

Tetrahedral α clusters in O–O collisions

Probing nuclear structure in relativistic collisions

Jin-Yu Hu

University of Science and Technology of China

In collaboration with Hao-jie Xu, Xiaobao Wang, and Shi Pu

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Outline

1. Motivation and question
2. Controlled sampling and the initial state
3. Hydrodynamic evolution and experimental data
4. Summary

Nuclear structure in high-energy collisions

The traditional picture

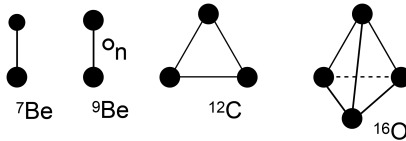
- Nuclei are deformed: prolate, oblate, or triaxial
- Low-energy probes (electron scattering, spectroscopy, Coulomb excitation) are electromagnetic
- They average over orientation and time, and probe protons, not neutrons

“Imaging by smashing”

- Crossing time $\tau = 2R_0/\Gamma < 0.1 \text{ fm}/c$, far below the rotational scale $10^3\text{--}10^4 \text{ fm}/c$
- The collision is an instantaneous snapshot of the ground-state nucleon distribution
- Shape $\rightarrow$ initial QGP geometry $\rightarrow$ collective expansion $\rightarrow$ flow

STAR Collaboration, Nature 635, 67 (2024).

α clustering in light nuclei



Nucleons form α clusters

- ${}^7, {}^9\text{Be}$, ${}^{12}\text{C}$, and ${}^{16}\text{O}$ have a prominent cluster structure in the ground state
- Clustering gives the nucleus a large intrinsic deformation, hence a specific initial geometry
- ${}^{16}\text{O}$: four α particles in a tetrahedral arrangement, related to Y_{32}

Cluster structure schematic: M. Rybczyński et al., Phys. Rev. C 97, 034912 (2018); W. Broniowski, E. Ruiz Arriola, Phys. Rev. Lett. 112, 112501 (2014).

Flow as the observable

- v_2 is sensitive to clustering in ${}^7, {}^9\text{Be}$, and v_3 to clustering in ${}^{12}\text{C}$ and ${}^{16}\text{O}$
- Clustered and uniform nuclei give qualitatively different v_3 fluctuations and v_2 - v_3 correlations
- ${}^{16}\text{O}+{}^{16}\text{O}$ is a stringent test of *ab initio* structure theory

First measurement of light-ion collisions at the LHC

O–O and Ne–Ne at $\sqrt{s_{\text{NN}}} = 5.36$ TeV

ATLAS Phys. Rev. C 113, 045205 (2026)

Measured v_2 – v_4 and flow fluctuations with two- and four-particle correlations.

ALICE Phys. Rev. Lett. 137, 082301 (2026)

Enhanced v_2 in central Ne–Ne relative to O–O supports geometry-driven flow.

CMS Phys. Rev. Lett. 137, 082302 (2026)

Measured $v_2\{2\}$, $v_2\{4\}$ and $v_3\{2\}$; Ne–Ne/O–O ratios probe nuclear structure.

O–O collisions: current research

- **G. Giacalone et al.**, PRL 135, 012302 (2025) — Ab initio + hydro: enhanced Ne–Ne/O–O v_2 .
- **P. Li et al.**, PRL 136, 082302 (2026) — Brink + hydro: distinguish 5α and $^{16}\text{O}+\alpha$ via Ne–Ne flow.
- **H.-C. Wang et al.**, Universe 11, 296 (2025) — AMPT: compare light-ion structures using v_2/v_3 .
- **X.-L. Zhao et al.**, PLB 874, 140254 (2026) — AMPT: confront oxygen shapes with STAR flow.
- **C. Loizides**, PRC 113, 014914 (2026) — TGlauberMC: O–O/Ne–Ne geometry and yields.
- **S. Prasad et al.**, PLB 860, 139145 (2025) — Hybrid hydro: oxygen clustering via flow fluctuations.
- **L. Constantin et al.**, PRC 113, 054901 (2026) — Compare hybrid, cascade and Angantyr in O–O.
- **This work: J.-Y. Hu et al.**, PRC 114, 034905 (2026) — Controlled sampling + hybrid hydro.

