Anisotropic flow fluctuation as a possible signature of clustered nuclear geometry in O-O collisions at the Large Hadron Collider

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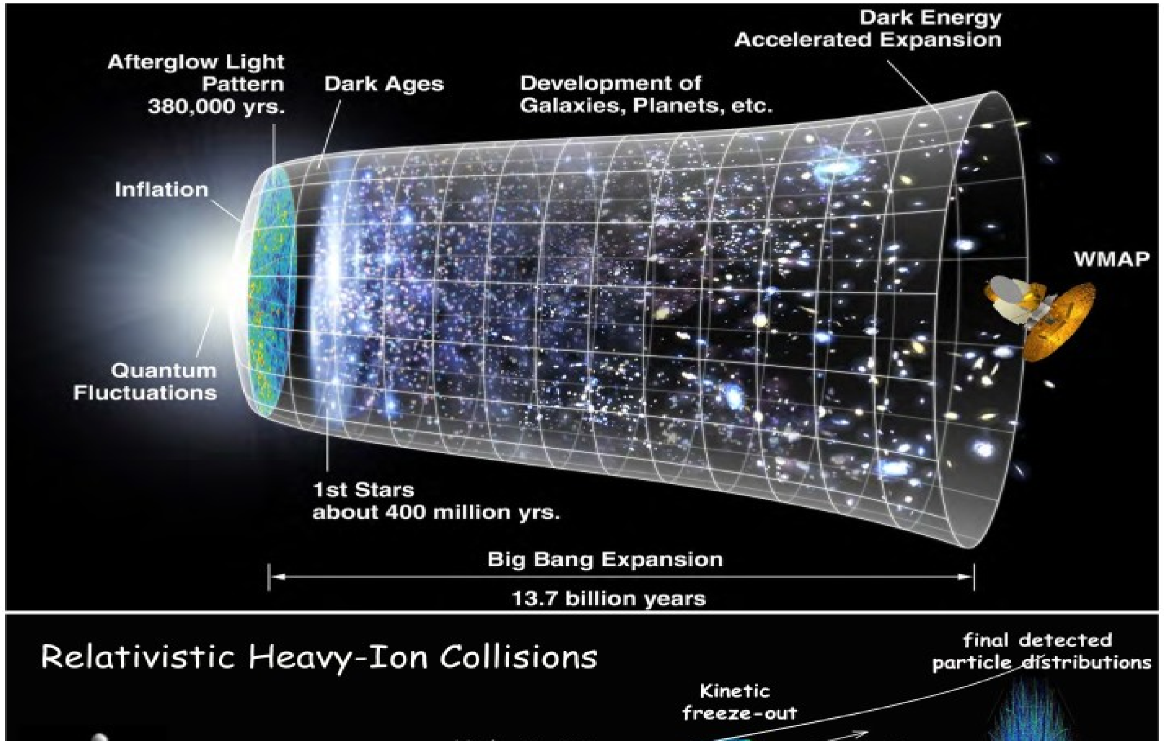
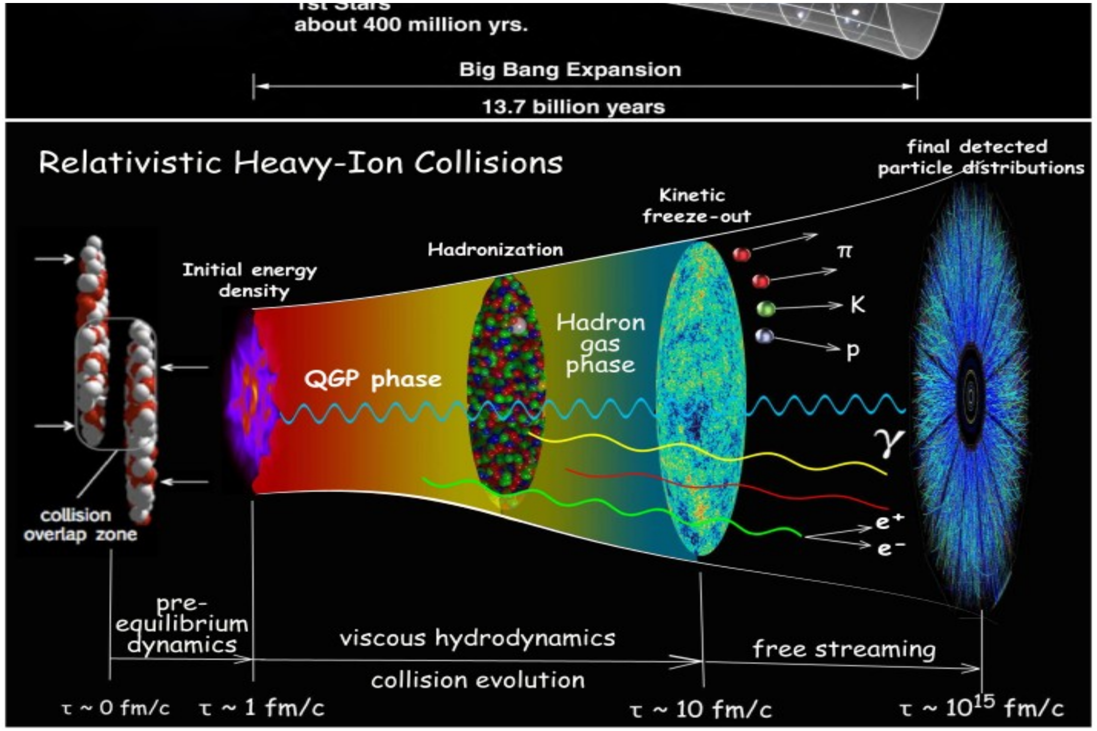
Motivation & definitions

Primordial matter in heavy-ion collisions

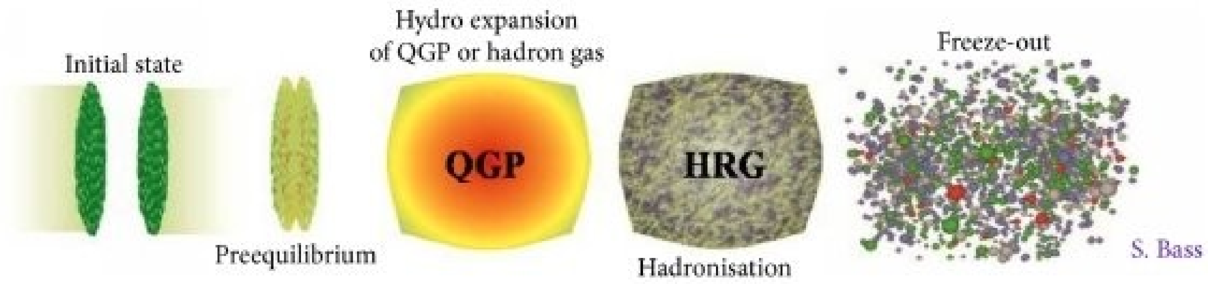
- **Quark-Gluon Plasma (QGP) research**

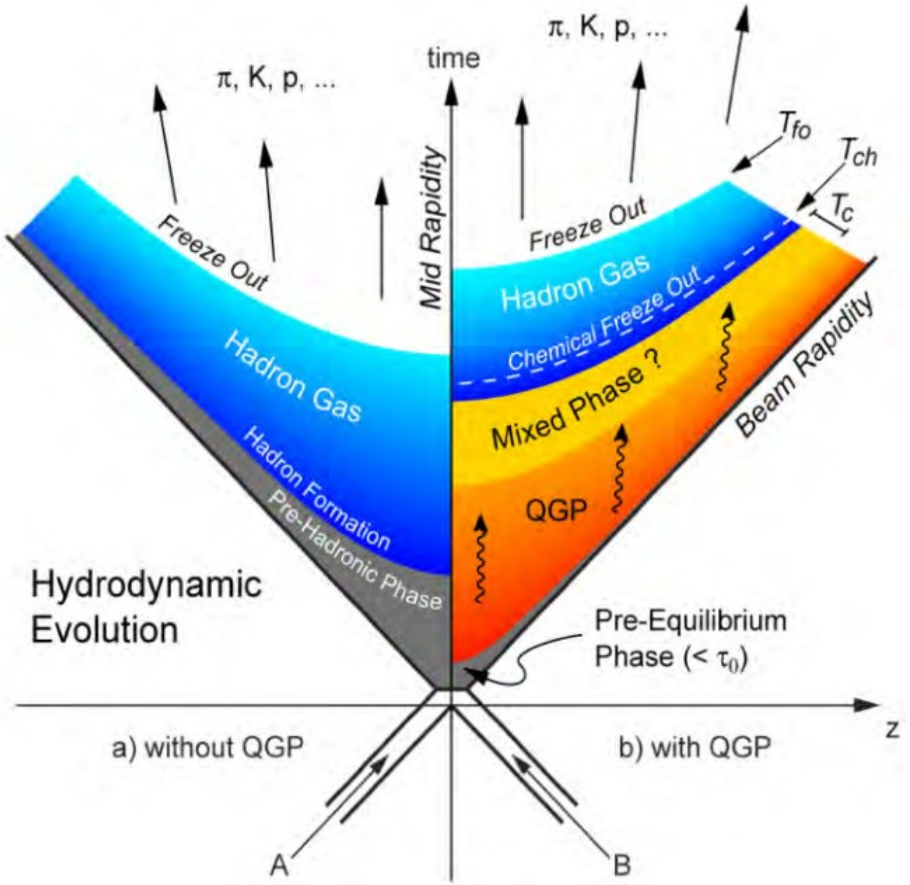




Primordial matter in heavy-ion collisions

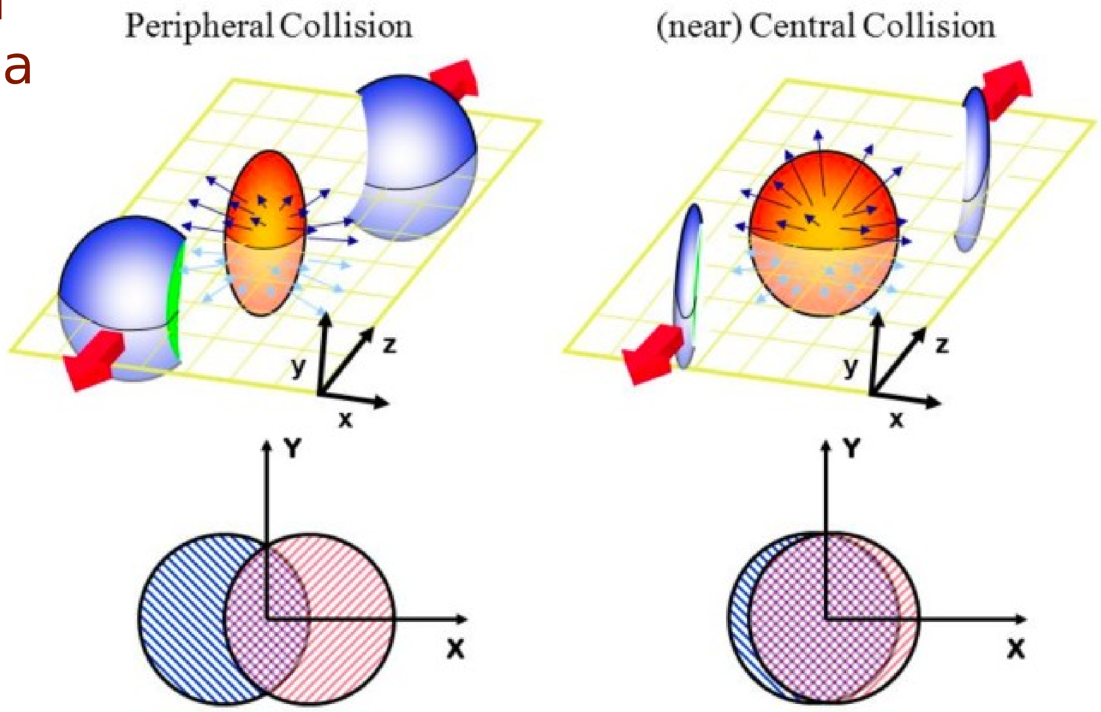
- **QGP in experimental vs theory points**
  - By colliding heavy-ions we can form small drop of the hot & dense primordial matter
  - No direct observations, just **signatures:** jet-quenching, correlations, collective effects, (**anisotropic) flow**…
  - Need a complex description, including QCD phenomenology,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





