THE UNIVERSITY OF TENNESSEE KNOXVILLE

Exploring the Feasibility of Imaging Atomic Nuclei at the Electron-Ion Collider

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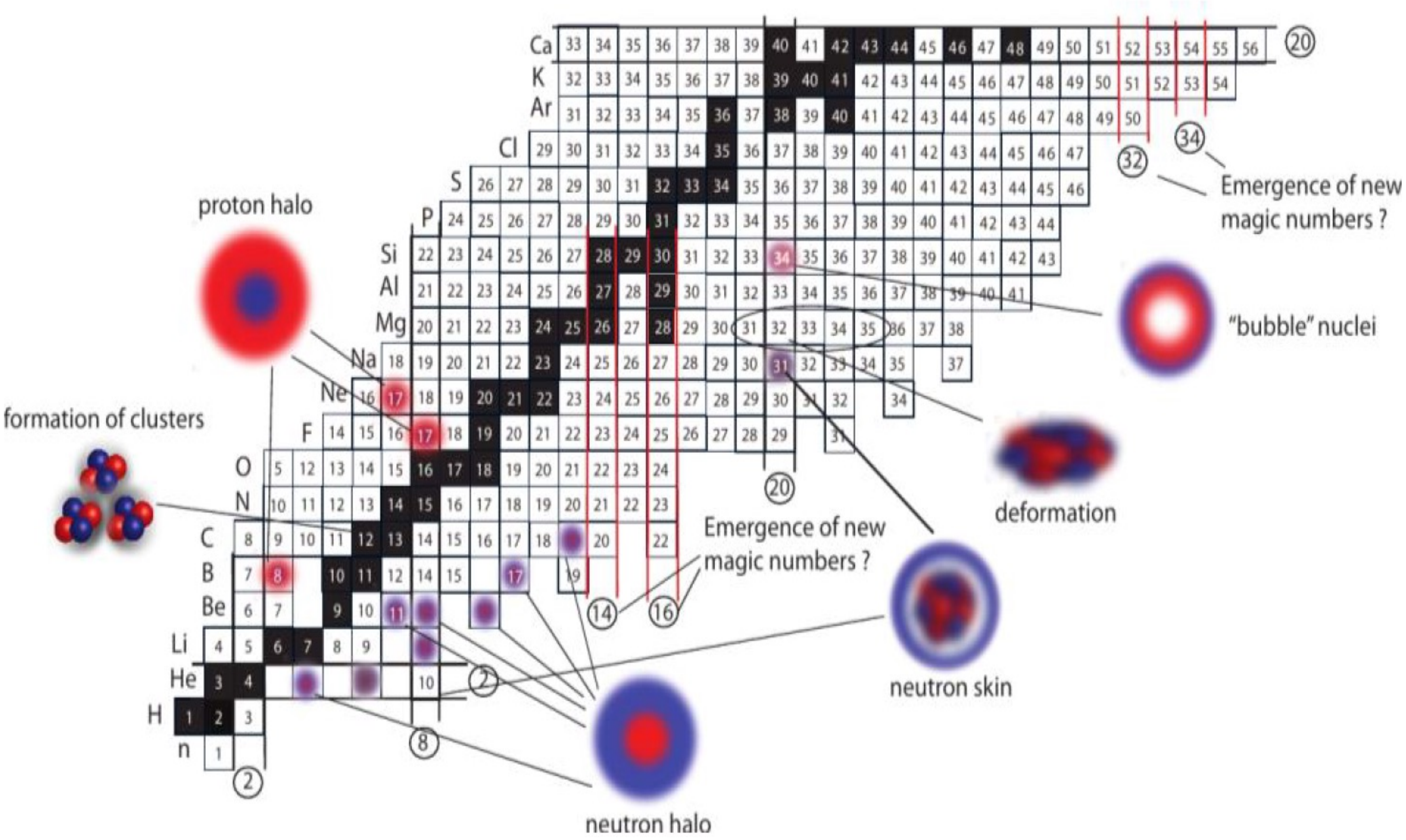
❖ Motivation

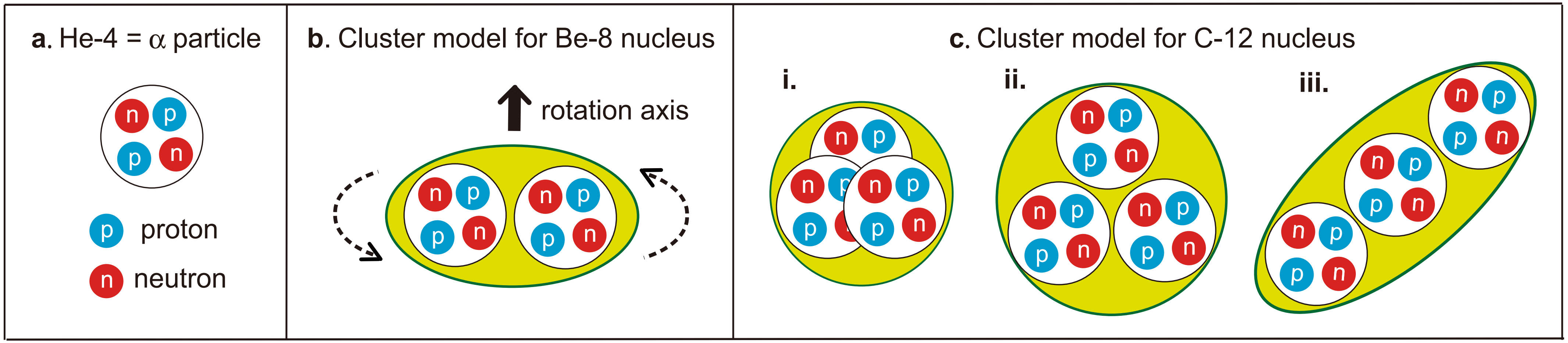
- ➢ The rich structure of atomic nuclei:
  - ✓ Clustering, halo, skin …
  - ✓ Quadrupole/octupole/hexdecopole deformations



❖ Motivation

The atomic nuclei carry non-trivial shapes and structures beyond the simple spherical Woods-Saxon distribution. For instance, it has been suggested that the wave functions of light nuclei, such as ^{12}C, contain alpha clustering. In such a scenario, the nucleus appears more like three α particles rather than six protons and six neutrons behaving independently.

Nature Communications, 13, 2234 (2022)



Such effects are essential for understanding the nuclear structure and can serve as a background estimate for other studies (e.g., the nuclear short-range correlation studies**).

