# On the newly formed nuclei at the NICA energies and how to find their origin

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## 1. Why to study the cluster formation?

- **Probing QGP Dynamics:** Heavy-ion collisions create the quark-gluon plasma (QGP), a state of matter where quarks and gluons are deconfined. Studying cluster formation helps understand how this plasma cools and transitions back into hadrons and light nuclei.
- **Exploring nuclear matter Equation of State (EoS):** The production of clusters provides data to constrain the equation of state of nuclear matter at high temperatures and densities, which is key to understanding phase transitions in QCD.
- **Stellar Nucleosynthesis:** The formation of light nuclei in heavy-ion collisions mimics processes that occur in stellar environments and supernovae. This provides valuable data for understanding nucleosynthesis in stars and the early universe.
- **Baryon Correlations:** Clusters are formed from correlated baryons. The study of cluster yields provides insights into the spatial and momentum correlations among baryons at the hadronization stage, offering a window into the evolution of the QGP.
- **Sensitivity to the Critical Point:** Clusters are particularly sensitive to the critical point: a) their production depends on local baryon density, which is strongly influenced by critical fluctuations; b) they form in the later stages of the collision, making them good probes of the freeze-out conditions where critical phenomena might manifest.
- **And more …**

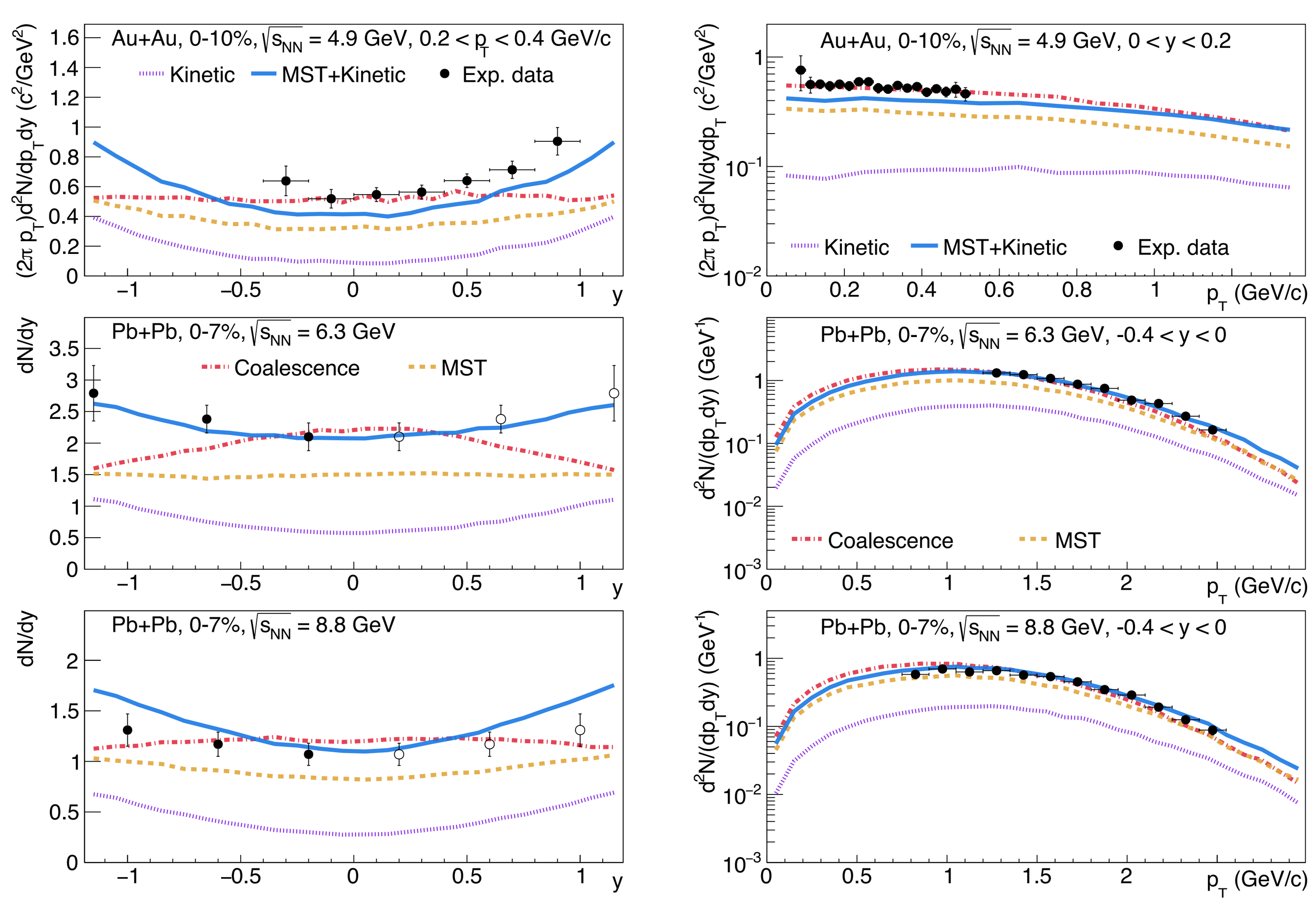
## 2. Mechanisms of the cluster formation in HIC

