Parton-Hadron-Quantum-Molecular Dynamics (PHQMD) - a Novel Microscopic N-Body Transport Approach for Heavy-Ion Dynamics and Hypernuclei Production

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&
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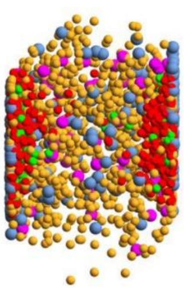
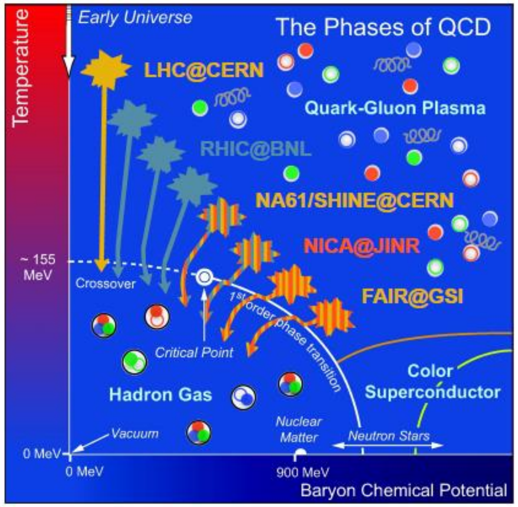


The 18th International Conference on Strangeness in Quark Matter (SQM 2019)
Bari, Italy, 10-15 June, 2019

The ‚holy grail‘ of heavy-ion physics:

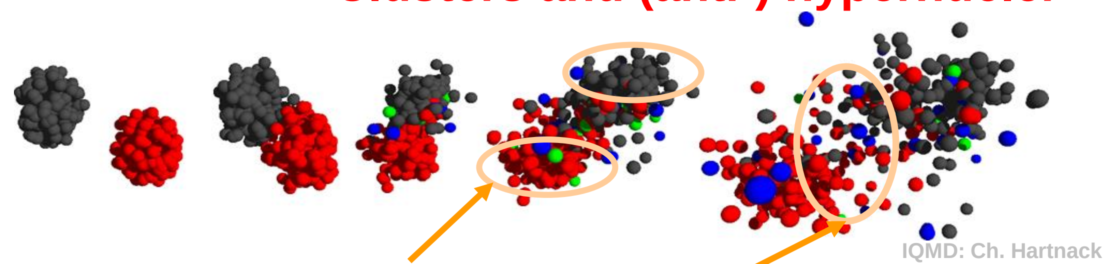
The phase diagram of QCD



Experimental observables:

...

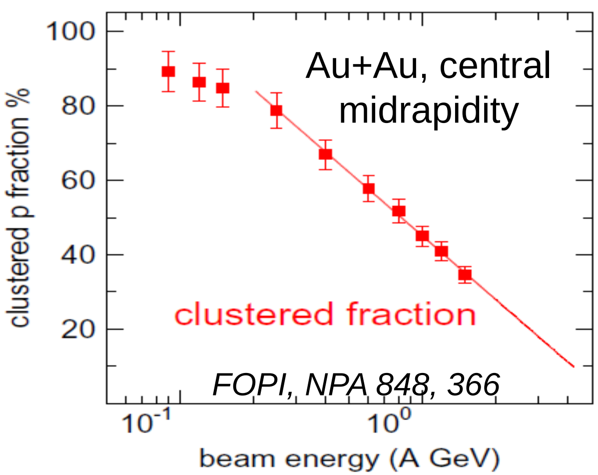
Clusters and (anti-) hypernuclei



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

! Hyperons are created in participant zone

- Clusters are very abundant at low energy

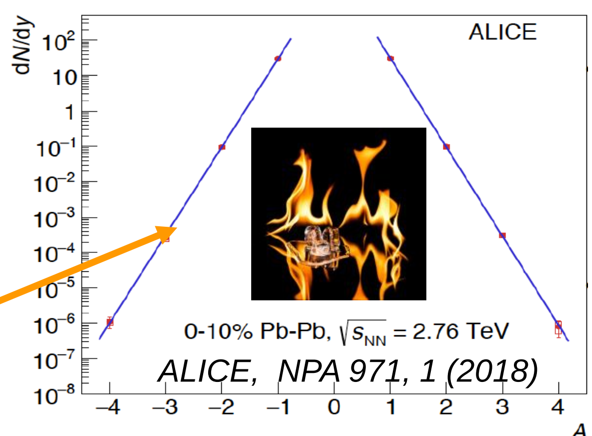


(Anti-) hypernuclei production:

- at mid-rapidity by Λ coalessance during expansion
- at projectile/target rapidity by rescattering/absorption of Λ by spectators

High energy HIC:

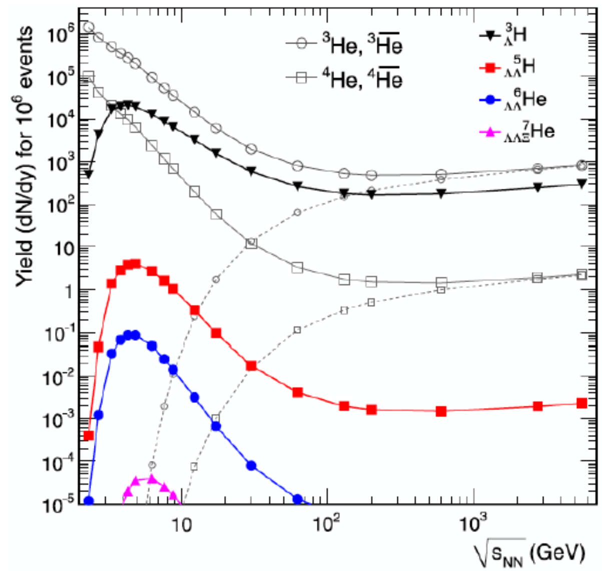
‚Ice in a fire‘ puzzle: how the weakly bound objects can be formed in a hot enviroment ?!



