Prospects for the study of the strangeness production at the NICA experiments

V. Kireyeu[1], **V. Kolesnikov**[1], **E. Bratkovskaya**[2,3], **A. Zinchenko**[1], **V. Vasendina**[1]

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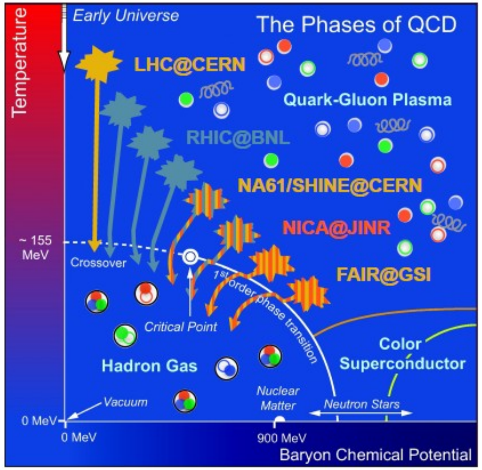
2020-10-05

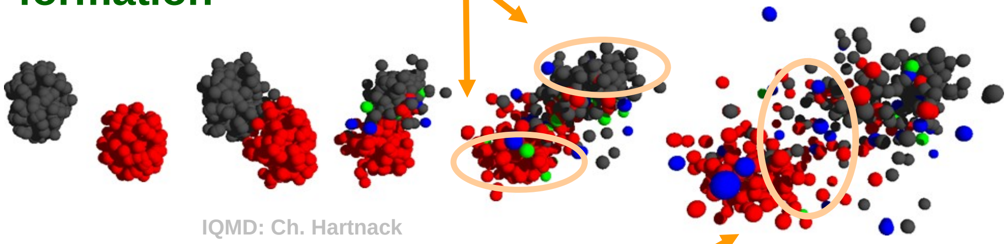
1 – JINR, Dubna
2 – GSI, Darmstadt
3 – Goethe Universität, Frankfurt am Main

Introduction

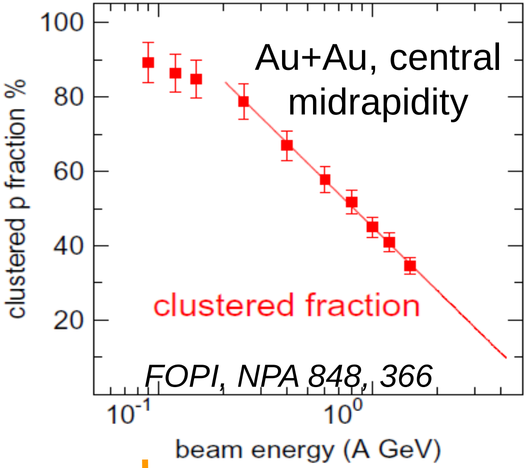
The phase diagram of QCD



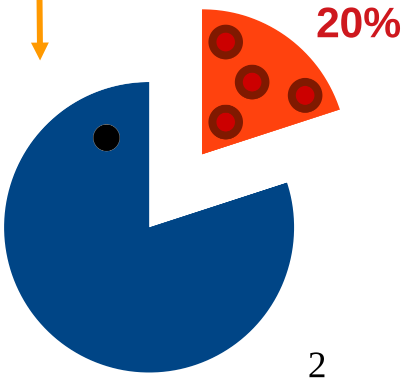
Projectile/target spectators: heavy cluster formation

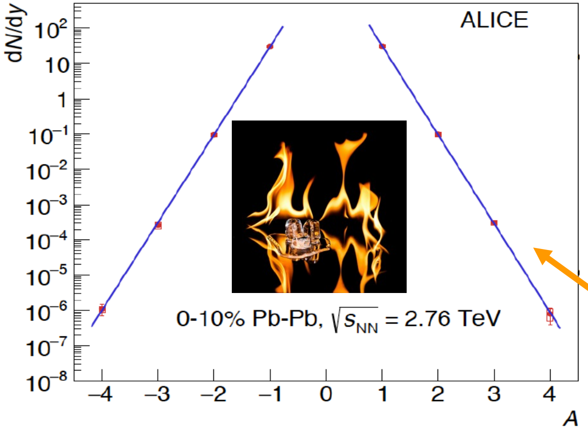


Midrapidity: light clusters



(it's a lot!)



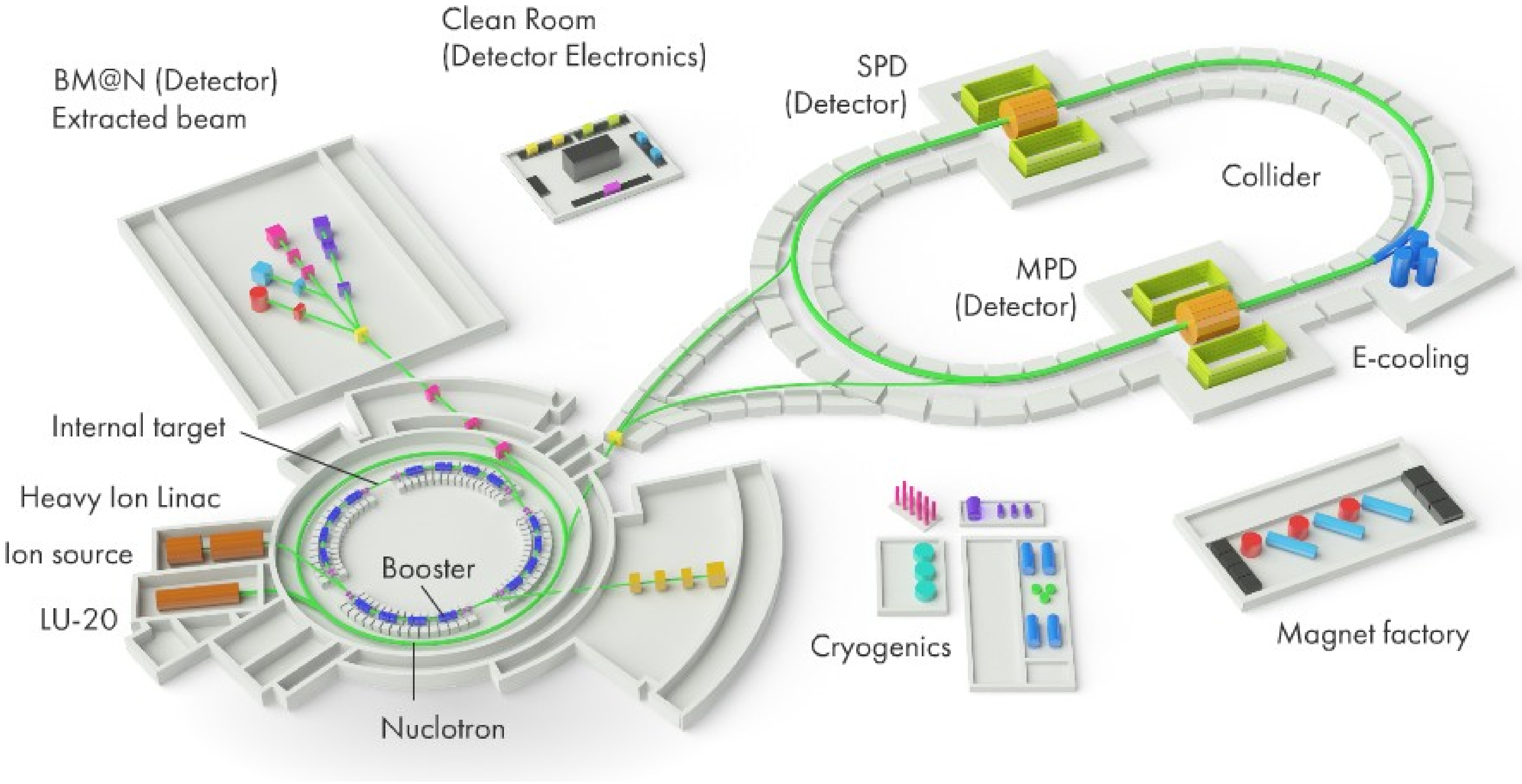


(Anti-) hypernuclei production:

- **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 environment?

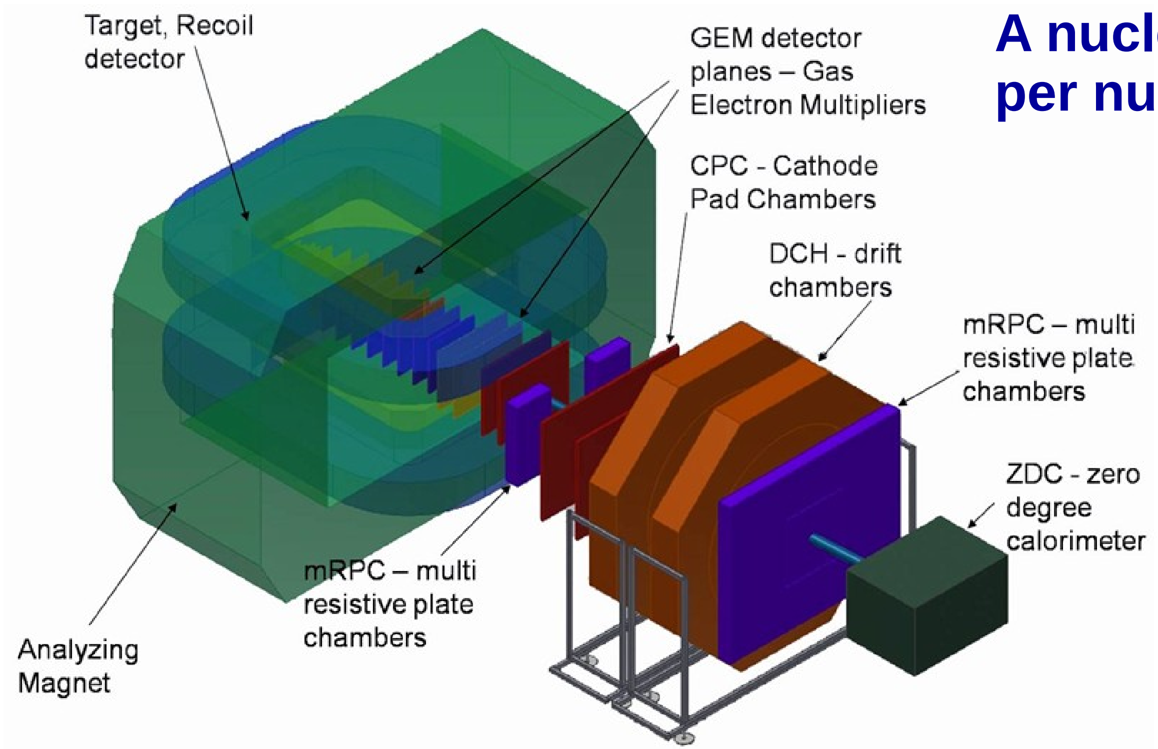
Nuclotron-based Ion Collider fAcility



$L = 10^{27}$ cm^{-2}s^{-1} – heavy ions beams, $L = 10^{32}$ cm^{-2}s^{-1} – polarized *p*, *d* beams

