Dynamical models for heavy-ion collisions

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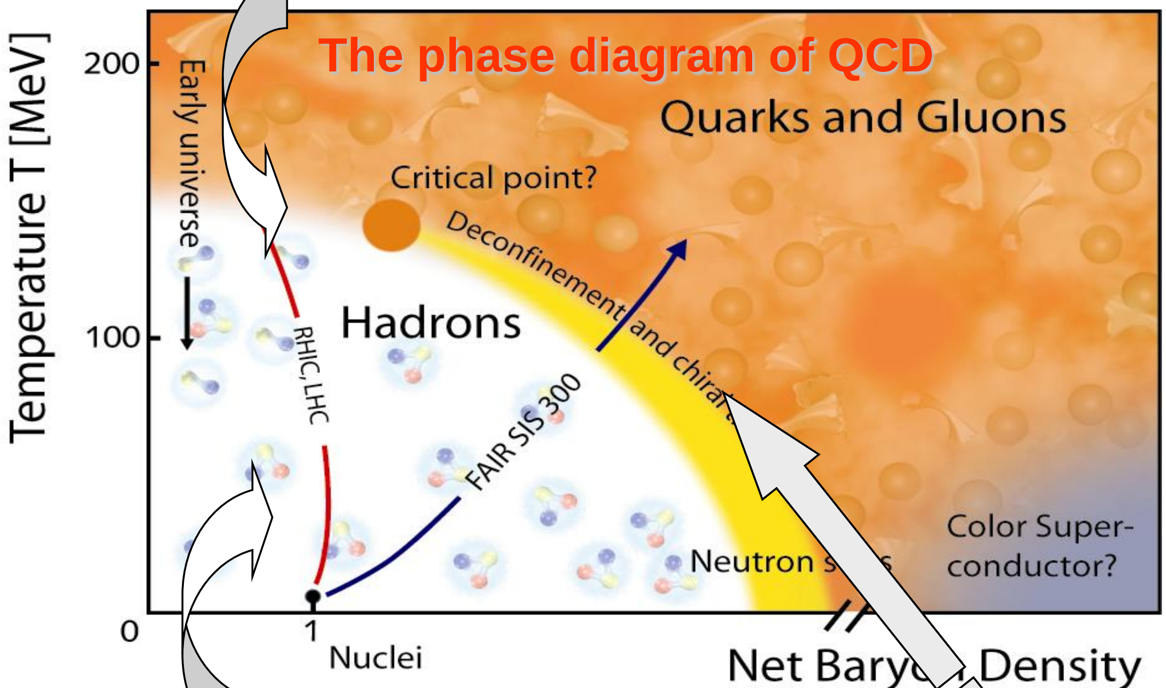
- ❑ Why do we need transport approaches in HI physics?
- ❑ Why is the BM@N/NICA physics so interesting?
- ❑ What kind of transport approaches are available?
- ❑ Some results for the BM@N/NICA energy regime

First Collaboration meeting of the MPD and BM@N experiments at the NICA facility
Dubna, April 11-13 2018

The challenges of heavy-ion physics I:

What we want to know

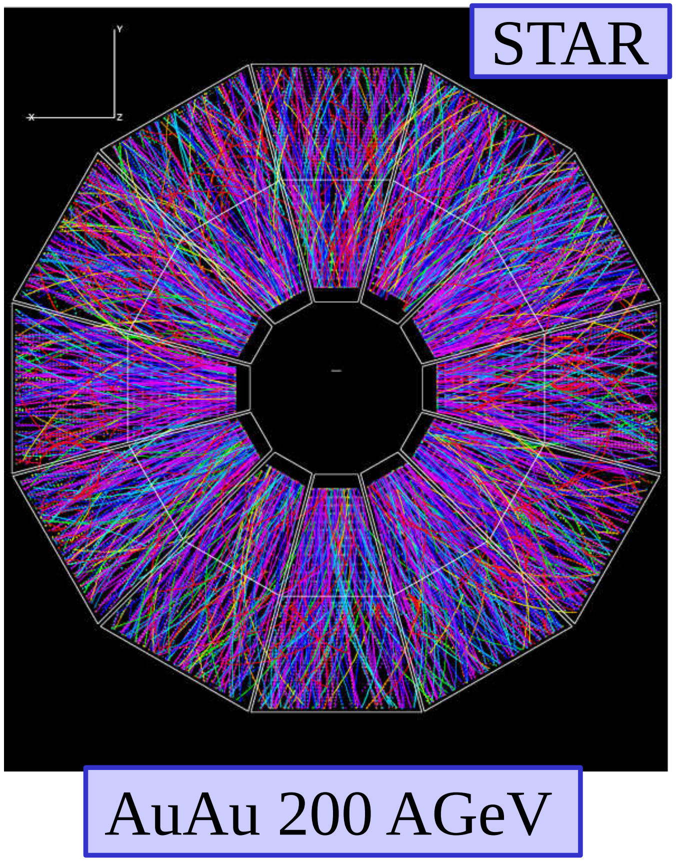
- The critical point



- in-medium properties of hadrons, and their production channels
- production of (hyper)fragments and fragments at midrapidity
- Study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma

The challenges of heavy-ion physics II:

What the experiments can provide:



Experiments deliver the momenta of thousands of particles of different masses

but

these particles contain only very indirectly the information on the interesting physics

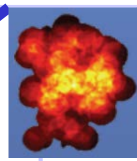
To extract the physical quantities from the experimental results is the task of transport theories

Dynamical models for HIC

Macroscopic

hydro-models:

- description of QGP and hadronic phase by hydrodynamical equations
  assuming local equilibrium
  Input:
- EoS with phase transition from QGP to HG
- initial conditions (e-b-e, fluctuating)



ideal
(Jyväskylä,SHASTA, TAMU, …)

viscous
(Romachkke,(2+1)D VISH2+1, (3+1)D MUSIC,…)

fireball models:

- no explicit dynamics: parametrized time evolution (TAMU)

Microscopic

Non-equilibrium microscopic transport models –

Parton-hadron models

QGP: lQCD EoS
massive quasi-particles
dynamical hadronization
HG: off-shell dynamics
(PHSD)

Partonic cascades

QGP: pQCD based massless partons
(Duke, BAMPS, …)

with hadronization by coalescence
(AMPT, HIJING)

Hadron (string,Regge) models

Cascade
(UrQMD, QGSM, HSD …)

Interactions among hadrons
(SMASH, IQMD (hadronic))

'Hybrid'

- Initial state: Gribov-Regge, Lund
- QGP phase: hydro with QGP EoS
- hadronic freeze-out
- after burner with on shell particles

(,hybrid'-UrQMD, EPOS, …)

Dynamical models for HIC

All approaches have their advantages and drawbacks.

Ideal hydrodynamics: only input: Equation of state (lQCD)
but to compare with data: initial condition + hadronization needed

The more sophisticated the approach the more input is needed

Microscopic models:
Elementary cross sections, (effective) masses, degrees of freedom ← (theory or exp.)
Theory of some of the ingredients needs improvement

Strategy to explore the physics:

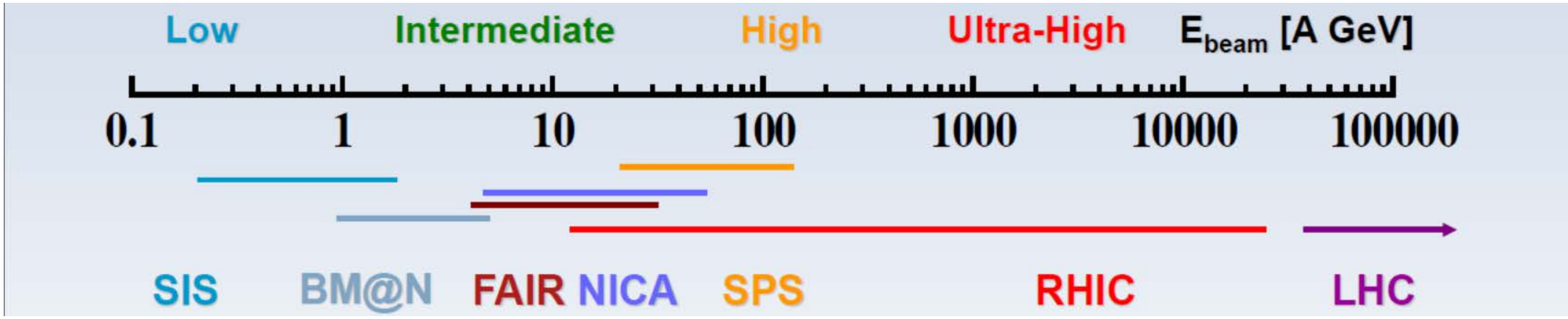
- use the results of many body theory, elementary particle theory, lQCD, different experiments

treat the unknown as parameter to be determined by comparison with data.

