Clusters in transport approaches
(and psMST library)

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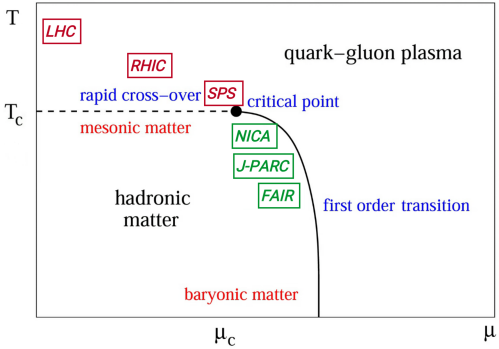
Outline

Introduction

Our Place in the Universe

Phase diagram of strongly interacting matter



Turko, L. "NA61/SHINE Experiment—Program beyond 2020", Particles 2018, 1, 296-304

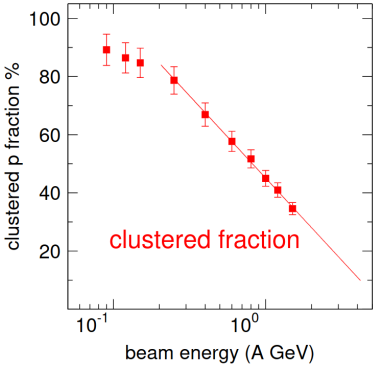
Early Universe:

- Large Hadron Collider (LHC)
- Relativistic Heavy Ion Collider (RHIC)

Neutron star mergers:

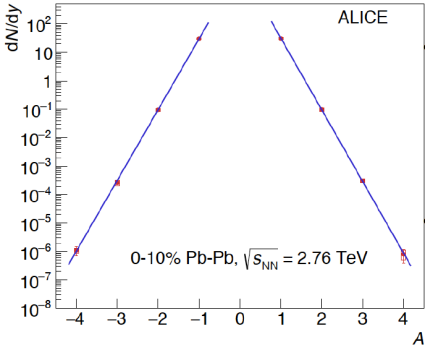
- Super Proton Synchrotron (SPS)
- Nuclotron based Ion Collider fAcility (NICA)
- Facility for Antiproton and Ion Research (FAIR)

Clusters in HIC: "Ice in Fire"



Nucl.Phys.A 848 (2010) 366-427

Low energy: up to 20% of protons in central Au+Au collisions are bound into the clusters.



Nucl.Phys.A 971 (2018) 1-20

High energy HIC – "Ice in a fire" puzzle: how the weakly bound objects can be formed in a hot environment?

Basic models for heavy-ion collisions

- **Statistical models**
  System is described by a (grand-) canonical ensemble of non-interacting fermions and bosons in thermal and chemical equilibrium. **No dynamics.**
- **Hydrodynamical models**
  Conservation laws + equation of state; assumption of local thermal and chemical equilibrium. **Simplified dynamics.**
- **Transport models**
  Based on transport theory of relativistic quantum many-body systems. Actual solutions – Monte Carlo simulations. **Full dynamics. Very complicated.**

Microscopic transport models provide a unique dynamical description of nonequilibrium effects in heavy-ion collisions.

Basic models for heavy-ion collisions

In order to understand the microscopic origin of clusters formation one needs:

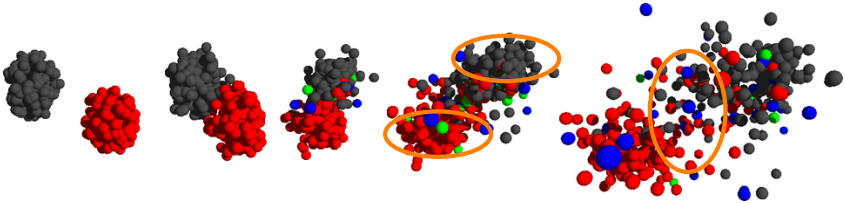
- a realistic model for the dynamical time evolution of the HIC
- dynamical modeling of cluster formation based on interactions

Cluster formation is sensitive to nucleon dynamics $\longrightarrow$ one needs to keep initial and final nucleon correlations by realistic nucleon-nucleon interactions in transport models:

- **Quantum-Molecular Dynamics (QMD)** – allows to keep correlations.
- **Mean-filed (MF) based models** – correlations are smeared out.