Future experiments at NICA: BM@N

Baryonic Matter at the Nuclotron: 1st experiment of the NICA project



A nucleus-nucleus collisions 1 – 4.5 GeV per nucleon → baryon dominated fireball

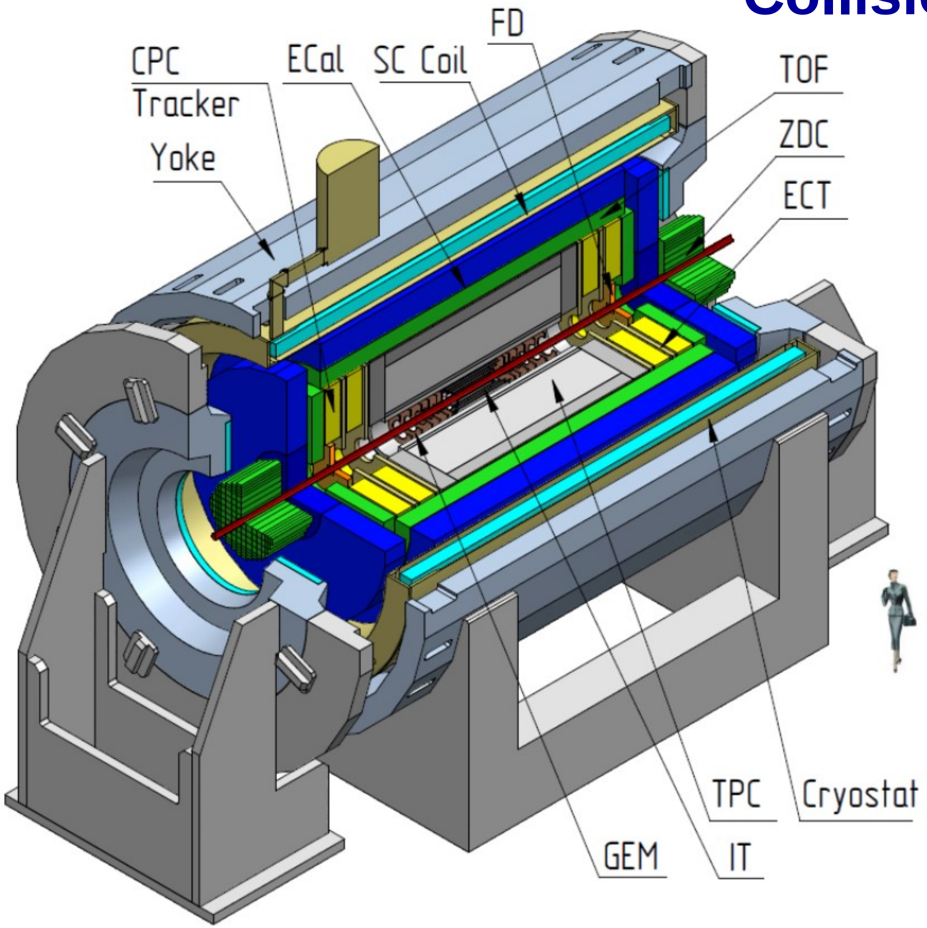
Densities up to 3x-4x normal baryon density

Strangeness kinematic threshold:

- **Strange mesons**
- **Hyperons**
- **Multi-strange particles**
- **Hypernuclei**

Future experiments at NICA: MPD

Multi Purpose Detector: study of hot and dense matter



Collision energy up to $\sqrt{s_{NN}}$ = 11 GeV (Au+Au)

Max net baryon density

Mixed phase similar to the matter in neutron star mergers

← NASA/Swift/Dana Berry

Models for the clusters and hypernuclei formation

Existing models for clusters formation:

Statistical model:

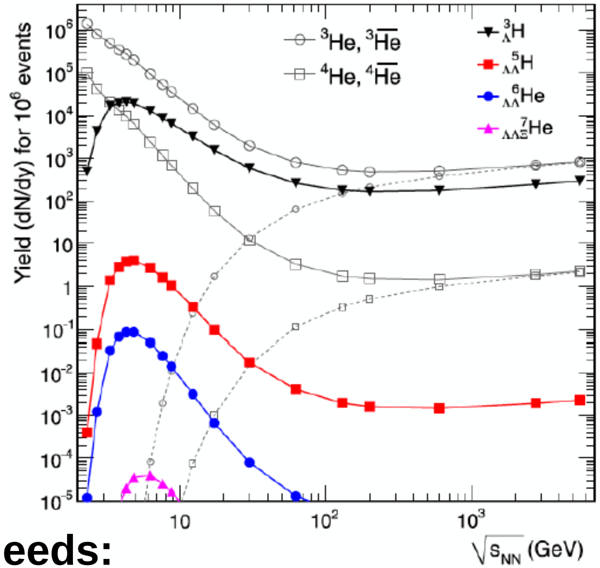
- assumption of thermal equilibrium (difficult to justify at target and projectile rapidity)
- strong sensitivity of nuclei yields to choice of T_{ch}
- binding energies are small compared to T_{ch}

Coalescence model:

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

But they don't provide information on the dynamics of clusters formation

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



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

=> 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

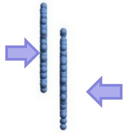
PHSD model

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

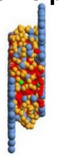
PHSD is a **non-equilibrium microscopic transport approach** for the description of **strongly-interacting hadronic and partonic matter** created in heavy-ion collisions

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

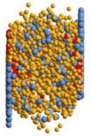
Initial A+A collision



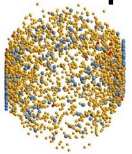
Partonic phase



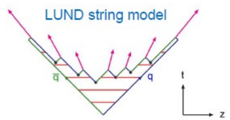
Hadronization



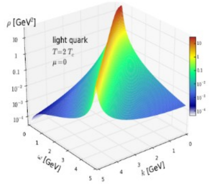
Hadronic phase



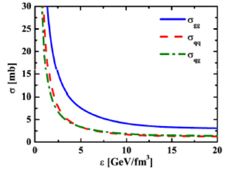
- **Initial A+A collisions** :
  N+N → string formation → decay to pre-hadrons + leading hadrons



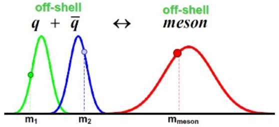
- **Formation of QGP stage** if local $\varepsilon > \varepsilon_{critical}$:
  dissolution of pre-hadrons → partons
- **Partonic phase - QGP:**
  QGP is described by the Dynamical QuasiParticle Model (DQPM) matched to reproduce lattice QCD EoS for finite T and μ_B (crossover)



- **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

PHQMD model

J. Aichelin, E. Bratkovskaya, A. Le Fèvre, V. Kireyeu, V. Kolesnikov, Y. Leifels, V. Voronyuk, and G. Coci, Phys. Rev. C 101, 044905

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)

↓

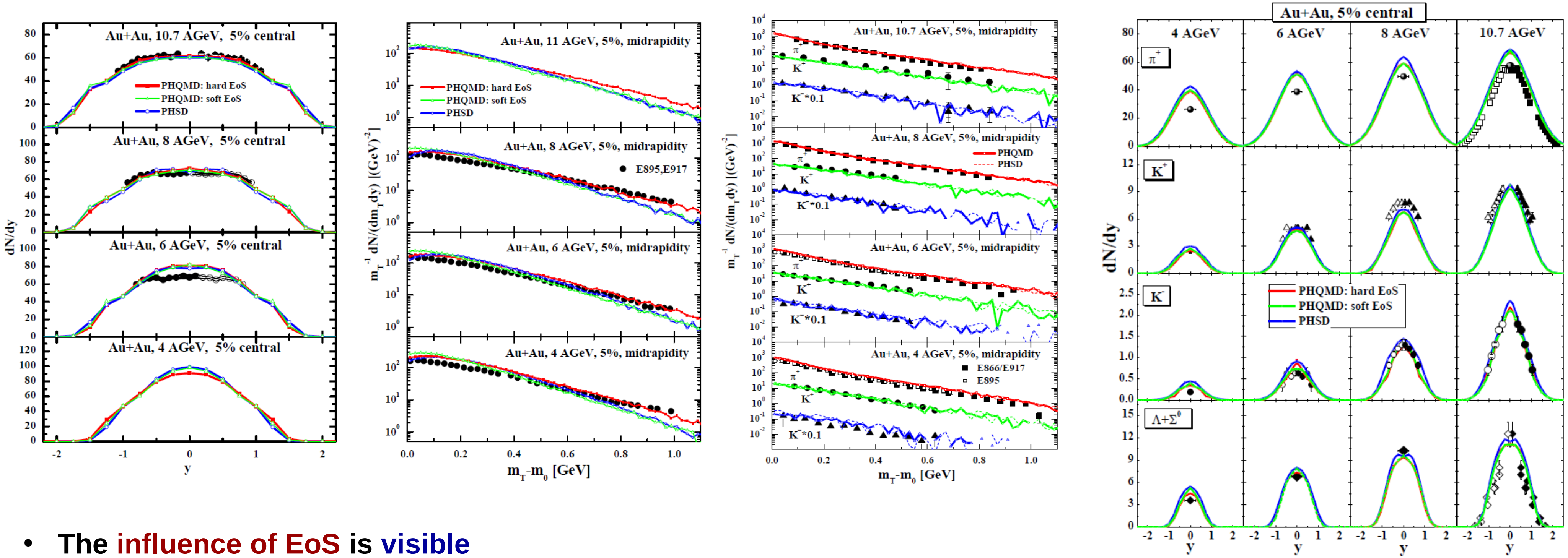
Propagation of partons (quarks, gluons) and mesons
+ collision integral = interactions of hadrons and partons (QGP)
from PHSD (Parton-Hadron-String Dynamics)