** *Lei Shen, Bo-Song Huang, and Yu-Gang Ma*
Phys.Rev.C 105 (2022) 1, 014603

❖ Motivation

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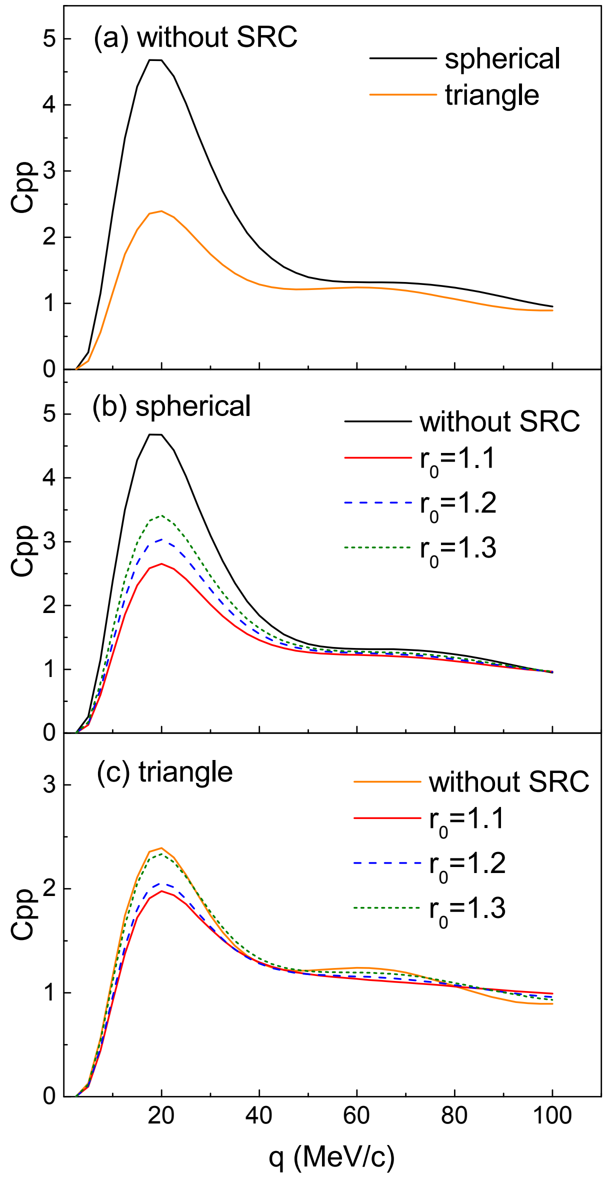


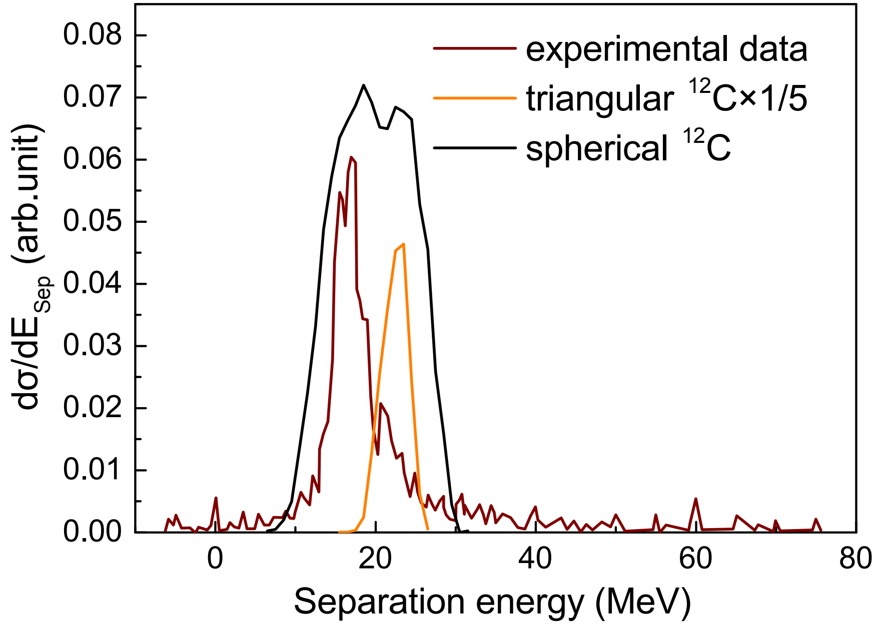


FIG. 3: Separation energy distribution of $^{12}C(p,2p)^{11}B$ at 250 MeV. The experimental data is plotted by the dashed line, while the spherical and triangle distribution simulations are shown by dark and orange lines, respectively.

Fetoscopy measurements can be sensitive to SRC and clustering.

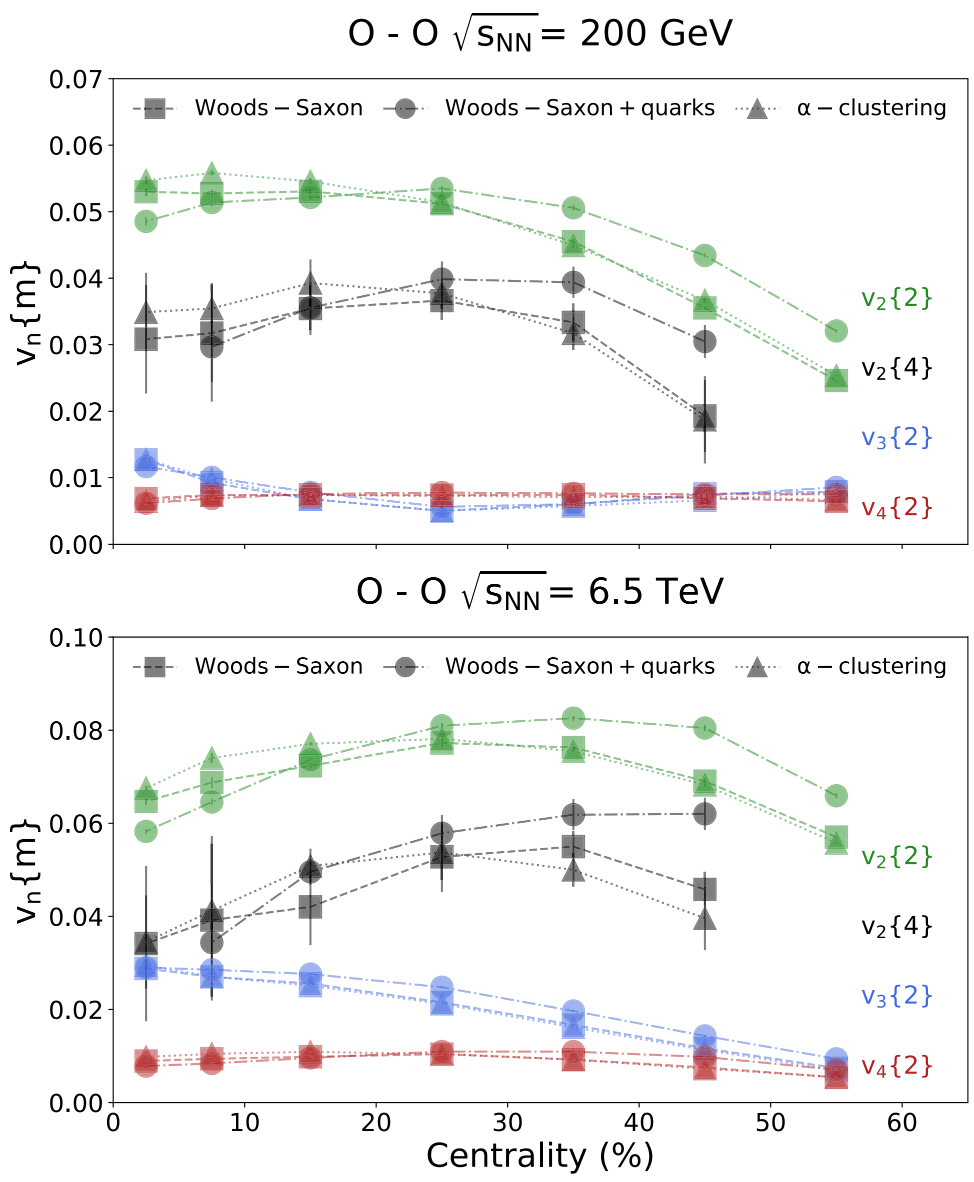
❖ Motivation

In heavy-ion collisions;

➢ No difference was observed between Woods-Saxon and α clustering

Clustering in heavy-ion collisions is too complicated to be measured.

