Probing the exotic nuclear structure of ^{16}O throught anisotropic flow fluctuations in O-O and p-O collisions at the LHC

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

Support: *Hungarian NKFIH grants, NEMZ_KI-2022-00031, 2024-1.2.5-TÉT-2024-00022, Wigner Scientific Computing Laboratory*

Ref.: O-O: Physics Letters B 860 (2025) 139145, p-O (in few days on the arXiv)

ACHT 2025, ELTE, Budapest, Hungary, 6th May 2025

Questions of this talk

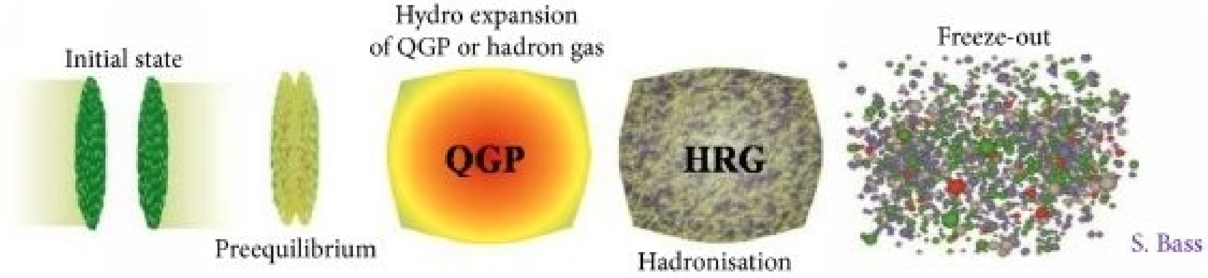
Can we

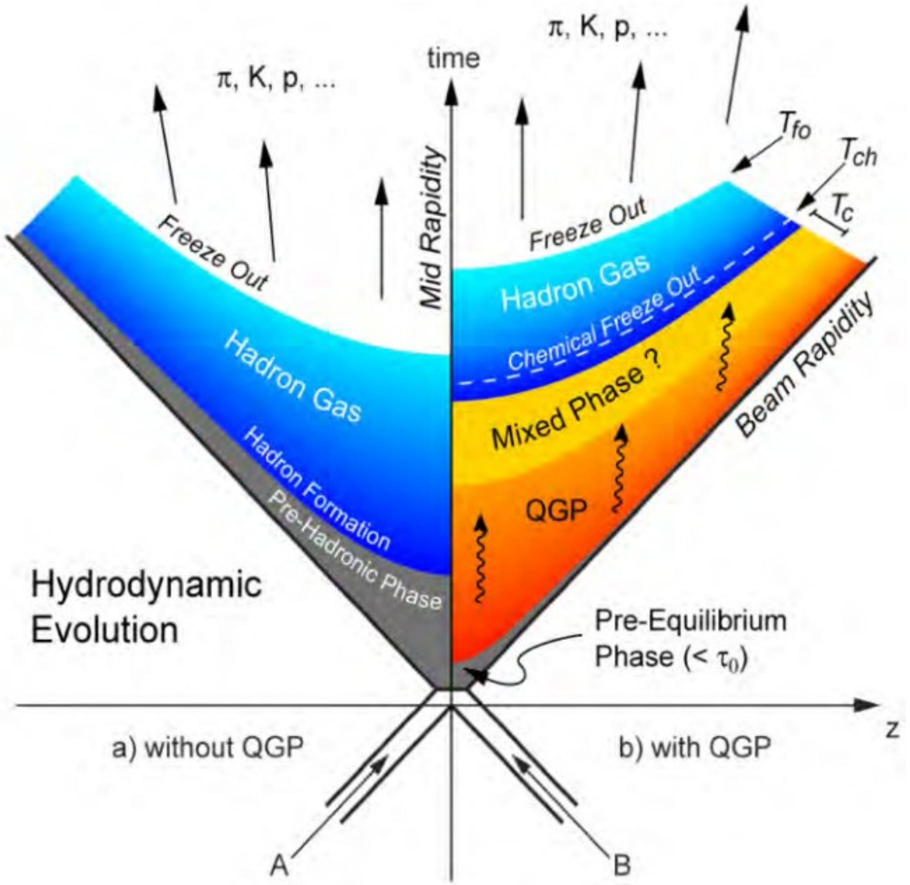
- **model the hydrodynamical evolution of small collisional systems?**
- **measure flow in the collisions of small systems?**
- **make difference in nuclear structure models of the ^{16}O?**
- **validate nuclear structure models in June 2025 at the LHC?**

Motivation & definitions

Primordial matter in heavy-ion collisions

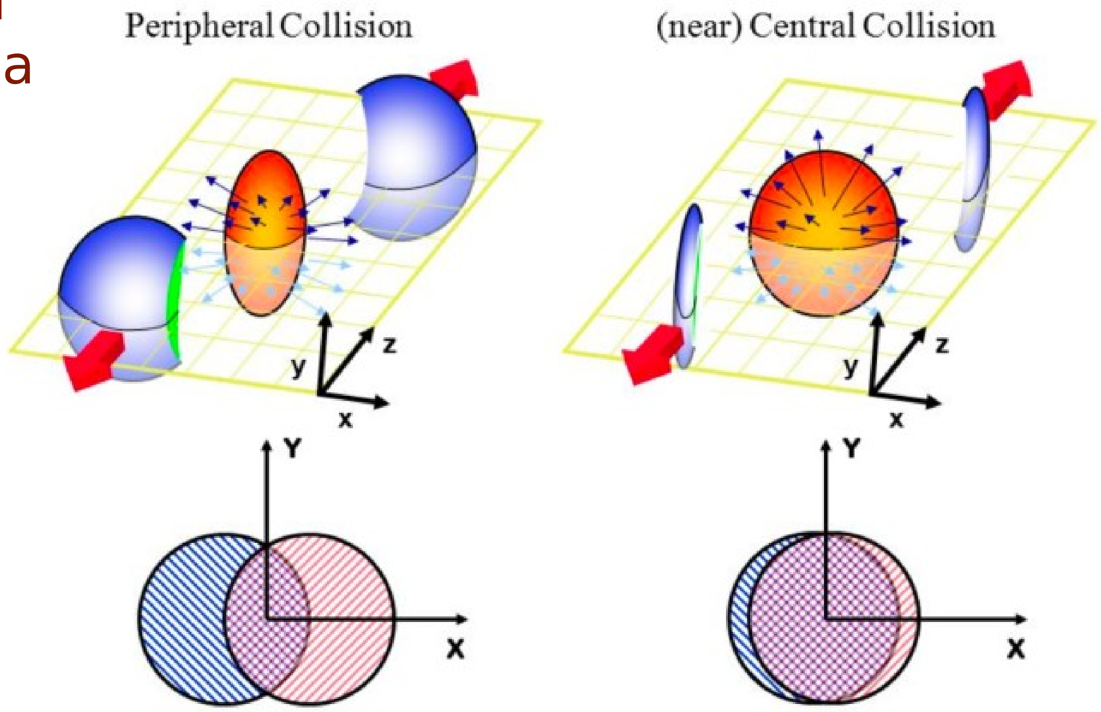
- **QGP in experimental vs theory points**
  - By colliding heavy-ions we can form small drop of the hot & dense primordial matter
  - No direct observations, just **signatures:** jet-quenching, correlations, collective effects, **(anisotropic) flow**…
  - Need a complex description, including QCD phenomenology, 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:**
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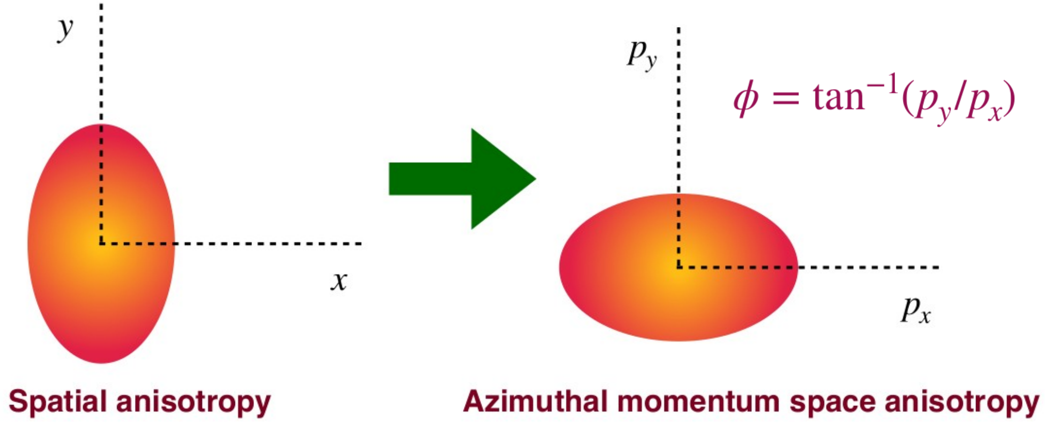
  - The n[th] harmonic coefficient of the Fourier expansion of azimuthal momentum distribution:

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



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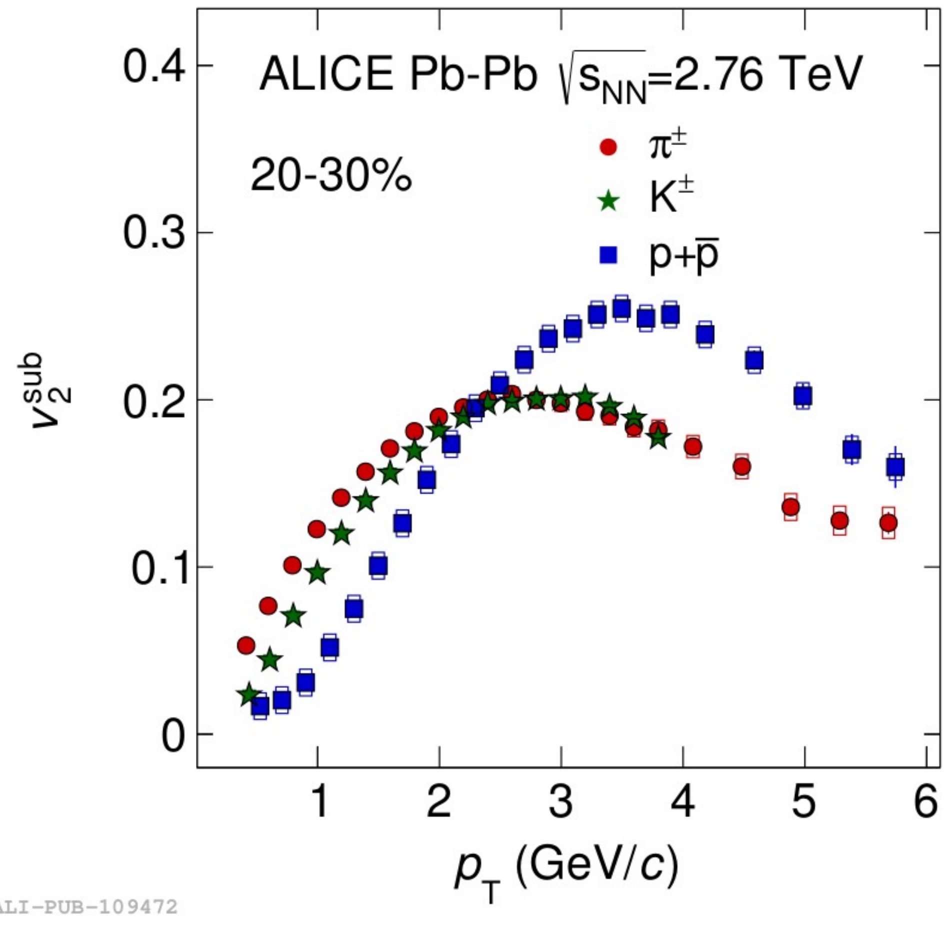
  - The $v_2(p_T, y) = \langle \cos(2(\phi - \psi_2)) \rangle$ directly reflects the initial spatial anisotropy of the nuclear overlap region in the transverse plane.



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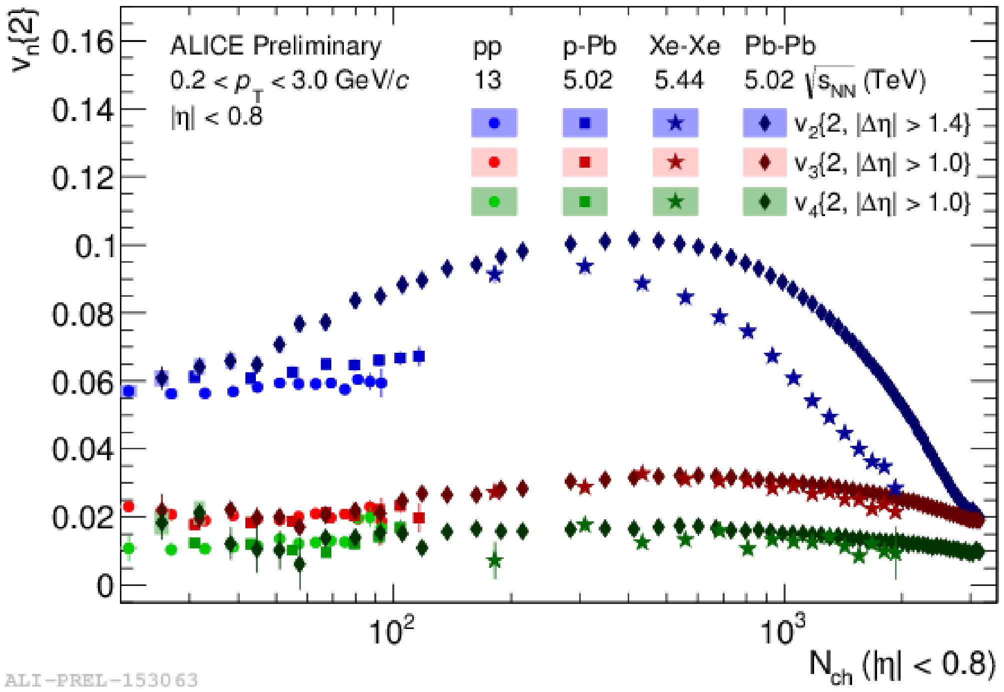
  - The $v_2(p_T, y) = \langle\cos(2(\phi - \psi_2))\rangle$ directly reflects the initial spatial anisotropy of the nuclear overlap region in the transverse plane.
  - Higher flow components can be measured



Future Nuclear Collisions at LHC

- **LHC Schedule with new nuclear collisions**
  - Run 2: p-p, p-Pb, Pb-Pb, XeXe

Breakthrough Prize in fundamental physics

LHC schedule	Run 1 2009 - 2013	Run 2 2015 - 2018
Collision systems	pp, pPb, Pb-Pb	pp, pPb, Xe-Xe, Pb-Pb

