Cluster and hyper-cluster production in HICs with PHQMD

S. Gläßel, J. Aichelin, E. Bratkovskaya, V. Kireyeu, V. Voronyuk, C. Blume, G. Coci, V. Kolesnikov, M. Winn

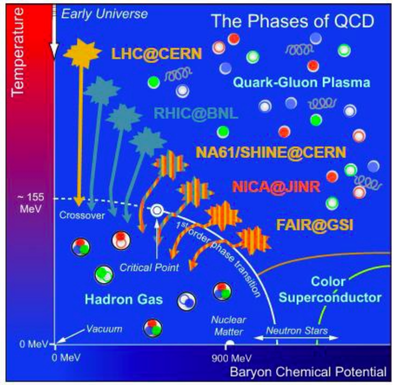
Motivation

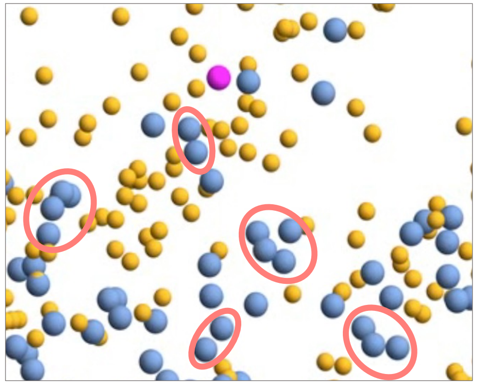
Exploring the **QCD-phase-diagram** with clusters as **experimental observables.**

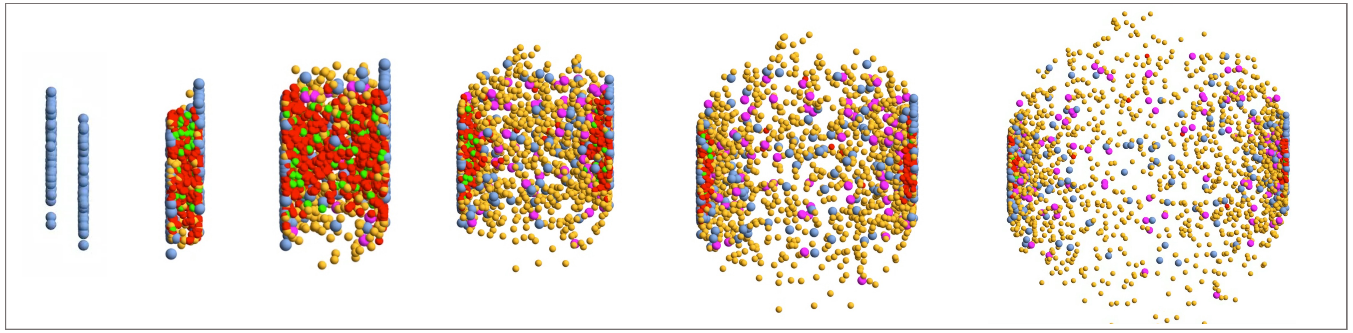
Understanding the **production of clusters** in relativistic heavy-ion collisions:
How can **weakly bound** clusters survive in the **hot and dense environment** of a HICs?

Challenge

Modeling the **time evolution of cluster formation** and the origin of their production.







DFG-grant BL 982/3-1 & DFG-grant BR 4000/7-1

PHQMD: dynamical evolution of HIC & cluster formation

PHSD + QMD + MST

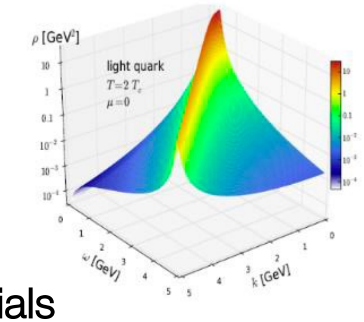
PHSD	QMD	MST
Interactions of hadrons Propagation of mesons QGP-phase	Propagation of baryons	Cluster identification

