Where are the challenges for the next decade in pp,pA and AA reactions at FAIR/NICA energies?

Joerg Aichelin

The interesting physics

- ❑ Transition between hadron and parton dominated energies
- ❑ A possible first order phase transition of strongly interacting matter
- ❑ Why dileptons and photons may reveal more than hadrons

a first approach to meet the challenges*

PHQMD (Parton-Hadron-Quantum-Molecular-Dynamics)

- a novel microscopic transport approach to study heavy ion reactions
  - ❑ Why?
  - ❑ First tests that things work correctly
  - ❑ What we know up to now

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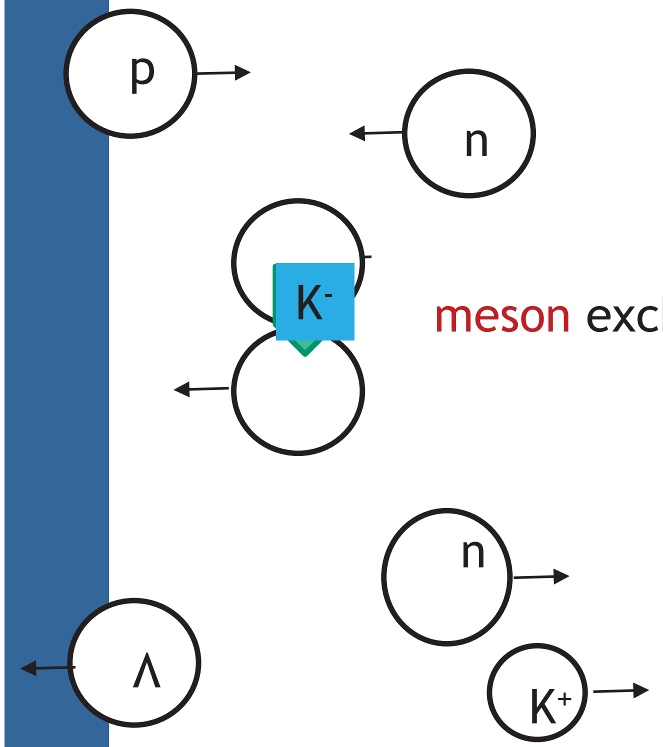
GDR "QCD" meeting Paris 25-27.11. 2019

How to describe elementary interactions among hadron?

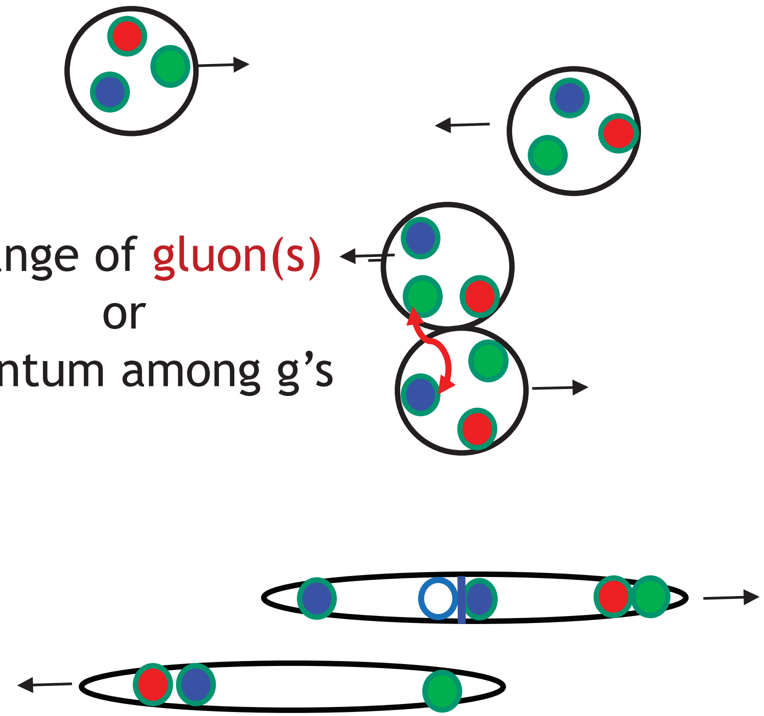
Example:

p+n → n+Λ+K



meson exchange

3-dim phase space
hadronic Feynman diagrams



exchange of gluon(s)
or
momentum among g's

Strings are formed which decay

longitudinal phase space
limited p_T
correlations (more Ωbar than Ω)

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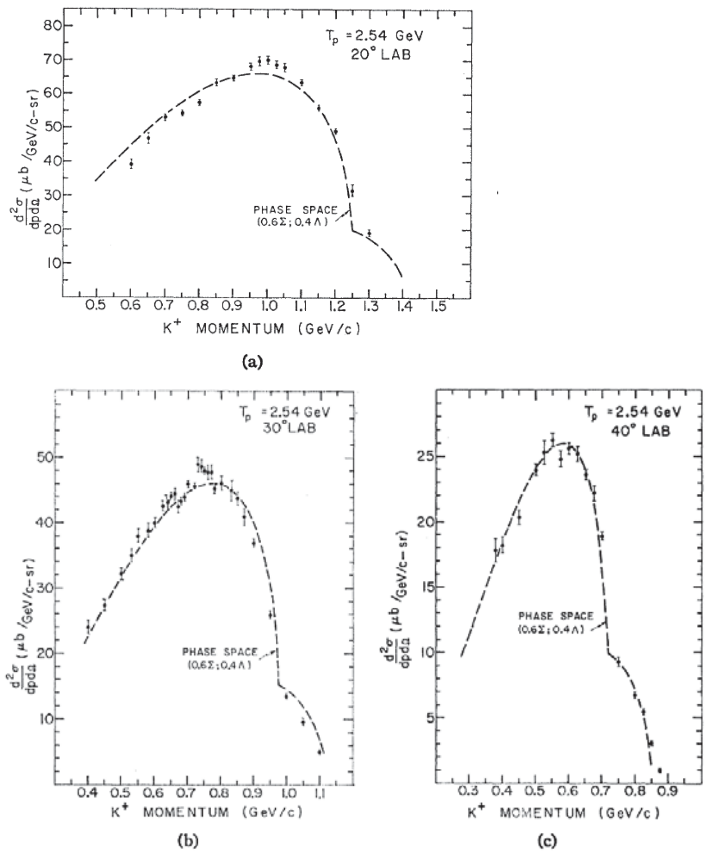
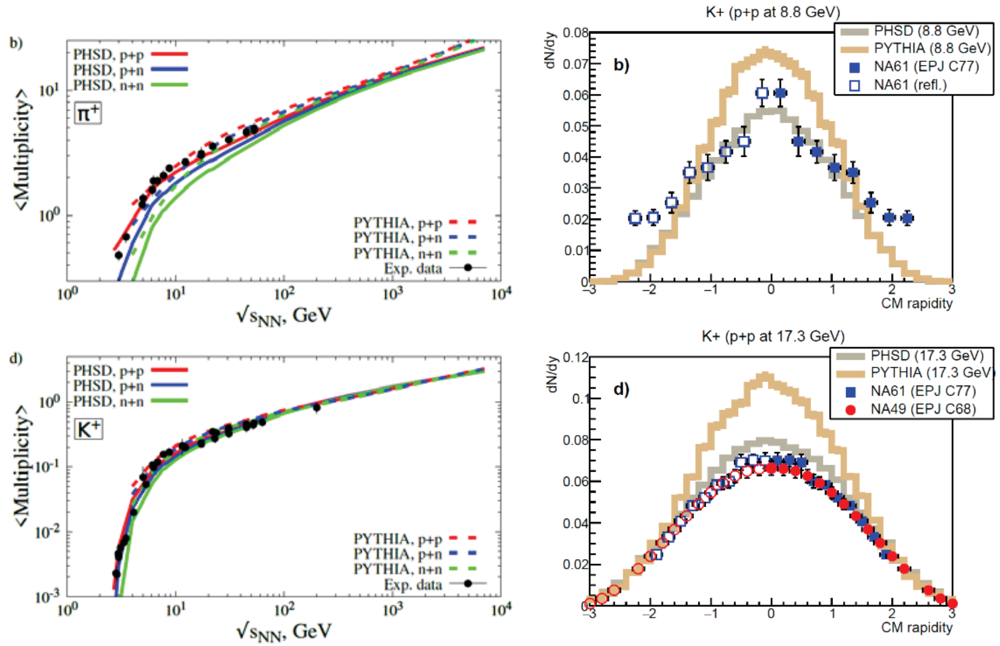
Experimental situation

