

Collective effects in light ion collisions from a hybrid approach

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in collaboration with

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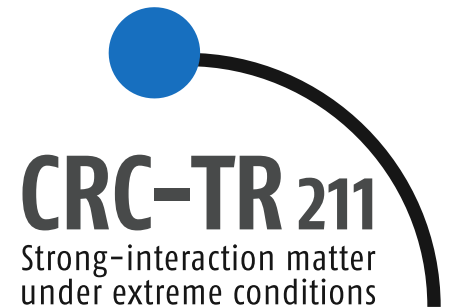
Based on arxiv:2509.05613



Light Ions Workshop 2026

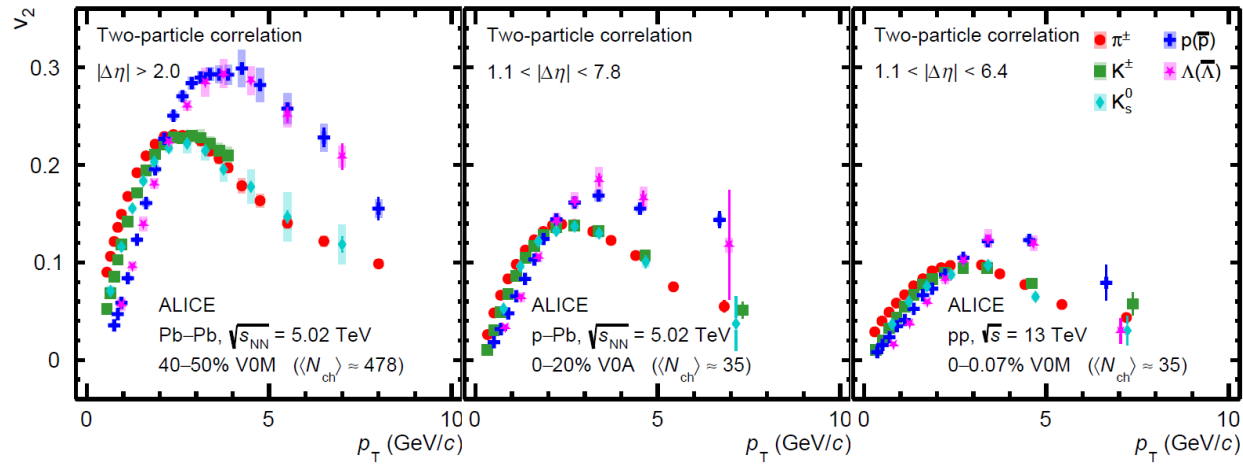
Heidelberg

September 24th, 2026

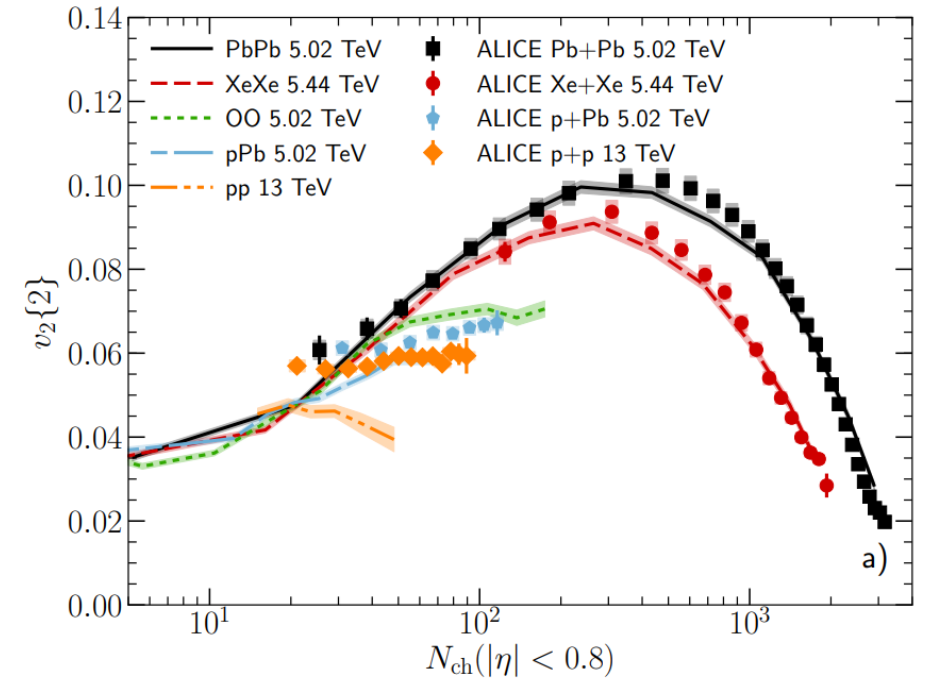


Motivation

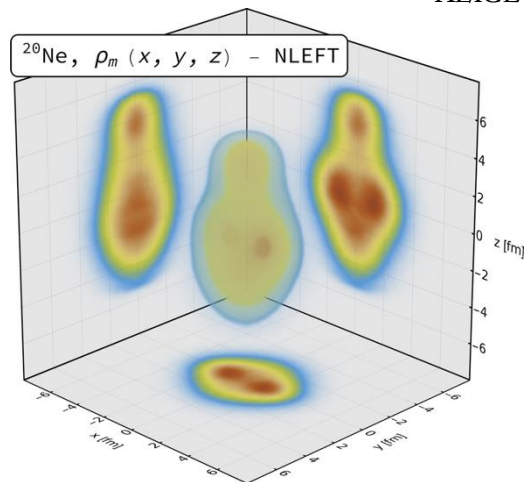
- Non-zero flow in p-p and p-Pb, what about O-O?



