Stony Brook University

Center for Frontiers in Nuclear Science

The physics of e+A collisions at the Electron-Ion Collider

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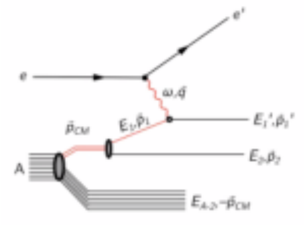
❖ The BeAGLE model:

PRD 106, 012007 (2022)



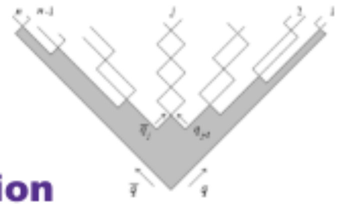
Primary interaction

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

Glauber handled by BeAGLE

PyQM: Nuclear Geometry + optional gluon radiation in medium.

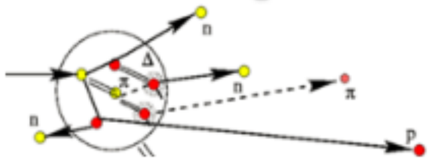
Hadronization handled by **PYTHIA6.**



Hadronization

Cascade process handled by **DPMJET.**

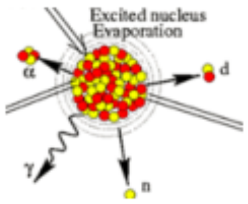
Formation time. Stochastic.



Intra-nuclear cascade

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

Nuclear remnant evaporation & breakup



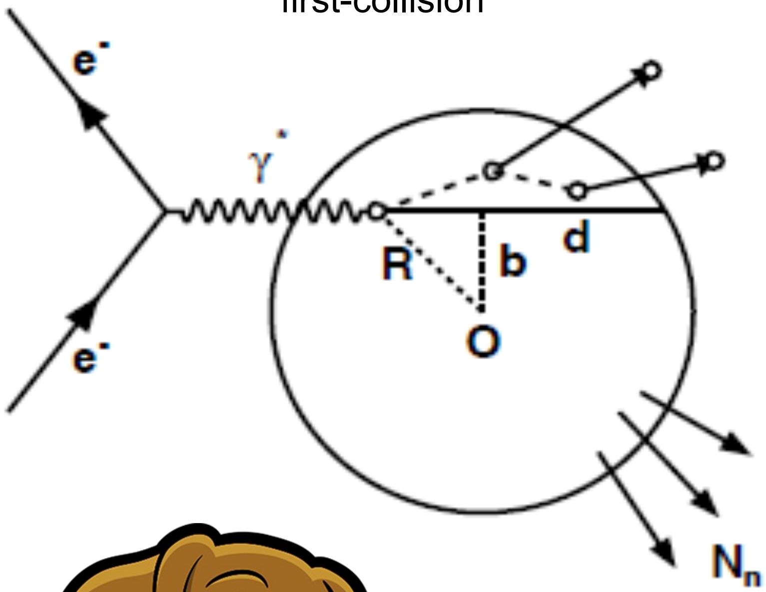
Some Nuclear Effects

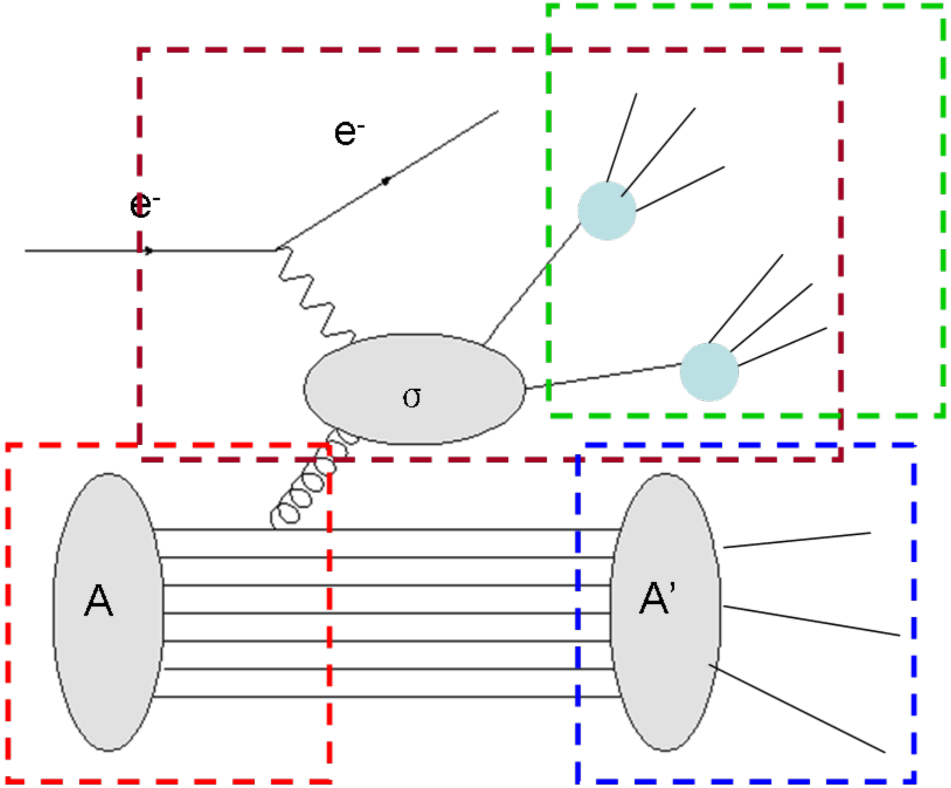
	In BeAGLE
Parton distribution functions	✓
Parton saturation (CGC etc.)	
Short-range correlations	✓ (GCF)
"Fermi motion"	✓
Partonic (or "dipole") MS	✓
Partonic gluon radiation	✓
Medium-modified hadronization	
Formation times	✓
Hadronic Cascade	✓
Nuclear evaporation, breakup	✓
Photonic de-excitation of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

❖ The BeAGLE model:

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

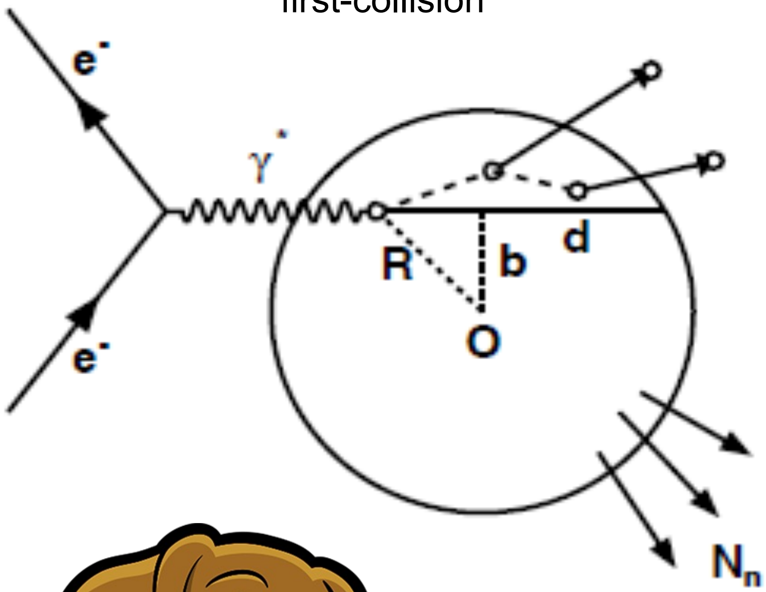
Energy loss effect from routine by Salgado&Wiedemann to simulate the nuclear fragmentation effect in cold nuclear matter

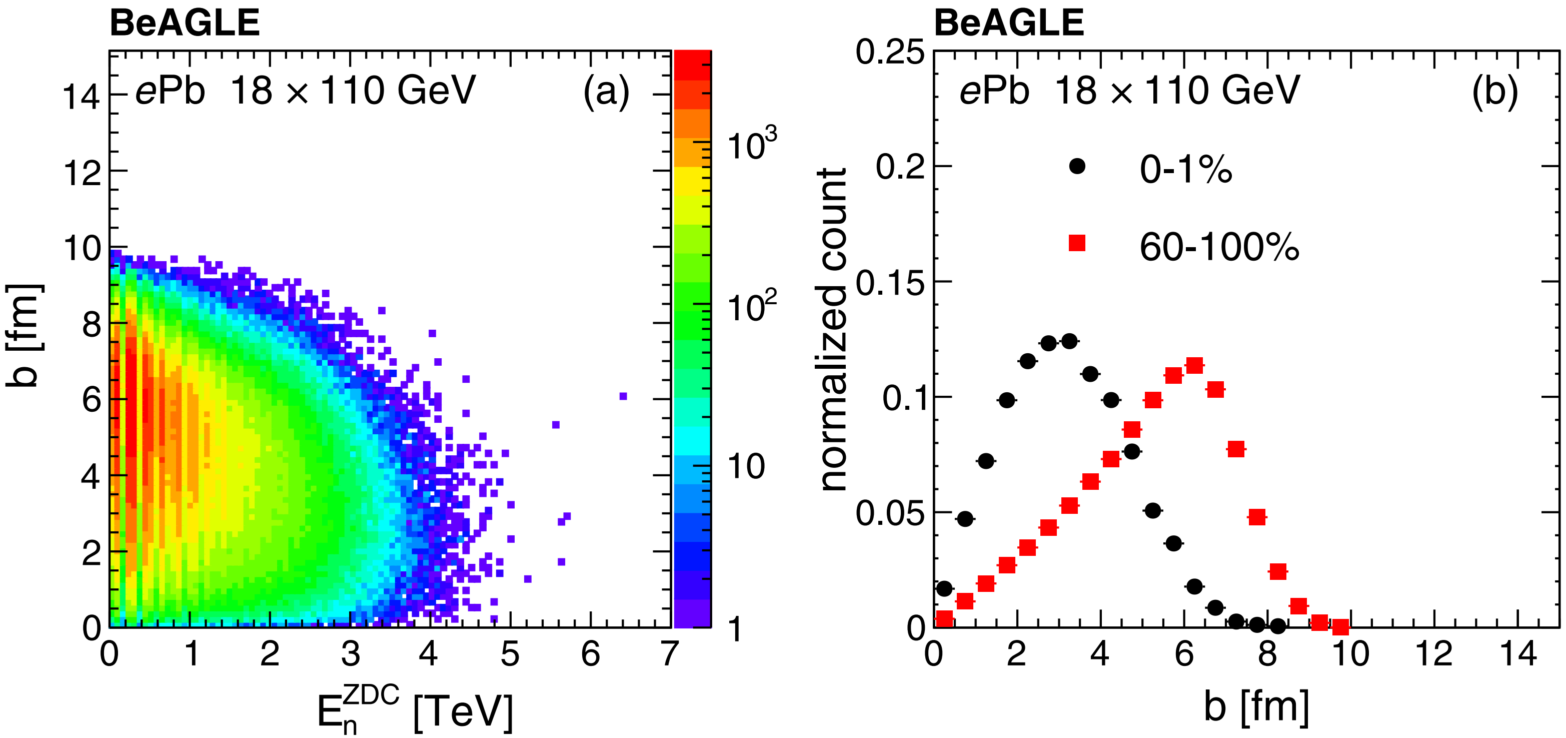
❖ The BeAGLE model:

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

PRD 106, 012007 (2022)

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

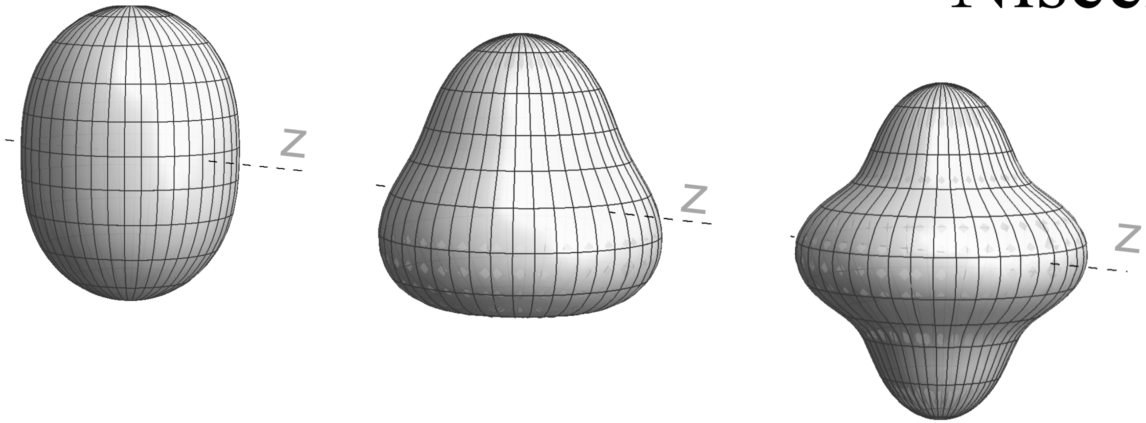


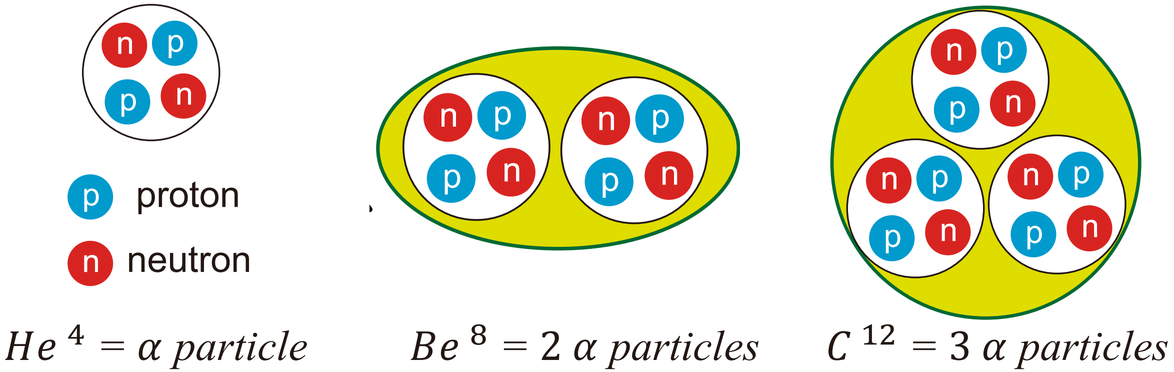


Neutrons in ZDC can be used for centrality definition.

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

Niseem Magdy





Can EIC provide additional constraints on nuclear structure?

