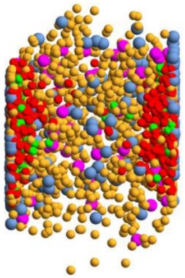
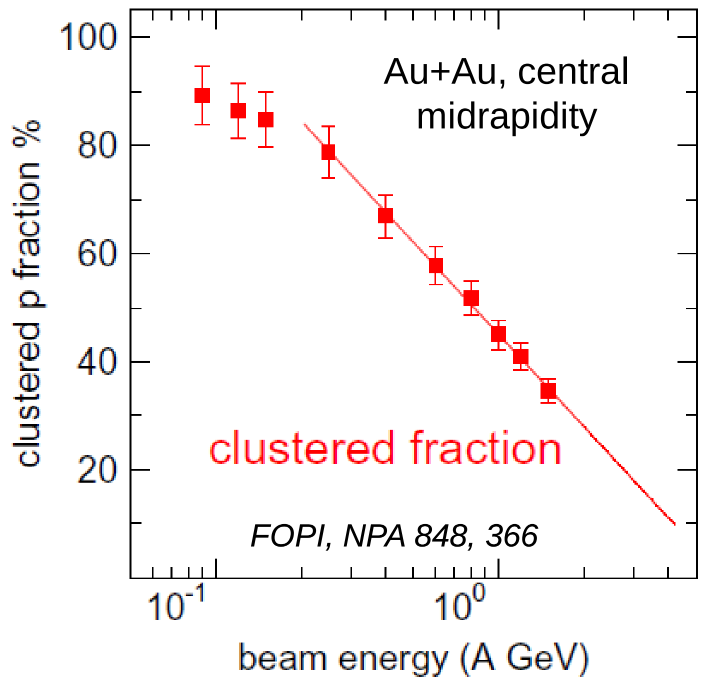
Clusters in Heavy Ion Collisions collisions
Why?, How?, Where are we?

Joerg Aichelin
(SUBATECH, Nantes)
&
Susanne Glaessel, Viktar Kireyeu,, Elena Bratkovskaya, Vadym Voronyuk, Christoph Blume, Gabriele Coci, Vadim Kolesnikov, Michael Winn, Christoph Hartnack
(Uni. Frankfurt & GSI, Darmstadt & SUBATECH, Nantes & JINR, Dubna)

PHQMD



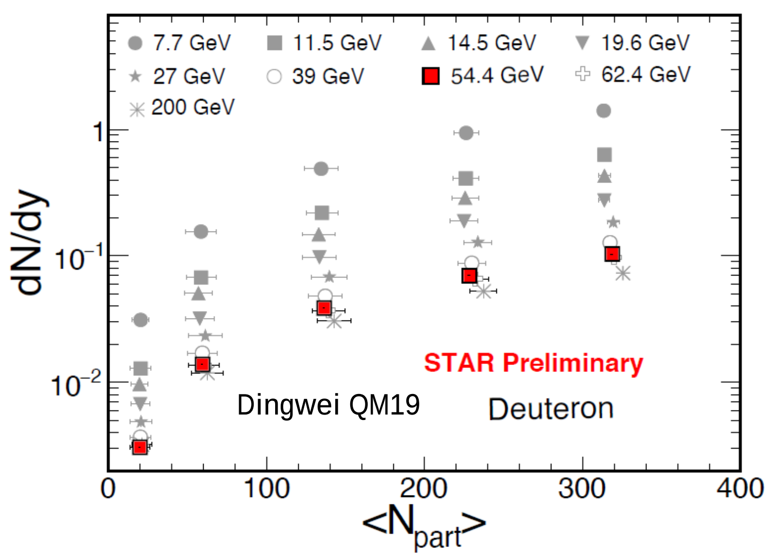
Clusters in HICs

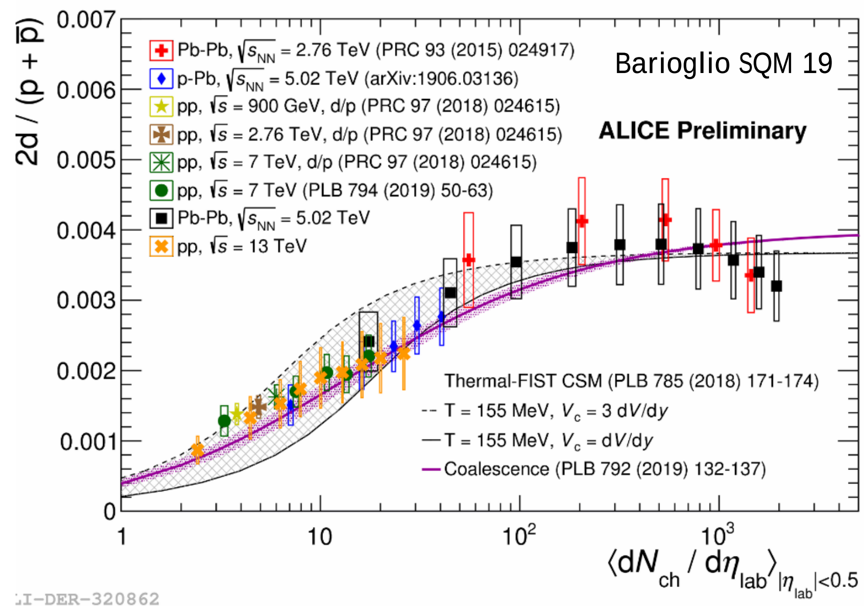


- Clusters are very abundant at low energy;
- at 3 AGeV in central Au+Au collisions ~20% of the baryons are in clusters!
- cluster production continues to STAR energies 1% - 0.3% of the nucleons are bound in d at y_{cm}
- decreases slightly up to LHC energies

→ **midrapidity clusters exist at all beam energies there fireball temperatures T>100 MeV**

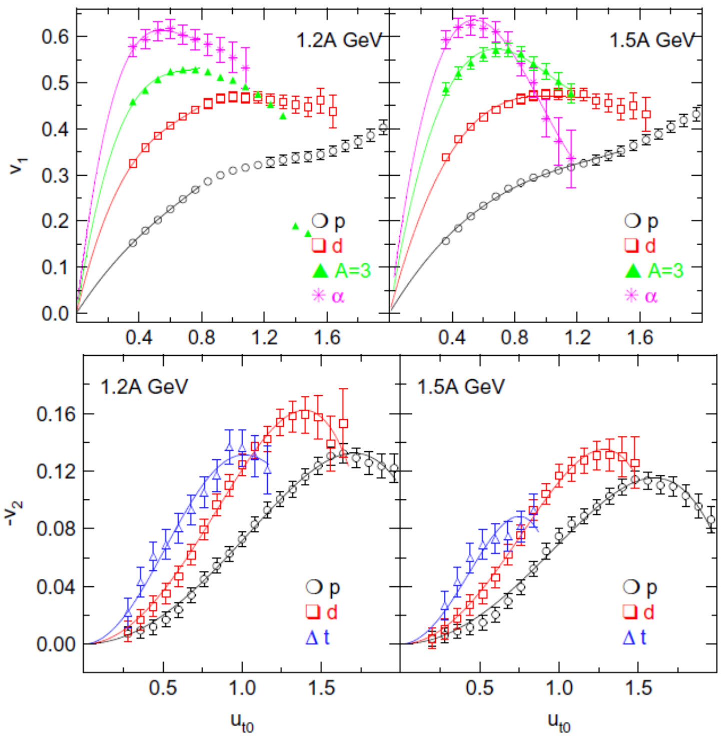
→ **production mechanism is heavily discussed**





There is more than multiplicity of clusters

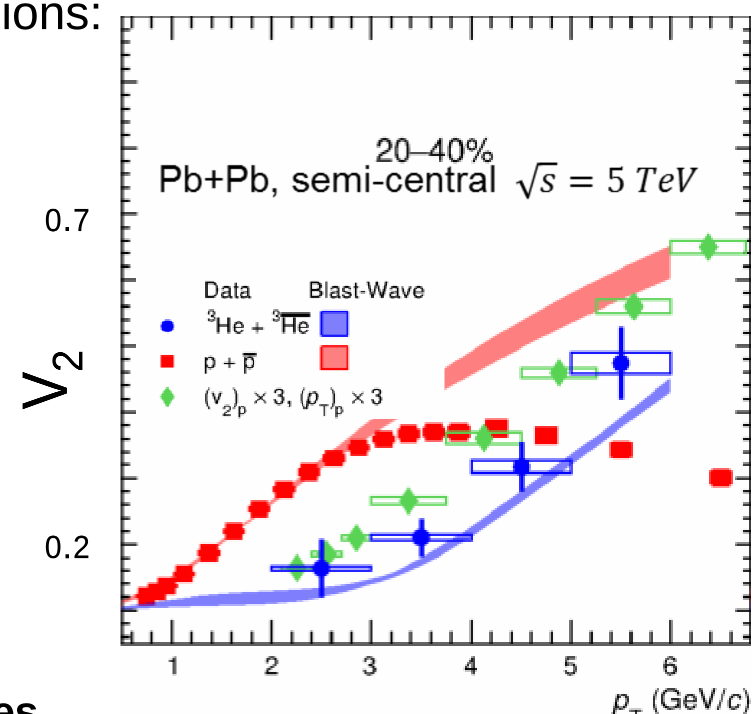
Au+Au, semi-central *FOPI, NPA 876,1*



Scaled transv. velocity

Baryons in clusters have quite different properties (v_1, v_2, dn/dp_T)

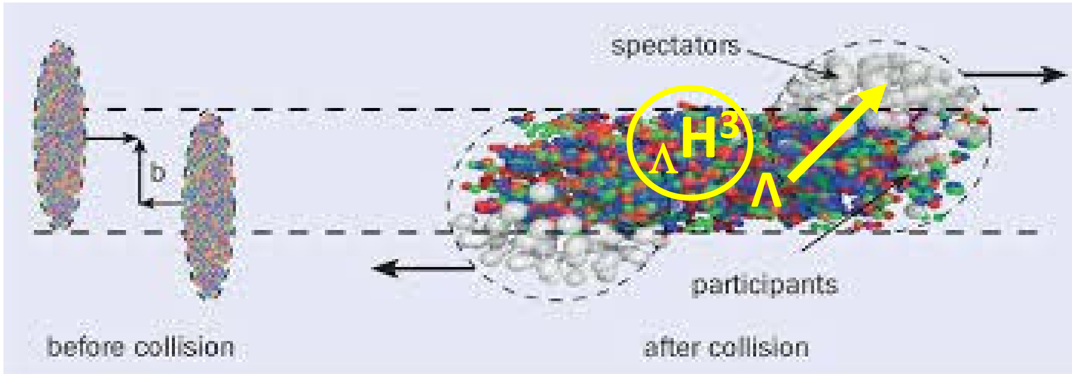
and explore therefore different phase space regions:



In addition, cluster open new physics opportunities

- **possible signals of a 1st order phase transition at finite μ**
- **fluctuations of the phase space densities of nucleons**
- **hyper-nucleus formation at mid as well as target/proj. rapidities**

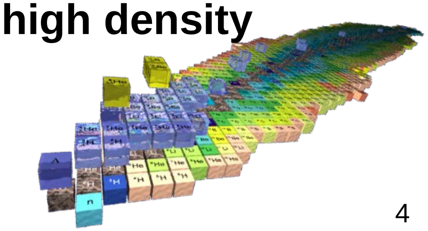
hyper-matter production has even more info



- **Access to the nuclear dynamics:**
  different mechanisms for hyper-nucleus production vs. rapidity:
  - at mid-rapidity : Λ – hyper-nuclei 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

Hyper-nuclei 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**

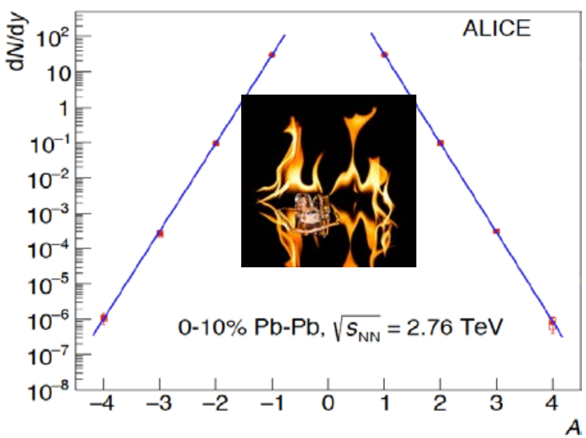


Last but not least: How it is possible that clusters are created ?

- **Freeze out temperature: 120 - 158 MeV**
  Binding energy of clusters: around 5 MeV/N
- **Clusters cannot survive a heat bath of more than 120 MeV. The first first collision with a heat bath constituent would destroy them**
- **But they exist!!!!!**

Ice in a fire‘ puzzle:

how the weakly bound objects can be formed and survive in a hot enviroment ?!



ALICE, NPA 971, 1 (2018)

Modeling of cluster production in heavy-ion collisions

We need two tools:

- ❑ a dynamical simulation of a heavy-ion reactions (including a late stage of baryons and mesons)
- ❑ a model which identifies clusters

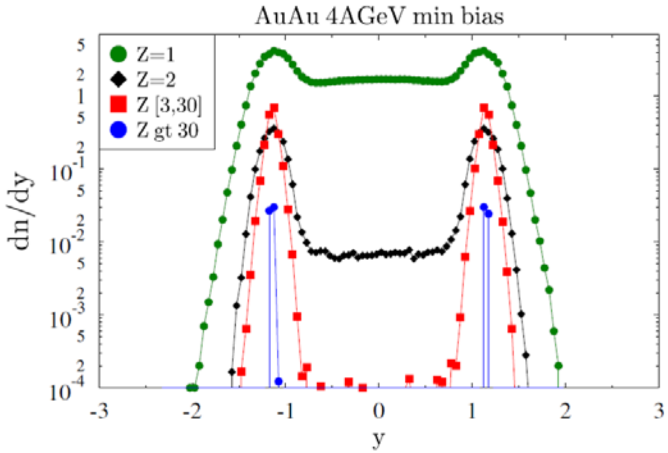
There are two ways:

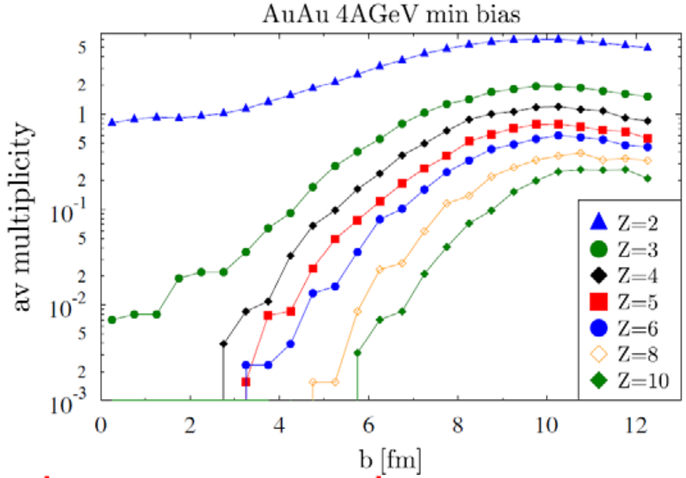
- ❑ hybrid model of cluster production - sudden transition from a dynamical model to clusterization via coalescence or statistical model

- ❑ dynamical cluster formation
  formation of clusters continuously during the time evolution

There are two types of clusters:

Midrapidity cluster dominating at small b (mostly newly formed)
Proj/target cluster dominating at larger b (initial final state correlations)





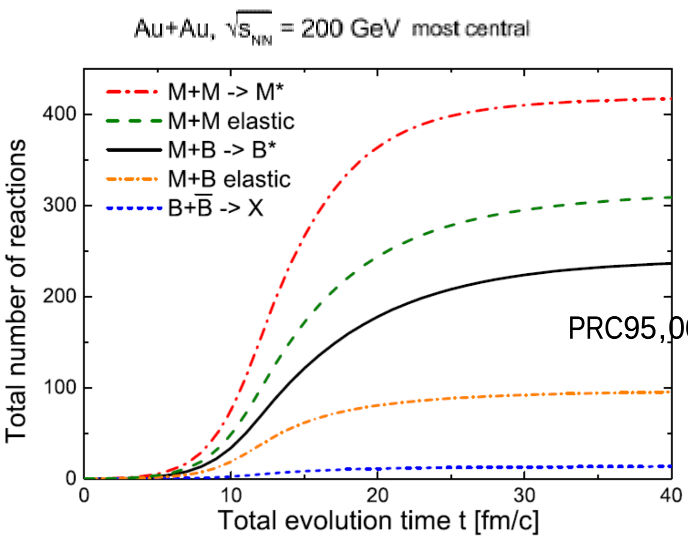
Transition smooth in b and $\sqrt{s}$: better we use the same approach

Hybrid models of cluster production

All hybrid models assume that heavy-ion reactions have three phases:

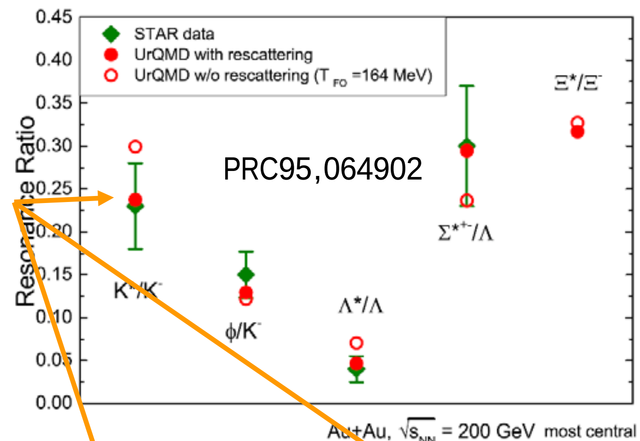
- a phase in which particles collide frequently
  a part of the system comes close to (local or global) equilibrium
- a sudden formation of clusters (given by a local temperature or time)
- a free streaming of clusters to the detector without further interactions

Problems: I) Dynamical models (UrQMD) do not show such a sudden transition but a very smooth fading away of the interactions. Late stage: MB -> B^* dominant

