Atomic nuclei imaging at the Electron-Ion Collider with the ePIC experiment

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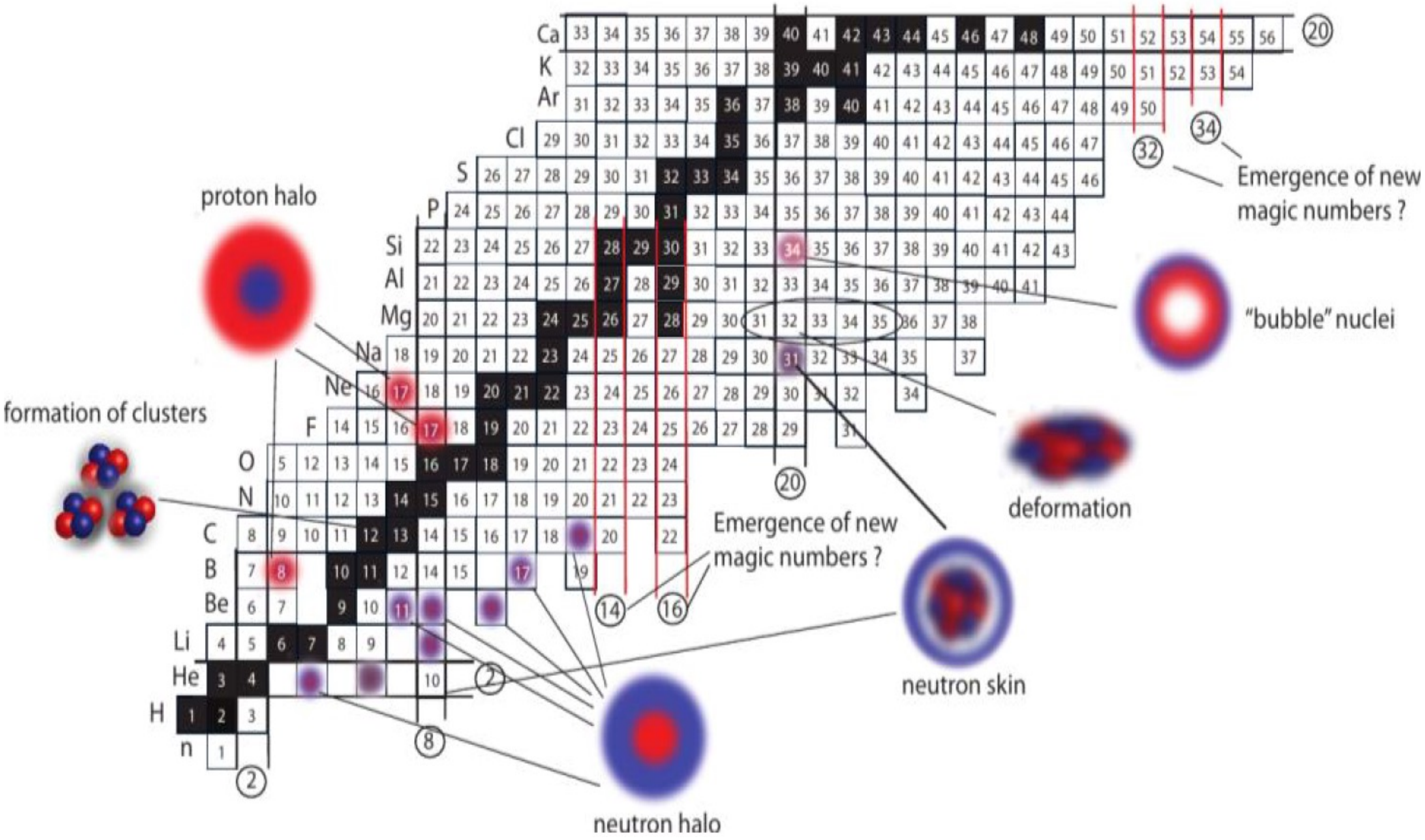
❖ Motivation

➢ The rich structure of atomic nuclei:

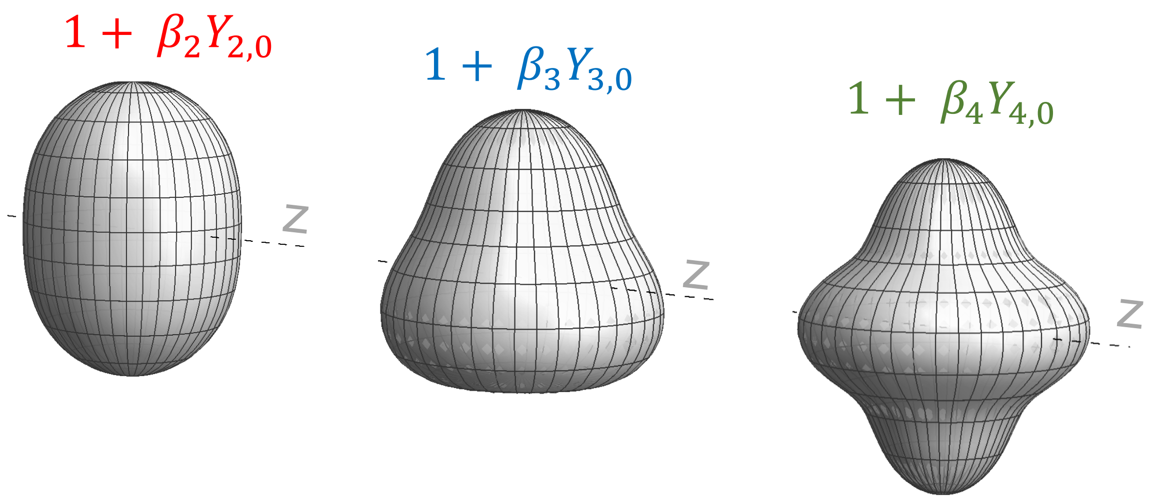
- ✓ Clustering, halo, skin …
- ✓ Quadrupole/octupole/hexdecopole deformations



❖ Motivation

The shape of the nucleus in nuclear physics is often modeled with a nucleon density profile of the Woods-Saxon $\rho(r, \theta, \phi)$.

- $Y_{n,0}$ are spherical harmonics
- β_n are deformation parameters
  - ✓ n=2 -> Quadrupole
  - ✓ n=3 -> Octupole
  - ✓ n=4 -> Hexadecapole



$$\rho(r, \theta, \phi) = \frac{\rho_0}{1 + e^{[r - R(\theta,\phi)/a_0]}}$$

$$R(\theta, \phi) = R_0 \left(1 + \beta_2 Y_{2,0}(\theta, \phi) + \beta_3 Y_{3,0}(\theta, \phi) + \beta_4 Y_{4,0}(\theta, \phi)\right)$$

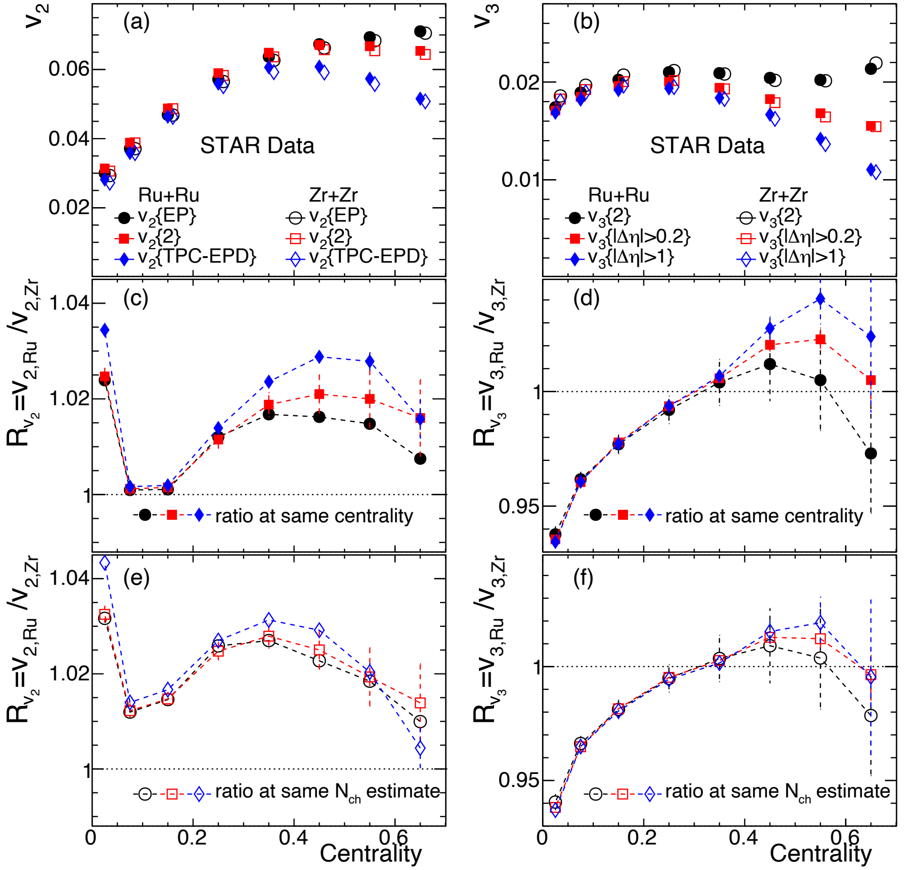
❖ Motivation

J. Jia
Phys. Rev. C 105 (2022) 1, 014905
J. Jia et al.
Phys.Lett.B 833 (2022) 137312

In heavy ion collisions;

	$n = 1$	$n = 2$	$n = 3$	$n = 4$
$\langle \varepsilon_n^2 \rangle$ (indep. rotation)	$\frac{2048}{3675\pi^3}\beta_3^2 = 0.018\beta_3^2$	$\frac{3}{4\pi}\beta_2^2 = 0.239\beta_2^2$	$\frac{2048}{245\pi^3}\beta_3^2 = 0.270\beta_3^2$	$\frac{35}{36\pi}\beta_4^2 + \frac{45}{28\pi^2}\beta_2^4 = 0.31\beta_4^2 + 0.16\beta_2^4$

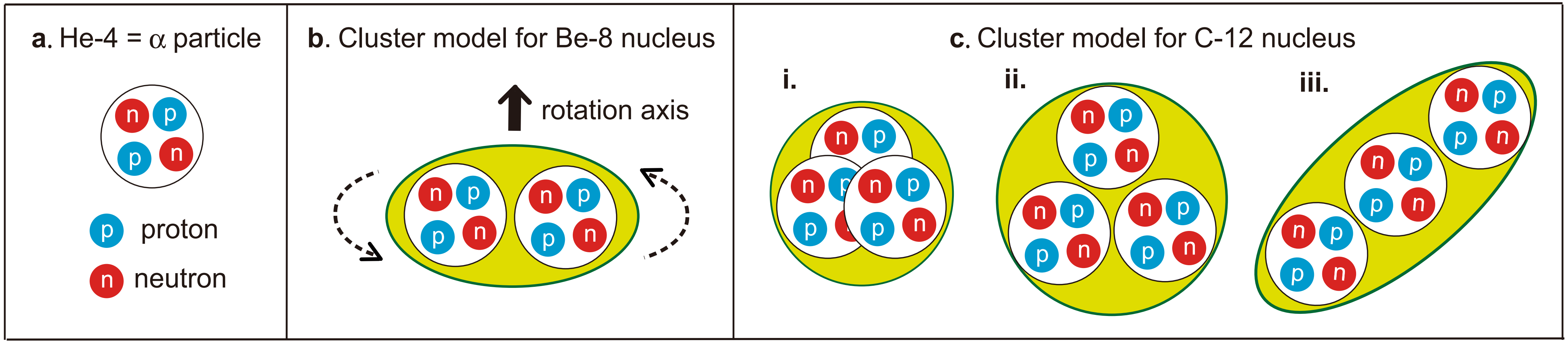
The ratio of the elliptic and triangular flow shows differences reflecting the β_2 and the β_3 dependence of Zr and Ru



❖ Motivation

➢ What can we learn about the nuclear shape and structure (α clustering)?