Phys.Rev.C 104 (2021) 4, L041901



❖ Motivation

Our study goals can be summarized as:

(1) Can the EIC detectors (ePIC and 2nd detector) differentiate between different geometries, such as spherical ^{12}C versus a triple-alpha cluster configuration of ^{12}C?

(2) How can the nuclear structure impact other EIC e+A physics programs?

To reach the project goals, we executed our plan in the following order:

(1) Identifying the EIC model simulations that can be used to study the alpha clustering in light nuclei.
- ✓ The BeAGLE model

(2) Modifying the EIC model simulations with initial nuclear configurations, which include alpha clustering.
- ✓ The nuclear shape and structure picture have been into the BeAGLE model

(3) Identify the physics observables that can be used in such work.
- ✓ Several observables have been introduced (e.g., mean energy observable)

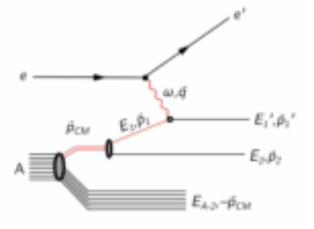
(4) Identify the study cavities that will need further investigation.

The BeAGLE model

Wan Chang et al., PRD 106, 012007 (2022)

❖ The BeAGLE model:

Wan Chang et al., PRD 106, 012007 (2022)



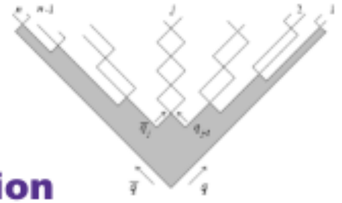
Primary interaction

Primary interaction treated by **PYTHIA6** for the hard collision.

Glauber handled by BeAGLE

PyQM: Nuclear Geometry + optional gluon radiation in medium.

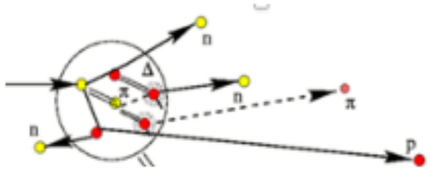
Hadronization handled by **PYTHIA6.**



Hadronization

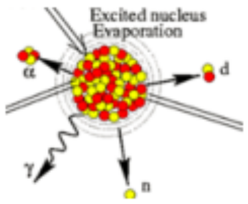
Cascade process handled by **DPMJET.**

Formation time. Stochastic.



Intra-nuclear cascade

Nuclear remnant evaporation and break up by **FLUKA.**



Nuclear remnant evaporation & breakup

Some Nuclear Effects

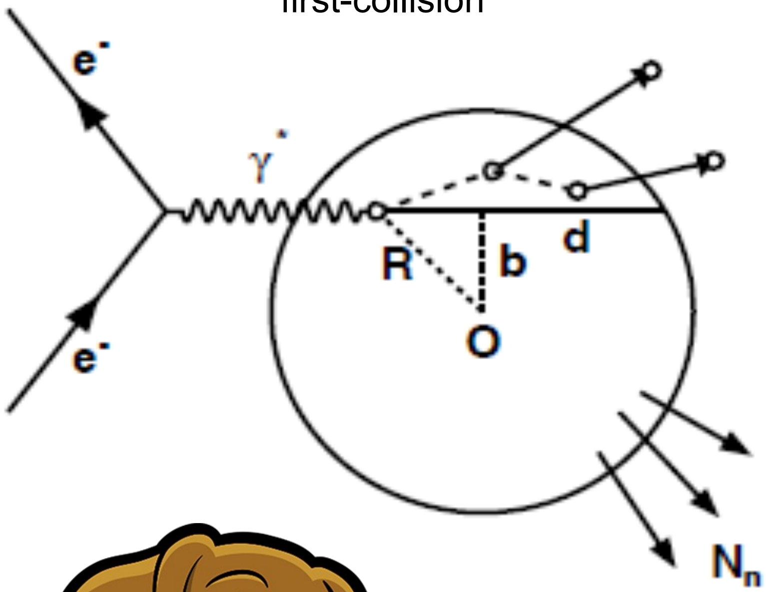
	In BeAGLE
• Parton distribution functions	✓
• Parton saturation (CGC etc.)	
• Short-range correlations	✓ (GCF)
• "Fermi motion"	✓
• Partonic (or "dipole") MS	✓
• Partonic gluon radiation	✓
• Medium-modified hadronization	
• Formation times	✓
• Hadronic Cascade	✓
• Nuclear evaporation, breakup	✓
• Photonic de-excitation of A*	✓

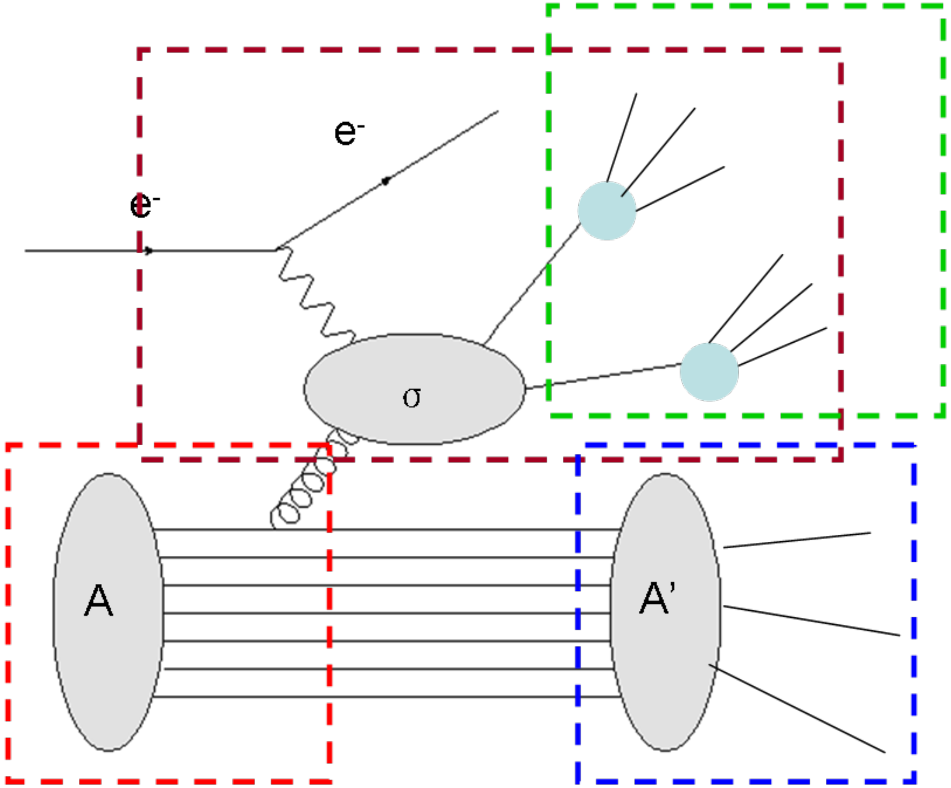
❖ The BeAGLE model:

Wan Chang et al., PRD 106, 012007 (2022)

$$d \equiv \int dz\, \rho/\rho_0$$

from $Z_{\text{first-collision}} \rightarrow \infty$





A hybrid model consisting of DPMJet and PYTHIA with nPDF EPS09.

Nuclear geometry by DPMJet and nPDF provided by EPS09.

Parton level interaction and jet fragmentation completed in PYTHIA.

