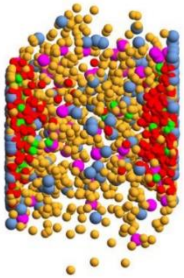
Midrapidity cluster formation in heavy-ion collisions

Elena Bratkovskaya
(GSI, Darmstadt & Uni. Frankfurt)
&
Susanne Glaessel, Viktar Kireyeu, Joerg Aichelin, Vadym Voronyuk, Christoph Blume, Gabriele Coci, Vadim Kolesnikov, Michael Winn, Jan Steinheimer, Marcus Bleicher

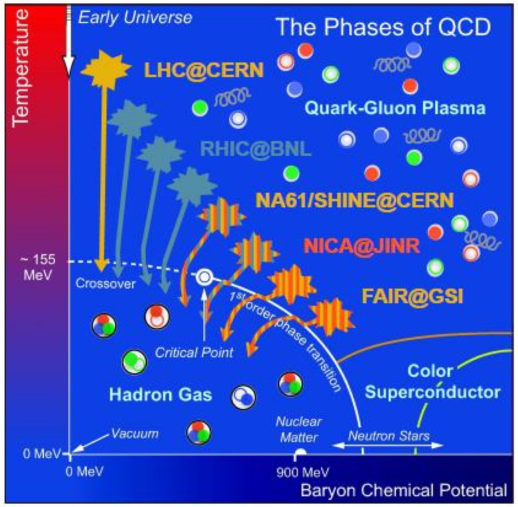
PHQMD

The 20th International Conference on Strangeness in Quark Matter (SQM 2022)
13 - 17 June 2022, Busan, South Korea



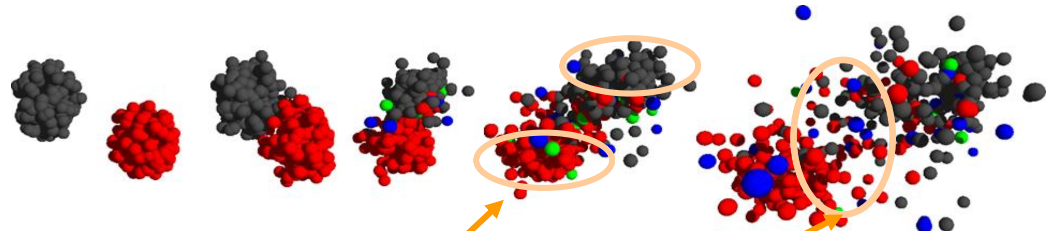
The ‚holy grail‘ of heavy-ion physics:

The phase diagram of QCD



Experimental observables:

... Clusters and (anti-) hypernuclei

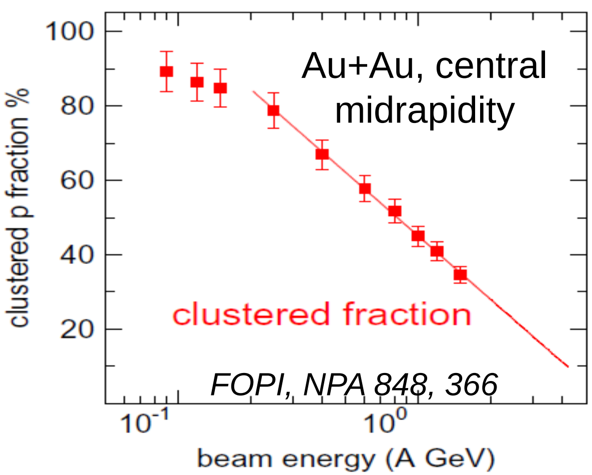


IQMD: Ch. Hartnack

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

! Hyperons are created in participant zone

- Clusters are very **abundant at low energy**

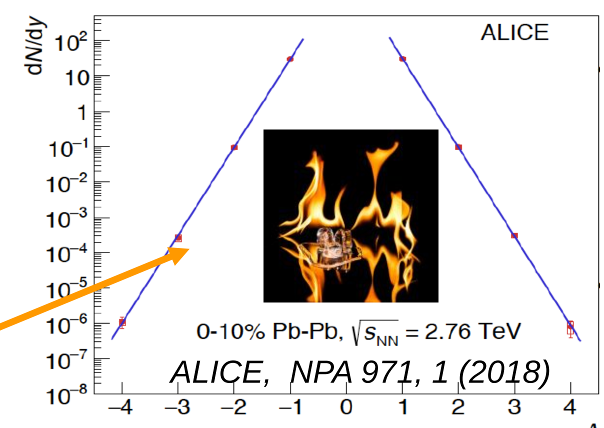


(Anti-) hypernuclei production:

- 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:

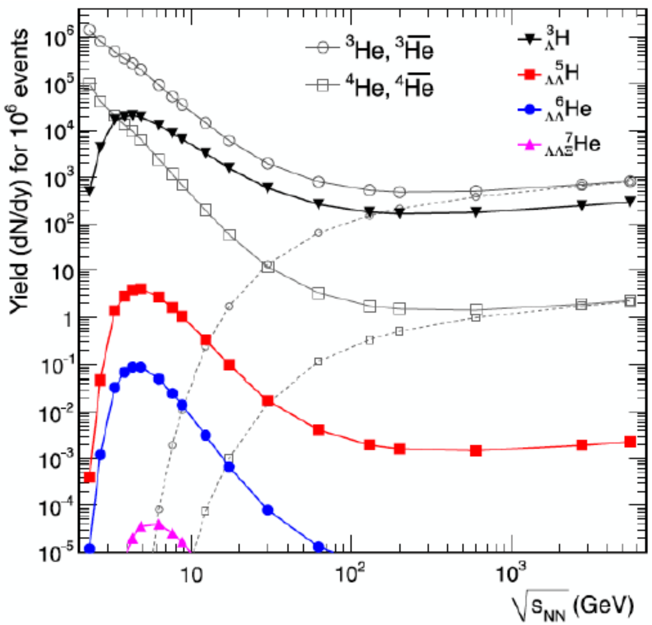
‚Ice in a fire‘ puzzle: how the weakly bound objects can be formed and survive in a hot enviroment ?!



Modeling of cluster and hypernuclei formation

<u>Existing models for clusters formation:</u>

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



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

➔ **don‘t provide information on the dynamical origin of clusters formation**

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:
– via potential interaction (potential mechanism) → discussed in this talk
-- by scattering (kinetic mechanism)

Cf. Posters: POS-LF-08: SMASH - Jan Staudenmaier
POS-RES-08: PHQMD – Gabriele Coci

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

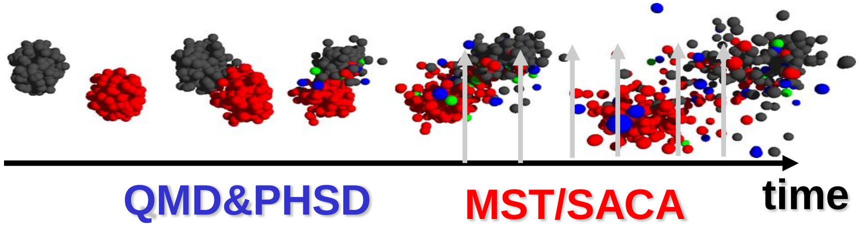
Realization: combined model PHQMD = (PHSD & QMD) & (MST/SACA)

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 $\psi(t) = \prod_{i=1}^{N} \psi(\mathbf{r}_i, \mathbf{r}_{i0}, \mathbf{p}_{i0}, t)$ **for N particles (neglecting antisymmetrization !)**

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

$$\psi(\mathbf{r}_i, \mathbf{r}_{i0}, \mathbf{p}_{i0}, t) = C\ \mathrm{e}^{-\frac{1}{4L}\left(\mathbf{r}_i - \mathbf{r}_{i0}(t) - \frac{\mathbf{p}_{i0}(t)}{m}t\right)^2} \cdot \mathrm{e}^{i\mathbf{p}_{i0}(t)(\mathbf{r}_i - \mathbf{r}_{i0}(t))} \cdot \mathrm{e}^{-i\frac{\mathbf{p}_{i0}^2(t)}{2m}t}$$

L=4.33 fm^2

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

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

QMD interaction potential and EoS

The expectation value of the Hamiltonian:

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

- **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):**

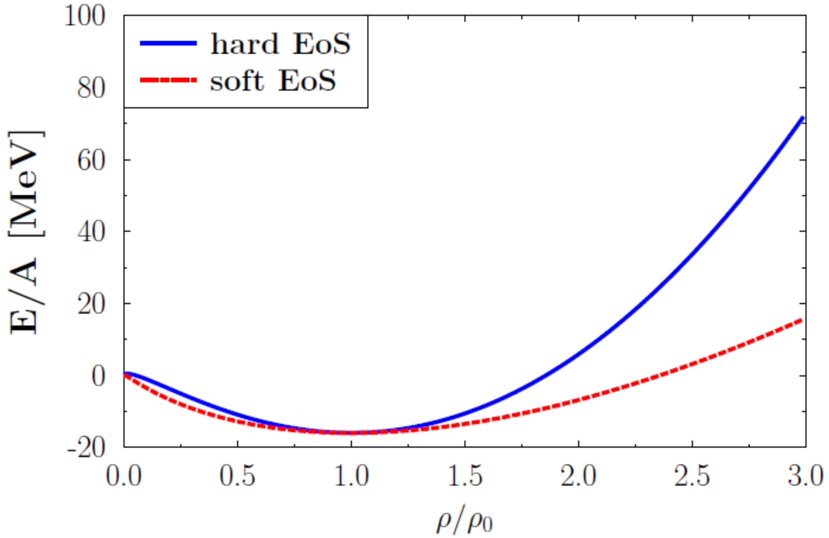
$$\rho_{int}(\mathbf{r_{i0}}, t) \rightarrow C \sum_j \left(\frac{4}{\pi L}\right)^{3/2} e^{-\frac{4}{L}(\mathbf{r}_{i0}^{T}(t) - \mathbf{r}_{j0}^{T}(t))^2} \times e^{-\frac{4\gamma_{cm}^2}{L}(\mathbf{r}_{i0}^{L}(t) - \mathbf{r}_{j0}^{L}(t))^2},$$

- **HIC ←→ EoS for infinite matter at rest**

- **compression modulus K of nuclear matter:**

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

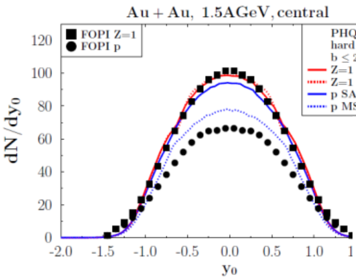
EoS for infinite matter at rest

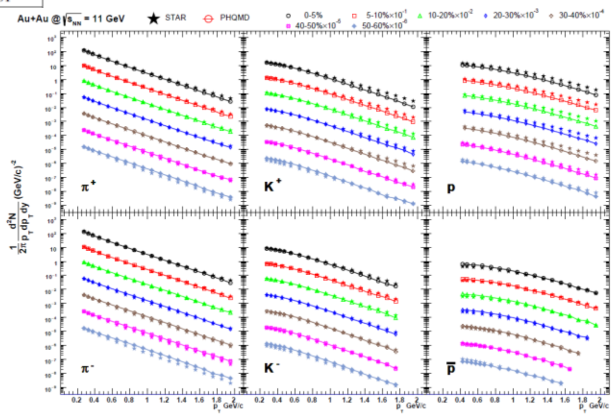


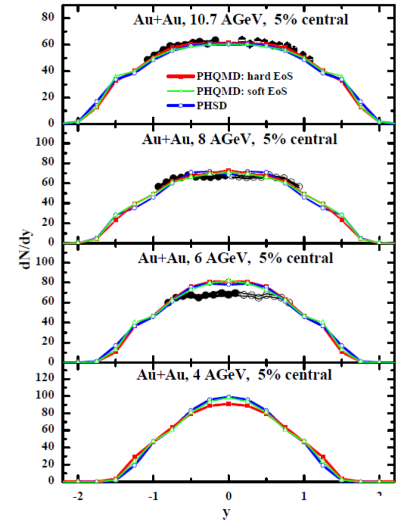
*Work in progress: implementation of momentum dependent potential (M. Winn)

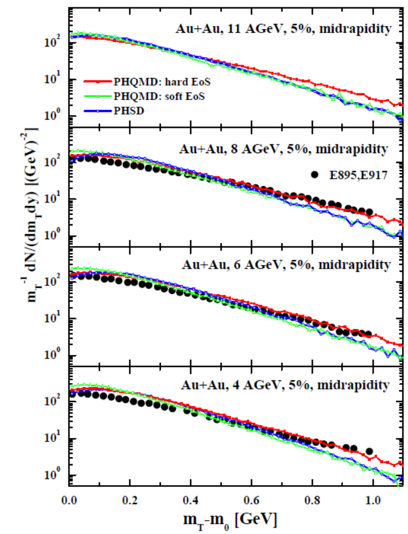
Highlights: PHQMD ‚bulk' dynamics from SIS to RHIC

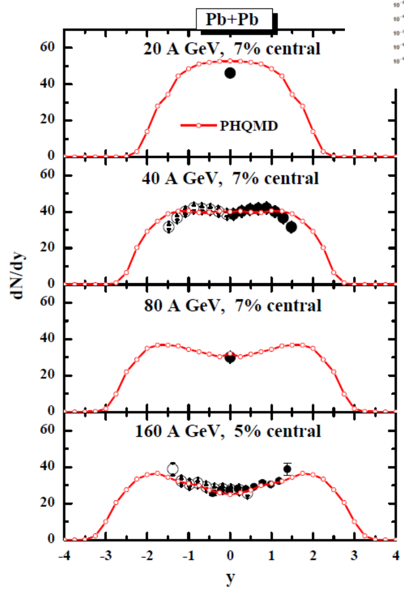
PHQMD: J. Aichelin et al., PRC 101 (2020) 044905

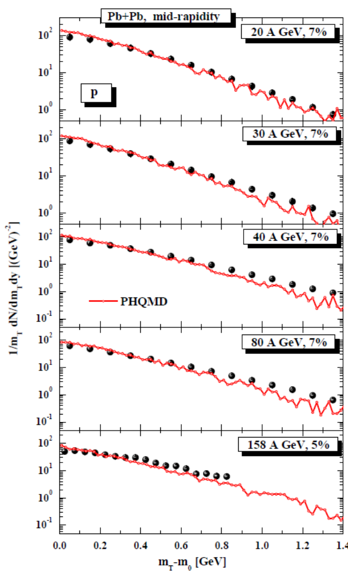


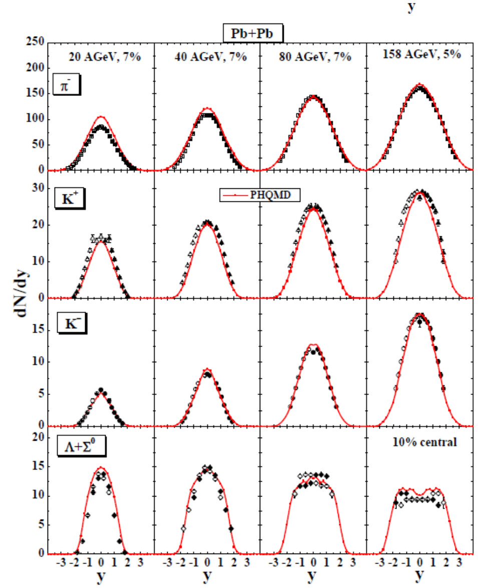


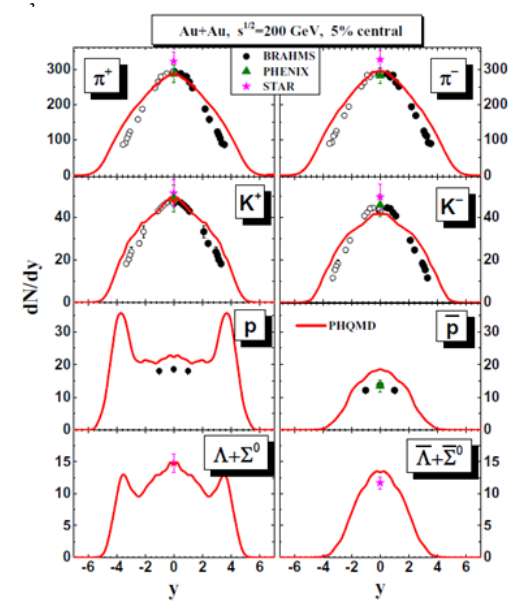












PHQMD provides a good description of **hadronic 'bulk' observables** from SIS to RHIC energies

Cluster recognition: Minimum Spanning Tree (MST)

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

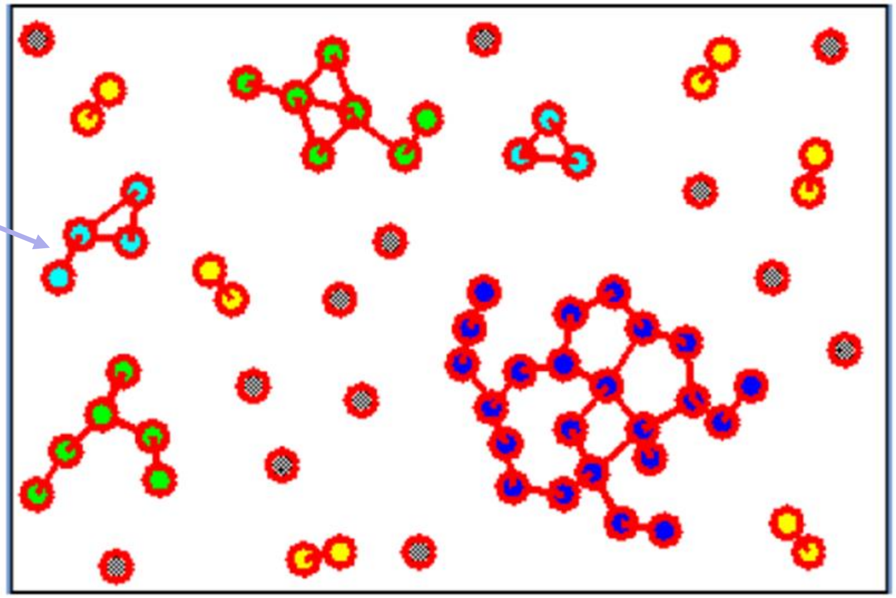
The Minimum Spanning Tree (MST) is a cluster recognition method applicable for the (asymptotic) final states where coordinate space correlations may only survive for bound states.