Modeling of cluster and hypernuclei formation

Existing models for clusters formation:

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



- **statistical model:**
  - assumption of thermal equilibrium (difficult to justify at target and projectile rapidity)
  - strong sensitivity of nuclei yields to choice of T_{ch}
  - binding energies are small compared to T_{ch}

- **coalescence model:**
  - determination of clusters at a given point in time by coalescence radii in coordinate and momentum spaces

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

In order to understand the microscopic origin of clusters 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 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

PHQMD

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

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

Parton-Hadron-Quantum-Molecular Dynamics

↓

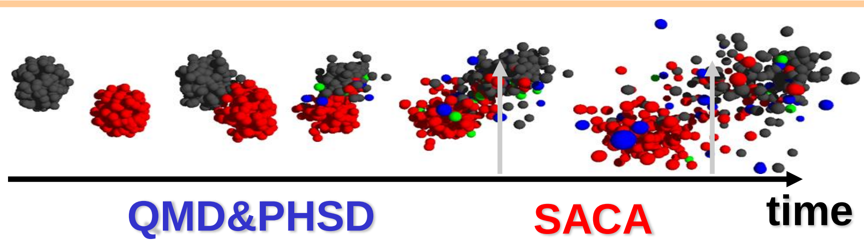
Initialization → propagation of baryons:
QMD (Quantum-Molecular Dynamics)

↓

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

↓

Clusters recognition:
SACA (Simulated Annealing Clusterization Algorithm)
vs. MST (Minimum Spanning Tree)



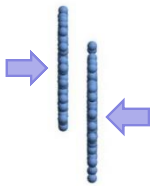
Parton-Hadron-String-Dynamics (PHSD)

collision integral
→ PHQMD

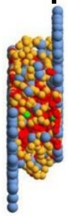
PHSD is a **non-equilibrium microscopic transport approach** for the description of **strongly-interacting hadronic and partonic matter** created in heavy-ion collisions

Dynamics: based on the solution of **generalized off-shell transport equations** derived from Kadanoff-Baym many-body theory

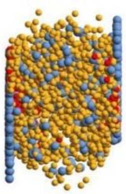
Initial A+A collision



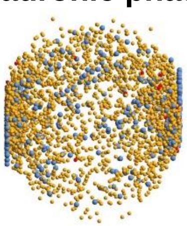
Partonic phase



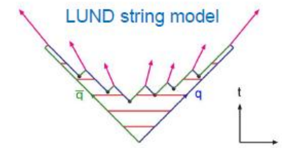
Hadronization



Hadronic phase

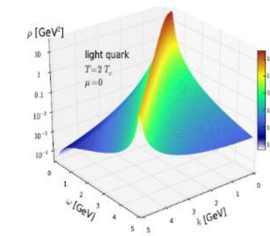


- **Initial A+A collisions** :
  N+N → string formation → decay to pre-hadrons + leading hadrons



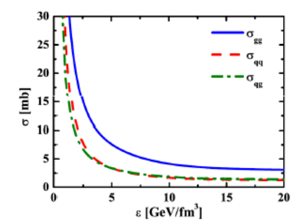
- **Formation of QGP stage** if local $\varepsilon > \varepsilon_{critical}$:
  dissolution of pre-hadrons → partons

- **Partonic phase - QGP:**
  QGP is described by the **Dynamical QuasiParticle Model (DQPM)** matched to reproduce **lattice QCD EoS** for finite T and μ_B (crossover)

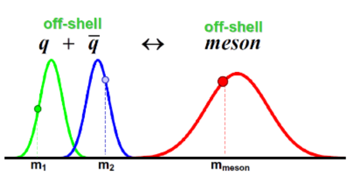


  - **Degrees-of-freedom:** strongly interacting quasiparticles: massive quarks and gluons (g,q,q_{bar}) with sizeable collisional widths in a self-generated mean-field potential

  - **Interactions:** (quasi-)elastic and inelastic collisions of partons



- **Hadronization** to colorless **off-shell mesons and baryons**:
  Strict 4-momentum and quantum number conservation



- **Hadronic phase: hadron-hadron interactions – off-shell HSD**

W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168 (2009) 3

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 $\psi_N = \prod_{i=1}^{N} f(r_i, p_i, r_{i0}, p_{i0}, t)$ **for N particles** **(neglecting antisymmetrization !)**

single-particle Wigner density of the nucleon "*i*"

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

L=4.33 fm²

$$f(\mathbf{r_i}, \mathbf{p_i}, \mathbf{r_{i0}}, \mathbf{p_{i0}}, t) = \frac{1}{\pi^3 \hbar^3} e^{-\frac{2}{L}(\mathbf{r_i} - \mathbf{r_{i0}}(t))^2} e^{-\frac{L}{2\hbar^2}(\mathbf{p_i} - \mathbf{p_{i0}}(t))^2}$$

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

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

QMD interaction potential and EoS

The expectation value of the Hamiltonian:

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

- **Skyrme potential (scalar)* :**

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

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

- **modifed interaction density:**

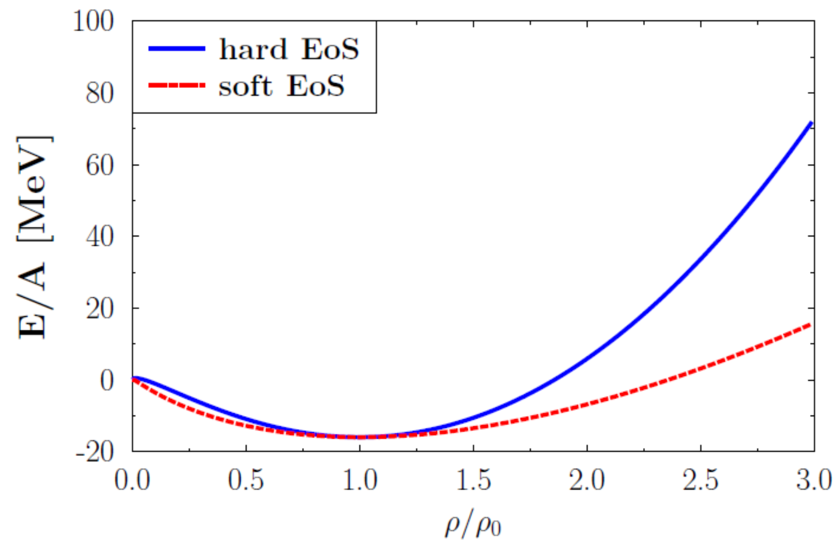
$$\rho_{int}(\mathbf{r}_{i0}, t) \rightarrow C \sum_j \left(\frac{4}{\pi L}\right)^{3/2} e^{-\frac{4}{L}(\mathbf{r}_{i0}^T(t) - \mathbf{r}_{j0}^T(t))^2} \times e^{-\frac{4\gamma_{cm}^2}{L}(\mathbf{r}_{i0}^L(t) - \mathbf{r}_{j0}^L(t))^2},$$

