Dynamical cluster and hypernuclei production in heavy-ion collisions

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PHQMD

The 37th edition of the Winter Workshop on Nuclear Dynamics
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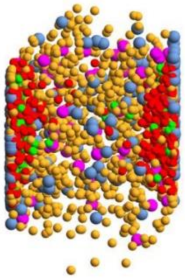
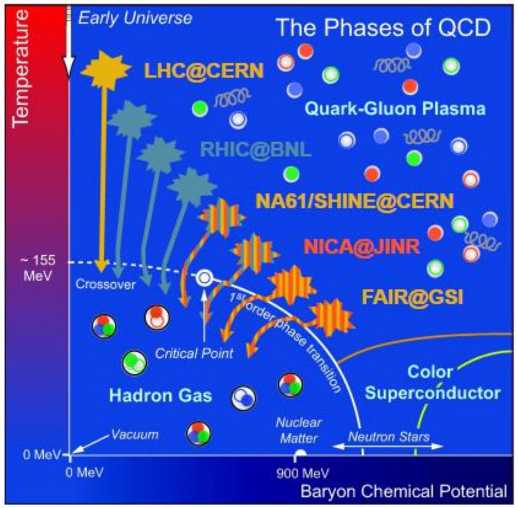


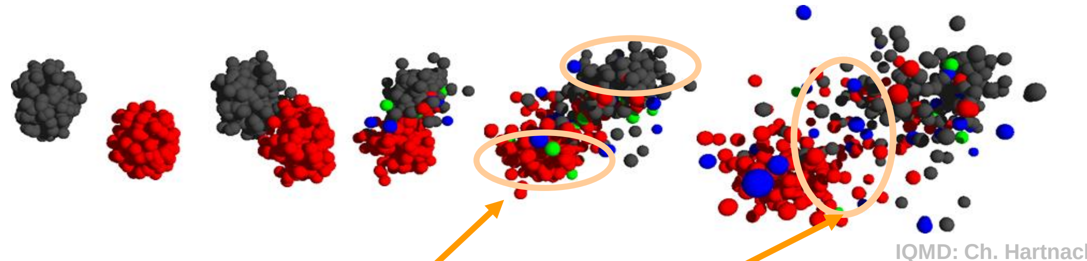
The ‚holy grail‘ of heavy-ion physics:

The phase diagram of QCD



Experimental observables:

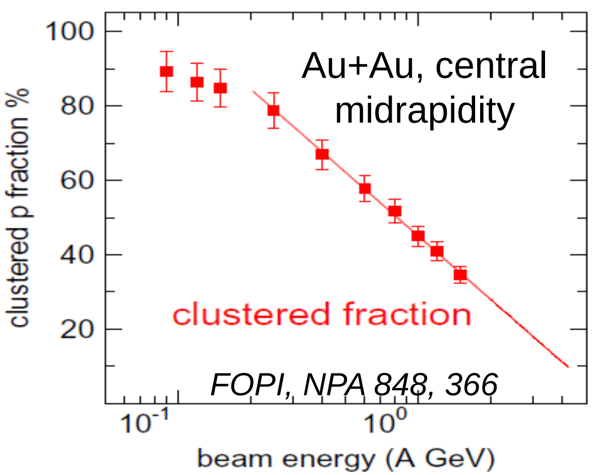
... Clusters and (anti-) hypernuclei



- projectile/target spectators➔ heavy cluster formation
- midrapidity➔ light clusters

! Hyperons are created in participant zone

- Clusters are very abundant at low energy

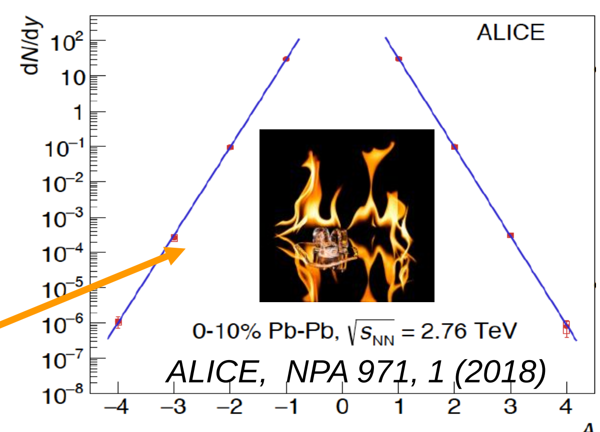


(Anti-) hypernuclei production:

- at mid-rapidity by coalescence of Λ with nucleons during expansion
- at projectile/target rapidity by rescattering/absorption of Λ by spectators

High energy HIC:

‚Ice in a fire‘ puzzle: how the weakly bound objects can be formed and survive in a hot enviroment ?!



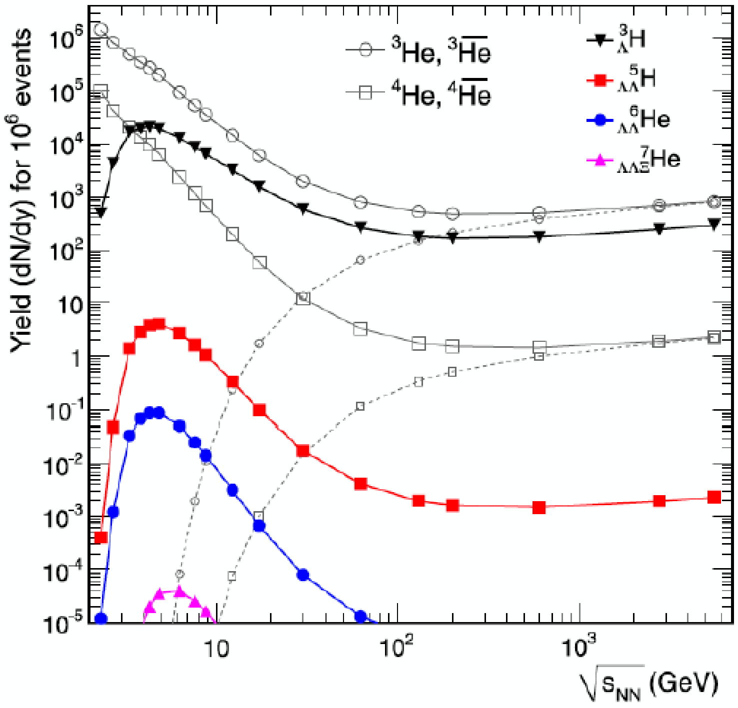
Modeling of cluster and hypernuclei formation

Existing models for clusters formation:

- **statistical model:**
  - **assumption of thermal equilibrium**
- **coalescence model:**
  - **determination of clusters at a given time by coalescence radii in coordinate and momentum space**

➔ **don't provide information on the dynamical origin of clusters formation**

A. Andronic et al., PLB 697, 203 (2011)



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 modeling of cluster formation based on interactions**

Cluster formation: QMD vs MF

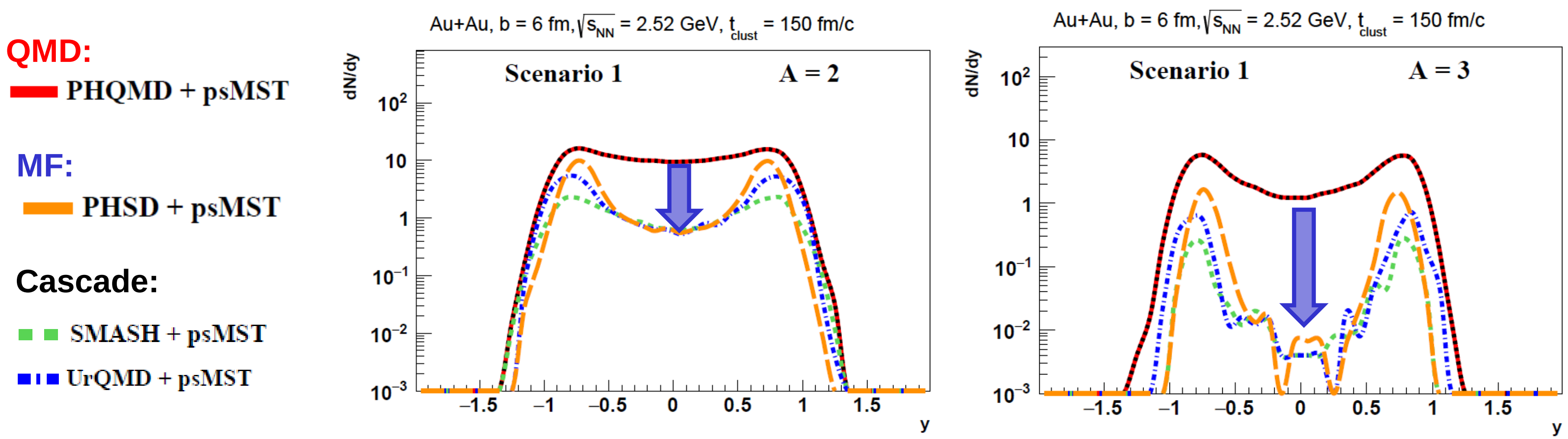
- Cluster formation is sensitive to nucleon dynamics

➔ One needs to keep the nucleon correlations (initial and final) by realistic nucleon-nucleon interactions in transport models:

- QMD (quantum-molecular dynamics) – allows to keep correlations
- MF (mean-field based models) – correlations are smeared out
- Cascade – no correlations by potential interactions

Example: Cluster stability over time:

V. Kireyeu, Phys.Rev.C 103 (2021) 5



PHQMD

PHQMD: a **unified n-body microscopic transport approach** for the description of heavy-ion collisions and **dynamical cluster formation** from low to ultra-relativistic energies

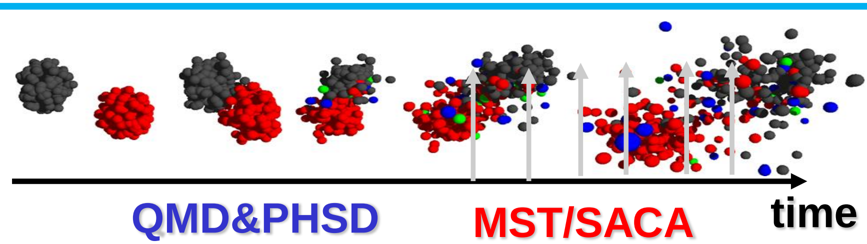
Realization: combined model **PHQMD = (PHSD & QMD) & (MST/SACA)**

