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

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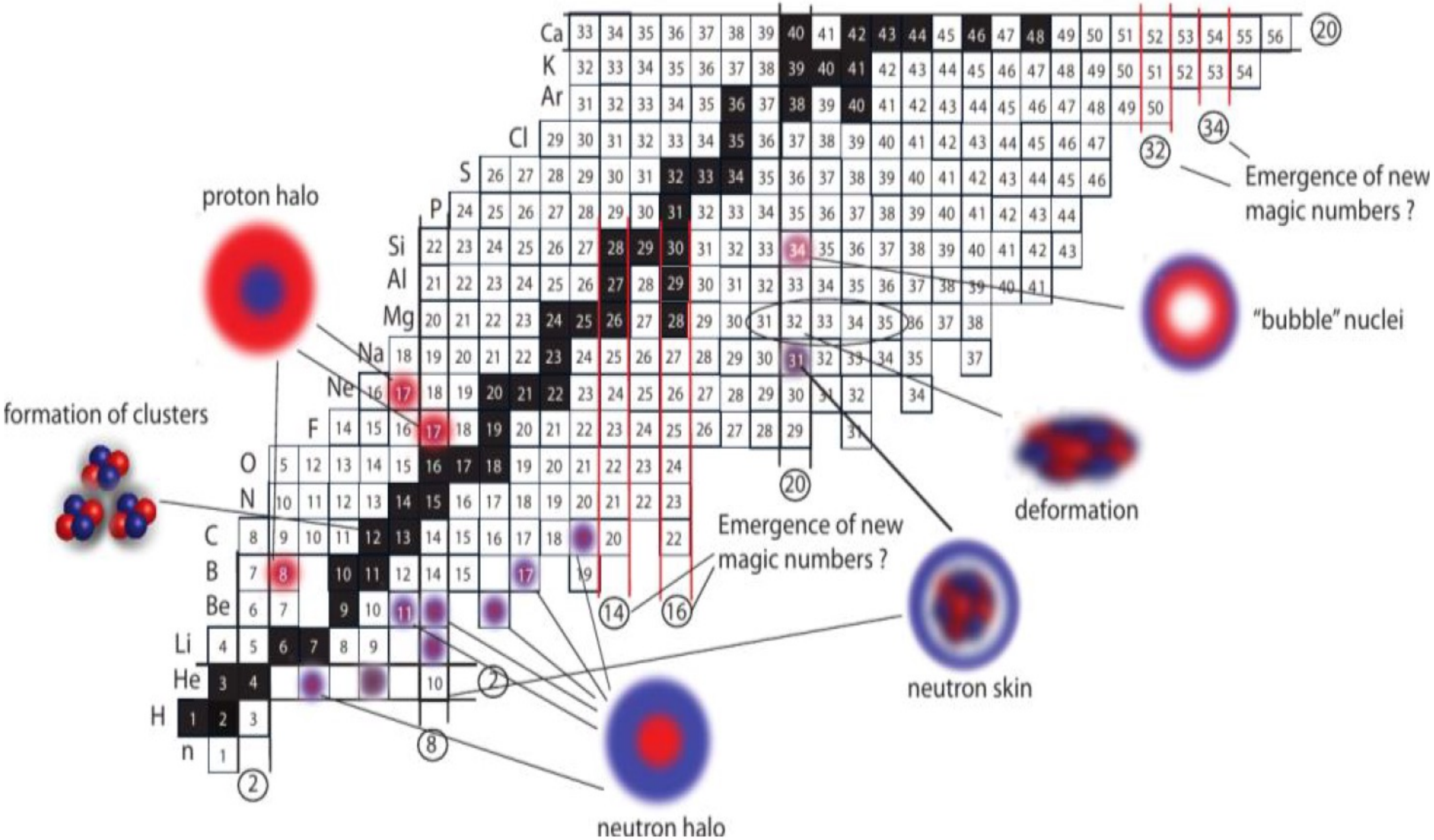
❖ Motivation

➢ The rich structure of atomic nuclei:

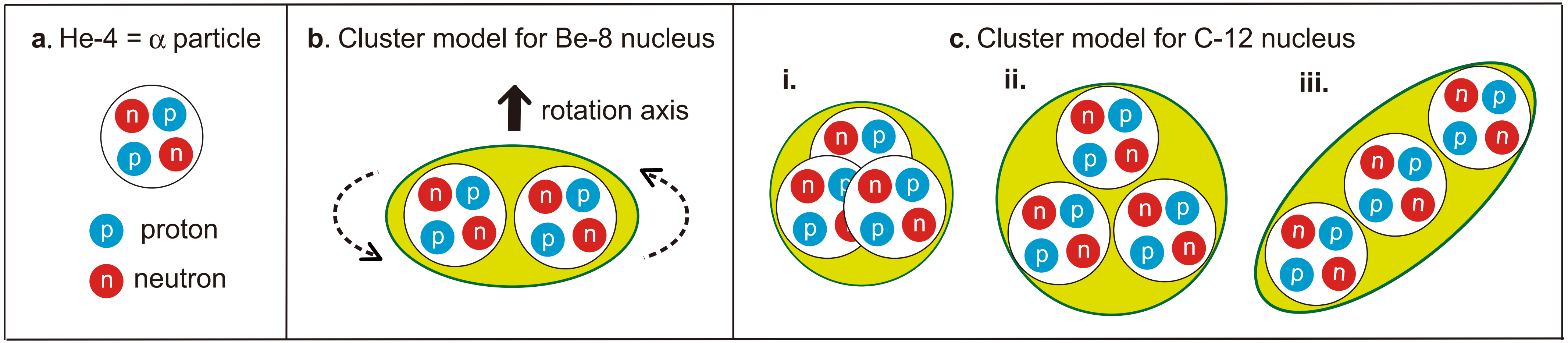
- ✓ Clustering, halo, skin …
- ✓ Quadrupole/octupole/hexdecopole deformations