Flow (v_n) in heavy-ion collisions

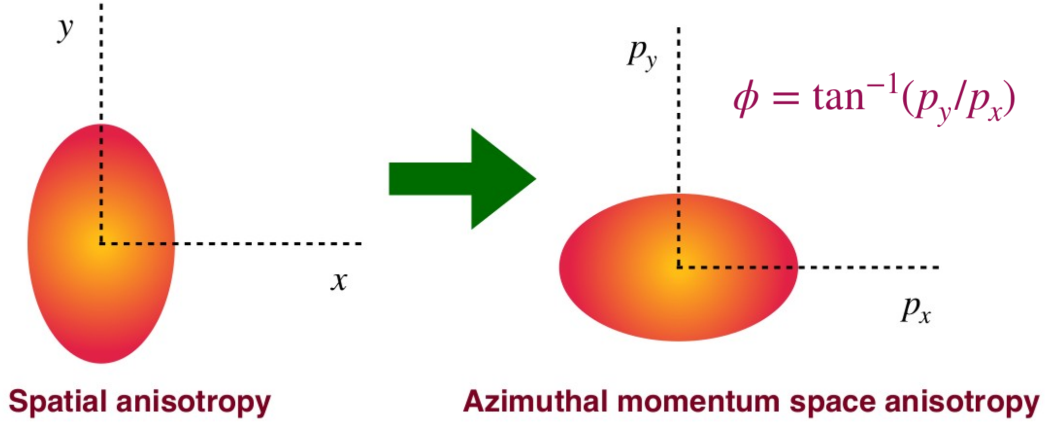
- **Experimental point:**
  - Flow describes the azimuthal momentum space anisotropy of particle emission for a non-central heavy-ion collision.



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:

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

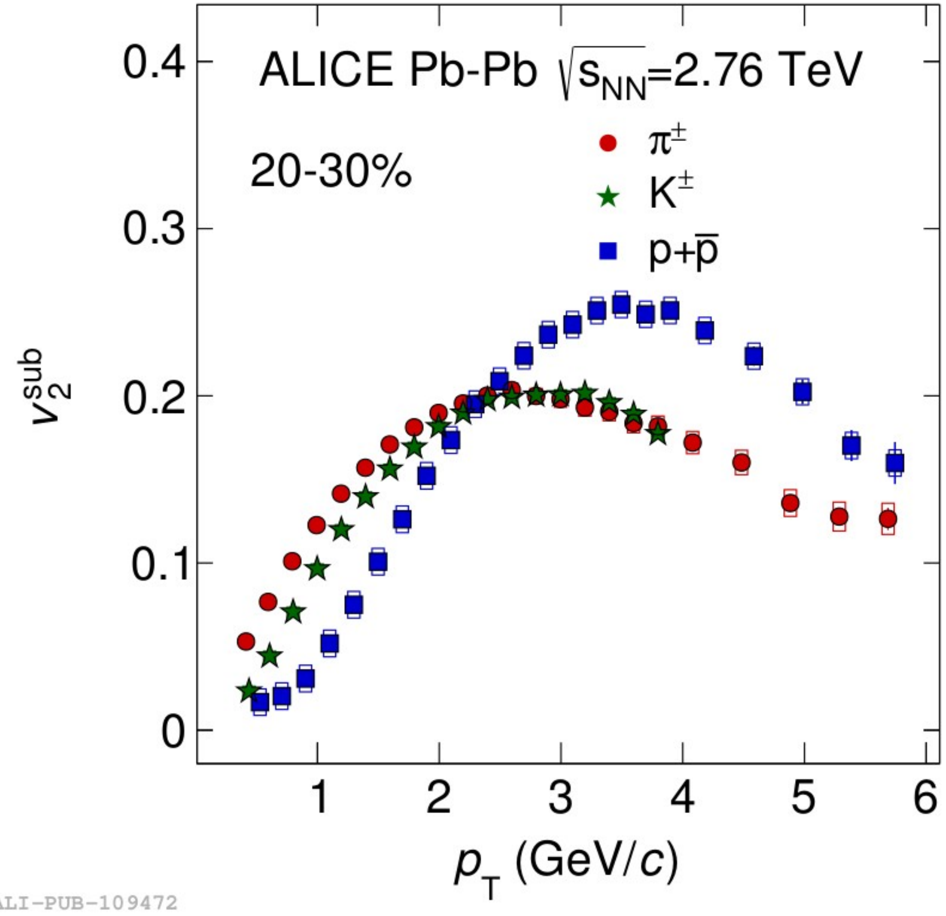


Flow (v_n) in heavy-ion collisions

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

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

  - 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.

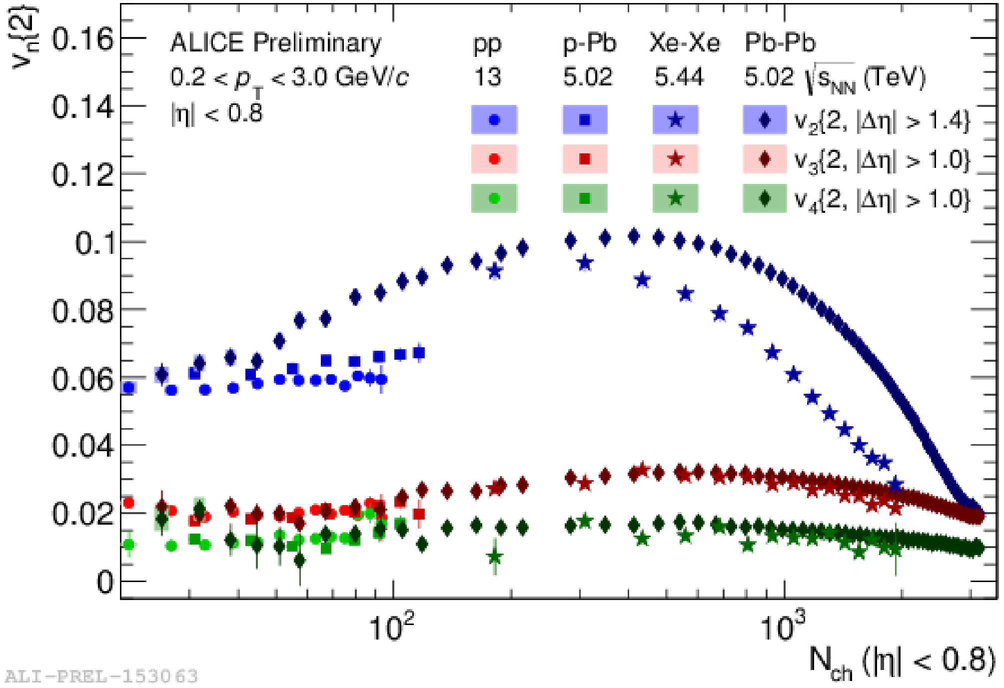


Flow (v_n) in heavy-ion collisions

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

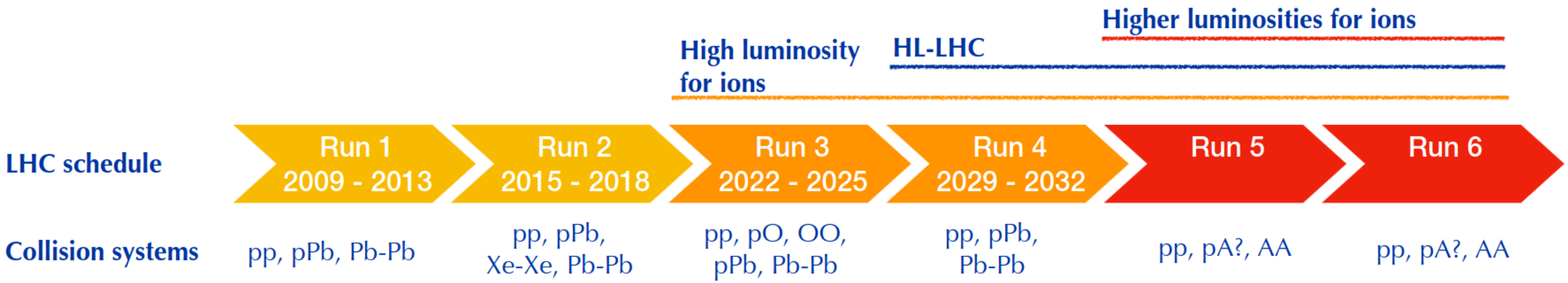
$$E\frac{d^3N}{dp^3} = \frac{d^2N}{p_T dp_T dy}\frac{1}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \psi_n)]\right)$$

  - 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: XeXe
  - Run 3: pO & OO



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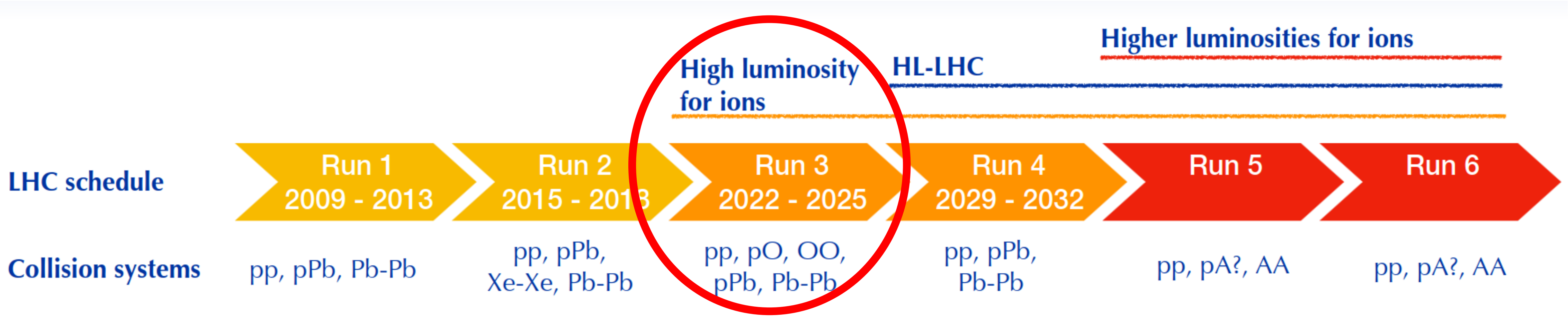
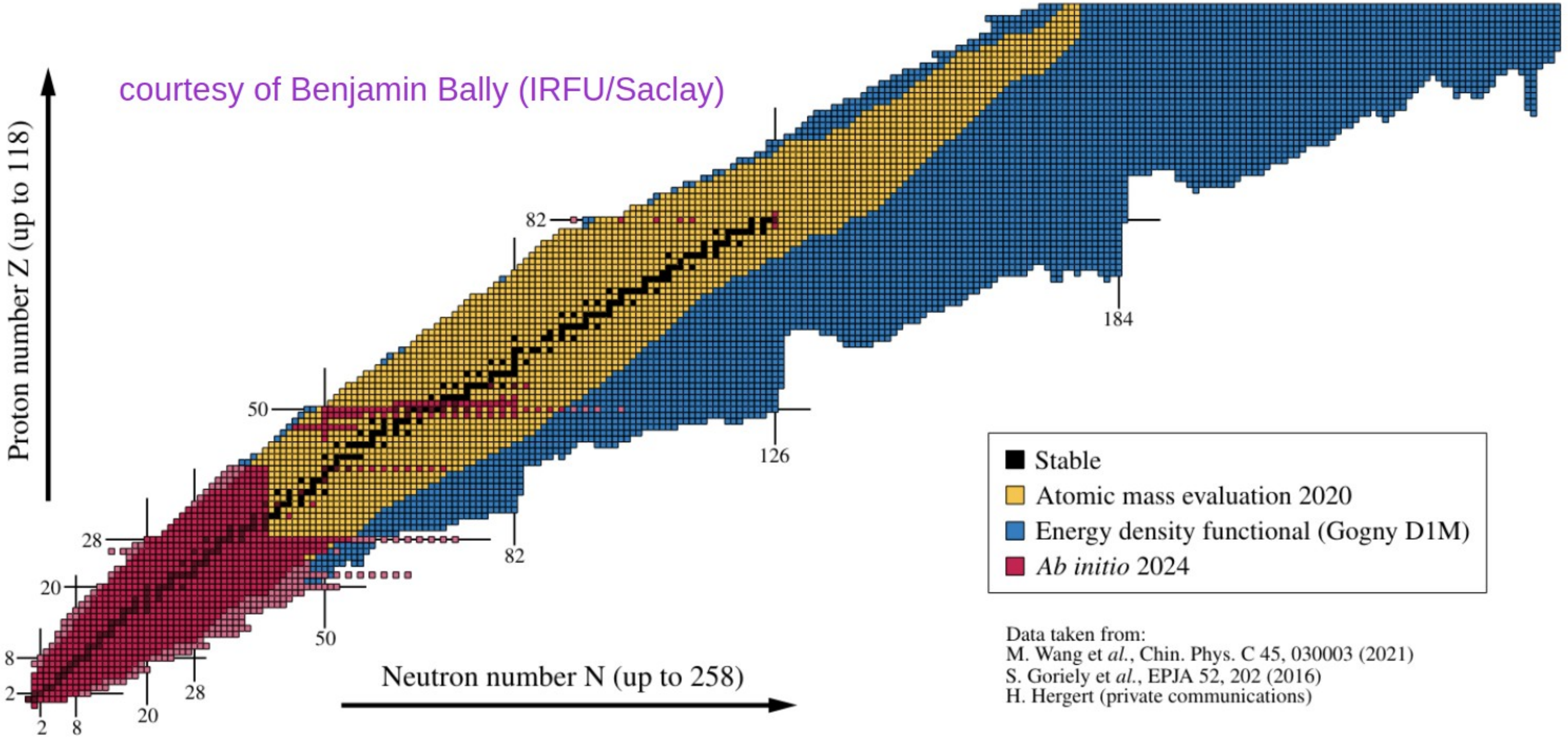