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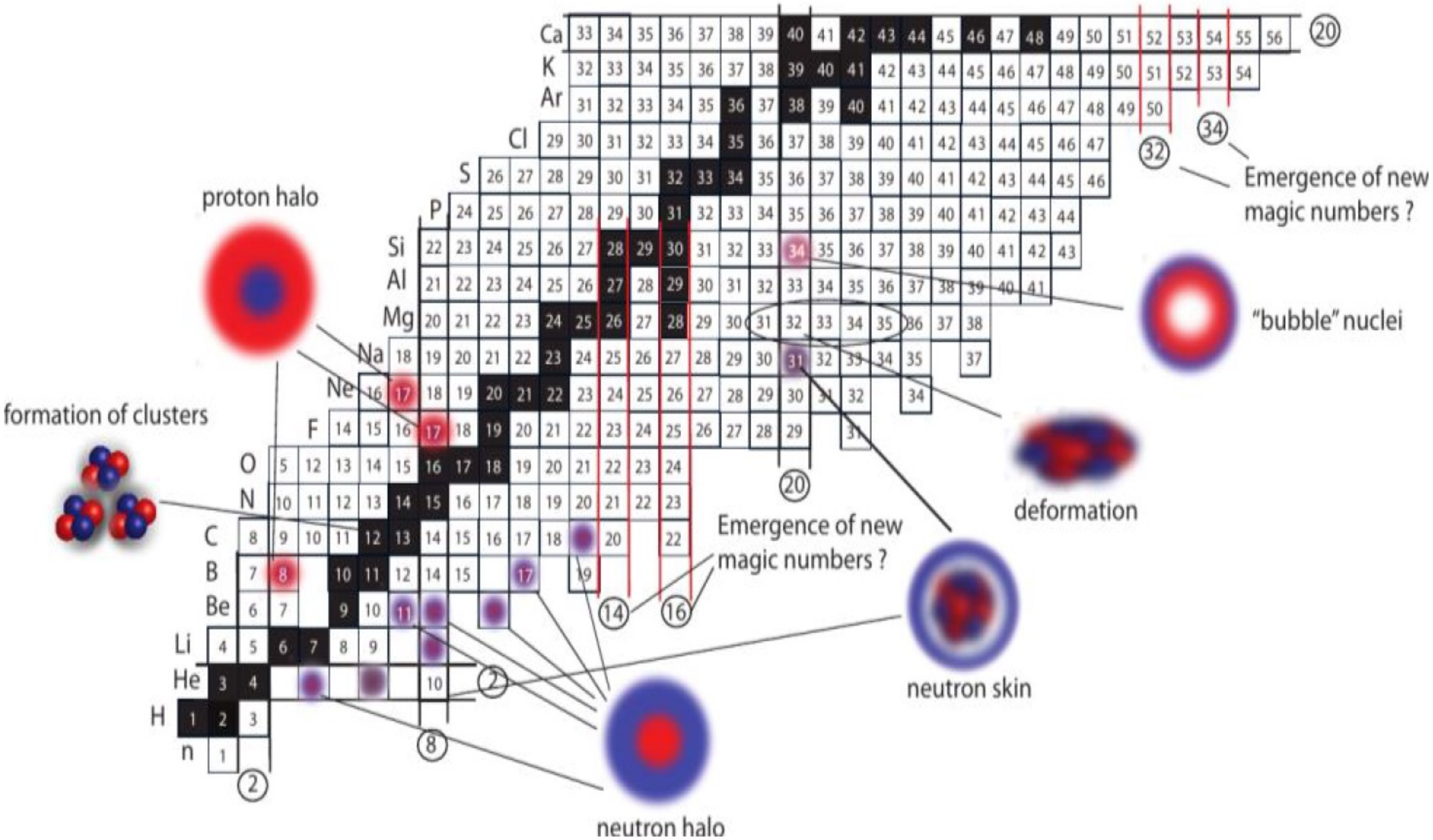
❖ Motivation

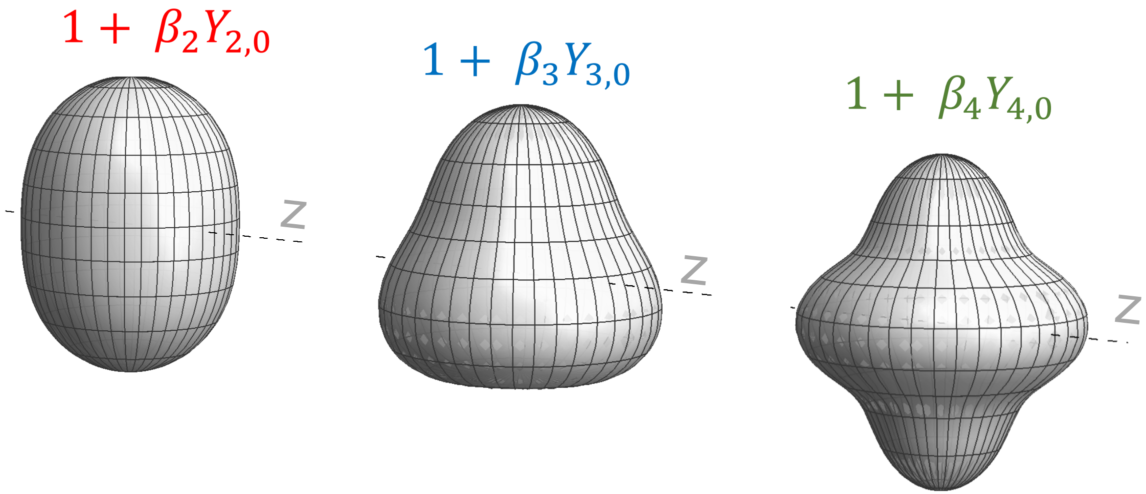
- ➢ The rich structure of atomic nuclei:
  - ✓ Clustering, halo, skin …
  - ✓ Quadrupole/octupole/hexdecopole deformations



❖ 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



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

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

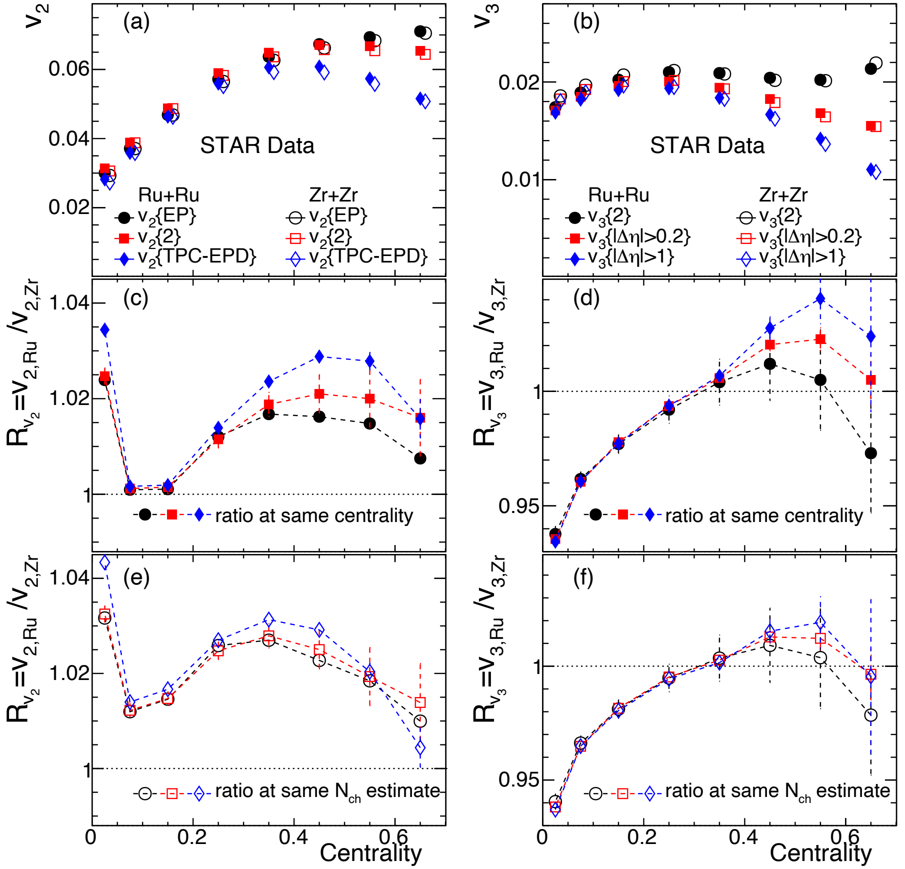
❖ Motivation

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)	$\frac{2048}{3675\pi^3}\beta_3^2 = 0.018\beta_3^2$	$\frac{3}{4\pi}\beta_2^2 = 0.239\beta_2^2$	$\frac{2048}{245\pi^3}\beta_3^2 = 0.270\beta_3^2$	$\frac{35}{36\pi}\beta_4^2 + \frac{45}{28\pi^2}\beta_2^4 = 0.31\beta_4^2 + 0.16\beta_2^4$

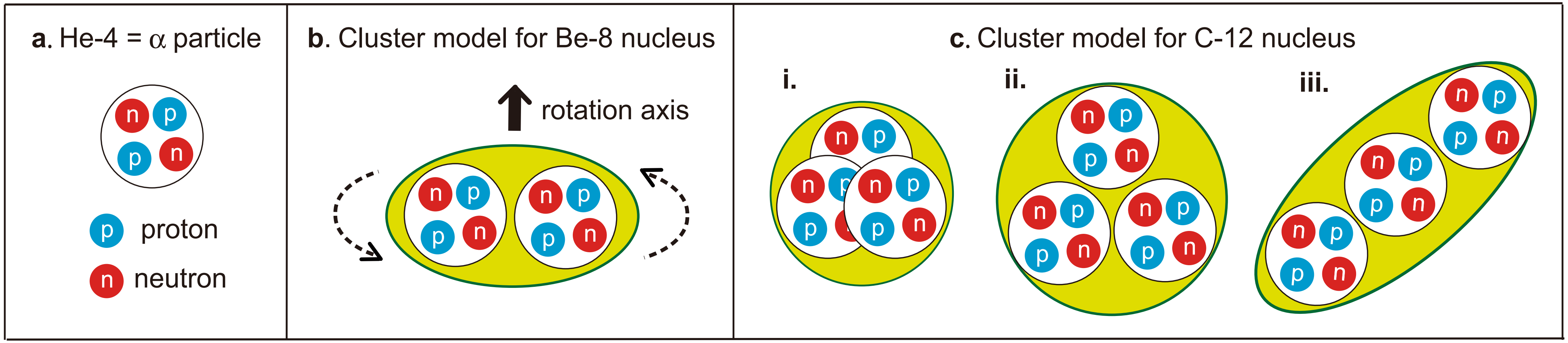
The ratio of the elliptic and triangular flow shows differences reflecting the β_2 and the β_3 dependence of Zr and Ru



❖ 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)

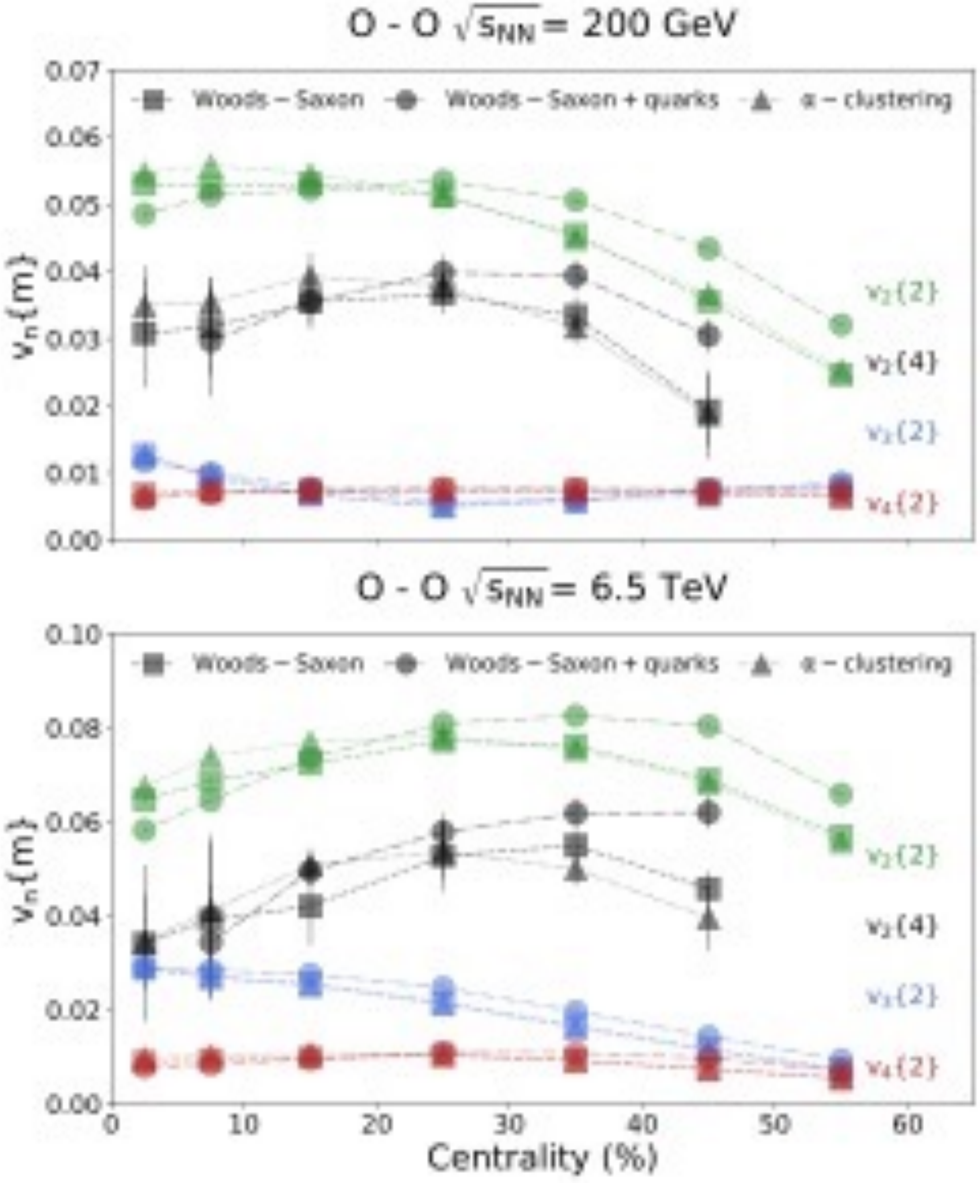
❖ Motivation

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.