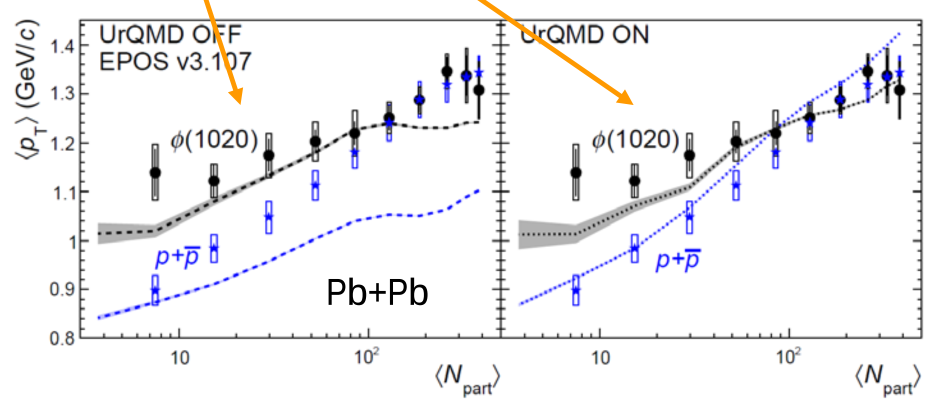


PRC95,064902

II) Final state interaction important



PRC95,064902

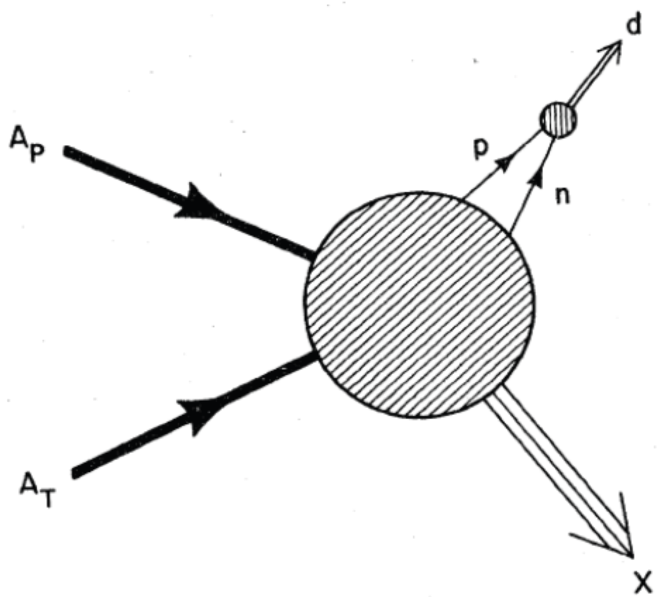


PRC93,014911

The sudden formation of clusters

Statistical model: describes very well the multiplicities in central collisions
but not the spectra (yield V,T,μ)
difficult to imagine how the cluster production takes place
d: E_b =2.2 MeV , rms radius = 1.7 fm
does not survive in heat bath of T>100 MeV
"ice in fire","snowball in hell"

Coalescence: goes back to Butler and Pearson PR129,836 (p+A)



d-production is a 3-body process
momentum has to be transferred to the third body

QM: in a static potential ~ $1/p^2$

$$n_d(p) \sim \frac{1}{p^2}\, n_n^2\left(\frac{p}{2}\right)$$

The sudden formation of clusters

In later approaches the three body character of the d-production has been neglected

- Schwarzschild and Zupanic PR129 854:

d is produced if in a sphere of momentum space $\sim p_0^3$ around a nucleon we find another nucleon:

$$n_d(p) \sim p_0^3 \; n_n^2\left(\frac{\mathbf{p}}{\mathbf{2}}\right)$$

- Kapusta PRC16,1493

d is produced in a fireball of a given volume V

$$n_d(p) \sim V \; n_n^2\left(\frac{\mathbf{p}}{\mathbf{2}}\right)$$

- Bond et al. , PLB 71, 43

$$n_d(p) \sim \frac{1}{V} n_n^2\left(\frac{\mathbf{p}}{\mathbf{2}}\right)$$

Sudden approximation in QM: sudden transition from a strongly interacting system to a noninteracting system

- Scheibl et al. PRC59,1585

Overlap of the Wigner density of the d with that of p and n

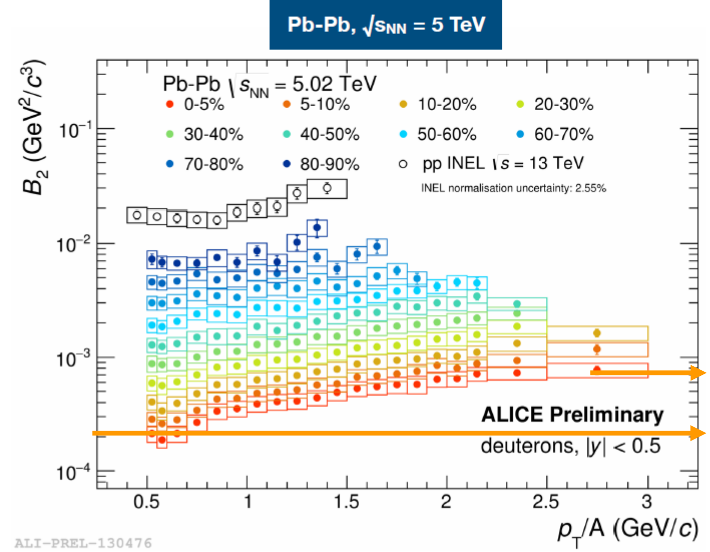
$$\frac{dN_\mathrm{d}}{d^3P_\mathrm{d}} = \frac{3}{(2\pi)^3}\int d^3r_\mathrm{d} \int \frac{d^3r\, d^3q}{(2\pi)^3}\,\mathcal{D}(\boldsymbol{r},\boldsymbol{q}) \times f_\mathrm{p}(q_+, r_+)\, f_\mathrm{n}(q_-^*; r_-)\,.$$

$$r_\pm = r_\mathrm{d} \pm \tfrac{1}{2} r$$

So it is not evident what we can learn from the experimental ratio for A=2

$$B(\mathbf{p}, V, p_0, V_{NN}) = \frac{n_d(\mathbf{p})}{n_n^2(\mathbf{p}/2)} \qquad B_A = \frac{E_A \frac{d^3N_A}{dp_A^3}}{\left(E_p \frac{d^3N_p}{dp_p^3}\right)^A}$$

because it depends on the model assumptions

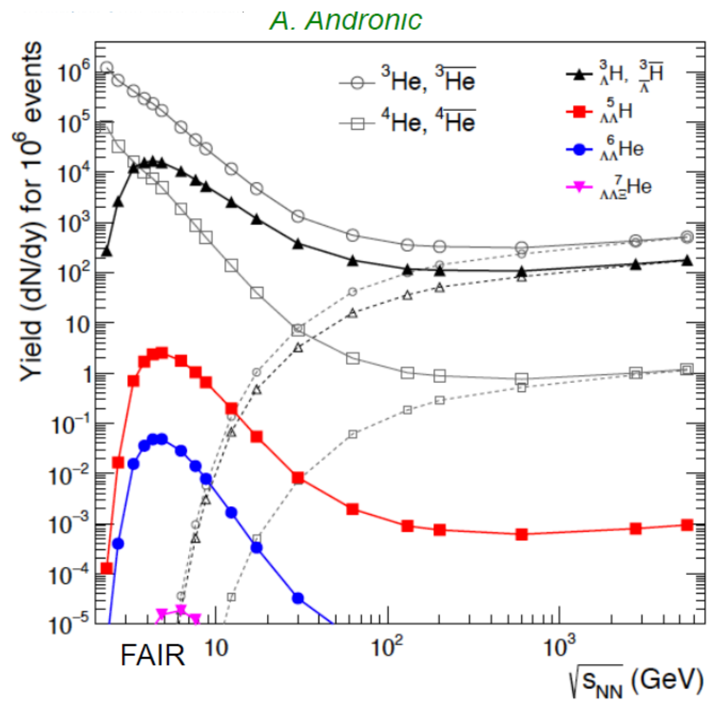


In addition: for large nuclei the coalescence model does not work

→ no general framework for cluster production

Additional caveats :

- ❑ before the sudden freeze out: d do not exist
- ❑ after sudden freeze out d cannot be produced (3-body process)
- ❑ theoretical results depend strongly on the sudden freeze out time
- ❑ Freeze out time depends on the fragment size if one wants to reproduce the data:
  Gossiaux, Keane (EOS) et al. PRC51, 3357



More general approach needed if one wants to exploit the physics potential of cluster production

Dynamical cluster production

Why does one need a new model ?

Present microscopic approaches:

- **VUU(1985), BUU(1985), HSD(1996), PHSD(2008), 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

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 (time dependent) 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)

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

For N particles:

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

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

For the QMD trial wavefct eq. (1) yields

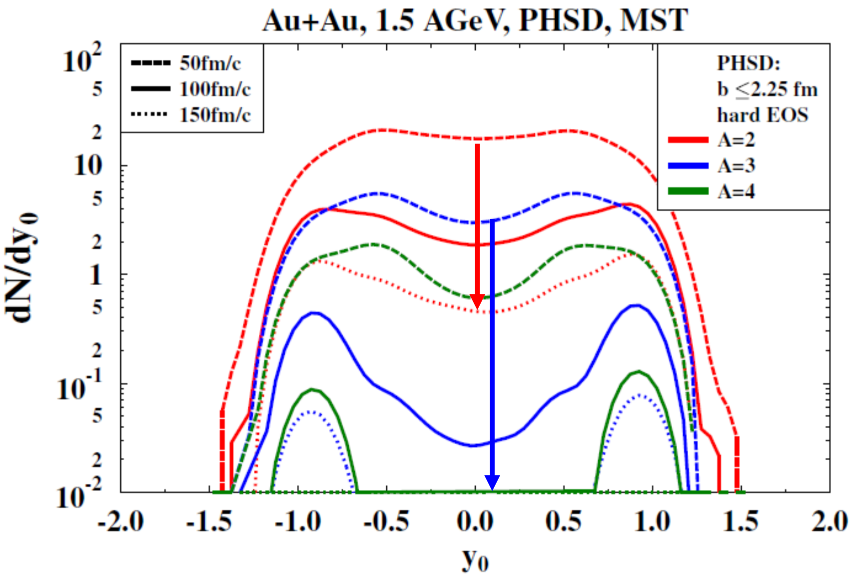
$$\frac{dq}{dt} = \frac{\partial < H >}{\partial p} \quad ; \quad \frac{dp}{dt} = -\frac{\partial < H >}{\partial q}$$

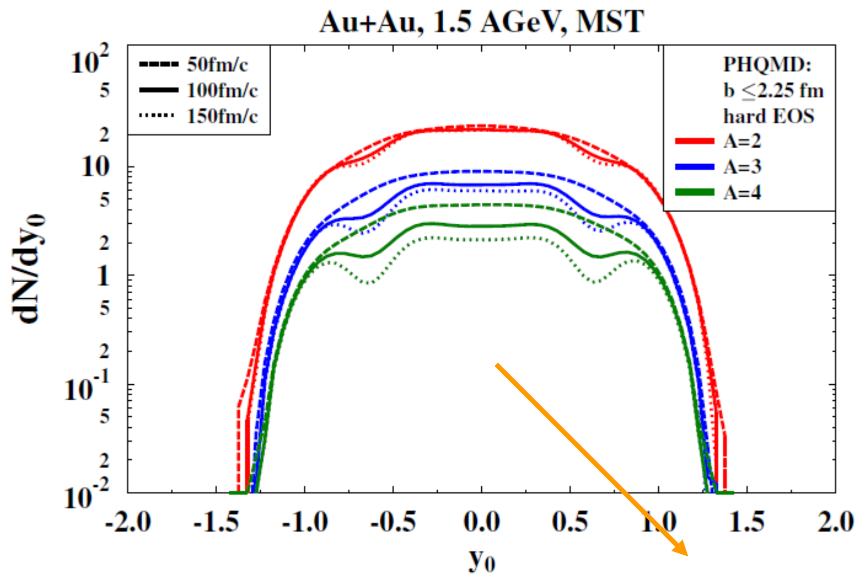
For Gaussian wavefct eq. of motion very similar to Hamilton's eqs.
(but only for Gaussians !!)

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 is strongly time dependent
-- fragments disappear with time
-- midrapidity fragments disappear early, projectile/target fragments later
(as expected from the underlying theory)
→ no common time for coalescence

I. Minimum Spanning Tree

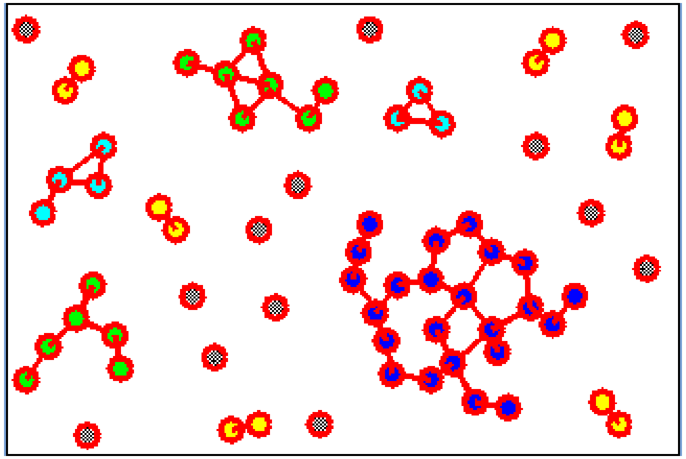
I. Minimum Spanning Tree (MST) is a cluster recognition method applicable for the (asymptotic) final state where coordinate space correlations may only survive for bound states.

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

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

$$|\vec{r}_i - \vec{r}_j| \leq 4\ fm$$

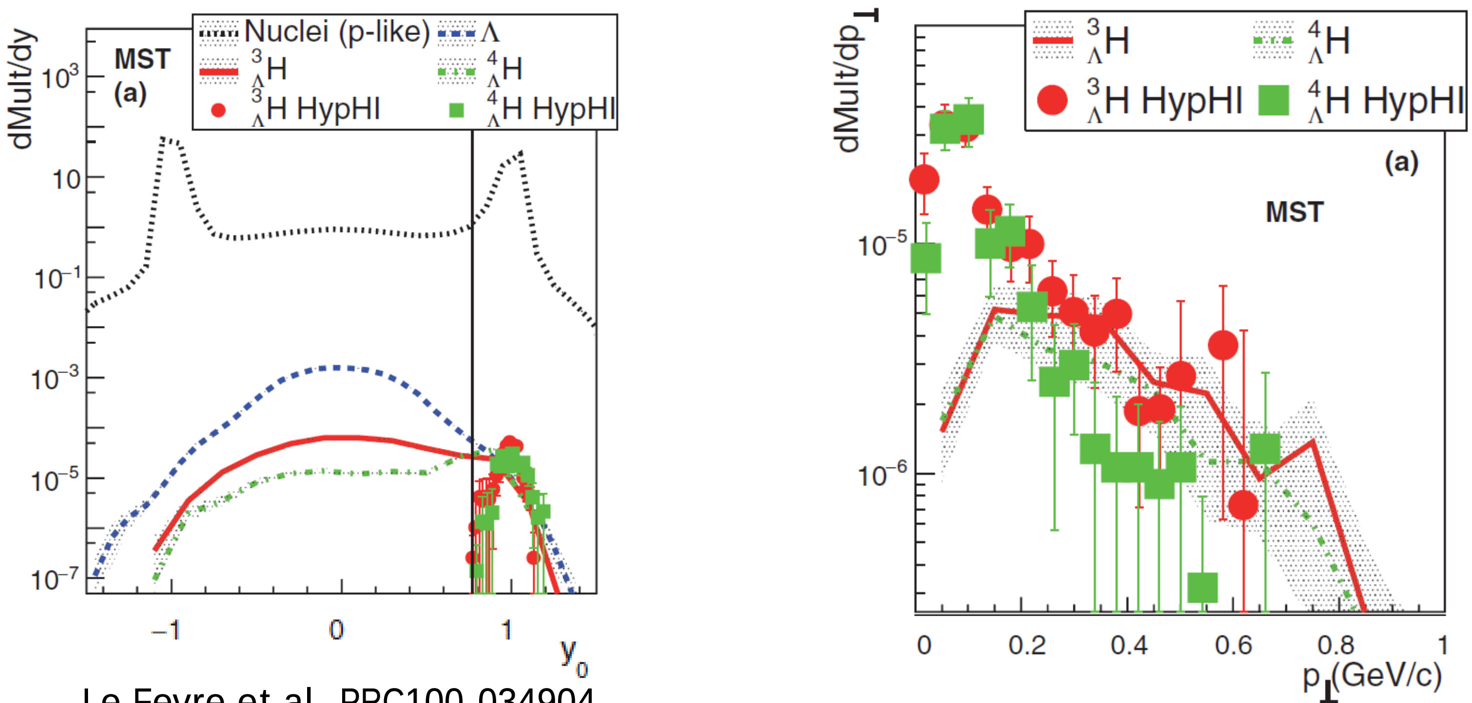
2. A particle is bound to a cluster if it is bound with at least one particle of the cluster.



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

Example: hyper-nuclei of HypHi (PLB747,129)

$^{6}Li + ^{12}C$ at 2*A* GeV



Le Fevre et al. PRC100,034904

Rapdity and p_T spectra of hyper-clusters are reproduced despite of the complicated physics:

- Modeling of Λ production
- Interface between participants and spectators
- Absorption of Λ by spectators

II.SACA or ECRA now FRIGA

If we want to identify fragments earlier one has to use momentum space info as well as coordinate space info

Idea by Dorso et al. (Phys.Lett.B301:328,1993**)** :

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

Simulations have shown that the most bound configuration is the precursor of the final fragment distribution

(has a large persistent coefficient)

How does this work?

