Exploring the role of initial α-clustered nuclear structure on final state flow coefficients via pC, pO and OO collisions at the LHC

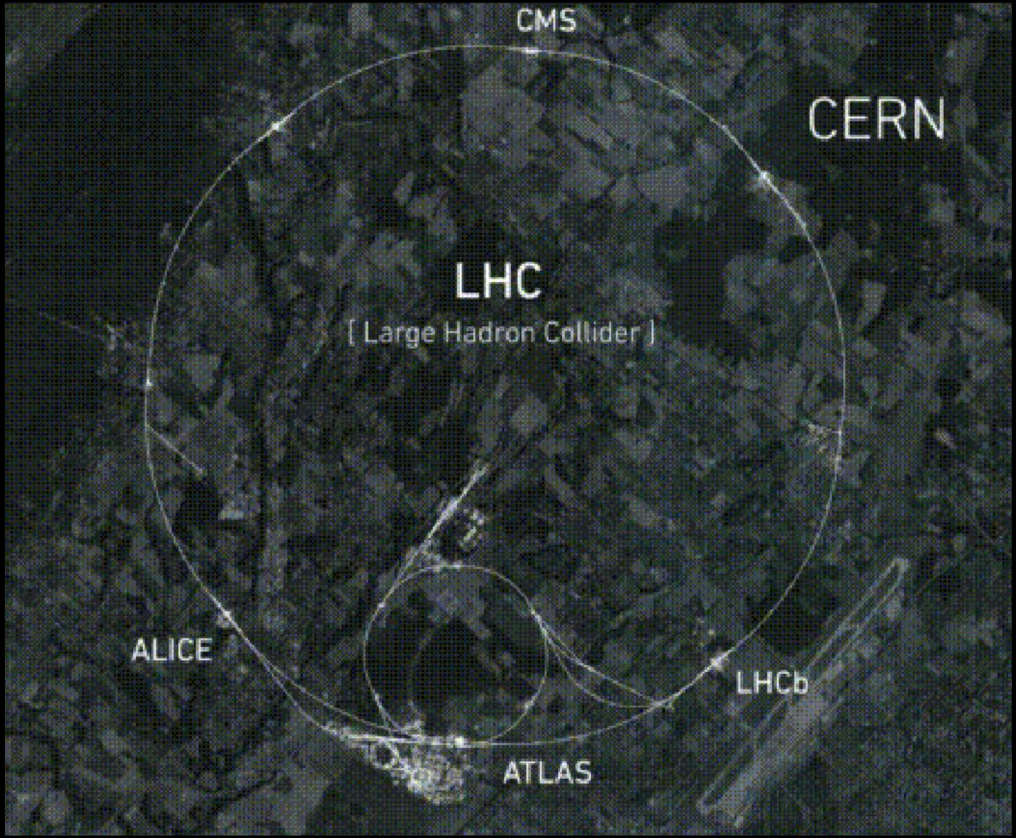
Based on:

A. Menon Kavumpadikkal Radhakrishnan, S. Prasad, N. Mallick and R. Sahoo, Eur. Phys. J. A **61**, 134 (2025).
A. Menon Kavumpadikkal Radhakrishnan, S. Prasad, N. Mallick, R. Sahoo and G. G. Barnaföldi, [arXiv:2505.22367 [hep-ph]].

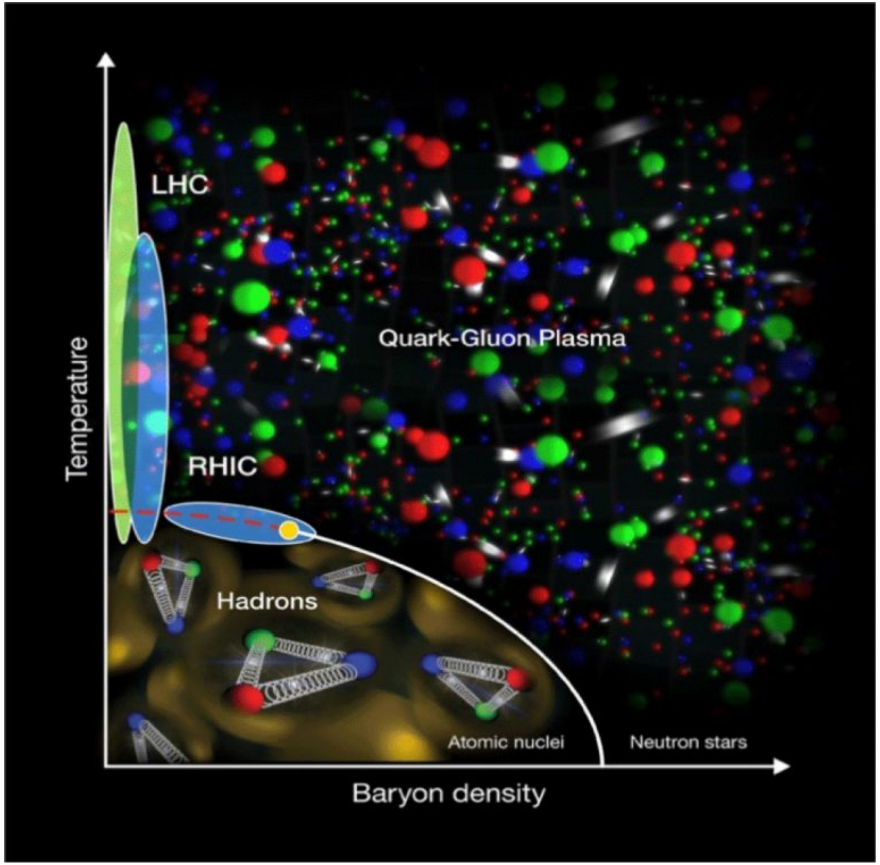
Aswathy Menon K. R.
Department of Physics
Indian Institute of Technology Indore
Email : *Aswathy.Menon@cern.ch*

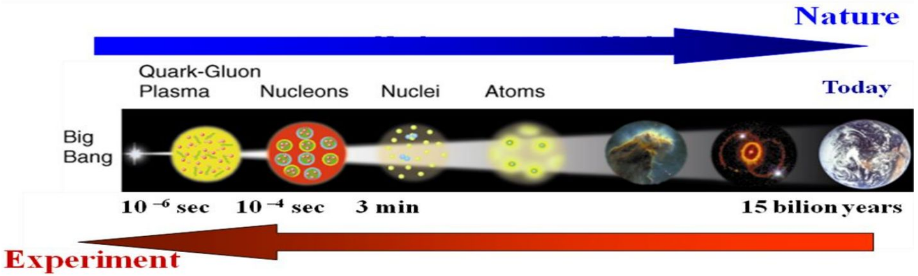
Outline

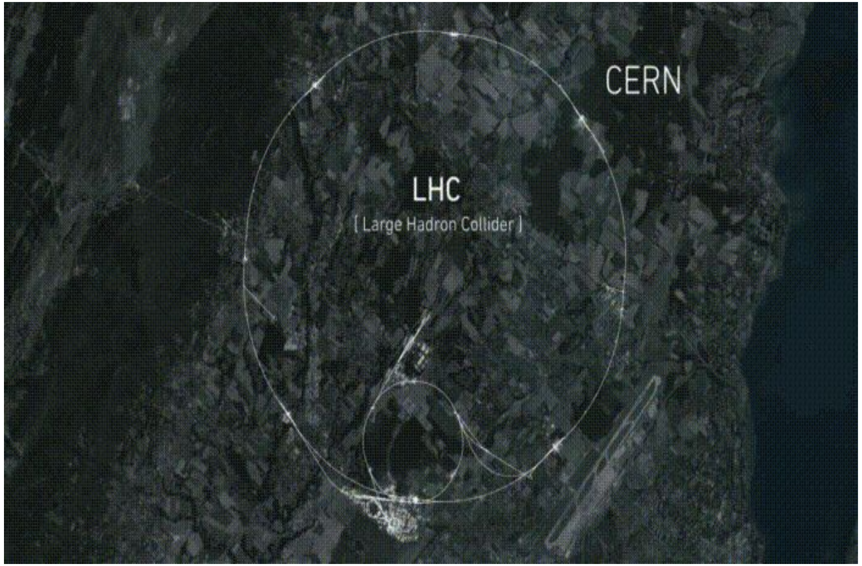
- ★ Relativistic heavy-ion collisions
- ★ Light-ion collisions
- ★ α-clustered nuclear structure
- ★ Anisotropic flow estimation
- ★ Results