Relativistic considerations

off-shell generalized transport equations based on **Kadanoff-Baym equations**

Dynamical Quasi Particle Model

quark / gluon spectral function $\rho_q\,(p,\omega)$:



mean-field potentials

Correlations between baryons

n-body transport approach

propagation of Gaussian wave functions ψ_i

QMD wave function for N particles $\psi_N = \prod_{i=1}^{N} \psi_i$

Skyrme potential

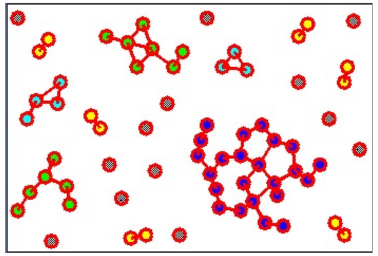
$$\langle V_{Skyrme}(\mathbf{r_{i0}},t)\rangle = \alpha\left(\frac{\rho_{int}(\mathbf{r_{i0}},t)}{\rho_0}\right) + \beta\left(\frac{\rho_{int}(\mathbf{r_{i0}},t)}{\rho_0}\right)^{\gamma}$$

interaction density $\rho_{int}(\mathbf{r_{i0}},t)$

=> formation of clusters due to potential interactions

Minimum Spanning Tree

1. Two baryons are bound if $|r_i - r_j| < 4.0$ fm
2. baryon is bound to cluster if bound with at least one baryon of cluster



PHQMD: J. Aichelin et al., PRC 101 (2020) 044905 & S. Gläßel et al., PRC 105, (2022) 014908

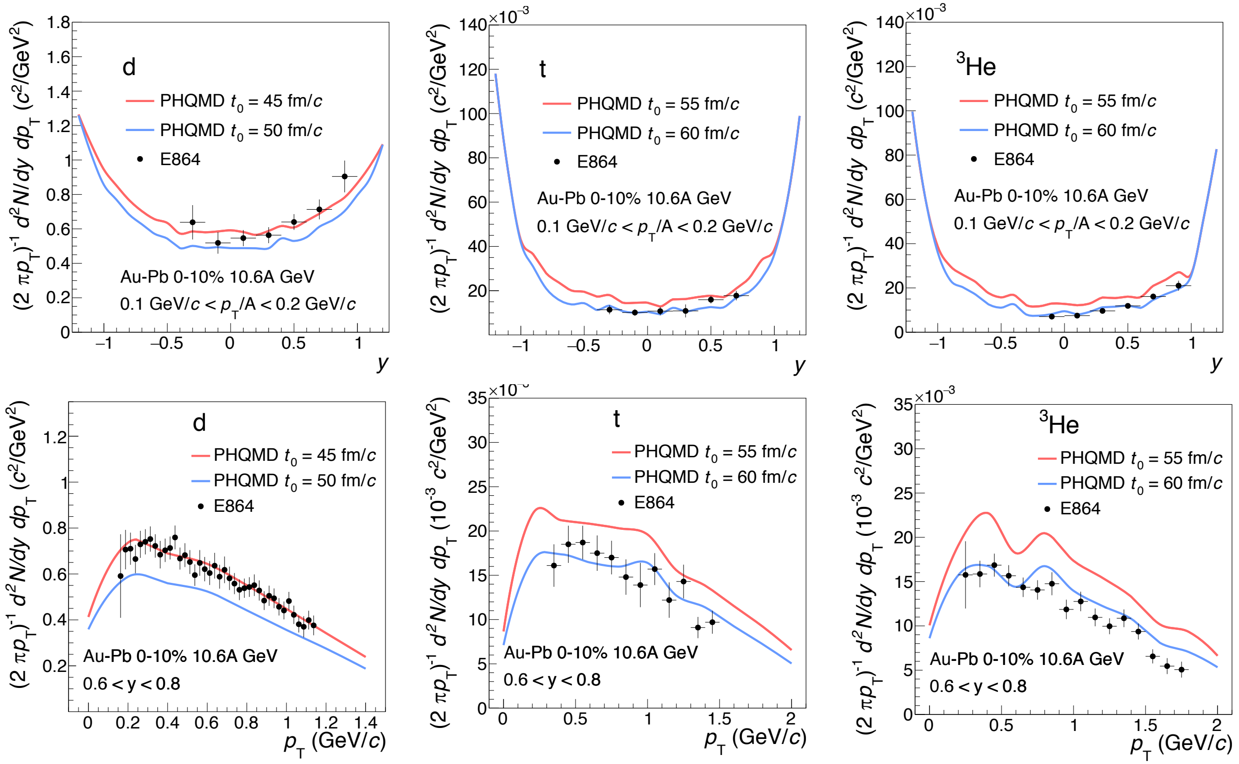
PHSD: W. Cassing, E.L. Bratkovskaya, Nucl. Phys. A 831, 215 (2009) MST: J. Aichelin, Phys. Rept. 202, 233 (1991)