↓

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

PHQMD: “bulk” at AGS

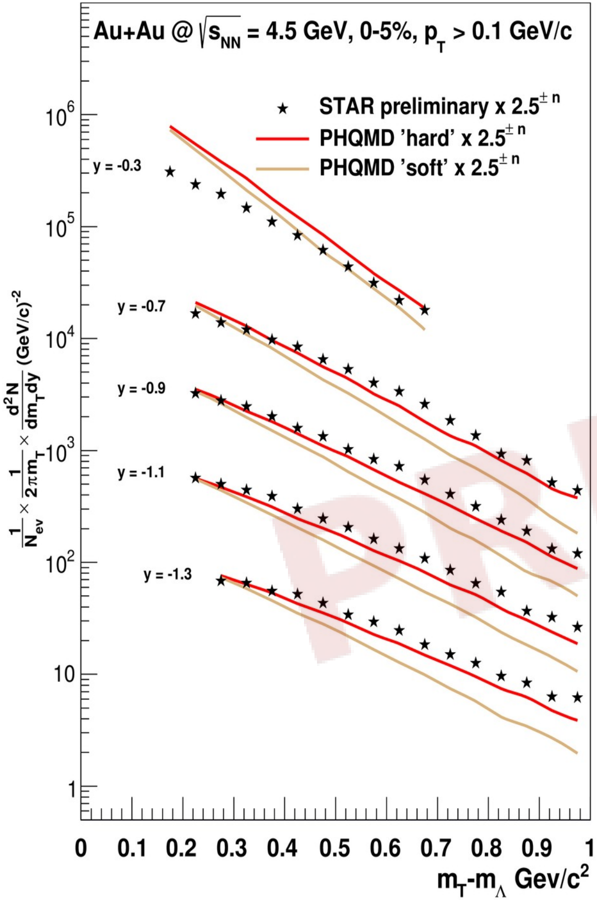
dn/dy and m_T distributions for p, π^+, K^+, K^-, $\Lambda+\Sigma^0$ from 5% central Au+Au collisions at 4, 6, 8, 10.7 A GeV



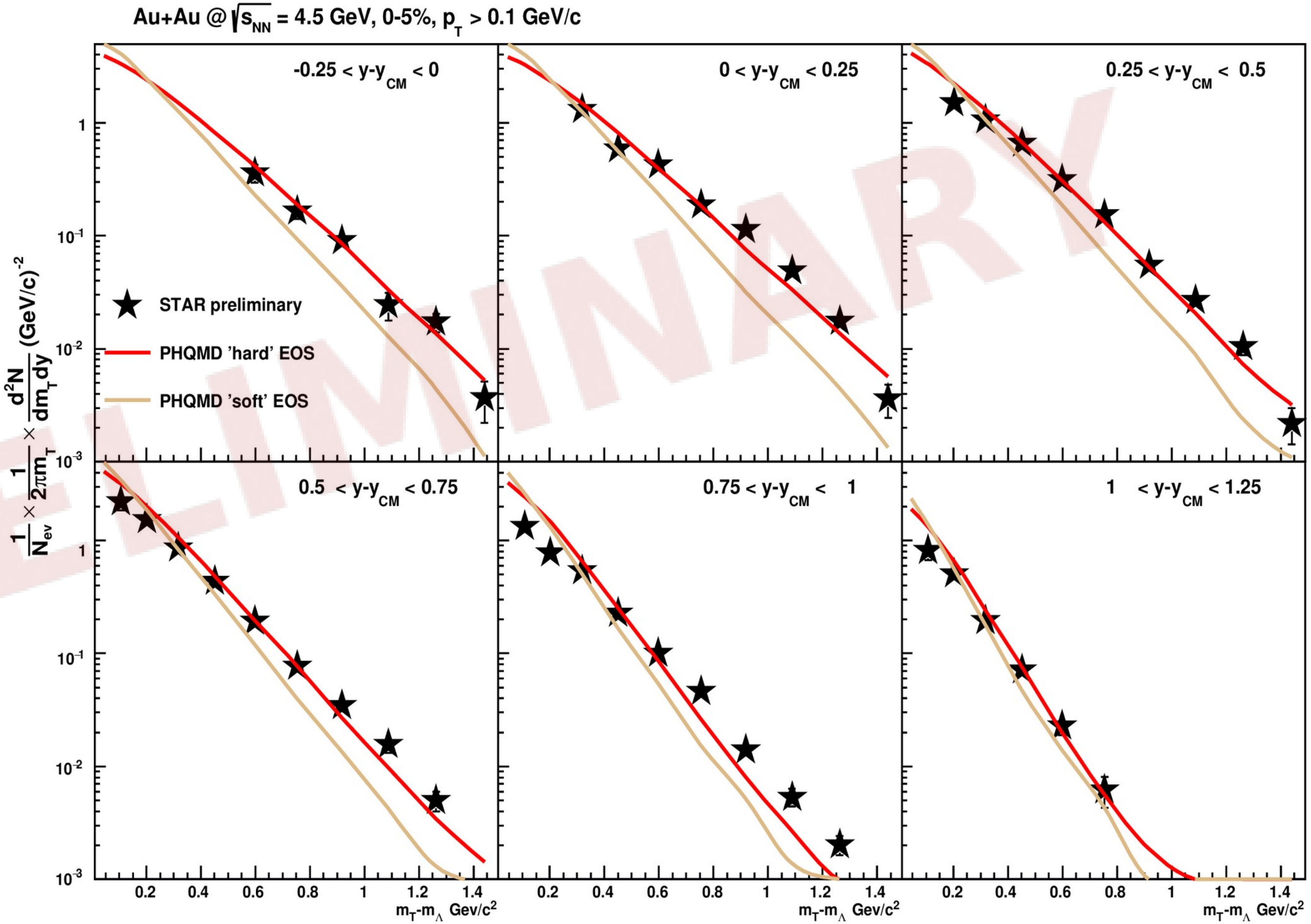
- The influence of EoS is visible
- m_T spectra of protons from PHQMD with a “hard” EoS are harder then with ‘soft’ EoS
- PHQMD results for the m_T spectra with “soft” EoS are in a good agreement with the PHSD spectra (with default “soft” EoS in the PHSD4.0) => QMD and MF dynamics gives similar results with similar EoS

PHQMD: “bulk” at STAR (fixed target)

Protons

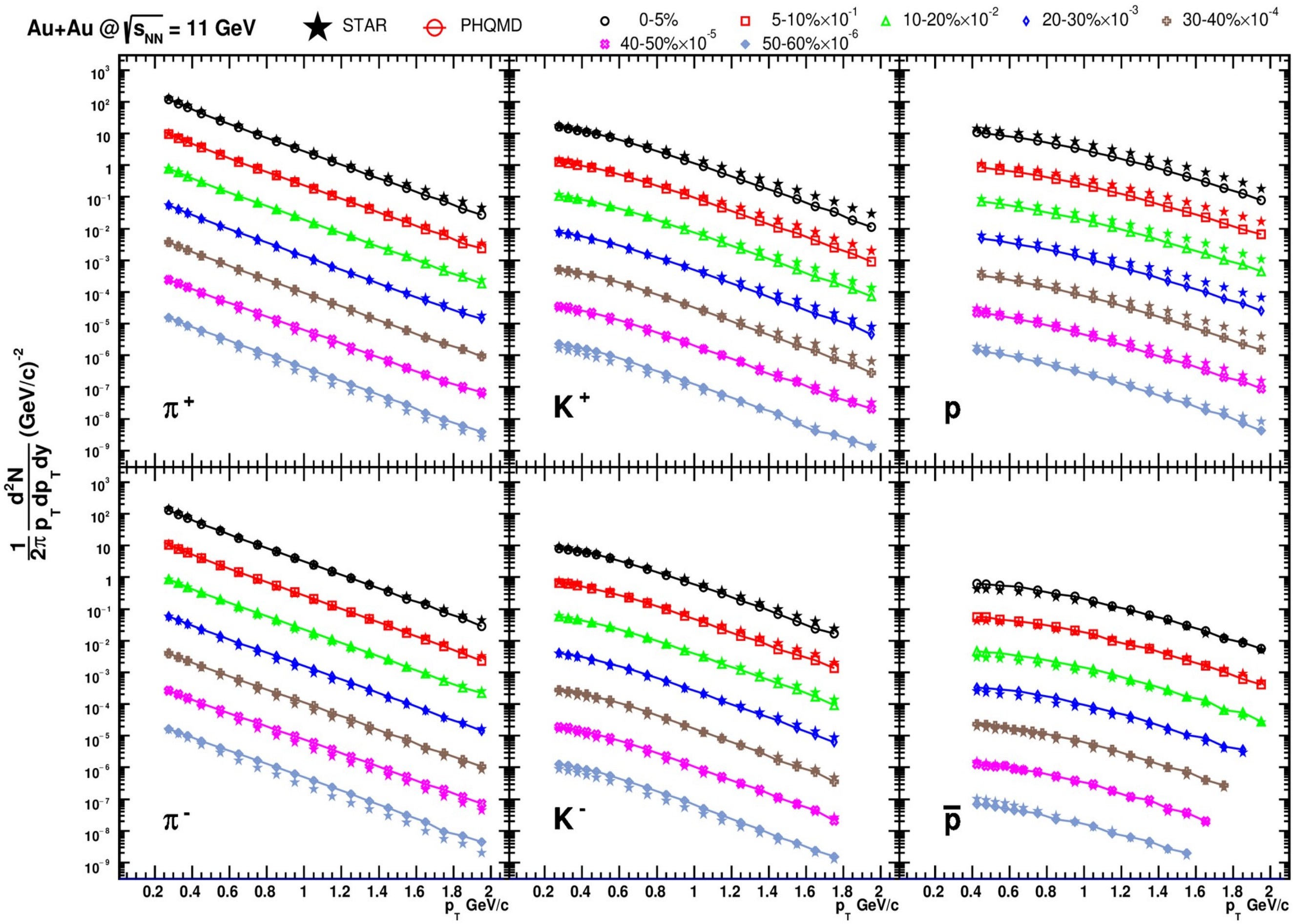


$\Lambda+\Sigma^0$



PHQMD “hard” EoS describes STAR experimental data slightly better than “soft” EoS.