Nuclei & nuclear structure

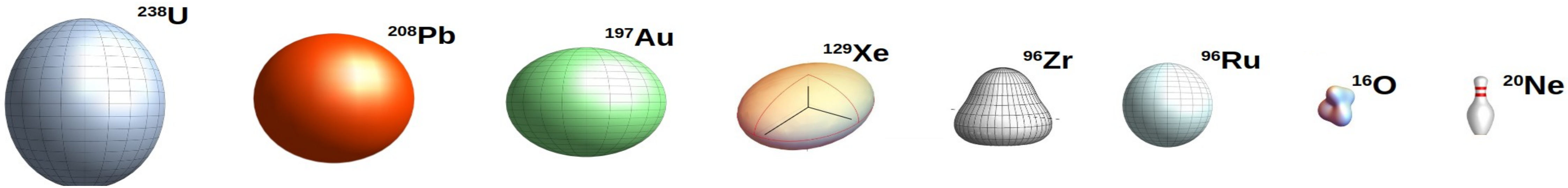
Nuclei for Future Nuclear Collisions

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



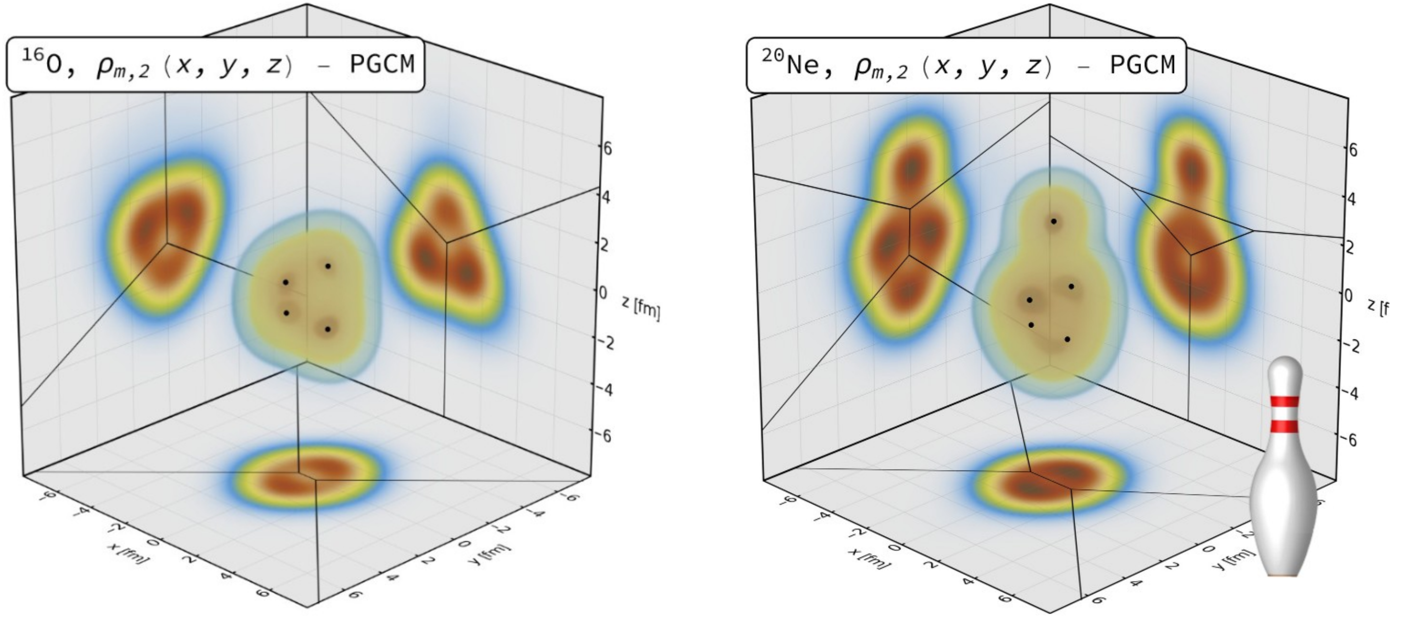
Nuclei for Future Nuclear Collisions

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



Nuclei for Future Nuclear Collisions

- **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)**

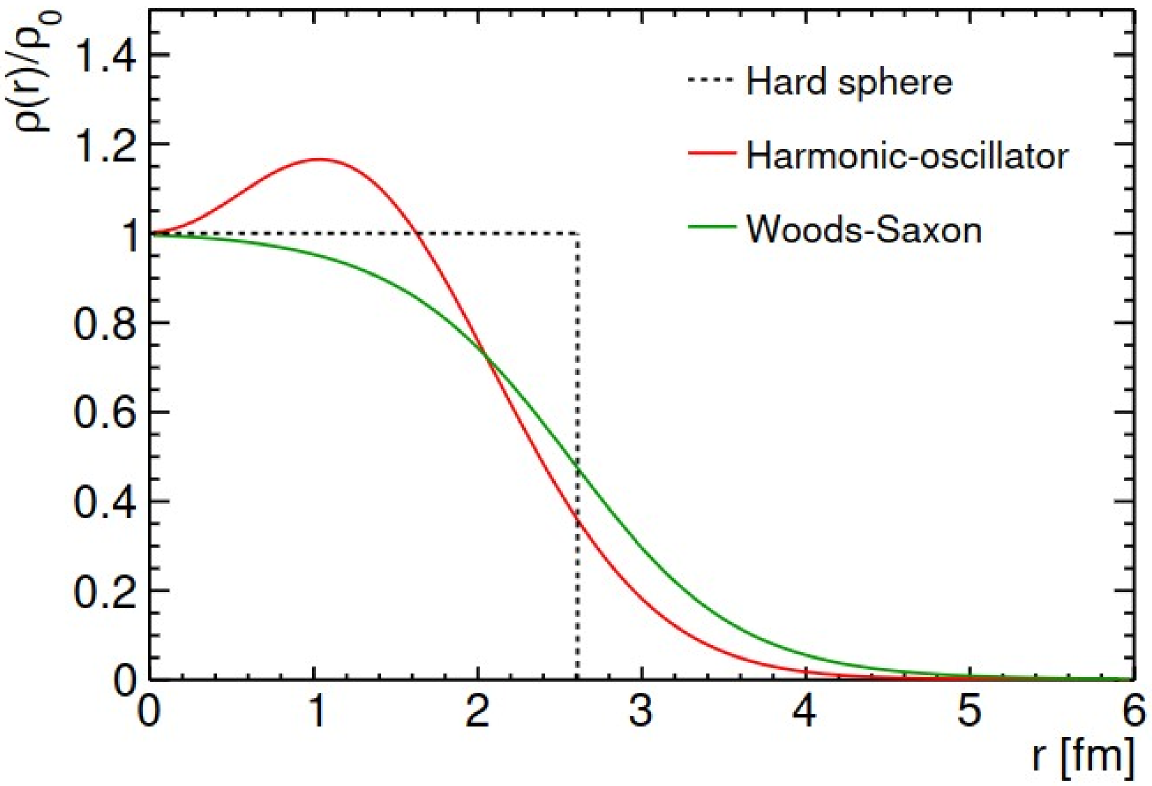
$$\rho(r) = \rho_0 \left[1 + \alpha\left(\frac{r}{a}\right)^2\right] \exp\left(\frac{-r^2}{a^2}\right)$$

- **Harmonic oscillator (HO)**

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

- Normalization:

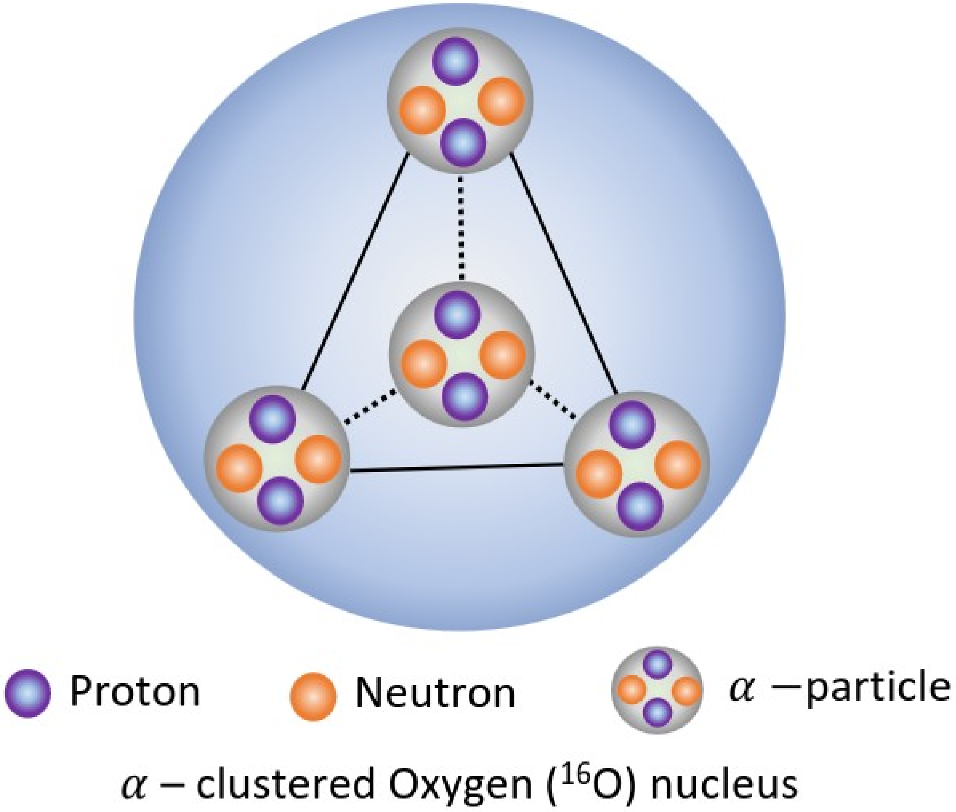
$$\int \rho(r) d^3 r = 4\pi \int \rho(r) r^2 dr = Ze$$