- **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



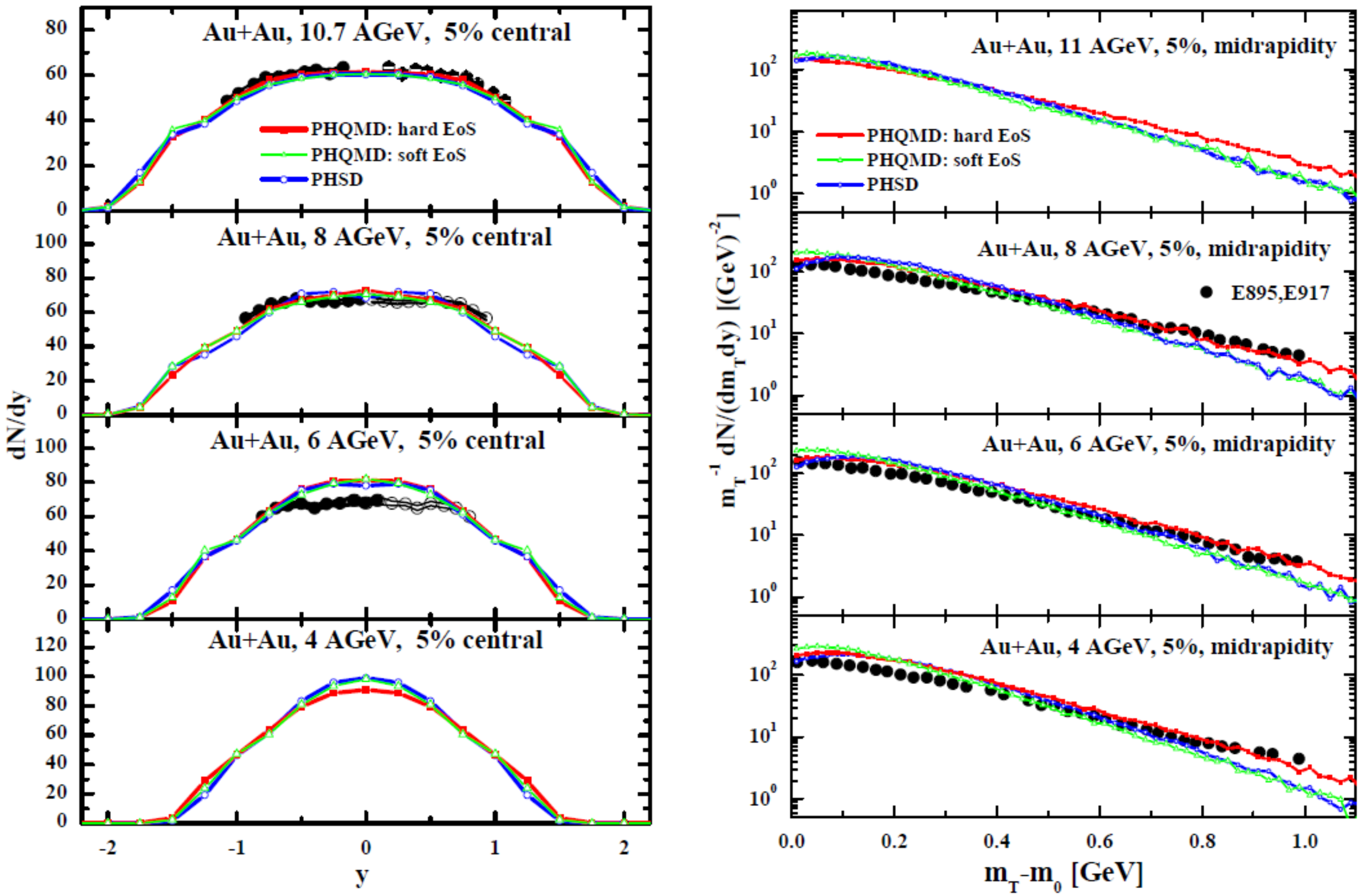
*Work in progress: implementation of momentum dependent potentials

First PHQMD results on ‚bulk‘ observables

Poster 145 by V. Kireyev

PHQMD: ‚bulk' dynamics at AGS/FAIR/NICA energies

The rapidity and m_T distributions for protons from 5% central Au+Au collisions at 4, 6, 8, 10.7 A GeV

