Collective effects in O-O collisions from a hybrid approach

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Transport Meeting

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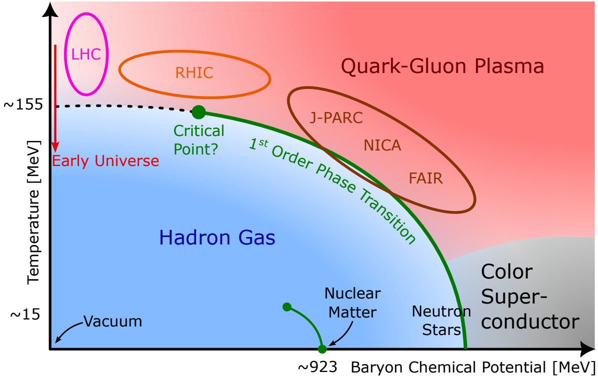
Outline

Motivation for small collision systems

Phase diagram of QCD

- At high temperature and pressure: transition from confined quarks (hadrons) to deconfined quark gluon plasma

- Lattice QCD: smooth phase transition at $\mu_b \approx 0$
- Where is the critical endpoint?
- **Goal:** Studying the limits of QGP formation in small collision systems



Signatures of QGP formation

- QGP behaves like an almost ideal fluid

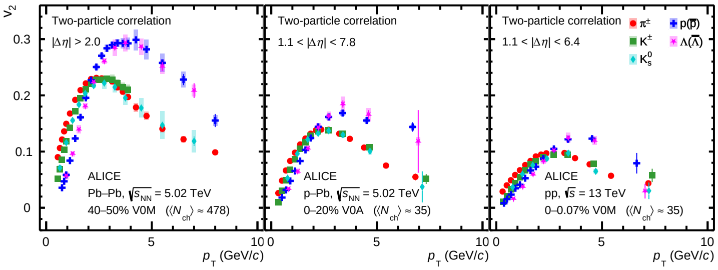
→ **Anisotropic Flow:** initial anisotropic density profile (almond shape) → particles are pushed outwards anisotropically

→ **Jet Quenching:** high p_T particles from initial hard scatterings travel through the created medium

- Data is well described by hybrid approaches:
  Pre-Equilibrium, Hydrodynamics, hadronic evolution

Collectivity in small systems

- **Anisotropic flow**
  observed in p-p: ✅



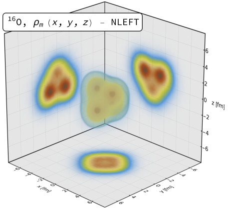
Observation of partonic flow in proton–proton and proton–nucleus collisions, ALICE Collaboration

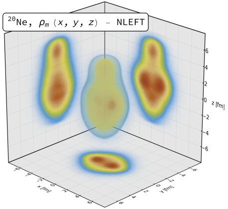
- **Jet quenching**
  observed in p-p: ❌

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T dy}{d^2 N_{pp}/dp_T dy}\Big|_{y=0}$$

Intermediate small systems: O and Ne

- Bridging region between high multiplicity p-p and low multiplicity Pb-Pb
- Sharper energy gradients and higher event-by-event fluctuations compared to heavy-ion collisions
- Nuclear clustering:
  $\rightarrow$ structure leaves imprint on energy profile
  $\rightarrow$ small timescales allow us to take snapshots
- Configurations can be obtained by Nuclear Lattice Effective Field Theory (NLEFT)





Giacalone et al.

Model Descriptions

SMASH initial conditions

- SMASH solves the relativistic Boltzmann equation numerically

$$p^\mu \partial_\mu f_i(\vec{x}, \vec{p}) + m_i F^\alpha \partial^p_\alpha f_i(\vec{x}, \vec{p}) = C^i_{coll}$$

- For the initial conditions, a hypersurface of constant proper time τ_0 is defined
- Particles that cross this hypersurface get removed from the evolution and stored for the hydrodynamical evolution

Hydrodynamic Evolution - vHLLE

- The particles are smeared according to

$$\Delta P^{\alpha}_{ijk} \;=\; P^{\alpha}\, C\, \exp\!\left(-\frac{\Delta x_i^2+\Delta y_j^2}{R_\perp^2} - \frac{\Delta \eta_k^2}{R_\eta^2}\,\gamma_\eta^2\,\tau_0^2\right)$$

- The system is governed by the conservation of energy and momentum, as well as the net-baryon, net-charge and net-strangeness.