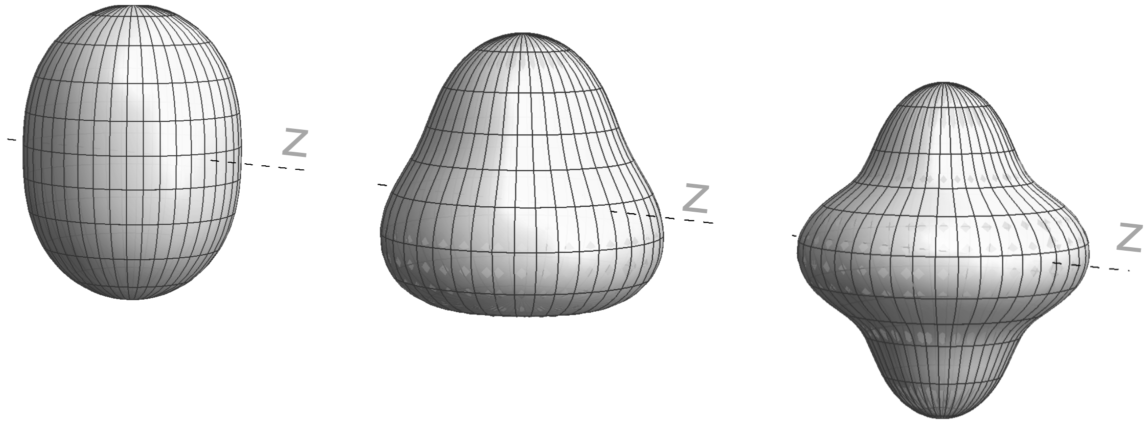
Phys.Rev.C 104 (2021) 4, L041901



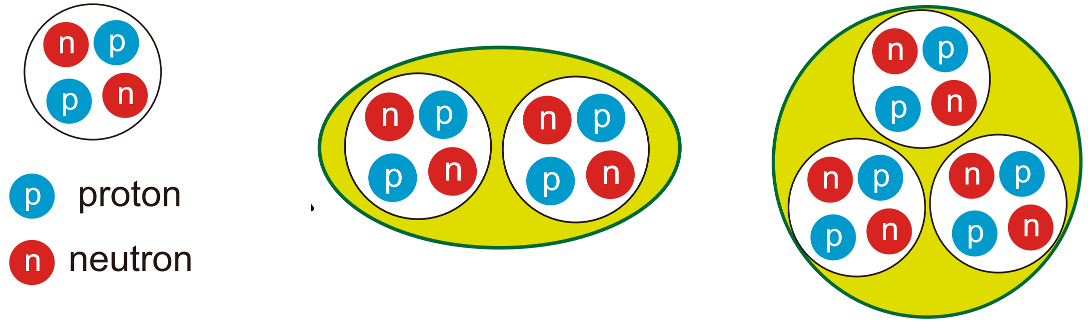
❖ Motivation

➢ 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 α clustering

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

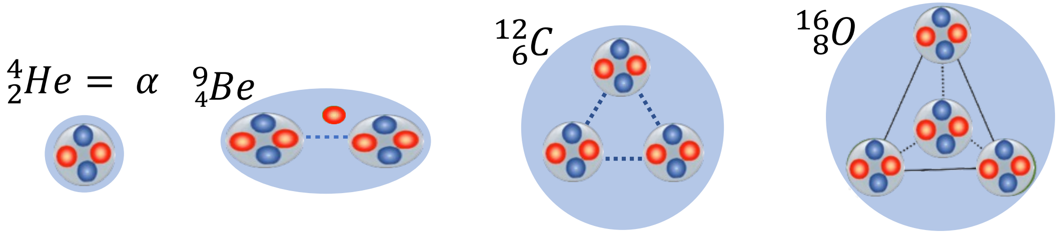
- ✓ The nuclear shape and structure picture have been into the BeAGLE model

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

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

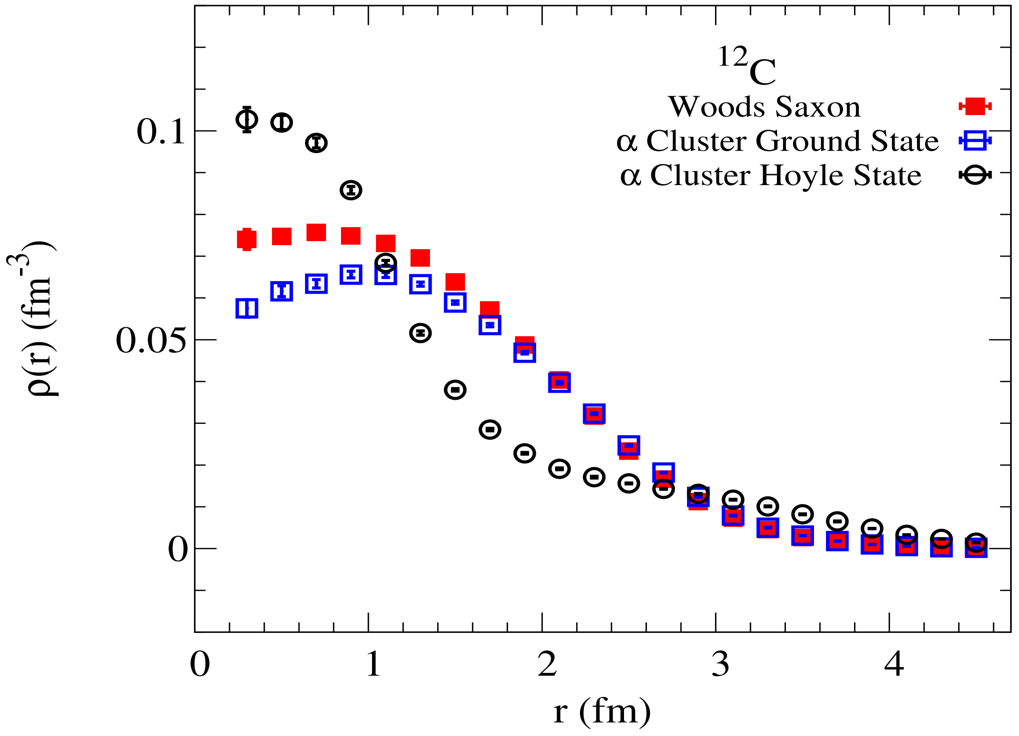
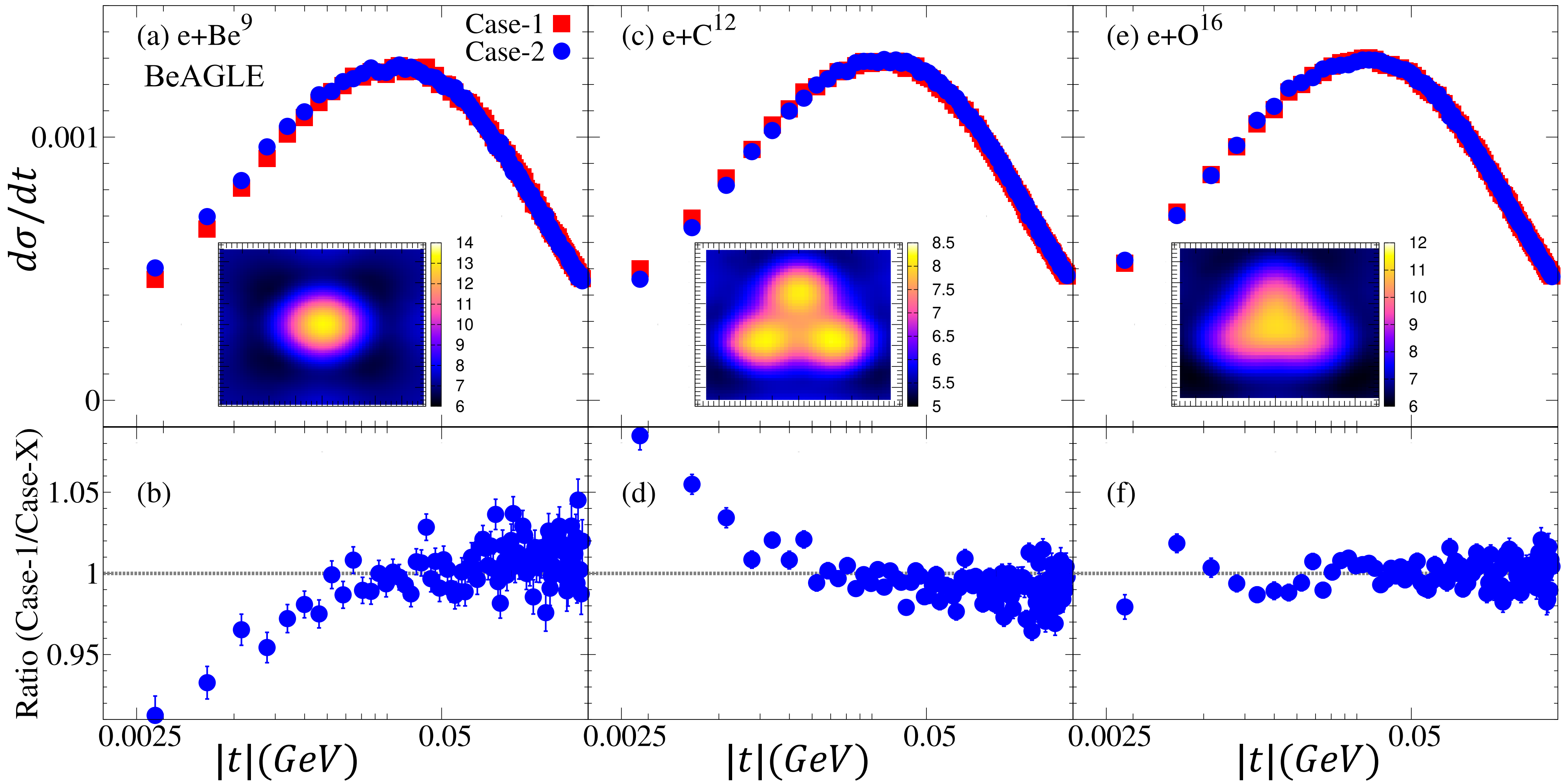


Figure.1: The normalized density distribution of the different configurations of the ^{12}C introduced into the BeAGLE model.

❖ 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}

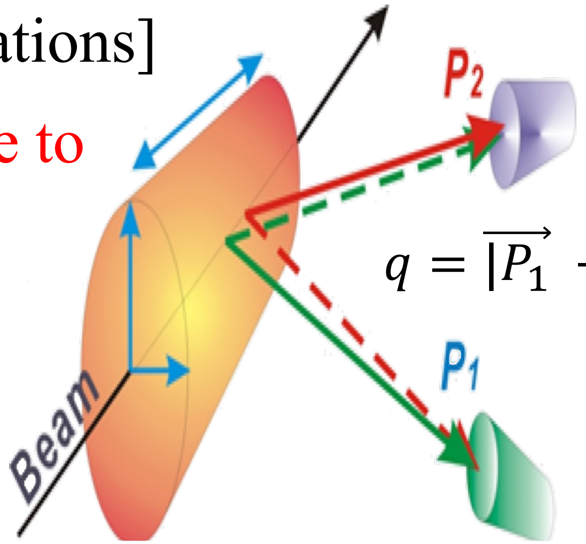
❖ The α clustering

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

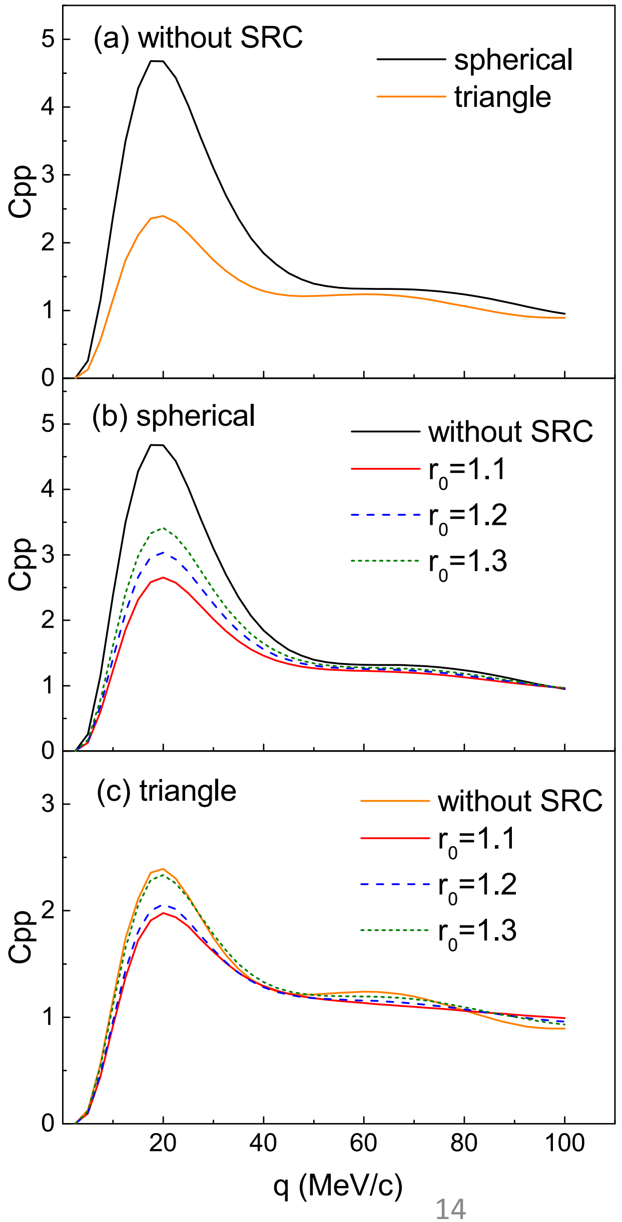
➢ Nuclei homogeneity

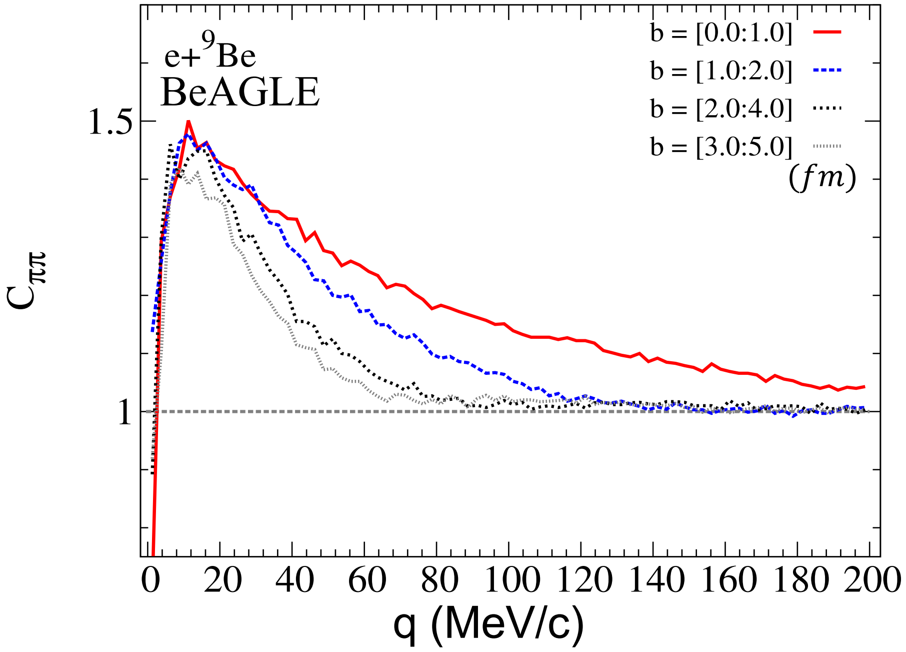
✓ The homogeneity of the system via femtoscopy measurements [two pion/proton correlations]

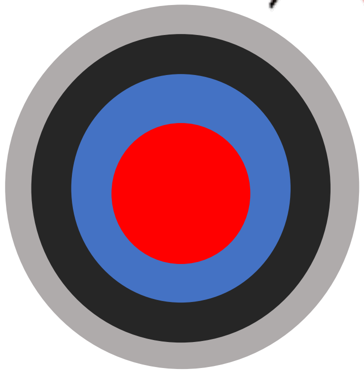
Femtoscopy measurements can be sensitive to SRC and clustering.