Parton-Hadron-Quantum-Molecular Dynamics

Initialization → propagation of baryons:
QMD (Quantum-Molecular Dynamics)

Propagation of partons (quarks, gluons) and mesons
+ collision integral = interactions of hadrons and partons (QGP)
from PHSD (Parton-Hadron-String Dynamics)

Cluster recognition:
SACA (Simulated Annealing Clusterization Algorithm)
or MST (Minimum Spanning Tree)



J. Aichelin et al., PRC 101 (2020) 044905;
S. Gläßel et al., PRC 105 (2022) 1

QMD propagation

- **Generalized Ritz variational principle**: $\delta \int_{t_1}^{t_2} dt < \psi(t)|i\frac{d}{dt} - H|\psi(t) >= 0.$

Assume that $\psi_N = \prod_{i=1}^{N} \psi_i(q_i, q_{0i}, p_{0i})$ **for N particles (neglecting antisymmetrization !)**

Ansatz: trial wave function for one particle "*i*" :
Gaussian with width *L* centered at r_{i0}, p_{i0}

L=4.33 fm^2

$$\psi_i(q_i, q_{0i}, p_{0i}) = Cexp[-(q_i - q_{0i} - \frac{p_{0i}}{m}t)^2/4L] \cdot exp[ip_{0i}(q_i - q_{0i}) - i\frac{p_{oi}^2}{2m}t]$$

- **Equations-of-motion (EoM) for Gaussian centers in coordinate and momentum space:**

$$\dot{r}_{i0} = \frac{\partial \langle H \rangle}{\partial p_{i0}} \qquad \dot{p}_{i0} = -\frac{\partial \langle H \rangle}{\partial r_{i0}}$$

Hamiltonian: $H = \sum_i H_i = \sum_i (T_i + V_i) = \sum_i (T_i + \sum_{j \neq i} V_{i,j})$

$$V_{i,j} = V(\mathbf{r_i}, \mathbf{r_j}, \mathbf{r_{i0}}, \mathbf{r_{j0}}, t) = V_{\text{Skyrme}} + V_{\text{Coul}}$$

QMD interaction potential and EoS

The expectation value of the Hamiltonian:

$$\langle H \rangle = \langle T \rangle + \langle V \rangle = \sum_i \left(\sqrt{p_{i0}^2 + m^2} - m\right) + \sum_i \langle V_{Skyrme}(\mathbf{r}_{i0}, t) \rangle$$

- **Skyrme potential** **('static') * :**

$$\langle V_{Skyrme}(\mathbf{r}_{i0}, t) \rangle = \alpha \left(\frac{\rho_{int}(\mathbf{r}_{i0}, t)}{\rho_0} \right) + \beta \left(\frac{\rho_{int}(\mathbf{r}_{i0}, t)}{\rho_0} \right)^{\gamma}$$

	α (MeV)	β (MeV)	γ	K [MeV]
S	-390	320	1.14	200
H	-130	59	2.09	380

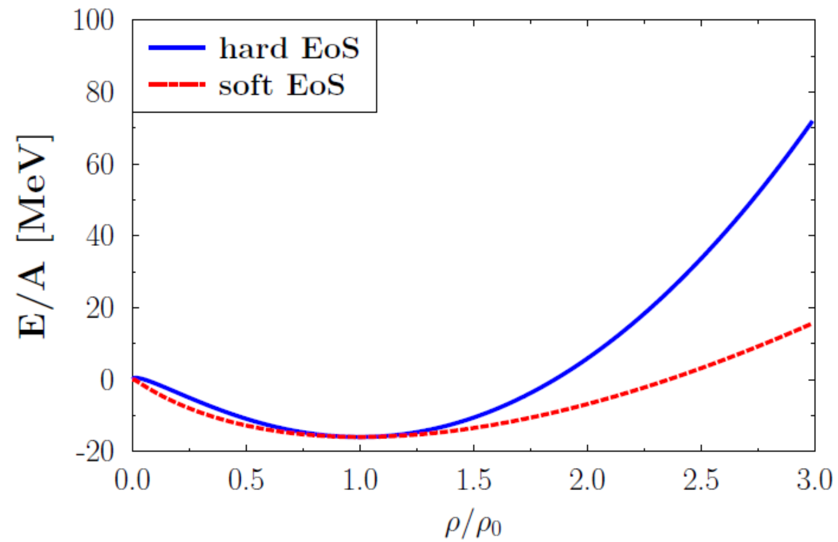
- **modifed interaction density (with relativistic extension):**

$$\rho_{int}(\mathbf{r}_{i0}, t) \rightarrow C \sum_j \left(\frac{4}{\pi L}\right)^{3/2} e^{-\frac{4}{L}(\mathbf{r}_{i0}^{T}(t) - \mathbf{r}_{j0}^{T}(t))^2} \times e^{-\frac{4\gamma_{cm}^2}{L}(\mathbf{r}_{i0}^{L}(t) - \mathbf{r}_{j0}^{L}(t))^2},$$

- **HIC ←→ EoS for infinite matter at rest**
- **compression modulus K of nuclear matter:**

$$K = -V \frac{dP}{dV} = 9\rho^2 \frac{\partial^2 (E/A(\rho))}{(\partial \rho)^2}\Big|_{\rho=\rho_0}.$$

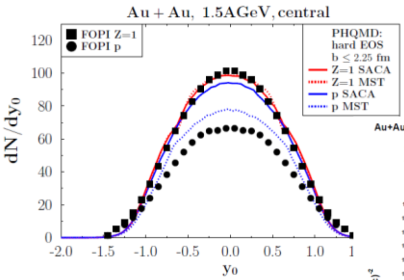
EoS for infinite matter at rest

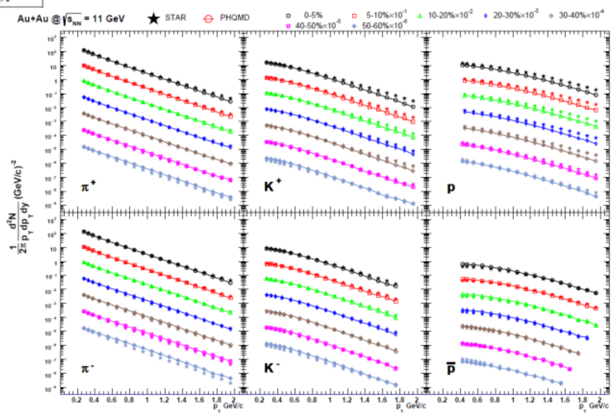


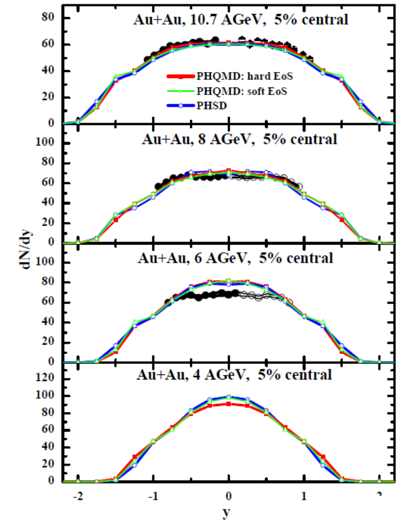
*Work in progress: implementation of momentum dependent potential (M. Winn)

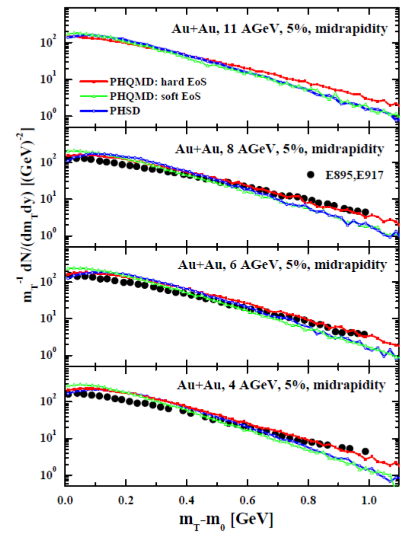
Highlights: PHQMD ‚bulk‘ dynamics from SIS to RHIC

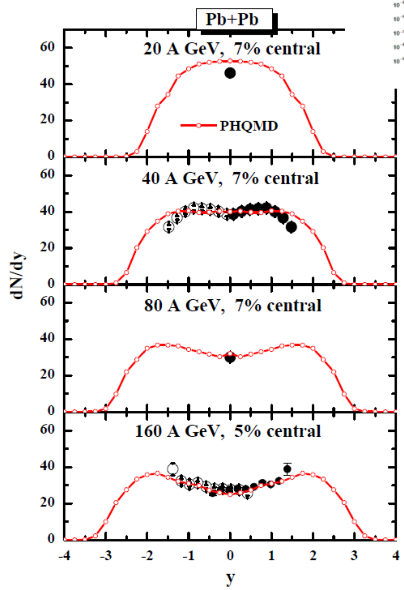
PHQMD: J. Aichelin et al., PRC 101 (2020) 044905