✓ Can α particles be the building blocks of some nuclei?
✓ Has direct experimental evidence ever been provided?



Nature Communications, 13, 2234 (2022)

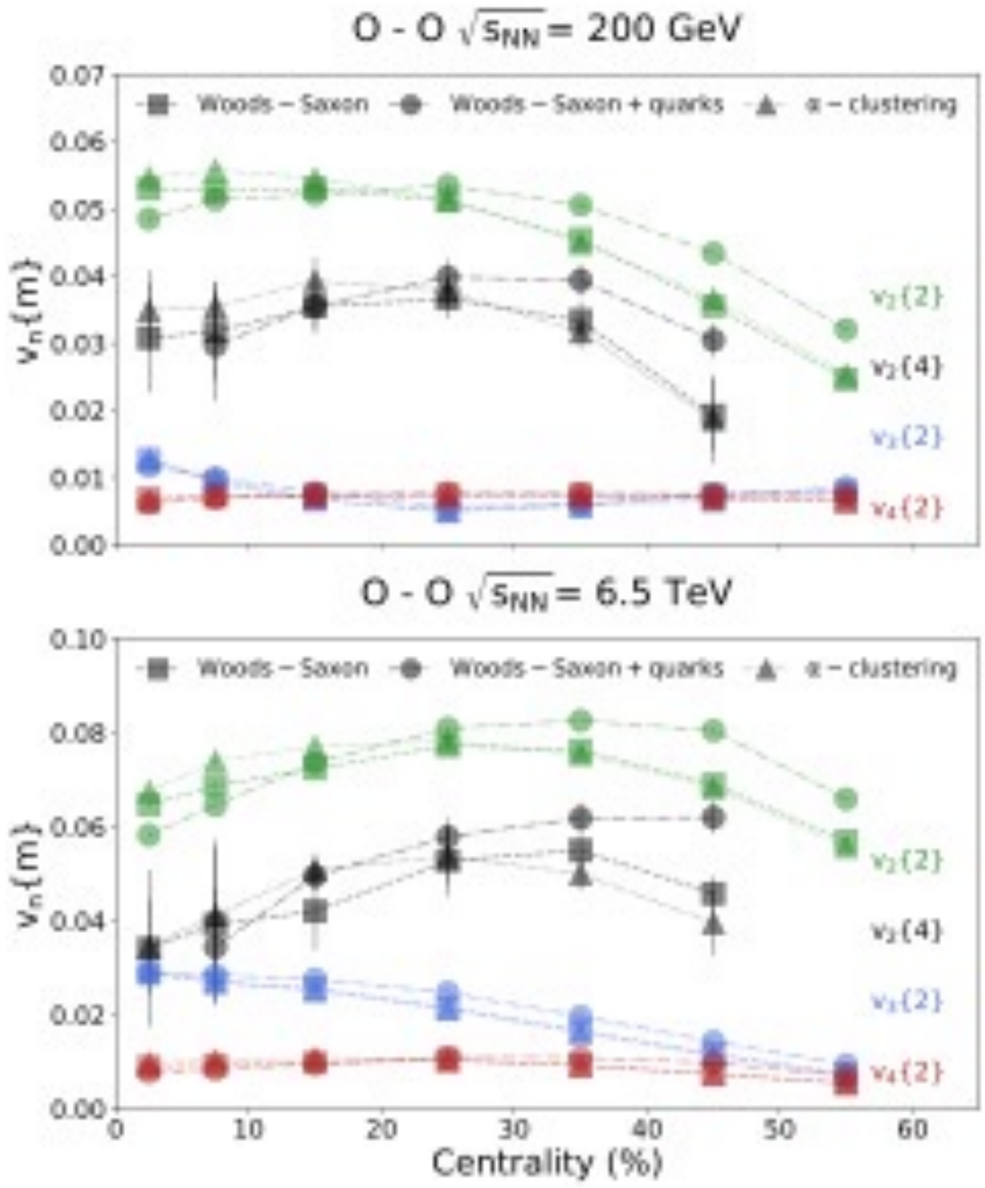
❖ Motivation

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.

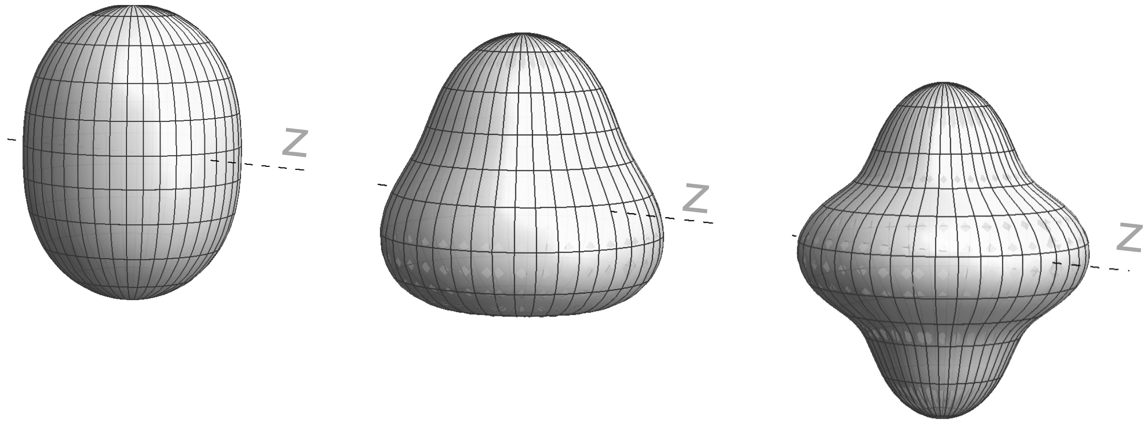
Phys.Rev.C 104 (2021) 4, L041901



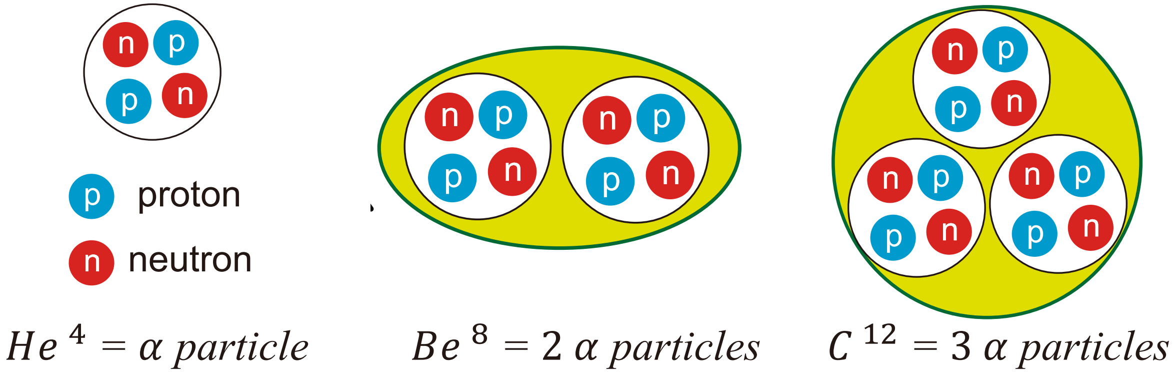
❖ Motivation

➢ EIC can be a unique tool for understanding the nuclear structure

✓ Understanding the nuclear deformation



✓ Understanding the α clustering



Can EIC provide additional constraints on nuclear deformation and the α clustering?

➢ Using the BeAGLE model

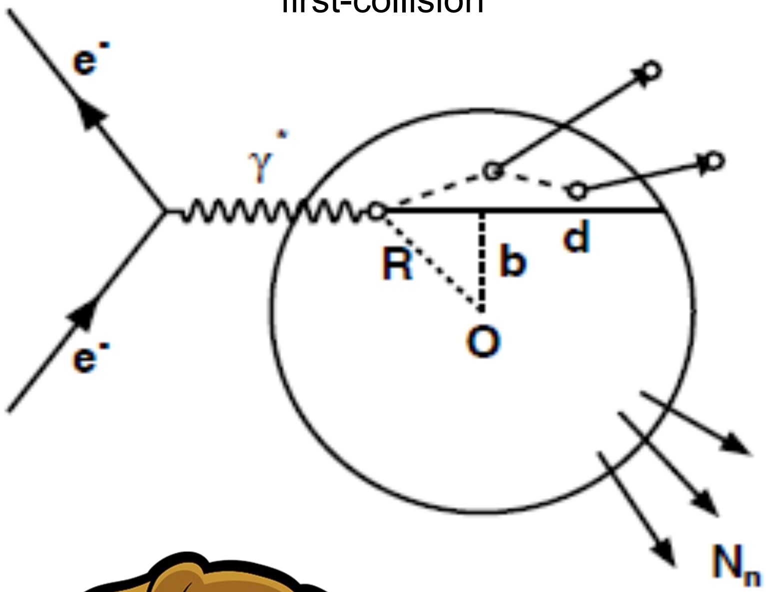
✓ Modifying the nucleus information in the model

