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Nuclear structure-driven anisotropic flow coefficients in pO and OO collisions at the LHC



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Based on:

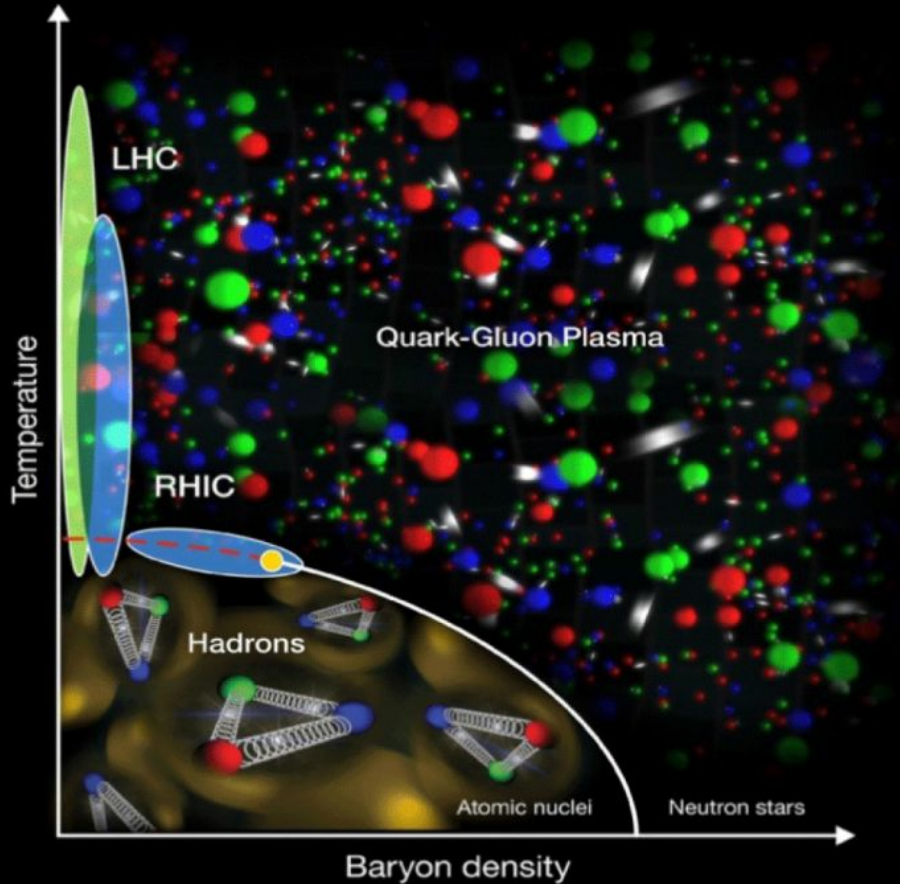
- A. Menon Kavumpadikkal Radhakrishnan, S. Prasad, N. Mallick, R. Sahoo and G. G. Barnaföldi, **Phys. Lett. B 870, 139941 (2025)**
- A. Menon Kavumpadikkal Radhakrishnan, S. Prasad, N. Mallick, R. Sahoo and G. G. Barnaföldi (*In Preparation*)

Outline

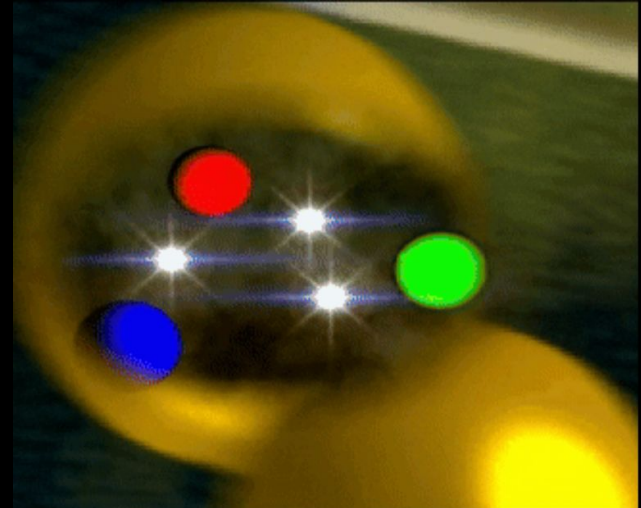
1. Relativistic heavy-ion collisions
2. Light-ion collisions
3. α -clustered nuclear structure
4. Anisotropic flow estimation
5. Results



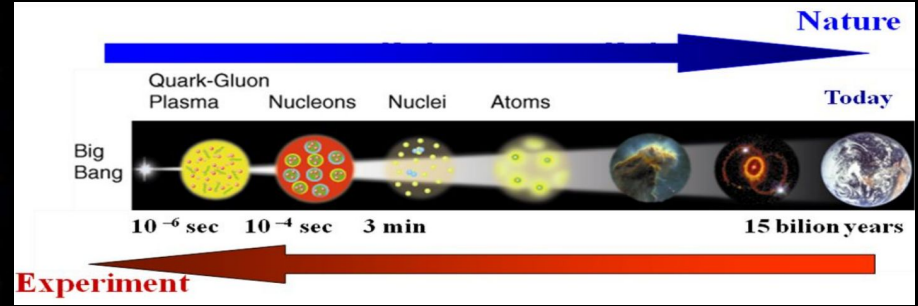
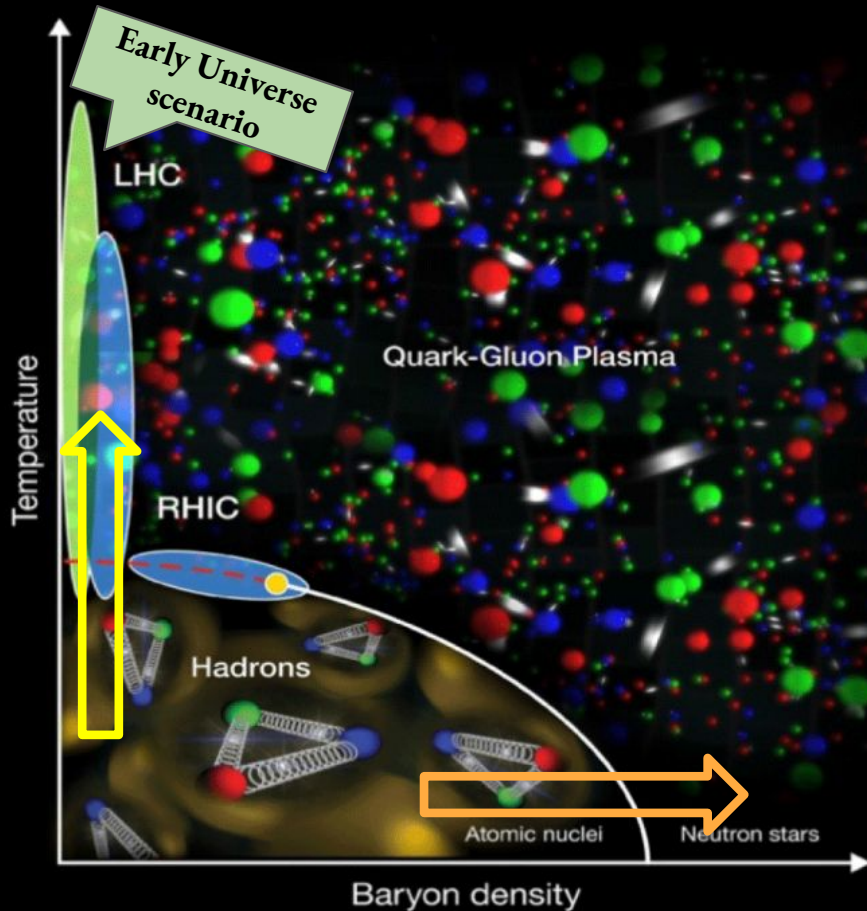
Why Relativistic collisions ?



- Nuclear matter is fundamentally composed of **quarks** and **gluons**, whose interactions are described by **Quantum Chromodynamics (QCD)**



Why Relativistic collisions ?