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

- Equation of state needed!
  $\rightarrow$ Chiral mean field EoS from QCD that is fitted to HRG at lower temperatures

Particlization and Hadronic Afterburner

- When the system reaches ε_{switch}: Construct hypersurface of constant energy density
- Each surface element is particlized individually in 2 steps:
    1. Sample number of particles of each species using a Poisson distribution
    2. Particles' momenta are sampled according to the Cooper-Frye formula

$$\frac{\mathrm{d}N}{\mathrm{d}\vec{p}} = \frac{\mathrm{g}}{(2\pi)^3} \int_\sigma \left[f_0(x,\vec{p}) + \delta f(x,\vec{p})\right] \frac{p^\mu}{E} \mathrm{d}\sigma_\mu$$

$\rightarrow$ Conservation laws only satisfied on average!

- Resulting particles are put into SMASH for hadronic evolution until kinetic freezeout

Angantyr

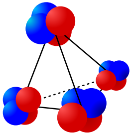
- Extrapolation of PYTHIA p-p events to A-A collisions
- Advanced Monte Carlo Glauber model to determine wounded nucleons

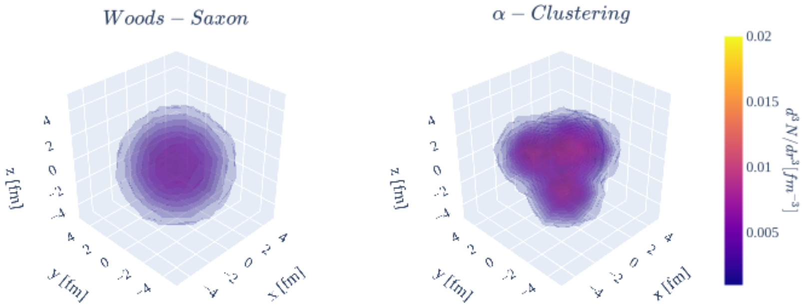
$\rightarrow$ Sub-collisions are combined to obtain full heavy-ion event

$\rightarrow$ No collective effects

Implementation of α-Clustered Oxygen

- Sample 4 helium nuclei with Woods-Saxon distribution
- Place each on the vertex of a regular tetrahedron





Results

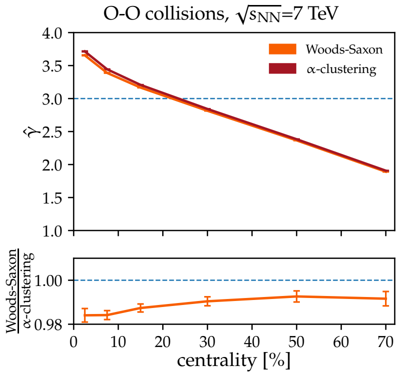
Applicabillity of hydrodynamics

- Assumption of local thermal equilibrium not necessarily true - especially in small systems!
- Assess degree of equilibration: Opacity

$$\hat{\gamma} = (5\eta/s)^{-1} \left(\frac{1}{a\pi} R \frac{dE_T}{d\eta_s} \right)^{\frac{1}{4}}$$

- Measure for the interaction rate in a medium
- Hydrodynamics found to be accurate to kinetic theory if $\hat{\gamma} > 3$

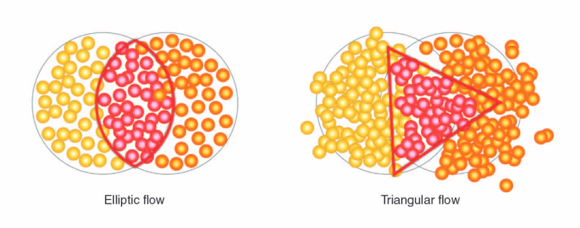
$\rightarrow$ Applicable in central collisions up to 20% in O-O



Werthman et al.

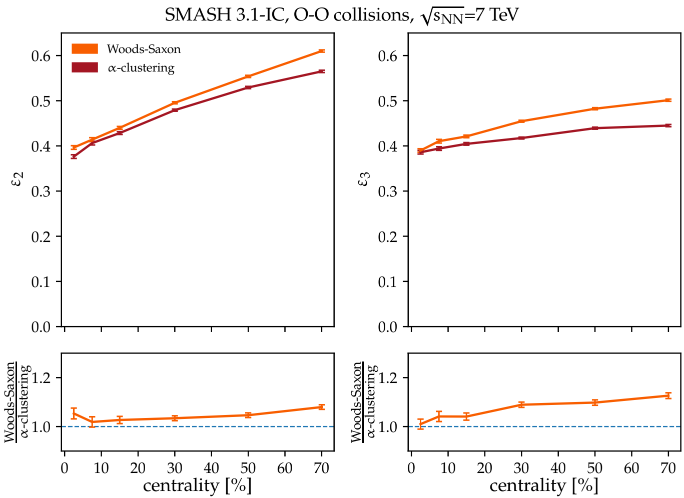
Eccentricity

- The Eccentricity describes the shape of the reaction zone in the transverse plane
- ϵ_2 and ϵ_3 are the ellipticity and triangularity, they measure how close to an ellipse or a triangle the shape is