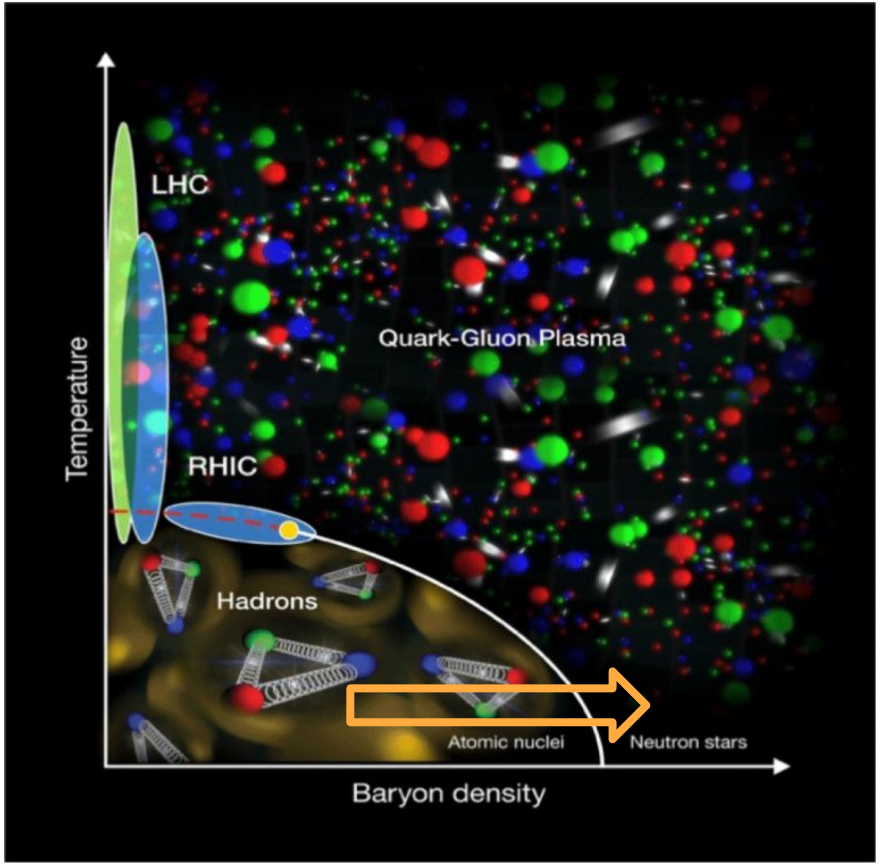
Why Relativistic collisions ?

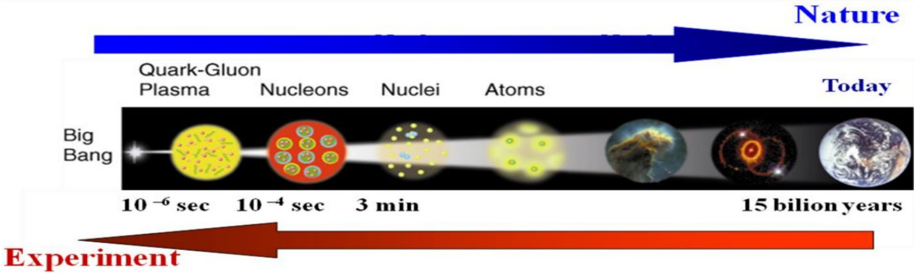


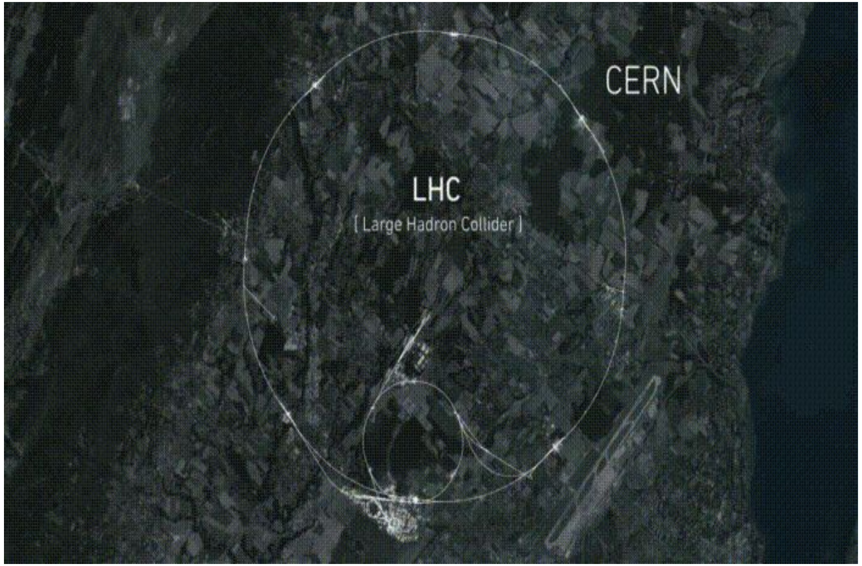




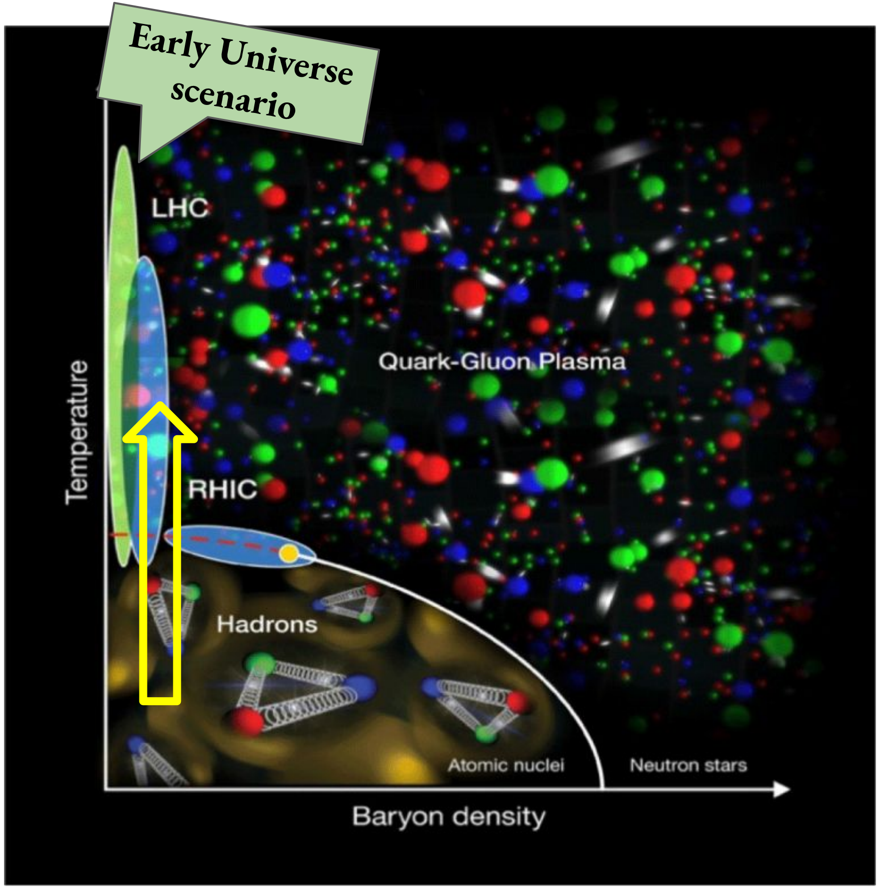
Why Relativistic collisions ?

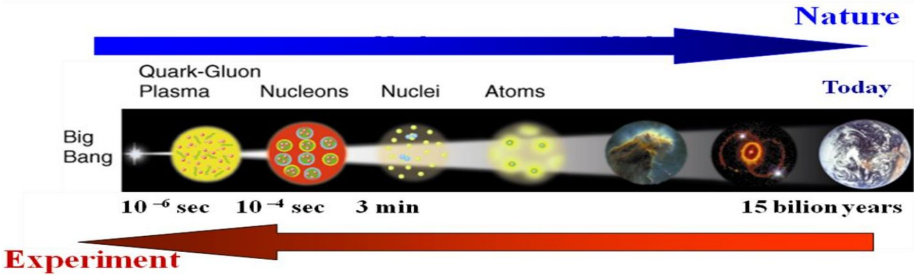


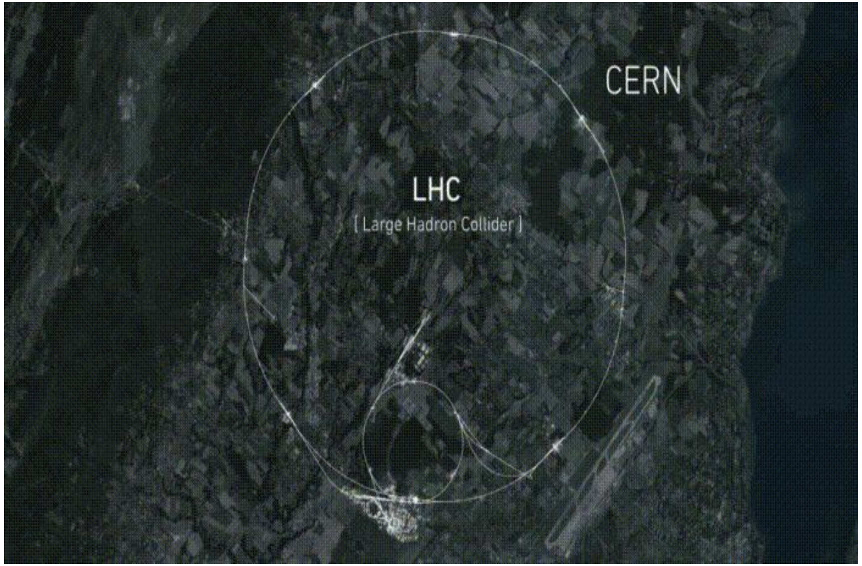




Why Relativistic collisions ?