$q = |\overrightarrow{P_1} - \overrightarrow{P_2}|$





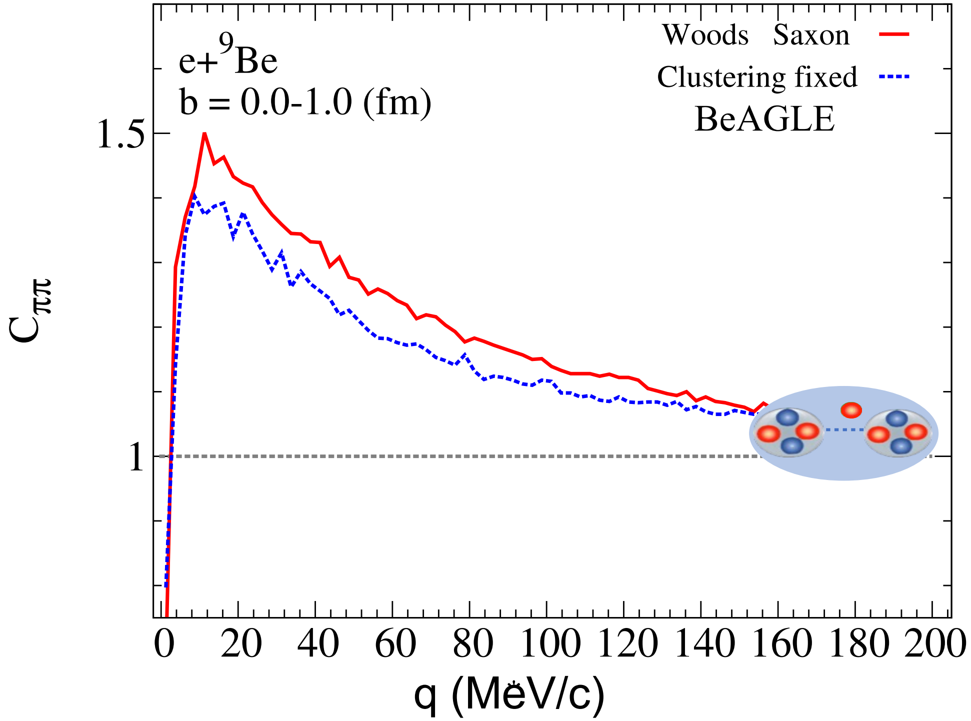


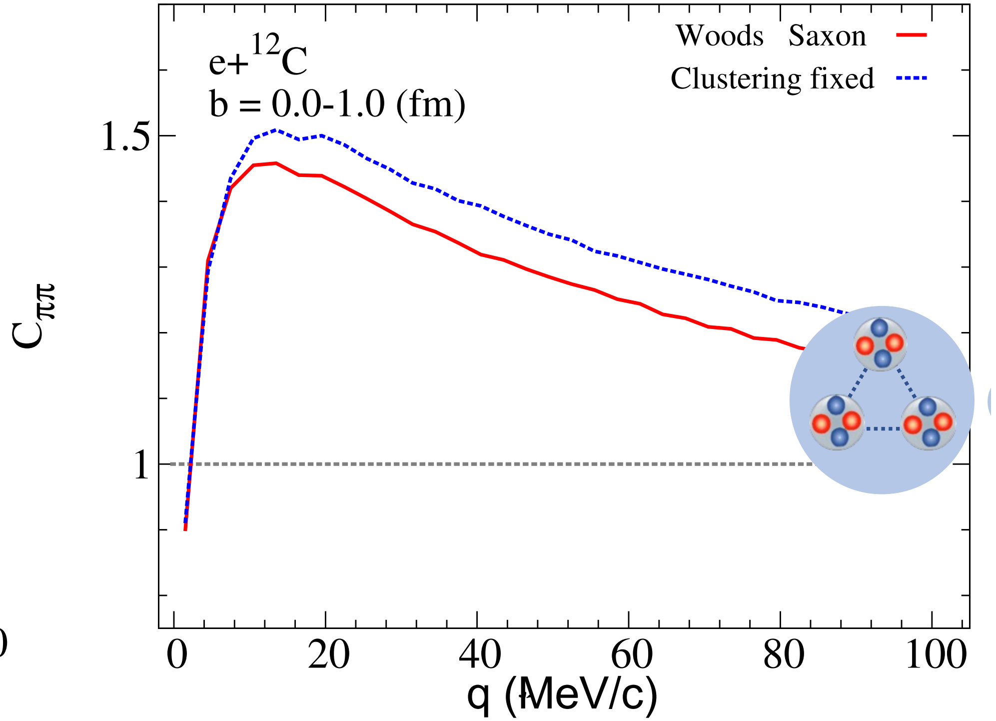
Femtoscopy measurements can be sensitive to the system size.

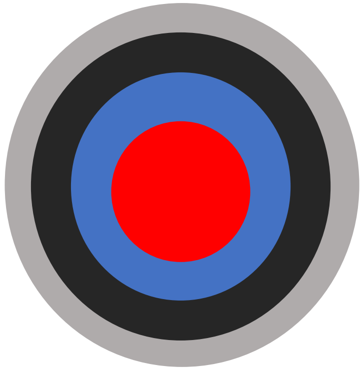
❖ The α clustering

➢ 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.

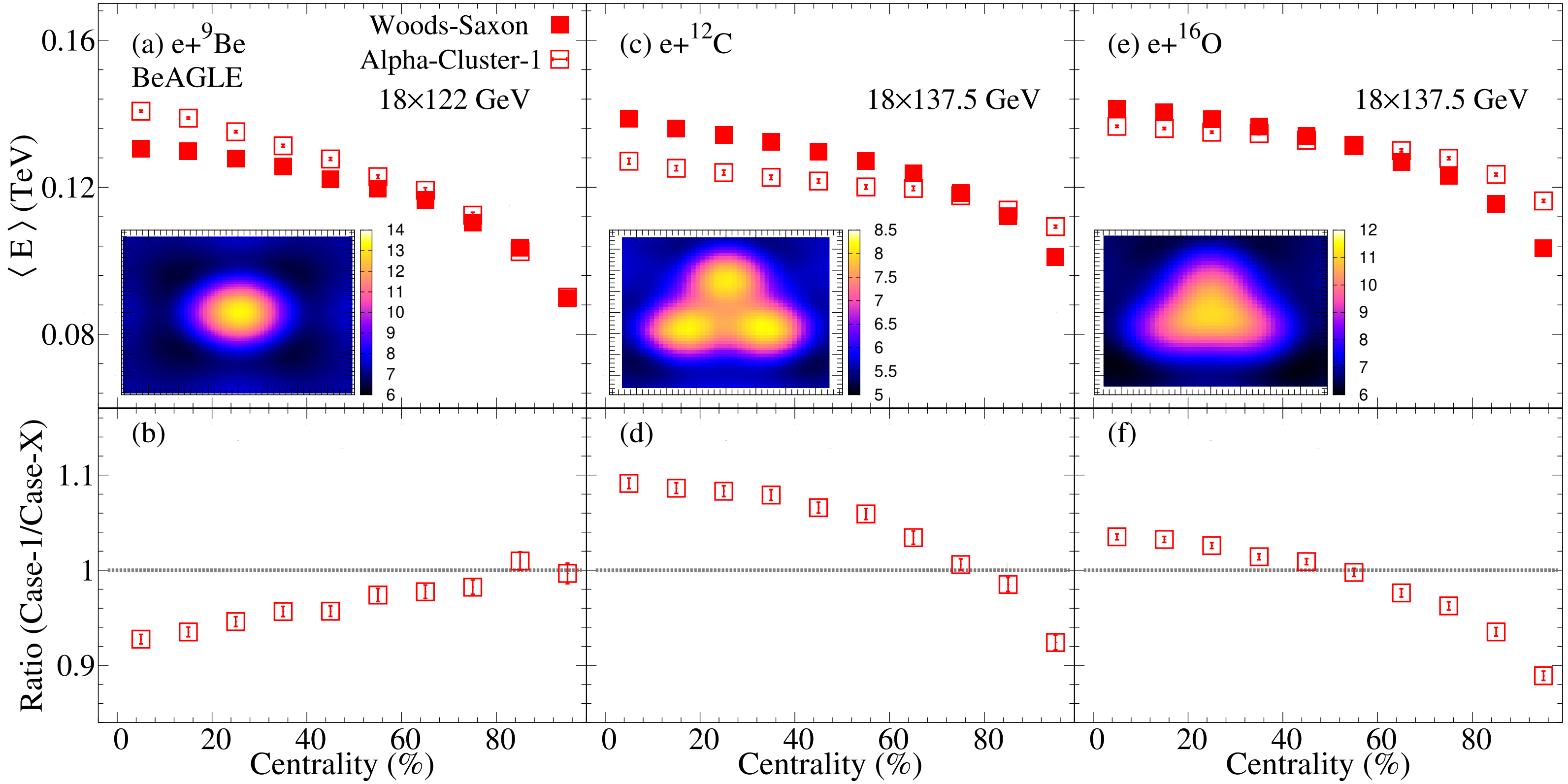
❖ The α clustering

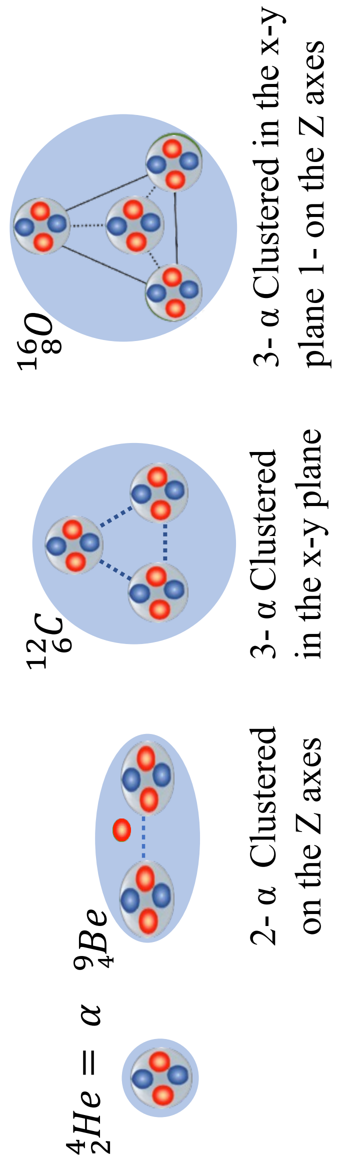
Identify the physics observables that can be used in such work.

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

The $\langle E \rangle$ in the forward B0 detector acceptant Vs centrality for fixed orientation nuclei.

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





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

❖ The α clustering

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

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The $\langle E \rangle$ in the forward B0 detector acceptant Vs centrality for fixed orientation nuclei.

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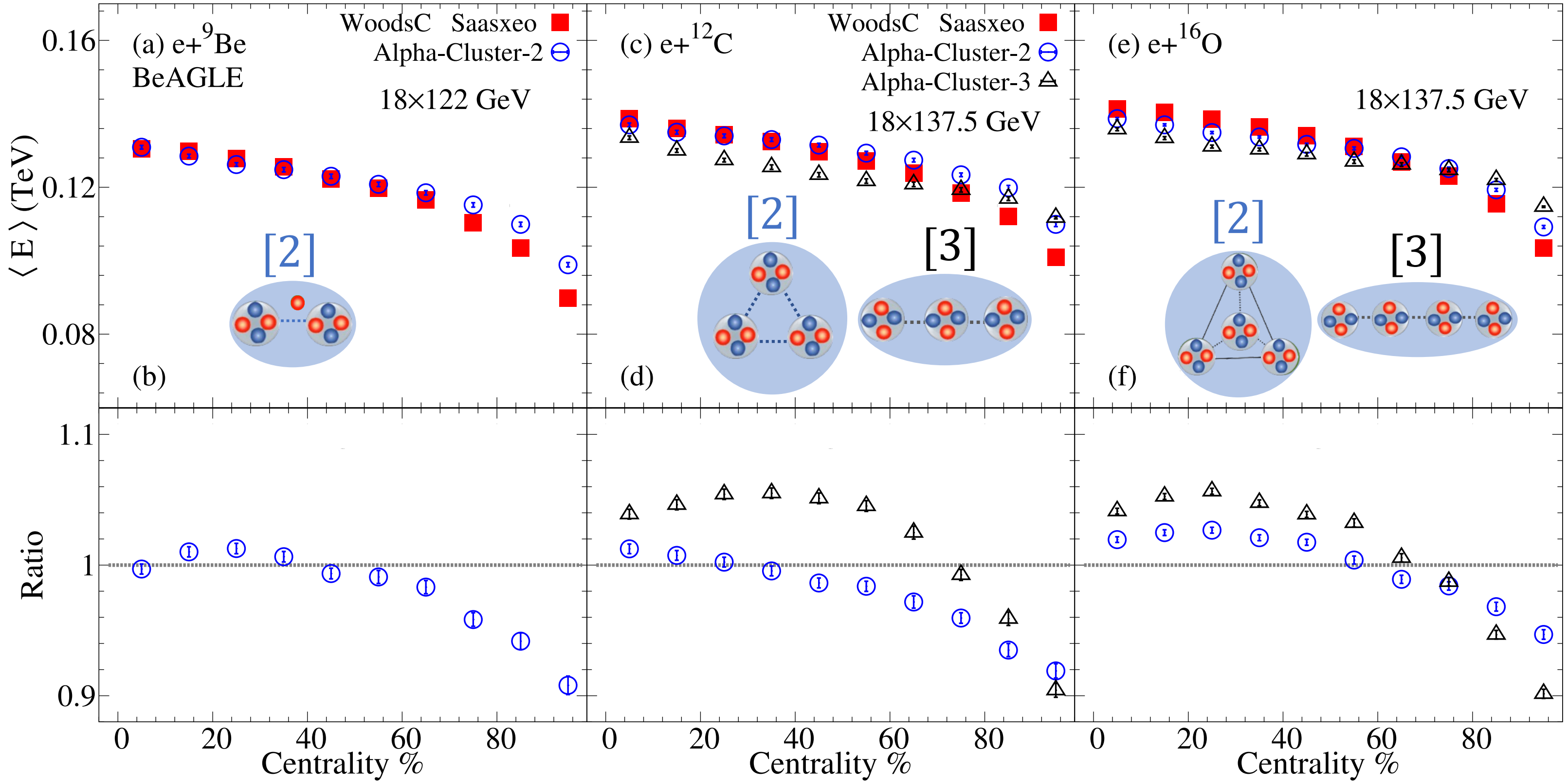
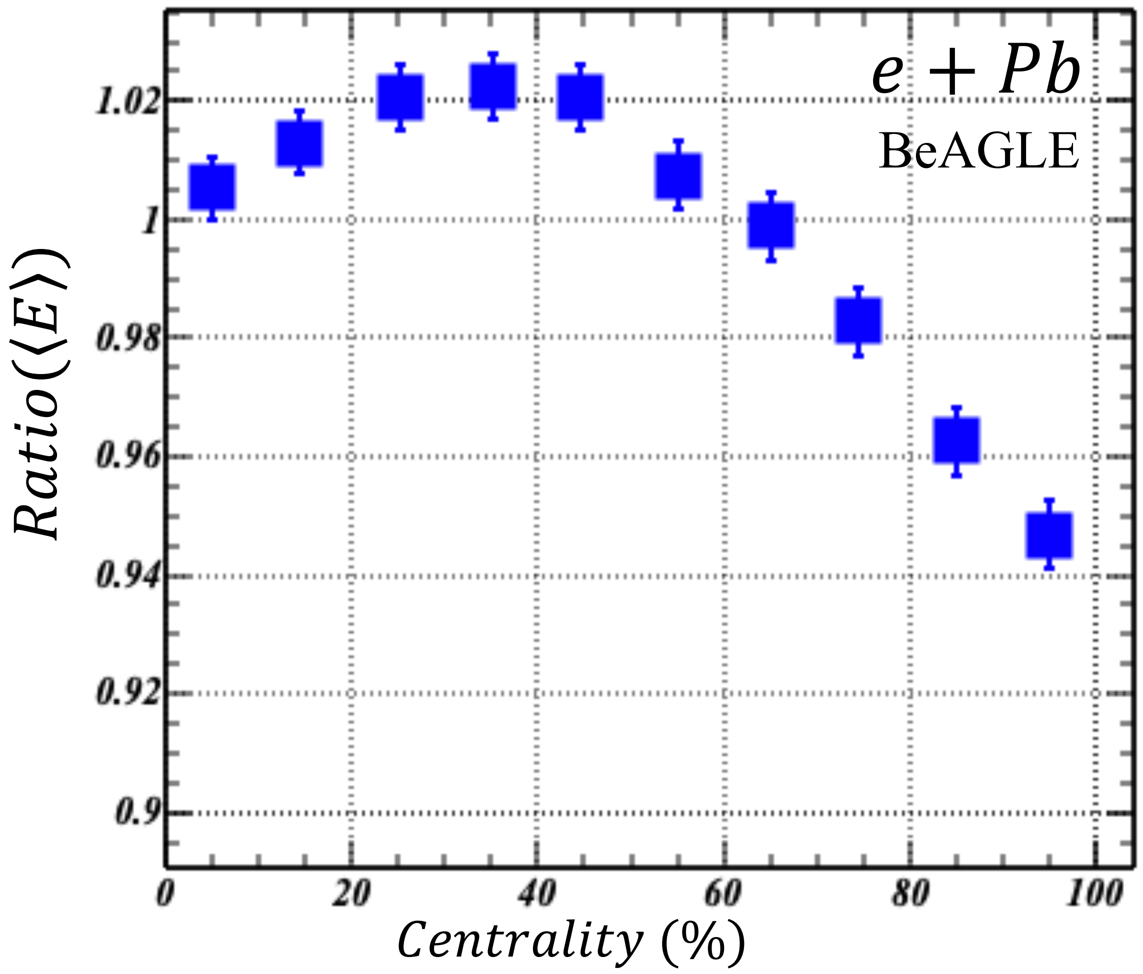