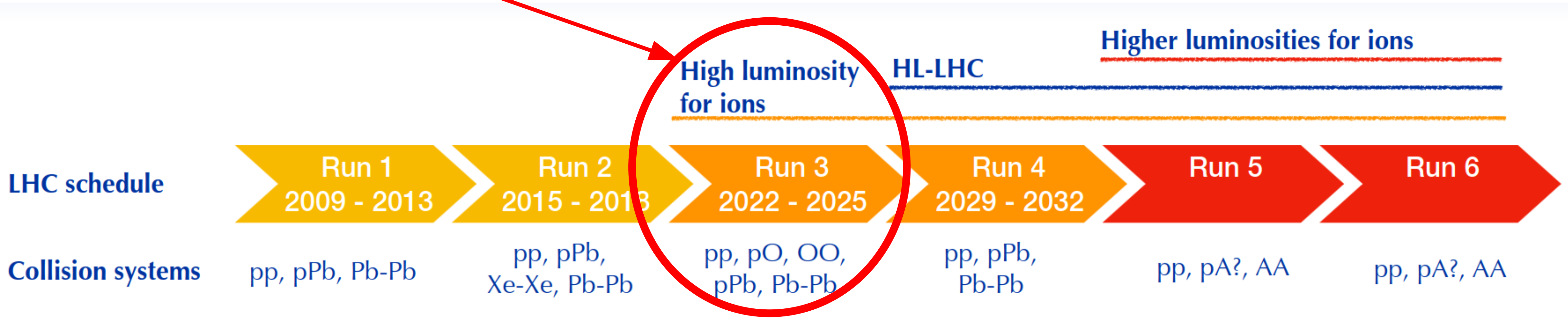
Breakthrough Prize in Fundamental Physics 2025 awarded to the four large LHC experiments for

"*… the exploration of nature at the shortest distances and most extreme conditions at CERN's Large Hadron Collider*"

- Price ceremony in Los Angeles, 5th April 2025 attended by spokespersons of the experiments
- Shared by all authors of run-2 publications (listed on web site)
- Prize money will be used for PhD studentship grants for a stay at CERN

Future Nuclear Collisions at LHC

- **LHC Schedule with new nuclear collisions**
  - Run 2: p-p, p-Pb, Pb-Pb, XeXe
  - Run 3: p-p, p-Pb, Pb-Pb, p-O, & O-O



Planned OO & pO Collisions at LHC

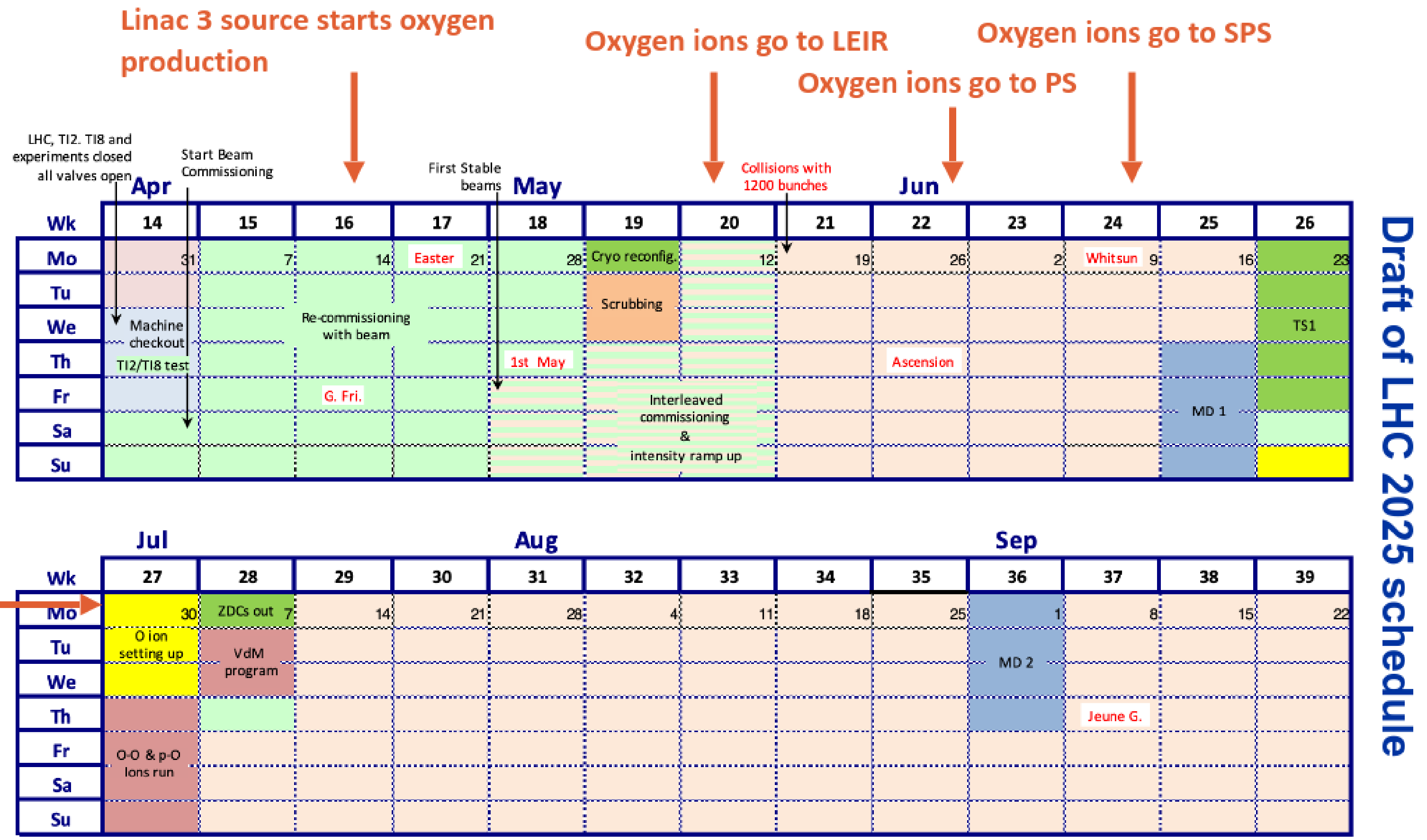
1-week oxygen pilot run at late June 2025 at LHC, 5.36 ATeV

3 days of p-O ALICE:

>2.5 nb^{-1}, ~10^{8} events

1 day of O-O ALICE:

~0.5 nb^{-1}, ~7x10^{7} events



Oxygen pilot run (6-8 days)

- 2-3 days O-O commissioning
- 1-1.5 days O-O physics
- 0.5-1 days p-O commissioning
- 2.5-3 days p-O physics

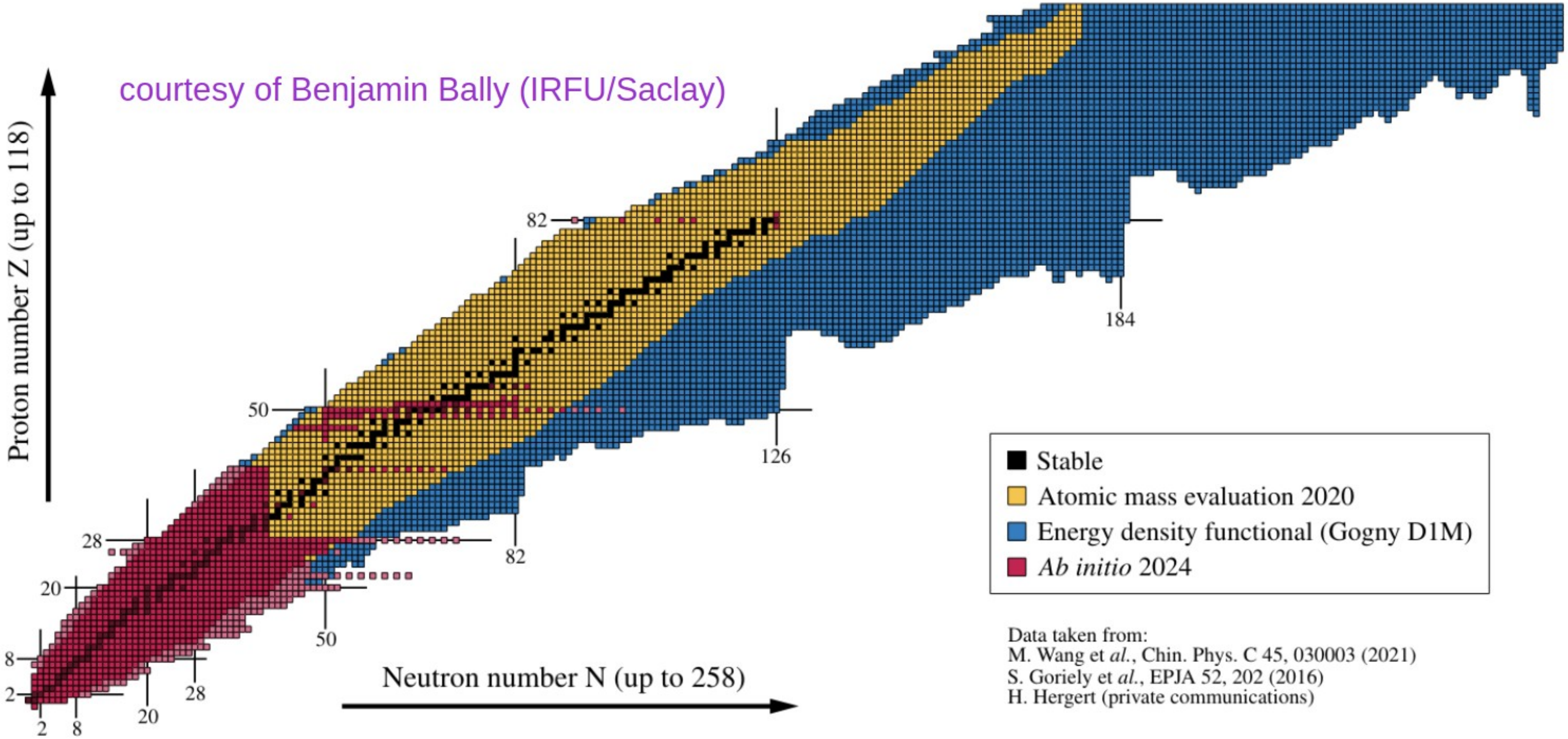
Optimistic scenario

R. Bruce et al IPAC21 paper

Nuclei & nuclear structure

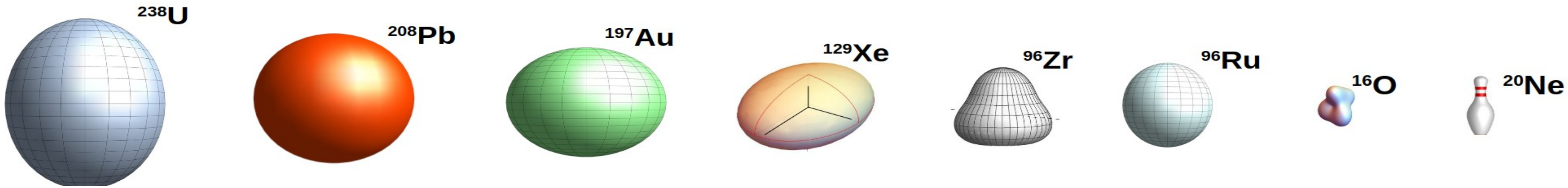
Nuclei for Future Nuclear Collisions

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



Nuclei for Future Nuclear Collisions

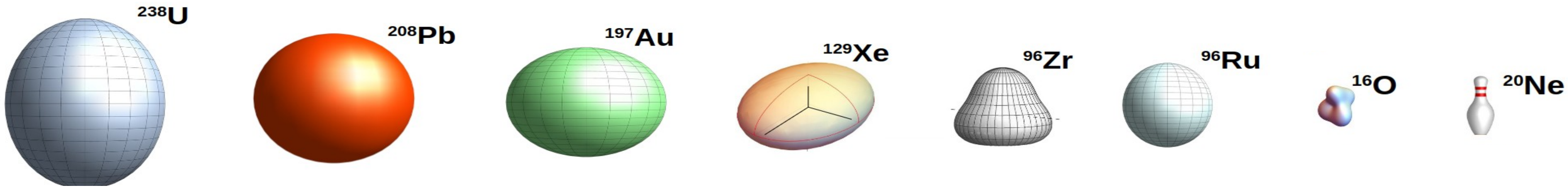
- **Experimental possibilities & interest**
  - Large deformed nuclei: uranium, gold, xenon
  - Smaller zirconium, rubidium, oxygen, neon



Nuclei for Future Nuclear Collisions

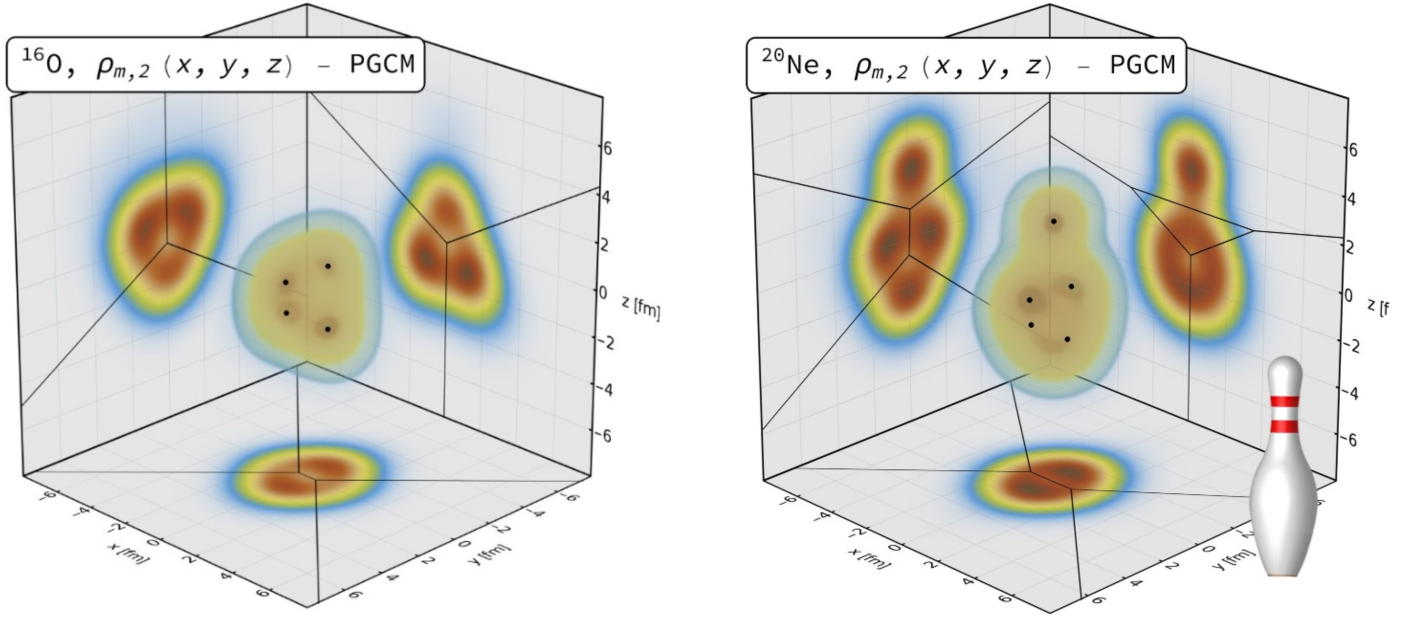
- **Experimental possibilities & interest**
  - Large deformed nuclei: uranium, gold, xenon
  - Smaller zirconium, rubidium, oxygen, neon

    → Similarly as “gombóc” in Hungarian….