In pp at E_{kin} = 2.54 Gev

K⁺ momentum as expected from hadronic 3 body phase space



$\sqrt{s}$ > 10 GeV: multiplicity and spectra as as expected from string decay



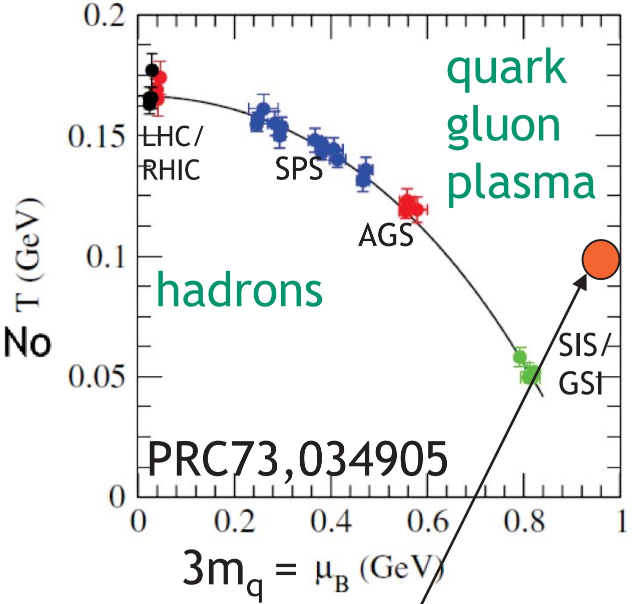
From which energy on partonic degrees of freedom become important?

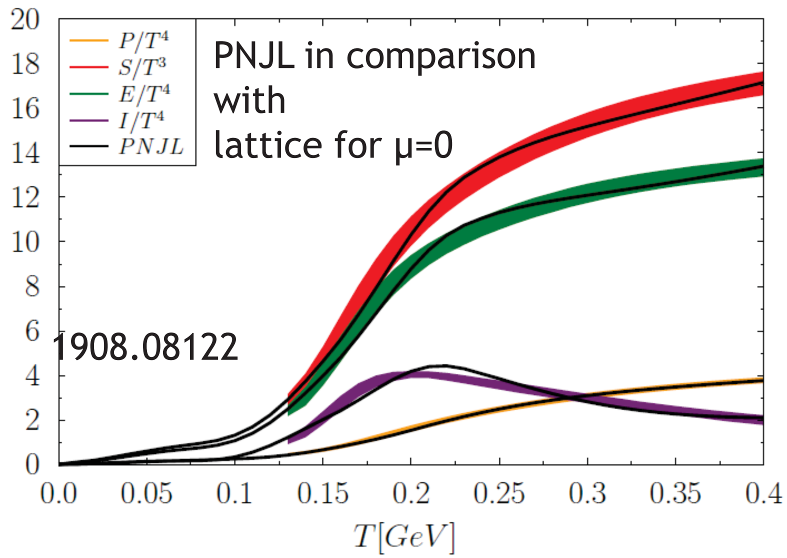
What happens between GSI/RHIC(LHC) energies in HI reactions?

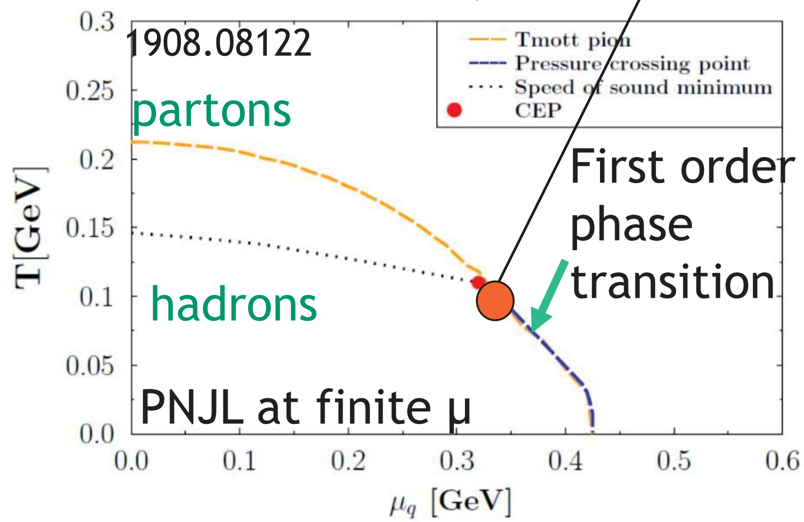
Statistical models: describe multiplicities of all observed hadrons 2.7 GeV<$\sqrt{s}$ < 8TeV by 2 parameters: μ and T

At energies < $\sqrt{s}$ =200 GeV we enter the domain of final μ. No guidance from lattice gauge calculations

Effective models like PNJL (in NLO in N_C + qg interactions): first order phase transition at finite μ.





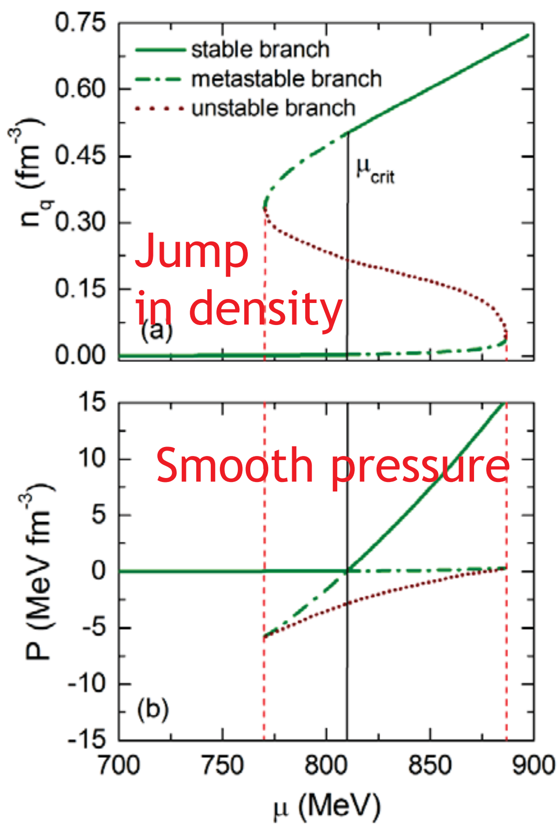


may be reachable in experiments

What happens at the phase transition?

Macroscopic thermal observables

microscopic behavior



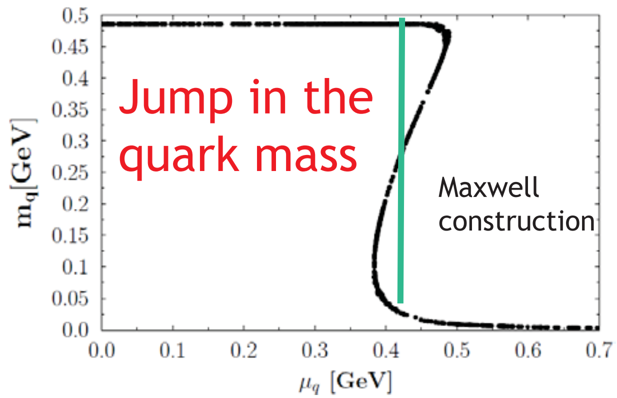
In infinite systems the phase transition is accompanied by a jump in density.

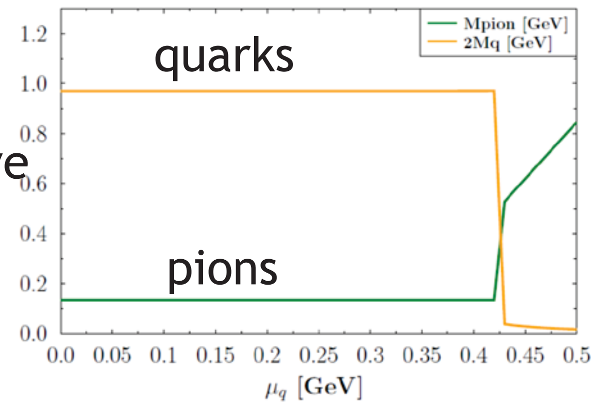
Challenge:

What happens when the system is rapidly expanding?