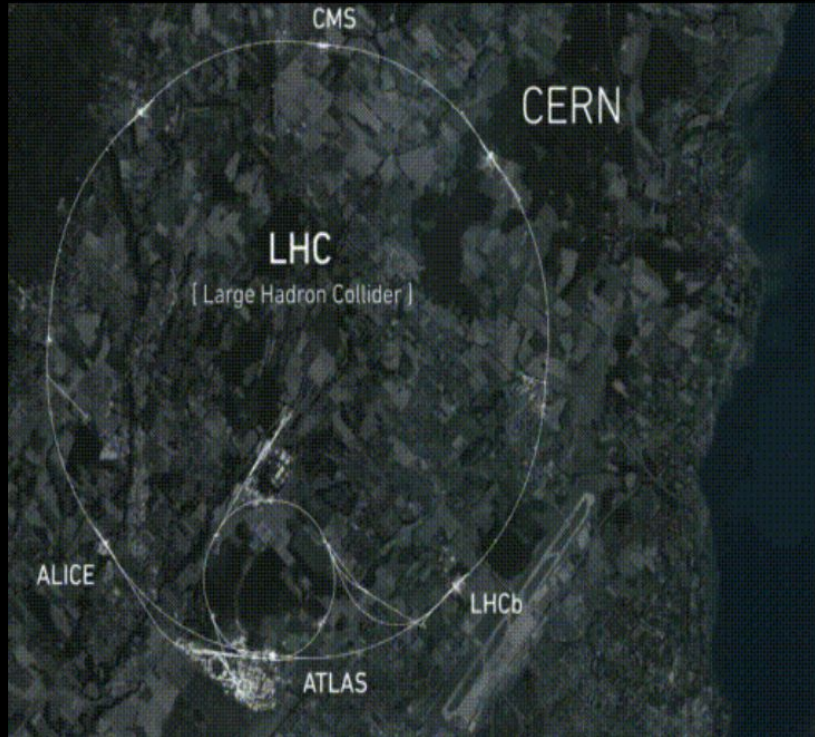


Quark-Gluon Plasma (QGP) :

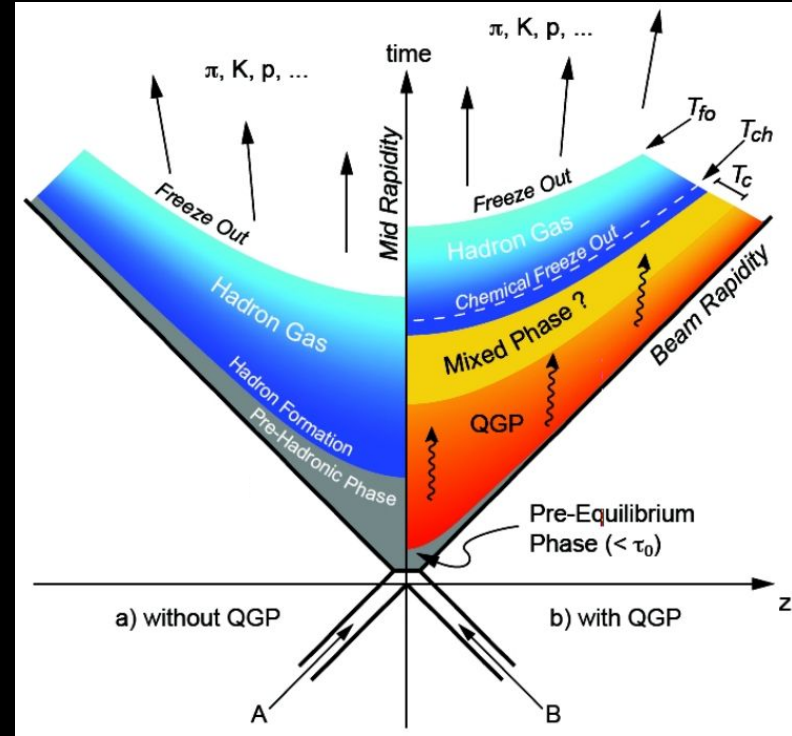
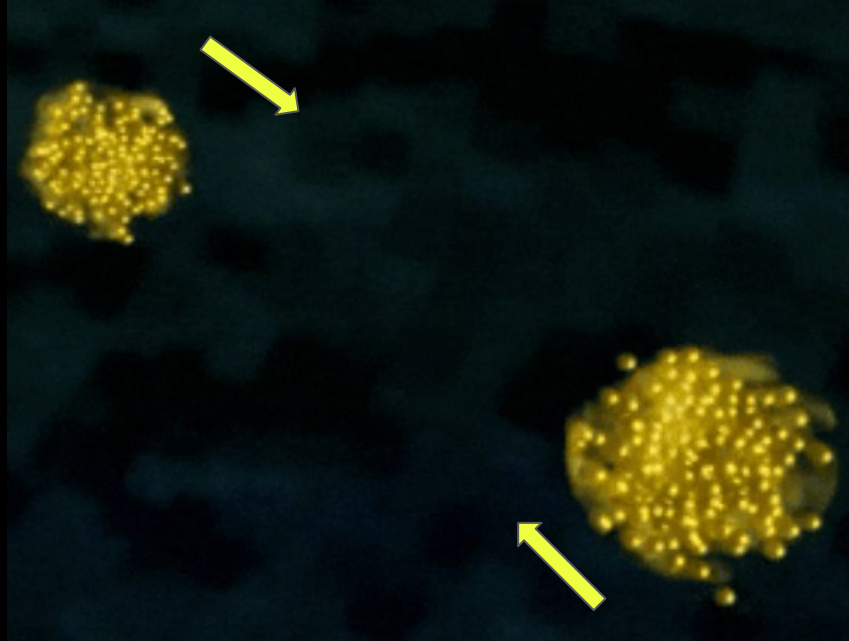
- ★ Deconfined state of quarks and gluons (partons) under local thermal equilibrium
- ★ The **Universe**, in the first few microseconds after the **Big Bang**, existed in QGP state

Why Relativistic collisions ?

- Through “**Little Bangs**”, LHC and RHIC try recreating the early-Universe scenario!

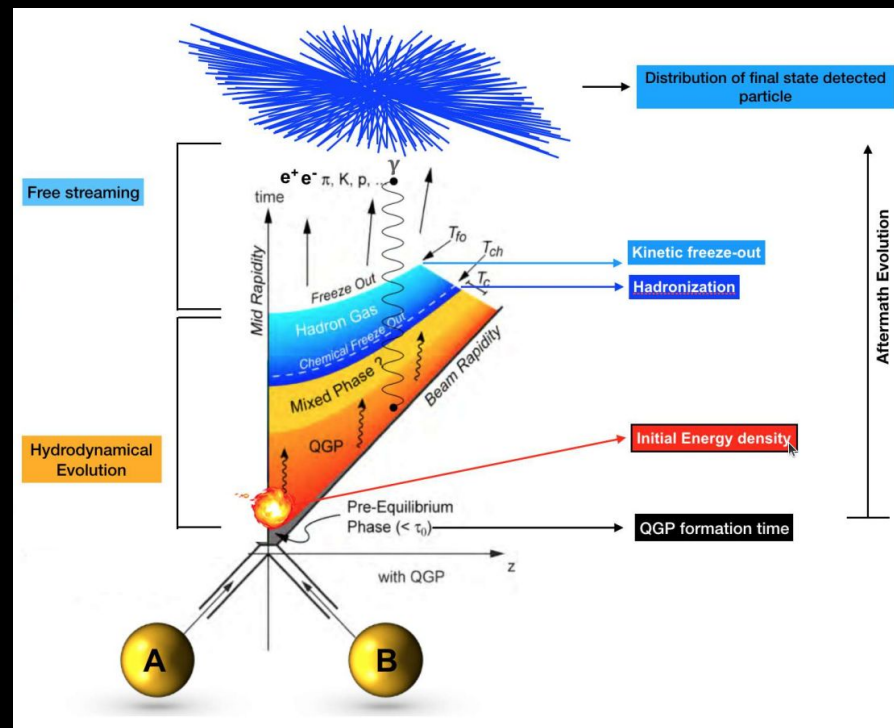
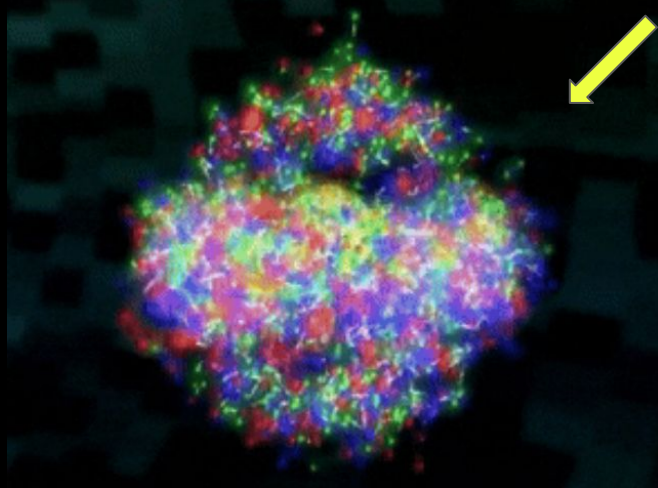
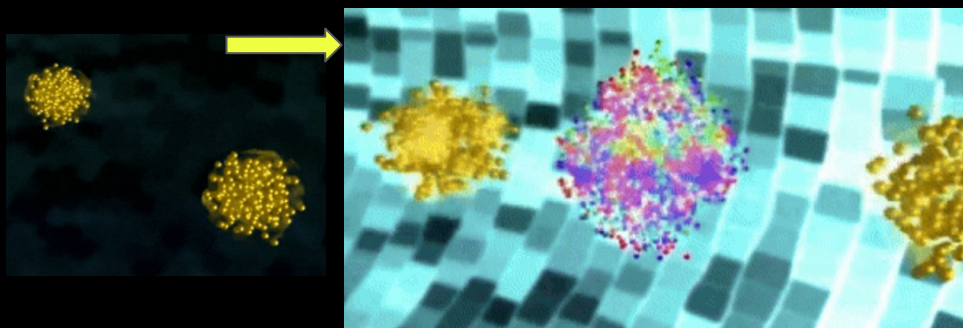


Space-time evolution of Relativistic collisions



High energetic beams travelling in opposite directions in separate beam-pipes, accelerating close to speed of light are made to collide...