❖ 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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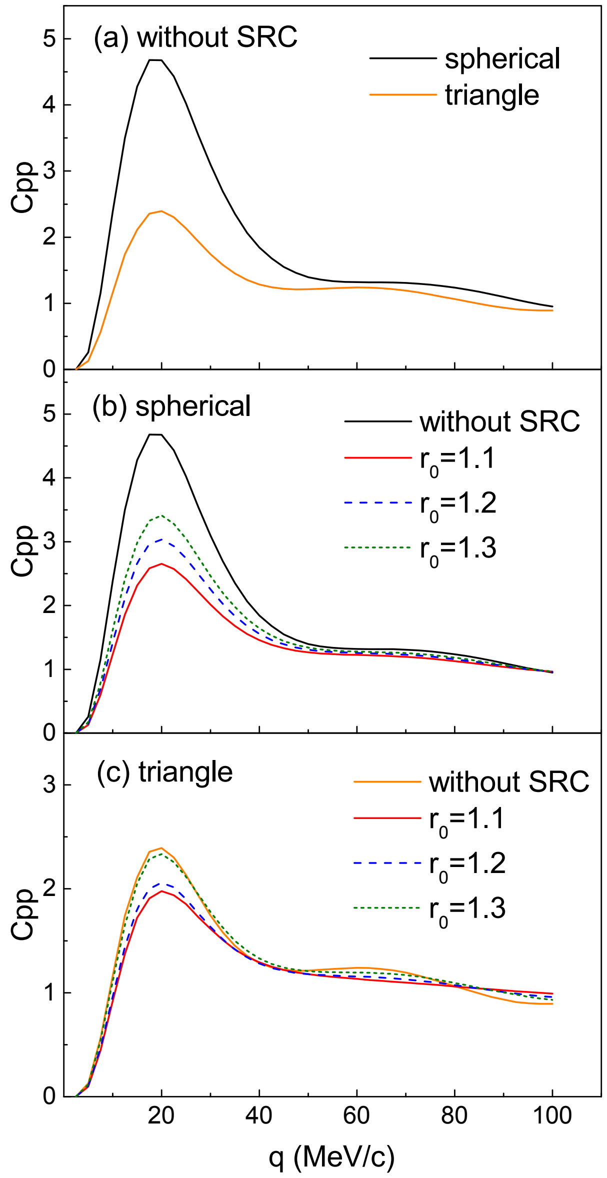


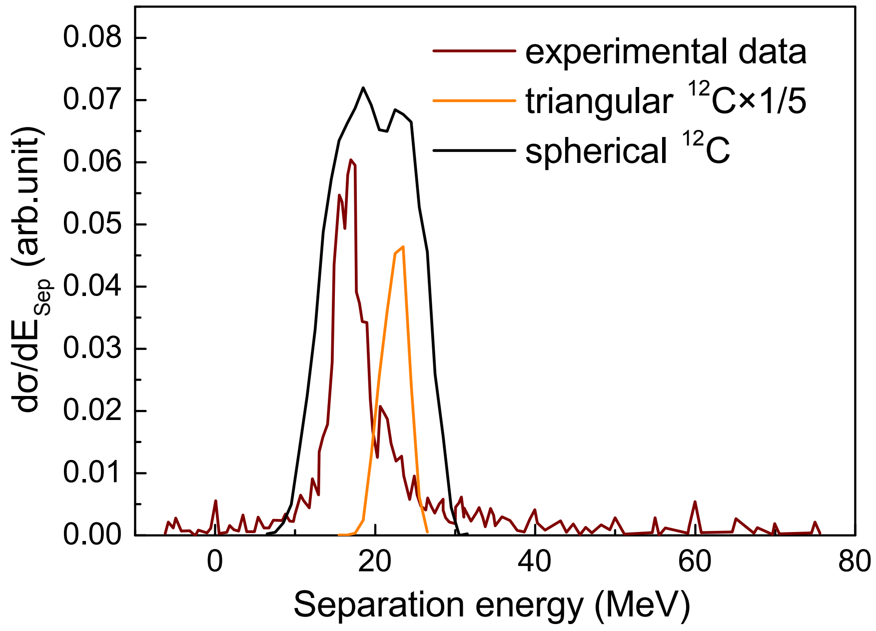


FIG. 3: Separation energy distribution of ^{12}C(p,2p)^{11}B at 250 MeV. The experimental data is plotted by the dashed line, while the spherical and triangle distribution simulations are shown by dark and orange lines, respectively.

Fetoscopy measurements can be sensitive to SRC and clustering.

❖ Motivation

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) Can we observe the clustering effect in the ^{12}C ground state?

(3) 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)

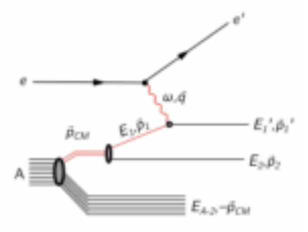
(4) Identify the study cavities that will need further investigation.