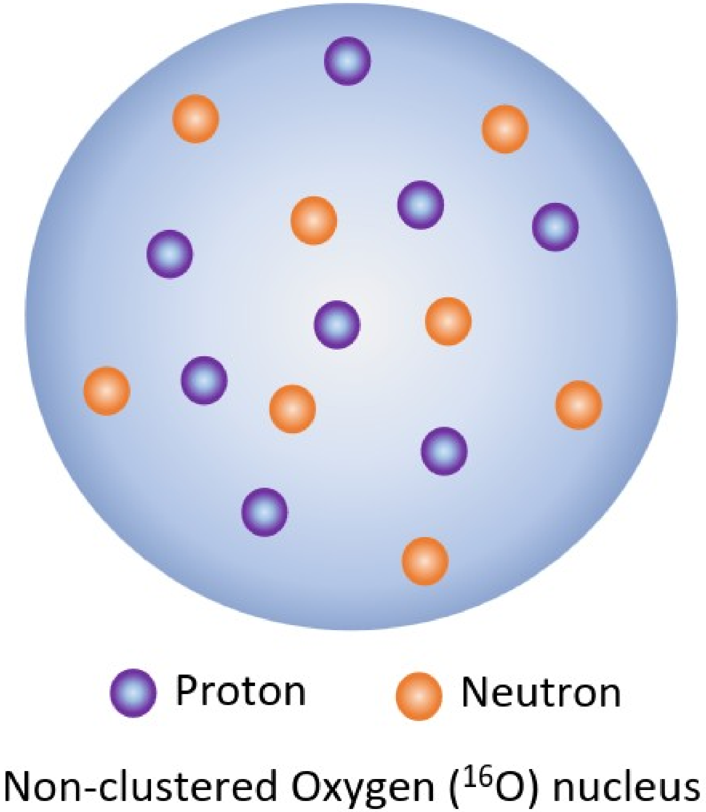


The shape of the oxygen

Nuclear structure description

– **Cluster model vs.** **Non-cluster model (Woods-Saxon)**

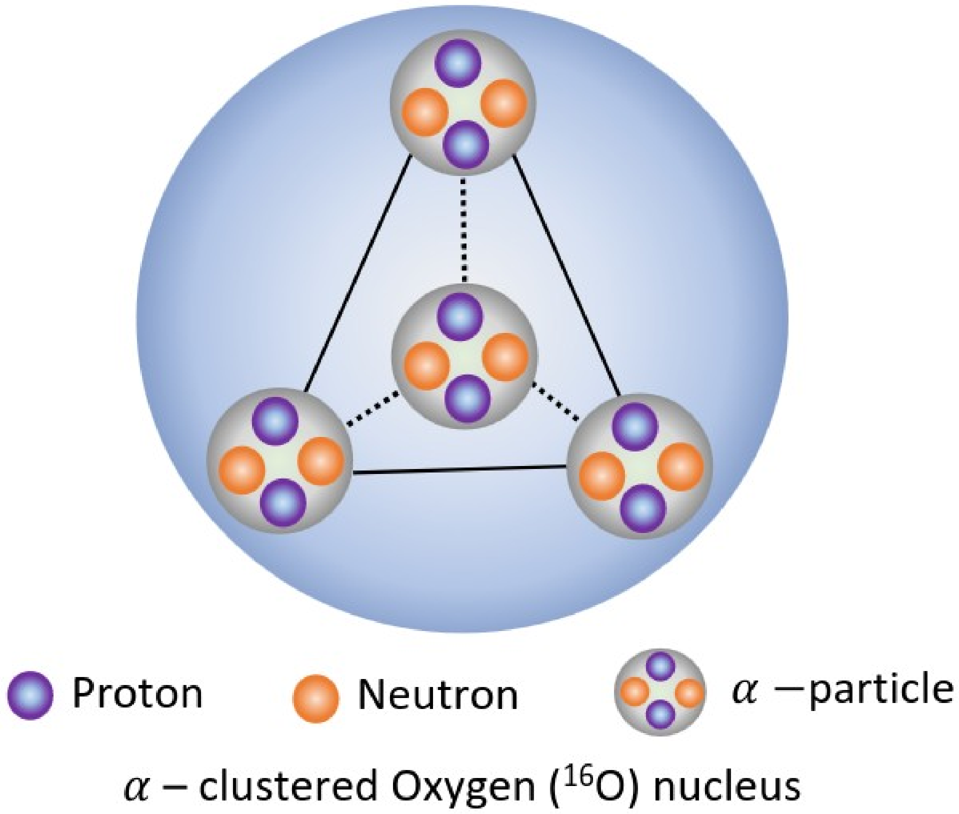




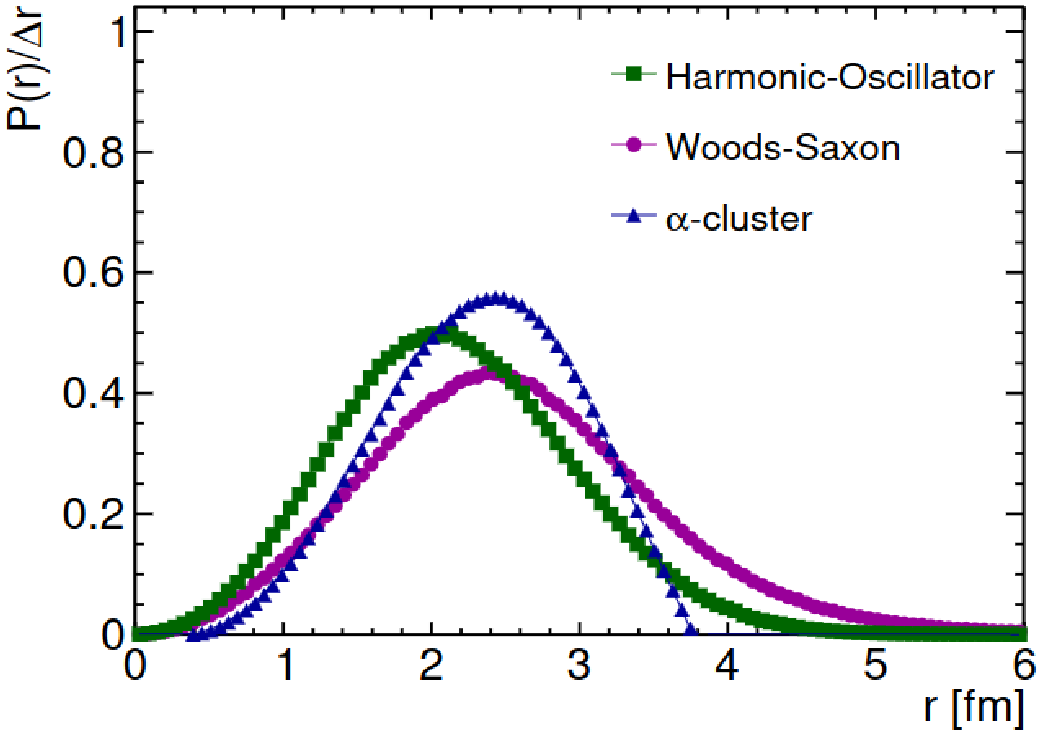
The shape of the oxygen

Nuclear structure description

- **Cluster model vs WS & HO**



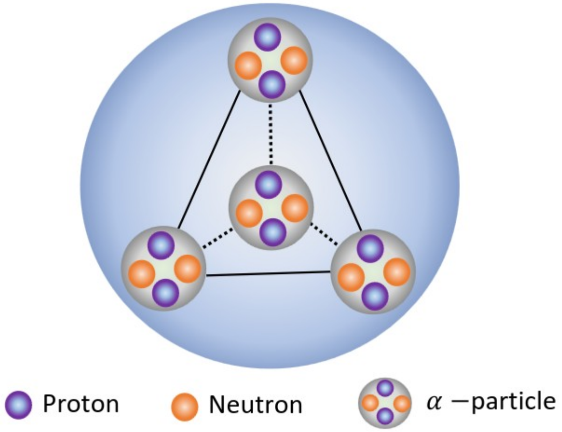
Probability of the radial position in O

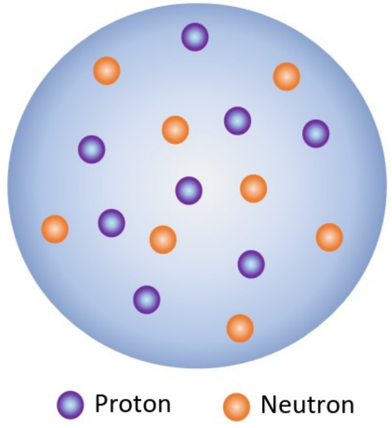


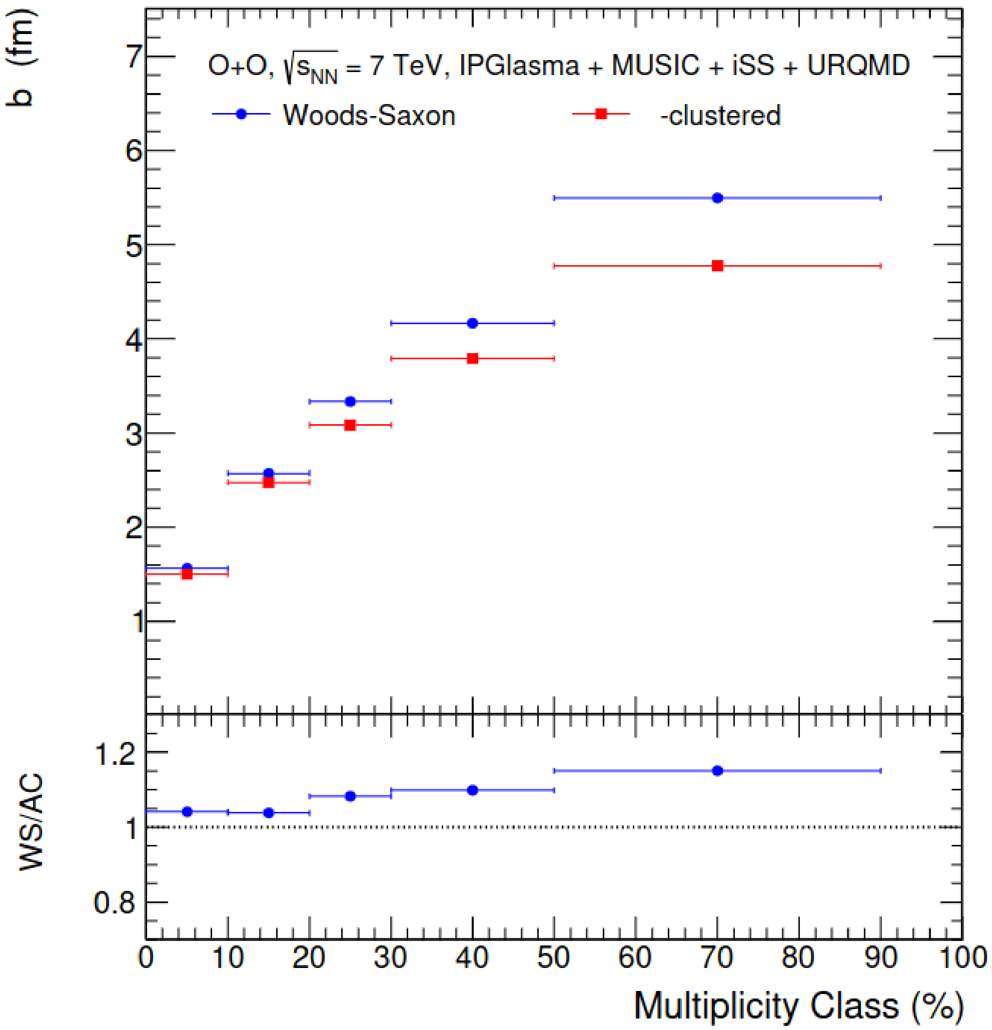
The shape of the OO collision

Nuclear structure description

- Cluster model vs WS



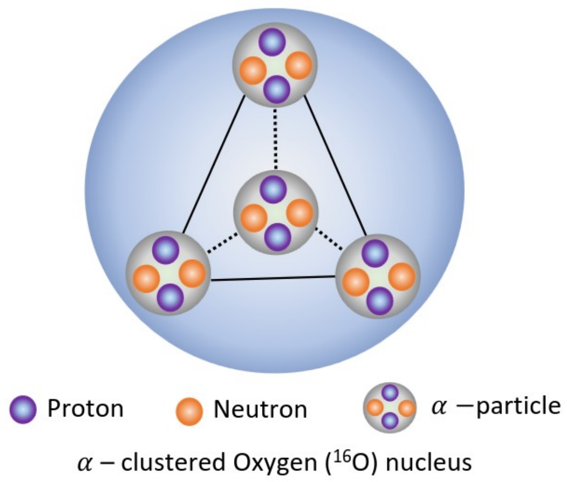


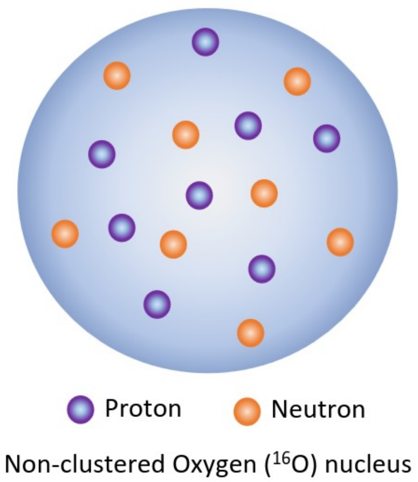