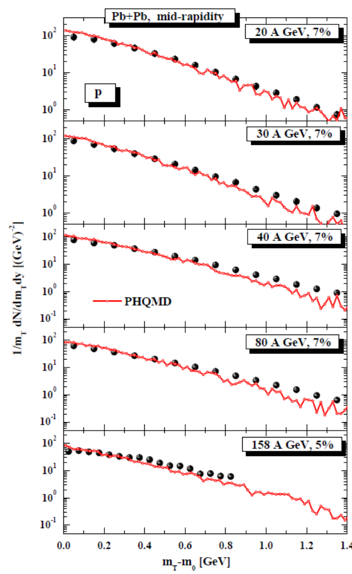


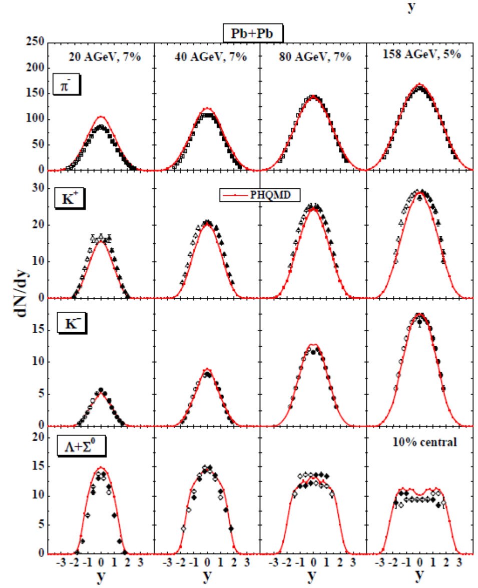


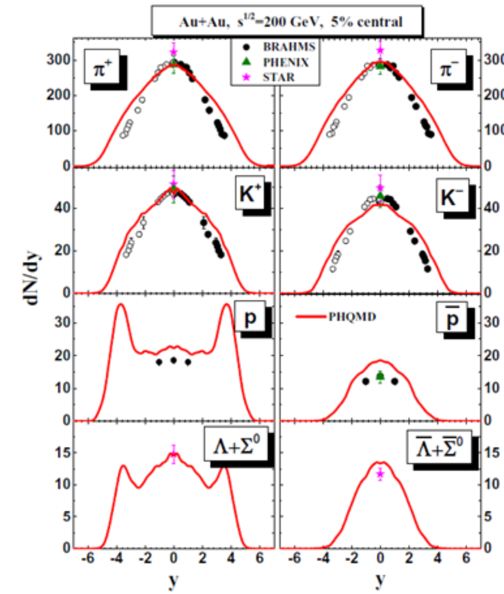












PHQMD provides a good description of hadronic 'bulk' observables from SIS to RHIC energies

Cluster recognition: Minimum Spanning Tree (MST)

R. K. Puri, J. Aichelin, J.Comp. Phys. 162 (2000) 245-266

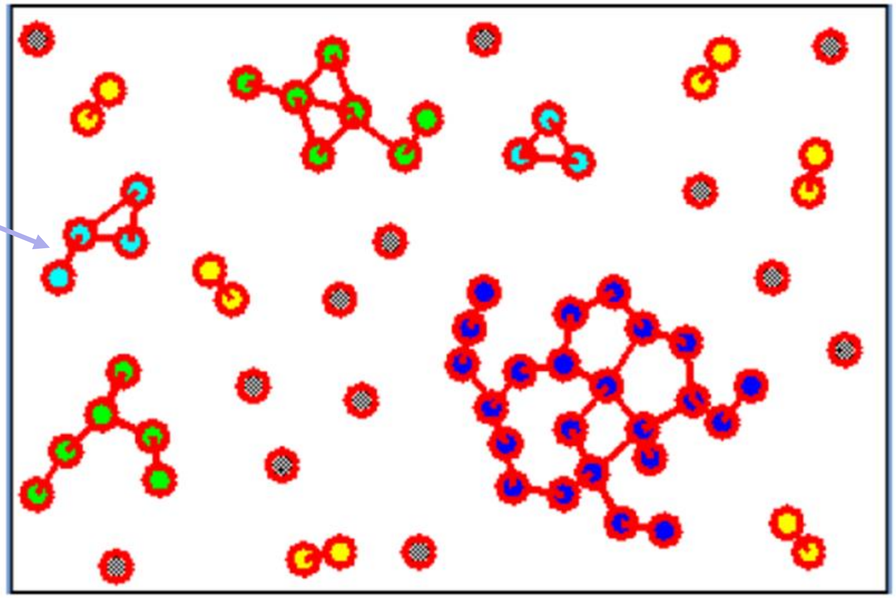
The Minimum Spanning Tree (MST) is a cluster recognition method applicable for the (asymptotic) final states where coordinate space correlations may only survive for bound states.

The MST algorithm searches for accumulations of particles in coordinate space:

1. Two particles are 'bound' if their distance in the cluster rest frame fulfills

$$|\vec{r_i} - \vec{r_j}| \leq 4 \text{ fm}$$

2. Particle is bound to a cluster if it bounds with at least one particle of the cluster.



* Remark:
inclusion of an additional momentum cuts (coalescence) 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)

Cluster stability in semi-classical models

Limitation of semi-classical models (as QMD):

- Clusters in QMD are semiclassical bound objects (with a binding energy close to the Weizsäcker mass formula) but not quantum system with a defined ground state

- In bound QMD clusters kinetic energy can be therefore accumulated by one of the nucleons which may escape (what is not possible in a quantum cluster)

→ We have therefore to fix a time at which we analyse the clusters. This choice influences the multiplicity. We verified that it does not influence the form of
- the rapidity distribution
- the p_T distribution
- ratio of particles

⇨ To compare the PHQMD results at different rapidities we have to chose the same 'physical time' :

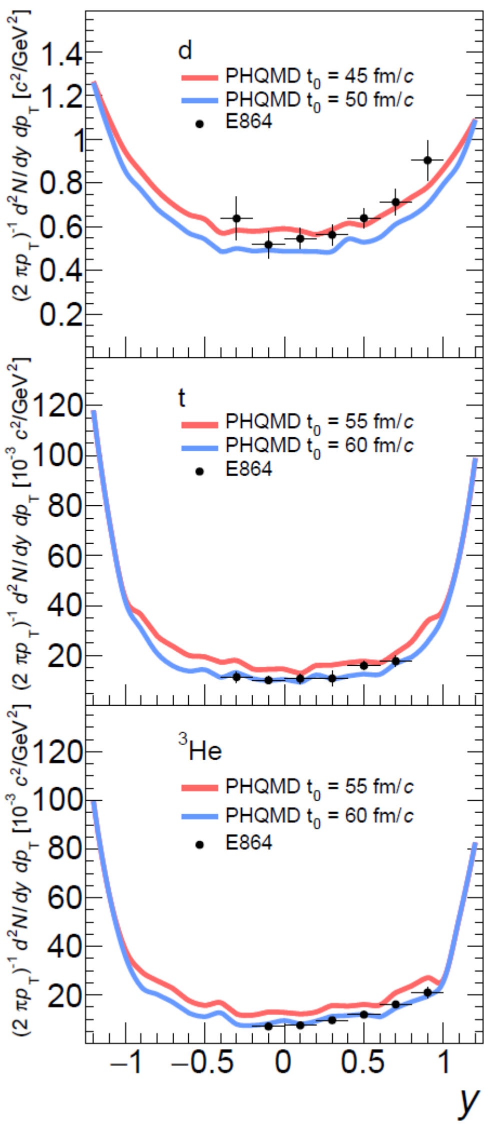
$$t = t_0 \cosh(y)$$

where t_0 is the time taken at y=0 (in the center-of-mass system) to compensate for the time dilatation