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)

- MST + extra condition: negative binding energy for identified clusters

Clusters in semi-classical QMD 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' :**

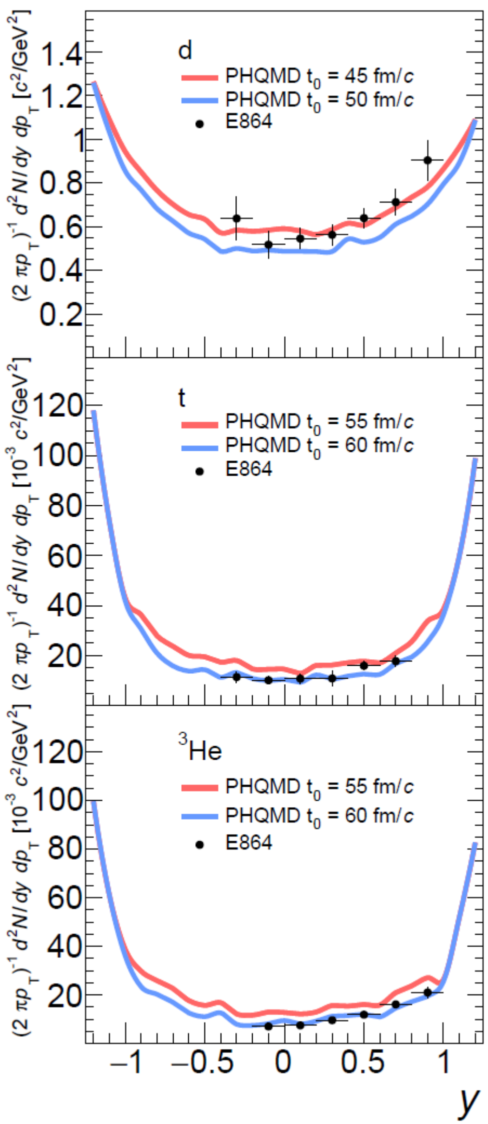
$$t = t_0 \cosh(y)$$

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

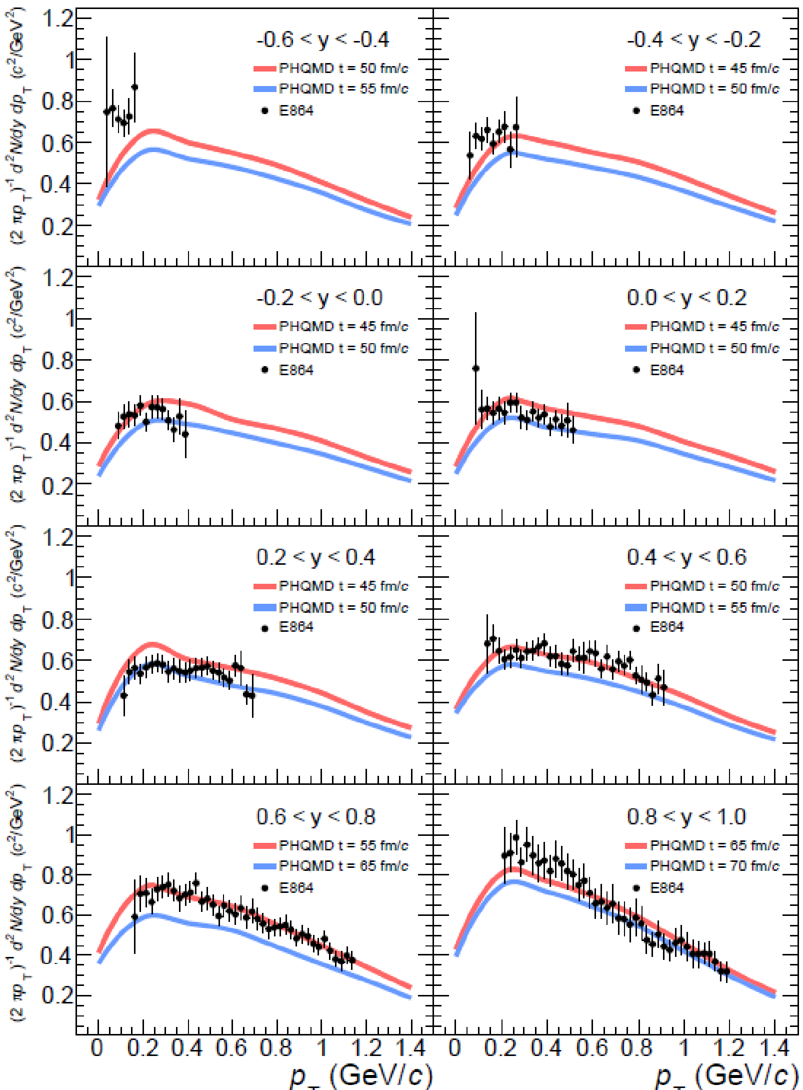
y- distributions of d, t, ^{3}He

Au+Pb@10.6 AGeV



p_T - distribution of deuterons

Au+Pb@10.6 AGeV



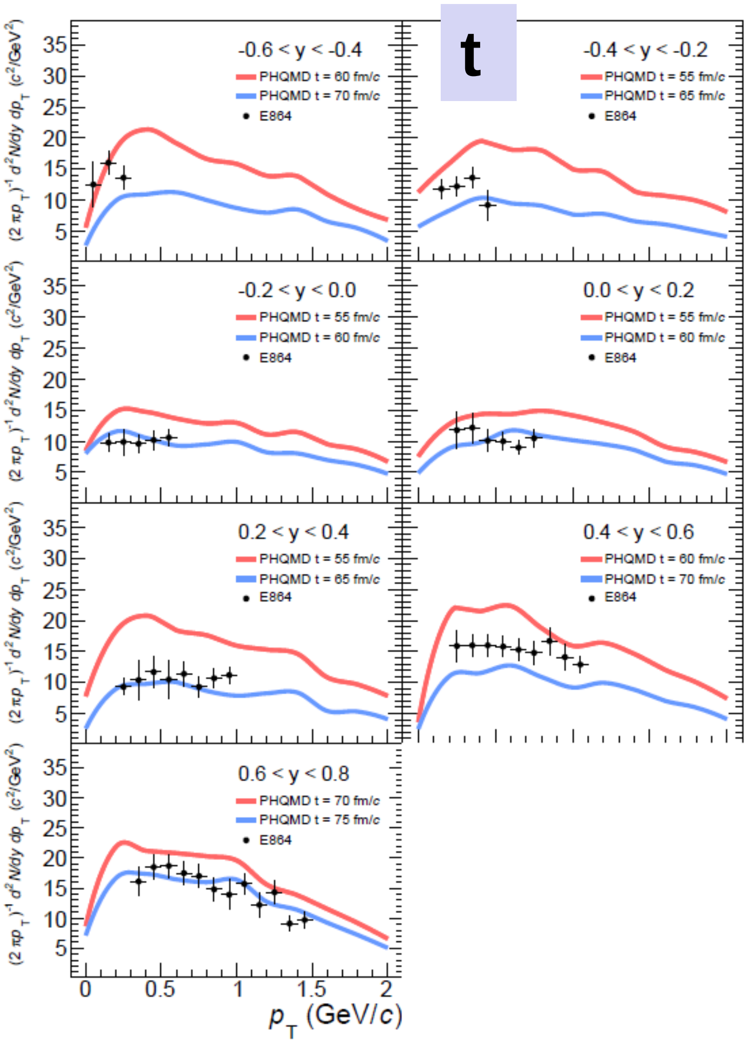
The PHQMD results are taken at $t = t_0 \cosh(y)$, where t_0 is the time at y=0