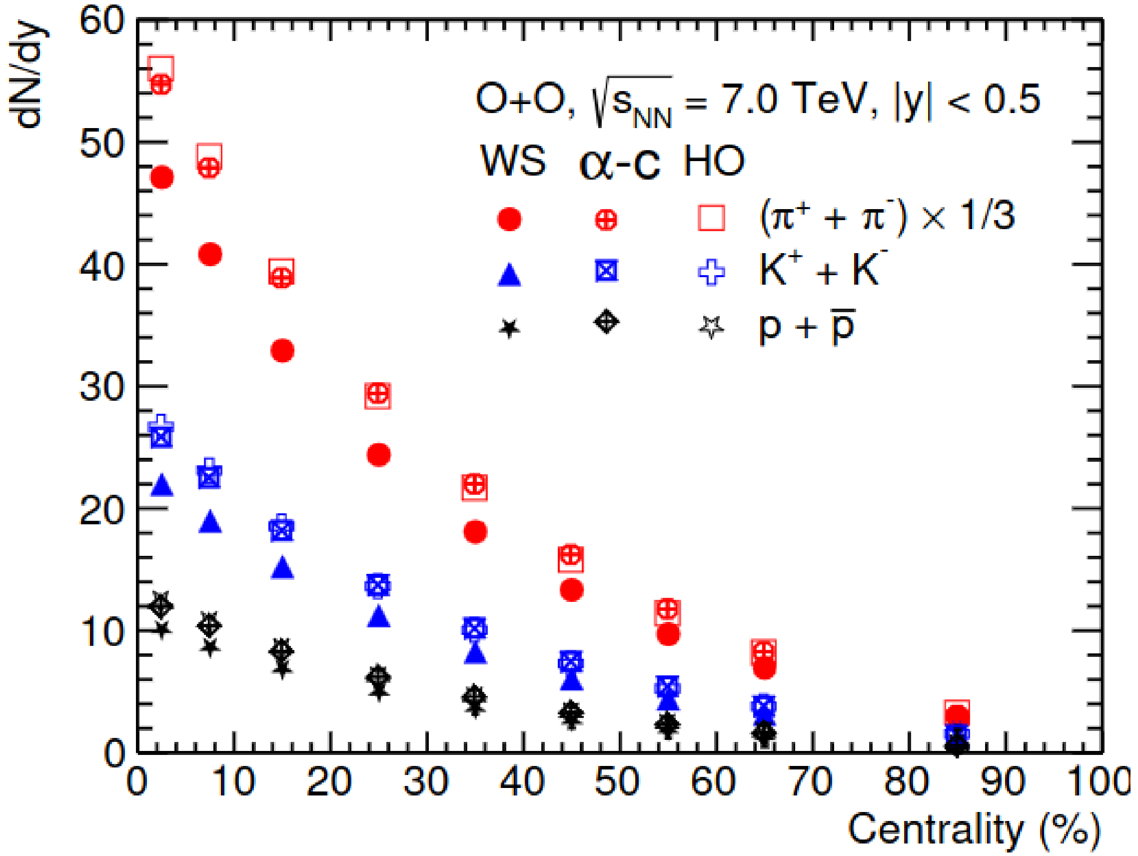
The shape of the OO collision

Nuclear structure description

- **Cluster model vs WS**



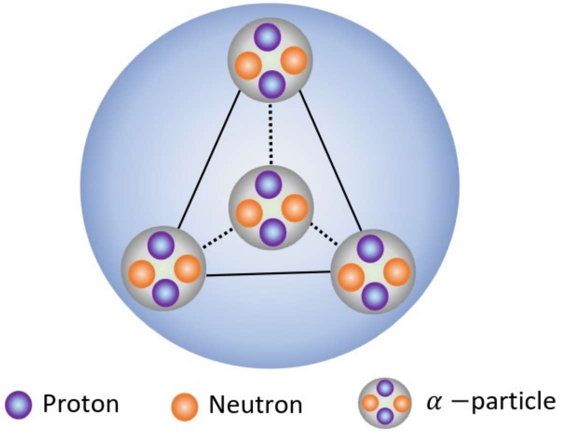




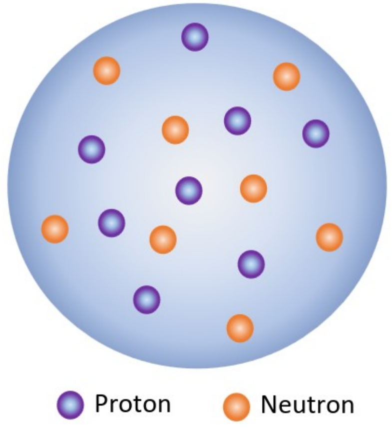
The shape of the OO collision

Nuclear structure description

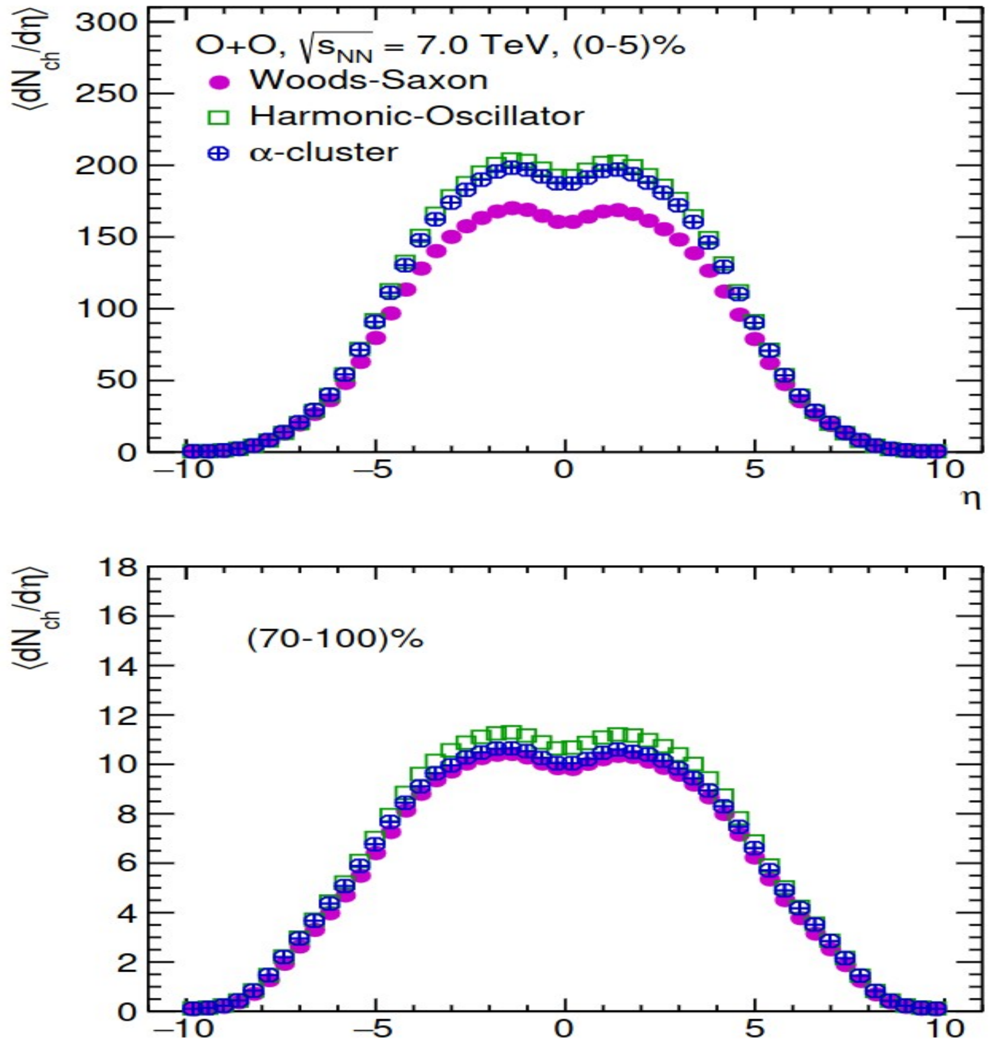
- **Cluster model vs WS**



α – clustered Oxygen (^{16}O) nucleus



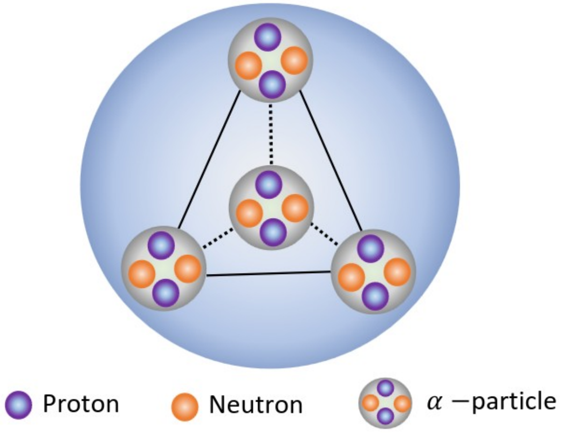
Non-clustered Oxygen (^{16}O) nucleus



The shape of the OO collision

Nuclear structure description

– **Cluster model vs WS**



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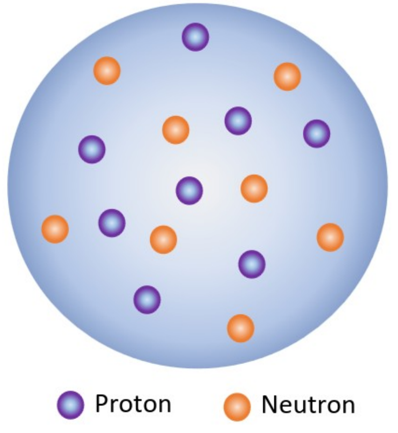