Cluster production in HIC at AGS energies

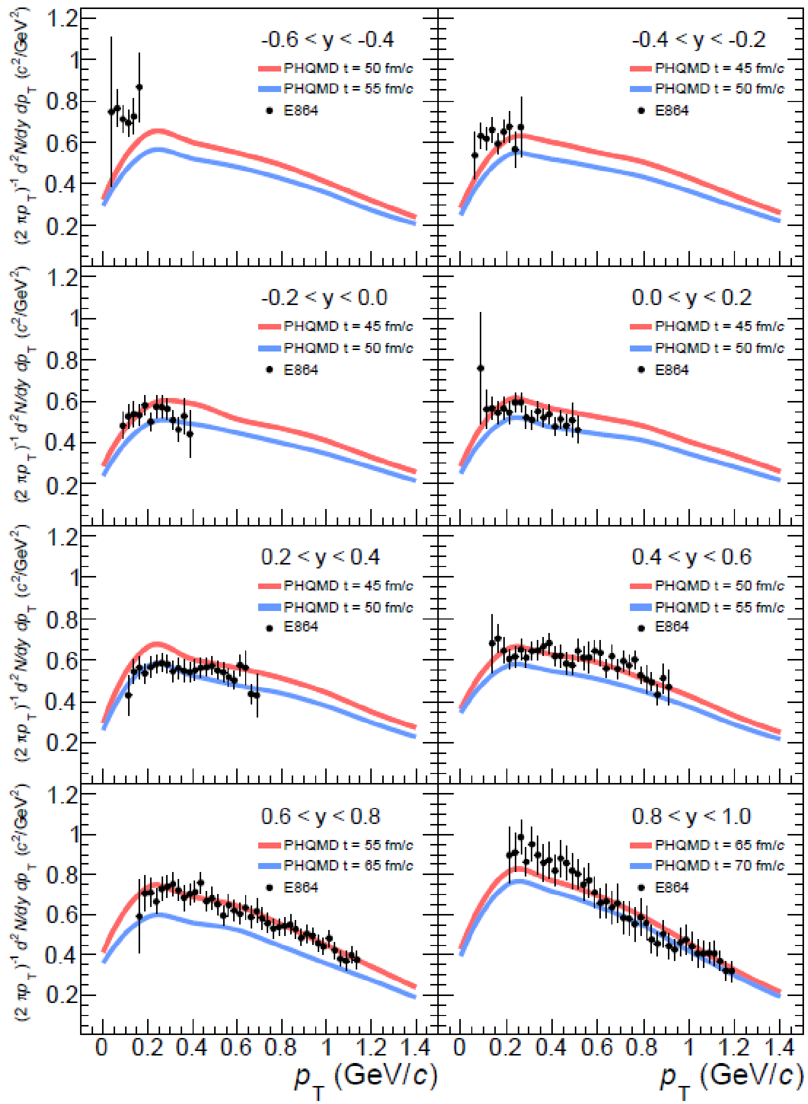
y- distributions of d, t, ^{3}He

Au+Pb@10.6 AGeV



p_T - distribution of deuterons

Au+Pb@10.6 AGeV



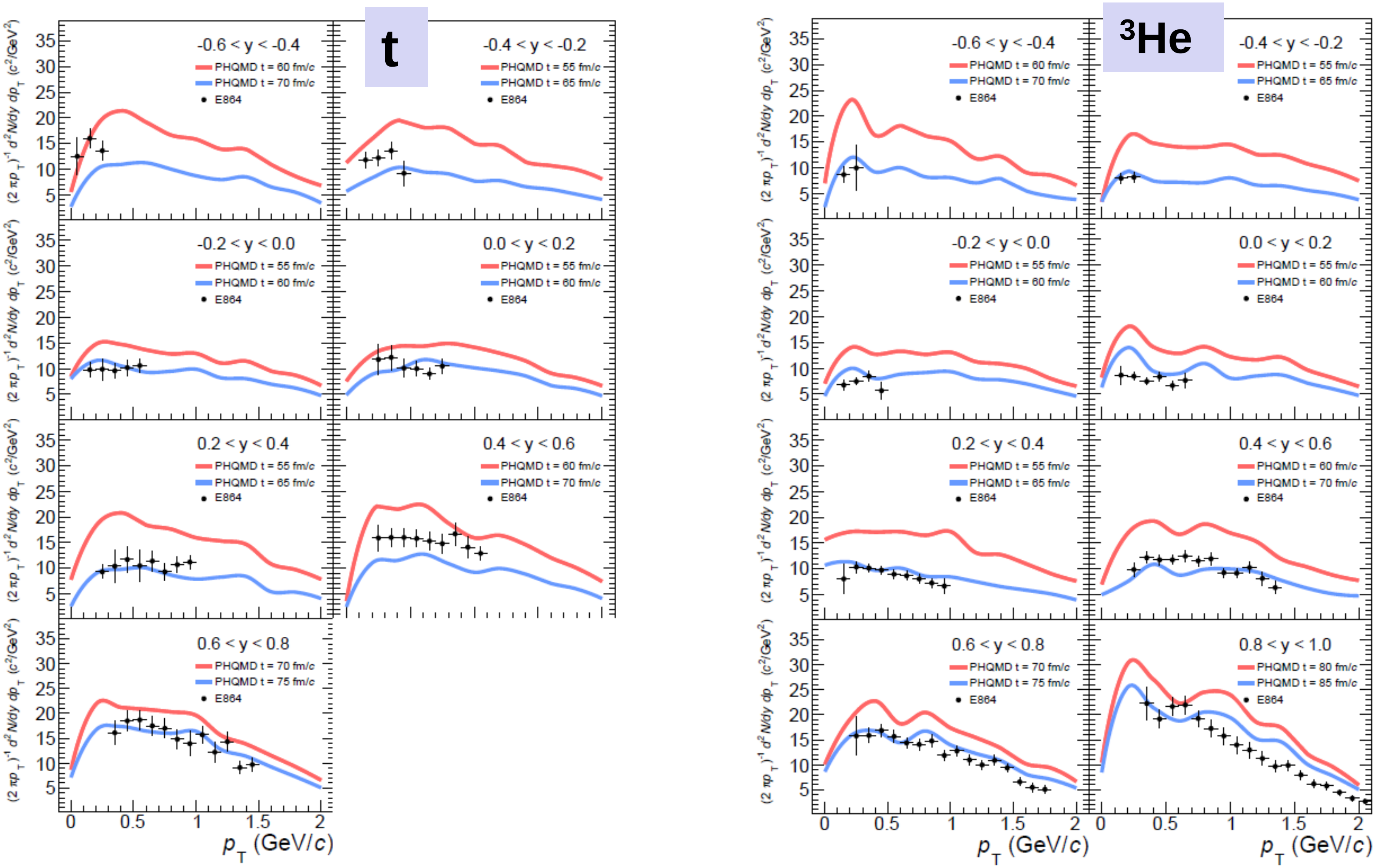
The PHQMD results are taken at $t = t_0\cosh(y)$, where t_0 is the time at y=0

S. Gläßel et al., PRC 105 (2022) 1

Cluster production in HIC at AGS energies

PHQMD

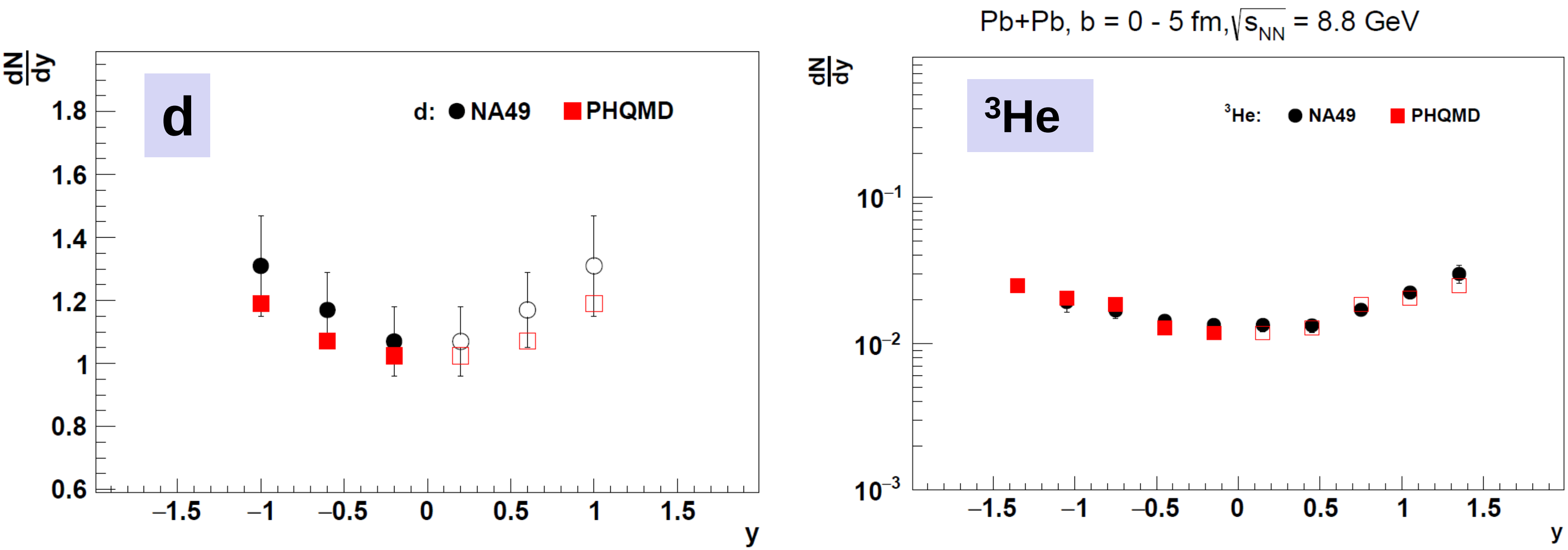
The p_T - distributions of t and ^{3}He from Au+Pb at 10.6 A GeV



S. Gläßel et al., Phys. Rev. C 105 (2022) 1

Cluster production in HIC at SPS energies

The rapidity distributions of d and ^{3}He from Pb+Pb at 30 A GeV



The PHQMD results for d and ^{3}He agree with NA49 data

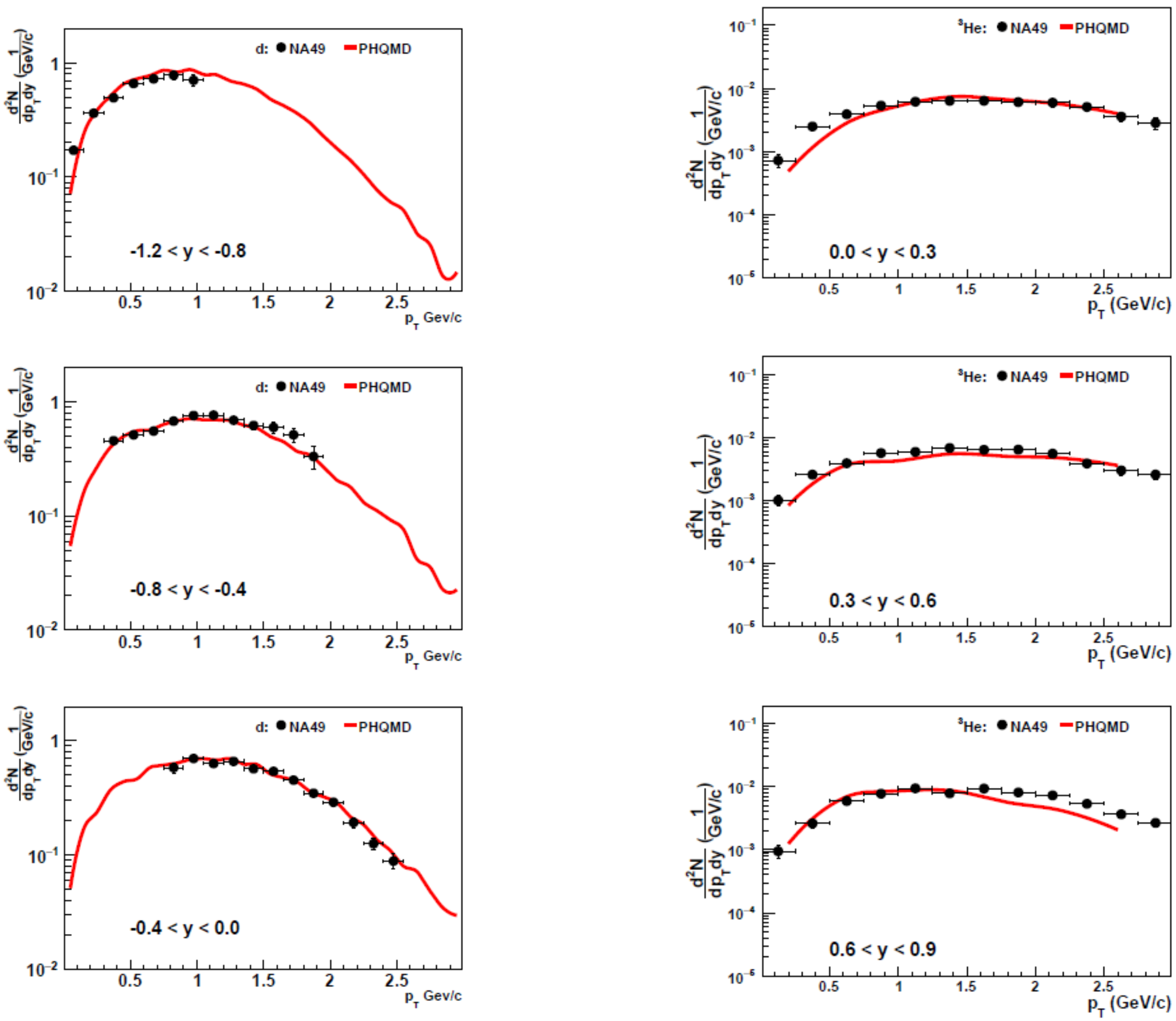
S. Gläßel et al., Phys. Rev. C 105 (2022) 1