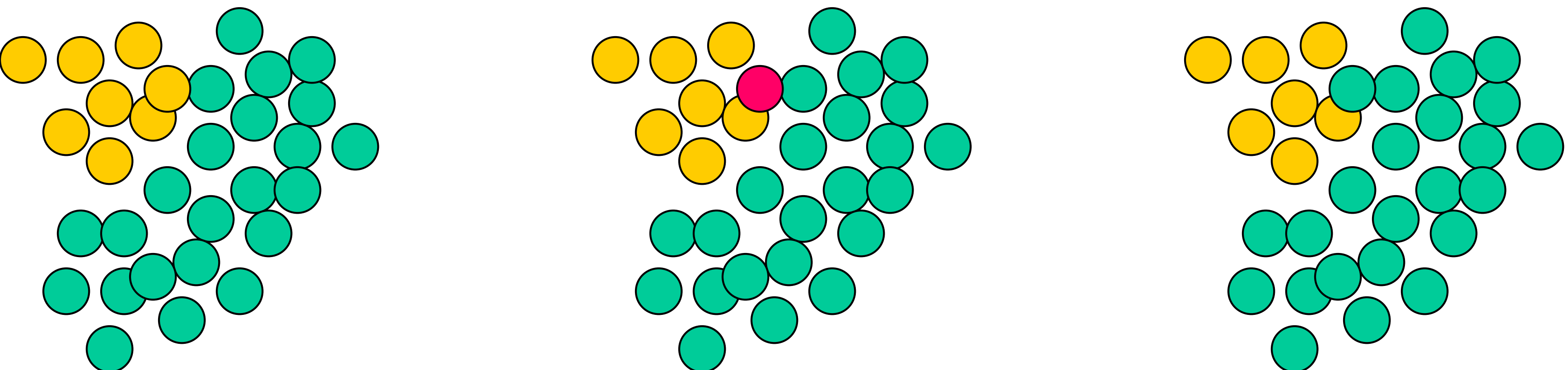
Simulated Annealing Procedure:

SACA: PLB301,328; J.Comp.Phys.162,245, NPA619,375

now FRIGA :**Nuovo Cim. C39,399 (including symmetry and pairing energy)**

Take randomly 1 nucleon out of a fragment

Add it randomly to another fragment



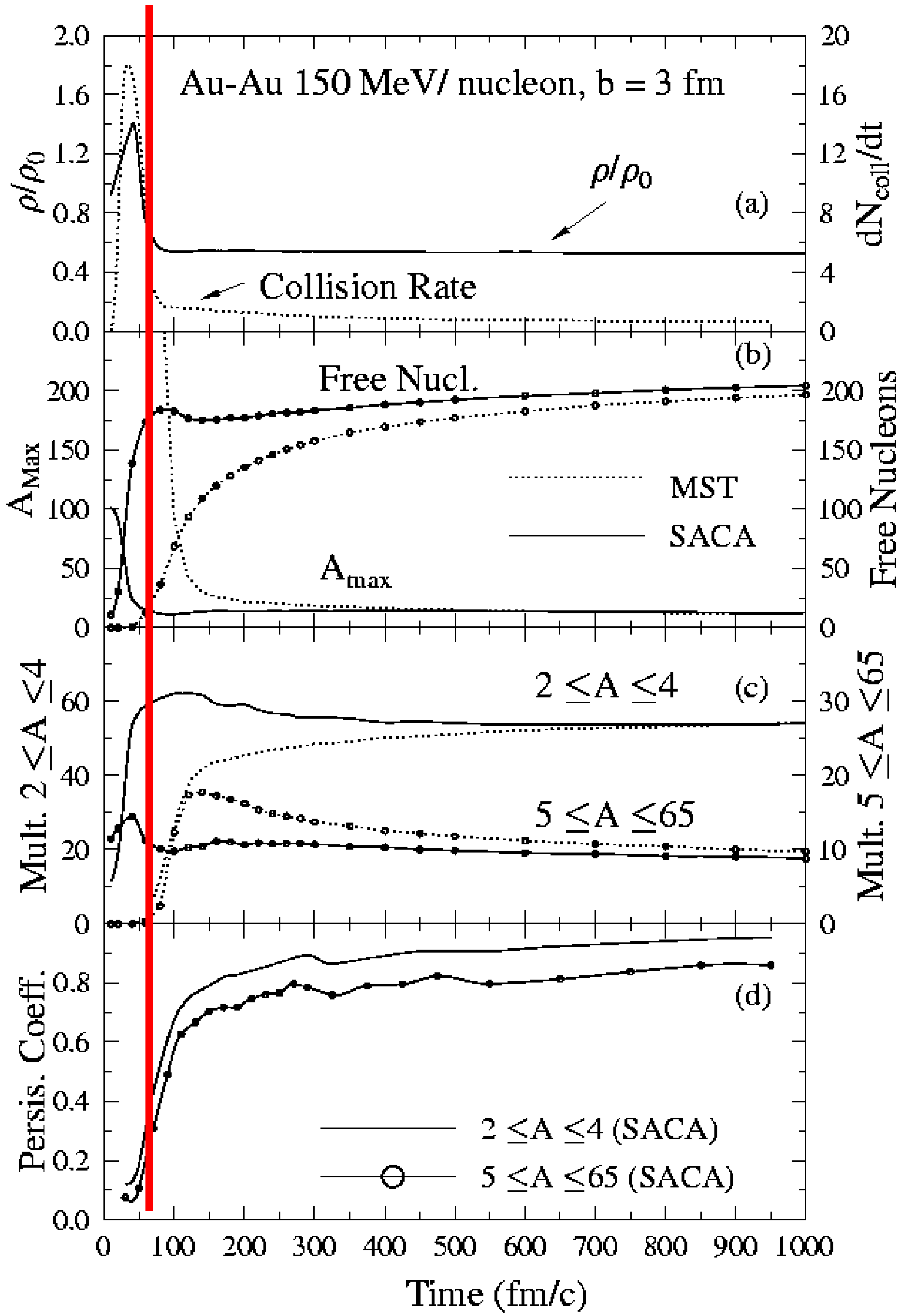
$E=E^{1}_{kin}+E^{2}_{kin}+V^{1}+V^{2}$

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

There is no interaction between clusters-> no energy conserv.

V is the nucleon-nucleon interaction

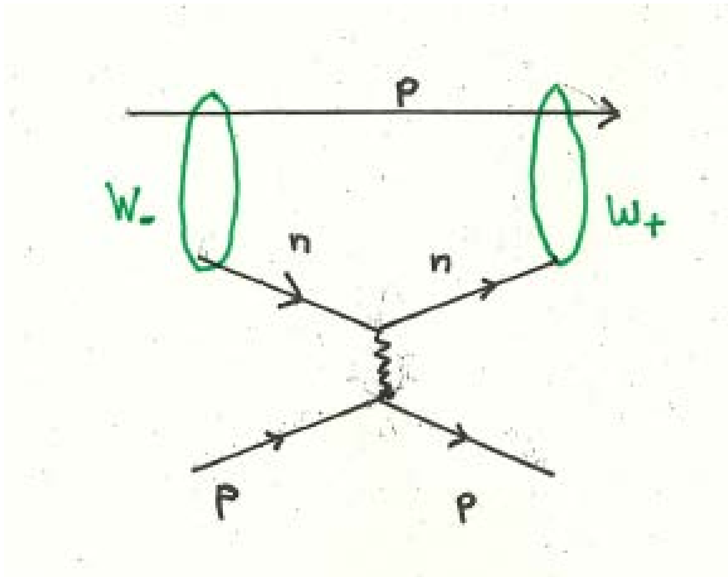
(mom. dep Skyrme, Coulomb, (Pairing, Symmetry) energy)



SACA can really identify the fragment pattern very early as compared to the Minimum Spanning Tree (MST) which assumes that two nucleons form a fragment if they are closed than r_{max} .

At $1.5t_{pass}$ Amax and multiplicities of intermediate mass fragments are determined

III. Wigner density formalism (Remler (NPA 402, 596))



Deuteron wave function

$$\Psi_d(\mathbf{r},\mathbf{R}) \propto exp^{-(\mathbf{r}-\mathbf{r_0})^2 L} exp^{-(\mathbf{R}-\mathbf{R_0})^2 L/4}$$

Deuteron Wigner density

$$\rho_d^W(\mathbf{r},\mathbf{p}) \propto exp^{-(\mathbf{r}-\mathbf{r_0})^2 L} exp^{-(\mathbf{p}-\mathbf{p_0})^2/L\hbar}$$

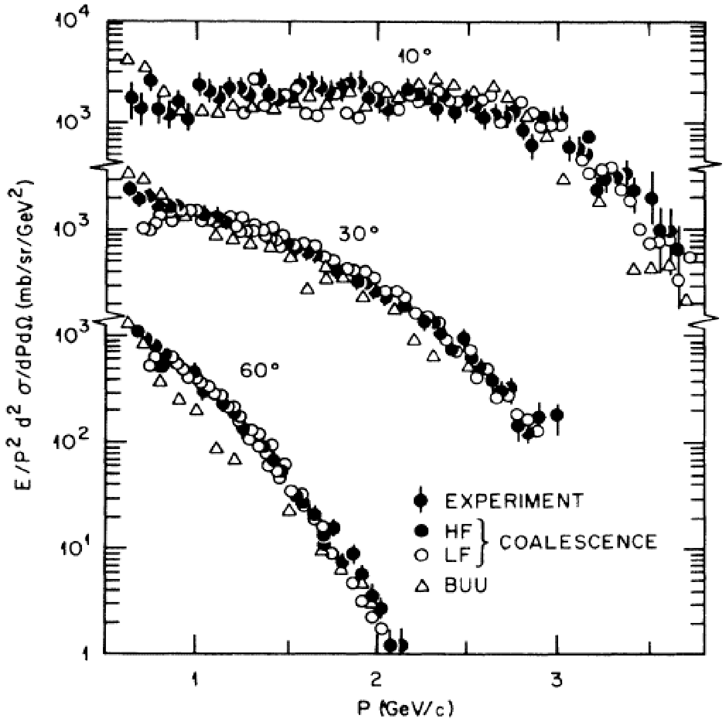
Yields for the rate

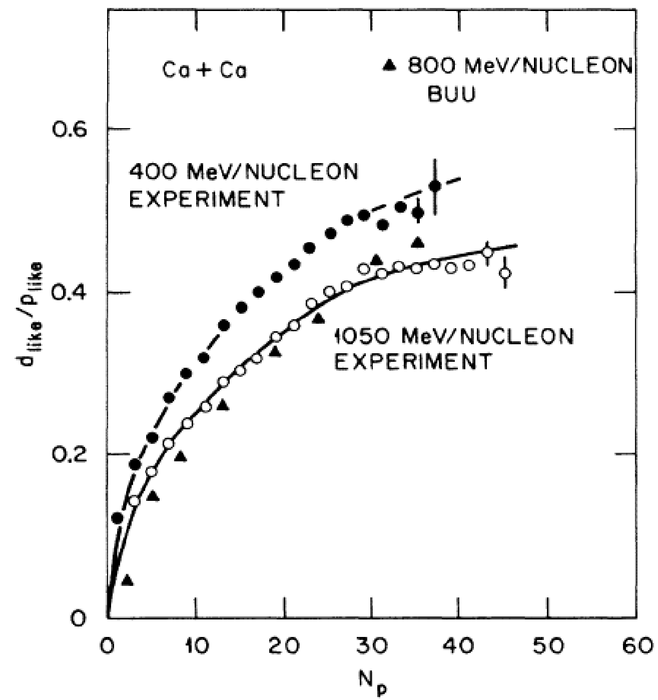
$$\Gamma(t) = \underbrace{\sum_{i=1,2}\sum_{j\geq 3}}_{coll\ between\ n\ or\ p\ and\ rest} \delta(t-t_{ij}(\nu)) \overbrace{\int \prod_i \frac{d^3p_i d^3x_i}{h^3} \underbrace{\rho_d^W(\mathbf{p_1},\mathbf{x_1},\mathbf{p_2},\mathbf{x_2})}_{Wigner\ density\ of\ d} [\rho_N^W(t+\epsilon) - \rho_N^W(t-\epsilon)]}^{W^+}$$

$$= \sum_{i=1,2}\sum_{j>3} \delta(t-t_{ij}(\nu))[\rho_d^W(t+\epsilon) - \rho_d^W(t-\epsilon)]$$

Easy to apply at SIS energies

Ca+Ca 800 AMeV (PRC35,1291)





At higher energies: role of baryonic resonances ?

role of mesons (large cross section with B

Conclusions about cluster models

Hybrid models (where one changes the modelling of the system)
- very useful to parametrize the data
- results are difficult to interpret
- say little about the mechanism of cluster formation

Dynamical models
- need a n-body approach for the dynamics of the nucleons

Minimum spanning tree (only applicable for $t \to \infty$)

Simulated annealing (SACA,FRIGA)
- can identify fragments during the HI reaction
- → allow for identifying when and how fragments are formed
- not easy to be applied for small clusters

Wigner density: tool based on quantum mechanics
only for small clusters

QMD models are quite successful to interpret cluster data
at low energy

PHQMD

PHQMD

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

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

Parton-Hadron-Quantum-Molecular Dynamics

↓

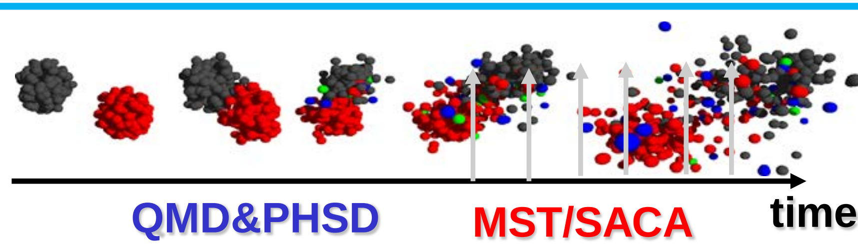
Initialization → propagation of baryons:
QMD (Quantum-Molecular Dynamics)

↓

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)
or MST (Minimum Spanning Tree)



J. Aichelin et al.,
PRC 101 (2020) 044905
& arXiv:1907.03860

QMD interaction potential and EoS

The expectation value of the Hamiltonian:

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

- **Skyrme potential ('static') * :**

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

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

- **modifed interaction density (with relativistic extension):**

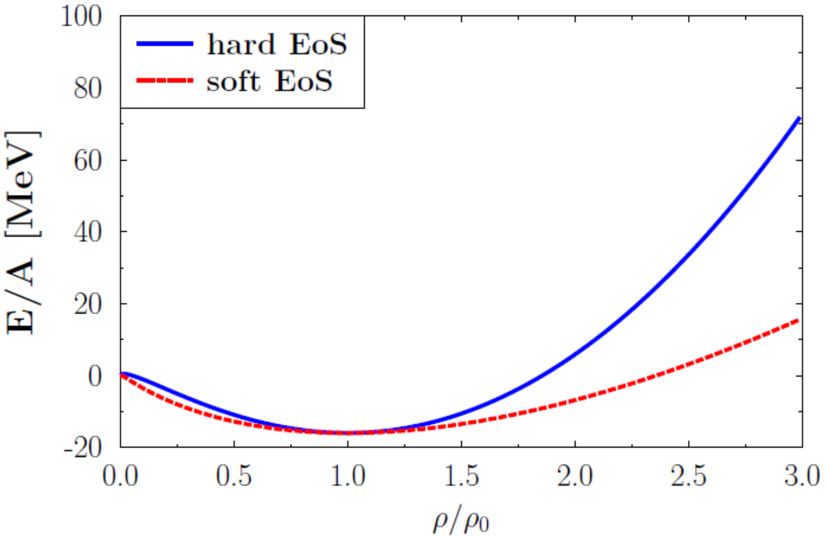
$$\rho_{int}(\mathbf{r}_{i0}, t) \rightarrow C \sum_j \left(\frac{4}{\pi L}\right)^{3/2} \mathrm{e}^{-\frac{4}{L}(\mathbf{r}_{i0}^{\mathrm{T}}(t) - \mathbf{r}_{j0}^{\mathrm{T}}(t))^2} \times \mathrm{e}^{-\frac{4\gamma_{cm}^2}{L}(\mathbf{r}_{i0}^{\mathrm{L}}(t) - \mathbf{r}_{j0}^{\mathrm{L}}(t))^2},$$

- **HIC ←→ EoS for infinite matter at rest**

- **compression modulus K of nuclear matter:**

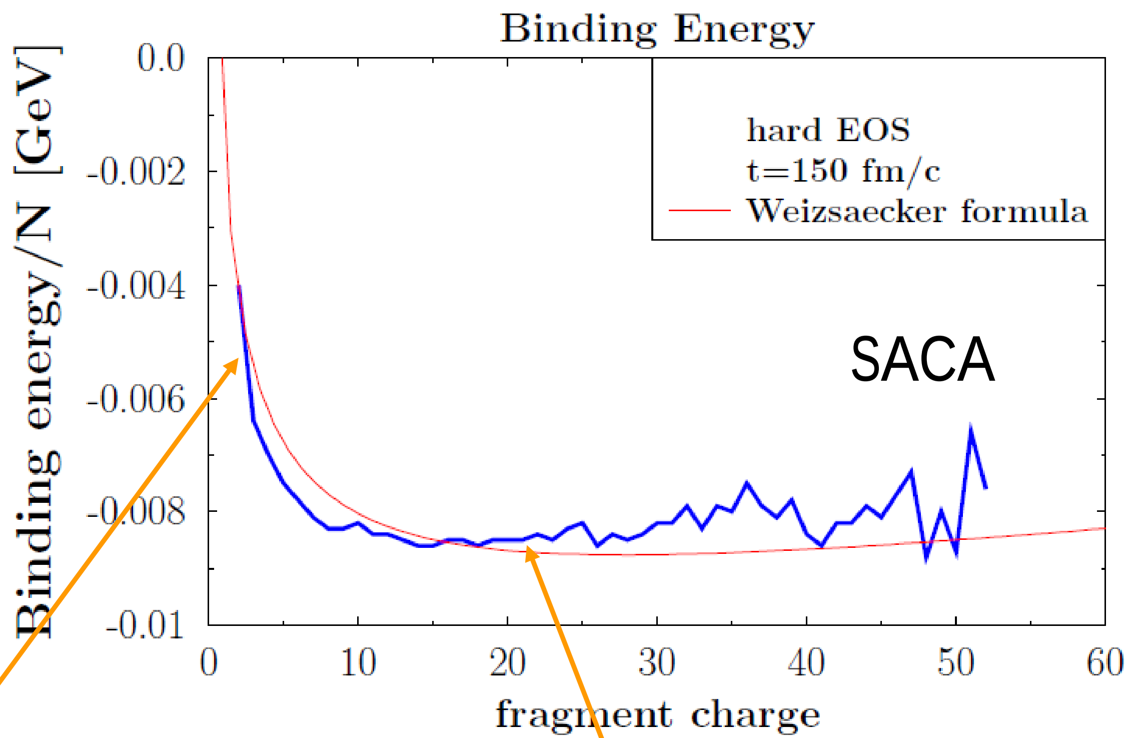
$$K = -V\frac{dP}{dV} = 9\rho^2 \frac{\partial^2(E/A(\rho))}{(\partial\rho)^2}\Big|_{\rho=\rho_0}$$

EoS for infinite matter at rest



*Work in progress: implementation of momentum dependent potential + symmetry energy (M. Winn)

N-body models can produce cluster with the right E_{bind}



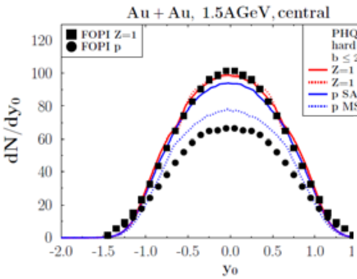
There are two kinds of fragments

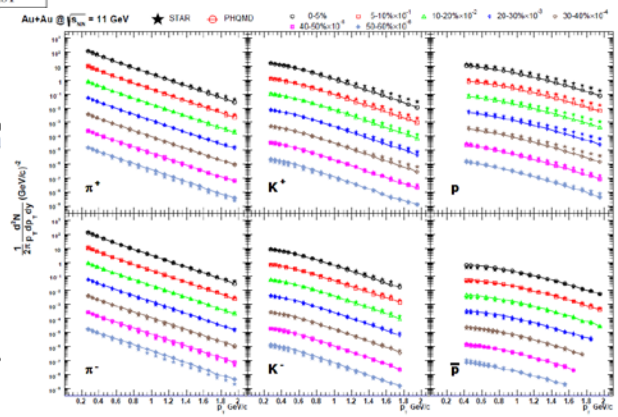
- formed from participant matter
  created during the expansion of the fireball
  "ice" (E_{bind} ≈8 MeV/N) in "fire"(T≥ 100 MeV)
  origin not known yet
  seen from SIS to RHIC
  (quantum effects may be important)

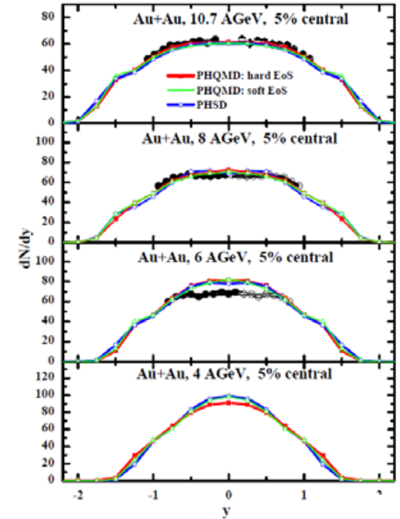
- formed from spectator matter
  close to beam and target rapidity
  initial-final state correlations
  HI reaction makes spectator matter unstable