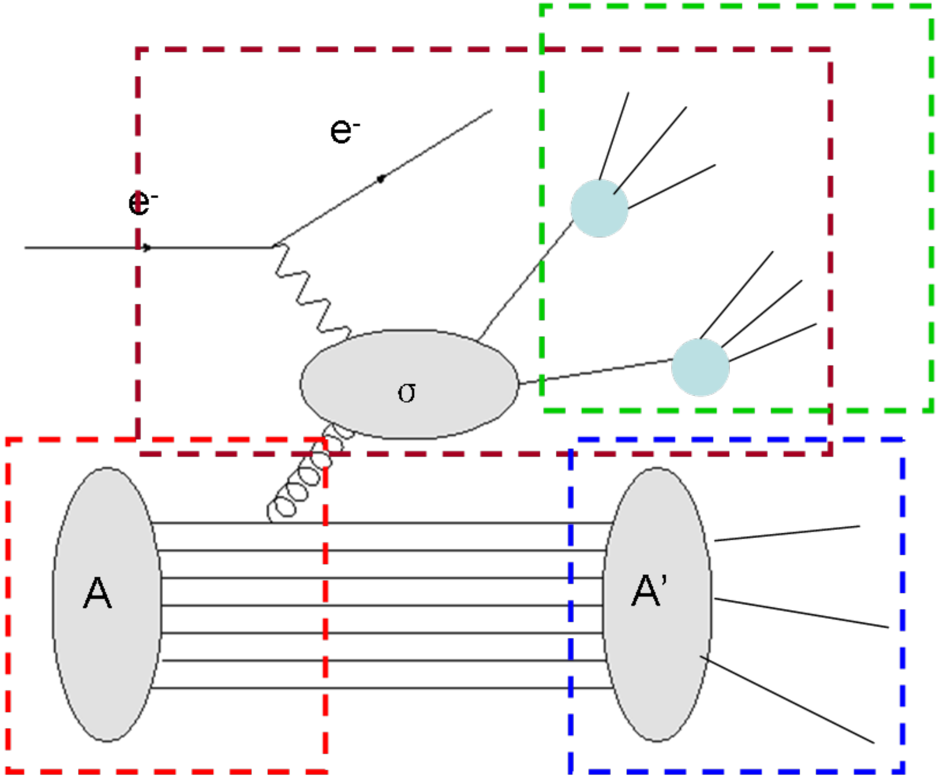
❖ The BeAGLE model:

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

PRD 106, 012007 (2022)

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.

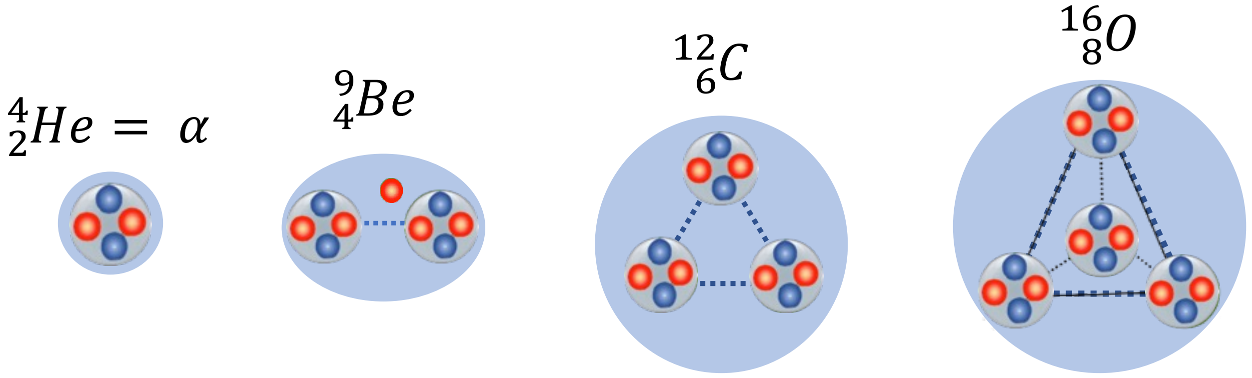
Nuclear evaporation (gamma dexcitation/nuclear fission/fermi break up) treated by DPMJet

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

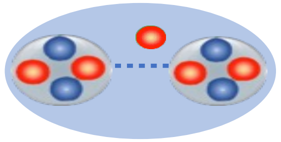
❖ The α clustering

Model Setup

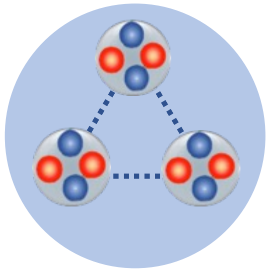
- The α clustering in ${}^{9}_{4}Be$, ${}^{12}_{6}C$, and ${}^{16}_{8}O$
  - ✓ Chose the center of the α cluster
  - ✓ Filled the α cluster with four nucleons
  - ✓ Generated random configuration event by event



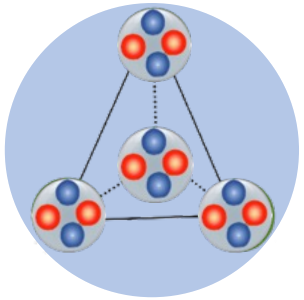
- The BeAGLE model is updated to consider the α clustering



2- α Clustered on the Z axes



3- α Clustered in the x-y plane



3- α Clustered in the x-y plane

1- α Clustered on the Z axes

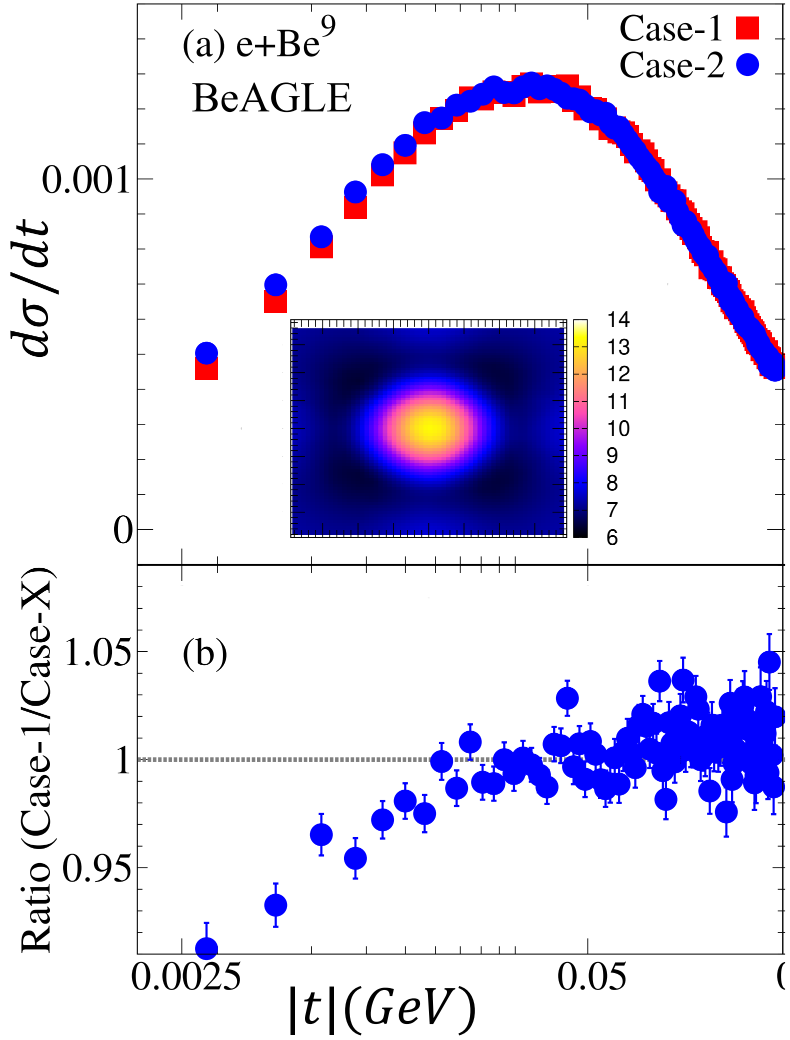
Potential measurements

- Incoherent scattering
- Nuclei homogeneity
- The system energy/momentum

❖ The α clustering

➢ Incoherent scattering

Case-1: Woods–Saxon
Case-2: Clustering fixed orientation



The inclusive $d\sigma/dt$ is sensitive to α clustering in Be^{9}, C^{12}, and O^{16}

❖ The α clustering

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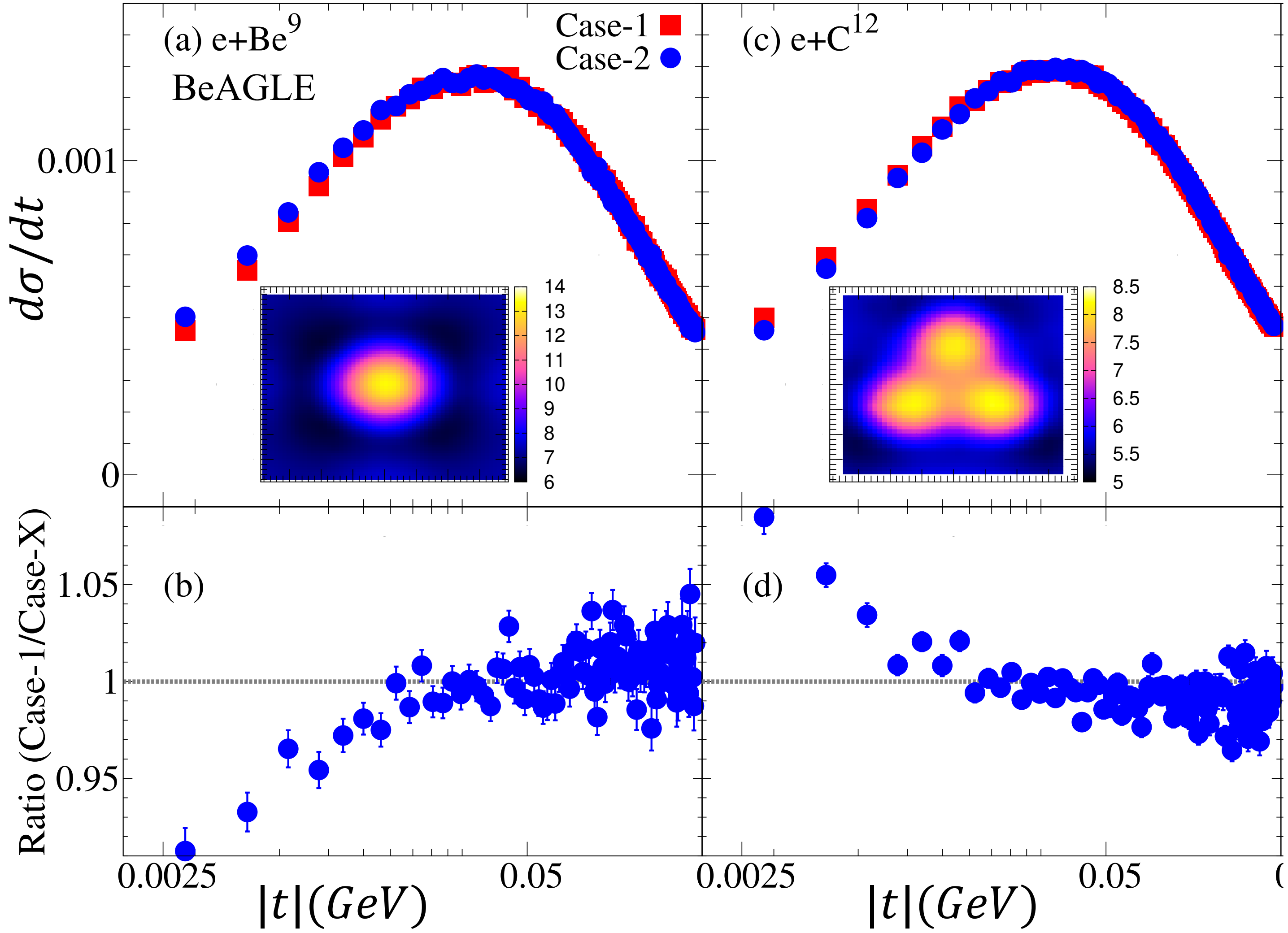