Nuclear evaporation (gamma dexcitation/nuclear fission/fermi break up) treated by DPMJet

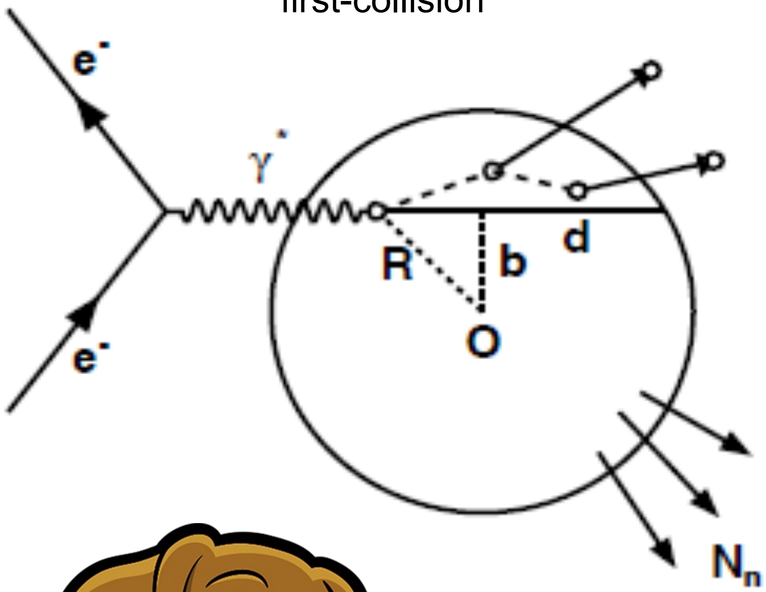
Energy loss effect from routine by Salgado&Wiedemann to simulate the nuclear fragmentation effect in cold nuclear matter

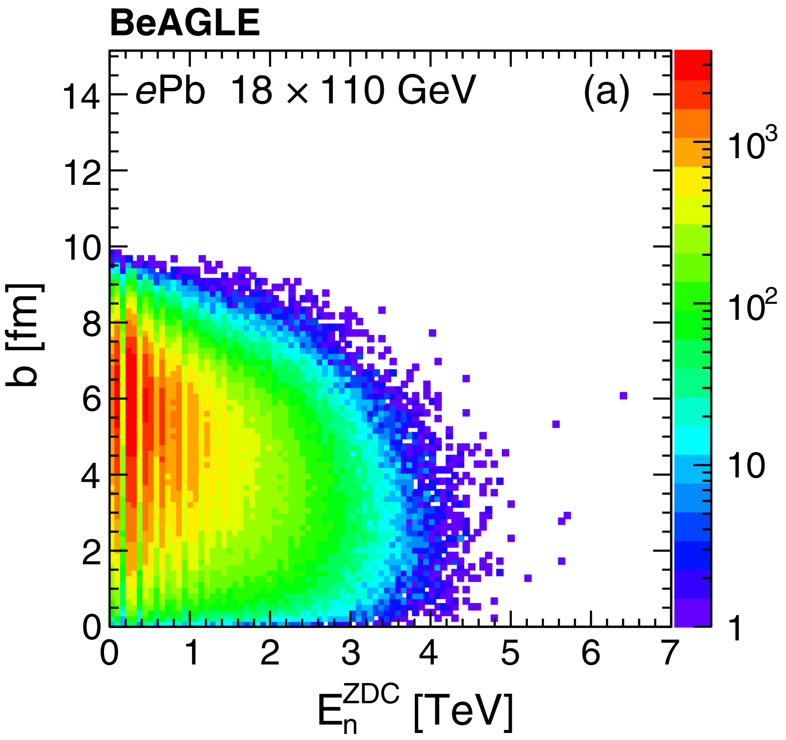
❖ The BeAGLE model:

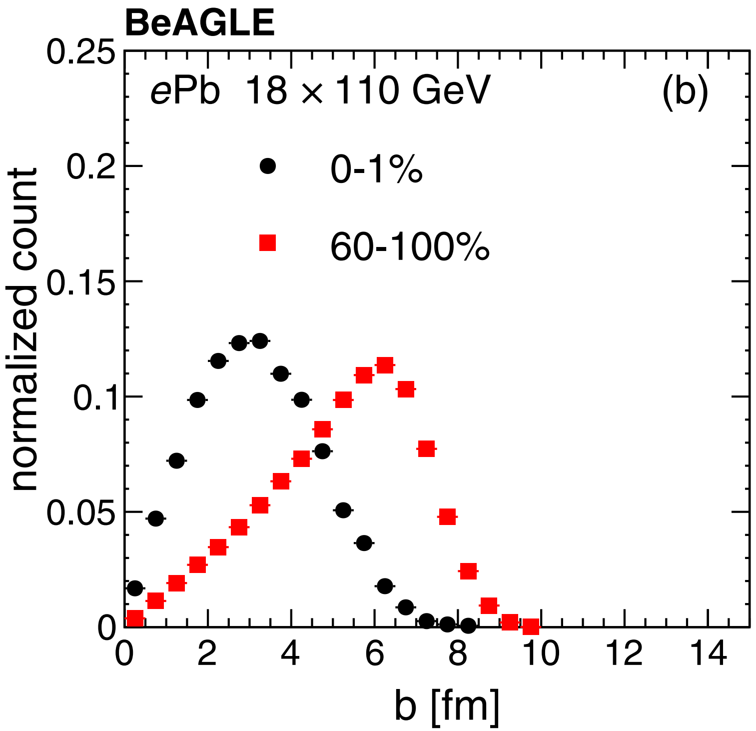
$d \equiv \int dz\ \rho/\rho_0$

from $Z_{\text{first-collision}} \rightarrow \infty$

Wan Chang et al., PRD 106, 012007 (2022)







Neutrons in ZDC can be used for centrality definition?

❖ The α clustering

Modifying the EIC model simulations with initial nuclear configurations, which include alpha clustering.

✓ The nuclear shape and structure picture have been into the BeAGLE model

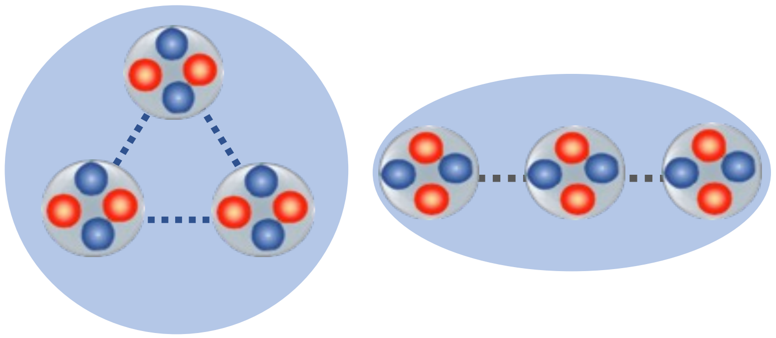
The α clustering implementation:

In ${}^{9}_{4}Be$, ${}^{12}_{6}C$, and ${}^{16}_{8}O$ we include the α clustering as:

✓ Chose the centers of the n-α clusters with a particular configuration

✓ Construct the α cluster with four nucleons

✓ Generated random configuration event by event



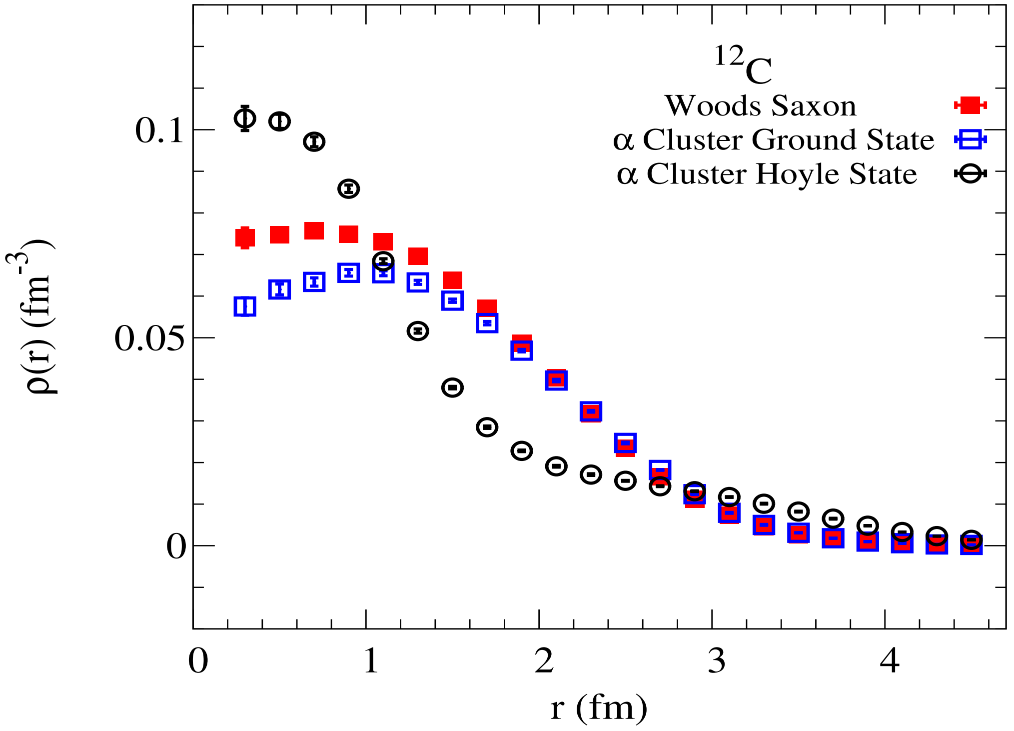
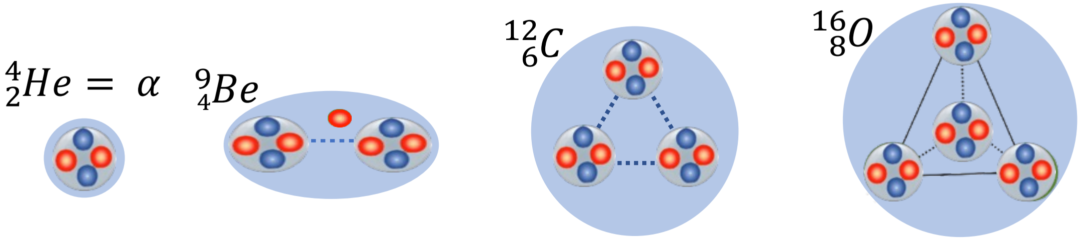


Figure.1: The normalized density distribution of the different configurations of the ^{12}C introduced into the BeAGLE model.

❖ The α clustering

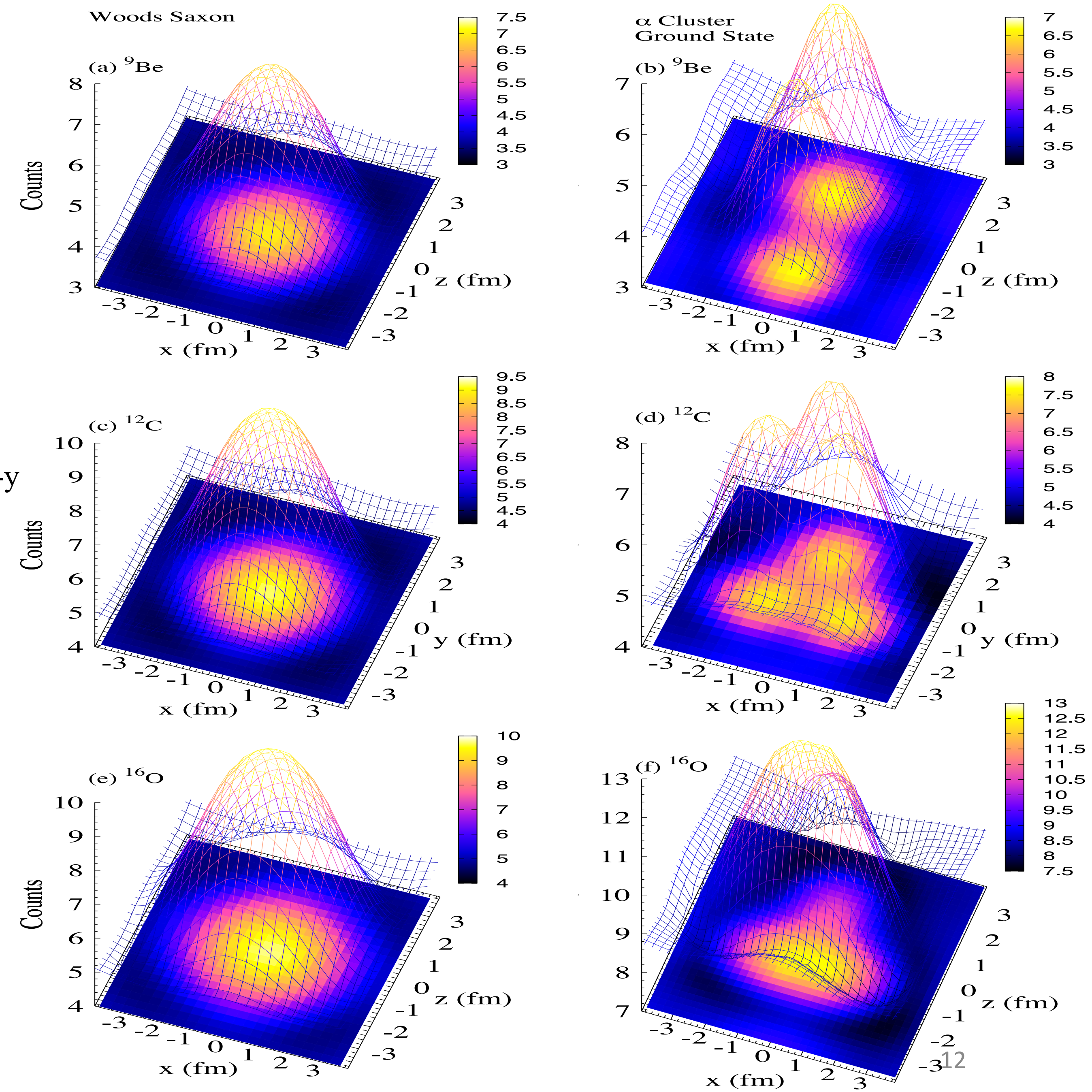
The BeAGLE model is updated to consider the α clustering



2- α Clustered on the Z axes

3- α Clustered in the x-y plane

3- α Clustered in the x-y plane 1- on the Z axes



❖ Potential measurements

➢ $\langle E \rangle$ at forward rapidity

Identify the physics observables that can be used in such work.

- ✓ Several observables have been introduced (e.g., mean energy observable)

The $\langle E \rangle$ in the forward B0 detector acceptant [$4.6 < \eta < 5.9$] Vs centrality.