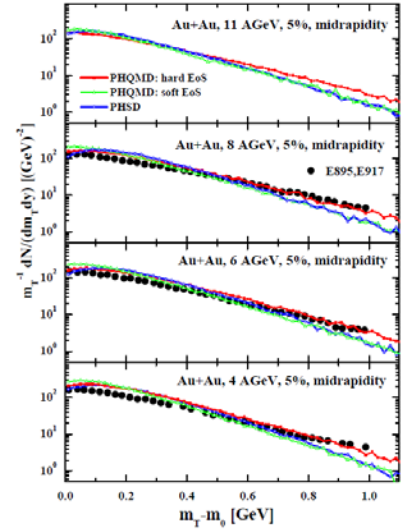
Highlights: PHQMD ‚bulk‘ dynamics from SIS to RHIC

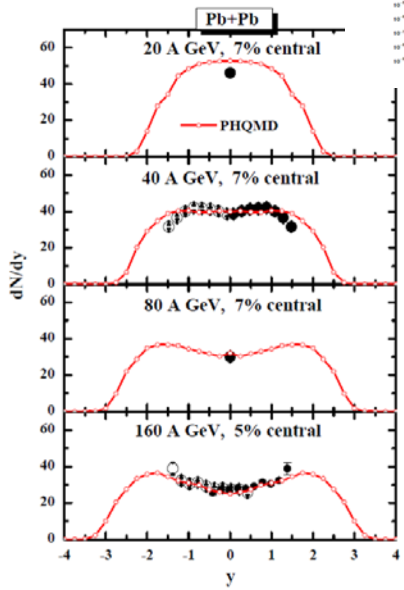
PHQMD: J. Aichelin et al., PRC 101 (2020) 044905

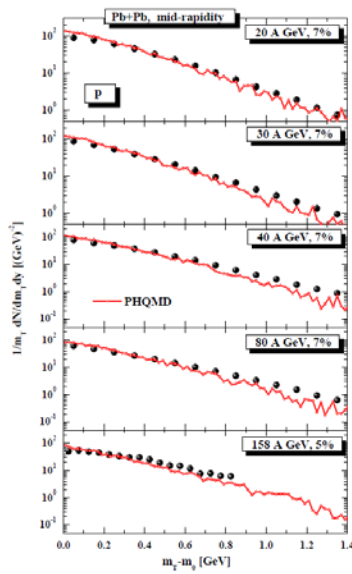


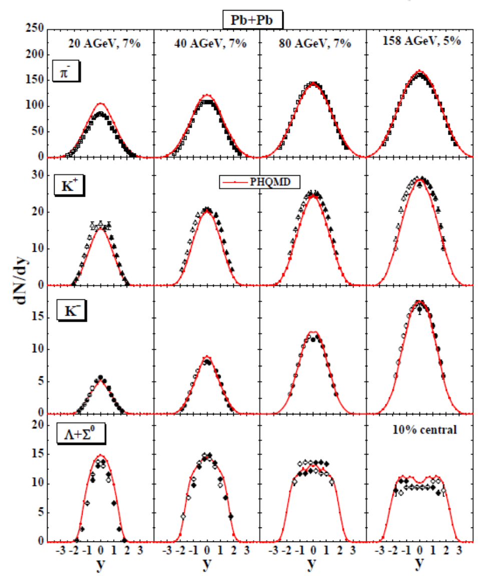


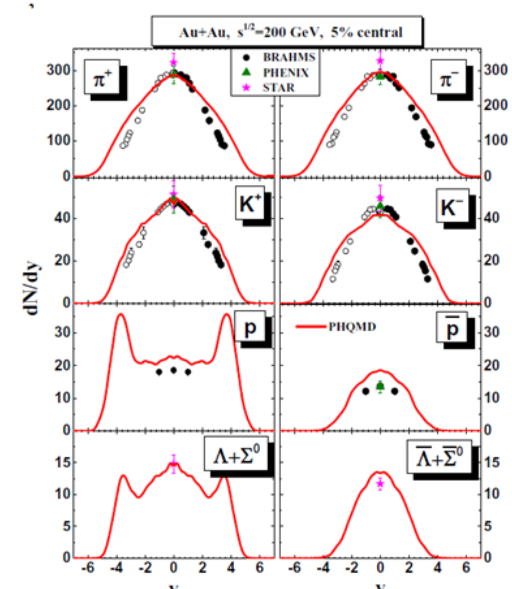










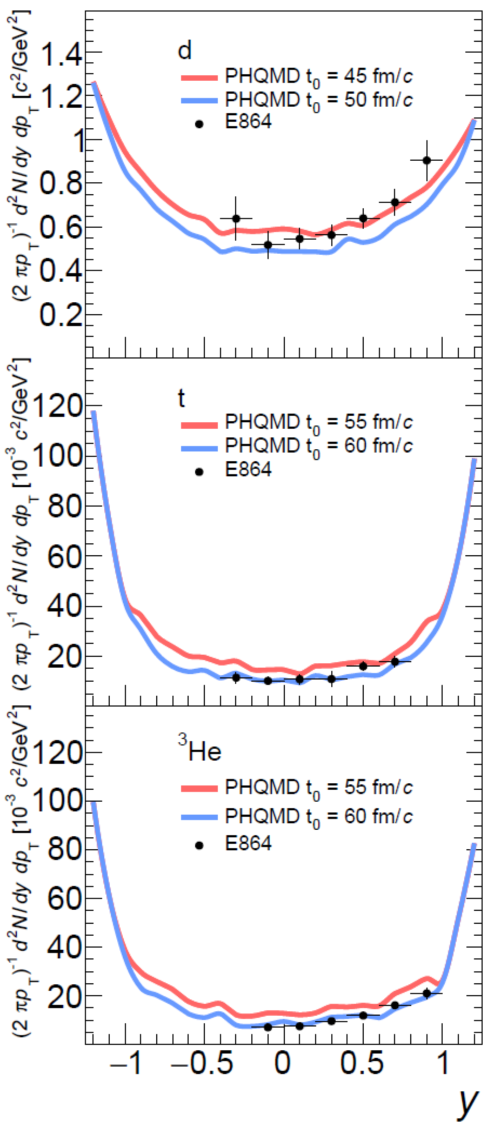


PHQMD provides a good description of hadronic ‘bulk’ observables from SIS to RHIC energies

Cluster production in HIC at AGS energies

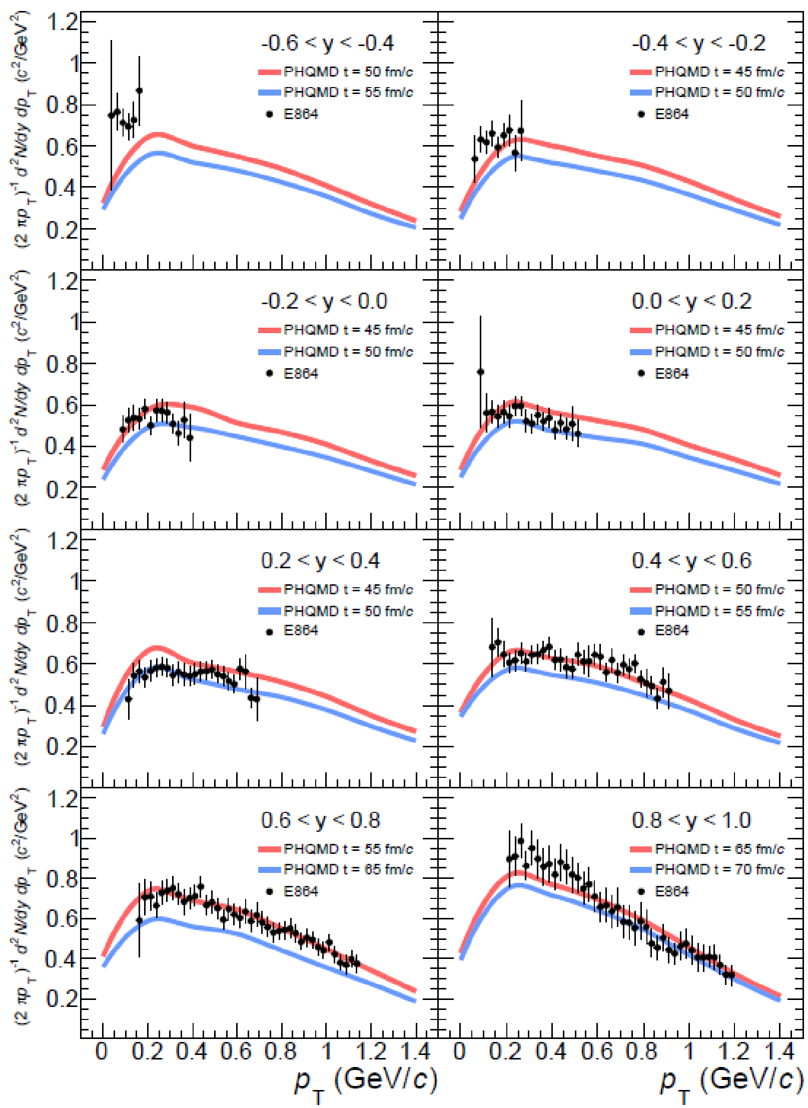
y- distributions of d, t, ^{3}He

Au+Pb@10.6 AGeV



p_T - distribution of deuterons

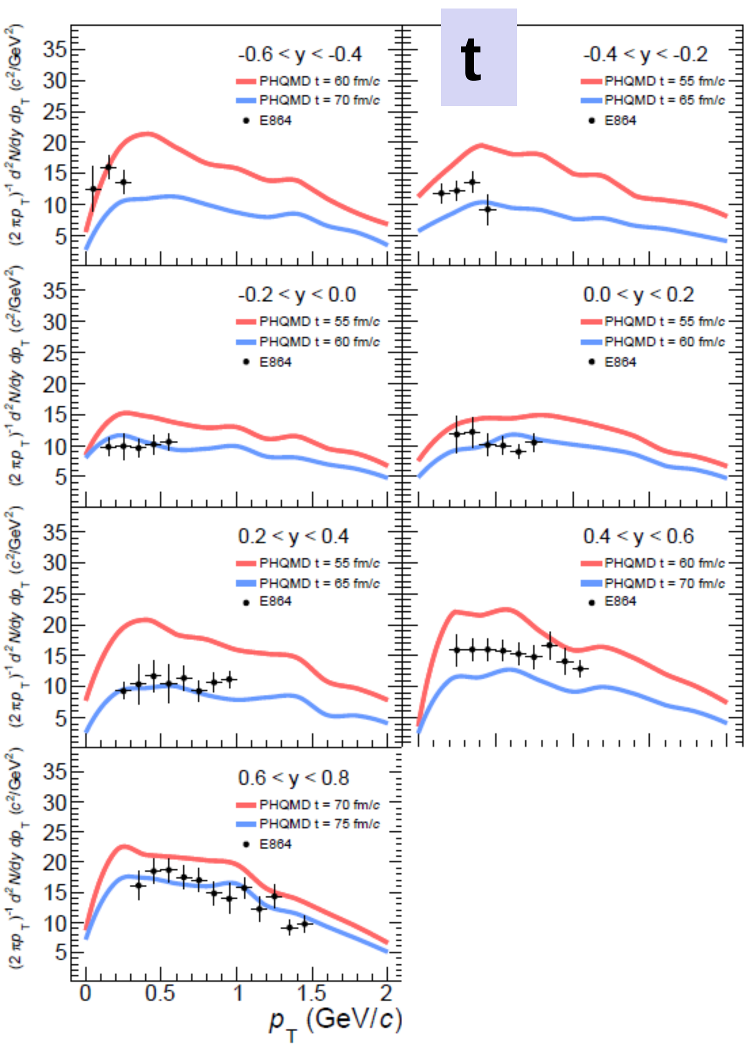
Au+Pb@10.6 AGeV

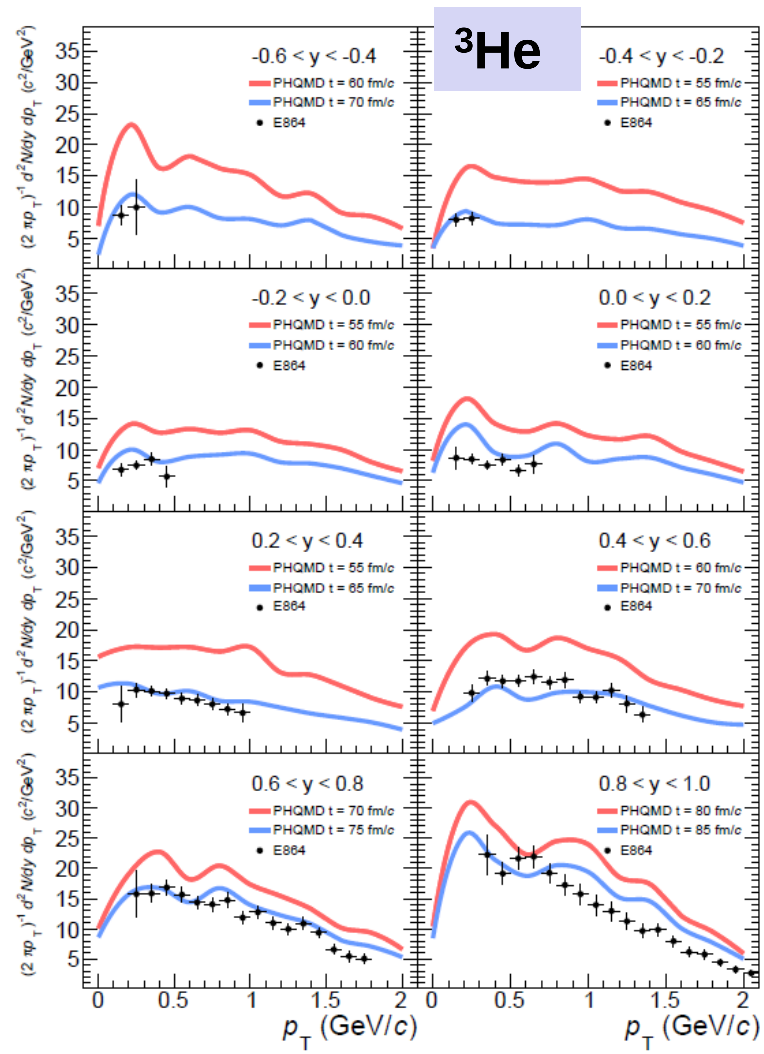


The PHQMD results are taken at $t = t_0 \cosh(y)$, where t_0 is the time at y=0

Cluster production in HIC at AGS energies

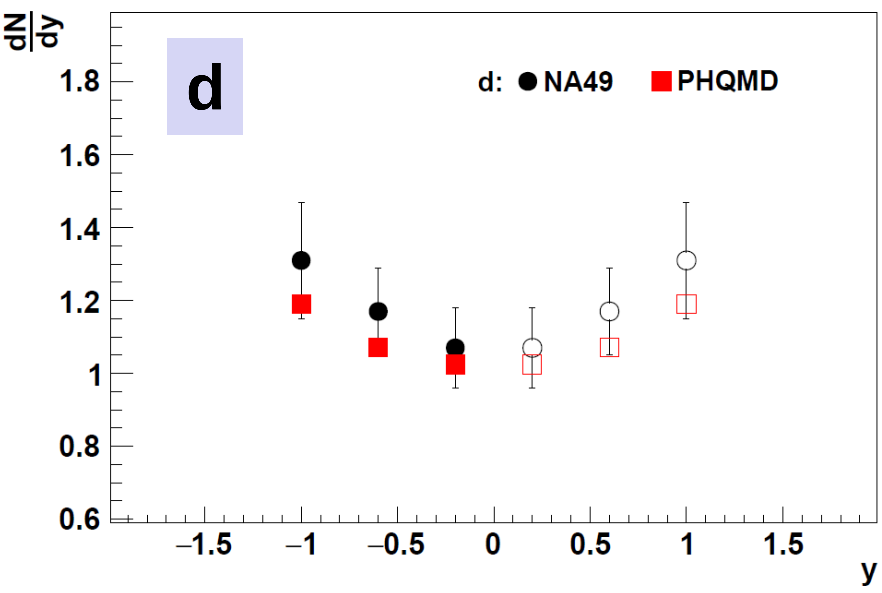
The p_T - distributions of t and ^{3}He from Au+Pb at 10.6 A GeV