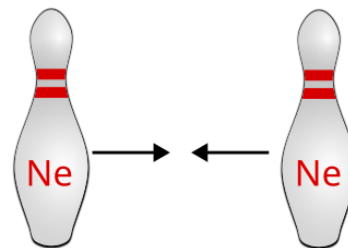
ALICE Collaboration arXiv:2411.09323



Schenke et. al. *Phys.Rev.C* 102 (2020) 4, 044905



Nuclear Structure



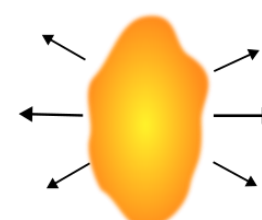
NLEFT

Spatial Anisotropy



Eccentricity ε_n

Momentum Anisotropy

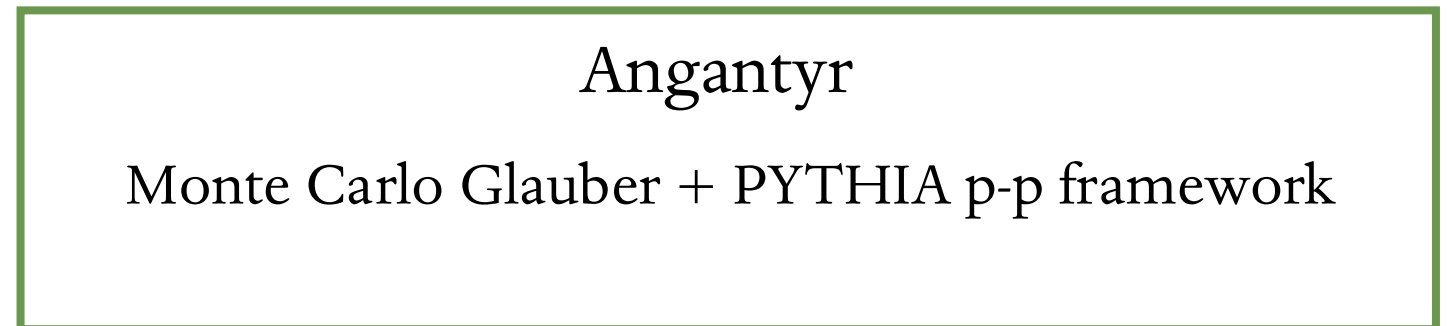
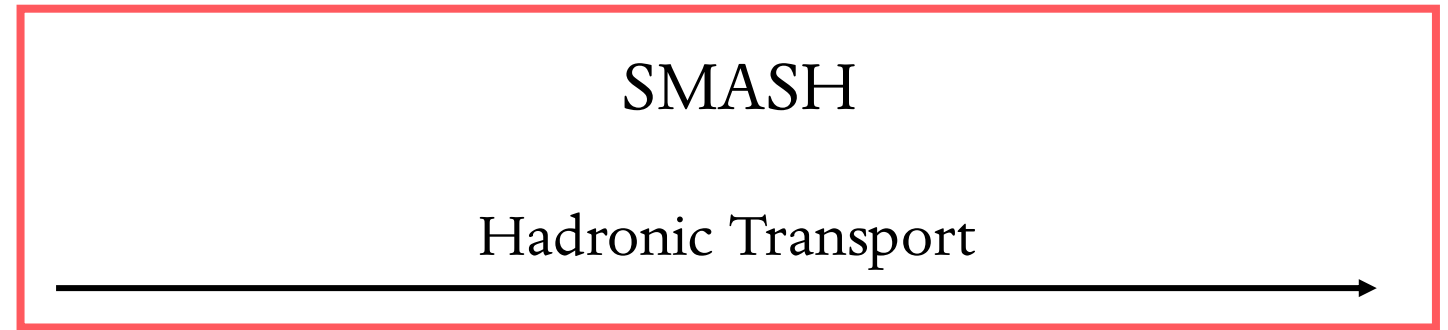


Elliptic Flow v_2
Triangular Flow v_3

Giacalone et. al. *Phys.Rev.Lett.* 135 (2025) 1, 012302

Plan of this work

- Compare models with and without hydrodynamic evolution on equal basis
 - Angantyr serves as baseline for no collective effects
- Analyze observables for collectivity like R_{AA} and v_n



