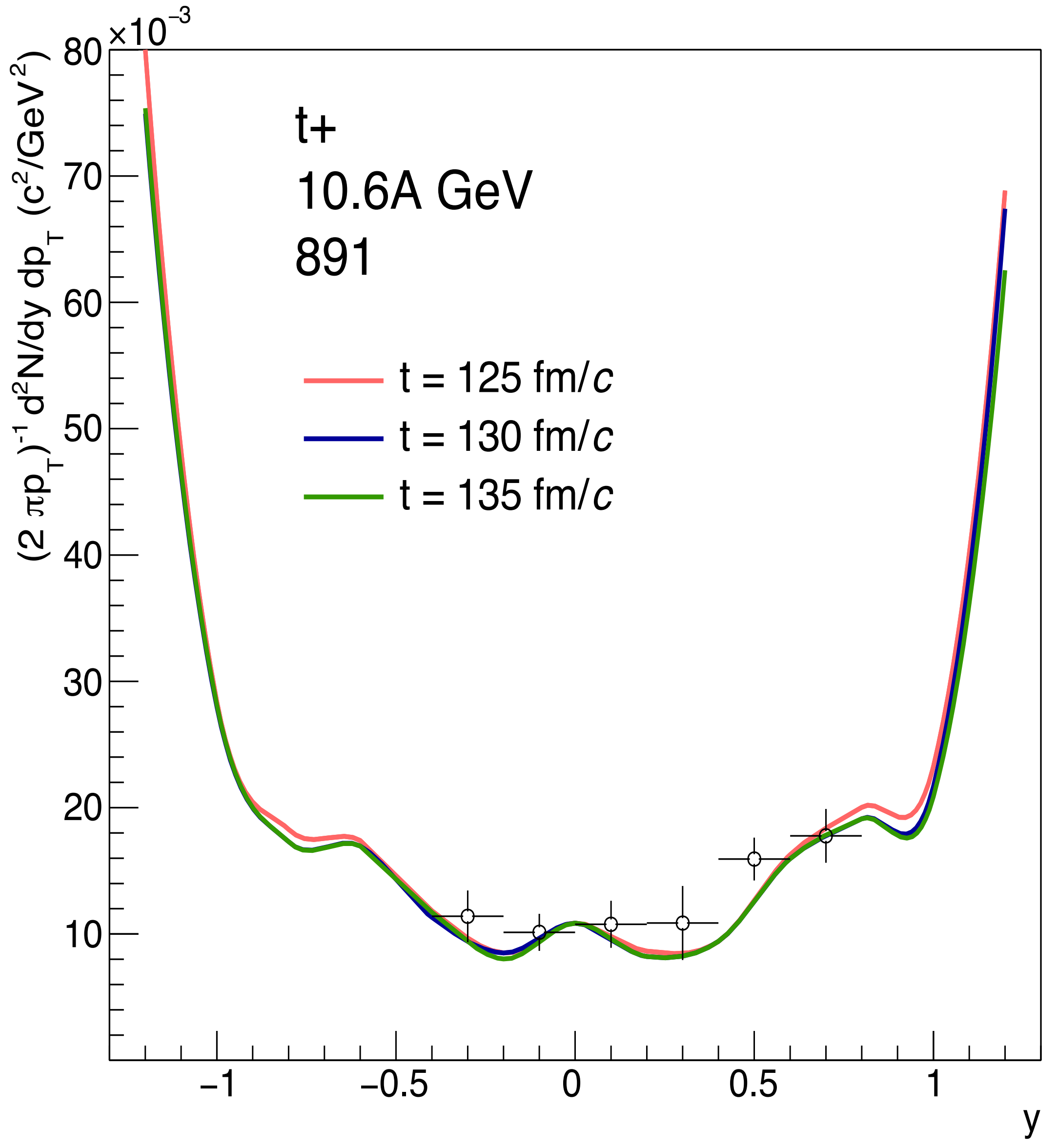


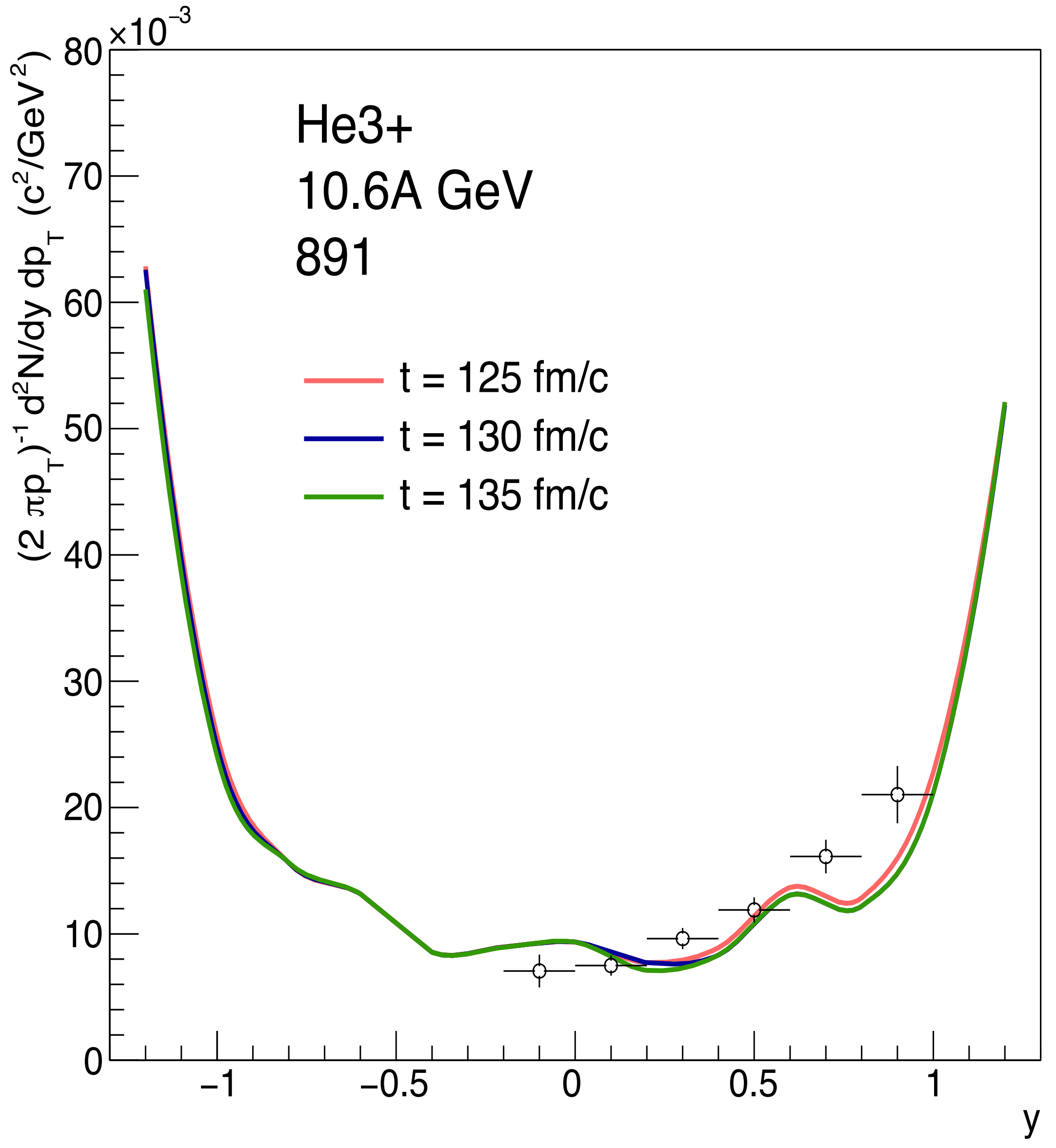
=> With stabilisation, multiplicity starts to drop slower at around 60 fm/c.

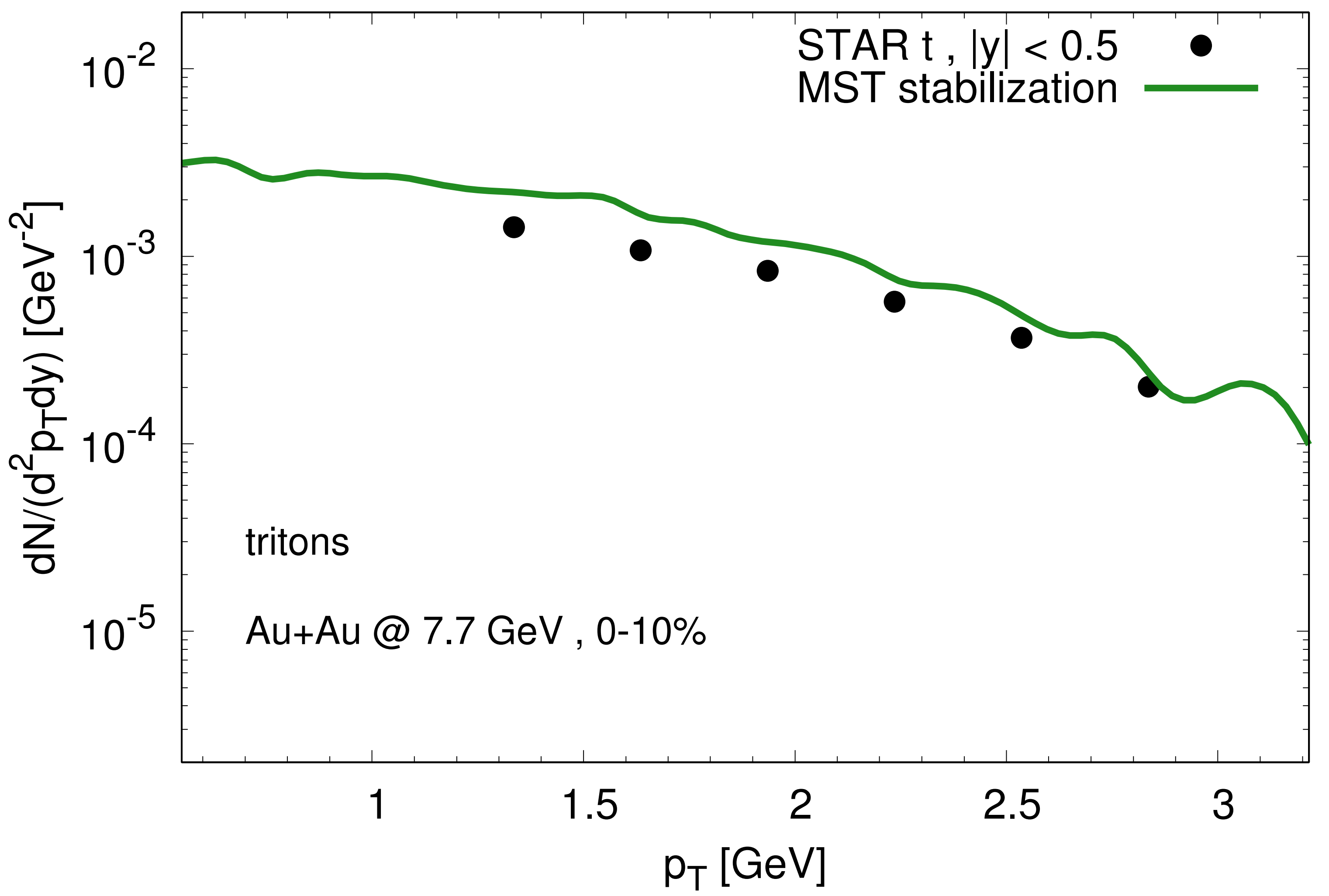
=> At the final time, deuteron multiplicity is ~2 times higher with stabilisation.