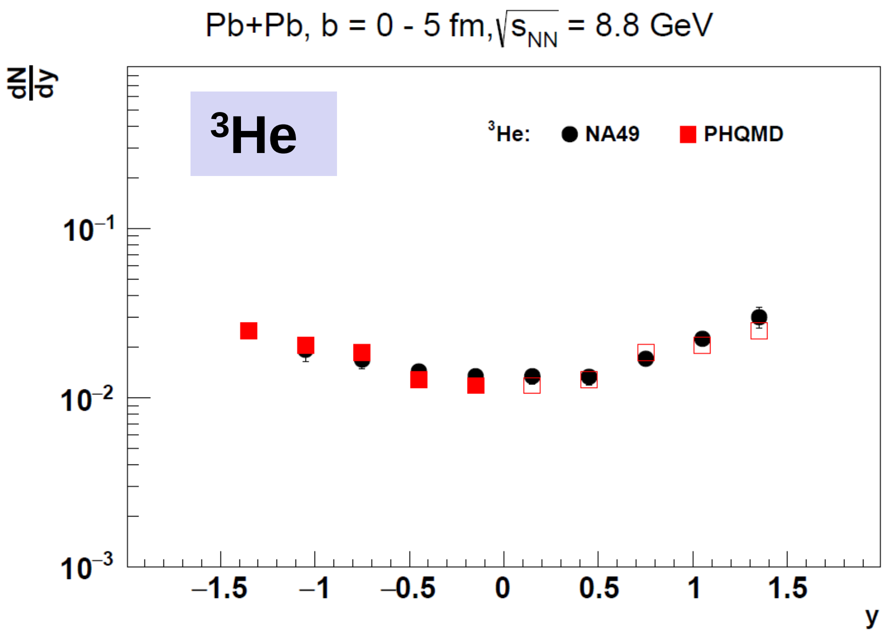




Cluster production in HIC at SPS energies

The rapidity distributions of d and ^{3}He from Pb+Pb at 30 A GeV



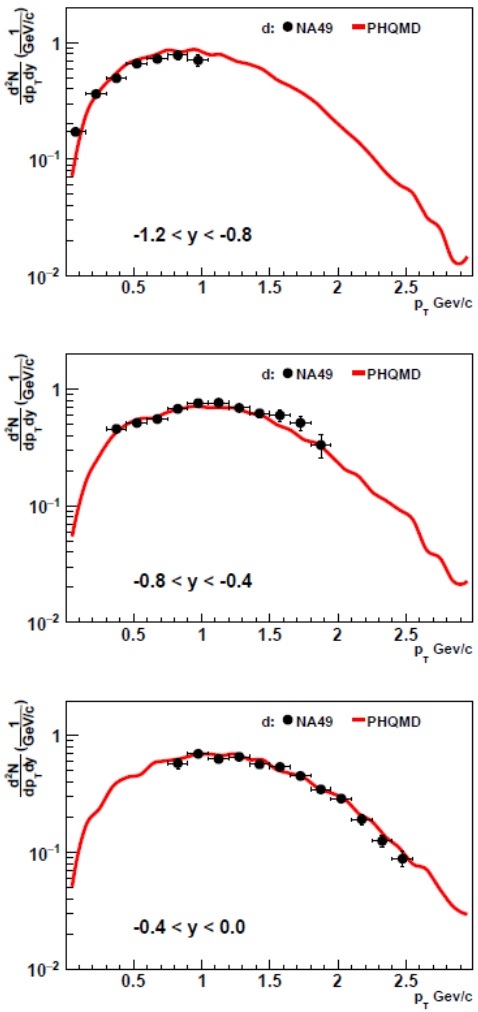


The PHQMD results for d and ^{3}He agree with NA49 data

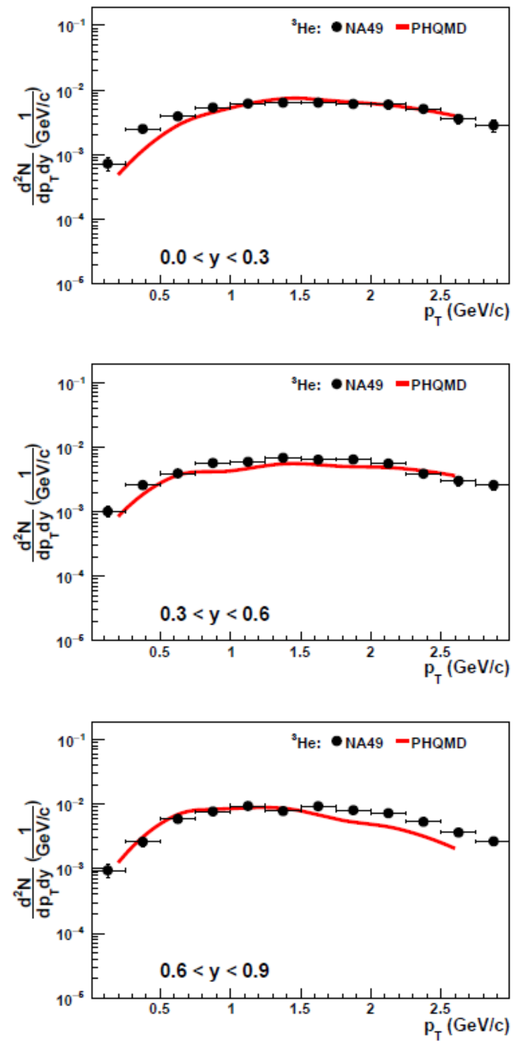
Cluster production in HIC at SPS energies

The p_T - distributions of d and ^3He from Pb+Pb at 30 A GeV

d

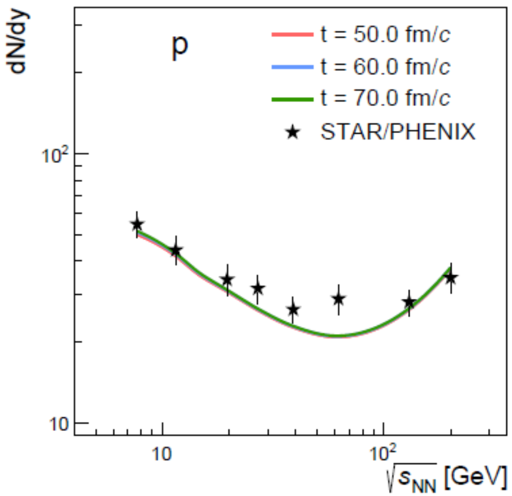


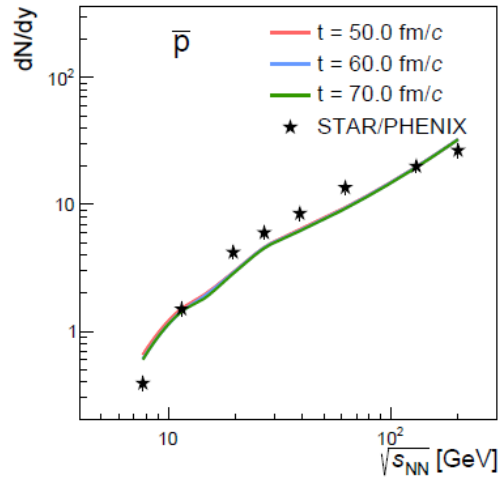
^{3}He

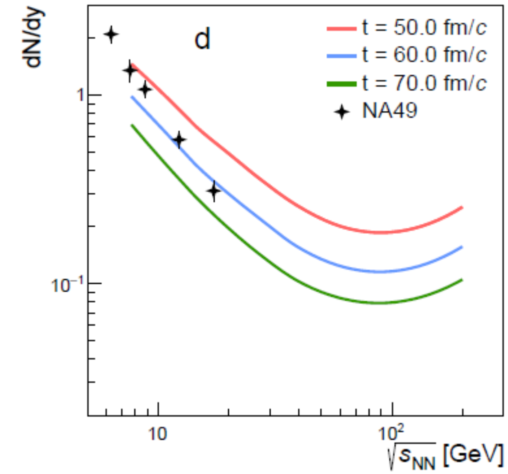


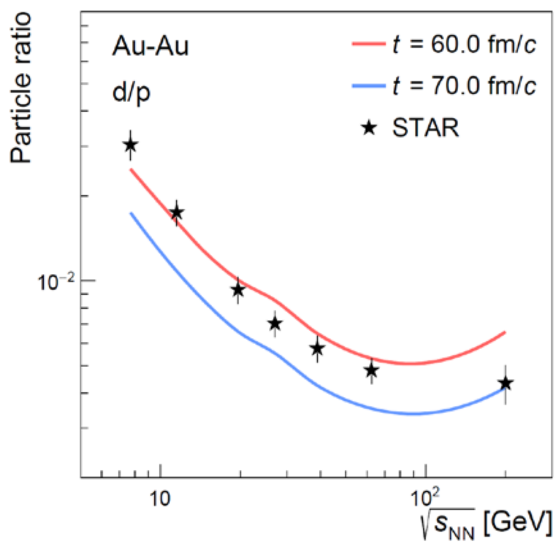
PHQMD

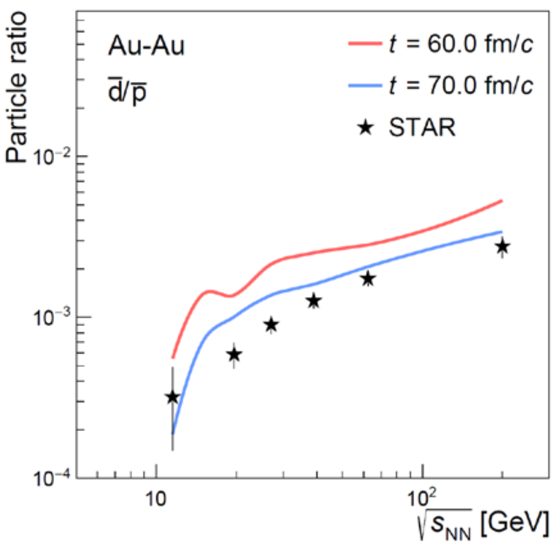
Excitation function of multiplicity of $p, \overline{p}, d, \overline{d}$





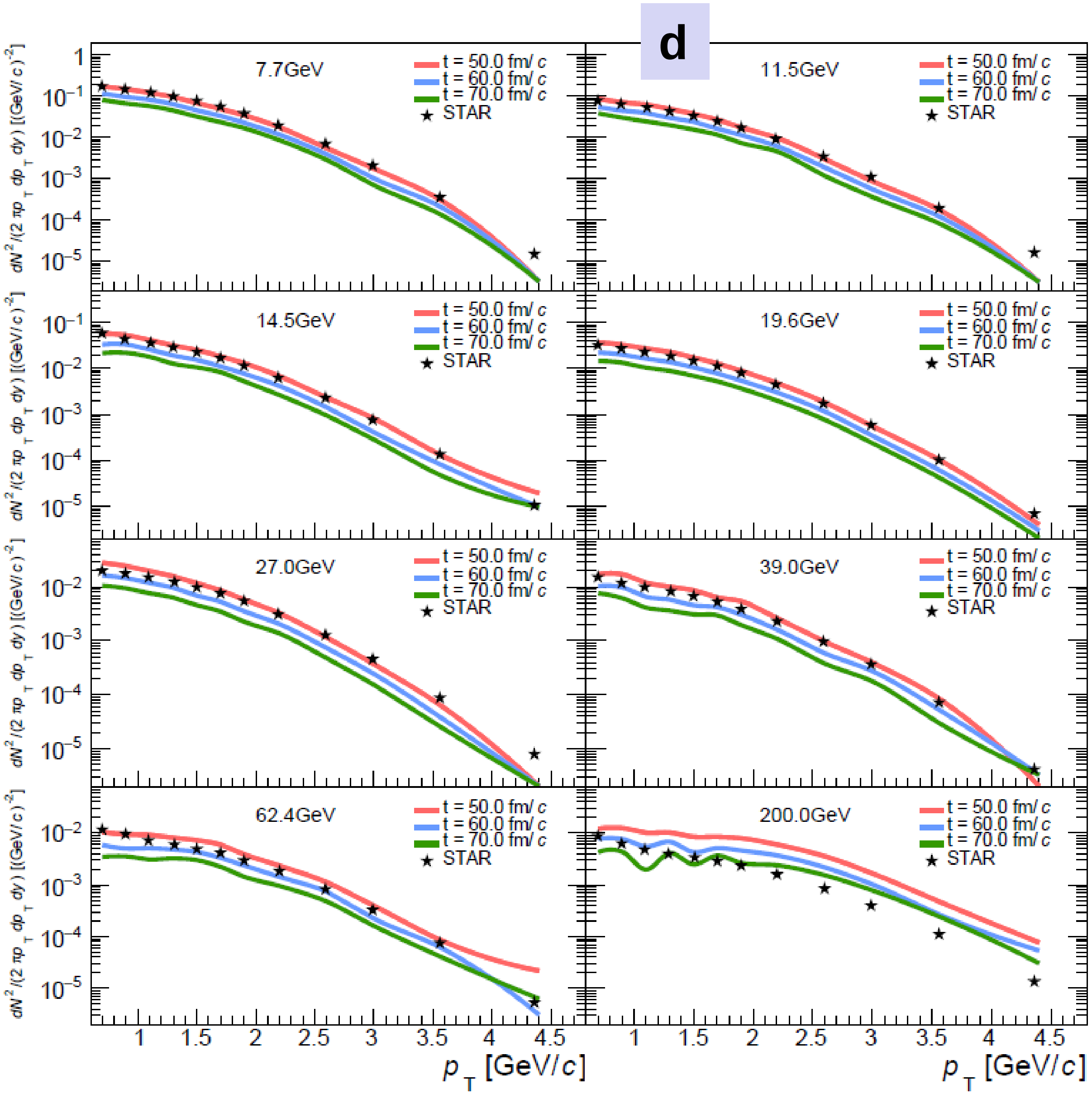






The $p, \overline{p}$ yields at y~0 are stable, the $d, \overline{d}$ yields are better described at *t= 60-70* fm/c

Deuteron p_T spectra from 7.7GeV to 200 GeV



Comparison of the PHQMD results for the deuteron p_T -spectra at midrapidity with STAR data

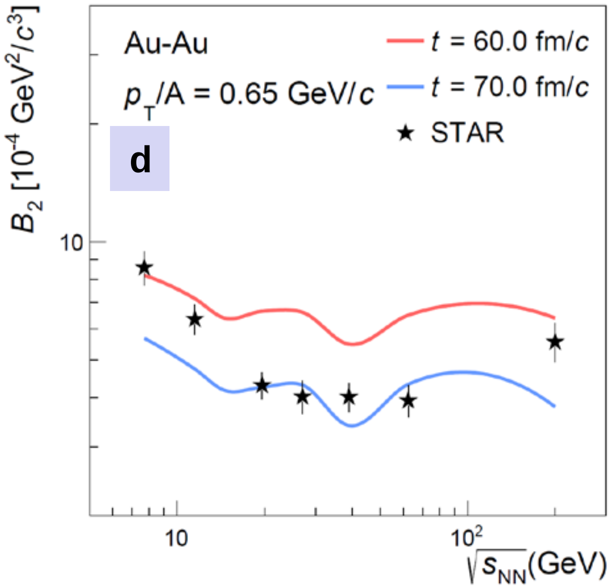
Coalescence parameter B_2 for deuterons

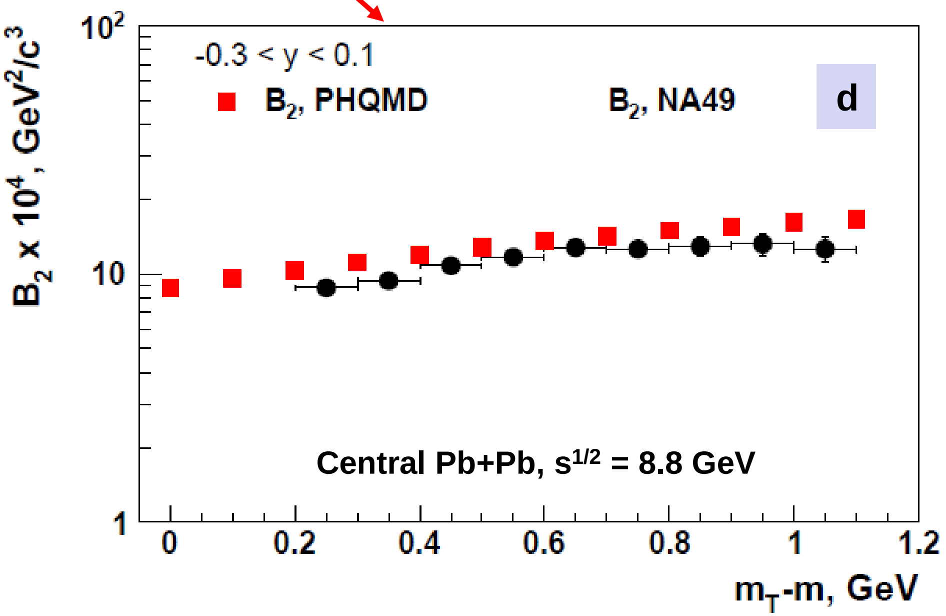
Coalescence parameter B_2:

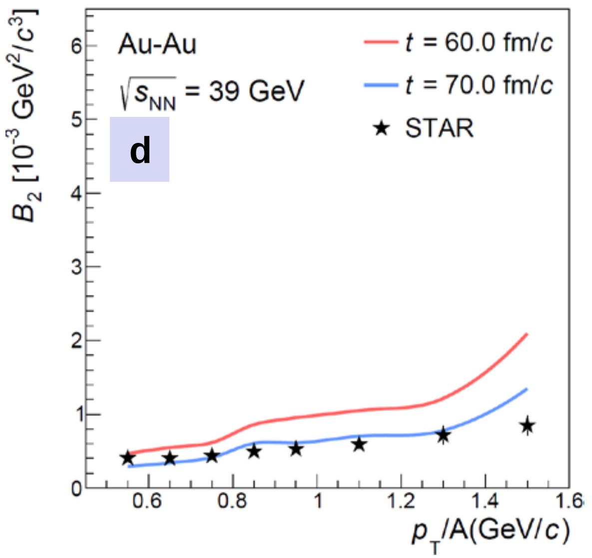
$$B_2 = \frac{E_d \frac{d^3 N_d}{d^3 P_d}}{\left(E_p \frac{d^3 N_p}{d^3 p_p}\Big|_{p_p = P_d/2}\right)^2}$$

Comparison of the PHQMD results with NA49 and STAR data

central Au+Au collisions



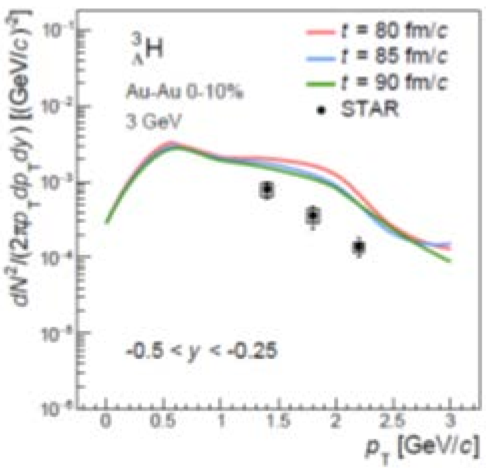


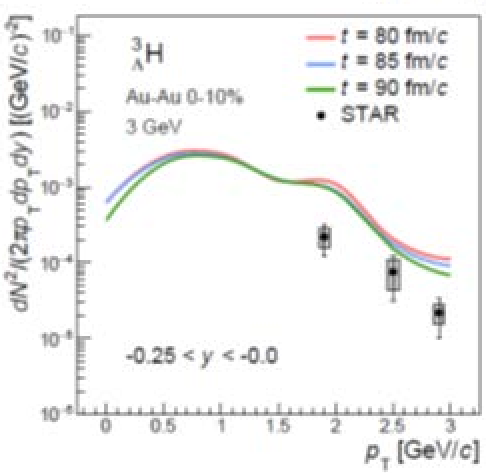


Hypernuclei production at $s^{1/2}$ = 3 GeV

The PHQMD comparison with most recent STAR fixed target p_T distribution of $^3H_\Lambda$, $^4H_\Lambda$ from Au+Au central collisions at $\sqrt{s}$ =3 GeV

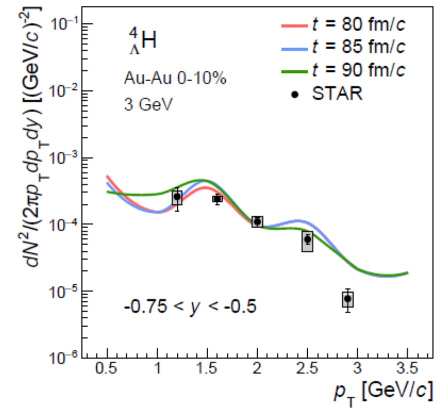
- **Assumption on nucleon-hyperon potential:**
  $V_{N\Lambda}$ = 2/3 V_{NN}