The BeAGLE model

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

❖ The BeAGLE model:

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



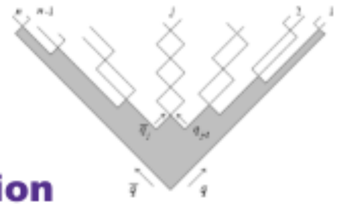
Primary interaction

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

Glauber handled by BeAGLE

PyQM: Nuclear Geometry + optional gluon radiation in medium.

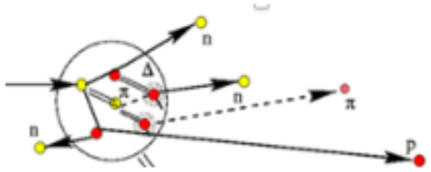
Hadronization handled by **PYTHIA6.**



Hadronization

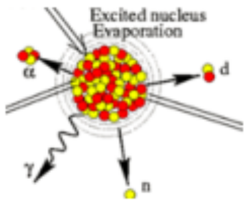
Cascade process handled by **DPMJET.**

Formation time. Stochastic.



Intra-nuclear cascade

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



Nuclear remnant evaporation & breakup

Some Nuclear Effects

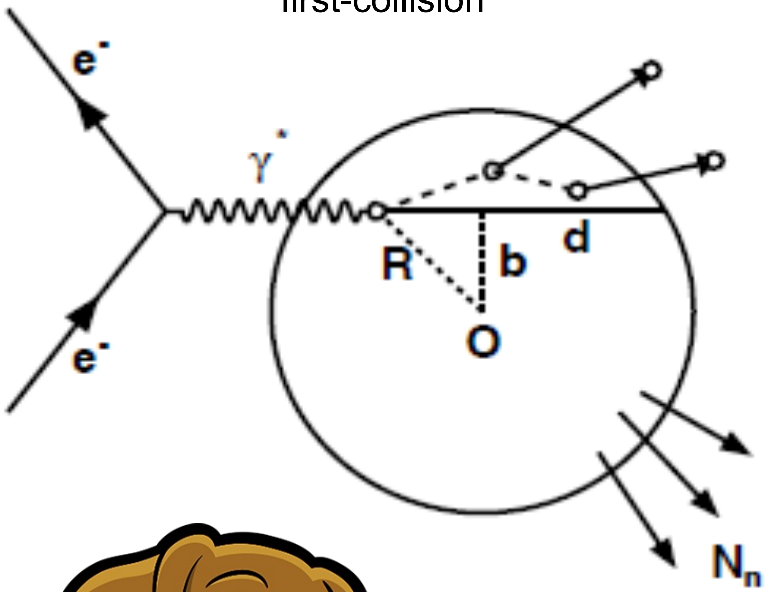
	In BeAGLE
• Parton distribution functions	✓
• Parton saturation (CGC etc.)	
• Short-range correlations	✓ (GCF)
• "Fermi motion"	✓
• Partonic (or "dipole") MS	✓
• Partonic gluon radiation	✓
• Medium-modified hadronization	
• Formation times	✓
• Hadronic Cascade	✓
• Nuclear evaporation, breakup	✓
• Photonic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

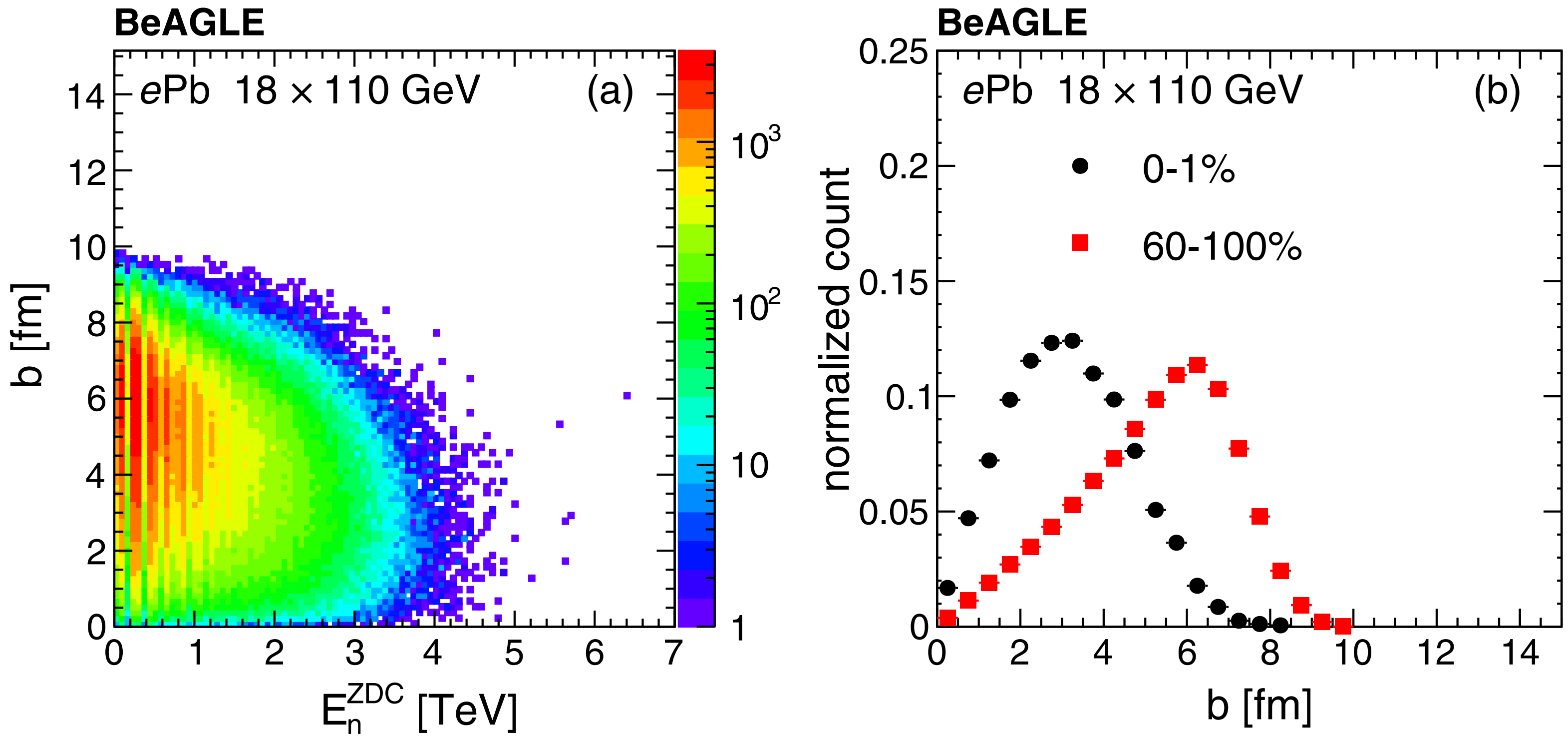
❖ The BeAGLE model:

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

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

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





Neutrons in ZDC can be used for centrality definition?

❖ The α clustering

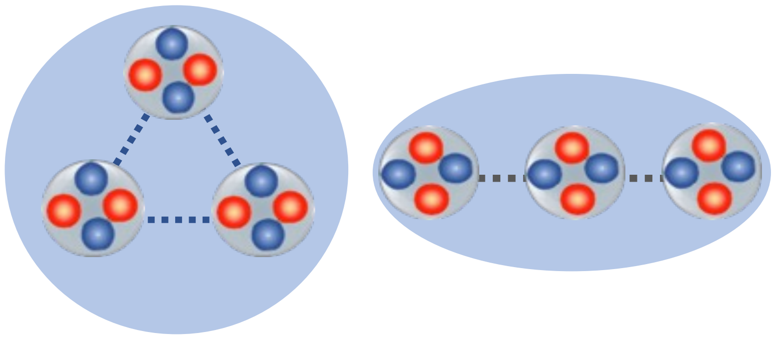
Modifying the EIC model simulations with initial nuclear configurations, which include alpha clustering.

✓ 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



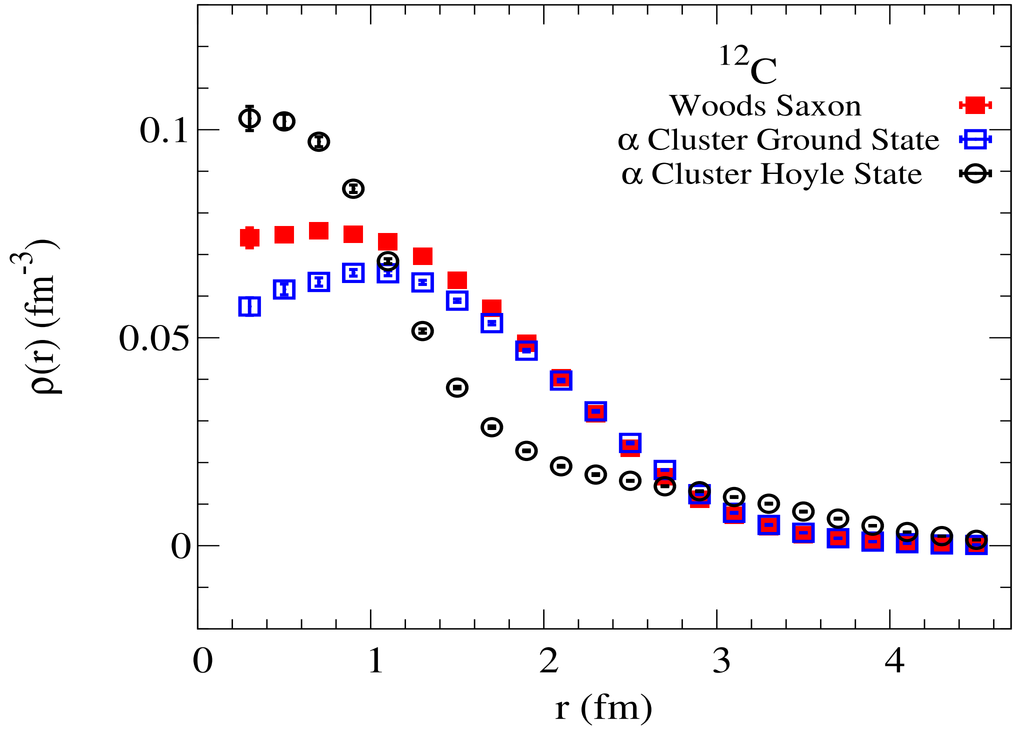
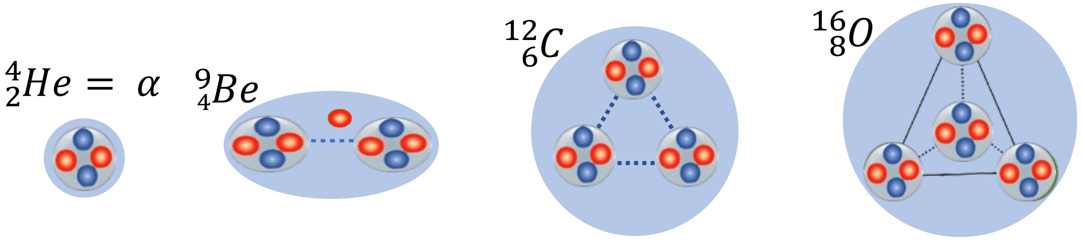


Figure.1: The normalized density distribution of the different configurations of the ^{12}C introduced into the BeAGLE model.