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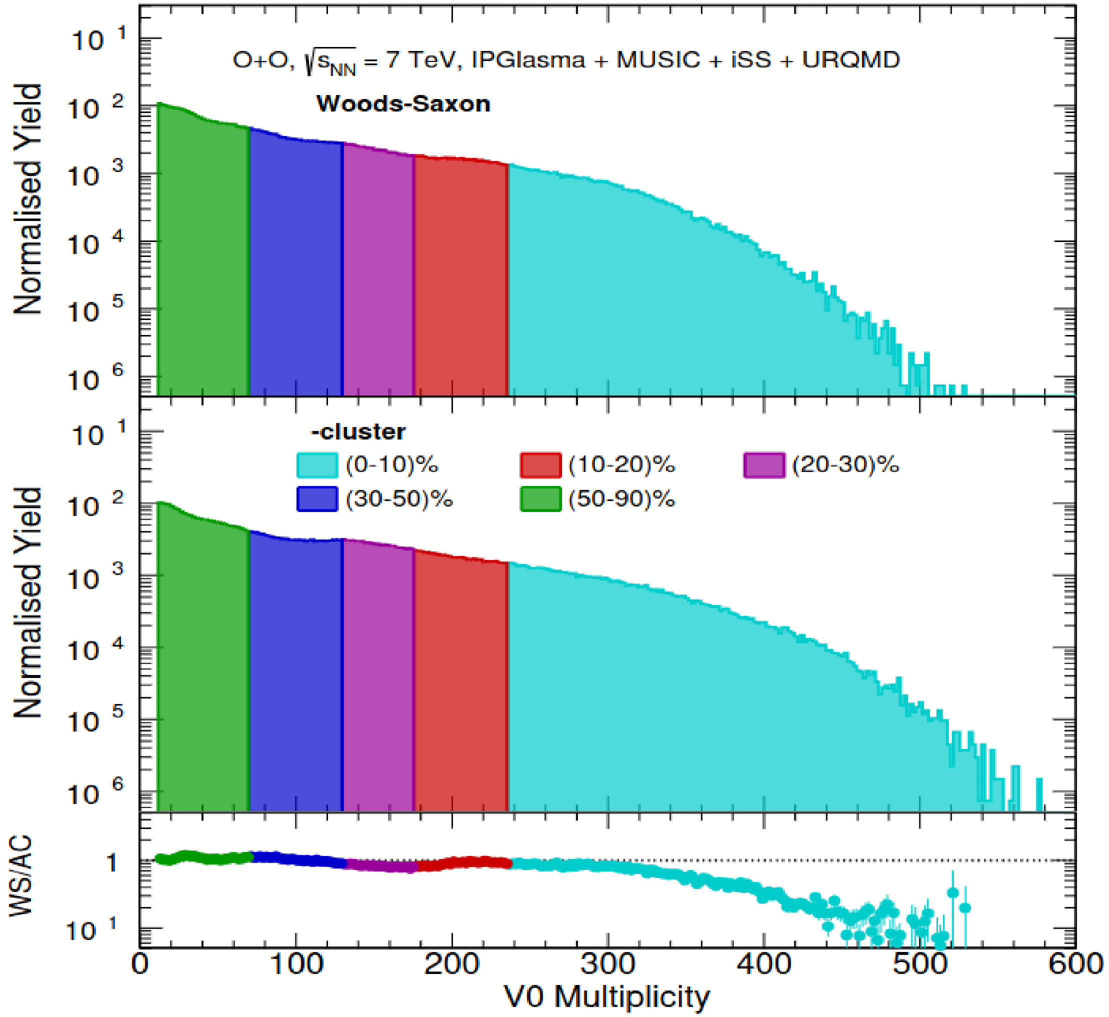


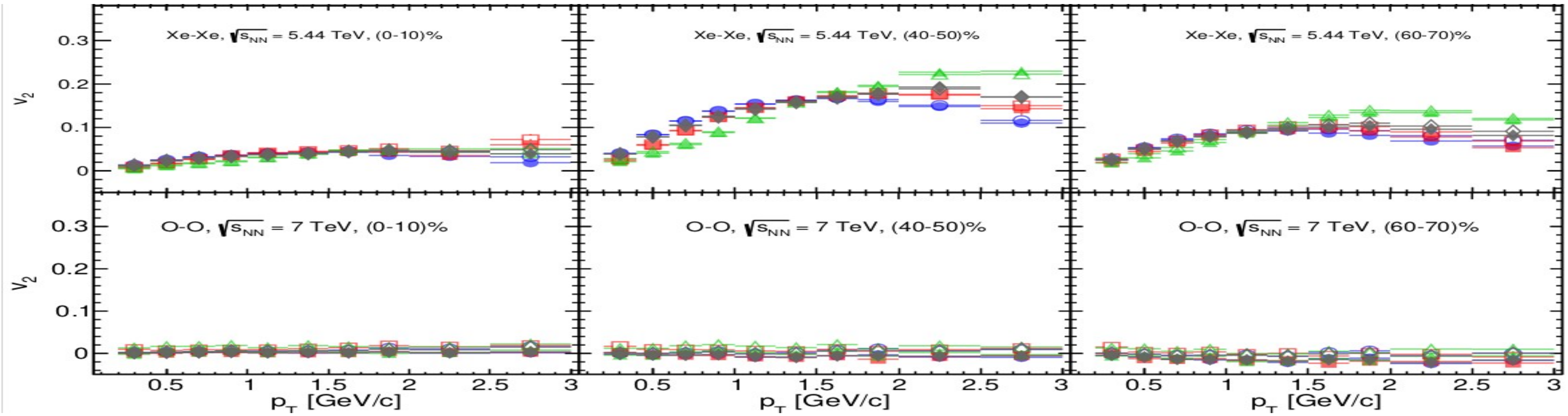
Calculating the flow in small systems

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:



The Model

- **A full hidro & Boltzmann transport with viscosity:**
  - IPGlasma
  - MUSIC
  - iSS
  - URQMD

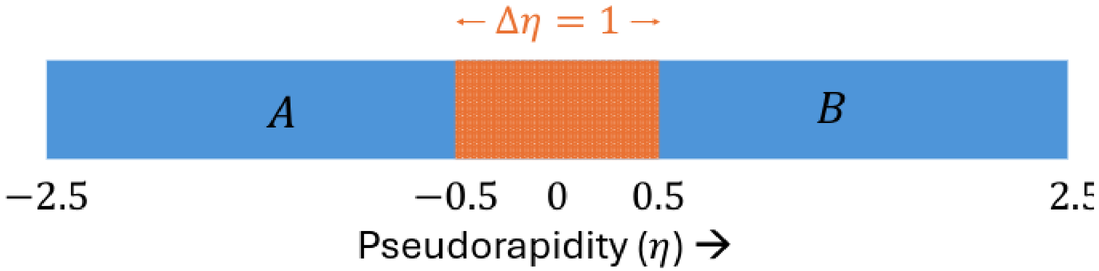
$$\langle 2\rangle = \frac{|Q_n|^2 - M}{M(M-1)},$$

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

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

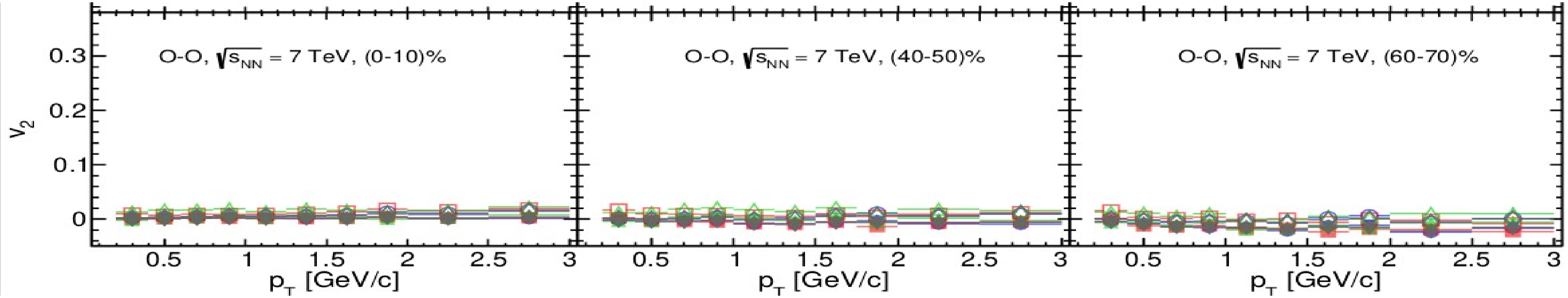
$$\boxed{v_n\{2\} = \sqrt{c_n\{2\}}, \quad v_n\{4\} = \sqrt[4]{-c_n\{4\}}}$$

- **Kinematical settings are:**
  - Energy (c.m.): 7 TeV O+O
  - Pseudorapidity: $|\eta| < 2.5$
  - Transverse momentum: $0.2 < p_T < 5.0$ GeV/c
  - Pseudorapidity gap: $|\Delta\eta| > 1.0$

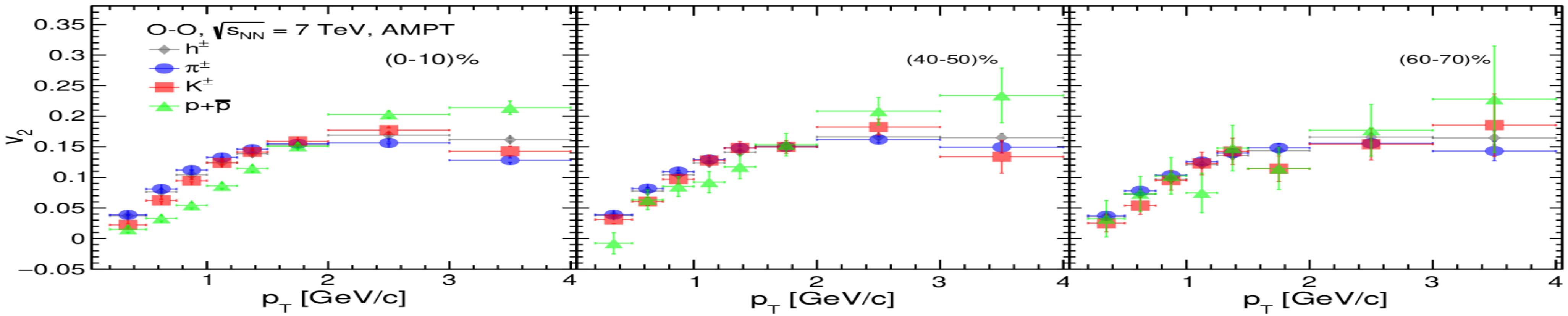


Calculating the flow

Event plane and average method



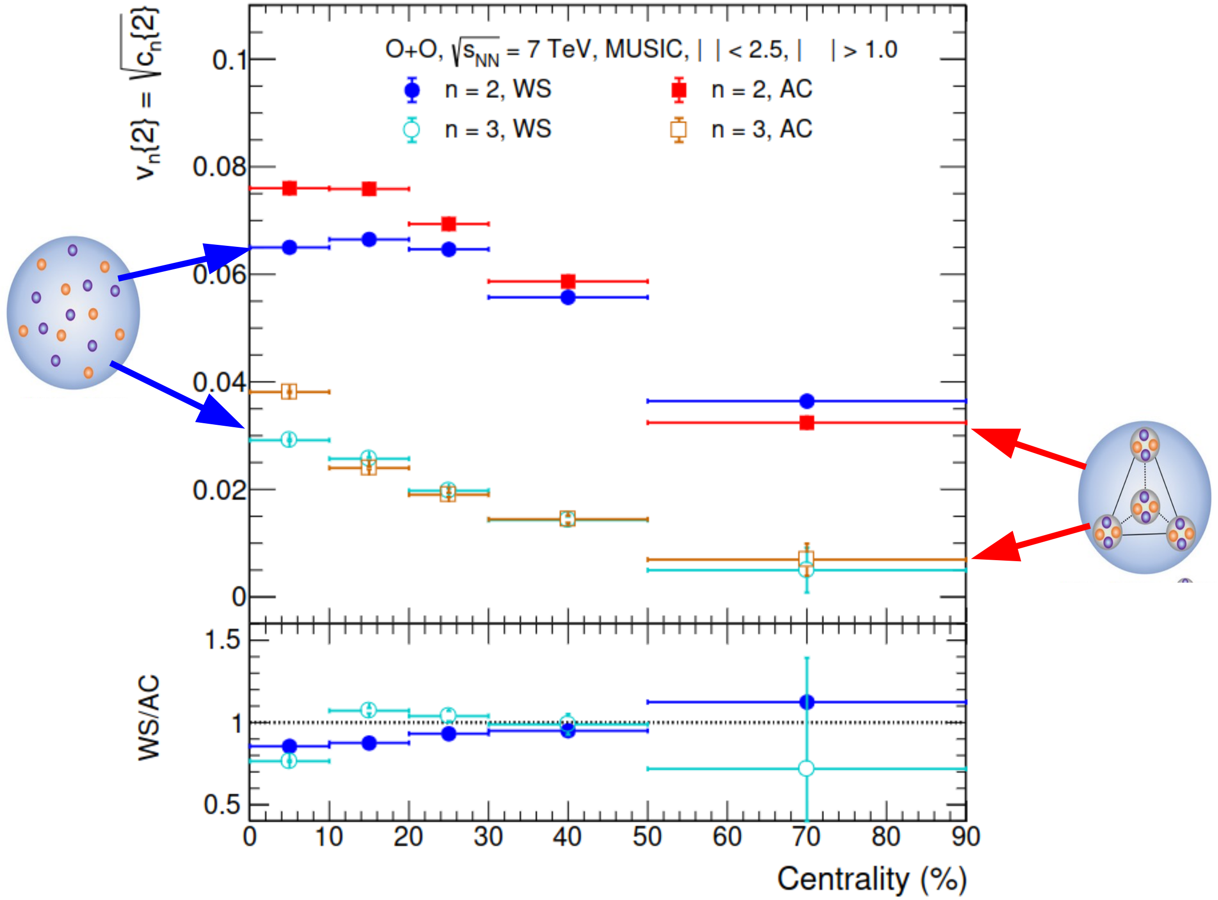
Multiparticle Q-cummulant method



Flow in oxygen-oxygen (OO)