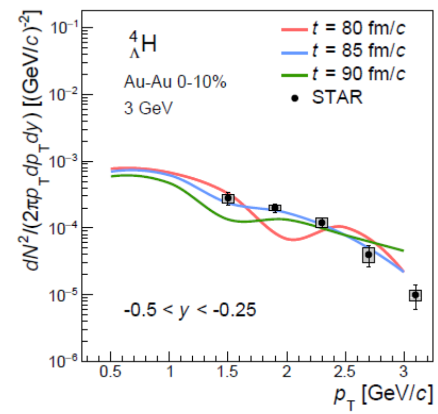


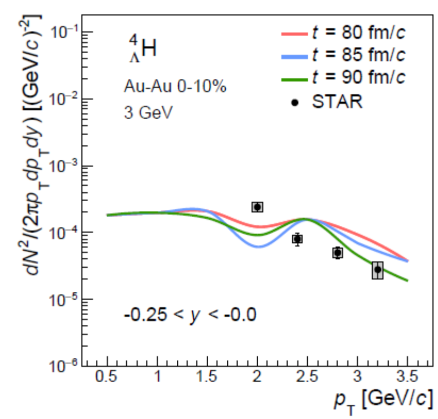


Star data preliminary

Good description in view of these very complex hypernuclei



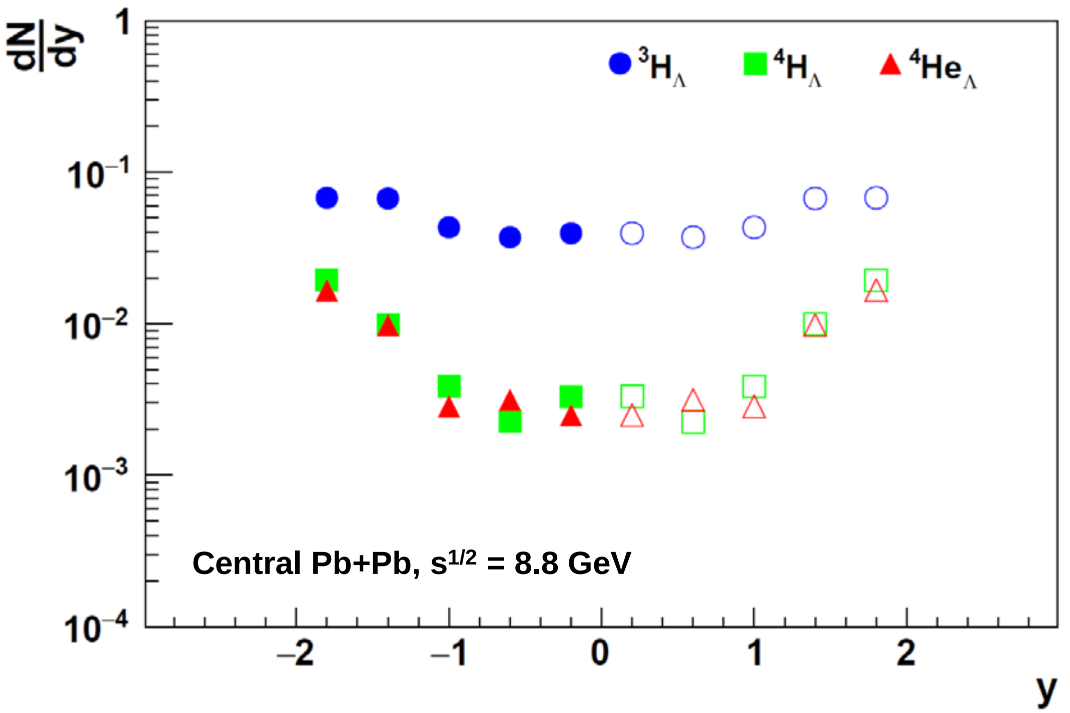




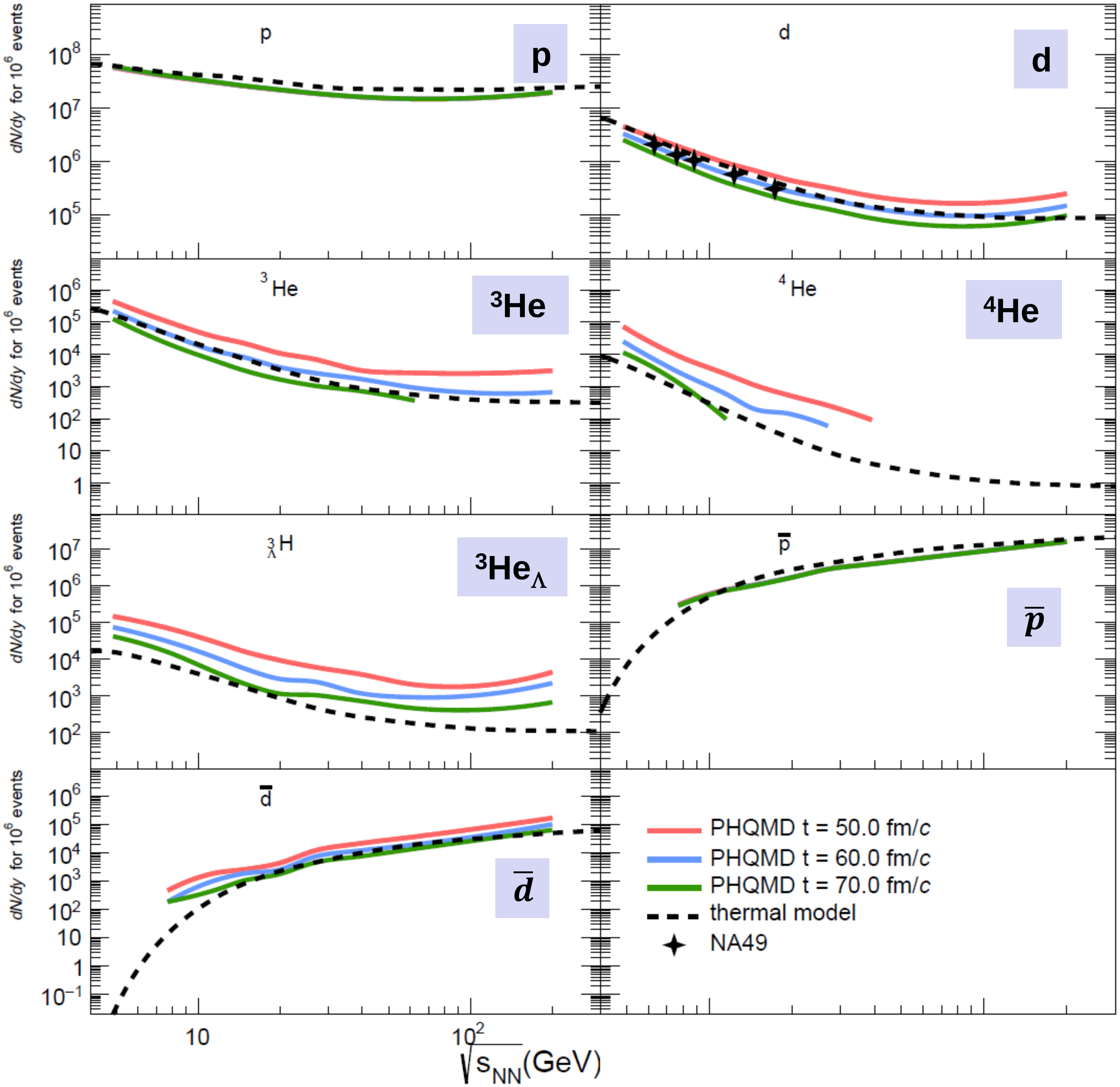
Hypernuclei production at $s^{1/2}$ = 8.8 GeV

The PHQMD predictions on the rapidity distribution of $^3H_\Lambda$, $^4H_\Lambda$ and $^4He_\Lambda$ from Pb+Pb central collisions at 30 A GeV ($s^{1/2}$ = 8.8 GeV)

- Assumption on nucleon-hyperon potential: $V_{N\Lambda} = 2/3\ V_{NN}$



The PHQMD excitation function of cluster production versus thermal model



Comparison of the PHQMD results for Cluster and hypernuclei $^3H_\Lambda$ with thermal model and NA49 data

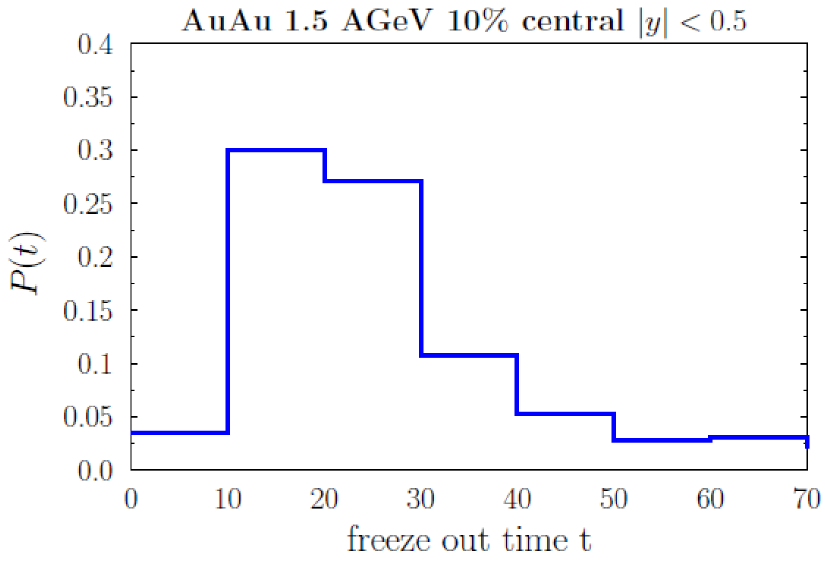
Thermal model:
A. Andronic et al., PLB 697 (2011) 203

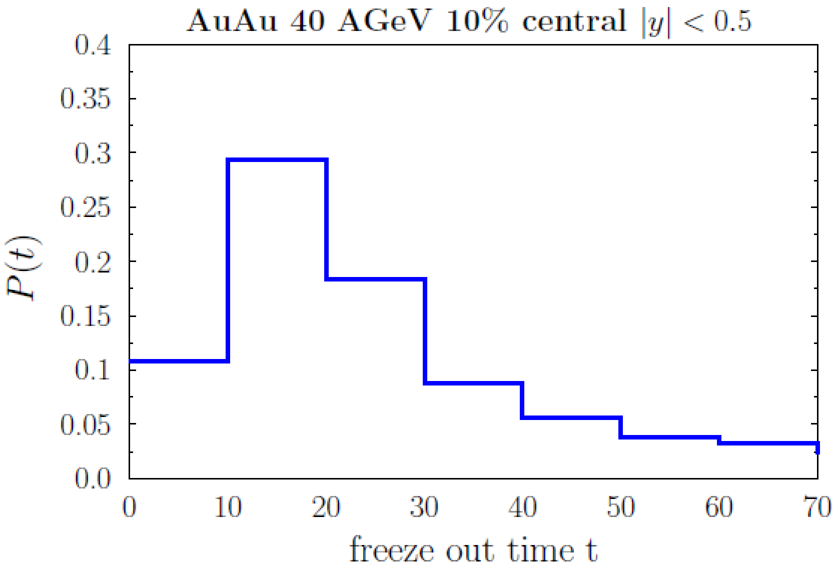
How are the clusters produced
‘ice in fire‘ puzzle

When does the system freeze out?

- The normalized distribution of the freeze-out time of baryons (nucleons and hyperons) which are finally observed at mid-rapidity |y|<0.5

  * Here freeze-out time is defined as a last elastic or inelastic collision, after that only potential interaction between baryons occurs



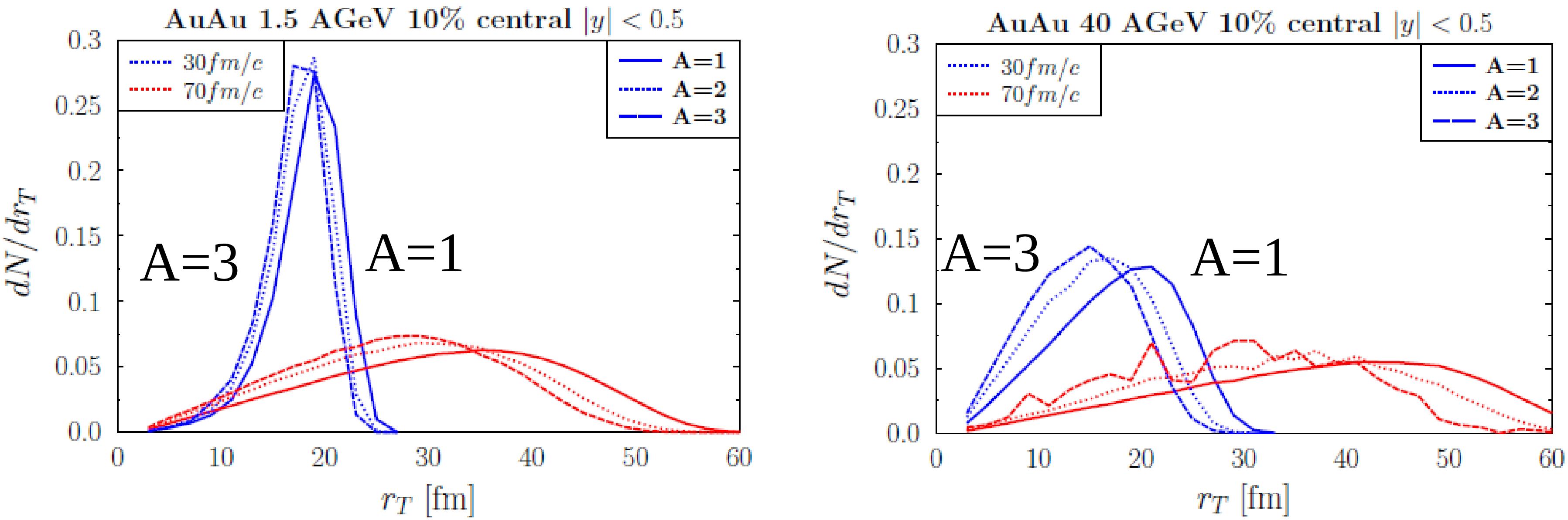


➔ Freeze-out time of baryons in Au+Au at 1.5 AGeV and 40 AGeV:

- similar profile since expansion velocity of mid-rapidity fireball is roughly independent of the beam energy

Where are the clusters formed?

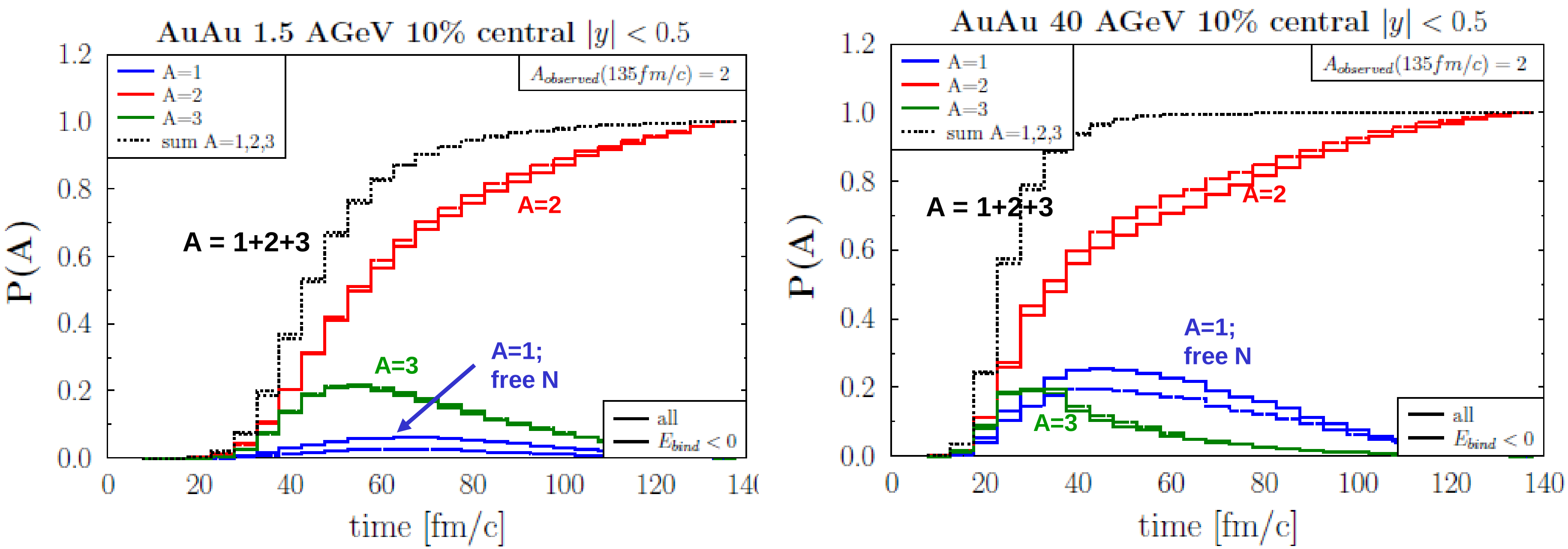
- The snapshot (taken at time 30 and 70 fm/c) of the **normalized distribution of the transverse distance r_T of the nucleons** to the center of the fireball.
- It is shown for A=1 (free nucleons) and for the nucleons in A=2 and A=3 clusters



➔ **Transverse distance profile** of **free nucleons and clusters are different**!
Clusters are mainly formed behind the "front" of free nucleons of the expanding fireball

Where are the clusters formed?

- The conditional probability P(A) that the nucleons, which are finally observed in A=2 clusters at time 135 fm/c, were at time *t* the members of A=1 (free nucleons), A=2 or A=3 clusters



➔ **Stable clusters (observed at 135 fm/c) are formed shortly after the dynamical freeze-out**

Summary

The PHQMD is a microscopic n-body transport approach for the description of heavy-ion dynamics and cluster formation
Clusters are identified by Minimum Spanning Tree model

combined model PHQMD = (PHSD & QMD) & (MST | SACA)

- provides the good description of 'bulk' observables from SIS to RHIC energies

- predicts the dynamical formation of clusters from SIS to RHIC energies due to the interactions among the nucleons

- reproduces cluster data on dN/dy and dN/dp$_T$ as well as ratios d/p and $\bar{d}/\bar{p}$ for HI collisions from AGS to top RHIC energies.

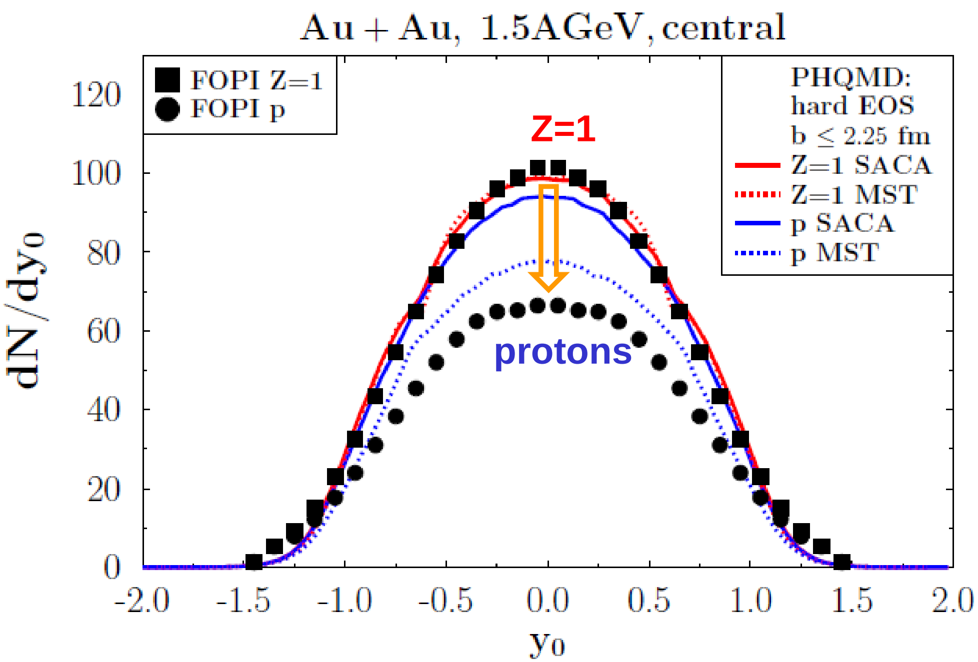
A detailed analysis reveals that clusters are formed
- shortly after elastic and inelastic collisions have ceased
- behind the front of the expanding energetic hadrons
- since the 'fire' is not at the same place as the 'ice', cluster can survive.