❖ The α clustering

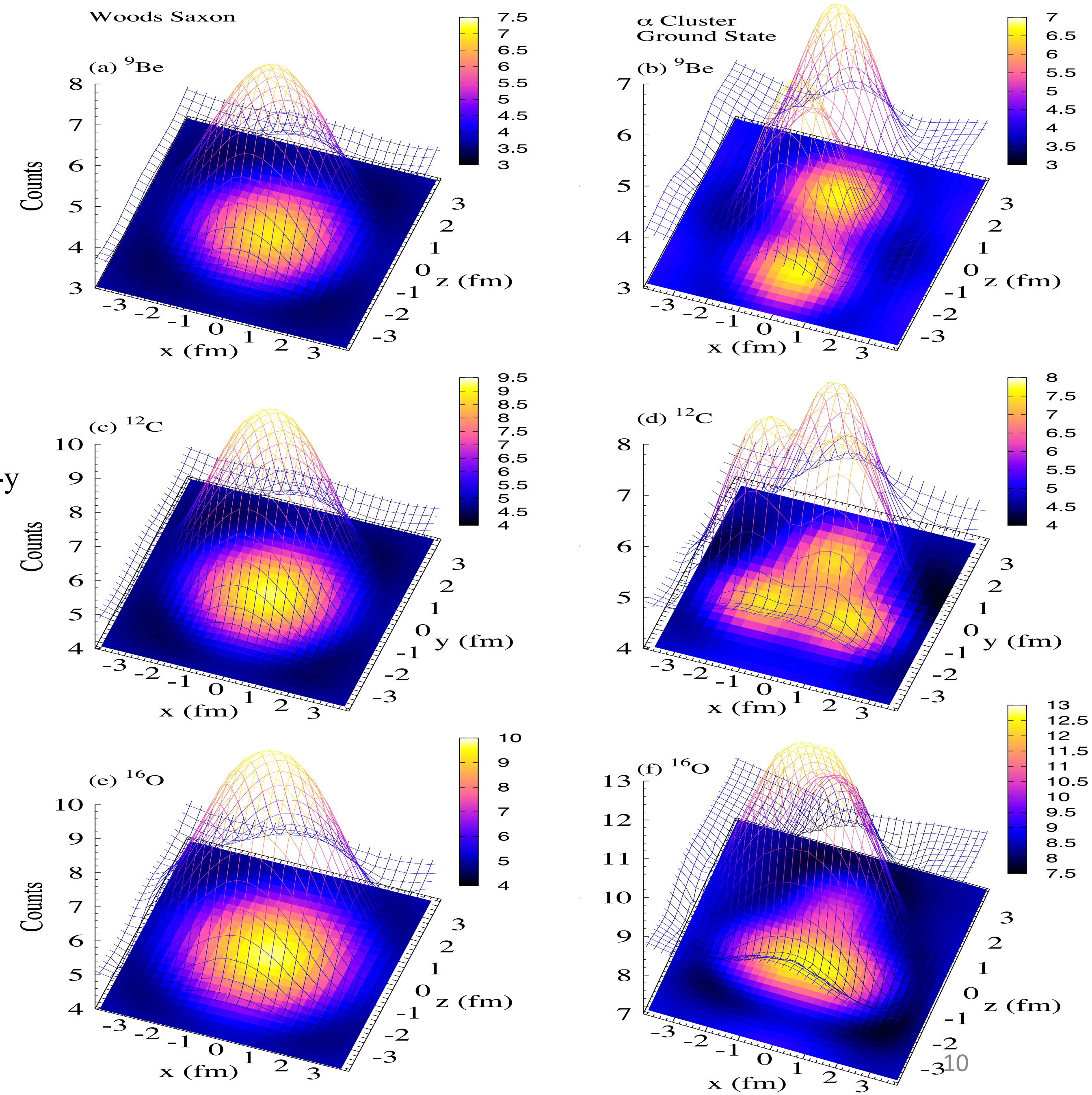
The BeAGLE model is updated to consider the α clustering



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

ID	Distribution	Orientation
Case-1	Wood-Saxon	Random
Case-2	α Cluster Ground State	Fixed
Case-3	α Cluster Ground State	Random
Case-4	α Cluster Hoyle State	Random