### No consensus on the mechanism of the cluster formation in HIC!

- **Coalescence:** All clusters are formed during kinetic **freeze-out**, occurring after the hadronic expansion phase. If the neighbouring nucleons with the appropriate charge are found within the coalescence radius in both coordinate and momentum space, these nucleons are deemed to form a deuteron or part of a light cluster. The coalescence radii are determined through fitting experimental multiplicities.
- **Kinetic mechanism:** Light clusters, such as deuterons, can be generated through inelastic reactions involving hadrons, such as NNπ → dπ and NNN → dN, where a pion or a nucleon acts as a 'catalyst' during the hadronic phase of heavy-ion collisions.
- **Potential mechanism:** The potential interaction among nucleons in the hadronic phase gives rise to bound clusters of various sizes, and their multiplicity is contingent upon the specifics of the expansion of the hot interaction zone and its composition. The **potential mechanism** for cluster formation focuses on the role of attractive nuclear forces that bind nucleons together to **form clusters dynamically** during the evolution of the heavy ion collision.

**Parton-Hadron-Quantum-Molecular Dynamics (PHQMD)** is the only one unique transport approach on the market which combine all three mechanisms of the clusters formation and three different nuclear matter equations of state: 'soft', 'hard' and 'soft momentum dependent'.

## 3. Identify mechanism with bulk observables

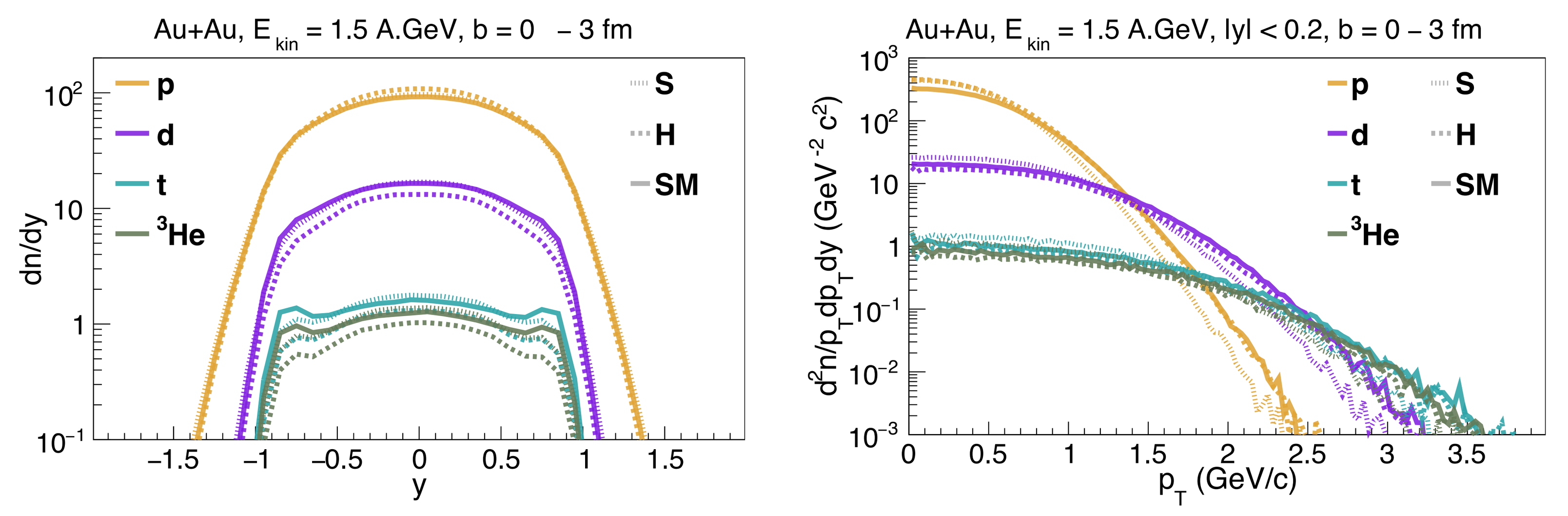



*V. Kireyeu* et al Phys.Rev.C 109, 044906 (2024)