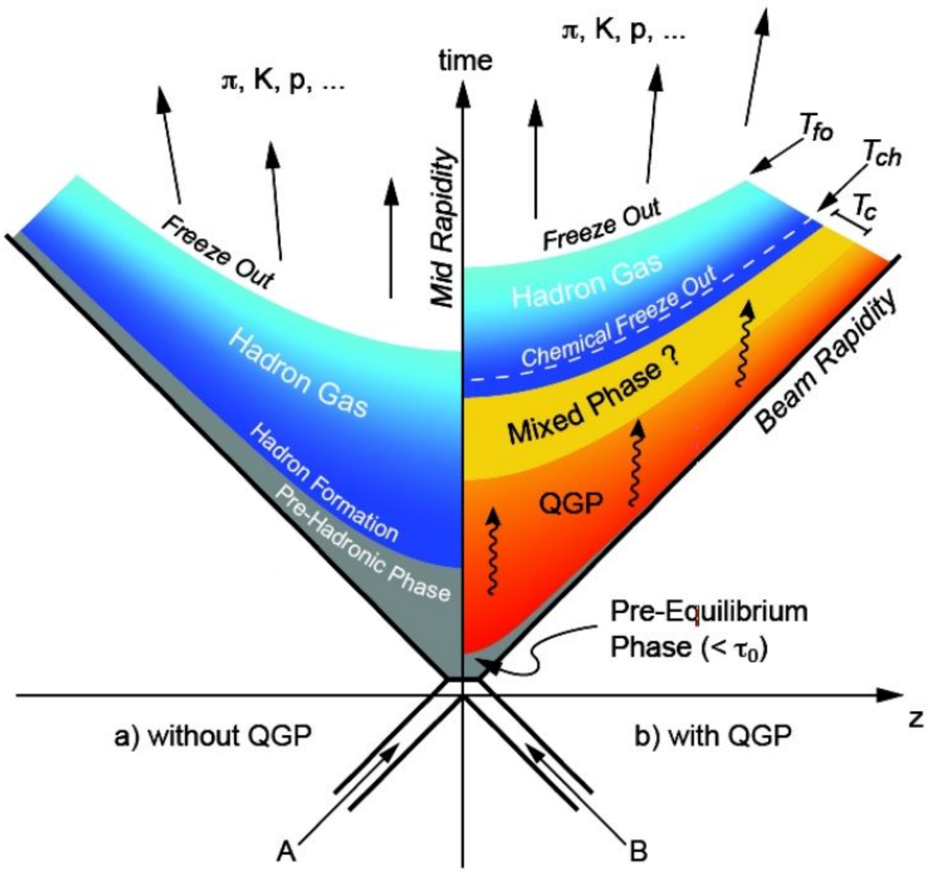




Space-time evolution of Relativistic collisions

Without QGP :

- Pre-hadronic phase
- Hadron Gas Phase
- Hadronic Freezeout



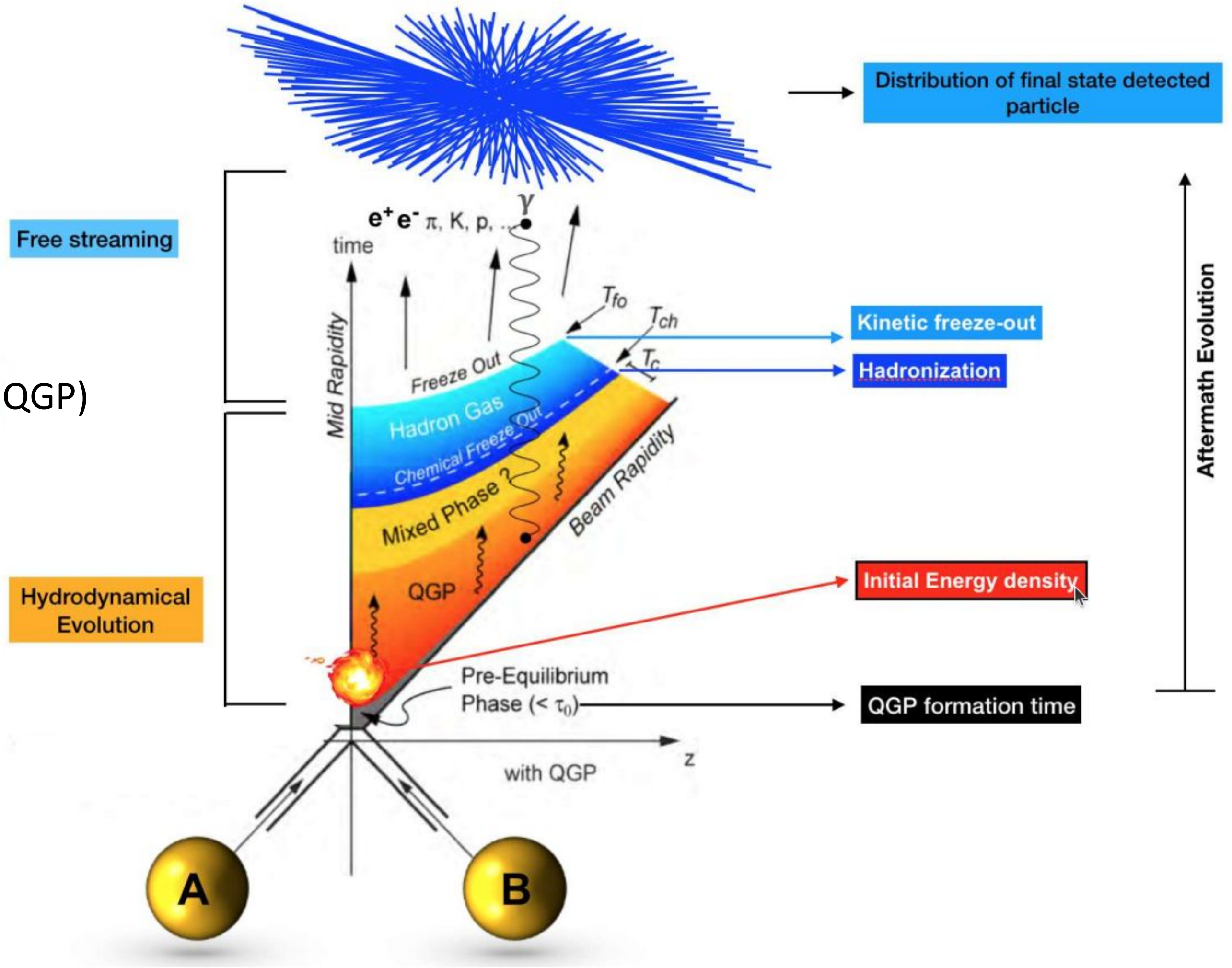
With QGP :

- Pre-Equilibrium phase
- QGP
- Mixed Phase
- Chemical Freezeout
- Hadronic Phase
- Kinetic Freezeout

Space-time evolution of Relativistic collisions

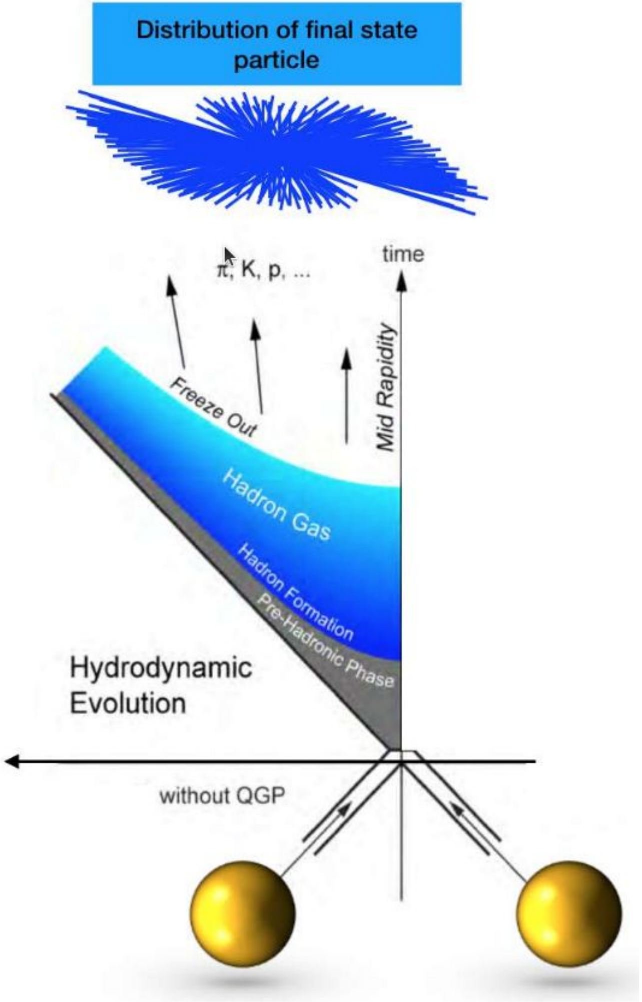
With QGP :

- Pre-Equilibrium phase
- Quark Gluon Plasma (QGP)
- Mixed Phase
- Chemical Freezeout
- Hadronic Phase
- Kinetic Freezeout