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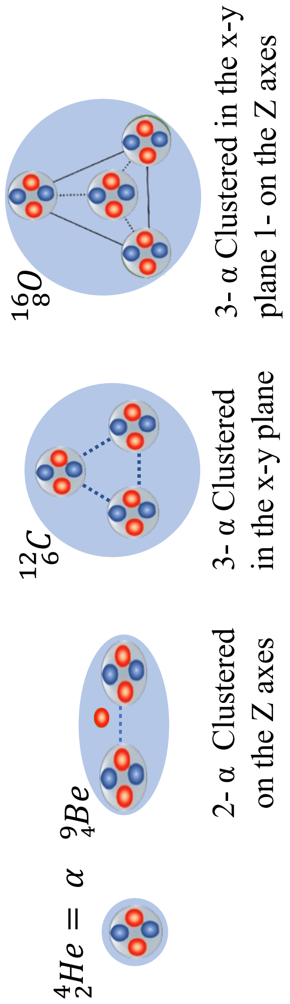

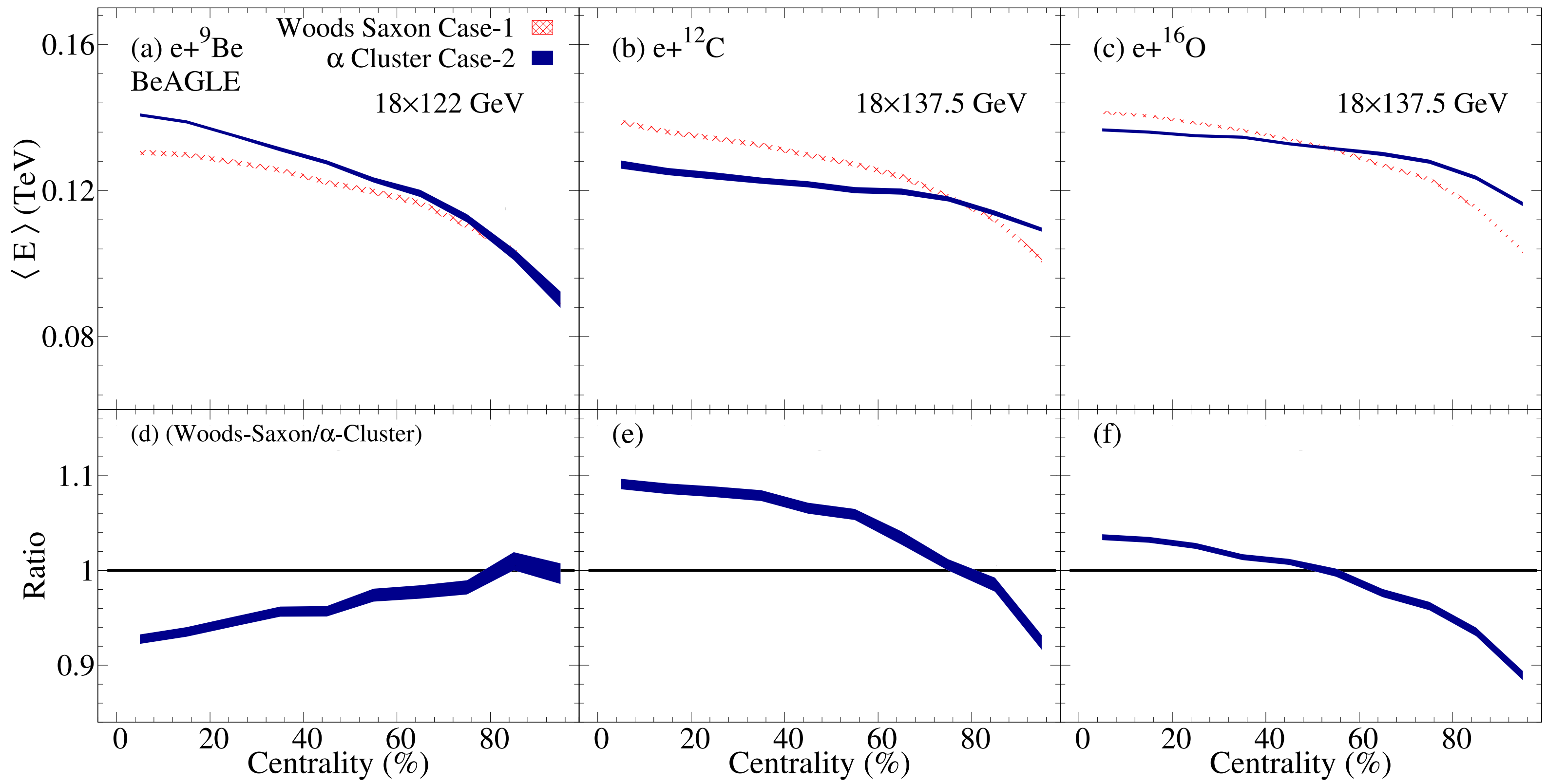

The $\langle E \rangle$ in B_0 is sensitive to α clustering in $^{9}_{4}Be$, $^{12}_{6}C$, and $^{16}_{8}O$