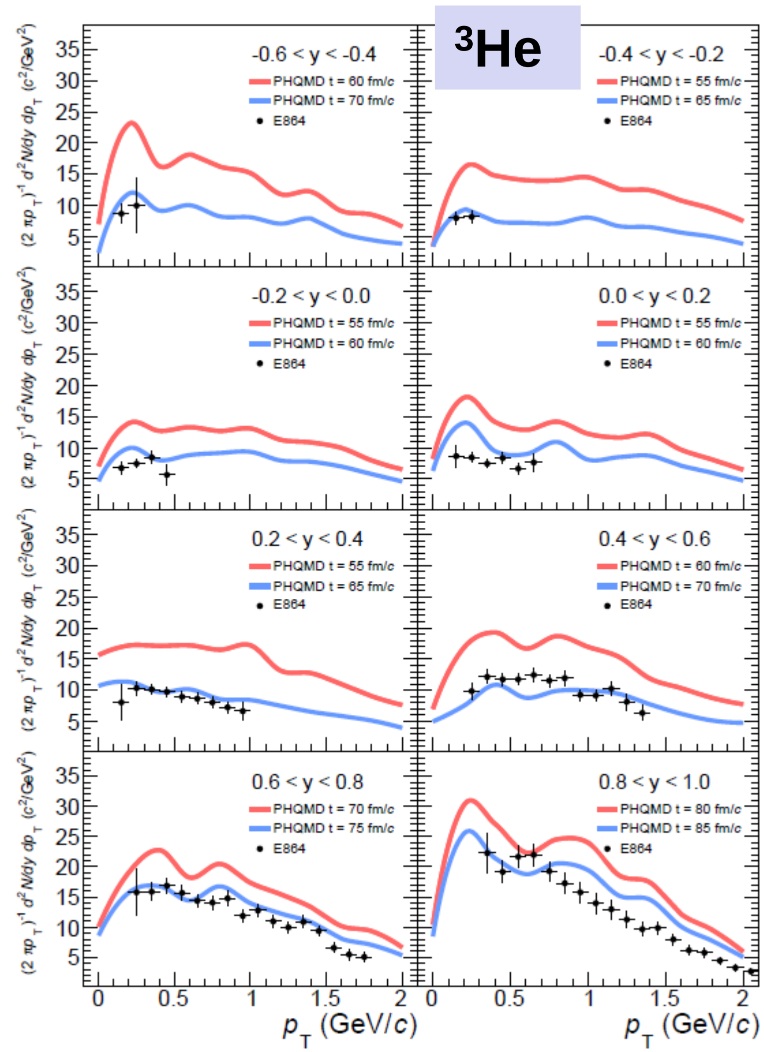
S. Gläßel et al., PRC 105 (2022) 1

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

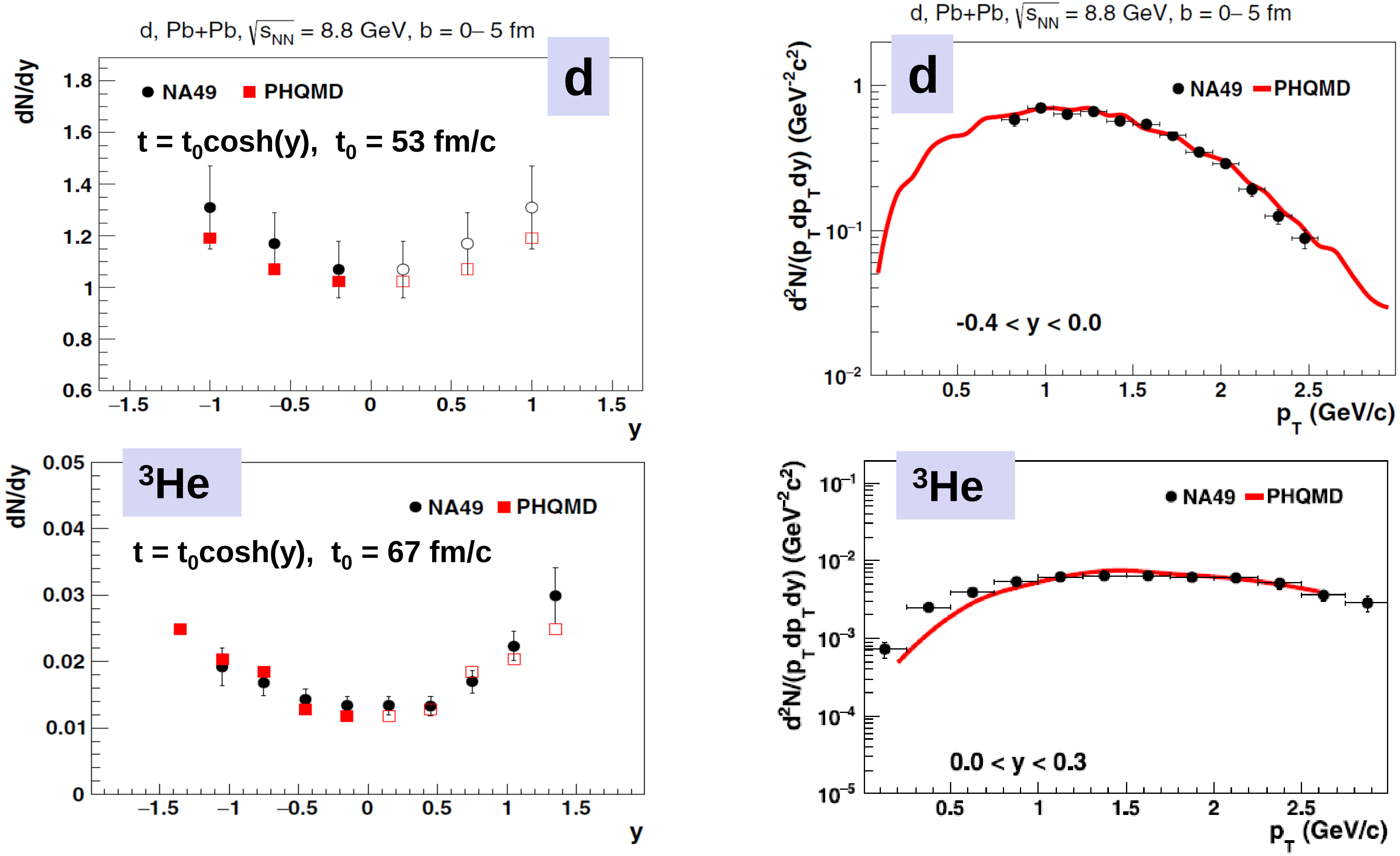




S. Gläßel et al., Phys. Rev. C 105 (2022) 1

Cluster production in HIC at SPS energies

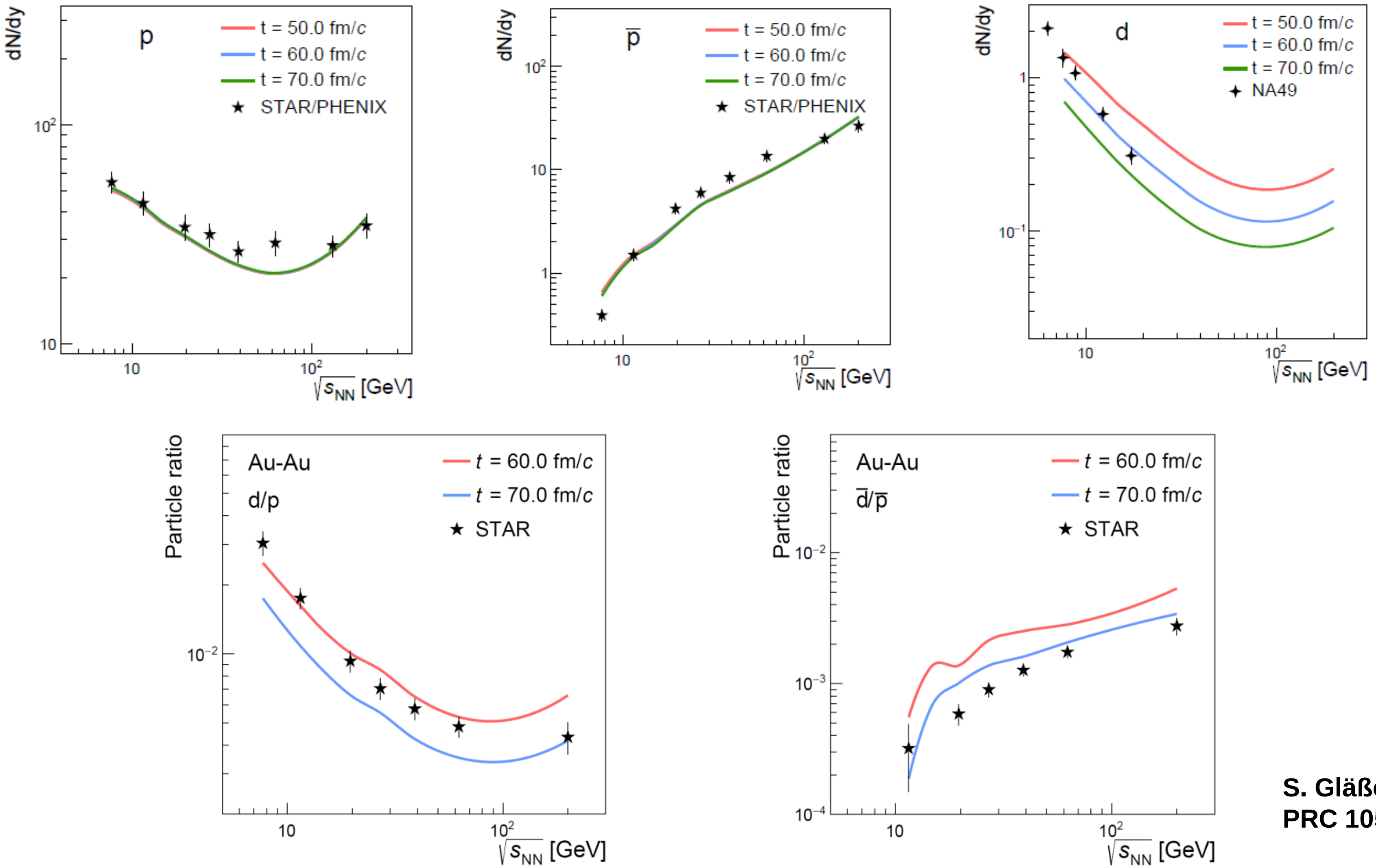
The rapidity and p_T-distributions of d and ^{3}He from Pb+Pb at 30 A GeV