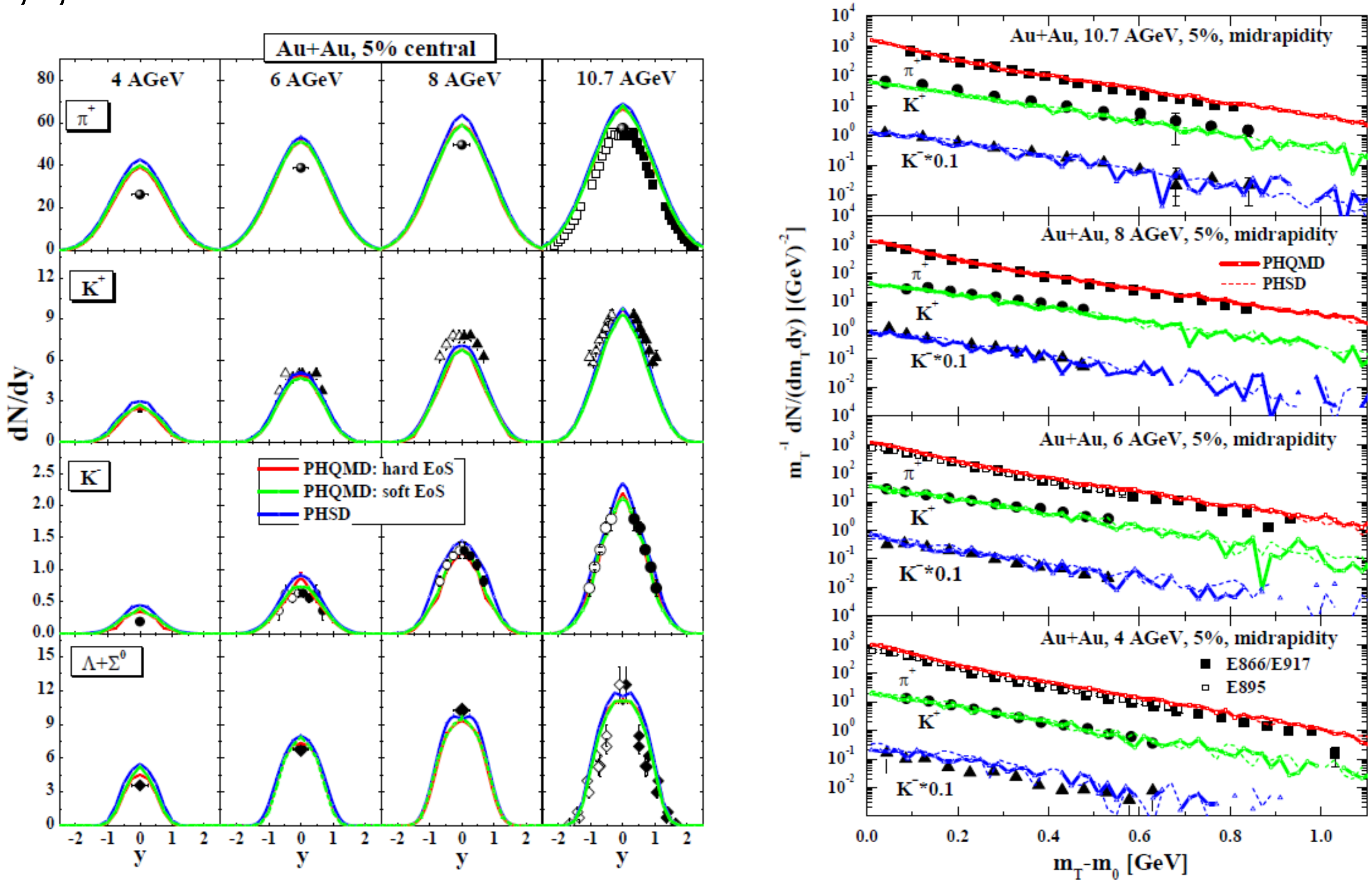


- the influence of EoS is slightly visible in rapidity spectra of protons
- m_T spectra of protons from PHQMD with a 'hard' EoS are harder then with 'soft' EoS
- PHQMD results for the m_T spectra with 'soft' EoS are in a good agreement with the PHSD spectra (using 'soft' EoS in default PHSD4.0 version)

  ➔ QMD and MF dynamics gives similar results with similar EoS

PHQMD: ‚bulk‘ dynamics at AGS/FAIR/NICA energies

The rapidity and m_T distributions for π^+, K^+, K^-, $\Lambda+\Sigma^0$ from 5% central Au+Au collisions at 4, 6, 8, 10.7 A GeV



- the influence of EoS is slightly visible in rapidity and m_T spectra of newly produced hadrons

Clusters in PHQMD:
MST & SACA

Cluster recognition: Minimum Spanning Tree (MST)

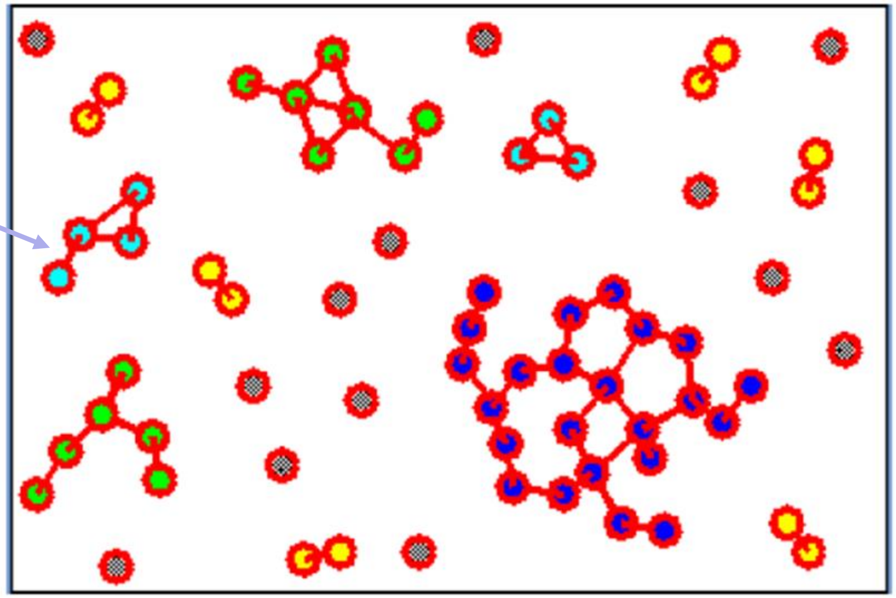
The Minimum Spanning Tree (MST) is a cluster recognition method applicable for the (asymptotic) final states where coordinate space correlations may only survive for bound states.

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

1. Two particles are 'bound' if their distance in coordinate space fulfills

$$\left|\vec{r}_i - \vec{r}_j\right| \leq 2.5\, fm$$

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

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

Simulated Annealing Clusterization Algorithm (SACA)