❖ Potential measurements

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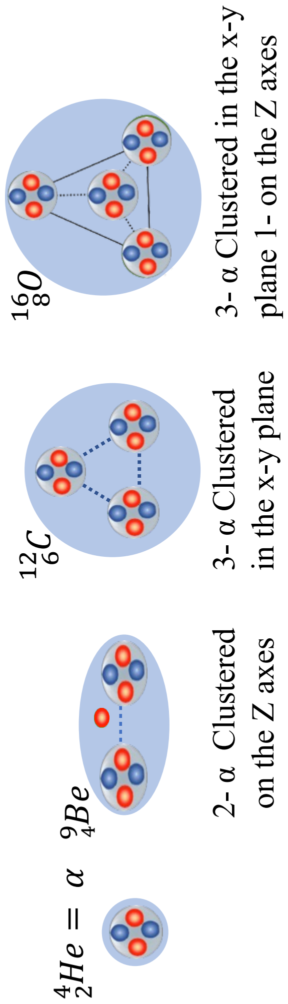
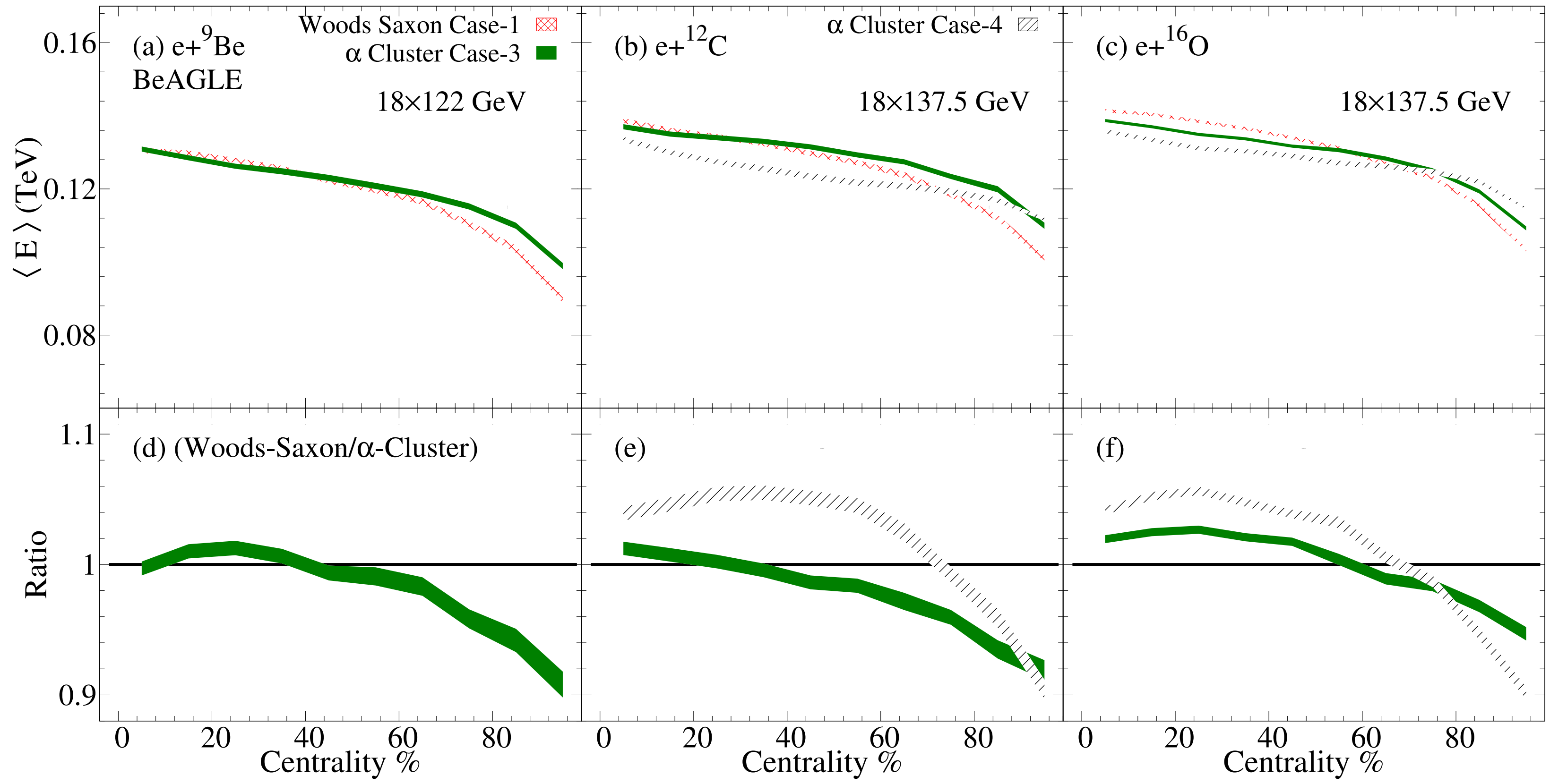
The $\langle E \rangle$ in the forward B0 detector acceptant $[4.5 < \eta < 5.9]$ Vs centrality.

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





The $\langle E \rangle$ in B_0 is sensitive to α clustering and clustering configurations in $^{9}_{4}Be$, $^{12}_{6}C$, and $^{16}_{8}O$

❖ Potential measurements

➢ $\langle E \rangle$ at forward rapidity

ID	Distribution	Orientation
Case-1	Wood-Saxon	Random
Case-2	α Cluster Ground State	Fixed
Case-3	α Cluster Ground State	Random
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The $\langle E \rangle$ in the forward B0 detector acceptant $[4.5 < \eta < 5.9]$ Vs centrality.

