Nuclear structure measurements in pO and OO collisions at LHC energies

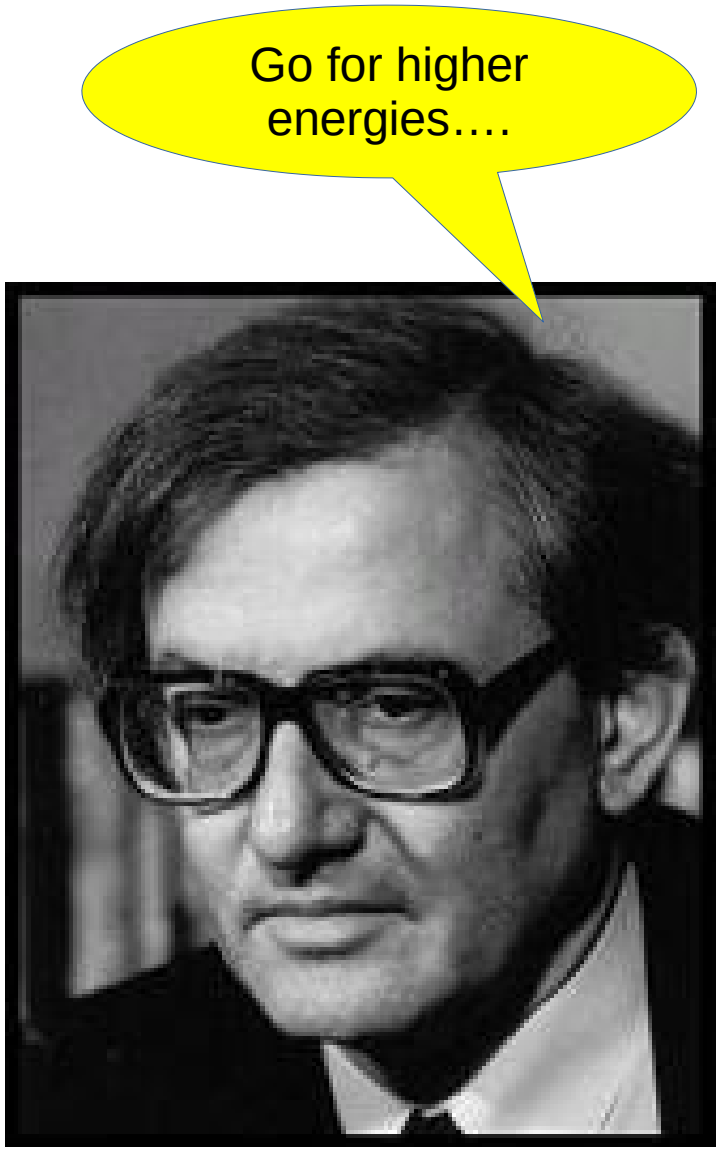
G.G. Barnaföldi, Aswathy Menon K.R., N. Mallick, S. Prasad, R. Sahoo

Support: *Hungarian NKFIH grants, 2025-1.1.5-NEMZ KI-2025-00005, 2025-1.1.5-NEMZ KI-2025-00013, 2024-1.2.5-TET-2024-00022NEMZ_KI-2022-00031, Wigner Scientific Computing Laboratory*

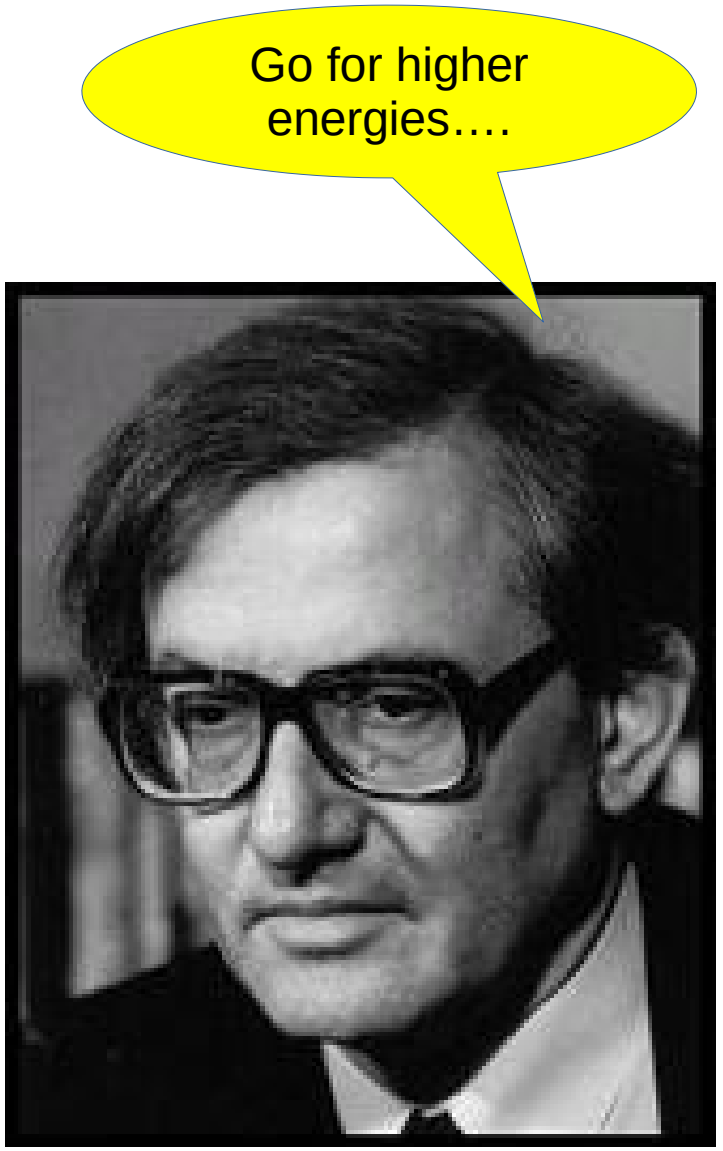
Refs.: OO: Physics Letters B 860 (2025) 139145, pO: Phys.Lett.B 870 (2025) 139941

Zimányi Winter School 2025, Budapest, Hungary, 5th December 2025

Wise men...

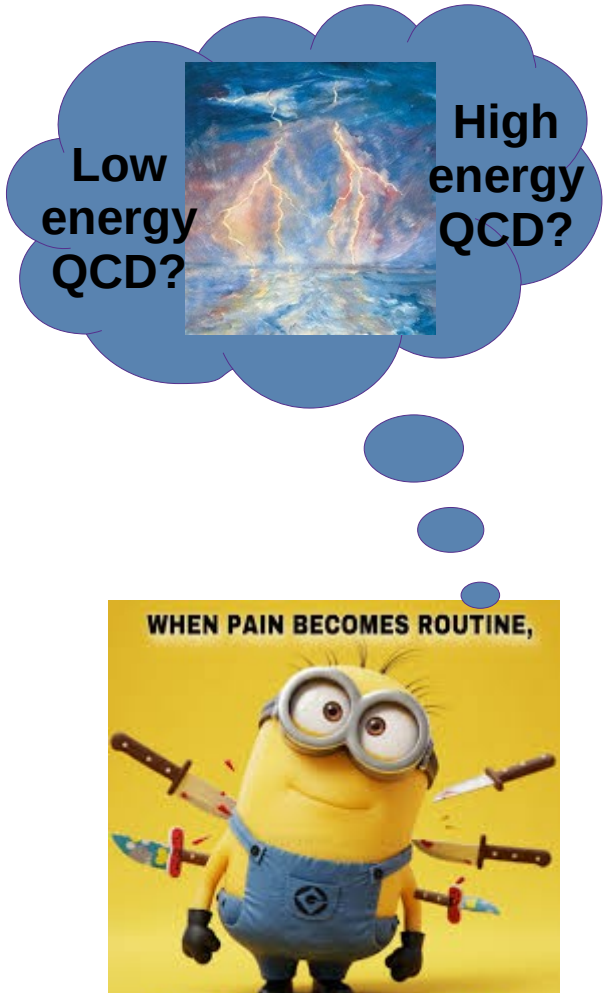


Wise men...



Wise men...

"Low energy is not bad..."



Go for higher energies….

Questions of this talk

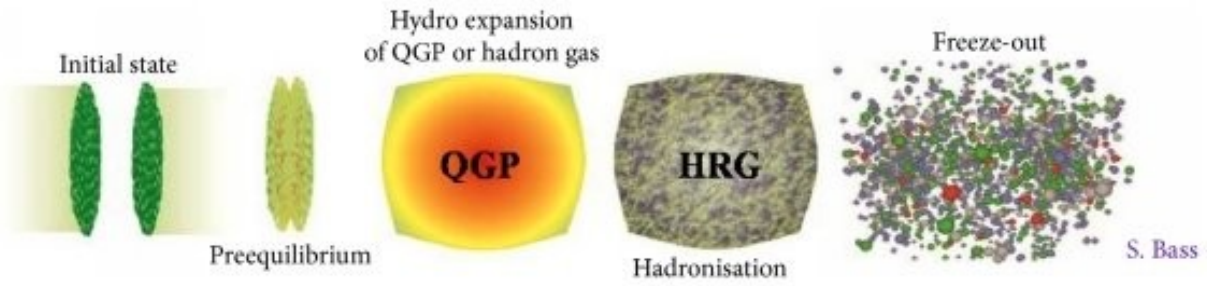
Can we

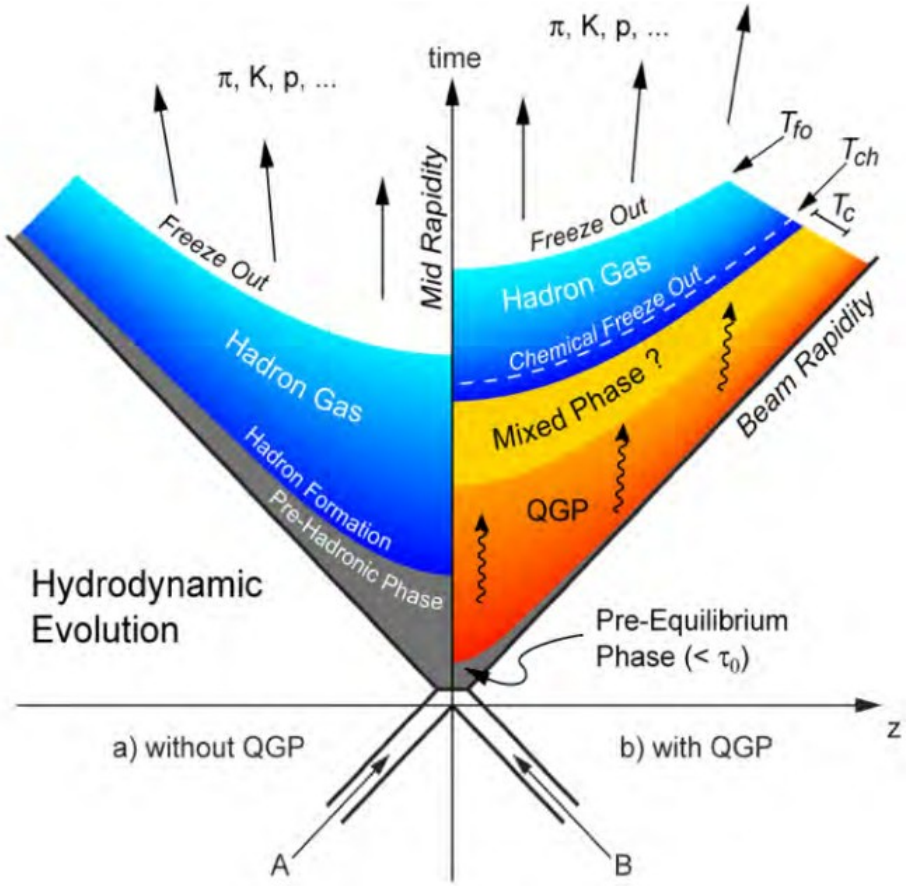
- **model the hydrodynamical evolution of small collisional systems?**
- **measure flow in the collisions of small systems?**
- **make difference in nuclear structure models of ^{16}O?**
- **validate nuclear structure models at the LHC energies?**

Motivation & definitions

Primordial matter in heavy-ion collisions

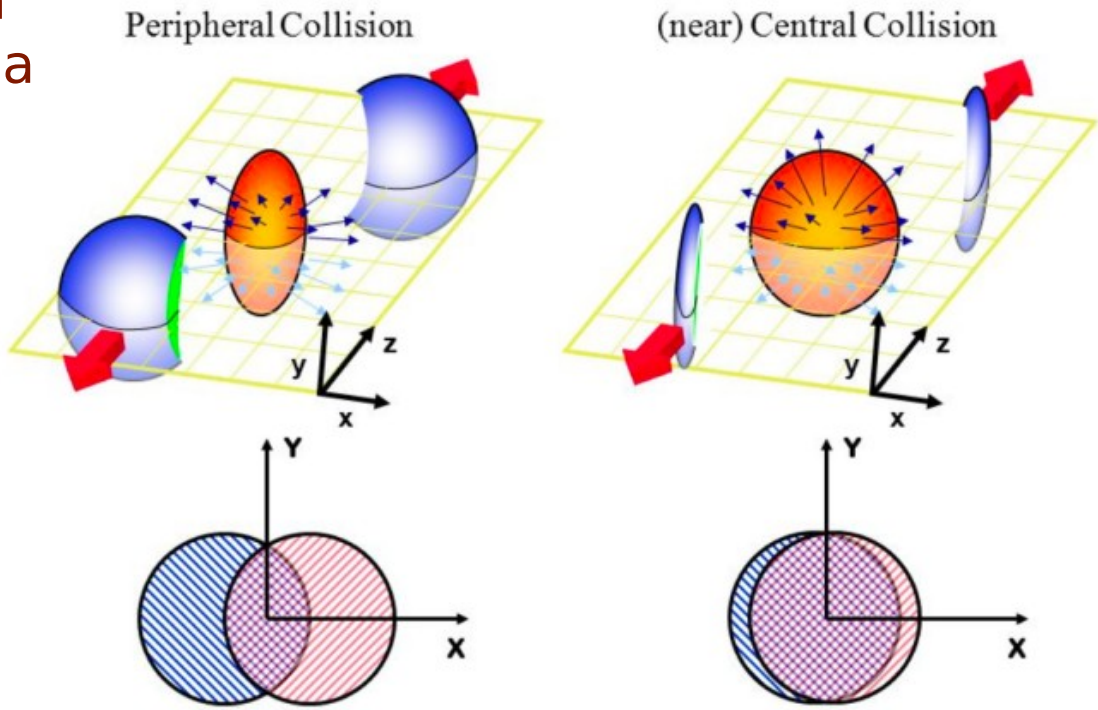
- **QGP in experimental vs theory points**
  - By colliding heavy-ions we can form small drop of the hot & dense primordial matter
  - No direct observations, just **signatures:** jet-quenching, correlations, collective effects, (**anisotropic) flow**…
  - Need a complex description, including QCD phenomenology, hydrodynamics, (non-equilibrium) thermodynamics





Flow (v_n) in heavy-ion collisions

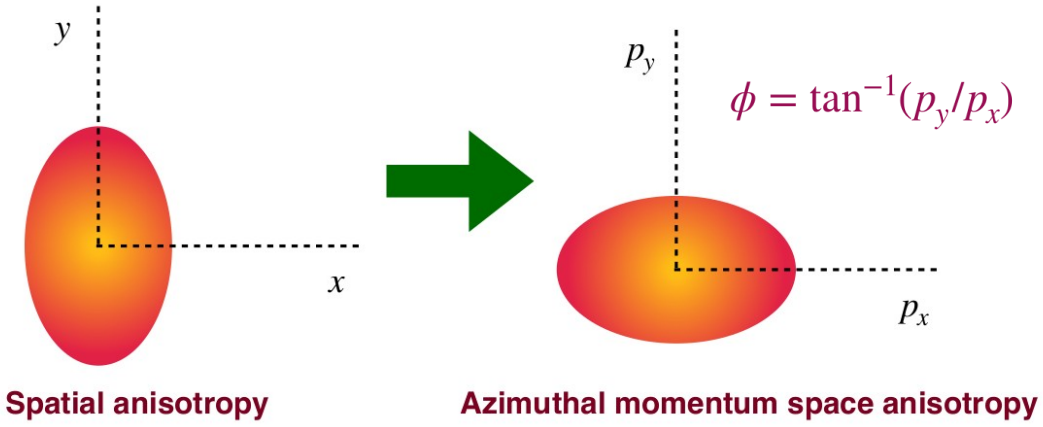
- **Experimental point:**
  - Flow describes the azimuthal momentum space anisotropy of particle emission for a non-central heavy-ion collision.



Flow (v_n) in heavy-ion collisions

- **Experimental point:**
  - Flow describes the azimuthal momentum space anisotropy of particle emission for a non-central heavy-ion collision.
  - The nth harmonic coefficient of the Fourier expansion of azimuthal momentum distribution:

$$E\frac{d^3N}{dp^3} = \frac{d^2N}{p_T dp_T dy}\frac{1}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \psi_n)]\right)$$

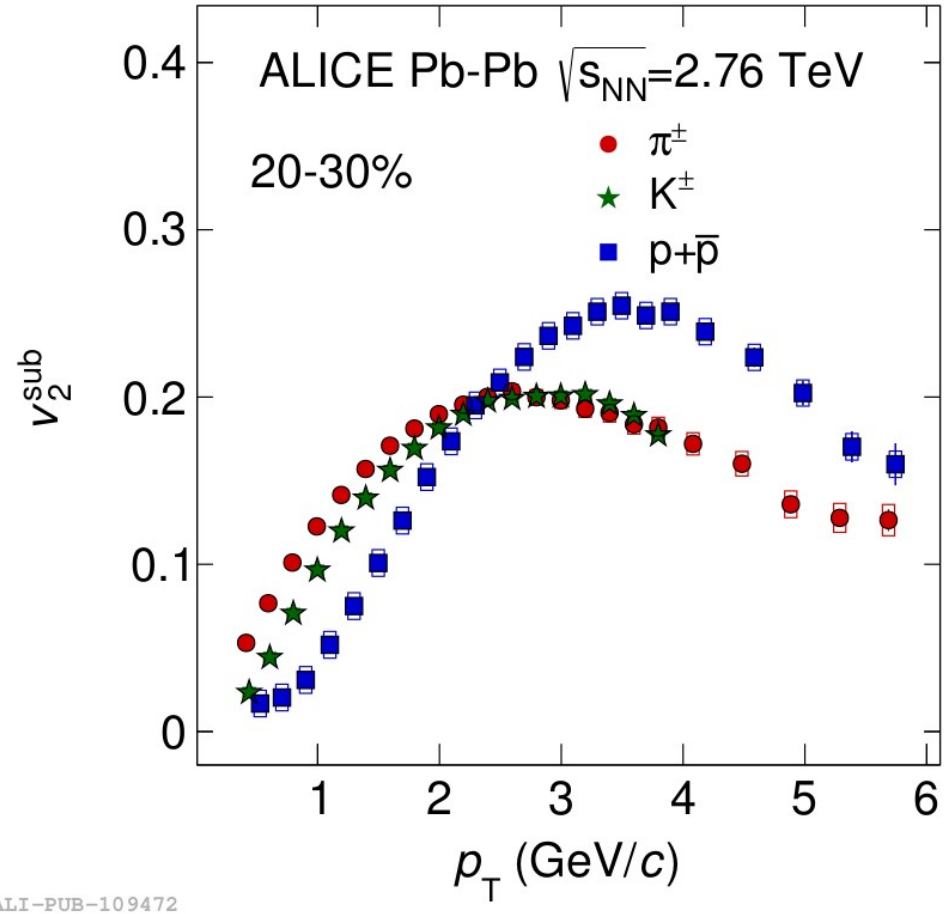


Flow (v_n) in heavy-ion collisions

- **Experimental point:**
  - Flow describes the azimuthal momentum space anisotropy of particle emission for a non-central heavy-ion collision.
  - The nth harmonic coefficient of the Fourier expansion of azimuthal momentum distribution:

$$E\frac{d^3N}{dp^3} = \frac{d^2N}{p_T dp_T dy}\frac{1}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \psi_n)]\right)$$

  - The $v_2(p_T, y) = \langle \cos(2(\phi - \psi_2)) \rangle$ directly reflects the initial spatial anisotropy of the nuclear overlap region in the transverse plane.

