Baryon clustering near a (hypothetical) QCD critical point

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Motivation

We propose new effects in heavy-ion collisions at the Beam Energy Scan (BES) of the Relativistic Heavy-Ion Collider which can signal the presence of a possible QCD critical point at a particular collision energy.

We focus on nucleon-nucleon (NN) interaction: at distances ~1 fm is mediated by the σ critical mode.

Nuclear forces appear as a strong cancellation of repulsion and attraction in the mean potential energy, and Fermi energy, producing binding energies of few MeV in infinite nuclear matter.

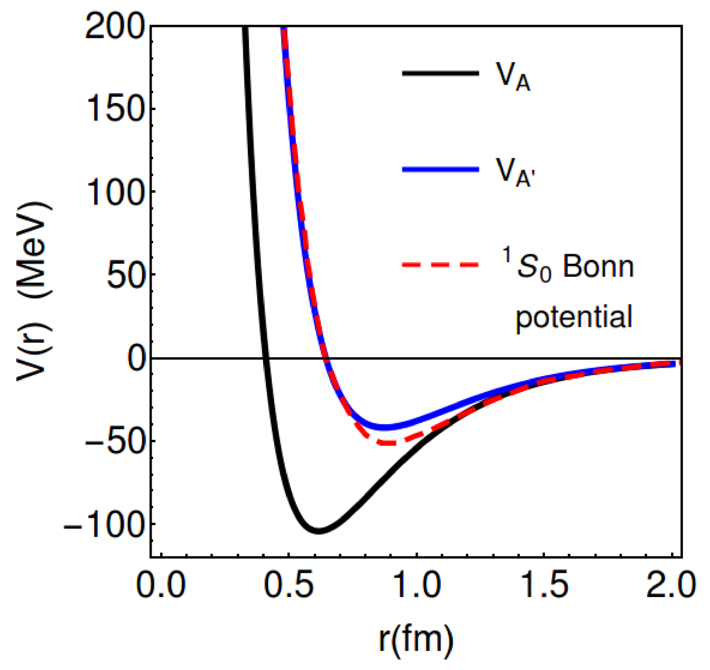
Walecka-Serot potential between nucleons:

$$V_A(r) = -\frac{g_\sigma^2}{4\pi r}e^{-m_\sigma r} + \frac{g_\omega^2}{4\pi r}e^{-m_\omega r} \; ; \qquad g_\sigma^2 = 267.1\left(\frac{m_\sigma^2}{m_N^2}\right) \; , \quad g_\omega^2 = 195.9\left(\frac{m_\omega^2}{m_N^2}\right)$$

Beyond mean field, the ω strength is increased to reduce the potential depth and make it closer to the phenomenological NN Bonn potential.

The shallow potential classically bounds few-nucleons close to T=0 (see Result 1). It can also reproduce binding energies of bulk nuclear matter in a semiclassical approach (see Ref. [1]).

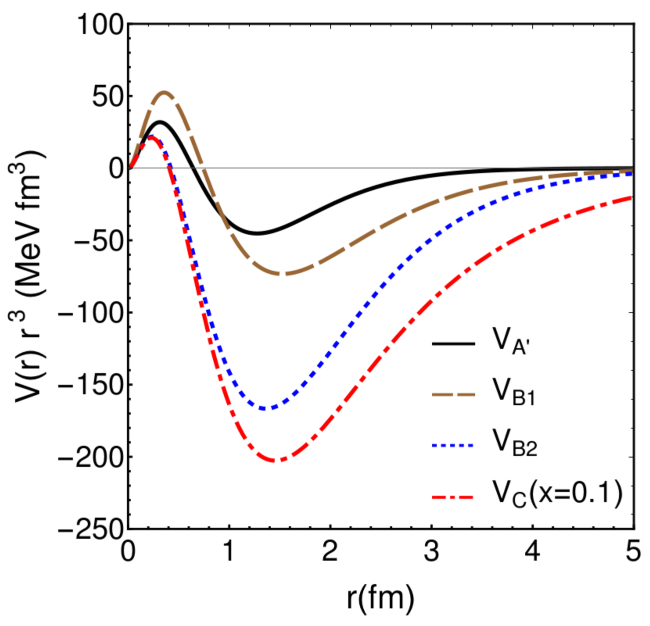
Close to the critical point T_c~100 MeV, this potential is unable to bind nucleons. However, modifications due to the σ mode strongly affects the NN interaction (see Method).