- Cross check with predictions of other observables

goal and necessity:
comprehensive understanding of all observables

Why is the BM@N / NICA energy regime so interesting ?



hadrons | **transition (mixed phase)** (where?,signature?) | **quark and gluons**

$\mu \approx \mu_B$ | first order phase transition at finite μ? | $\mu \approx 0$

other challenges for BM@N/NICA:

Φ, Ξ production → excitation function in pp AA

excitation function ← v_2 (part)≠v_2 (antipart) ($\sqrt{s} = 7.7$ AGeV)

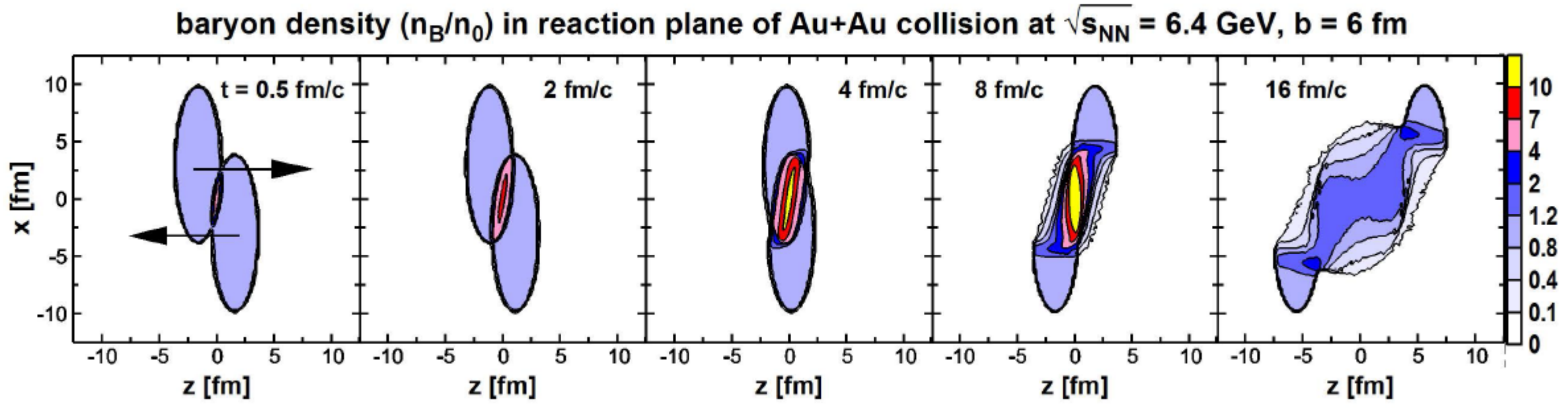
no Ω excitation function ← Ω Ξ, centrality dependence

few hypernuclei | right energy for hyper nucleus prod.? | very few hypernuclei

Models suited for BM@N and NICA energies

Hydrodynamics

++: only input: equation of state (test of different EOS)



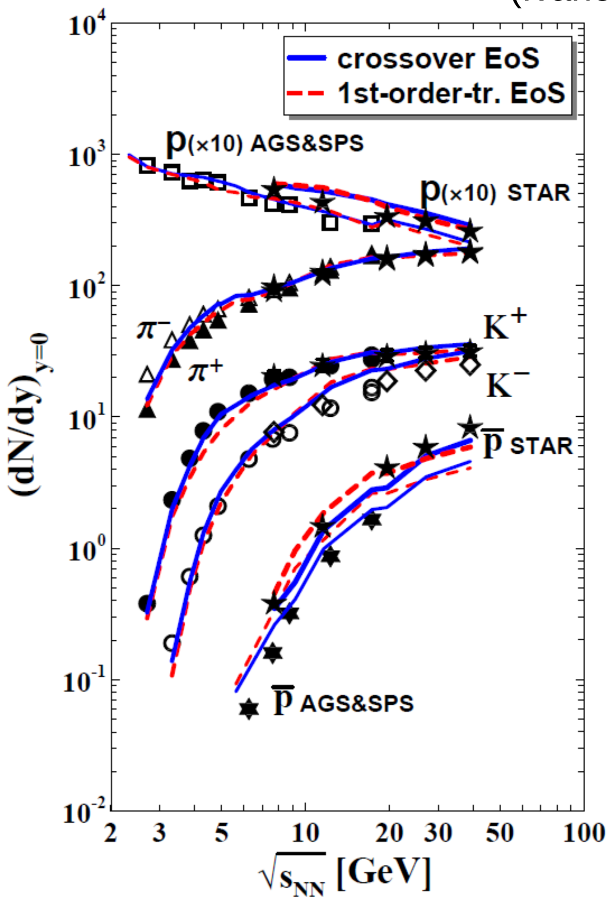
Ivanov et al. 1801.01764

to compare with data more input needed:

- -: initial condition
- -: hadronisation: according to grand canonical distribution functions
- -: eventually hadronic rescattering
  (importance seen by too low multiplicities of resonances)

BM@N/NICA physics needs more sophistication:

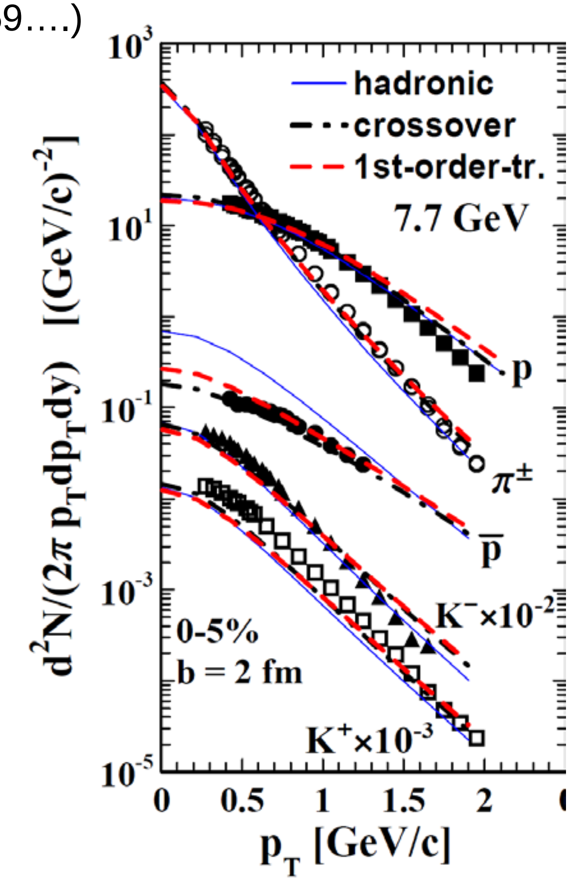
Three fluid hydrodynamics (proj, target, midrapidity source)
with phenomenomogical interaction between the fluids
(Ivanov et al. 1801.01764, 1711.07959….)



very useful results
for the bulk parts

Low p_T particle
spectra →

← Excitation function



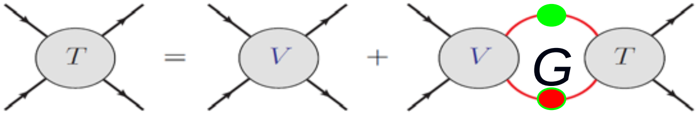
but fails in details by construction (using grand canonical particle production)
- if energy conservation becomes important (high p_T, multistrange baryons)
- if non equilibrium effects become important (details of spectra)
- if the conservation of quantum numbers becomes important

BUU (VUU, QGSM, AMPT, SMASH) equation

Boltzmann (Vlasov)-Uehling-Uhlenbeck equation (in non-relativistic form!)
- propagation of particles in the self-generated HF mean-field potential with an
- on-shell collision term:

$$\boxed{\frac{d}{dt} f(\vec{r},\vec{p},t) \equiv \frac{\partial}{\partial t} f(\vec{r},\vec{p},t) + \frac{\vec{p}}{m}\vec{\nabla}_{\vec{r}}\, f(\vec{r},\vec{p},t) - \vec{\nabla}_{\vec{r}} U(\vec{r},t)\,\vec{\nabla}_{\vec{p}} f(\vec{r},\vec{p},t) = \left(\frac{\partial f}{\partial t}\right)_{coll}}$$

$$\mathrm{U_j} = \langle \phi_\mathrm{i} | \mathrm{T_{ij}} | \phi_\mathrm{i} \rangle \quad ; \quad \mathrm{T_{ij}} = \mathrm{V_{ij}} + \mathrm{V_{il}}\,\mathrm{G}(\rho, \mathrm{T})\,\mathrm{T_{lj}}$$



already a quantal approach: self generated mean field ~ Re T(Brückner G-matrix) NOT V_{NN}

collision term ~ Im T

Probability including Pauli blocking of fermions

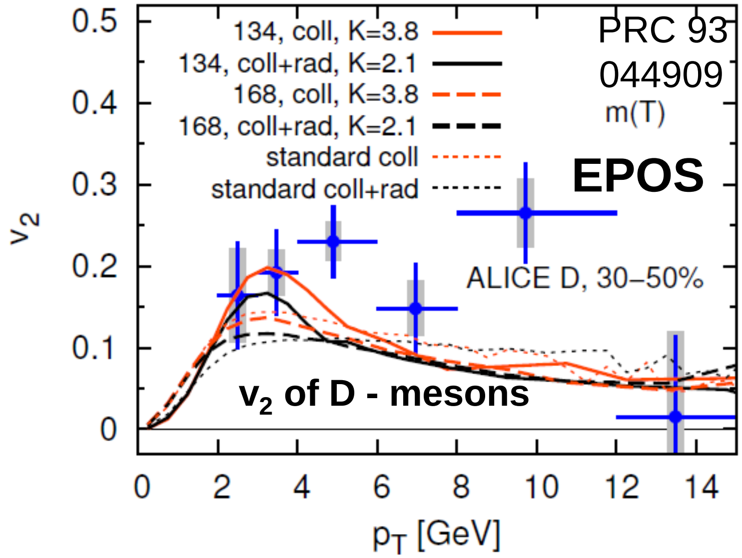
$$\left(\frac{\partial f}{\partial t}\right)_{coll} \Rightarrow \frac{1}{((2\pi)^3)^3}\int d^3p_2\, d^3p_3\, d^3p_4 \cdot w(1+2 \rightarrow 3+4)\cdot P$$

$$\times (2\pi)^3 \delta^3(\vec{p}_1 + \vec{p}_2 - \vec{p}_3 - \vec{p}_4)\,(2\pi)\delta\!\left(\frac{\vec{p}_1}{2m_1} + \frac{\vec{p}_2}{2m_2} - \frac{\vec{p}_3}{2m_3} - \frac{\vec{p}_4}{2m_4}\right)$$

