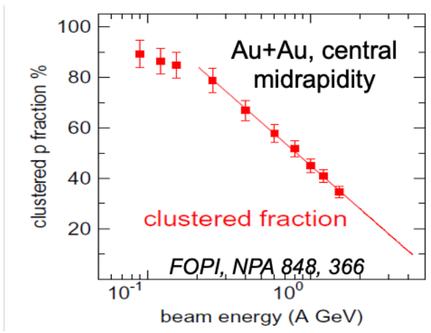
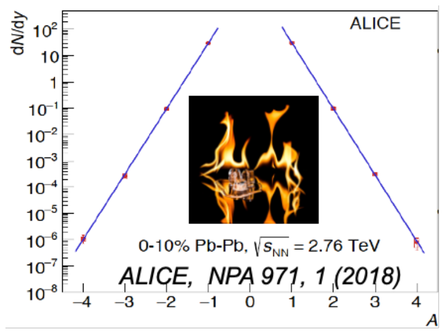
Nuclei dynamics in the heavy ion collisions «Ice in a fire» puzzle solved?

V. Kireyeu for the PHQMD team

1. The puzzle: how the weakly bound objects can be formed and survive in a hot environment?





2. Modelling of cluster formation in HIC

Statistical models: production of nuclei depending on T and μ_B at chemical freeze-out & particle mass

Coalescence models: formation of nuclei by nucleons & hyperons that are close in coordinate and momentum spaces at freeze-out time

No **dynamical cluster formation during time evolution!**

No information on the dynamics of clusters formation & microscopic origin!

Solution: transport models — **dynamical cluster formation** based on interactions.

3. QMD vs Mean Field

Cluster formation is sensitive to nucleon dynamics

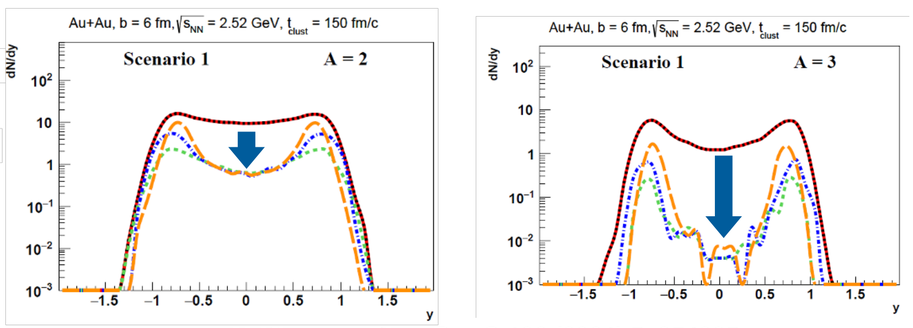
> it's important to keep the nucleon correlations by realistic nucleon-nucleon interactions in transport models:

- **QMD** (quantum-molecular dynamics) – allows to keep correlations, **full nucleon-nucleon force -> cluster get stable**
- **MF** (mean-field based models) – correlations are smeared out, **(full nucleon-nucleon force)/N** which cannot keep the cluster together **-> at large time no clusters anymore**
- **Cascade** – no correlations by potential interactions

QMD: PHQMD + psMST

MF: PHSD + psMST

Cascade: SMASH + psMST, UrQMD + psMST



V. Kireyeu, Phys.Rev.C 103 (2021) 5, 054905

4. How to make or find clusters?

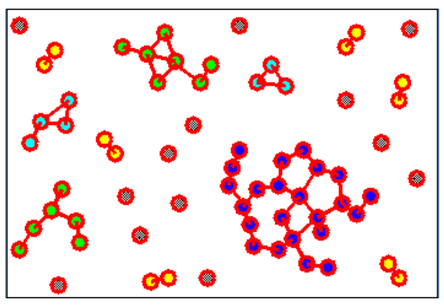
Minimum Spanning Tree

Algorithm: search for accumulations of particles in coordinate space

1. Two particles i & j are bound if:

$$|r_i - r_j| < 4.0 \text{ fm}$$

2. Particle is bound to cluster if bound with at least one particle of cluster



Coalescence (for deuterons)

- Calculations are performed at the **«freeze-out»**.
- The relative momentum ΔP and distance ΔR between the proton and the neutron are calculated in the p-n CM frame.
- If ΔP < 0.285 GeV and ΔR < 3.575 fm, a deuteron may be formed with the probability Pd = 3/8 (the spin-isospin combinatorial factor).

«psMST» library: **MST and coalescence** for any model!