- **Rapidity distribution** has a different shape.
- **Transverse momentum** distributions has different slope at low $p_T$

**Low $p_T$ data are needed — possible contribution from NICA/MPD!**

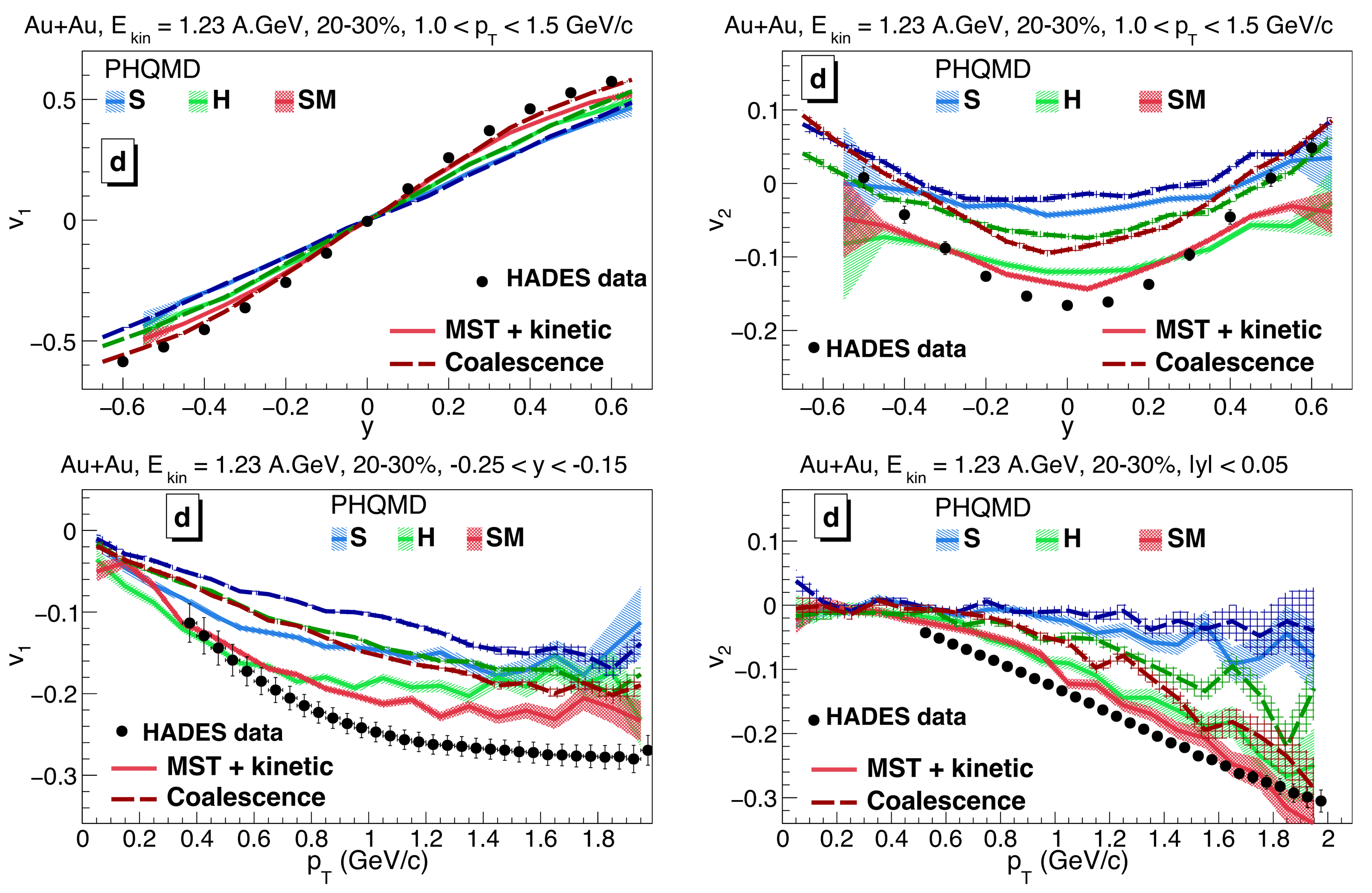
## 4. Identify EoS with cluster observables




- **Lower multiplicity for the 'hard' EoS** is also visible for larger clusters: S and SM produce around 30% more A = 3 clusters than H.
- The **S EoS** leads to much **softer transverse momentum spectra** of protons and light clusters compared with the SM EoS and H EoS.