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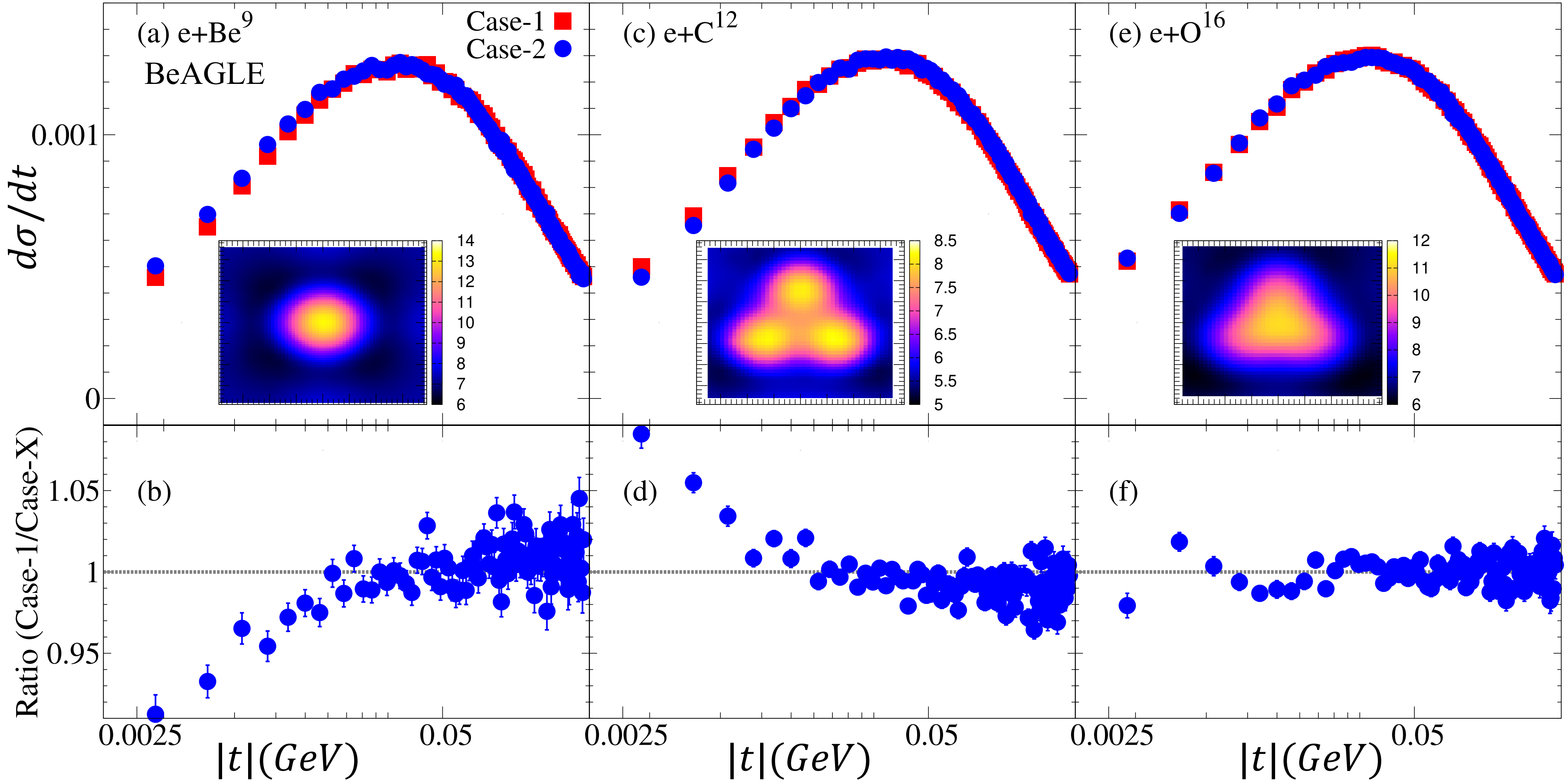

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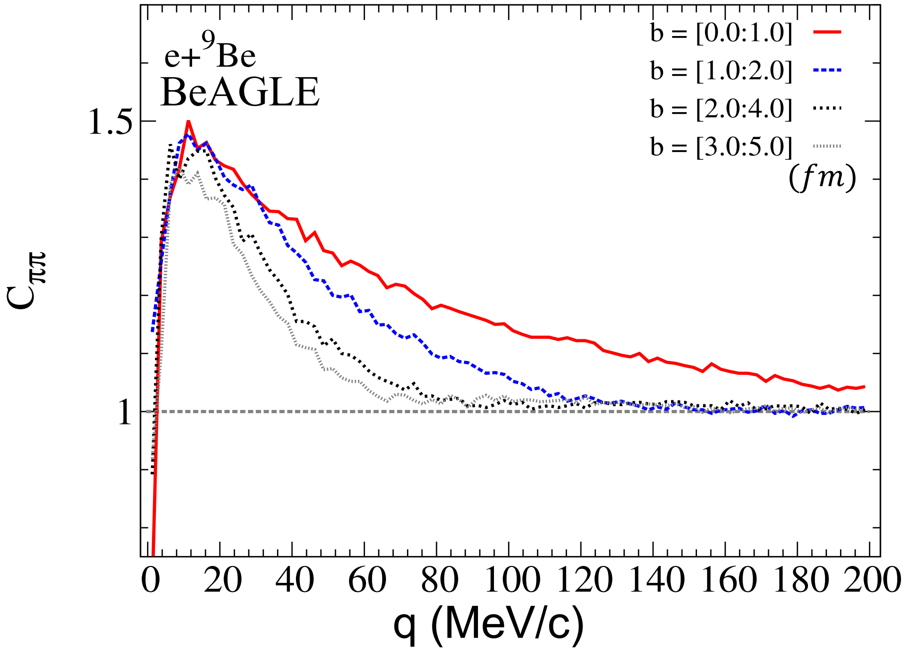
❖ The α clustering

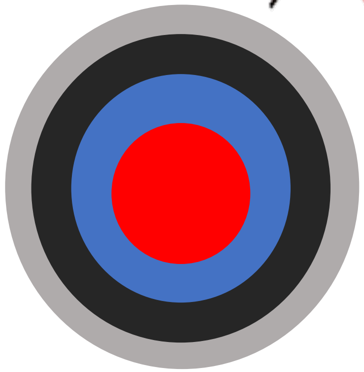
Lei Shen, Bo-Song Huang, and Yu-Gang Ma
Phys.Rev.C 105 (2022) 1, 014603

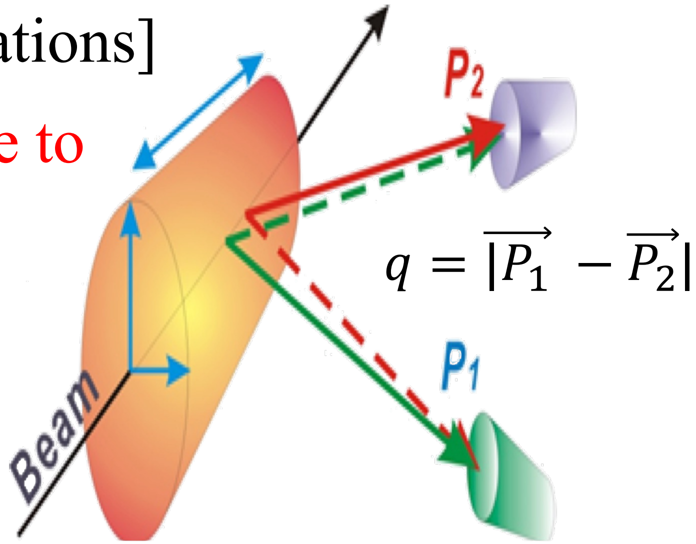
➢ Nuclei homogeneity

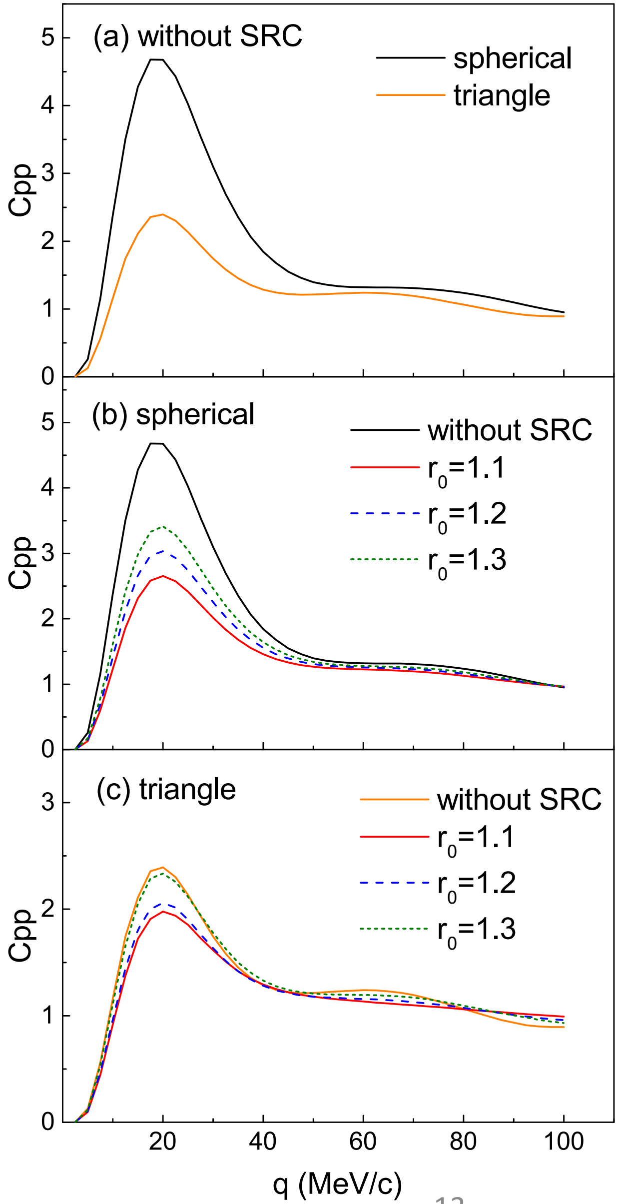
- ✓ The homogeneity of the system via femtoscopy measurements [two pion/proton correlations]

Femtoscopy measurements can be sensitive to SRC and clustering.