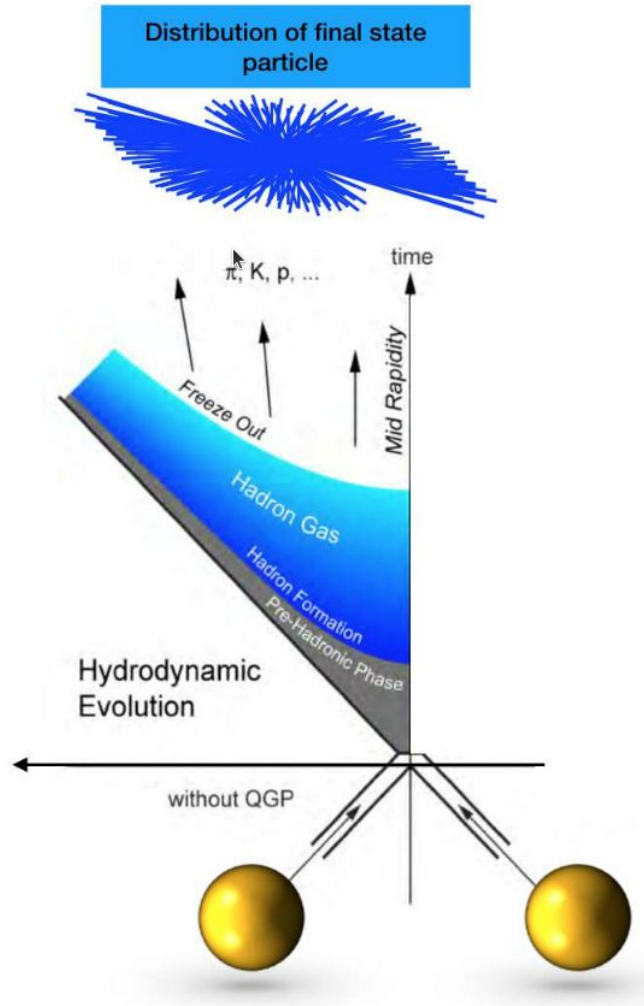
Space-time evolution of Relativistic collisions



Heavy-Ion
Collisions

Without QGP :

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

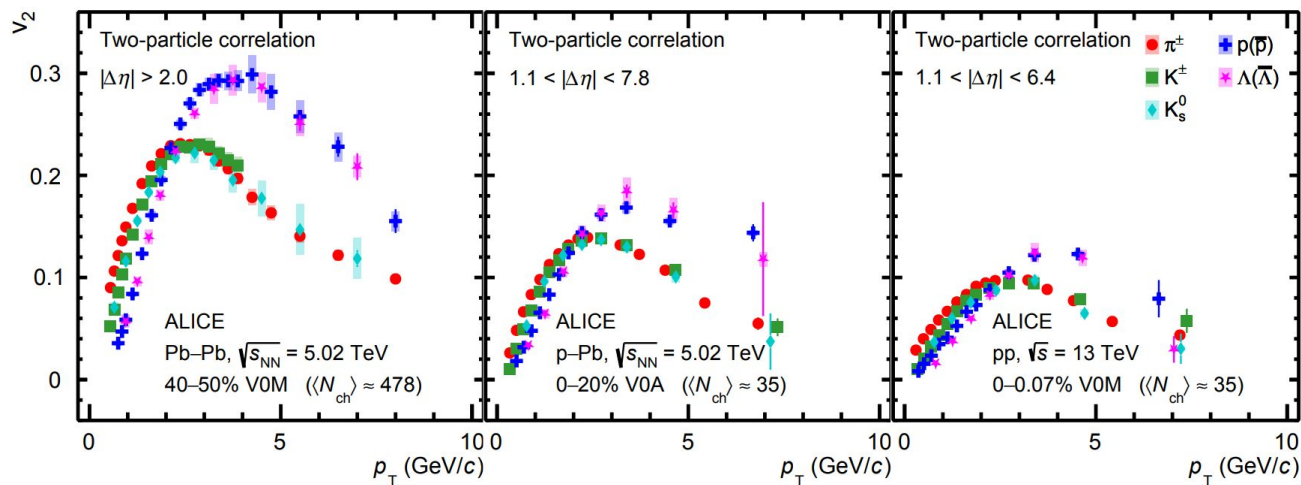


This picture of space-time evolution is expected to occur in **hadronic collisions**, where formation of QGP is least anticipated



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

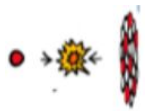


S. Acharya et al. [ALICE], *Nature Commun.* 17, 2585 (2026)

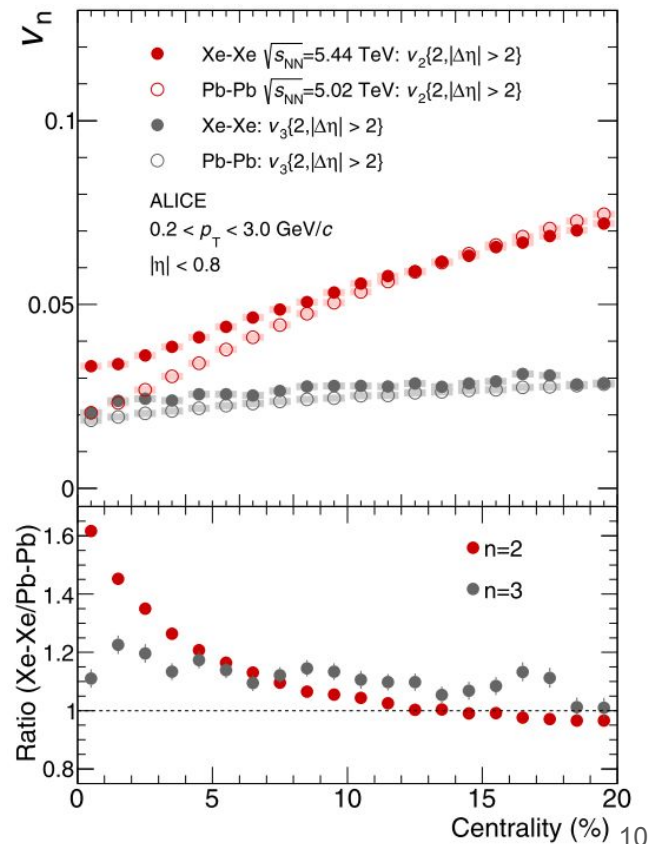
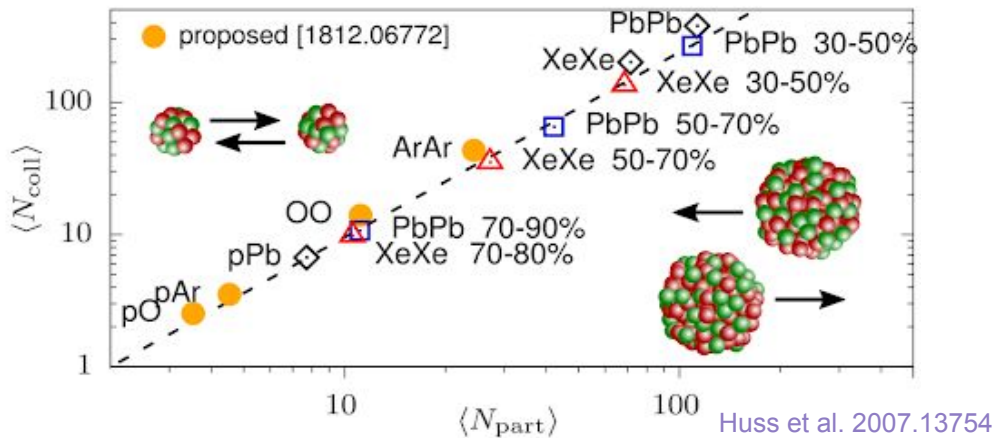
Focus :
SMALL
COLLISION
SYSTEMS