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

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

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



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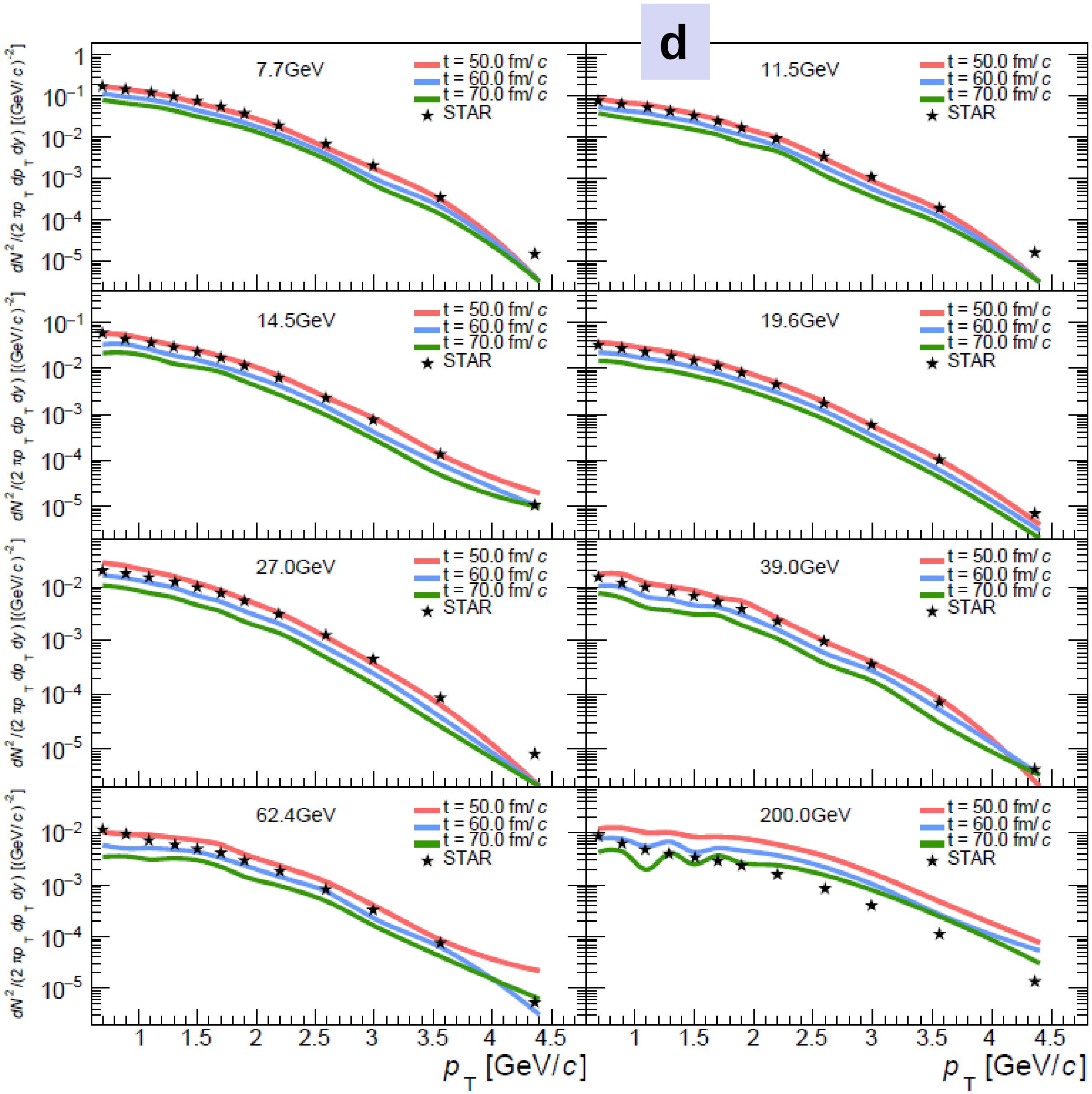
The p, $\overline{p}$ yields at y~0 are stable, the d, $\overline{d}$ yields are better described at *t= 60-70* fm/c

Deuteron p_T spectra from 7.7GeV to 200 GeV



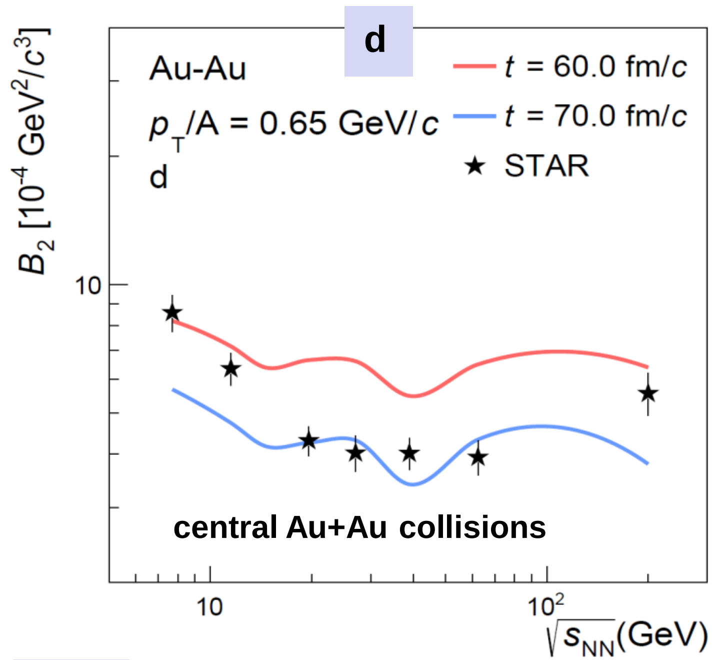
Comparison of the PHQMD results for the deuteron p_T-spectra at midrapidity with STAR data

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

Coalescence parameter B_2 for d and ^{3}He

Coalescence parameter B_2:

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



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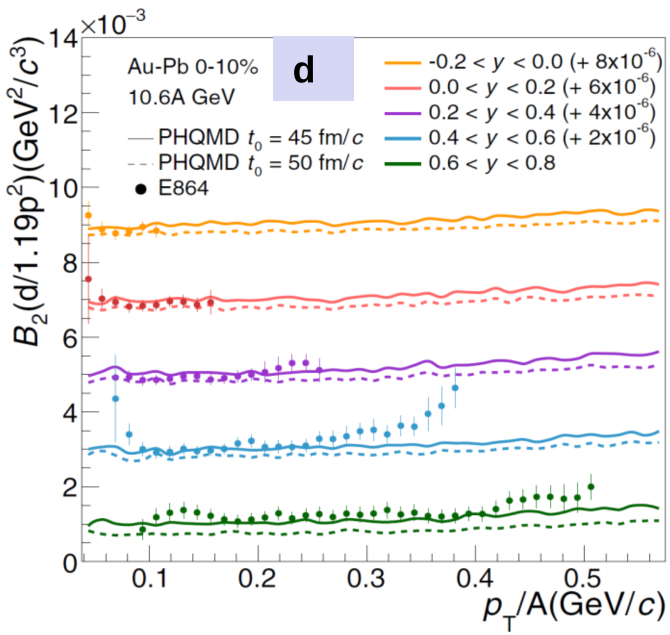
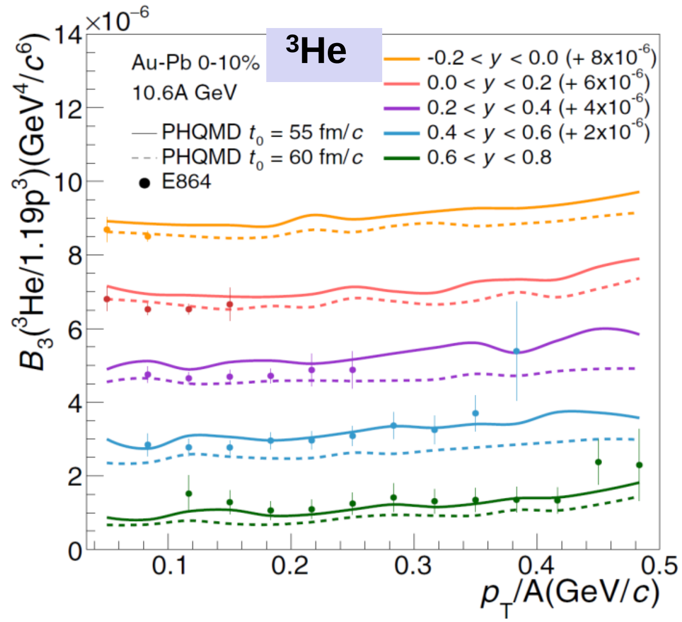