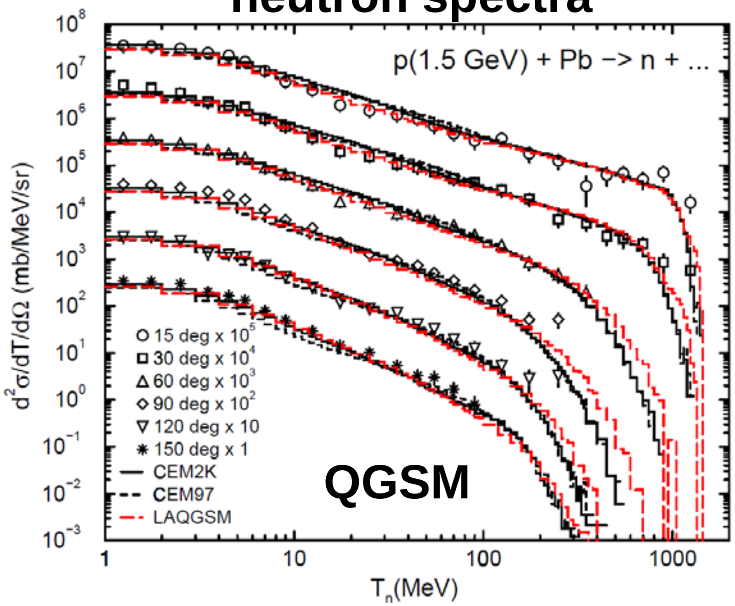
Transition probability for *1+2→3+4:*
$$w(1+2 \rightarrow 3+4) \Rightarrow \upsilon_{12}\cdot\frac{d^3\sigma}{d^3q}$$

Collision integral can easily be extended to inelastic collisions

These transport approaches have been used for numerous studies

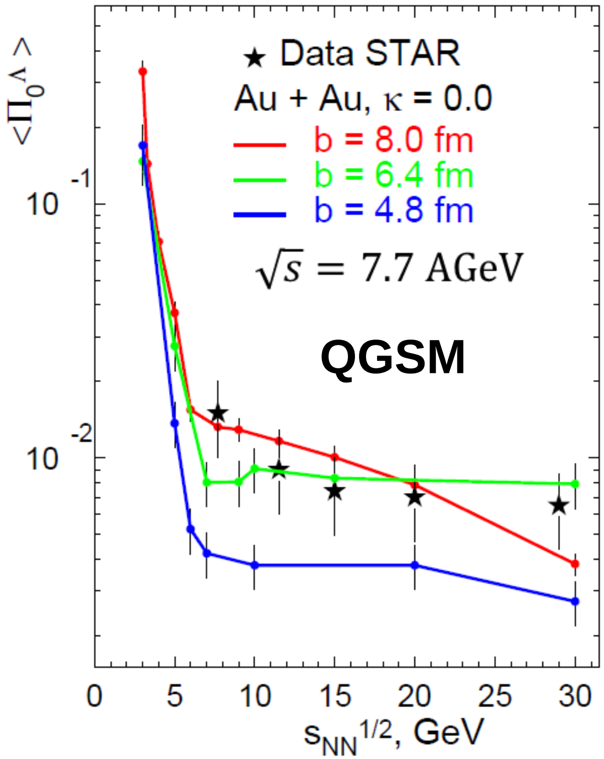


neutron spectra



K. Gudima, S. Mashnk, A. Sierk, nucl-th/001164

Λ polarisation



M. Baznat, K. Gudima, G. Prokhorov, A. Sorin, O. Teryaev and V. Zakharo, J.Phys.Conf.Ser.938,012063

Medium affects particle properties

In a dense and hot environment

- ❑ hadrons (partons) are not „on shell“ ($E^2 = p^2 + m^2$) but develop a spectral function
- ❑ resonances modify their properties (width, life time)

➔ broad spectral function ➔ particles cannot be treated as quasi-particles
but are quantum objects
need resummation of the in-medium scattering matrix

❑ semi-classical BUU

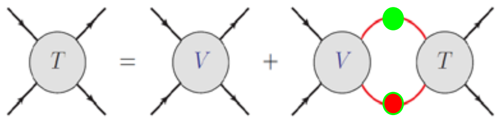
resummed 2 particle scattering matrix

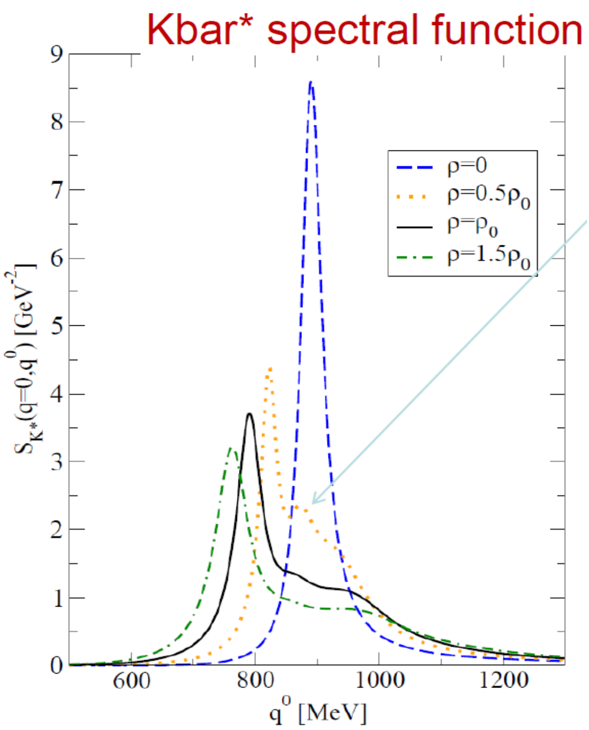
❑ Kadanoff Baym equation

first order gradient expansion

Numerical realization: PHSD

(Parton Hadron String Dynamics)





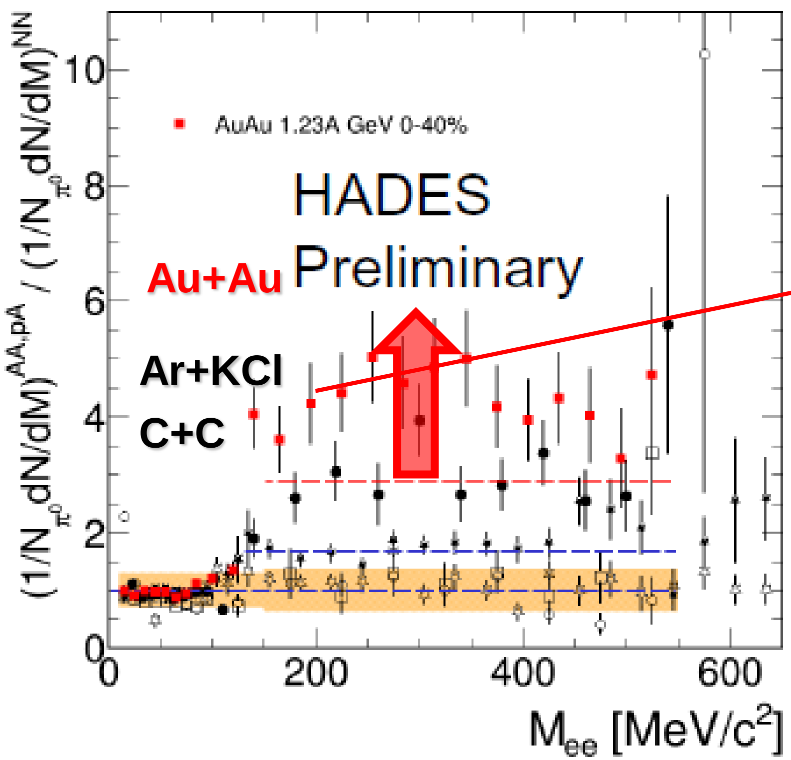
Λ(1783)N^{-1} and Σ(1830)N^{-1} exitations

Barcelona / Valencia group

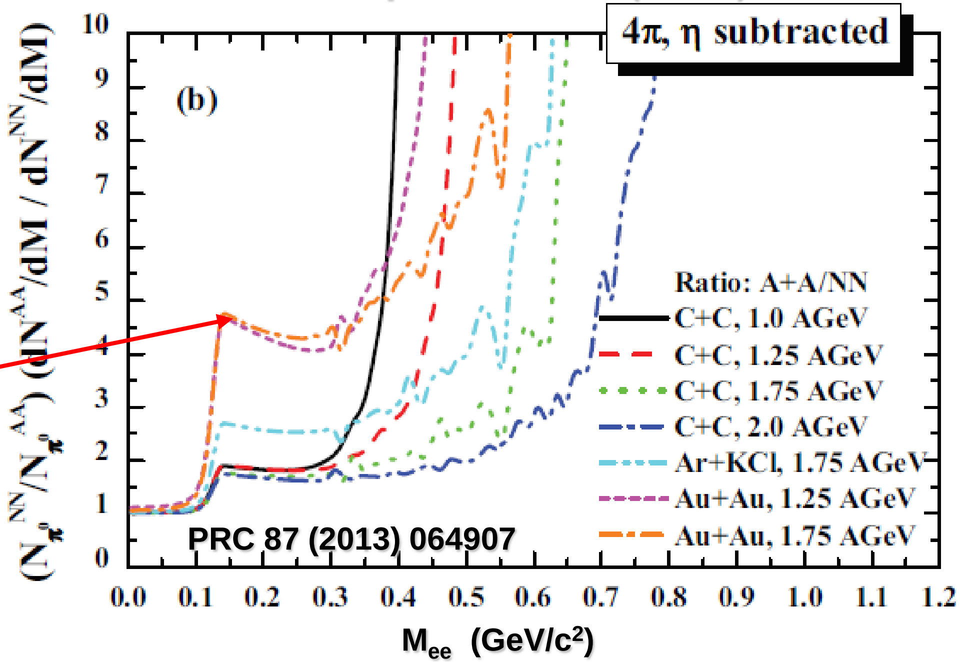
(P)HSD – transport approach based on Kadanoff Baym eqs.