Which observables are sensitive (fragments, fluctuations, multi-strange baryons????)

How to model such a situation on the computer to interpret the experimental results?

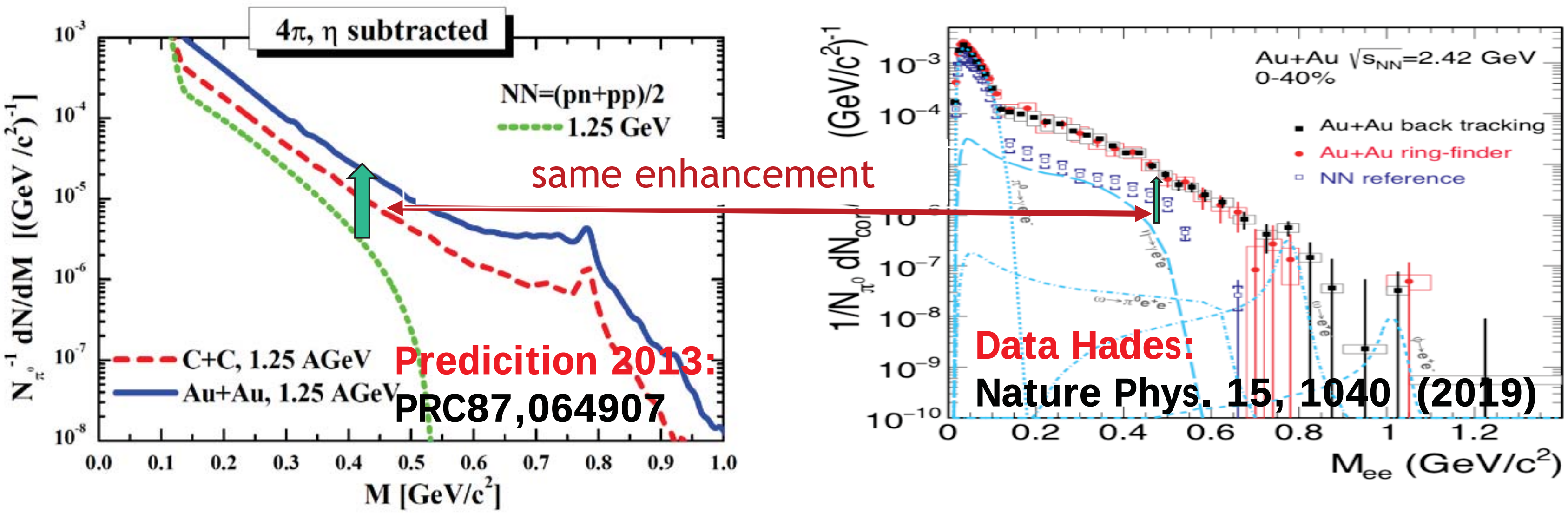




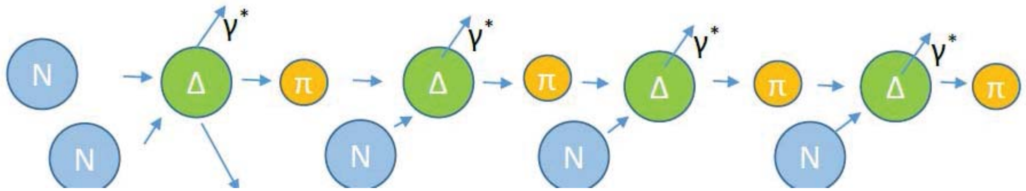
How to learn more about the HI reaction?

Hadronic probes test usually the final phase of the heavy ion collisions (exceptions: jets, heavy mesons, collective effects)

More insight → new probes: γ and dileptons spectra: first successes to reveal new physics



Reason: each Δ produces a γ^* but all Δ together one π

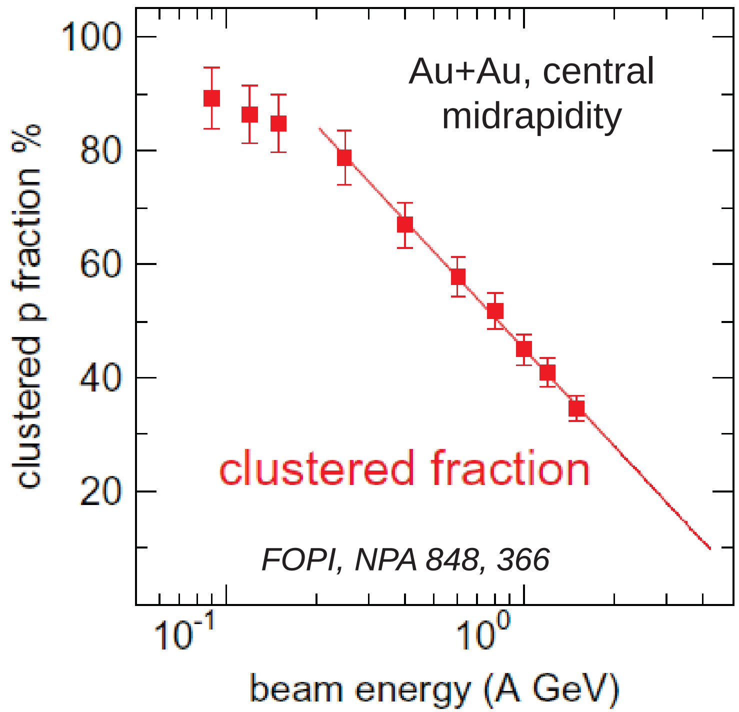


Low mass M: the γ^* / π^0 ratio mesures number of generations of Δ during a heavy ion collisions

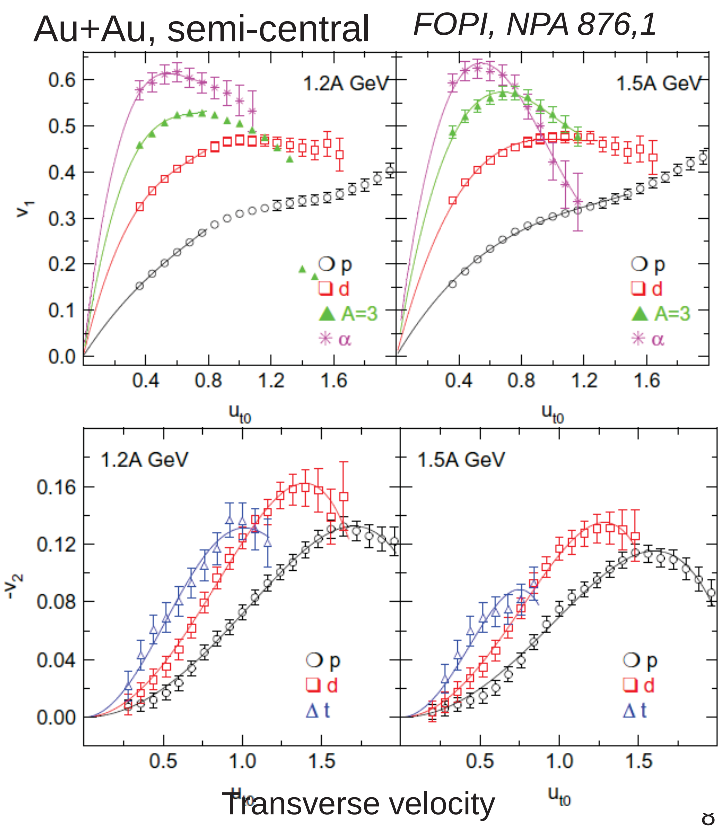
Dileptons may explore many other reaction details

PHQMD
(Parton-Hadron-Quantum-Molecular-Dynamics)