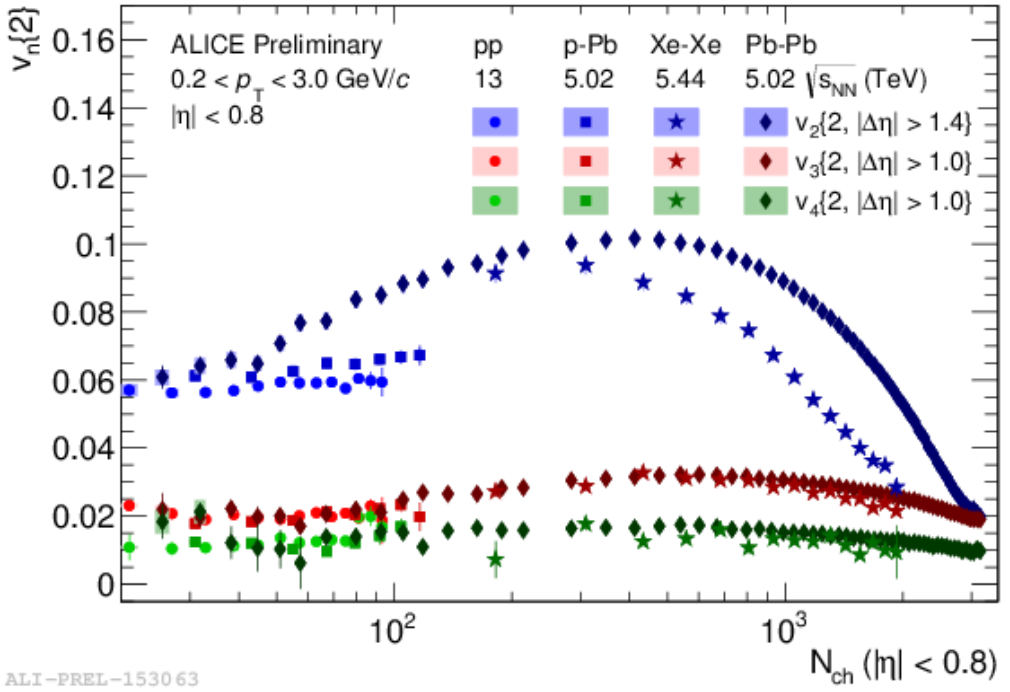


Flow (v_n) in heavy-ion collisions

- **Experimental point:**
  - Flow describes the azimuthal momentum space anisotropy of particle emission for a non-central heavy-ion collision.
  - The nth harmonic coefficient of the Fourier expansion of azimuthal momentum distribution:

$$E\frac{d^3N}{dp^3} = \frac{d^2N}{p_T dp_T dy}\frac{1}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \psi_n)]\right)$$

  - The $v_2(p_T, y) = \langle\cos(2(\phi - \psi_2))\rangle$ directly reflects the initial spatial anisotropy of the nuclear overlap region in the transverse plane.
  - Higher flow components can be measured

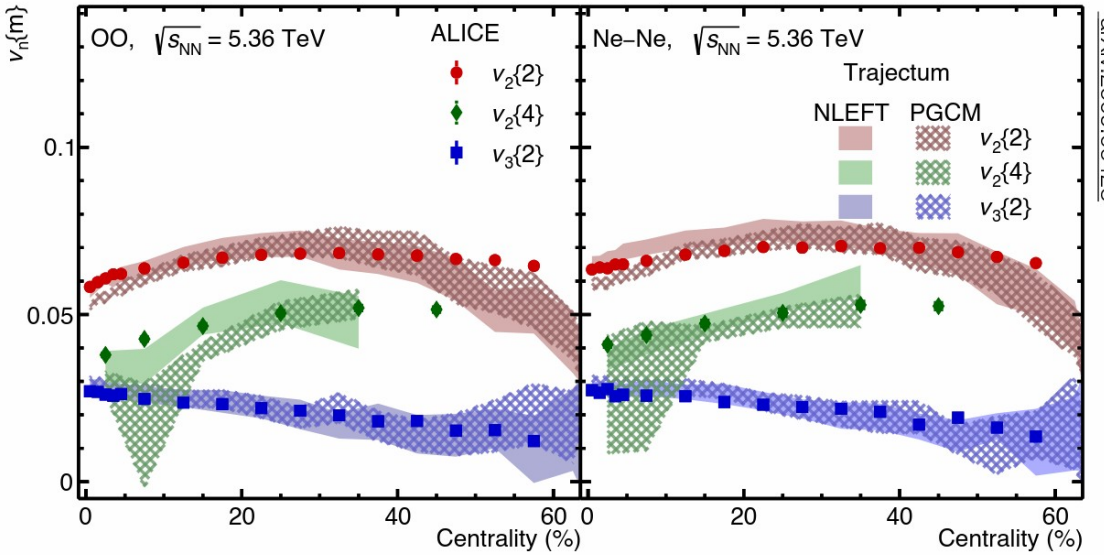


Flow (v_n) in heavy-ion collisions

- **Experimental point:**
  - Flow describes the azimuthal momentum space anisotropy of particle emission for a non-central heavy-ion collision.
  - The nth harmonic coefficient of the Fourier expansion of azimuthal momentum distribution:

$$E\frac{d^3N}{dp^3} = \frac{d^2N}{p_T dp_T dy}\frac{1}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \psi_n)]\right)$$

  - The $v_2(p_T, y) = \langle\cos(2(\phi - \psi_2))\rangle$ directly reflects the initial spatial anisotropy of the nuclear overlap region in the transverse plane.
  - Higher flow components can be measured

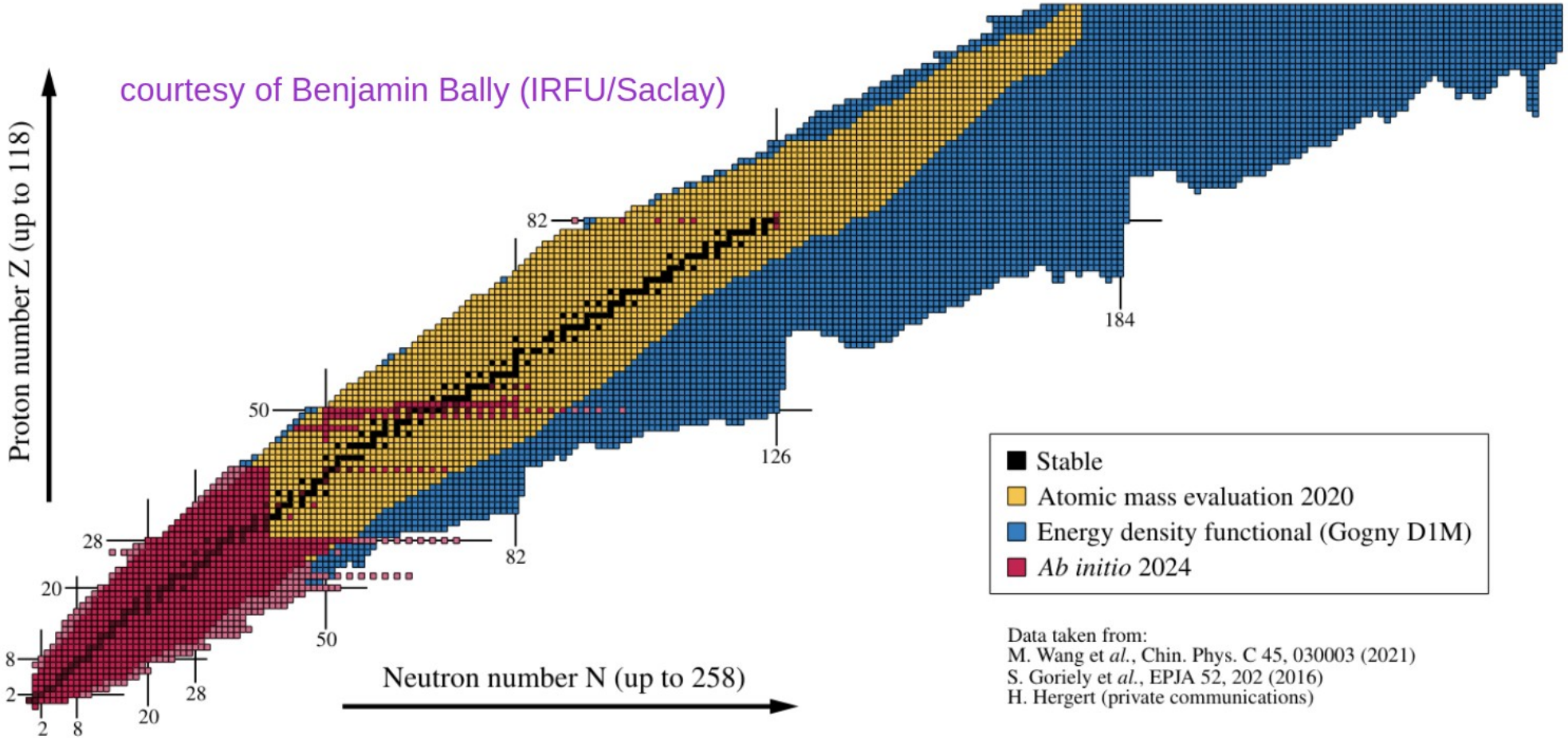


arXiv:2509.06428

Nuclei & nuclear structure

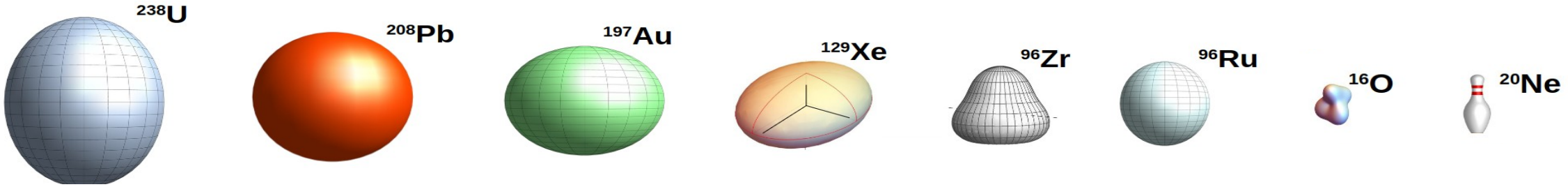
Nuclei for Nuclear Collisions

- **High-mass and deformed nuclei are in the focus:**



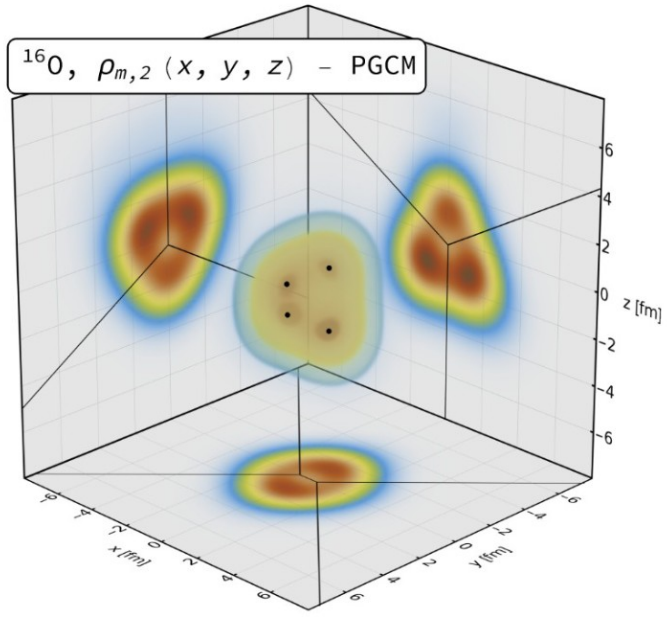
Nuclei for Nuclear Collisions

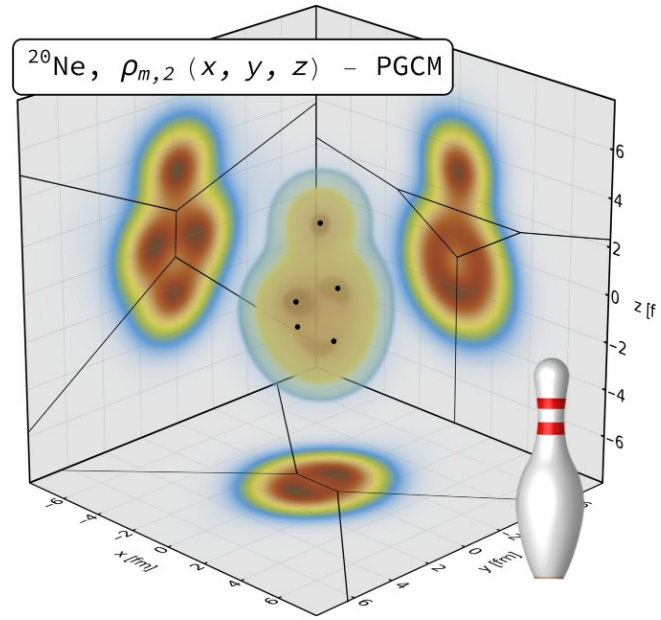
- **Experimental possibilities & interest**
  - Large deformed nuclei: uranium, gold, xenon
  - Smaller zirconium, rubidium, oxygen, neon



Nuclei for Nuclear Collisions

- **Oxygen and Neon are unique**
  - Oxygen is a double magic nucleus, since both shells are closed shell. In cluster model Tetrahedron shape.
  - Neon, has bowling pin shape, even more complicated geometry





Ancillary files (details):
- NLEFT_dmin_0.5fm_negativeweights_Ne.h5
- NLEFT_dmin_0.5fm_negativeweights_O.h5
- NLEFT_dmin_0.5fm_positiveweights_Ne.h5
- NLEFT_dmin_0.5fm_positiveweights_O.h5
- PGCM_clustered_dmin0_Ne.h5
- PGCM_clustered_dmin0_O.h5
- PGCM_uniform_dmin0_Ne.h5
- PGCM_uniform_dmin0_O.h5

arXiv:2402.05995

The shape of the oxygen

Modeling the oxygen

- **Woods-Saxon (WS)**

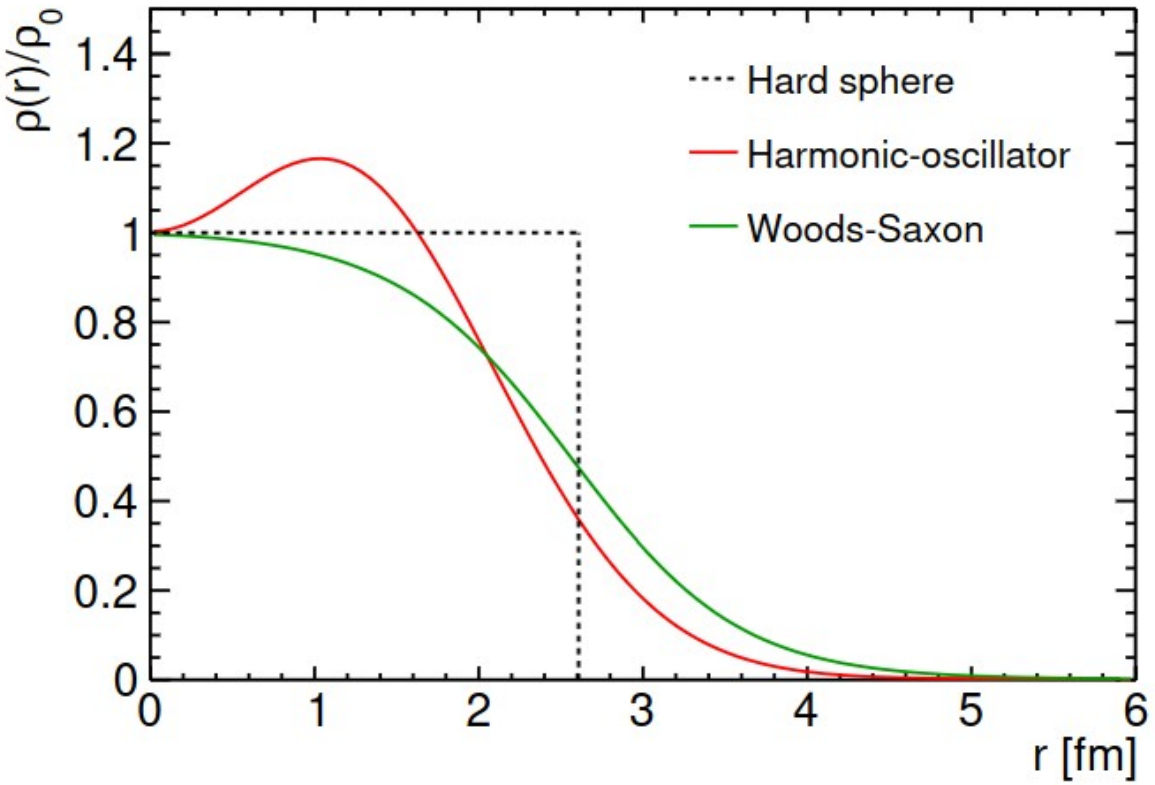
$$\rho(r) = \rho_0 \left[1 + \alpha \left(\frac{r}{a}\right)^2\right] \exp\left(\frac{-r^2}{a^2}\right)$$

- **Harmonic oscillator (HO)**

$$\rho(r) = \frac{\rho_0 (1 + w(\frac{r}{r_0})^2)}{1 + \exp(\frac{r - r_0}{a})}$$

- Normalization:

$$\int \rho(r) d^3r = 4\pi \int \rho(r) r^2 dr = Ze$$

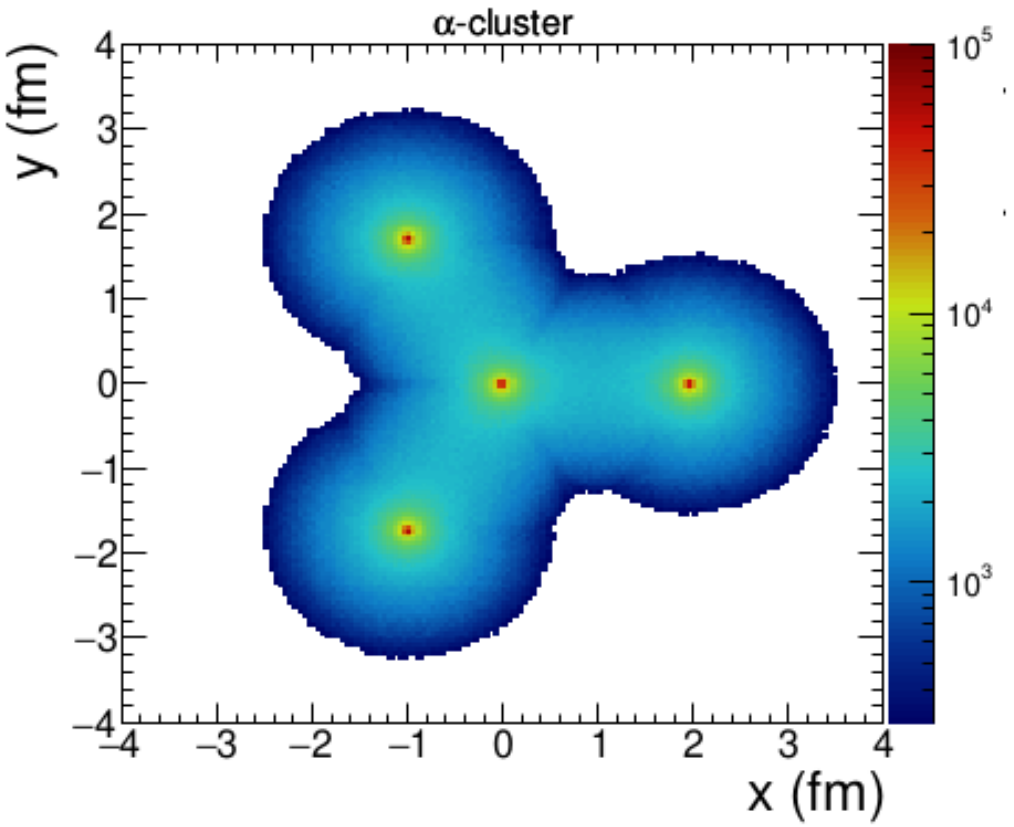


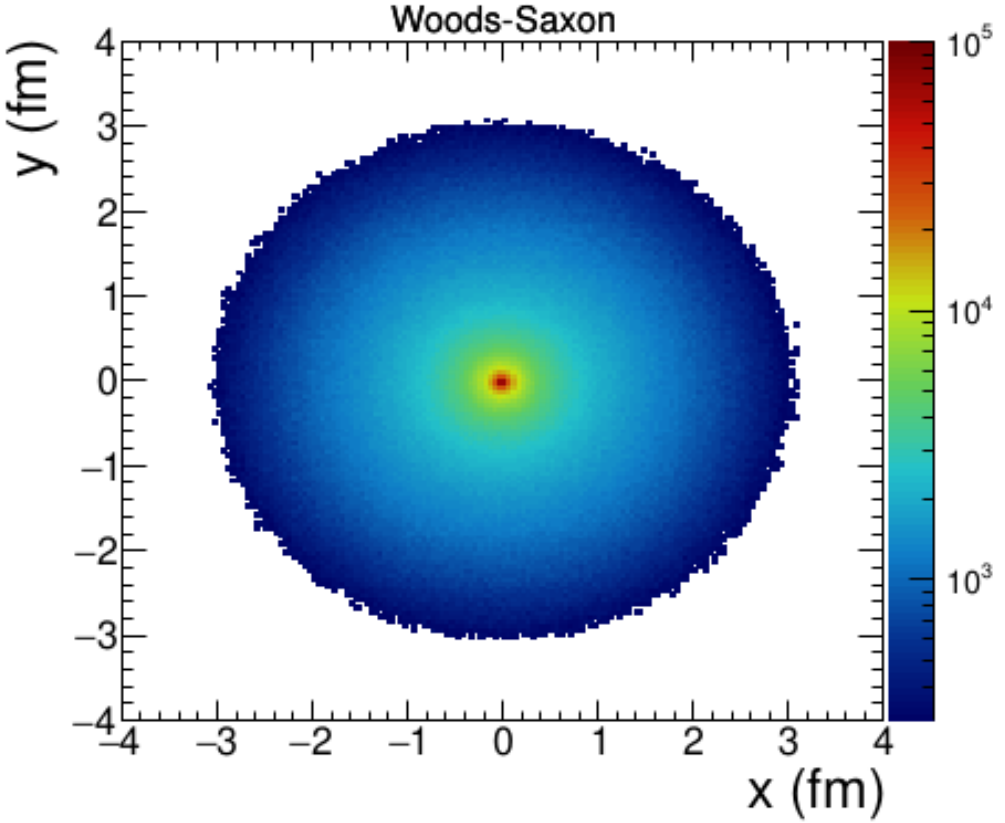
The shape of the oxygen

Nuclear structure description

- **Cluster model vs.**

Non-cluster model (Woods-Saxon)