The $\langle E \rangle$ in B_0 is sensitive to α clustering and clustering configurations in Be^9, C^{12}, and O^{16}

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

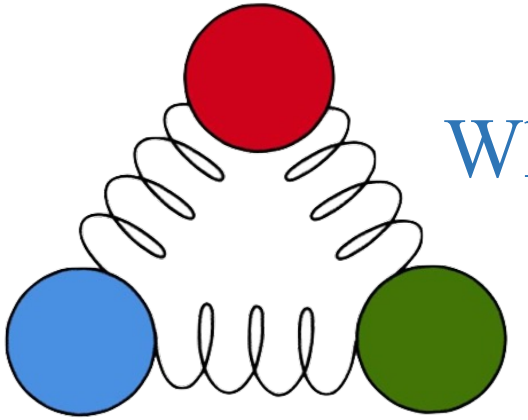
✓ The ratio of the undeformed to deformed Pb



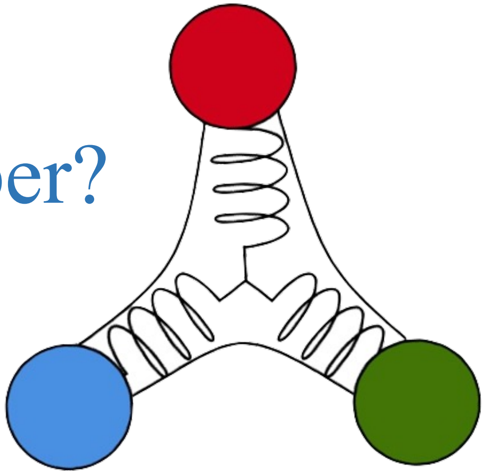
Neutrons and Protons from all sources in forward rapidity show sensitivity to β_2 and β_4 deformation in different centrality selections.

Search for baryon junctions in isobar collisions at EIC

Niseem Magdy



What carries the baryon number?



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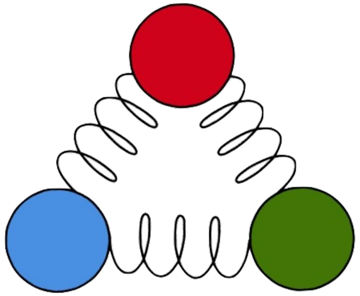
What carries the baryon number?

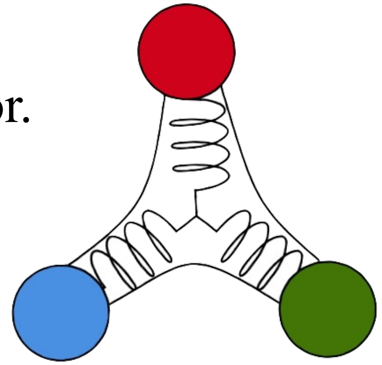
Baryon number: carried by the valence quarks? This is an assumption $B = \frac{1}{3}(n_q - n_{\bar{q}})$

- ✓ $\pm\frac{1}{3}B$ to each quark and antiquark cannot be inferred from QCD's first principles for baryons!
- ✓ Valence quarks carry most of the momentum and are contracted into thin "pancakes" at high energy.
- ✓ Quarks have less time to interact due to contracted longitudinal length



The string junction?

- ✓ Non-perturbative configuration of gluons represented by a locally gauge-invariant state vector.
- ✓ Carries lower momentum and is less contracted
- ✓ Made of low-x gluons and has more time to interact with other partons
- ✓ Enhanced baryon transport to mid-rapidity



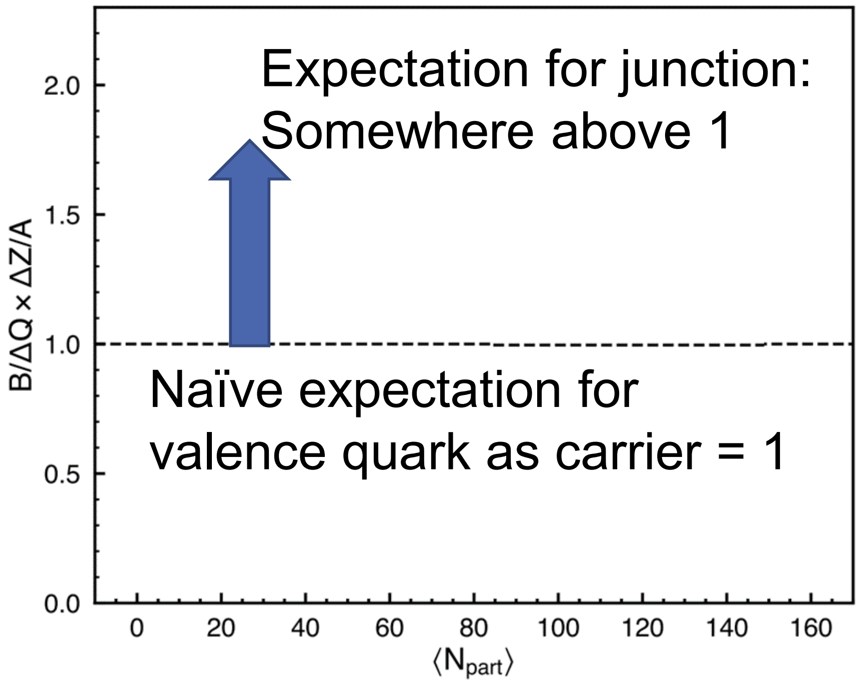
Neither of these scenarios has been verified experimentally.

What carries the baryon number?

Several methods are suggested to test the hypothesis:

- Net-Baryon in e+A collisions
  - ✓ The photon excepted has almost zero virtuality
  - ✓ Probes the nucleus at low-x

- Net-Baryon vs. Net-Electric charge in Isobar collisions
  - ✓ The ratio $B/\Delta Q * \Delta Z/A$ can be used to differentiate different carriers
    - Valence quarks carry B and Q if $(B/\Delta Q * \Delta Z/A) = 1$
    - Junction carry B (i.e., B is enhanced) if $B/\Delta Q * \Delta Z/A > 1$



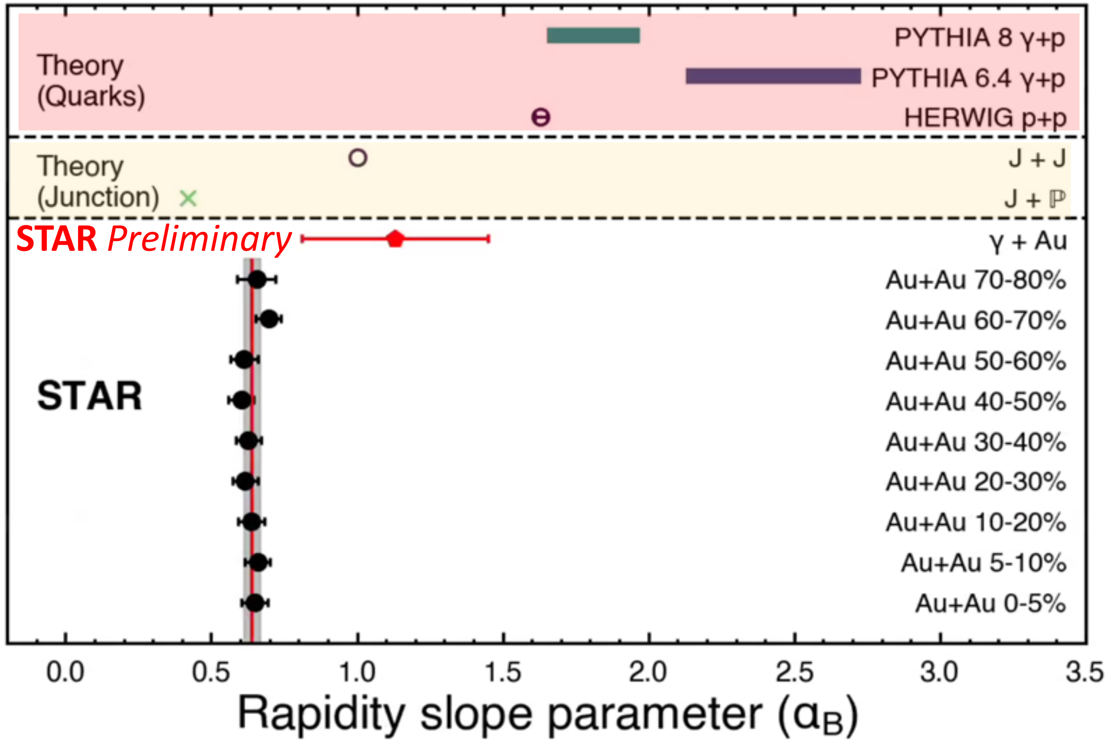
At the RHIC

The $dN/dy|_{Net-p}$

If the junction hypothesis is true:

- Interact with a junction in the target nucleus
- Enhanced creation of mid-rapidity baryons
  - ✓ Junction interaction time > quark interaction time
  - ✓ More baryons are stopped in the junction picture
- Regge theory prediction:
  - ✓ $\frac{dN}{dy} \propto e^{\alpha_B (y - y_{beam})}$
  - ✓ α_B is related to Regge intercept of junctions ($\alpha_B \sim 0.5$)

Chun Yuen Tsang (QM 2023)



STAR preliminary results point out that:

- $\alpha_B \sim 0.6$ for Au+Au
- $\alpha_B \sim 1.0$ for γ+Au
- Predicted values from:
  - ✓ HERWIG and PYTHIA disagree with the data
  - ✓ Junction-Junction (J+J) and Junction-Pomeron (J+P) are more compatible with data

[1] STAR, PRC **79**, 034909 (2009)
[2] STAR, PRC **96,** 044904 (2017)
[3] Christiansen, J. R. & Skands, P. Z. JHEP 08, 003 (2015)
[4] Kharzeev, Phys. Lett. B 378, 238– 246 (1996)

At the RHIC

Isobaric ratio

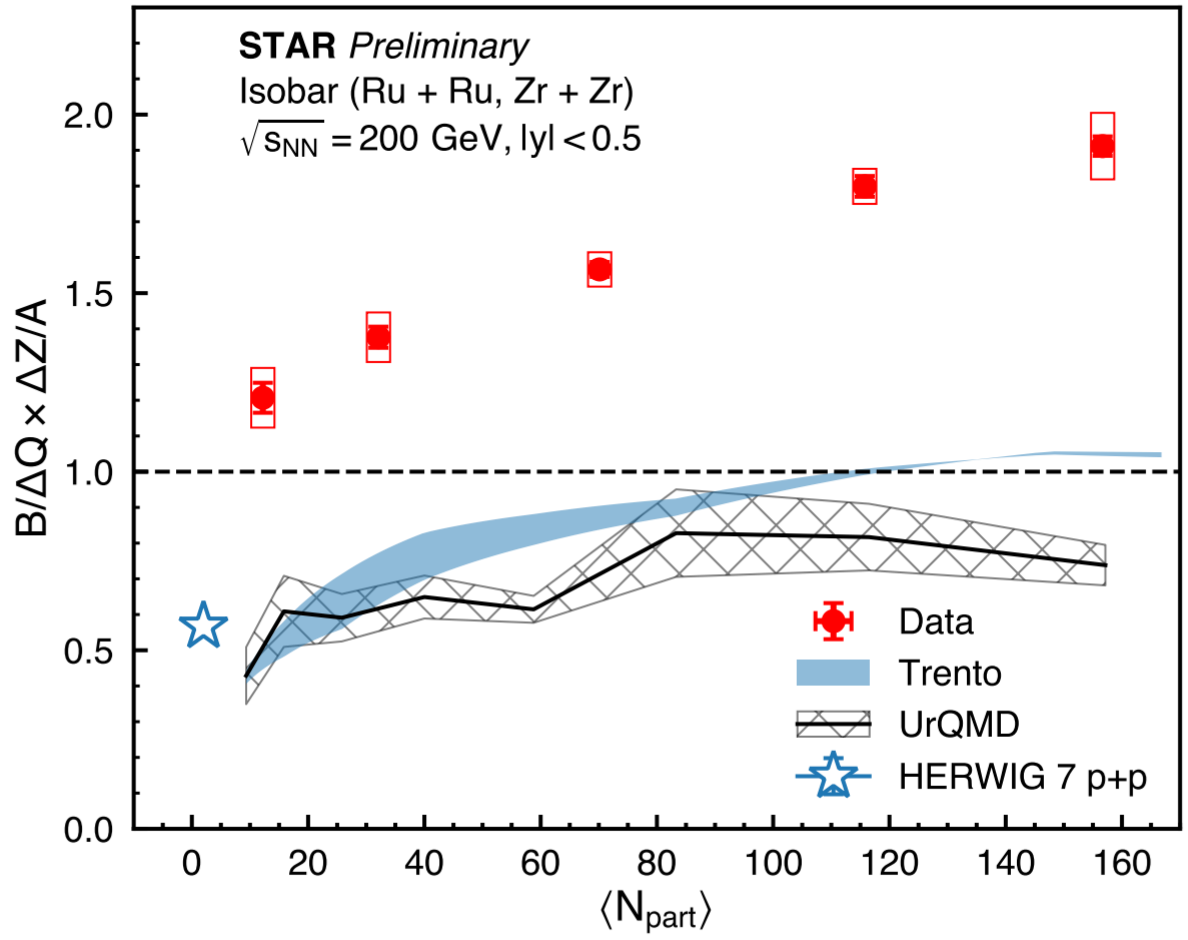
Chun Yuen Tsang (QM 2023)