Clusters in HICs



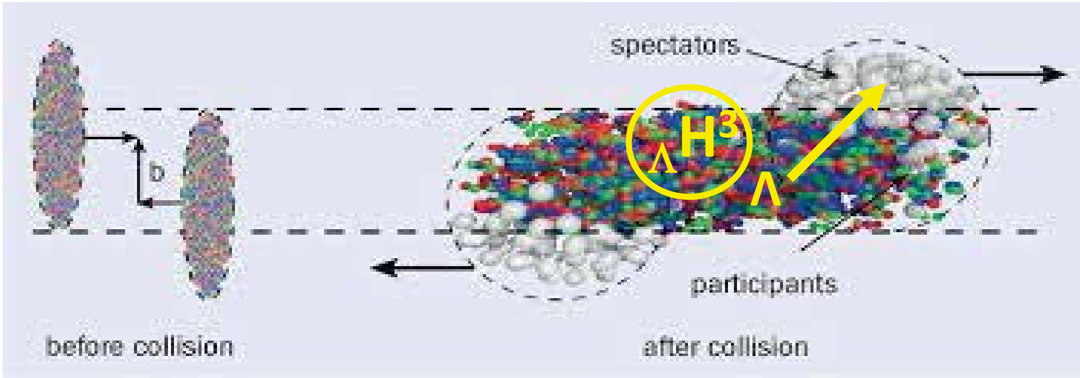
- Clusters are very **abundant at low energy;**
- at **3 AGeV** in central Au+Au collisions **~20% of the baryons are in clusters!**
- … and baryons in clusters have quite different properties (v_1, v_2, dn/dp_T)



➔ **Understanding of cluster formation is needed**

- for proper description of nucleon observables (v_1, v_2, dn/dp_T)
- to explore new physics opportunities like
  - hyper-nucleus formation
  - possible signals of the 1st order phase transition
  - cluster formation at midrapidity (RHIC, LHC)

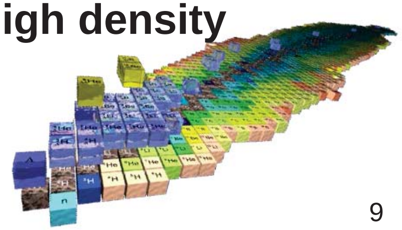
Why do we study especially hypermatter production?



- **Access to the nuclear dynamics:**
  different mechanisms for hypernucleus production vs. rapidity:
  - at mid-rapidity : Λ-coalescence - hypernuclei test the phase-space distribution of baryons in the expanding participant matter
  - at target/projectile y: Λ-absorption by spectators - elucidates the physics at the interface between spectator and projectile matter

Hypernuclei as bound objects:

- **give access to the third dimension of the nuclear chart (strangeness)**
- **give information on hyperon-nucleon and hyperon-hyperon interactions**
- **important e.g. for neutron stars (production of hypermatter at high density and low temperature)**
- **new field of hyperon spectroscopy**



Modelling of cluster and hypernucleus formation

Present microscopic approaches:

- VUU(1985), BUU(1985), (P)HSD(96), SMASH(2016) solve the time evolution of the one-body phase-space density in a mean field → no dynamical fragments

- UrQMD is a n-body model but makes clusterization via coalescence and a statistical fragmentation model

- QMD is a n-body model but is limited to energies < 1.5 AGeV
  → describes fragments at SIS energies,
  but conceptually not adapted for NICA/FAIR energies and higher

In order to understand the microscopic origin of cluster formation one needs:
- a realistic model for the dynamical time evolution of HICs
- dynamical modelling of cluster formation based on interactions

Dynamical modelling of cluster formation is a complex task which involves:
the fundamental nuclear properties, quantum effects, variable timescales

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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

↓

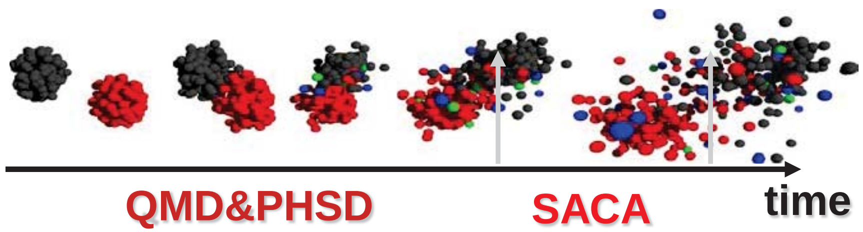
Initialization → propagation of baryons:
QMD (Quantum-Molecular Dynamics)

↓

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)



Transport eqs. for N-body theories like (PH)QMD,AMD,FMD

Roots in Quantum Mechanics

Remember QM cours when you faced the problem

- we have a Hamiltonian $\hat{H} = -\frac{\hbar^2\nabla^2}{2m} + V$
- the Schrödinger eq.

$$\hat{H}|\psi_j >= E_j|\psi_j >$$

has no analytical solution

- we look for the ground state energy

Walther Ritz

Ritz variational principle:

Assume a trial function $\psi(q,\alpha)$ which contains one adjustable parameter α, which is varied to find the lowest energy expectation value:

$$\frac{d}{d\alpha} < \psi|\hat{H}|\psi >= 0 \rightarrow \alpha_{min}$$

determines α for which $\psi(q,\alpha)$ is closest to the true ground state and $< \psi(\alpha_{min})|\hat{H}|\psi(\alpha_{min}) >= E_0(\alpha_{min})$ closest to true ground state E

Extended Ritz variational principle (Koonin, TDHF)

Take trial wavefct with time dependent parameters and solve

$$\delta \int_{t_1}^{t_2} dt < \psi(t)| i\frac{d}{dt} - H |\psi(t) >= 0. \qquad (1)$$

QMD trial wavefct for particle i with p_{oi} (t) and q_{oi} (t)

$$\psi_i(q_i, q_{0i}, p_{0i}) = C exp[-(q_i - q_{0i} - \frac{p_{0i}}{m}t)^2/4L] \cdot exp[i p_{0i}(q_i - q_{0i}) - i\frac{p_{oi}^2}{2m}t]$$

For N particles:

$$\psi_N = \prod_{i=1}^{N} \psi_i(q_i, q_{0i}, p_{0i})$$ QMD

$$\psi_N^F = Slaterdet[\prod_{i=1}^{N} \psi_i(q_i, q_{0i}, p_{0i})]$$ AMD/FMD

For the QMD trial wavefct eq. (1) yields

$$\frac{dq}{dt} = \frac{\partial < H >}{\partial p} \quad ; \quad \frac{dp}{dt} = -\frac{\partial < H >}{\partial q}$$

For Gaussian wavefct eq. of motion very similar to Hamilton’s eqs.
(but only for Gaussians !!)

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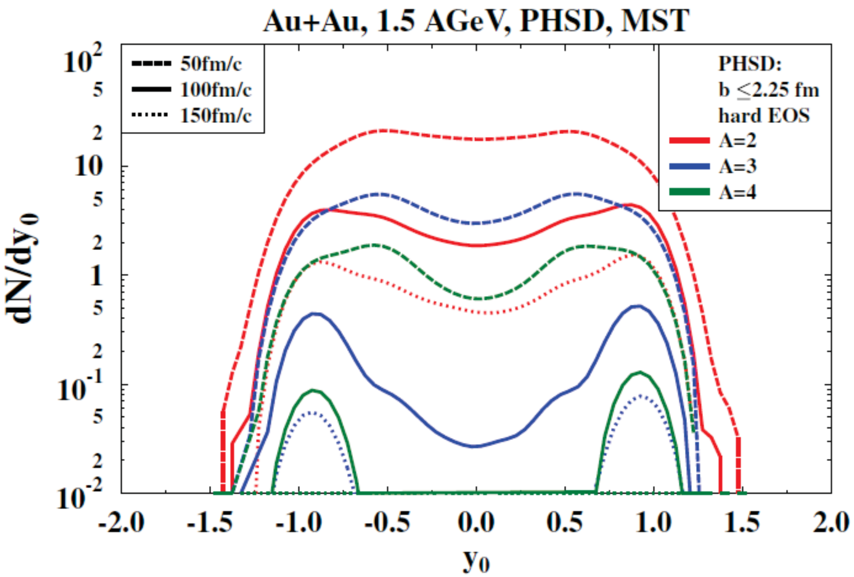
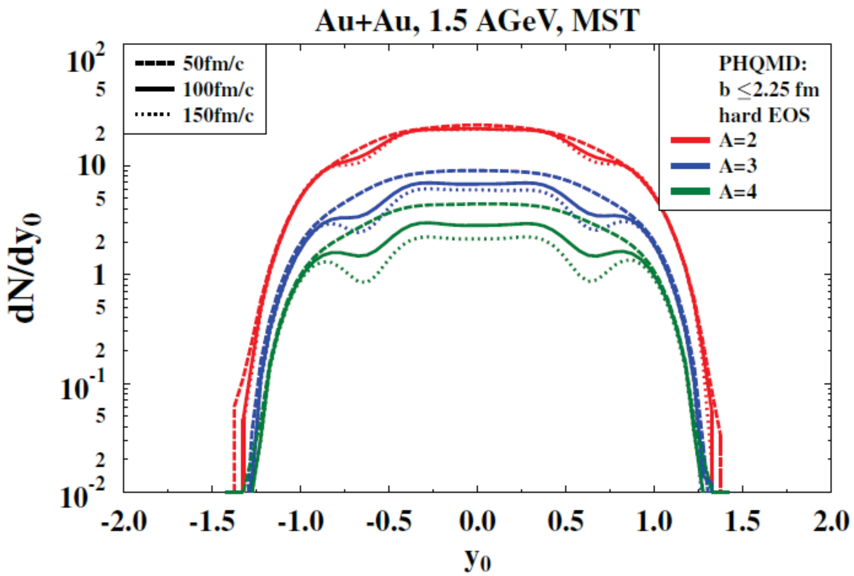
Time dependence of cluster formation: QMD vs. MF