Cluster production in HIC at SPS energies

PHQMD

The p_T - distributions of d and ^{3}He from Pb+Pb at 30 A GeV

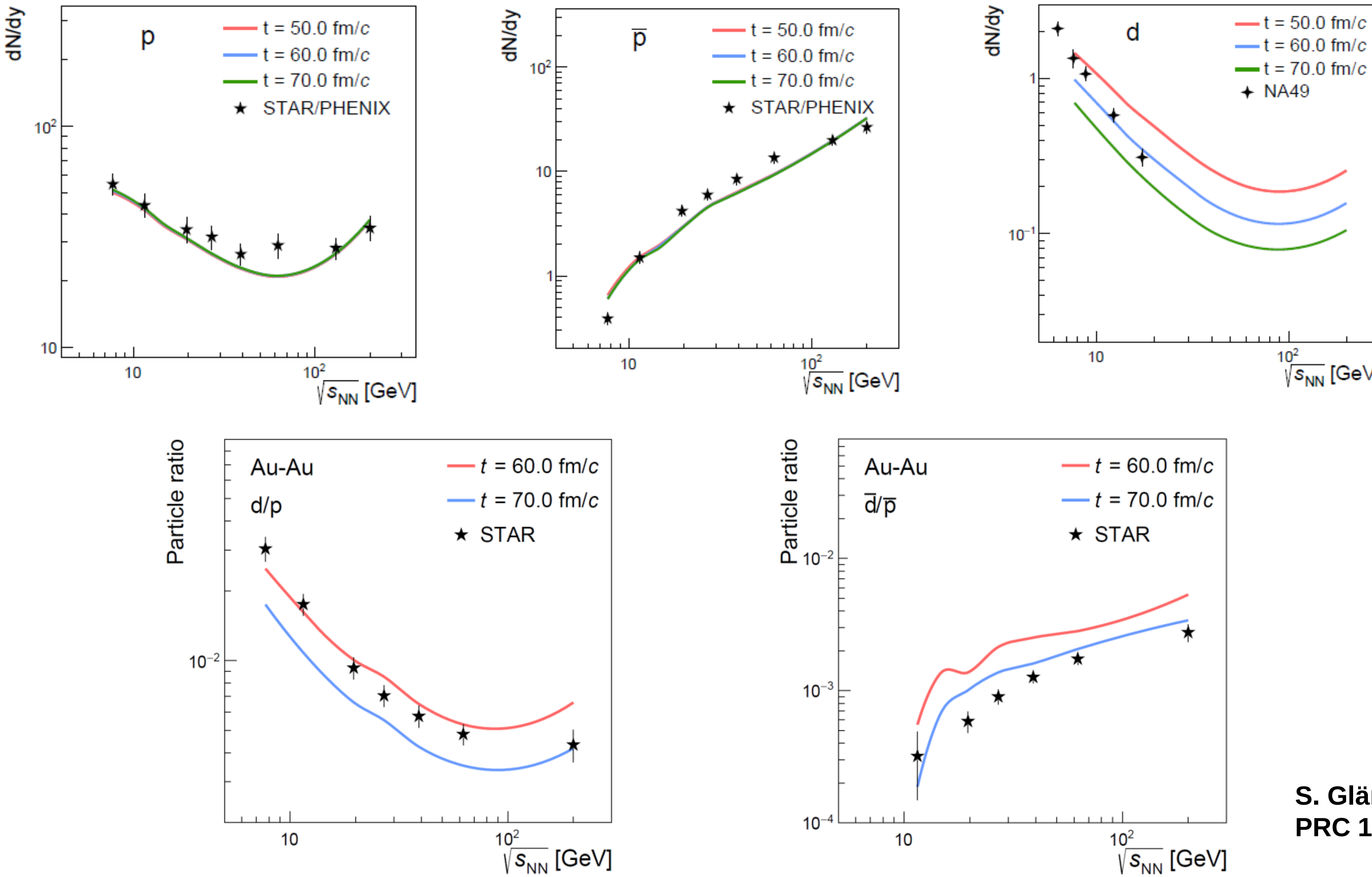
d



^{3}He

S. Gläßel et al., Phys. Rev. C 105 (2022) 1

Excitation function of multiplicity of $p, \bar{p}, d, \bar{d}$



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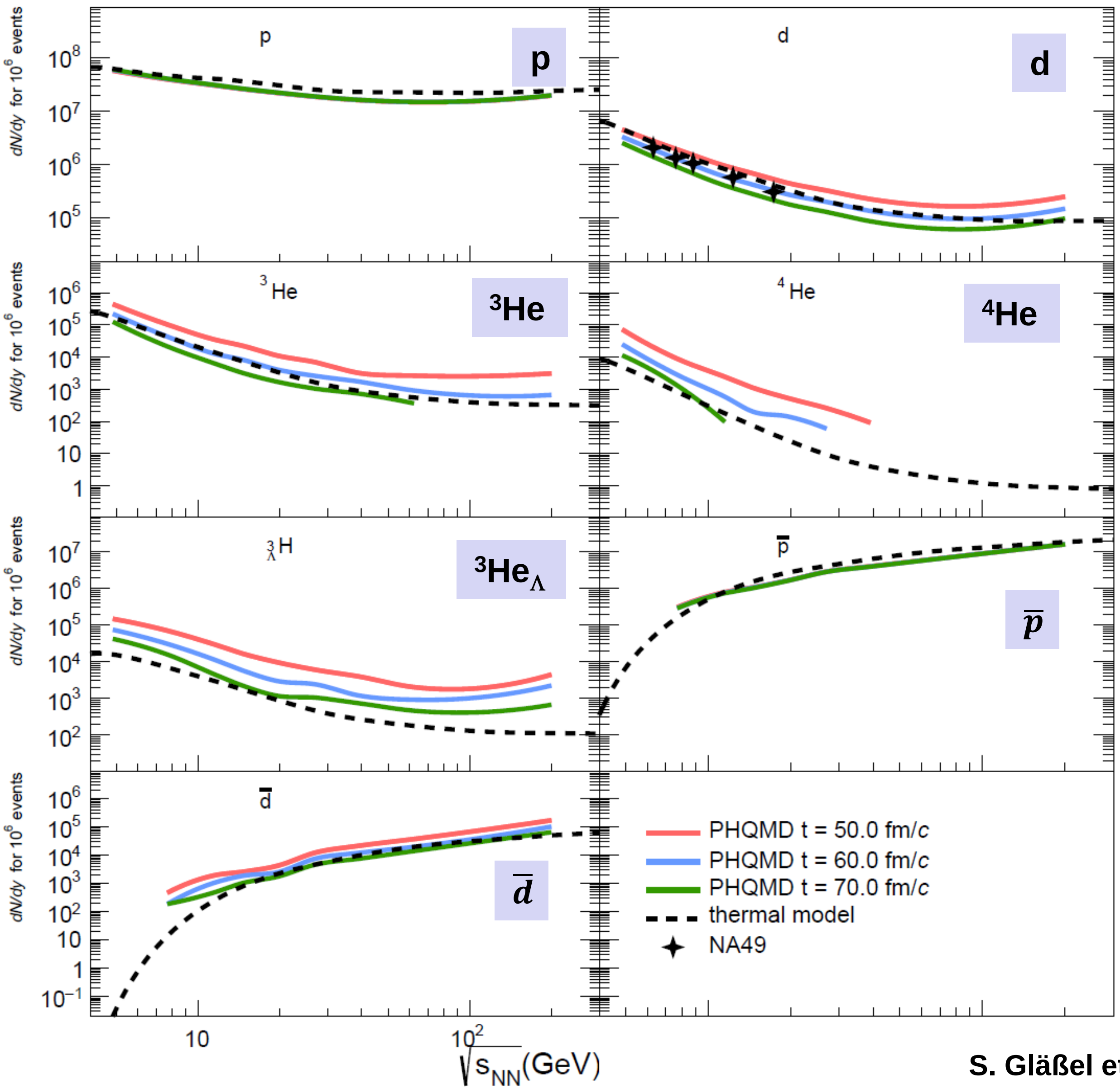
The p, $\bar{p}$ yields at y~0 are stable, the d, $\bar{d}$ yields are better described at *t= 60-70* fm/c