Dileptons at SIS (HADES): Au+Au

CPOD-2016:
HADES preliminary: Au+Au, 1.23 A GeV



- **HSD predictions (2013)**



❑ **Strong in-medium enhancement** of dilepton yield in Au+Au vs. NN :

1) the **multiple Δ regeneration** – dilepton emission from intermediate Δ's which are part of the reaction cycles Δ→πN; πN →Δ and NN→NΔ; NΔ→NN

2) the **pN bremsstrahlung** which scales with N_{bin} and not with N_{part} , i.e. pions;

Physics explored **transport approaches**

Transport approaches presented so far
allow to investigate

Observables:

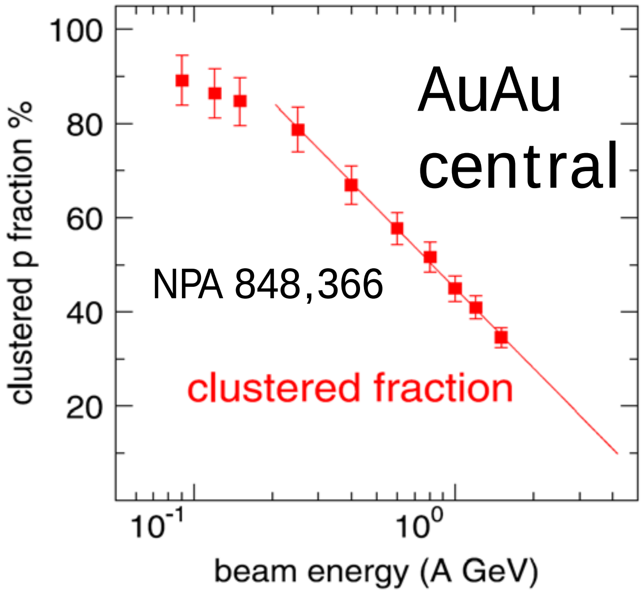
- Multiplicity of hadrons ($\sqrt{s}$) → (in medium) cross section
- Particle ratios → resonance suppression
- In-plane flow → interaction potential between hadrons
- Elliptic flow(light had) → spatial geometry of the interaction zone
- Elliptic flow (heavy had) → interaction of heavy quarks with QGP
- Dileptons→ production of resonances, heavy mesons
- Suppression of multi strange baryons → limited phase space
- Photons → more than bremsstrahlung?
- Vorticity → Λ polarization

So why do we need more sophisticated model?

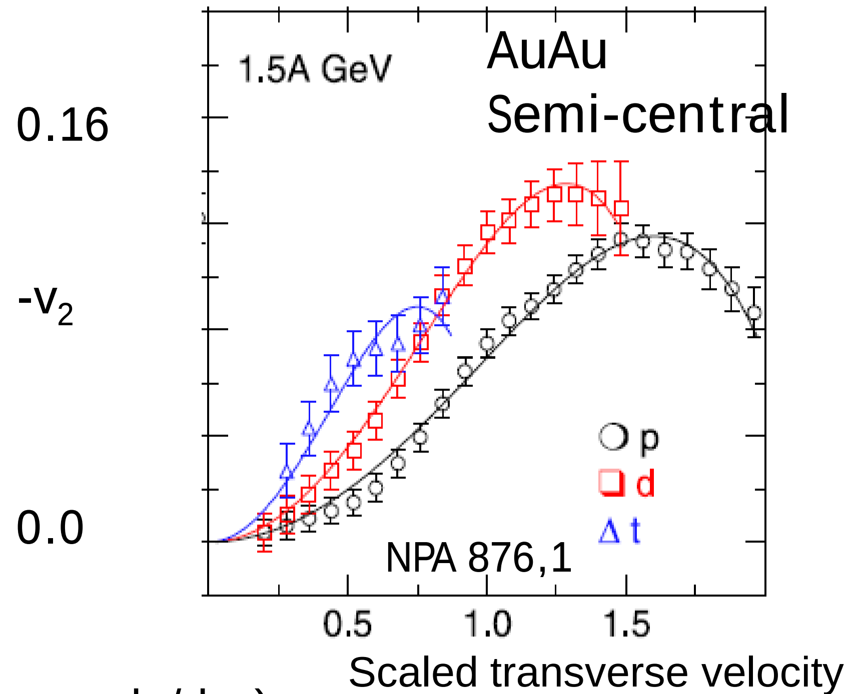
Many nucleons are in clusters

At 3 AGeV, even in central collisions:

20% of the baryons are in clusters



… and baryons in clusters have quite different properties



Without dynamical formation of fragments

- we cannot describe the nucleon observables (v_{1}, v_2, dn/dp_T)

- we cannot explore the new physics opportunities like
  - hyper-nucleus formation
  - 1st order phase transition
  - fragment formation at midrapidity (RHIC, LHC)

Fragments → time evolution of N-body phase-space density (QMD, AMD, FMD)

Classical, non-relativistically:
if one has a given Hamiltonian

$$H(\mathbf{r}_1, .., \mathbf{r}_N, .., \mathbf{p}_1, .., \mathbf{p}_N, t)$$

and a given initial condition

$$\mathbf{r}_1(t=0), ..., \mathbf{r}_N(t=0), \mathbf{p}_1(t=0), .., \mathbf{p}_N(t=0)$$

one solves the Hamilton eqs.

$$\frac{d\mathbf{r}_i}{dt} = \frac{\partial H}{\partial \mathbf{p}_i}; \quad \frac{d\mathbf{p}_i}{dt} = -\frac{\partial H}{\partial \mathbf{r}_i}$$

fully relativistic version (PRC 87, 034912) too time consuming (but also not necessary)

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 a 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 (after Lorentz-transf.) nonrelativistic kinematics can be applied.

Quantal N-body dynamics is based on a variational principle (Koonin, TDHF)

Take trial wavefct with time dependent parameters and solve

$$\frac{< \psi_N | i \frac{d}{dt} \hat{H} | \psi_N >}{< \psi_N | \psi_N >} = 0 \qquad (1)$$

QMD trial wavefct for one particle (Gaussian):

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

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

For this 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.

Potential: density dependent two body potential adjusted to nuclear EOS

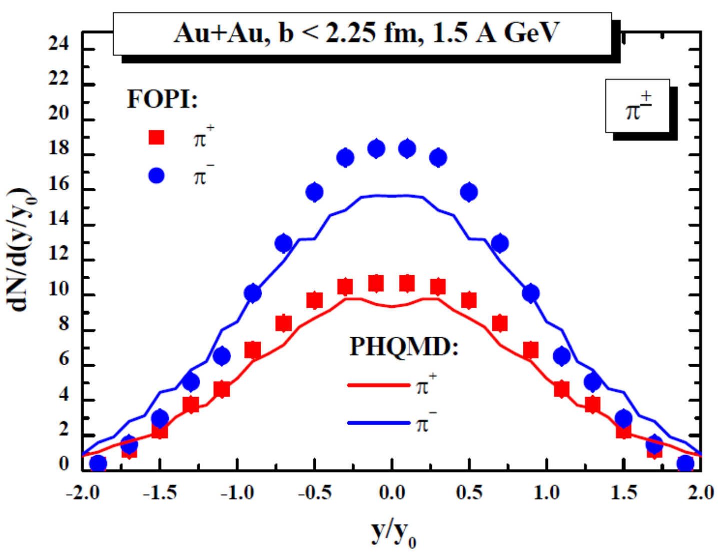
All elastic and inelastic collisions are treated as in PHSD - therefore the spectra of produced particles are similar to PHSD results