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O–O: from nuclear structure to flow

Geometry and collective response

$$v_n \simeq \kappa_n \epsilon_n \quad (n = 2, 3)$$

Li Yan, Chin. Phys. C 42, 042001 (2018);
arXiv:1712.04580

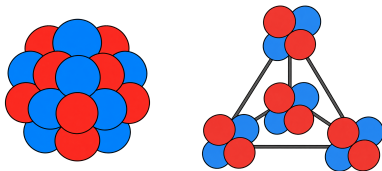
ϵ_n : initial transverse eccentricity

κ_n : response from medium evolution

Collision energy: $\sqrt{s_{\text{NN}}} = 5.36 \text{ TeV}$

A testable geometric signature

- Four α clusters are arranged according to the Y_{32} symmetry
- Initial geometry and event-by-event correlations affect v_2 and v_3



Flow mixes deformation, correlations, and model dependence

Two sources of a cluster signal

One-body density $\rho(\mathbf{r})$

- Describes the average spatial shape
- Tetrahedral Y_{32} deformation or a spherical reference density

Multi-nucleon correlations

- Describe the joint distribution of nucleons
- Encode cluster compactness and event-by-event correlations

Comparing existing configurations often changes both the mean density and cluster compactness. Differences between initial-state models can be even larger.

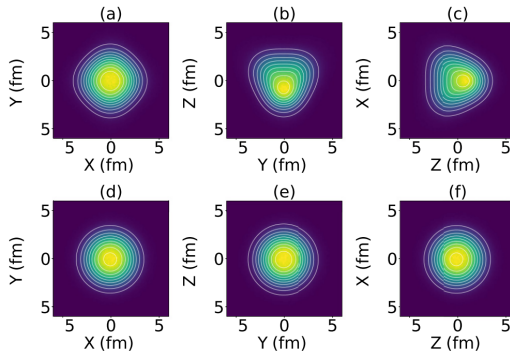
Fix the one-body density; vary cluster correlations

DFT one-body density profiles

Skyrme energy-density functional

Tetrahedral (upper row): anisotropic
 $\hat{Q}_{32} = 40 \text{ fm}^3$, $\beta_{32} = 0.339$

Spherical (lower row): isotropic
 $\hat{Q}_{32} = 0$



Density profiles from the DFT calculation of X.B. Wang et al., Phys. Lett. B 790, 498 (2019).

Controlled sampling and its compactness range

Controlled sampling at fixed density

$$f_i(\mathbf{r}) = \omega_i(\mathbf{r})f(\mathbf{r}), \quad i = 1, 2, 3, 4$$

$$\omega_i(\mathbf{r}) = \frac{\exp[-\chi|\mathbf{r} - \mathbf{C}_i|^2]}{\sum_{j=1}^4 \exp[-\chi|\mathbf{r} - \mathbf{C}_j|^2]}$$

$$\sum_{i=1}^4 \omega_i(\mathbf{r}) = 1 \quad \implies \quad \sum_{i=1}^4 f_i(\mathbf{r}) = f(\mathbf{r})$$

- $\chi = 0$: independent sampling without extra cluster weighting
- $\chi > 0$: cluster-induced correlations; larger χ means tighter clusters

Physical range of the scan

Fixed density	$\chi = 0$	$\chi = 2$
Tetrahedral $\hat{Q}_{32} = 40$	2.37	1.60
Spherical $\hat{Q}_{32} = 0$	2.25	1.62

Root-mean-square cluster size inside oxygen; $\hat{Q}_{32}$ in fm³, sizes in fm.

- Cluster size and the observables saturate with χ
- Fixing the one-body density limits the achievable compactness

Initial-state models and centrality

MC Glauber

$$N_{\text{ch}} \propto (1 - x) \frac{N_{\text{part}}}{2} + x N_{\text{coll}}, \quad x = 0.1$$

C. Loizides, J. Nagle, P. Steinberg, SoftwareX 1–2, 13 (2015).

TRENTo

$$N_{\text{ch}} \propto \int dx dy \left(\frac{T_A^p + T_B^p}{2} \right)^{1/p}, \quad p \rightarrow 0$$

J. S. Moreland, J. E. Bernhard, S. A. Bass, Phys. Rev. C 92, 011901(R) (2015).

- $p \rightarrow 0$ gives the geometric-mean limit of the reduced thickness
- Centrality is ranked by initial entropy, a proxy for multiplicity
- Both models receive the same nuclear configurations to test model dependence

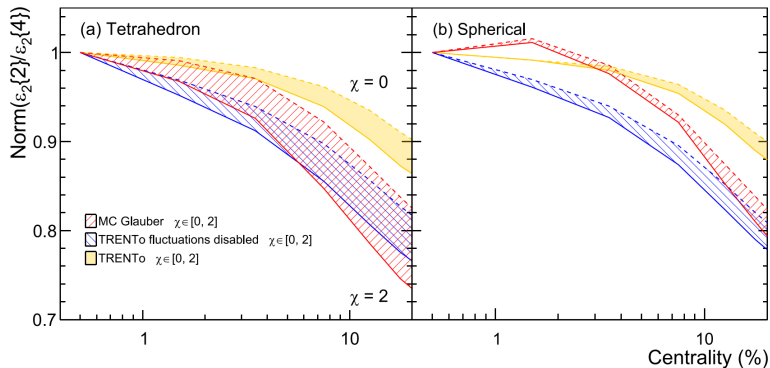
Complementary ratios and normalization

- $\epsilon_n\{2\} = \langle \epsilon_n^2 \rangle^{1/2}$ and $\epsilon_n\{4\} = (2\langle \epsilon_n^2 \rangle^2 - \langle \epsilon_n^4 \rangle)^{1/4}$: two- and four-particle cumulants of the initial eccentricity
- $\epsilon_2\{2\}/\epsilon_2\{4\}$: same-harmonic cumulant ratio, mainly probing fluctuations and initial-state modeling
- $\epsilon_2\{2\}/\epsilon_3\{2\}$: second-to-third harmonic ratio, responding to both deformation and cluster correlations