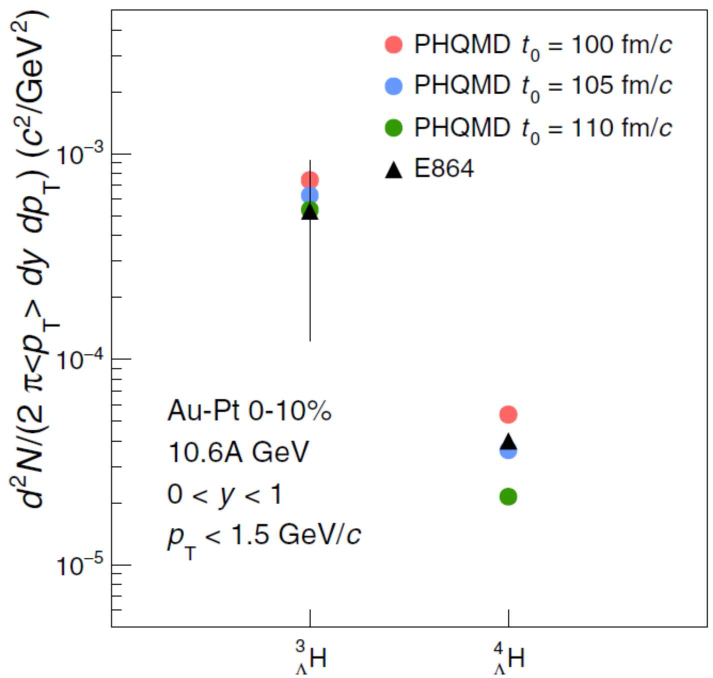


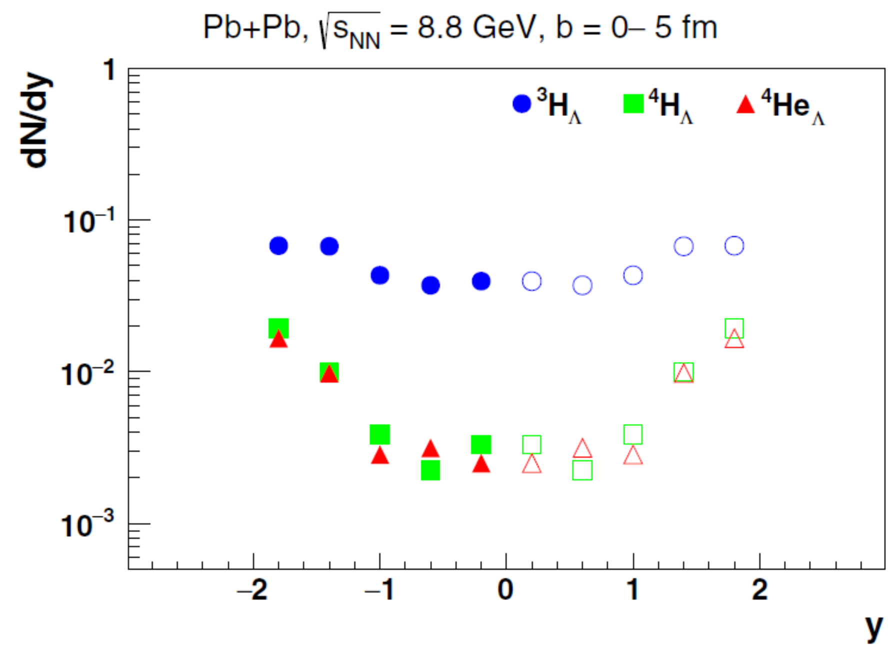
$$t = t_0 \cosh(y)$$

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





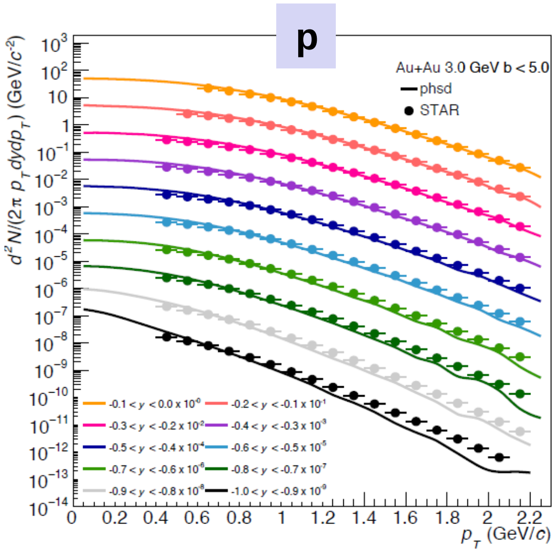
- Assumption on nucleon-hyperon potential: $V_{N\Lambda} = 2/3\ V_{NN}$

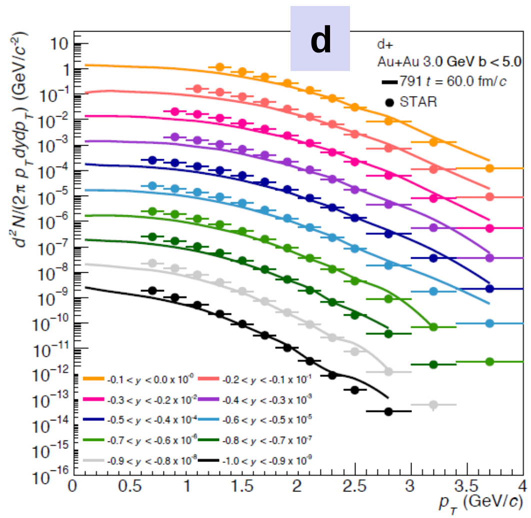
S. Gläßel et al., Phys. Rev. C 105 (2022) 1

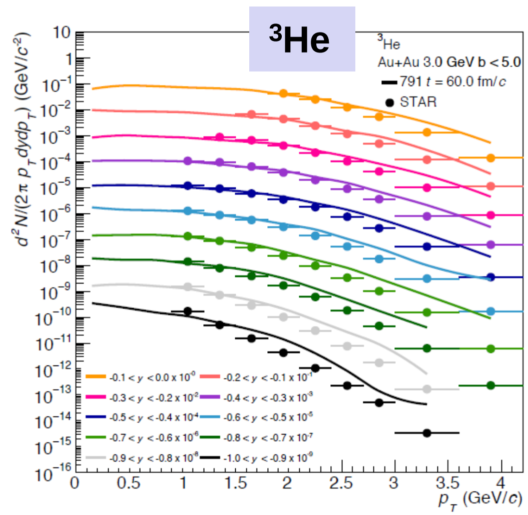
Light cluster production at $s^{1/2}$ = 3 GeV

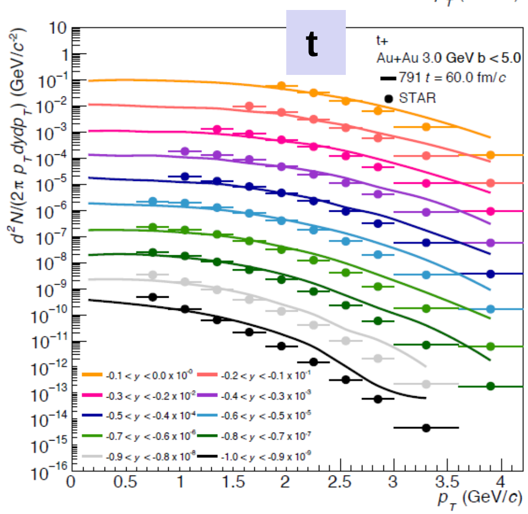
The PHQMD **comparison with recent (preliminary) STAR fixed target p_T distribution** of **p, d, t, ^{3}H, ^{4}H** from Au+Au central collisions at $\sqrt{s} = 3$ GeV