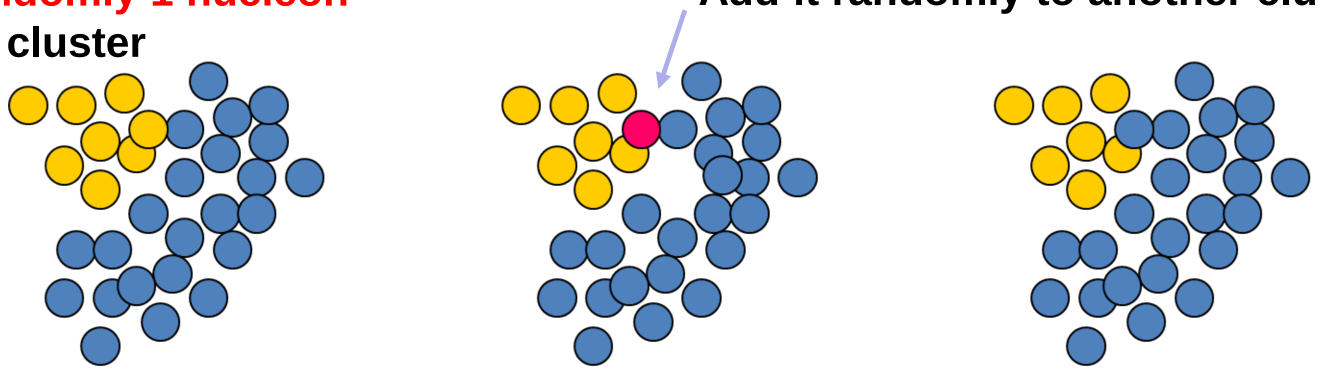
Basic ideas of clusters recognition by SACA:

Based on idea 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:**

Take randomly 1 nucleon out of a cluster

Add it randomly to another cluster



$E=E^{1}_{kin}+E^{2}_{kin}+V^{1}+V^{2}$

$E'=E^{1'}_{kin}+E^{2'}_{kin}+V^{1'}+V^{2'}$

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**

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

Cluster recognition by SACA

- ❑ **SACA searches for the most bound configurations ➔ clusters**
  Clusters are bound by potential interactions between nucleons V_i
  V_i – Skyrme potential (as in PHQMD!)

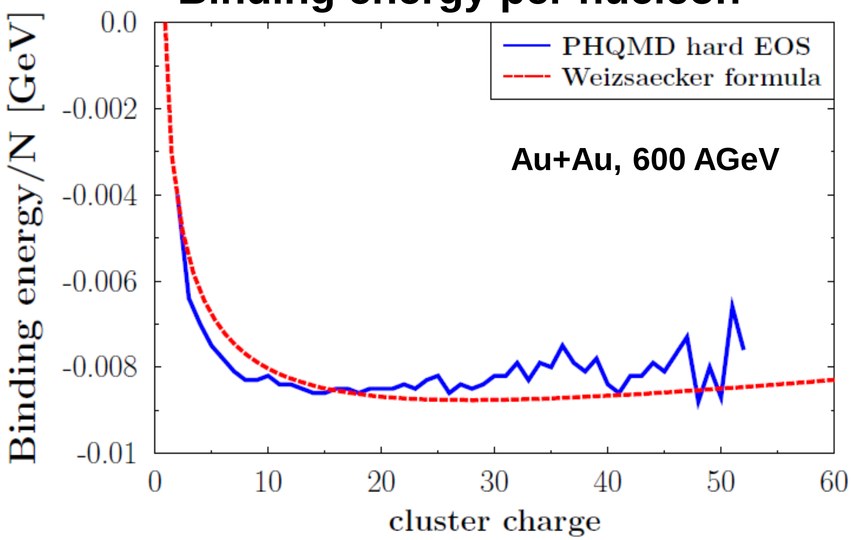
- ❑ **Binding energy (SACA) vs. Weizsaecker formula**

There are two kinds of clusters:

I) Heavy clusters formed from spectator matter close to beam and target rapidity:
- **initial-final state correlations**
- **HIC makes spectator matter unstable**

II) Light clusters formed from participant matter created during the expansion of the fireball ➔
"ice" (E_{bind} ≈-8 MeV/N) in "fire"(T≥ 100 MeV)
- **origin is not well understood**
- **seen from SIS to RHIC**
- **quantum effects may be important**

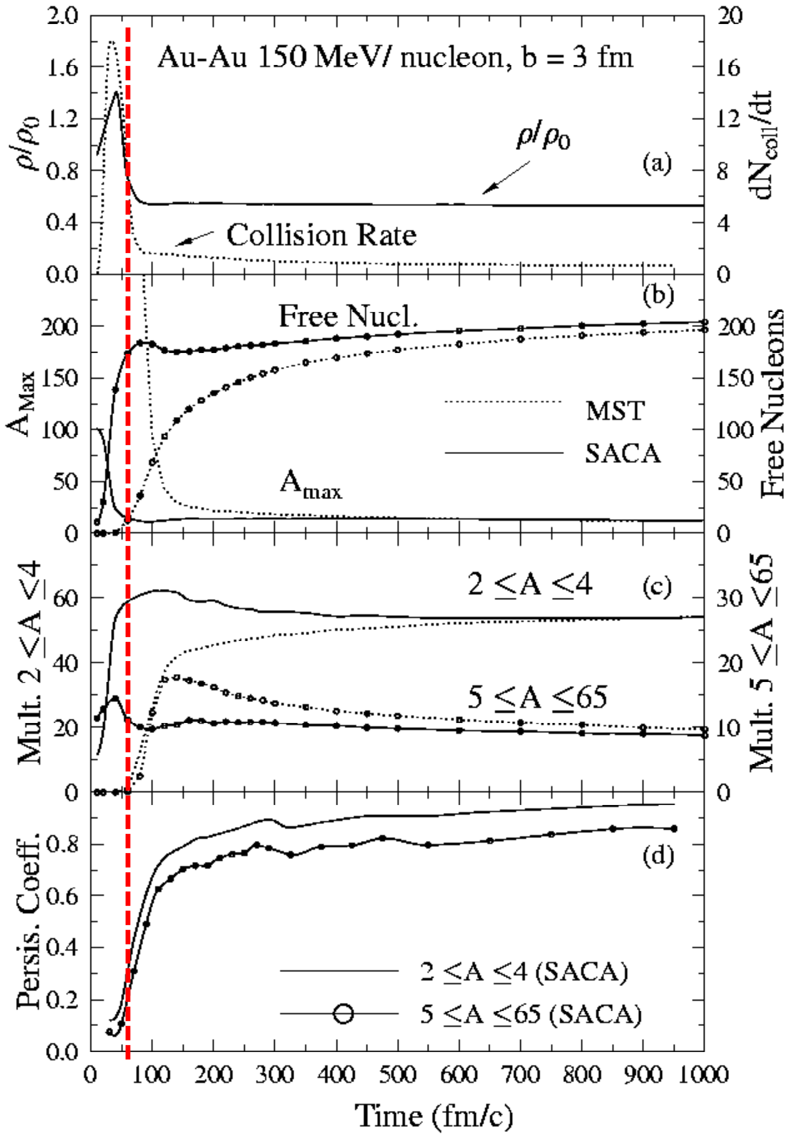
Binding energy per nucleon



➔ average binding energy of the clusters identified by SACA at late times (150 fm/c) is in agreement with Weizsaecker formula