Nuclei for Future 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)**

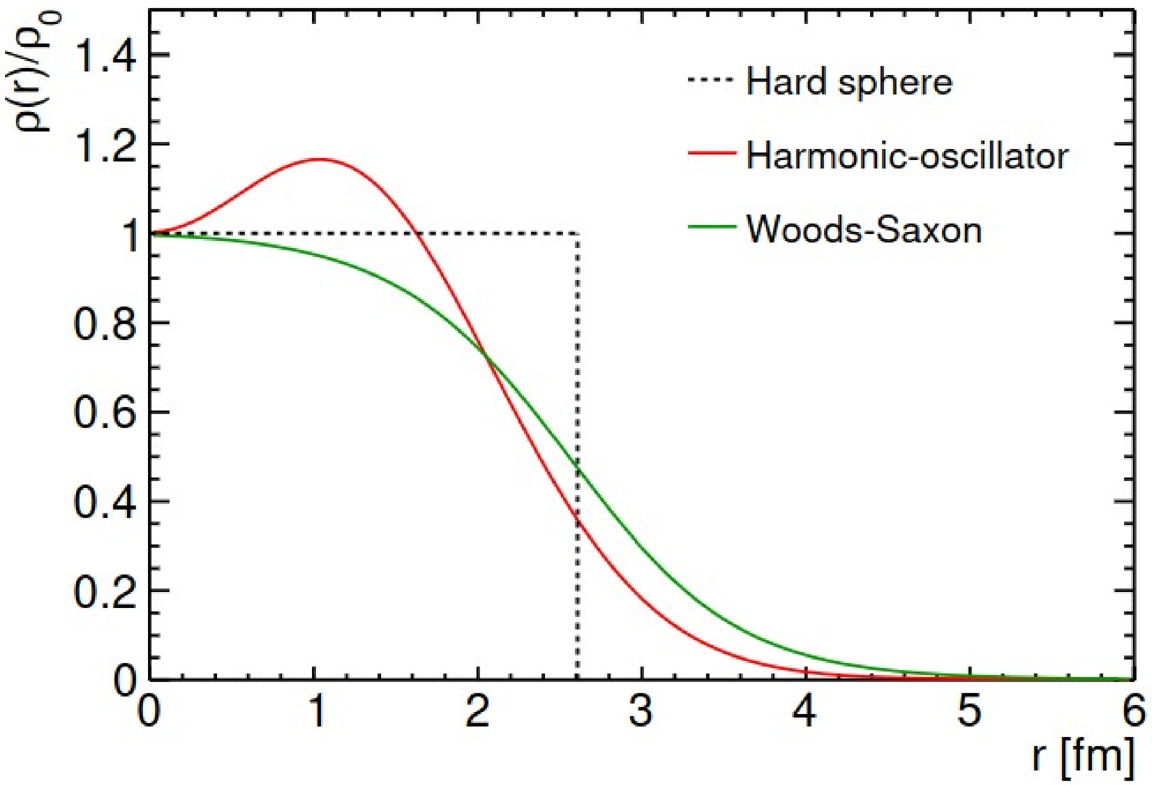
$$\rho(r) = \rho_0 \left[1 + \alpha \left(\frac{r}{a}\right)^2\right] \exp\left(\frac{-r^2}{a^2}\right)$$

- **Harmonic oscillator (HO)**

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

- Normalization:

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

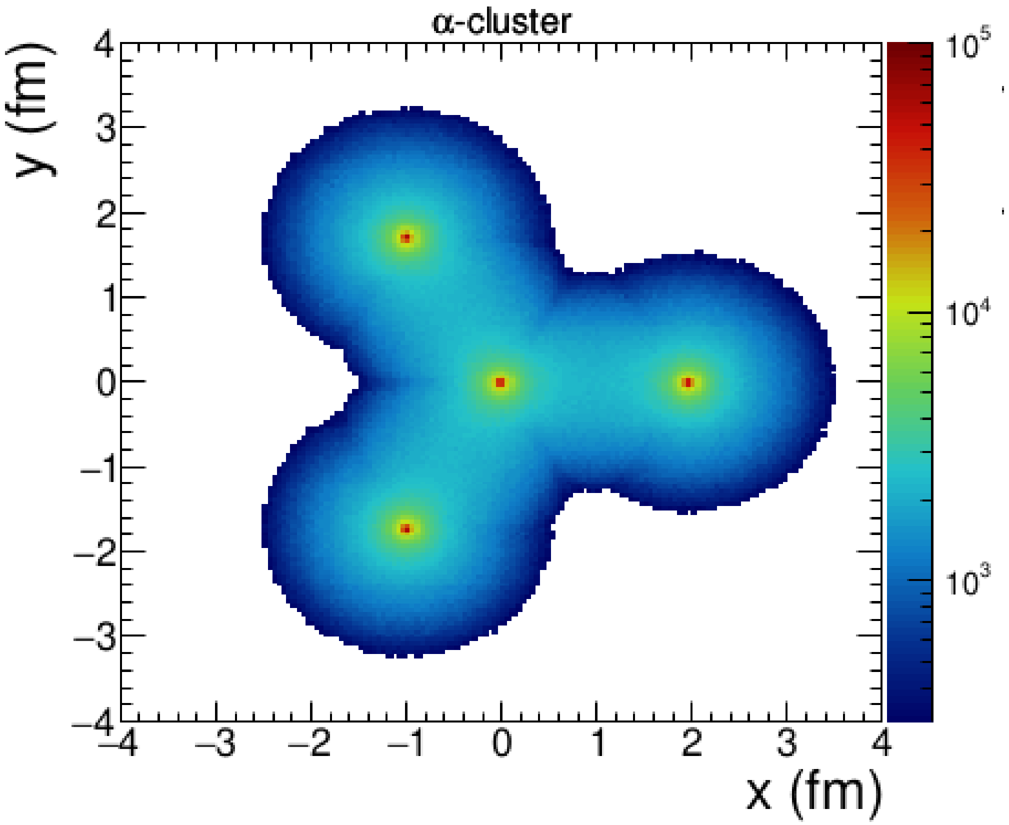


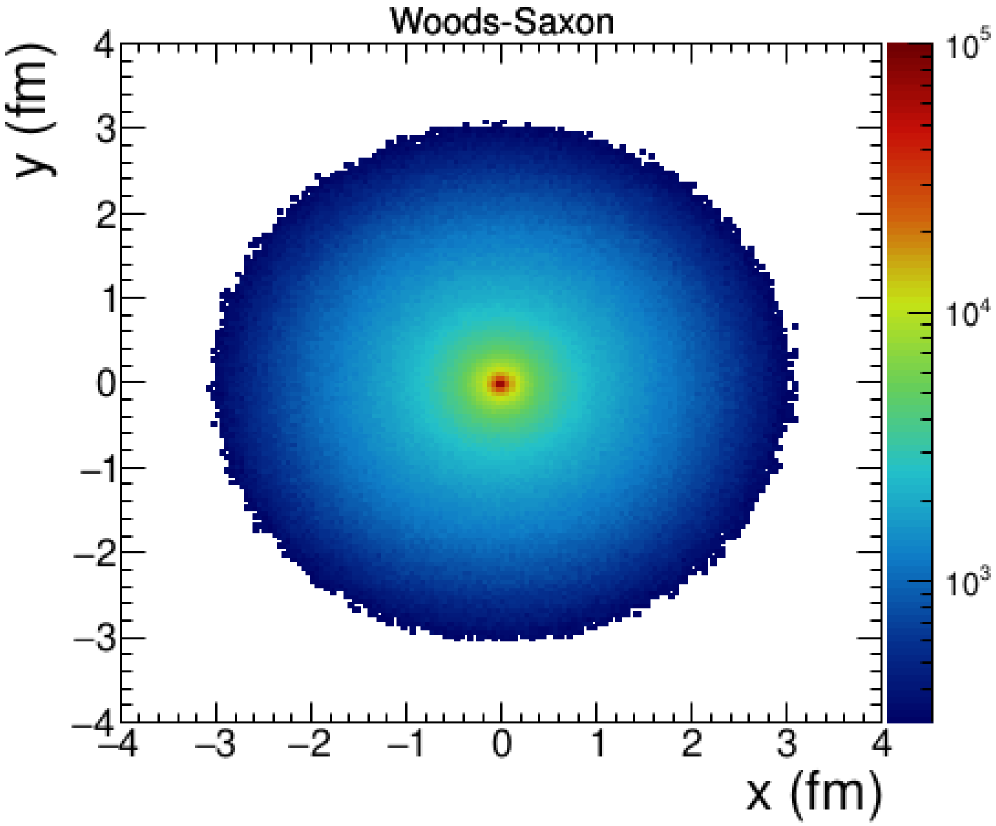
The shape of the oxygen

Nuclear structure description

- Cluster model vs.

Non-cluster model (Woods-Saxon)





The shape of the oxygen

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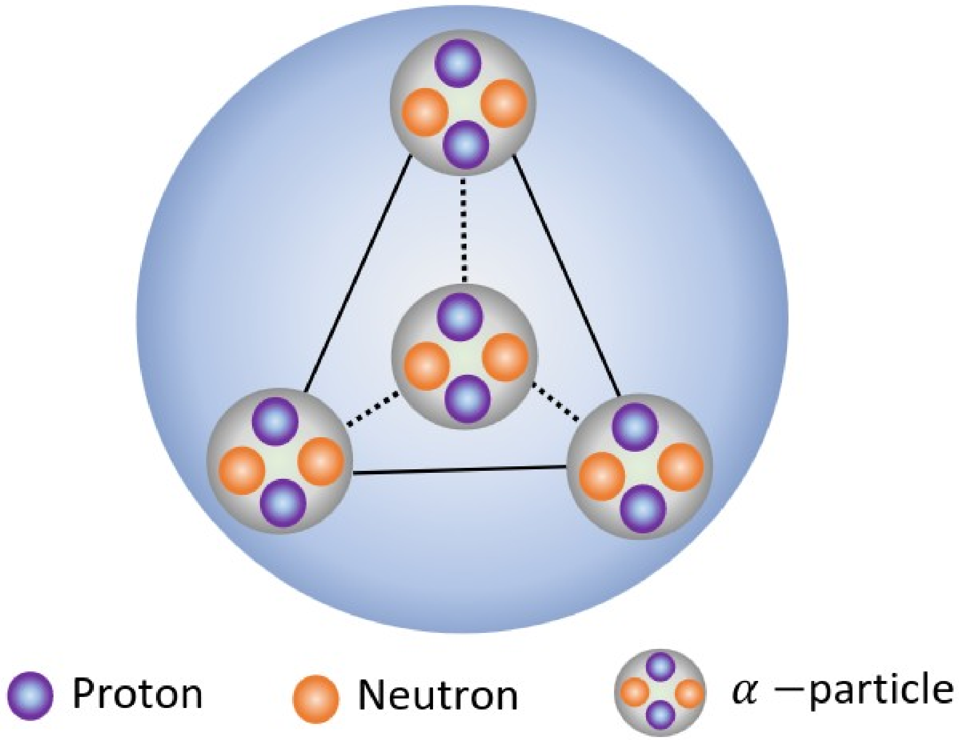
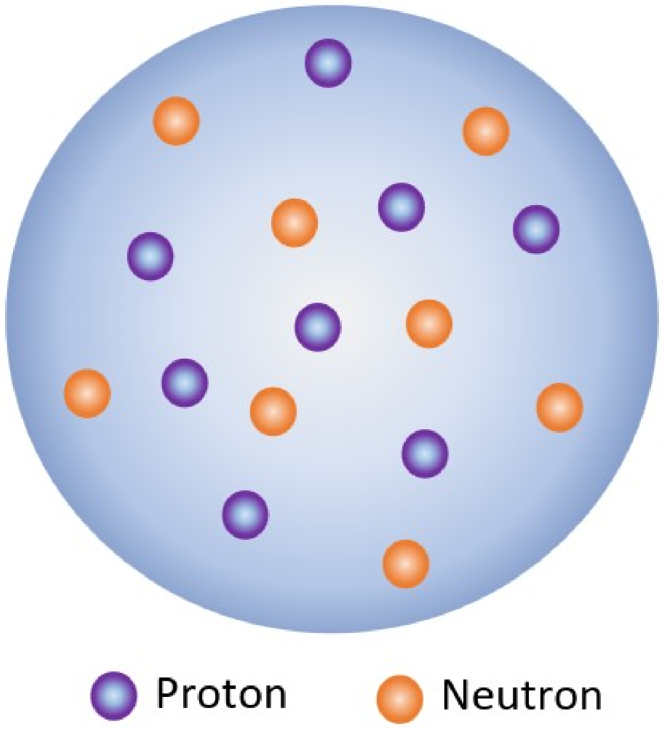