Without QGP :

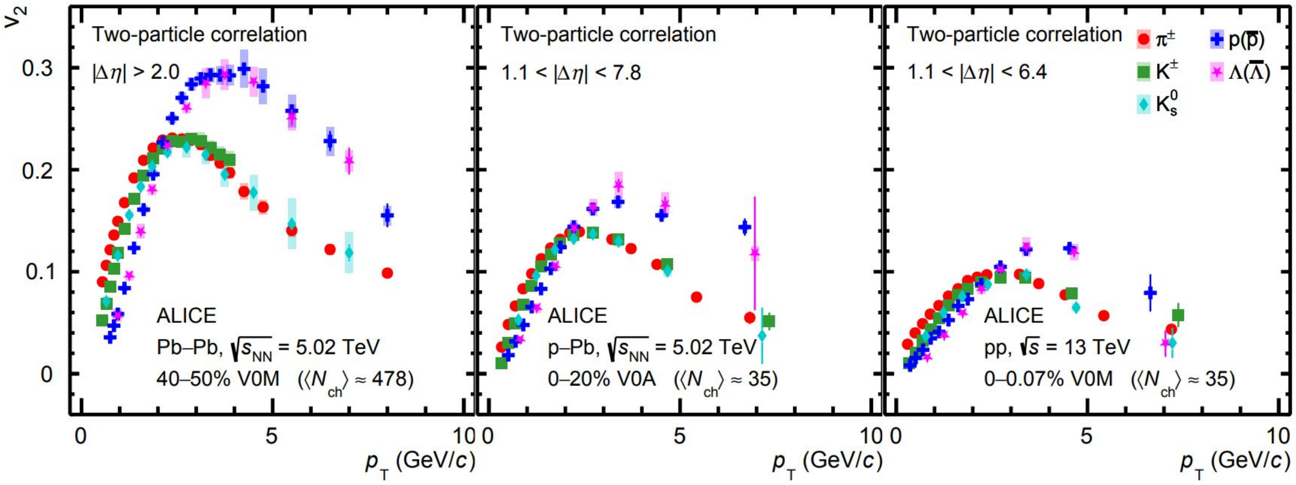
- Pre-hadronic phase
- Hadron Gas Phase
- Hadronic Freezeout



This picture of space-time evolution is expected to occur in **hadronic collisions**, where formation of QGP is least anticipated

Motivation

- Through relativistic heavy-ion collisions, we search for indirect **signatures of QGP**
- Small collisions like **pp collisions provide baseline measurements** as medium formation is not expected here
- But presence of heavy-ion like signatures are now observed in small collision systems too!
  - ➢ **High-multiplicity pp** and **p-Pb collisions** show signatures of collective flow and strangeness enhancement

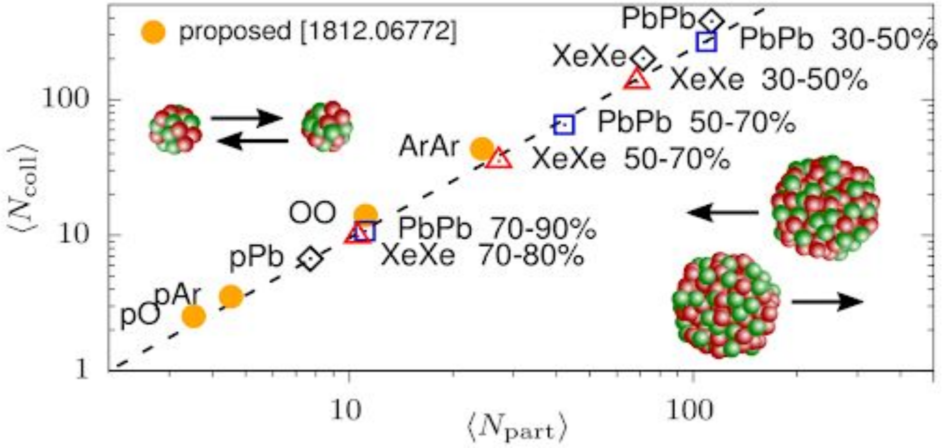


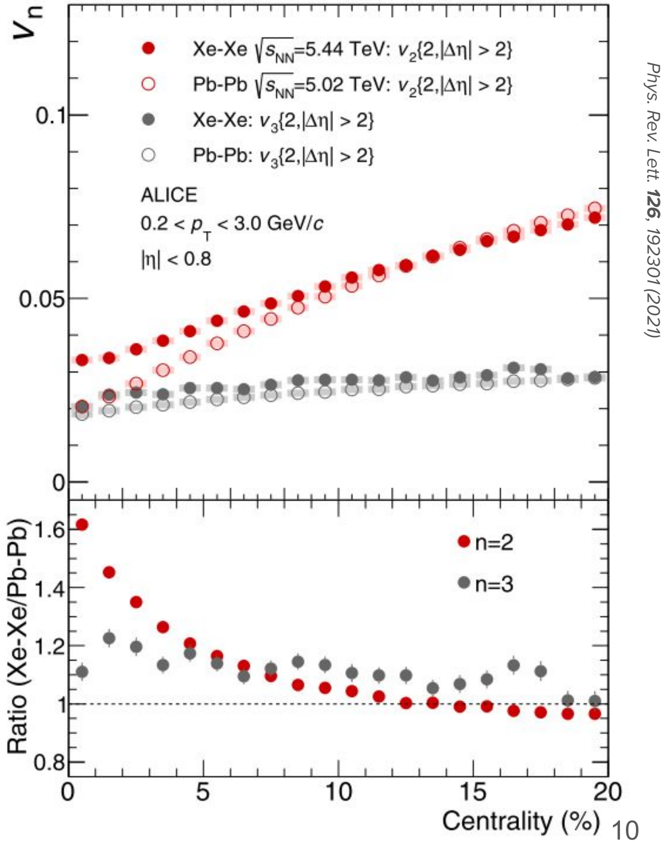
S. Acharya et al. [ALICE], [arXiv:2411.09323]

Focus : SMALL COLLISION SYSTEMS

p-O and O-O collisions took place in the Run 3 at the LHC in 2025

pO and OO collisions at the LHC





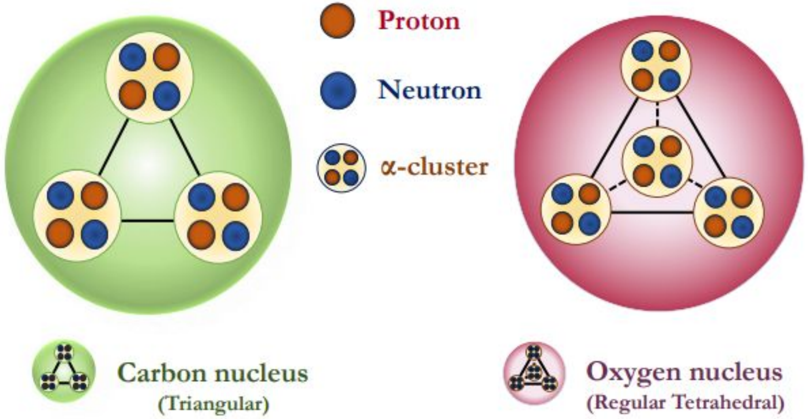
1. PERFECT SYSTEM SIZE to fill multiplicity gap between pp, p-Pb and Pb-Pb

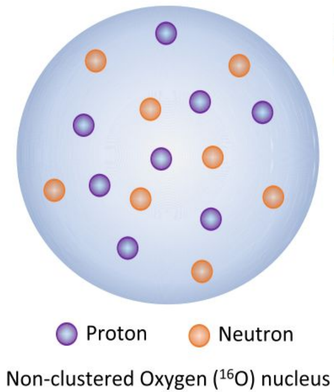
2. To investigate jet quenching effects & comprehend COLLECTIVE PHENOMENA in p-Pb

3. p-O studies help COSMIC AIR SHOWER MODELLING

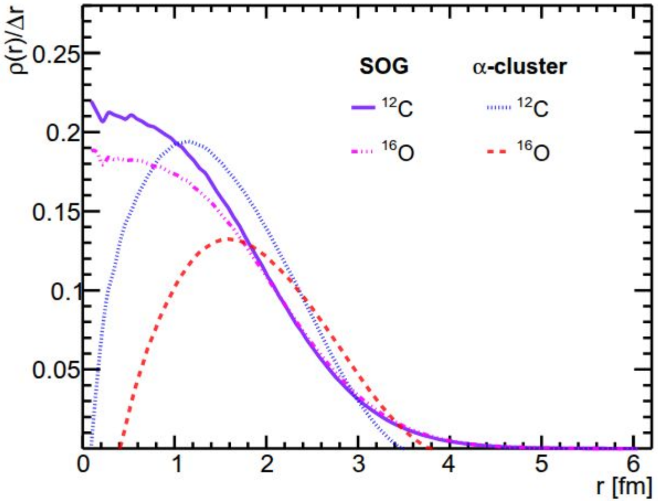
4. Effect of initial CLUSTERED geometry on final-state azimuthal correlations