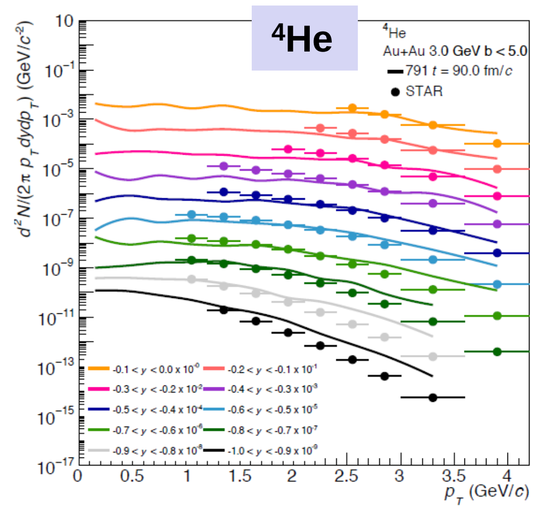
PHQMD: t = 60 fm/c











(preliminary) STAR data – talk by Hui Liu at QM'2022

➔ **Good description of cluster production**

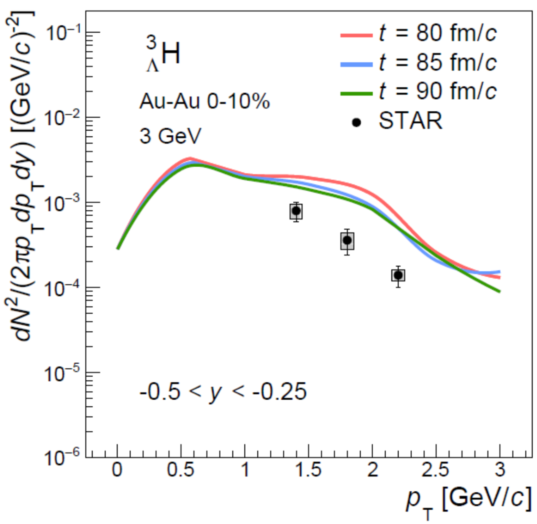
S. Gläßel, PHQMD calculations

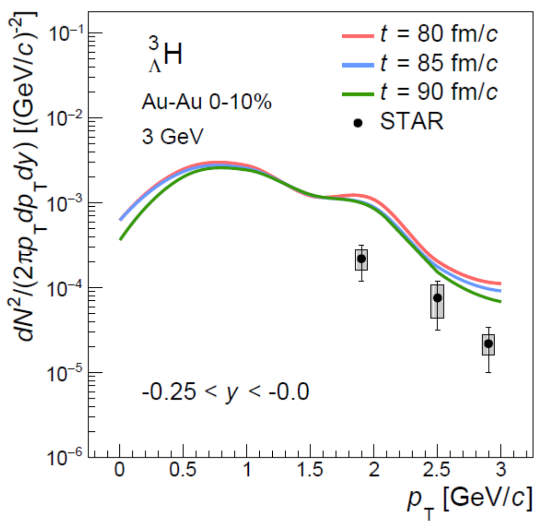
Hypernuclei production at $s^{1/2}$ = 3 GeV

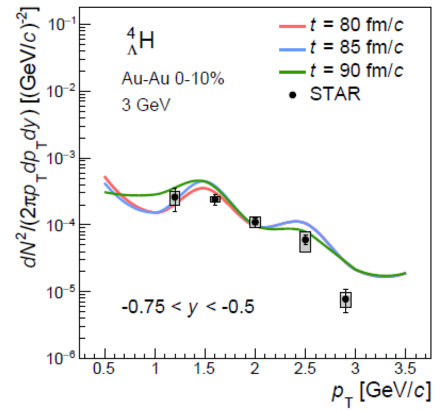
The PHQMD comparison with recent STAR fixed target p_T distribution of $^3H_\Lambda$, $^4H_\Lambda$ from Au+Au central collisions at $\sqrt{s}$ =3 GeV

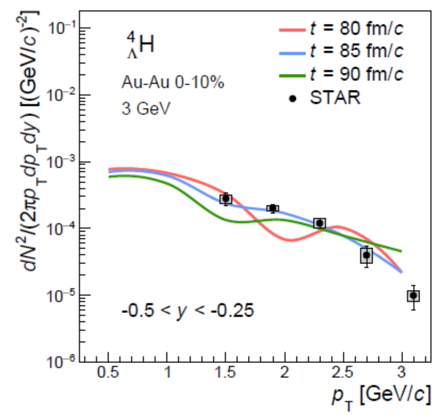
STAR: Phys. Rev. Lett. 128, 202301 (2022)

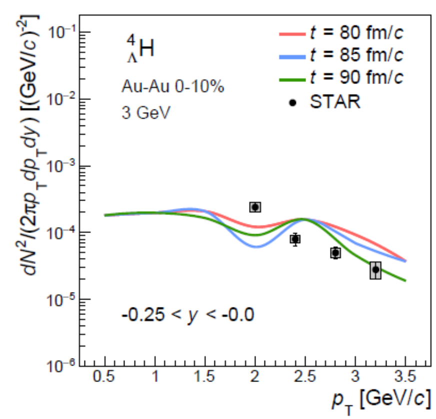
- **Assumption for nucleon-hyperon potential: $V_{N\Lambda}$ = 2/3 V_{NN}**











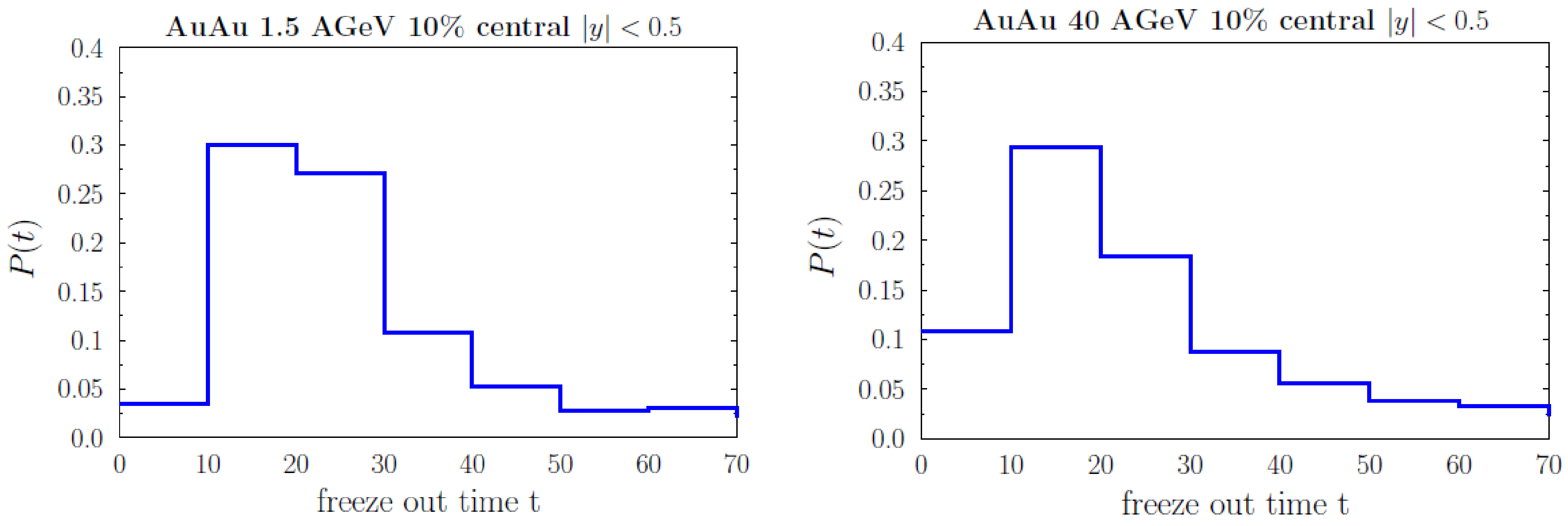
➔ Reasonable description of hypernuclei production at $\sqrt{s}$ =3 GeV

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

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**



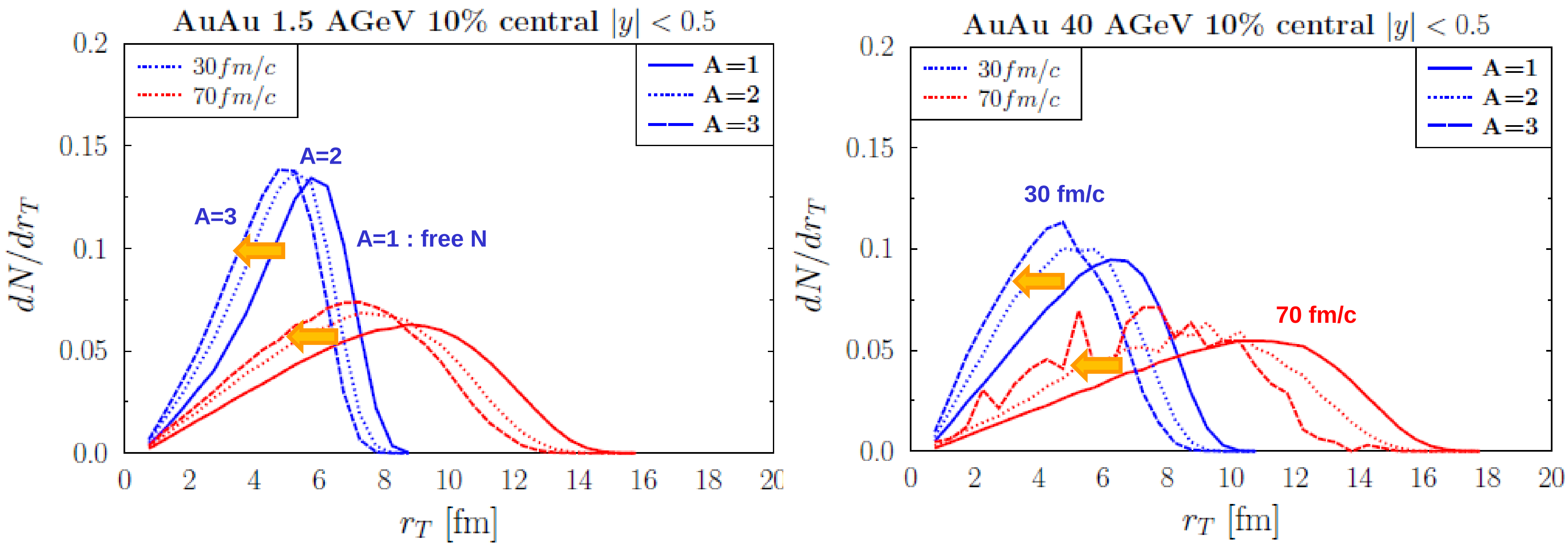
➔ **Freeze-out time of baryons in Au+Au at 1.5 AGeV and 40 AGeV:**