α – clustered Oxygen (^{16}O) nucleus

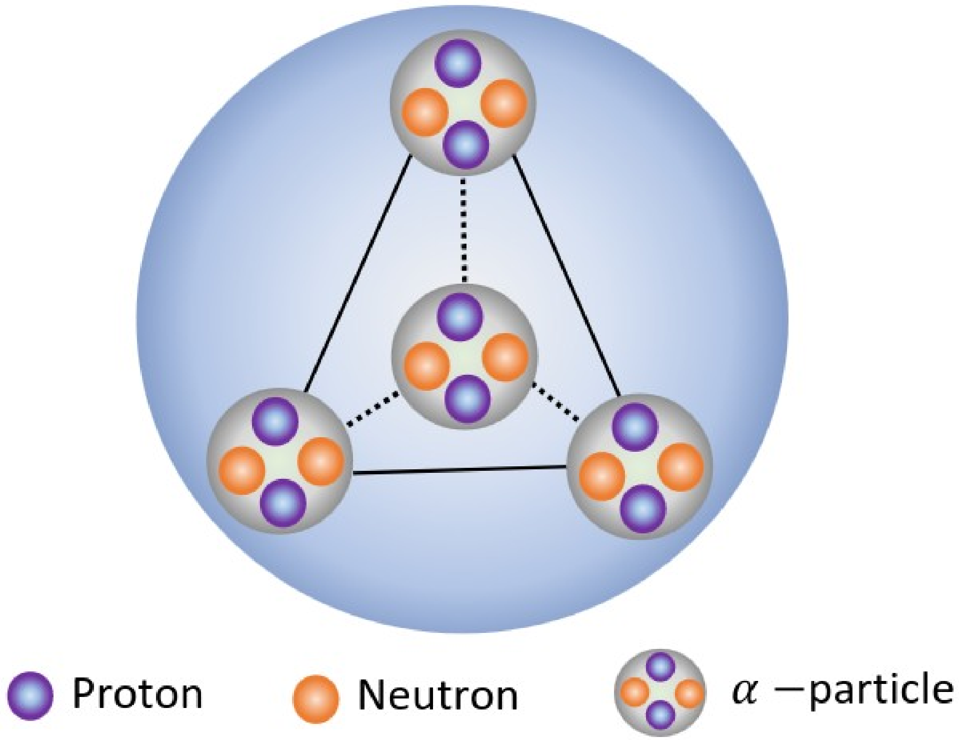


Non-clustered Oxygen (^{16}O) nucleus

The shape of the oxygen

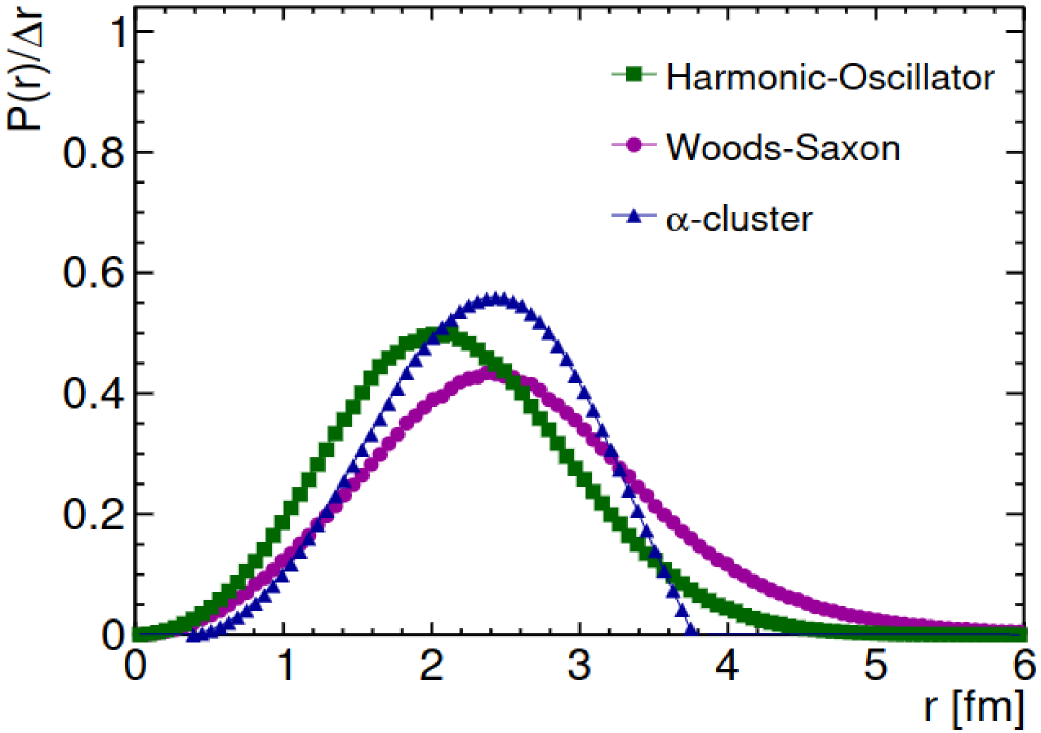
Nuclear structure description

- **Cluster model vs WS & HO**



α – clustered Oxygen (^{16}O) nucleus

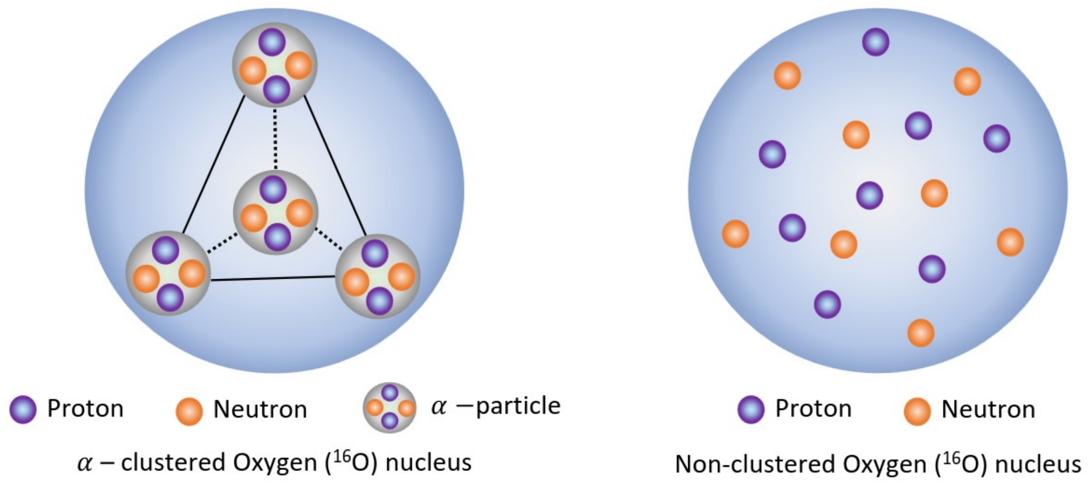
Probability of the radial position in O

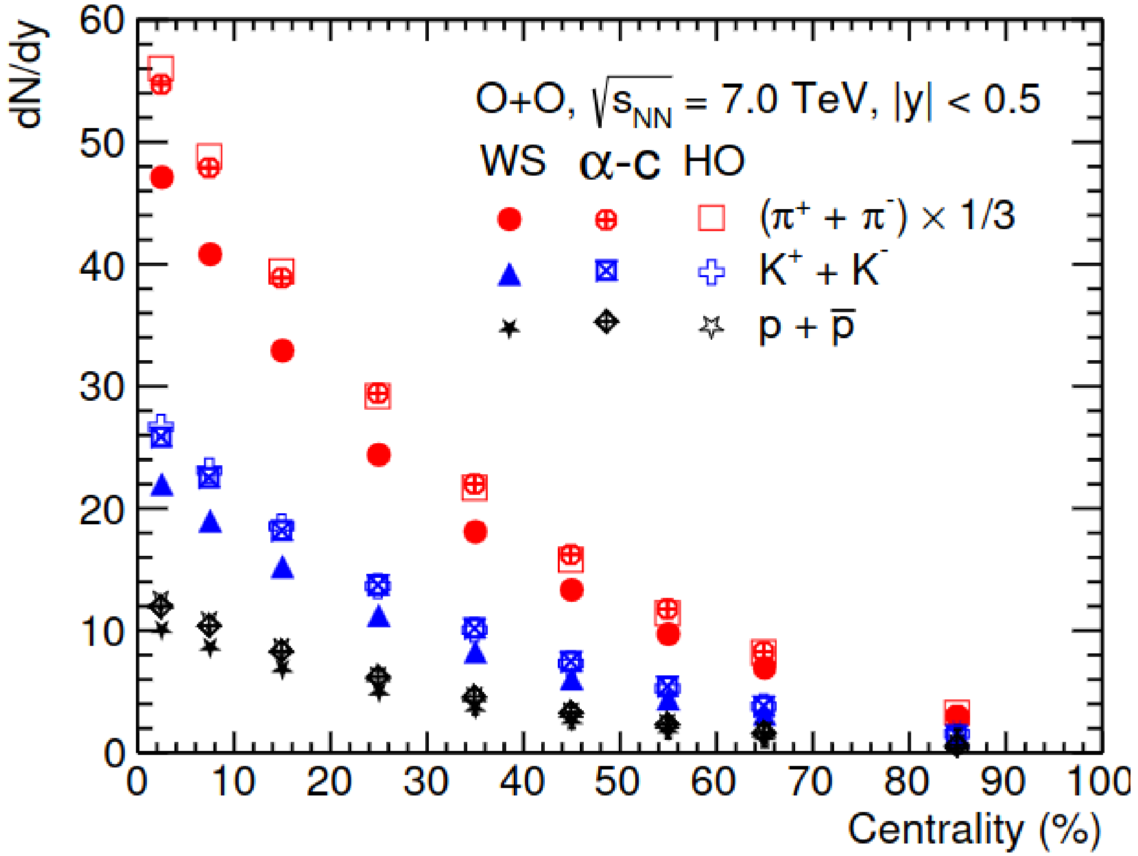


The shape of the OO collision

Nuclear structure description

- **Cluster model vs WS**





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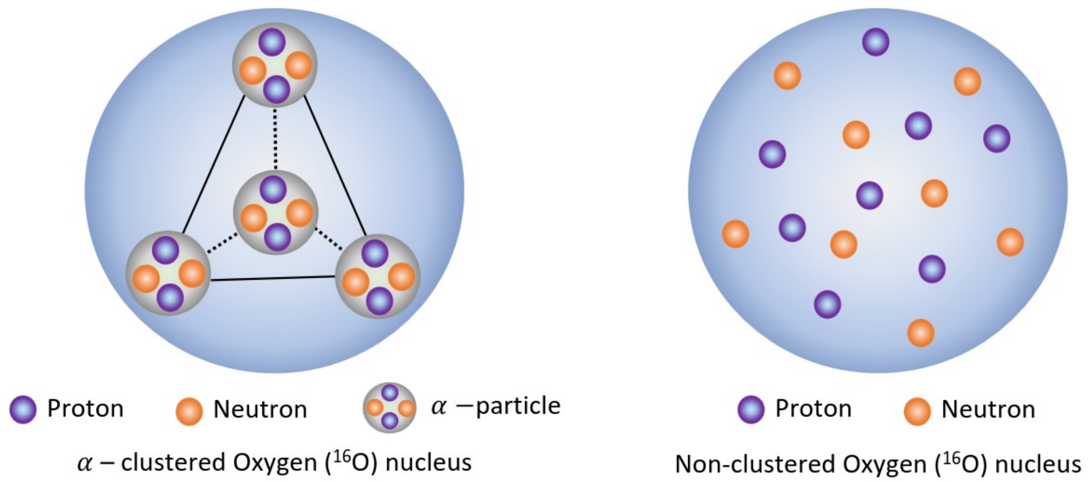