Method

We consider several NN potentials with increasing degree of criticality (due to decrease of σ mass close to T_c):

$$\begin{aligned}
V_{A'}(r) &: V_A(r) \text{ with } g_\omega^2 \to 1.4 g_\omega^2 \\
V_{B_1}(r) &: V_{A'}(r) \text{ with } m_\sigma^2 \to \frac{m_\sigma^2}{2}, g_\sigma^2 \to 2g_\sigma^2 \\
V_{B_2}(r) &: V_{A'}(r) \text{ with } m_\sigma^2 \to \frac{m_\sigma^2}{2} \\
V_C(r;x) &: (1-x)V_{B_2}(r) + x\left[V_{A'}(r) \text{ with } m_\sigma^2 \to \frac{m_\sigma^2}{6}\right]
\end{aligned}$$



These potentials are implemented into a classical molecular dynamics with thermal noise.
We extract physical properties from phase space distribution.
Quantum effects are neglected at T~100 MeV, but needed for cold nuclear matter (see [1]).

Molecular Dynamics + Langevin Equation

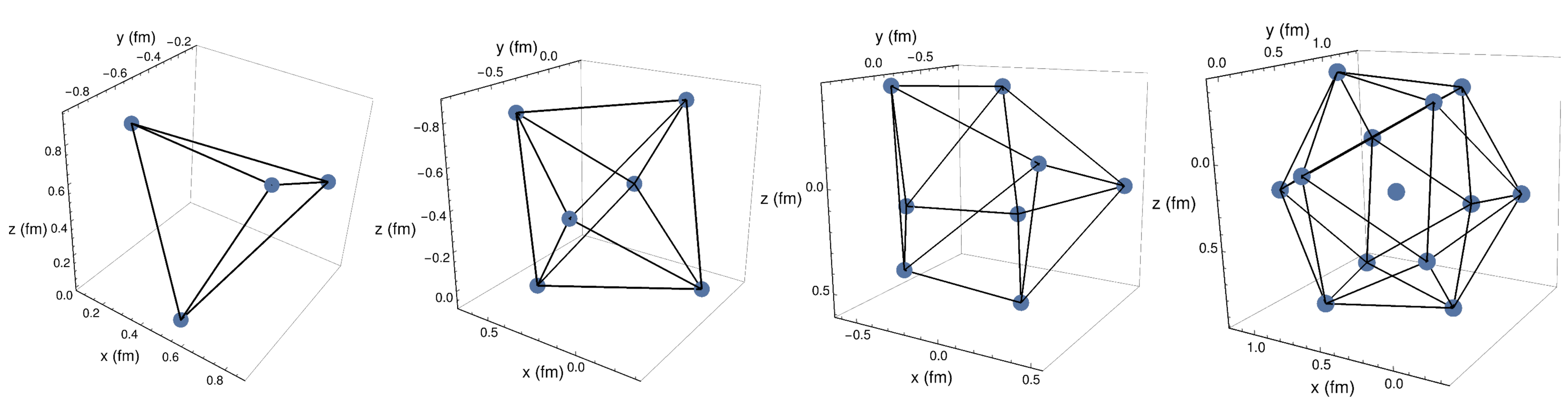
$$\begin{cases}
\frac{d\mathbf{x}_i}{dt} = \frac{\mathbf{p}_i}{m_N} \\
\frac{d\mathbf{p}_i}{dt} = -\sum_{j\neq i}\frac{\partial V(|\mathbf{x}_i - \mathbf{x}_j|)}{\partial \mathbf{x}_i} - \lambda \mathbf{p}_i + \boldsymbol{\xi}_i
\end{cases}
\qquad
\begin{aligned}
\langle \boldsymbol{\xi}_i(t)\rangle &= 0 \\
\langle \xi_i^a(t)\xi_j^b(t')\rangle &= 2T\lambda m_N \delta^{ab}\delta_{ij}\delta(t-t')
\end{aligned}$$

T is fixed by fast particles (pions, kaons), while nucleon dynamics is dominated by the pairwise potential.
Baryon diffusion constant λ is taken from URASiMA simulations.