- ✓ Centrality is defined via the cutting on the impact parameter.

$$\langle E \rangle = \frac{\sum_{i=1}^{M} w_i E_i}{\sum_{i=1}^{M} w_i}$$

Energy of particle i at $4.6 < \eta < 5.9$

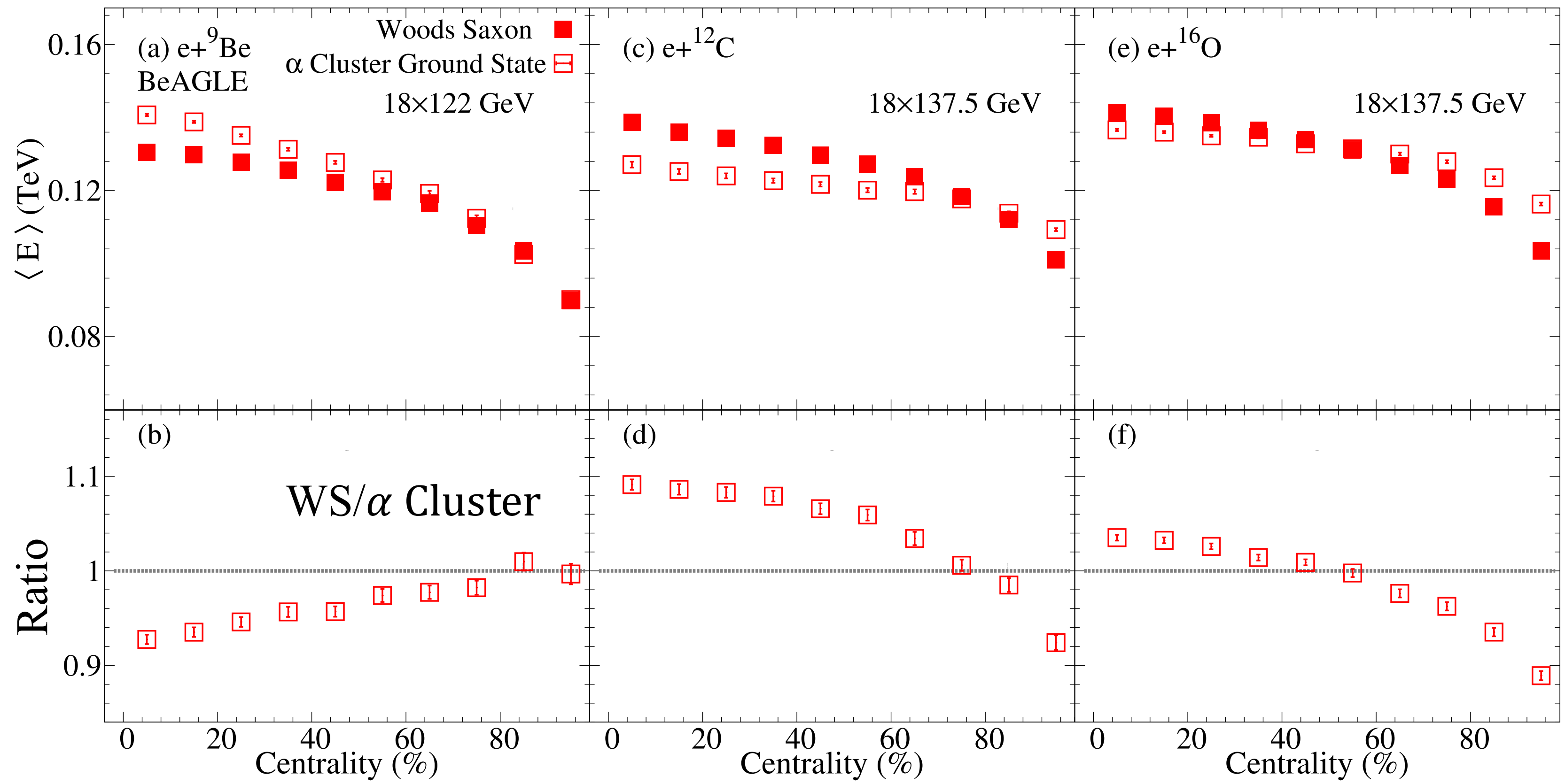
Expected efficiency

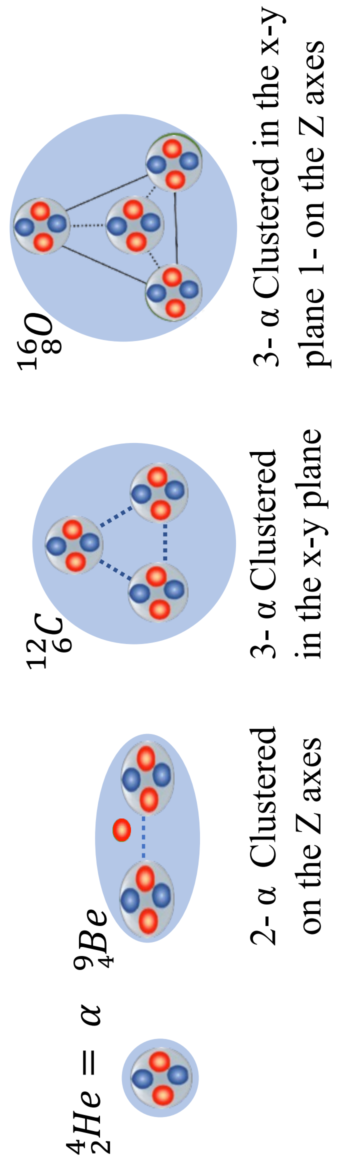
❖ Potential measurements

➢ $\langle E \rangle$ at forward rapidity

The $\langle E \rangle$ in the forward B0 detector acceptant $[4.6 < \eta < 5.9]$ Vs centrality.

- ✓ Centrality is defined via the cutting on the impact parameter.
- ✓ Fixed orientation