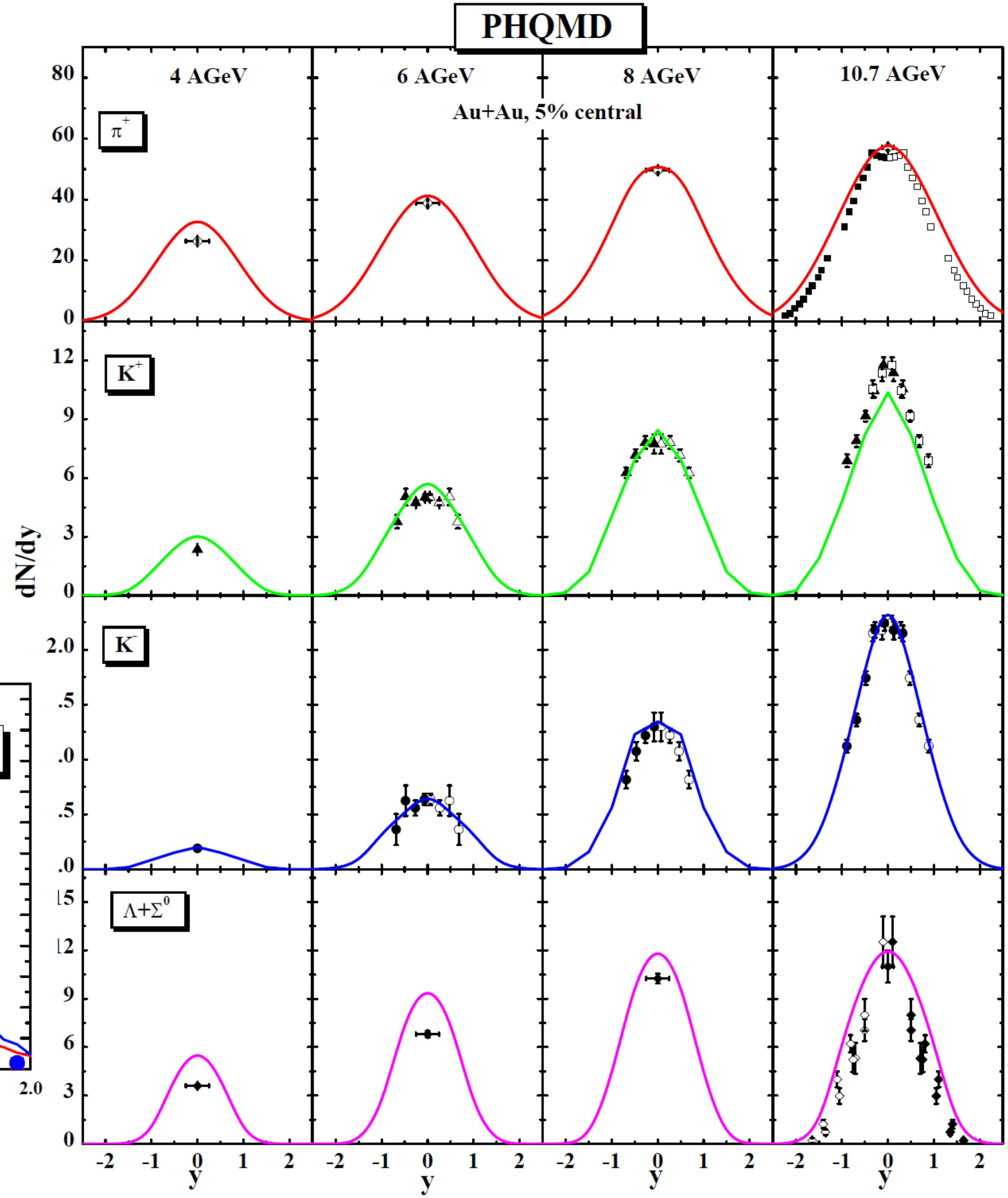
→ PHQMD : Parton Hadron Quantum Molecular Dynamics

First Results of PHQMD

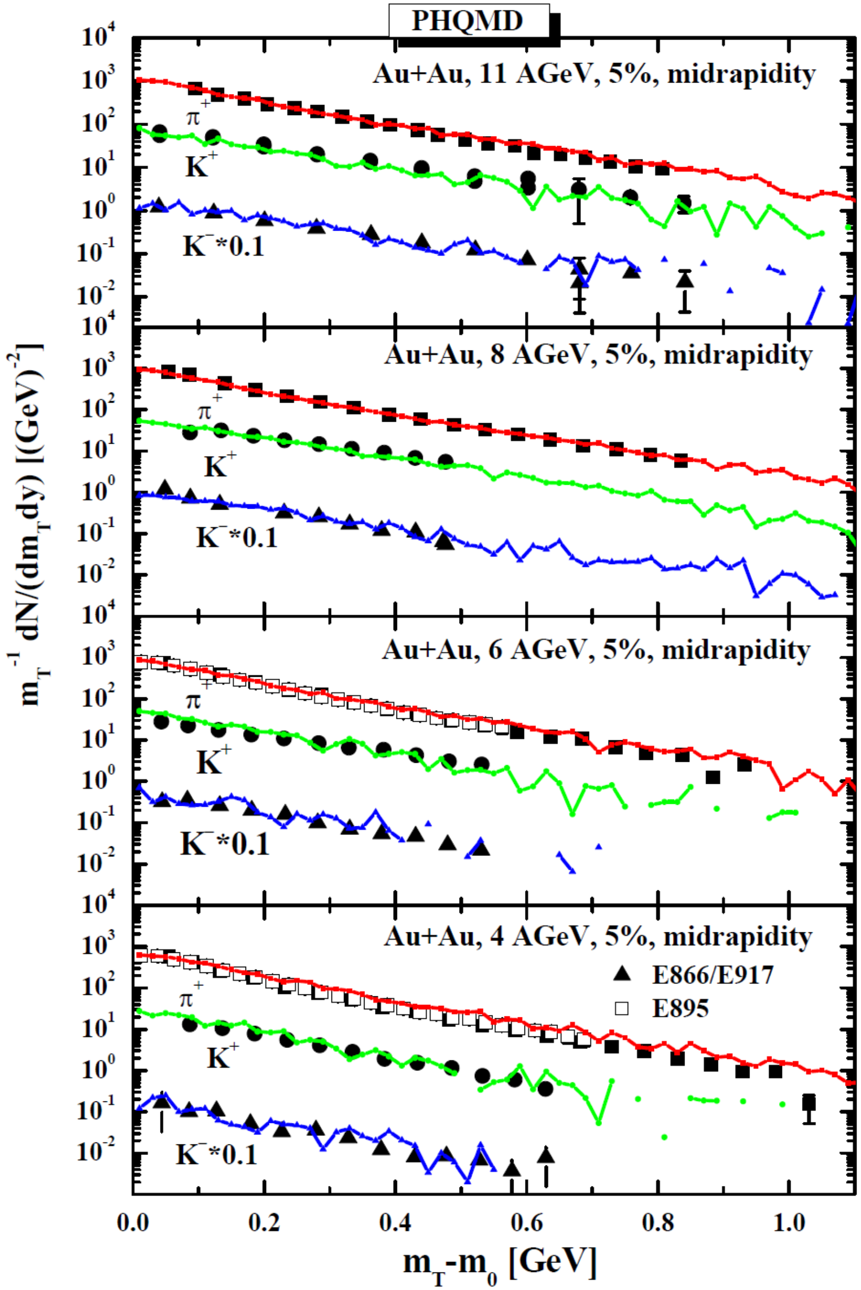
Produced particles
(dominated by collisions)

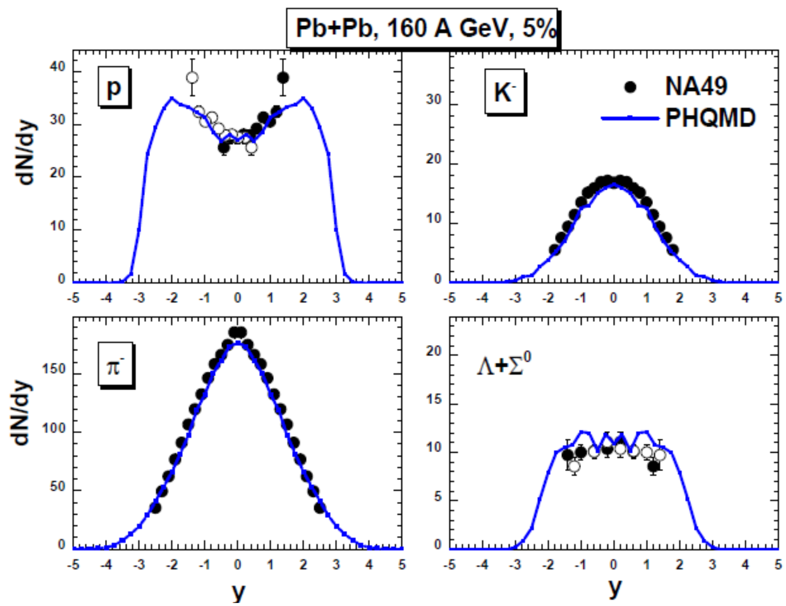
are in agreement with experiment
at SIS/AGS/NICA/FAIR energies

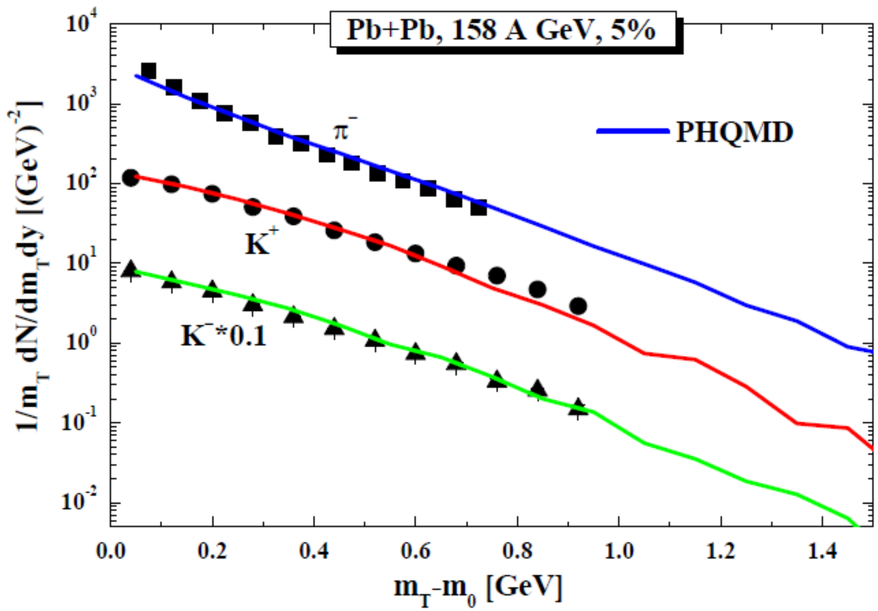




AGS and SPS energies







How to define fragments in transport theories which propagate nucleons ?