SACA vs MST

IQMD with SACA and MST



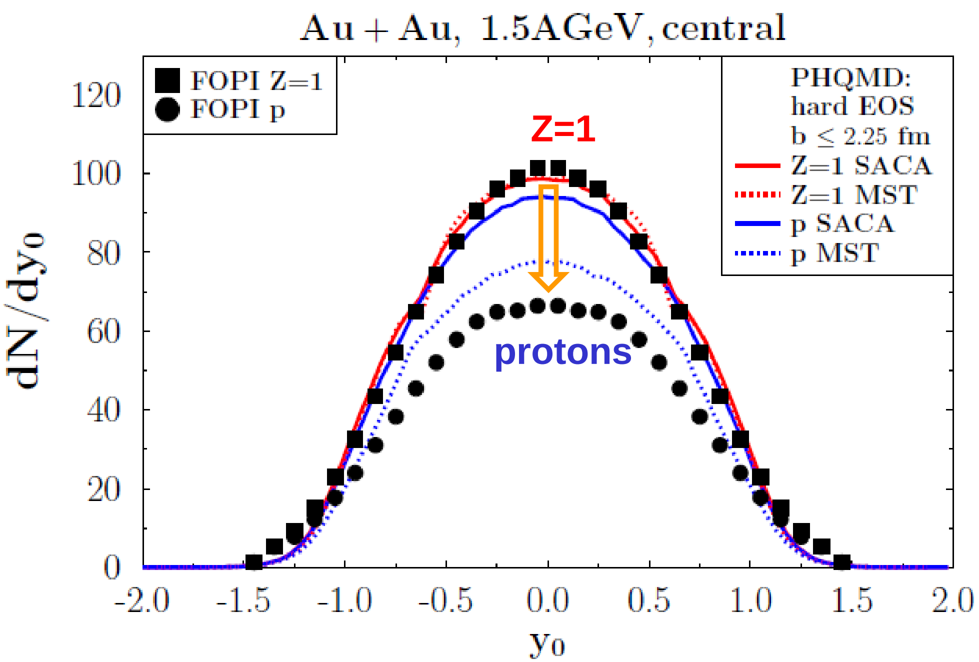
- **SACA can identify the fragment pattern very early in time as compared to the Minimum Spanning Tree (MST) which requires a maximal distance in coordinate space between two nucleons to form a cluster**
- **→ MST applicable at the latest stage of reactions**

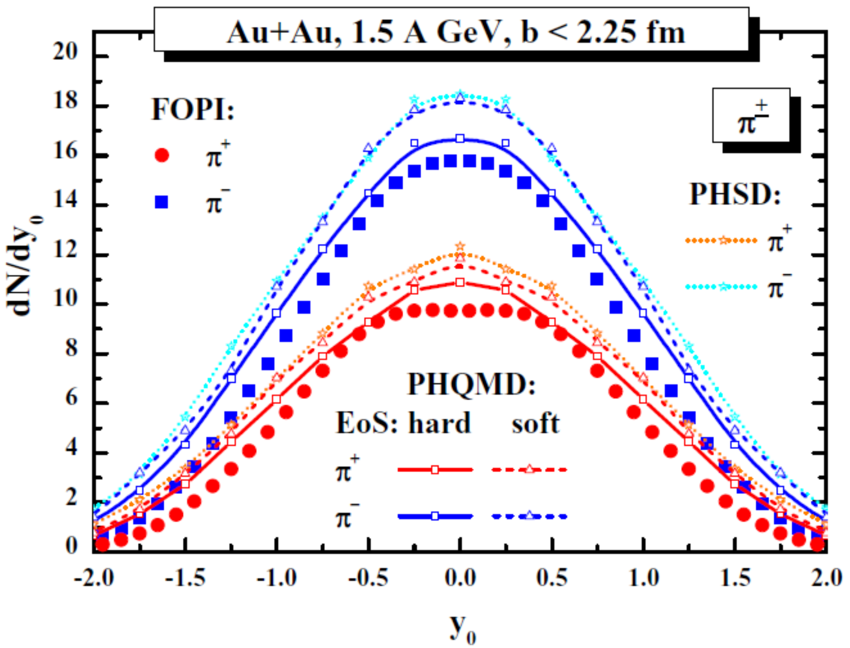
- **Advantage of SACA :**
  the origin of fragment formation can be studied (role of Coulomb energies, density, flow details, strangeness...)

P.B. Gossiaux, R. Puri, Ch. Hartnack, J. Aichelin, Nuclear Physics A 619 (1997)

PHQMD: light clusters and ‚bulk' dynamics at SIS

Scaled rapidity distribution $y_0 = y/y_{proj}$ in central Au+Au reactions at 1.5 AGeV





- ➢ **30% of protons are bound in clusters at 1.5 A GeV**
- ➢ **Presently MST is better identifying light clusters than SACA**
  ➔ To improve in SACA: more realistic potentials for small clusters, quantum effects

- ❑ **Pion spectra are sensitive to EoS: better reproduced by PHQMD with a 'hard' EoS**
- ❑ **PHQMD with soft EoS is consistent with PHSD (default – soft EoS)**

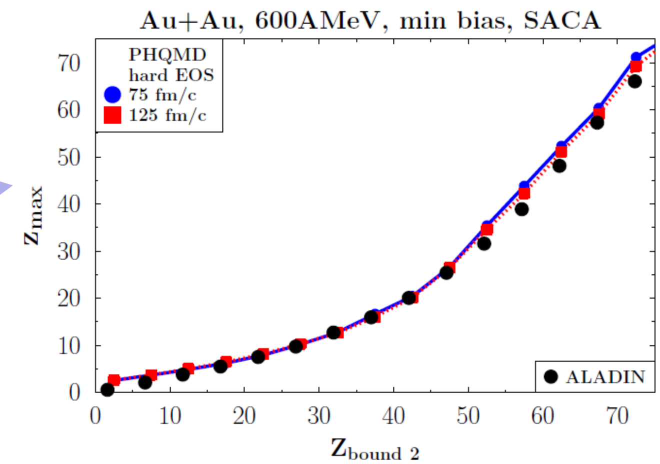
  *** To improve in PHQMD: momentum dependent potentials**