Stable light nuclei at $\sqrt{s_{NN}}$ = 4.9 and 7.7 GeV with aMST







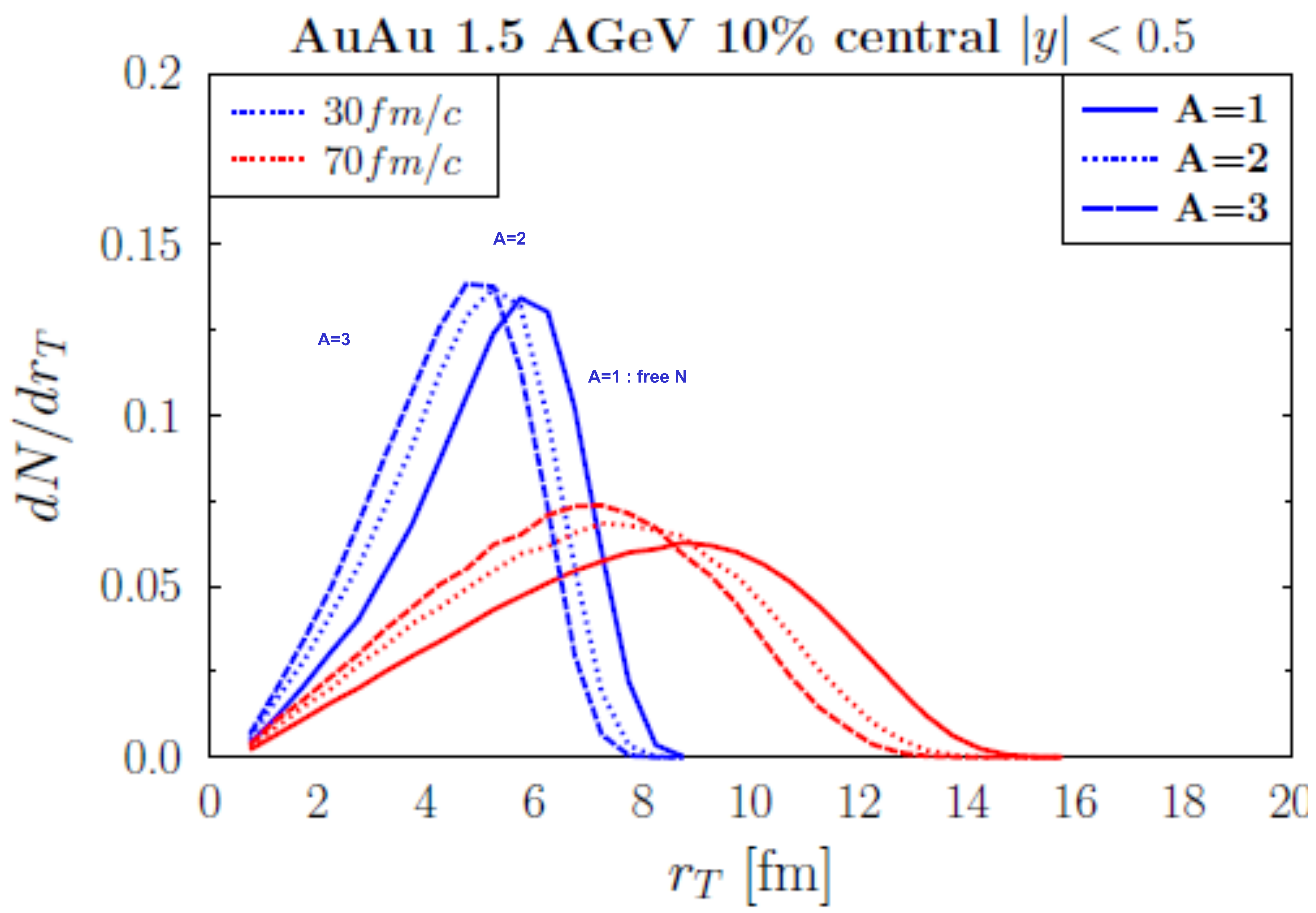


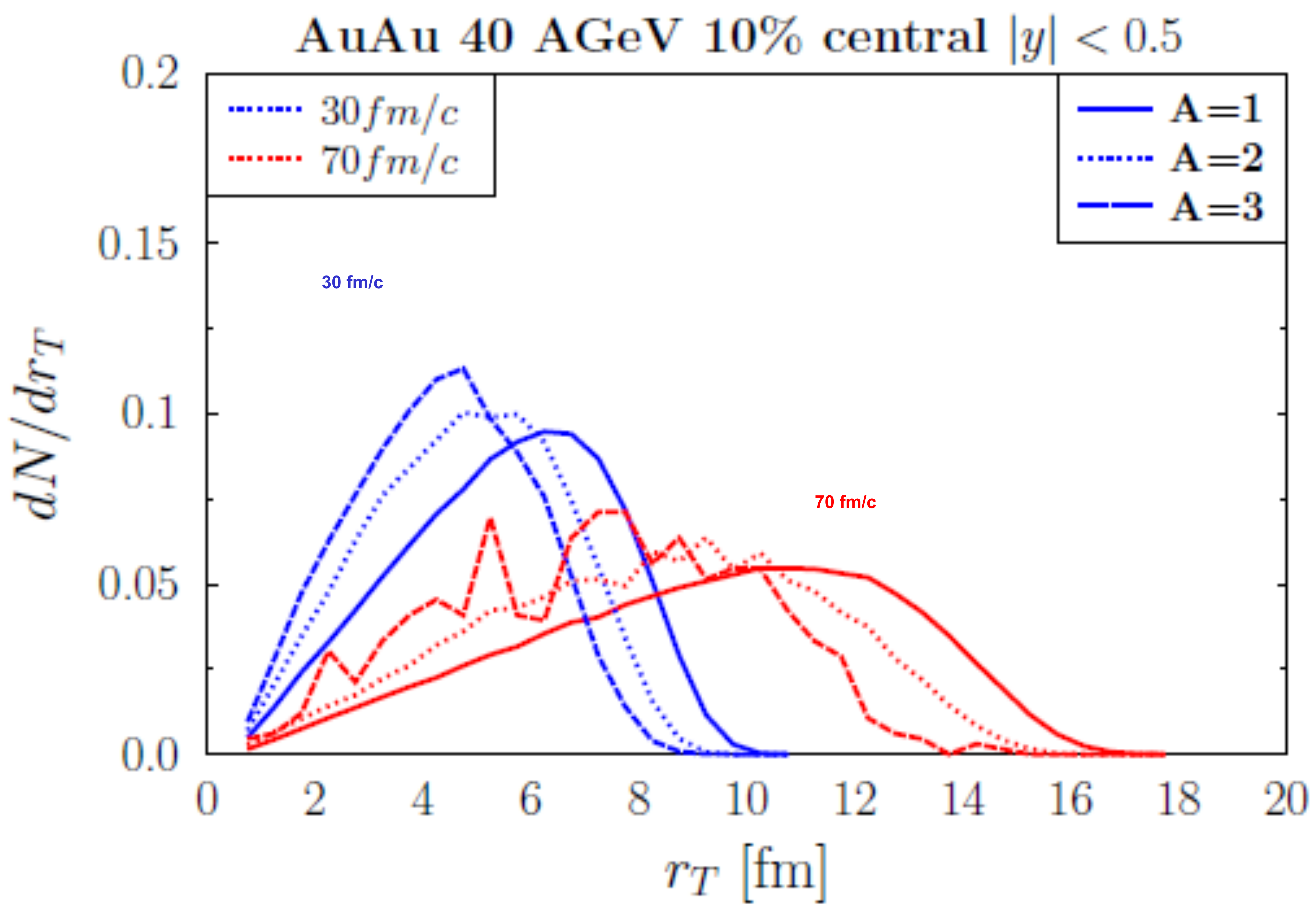
PHQMD with stabilisation procedure fits the experimental data at $\sqrt{s_{NN}}$ = 4.9 and 7.7 GeV very well for triton and ^{3}He.

Deuterons are underestimated => contribution of deuterons formed by inelastic scattering.

Where clusters are formed?

The MST snapshot (taken at time 30 and 70 fm/c) of the normalized distribution of the transverse distance r_T of the nucleons to the center of the fireball.
It is shown for A=1 (free nucleons) and for the nucleons in A=2 and A=3 clusters