The PHQMD excitation function of cluster production versus thermal model

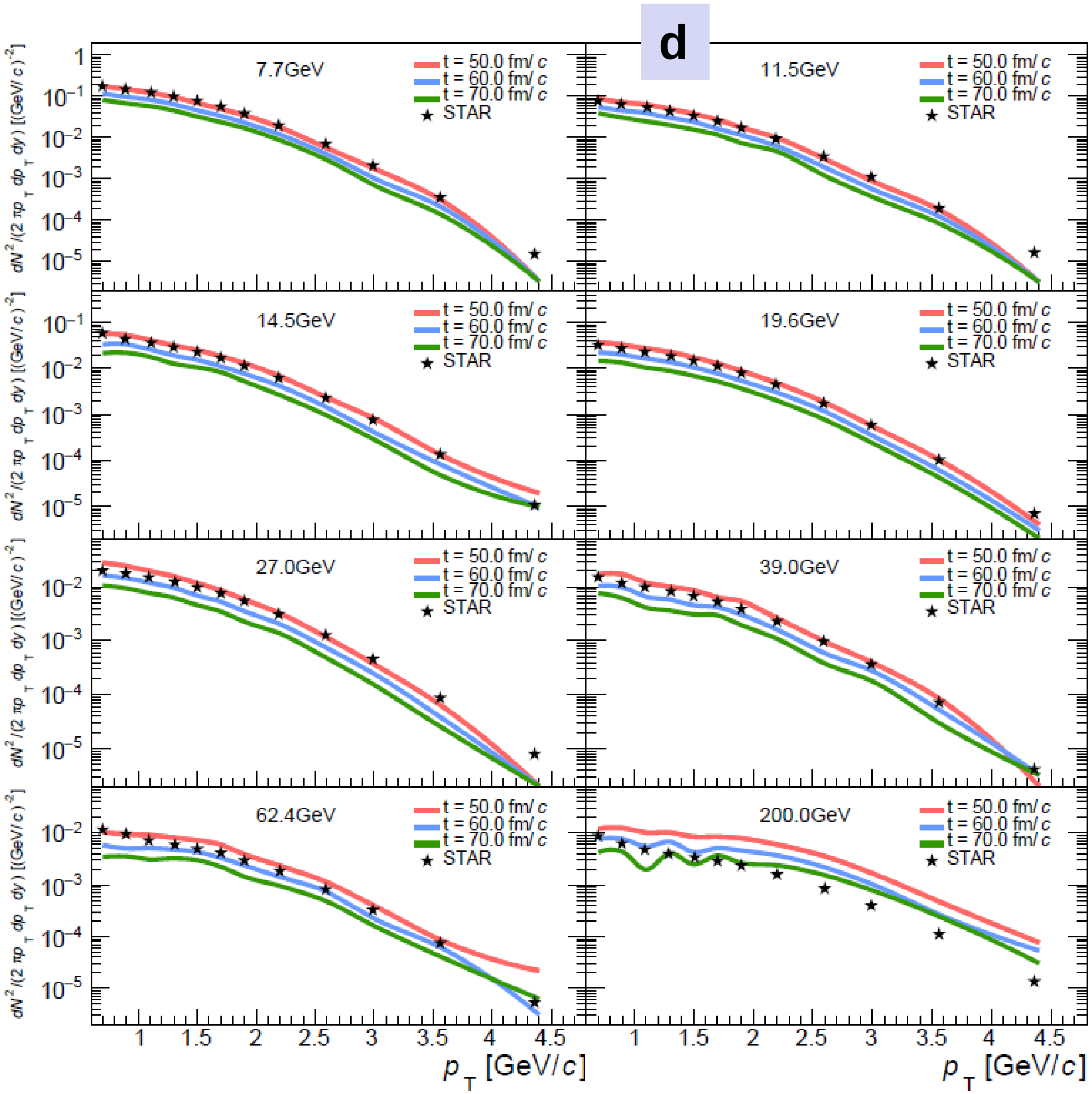


Comparison of the PHQMD results for cluster and hypernuclei $^3H_\Lambda$ with thermal model and NA49 data

Thermal model:
A. Andronic et al., PLB 697 (2011) 203

S. Gläßel et al., Phys. Rev. C 105 (2022) 1

Deuteron p_T spectra from 7.7GeV to 200 GeV



Comparison of the PHQMD results for the deuteron p_T-spectra at midrapidity with STAR data

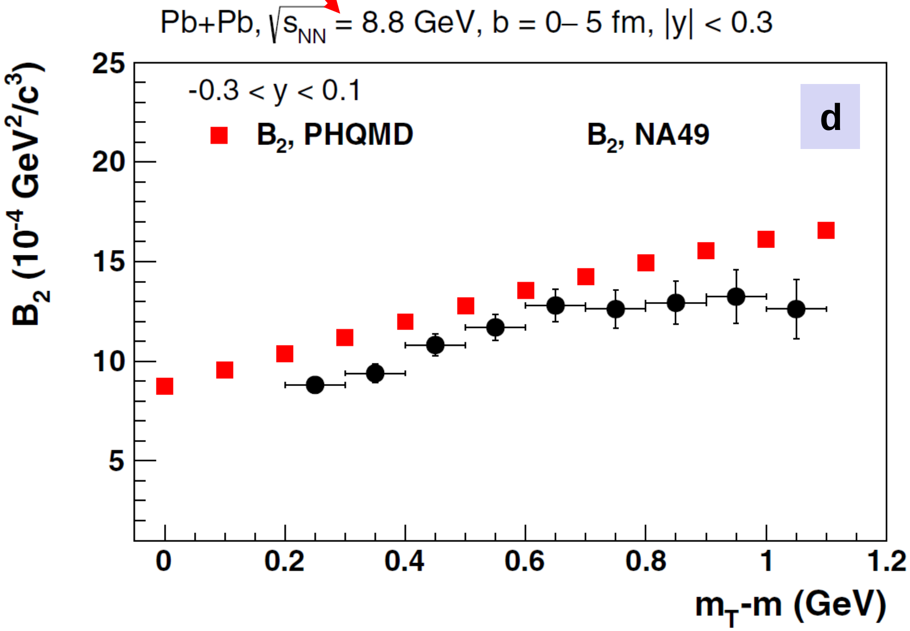
S. Gläßel et al., Phys. Rev. C 105 (2022) 1

Coalescence parameter B_2 for deuterons

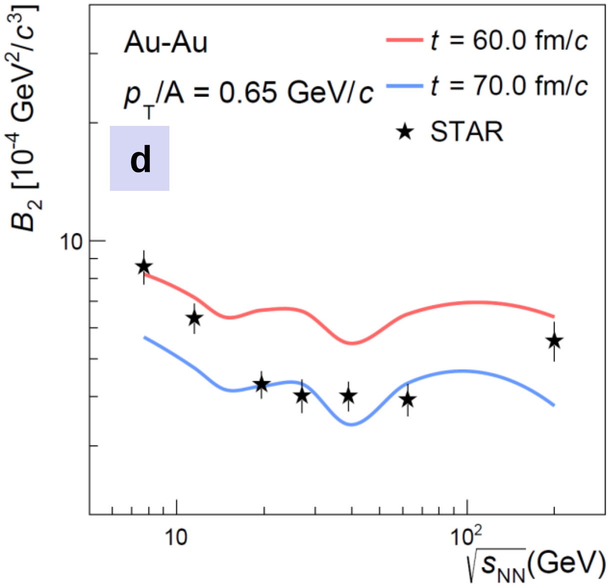
Coalescence parameter B_2:

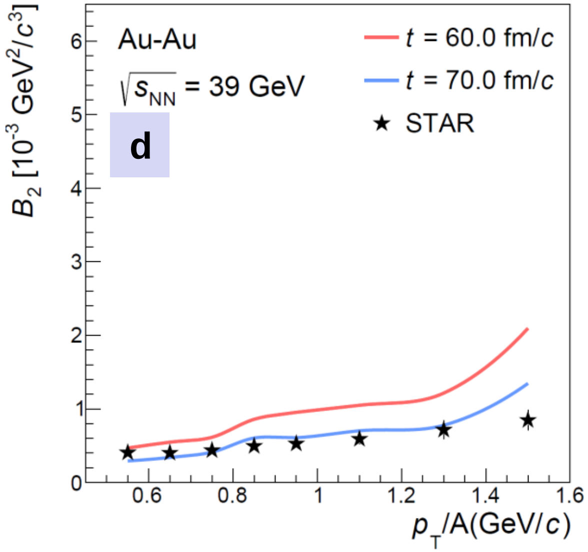
$$B_2 = \frac{E_d \frac{d^3 N_d}{d^3 P_d}}{\left(E_p \frac{d^3 N_p}{d^3 p_p}|_{p_p = P_d/2}\right)^2}$$