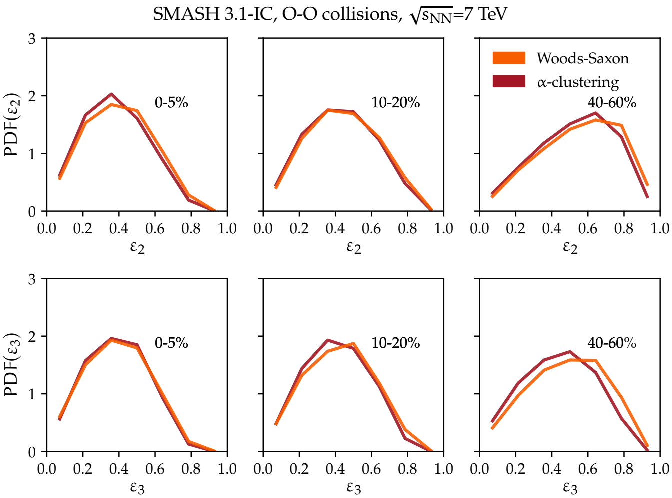
$$|\epsilon_n| = \frac{\sqrt{\langle r^n sin(n\varphi)\rangle^2 + \langle r^n cos(n\varphi)\rangle^2}}{\langle r^n \rangle}$$

Eccentricity



- As expected, both ε_2 and ε_3 increase with centrality
- Woods–Saxon generates higher eccentricities across all centrality classes
- No significant ε_3 enhancement from clustering visible in central collisions

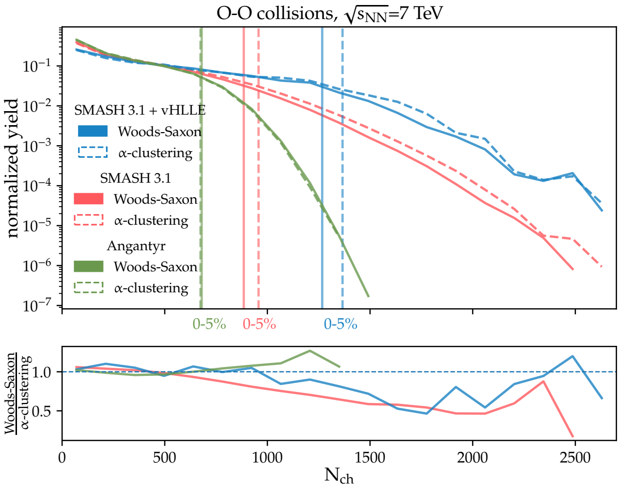
Eccentricity Distribution



- Similar between centrality classes and distributions

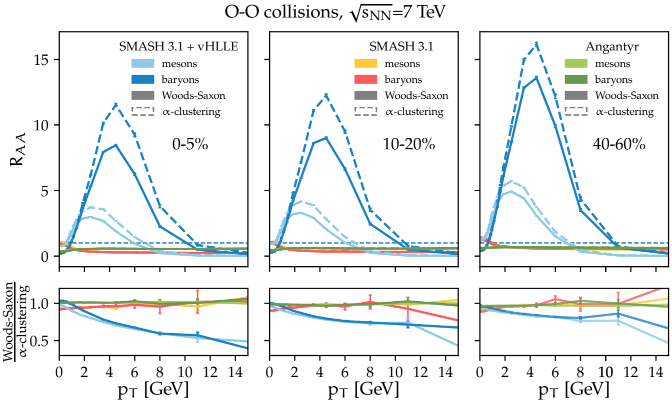
$\rightarrow$ Random orientations and event-by-event fluctuations dilute geometric effects

Centrality Selection



- Centrality determined via final state charged particle multiplicity N_{ch} in rapidity region $|y| < 2.5$
- Results reflect entropy production of the 3 models:
  - → Angantyr has no hadronic rescatterings
  - → Hybrid has viscous effects
- α-clustered configuration yields slightly higher multiplicities