We stress the importance of **correlations** between nucleons for binding and eventual clustering (Boltzmann's *Stosszahlansatz* is not enough to describe this phenomenon).

Result 1: Small-size clusters at low T

Molecular dynamics + Langevin with $V_{A'}$ potential at T=10^{-3} MeV with N=4, 6, 8 and 13 nucleons



Spatial configurations and binding energies checked against direct minimization of the potential.

Resulting geometries coincide with Platonic solids except for N=8 (as known for Lennard-Jones potential).

References

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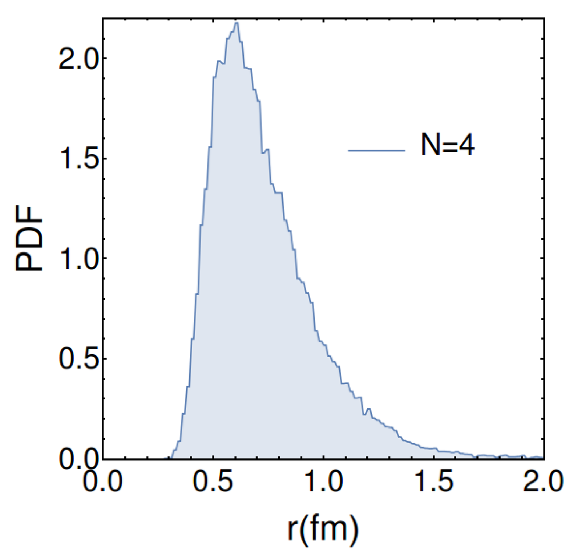
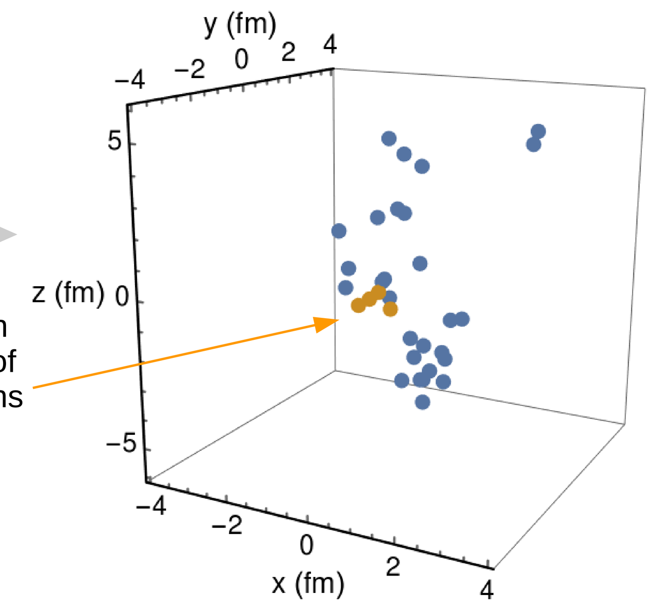
Result 2: Few-nucleon clustering: light nuclei production

For freeze-out conditions at BES the potential $V_{A'}$ cannot produce clustering of nucleons.
However, V_C is able to form clusters (e.g. He-4) at temperatures T~100 MeV within a few Fermi/c.



PDF of distances between nucleons at T=120 MeV for N=4.
At T=0, a Dirac delta sits at the minimum of the potential.

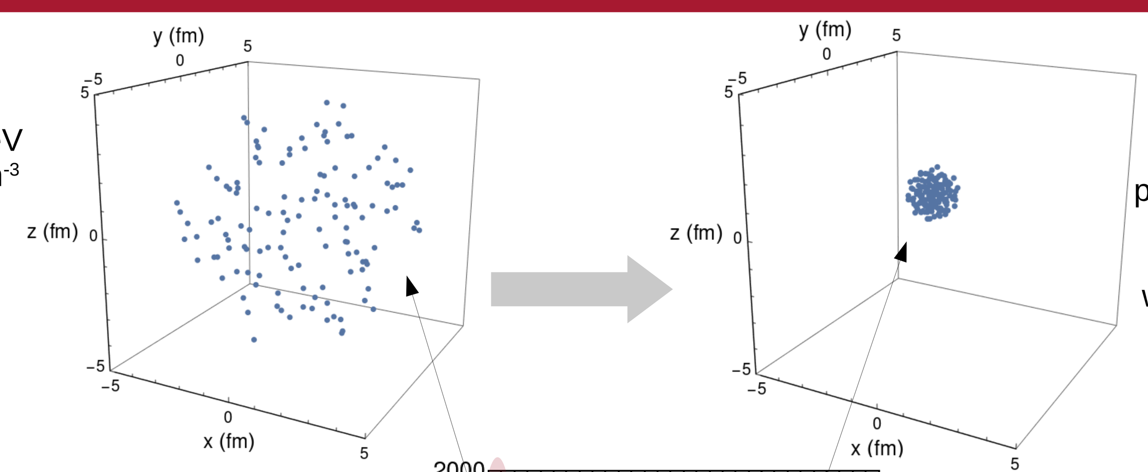
PDF is used to define an identification procedure of N=4 clusters in simulations with more nucleons