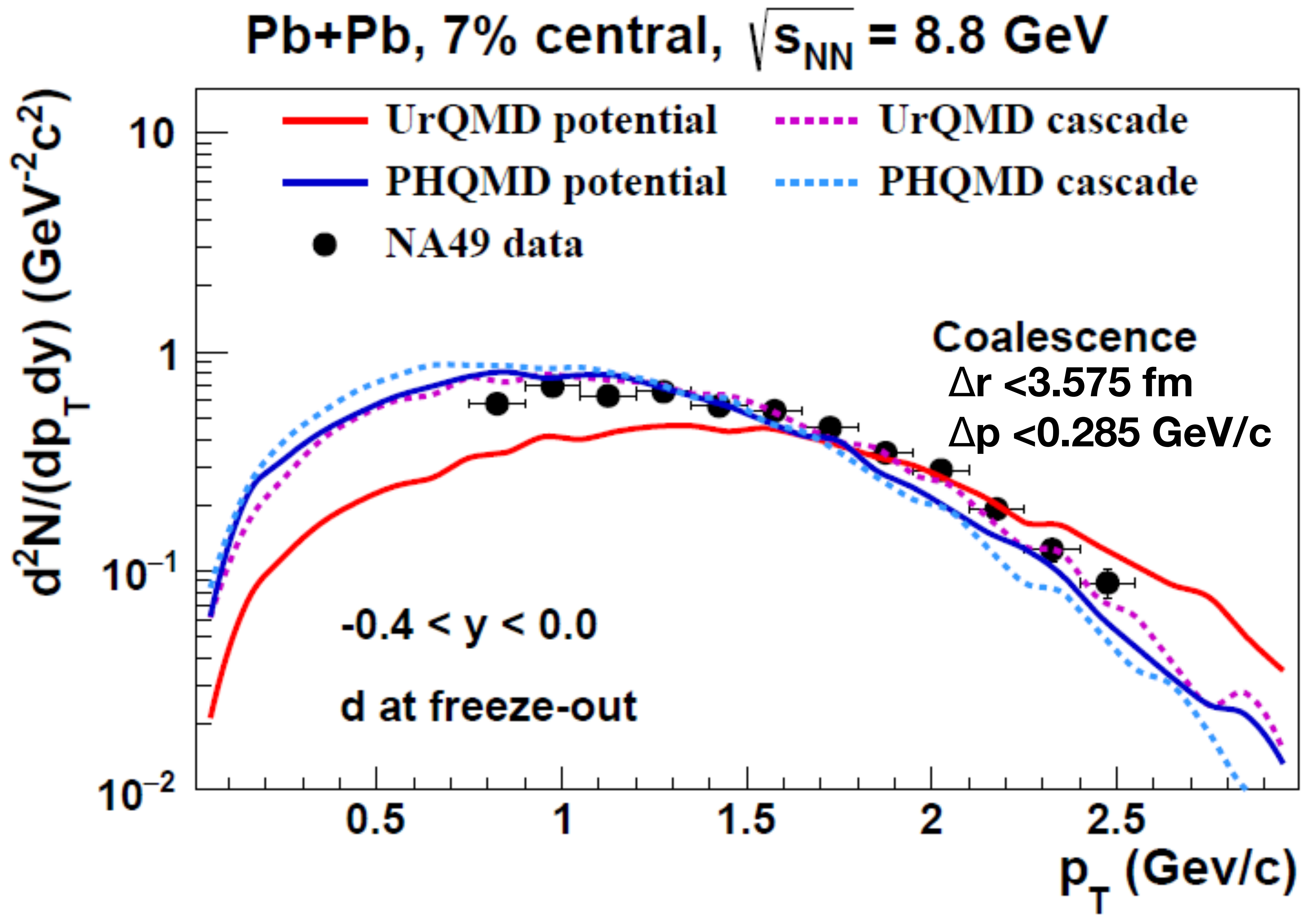


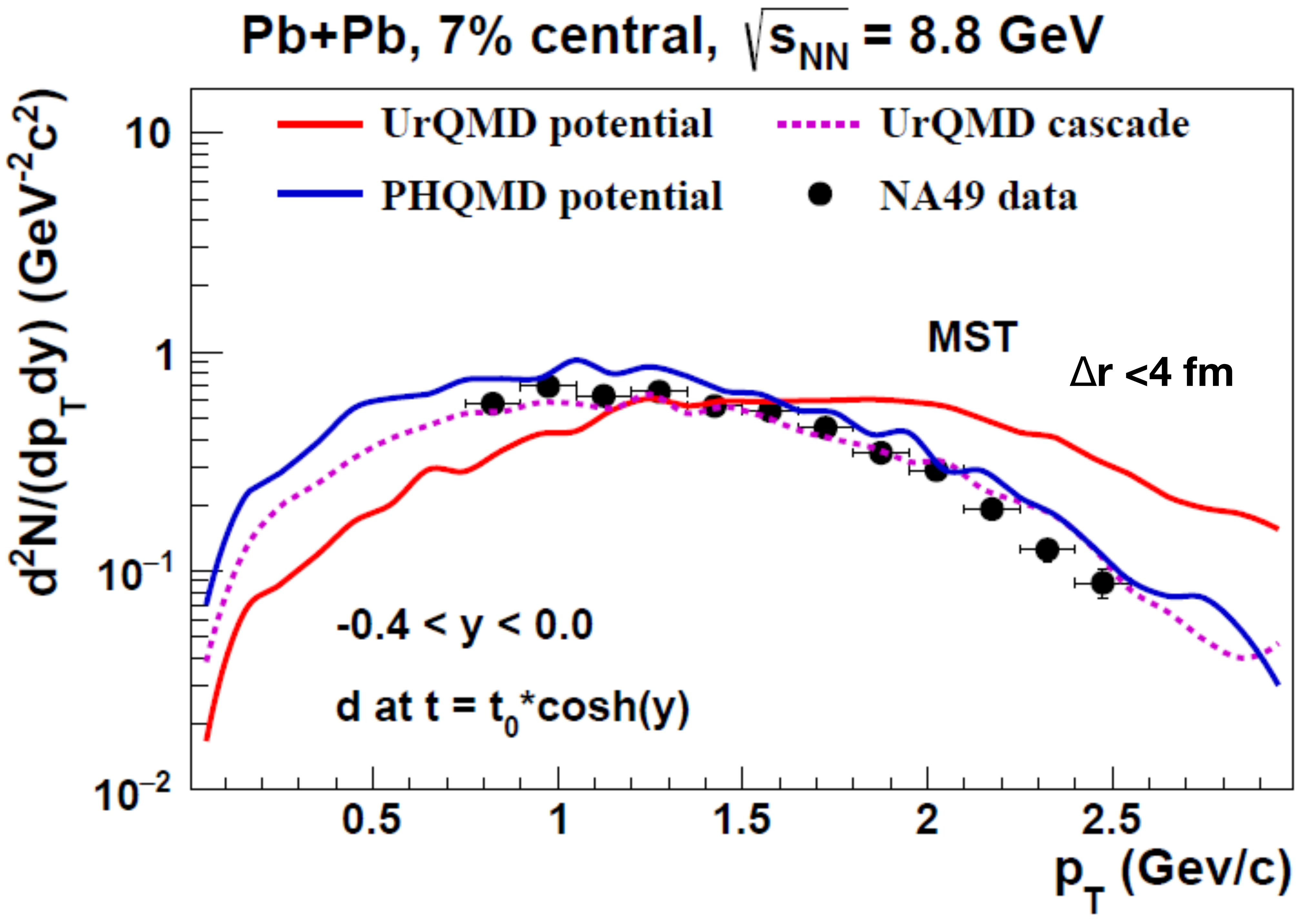


Transverse distance profile of free nucleons and clusters are different!
Clusters are mainly formed **behind the 'front' of free nucleons** of expanding fireball
'ice' is behind the 'fire' —> cluster can survive

S. Gläßel et al., PRC 105 (2022) 1

Where clusters are formed?

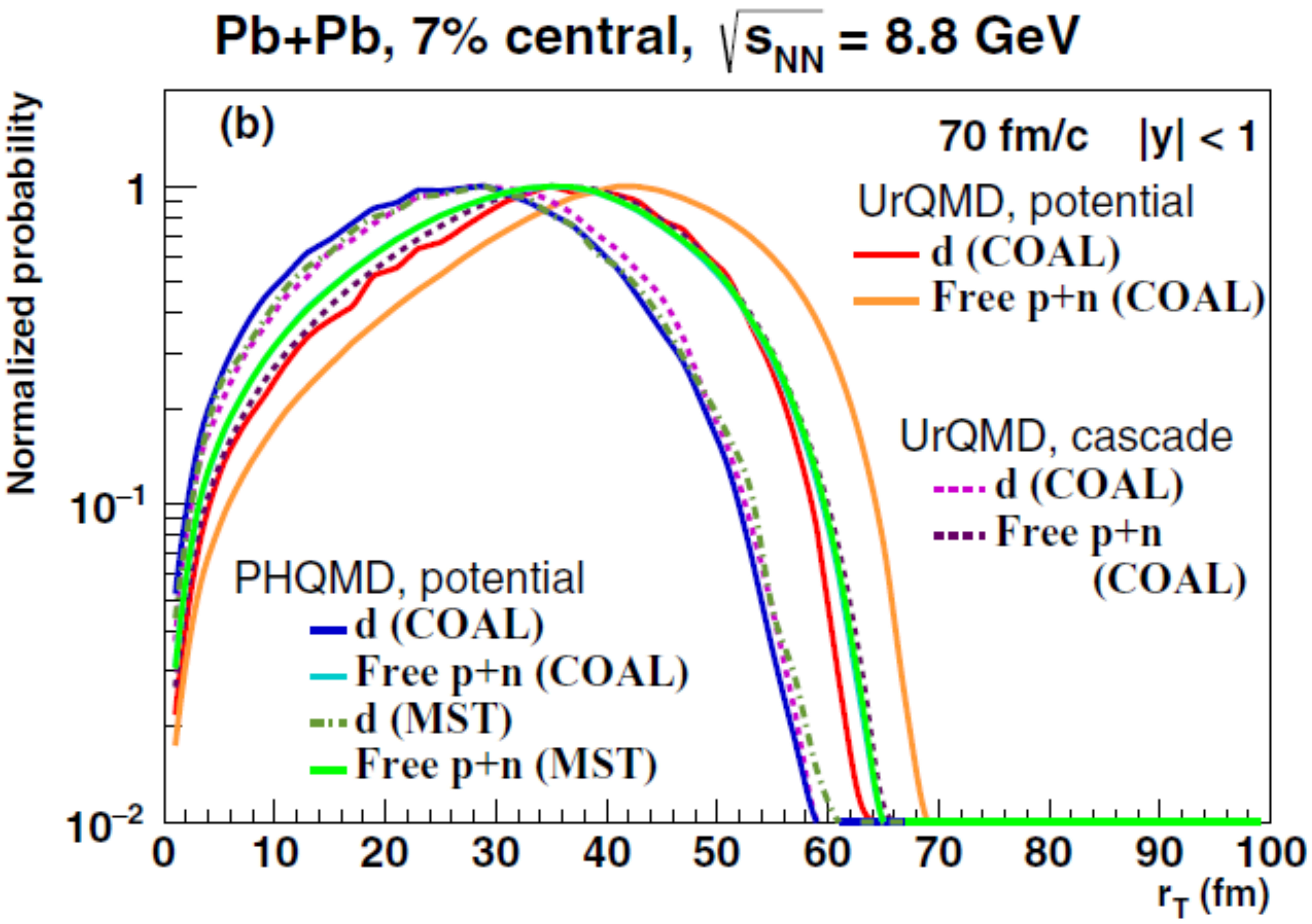




- Coalescence and MST give very similar multiplicities and y- and pT –distributions
- PHQMD and UrQMD results in the cascade mode are very similar
- Deuteron production is sensitive to the realization of potential in transport approaches

V. Kireyeu et al., PRC 105 (2022) 044909

Where clusters are formed?



Coalescence as well as the MST procedure show that the **deuterons remain in transverse direction closer to the center** of the heavy-ion collision than free nucleons

deuterons are behind the fast nucleons (and pion wind)

V. Kireyeu et al., PRC 105 (2022) 044909

Kinetic mechanism for cluster production

Kinetic mechanism for deuteron formation

Gabriele Coci et al., in preparation

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

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

$$\pi^{+} + n + n \leftrightarrow \pi^{0} + d$$

$$\pi^{0} + p + p \leftrightarrow \pi^{+} + d$$

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

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

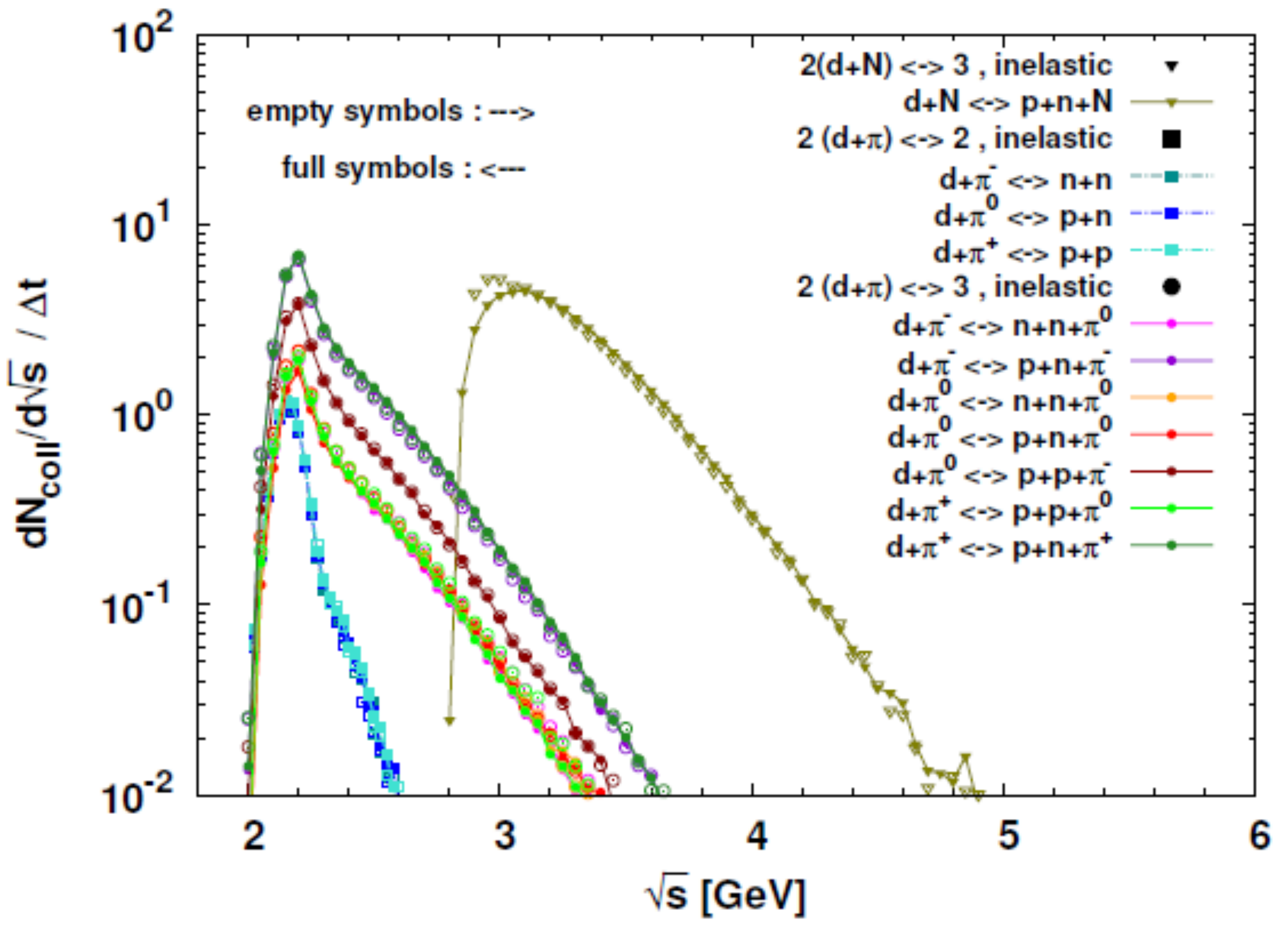
$$P_{3,2}(\sqrt{s}) = F_{spin} F_{iso} P_{2,3}(\sqrt{s}) \frac{E_1^f E_2^f}{2E_3 E_4 E_5} \frac{R_2(\sqrt{s}, m_1, m_2)}{R_3(\sqrt{s}, m_3, m_4, m_5)} \frac{1}{\Delta V_{cell}}$$

NNπ expanded as superposition of eigenstates of total isospin T

$$|N, N, \pi\rangle = \sum_T \sum_{T_3=-T}^{-T} \langle T, T_3 | N, N, \pi\rangle \, |T, T_3\rangle$$

Fourier coefficient of eigenstate of total isospin 1 (= T(d π)=T(π))