PHQMD-simulations and experimental data (AGS & SPS)

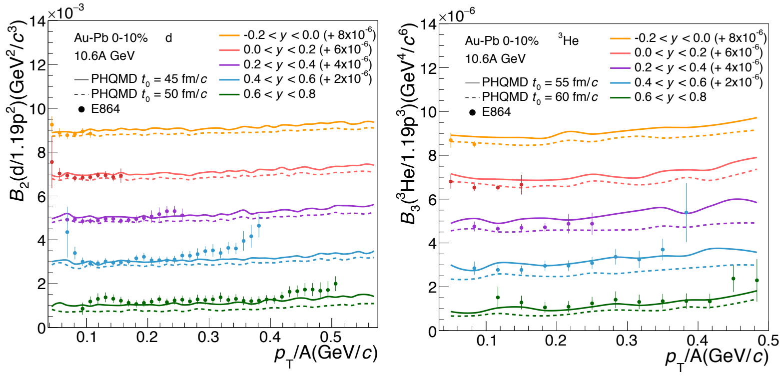
E864 data: Au-Pb 0-10 % 10.6 AGeV

y

p_T

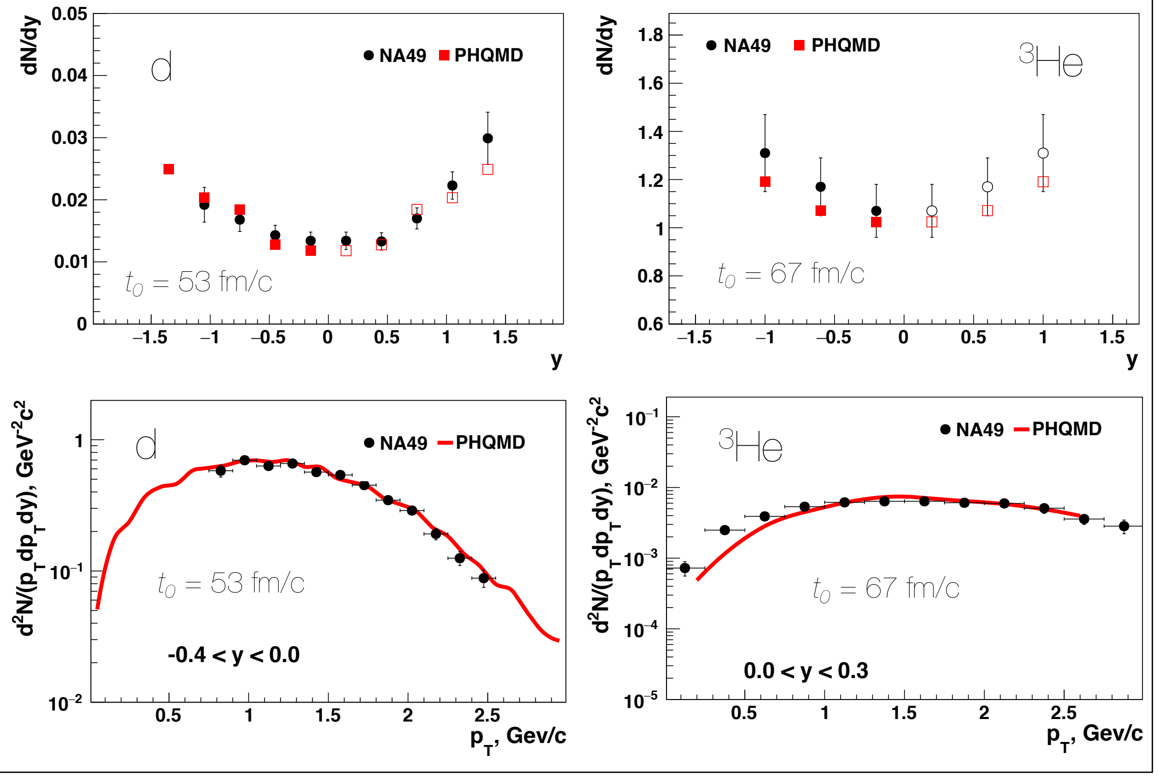


B_A



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

NA49 data: Pb-Pb 0-10 % 40 AGeV



=> Experimental rapidity- & p_T-distributions for