The origin of clusters

Projectile/target spectators: heavy cluster formation
Midrapidity: light clusters



IQMD: Ch. Hartnack

(Anti-)hypernuclei production:

- at mid-rapidity by Λ coalescence during expansion
- at projectile/target rapidity by re-scattering/absorption of Λ by spectators

Cluster

Phase-space Minimum Spanning Tree (psMST)

"Cluster dynamics studied with the phase-space Minimum Spanning Tree approach", V. Kireyeu, *Phys. Rev. C 103, 054905 (2021), arXiv:2103.10542*

- **Open source** C++ library licensed under the terms of the **GNU GPLv3**.
- Based on the idea of the **MST** algorithm (**proximity criteria**).
- **Momentum criteria**: psMST can be used to study the influence of the **momentum** correlations of nucleons and hyperons for the formation of (hyper)nuclei.
- Can be applied to **all transport models** which propagate hadrons.

Previously "Naive Clusterization", "Kinetic Clusterization".

Models and systems

Models: **PHSD-4.0**, **PHQMD-2.0**, **SMASH-2.0** and **UrQMD-3.4**.

Systems: ^{40}Ar+^{27}Al, ^{40}Ar+^{64}Cu, ^{40}Ar+^{119}Sn, ^{40}Ar+^{208}Pb at $E_{lab} = 3.2$ AGeV.

Two time steps: 40 and 150 fm/c.

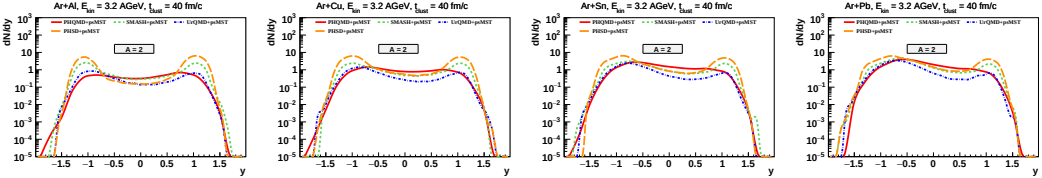
Statistics: 25k events for each system within each model.

psMST: pure "MST" mode, coordinate space information without momentum checks

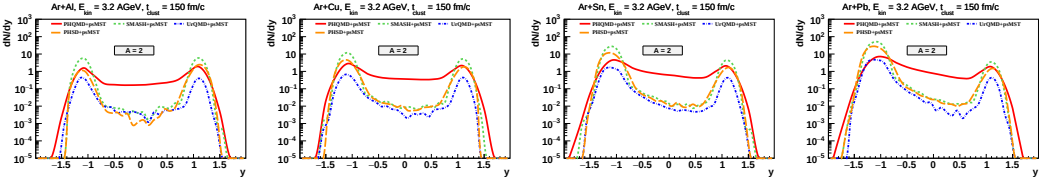
A = 2

Ar+Al | Ar+Cu | Ar+Sn | Ar+Pb

40 fm/c



150 fm/c



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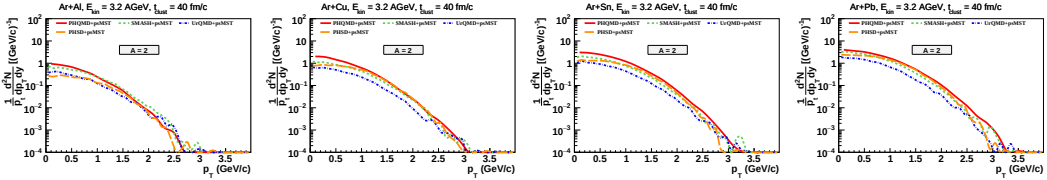
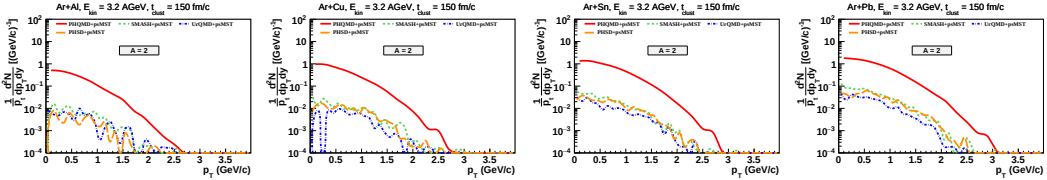