Nuclear Modification Factor



$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{d^2N_{AA}/dp_T dy}{d^2N_{pp}/dp_T dy}\Big|_{y=0}$$

- Angantyr and SMASH transport nearly constant
- Hybrid shows expected result for thermal spectra over vacuum spectra

- Mass ordering: Baryons show higher R_{AA}

→ Interpretation: radial flow pushes particles, α-clustered configurations create denser medium

Anisotropic Flow

Goal: Fourier-decomposition of azimuthal particle distribution

$$\frac{dN}{d\phi} = \frac{1}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n cos(n(\phi - \Psi_n))\right)$$

Problem: Non-flow $\rightarrow$ correlations that do not originate from collective flow

- Sources: particle decays, Coulomb interactions, back-to-back jets

$\rightarrow$ Mostly short ranged (small Δy and $\Delta\varphi$)

$\rightarrow$ Scaling with $\frac{1}{N-1}$

Cumulant Method

- Flow coefficients v_n are extracted from multi-particle azimuthal correlations
- Cumulants capture the genuinely correlated part of a distribution function:

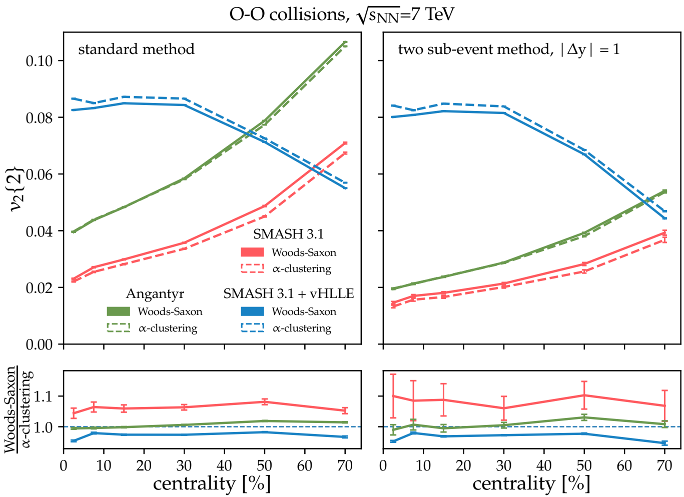
$$c_n\{2\} = \langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle$$
$$c_n\{4\} = \langle\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle\rangle - 2\langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle^2$$

- Corresponding flow coefficients:

$$v_n\{2\} = \sqrt{c_n\{2\}} \qquad v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

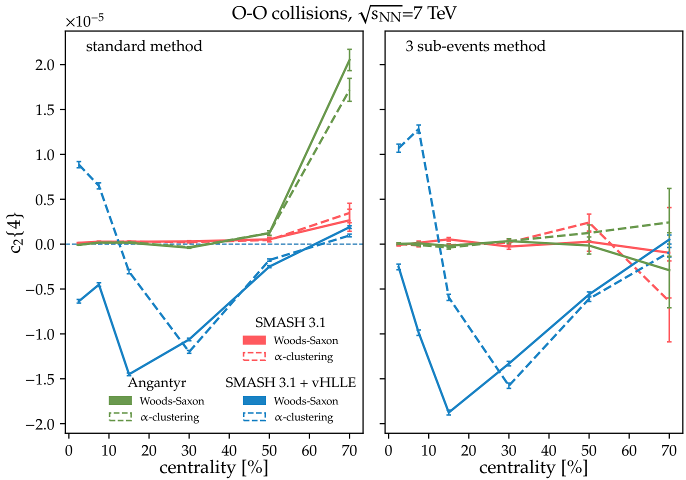
→ k-particle cumulant does not contain contributions from lower order particle correlations

Elliptic Flow



- Hybrid: highest v_2 in central collisions, decreasing in less central events
- SMASH and Angantyr: Opposite trend (Non-flow)
- Sub-event method can significantly reduce non-flow effects

4-particle cumulant $c_2\{4\}$



- Angantyr and SMASH transport close to zero (mostly)
- Incorrect sign prohibits calculation of $v_2\{4\}$
- In general, Correct/Incorrect sign does not mean the flow is collective or not

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

Flow Fluctuations

- Cumulants give estimates for the squared/quadrupled flow coefficients

→ Biased by event-by-event fluctuations

→ Sources: Multiplicity fluctuations, fluctuating initial geometry

Impact of flow fluctuations:

$$v_n^2\{2\} = \langle v_n \rangle^2 + \sigma_{v_n}^2 \qquad v_n^2\{4\} \approx \langle v_n \rangle^2 - \sigma_{v_n}^2$$