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

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

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

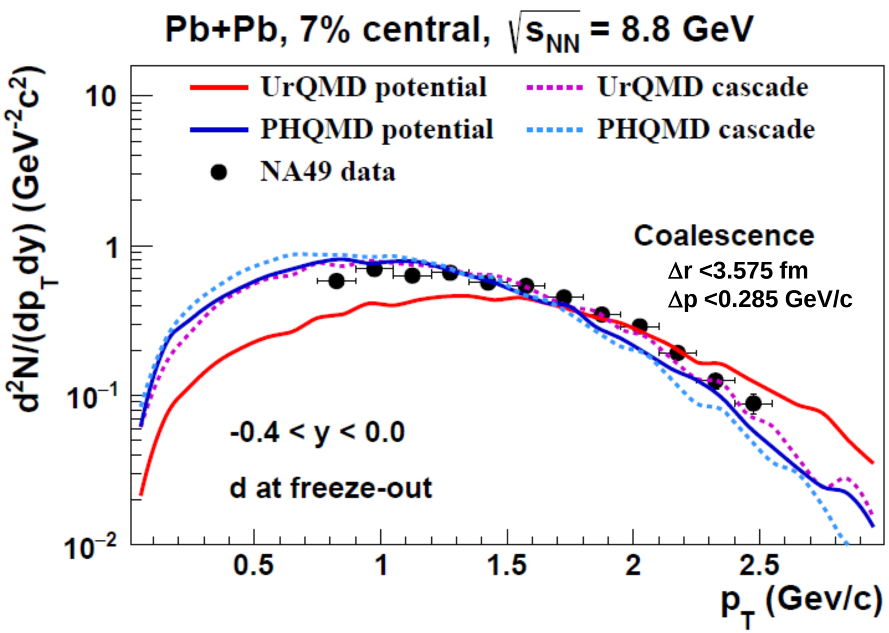


➔ **Transverse distance profile** of **free nucleons and clusters are different**!
Clusters are mainly formed behind the "front" of free nucleons of the expanding fireball

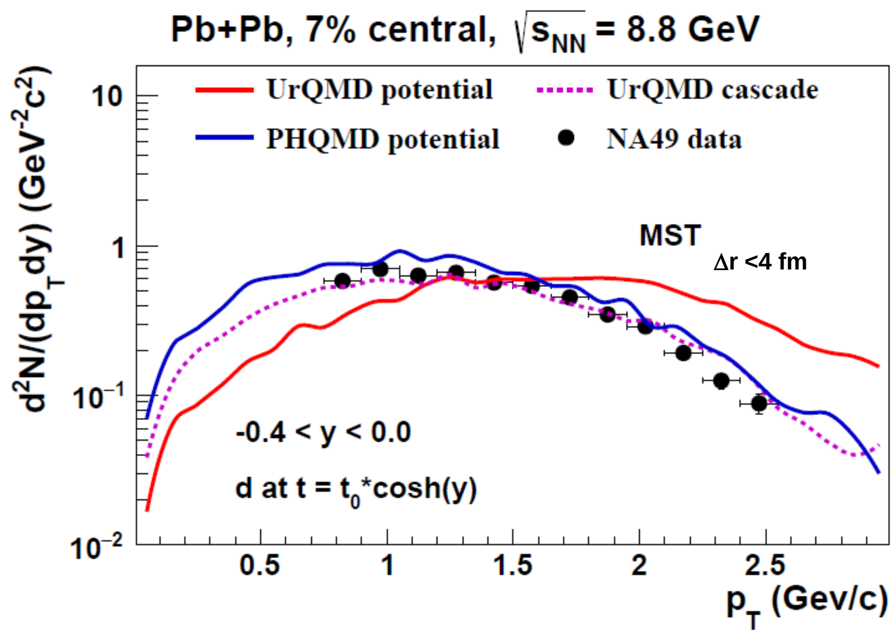
S. Gläßel et al., Phys. Rev. C 105 (2022) 1

Comparison of the coalescence and MST for d

Coalescence



MST

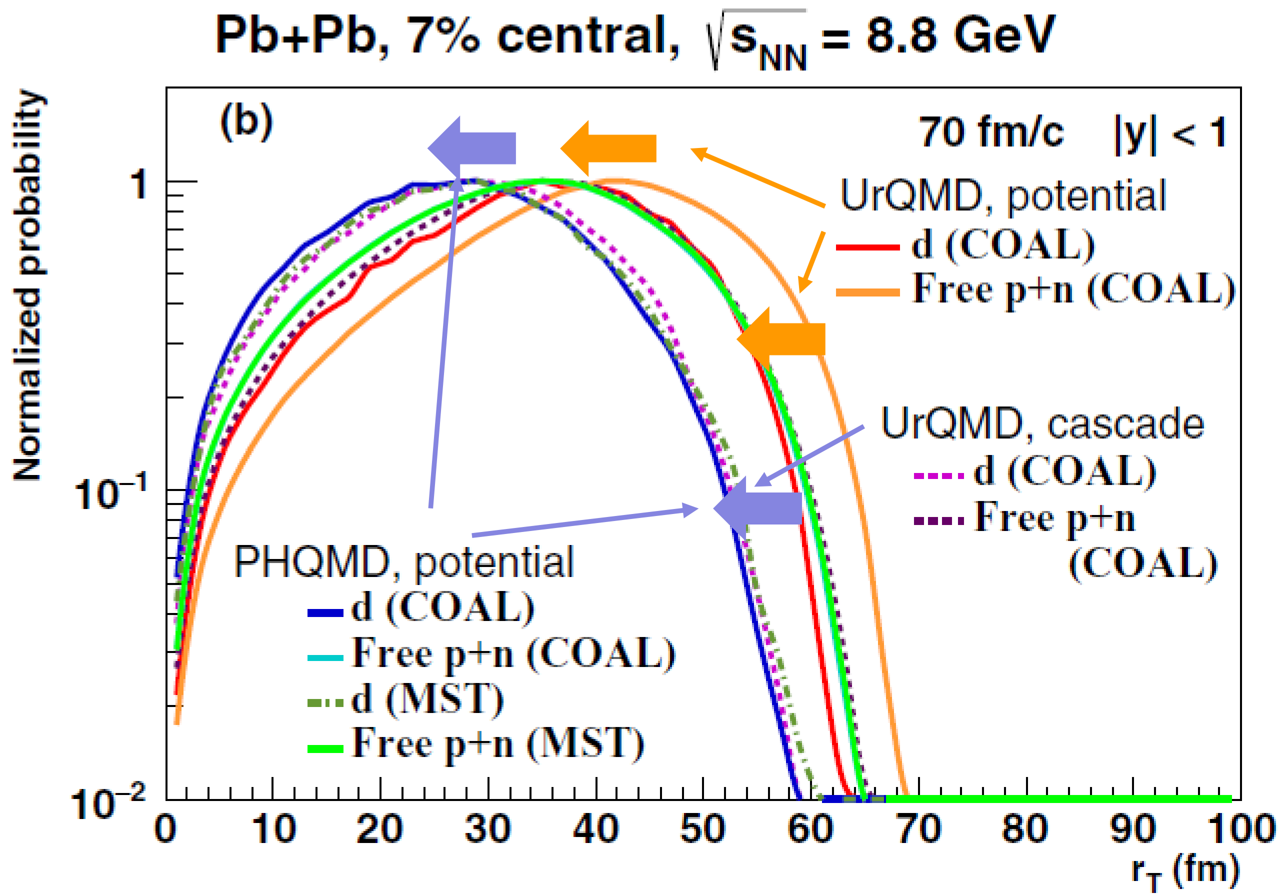


➔ Coalescence and MST give very similar multiplicities and y- and p_T –distributions
➔ PHQMD and UrQMD results in the cascade mode are very similar
➔ Deuteron production is sensitive to the realization of potential in transport approaches

Coalescence in UrQMD – cf. talk by Tom Reichert (PA-RES, 14.04.22)

V. Kireyeu, J. Steinheimer, M. Bleicher, J. Aichelin, E.B., Phys. Rev. C 105 (2022) 044909

Comparison of the coalescence and MST for d



➔ **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.**

V. Kireyeu, J. Steinheimer, M. Bleicher, J. Aichelin, E.B., Phys. Rev. C 105 (2022) 044909

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)

- 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.

- Coalescence and MST give very similar deuteron distributions within the PHQMD and UrQMD transport approaches

- In progress: PHQMD with potential + kinetic mechanisms for deuteron production
  POS-RES-08: PHQMD – Gabriele Coci

Thank you for your attention !

Thanks to the Organizers !