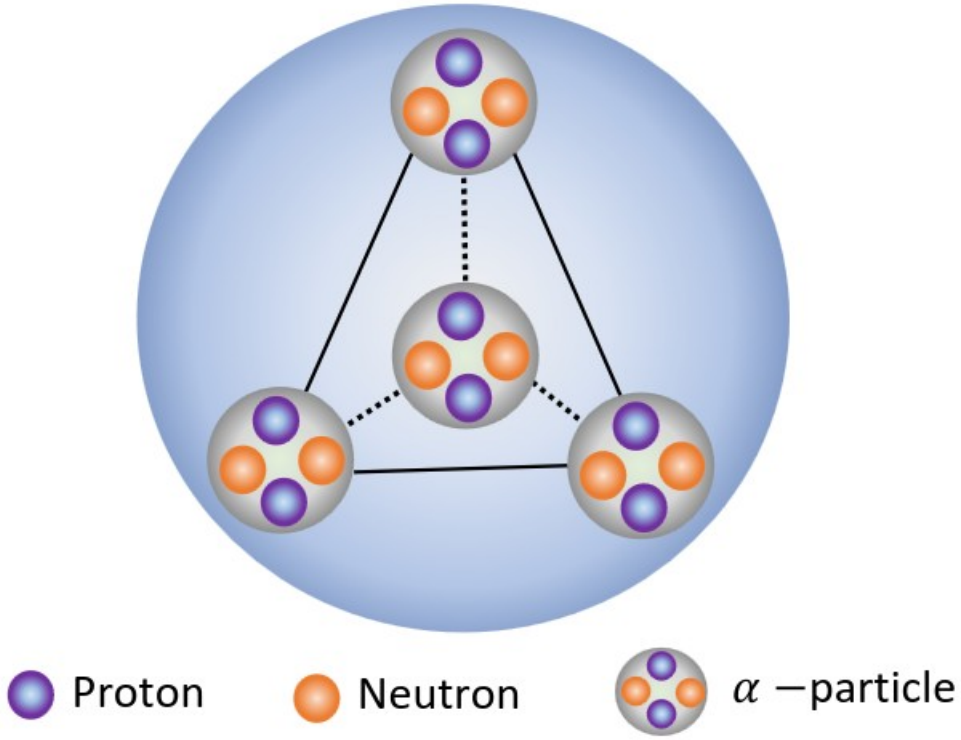


The shape of the oxygen

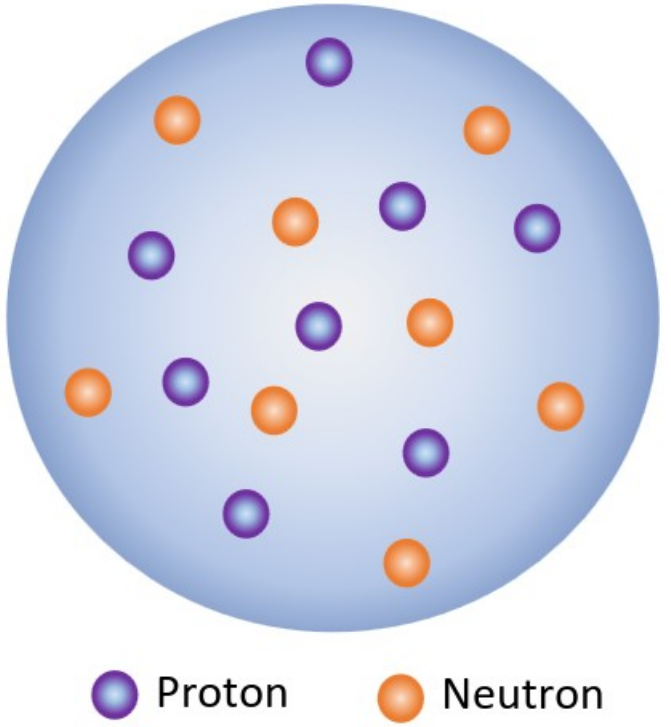
Nuclear structure description

- **Cluster model vs.**

Non-cluster model (Woods-Saxon)



α – clustered Oxygen (^{16}O) nucleus

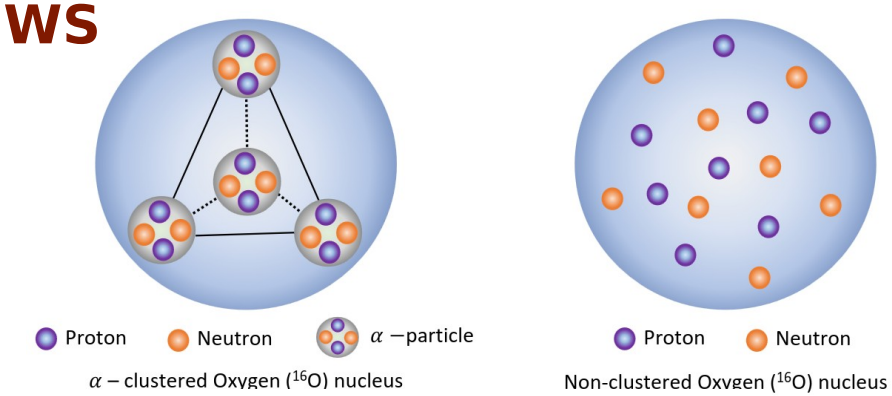


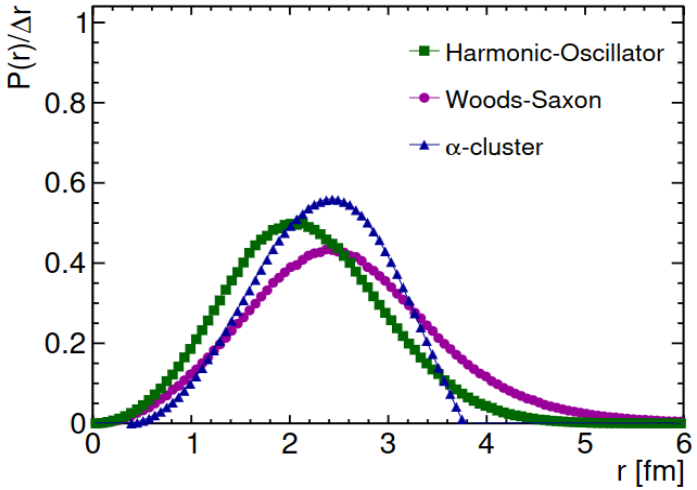
Non-clustered Oxygen (^{16}O) nucleus

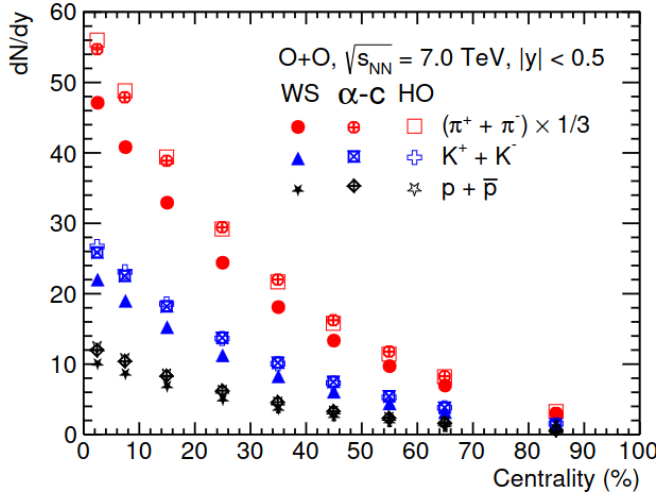
The shape of the OO collision

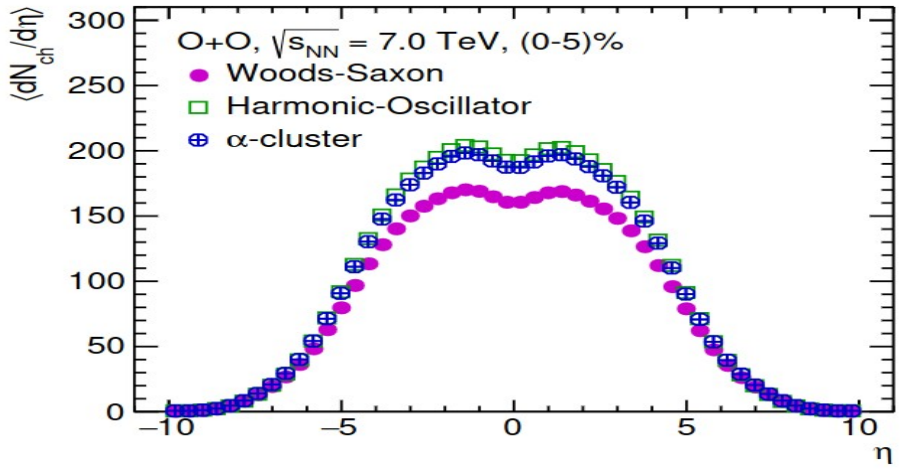
Nuclear structure description

- **Cluster model vs WS**





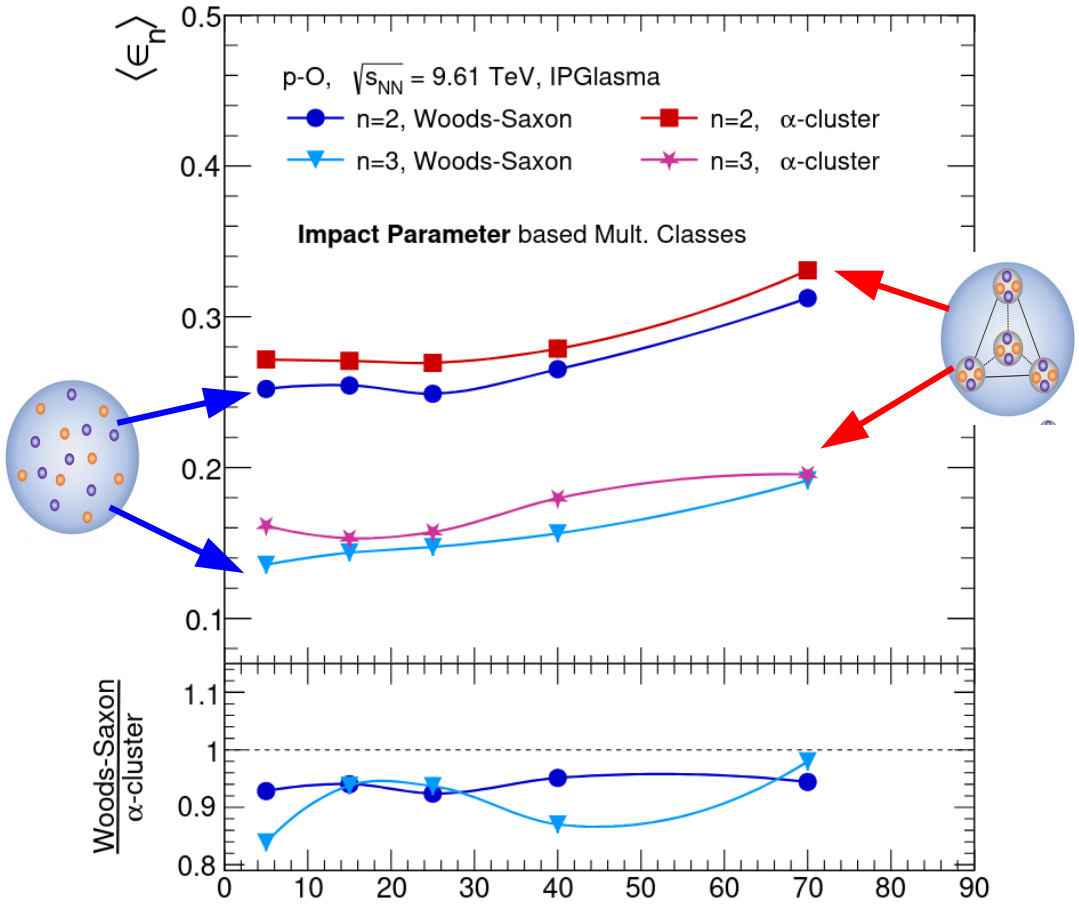




Excentricity in p-O & O-O

Excentricity in p-O

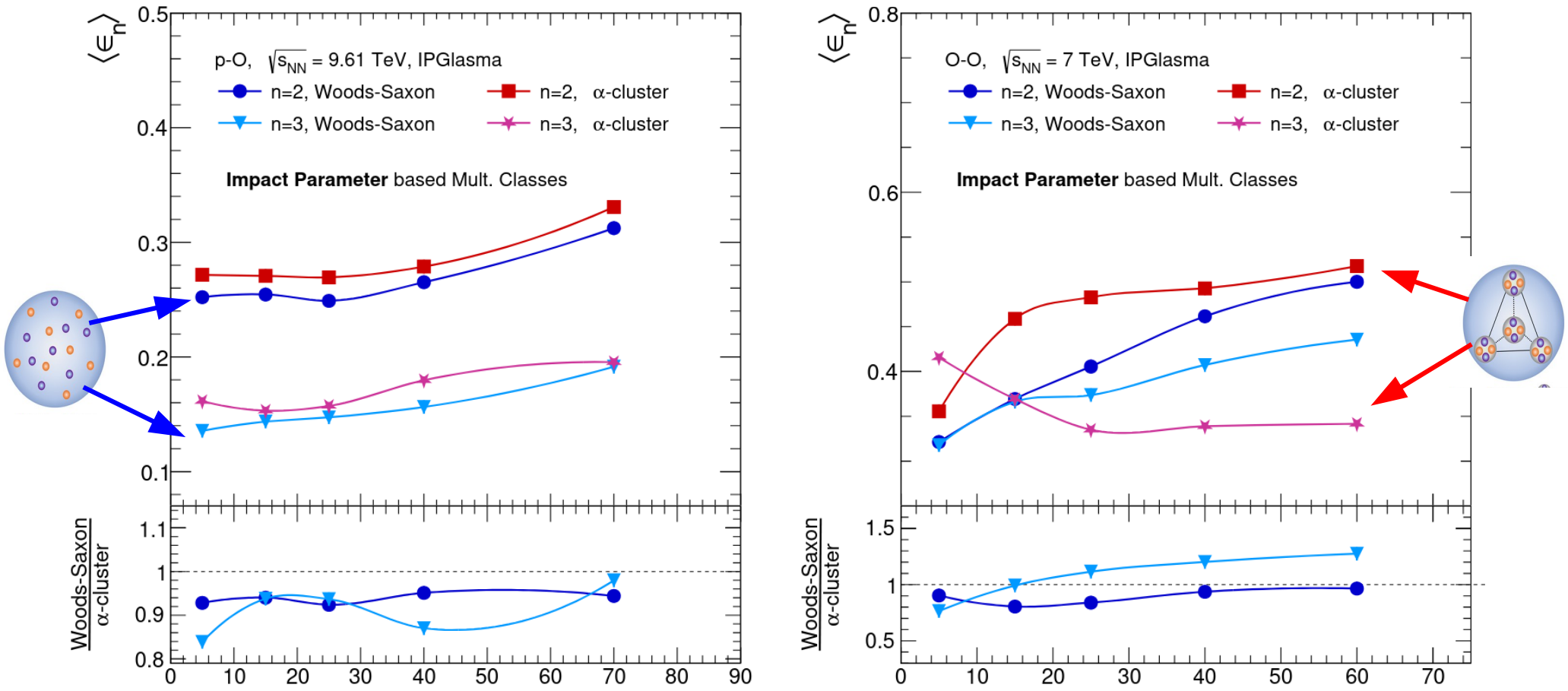
$$\epsilon_n = \frac{\sqrt{\langle r^n cos(n\phi_{\rm part})\rangle^2 + \langle r^n \sin(n\phi_{\rm part})\rangle^2}}{\langle r^n \rangle}$$



Excentricity in p-O & O-O

Excentricity in p-O & *O-O*

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



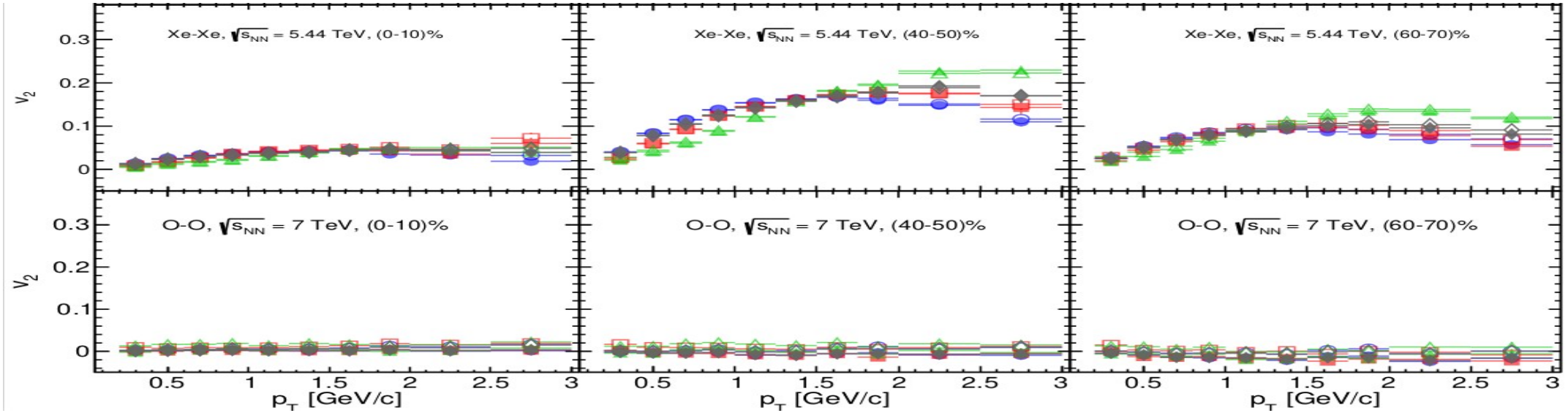
Calculating the flow in small systems

Calculating the flow

Event plane and average method

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

- Need to determine the event plain, which fails for small nuclei:



Calculating the flow

Event plane and average method

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

Multiparticle Q-cummulant method

- Flow vector $Q_n = \sum_{j=1}^{M} e^{in\phi_j}$
- The 2- and 4-particle cummulants are:

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

$$\langle 4 \rangle = \frac{|Q_n|^4 + |Q_{2n}|^2 - 2 \cdot \mathrm{Re}[Q_{2n} Q_n^* Q_n^*]}{M(M-1)(M-2)(M-3)} - 2\frac{2(M-2) \cdot |Q_n|^2 - M(M-3)}{M(M-1)(M-2)},$$

$$c_n\{2\} = \langle\langle 2 \rangle\rangle,$$

$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2 \cdot \langle\langle 2 \rangle\rangle^2$$

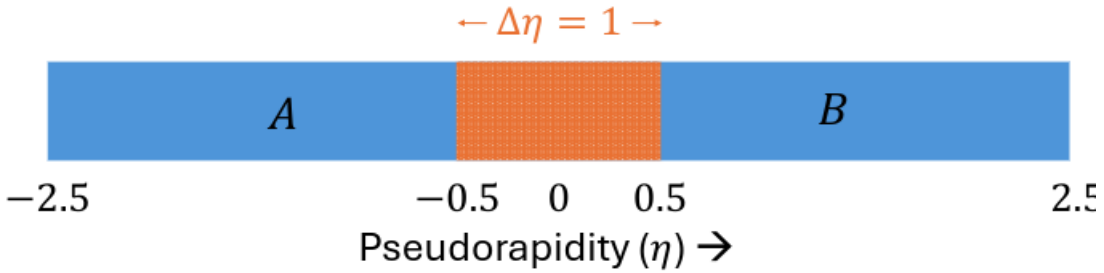
$$v_n\{2\} = \sqrt{c_n\{2\}},$$

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

Calculating the flow

Suppressing the non-flow contribution:

- Kinematical cut: 2 sub-events, A&B are intoduced, with a rapidity gap:



$$\langle 2 \rangle_{\Delta\eta} = \frac{Q_n^A \cdot Q_n^{B*}}{M_A \cdot M_B} \rightarrow v_n\{2, |\Delta\eta|\}(p_T) = \frac{d_n\{2, |\Delta\eta|\}}{\sqrt{c_n\{2, |\Delta\eta|\}}}$$

- Differential flow cummulants:

$$d_n\{2\} = \langle\langle 2' \rangle\rangle, \quad d_n\{4\} = \langle\langle 4' \rangle\rangle - 2\langle\langle 2' \rangle\rangle\langle\langle 2 \rangle\rangle \rightarrow d_n\{2, |\Delta\eta|\} = \langle\langle 2' \rangle\rangle_{\Delta\eta}$$

- Mean and the fluctuations of the flow & ratio:

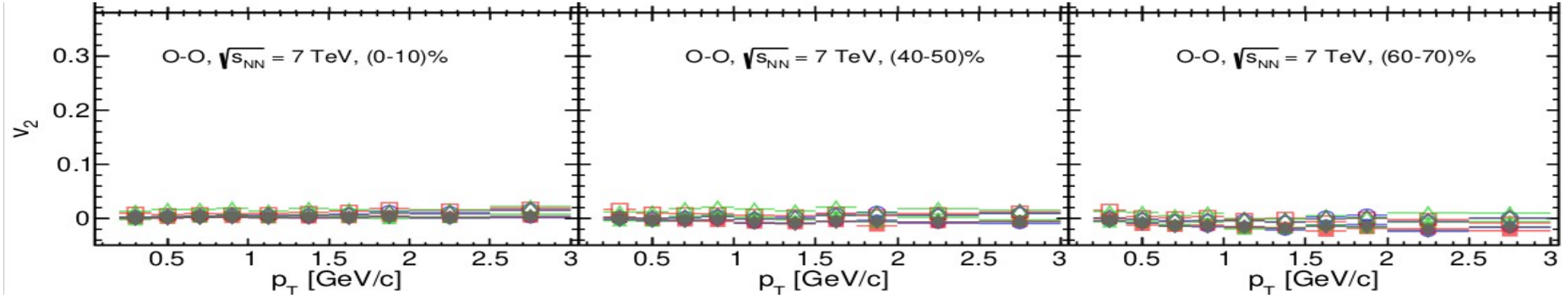
$$\langle v_n \rangle = \sqrt{\frac{v_n^2\{2\} + v_n^2\{4\}}{2}}$$

$$\sigma_{v_n} = \sqrt{\frac{v_n^2\{2\} - v_n^2\{4\}}{2}}$$

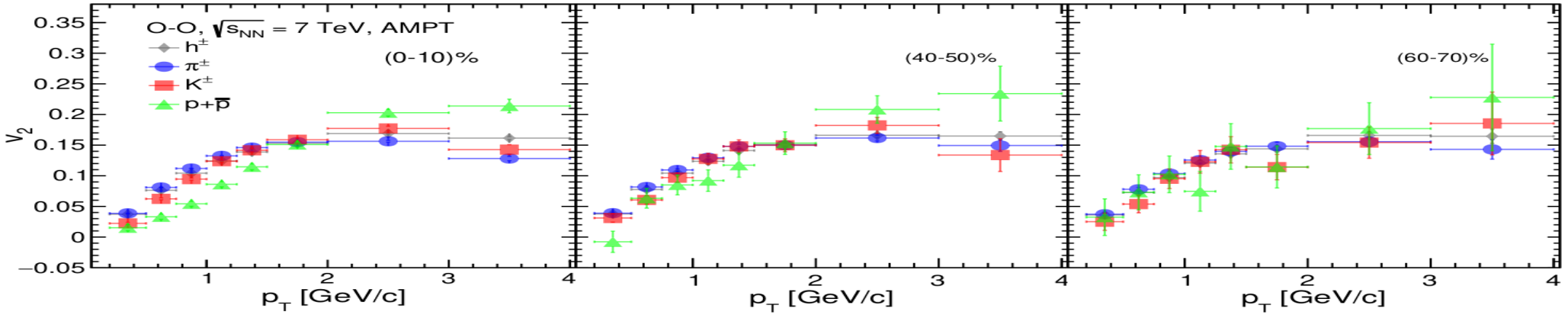
$$\rightarrow F(v_n) = \frac{\sigma_{v_n}}{\langle v_n \rangle}$$

Calculating the flow

Event plane and average method

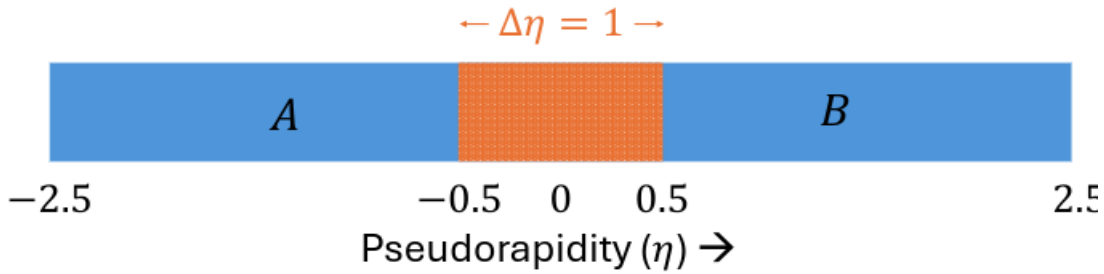


Multiparticle Q-cummulant method



The Model

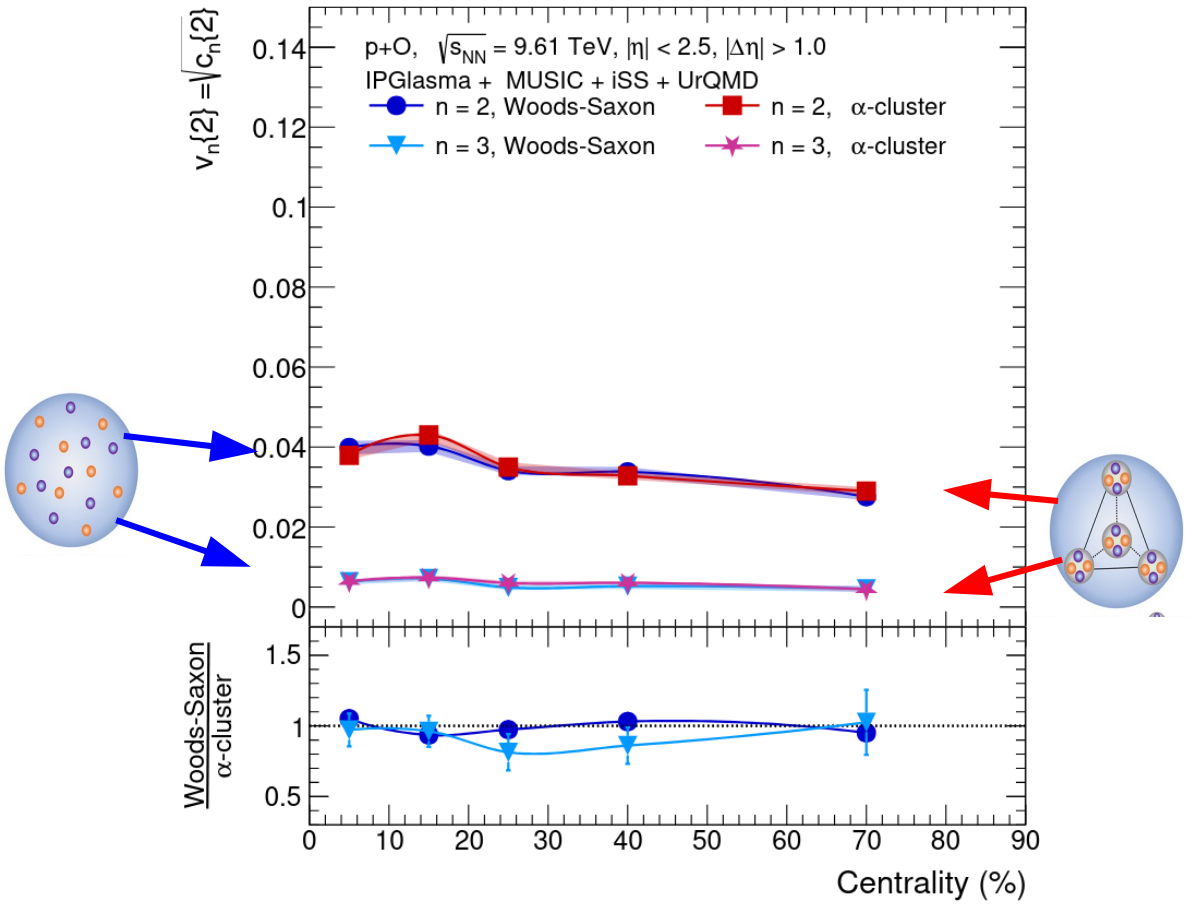
- **A full hidro & Boltzmann transport with viscosity:**
  - IPGlasma
  - MUSIC
  - iSS
  - URQMD
- **Kinematical settings are:**
  - Energy (c.m.): 7 TeV O+O
  - Pseudorapidity: $|\eta| < 2.5$
  - Transverse momentum: $0.2 < p_{\mathrm{T}} < 5.0$ GeV/c
  - Pseudorapidity gap: , $|\Delta\eta| > 1.0$



Flow in oxygen collisions: p-O & O-O

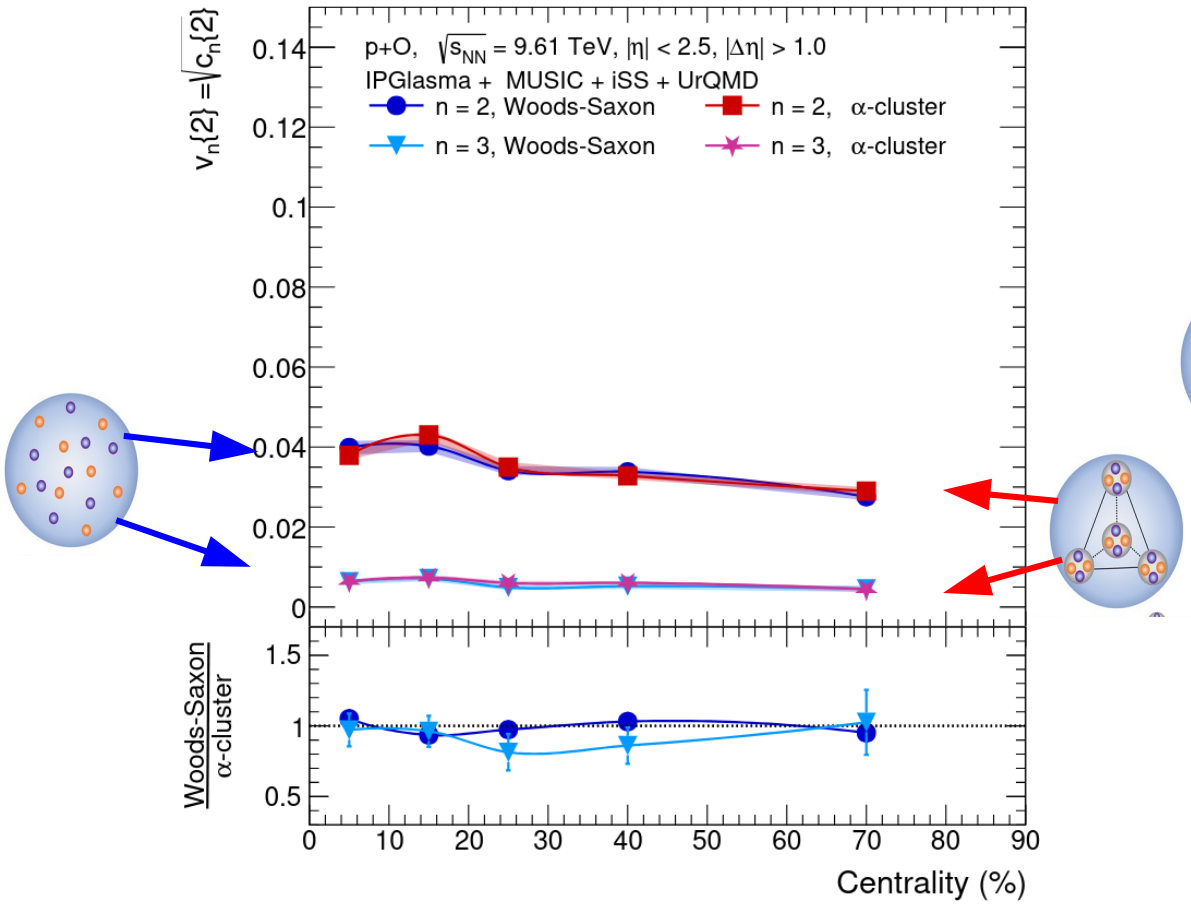
Flow components in pO & OO @ LHC

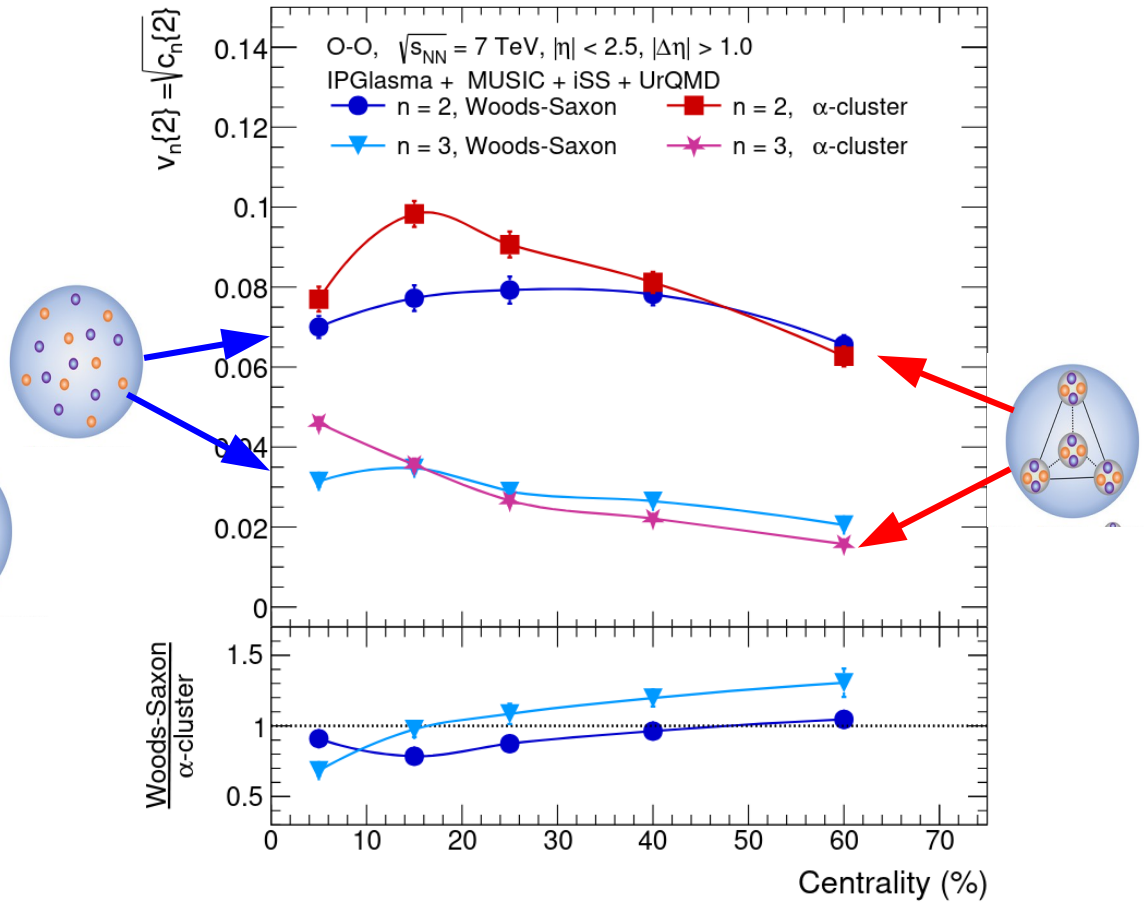
2-cummulants based v_n & c_n calculations for p-O



Flow components in pO & OO @ LHC

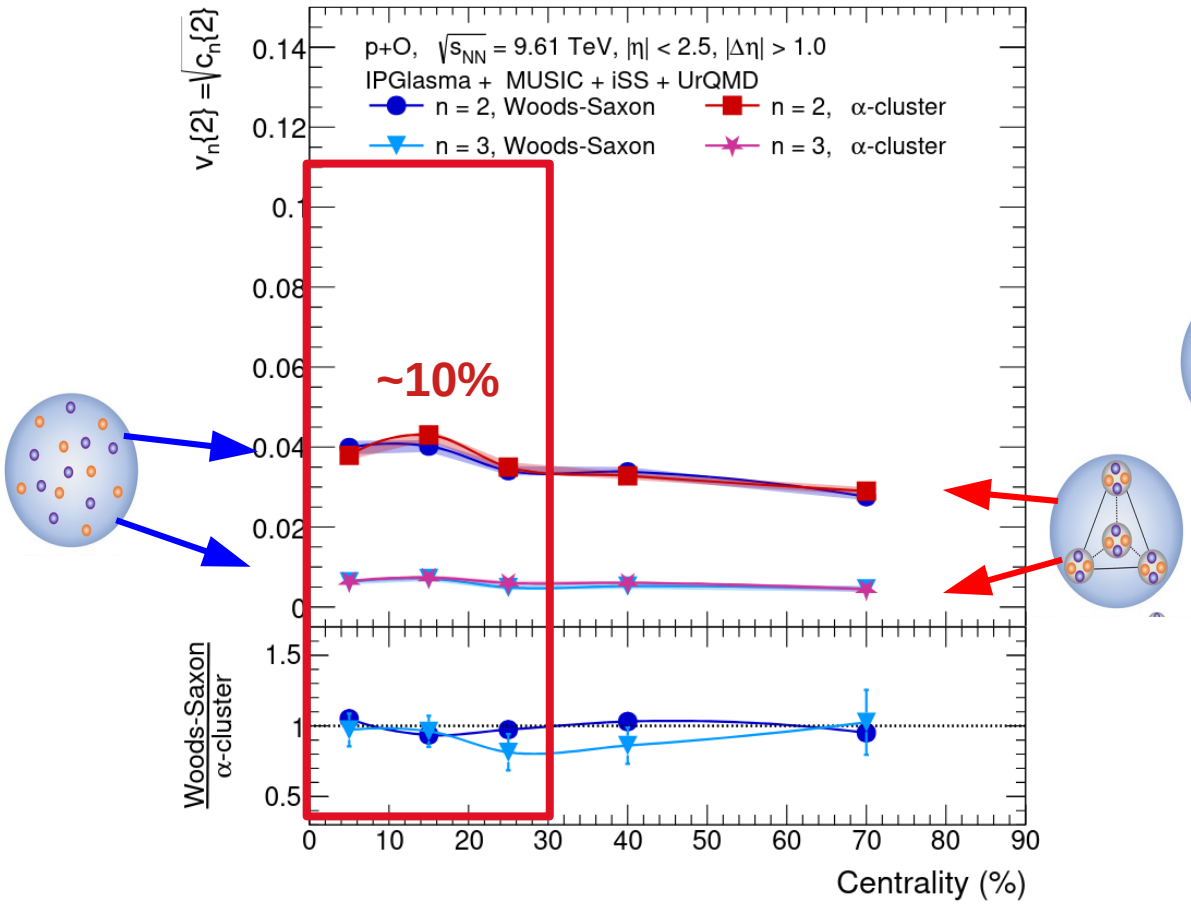
2-cummulants based v_n & c_n calculations for p-O & O-O