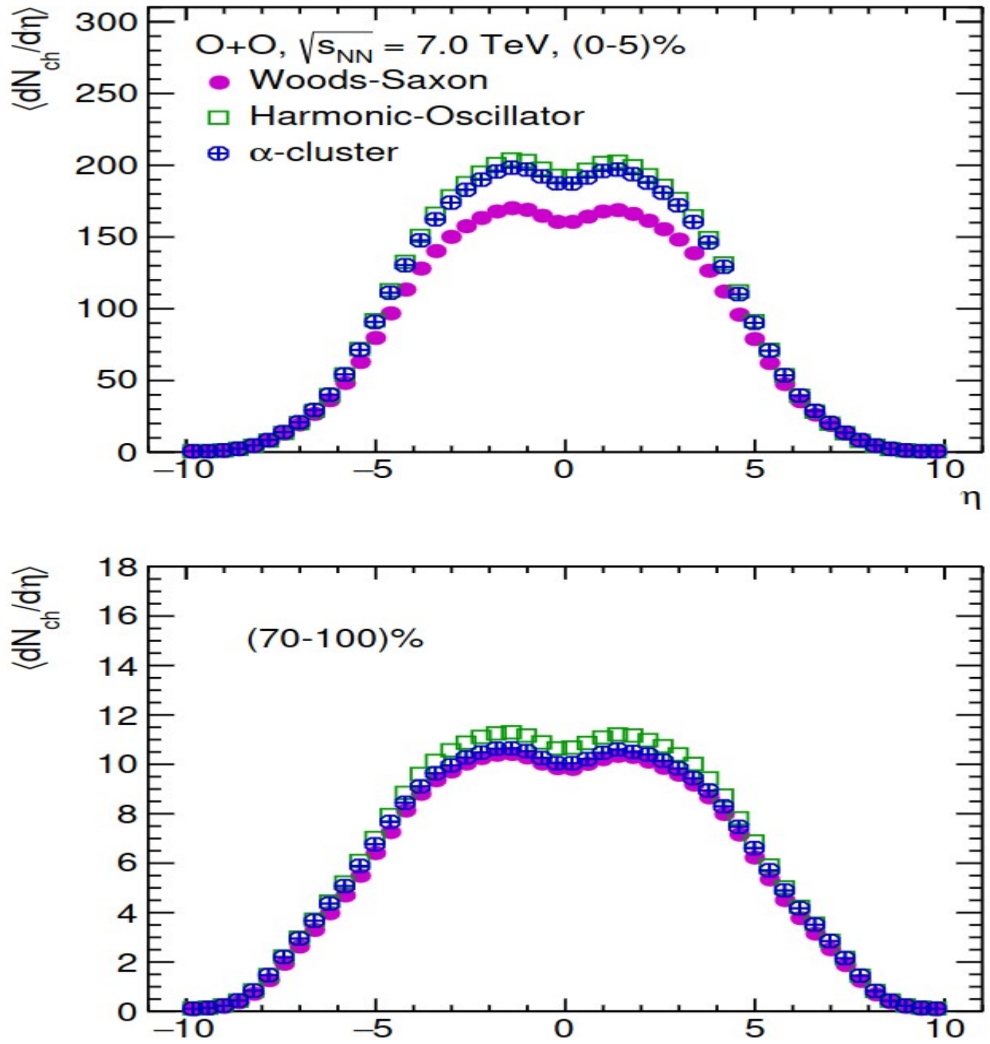

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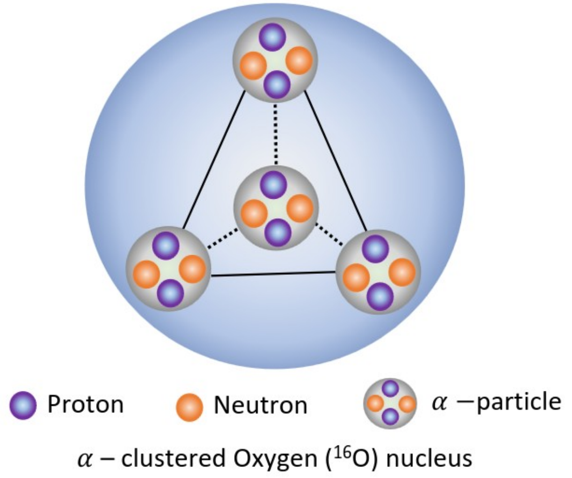
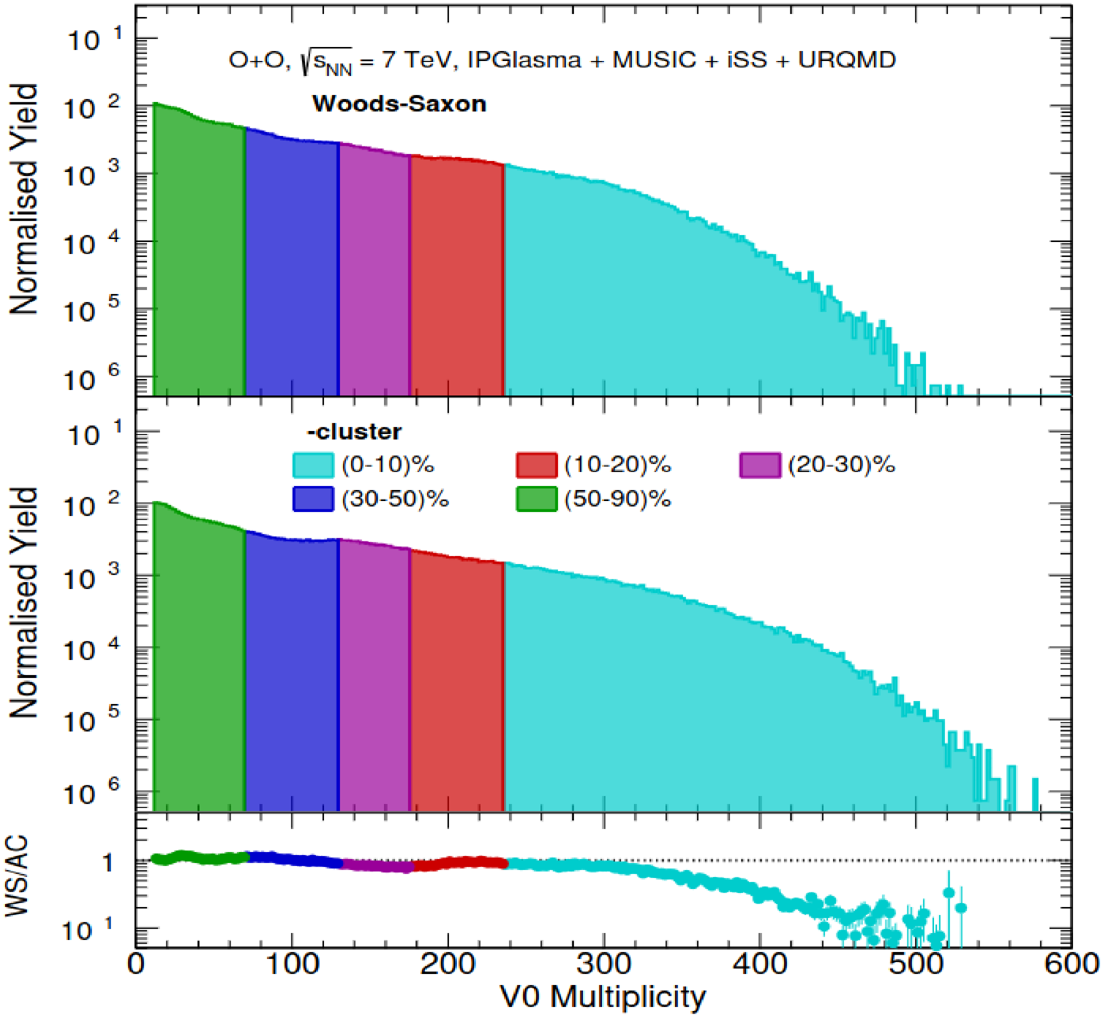
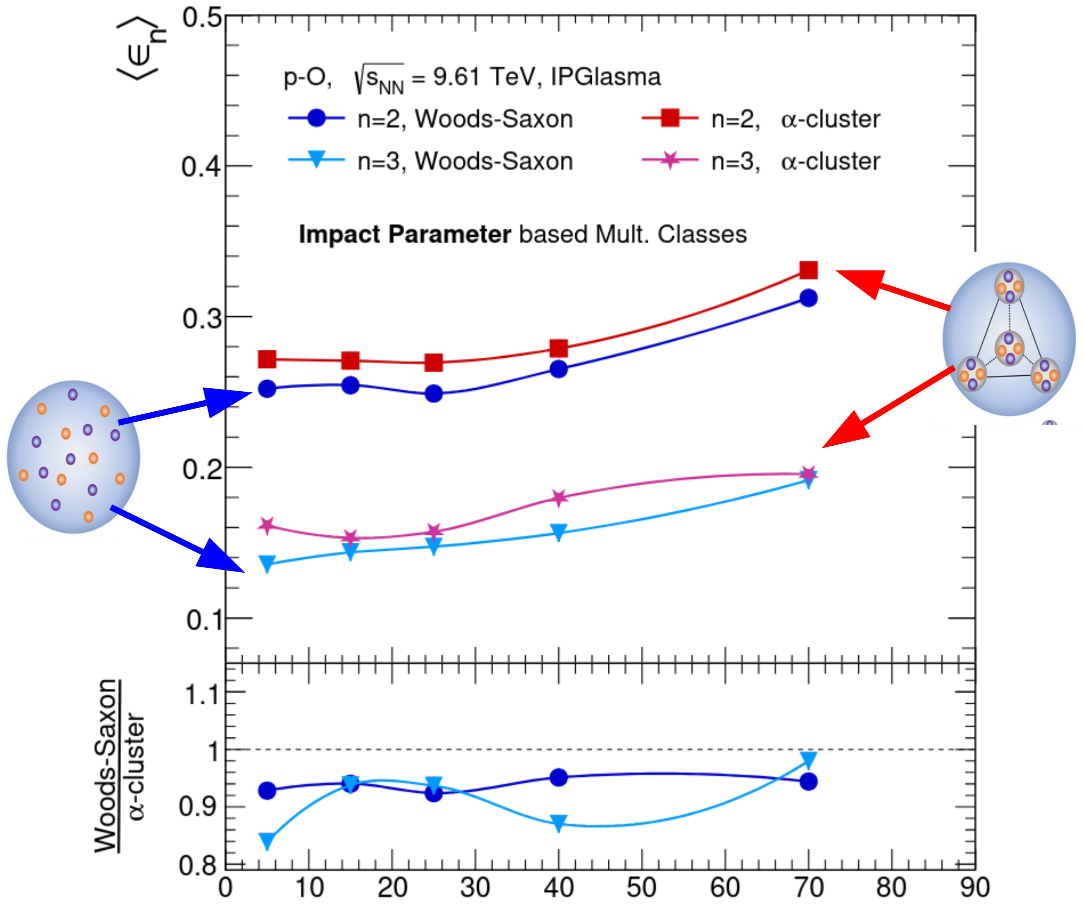




Excentricity in p-O & O-O

Excentricity in p-O

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



Excentricity in p-O & O-O

Excentricity in p-O & *O-O*

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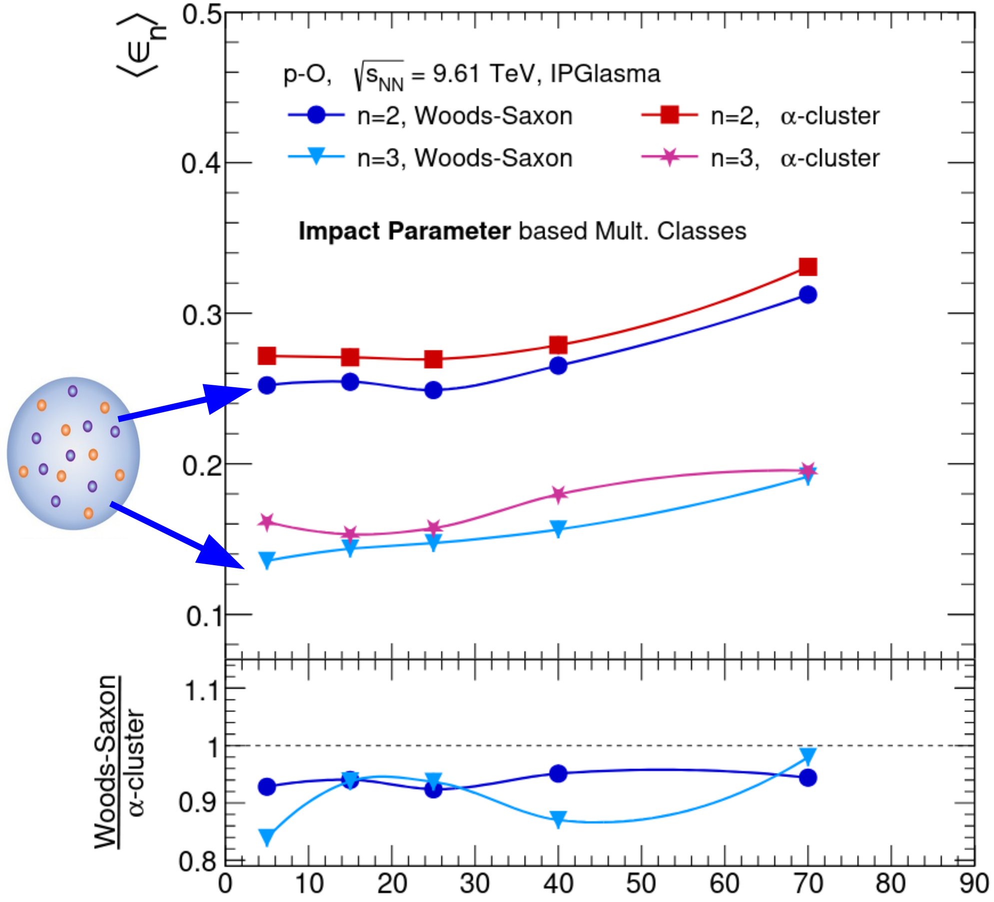
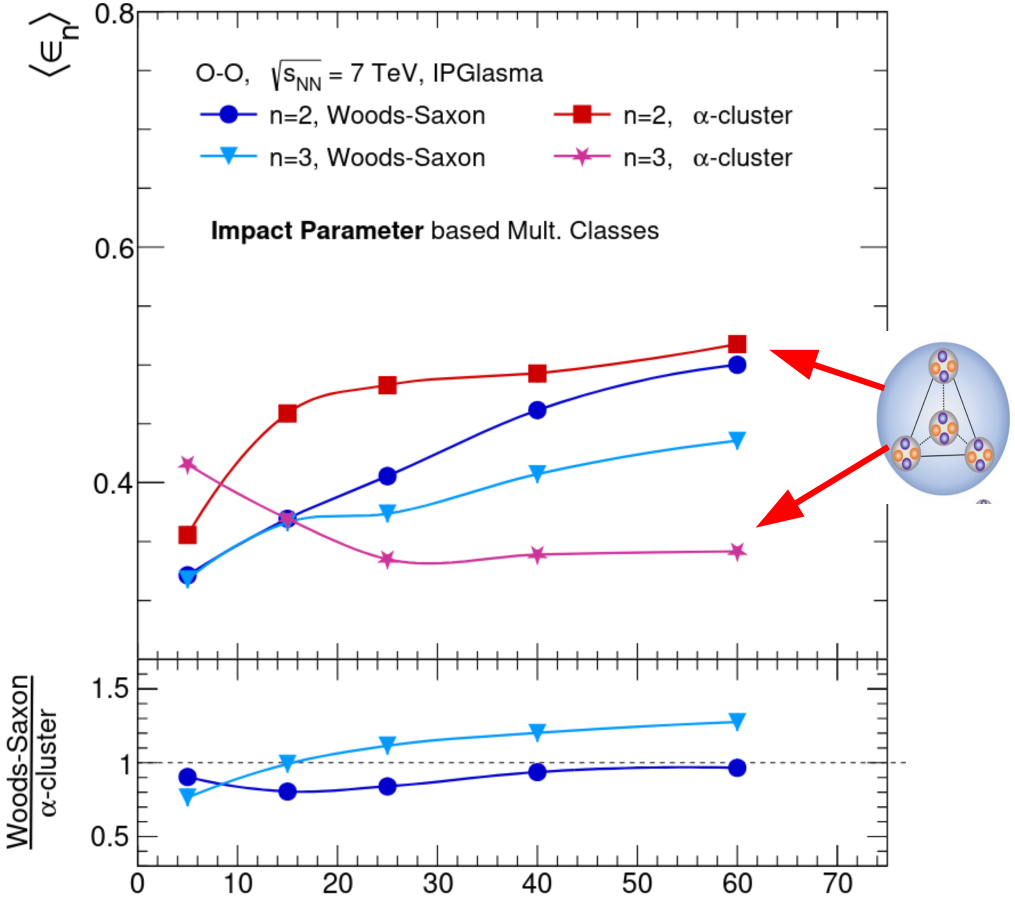




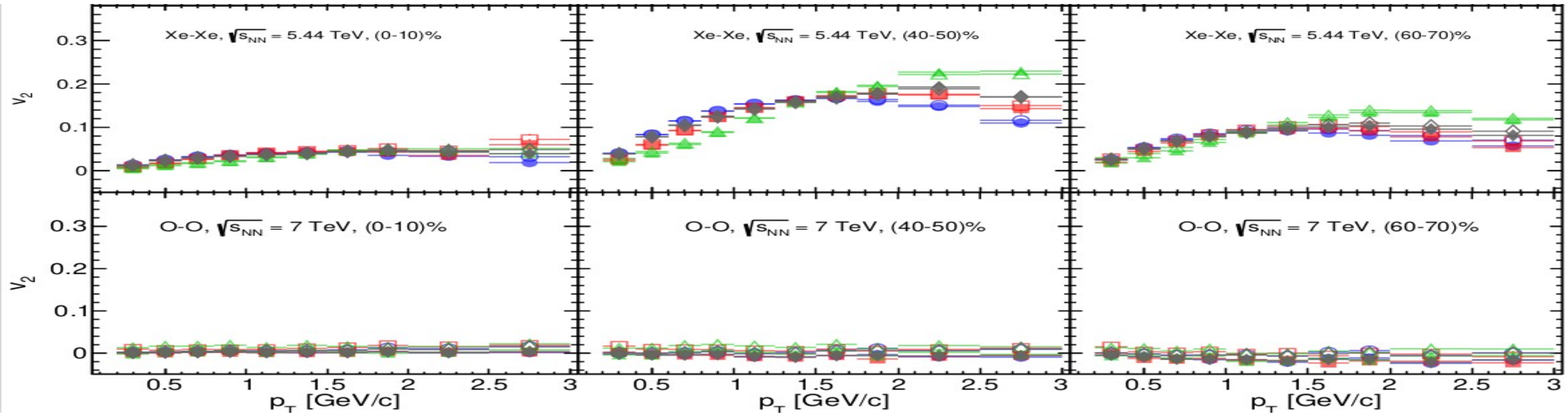
Calculating the flow in small systems

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:

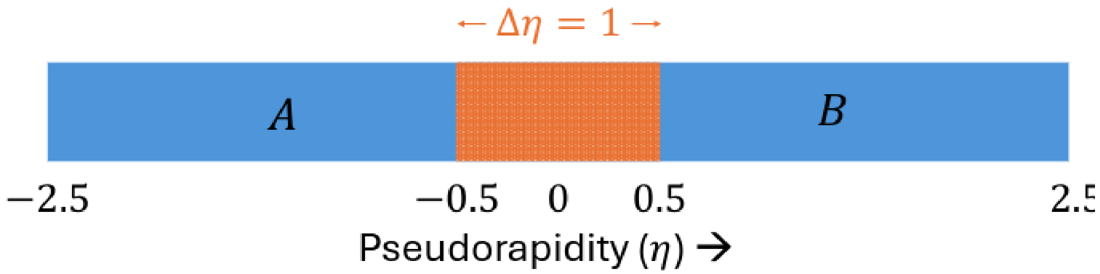
$$\langle 2 \rangle = \frac{|Q_n|^2 - M}{M(M-1)},$$

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

$$\longrightarrow \quad c_n\{2\} = \langle\langle 2 \rangle\rangle, \quad c_n\{4\} = \langle\langle 4 \rangle\rangle - 2 \cdot \langle\langle 2 \rangle\rangle^2 \quad \longrightarrow \quad \boxed{v_n\{2\} = \sqrt{c_n\{2\}}, \quad v_n\{4\} = \sqrt[4]{-c_n\{4\}}}$$

Calculating the flow

Suppressing the non-flow contribution:



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

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

- Differential flow cummulants:

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

- Mean and the fluctuations of the flow & ratio:

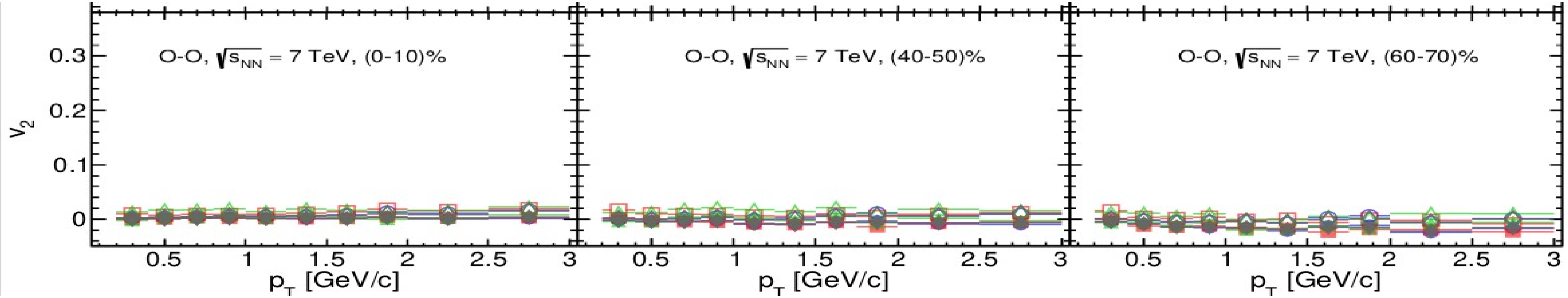
$$\langle v_n \rangle = \sqrt{\frac{v_n^2\{2\} + v_n^2\{4\}}{2}}$$

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

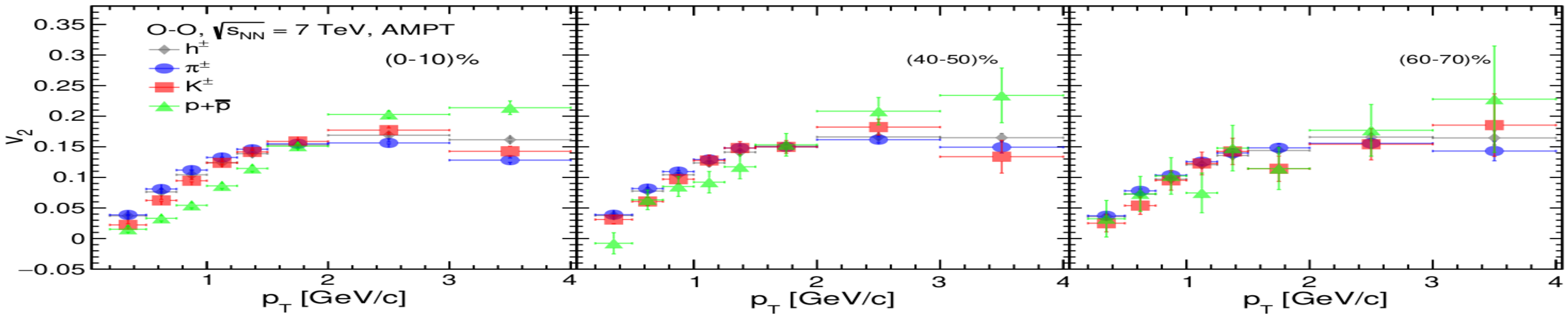
$$\boxed{F(v_n) = \frac{\sigma_{v_n}}{\langle v_n \rangle}}$$

Calculating the flow

Event plane and average method

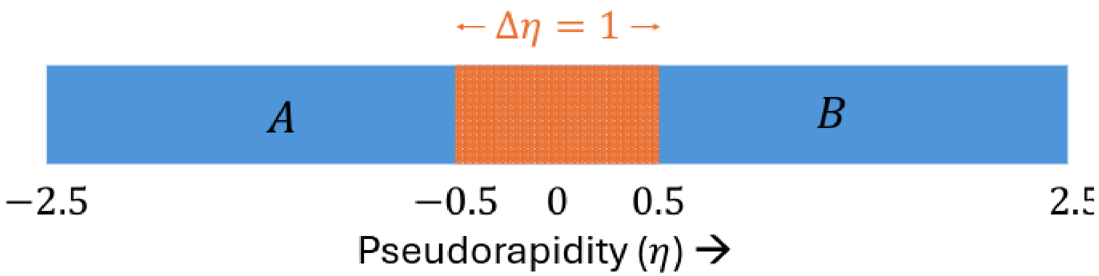


Multiparticle Q-cummulant method



The Model

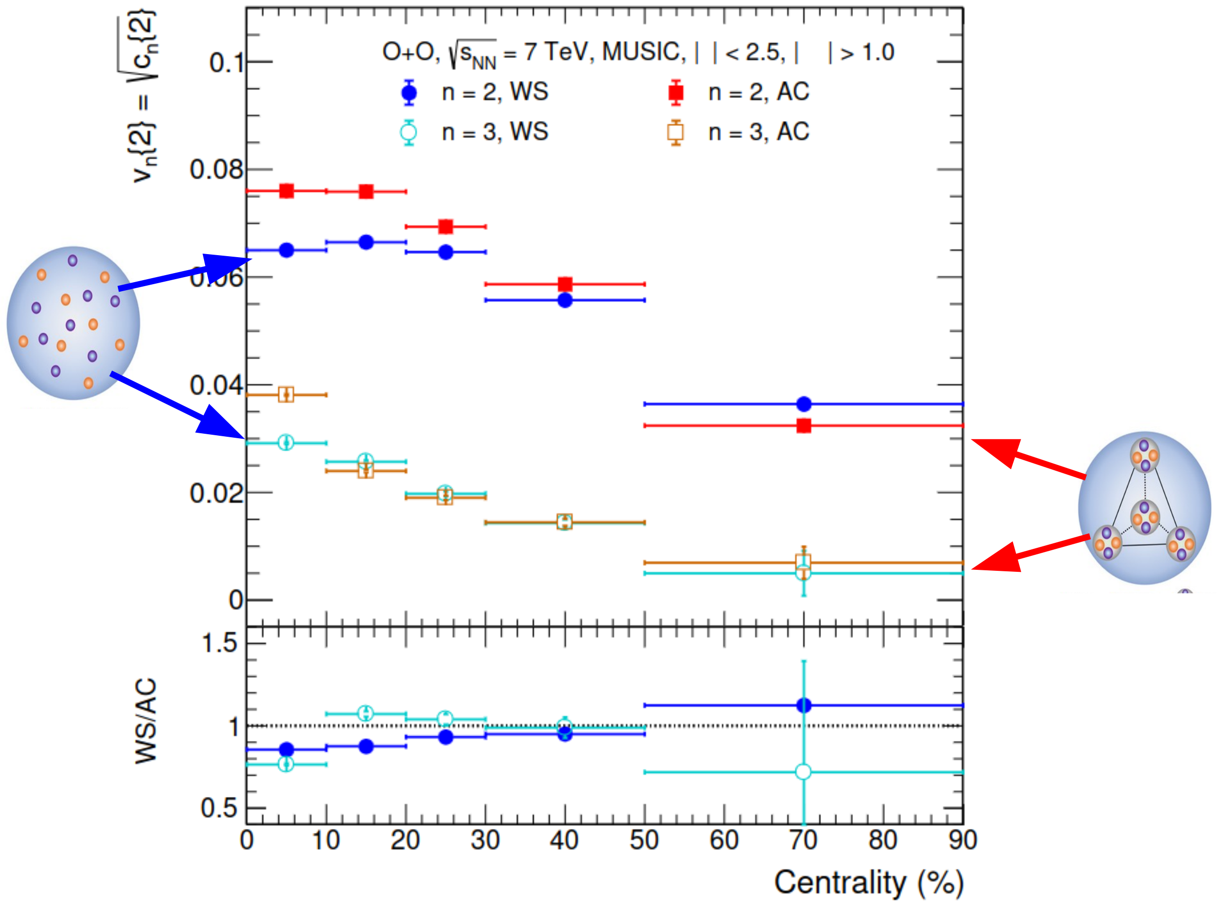
- **A full hidro & Boltzmann transport with viscosity:**
  - IPGlasma
  - MUSIC
  - iSS
  - URQMD
- **Kinematical settings are:**
  - Energy (c.m.): 7 TeV O+O
  - Pseudorapidity: $|\eta| < 2.5$
  - Transverse momentum: $0.2 < p_{\mathrm{T}} < 5.0\ \mathrm{GeV}/c$
  - Pseudorapidity gap: $|\Delta\eta|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