p0 and 00
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

p-O studies help COSMIC AIR SHOWER MODELLING

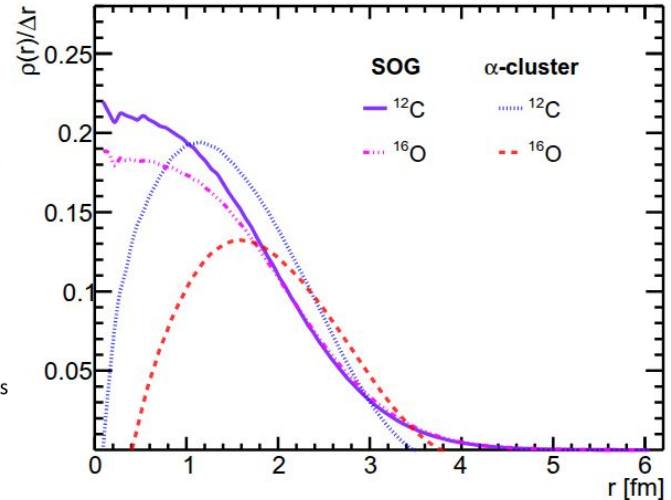
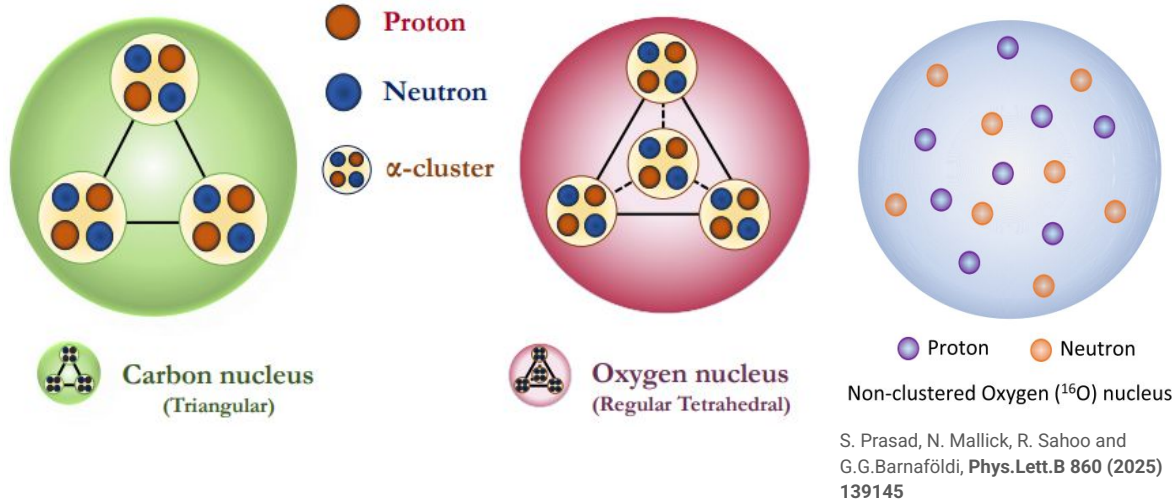
3

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

4

Effect of initial CLUSTERED geometry on final-state azimuthal correlations

α -clustering in O nuclei



α - cluster density profile

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

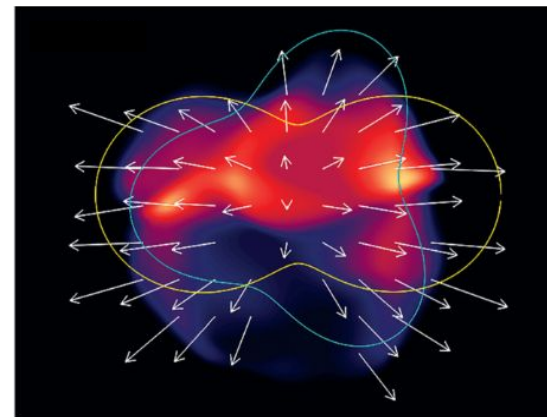
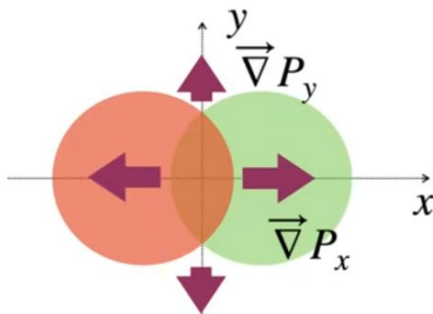
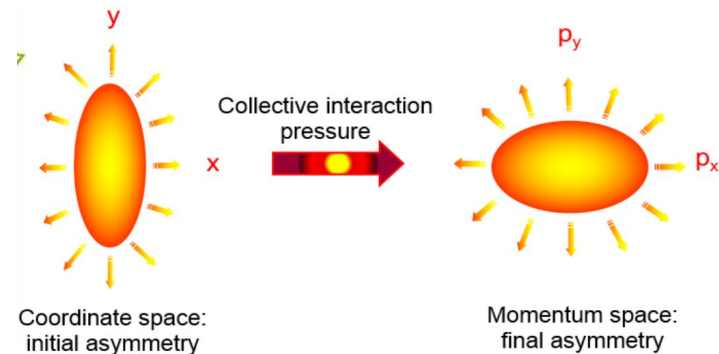
Anisotropic flow

- In non-central collisions, **spatial asymmetry** along different directions leads to **hierarchy of pressure gradients**: $\vec{\nabla} P_x \gg \vec{\nabla} P_y$
- 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 $v_n = \langle \cos[n(\phi - \psi_n)] \rangle$

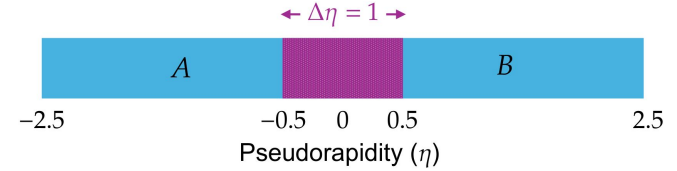
is the **n^{th} order anisotropic flow coefficient**



$v_2 \Rightarrow$ 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

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

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

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

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

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

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

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

$$v_n\{2\}(p_T) = \frac{d_n\{2\}}{\sqrt{c_n\{2\}}}$$

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

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

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

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

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



IP-Glasma+MUSIC+iSS+UrQMD

We simulate these pO, OO and Ne-Ne collisions using **event generators**, where entire evolution of the collision are modelled

Hybrid Hydrodynamic model : IP-Glasma + MUSIC + iSS + UrQMD

- ★ **IP-Glasma** : EbyE initial conditions (switching time of 0.4 fm) → Classical YM equations solved
- ★ **MUSIC** : Relativistic Viscous hydrodynamic equations solved (EoS s95p-v1.2 and $\eta/s = 0.12$)
- ★ **iSS** : Particlization using Cooper–Frye prescription (freeze-out hypersurface is constructed when local $\epsilon = 0.18 \text{ GeV}/\text{fm}^3$)

To improve statistical precision without rerunning the hydrodynamic evolution, **each IP-Glasma + MUSIC event is oversampled 200 times** using iSS.

- ★ **UrQMD** : Propagation of sampled hadrons to account for hadronic re-scatterings and decays, resulting in a more realistic dynamical freeze-out of different hadronic species

Such a realistic event generation is **COMPUTATIONALLY EXPENSIVE**

Wigner GPU machinery performs the entire event generation from initial collision to final-state particle transport :)

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★ **MUSIC** : R **1. IP-Glasma: Classical Yang–Mills evolution**

★ **iSS** : Particl The IP-Glasma model generates fluctuating initial conditions by solving classical Yang–Mills equations for $8 \text{ GeV}/\text{fm}^3$

To improve statisti

is oversampled

200 times using iS The equations are essentially:

★ **UrQMD** : $[D_\mu, F^{\mu\nu}] = J^\nu$

1 a more realistic

dynamical f

These are highly non-linear partial differential equations on a 3D lattice.

For every collision event:

- gluon fields fluctuate differently,
- color charges vary event-by-event,
- lattice evolution must be performed numerically.

Wigner GPU 1

le transport :)

This requires huge matrix operations and parallel computations.



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★ **iSS** : Particlization

2. **MUSIC: Relativistic viscous hydrodynamics**

To improve statistical p

200 times using iSS.

After the initial stage, MUSIC evolves the quark-gluon plasma by solving relativistic viscous hydrodynamic equations:

$$\partial_\mu T^{\mu\nu} = 0$$

★ **UrQMD** : Prop

where the energy-momentum tensor includes viscous corrections.

dynamical freeze

MUSIC solves coupled non-linear PDEs across spacetime grids for every time step.

Why expensive?

- Millions of grid cells,
- tiny time steps,
- many coupled variables,
- event-by-event fluctuations,
- viscosity terms increase numerical complexity.

Wigner GPU mac

For realistic statistics, this must be repeated for millions of events.

then local $\epsilon = 0.18 \text{ GeV/fm}^3$)

MUSIC event is oversampled

ays, resulting in a more realistic

NSIVE

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- ★ **UrQMD** : Propagation of sampled hadrons to account for hadronic re-scatterings and decays, resulting in a more realistic dynamic
- 1 hydro evolution
 - 200 particlization samplings
 - massive hadron production.

Wigner GP

This dramatically increases particle statistics but also multiplies CPU/GPU workload. *transport :)*

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- ★ **UrQMD** : Propagation of sampled hadrons to account for hadronic re-scatterings and decays, resulting in a more realistic dynamical freeze-out of different hadronic species

For high-multiplicity events, tracking all particle interactions becomes computationally intensive.