light nuclei are reproduced at E_{lab} = 10.6 AGeV & 40 AGeV.

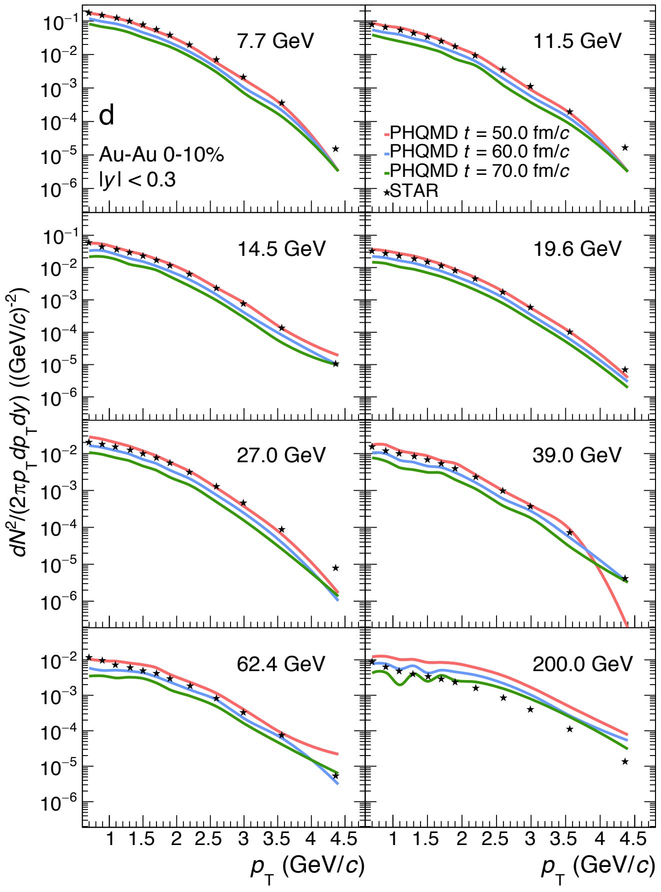
=> Probability that baryons with p_T/A form a cluster with size A almost independent of p_T (only slight increase).

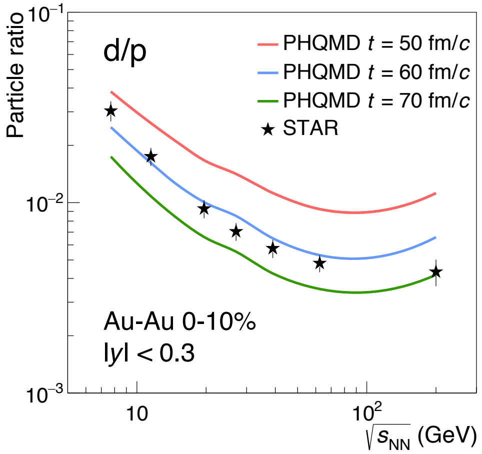
E864: T. A. Armstrong et al. (E864), Phys. Rev. C 61, 064908 (2000)