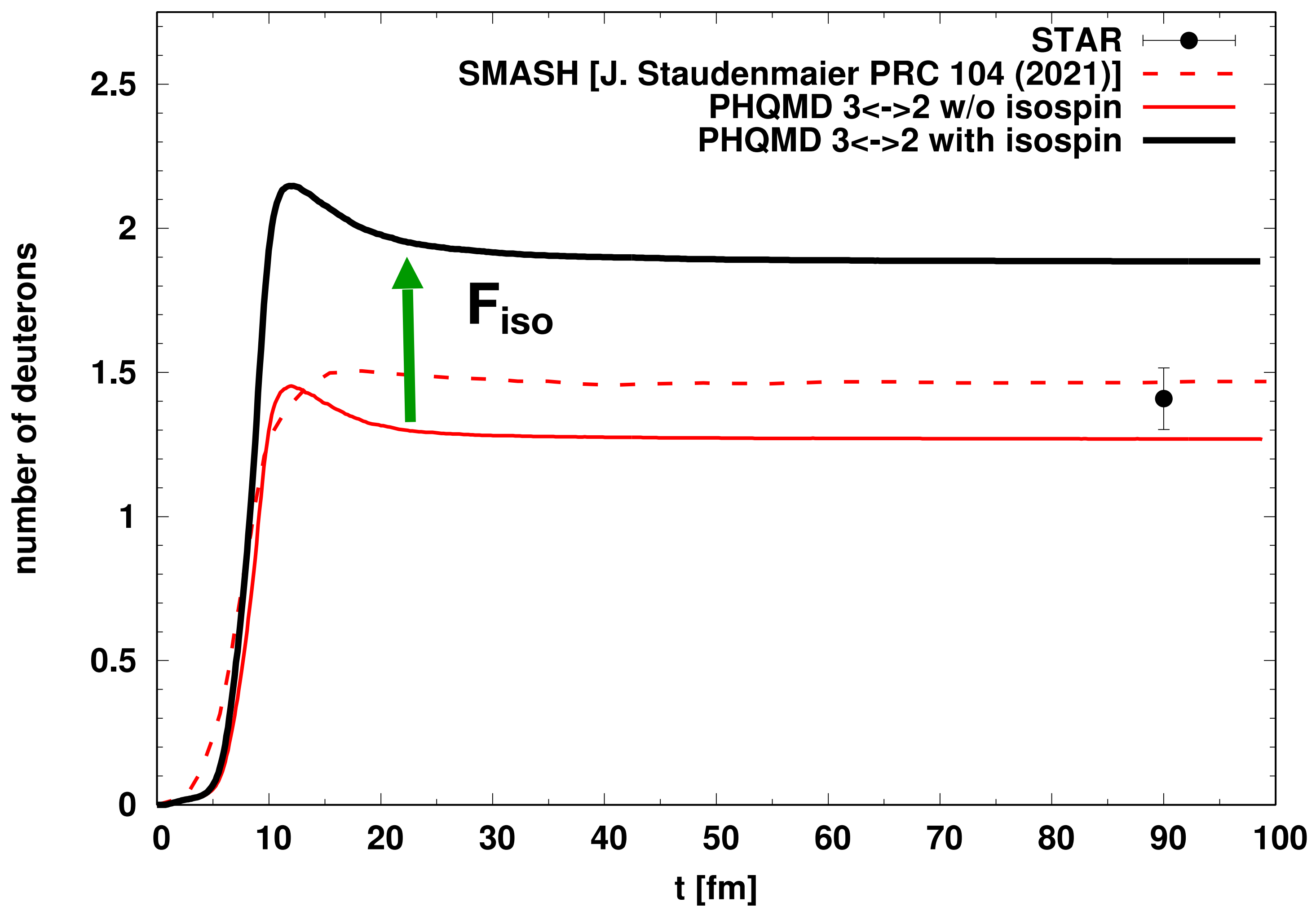
$$F_{iso} = |\langle N, N, \pi | T(d+\pi) = 1, T_3\rangle|^2$$

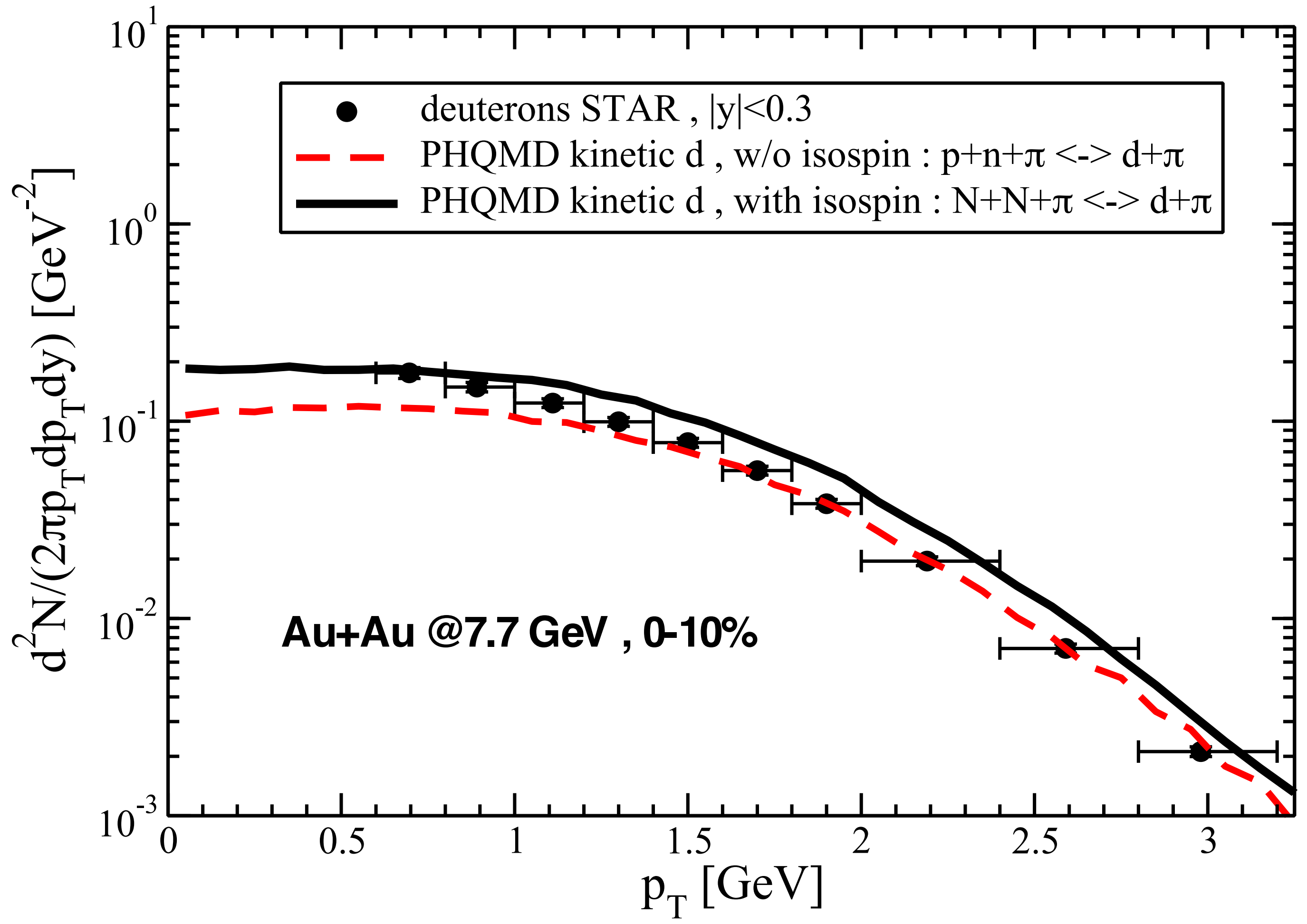


For the realistic description of HICs:
Important to account for all possible isospin channels !

Kinetic mechanism for deuteron formation

Gabriele Coci et al., in preparation



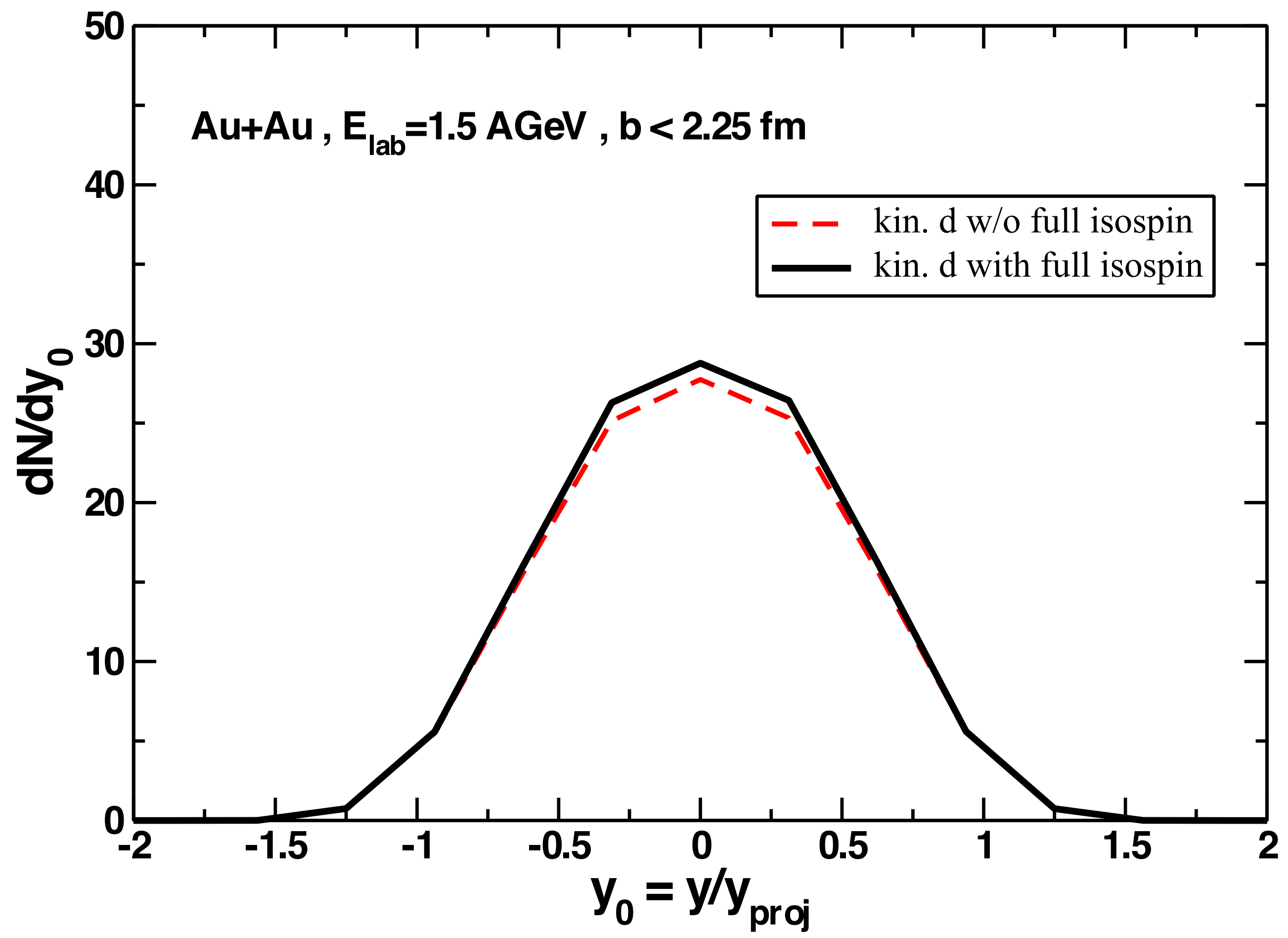


RHIC BES energy √s = 7.7 GeV:

- Hierarchy due to large π abundance
  π+N+N -> π+d >> N+p+n -> N+d
- Inclusion of all isospin channels enhances deuteron yield ~ 50%.
- p_T slope is not affected

GSI SIS energy √s < 3GeV :

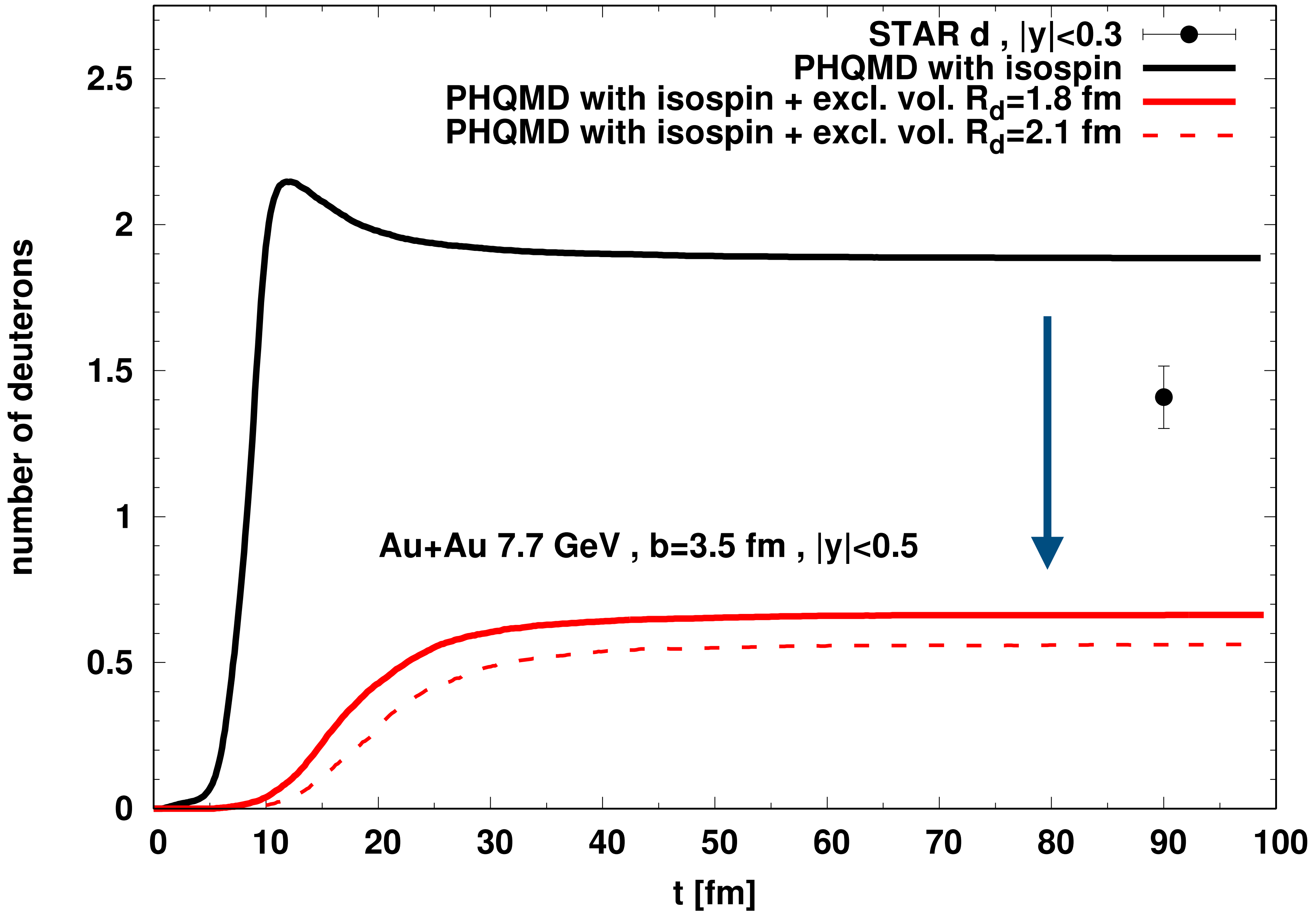
- Baryon dominated matter
- Enhancement due to inclusion of isospin π+N+N channels is negligible