Comparison of the PHQMD results with NA49 and STAR data



central Au+Au collisions





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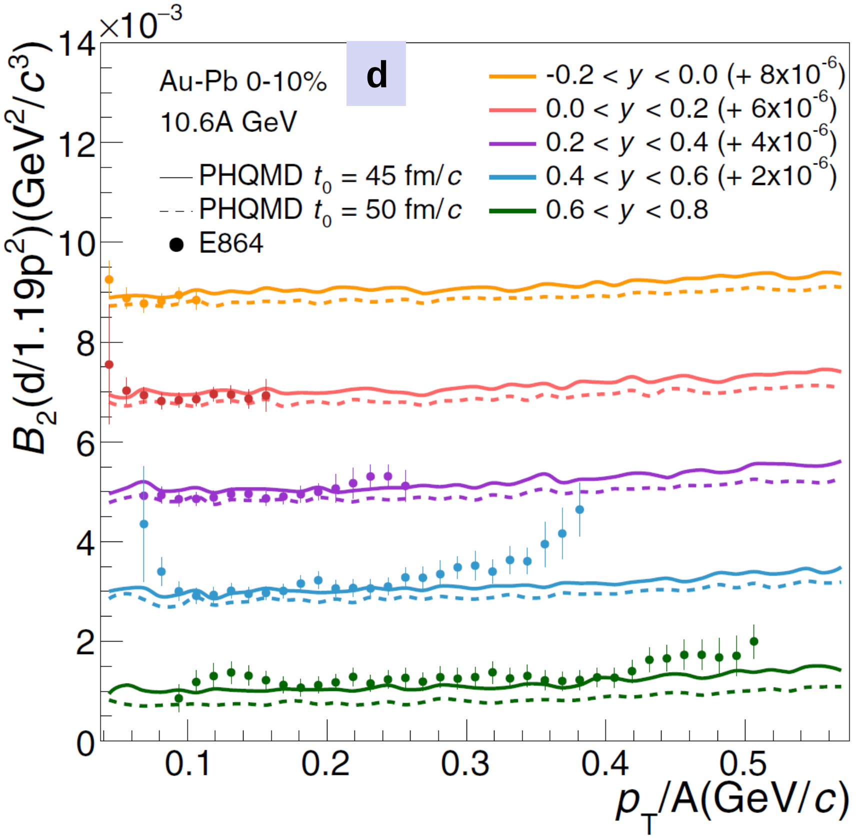
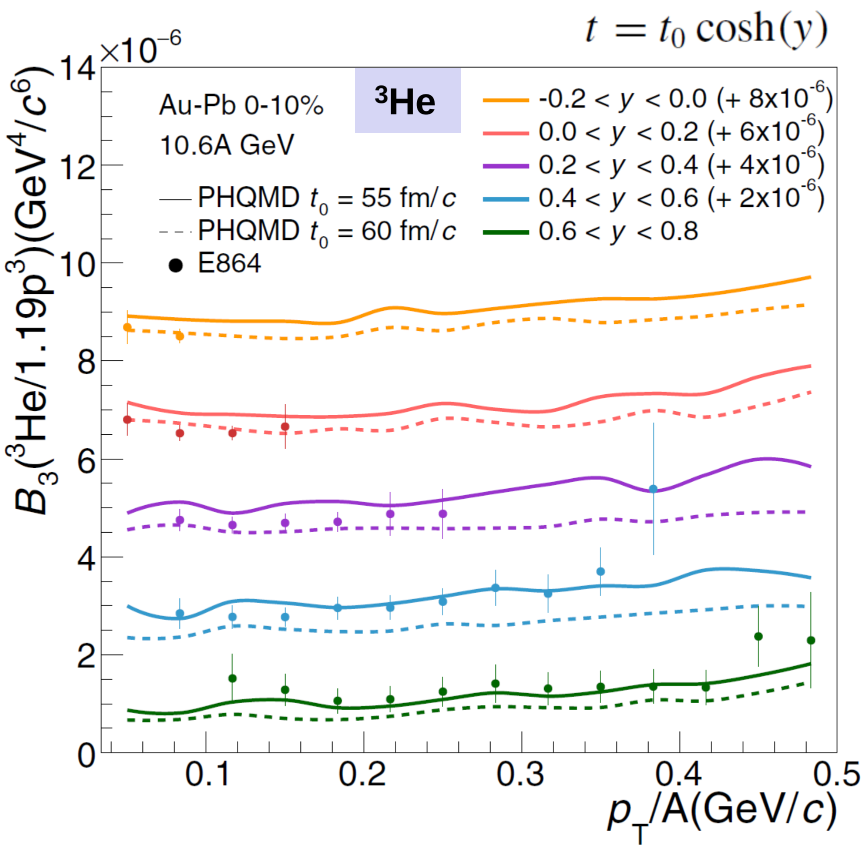
Coalescence parameter B_2 for deuterons





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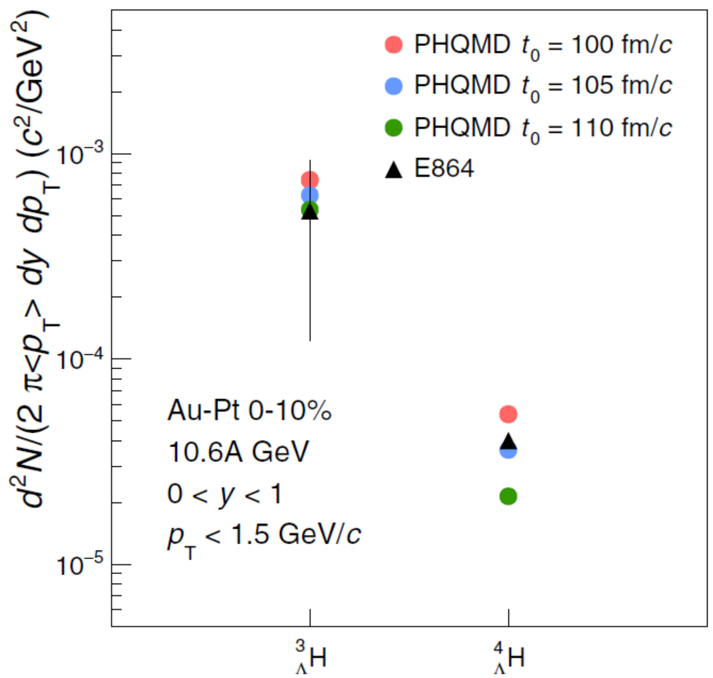
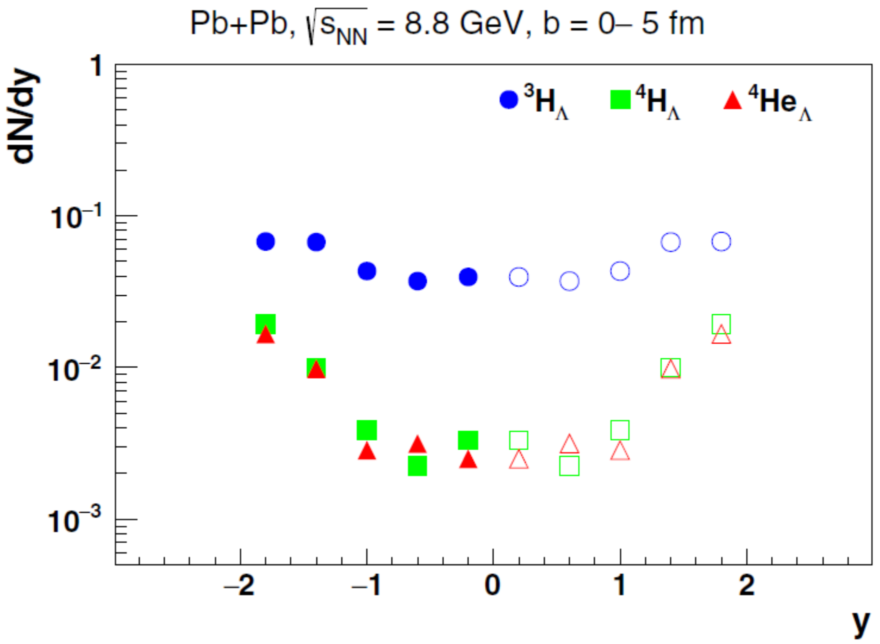
Hypernuclei production at 10.6 and 30 AGeV

The PHQMD results for hypernuclei production in Au+Pt central collisions at 10.6 A GeV



The PHQMD predictions for dN/dy of $^3H_\Lambda$, $^4H_\Lambda$ and $^4He_\Lambda$ from central Pb+Pb collisions at 30 A GeV ($s^{1/2}$ = 8.8 GeV)



- **Assumption on nucleon-hyperon potential:** $V_{N\Lambda} = 2/3\ V_{NN}$

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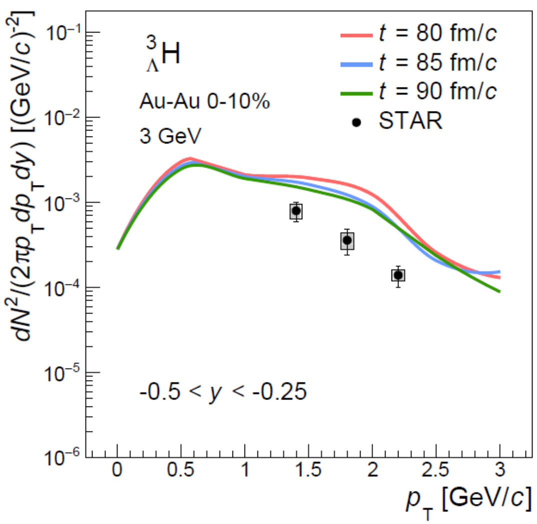
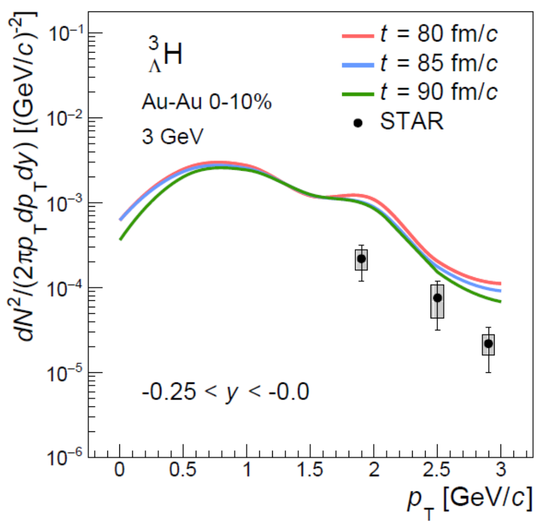
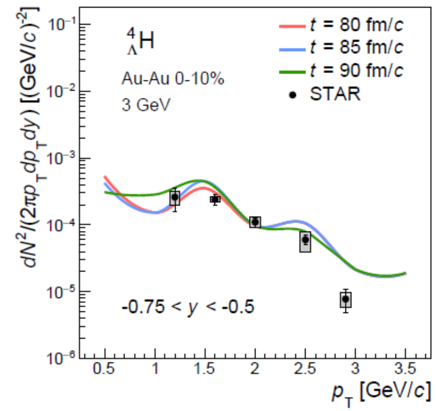
Hypernuclei production at $s^{1/2}$ = 3 GeV

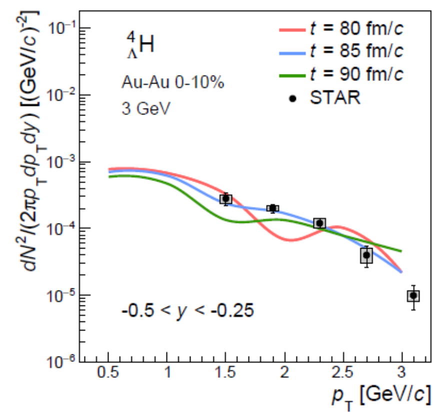
The PHQMD comparison with most recent (preliminary!) STAR fixed target p_T distribution of $^3H_\Lambda$, $^4H_\Lambda$ from Au+Au central collisions at $\sqrt{s}$ =3 GeV

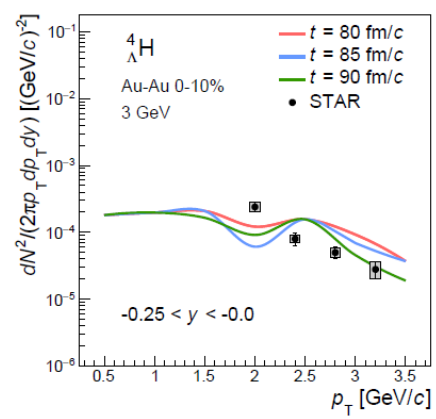
- **Assumption for nucleon-hyperon potential: $V_{N\Lambda} = 2/3\ V_{NN}$**