mean field propagation
all two or more body correlation suppressed



QMD propagation
correlations present



QMD propagation: number of clusters are stable vs. time
(MST finds at 50 fm/c almost the same clusters as at 150fm/c)

MF propagation (per construction not suited for cluster studies):

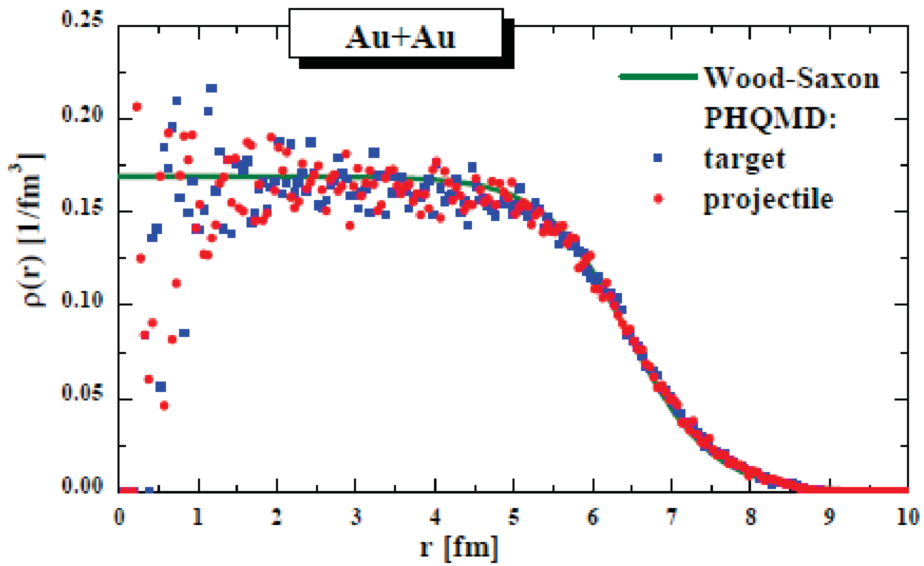
-- number of fragments strongly time dependent
-- fragments disappear with time
-- midrapidity fragments disappear early, projectile/target fragments later
→ no common time for coalescence

Realisation

PHQMD

Initial condition:
to describe fragment formation and
to guaranty the stability of nuclei

The initial distributions of nucleons in proj and targ has to be carefully modelled:
- Right density distribution
- Right binding energy



local Fermi gas model for the momentum distribution

Potential in PHQMD

above ε=0.5 GeV/fm^3 transition to QGP like in PHSD
Below:
Relativistic molecular dynamics (PRC 87, 034912) too time consuming

The potential interaction is most important in two rapidity intervals:
- at beam and target rapidity where the fragments are initial – final state correlations and created from spectator matter
- at midrapidity where – at the late stage - the phase space density is sufficiently high that small fragments are formed

In both situations we profit from the fact that the relative momentum between neighboring nucleons is small and therefore nonrelativistic kinematics can be applied. Potential interaction between nucleons

$$V_{i,j} = V(\mathbf{r_i}, \mathbf{r_j}, \mathbf{r_{i0}}, \mathbf{r_{j0}}, t) = V_{\text{Skyrme}} + V_{\text{Coul}}(+V_{mom})$$
$$= \frac{1}{2} t_1 \delta(\mathbf{r_i} - \mathbf{r_j}) + \frac{1}{\gamma+1} t_2 \delta(\mathbf{r_i} - \mathbf{r_j})\, \rho^{\gamma-1}(\mathbf{r_i}, \mathbf{r_j}, \mathbf{r_{i0}}, \mathbf{r_{j0}}, t)$$
$$+ \frac{1}{2} \frac{Z_i Z_j e^2}{|\mathbf{r_i} - \mathbf{r_j}|}(+V_{mom}),$$

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$$\langle V(\mathbf{r_i},t)\rangle = \sum_{j\neq i}\int d^3r d^3r' d^3p d^3p' \\ V(\mathbf{r},\mathbf{r}',\mathbf{r_i},\mathbf{r_j}) f(\mathbf{r},\mathbf{p},\mathbf{r_i},\mathbf{p_i},t) f(\mathbf{r}',\mathbf{p}',\mathbf{r_j},\mathbf{p_j},t)$$

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

To describe the potential interactions in the spectator matter we transfer the Lorentz-contracted nuclei back into the projectile and target rest frame, neglecting the small time differences

$$\rho_{int}(\mathbf{r_i},t) \rightarrow C\sum_j \left(\frac{4}{\pi L}\right)^{3/2} e^{-\frac{4}{L}(\mathbf{r_i^T}(t)-\mathbf{r_j^T}(t))^2} \cdot e^{-\frac{4\gamma_{cm}^2}{L}(\mathbf{r_i^L}(t)-\mathbf{r_j^L}(t))^2}.$$

For the midrapidity region γ → 1. and we can apply nonrelativisitic kinematics as well

All elastic and inelastic cross sections from PHSD – therefore at high energy the spectra of produced particles are similar to PHSD results (however initial distribution is different in PHSD and PHQMD)