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

Flow components in O-O @ 7TeV

2-cummulants based calculation of v_2 & v_3



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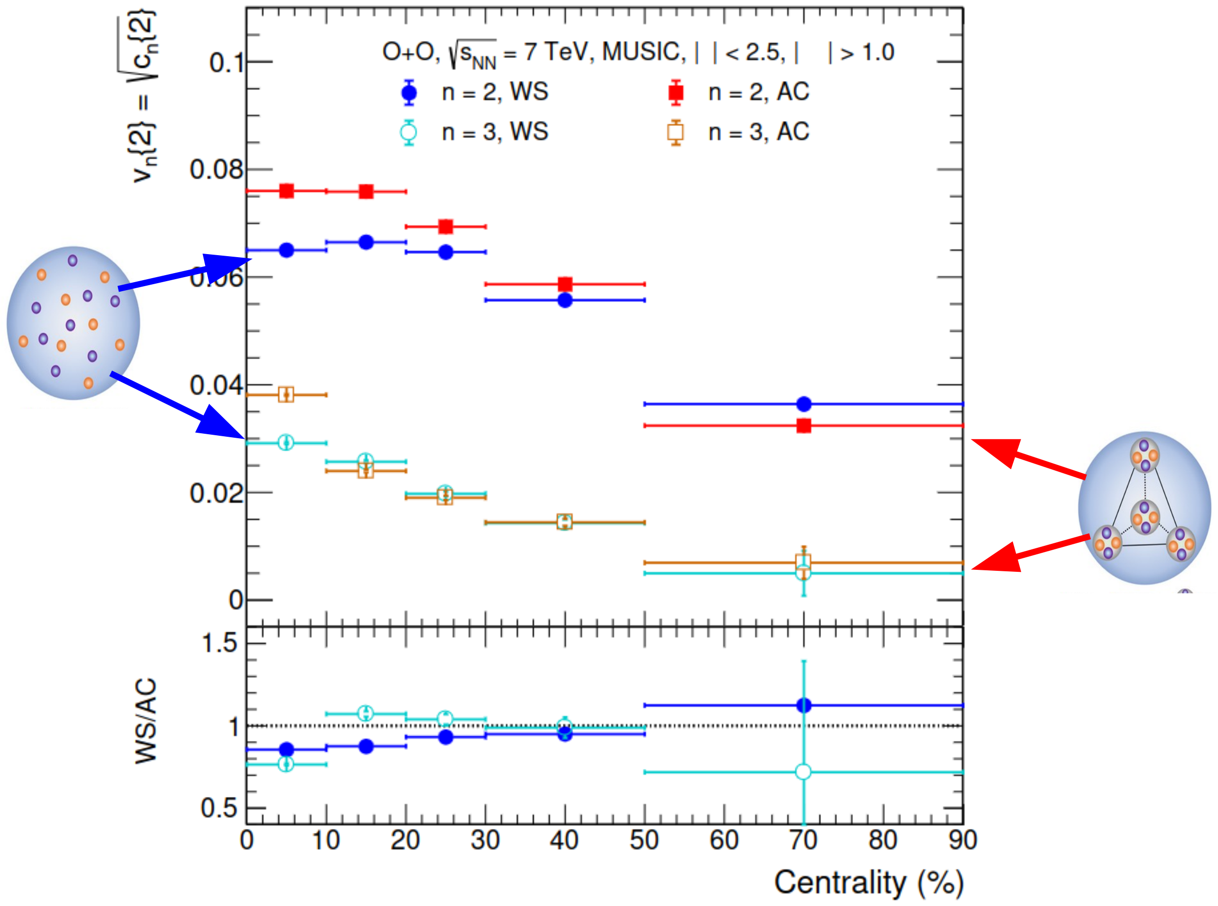
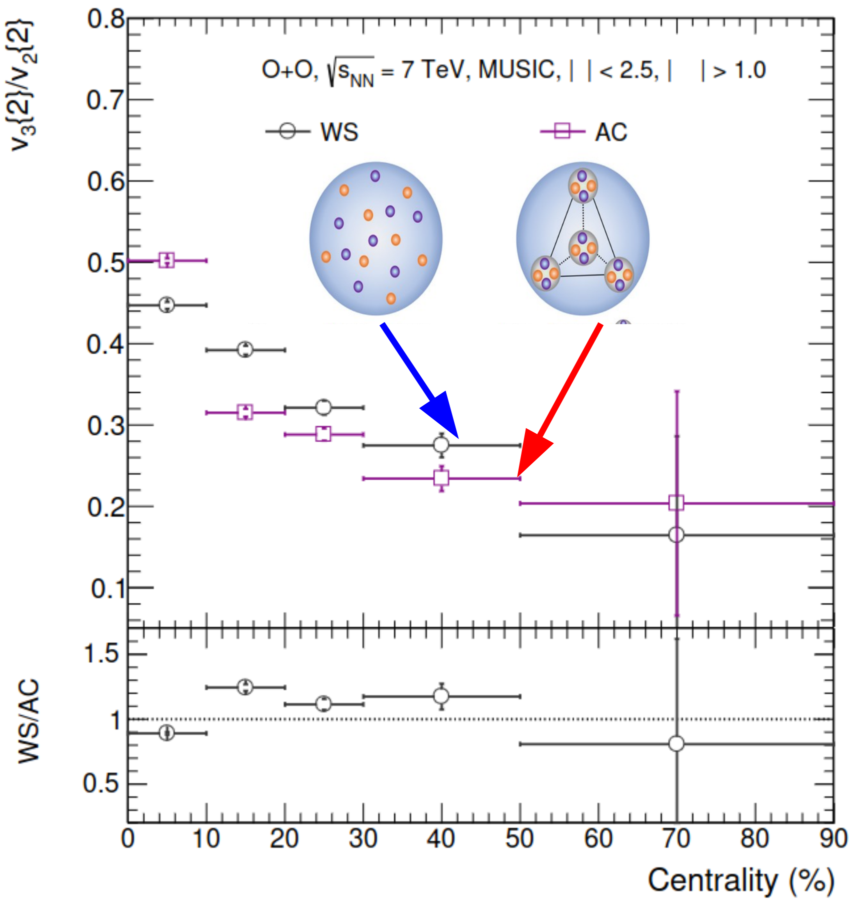
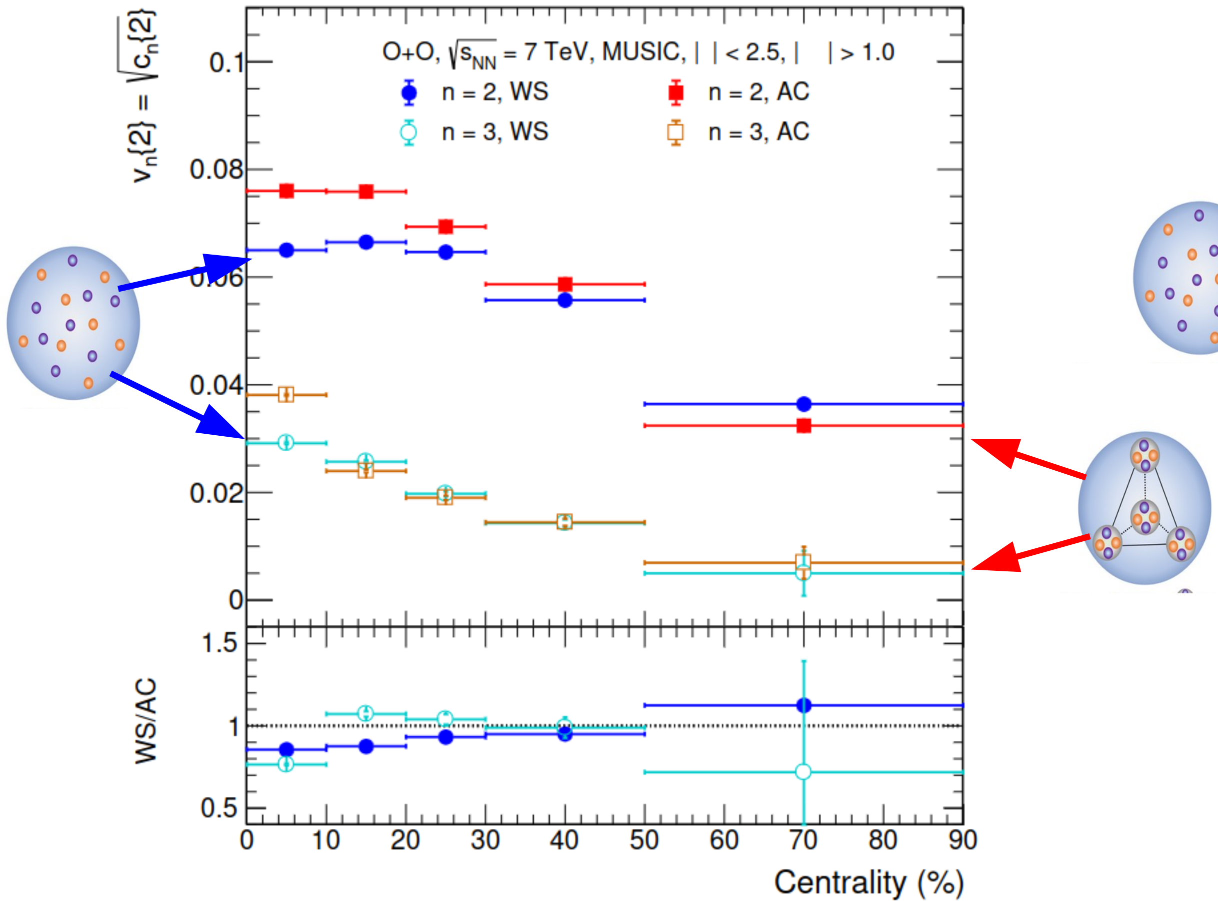
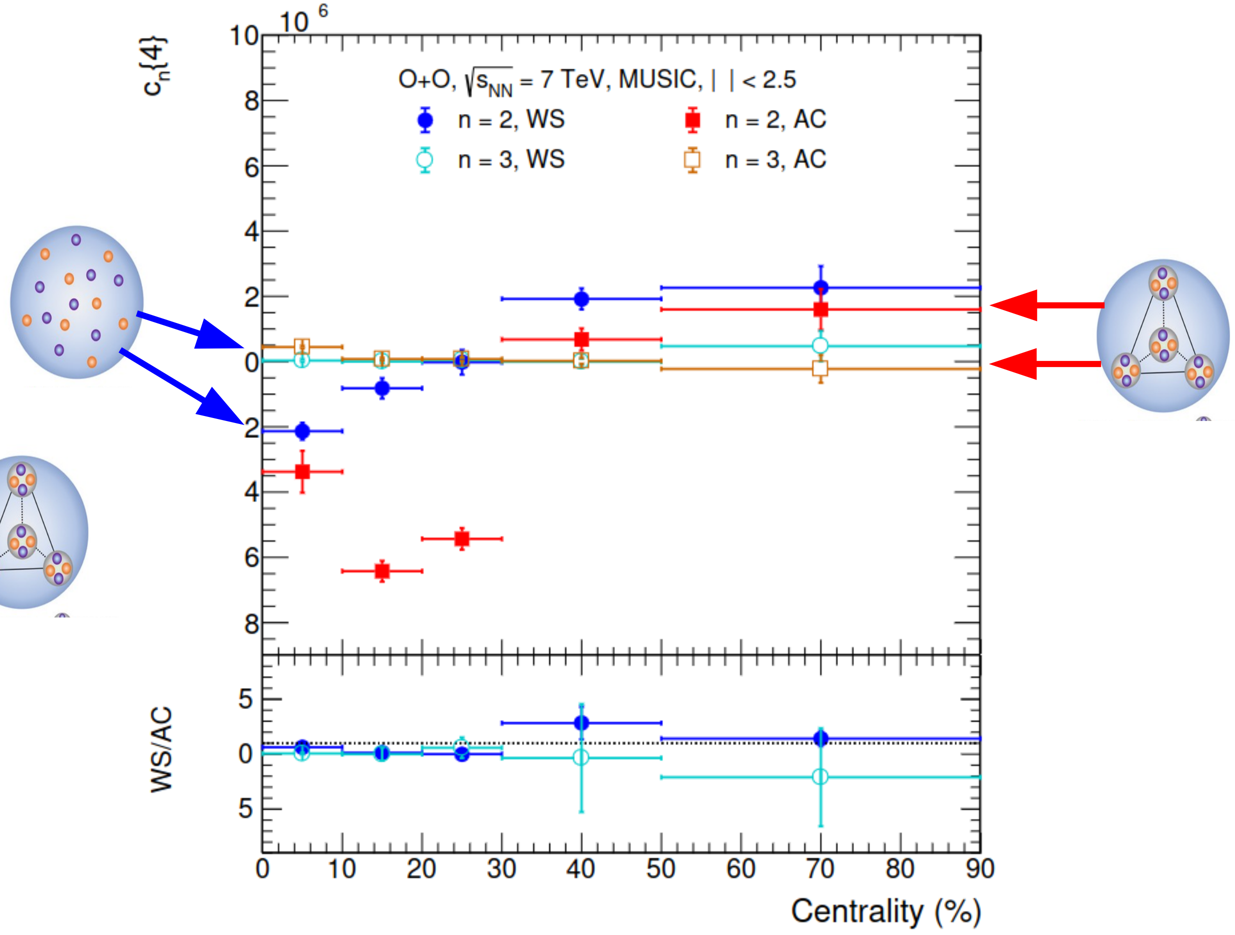




Flow components in O-O @ 7TeV

2- & 4-cummulants based v_n & c_n calculations





Flow components in O-O @ 7TeV

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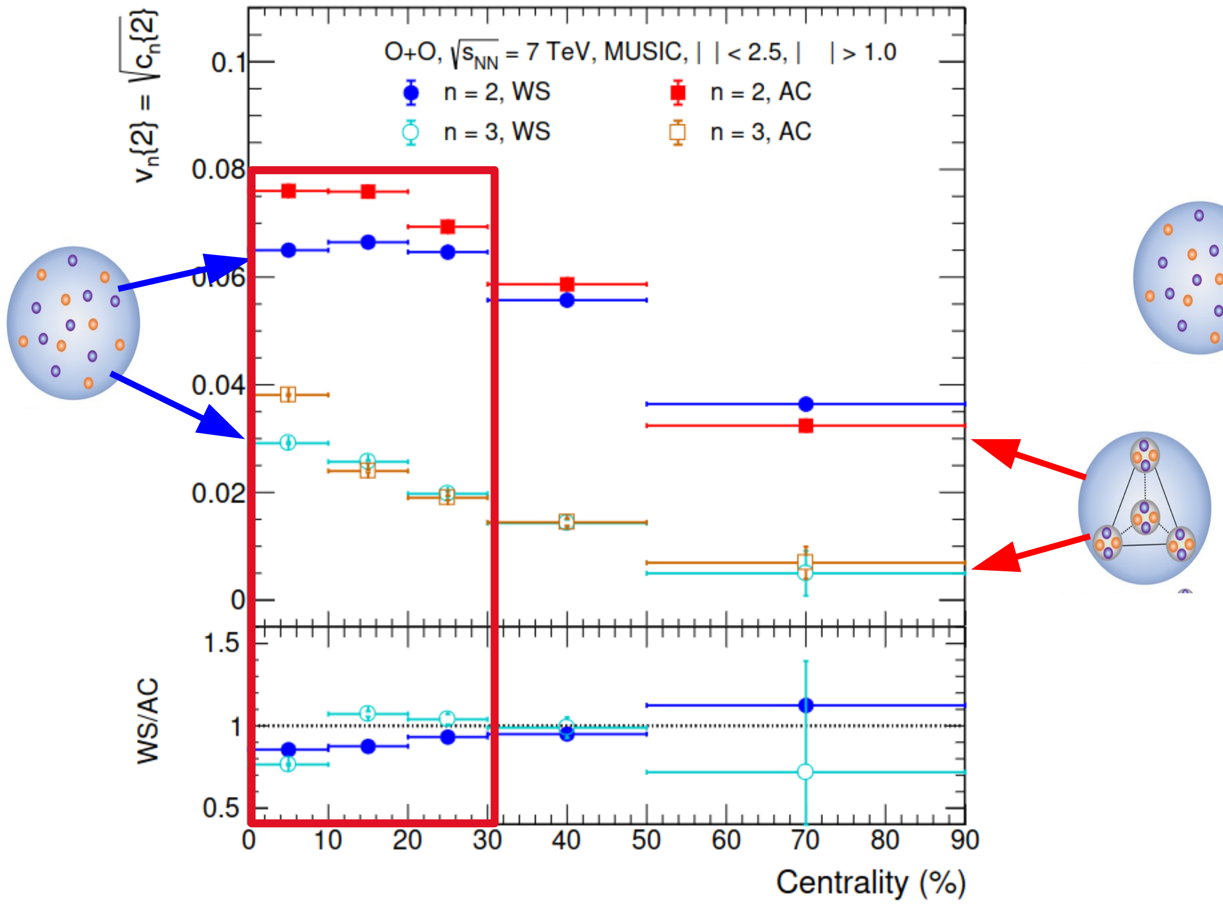
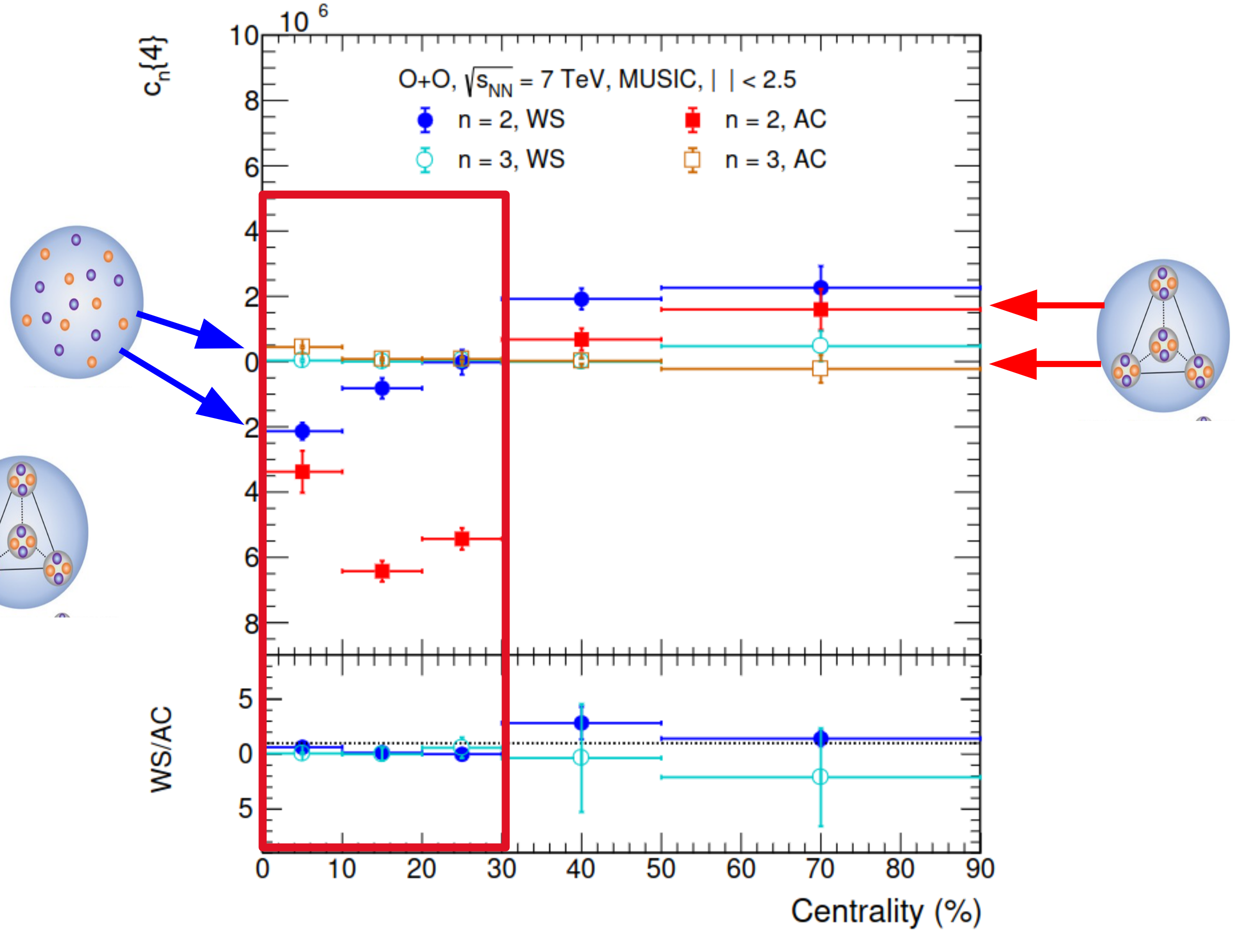
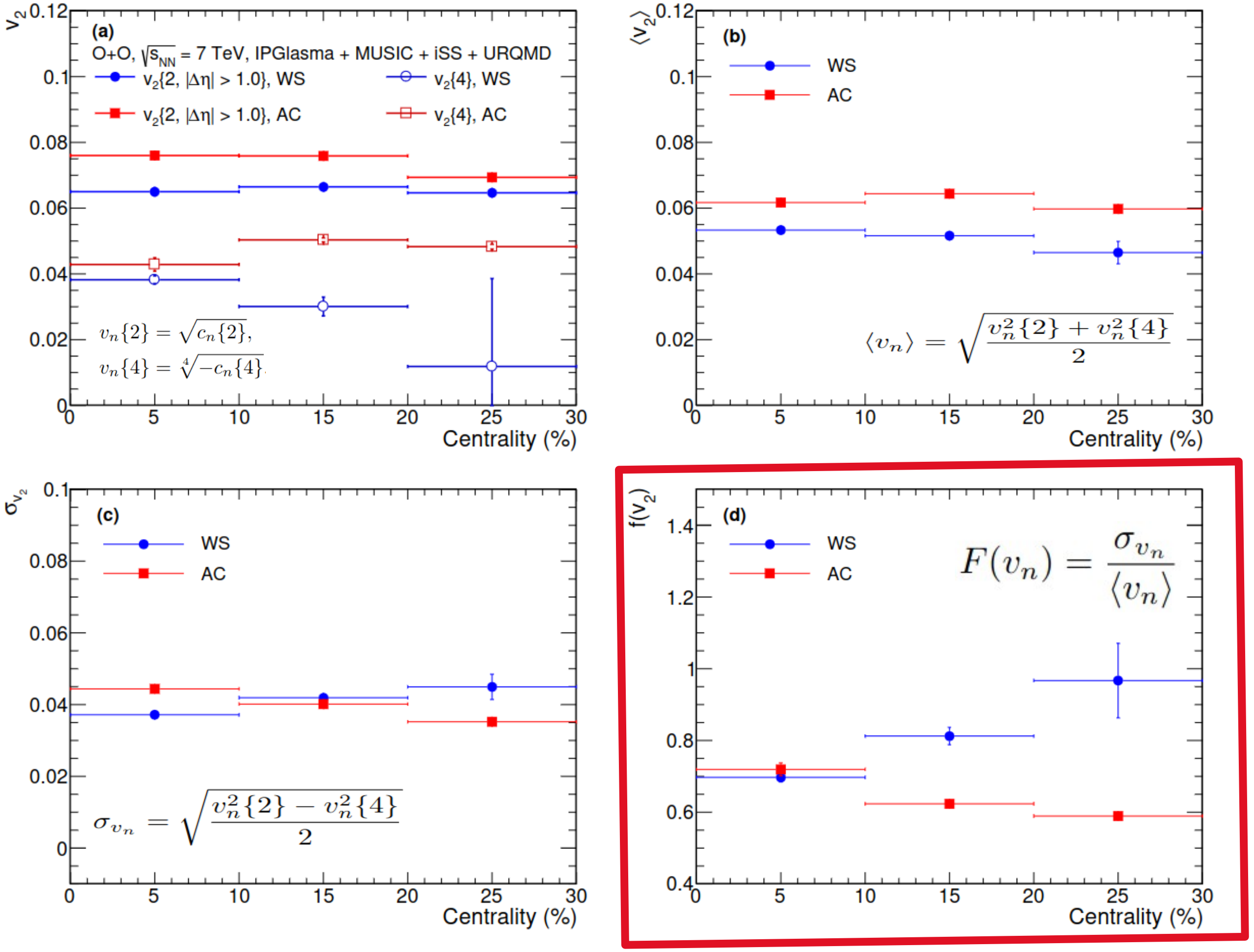