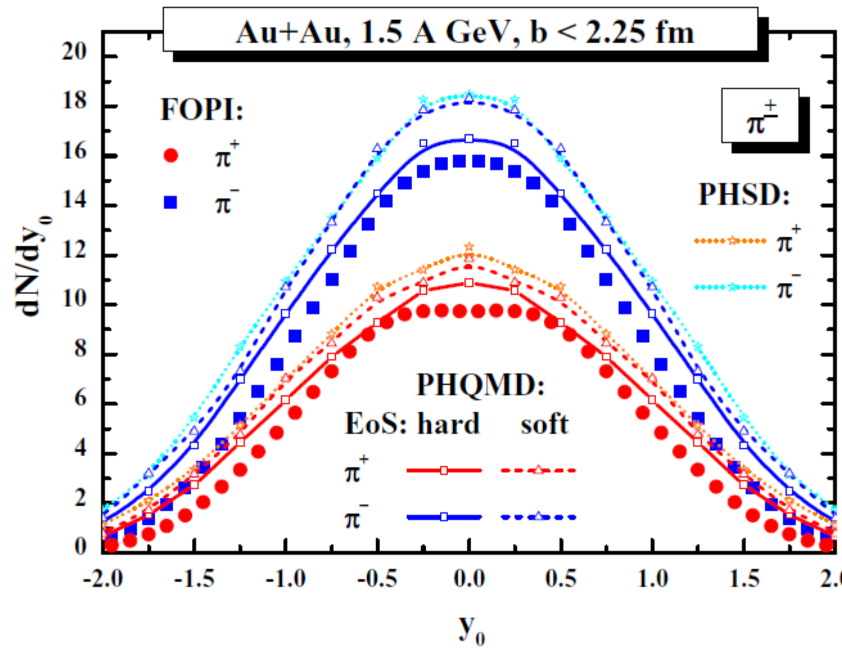
Outlook:
- extension to LHC energies and study of hyper-nuclei with more realistic potentials

Thank you for your attention !

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**

Cluster formation: QMD vs MF

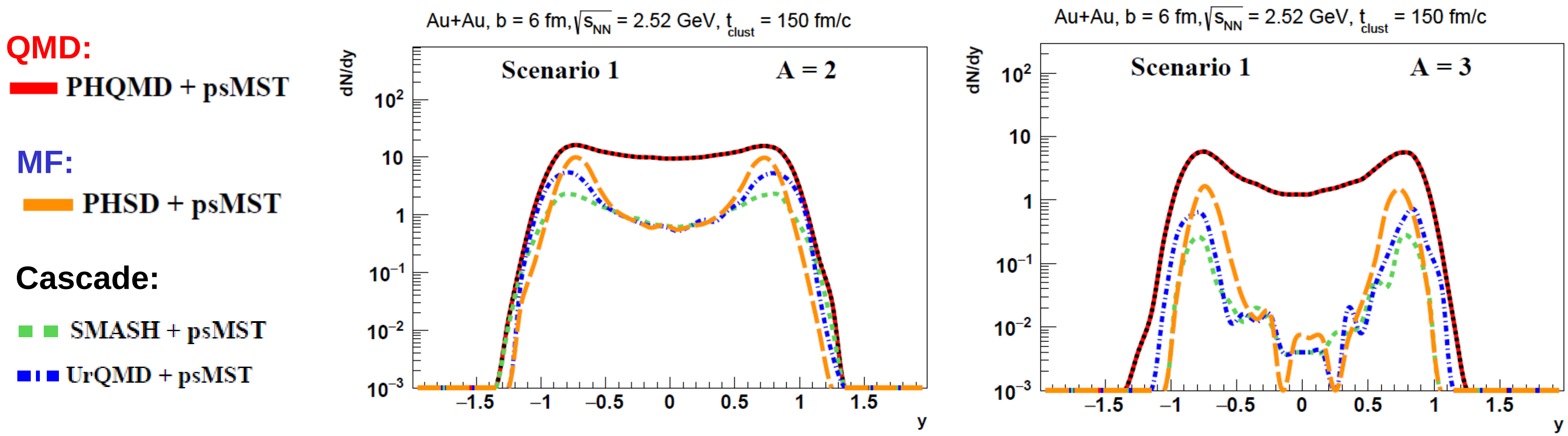
- Cluster formation is sensitive to nucleon dynamics

➔ 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
- Cascade – no correlations by potential interactions

Example: Cluster stability over time:

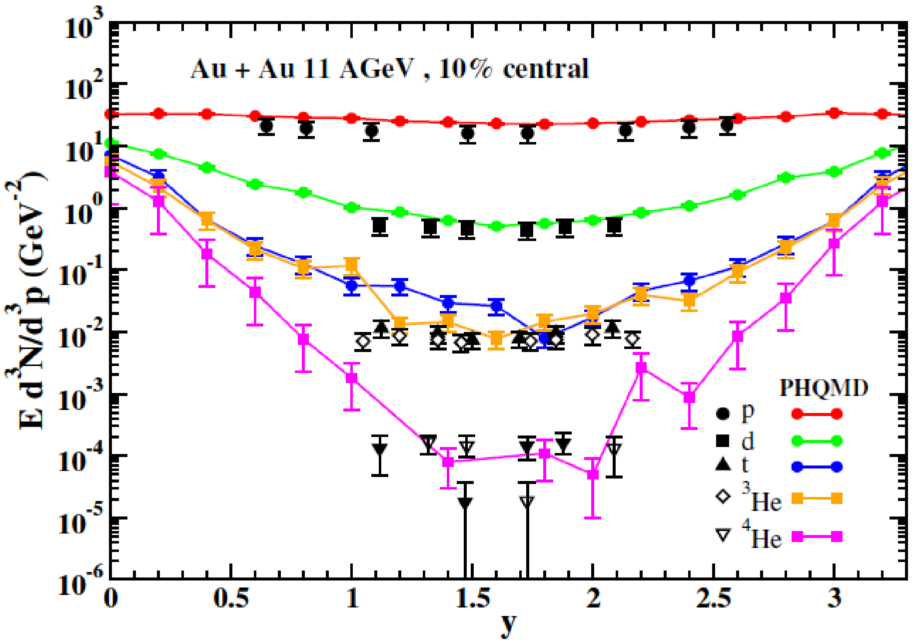
V. Kireyeu, 2103.10542



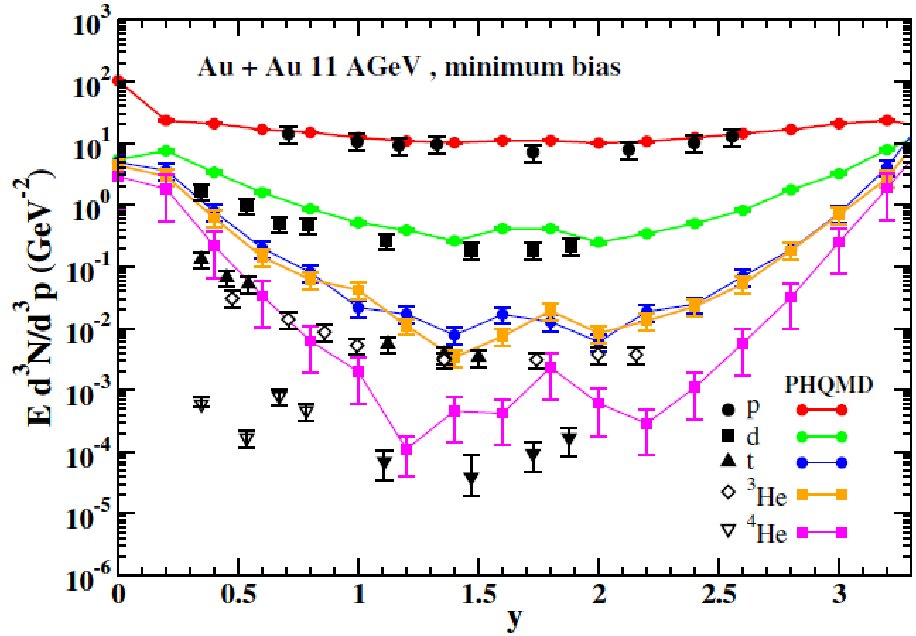
PHQMD: light clusters at AGS energies

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



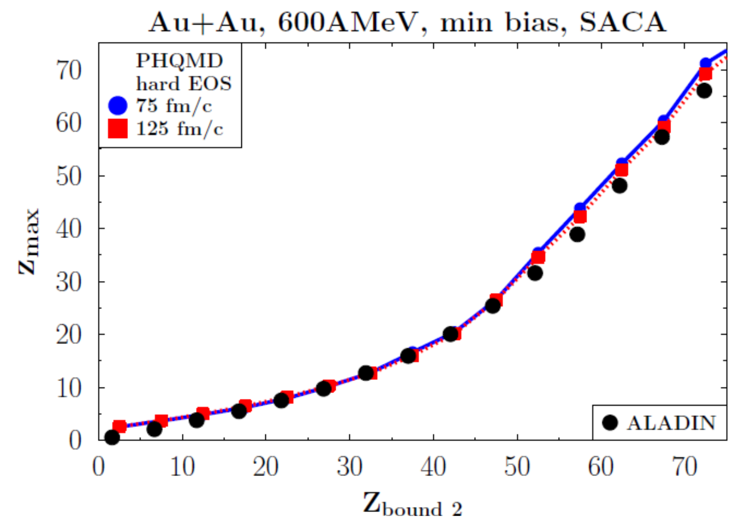
Au+Au, 11 AGeV, minimal bias



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

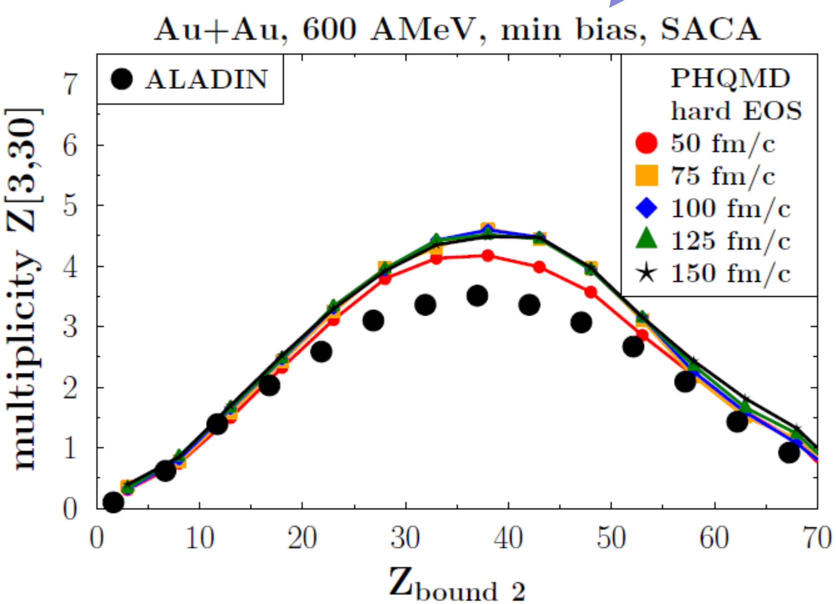
PHQMD: heavy clusters

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

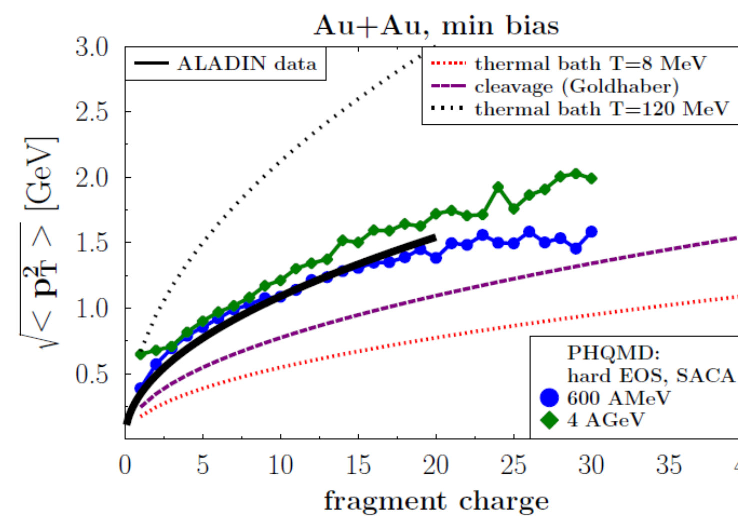


PHQMD with SACA shows an agreement with ALADIN data for very complex cluster observables as

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



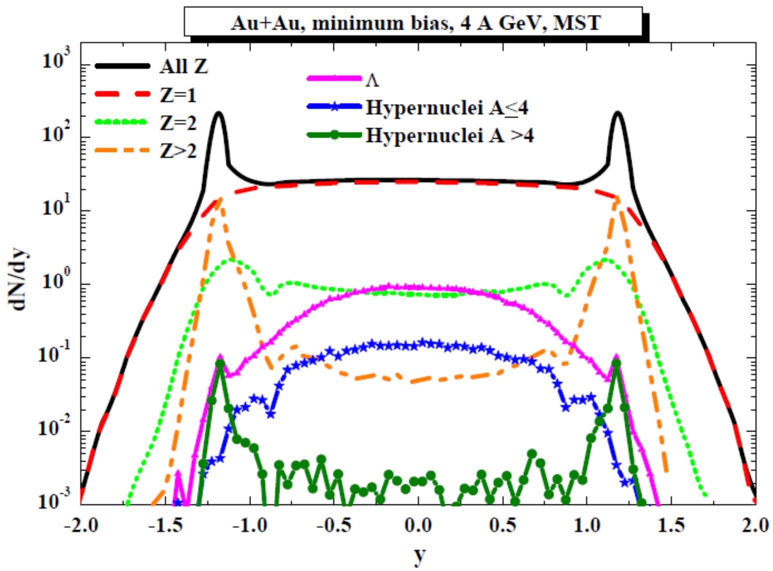
$$Z_{bound\ 2} = \sum_i Z_i\, \Theta(Z_i - (1+\epsilon)) \quad (\epsilon < 1)$$

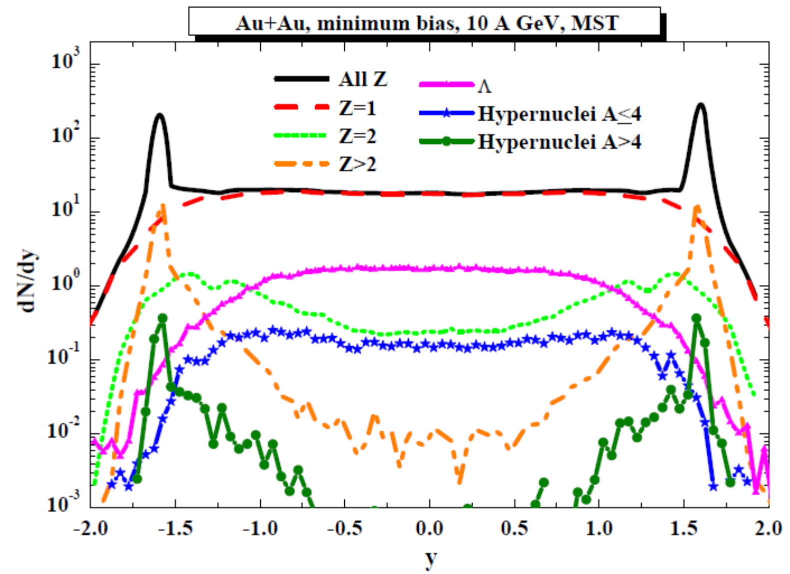


PHQMD shows $\sqrt{p_T^2(Z)} \propto \sqrt{Z}$ dependence as exp. data

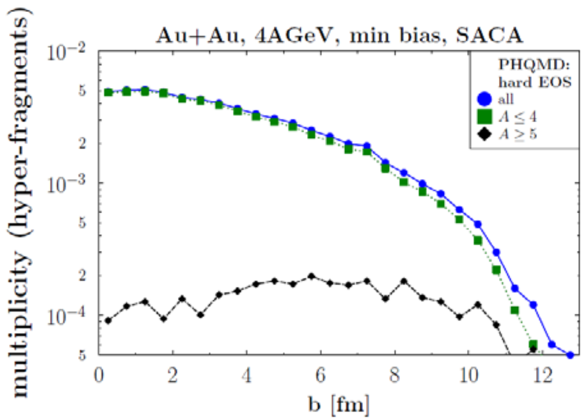
PHQMD: hypernuclei

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

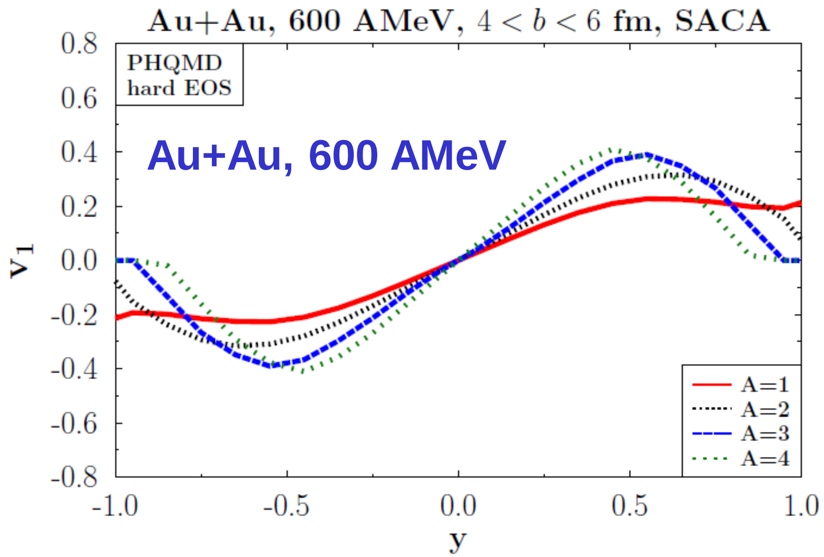


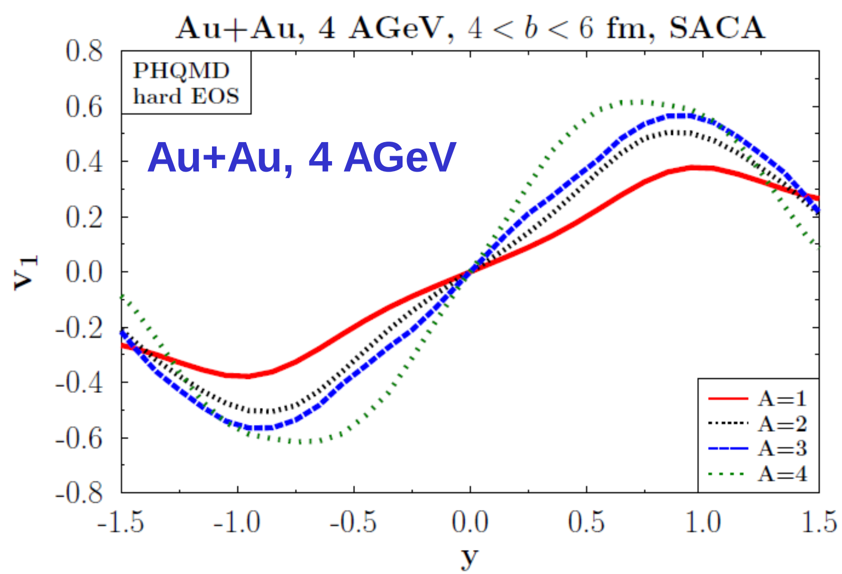
- **Central collisions → light hypernuclei**
- **Peripheral collisions → heavy hypernuclei**