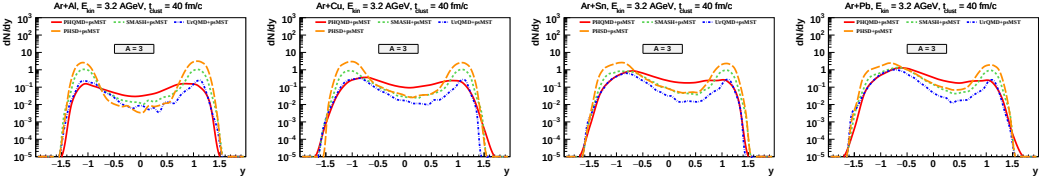
150 fm/c



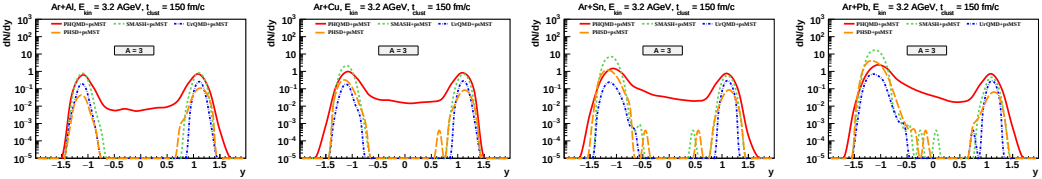
A = 3

Ar+Al | Ar+Cu | Ar+Sn | Ar+Pb

40 fm/c



150 fm/c



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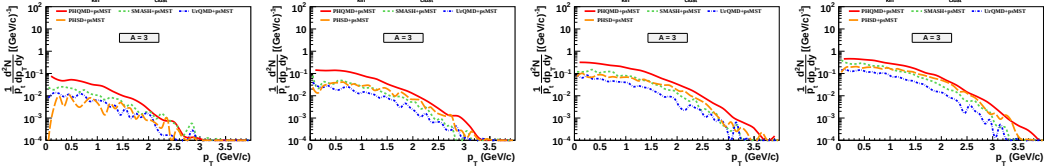
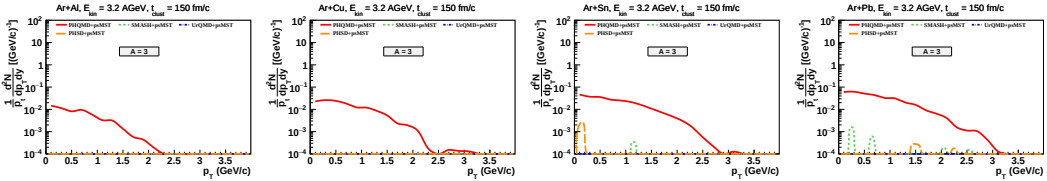


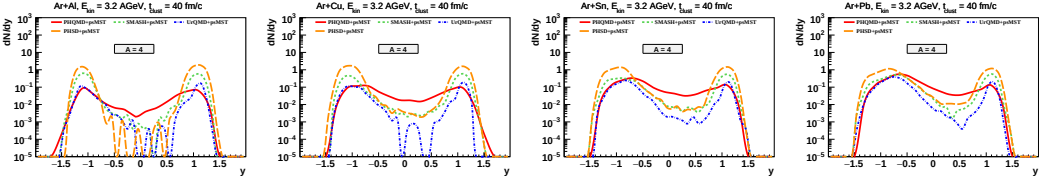
150 fm/c



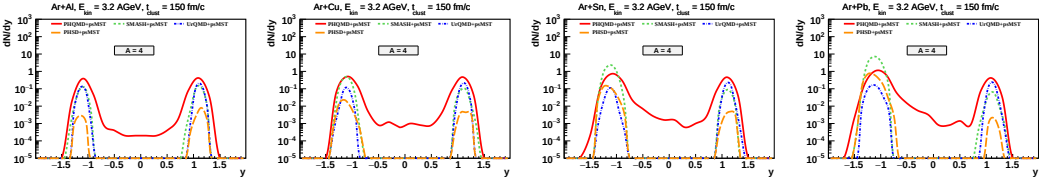
A = 4

Ar+Al | Ar+Cu | Ar+Sn | Ar+Pb

40 fm/c



150 fm/c



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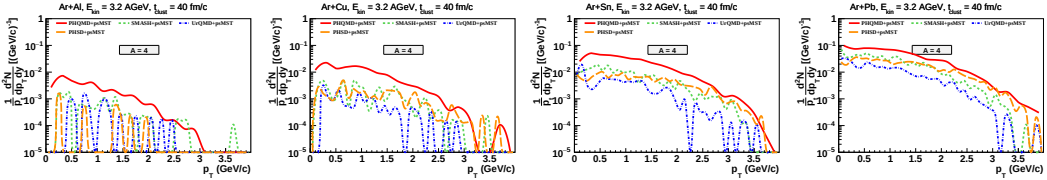
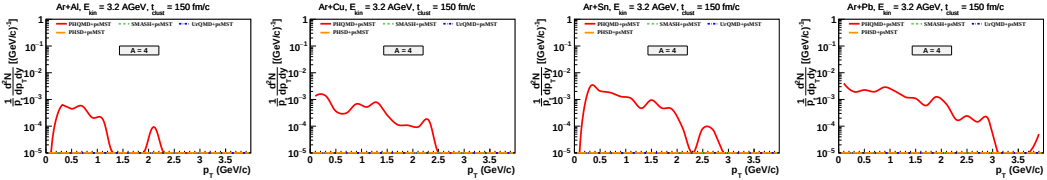