Simulation with N=32, T=120 MeV, Δt=5 fm/c

Result 3: Big clusters close to critical transition

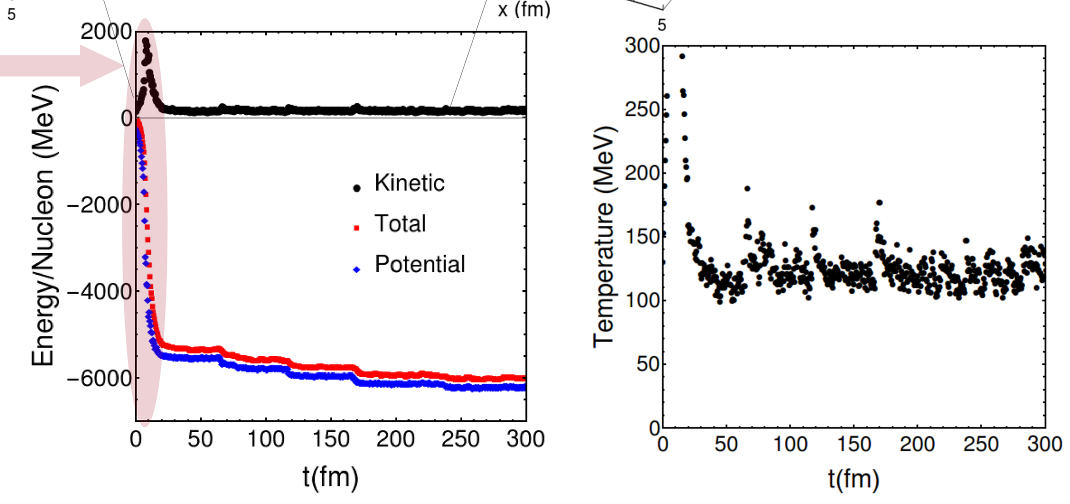
N=128
T=120 MeV
n=0.16 fm^{-3}



At long times all particles eventually fall into a big cluster (except for outliers with high momentum)

Medium at BES only has a few Fermi/c to interact. We can expect few-nucleon partially-bound systems (see Result 2)

Signatures on cumulants/moments of (net-)proton distribution at freeze-out?