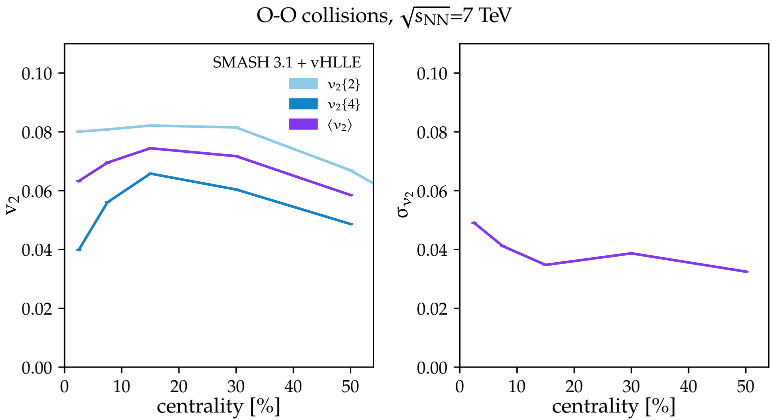
Unbiased flow estimate:

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

Flow fluctuations:

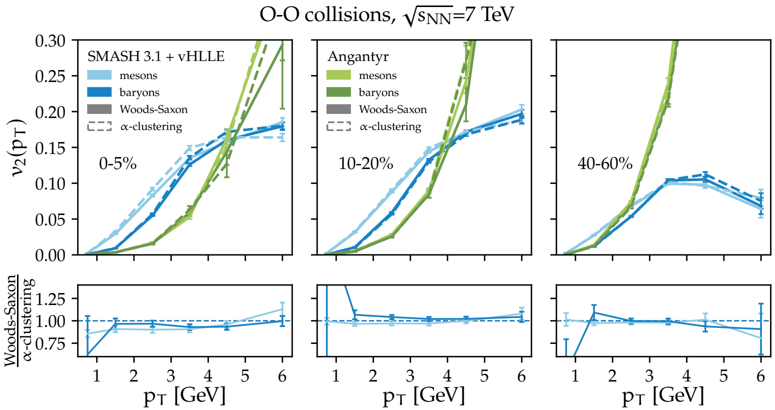
$$\sigma_{v_n} = \sqrt{\frac{v_n^2\{2\} - v_n^2\{4\}}{2}}.$$

Unbiased Flow Results



- Finally, the expected v_2 picture in heavy-ion collisions emerges!
- Flow fluctuations highest in central collisions $\rightarrow$ Multiplicity fluctuations

Differential Flow



- Hybrid: Mass ordering at low p_T visible, no baryon meson splitting at high p_T
  $\rightarrow$ No individual parton description
- Angantyr: Non-flow goes through the roof once the number of particles decreases

Conclusions

Conclusion & Outlook

- Hydrodynamic evolution causes big enhancement of v_2 in central to mid-central collisions

$\rightarrow$ Non-flow and flow fluctuations need to be considered

$\rightarrow$ The α-clustered configuration creates a denser medium, making a hydrodynamic description especially sensitve to the nuclear structure

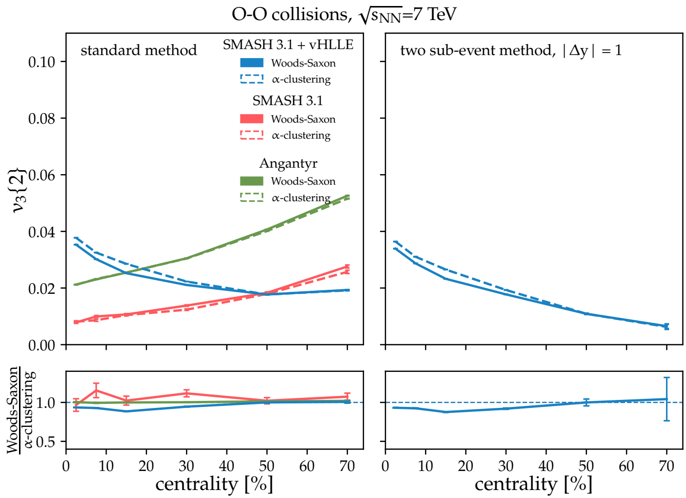
Outlook:

- NLEFT configurations are available now
- Compare to Ne-Ne collisions

$\rightarrow$ Light ions run at LHC in July 2025

Backup

Triangular Flow



- Hybrid: similar picture
- SMASH and Angantyr: dominated by non-flow again

→ Flow from sub-event method is imaginary!

Triangular Flow