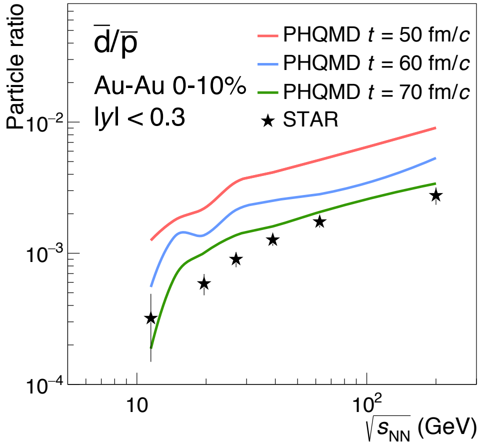
NA49: T. Anticic et al. (NA49), Phys. Rev. C 94, 044906 (2016)

PHQMD-simulations and experimental data (RHIC)

STAR data: Au-Au 7.7– 200 GeV 0-10 % - light nuclei



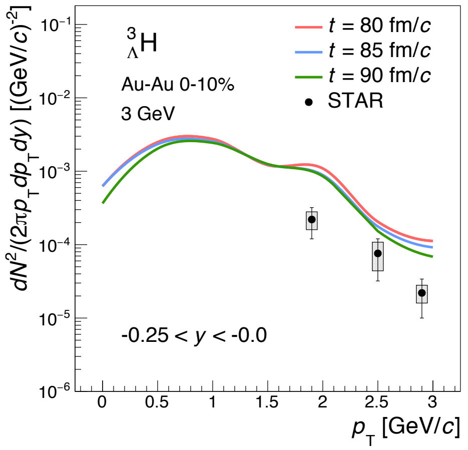


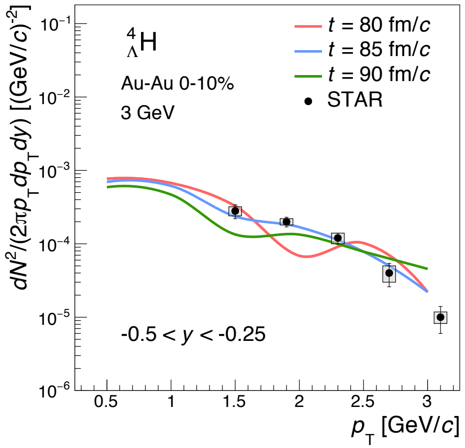


=> p_T-distributions for deuterons are reproduced for $\sqrt{s}$ = 7.7 – 200 GeV.

=> d/p & $\bar{d}/\bar{p}$ are reproduced for $\sqrt{s}$ = 4.85 to 200 GeV.

STAR data: Au-Au 3 GeV 0-10 % - hypernuclei





=> Trend of experimental STAR* ${}^{3}_{\Lambda}H$ & ${}^{4}_{\Lambda}H$ p_T- spectra is well produced.

=> Yields are slightly overpredicted.

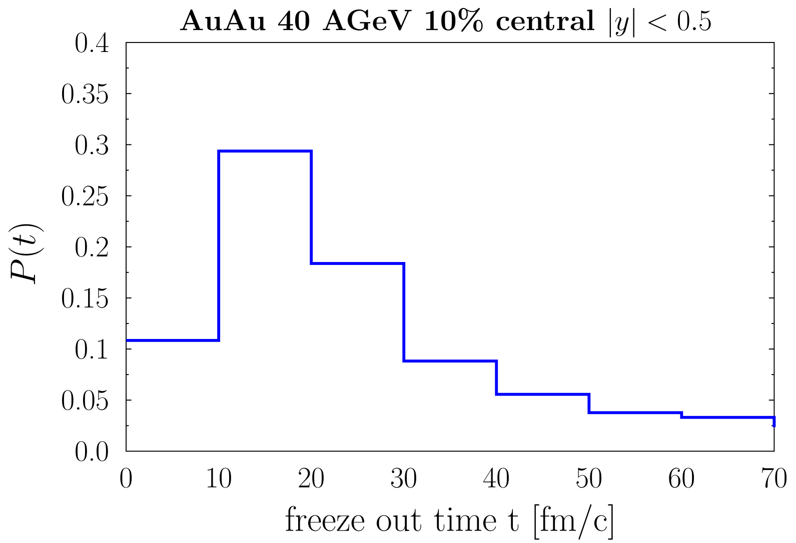
=> Simple hyperon-nucleon interaction in PHQMD (= 2/3 of the nucleon-nucleon interaction)