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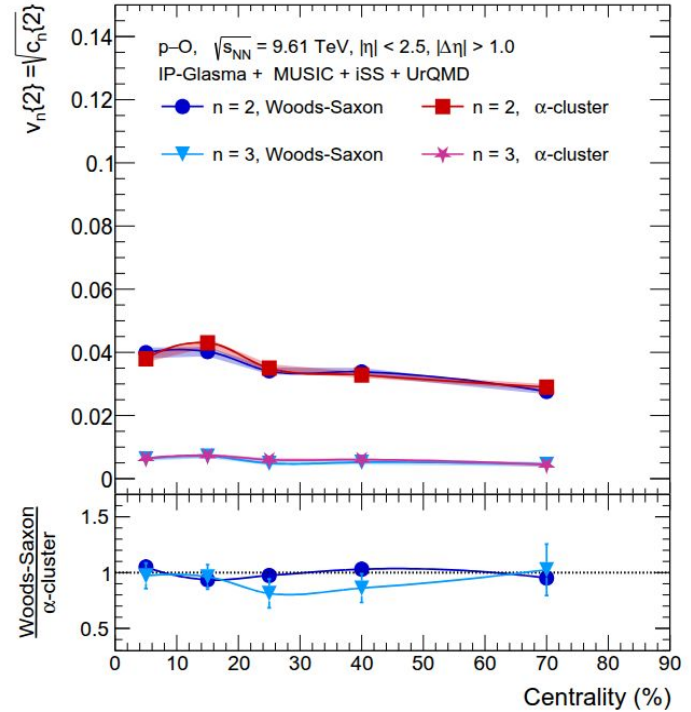
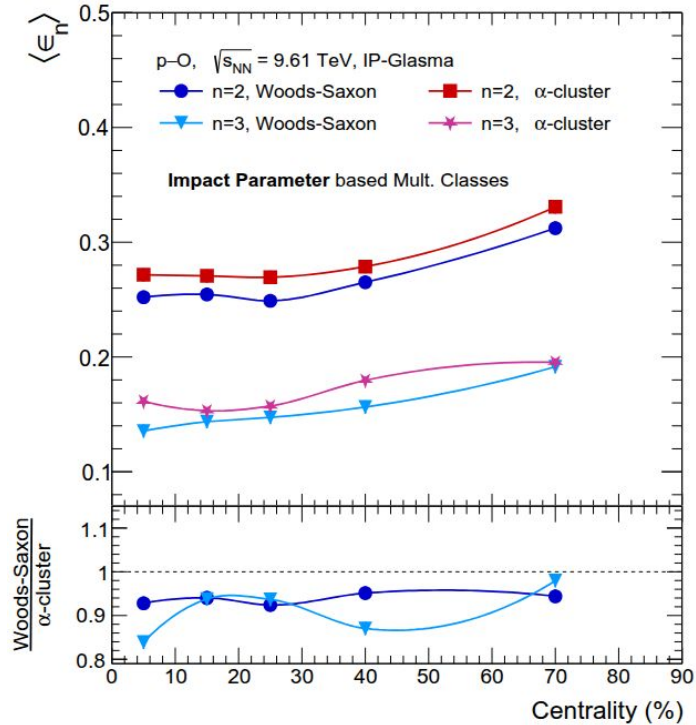
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GPU machinery from Wigner Scientific Computing Laboratory performs the entire event generation from initial collision to final-state particle transport :)

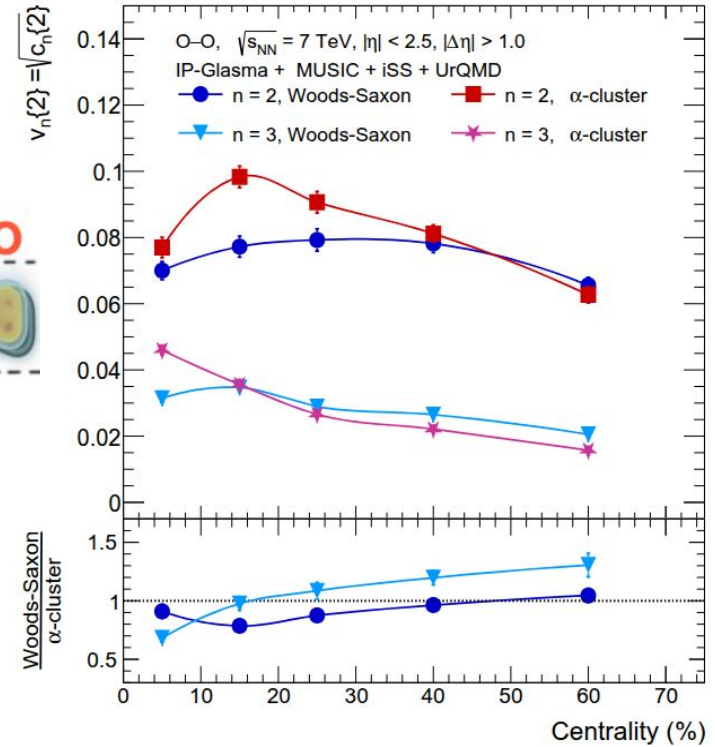
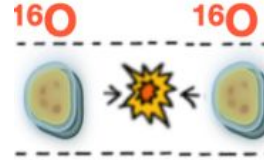
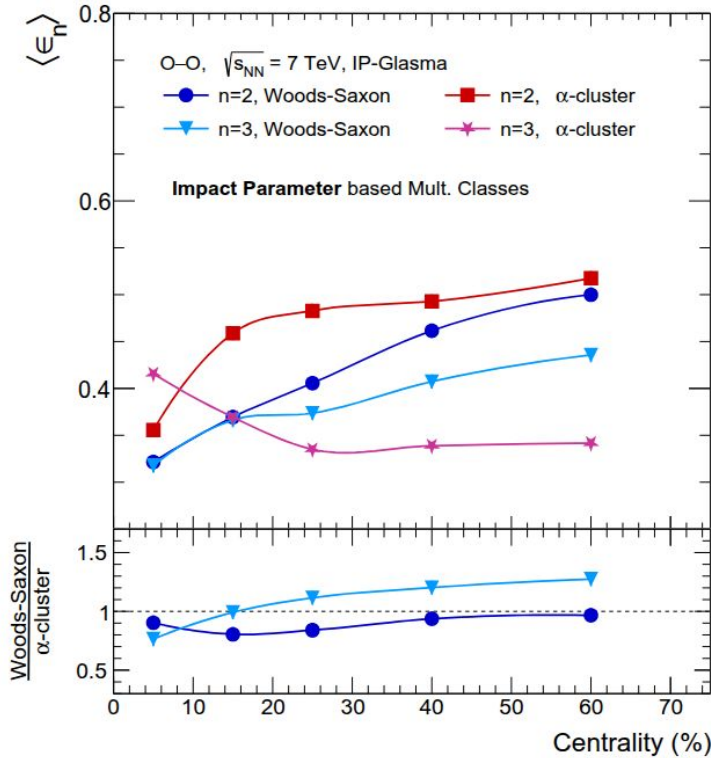
Results

Initial spatial anisotropies, such as, **eccentricity** (ϵ_2), **triangularity** (ϵ_3), etc., are quantified as: $\epsilon_n = \frac{\sqrt{(\iint_A r^n \epsilon(x, y) \cos(n\phi_{\text{part}}) dx dy)^2 + (\iint_A r^n \epsilon(x, y) \sin(n\phi_{\text{part}}) dx dy)^2}}{\iint_A r^n \epsilon(x, y) dx dy}$