Kinetic mechanism for deuteron formation

Gabriele Coci et al., in preparation

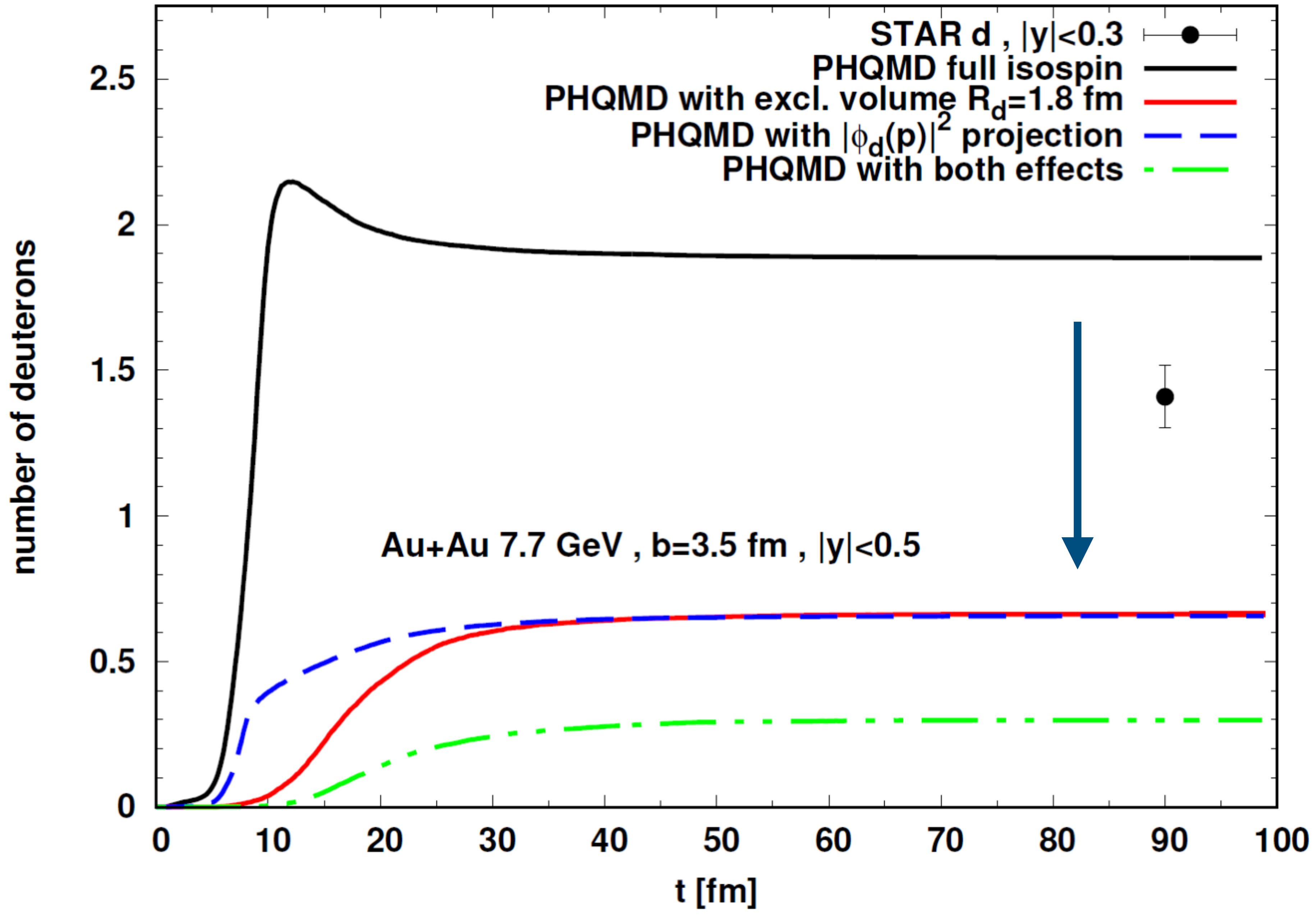
1) the finite-size of *d* in **coordinate space** (d is not a point-like particle) – for in-medium d production: assume that a deuteron can not be formed in a high density region, i.e. if there are other particles (hadrons or partons) inside the 'excluded volume' R_d ~ 1.8 fm



Strong reduction of d production!
p_T slope is not affected by excluded volume condition

2) the **momentum correlations** of *p* and *n* inside *d*: QM properties of deuteron must be also in momentum space -> **momentum correlations of pn-pair**

- For a "candidate" deuteron calculate the relative momentum p of the interacting pn-pair in the deuteron rest frame
- The probability of the pn-pair to bind into a final deuteron with momentum p is given by the projection on DWF



Strong reduction of d production by projection on DWF

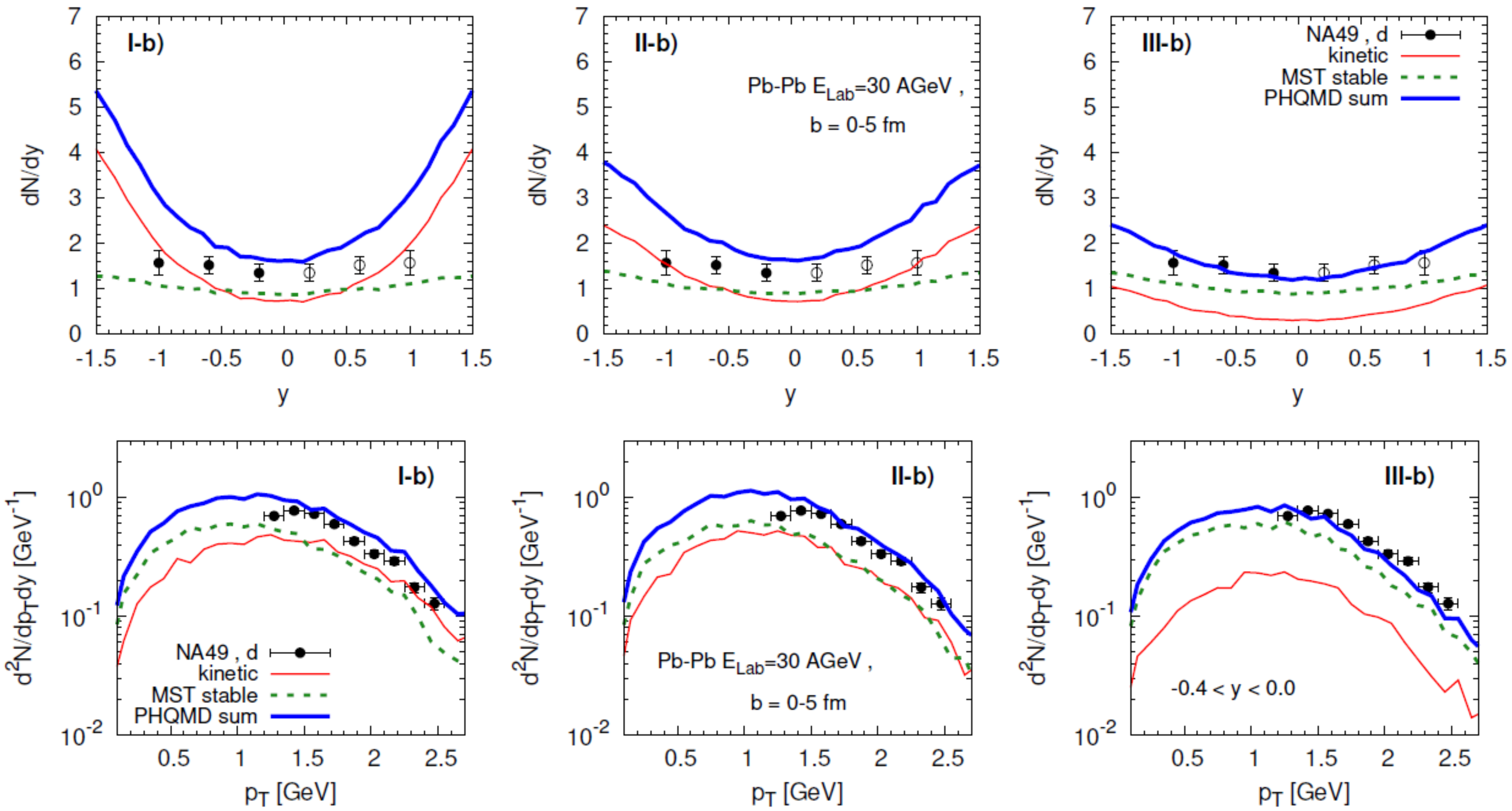
Kinetic vs potential deuteron formation

Gabriele Coci et al., in preparation

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:

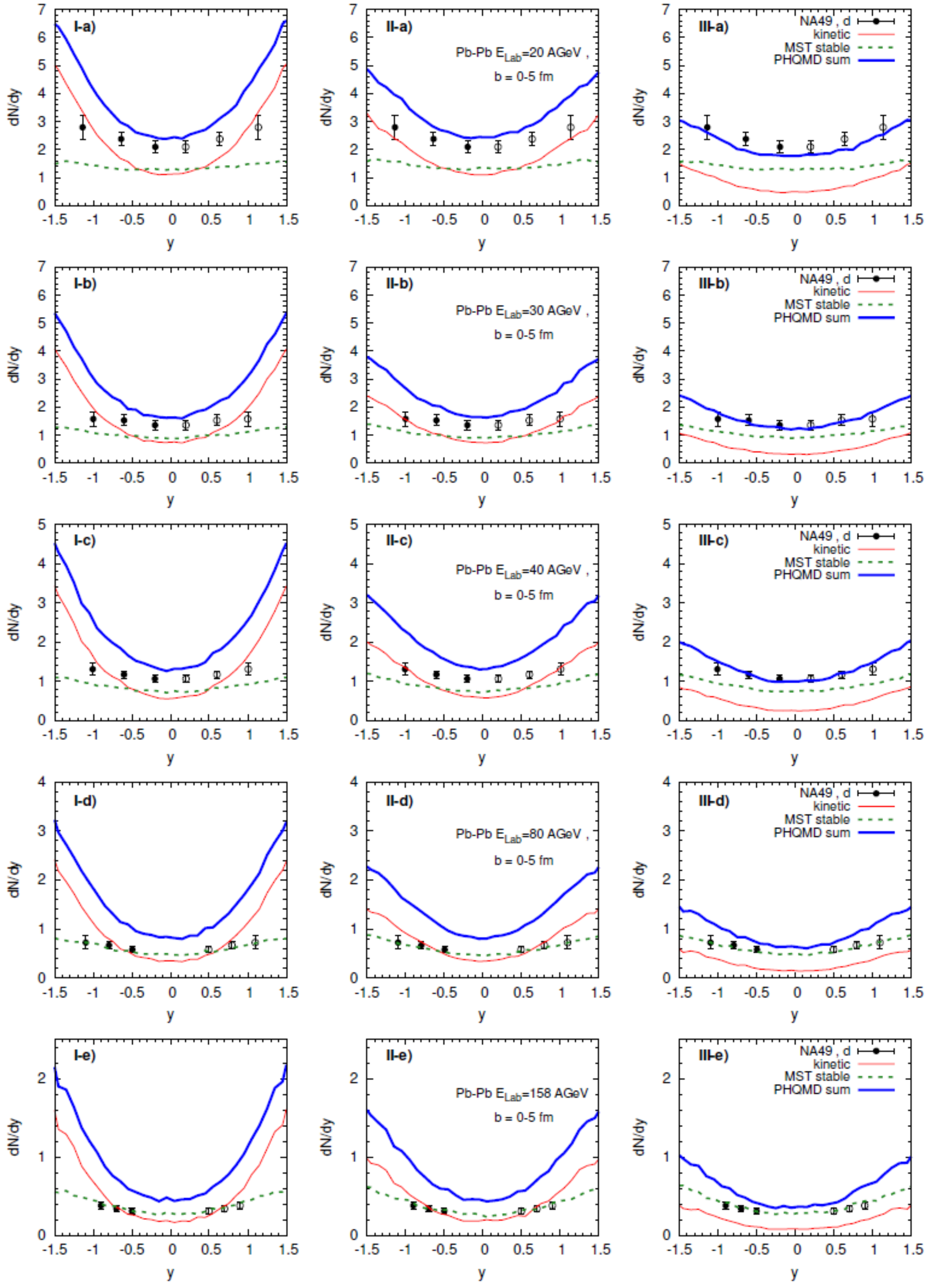
1) excluded-volume 2) Momentum projection 3) both effects