PHQMD: “bulk” at STAR



PHQMD “hard” EoS: good agreement with RHIC BES experimental data

STAR ‘bulk’ data: Phys. Rev. C 96, 044904 (2017)

Cluster recognition: MST

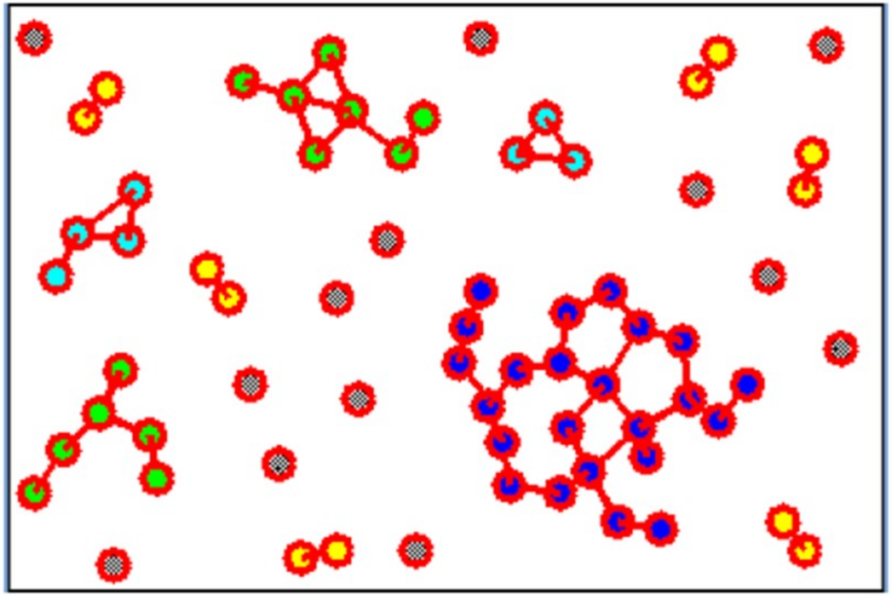
The Minimum Spanning Tree (MST) is a cluster recognition method applicable for the (asymptotic) final states where coordinate space correlations may only survive for bound states.

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

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

$$|\mathbf{r}_i - \mathbf{r}_j| \leq 4.0\ fm$$

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



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

Cluster recognition: SACA

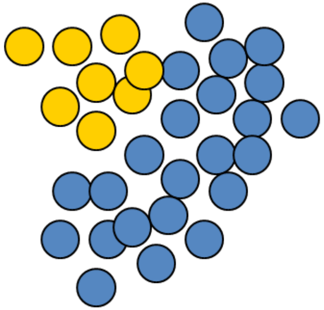
Simulated Annealing Clusterization Algorithm:

Based on idea by Dorso and Randrup (Phys.Lett. B301 (1993) 328)

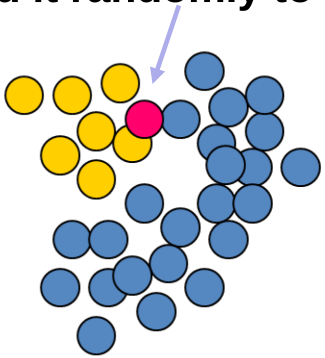
- Take the positions and momenta of all nucleons at time *t*
- Combine them in all possible ways into all kinds of clusters or leave them as single nucleons
- Neglect the interaction among clusters
- Choose that configuration which has the highest binding energy:

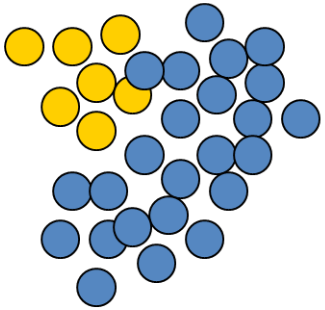
Take randomly 1 nucleon out of a cluster

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

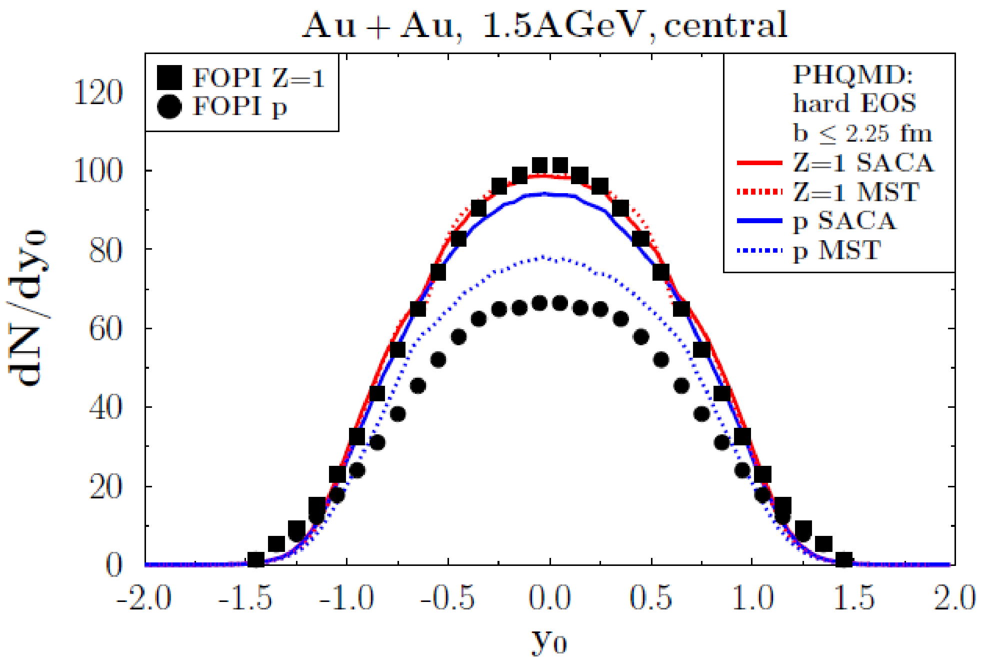
If E’ > E take the old configuration with a probability depending on E’-E

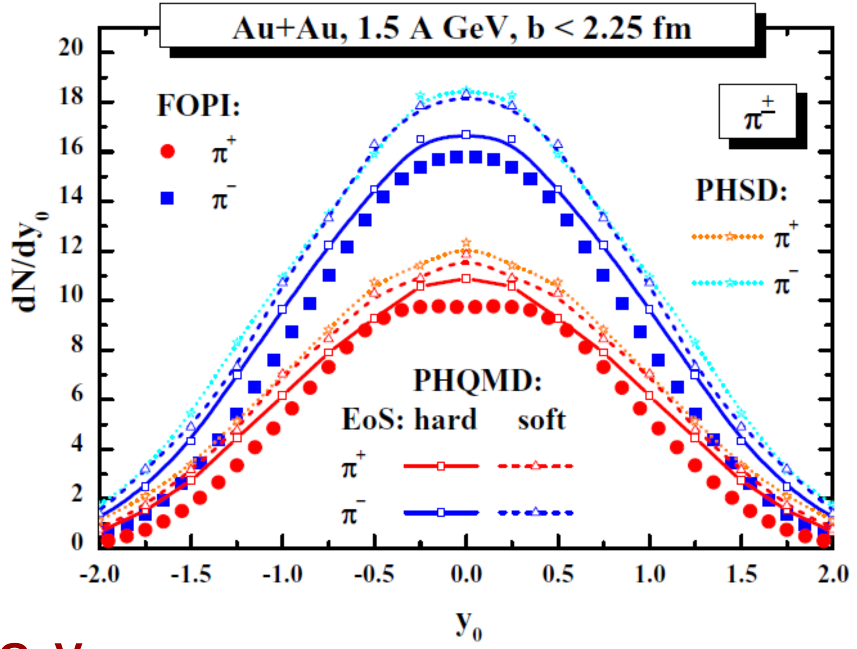
Repeat this procedure many times: leads automatically to finding of the most bound configurations