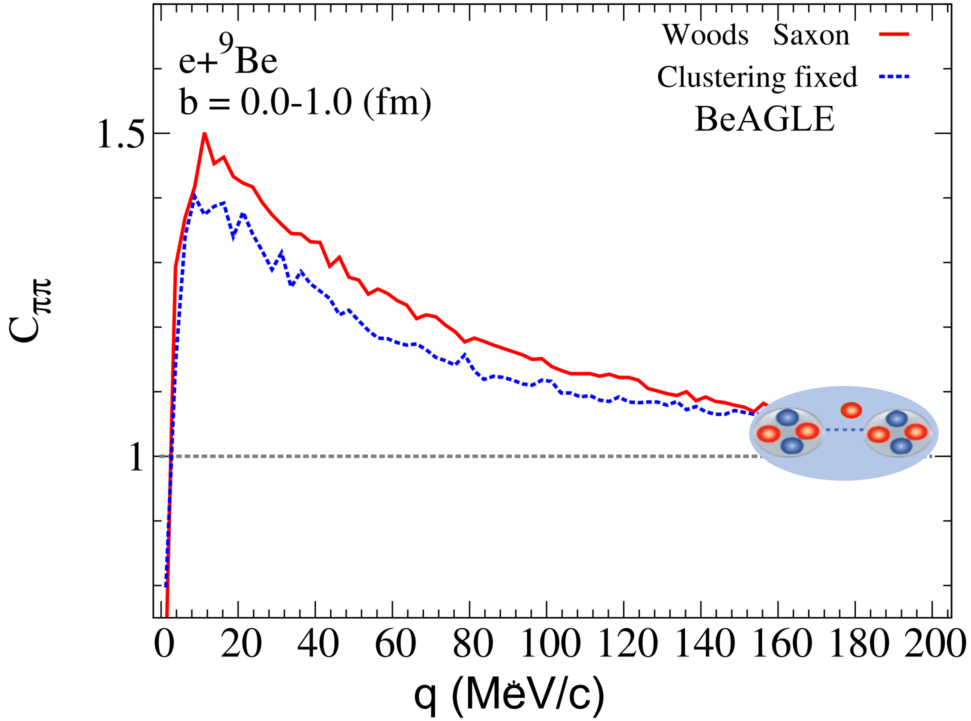


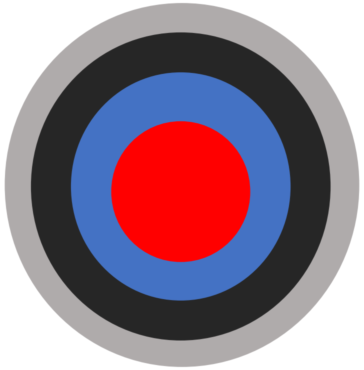
Femtoscopy measurements can be sensitive to the system size.

❖ The α clustering

➢ Nuclei homogeneity

Case-1: Woods–Saxon
Case-2: Clustering fixed orientation





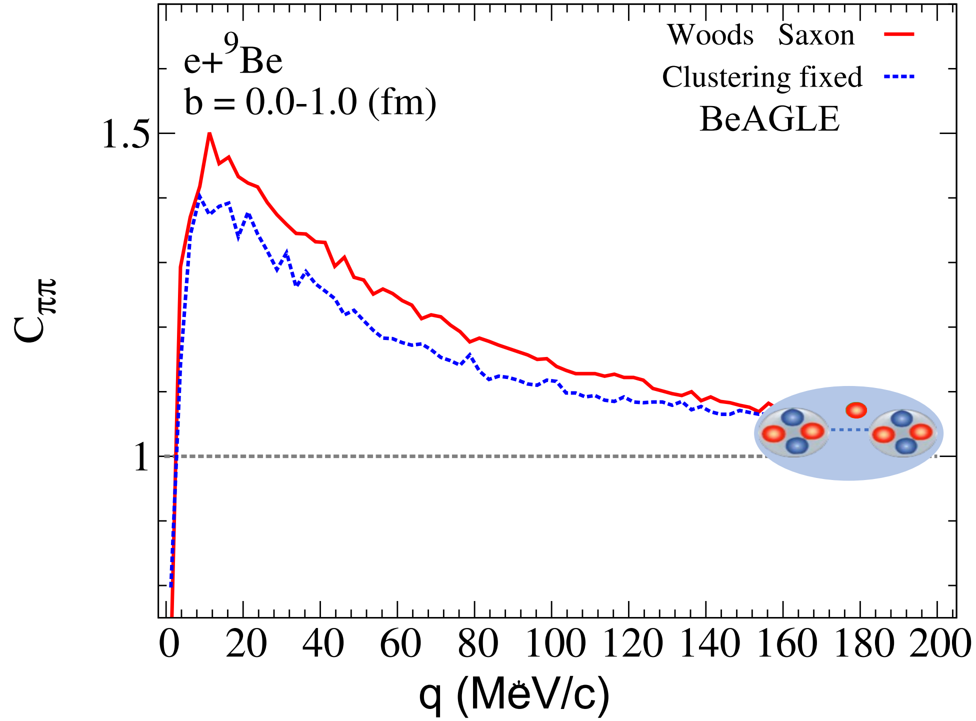
Femtoscopy measurements can be sensitive to the clustering.

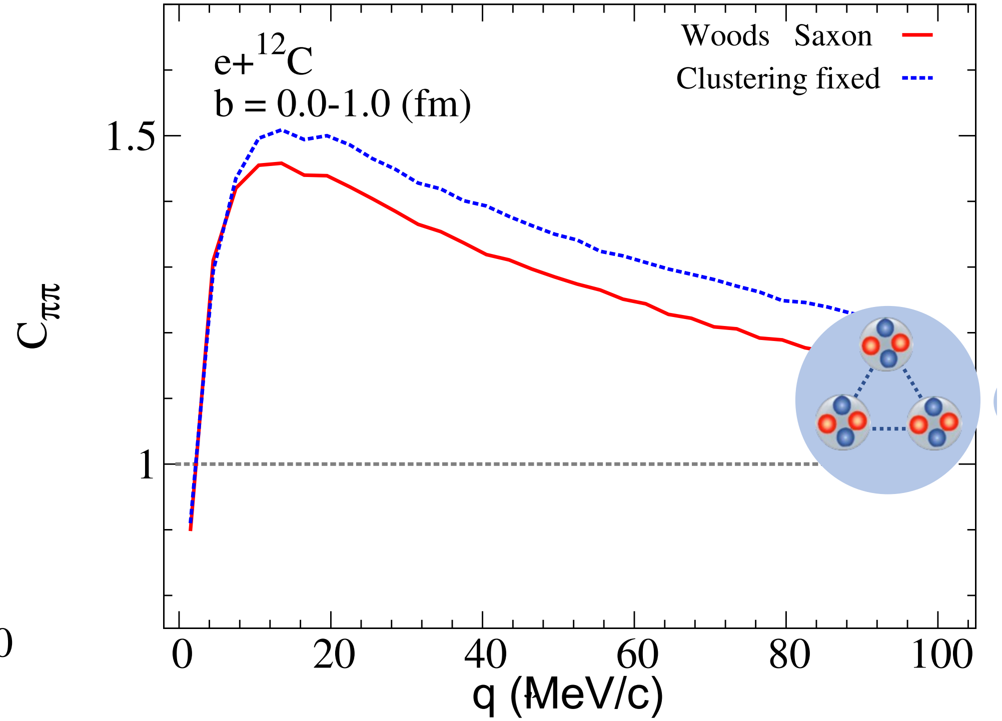
We are planning to extend the study to the SRC effect.

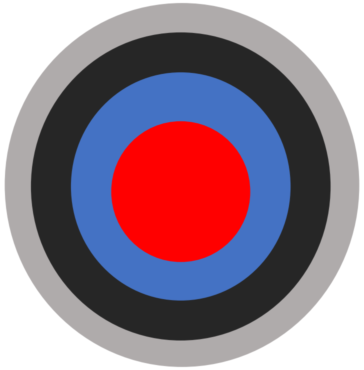
❖ The α clustering

➢ Nuclei homogeneity

Case-1: Woods–Saxon
Case-2: Clustering fixed orientation







Femtoscopy measurements can be sensitive to the clustering.