α-clusters in O and C nuclei





S. Prasad, N. Mallick, R. Sahoo and G.G.Barnaföldi, **Phys.Lett.B 860 (2025) 139145**



α- cluster density profile

- ❖ ^{4}He nuclei with two protons and two neutrons is called an α-particle
- ❖ Light nuclei having ***4n*** nucleons can possess ***α*-clustered** nuclear structure → Ex.: ^{8}Be, ^{12}C, ^{16}O etc.
- ❖ ***α*-clustering** provides additional stability to nucleus

A. Menon Kavumpadikkal Radhakrishnan, S. Prasad, N. Mallick and R. Sahoo, **Eur. Phys. J. A 61, 134 (2025)**

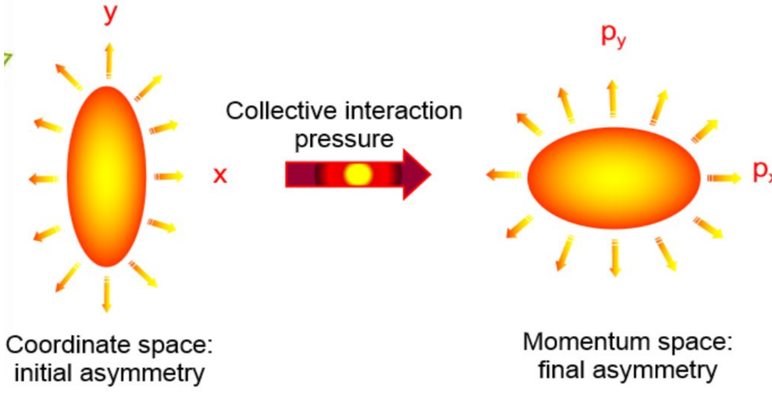
Anisotropic flow

- In non-central collisions, **spatial asymmetry** along different directions leads to **hierarchy of pressure gradients** : $\vec{\nabla} P_x >> \vec{\nabla} P_y$
- Strong pressure gradients convert **initial spatial anisotropy** to final-state azimuthal **momentum space anisotropy**, via the collective expansion of the medium
- Anisotropic transverse expansion/**anisotropic flow** is quantified via coefficients of Fourier expansion of the azimuthal distribution of final state particles:

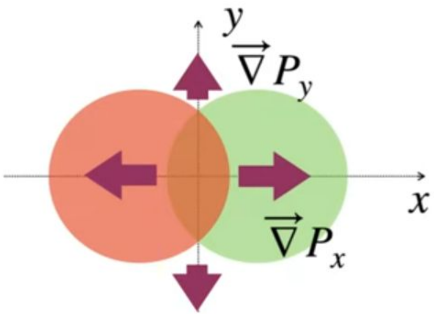
$$\frac{dN}{d\phi} = \frac{1}{2\pi}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \psi_n)]\right)$$

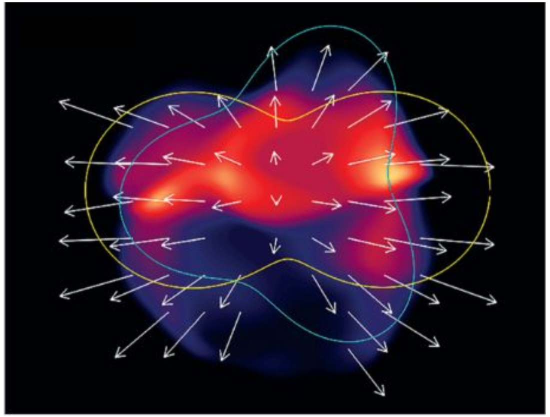
$$where \quad v_n = \langle \cos[n(\phi - \psi_n)] \rangle$$

is the **n^th order anisotropic flow coefficient**



R. Pasechnik, M. Šumbera, Universe 3, 7 (2017)

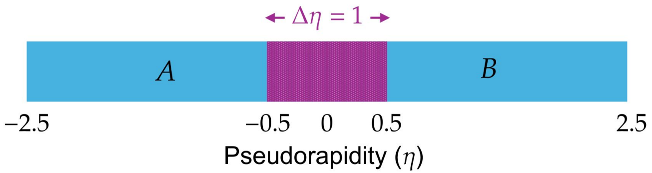




$v_2 \Rightarrow$ Elliptic Flow
$v_3 \Rightarrow$ Triangular Flow

Anisotropic Flow Estimation

- In this study, estimation of v_n is done by **two-particle Q-cumulant method**
- Pseudorapidity gap in the sub-events helps in suppressing non-flow contributions



S. Prasad, N. Mallick, R. Sahoo and G.G.Barnaföldi, *Phys.Lett.B* 860 (2025) 139145

$$Q_n = \sum_{j=1}^{M} e^{in\phi_j}$$

$$\langle 2 \rangle = \frac{|Q_n|^2 - M}{M(M-1)}$$

$$c_n\{2\} = \langle\langle 2 \rangle\rangle = \frac{\sum_{i=1}^{N_{\mathrm{ev}}} (W_{\langle 2 \rangle})_i \langle 2 \rangle_i}{\sum_{i=1}^{N_{\mathrm{ev}}} (W_{\langle 2 \rangle})_i}$$

$$v_n\{2\} = \sqrt{c_n\{2\}}$$

$$p_n = \sum_{j=1}^{m_p} e^{in\phi_j} \qquad q_n = \sum_{j=1}^{m_q} e^{in\phi_j}$$

$$\langle 2' \rangle = \frac{p_n Q_n^* - m_q}{m_p M - m_q}$$

$$d_n\{2\} = \langle\langle 2' \rangle\rangle = \frac{\sum_{i=1}^{N_{\mathrm{ev}}} (w_{\langle 2' \rangle})_i \langle 2' \rangle_i}{\sum_{i=1}^{N_{\mathrm{ev}}} (w_{\langle 2' \rangle})_i}$$

$$v_n\{2\}(p_{\mathrm{T}}) = \frac{d_n\{2\}}{\sqrt{c_n\{2\}}}$$

$$\langle 2 \rangle_{\Delta\eta} = \frac{Q_n^A \cdot Q_n^{B*}}{M_A \cdot M_B}$$

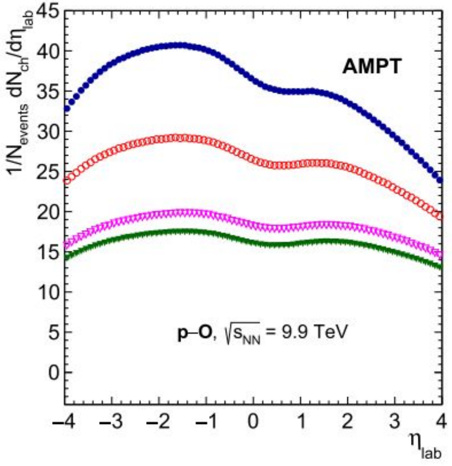
$$c_n\{2, |\Delta\eta|\} = \langle\langle 2 \rangle\rangle_{\Delta\eta}$$

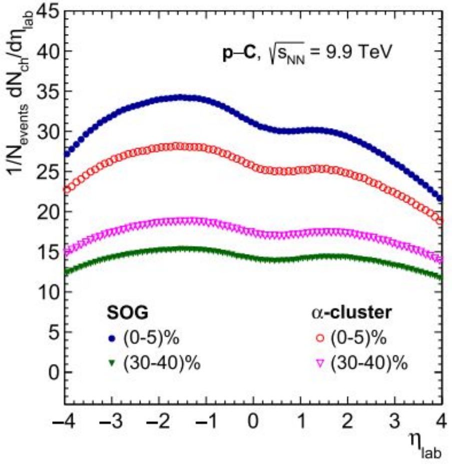
$$\langle 2' \rangle_{\Delta\eta} = \frac{p_{n,A} Q_{n,B}^*}{m_{p,A} M_B}$$

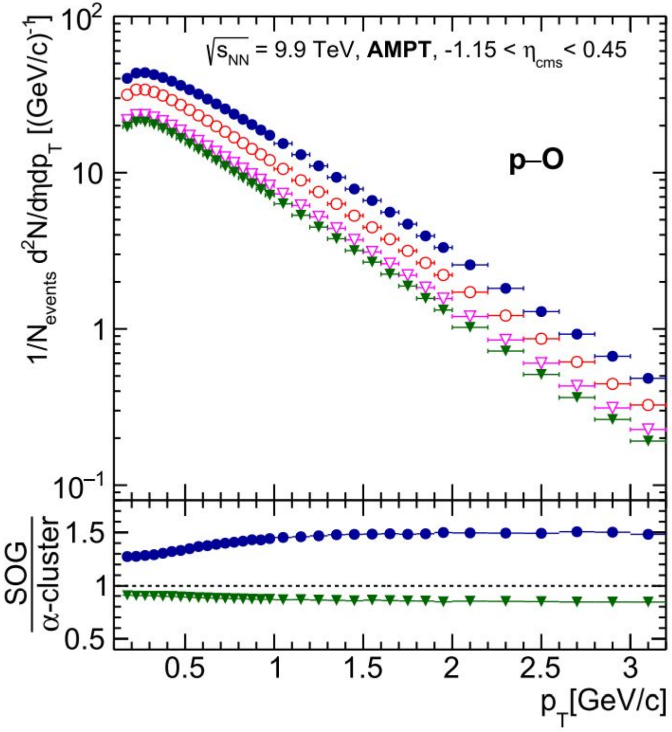
$$d_n\{2, |\Delta\eta|\} = \langle\langle 2' \rangle\rangle_{\Delta\eta}$$