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

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





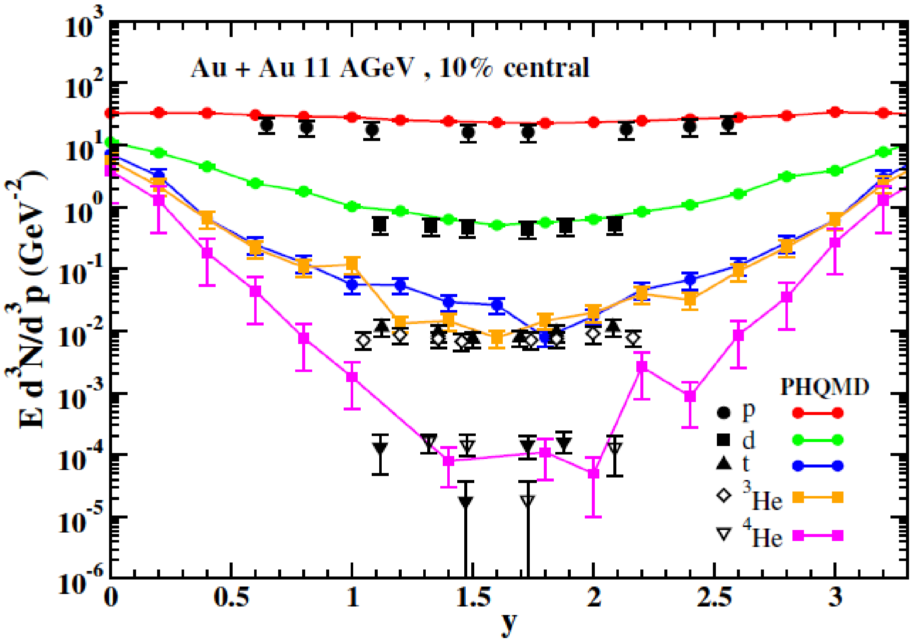
- **30% of protons are bound in clusters at 1.5 A GeV**
- **Presently MST is better identifying light clusters than SACA => To improve in SACA: more realistic potentials for small clusters, quantum effects**
- **Pion spectra are sensitive to EoS: better reproduced by PHQMD with a “hard” EoS**
- **PHQMD with soft EoS is consistent with PHSD**

  (To improve in PHQMD: momentum dependent potentials)

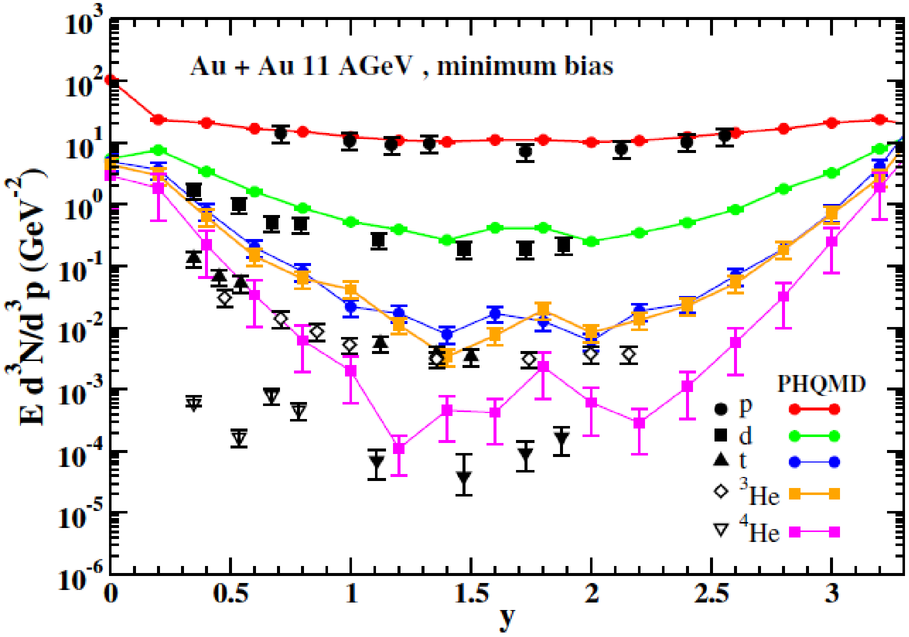
PHQMD: light clusters at AGS

The invariant multiplicities for p, d, t, ^{3}He, ^{4}He at p_T <0.1 GeV versus rapidity

Au+Au, 11 AGeV, 10% central



Au+Au, 11 AGeV, minimal bias



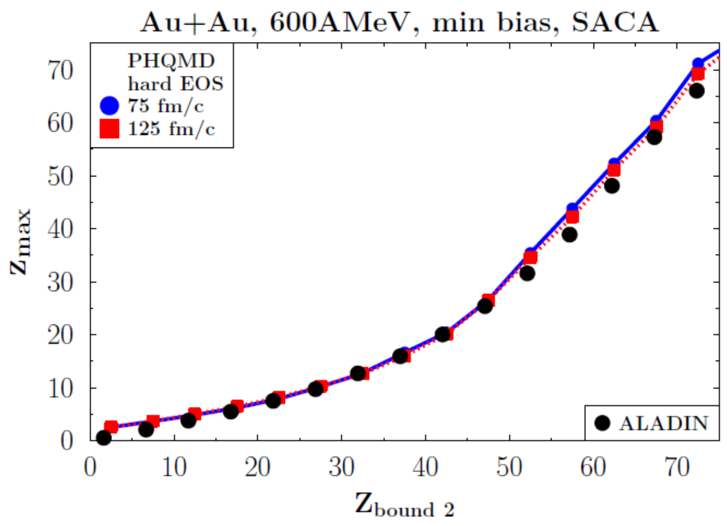
PHQMD: clusters recognition by MST provides a reasonable description of exp. data on light clusters at AGS energies

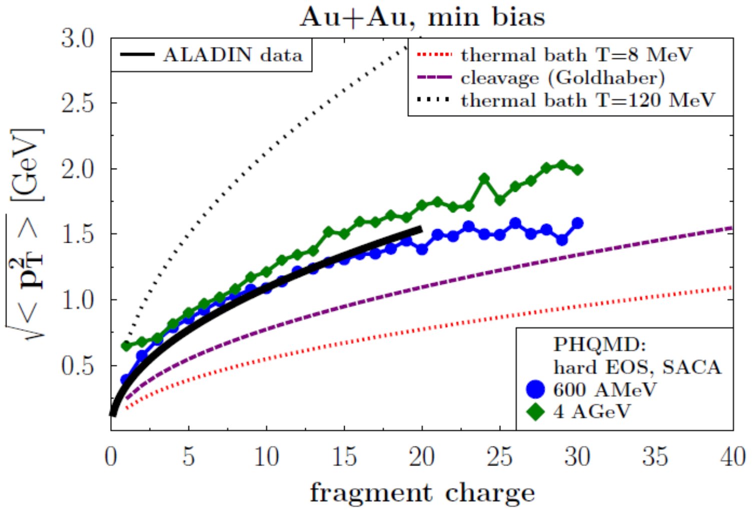
PHQMD: heavy clusters

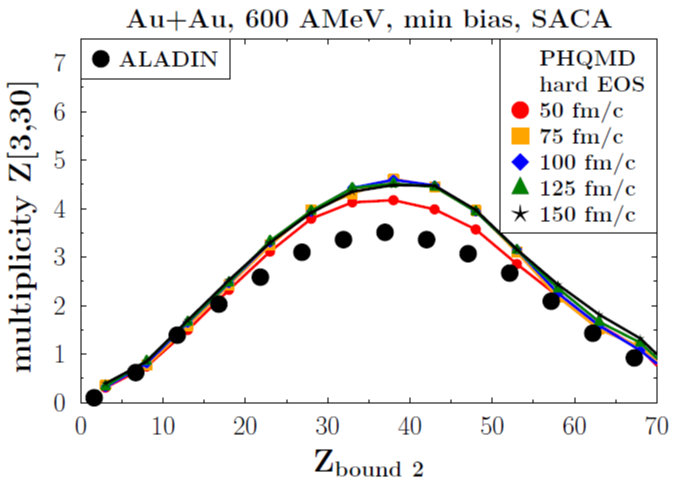
Heavy clusters (spectator fragments): experim. measured up to E_{beam} = 1 AGeV (ALADIN Collab.)

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

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



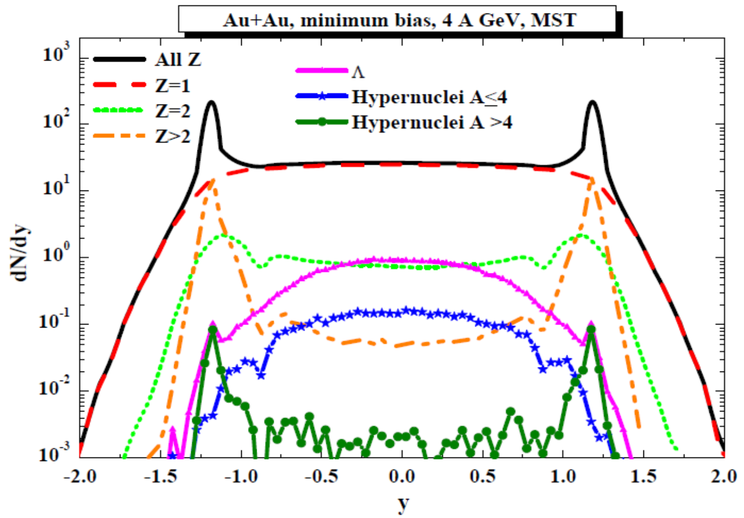


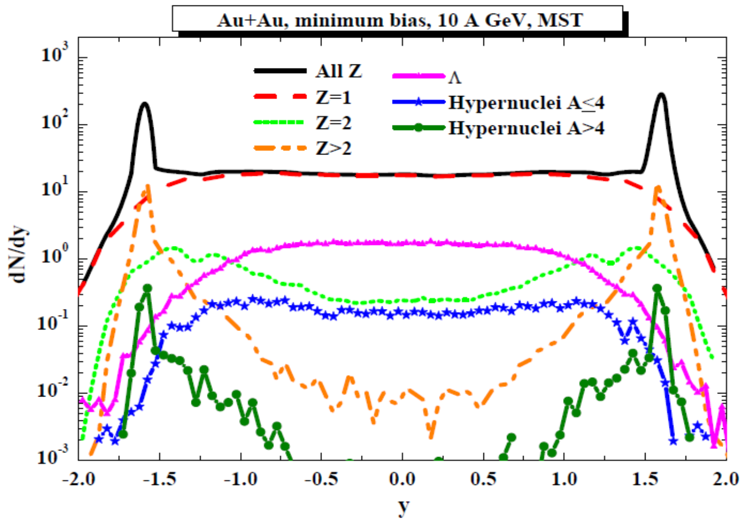


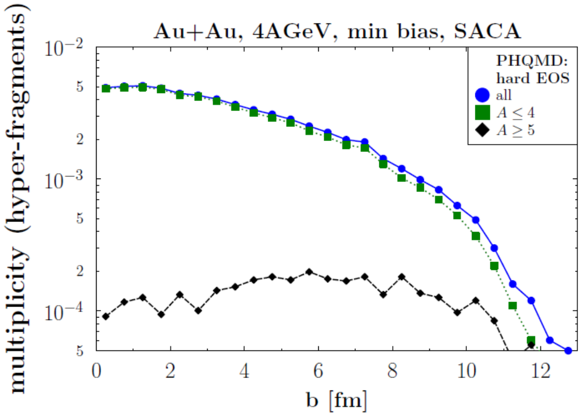
$$Z_{\text{bound }2} = \sum_i Z_i\, \Theta(Z_i - (1+\epsilon))$$