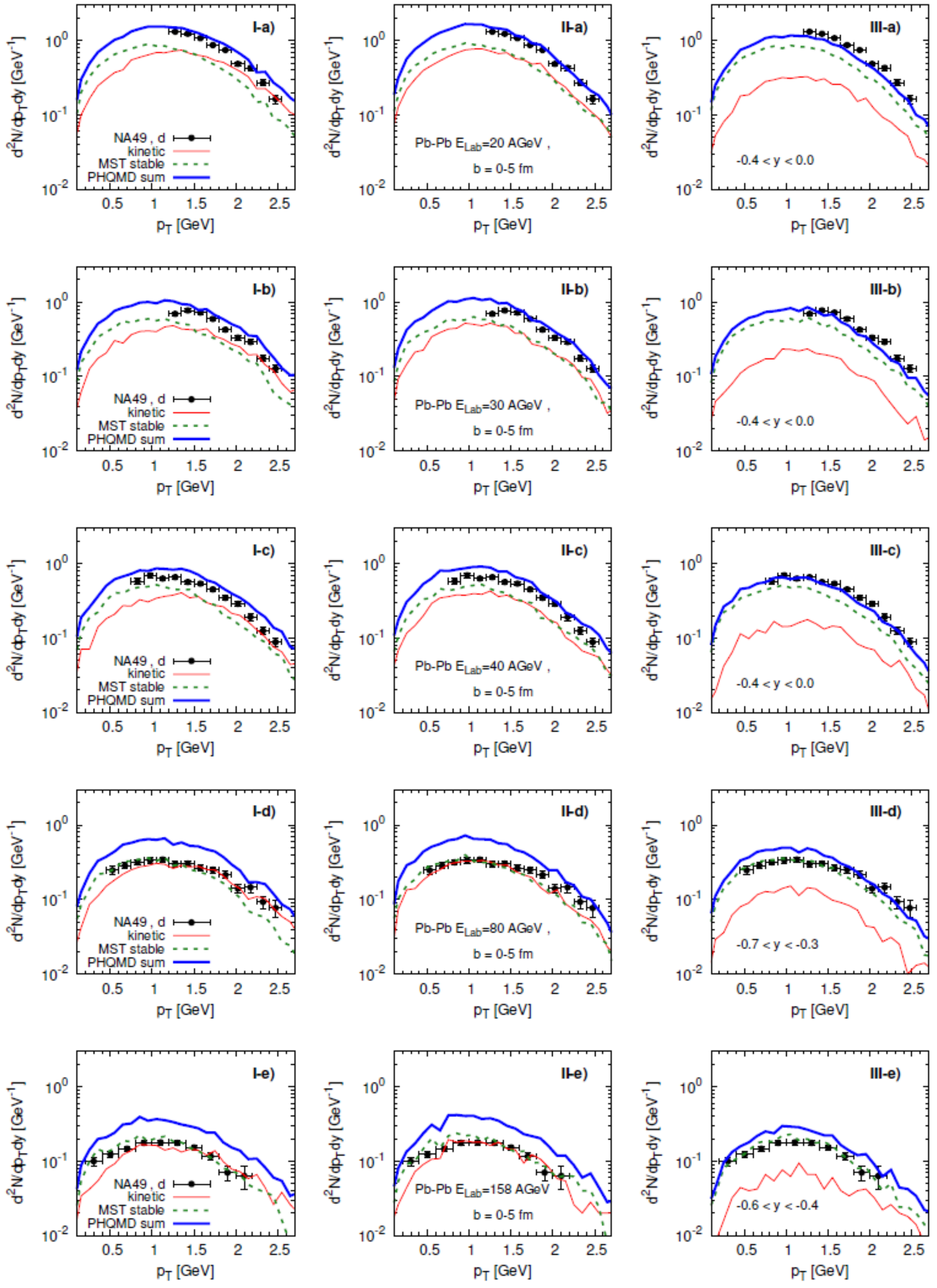


Good description of mid-rapidity NA49 data [PRC 94 (2016) 04490699]

Kinetic vs potential deuteron formation

Gabriele Coci et al., in preparation





Total deuteron production = **Kinetic mechanism with finite-size effects**
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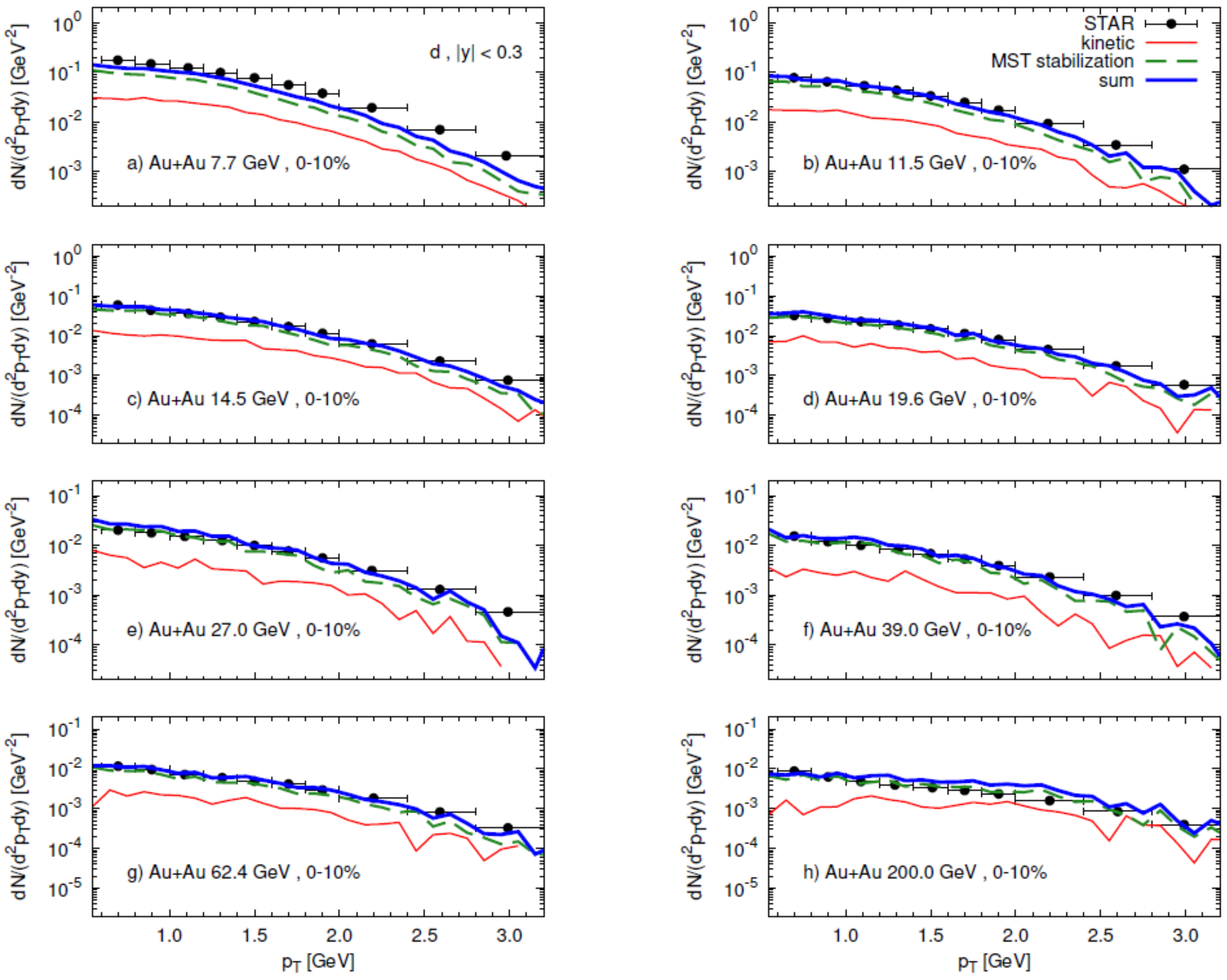
Kinetic vs potential deuteron formation

Gabriele Coci et al., in preparation

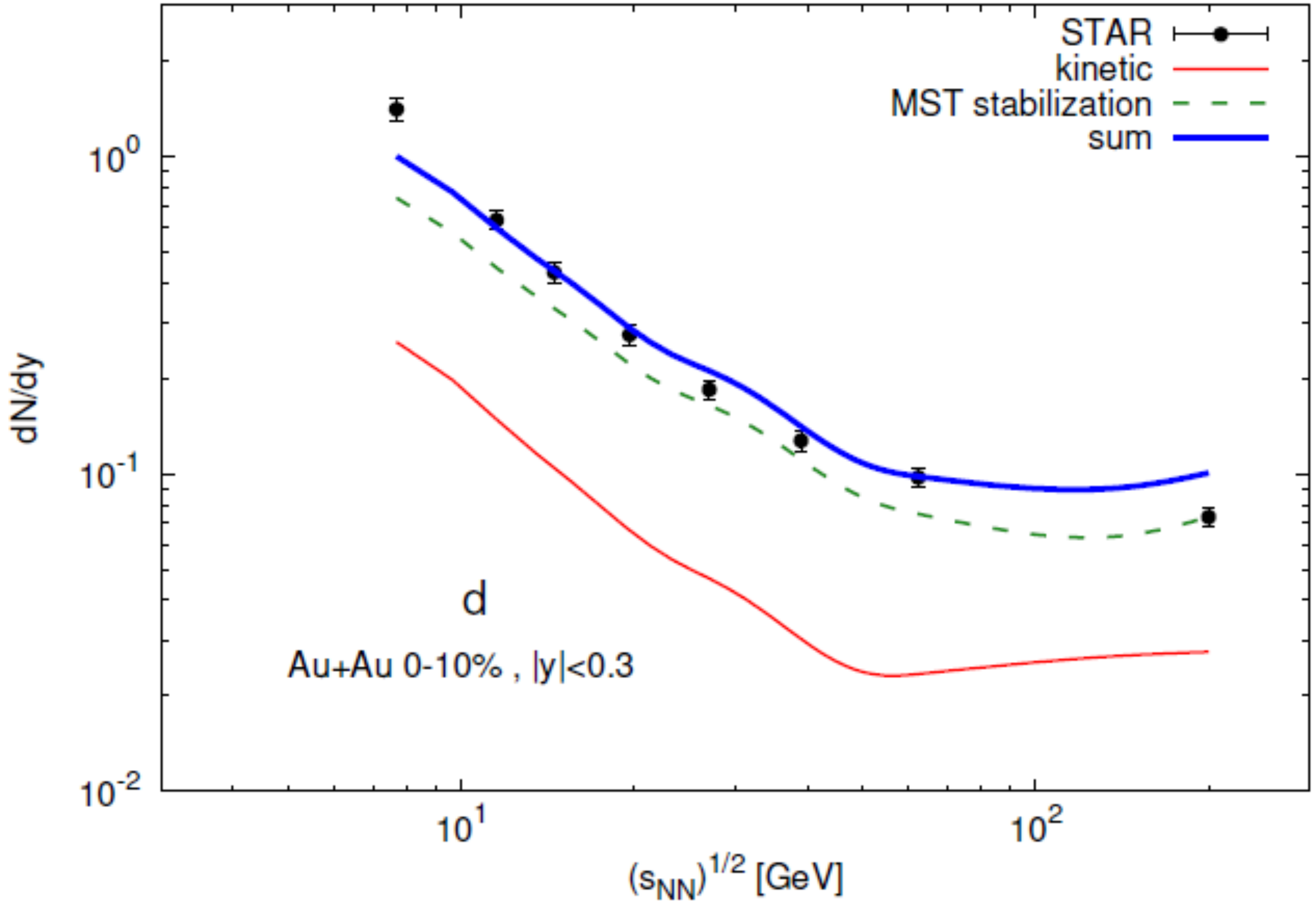


Good description of mid-rapidity STAR data [PRC 99, (2019)]