Flow components in O+O @ 7TeV

2-cummulants based calculation of v_2 & v_3



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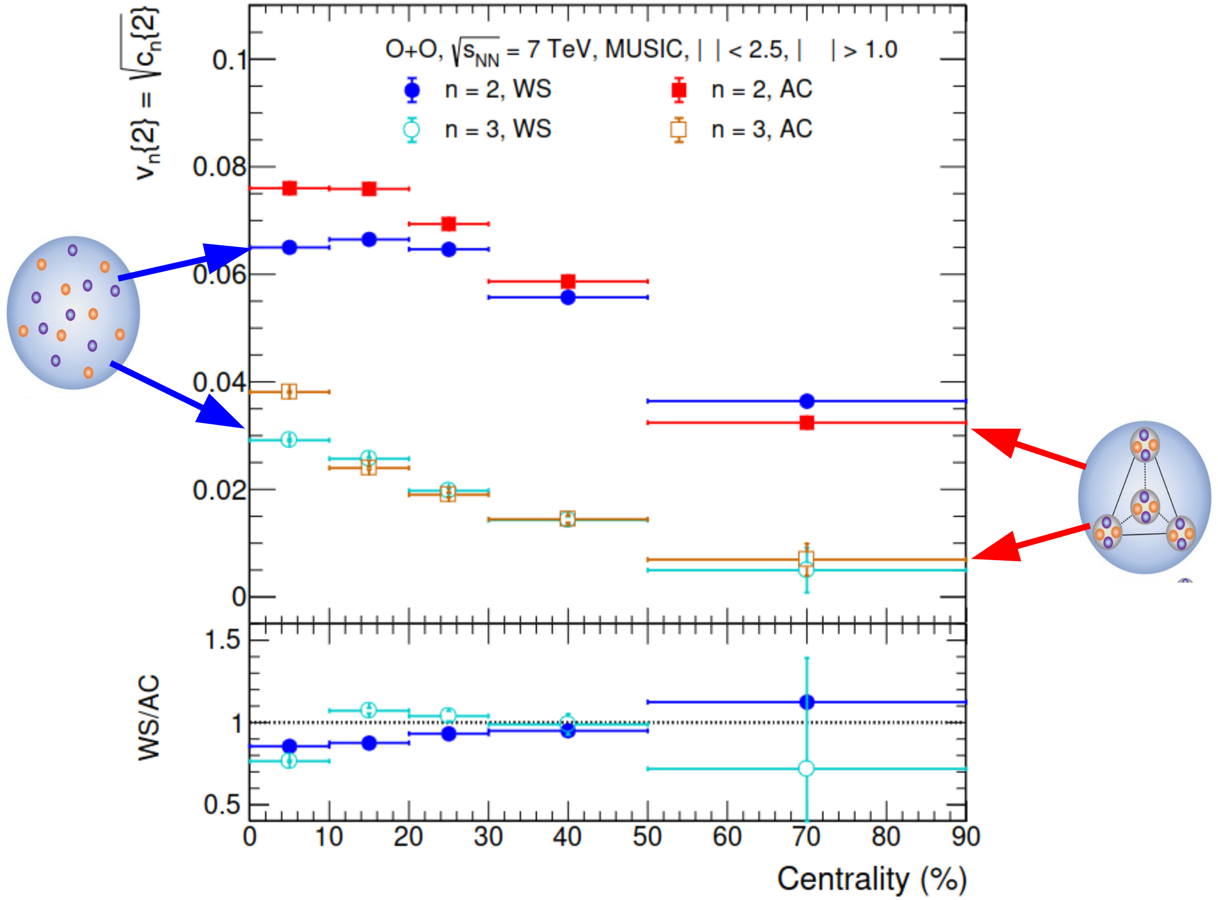
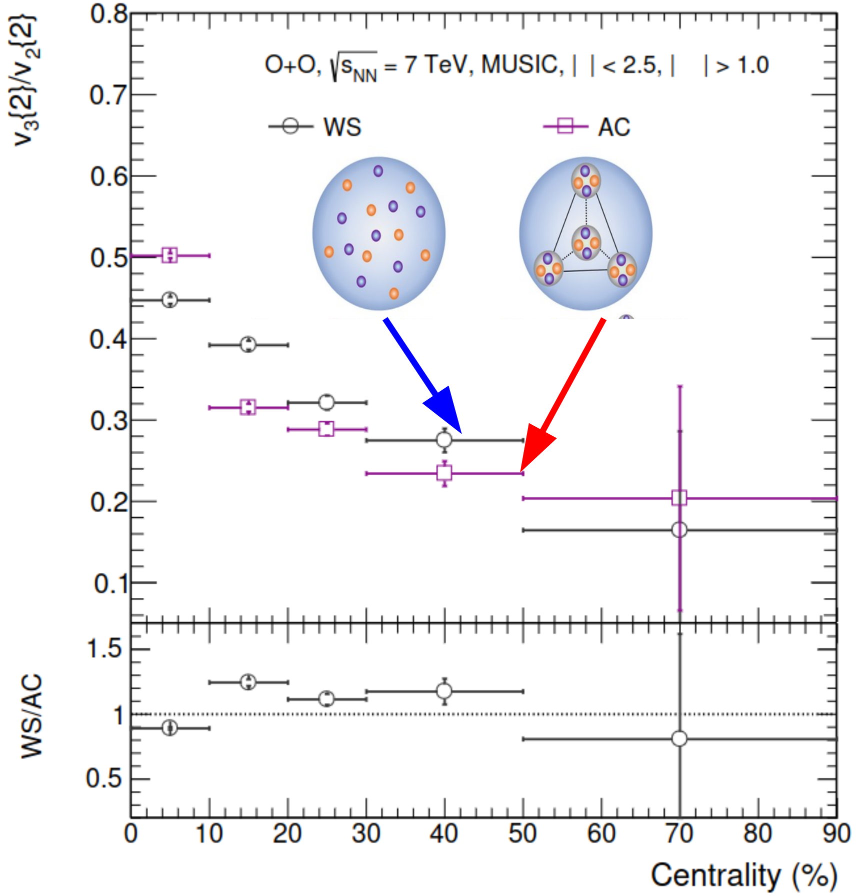
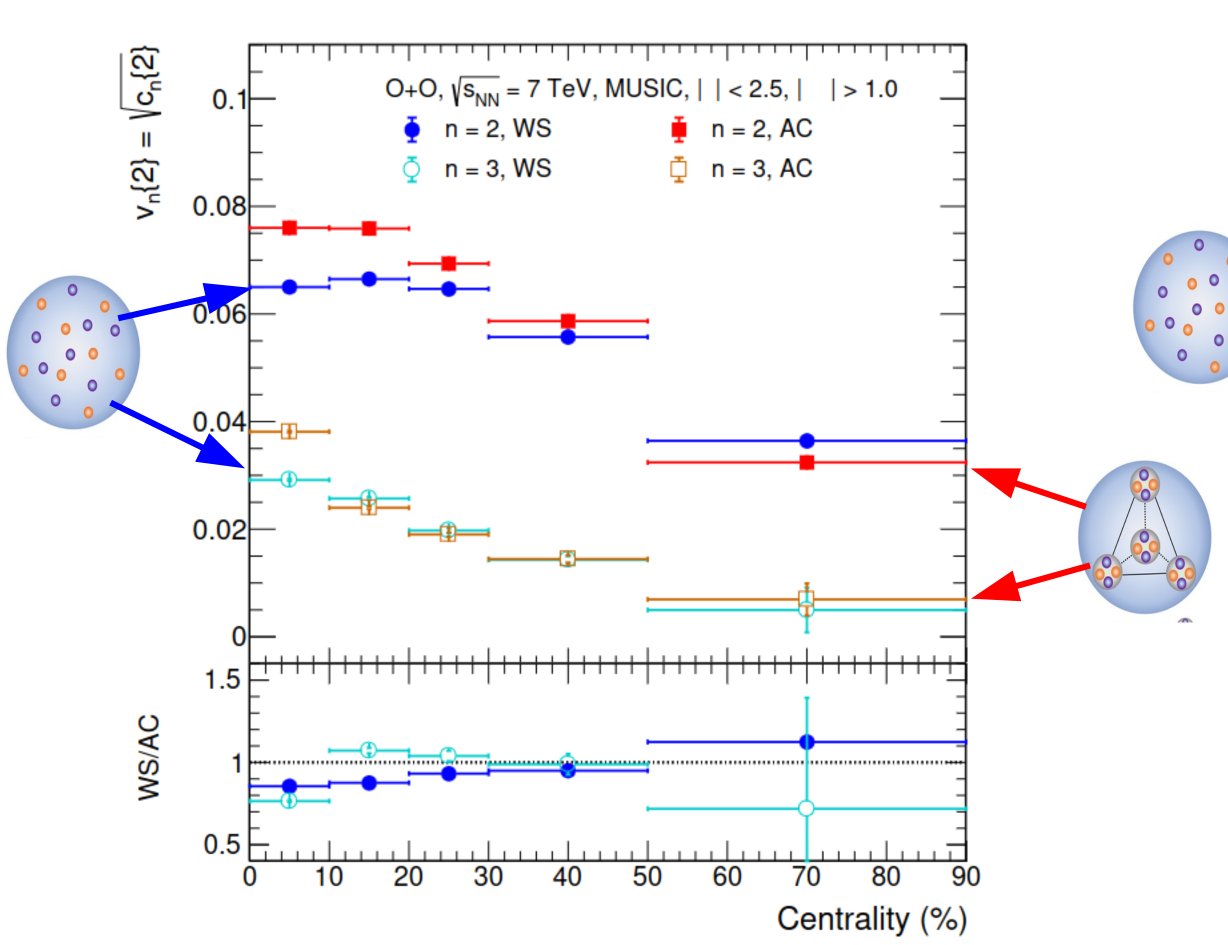
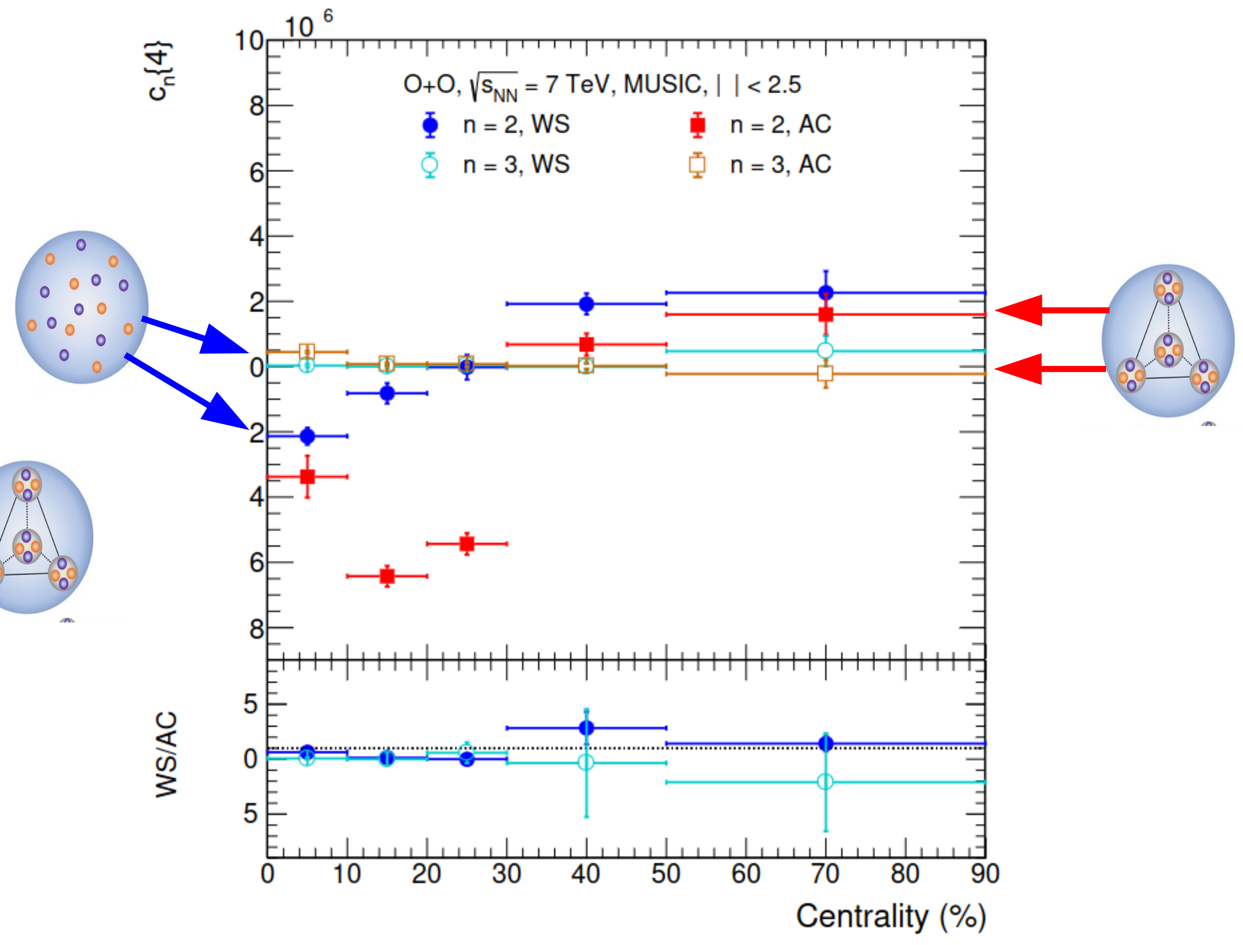