$$\text{Norm}(X) = \frac{X(\text{given centrality})}{X(0-1\% \text{ centrality})}$$

The normalization cancels common systematic uncertainties, so the centrality trend is compared on equal footing.

Probe 1: $\text{Norm}(\epsilon_2\{2\}/\epsilon_2\{4\})$



Red: MC Glauber. Blue/yellow: TRENTo without/with weight fluctuations.

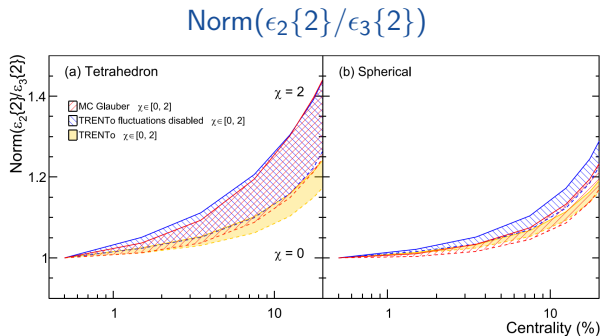
TRENTo weight fluctuations

Each entropy-deposition source has a random weight w drawn from a Γ distribution.

$$\langle w \rangle = 1, \quad \text{Var}(w) = 1/k$$

- Turning off weight fluctuations ($k \rightarrow \infty$) moves TRENTo predictions toward MC Glauber
- Source-weight fluctuations can suppress centrality differences caused by cluster structure
- $\text{Norm}(v_2\{2\}/v_2\{4\})$ can constrain the initial-state fluctuation scheme

Probe 2: deformation and correlations



- Tetrahedral geometry and larger χ steepen the centrality trend.
- TRENTo Γ -weight fluctuations weaken the separation.
- **Partial compensation:** spherical nuclei with $\chi = 2$ can resemble tetrahedral nuclei with $\chi = 0$.

A steep trend disfavors weak deformation with weak correlations.

The trend alone cannot determine $\hat{Q}_{32}$ and χ separately.

VMC inputs and hybrid hydrodynamics

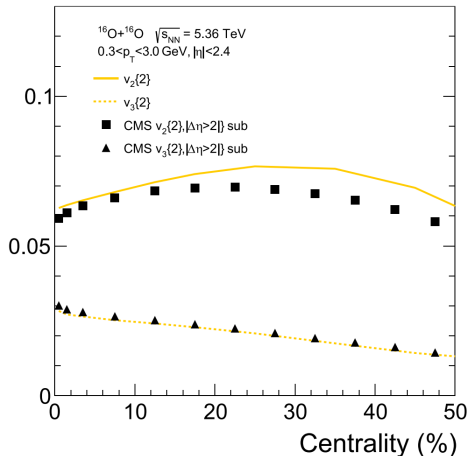
Connecting the controlled setup to microscopic nuclei

- Variational Monte Carlo (VMC) configurations provide an independent input
- Their initial-state trend resembles stronger Y_{32} deformation plus stronger correlations

Dynamical check with iEBE-VISHNU

- TRENTo initial state, $(2 + 1)$ D viscous hydrodynamics, UrQMD afterburner
- 5×10^6 hydrodynamic events; 10 UrQMD oversamples per event
- Current $v_2\{4\}$ statistical uncertainty is large; focus on $v_2\{2\}$ and $v_3\{2\}$

Final-state $v_2\{2\}$ and $v_3\{2\}$



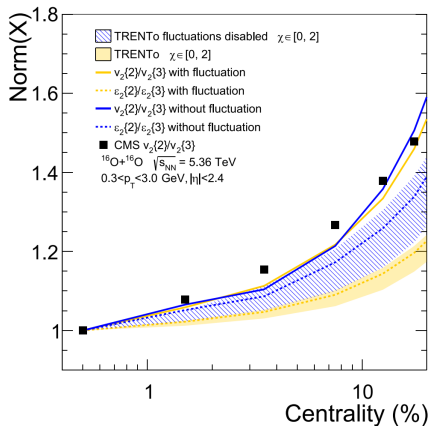
Comparison with CMS data

- The simulation reproduces both magnitudes and the centrality trend
- Magnitudes alone do not establish the structure: the residual difference lies within initial-state and medium uncertainties

$0.3 < p_T < 3.0$ GeV, $|\eta| < 2.4$, and $|\Delta\eta| > 2$.