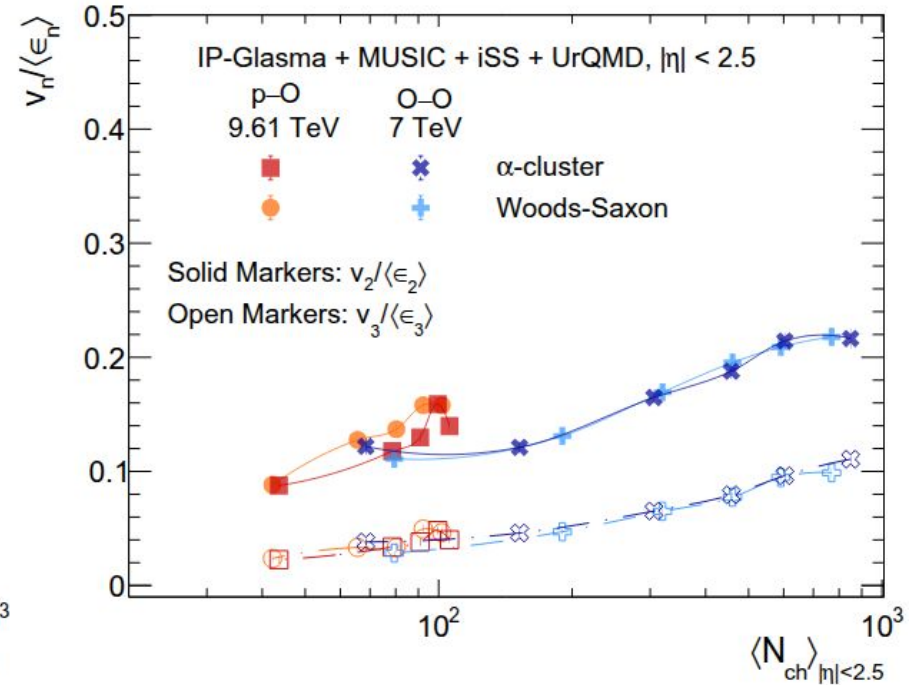
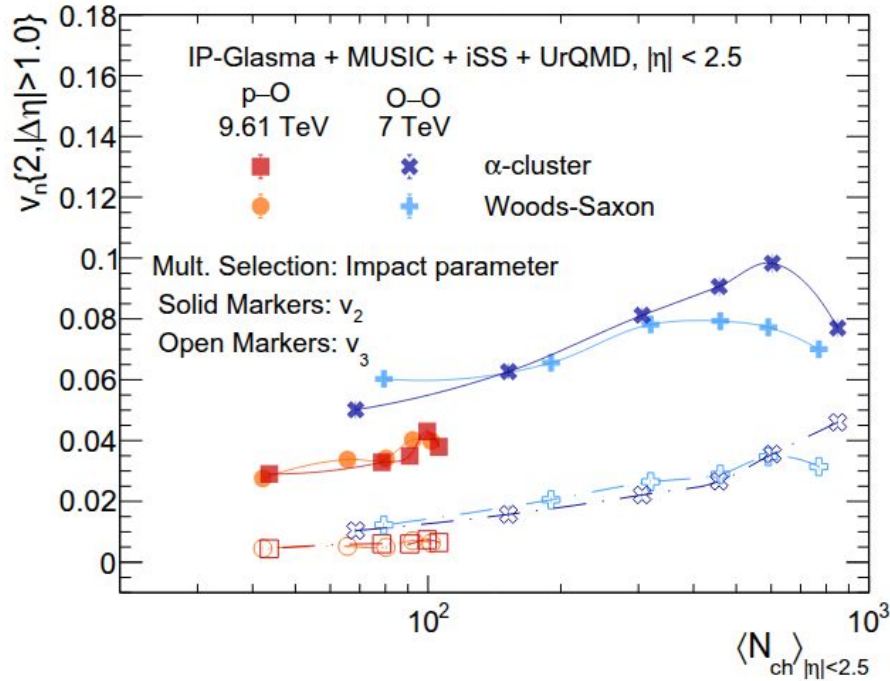
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A. Menon Kavumpadikkal Radhakrishnan, S. Prasad, N. Mallick, R. Sahoo and G. G. Barnaföldi, *Phys. Lett. B* 870, 139941 (2025)



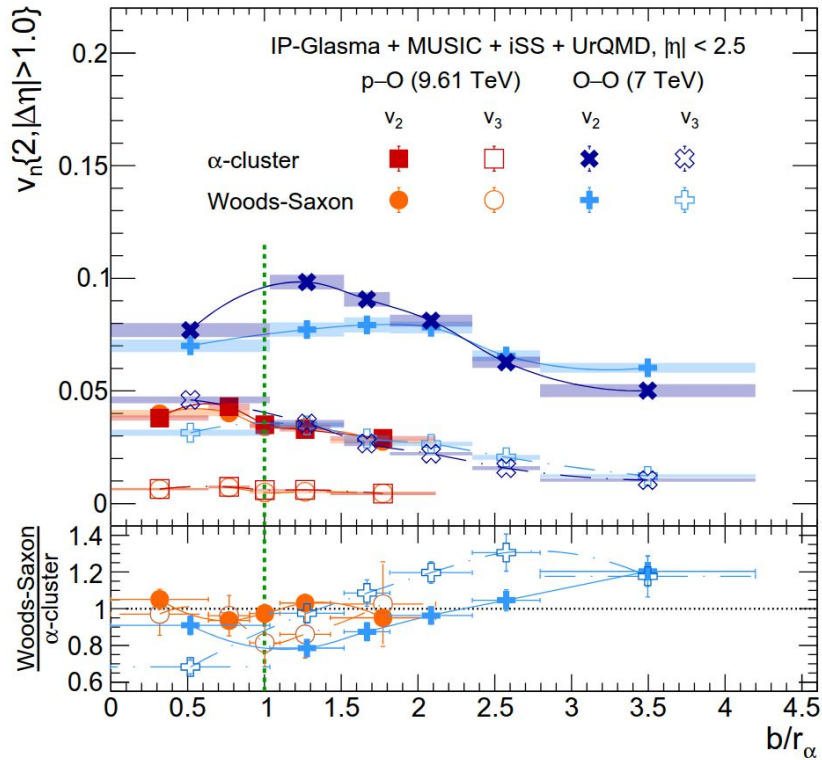
★ Distinction due to nuclear density profiles is better evident in OO than from pO collisions.

Results

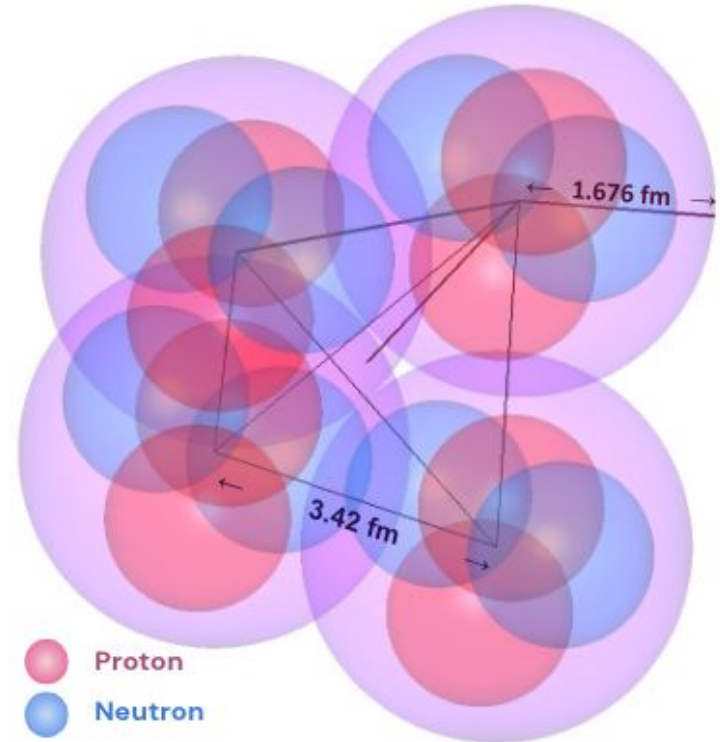


- ★ Effects from α -clustering gets pronounced at higher multiplicities (10-20% centrality)
- ★ Response coefficient is multiplicity-dependent than being collision-system-dependent?

Results



A. Menon Kavumpadikkal Radhakrishnan, S. Prasad, N. Mallick,
R. Sahoo and G. G. Barnaföldi, *Phys. Lett. B* **870**, 139941 (2025)

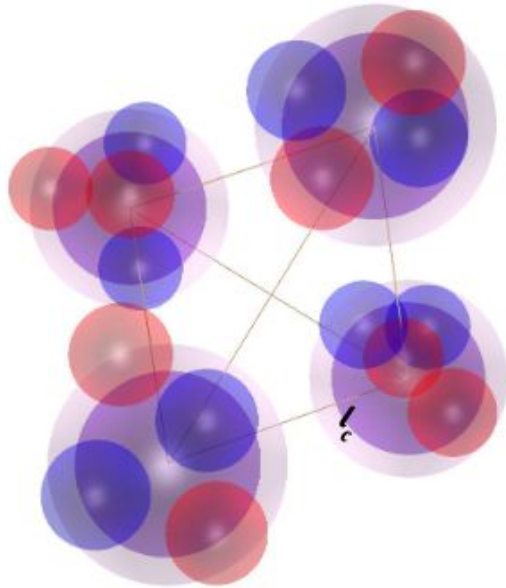


- ★ The effects of α -clustering in O–O collisions are observed to manifest well in the region $b/r_\alpha \lesssim 1$; therefore it is comparable with the size of the ^4He !