PHQMD: hypernuclei

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







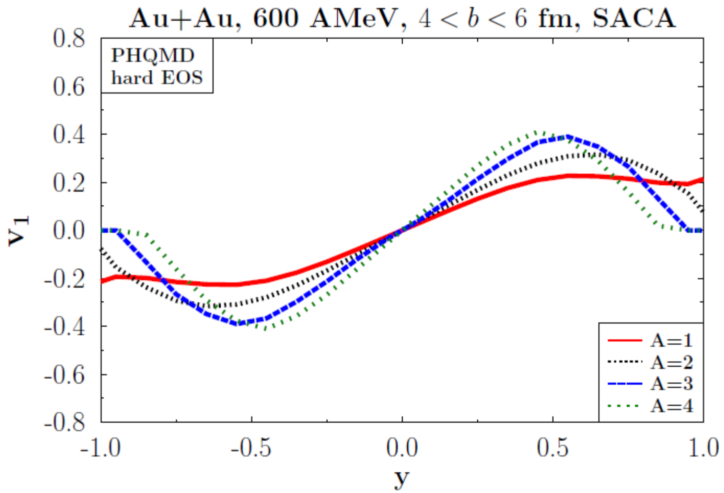
Central collisions → light hypernuclei

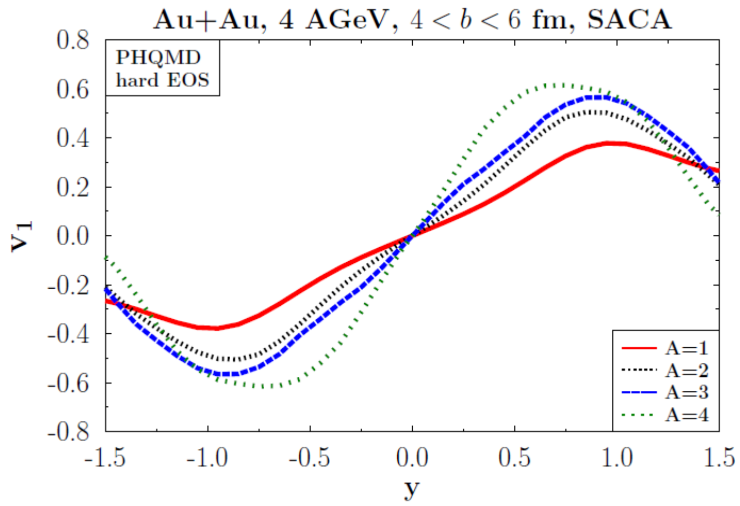
Peripheral collisions → heavy hypernuclei

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

→ Possibility to study ΛN interaction

PHQMD: collectivity of clusters





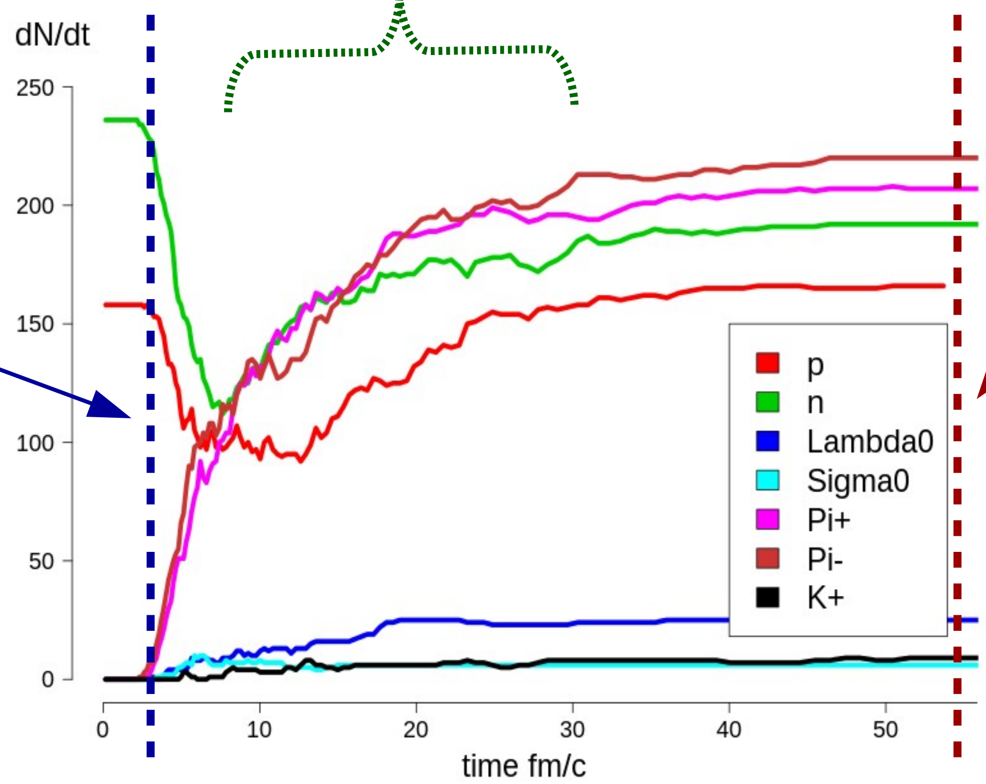
PHQMD with hard EoS, with SACA:
v_1 of light clusters (A=1,2,3,4) vs rapidity
for mid-central Au+Au at 600 AMeV, 4AGeV

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

Clusterization time question

Maybe here..?

Too early



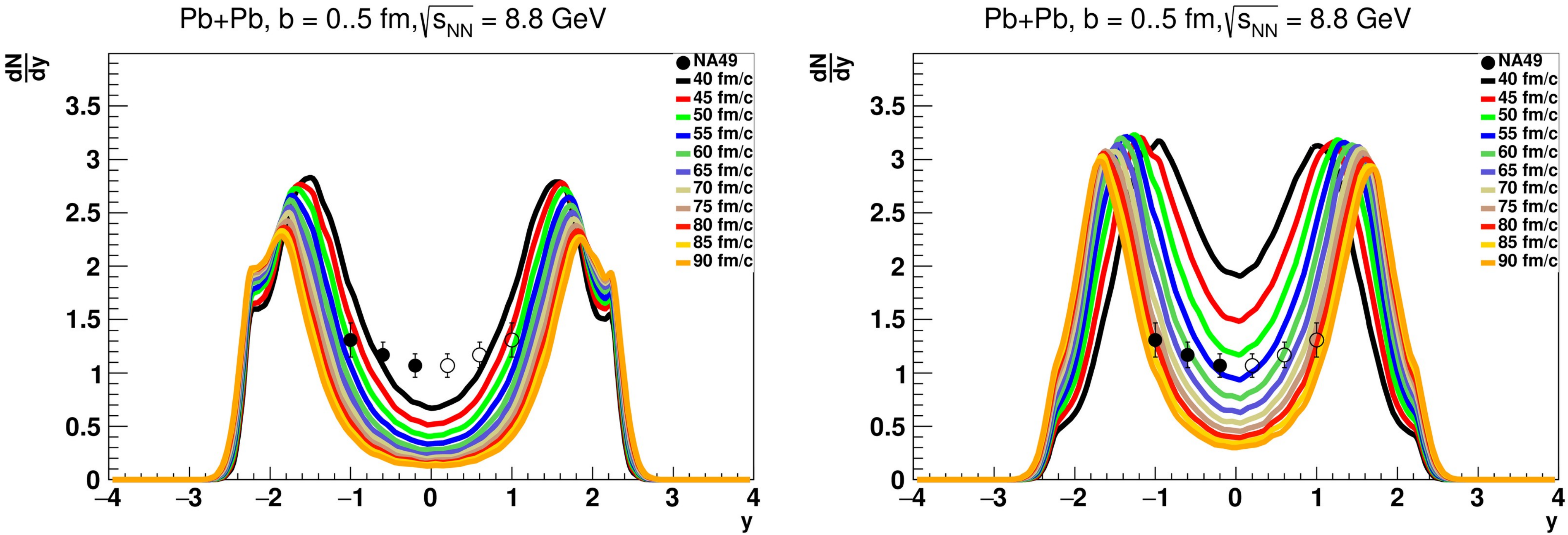
Oops...