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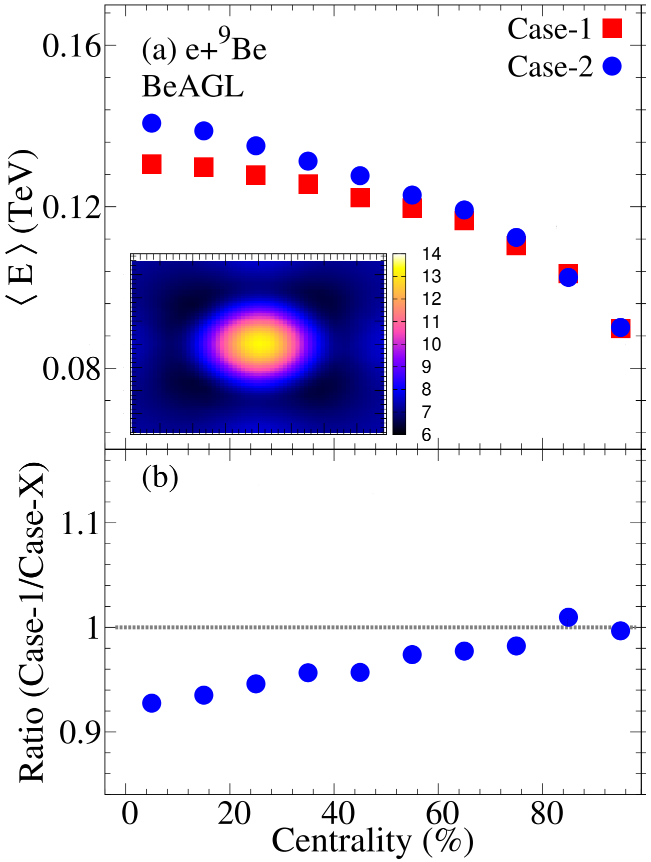
❖ The α clustering

➢ The system energy/momentum

✓ The $\langle E \rangle$ and/or $\langle p \rangle$ measured in the forward detector is related to the impact parameter and the number of collisions

Case-1: Woods–Saxon
Case-2: Clustering fixed orientation



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

❖ The α clustering

➢ The system energy/momentum

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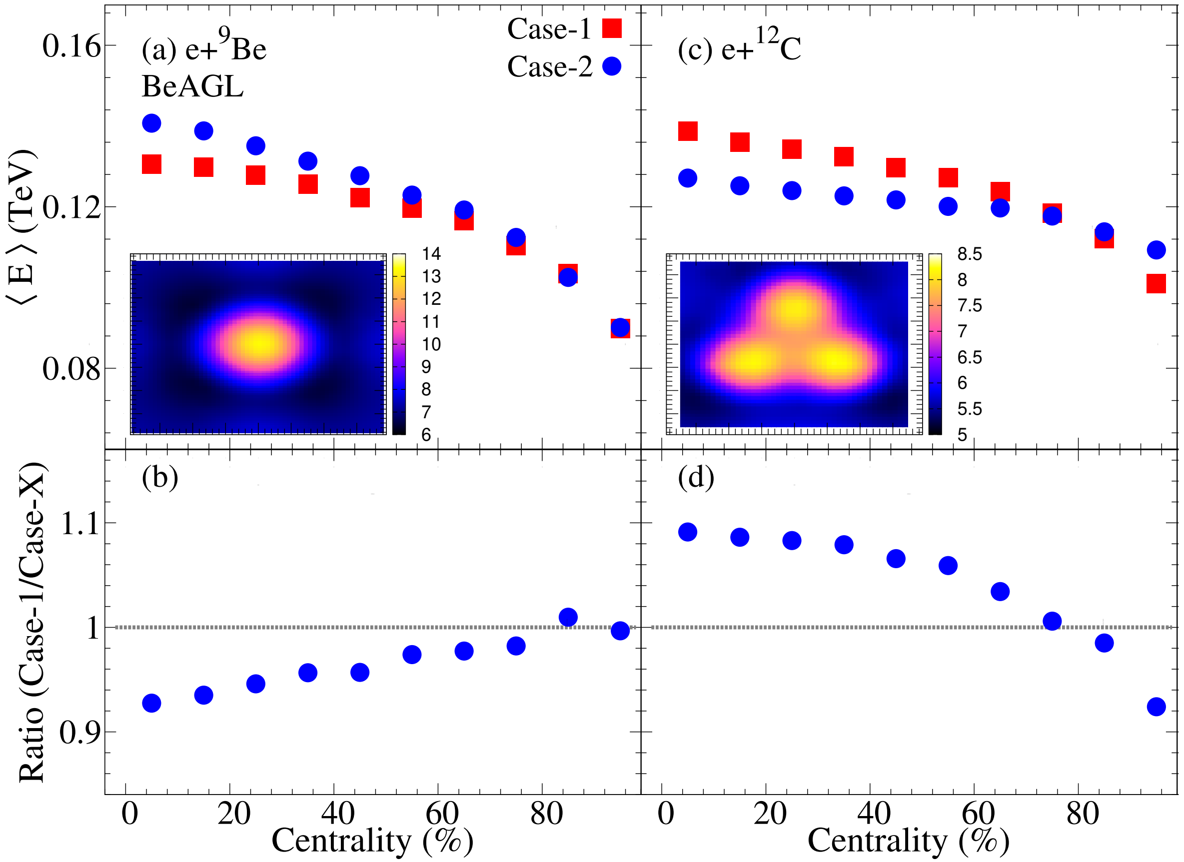
Case-2: Clustering fixed orientation



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❖ The α clustering

➢ The system energy/momentum

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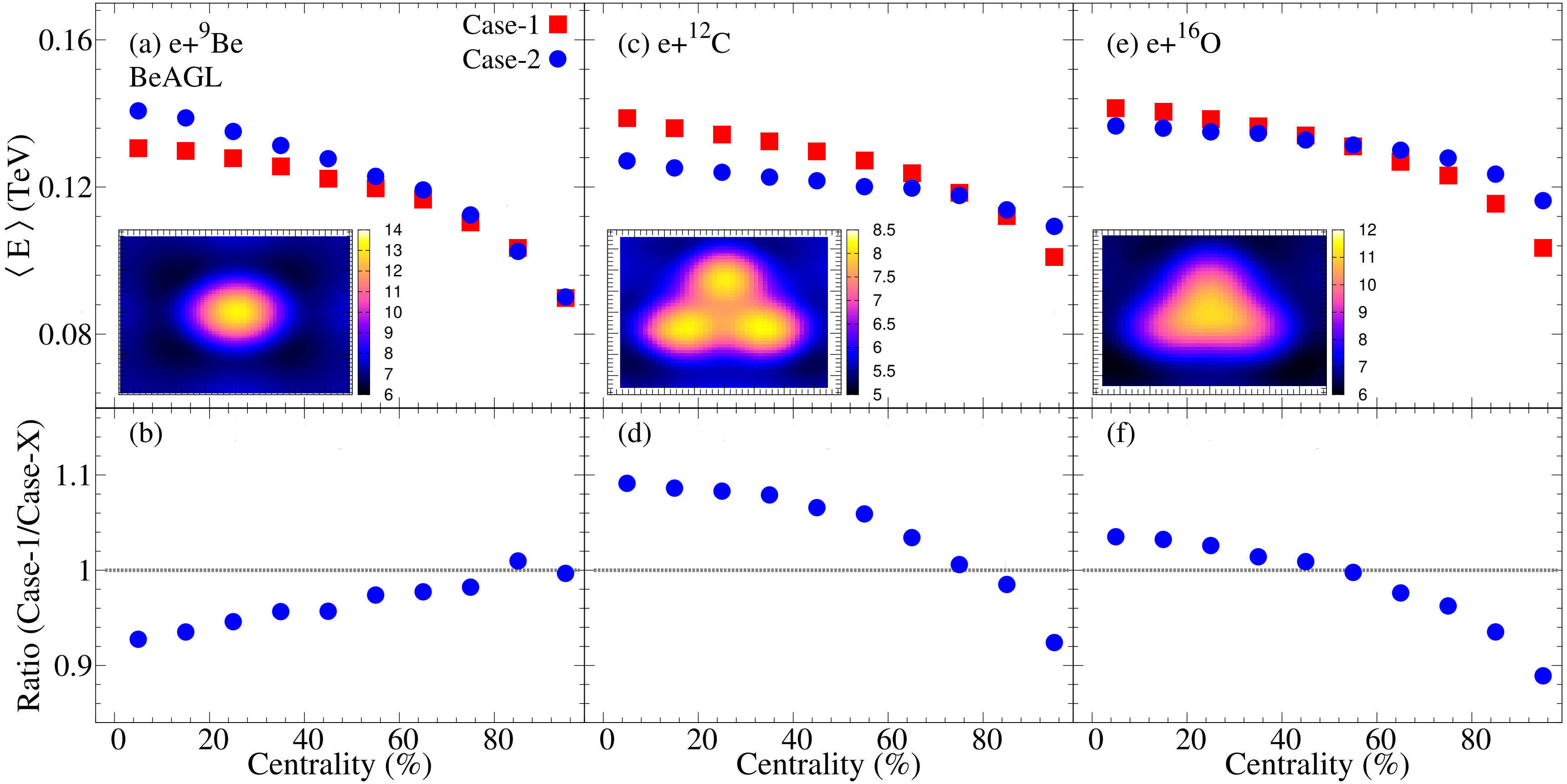
Case-1: Woods–Saxon
Case-2: Clustering fixed orientation



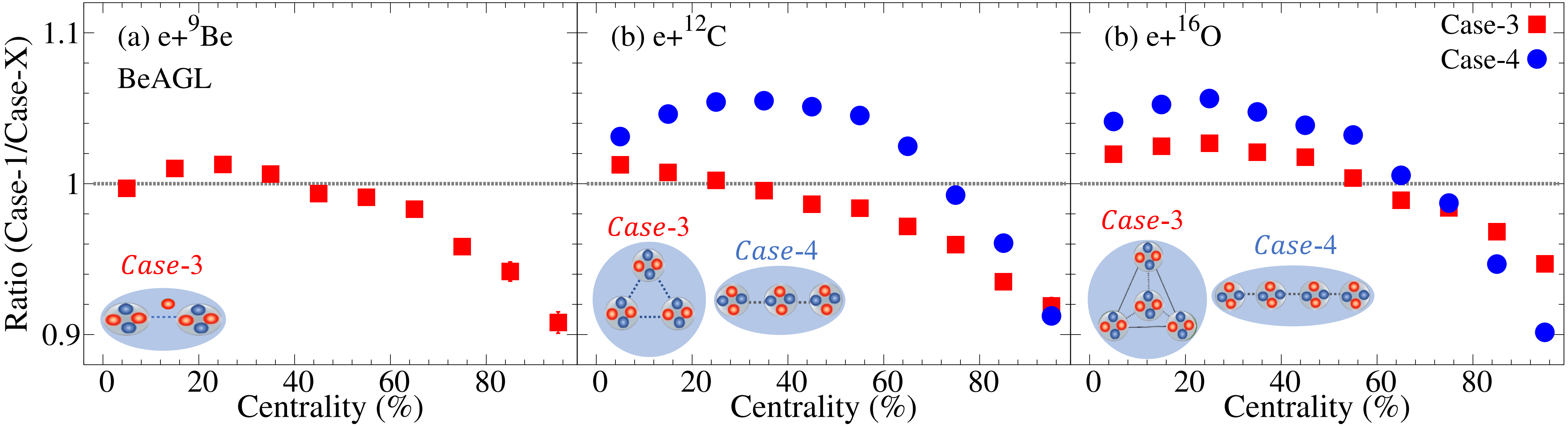
The $\langle E \rangle$ in B_0 is sensitive to α clustering in Be^9, C^{12}, and O^{16}