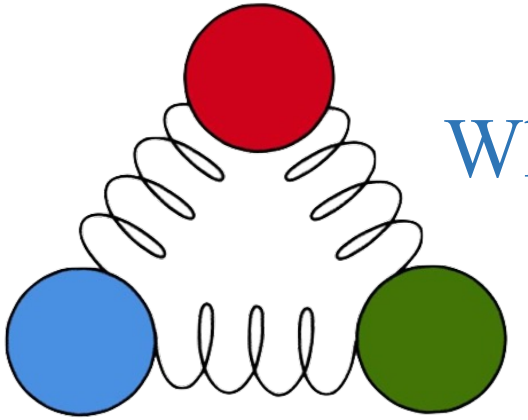
Net-Baryon vs. Net-Electric charge in Isobar collisions

- The ratio $B/\Delta Q*\Delta Z/A$ can be used to differentiate different carriers
  - Valence quarks carry B and Q if $(B/\Delta Q*\Delta Z/A) = 1$
  - Junction carry B (i.e., B is enhanced) if $(B/\Delta Q*\Delta Z/A) > 1$

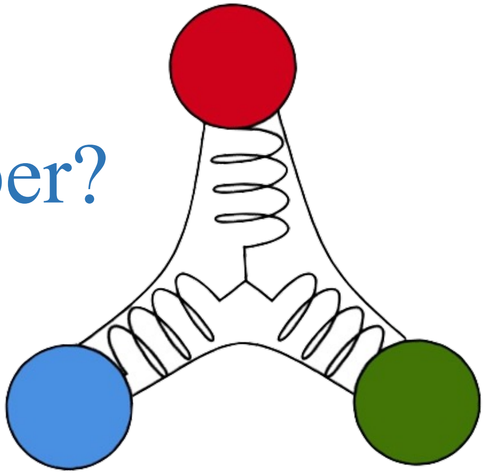
STAR preliminary results point out that:

- $(B/\Delta Q*\Delta Z/A) > 1$
- Model calculations:
  - ✓ All presented models cannot describe the data
  - ✓ Trento model accounts for initial conditions only, and it's consistent with changes in neutron skin thickness differences





What carries the baryon number?



At RHIC:

- ➢ RHIC nuclear energy is at a sweet spot but has limited acceptance in rapidity Q2 and x

At EIC:

- ➢ Suitable energy range, good acceptance in rapidity (extended from 2.5 to 6.0) Q2 and x
  - ✓ Low-pt PID is needed to study the charge and baryon transports

Can EIC answer such a question?

At the EIC

The $dN/dy|_{Net-p}$

If the junction hypothesis is true:

- Interact with a junction in the target nucleus

- Enhanced creation of mid-rapidity baryons
  - ✓ Junction interaction time > quark interaction time
  - ✓ More baryons are stopped in the junction picture

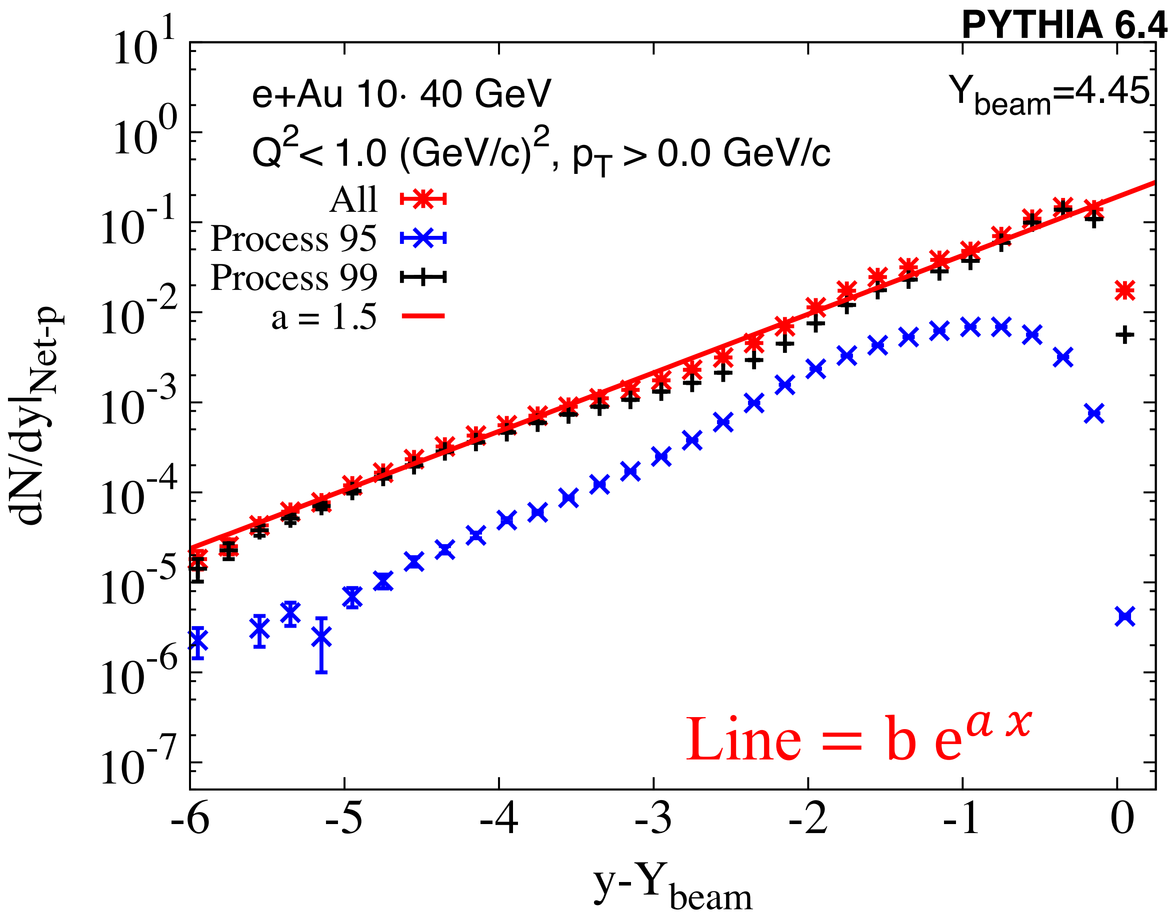
- Regge theory prediction:
  - ✓ $\frac{dN}{dy} \propto e^{\alpha_B (y - y_{beam})}$
  - ✓ α_B is related to Regge intercept of junctions ($\alpha_B \sim 0.5$)

α_B from PYTHIA is larger than the prediction for the junction expectation

What is the x and Q^2 dependence of α_B?

Ongoing work

(J. D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685 (2022)).



95 is soft, non-diffractive VMD low p_T

99 is LO DIS

At the EIC

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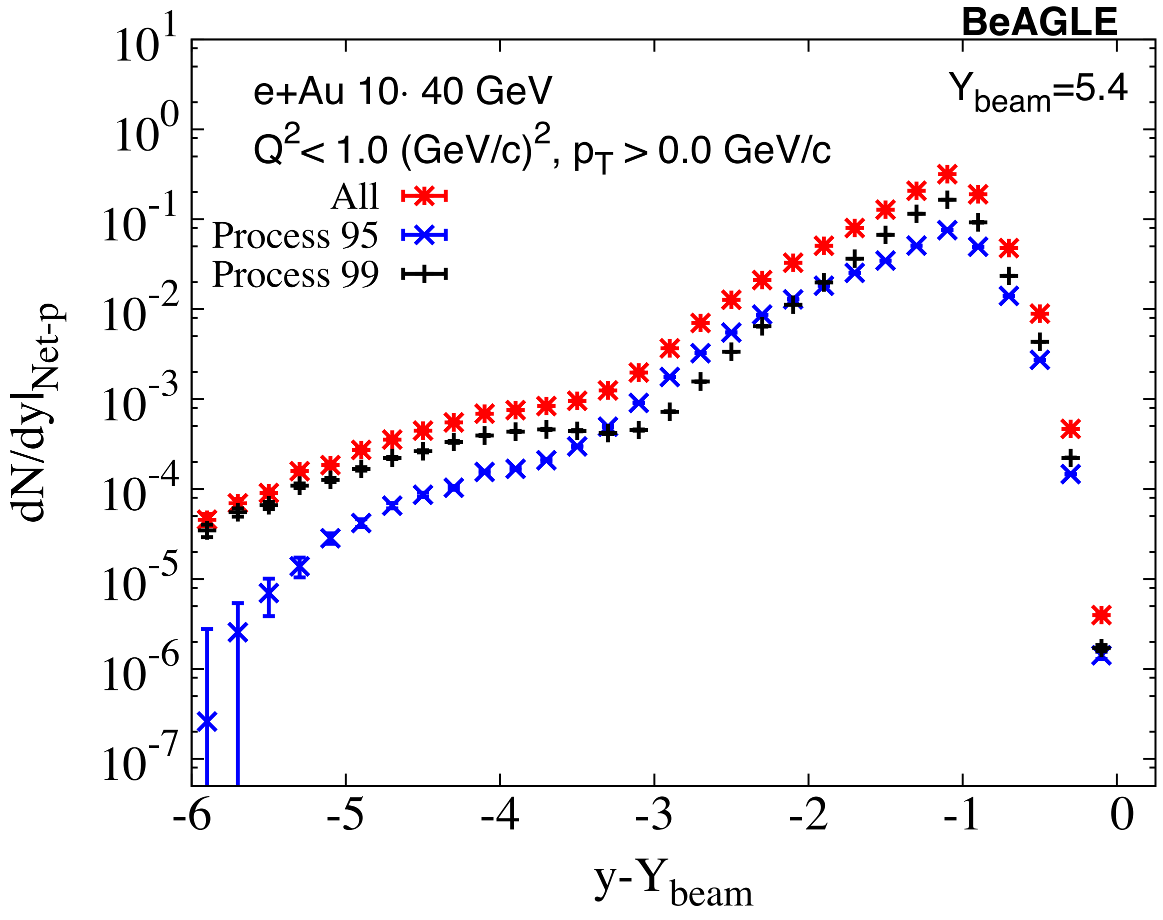

95 is soft, non-diffractive VMD low p_T
99 is LO DIS

BeAGLE results suggest two slopes (larger than 1.0) depending on the rapidity range

What is the x and Q^2 dependence of α_B?
Ongoing work

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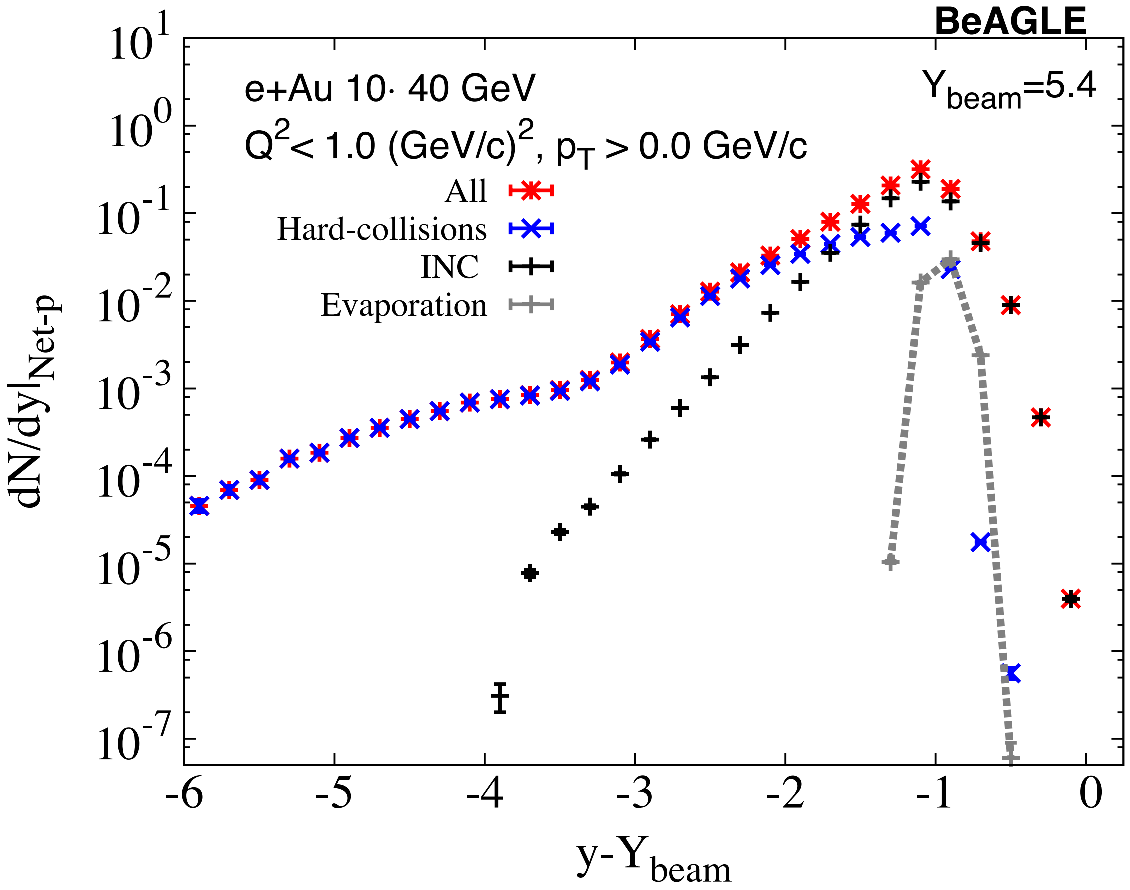
  - ✓ $\frac{dN}{dy} \propto e^{\alpha_B (y-y_{beam})}$
  - ✓ α_B is related to Regge intercept of junctions ($\alpha_B \sim 0.5$)