Answer is dynamic clusters formation

PHQMD: time evolution in Pb+Pb @ $\sqrt{s_{NN}}$ = 8.8 GeV

Deuterons

Experimental data: NA49



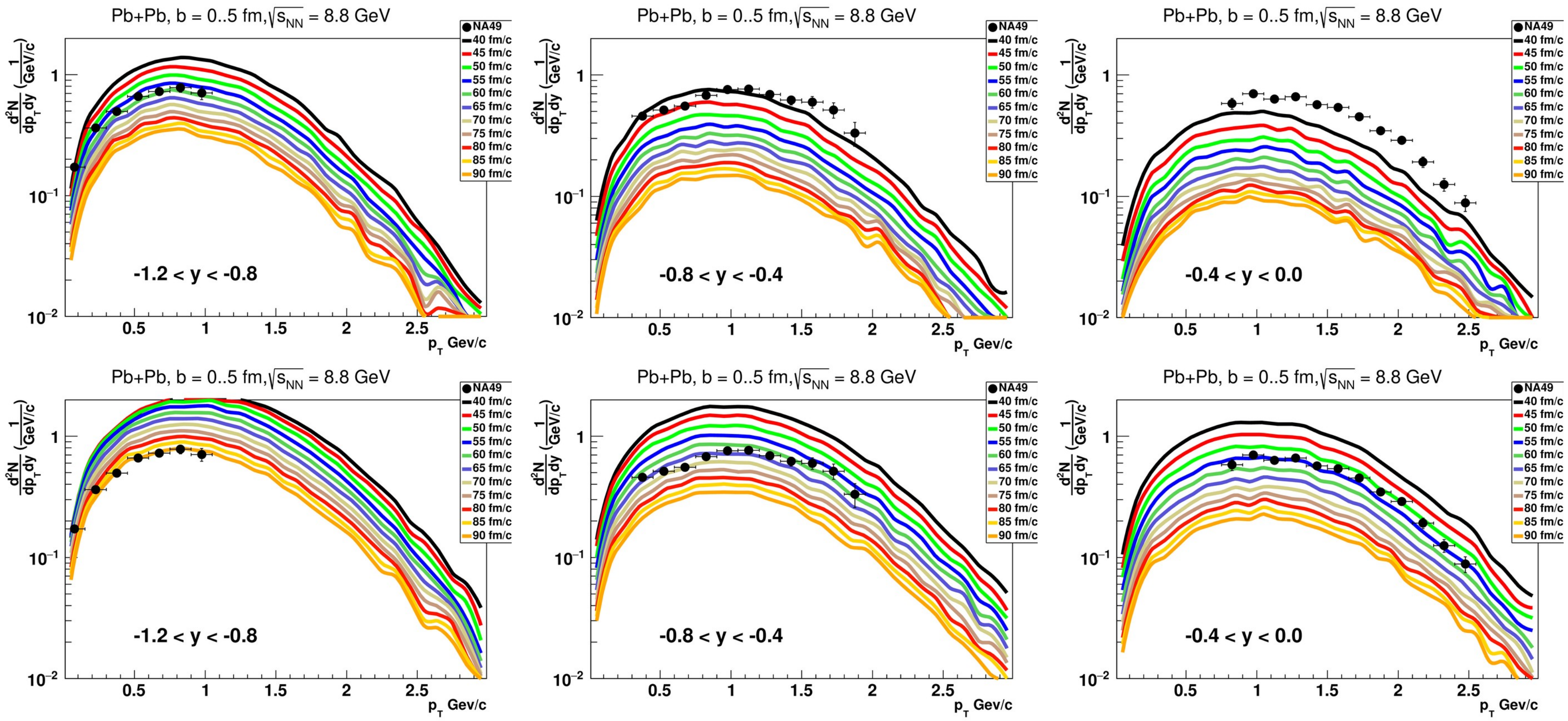
MST radius 2.5 fm

MST radius 4.0 fm

PHQMD: time evolution in Pb+Pb @ $\sqrt{s_{NN}}$ = 8.8 GeV

Deuterons

Experimental data: NA49



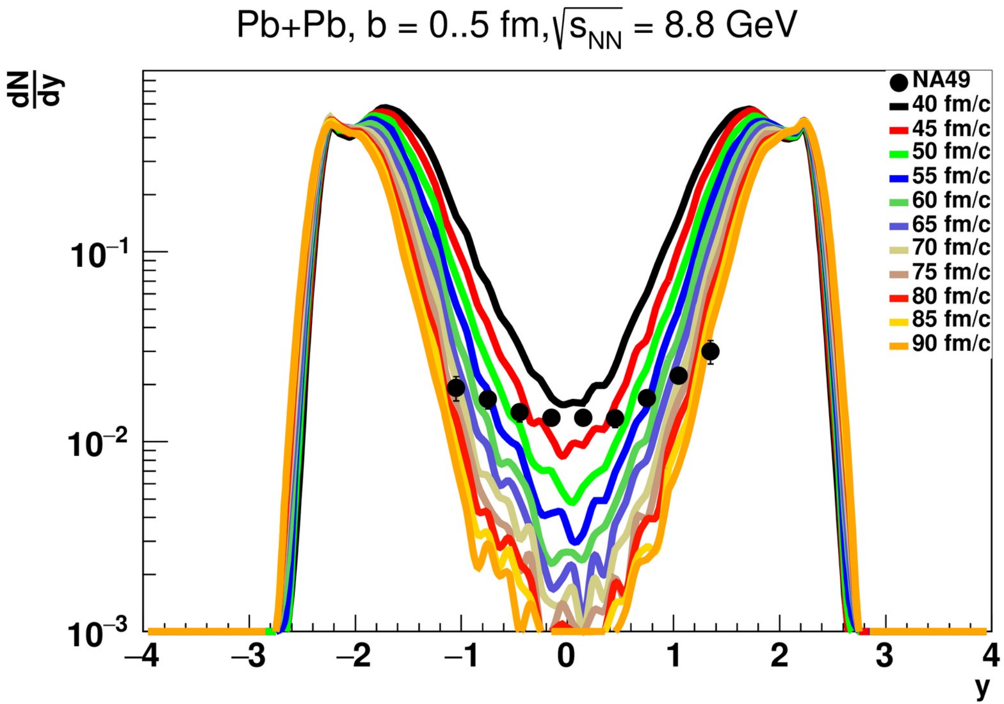
MST radius 2.5 fm

MST radius 4.0 fm

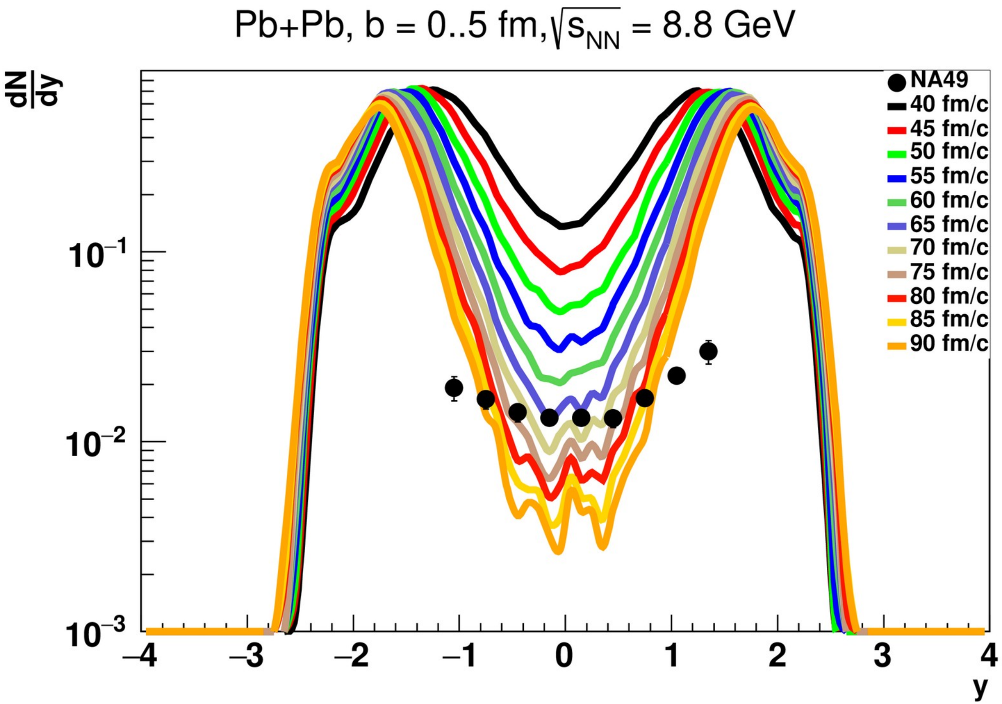
PHQMD: time evolution in Pb+Pb @ $\sqrt{s_{NN}}$ = 8.8 GeV