Flow components in O-O @ 7TeV

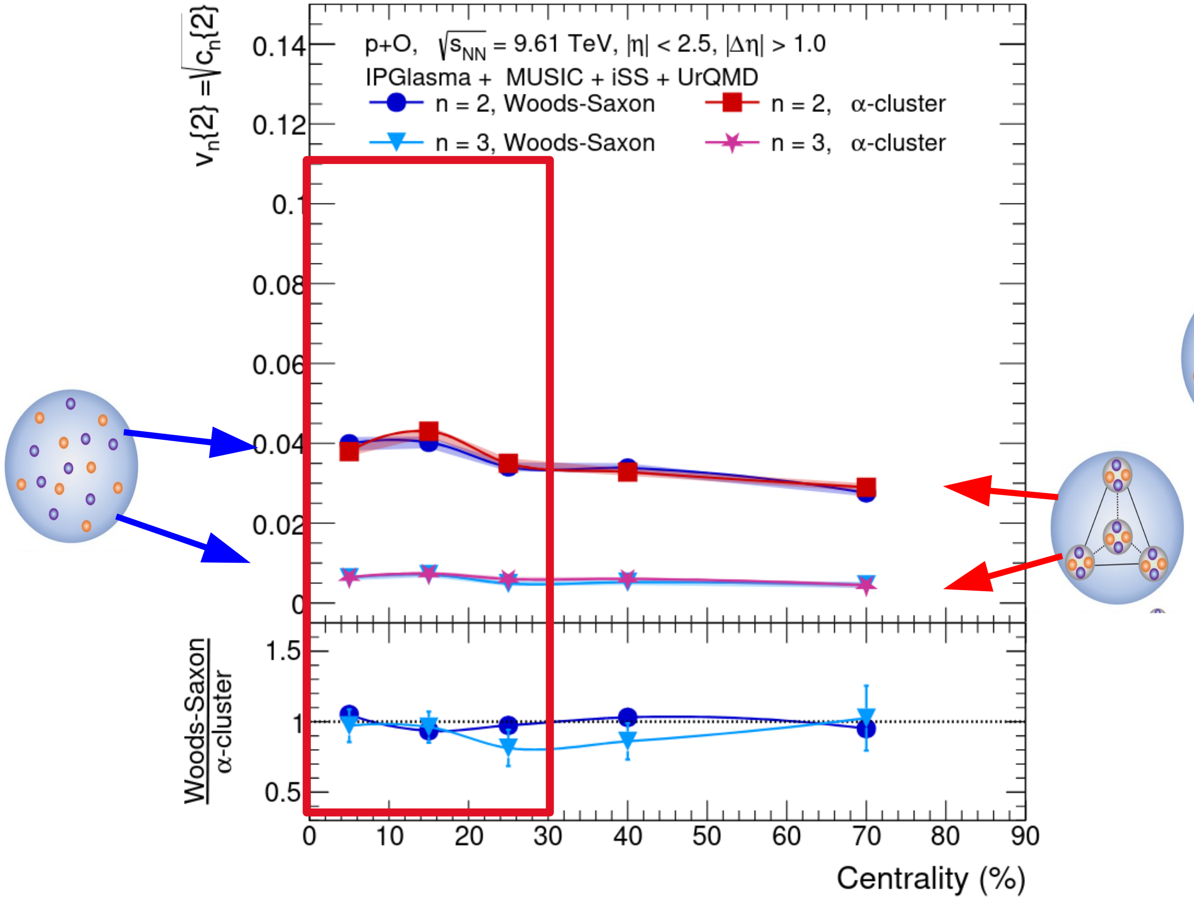
2- & 4-cummulants based calculations

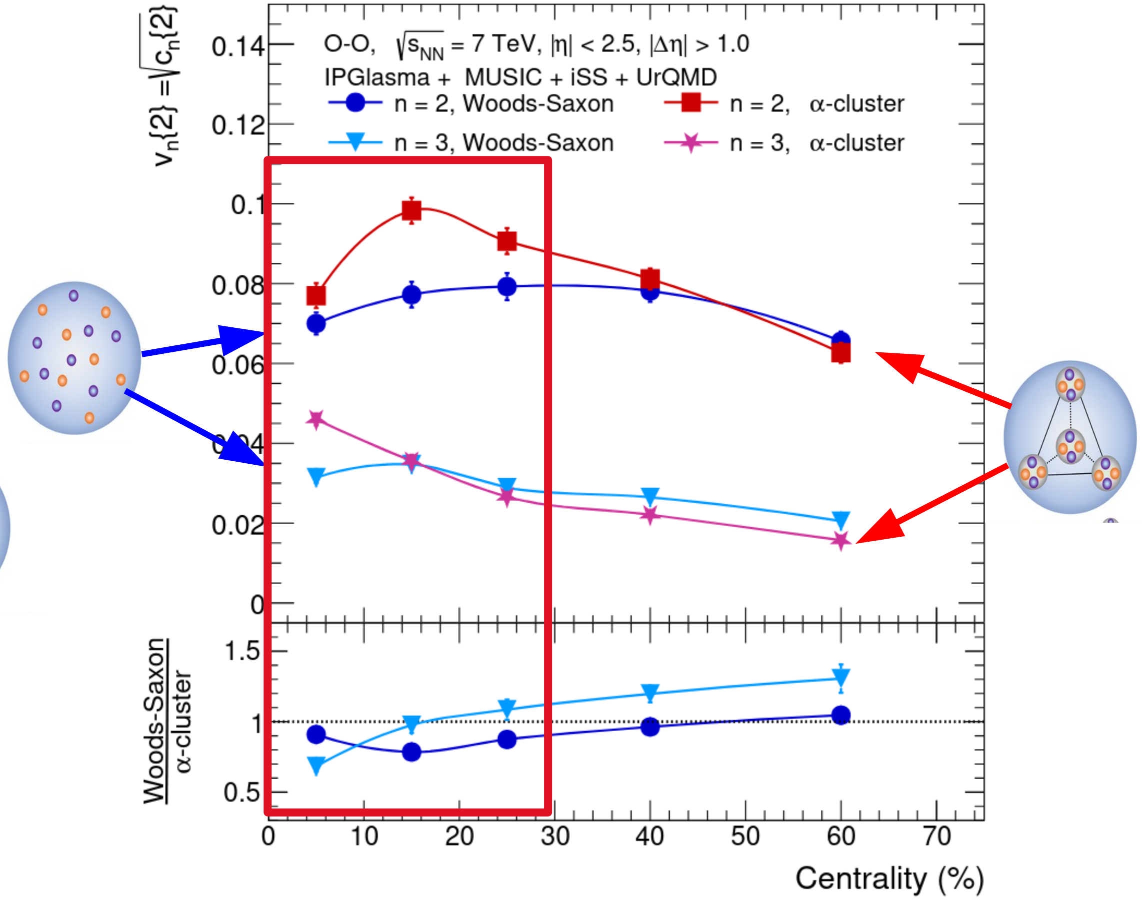
- Flow and fluctuation measures changed significantly in the most central 0-30% regime
- Alpha-cluster has larger values, than Wood-Saxon profile
- Higher cummulants has higher effect at larger centrality
- Clearly visible on the relative measure: $$F(v_n) = \frac{\sigma_{v_n}}{\langle v_n \rangle}$$



Flow components in p-O @ 9.61TeV

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





Some answers…

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!

- **validate nuclear structure models in June 2025 at the LHC?**

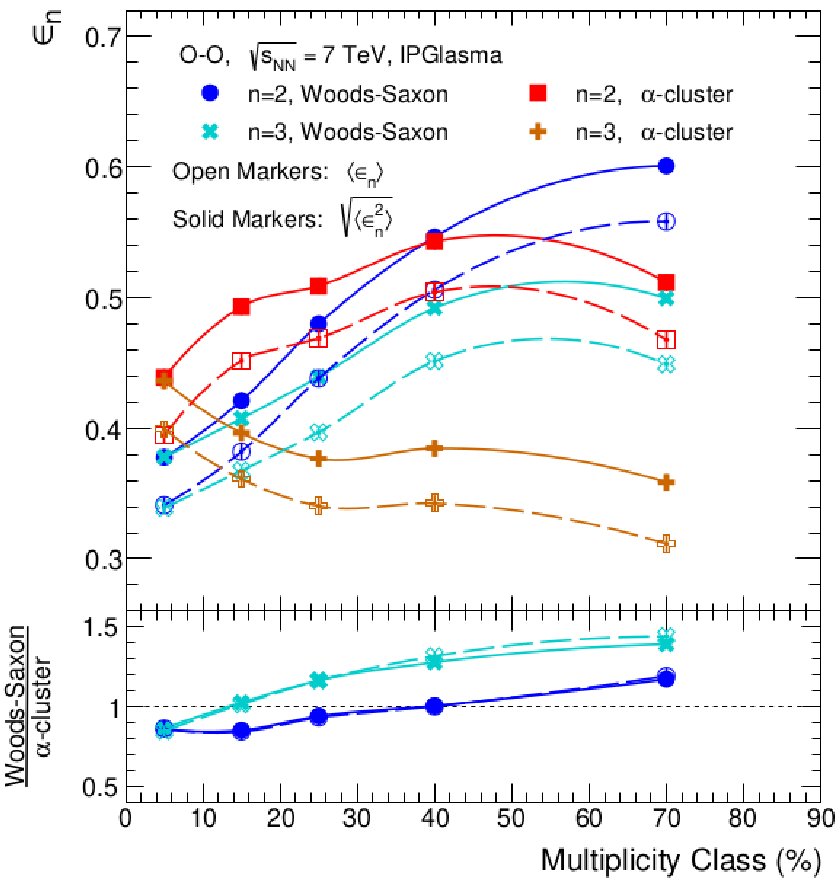
To take away…

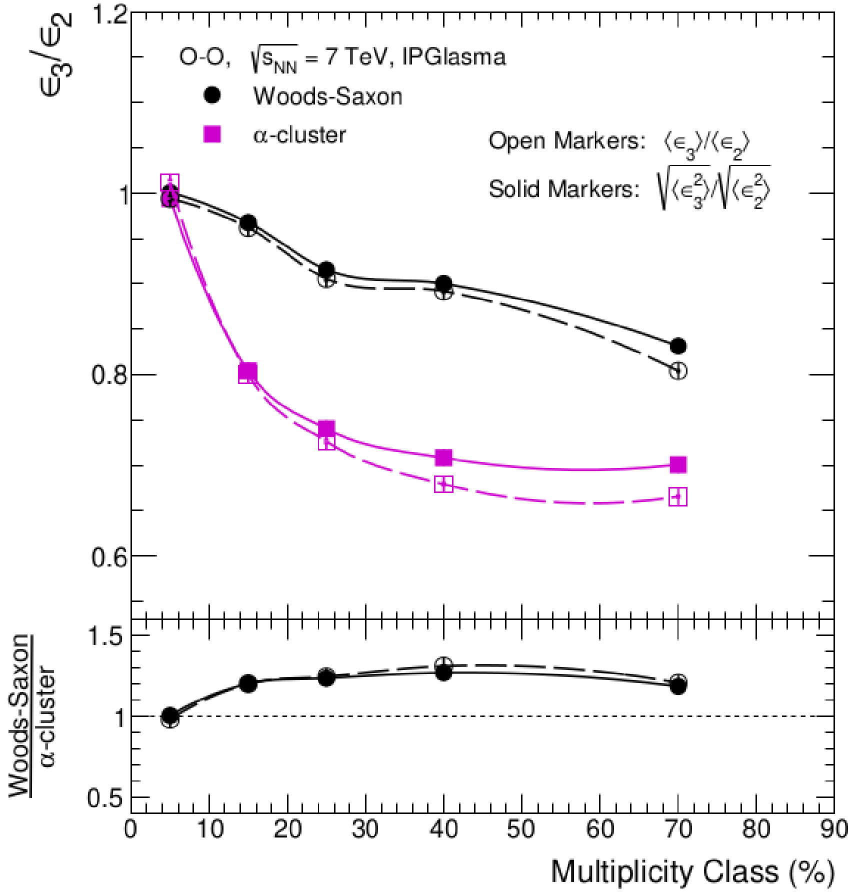
Yes, we can measure this remarkable effect in O-O and a smaller in p-O collisions, so nuclear structure models can be validated at TeV energy at the LHC!

Thank You!

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