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)

Kinetic vs potential deuteron formation

Gabriele Coci et al., in preparation

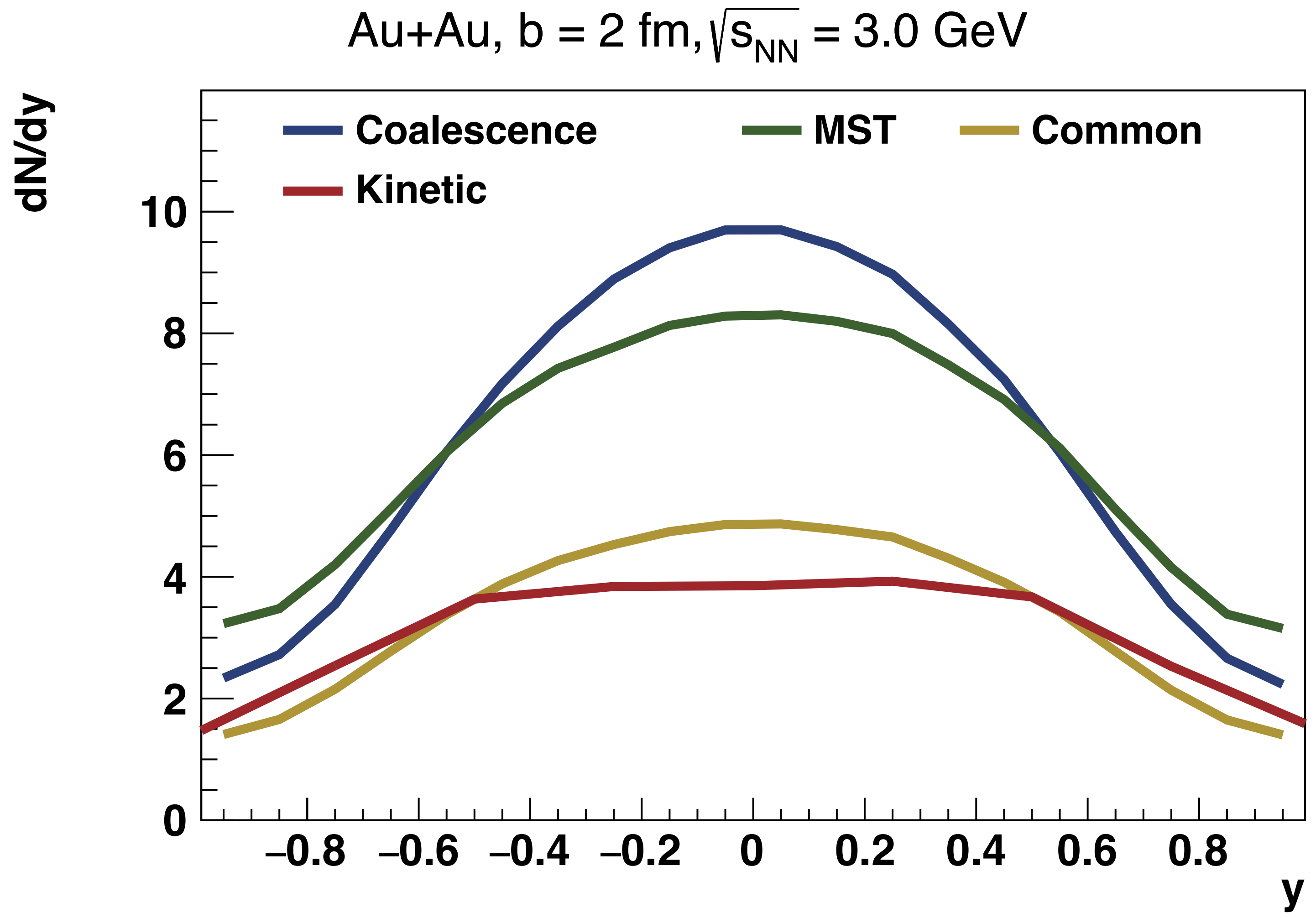


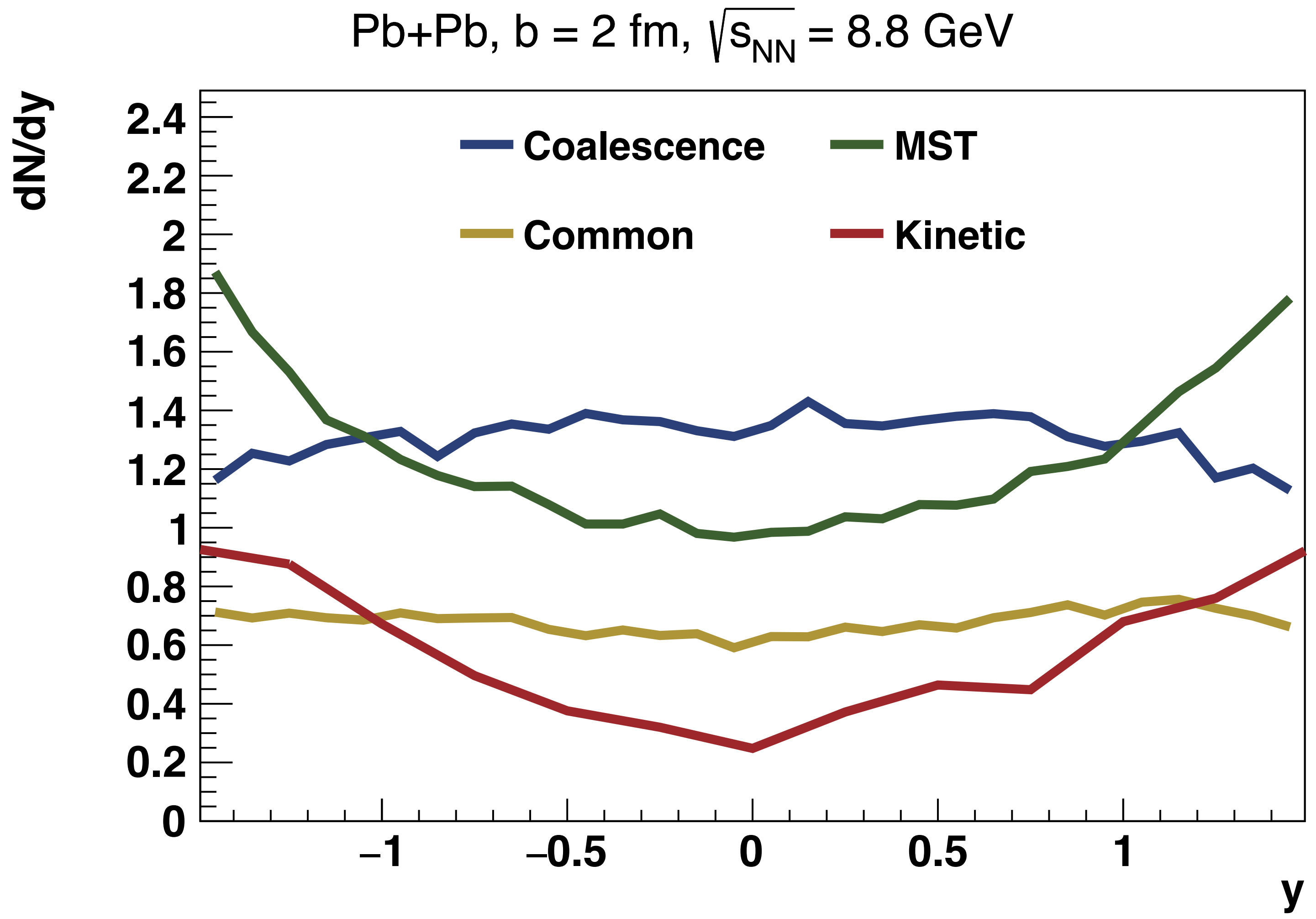
- **PHQMD provides a good description of STAR data on d yield at midrapidity**
- **The potential mechanism is dominant for d production at all energies!**

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)

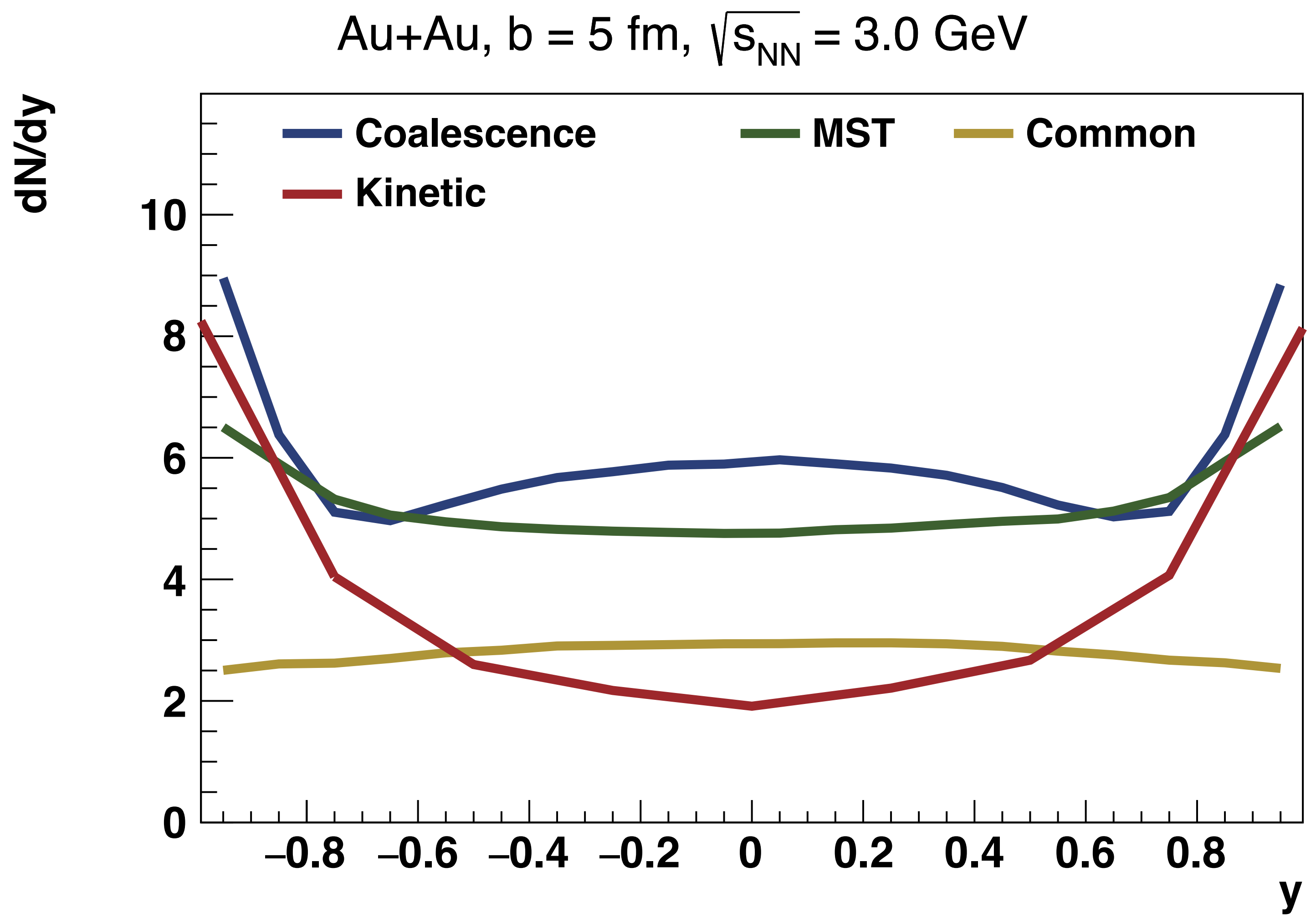
Can the deuteron formation mechanism be identified experimentally?