Case-1: Woods–Saxon
Case-3,4: Clustering random orientation

❖ The α clustering

➢ The system energy/momentum

✓ The $\langle E \rangle$ and/or $\langle p \rangle$ measured in the forward detector is related to the impact parameter and the number of collisions



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

❖ Conclusions

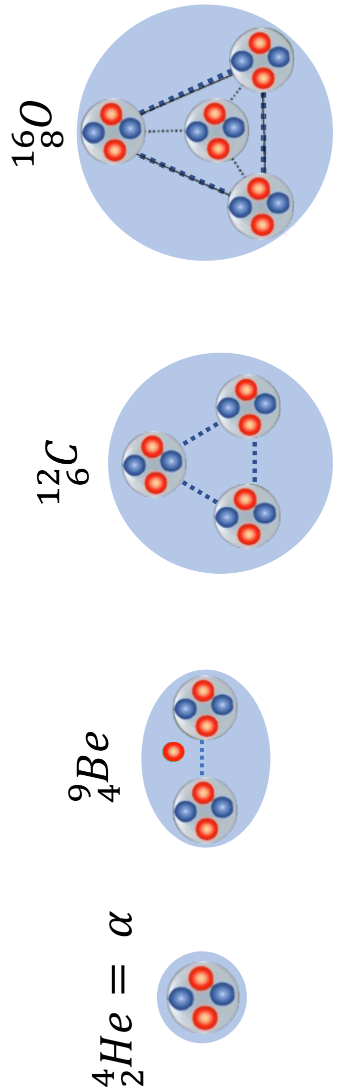
We investigated the ability to use the EIC to study the α clustering in $^{9}_{4}Be$, $^{12}_{6}C$, and $^{16}_{8}O$:

- **We proposed three measurements**
  - ✓ Incoherent scattering
  - ✓ Nuclei homogeneity
  - ✓ The system energy/momentum

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

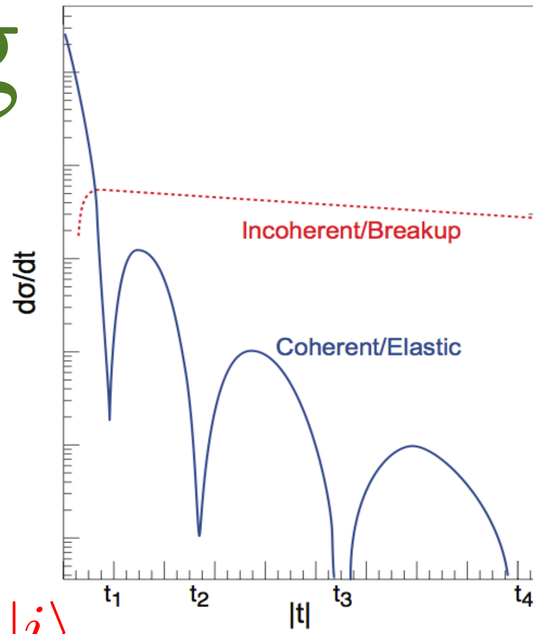
Such measurements can be achieved by comparing different isotopes of $_{4}Be$, $_{6}C$, $_{8}O$, …

Thank You



❖ Third Measurement

Incoherent Scattering



Good, Walker:

Nucleus dissociates ($f \neq i$):

$$\sigma_{\text{incoherent}} \propto \sum_{f\neq i} \langle i|\mathcal{A}|f\rangle^{\dagger} \langle f|\mathcal{A}|i\rangle$$

complete set

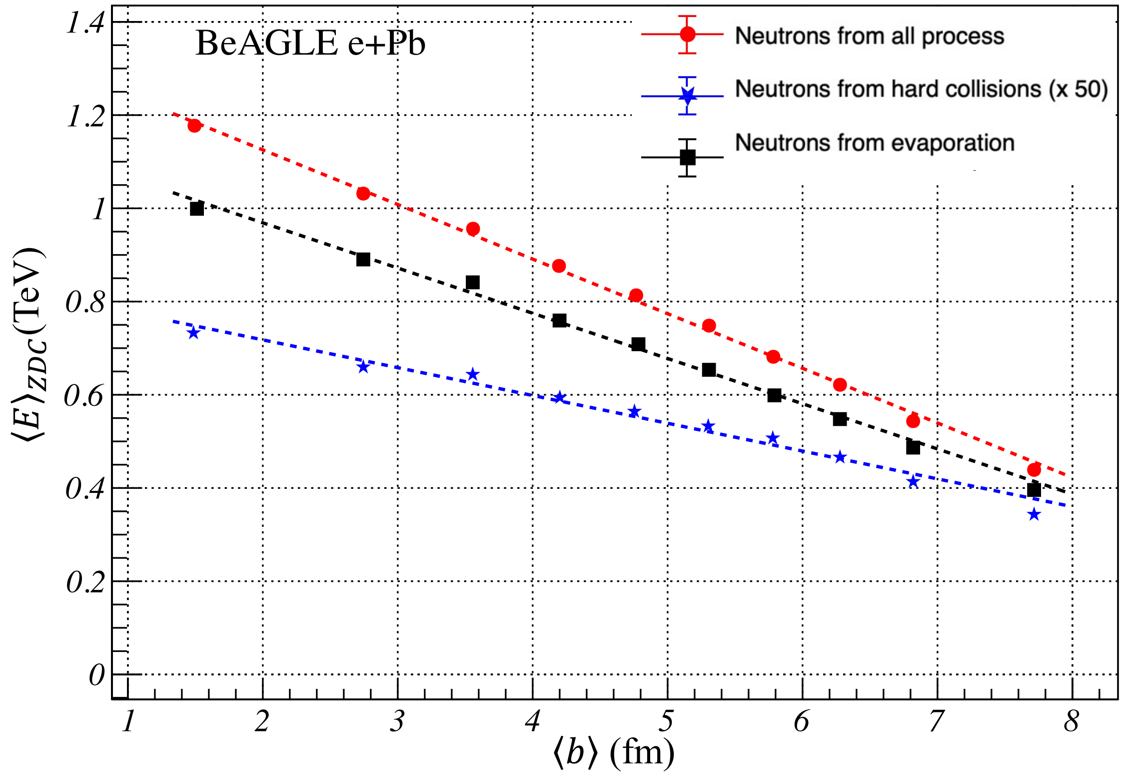
$$= \sum_{f} \langle i|\mathcal{A}|f\rangle^{\dagger} \langle f|\mathcal{A}|i\rangle - \langle i|\mathcal{A}|i\rangle^{\dagger} \langle i|\mathcal{A}|i\rangle$$

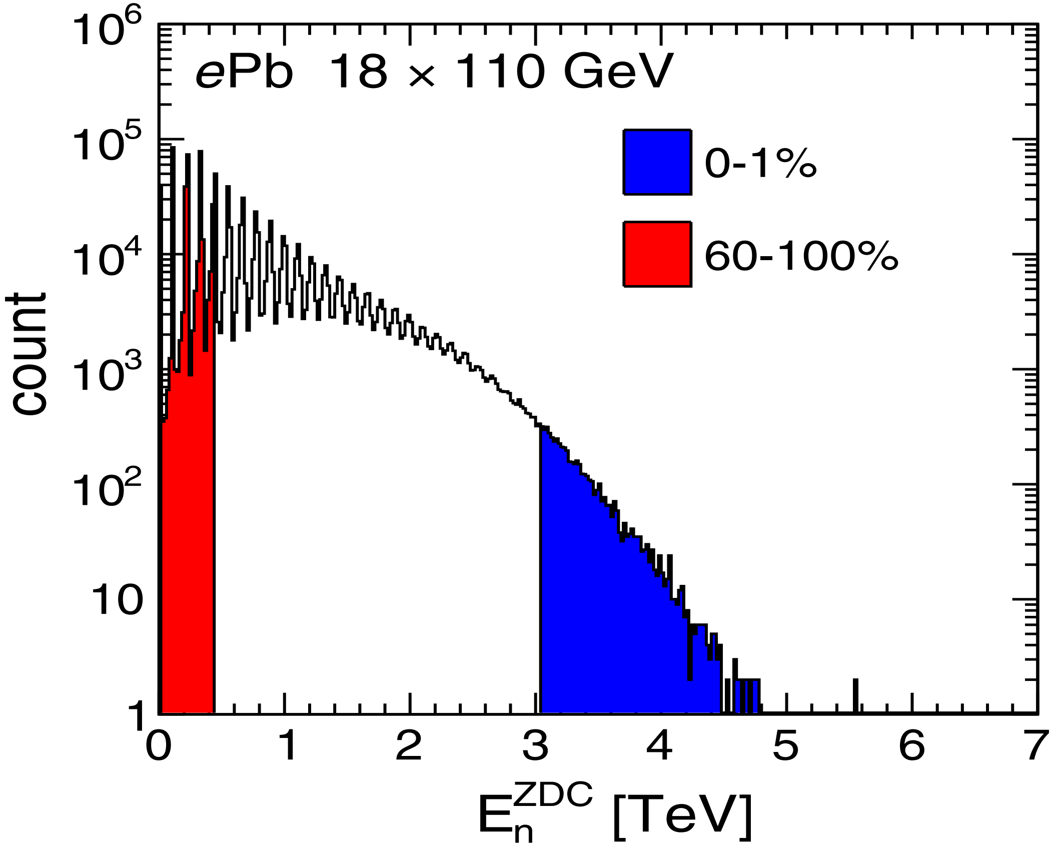
$$= \left\langle i \left| |\mathcal{A}|^2 \right| i \right\rangle - |\langle i|\mathcal{A}|i\rangle|^2 = \left\langle |\mathcal{A}|^2 \right\rangle - |\langle \mathcal{A}\rangle|^2$$

The incoherent CS is the variance of the amplitude!!

$$\frac{d\sigma_{\text{total}}}{dt} = \frac{1}{16\pi} \left\langle |\mathcal{A}|^2 \right\rangle \qquad \frac{d\sigma_{\text{coherent}}}{dt} = \frac{1}{16\pi} |\langle \mathcal{A}\rangle|^2$$

❖ Correlations of the $\langle E_{ZDC}\rangle$ and impact parameter



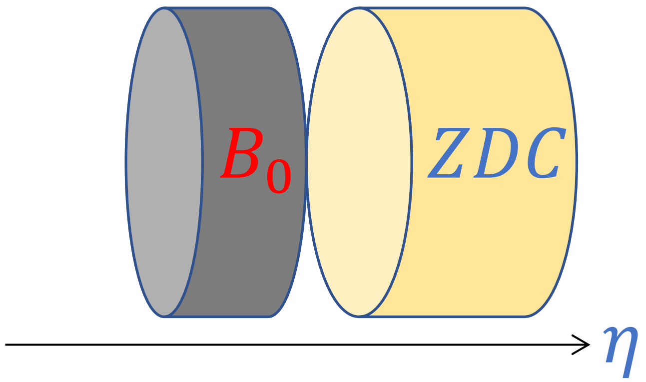


Neutrons from all sources can be used for centrality definition.