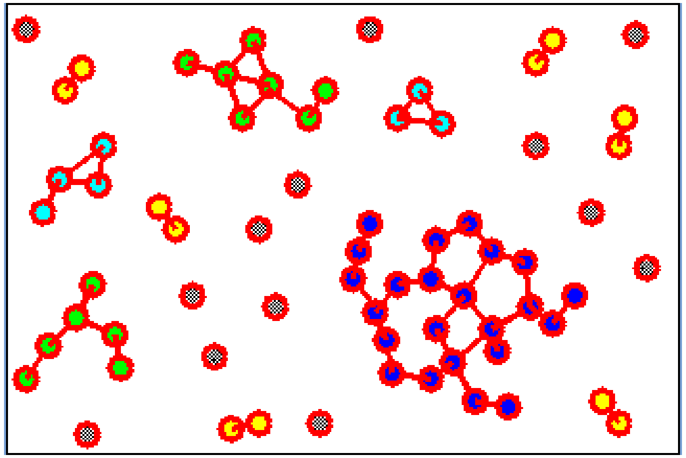
I. **Minimum Spanning Tree** (MST) is a cluster recognition method applicable for the **(asymptotic t → ∞) final state** where coordinate space correlations only survive for bound states.

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

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

$$\left| r_i - r_j \right| \leq 2.5\, fm$$

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



Particles with large relative momentum are finally not at the same position
→ Additional momentum cuts (coalescence) change little:

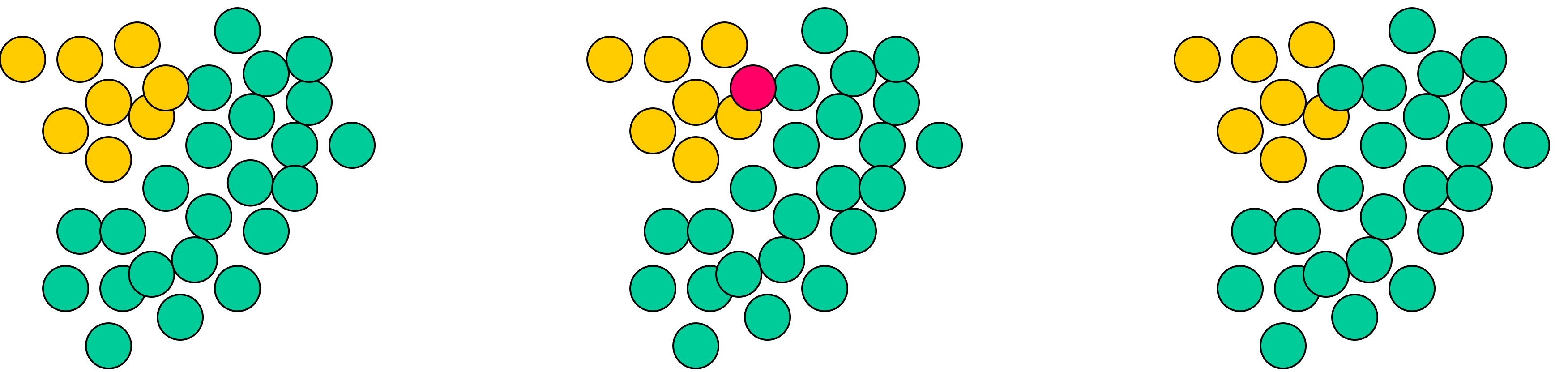
Drawback: Does not allow to study HOW the fragment are formed

Early Fragment identification (SACA/FRIGA)

PLB301:328,1993
Nuovo Cim. C39 (2017) 399

a) Take the positions and momenta of all nucleons at time t.
b) Combine them in all possible ways into all kinds of fragments or leave them as single nucleons
c) Neglect the interaction among clusters
d) Choose that configuration which has the highest binding energy

This configuration has a large overlap with the final fragment distribution



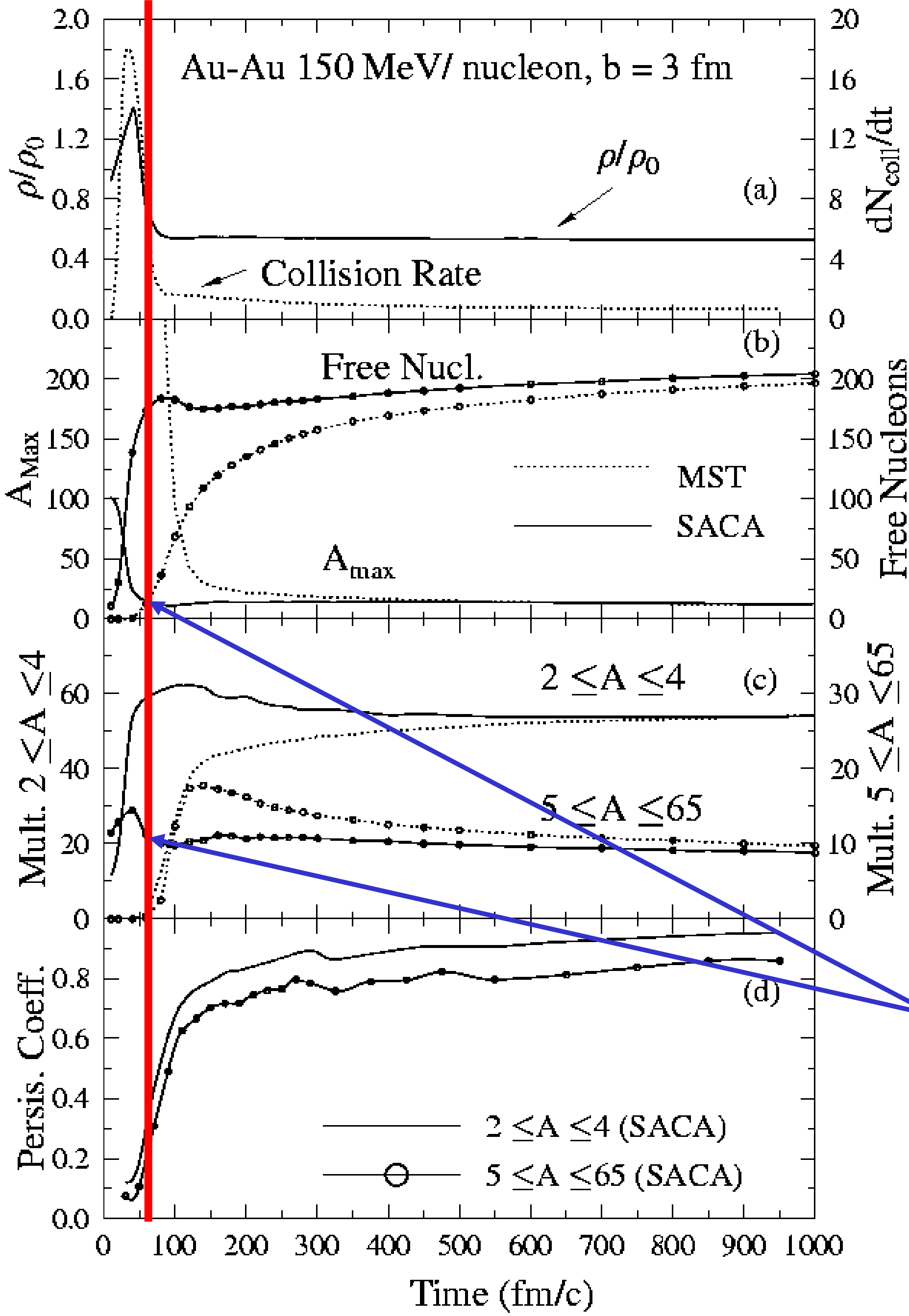
Take randomly 1 nucleon out of a fragment

Add it randomly to another Fragment

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

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

If E' < E take the new configuration
If E' > E take the old with a probability depending on E'-E
Repeat this procedure many times → Leads automatically to the most bound configuration