➔ **Reasonable description of hypernuclei production at $\sqrt{s}$ =3 GeV**

(Cf. the talk by Yuanjing Ji)

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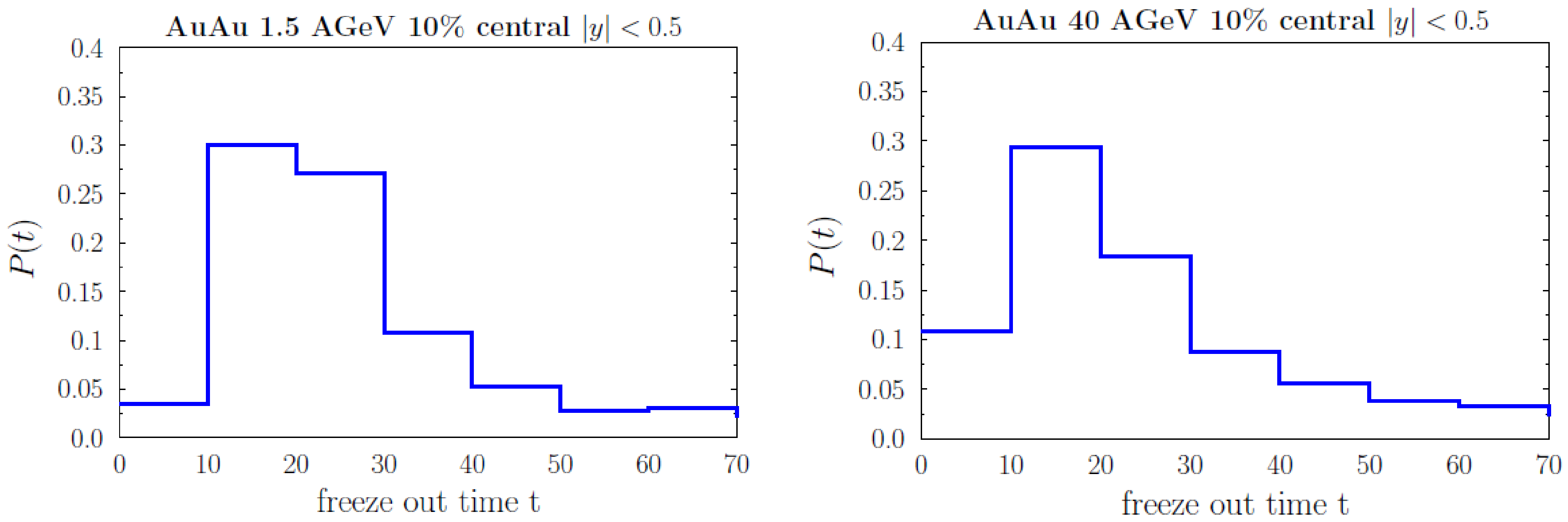
When does the system freeze out?

- The normalized distribution of the freeze-out time of baryons (nucleons and hyperons) which are finally observed at mid-rapidity |y|<0.5

  * Here freeze-out time as defined as a last elastic or inelastic collision, after that only potential interaction between baryons occurs



➔ **Freeze-out time of baryons in Au+Au at 1.5 AGeV and 40 AGeV:**

- **similar profile since expansion velocity of mid-rapidity fireball is roughly independent of the beam energy**

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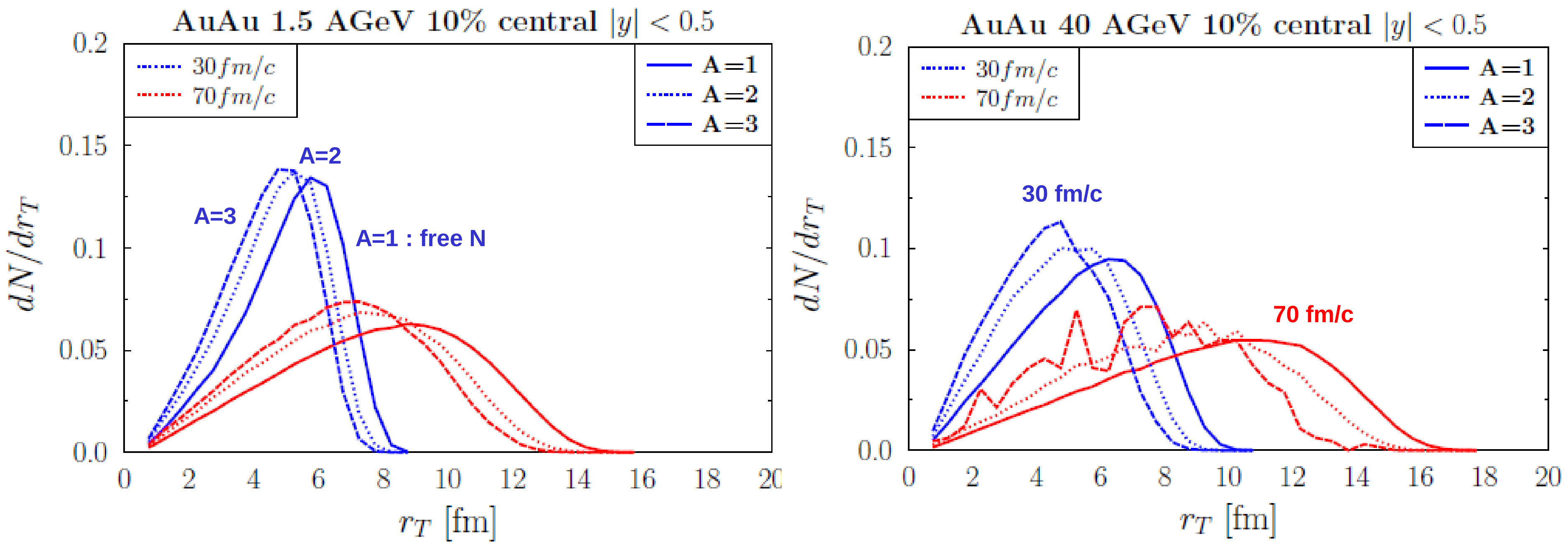
Where are the clusters formed?

- The 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 the expanding fireball**

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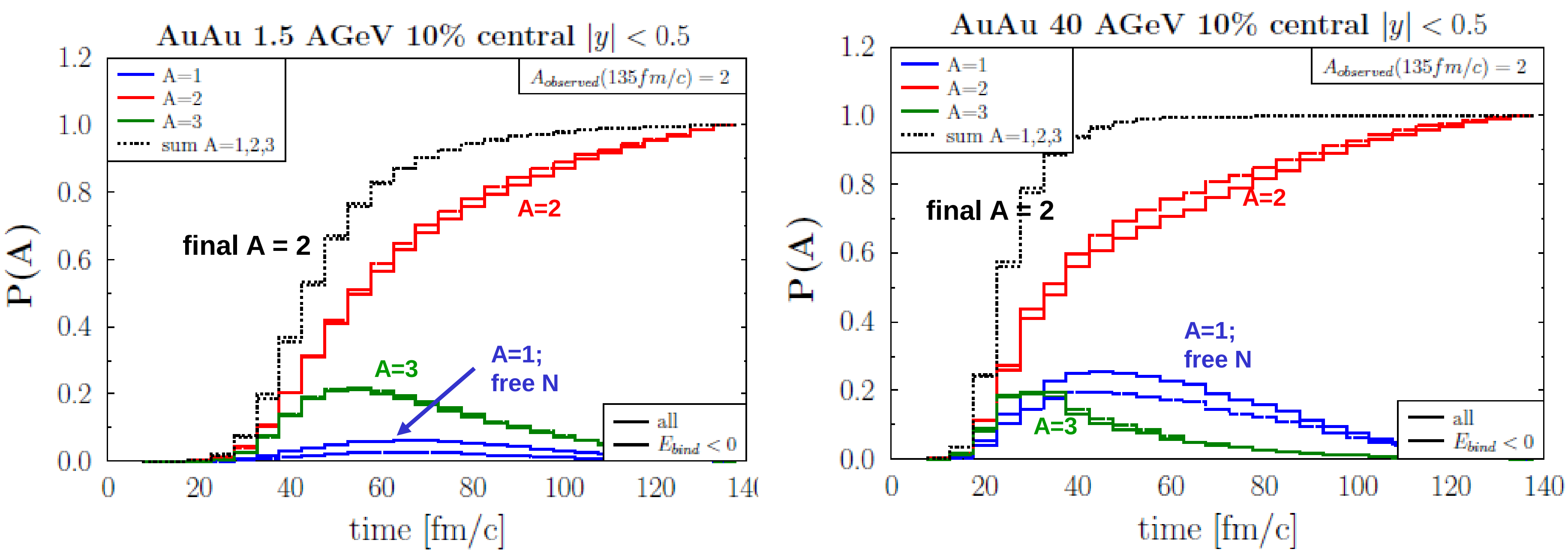
When are the A=2 clusters formed?

- The conditional probability **P(A)** that the nucleons, which are finally observed in A=2 clusters at time 135 fm/c, were at time *t* the members of A=1 (free nucleons), A=2 or A=3 clusters



➔ **Stable clusters (observed at 135 fm/c) are formed shortly after the dynamical freeze-out**

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Summary

The PHQMD is a microscopic n-body transport approach for the description of heavy-ion dynamics and cluster formation
Clusters are identified by Minimum Spanning Tree model

combined model PHQMD = (PHSD & QMD) & (MST | SACA)

- provides the good description of 'bulk' observables from SIS to RHIC energies
- predicts the dynamical formation of clusters from SIS to RHIC energies due to the interactions among the nucleons
- reproduces cluster data on dN/dy and dN/dp_T as well as ratios d/p and $\bar{d}/\bar{p}$ for HI 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.

Outlook:

- extension to LHC energies and study of hyper-nuclei with more realistic potentials