J. Adam et al. (STAR), Phys. Rev. C 99, 064905 (2019)

M. S. Abdallah (STAR Collaboration) et al., arXiv:2110.09513.

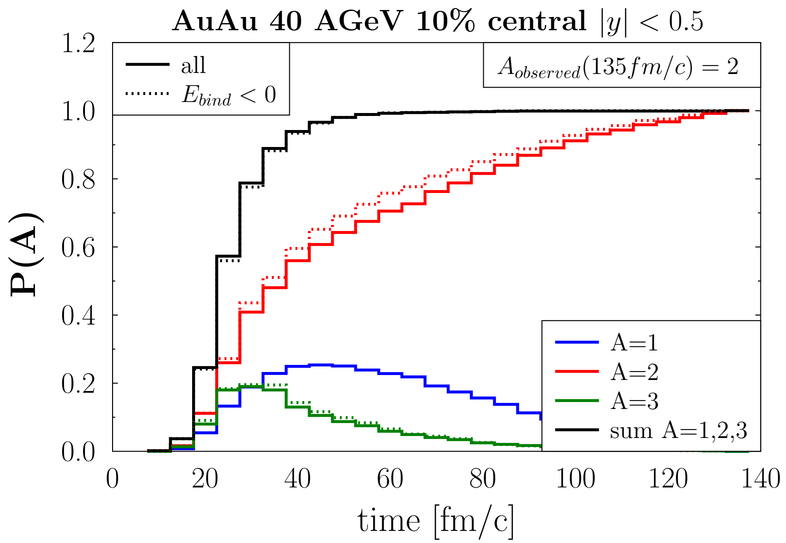
When & where are clusters formed?

freeze-out time of baryon (last collision)



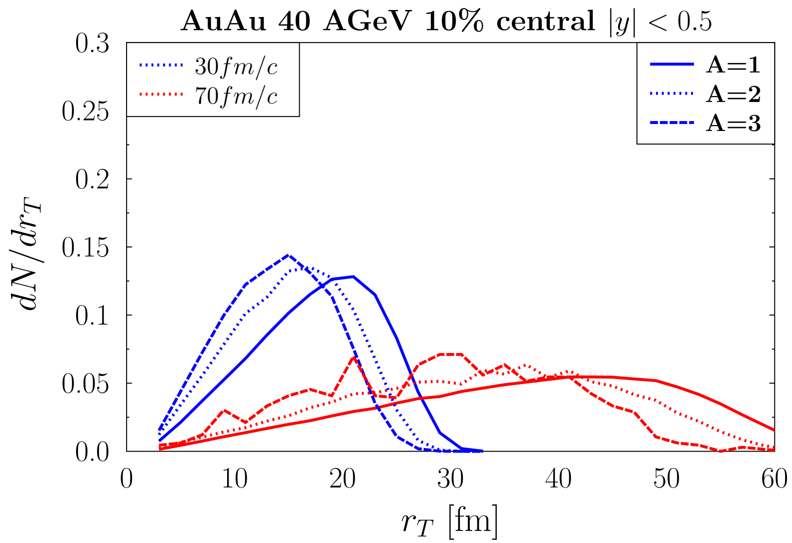
=> Collisions of baryons essentially over after t = 40 fm/c

formation time of stable clusters



=> Clusters formed shortly after collisions have ceased

transverse distance to fireball center



=> Clusters formed behind the front of expanding energetic hadrons

Since the 'fire' is not at the same place as the 'ice', clusters can survive.