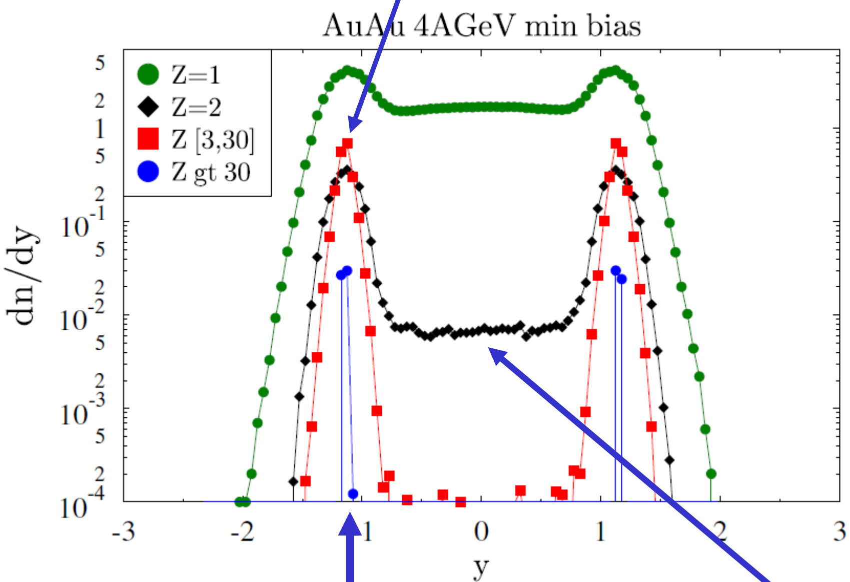


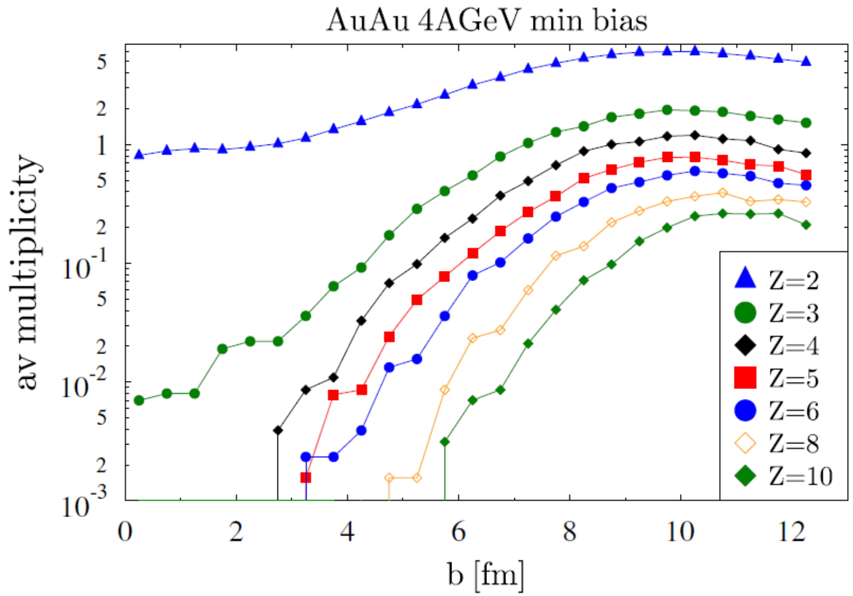
SACA/FRIGA can identify the fragment pattern very early as compared to the Minimum Spanning Tree (MST) which requires a minimal distance in coordinate space between two nucleons to form a fragment

After $t=1.5t_{pass}$ Amax and multiplicities of intermediate mass fragments do not change anymore

First Results of PHQMD

- Only for 10% most central events fragments do not play a role
- Heavy fragments appear only in the residue rapidity range
- Complicated fragment pattern for larger impact parameters (acceptance??)
- M_Z (b) is different for each fragment charge





b dependence non-trivial

There are two kinds of fragments

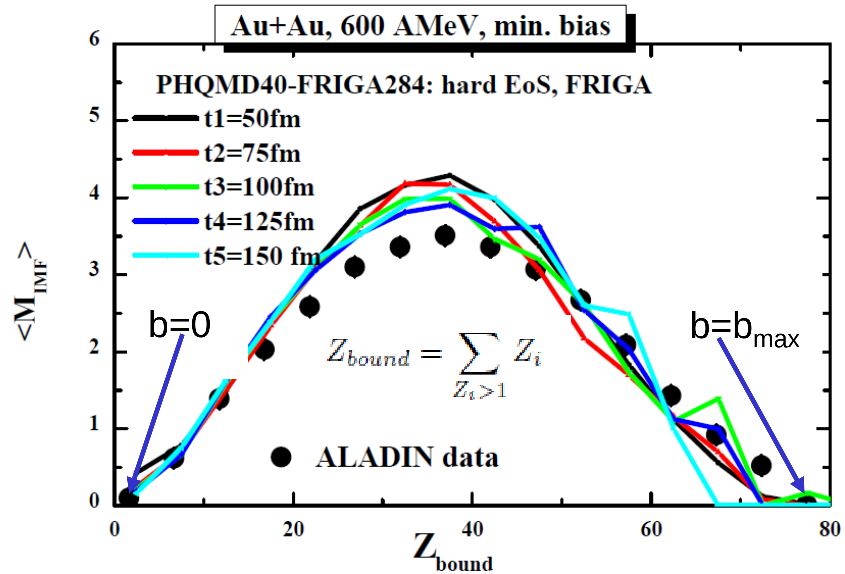
- formed from spectator matter
  close to beam and target rapidity
  initial-final state correlations
  HI reaction makes spectator matter unstable

- formed from participant matter
  created during the expansion of fireball
  "ice" (E_{bind} ≈8 MeV/N) in "fire"(T≥ 100MeV)
  origin not known yet
  seen from SIS to RHIC
  (quantum effects are important)

First Results of PHQMD

Spectator Fragments

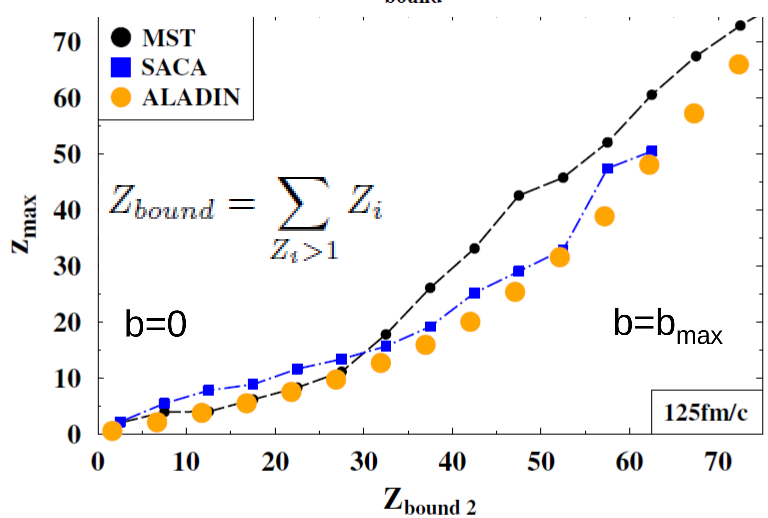
exp. measured up to E_{beam} =1 AGeV (ALADIN)

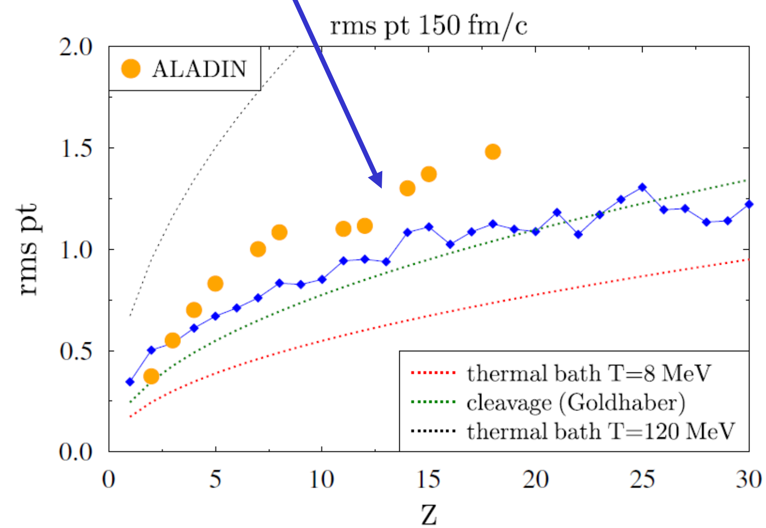


agreement for very complex fragment observables like the

- Energy independence of “rise and fall”
- Largest fragment (Z_{bound})