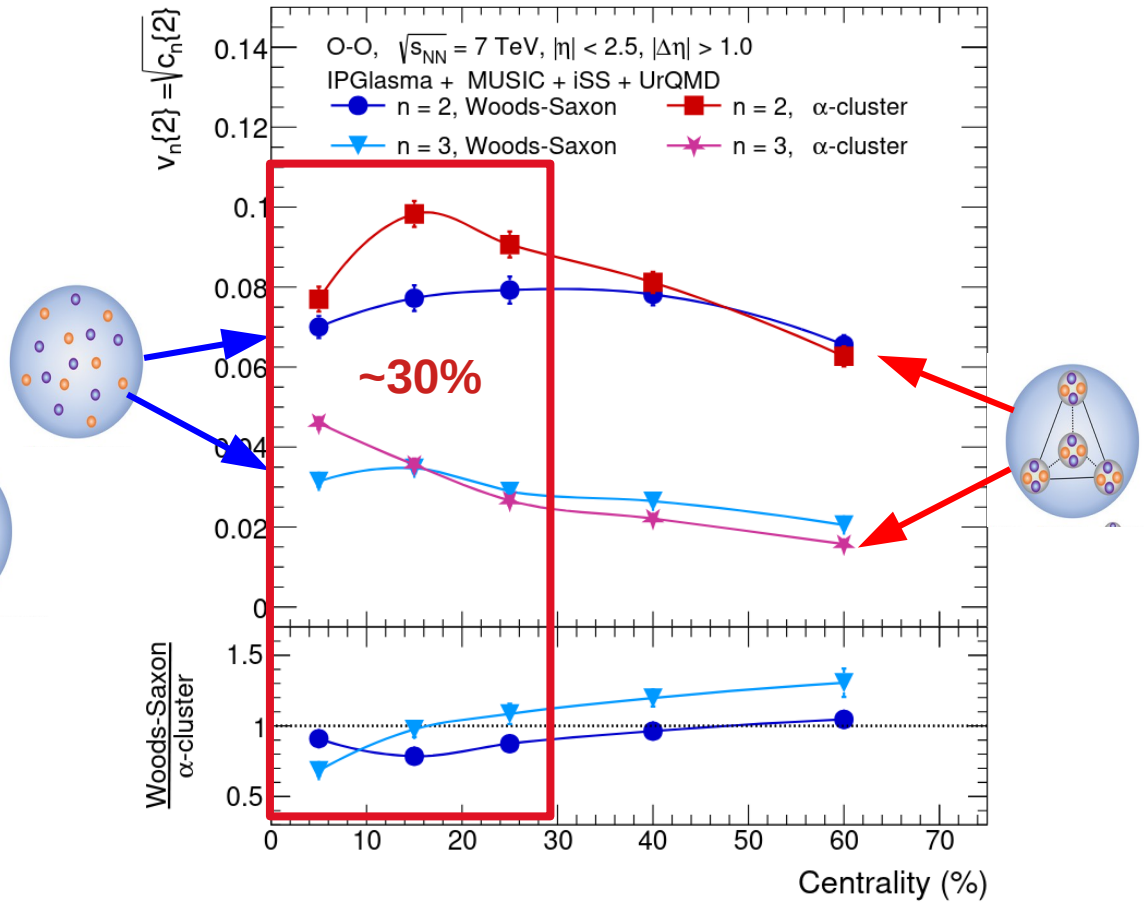




Flow components in pO & OO @ LHC

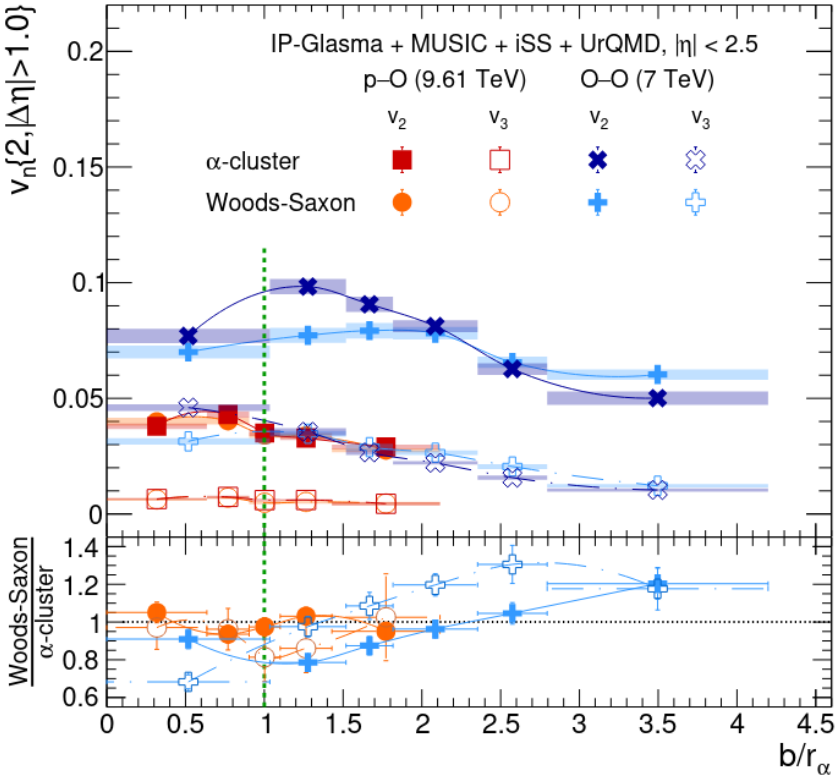
2-cummulants based v_n & c_n calculations for p-O & O-O

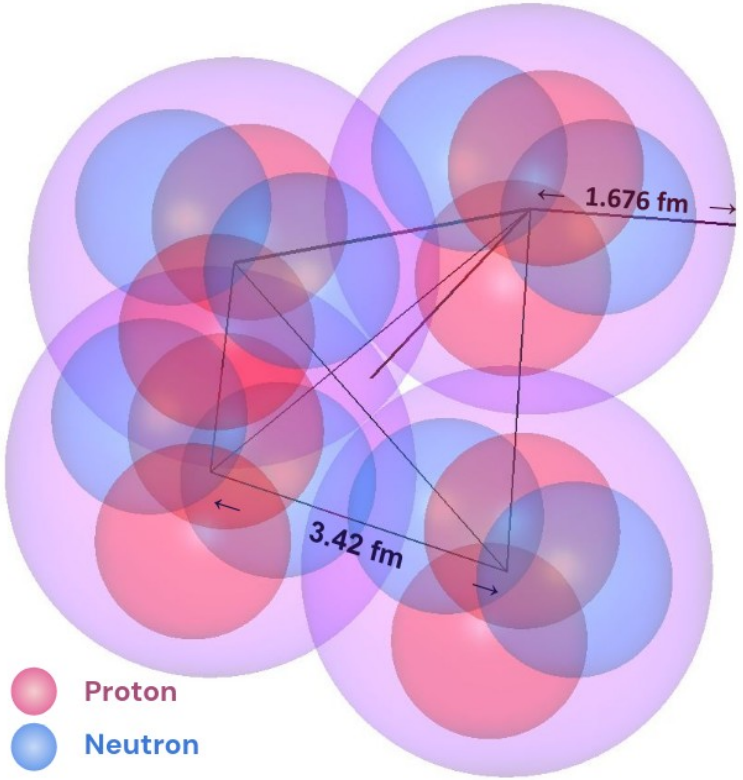




Flow components *vs* structure @ LHC

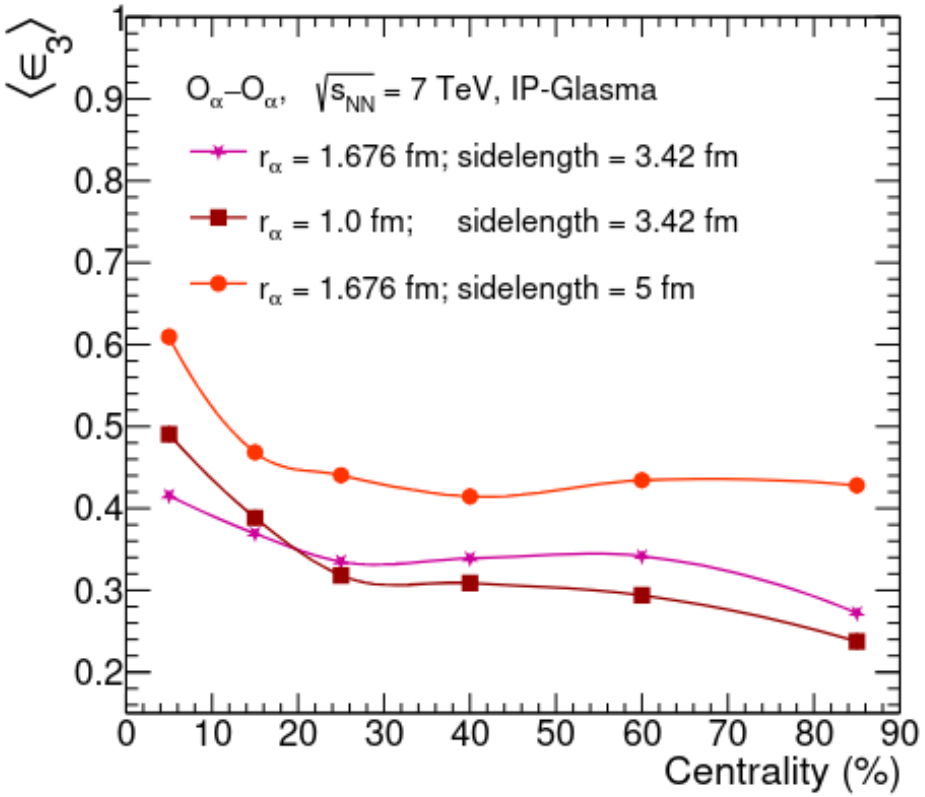
2-cummulants based v_n (b) calculations for p-O & O-O

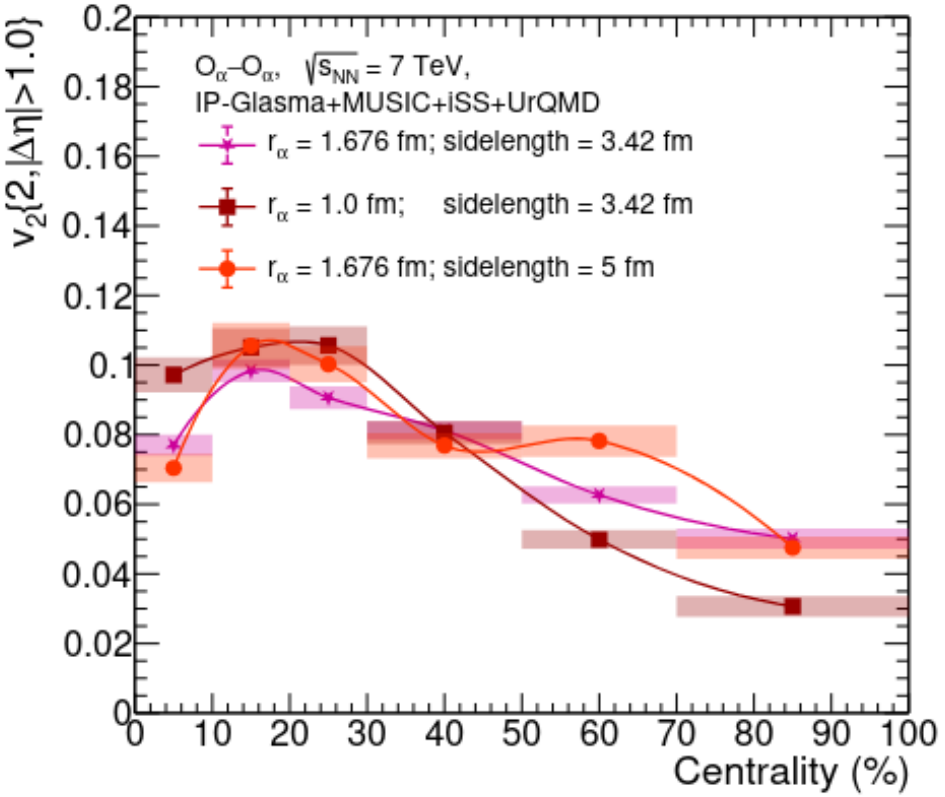


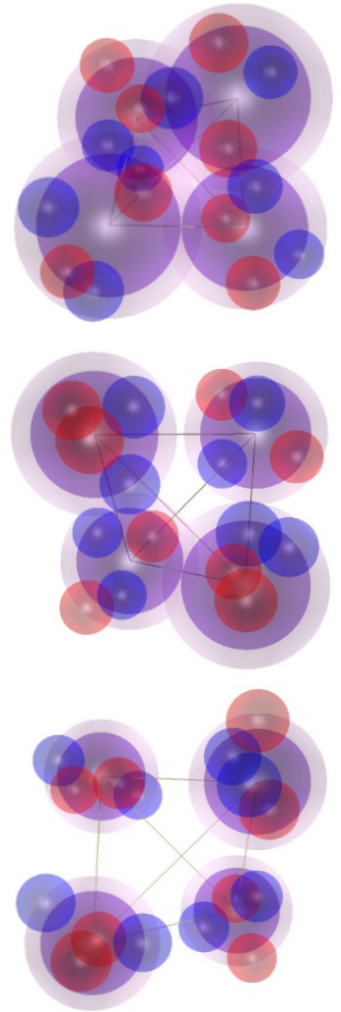


Flow components *vs* structure @ LHC

2-cummulants based v_n & ε_n calculations for p-O & O-O

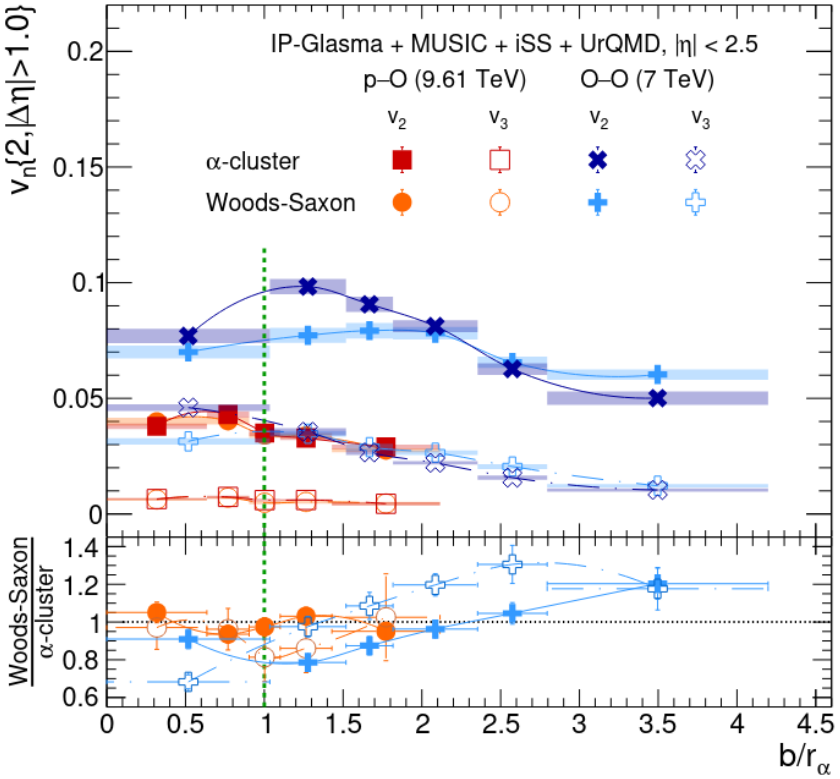


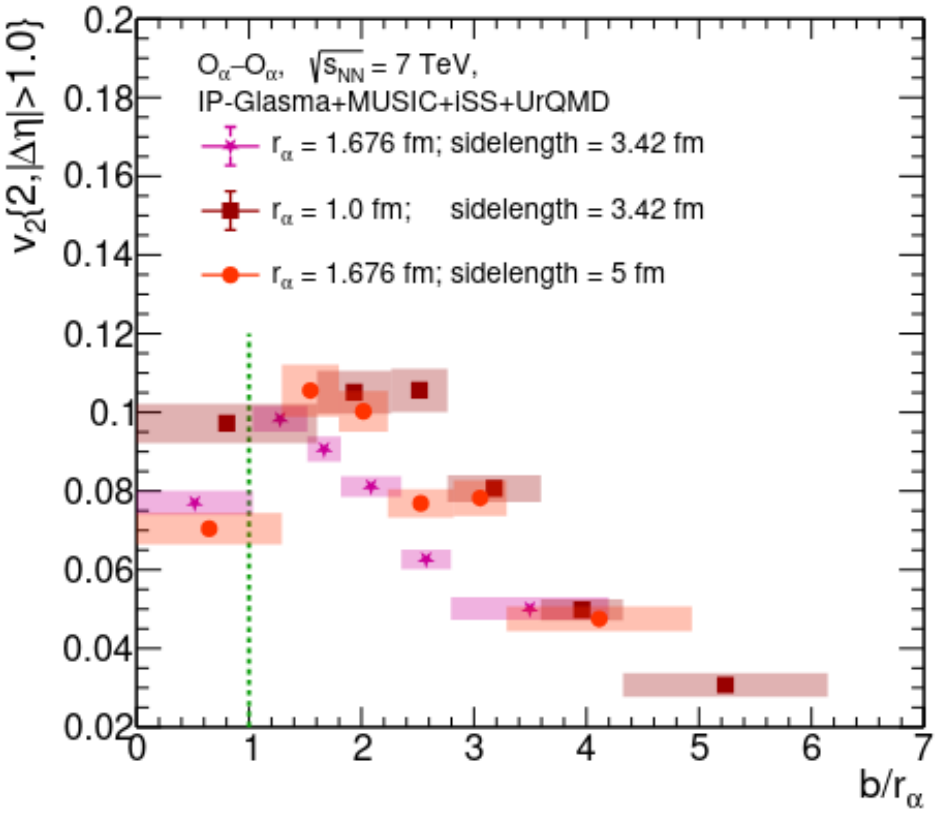


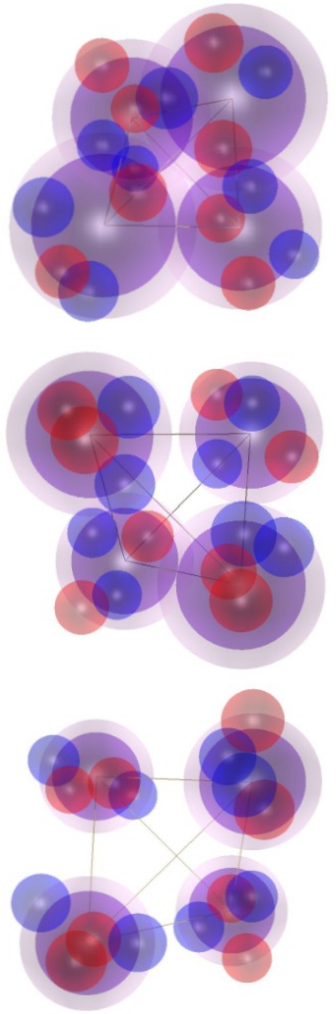


Flow components *vs* structure @ LHC

2-cummulants based v_n(b) calculations for p-O & O-O







Some answers to take away...