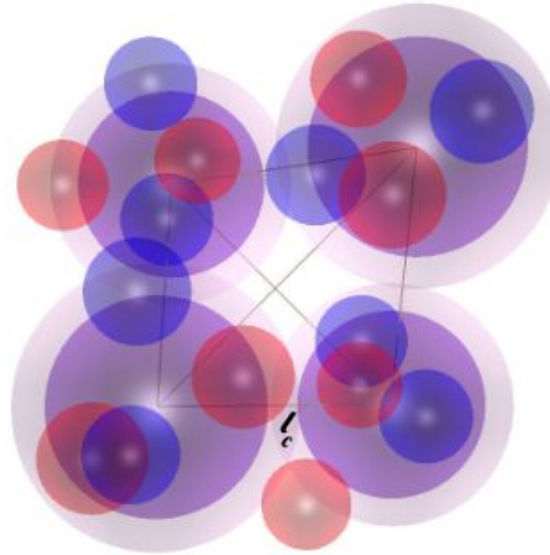
Results

- Does the compactness of α -cluster influence the peak positions of ν_2 ?
- **4 different Oxygen nuclear configurations:**

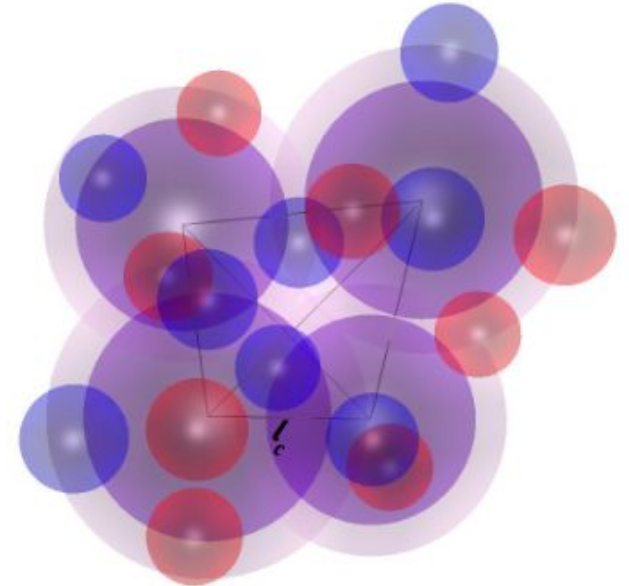
Woods-Saxon, **Compact** α -cluster, **Default** α -cluster, **Loose** α -cluster



COMPACT



DEFAULT

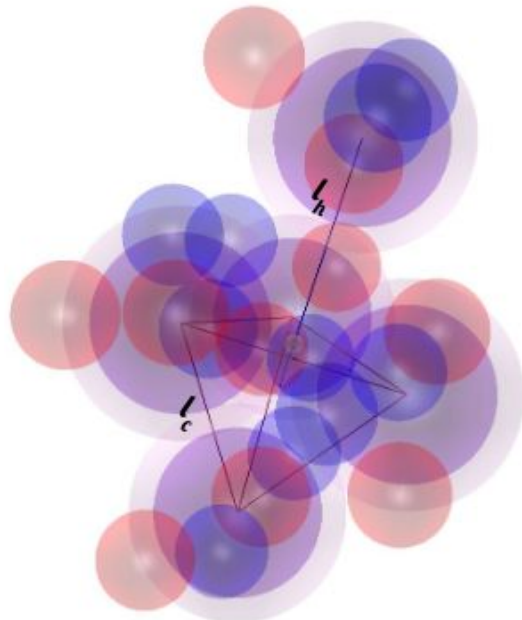


LOOSE

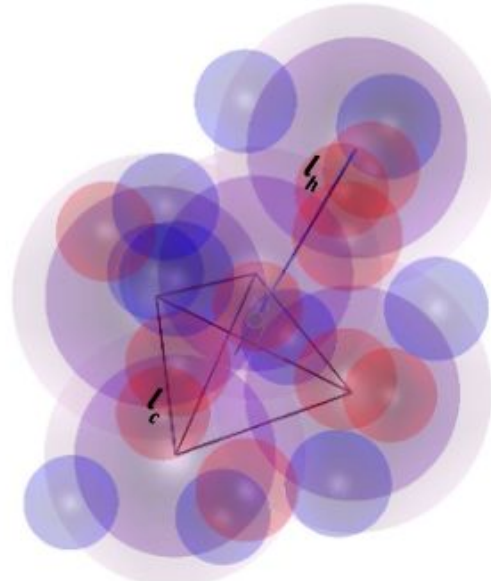
Results

- Does the compactness of α -cluster influence the peak positions of v_2 ?
- **4 different Neon nuclear configurations:**

Woods-Saxon, **Compact** α -cluster, **Default** α -cluster, **Loose** α -cluster

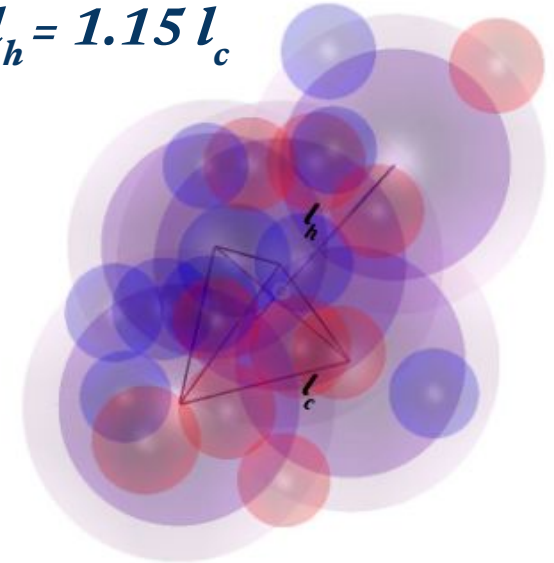


COMPACT



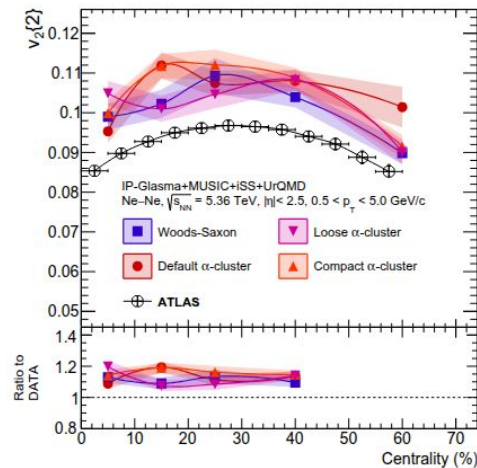
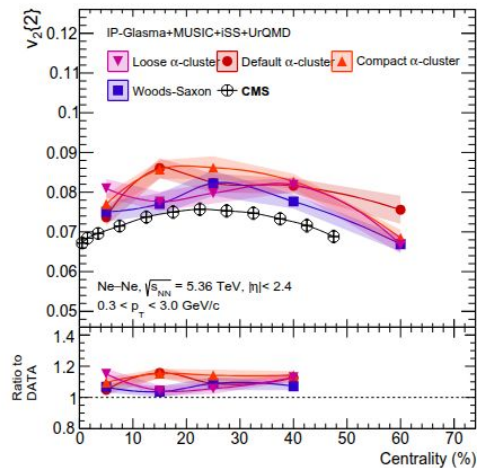
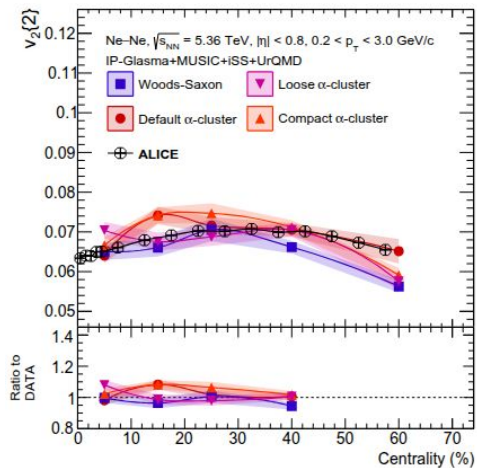
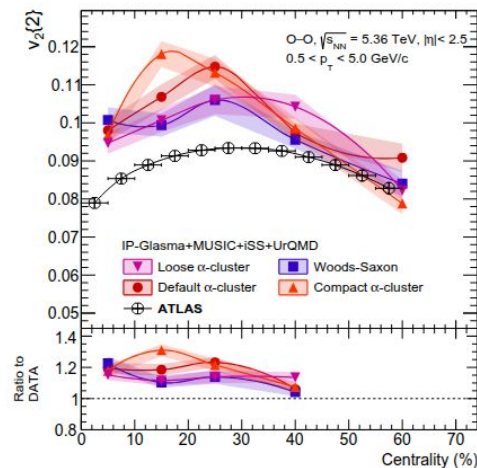
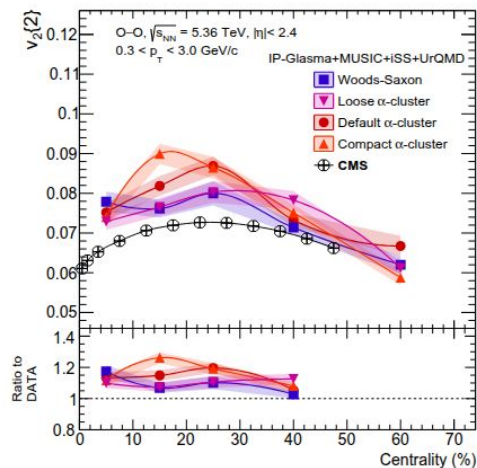
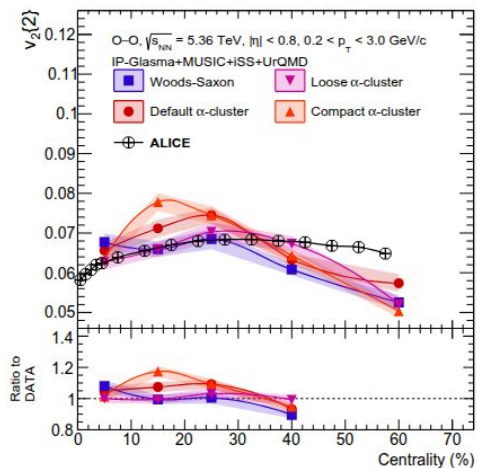
DEFAULT