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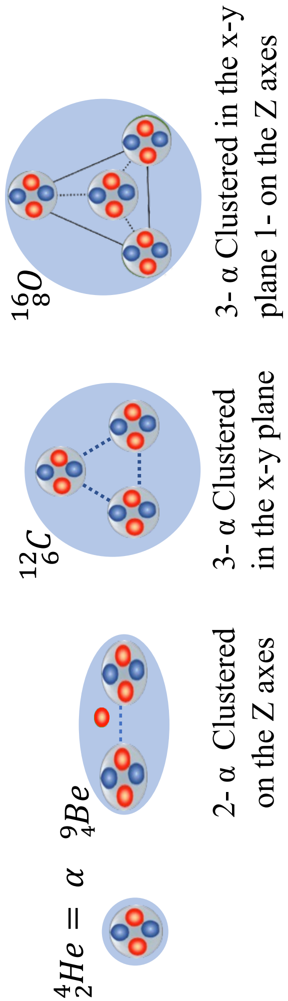

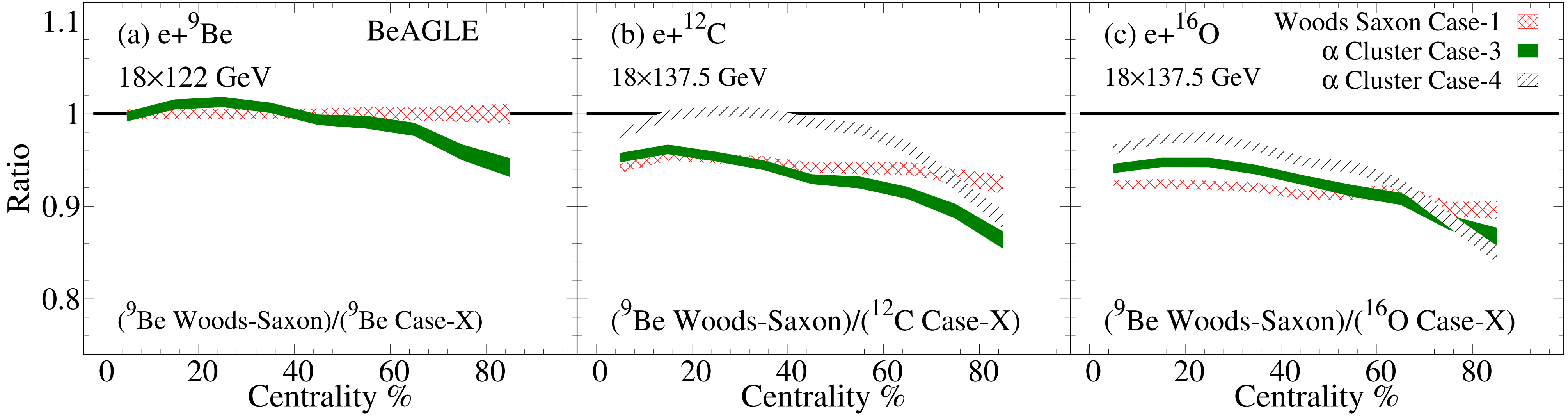

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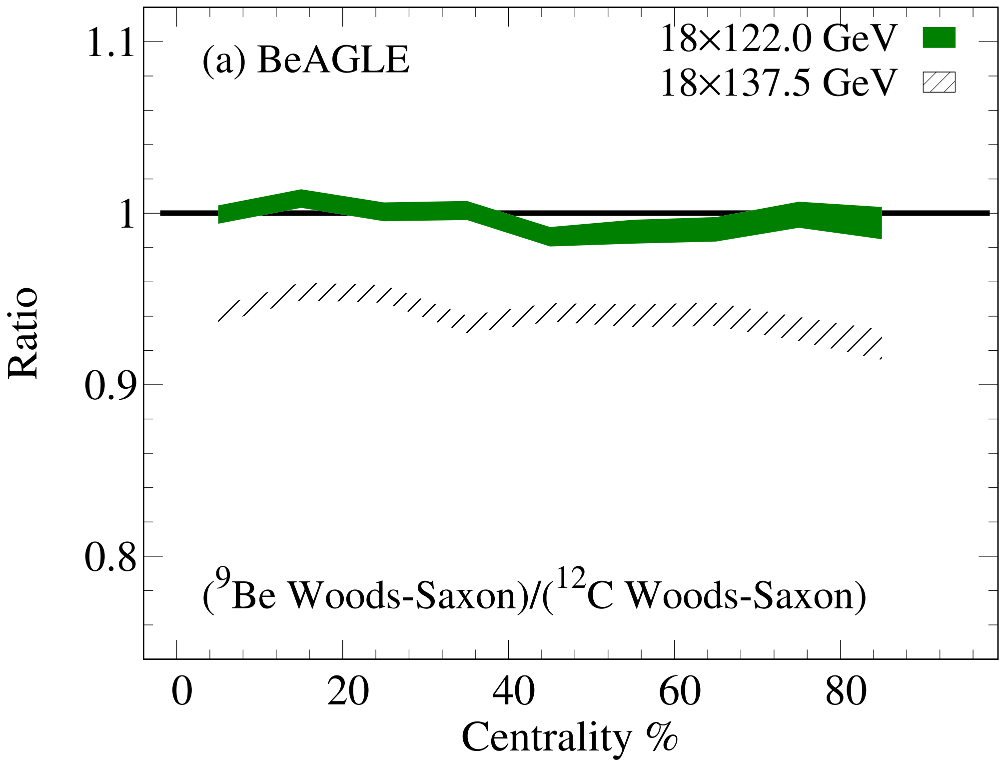
❖ Potential measurements

- ➢ $\langle E \rangle$ at forward rapidity
  - ✓ e+A Group homework

The ratio between ^{9}Be and ^{12}C at

- ➢ Same momentum
  - ✓ No centrality dependance close to unity within 1%
- ➢ Different energy
  - ✓ No centrality dependance close to 6%



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)

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

Thank You