Flow components in O+O @ 7TeV

2- & 4-cummulants based v_n & c_n calculations





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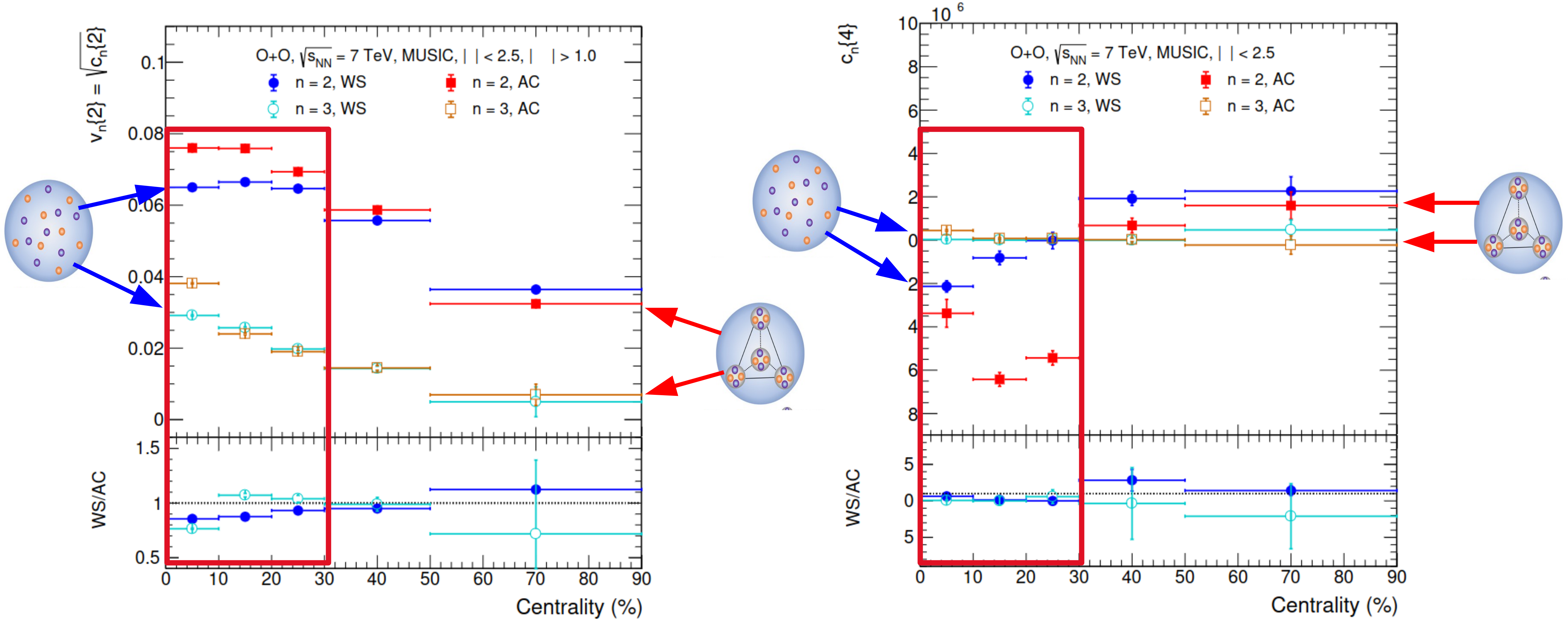
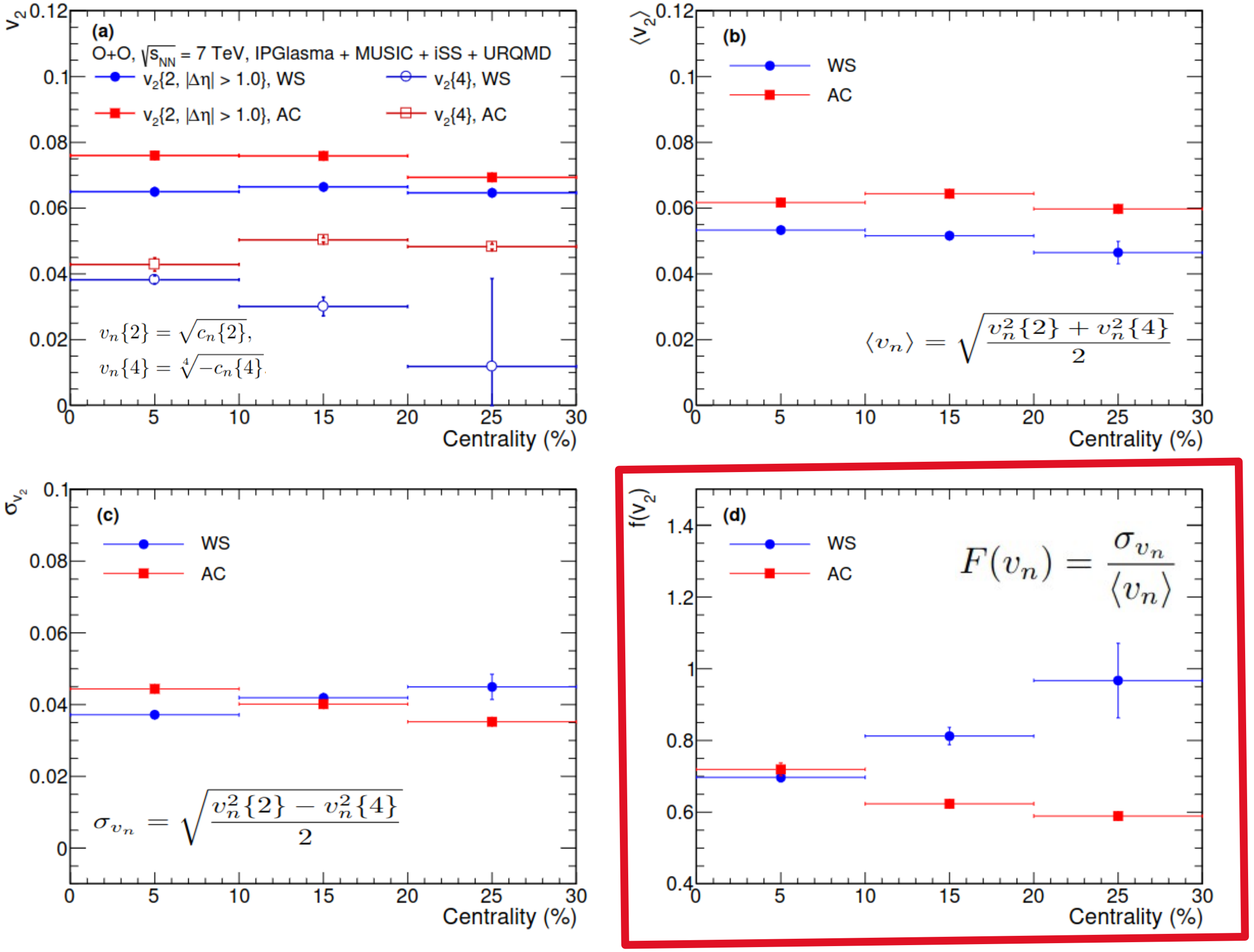


Flow components in O+O @ 7TeV

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



Conclusions

- **In a IPGlasma+MUSIC+iSS+URQMD = “realistic model”**
  - It is possible to calculate the flow for small system like OO
    - → event plane method fails
    - → 2- & 4-cummulants can be calculated for v2
    - → v3 can not be calculated for 4-cummulant
    - → Need for a kinematical cut to reduce non-flow
- **Nuclear structure has consequences on the flow**
  - Nuclear structure matters in the calculations
    - → Alpha Cluster method is stronger than Woods-Saxon
    - → Relevant difference is in centra O+O collisions
    - → **Comparable with the size of the alpha cluster**

Thank You!

Can we prove the model’ validity in heavy-ion collisions?

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:

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

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

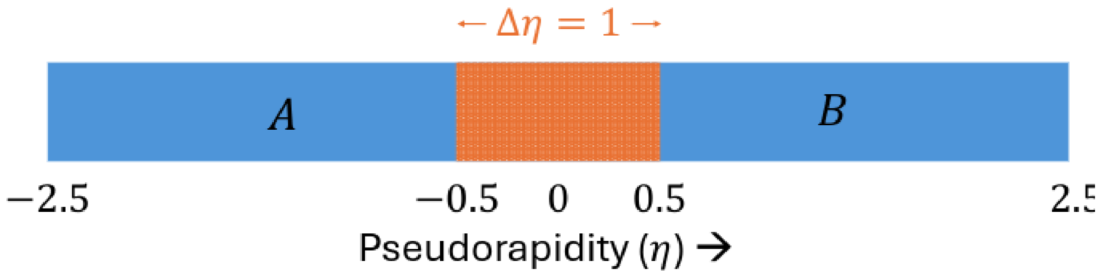
$$\longrightarrow \quad c_n\{2\} = \langle\langle 2 \rangle\rangle, \quad c_n\{4\} = \langle\langle 4 \rangle\rangle - 2 \cdot \langle\langle 2 \rangle\rangle^2$$

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

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:

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

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

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

Flow components in O+O @ 7TeV

2-cummulants based $v_n(p_T)$ calculations

Centrality