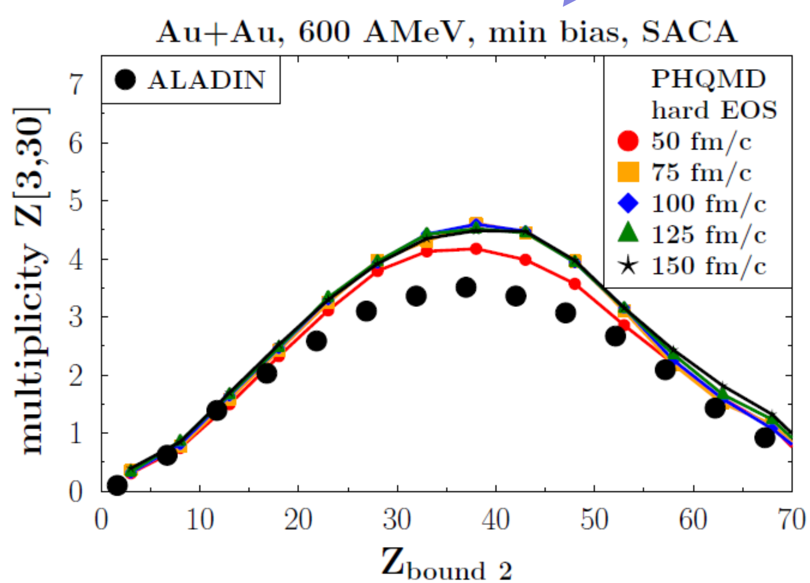
PHQMD: heavy clusters

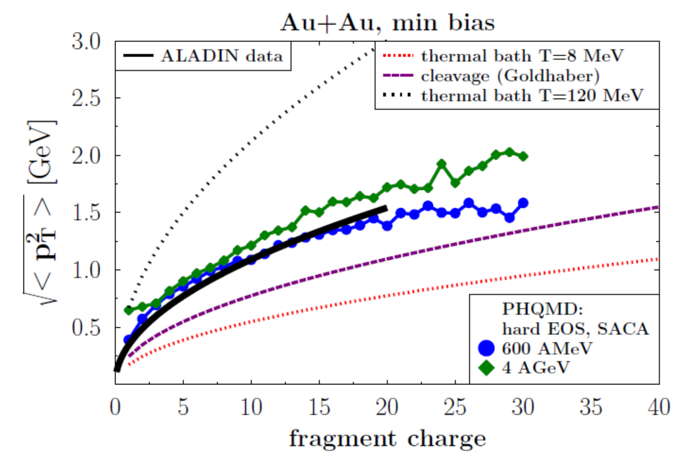
Heavy clusters (spectator fragments):
experim. measured up to E_{beam} =1 AGeV (ALADIN Collab.)

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

- Largest fragments (Z_{bound})
- Energy independent 'rize and fall'
- Rms p^2_T





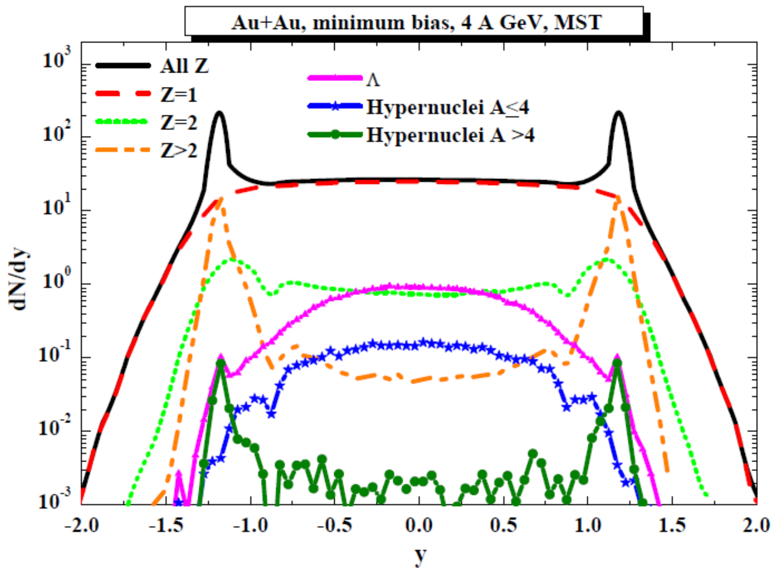


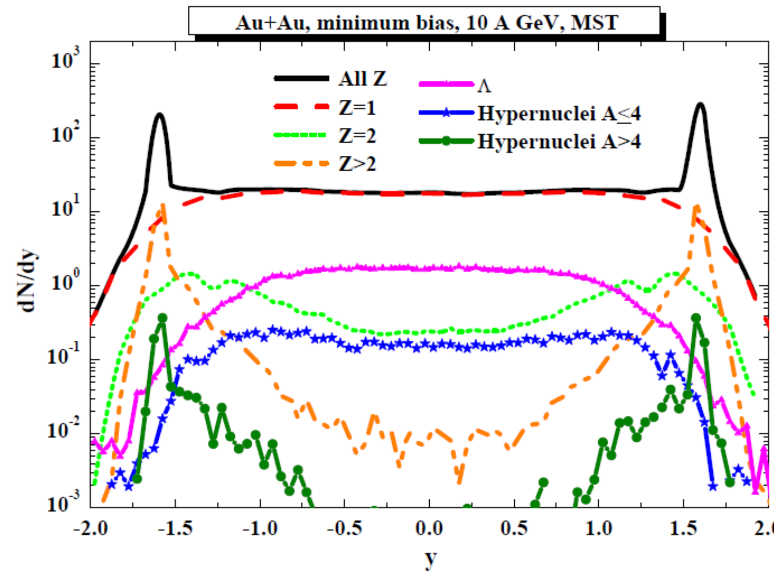
$$Z_{\text{bound 2}} = \sum_i Z_i \, \Theta(Z_i - (1+\epsilon)) \quad (\epsilon < 1)$$