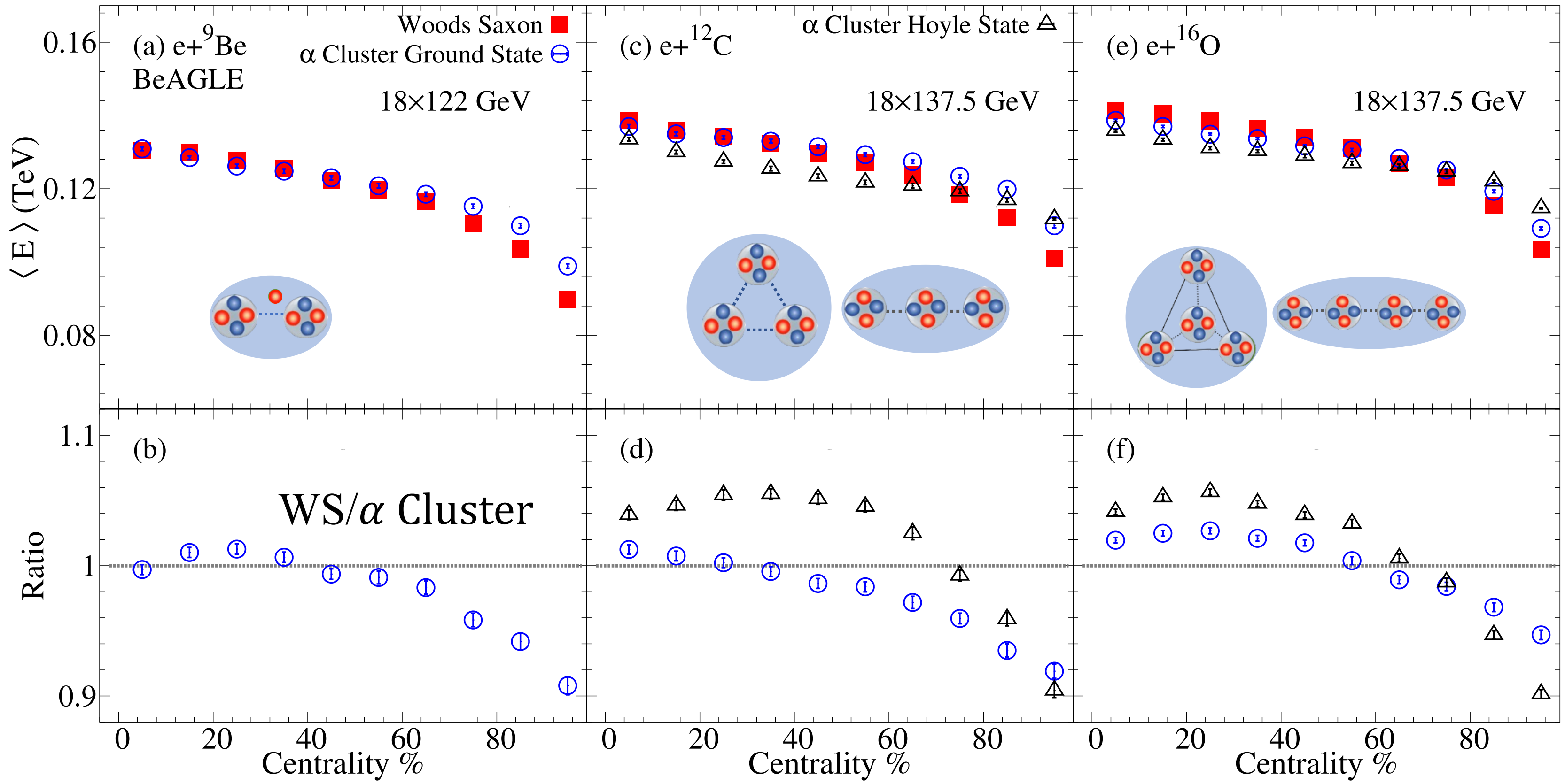
The $\langle E \rangle$ in B_0 is sensitive to α clustering in Be^9, C^{12}, and O^{16}

❖ Potential measurements

➢ $\langle E \rangle$ at forward rapidity

The $\langle E \rangle$ in the forward B0 detector acceptant $[4.5 < \eta < 5.9]$ Vs centrality.

- ✓ Centrality is defined via the cutting on the impact parameter.
- ✓ Random orientation

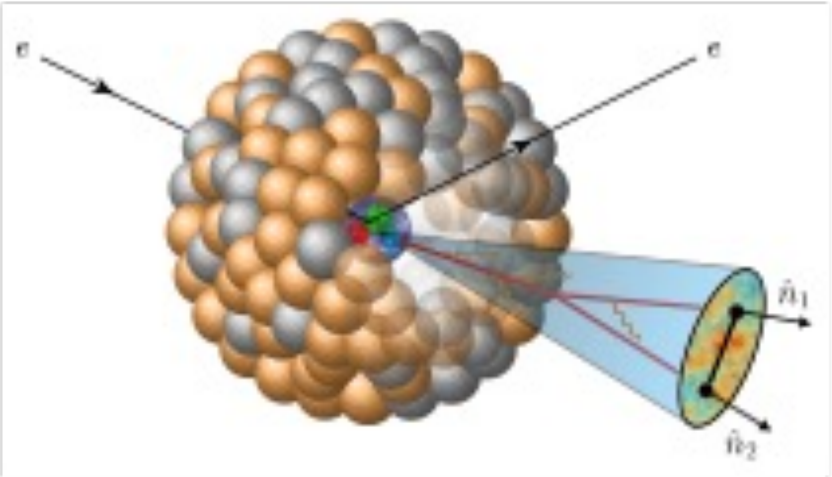


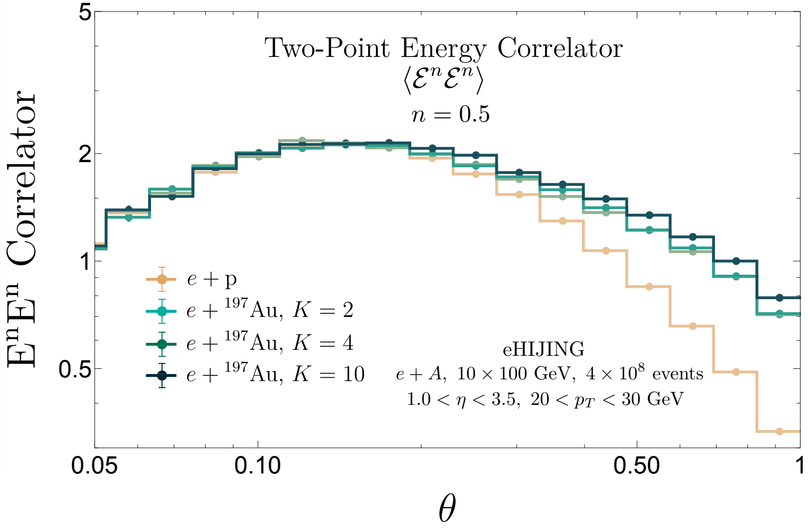
The $\langle E \rangle$ in B_0 is sensitive to α clustering and clustering configurations in Be^9, C^{12}, and O^{16}

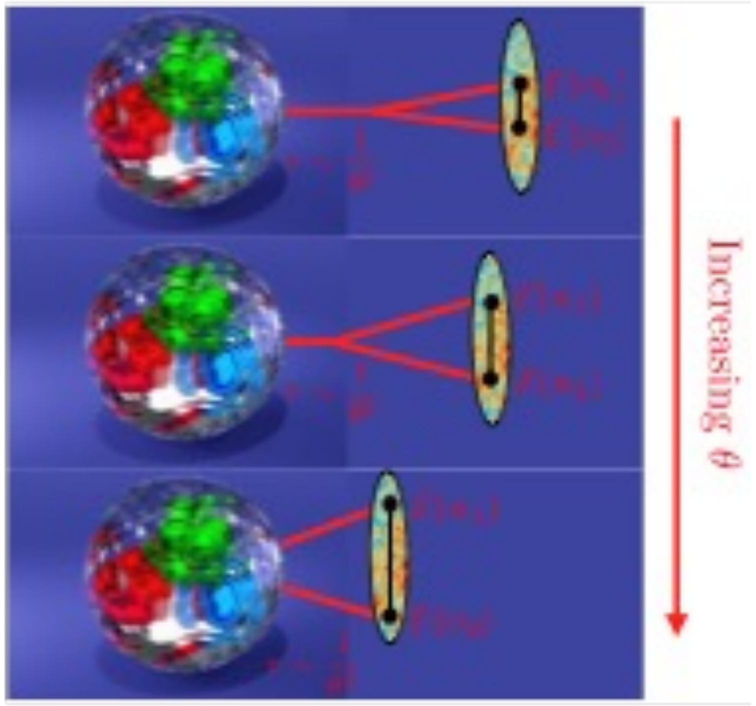
❖ Potential measurements

➢ The E-E Correlations

Angular scales in the two-point energy correlator map the time evolution of the jet.







The size of the nucleus represents a scale that will be imprinted in the angular structure of the correlator.

➢ Only size or size and structure?