95 is soft, non-diffractive VMD low p_T
99 is LO DIS

BeAGLE results suggest two slopes (larger than 1.0) depending on the rapidity range

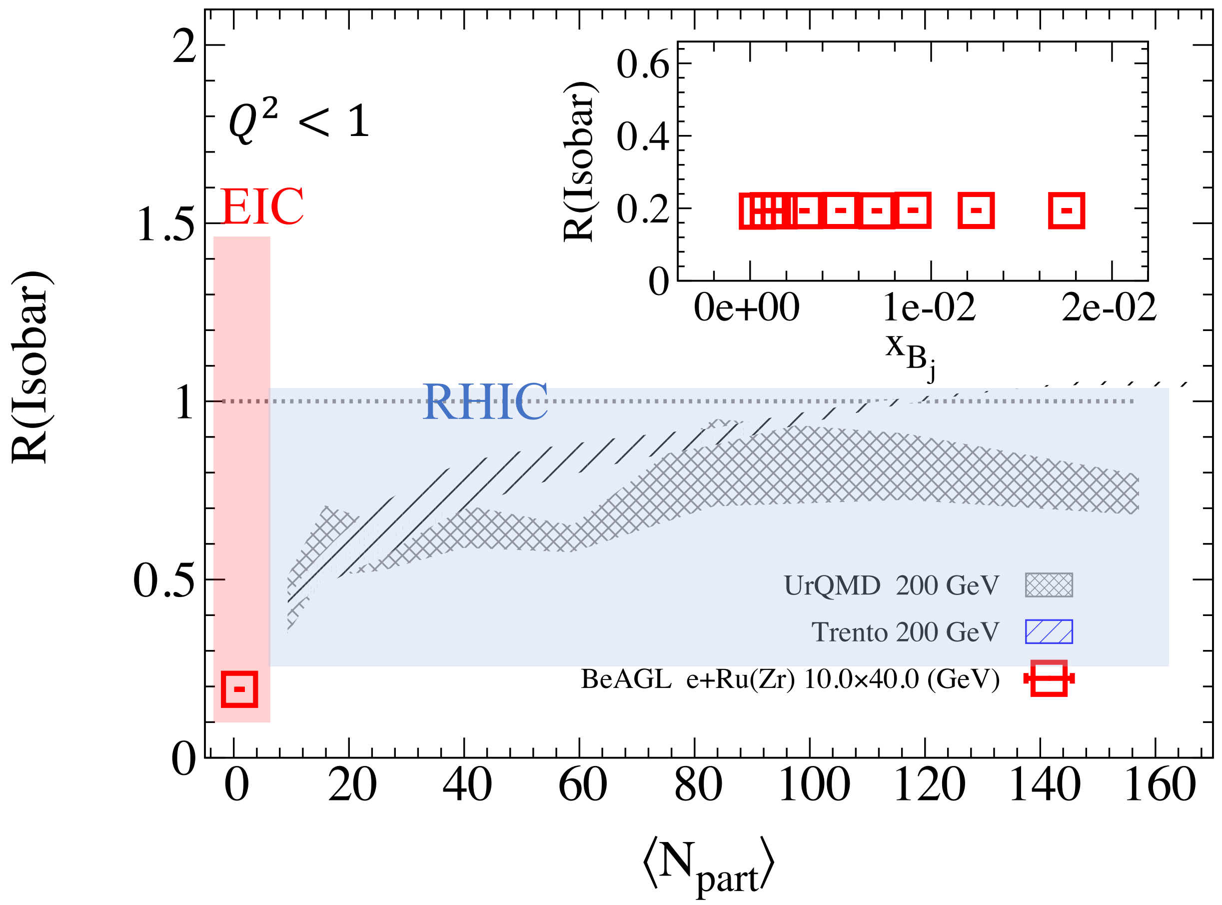
What is the x and Q^2 dependence of α_B?

Ongoing work

At the EIC

Isobaric ratio

- Net-Baryon vs. Net-Electric charge in Isobar collisions
  - ✓ The ratio B/ΔQ*ΔZ/A can be used to differentiate different carriers
    - Valence quarks carry B and Q if (B/ΔQ*ΔZ/A) <= 1
    - Junction carry B (i.e., B is enhanced) if B/ΔQ*ΔZ/A > 1



- $R(Isobar)$ is independent of x_{B_j}
  - ✓ Consistent with the quark's scenario

BeAGLE shows value consistent with the quark's scenario

At the EIC

Isobaric ratio

- Net-Baryon vs. Net-Electric charge in Isobar collisions
  - ✓ The ratio B/ΔQ*ΔZ/A can be used to differentiate different carriers
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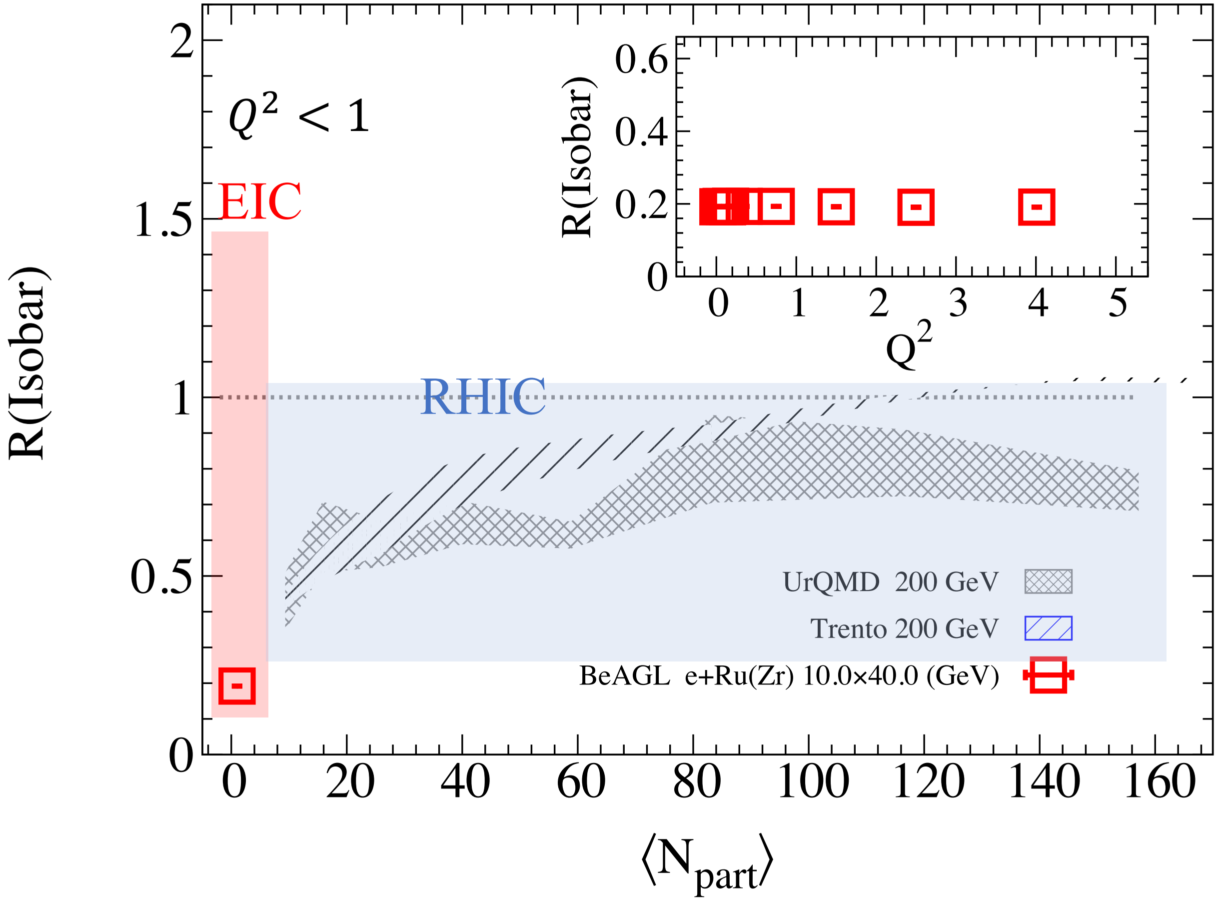


- $R(Isobar)$ is independent of Q^2

BeAGLE shows value consistent with the quark's scenario

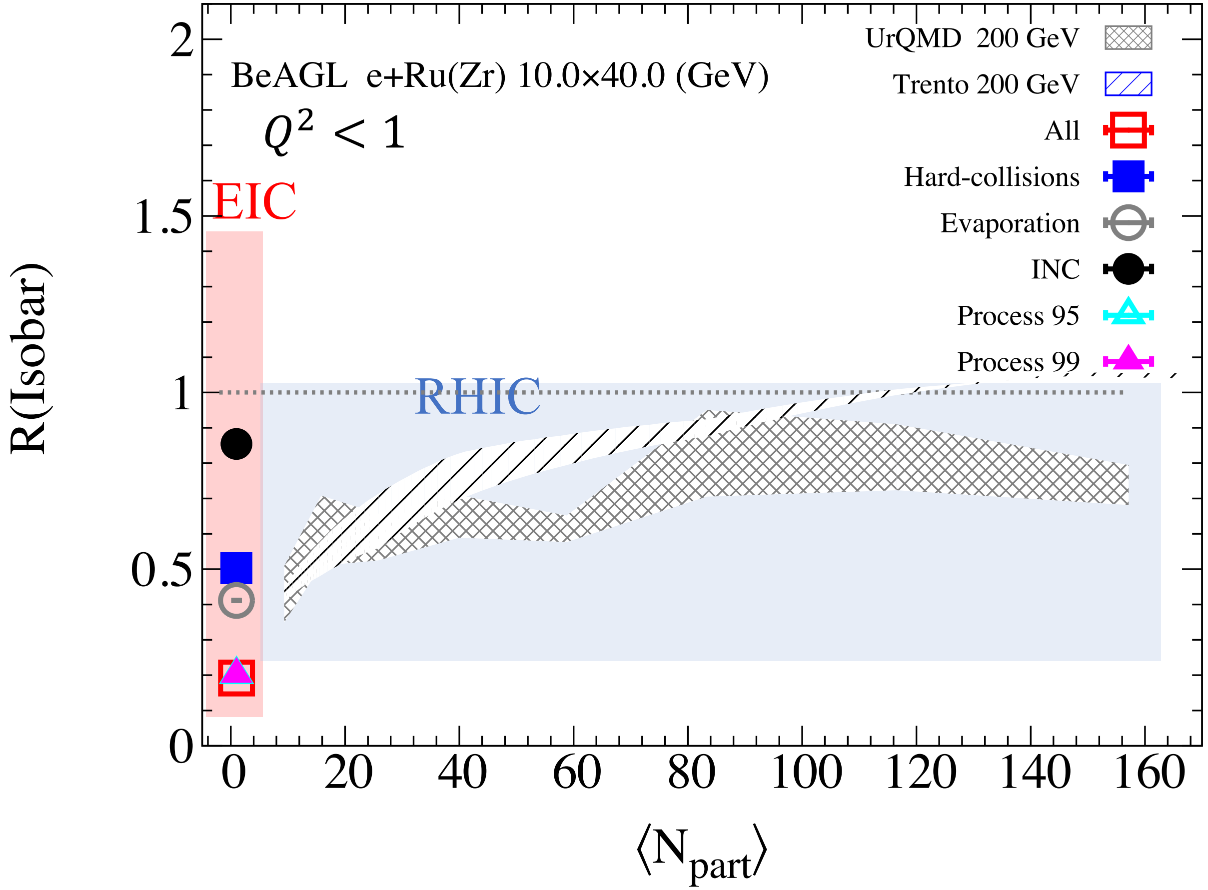
At the EIC

Isobaric ratio

- Net-Baryon vs. Net-Electric charge in Isobar collisions
  - ✓ The ratio $B/\Delta Q*\Delta Z/A$ can be used to differentiate different carriers
    - Valence quarks carry B and Q if $(B/\Delta Q*\Delta Z/A) = 1$
    - Junction carry B (i.e., B is enhanced) if $B/\Delta Q*\Delta Z/A > 1$

- $R(Isobar)$ show dependence on the BeAGLE processes

BeAGLE shows value consistent with the quark's scenario



95 is soft, non-diffractive VMD low p_T
99 is LO DIS

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.

We investigated the ability to use the EIC to study baryon junctions in isobar collisions:

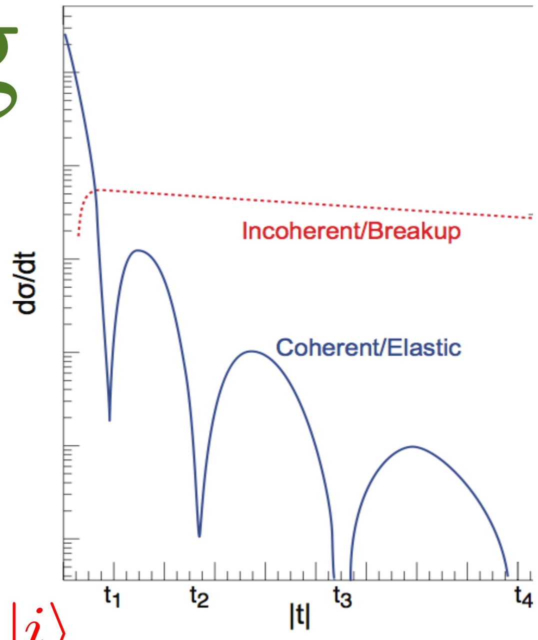
- The net-baryon yield slopes from PYTHIA and BeAGLE simulations are much steeper than expected from the baryon junction picture
- The isobaric ratios in BeAGLE are shown to be less than 1.0
  - ✓ Independent of x_B
  - ✓ Independent of Q^2

Consistent with the quark's scenario.