PHQMD shows $\sqrt{p_T^2(Z)} \propto \sqrt{Z}$ dependence as exp. data

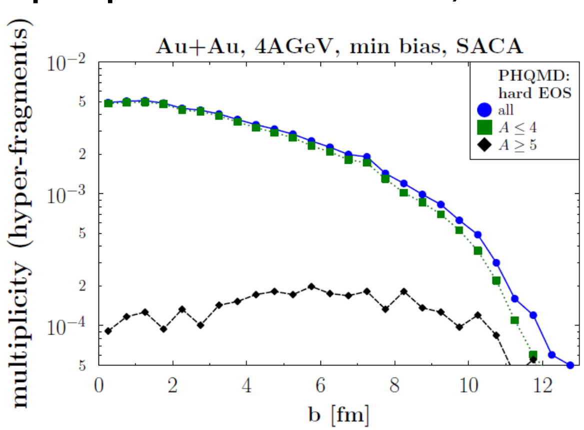
PHQMD: hypernuclei

PHQMD results (with a hard EoS and MST algorithm) for the rapidity distributions of all charges, Z = 1 particles, Z=2, Z>2, as well as Λ's, hypernuclei A≤4 and A>4 for Au+Au at 4 and 10AGeV





The multiplicity of light hypercluster vs. impact parameter b for Au+Au, 4 AGeV

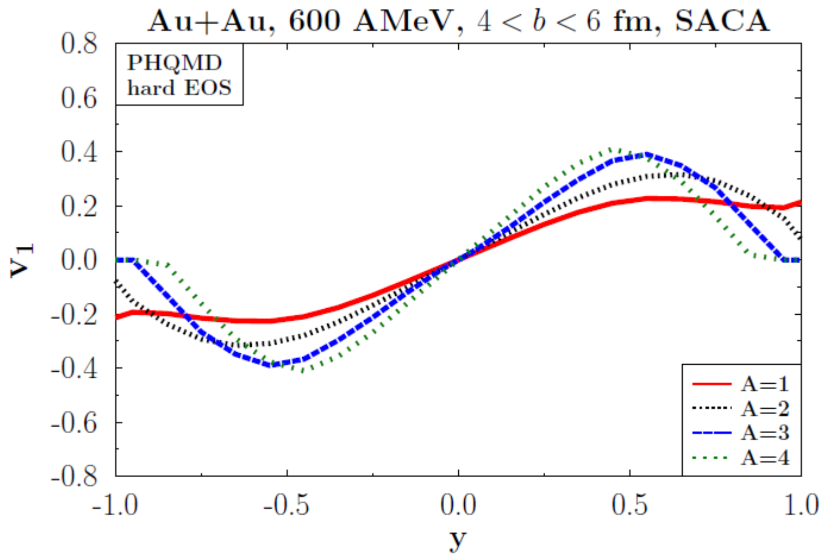


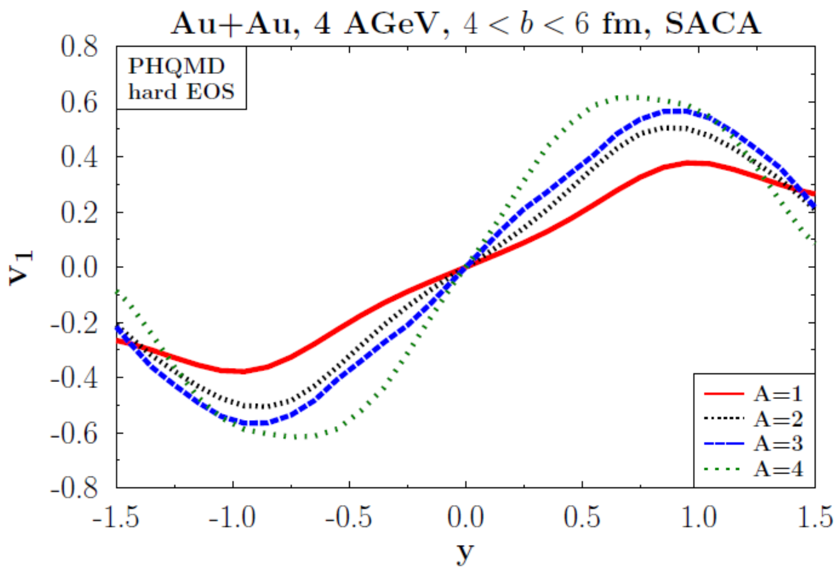
- **Central collisions → light hypernuclei**
- **Peripheral collisions → heavy hypernuclei**

Penetration of Λ's, produced at midrapidity, to target/projectile region due to rescattering

→ Possibility to study ΛN interaction

PHQMD: collectivity of clusters





PHQMD with hard EoS, with SACA:
v_1 of light clusters (A=1,2,3,4) vs rapidity
for mid-central Au+Au at 600 AMeV, 4AGeV

- **v_1 : quite different for nucleons and fragments (as seen in experiments)**
- **Nucleons come from participant regions (→ small density gradient) while fragments from interface spectator-participant (strong density gradient)**
- **v_1 increases with E_{beam} → larger density gradient**

Summary

The PHQMD is a microscopic n-body transport approach for the description of heavy-ion dynamics and cluster formation

combined model PHQMD = (PHSD & QMD) & SACA

PHQMD

- **provides the good description of hadronic 'bulk' observables – from SIS to RHIC energies**
- **shows sensitivity to EoS: m_T spectra of baryons**
- **predicts the dynamical formation of clusters from low to ultra-relativistic energies**
- **allows to understand the proton spectra and the properties of clusters (dn/dp_Tdy, v_1,v_2, fluctuations)**
- **allows to understand clusters formation in the participant and spectator region (consistent with available fragment data by ALADIN collaboration)**
- **allows to understand the formation of hypernuclei**

❖ ***PHQMD : under development***

Thank you for your attention !

Thanks to the Organizers !

STRANGENESS IN QUARK MATTER

SQM

Bari

2019