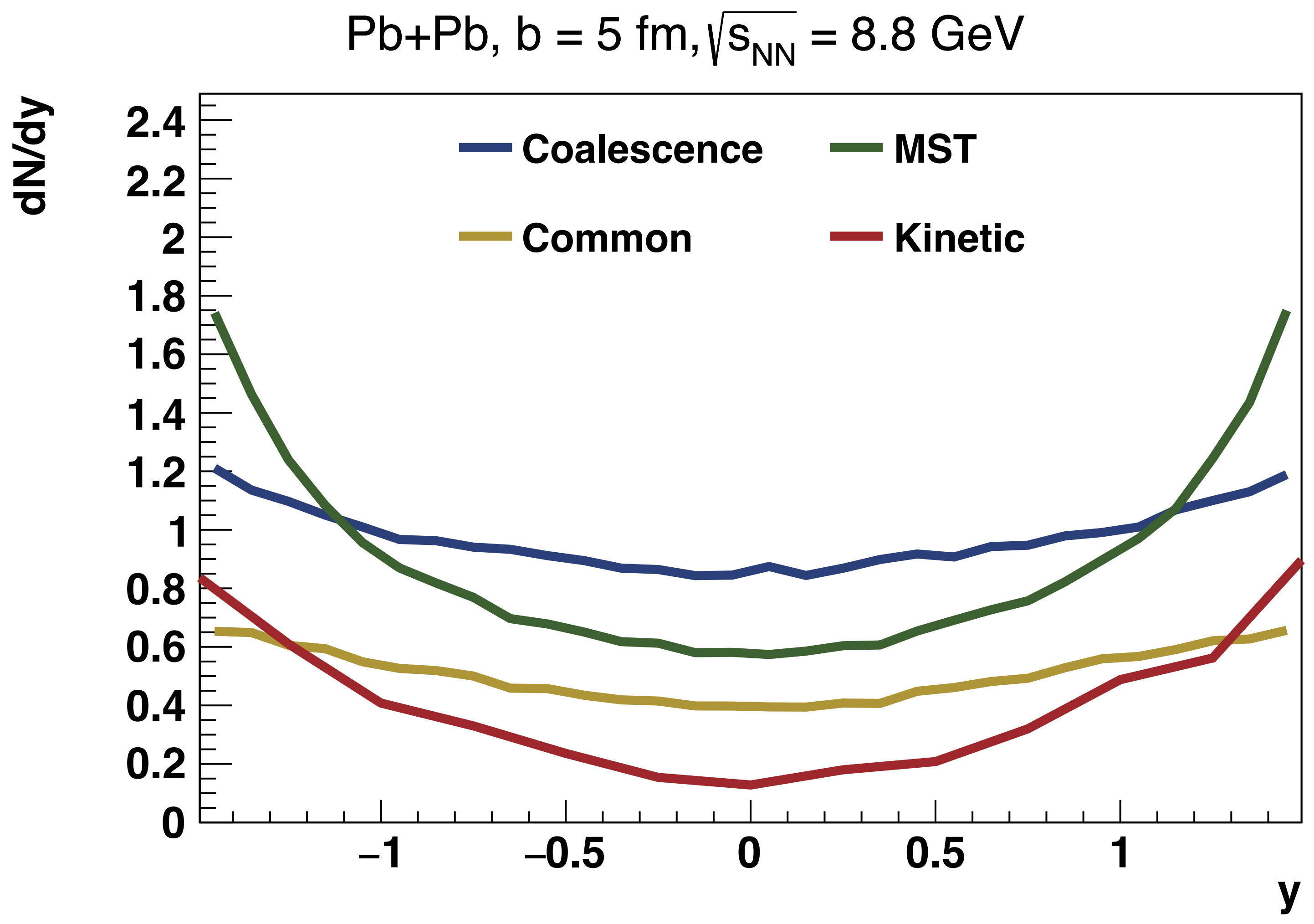
V. Kireyeu, in progress

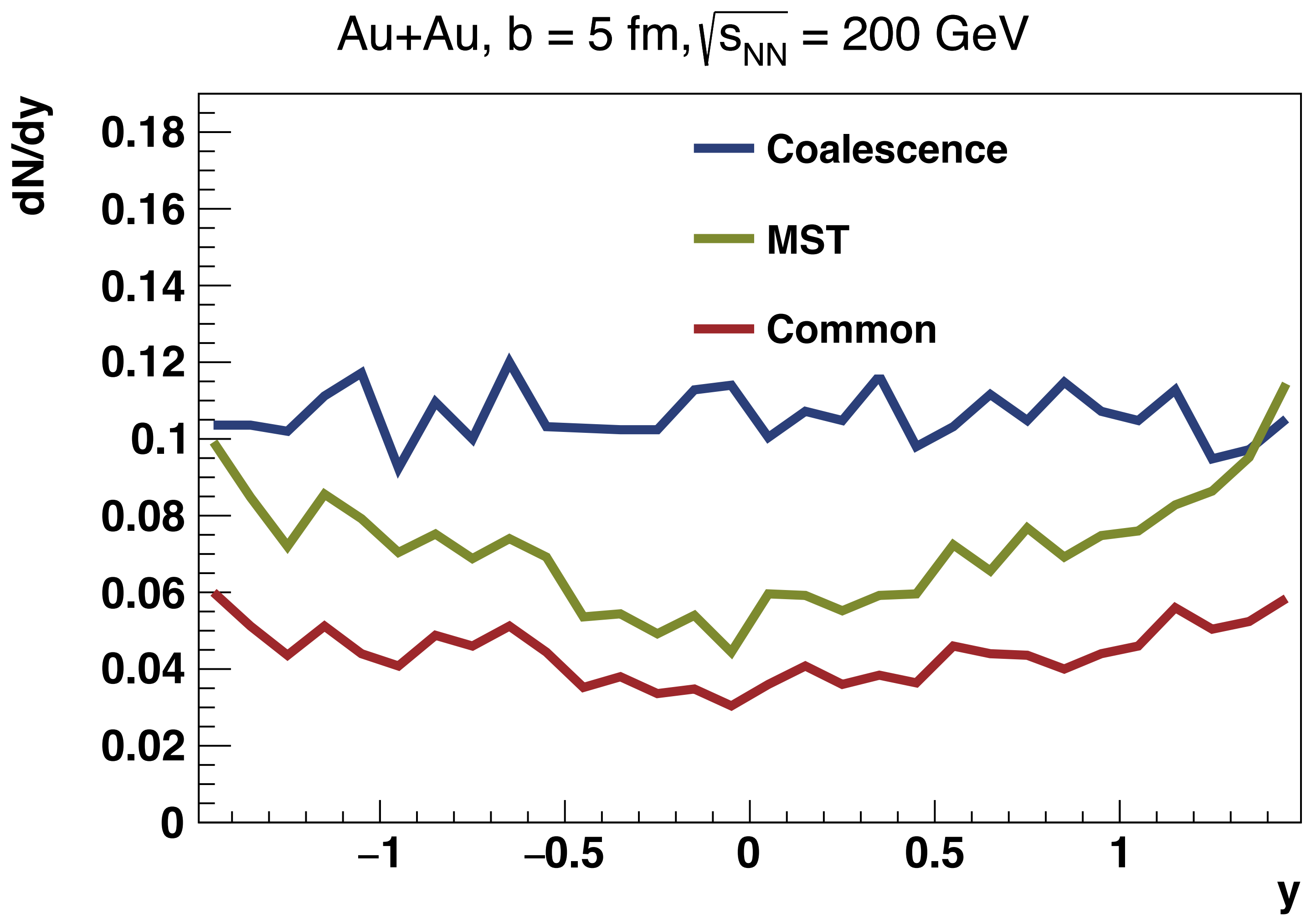




- **At mid-rapidity only ~50%** of coalescence deuterons (at freeze-out) are found by MST.
- Rapidity and pT distributions from MST and coalescence have a **different shape —> distinguishable in experiments!**







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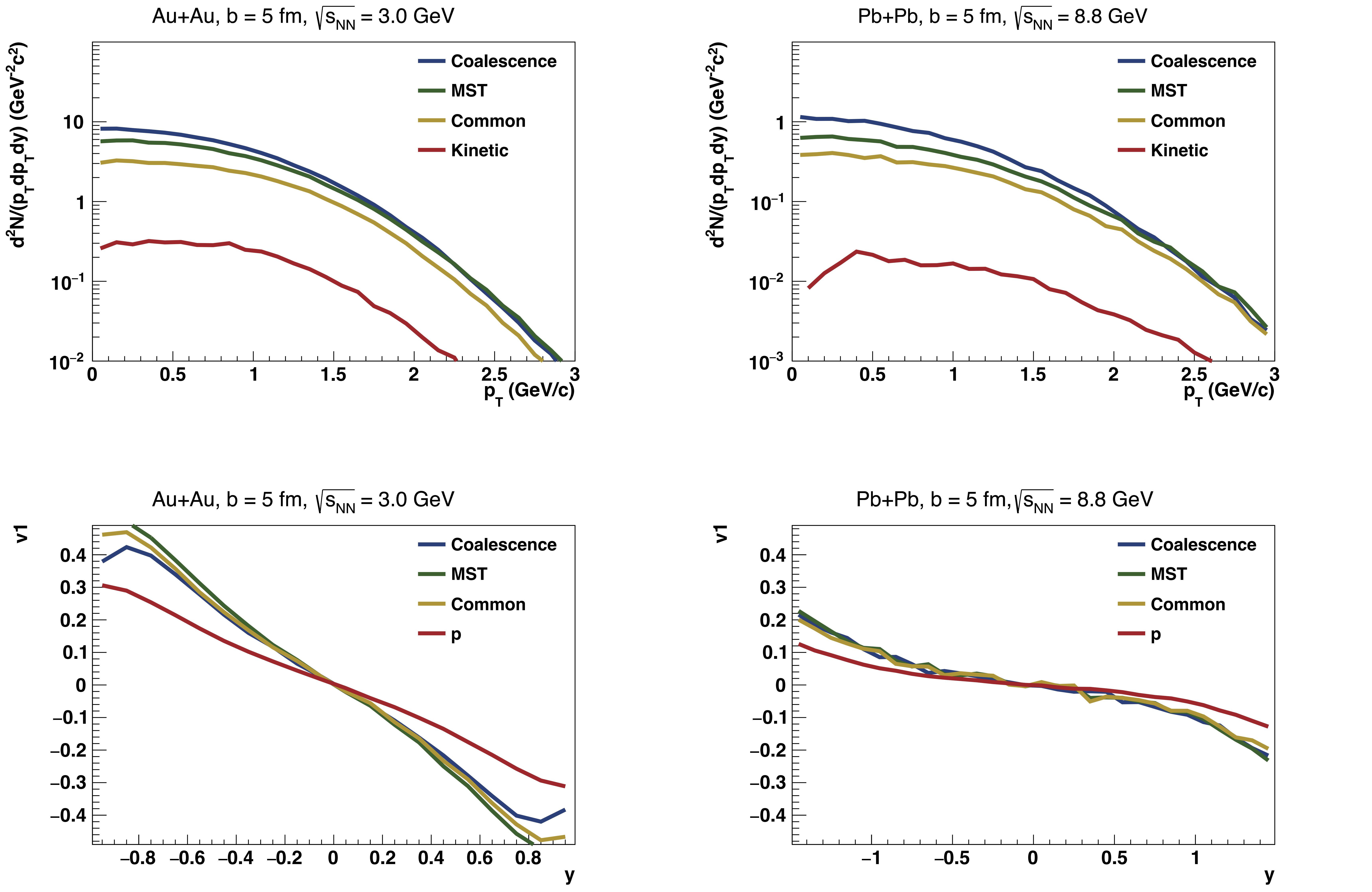

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Summary

- **The PHQMD** is a microscopic n-body transport approach for the description of heavy-ion dynamics and cluster and hypernuclei formation
- Clusters are formed **dynamically by potential interactions** among nucleons and hyperons and identified by Minimum Spanning Tree model
- **Kinetic mechanism** for deuteron production is implemented in the PHQMD with inclusion of **full isospin** decomposition for hadronic reactions which enhances d production
- However, **accounting for the quantum properties** of the deuteron, modelled by the finite-size excluded volume effect in coordinate space and projection of relative momentum of the interacting pair of nucleons on the deuteron wave-function in momentum space, leads to a **strong reduction of d** production, especially at target/projectile rapidities
- The PHQMD reproduces cluster and hypernuclei data on dN/dy and dN/dp_T as well as ratios d/p and $\bar{d}/\bar{p}$ for heavy-ion collisions from AGS to top RHIC energies
- A detailed analysis reveals that **stable clusters are formed**:
    - shortly after elastic and inelastic collisions have ceased
    - behind the front of the expanding energetic hadrons
    - **since the 'fire' is not at the same place as the 'ice', cluster can survive**
- PHQMD and UrQMD give very **similar coalescence and MST distributions of deuterons**
- Shape of y-and p_T- distributions depends on a **production mechanism ➔ possibility to distinguish between production mechanisms experimentally!**

Thank you for your attention!

Thanks to the Organisers!

https://phqmd.gitlab.io/