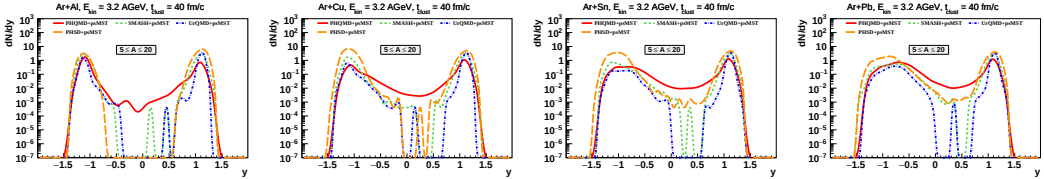
150 fm/c



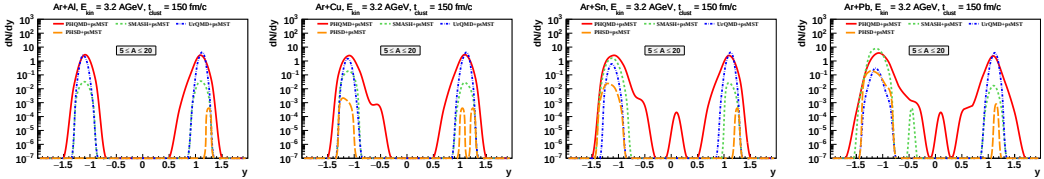
$5 \leq A \leq 20$

Ar+Al | Ar+Cu | Ar+Sn | Ar+Pb

40 fm/c



150 fm/c



Conclusions

Conclusions

- The **psMST** algorithm has been applied to **QMD-based PHQMD-2.0** (density dependent 2-body potential), mean field based **PHSD-4.0** (mean-field potential for baryons) and two models **SMASH-2.0** and **UrQMD-3.4**, both in the cascade mode without potentials.
- The **PHQMD with psMST** predicts more clusters in the mid-rapidity region than the other models $\longrightarrow$ the n-body quantum molecular dynamics allows to keep the potential induced spacial correlations of baryons.
- The **psMST** library is an **open source tool** which can be used in the stand-alone mode or can be integrated into experimental software frameworks for the simulations of the clusters production.

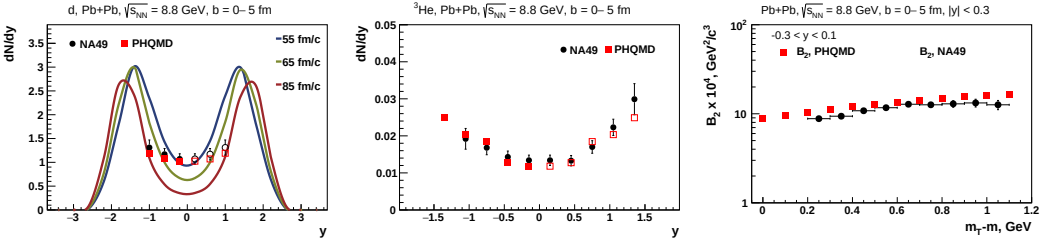
Clusters at low energies are sensitive to the potential interactions.

Extra

Further reading

- **PHSD:** W. Cassing, E.L. Bratkovskaya, *Nucl. Phys. A 831, 215 (2009), arXiv:0907.5331*
- **PHQMD, MST, SACA:** J. Aichelin et. al., *Phys. Rev. C 101, 044905, arXiv:1907.03860*
- **FRIGA:** A. Le Fèvre et al., *Phys. Rev. C 100, 034904, arxiv:1906.06162*
- **SMASH:** J. Weil et al., *Phys. Rev. C 94, 054905 (2016), arXiv:1606.06642*
  Used SMASH code version: *https://doi.org/10.5281/zenodo.4336358*
- **UrQMD:** M. Bleicher et al., *J. Phys. G 25, 1859 (1999), arXiv:hep-ph/9909407*
  Coalescence in the UrQMD approach: Sukanya Sombun et. al., *Phys. Rev. C 99, 014901 (2019), arXiv:1805.11509*
- **psMST:** `https://gitlab.com/vkireyeu/psmst`

PHQMD current status



"Cluster and hyper-cluster production in relativistic heavy-ion collisions within the PHQMD approach", Susanne Gläßel et al., e-print: *arXiv:2106.14839*

Agreement with the experimental data in the energy range from the E864 to the top RHIC (and even with the new STAR hypernuclei results).