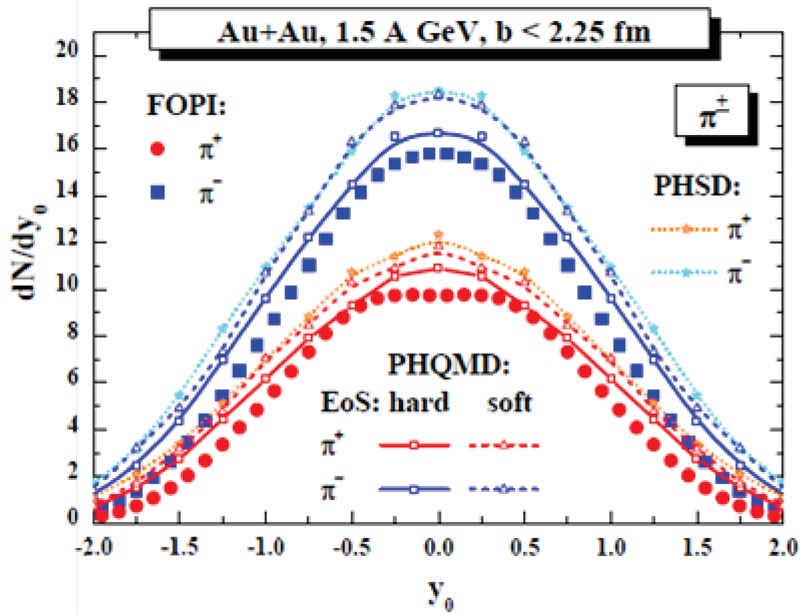
Results

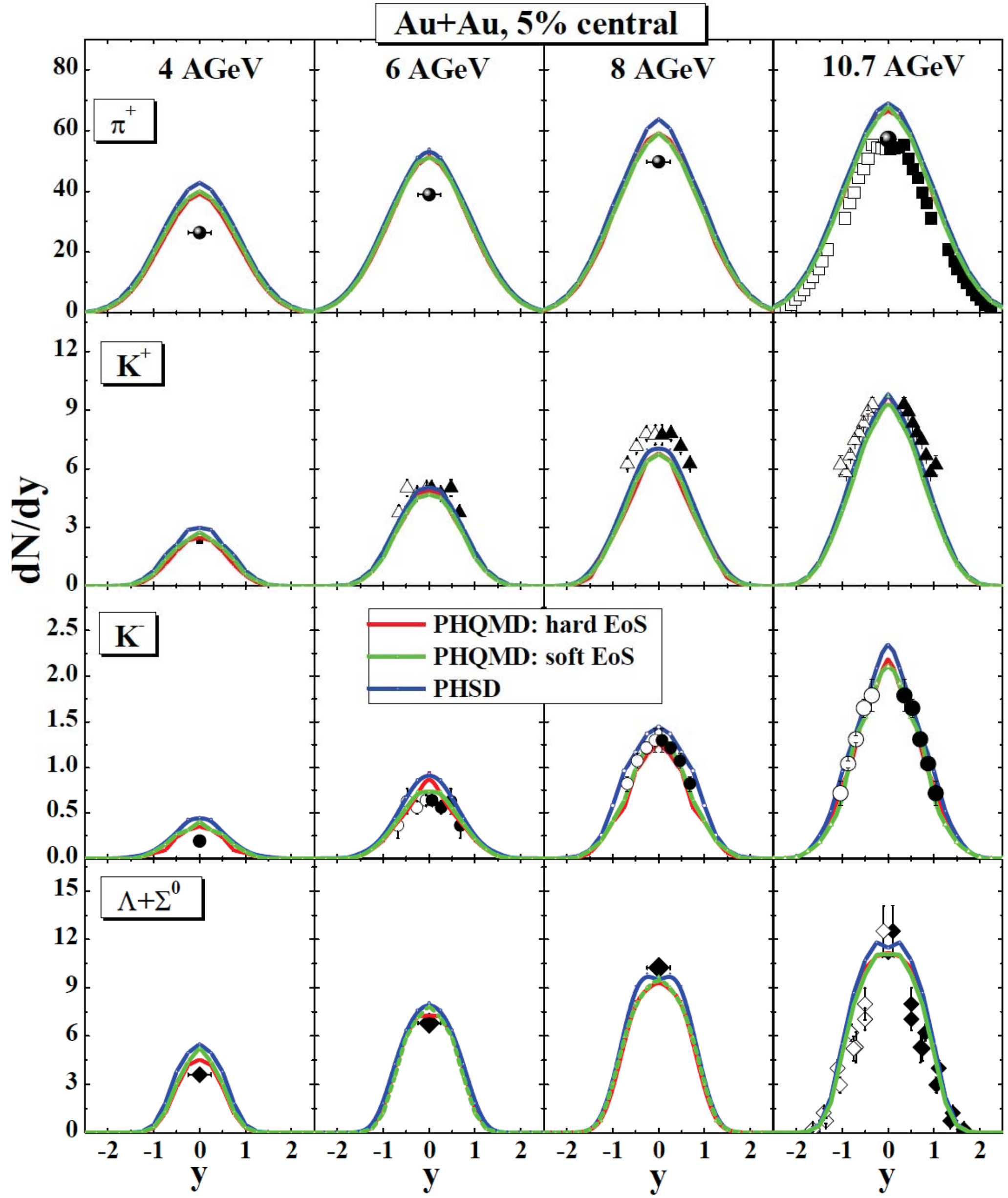
First Results of PHQMD

Produced particles

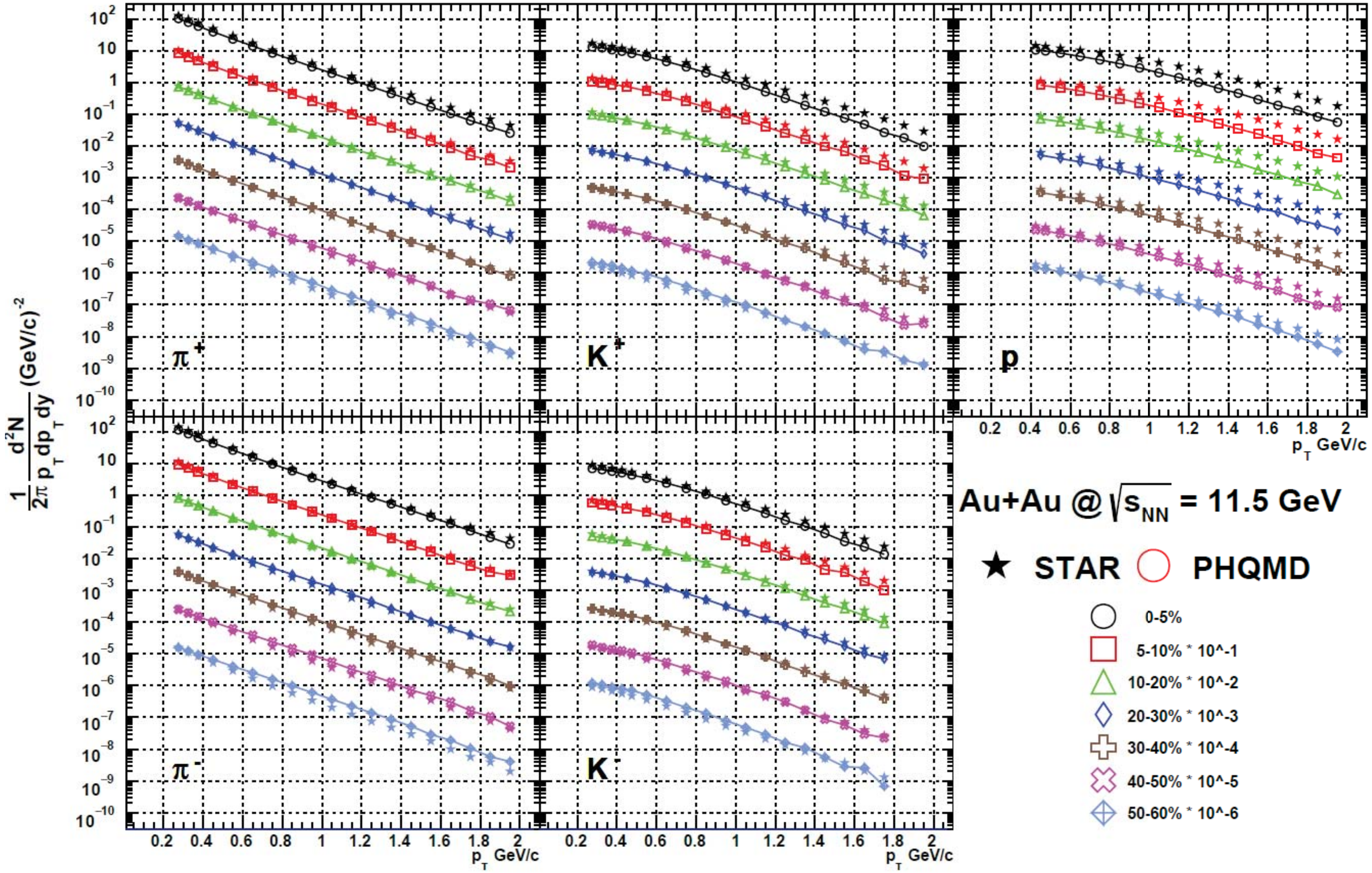
are well reproduced
at SIS/NICA/FAIR energies

(dominated by collisions)