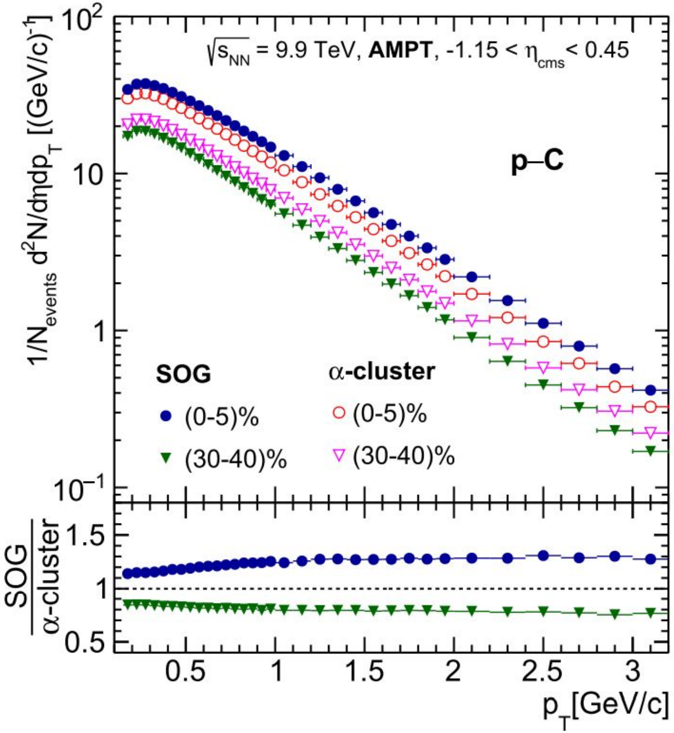
$$v_n\{2, |\Delta\eta|\}(p_{\mathrm{T}}) = \frac{d_n\{2, |\Delta\eta|\}}{\sqrt{c_n\{2, |\Delta\eta|\}}}$$

Results









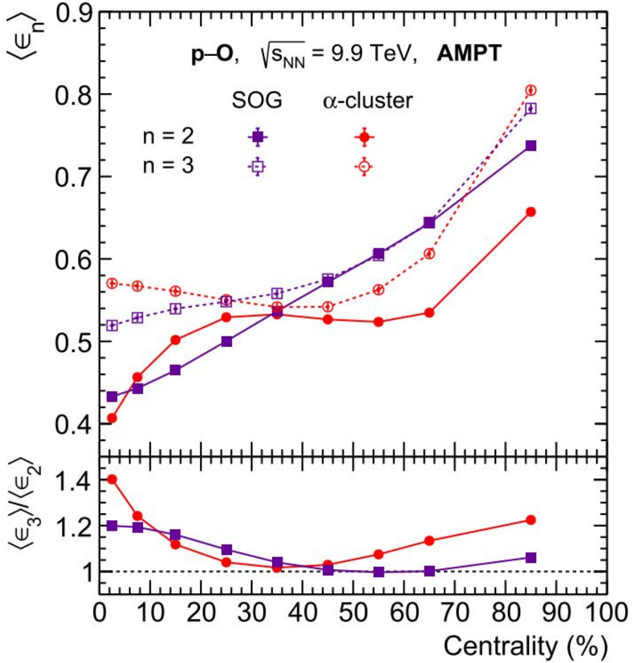
A. Menon Kavumpadikkal Radhakrishnan, S. Prasad, N. Mallick and R. Sahoo, Eur. Phys. J. A **61**, 134 (2025)

Results

Initial spatial anisotropies, such as, **eccentricity** (ϵ_2), **triangularity** (ϵ_3), etc., are quantified as:

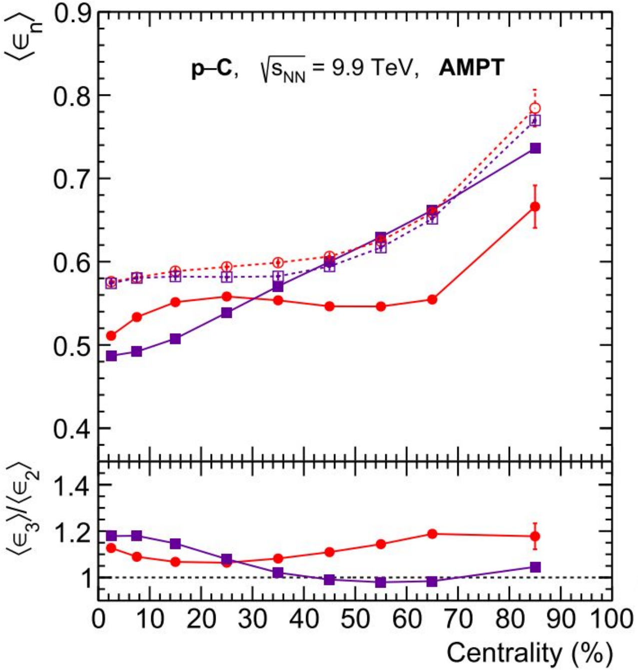
D. Behera, S. Prasad, N. Mallick and R. Sahoo, Phys. Rev. D **108**, 054022 (2023)

$$\epsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi_{\text{part}})\rangle^2 + \langle r^n \sin(n\phi_{\text{part}})\rangle^2}}{\langle r^n \rangle}$$



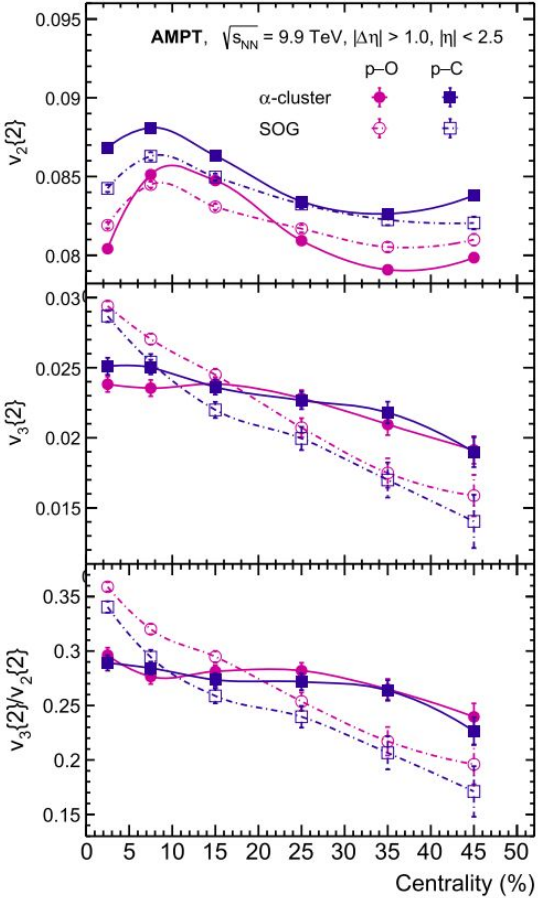
★ Trends of $\langle \epsilon_n \rangle$ and $\langle \epsilon_3 \rangle / \langle \epsilon_2 \rangle$ for α-cluster profiles are closely **similar to that in O-O** collisions at $\sqrt{s_{\text{NN}}} = 7\ TeV$

★ **$\langle \epsilon_3 \rangle / \langle \epsilon_2 \rangle$ shows a hike** at most central p-O collisions (absent in p-C)