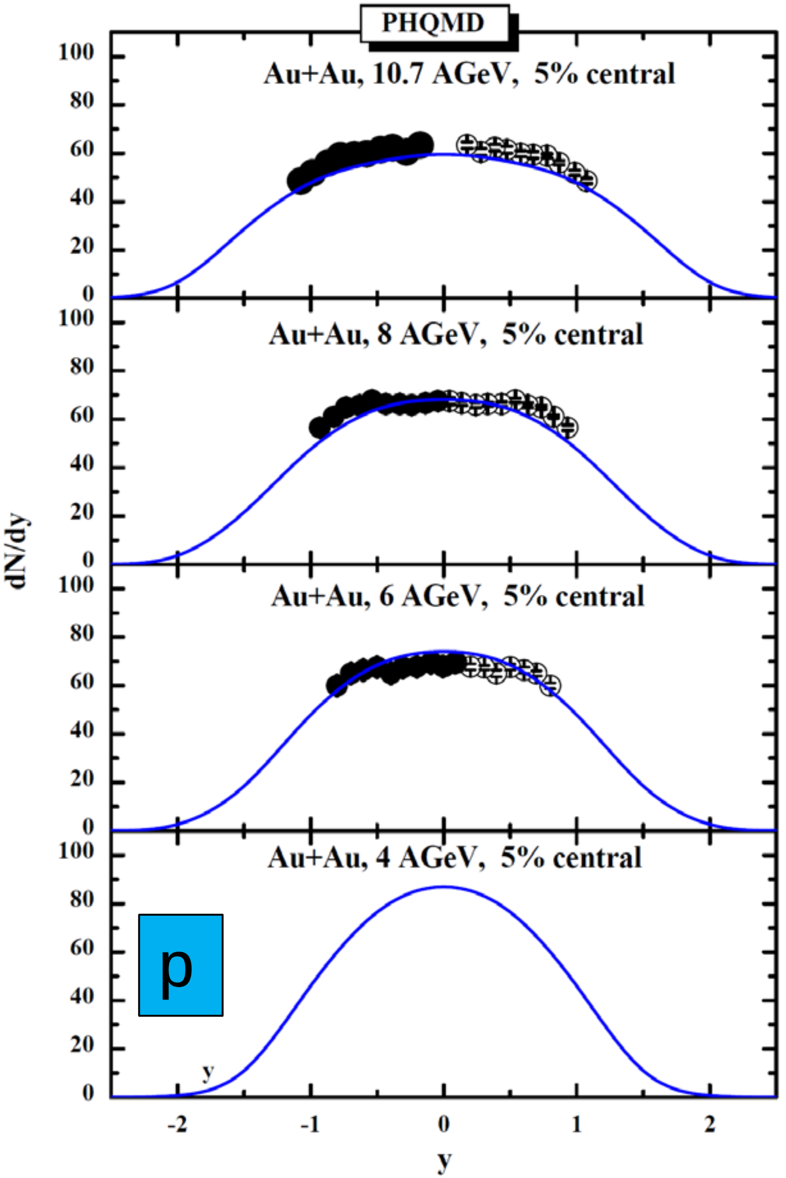
rms(p_t) shows $\sqrt{Z}$ dependence

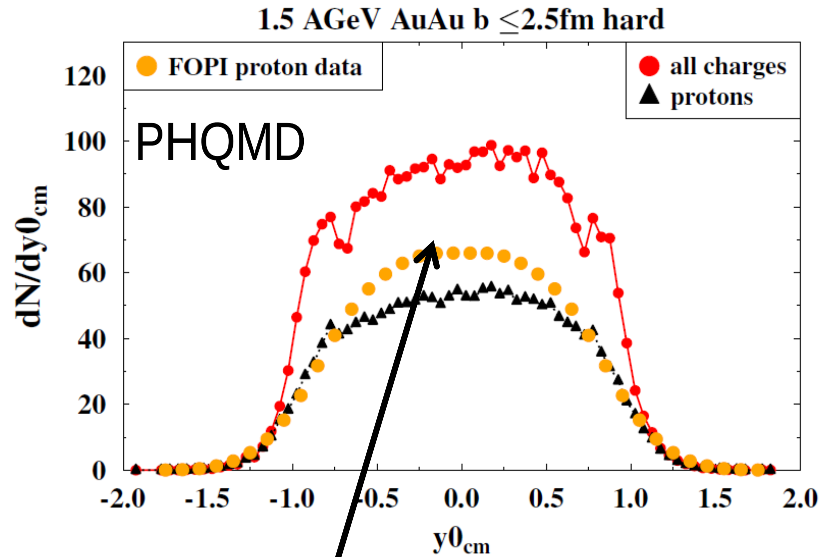




First Results of PHQMD

Protons at midrapidity well described

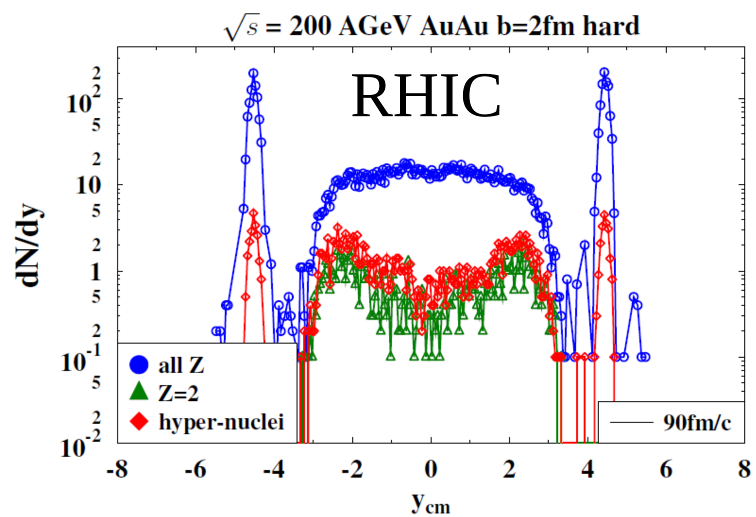




1.5 AGeV central

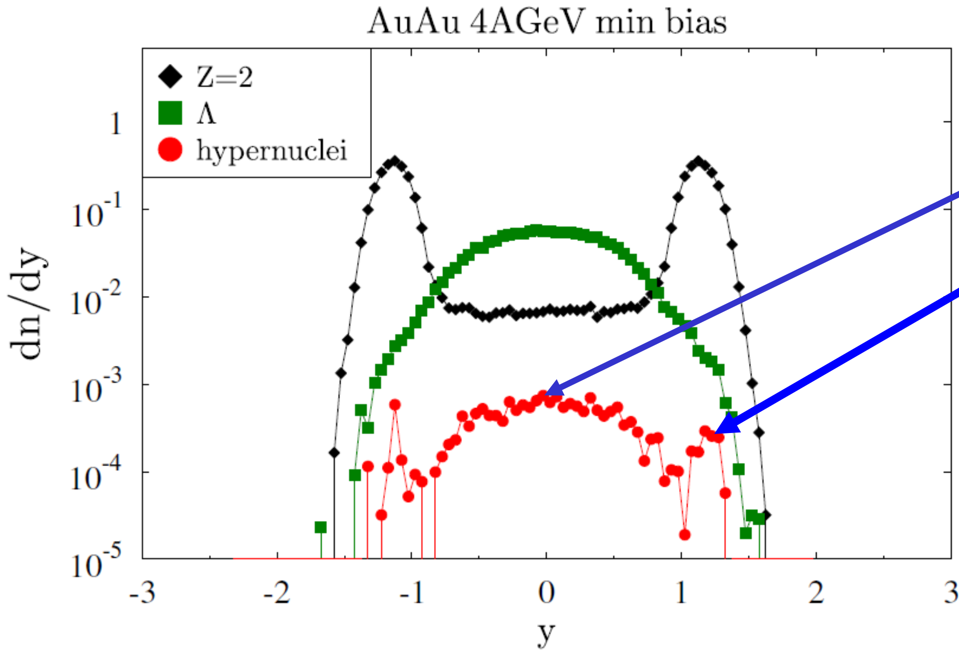
- 30% of protons bound in cluster

To improve: better potential for small clusters



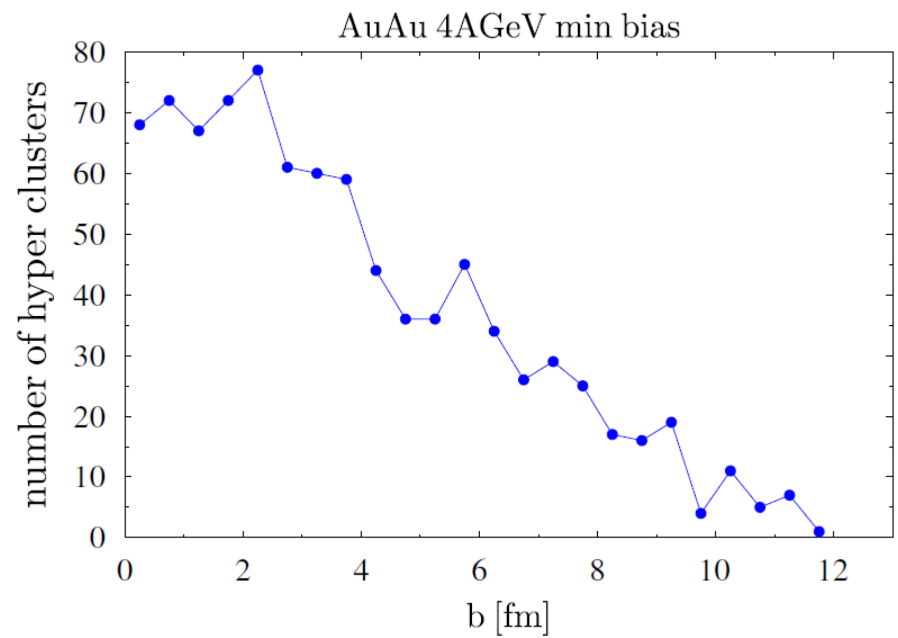
.. and what about hyper-nuclei ?

First Results of PHQMD



There are hyper-nuclei
- at midrapidity (small)
- at beam rapidity (large)
  few in number but
  more than in other reactions
  to create hyper-nuclei

Central collisions → light hyper-nuclei
Peripheral collisions → heavy hyper-nuclei



Conclusions and Perspectives

BM@N/NICA energies are very interesting

- transition between hadron and parton as degrees-of-freedom
- massive hyper-nucleus production
- possibility to solve problems left from SIS and RHIC

an intensive collaboration between transport and experimental groups is necessary to exploit this physics

transport approaches are developed but need to be further advanced with experimental and theoretical input

So the future is bright. Let’s start !!