.. And also the most recent STAR data at 11.5 AGeV



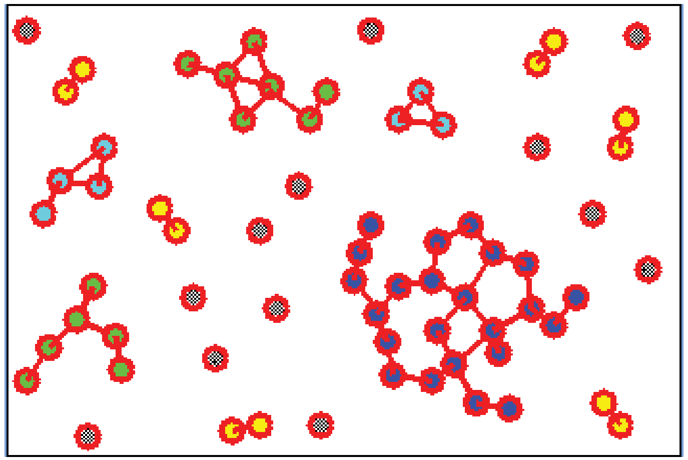
MST cluster recognition algorithm

I. Mininum Spanning Tree (MST) is a cluster recognition method applicable for the (asymptotic) final state 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 $|\vec{r}_i - \vec{r}_j| \leq 2.5\ fm$

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



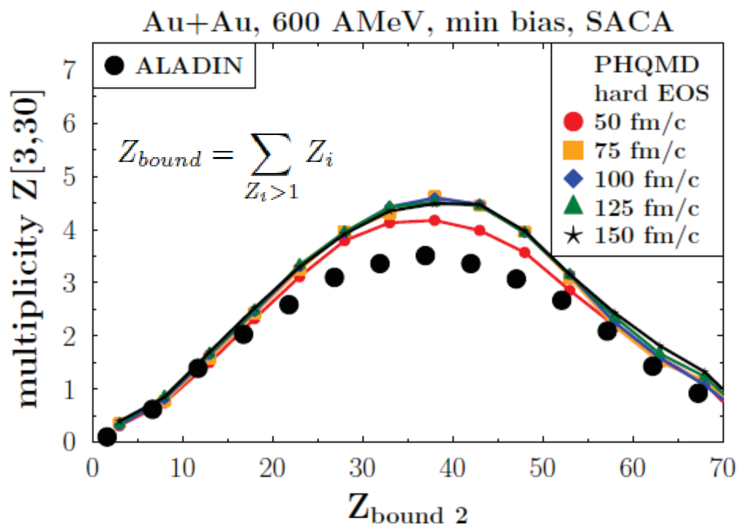
Additional momentum cuts (coalescence) change little:
large relative momentum -> finally not at the same position

Fragment formation in PHQMD

First Results of PHQMD

Spectator Fragments

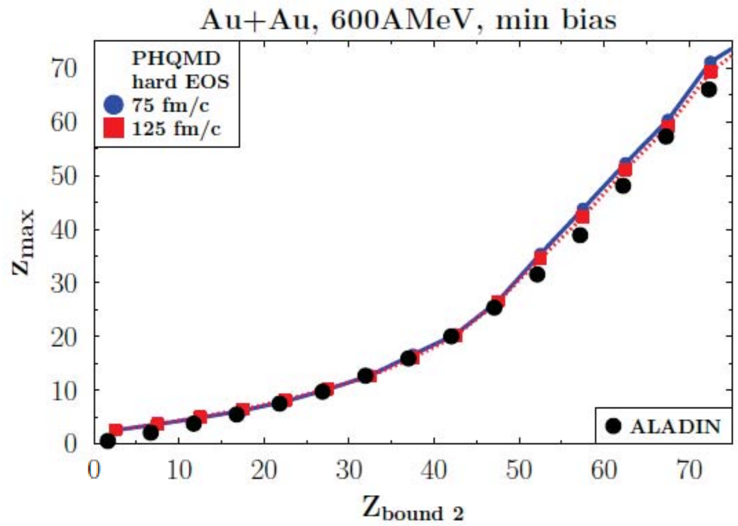
experm. measured up to E_{beam} =1 AGeV (ALADIN)

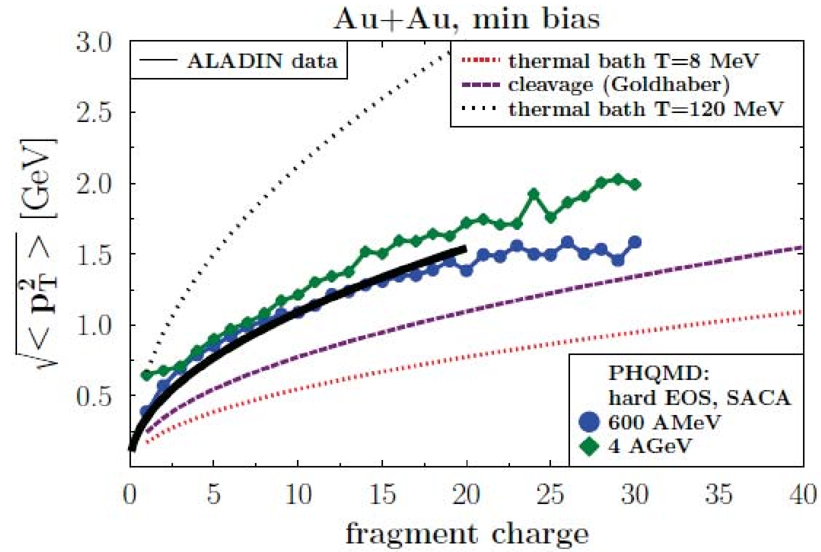


agreement for very complex fragment observables like the

- ❑ energy independent "rise and fall"
- ❑ largest fragment (Z_{bound})