Can we

- **model the hydrodynamical evolution of small collisional systems?**

  → Yes, with the IPGlazma + MUSIC + ISS + URQMD

- **measure flow in the collisions of small systems?**

  → Yes, we can calculate IF non-flow components are removed ($|\eta|>1.0$):

  v_2 with 2- & 4-cummulant, but v_3 with 2-cummulant only

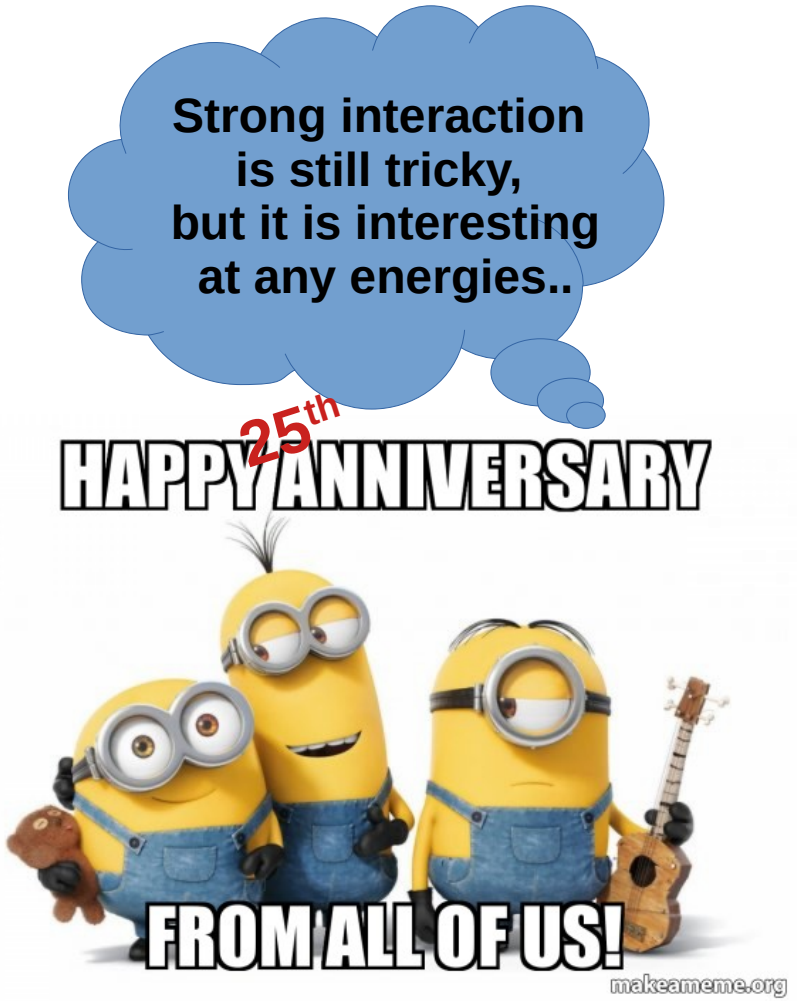
- **make difference in nuclear structure models of the ^{16}O?**

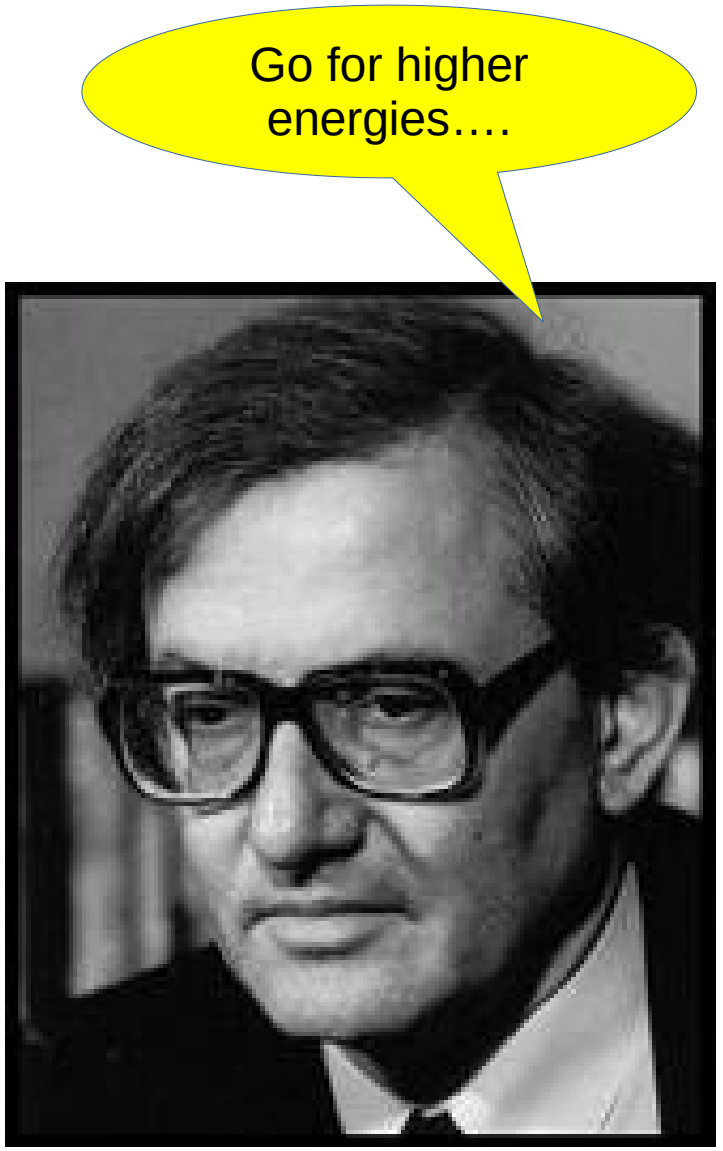
  → Yes, the difference of WS vs. α-cluster can be 20-30% in O-O and <10% p-O!

  → Remarkable sensitivity on the α-cluster parameters

Wise men...

“Low energy is not bad...”

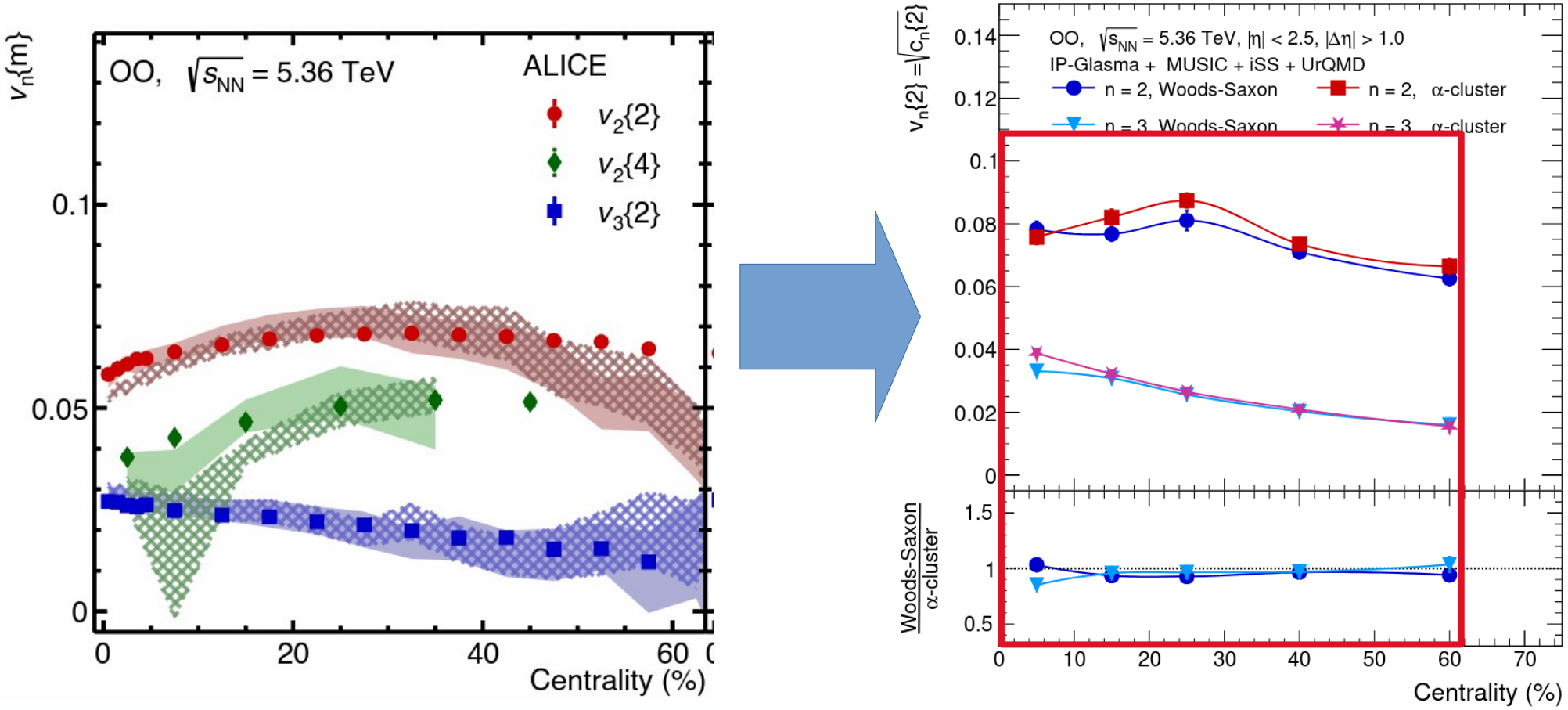

Strong interaction is still tricky, but it is interesting at any energies..
25th
HAPPY ANNIVERSARY
FROM ALL OF US!
makeameme.org


Go for higher energies….

Backup

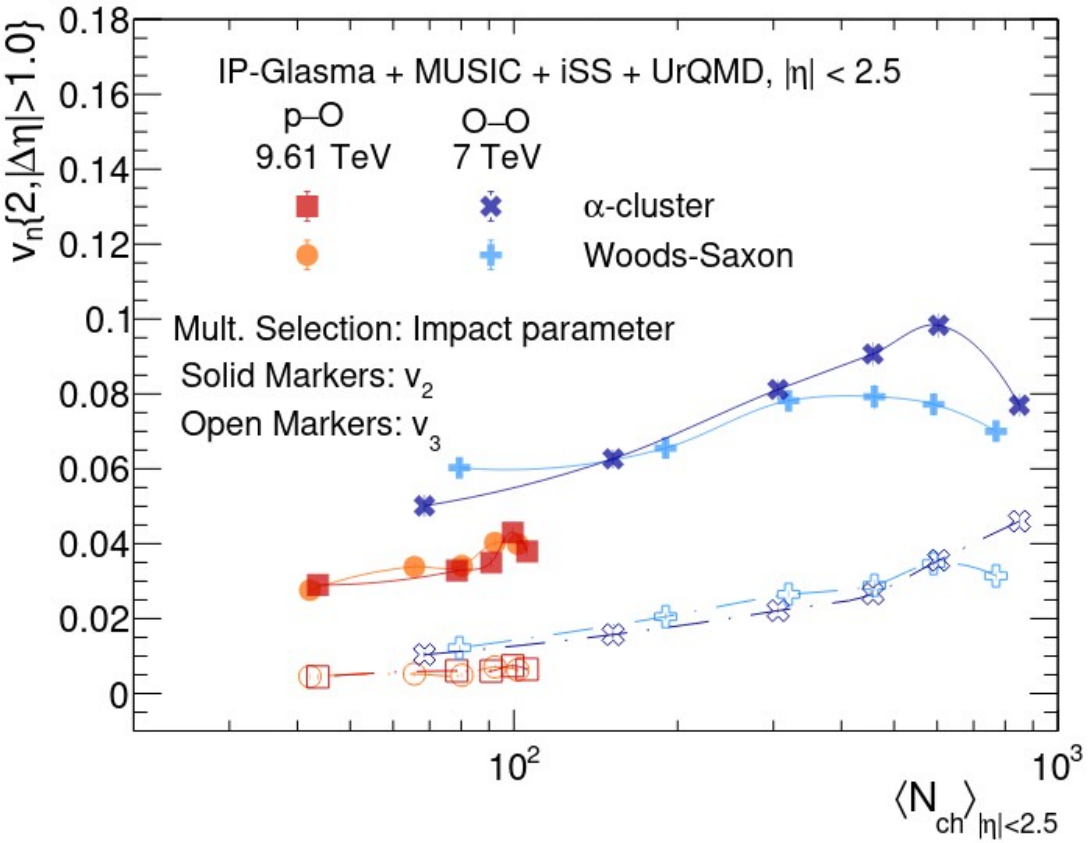
Flow components in OO @ LHC

2-cummulants based v_n calculations for O-O vs ALICE arxiv:2509.06428



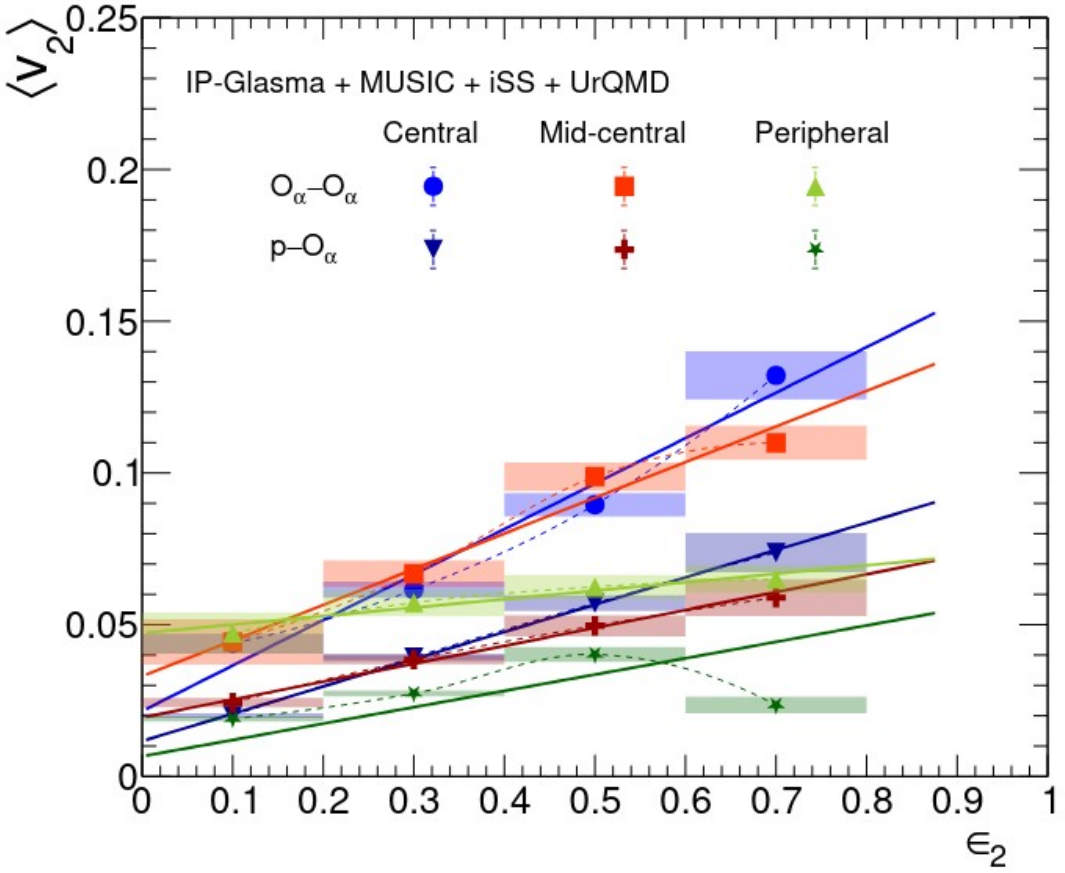
Flow components *vs* multiplicity @ LHC

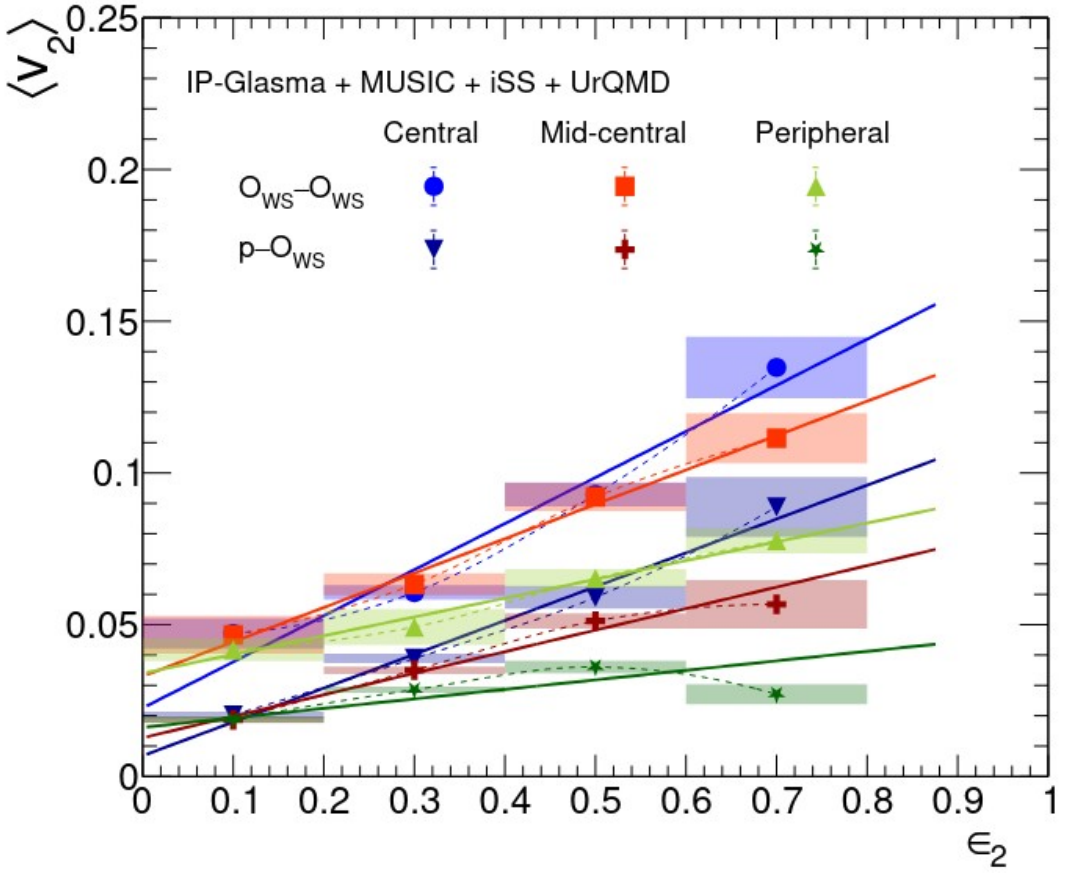
2-cummulants based v_n & c_n calculations for p-O & O-O