$$l_h = 1.15 l_c$$



LOOSE

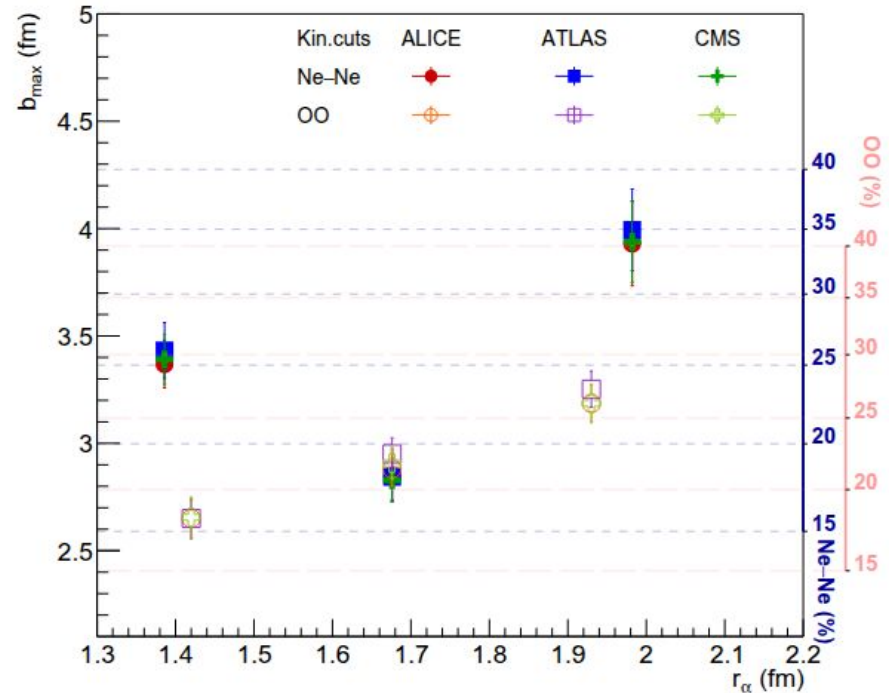
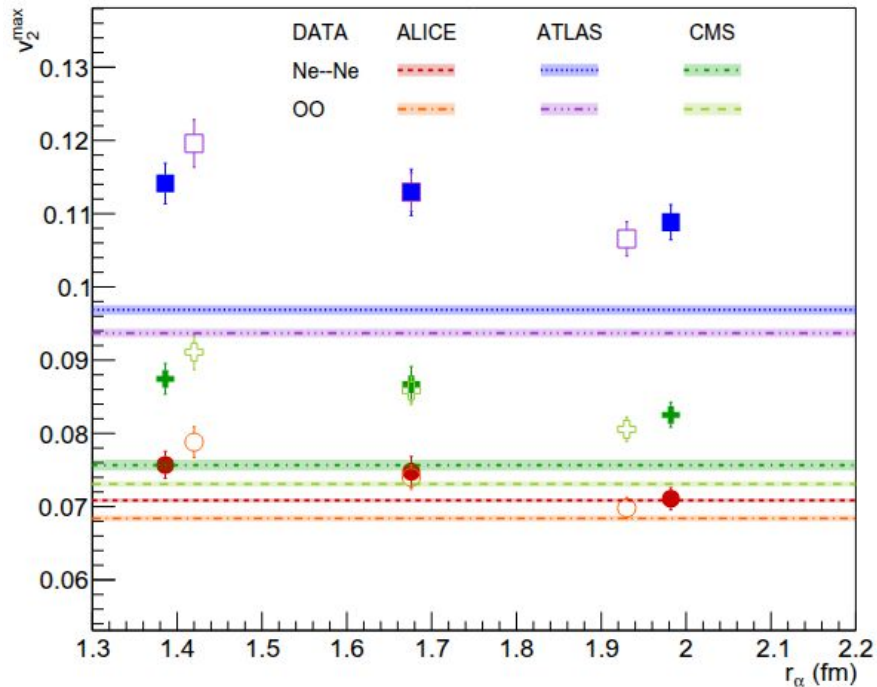
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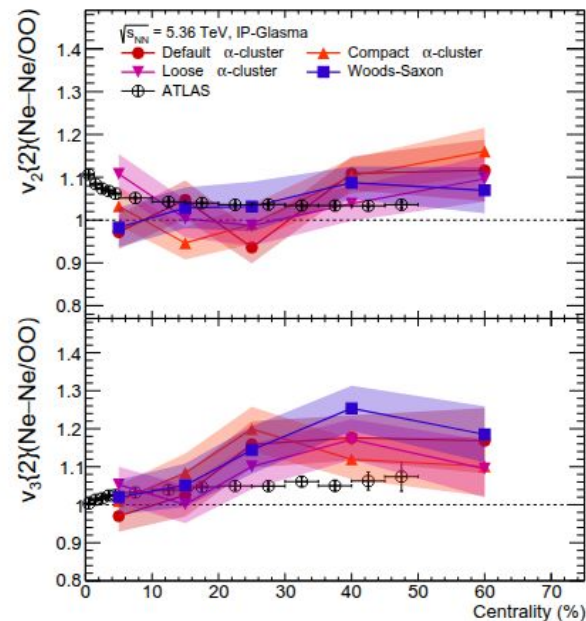
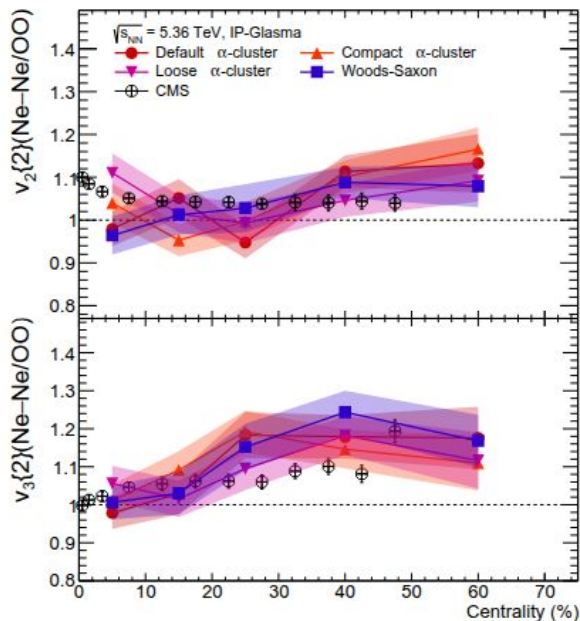
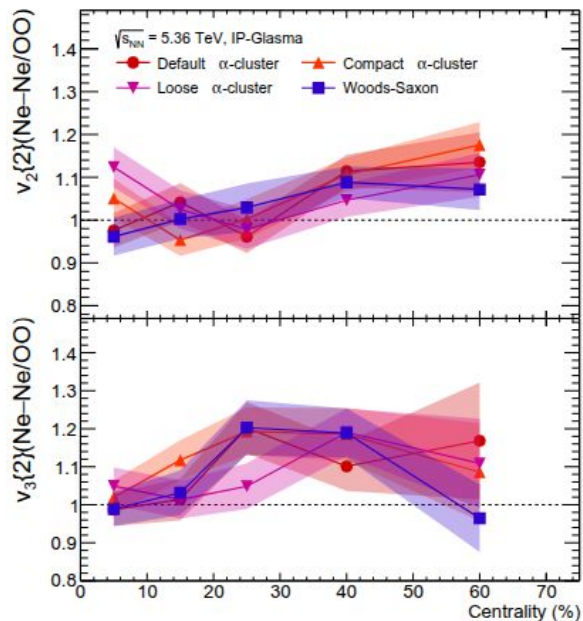
Compactness of α -cluster is observed to influence the peak positions of v_2

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Results



Results



By scanning the α -cluster radius and inter-cluster separation, we look forward to further identify the parameter range most consistent with the data.

Summary & Outlook

- 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 **OO** collisions (from impact parameter based centrality classification) using IP-Glasma+MUSIC+iSS+UrQMD at LHC energies
- 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 $b/r_\alpha \lesssim 1$** \rightarrow 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...

These results might be able to establish **anisotropic flow in TeV light-ion collisions** as a quantitative **probe of the structure of light nuclei** which is a **low-energy nuclear physics research** field!