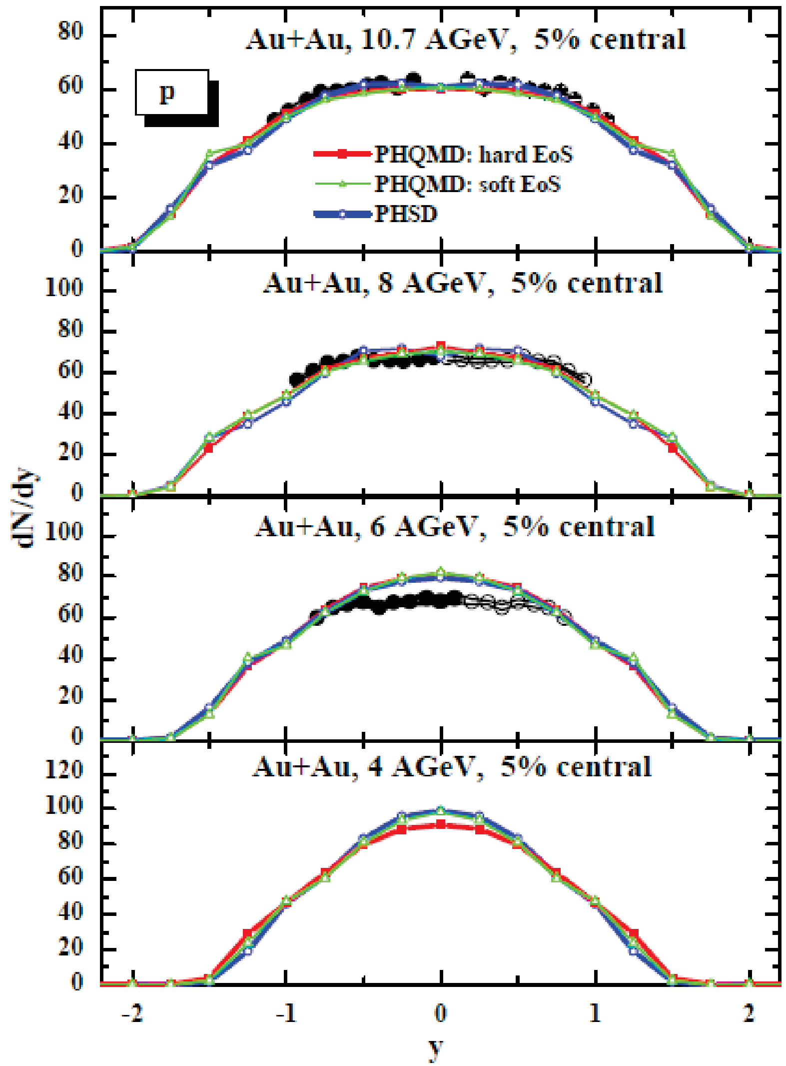
rms(p_t) shows $\sqrt{Z}$ dependence



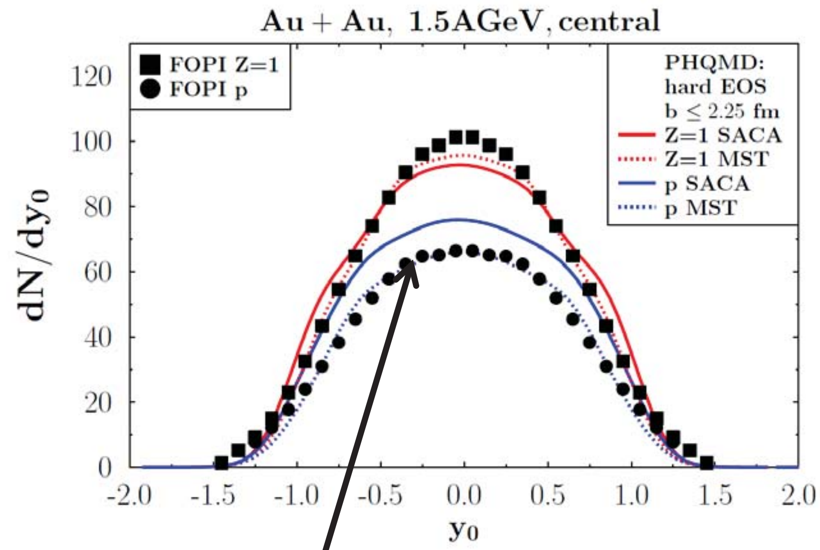


First Results of PHQMD

Protons at midrapidity well described



midrapidity fragment production increases with decreasing energy



1.5 AGeV central

➢ 30% of protons bound in cluster

To improve: better potential for small clusters

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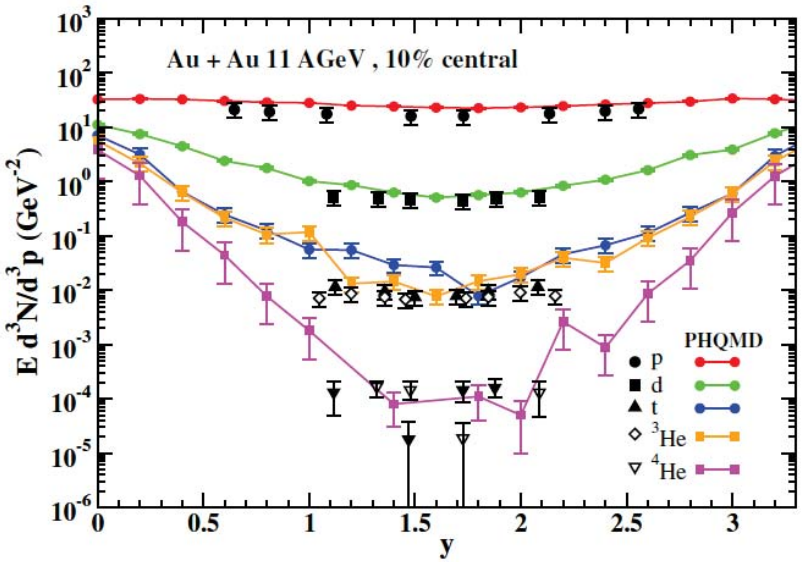
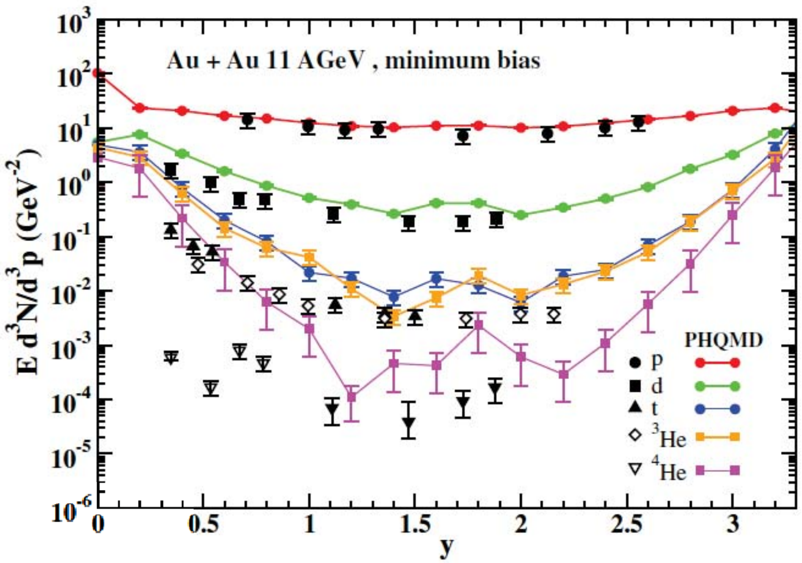
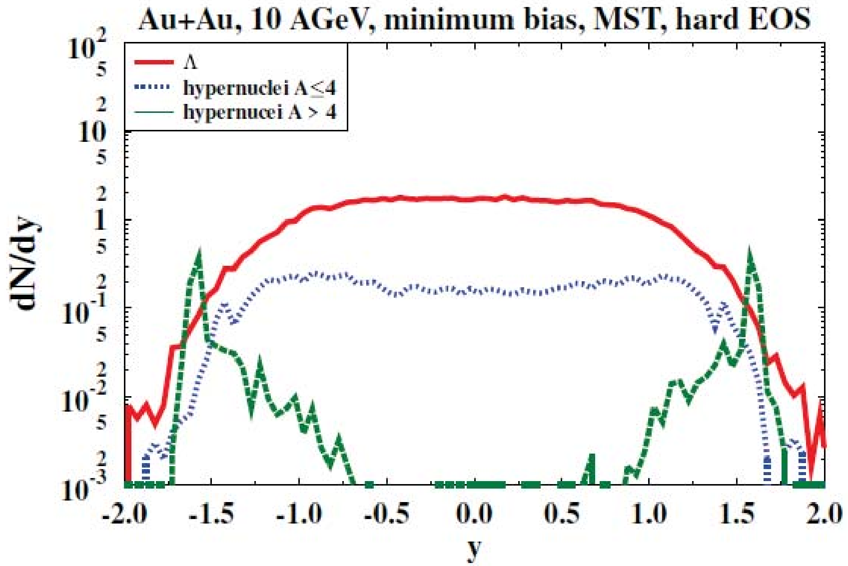
Cluster production at AGS/FAIR energies

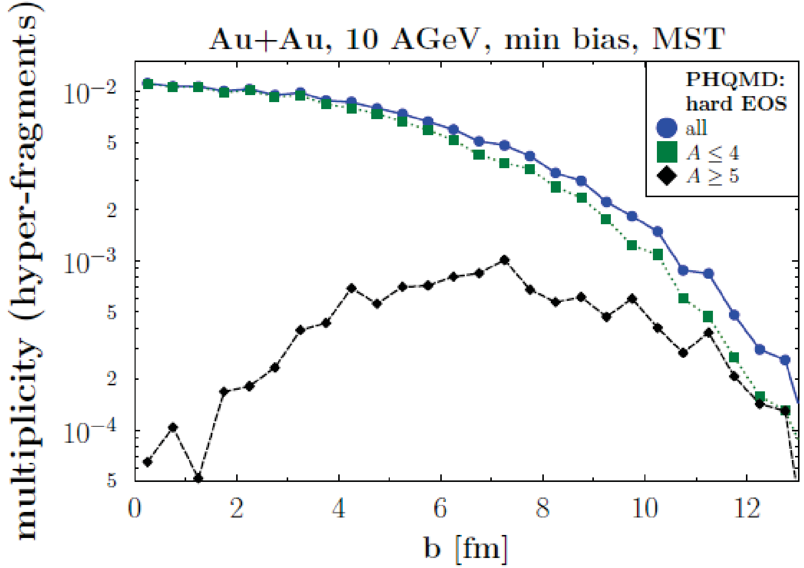
d,t,He





hyper-nuclei





Conclusions

We presented a new model, PHQMD, for the NICA/CBM energies which allows - in contrast to all other models - to predict the

dynamical formation of fragments

- allows to understand the proton spectra and the properties of light fragments ($dn/dp_T dy$, v_1,v_2, fluctuations)
- allows to understand fragment formation in participant and spectator region
- allows to understand the formation of hypernuclei
- should allow to understand fragment formation at RHIC/LHC

Very good agreement with the presently available fragment data as well as with the AGS/SPS single particle spectra

But a lot has still to be done!!