### HADES data insights

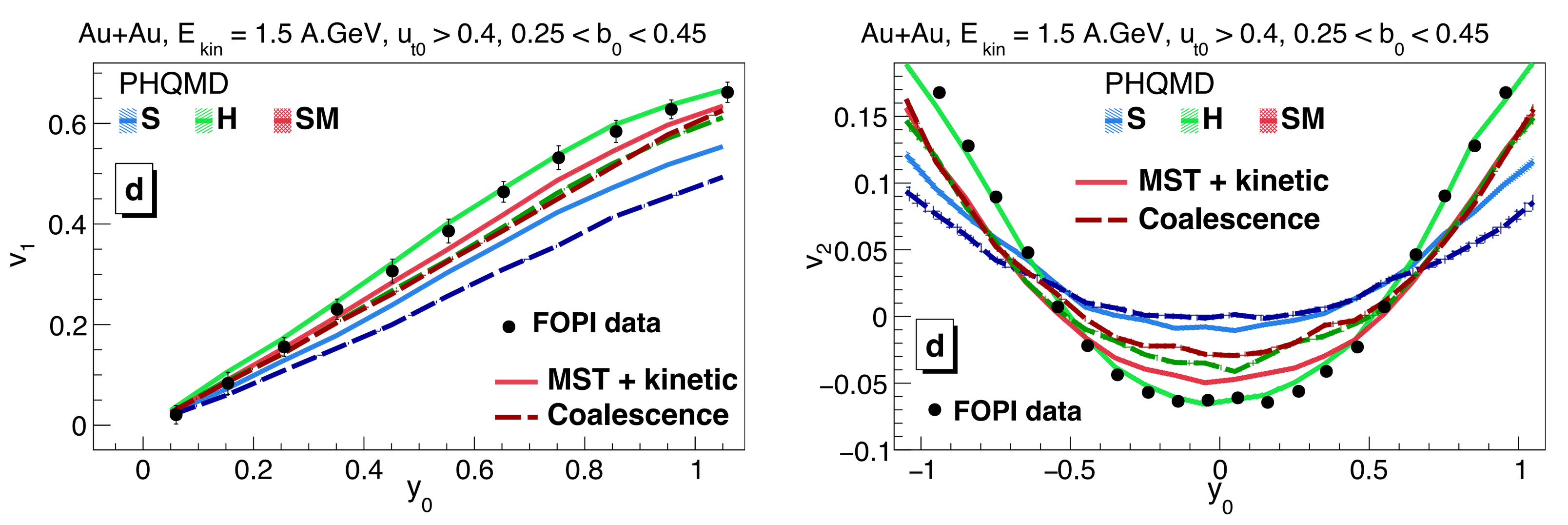
Phys. Rev. Lett. 125, 262301 (2020)




- **Strong EoS dependence!**
- **HADES data favour a soft momentum dependent potential (SM).**
- **v1 and v2 are sensitive to the cluster production mechanism.**

### FOPI data insights

Nucl. Phys. A 876, 1 (2012)




- **FOPI data** favour a **hard** or **soft momentum dependent** potential.
- **v1 and v2 are sensitive to the cluster production mechanism.**

## Summary

- The PHQMD calculations confirm that the **EoS has a strong influence on** the rapidity and on the transverse momentum dependence of **v1 and v2 of protons and light clusters** created in heavy-ion collisions at SIS energies.
- The comparison of the PHQMD calculations with a S, H and SM EoS shows that the **best description** of the experimental proton data on v1,v2 at SIS energies is obtained by calculations **with the soft momentum-dependent** interaction. For light clusters calculations with a SM and a H EoS provide quite similar results.
- The **soft static EOS** with a compression modulus of K = 200 MeV **is not supported** by the FOPI and HADES experimental data.
- Deuterons formed by **potential and kinetic** mechanisms have **other v1 and v2 coefficients than** that produced by **coalescence**. The difference is sufficiently large that it may help to identify the cluster production mechanism realised in nature.
- **The NICA experiments may help the theory** with the new precise measurements in the low $p_T$ region to finally identify the mechanism of the cluster production.

*New paper!*

***V. Kireyeu*** *et al «Constraints on the equation-of-state from low energy heavy-ion collisions within the PHQMD microscopic approach with momentum-dependent potential» arXiv:2411.04969*