Kyle Devereaux, Wenqing Fan, Weiyao Ke, Kyle Lee, Ian Moult
arXiv:2303.08143

❖ Potential measurements

➢ The E-E Correlations

✓ Jets Reconstruction

Jet Definition

- Anti-k_T algo.
- R = 1.0
- $|\eta_{jet}| < 3.5$

The EEC cuts

- $p_{T,jets} > 5.0$ GeV/c
- Inside the jet $p_T > 0.5$ GeV/c
- n = 0.5

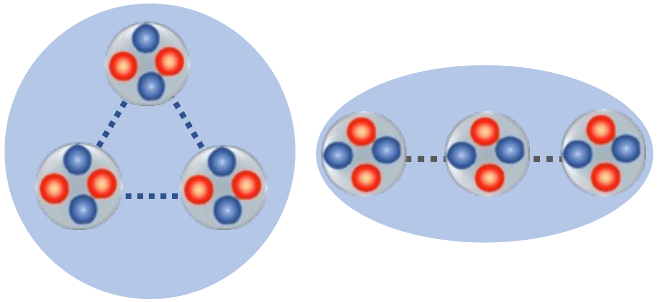
$$EEC = \sum_{jets} \sum_{i \neq j} \left(\frac{E_i \, E_j}{p_{T,jet}^2} \right)^n$$

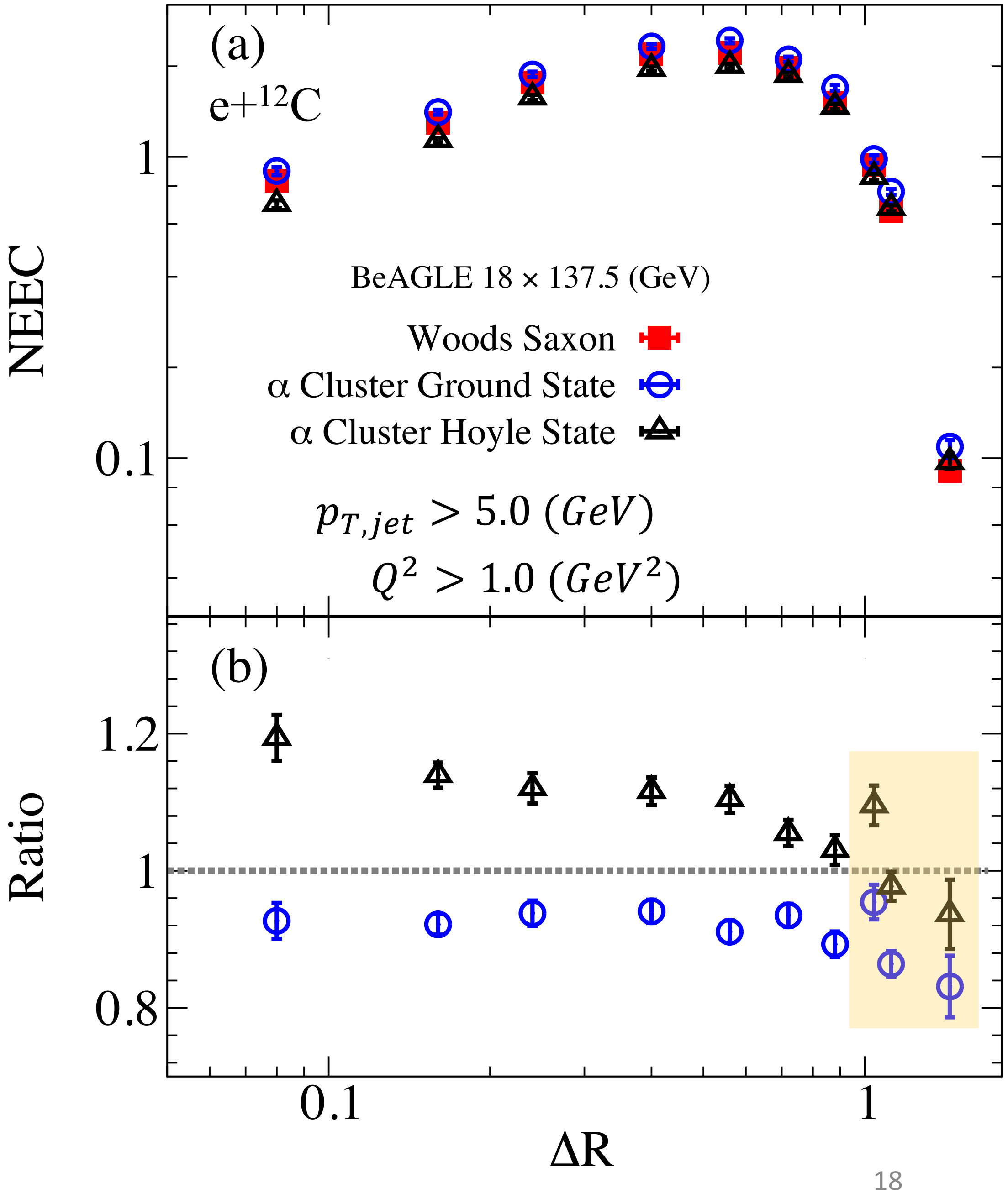
$$NEEC = \frac{1}{EEC} \frac{d\, EEC}{d\, \Delta R}$$

❖ Potential measurements

➢ The E-E Correlations

✓ The EEC vs ΔR





With respect to the Woods-Saxon case:

- ✓ More correlation for the ground state.
- ✓ There is less correlation for the Hoyle-State configuration.

The EEC in ePIC mid-rapidity detector is sensitive to α clustering and clustering configurations in ^{12}C

Conclusions

We investigated the ability to use the EIC to study the α clustering in $^{9}_{4}Be$, $^{12}_{6}C$, and $^{16}_{8}O$:

- The $\langle E \rangle$ in $B0$ is sensitive to α clustering in $^{9}_{4}Be$, $^{12}_{6}C$, and $^{16}_{8}O$
- The $\langle E \rangle$ in $B0$ is sensitive to α clustering configuration (i.e., GS and HS)
- The EEC is sensitive to α clustering and clustering configurations

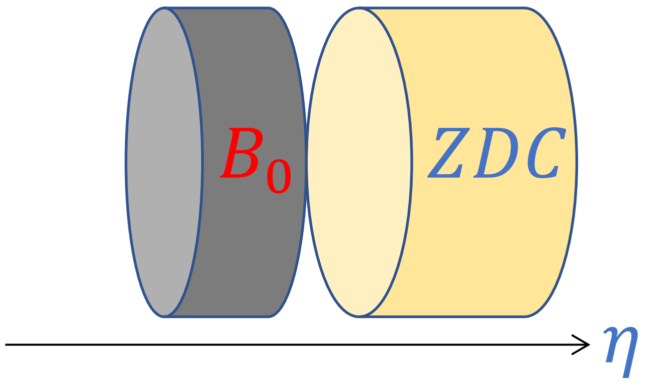
Our proposed measurements are sensitive to α clustering and its configuration.

Thank You

❖ The detector's acceptance:

Caption text

Detector	Acceptance	Notes
Zero-Degree Calorimeter (ZDC)	$\theta < 5.5$ mrad ($\eta > 6$)	About 4.0 mrad at $\phi \sim \pi$
B0 Detector	$5.5 < \theta < 20.0$ mrad ($4.6 < \eta < 5.9$)	Silicon tracking + EM preshower



➢ In this current study, we are using: ZDC and B_0 detectors