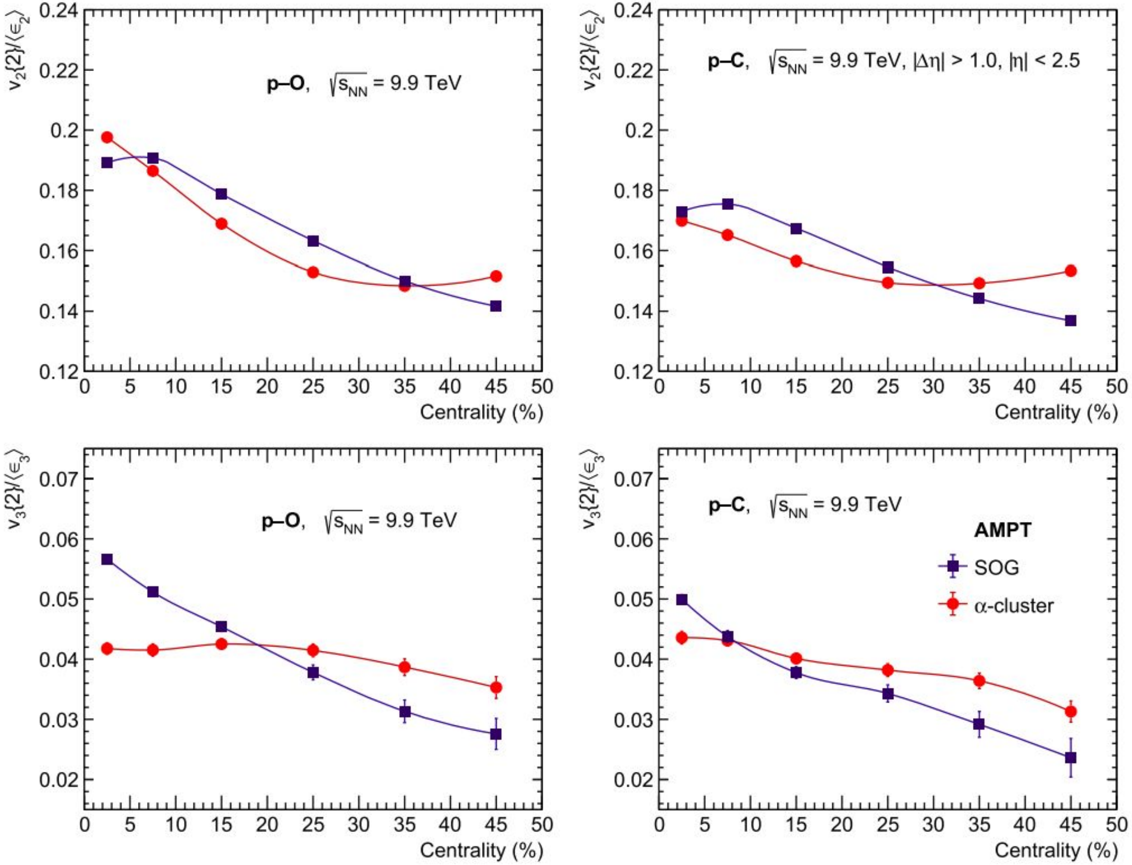


A. Menon Kavumpadikkal Radhakrishnan, S. Prasad, N. Mallick and R. Sahoo, Eur. Phys. J. A **61**, 134 (2025)

Results

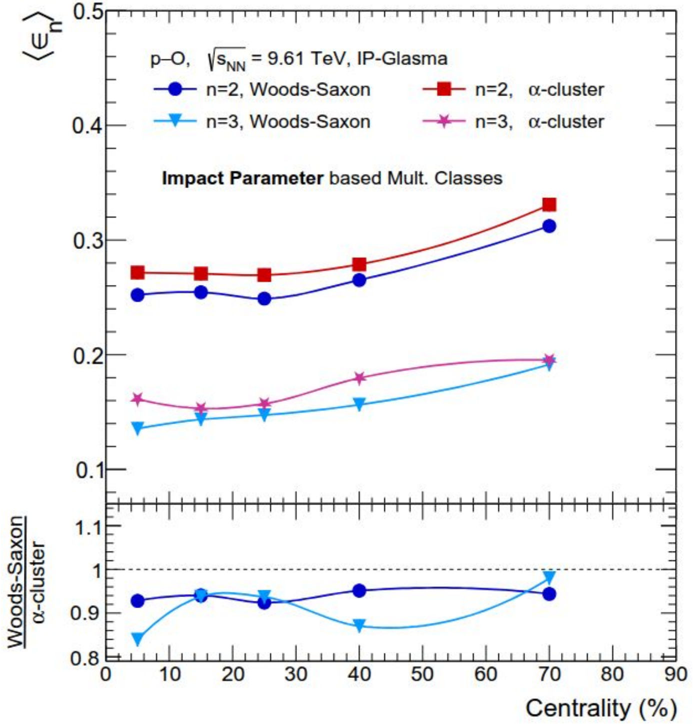


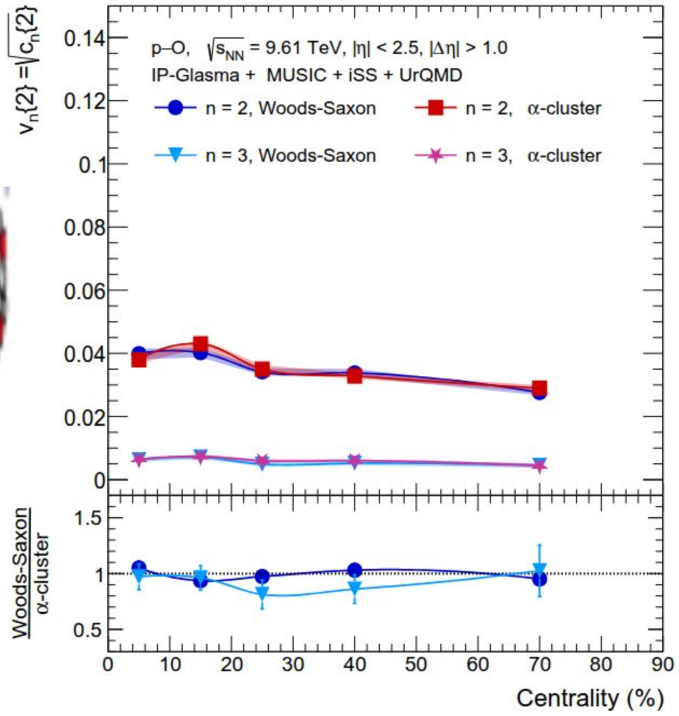
A. Menon Kavumpadikkal Radhakrishnan, S. Prasad, N. Mallick and R. Sahoo,
Eur. Phys. J. A **61**, 134 (2025)



Results

$$\epsilon_n = \frac{\sqrt{\left(\iint_A r^n \varepsilon(x,y)\cos(n\phi_{\text{part}})\mathrm{d}x\ \mathrm{d}y\right)^2 + \left(\iint_A r^n \varepsilon(x,y)\sin(n\phi_{\text{part}})\mathrm{d}x\ \mathrm{d}y\right)^2}}{\iint_A r^n \varepsilon(x,y)\mathrm{d}x\ \mathrm{d}y}$$