Flow components *vs* multiplicity @ LHC

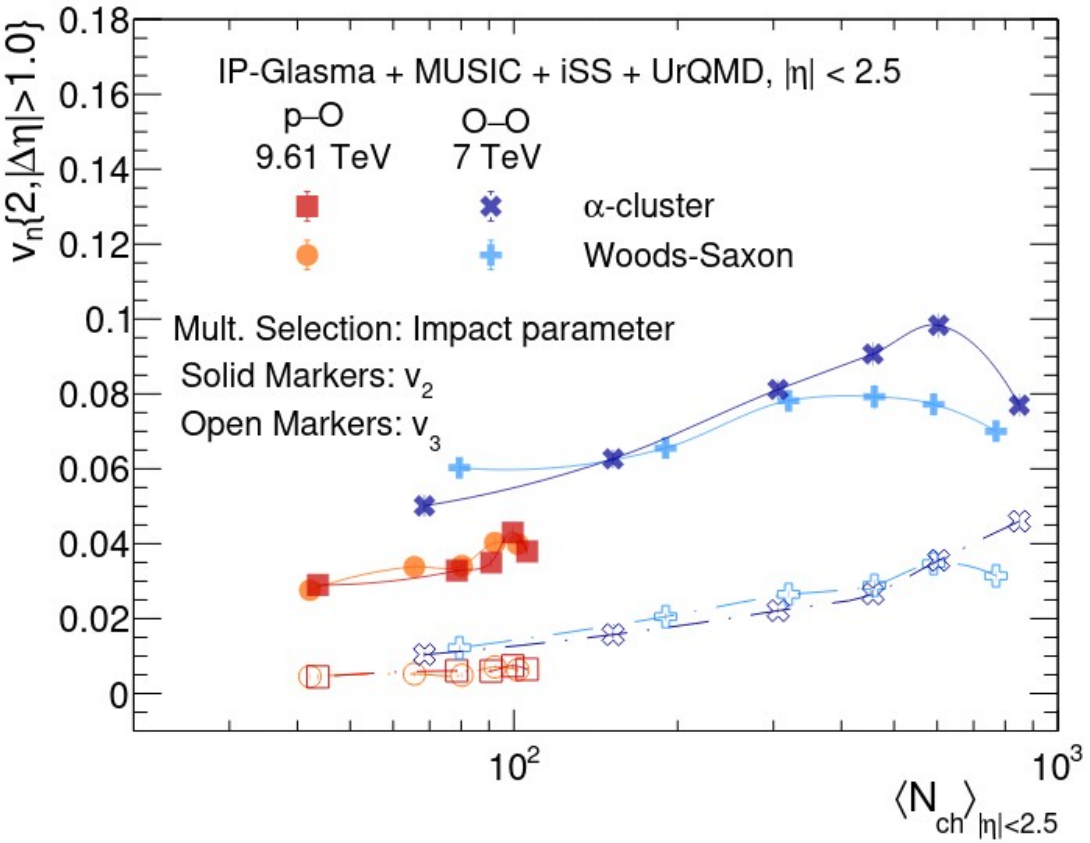
2-cummulants based v_n & ε_n calculations for p-O & O-O

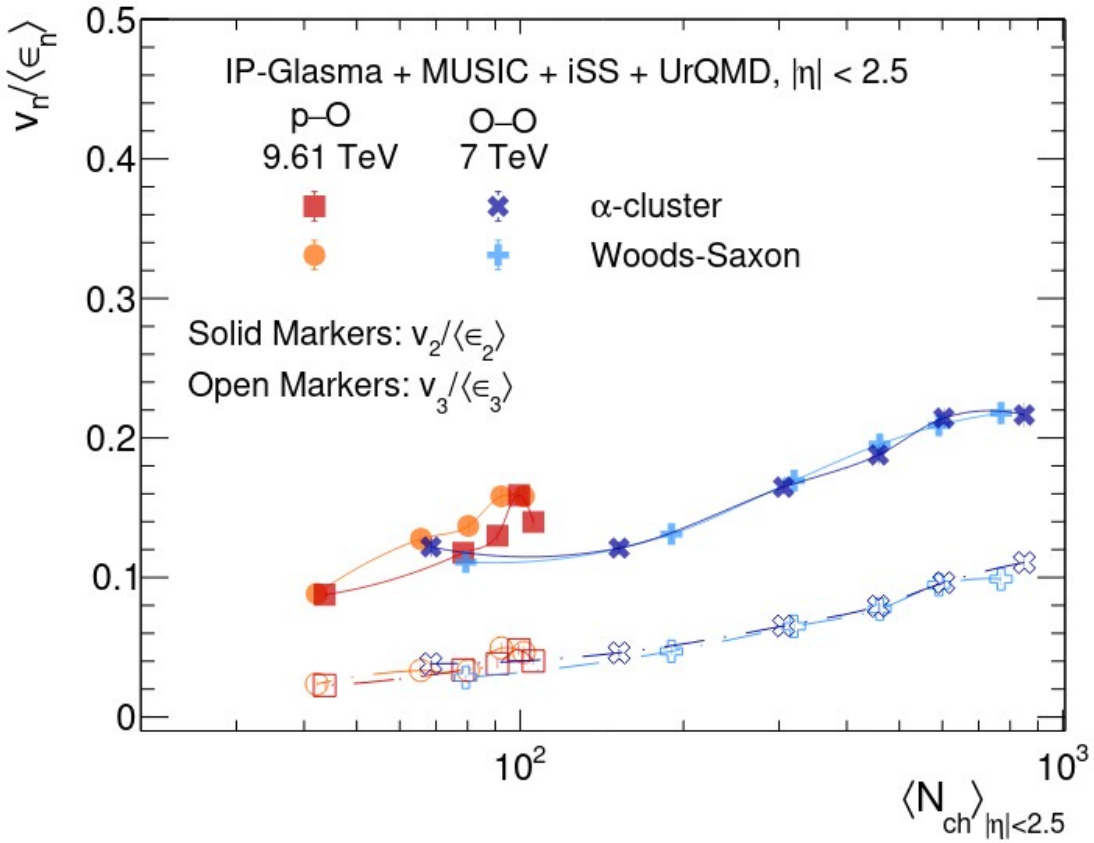




Flow components *vs* multiplicity @ LHC

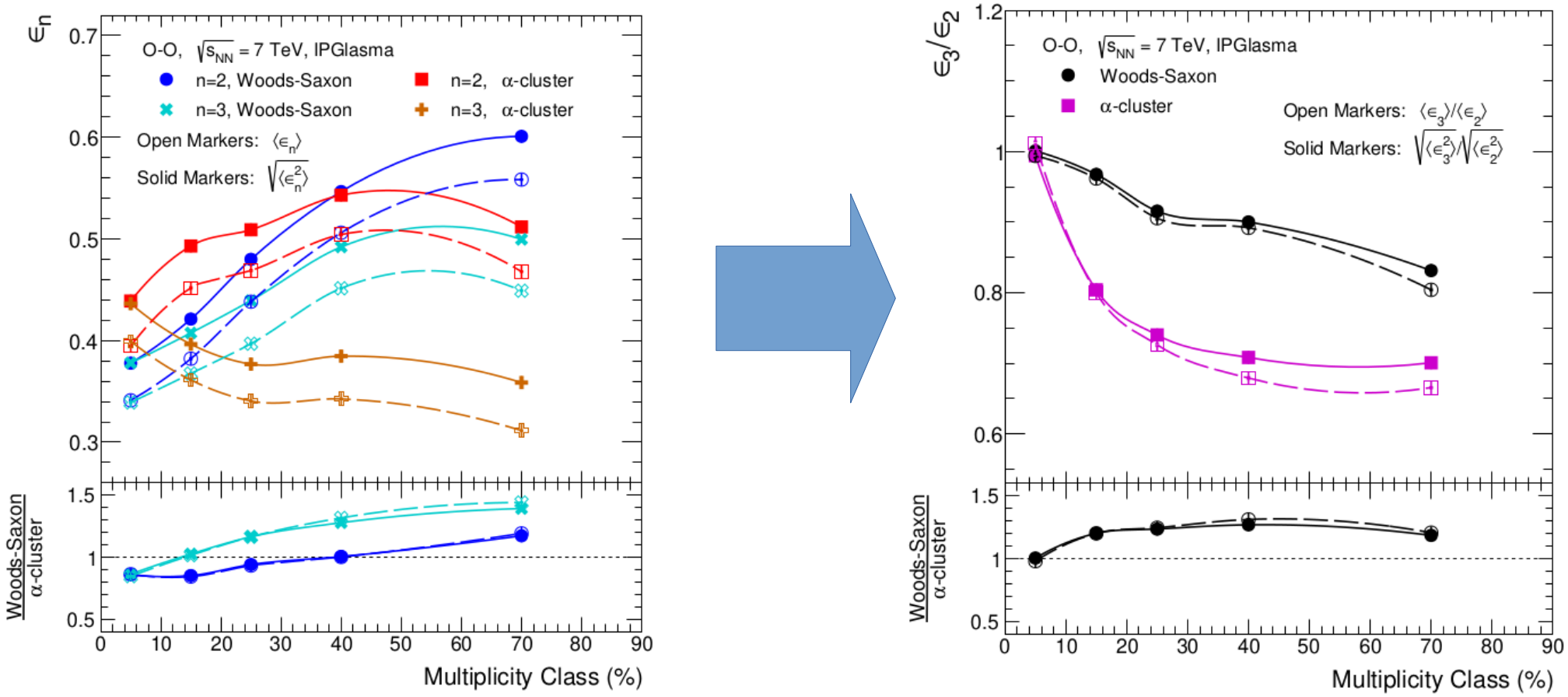
2-cummulants based v_n/ε_n calculations for p-O & O-O





Eccentricity in O+O @ 7TeV

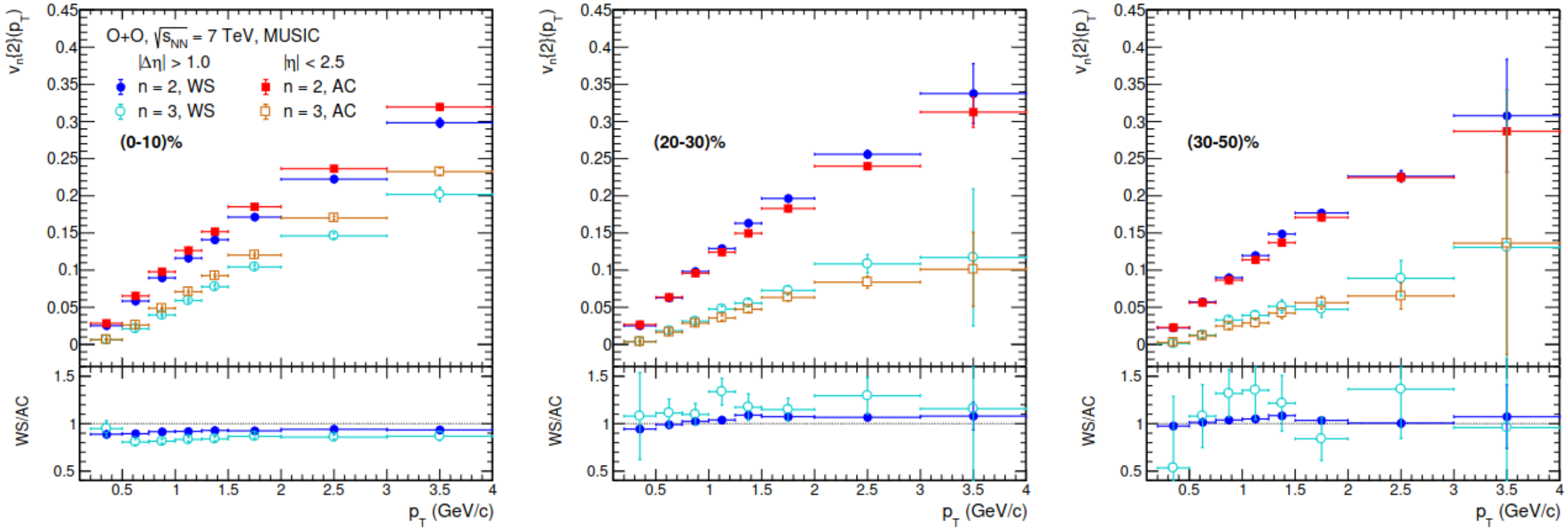
Eccentricity *vs* multiplicity for v2 and v3 and Woods-Saxon/Cluster



Flow components in O+O @ 7TeV

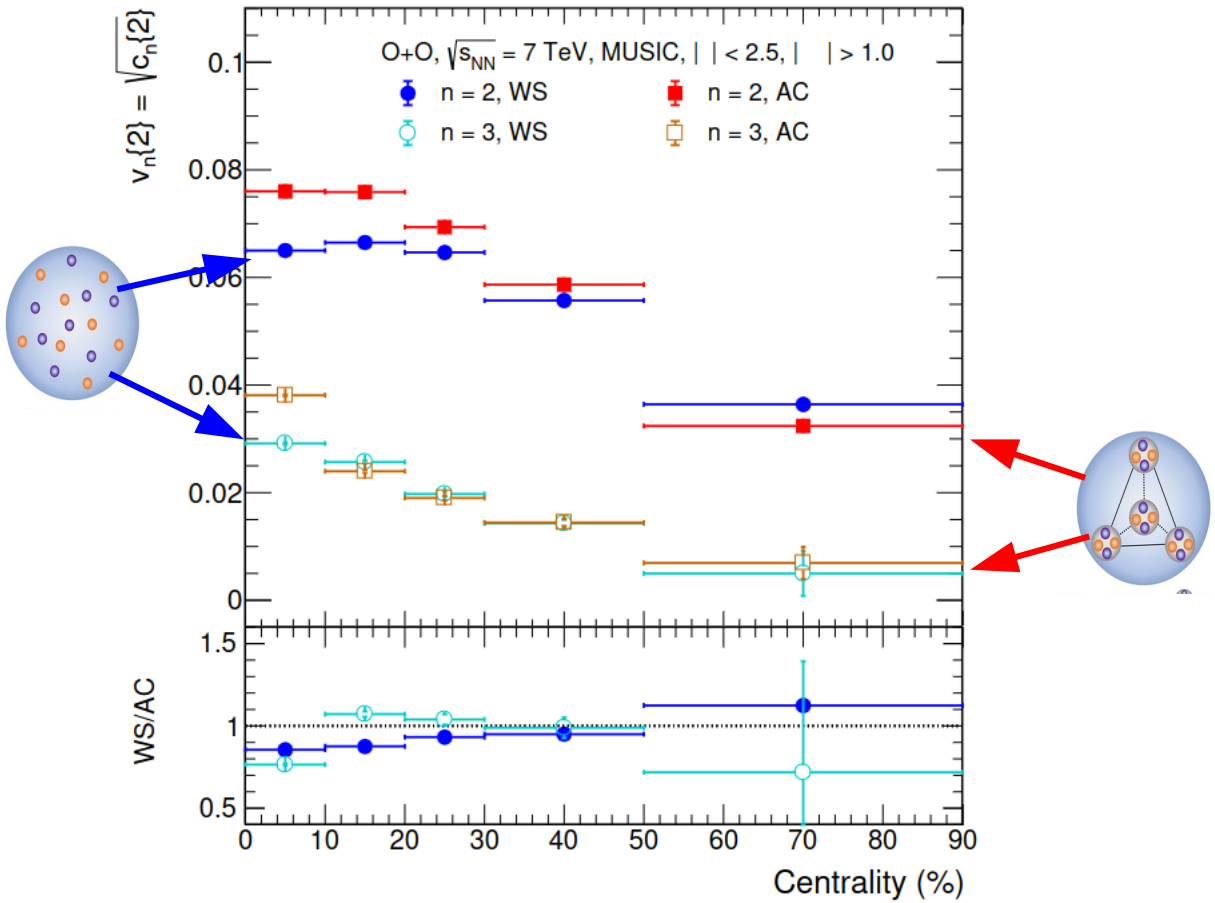
2-cummulants based $v_n(p_T)$ calculations

Centrality



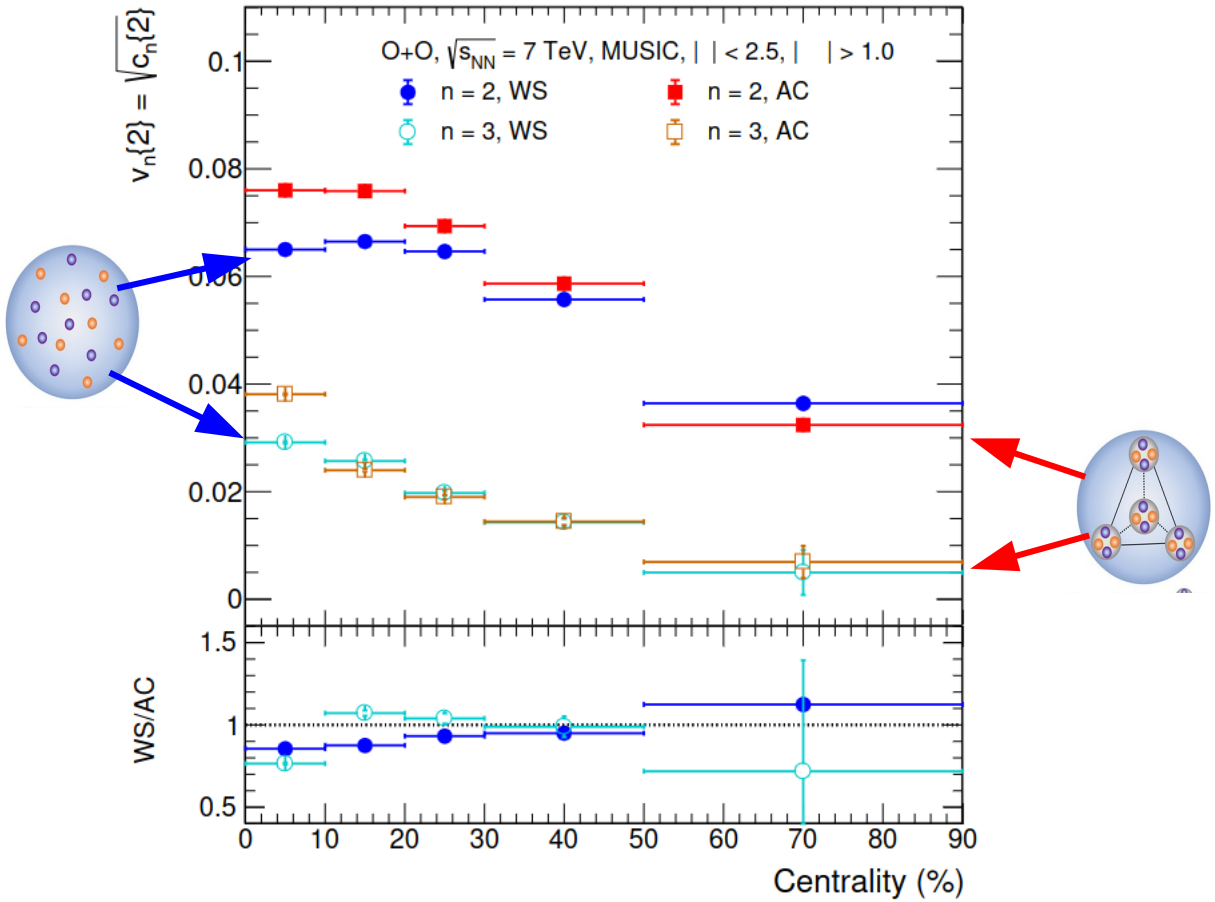
Flow components in O-O @ 7TeV

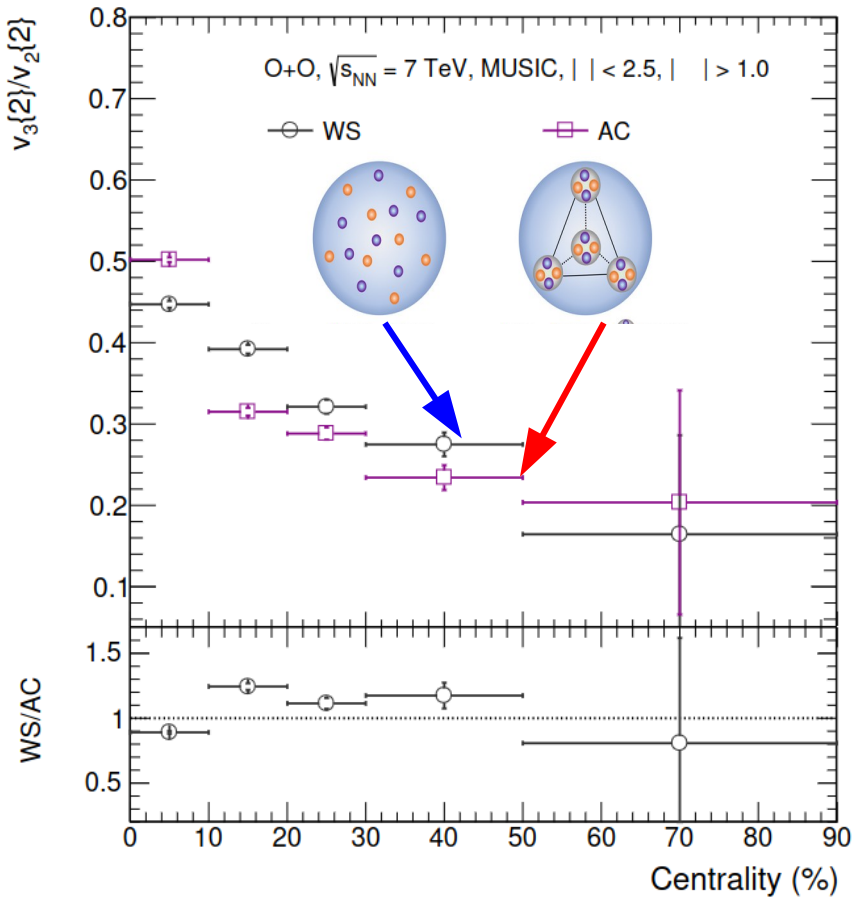
2-cummulants based calculation of v_2 & v_3