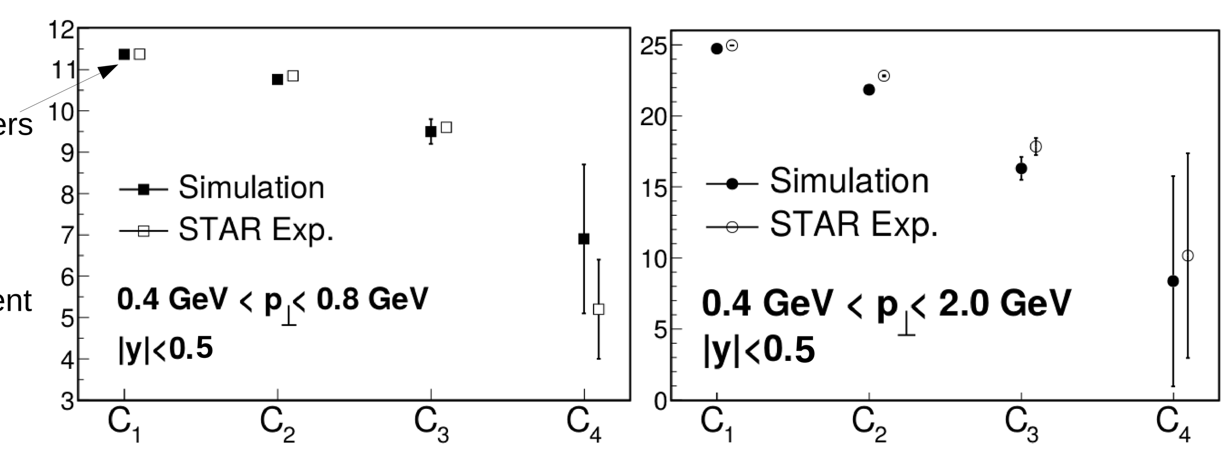


Result 4: Effect on kurtosis

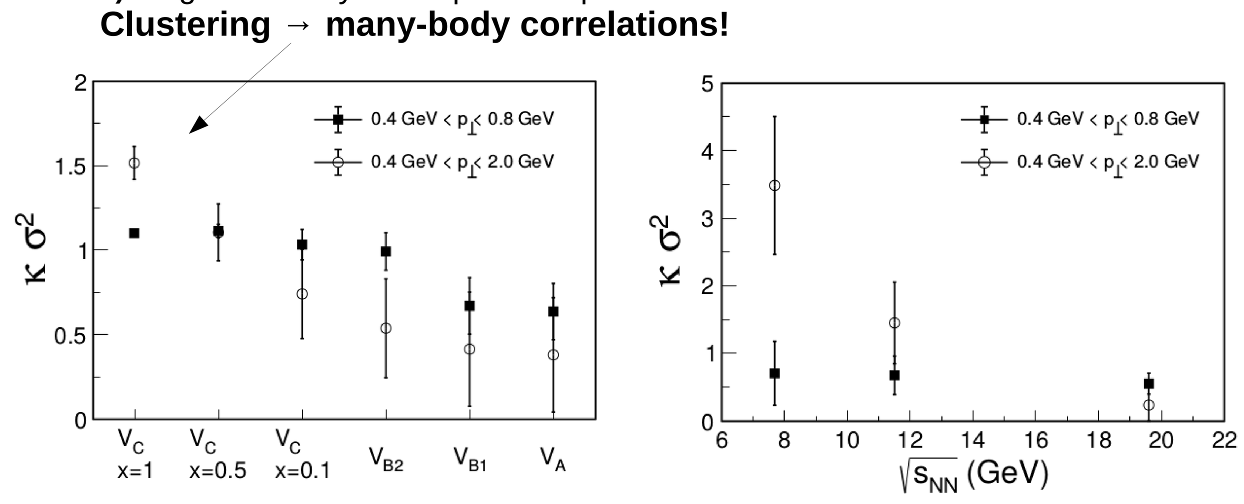
1) With freeze-out experimental conditions, we run N_{ev}=10^5 simulations with N=32 particles in a non-expanding frame during Δt=5 fm/c. A final boost matches *y* and p_T distributions.
A system with noncritical $V_{A'}$ is calibrated to $s^{1/2}_{NN}$=19.6 GeV (close to Poisson expectations).
We cannot simulate larger energies due to the absence of antiprotons.

2) We rescale our numbers to fix average number of protons in one cut.

Other proton cumulants match well with experiment for both cuts.



3) Larger criticality of NN potential produce an increase of kurtosis.
Clustering → many-body correlations!



STAR data. Two cuts:

0.4 GeV < p_T < 0.8 GeV
|y| < 0.5
(from Ref. [3])

0.4 GeV < p_T < 2 GeV
|y| < 0.5
(from Ref. [4], STAR preliminary)

Conclusions

1) NN potential is very sensitive to the QCD critical mode σ.

2) Usual potentials for infinite nuclear matter are not able to produce binding around T~100 MeV.

3) NN potential reflecting σ-mass suppression close to T_c allows for substantial nuclear clustering.

4) In HICs, finite duration and radial expansion prevent big agglomeration, but small clusters can be formed.

ENHANCED LIGHT ION PRODUCTION IN BES CLOSE TO CRITICAL POINT

5) Clustering induces NN correlations producing an enhancement of kurtosis close to T_c.

INCREASE OF KURTOSIS SIGNALS CRITICAL REGION DUE TO CLUSTERING

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