V. Kireyeu, Phys.Rev.C 103 (2021) 5, 054905

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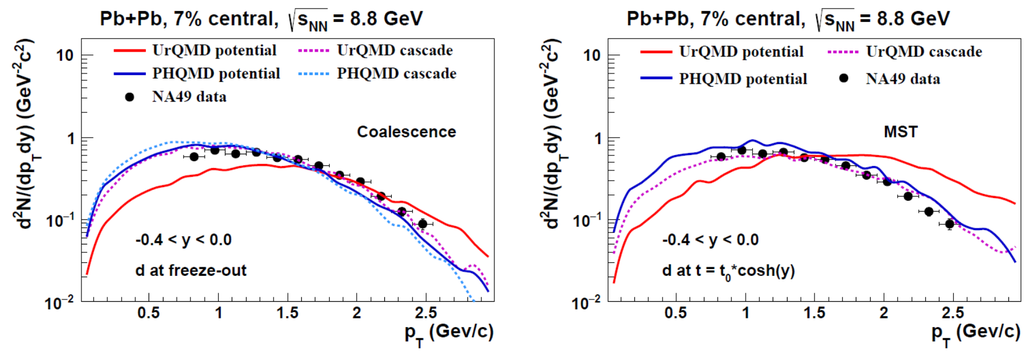
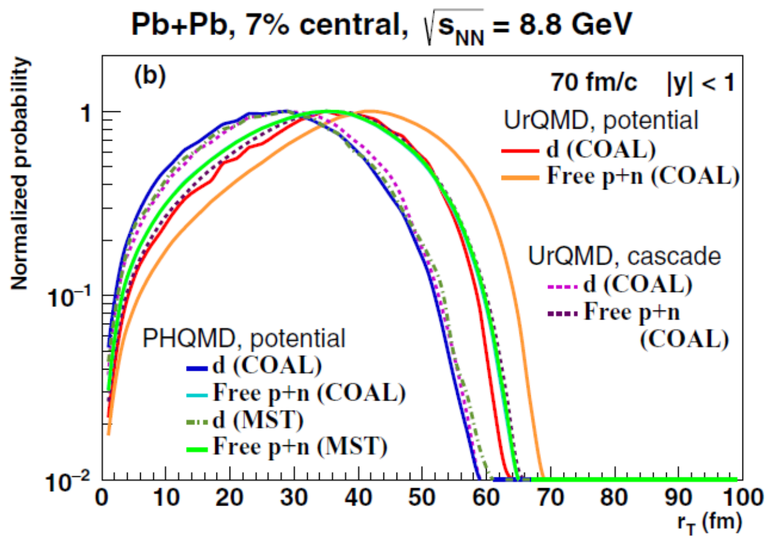
5. Coalescence and MST: the unexpected similarity



- **Coalescence and MST** give very similar multiplicities and y and pT distributions
- PHQMD and UrQMD results in the cascade mode are very similar
- Deuteron production is sensitive to the realisation of potential in transport approaches



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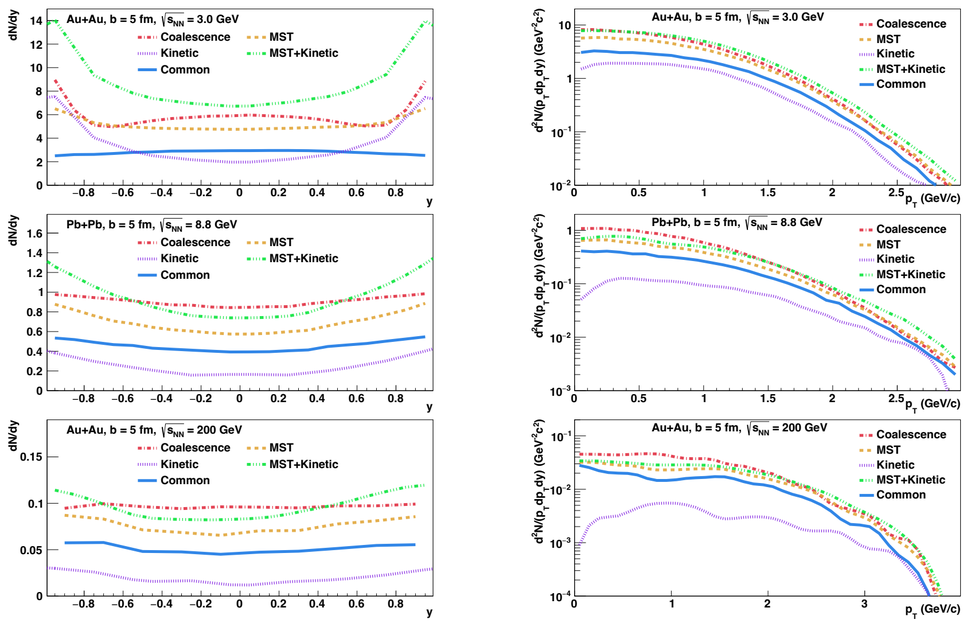
Coalescence as well as the MST procedure show that the **deuterons remain in transverse direction closer to the center** of the heavy-ion collision than free nucleons. **Deuterons are behind** the fast nucleons.

«Ice in a fire» puzzle solved?

6. Can we identify the mechanism experimentally?



V. Kireyeu et. al, arxiv:2304.12019

- **At mid-rapidity only ~50%** of coalescence deuterons (at freeze-out) are found by MST.
- **Rapidity distribution** has a different shape.
- **Transverse momentum** distributions has different slope at low p_T

Summary

- A detailed analysis reveals that **stable 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.**
- PHQMD and UrQMD give very **similar coalescence and MST distributions of deuterons.**
- Shape of y-and p_T- distributions depends on a **production mechanism → possibility to distinguish between production mechanisms experimentally!**