Flow components in O-O @ 7TeV

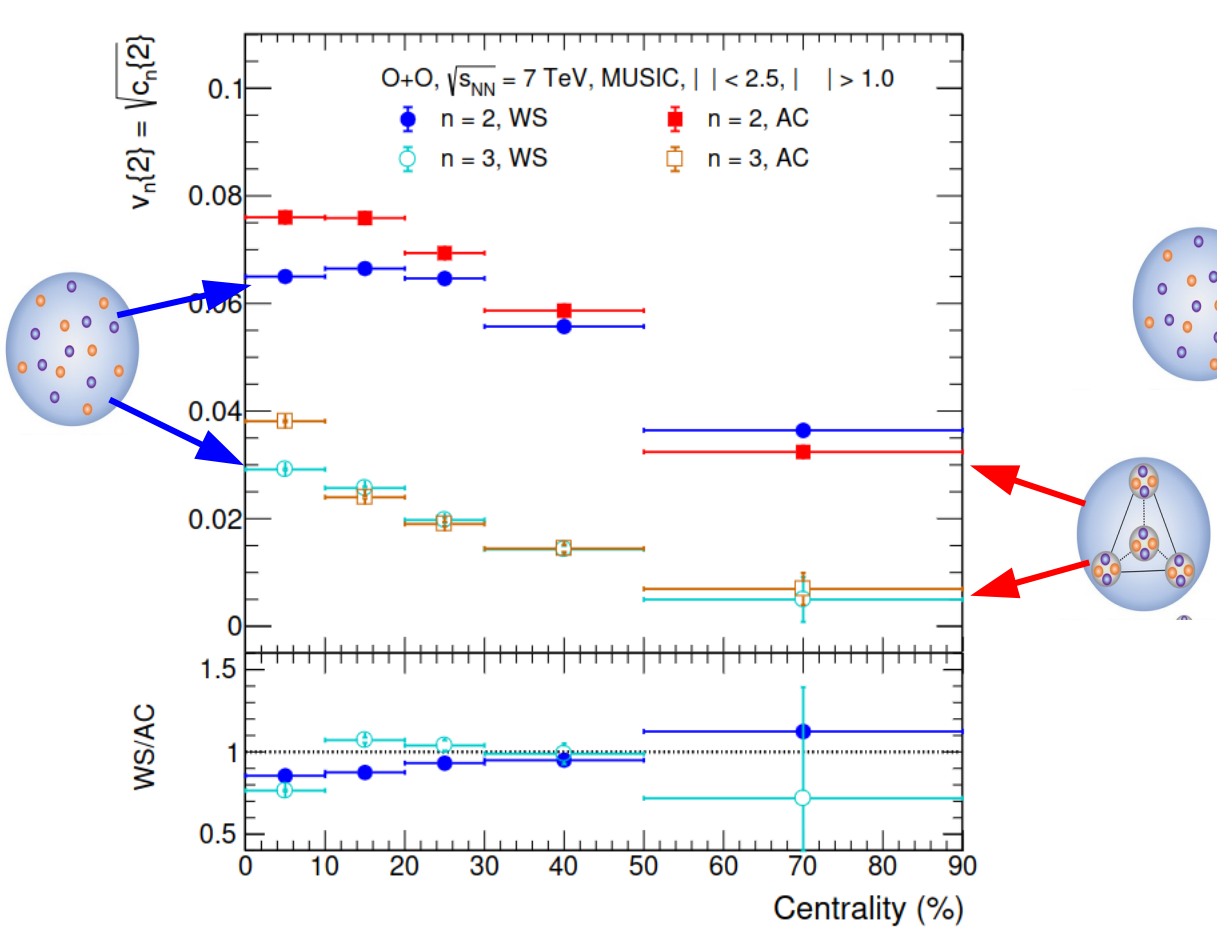
2-cummulants based calculation of v_2 & v_3

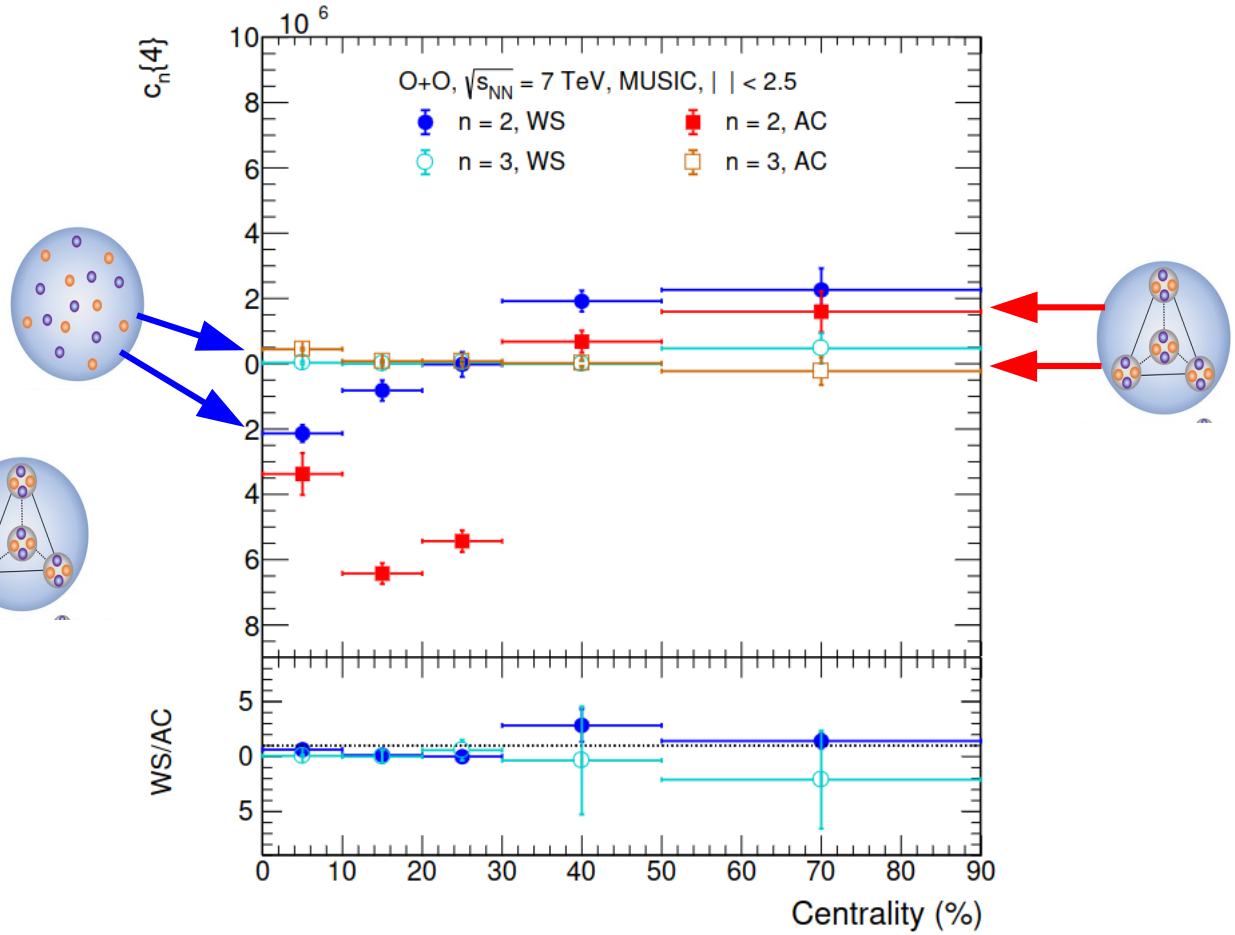




Flow components in O-O @ 7TeV

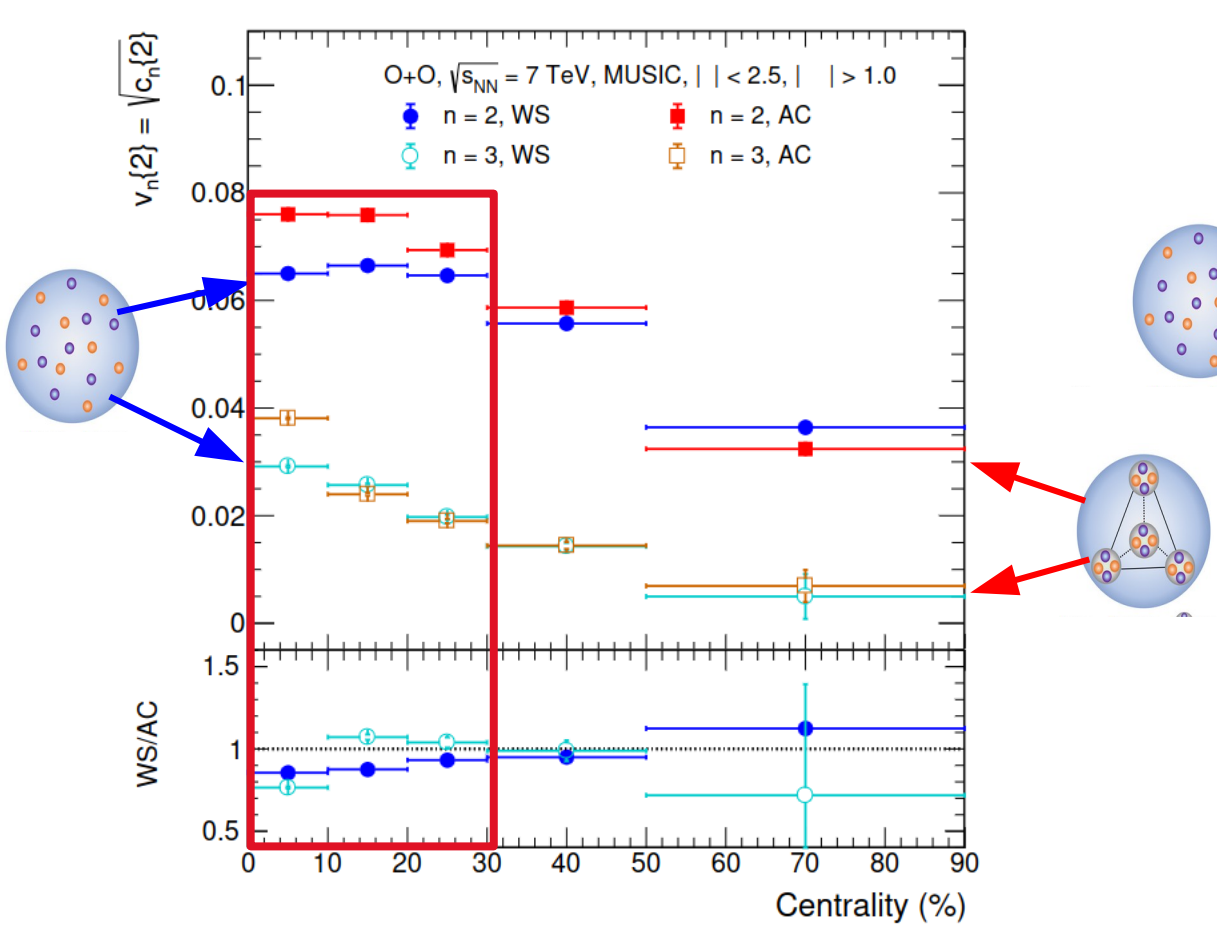
2- & 4-cummulants based v_n & c_n calculations

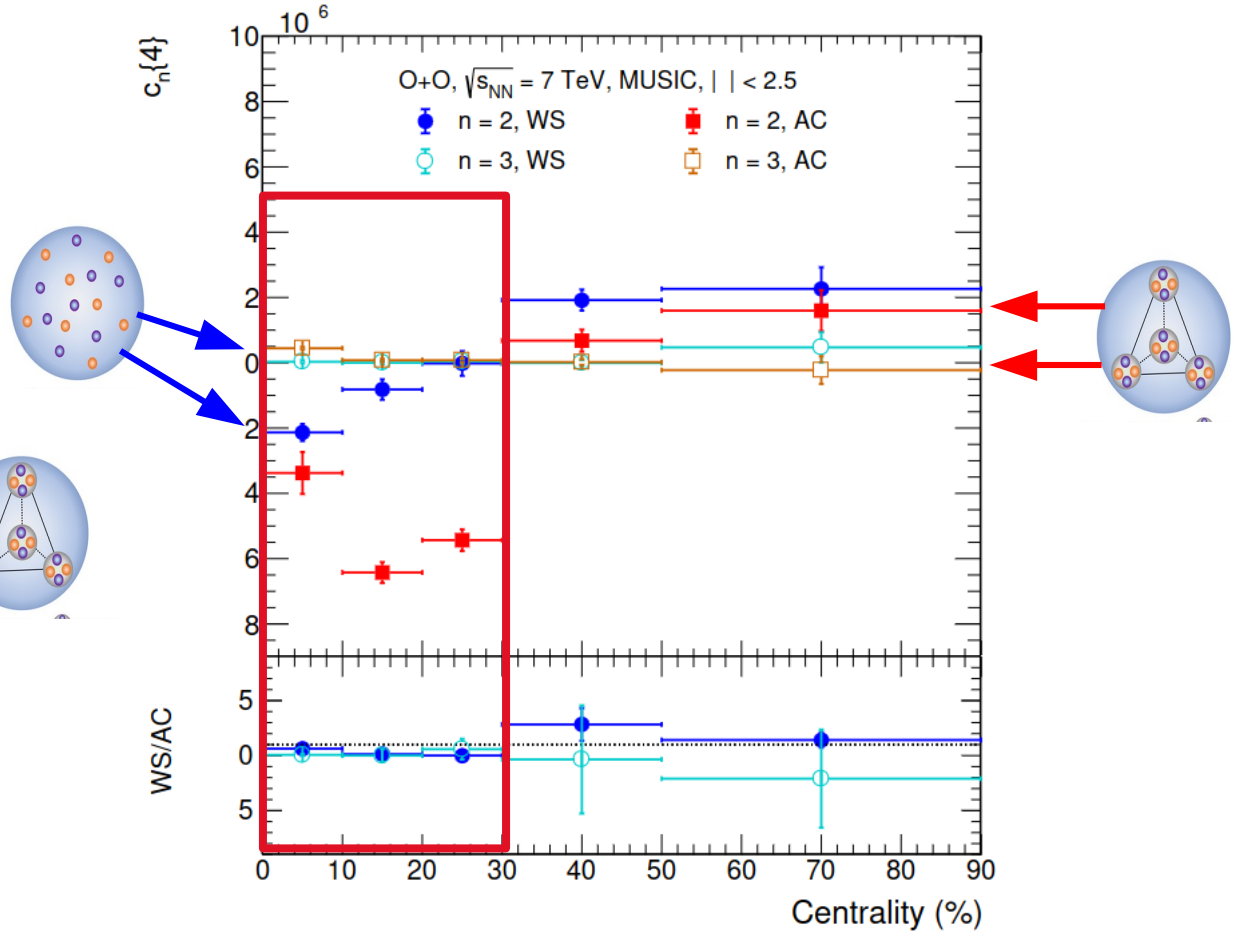




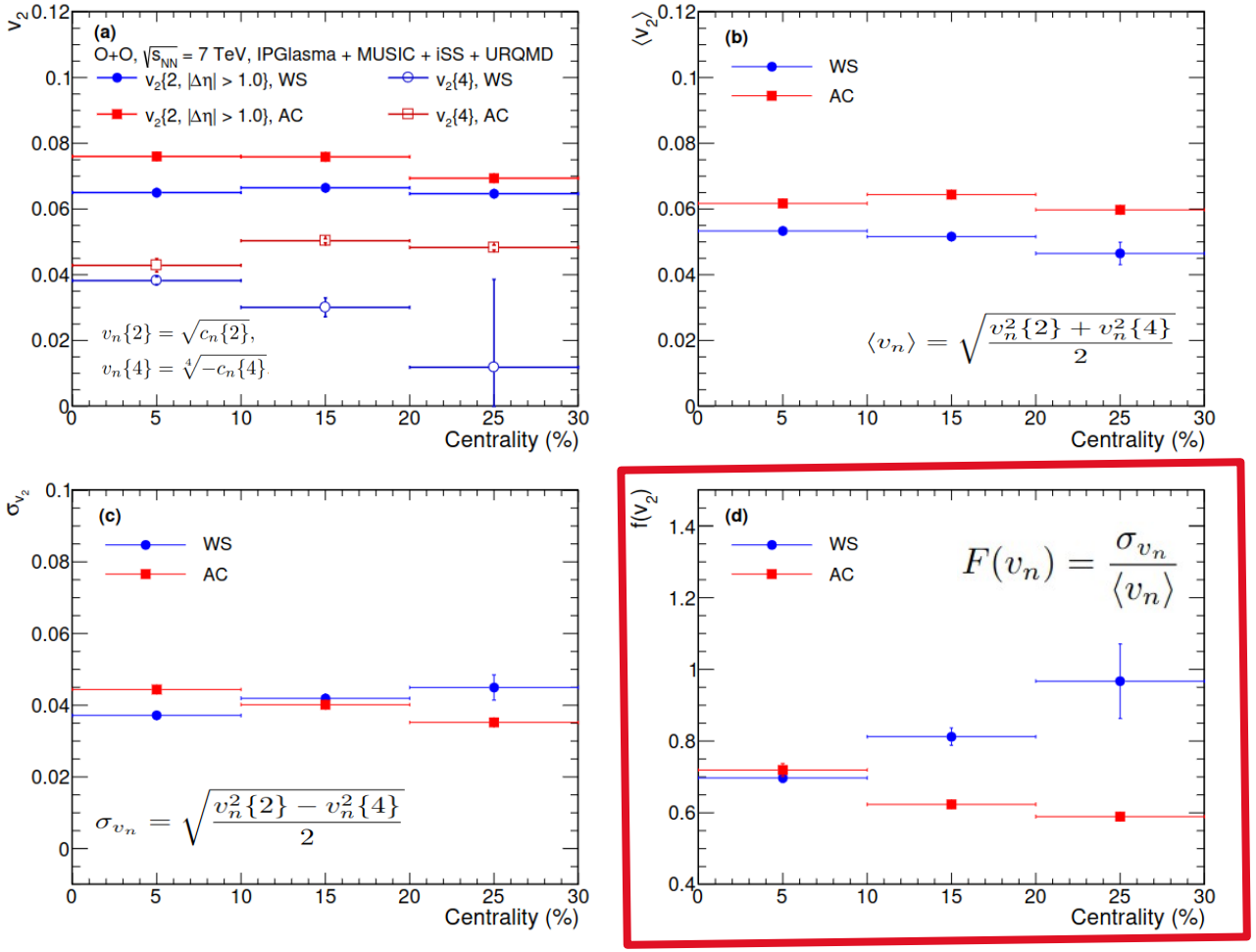
Flow components in O-O @ 7TeV

2- & 4-cummulants based v_n & c_n calculations





Flow components in O-O @ 7TeV

2- & 4-cummulants based calculations

- Flow and fluctuation measures changed significantly in the most central 0-30% regime
- Alpha-cluster has larger values, than Wood-Saxon profile
- Higher cummulants has higher effect at larger centrality
- Clearly visible on the relative measure: $F(v_n) = \frac{\sigma_{v_n}}{\langle v_n \rangle}$