^{3}He

Experimental data: NA49



MST radius 2.5 fm

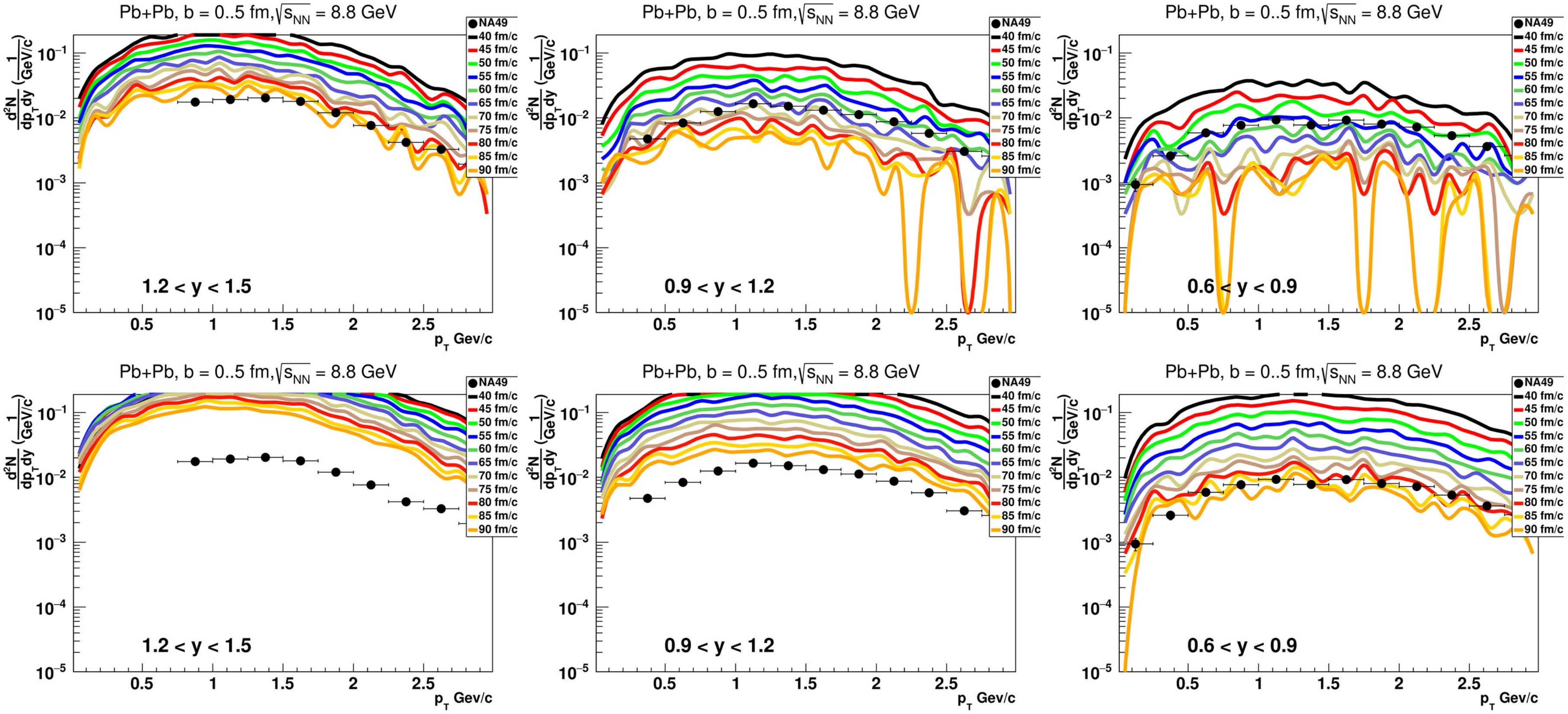


MST radius 4.0 fm

PHQMD: time evolution in Pb+Pb @ $\sqrt{s_{NN}}$ = 8.8 GeV

^{3}He

Experimental data: NA49

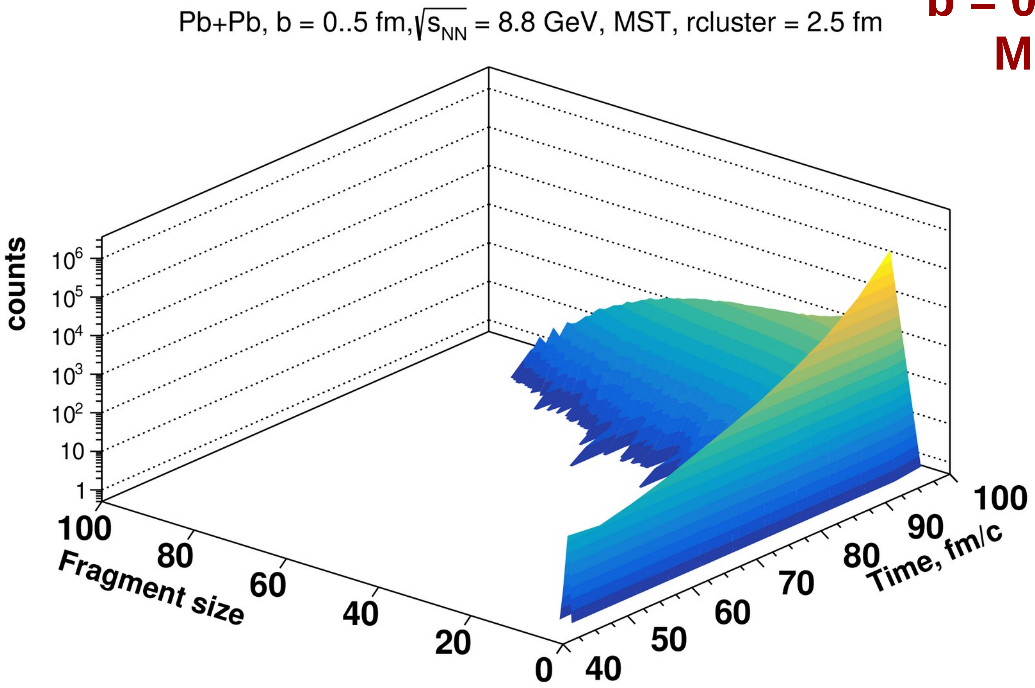


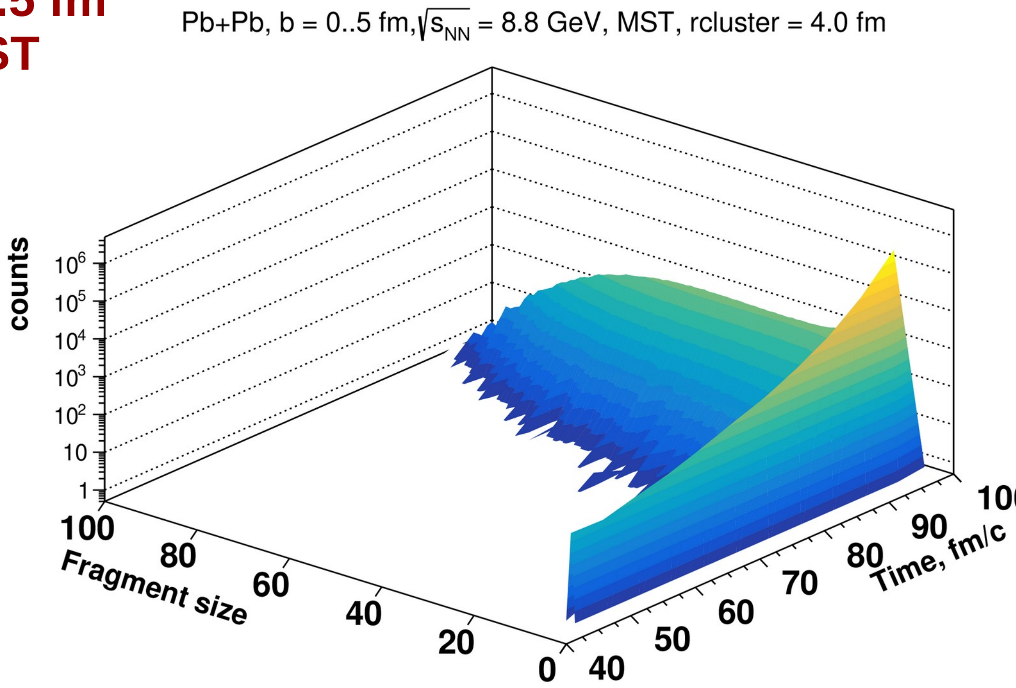
MST radius 2.5 fm

MST radius 4.0 fm

PHQMD: clusters stability

Pb+Pb @ $\sqrt{s_{NN}}$ = 8.8 GeV
b = 0..5 fm
MST



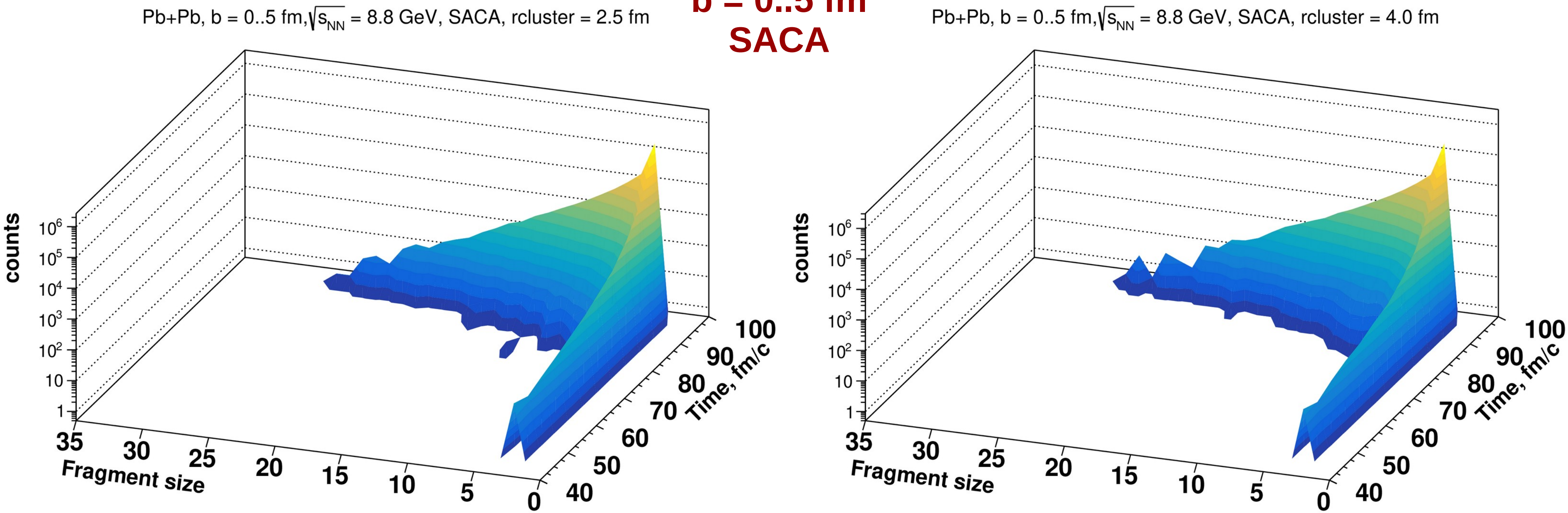


Maximal fragment size > 70

Light fragments may be stable starting from early time steps.
Stable here is a cluster which does not change its internal structure up to the final time step.

PHQMD: clusters stability

Pb+Pb @ $\sqrt{s_{NN}}$ = 8.8 GeV
b = 0..5 fm
SACA



Maximal fragment size < 30

Light fragments may be stable starting from early time steps.
Stable here is a cluster which does not change its internal structure up to the final time step.

PHQMD: hypernuclei performance at BM@N

PHQMD: hypernuclei performance at MPD

Summary

under construction

Density frontier is an interesting area of the QCD phase diagram and its study could lead to interesting discoveries

Future NICA experiments are designed for the study of HIC at the strangeness threshold energies and maximal net baryon densities

The PHQMD is a microscopic n-body transport approach for the description of heavy-ion dynamics and cluster formation which may provide the theory for the hypernuclei formation in the hot and dense matter of NICA experiments (good agreement with the existing data!).