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

→ Possibility to study ΛN interaction

PHQMD: collectivity of clusters



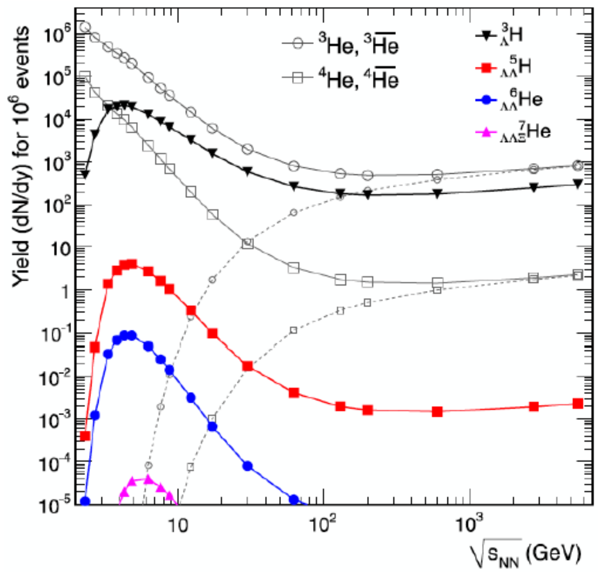


PHQMD with hard EoS, with SACA:
v_1 of light clusters (A=1,2,3,4) vs rapidity
for mid-central Au+Au at 600 AMeV, 4AGeV

- **v_1 : quite different for nucleons and 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}**
- **→ larger density gradient**

Modeling of cluster and hypernuclei formation

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



Existing models for clusters formation:

- **statistical model:**
  - **assumption of thermal equilibrium**
- **coalescence model:**
  - **determination of clusters at a given time by coalescence radii in coordinate and momentum spaces**

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

In order to understand a microscopic origin of cluster formation one needs a realistic model for the dynamical time evolution of the HIC
→ **transport models:**
- **dynamical modeling of cluster formation based on interactions**

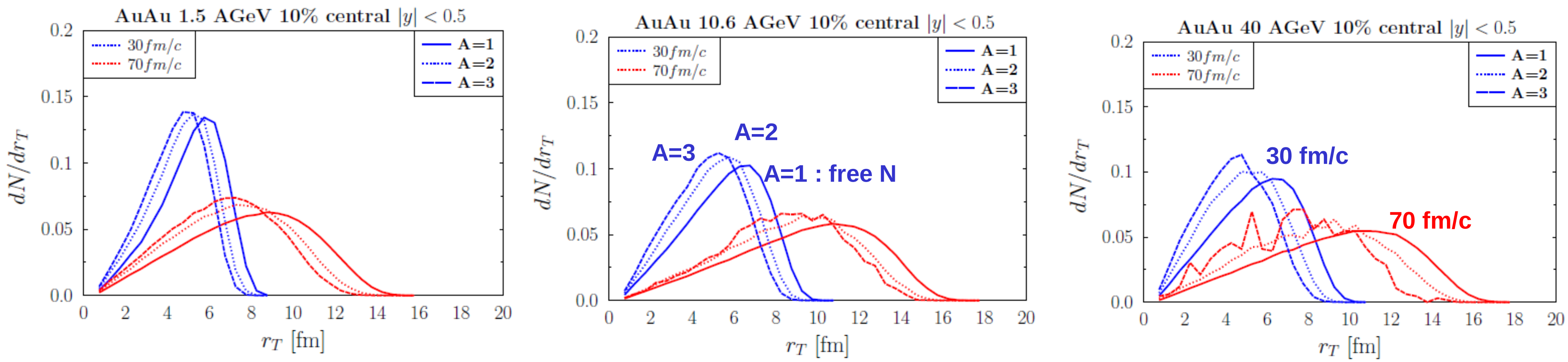
- **Cluster formation is sensitive to nucleon dynamics**

➔ **One needs to keep the nucleon correlations (initial and final) by realistic nucleon-nucleon interactions in transport models:**

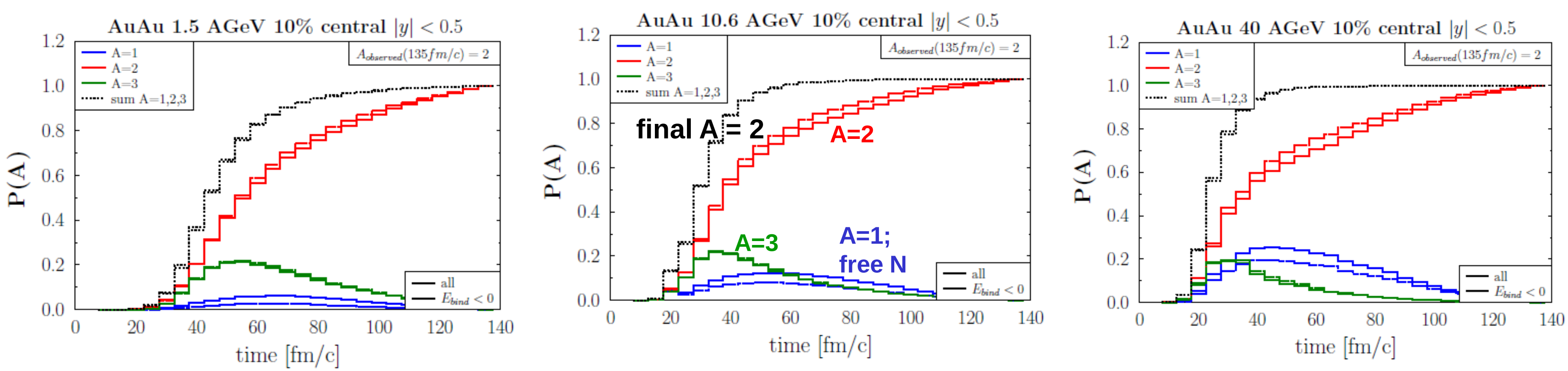
- **QMD (quantum-molecular dynamics) – allows to keep correlations**
- **MF (mean-field based models) – correlations are smeared out**

Where are the clusters formed?

- The normalized distribution of the **transverse distance** of the nucleons, observed at midrapidity (A=1,2,3)



- The probability distribution P(A) of the formation time of clusters at midrapidity
  - the probabilities that the **finally observed A = 2** cluster has been at time *t* a **part** of A=1 (free nucleons), A=2 or A=3 clusters



➔ **Stable clusters are formed during dynamical freeze-out**

Cluster stability in semi-classical models

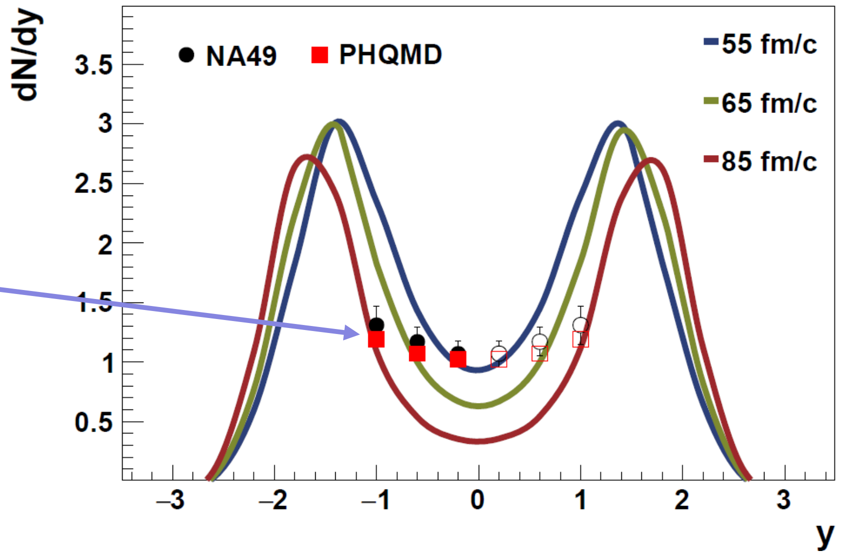
Problems of the semi-classical models (as QMD):
QMD cannot project the n-body density on the ground state of a cluster as a quantum system of fermions
Quantum ground state has to respect a minimal average kinetic energy of the nucleons while the semi-classical (QMD) ground state - not!

➔ nucleons may still be emitted from the clusters even if in the corresponding quantum system this is not possible anymore
= QMD clusters are not fully stable over time
➔ the multiplicity of clusters is time dependent

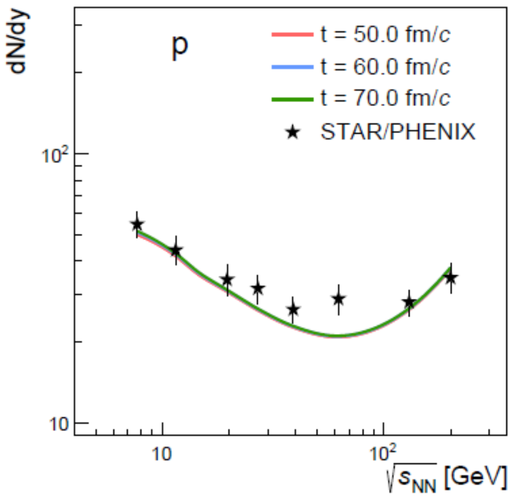
In this study the PHQMD results are taken at 'physical time' :

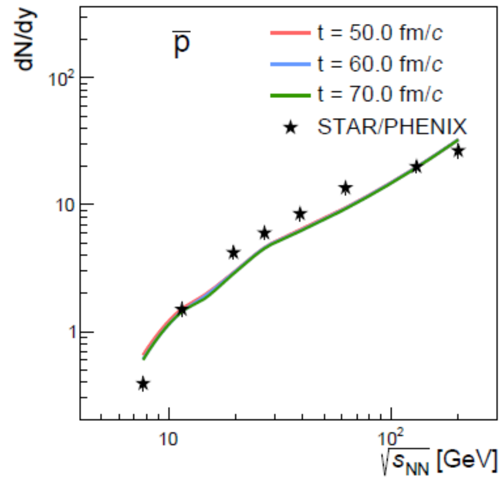
$$t = t_0 \cosh(y)$$

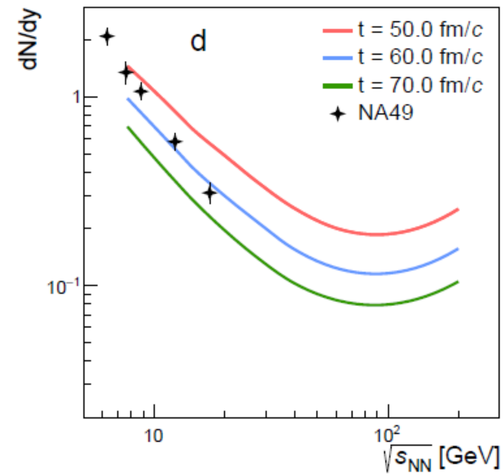
where t_0 is the time selected as a best description of the cluster multiplicity at y=0

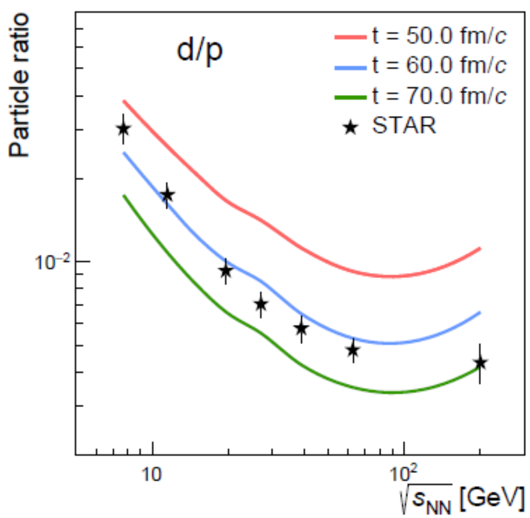


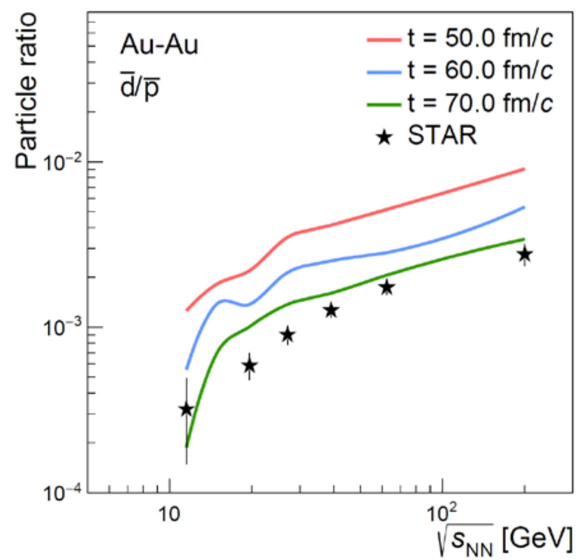
Excitation function of multiplicity of $p, \bar{p}, d, \bar{d}$











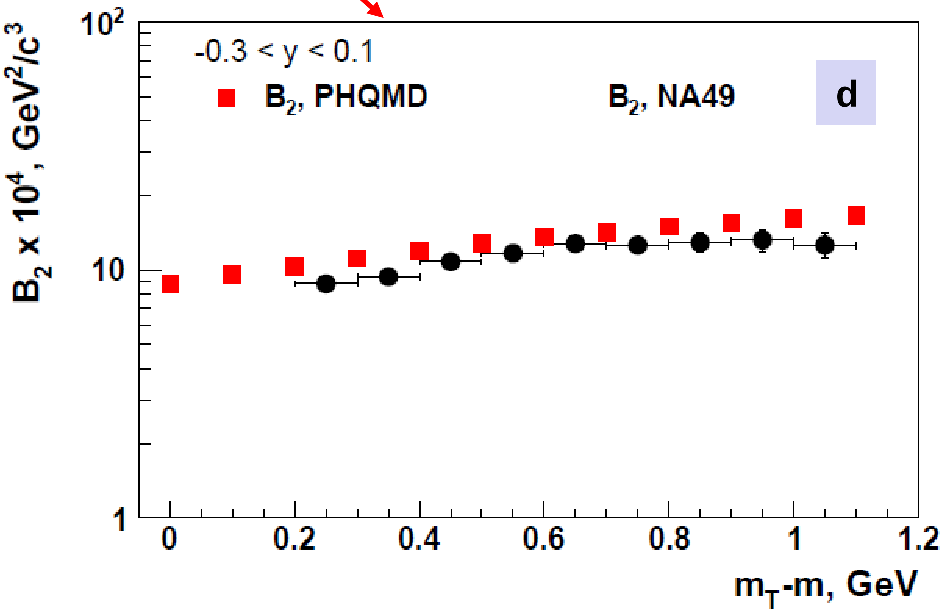
The p, $\bar{p}$ yields at y~0 are stable, the d, $\bar{d}$ yields are better described at *t= 60-70* fm/c

Coalescence parameter B_2 for deutrons

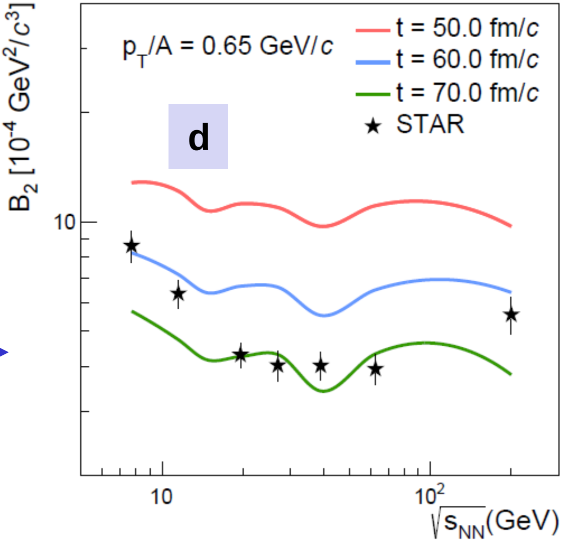
Coalescence parameter B_2:

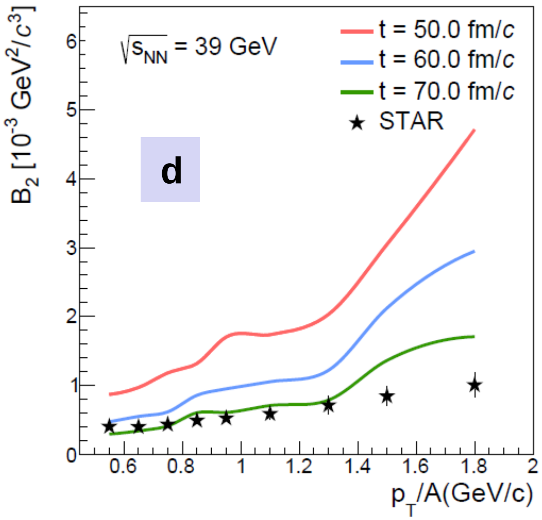
$$B_2 = \frac{E_d \frac{d^3 N_d}{d^3 P_d}}{\left(E_p \frac{d^3 N_p}{d^3 p_p}|_{p_p = P_d/2}\right)^2}$$

Comparison of the PHQMD results with NA49 and STAR data



central Au+Au collisions





Summary

The PHQMD is a microscopic n-body transport approach for the description of heavy-ion dynamics and cluster formation
Clusters are identified by Minimum Spanning Tree model

combined model PHQMD = (PHSD & QMD) & (MST | SACA)

PHQMD

- provides the good description of hadronic 'bulk' observables from SIS to RHIC energies

- predicts the dynamical formation of clusters from low to ultra-relativistic energies due to the interactions

- allows to study the origin as well as the properties of cluster formation (rapidity and p_T spectra)

- allows to study the formation of hypernuclei originated from ΛN interactions