❖ 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

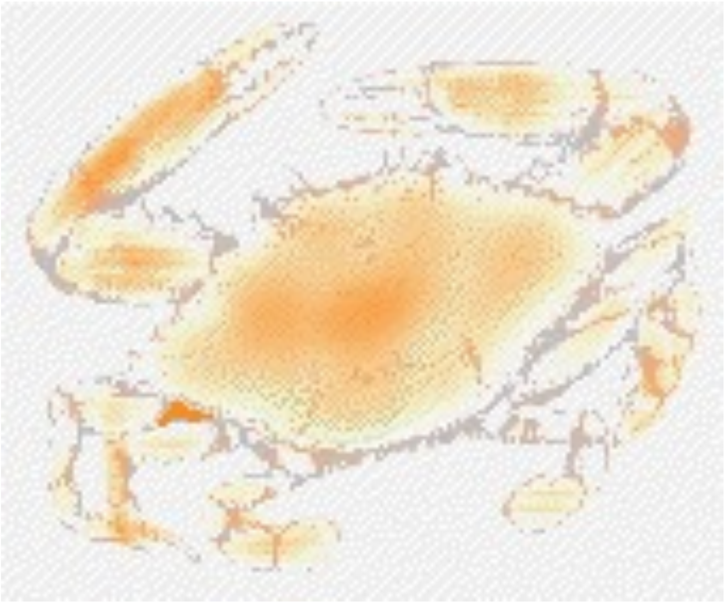


➢ In this current study, we are using: ZDC and B_0 detectors

❖ We use a hadronic afterburner that introduces such information.

$$\vec{C}\left(\vec{k}^*\right) = \frac{\int \vec{S}\left(\vec{r}^*, \vec{k}^*\right) \left|\Psi_{\vec{k}^*}\left(\vec{r}^*\right)\right|^2 d^4\vec{r}^*}{\int \vec{S}\left(\vec{r}^*, \vec{k}^*\right) d^4\vec{r}^*}, \qquad (10)$$

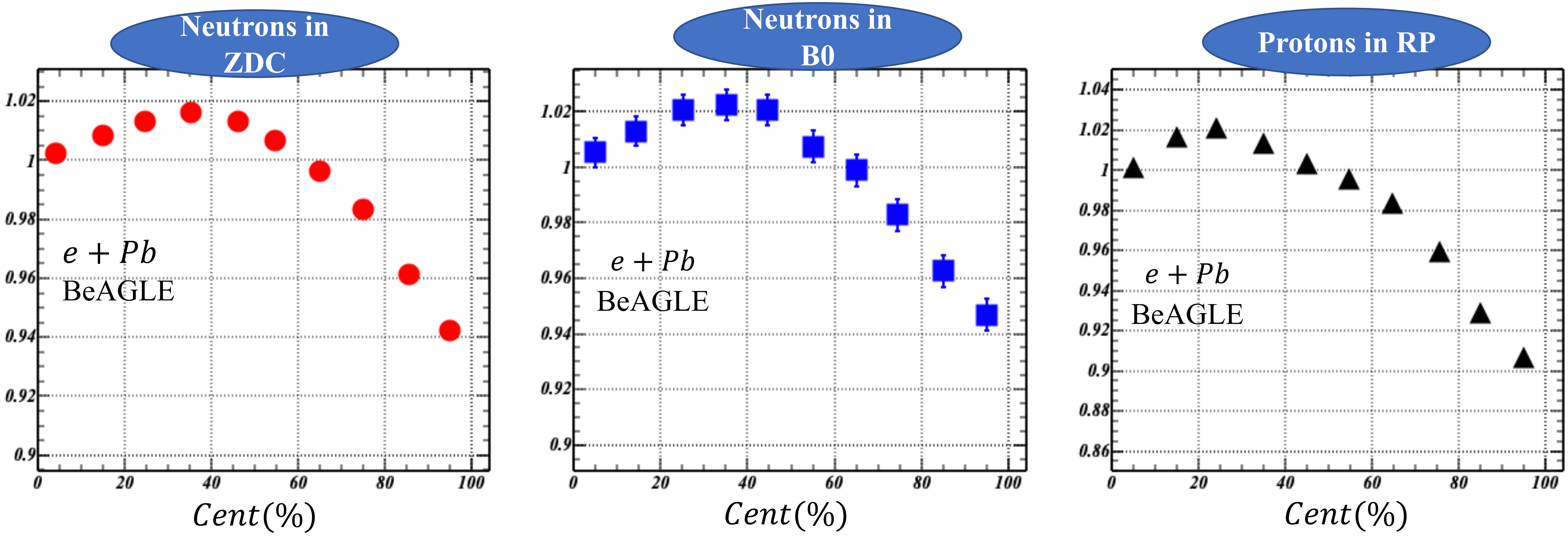
where $\vec{r}^* = \vec{x}_1 - \vec{x}_2$ is the relative distance of two particles at their kinetic freeze-out, $\vec{k}^*$ is half of the relative momentum between two particles and later one we use q for the same quantity, $\vec{S}\left(\vec{r}^*, \vec{k}^*\right)$ is the probability to emit a particle pair with given $\vec{r}^*$ and $\vec{k}^*$, *i.e.*, the source emission function, and $\Psi_{\vec{k}^*}\left(\vec{r}^*\right)$ is Bethe-Salpeter amplitude which can be approximated by the outer solution of the scattering problem [59].



Scott Pratt, model

➢ Deformed Pb ($\beta_2 = 0.28, \beta_4 = 0.093$)

✓ The ratio of the undeformed to deformed Pb

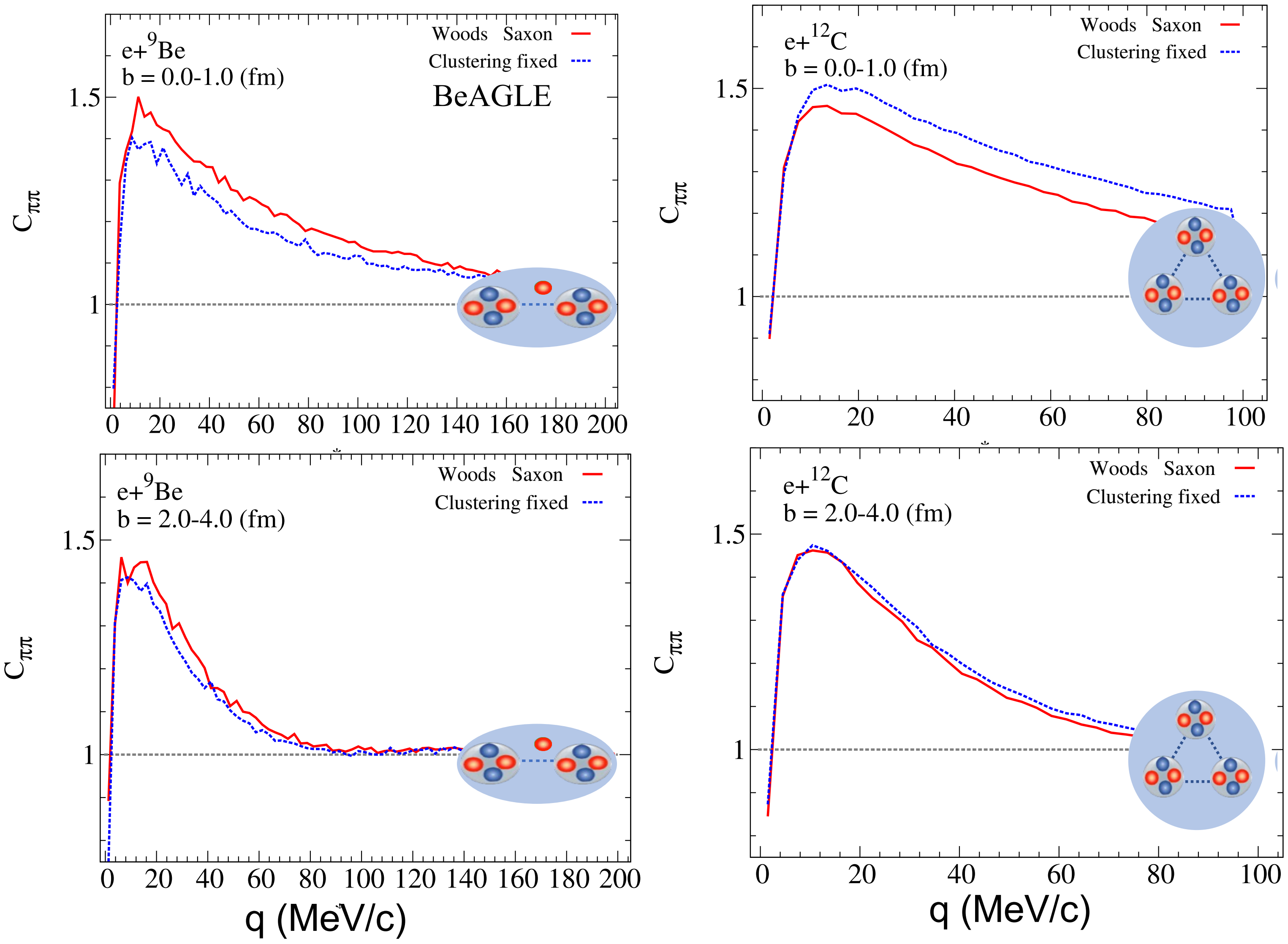


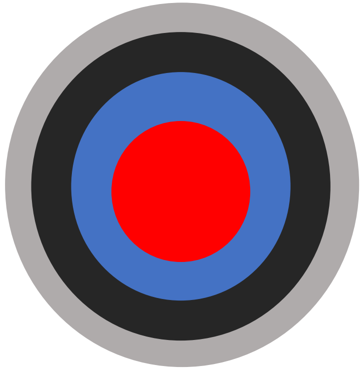
Neutrons and Protons from all sources in forward rapidity show sensitivity to β_2 and β_4 deformation in different centrality selections.

❖ The α clustering

➢ Nuclei homogeneity

Case-1: Woods–Saxon
Case-2: Clustering fixed orientation





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