CMS Collaboration, Phys. Rev. Lett. 137, 082302 (2026).

From initial geometry to final-state flow



What the plot compares

- Dashed: initial eccentricity ratio
- Solid: final-state flow ratio
- Black points: CMS data

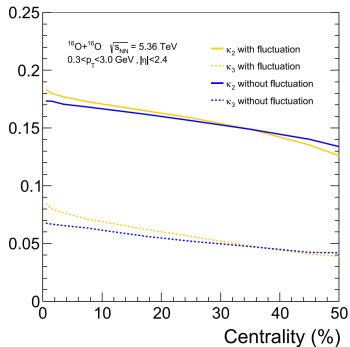
The centrality dependence of κ_2/κ_3 separates the initial- and final-state trends.

The final ratio is less sensitive to source-weight fluctuations.

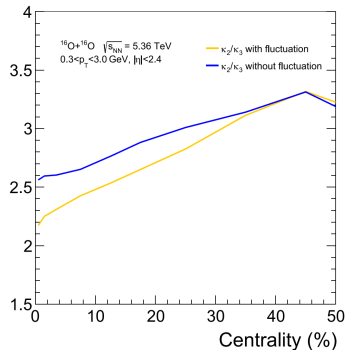
CMS Collaboration, Phys. Rev. Lett. 137, 082302 (2026).

Colors distinguish TRENTo weight-fluctuation settings; shaded bands are not statistical errors.

Centrality dependence of κ_2/κ_3



Responses κ_2 and κ_3



Response ratio κ_2/κ_3

$$\text{Norm}\left(\frac{v_2\{2\}}{v_3\{2\}}\right) \simeq \text{Norm}\left(\frac{\kappa_2}{\kappa_3}\right) \text{Norm}\left(\frac{\epsilon_2\{2\}}{\epsilon_3\{2\}}\right)$$

Summary

Method Vary χ at a fixed one-body density to separate mean deformation from multi-nucleon correlations.

Initial state The two normalized ratios are complementary: the same-harmonic ratio tests source-weight fluctuations, while the second-to-third harmonic ratio constrains deformation and correlations jointly — with parameter compensation.

Final state VMC hybrid simulations reproduce the flow magnitudes; extracting the structure quantitatively requires control of κ_2/κ_3 , a joint comparison of initial state, final state and data, and possibly $p+^{16}\text{O}$.

Thank you

Backup 1: model parameters

Initial / pre-equilibrium	Value	QGP medium	Value
Norm	20.0	$(\eta/s)_{\text{hrg}}$	0.2
p	0.0	$(\eta/s)_{\text{min}}$	0.2
k	0.19	$(\eta/s)_{\text{slope}}$	1.6 GeV^{-1}
r_{cp}	0.5 fm	$(\eta/s)_{\text{crv}}$	-0.29
n_c	6.0	$(\zeta/s)_{\text{max}}$	0.032
ω_c	0.43 fm	$(\zeta/s)_{\text{width}}$	0.024 GeV
τ_{fs}	0.37 fm/c	$(\zeta/s)_{\tau_{\text{peak}}}$	0.175 GeV
		T_{switch}	0.151 GeV

Parameters follow an earlier Bayesian-calibrated setup, adjusted for a reasonable O+O description.

Bayesian calibration: J. S. Moreland, J. E. Bernhard, S. A. Bass, Phys. Rev. C 101, 024911 (2020).

Backup 2: main references

- [This work](#) J.-Y. Hu, H.-j. Xu, X. Wang, S. Pu, Phys. Rev. C 114, 034905 (2026).
- [DFT density](#) X.B. Wang et al., Phys. Lett. B 790, 498 (2019).
- [MC Glauber](#) C. Loizides, J. Nagle, P. Steinberg, SoftwareX 1–2, 13 (2015).
- [TRENTo](#) J. S. Moreland et al., Phys. Rev. C 92, 011901(R) (2015).
- [Hybrid model](#) C. Shen et al., Comput. Phys. Commun. 199, 61 (2016).
- [Bayesian calibration](#) J. S. Moreland, J. E. Bernhard, S. A. Bass, Phys. Rev. C 101, 024911 (2020).
- [VMC / QMC](#) J. Carlson et al., Rev. Mod. Phys. 87, 1067 (2015).
- [ATLAS data](#) G. Aad et al. (ATLAS Collaboration), Phys. Rev. C 113, 045205 (2026).
- [ALICE data](#) ALICE Collaboration, Phys. Rev. Lett. 137, 082301 (2026).
- [CMS data](#) CMS Collaboration, Phys. Rev. Lett. 137, 082302 (2026).