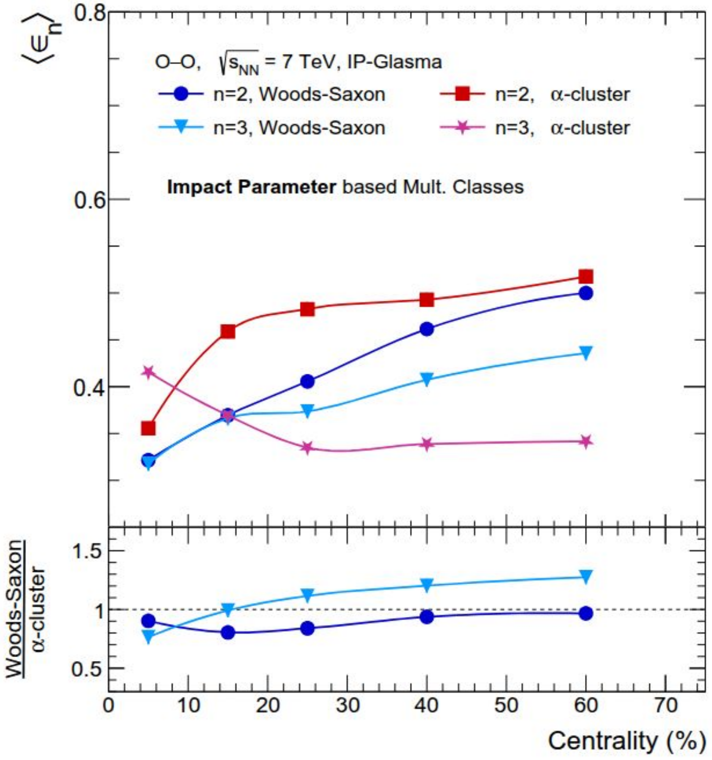


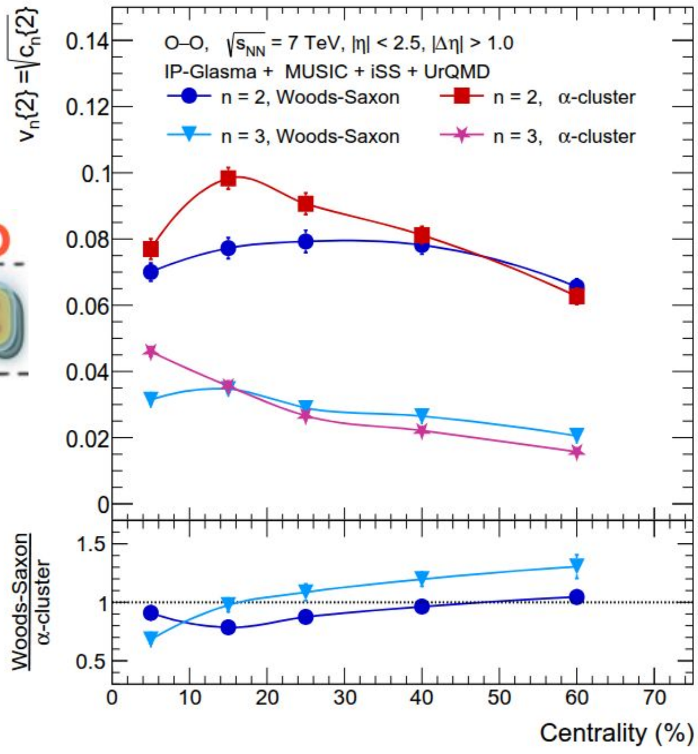


A. Menon Kavumpadikkal Radhakrishnan, S. Prasad, N. Mallick, R. Sahoo and G. G. Barnaföldi, arXiv:2505.22367 [hep-ph]

Results

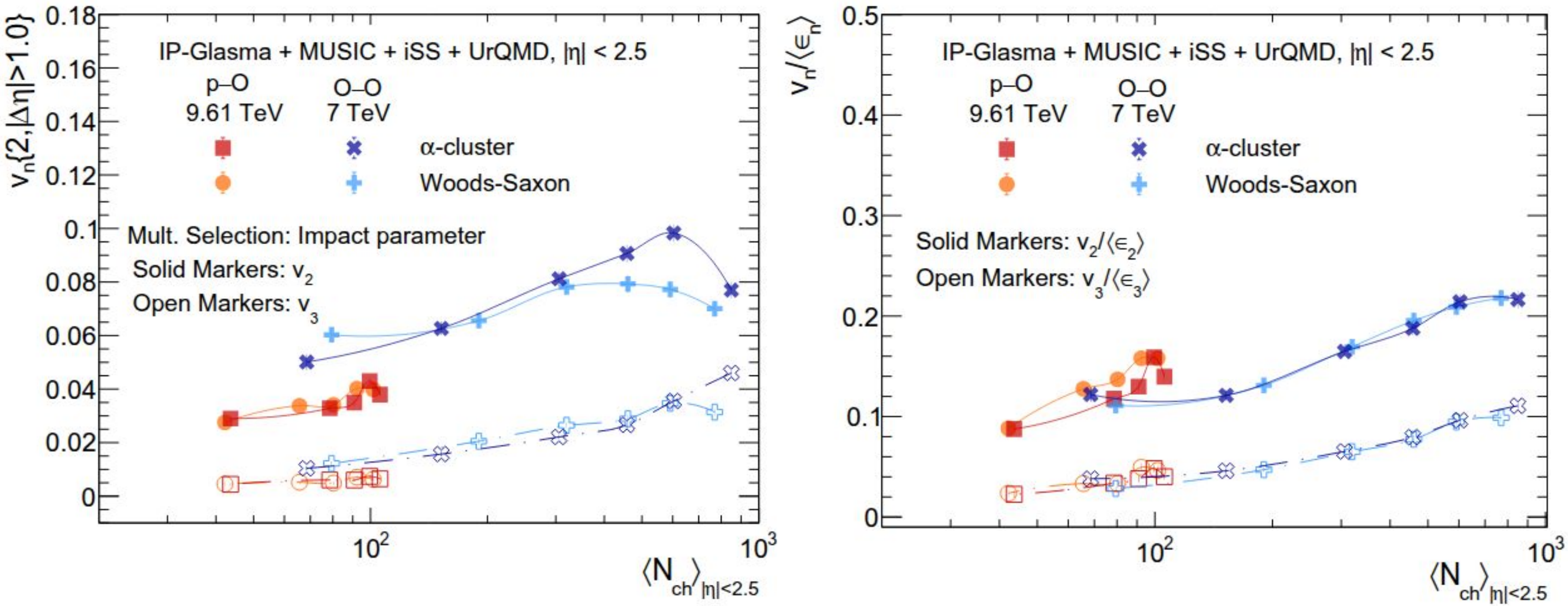
A. Menon Kavumpadikkal Radhakrishnan, S. Prasad, N. Mallick, R. Sahoo and G. G. Barnaföldi, arXiv:2505.22367 [hep-ph]





★ Distinction due to nuclear density profiles is better evident in OO than from pO collisions.

Results

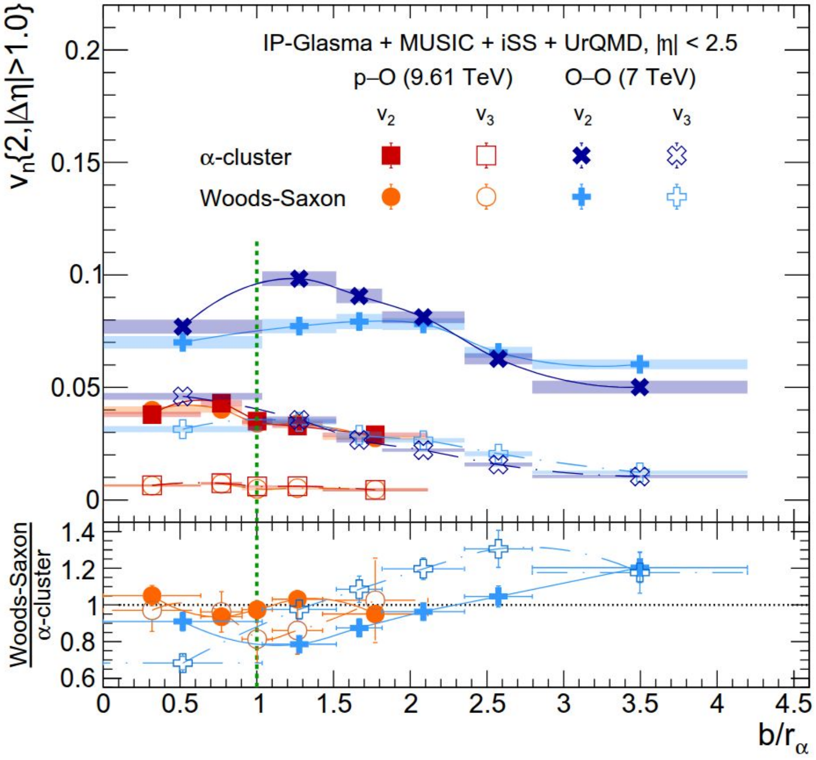


★ Effects from α-clustering gets pronounced at higher multiplicities (10-20% centrality)

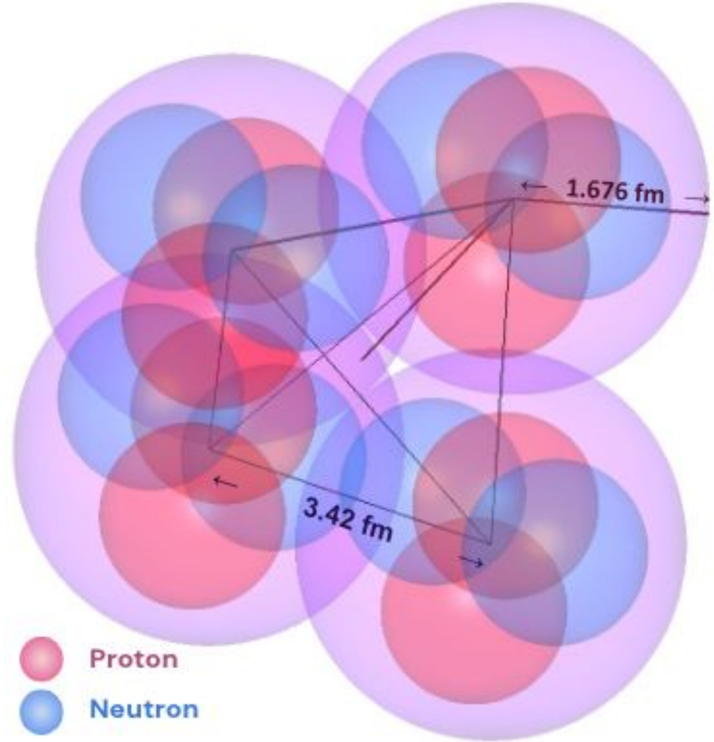
★ Response coefficient is multiplicity-dependent than being collision-system-dependent?

A. Menon Kavumpadikkal Radhakrishnan, S. Prasad, N. Mallick, R. Sahoo and G. G. Barnaföldi, arXiv:2505.22367 [hep-ph]

Results



A. Menon Kavumpadikkal Radhakrishnan, S. Prasad, N. Mallick, R. Sahoo and G. G. Barnaföldi, arXiv:2505.22367 [hep-ph]

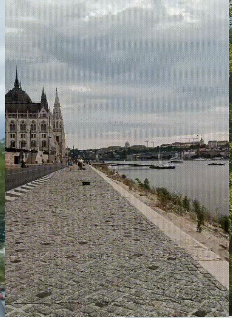


★ The effects of α-clustering in O–O collisions are observed to manifest well in the region $b/r_\alpha \lesssim 1$; therefore it is comparable with the size of the ^{4}He!

Summary and Outlook

- For the first time, a systematic study on the effects of initial nuclear density profiles (α-cluster nuclear geometry especially) on final state flow coefficients is reported for **pO** and **pC** collisions using AMPT model and for **pO** and **OO** collisions (from impact parameter based centrality classification) using IP-Glasma+MUSIC+iSS+UrQMD at LHC energies
- **α-cluster profile maintains a similar but unique qualitative behavior** throughout the collision systems, pC, pO and OO (AMPT)
- Effects of α-clustering are more prominent in OO collisions than pO and they are **pronounced in (10-20%)** centrality class. Proton might not be a good probe to study α-cluster structure
- α-clustering effects might **manifest well near** $b/r_\alpha \lesssim 1$ → needs further confirmation from other realistic nuclear collisions (C-C, Ne-Ne etc.)

Work is in progress to look into the effects of the compactness of α-clustering on the final state v_n and to extend our study to Ne-Ne collisions...


Thank

You :)