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

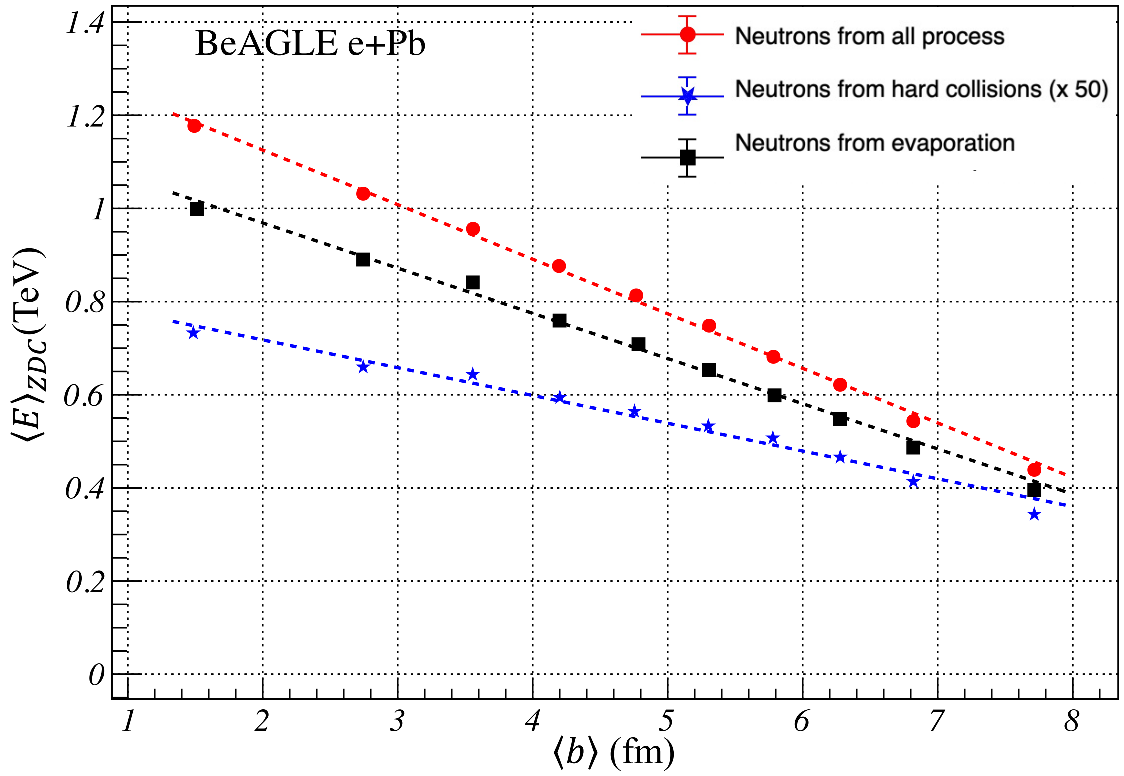
$$= \sum_{f} \langle i|\mathcal{A}|f\rangle^{\dagger} \langle f|\mathcal{A}|i\rangle - \langle i|\mathcal{A}|i\rangle^{\dagger} \langle i|\mathcal{A}|i\rangle$$

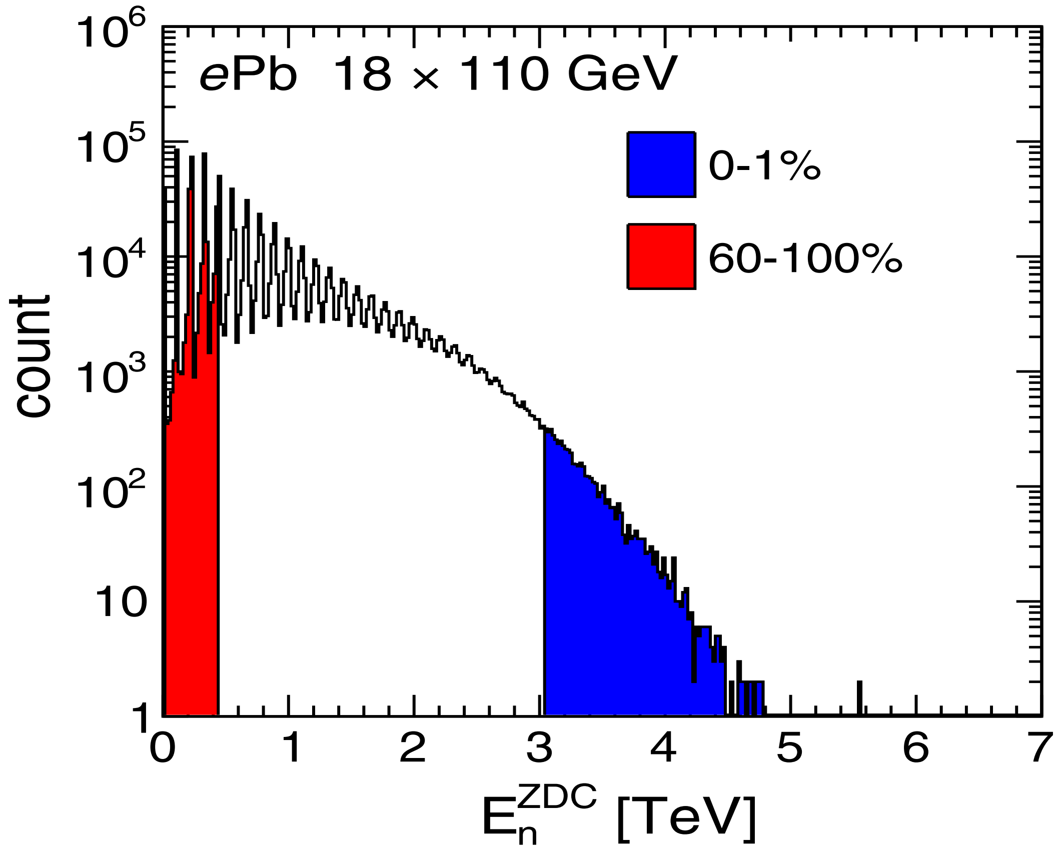
$$= \left\langle i \left||\mathcal{A}|^2\right| i \right\rangle - |\langle i|\mathcal{A}|i\rangle|^2 = \left\langle |\mathcal{A}|^2 \right\rangle - |\langle \mathcal{A}\rangle|^2$$

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



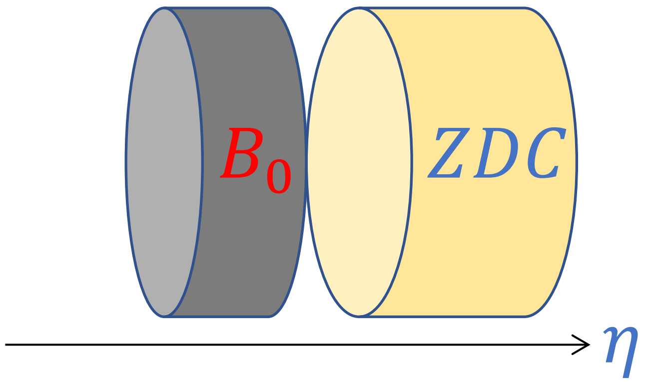


Neutrons from all sources can be used for centrality definition.

❖ 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

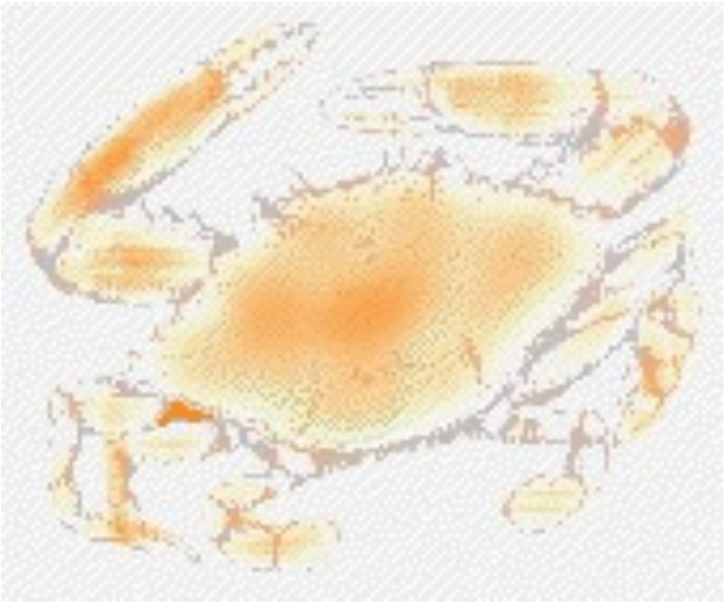


➤ In this current study, we are using: ZDC and B_0 detectors

❖ We use a hadronic afterburner that introduces such information.

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

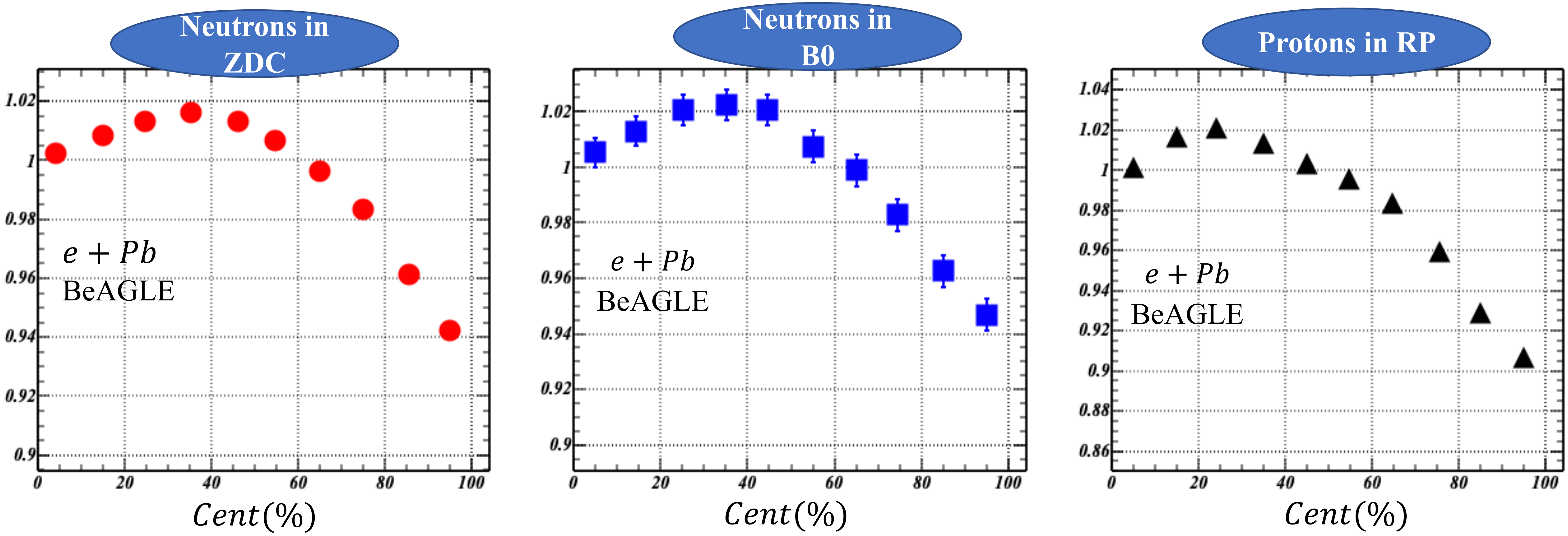
where $\vec{r}^{*}=\vec{x}_1-\vec{x}_2$ is the relative distance of two particles at their kinetic freeze-out, $\vec{k}^{*}$ is half of the relative momentum between two particles and later one we use q for the same quantity, $\vec{S}\left(\vec{r}^{*},\vec{k}^{*}\right)$ is the probability to emit a 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

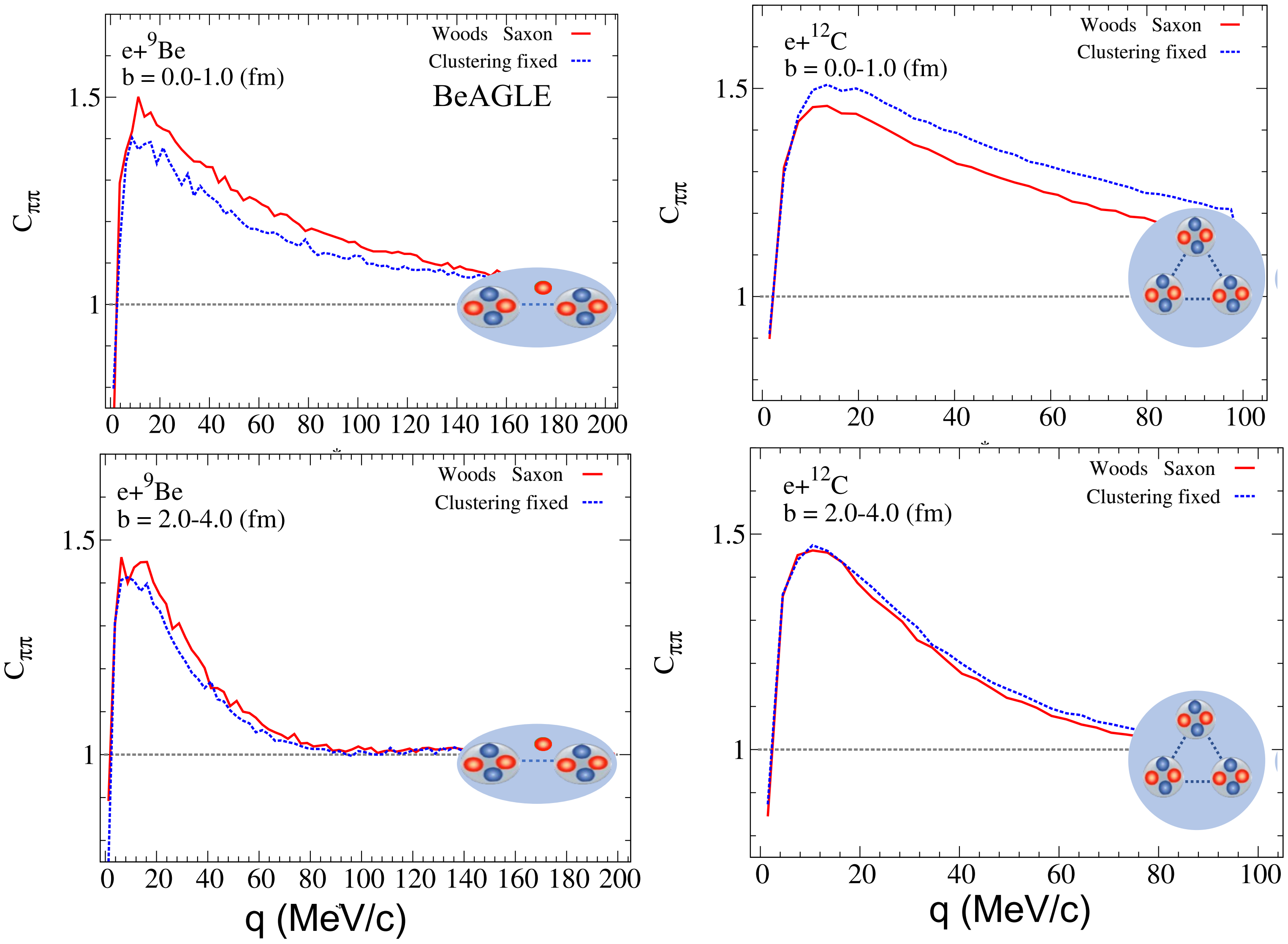


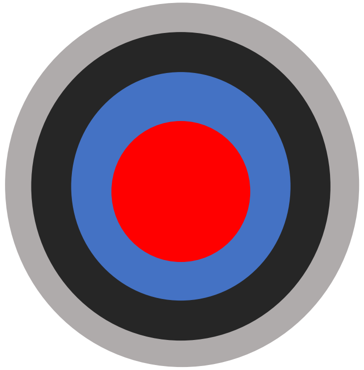
Neutrons and Protons from all sources in forward rapidity show sensitivity to β_2 and β_4 deformation in different centrality selections.

❖ The α clustering

➢ Nuclei homogeneity

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





Femtoscopy measurements can be sensitive to the clustering.

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