The SMASH-vHLE hybrid

SMASH Initial Conditions

- Boltzmann equation
$$p^\mu \partial_\mu f_i(\vec{x}, \vec{p}) + m_i F^\alpha \partial_\alpha^p f_i(\vec{x}, \vec{p}) = C_{\text{coll}}^i$$
- PYTHIA for string excitations
- Particles are removed from evolution upon crossing a τ -hypersurface

$$\tau_{\text{switch}} = 0.735 \text{ fm}$$

vHLE

- (3+1)D viscous hydrodynamics in the Israel-Stewart framework
- Particles from IC are smeared by Lorentz-contracted Gaussian

$$\Delta K \propto \exp\left(-\frac{\Delta x^2 + \Delta y^2}{R_\perp^2} - \frac{\Delta \eta^2}{R_\eta^2} \gamma_\eta^2 \tau_0^2\right)$$

$$R_\perp = 0.65 \text{ fm} \quad R_\eta = 1.66 \text{ fm}$$

Particlization & Afterburner

- Cooper-Frye sampling at hypersurface of constant energy density $\varepsilon_{\text{switch}}$
- Hadronic transport for rescatterings

$$\varepsilon_{\text{switch}} = 0.33 \text{ GeV/fm}^3$$



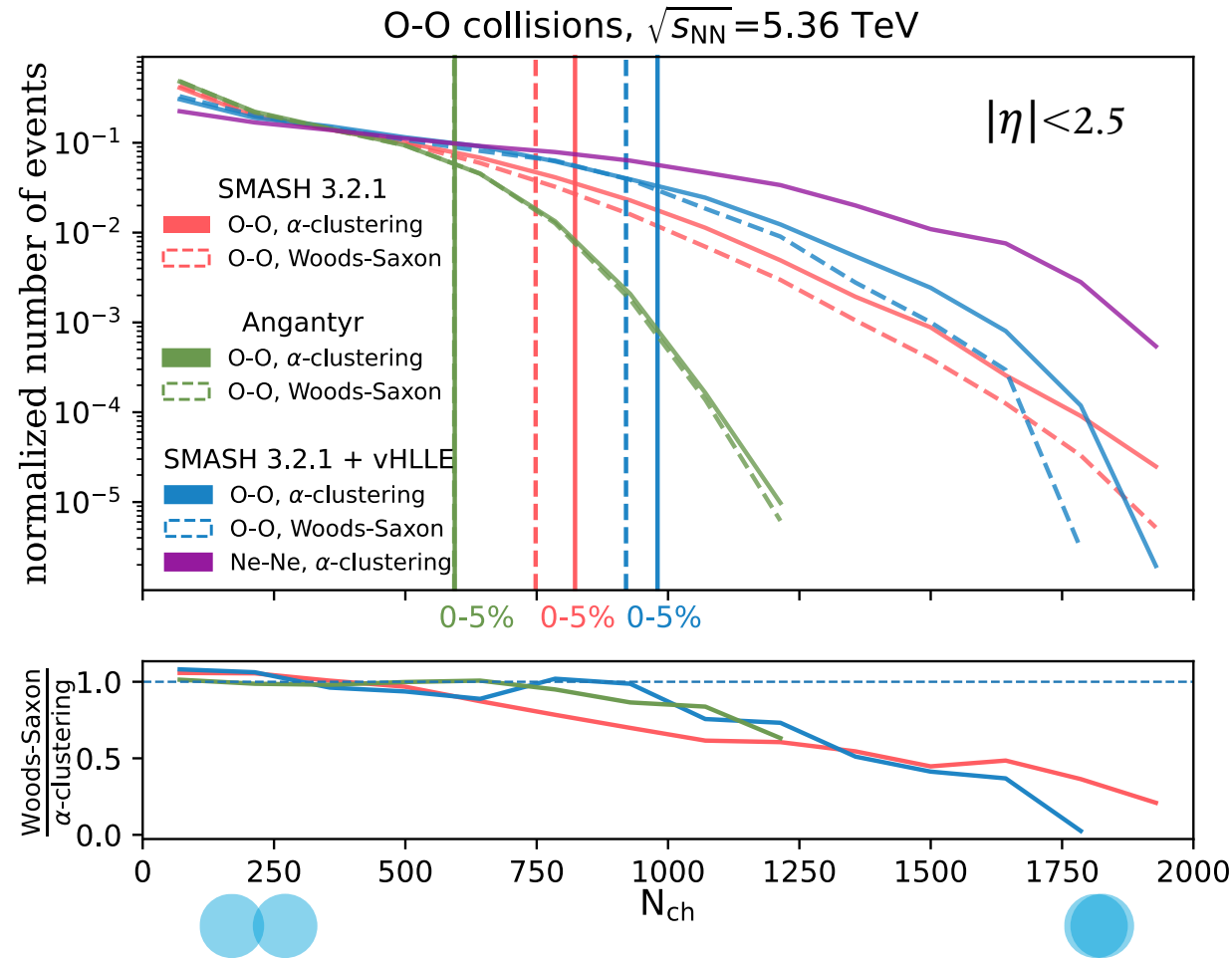
IC & Initial Propagation

QGP & Hydrodynamic Expansion

Hadronic Rescattering

Bayesian analysis by N. Götz et. al.
Phys.Rev.C 112 (2025) 1, 014910

Centrality Selection

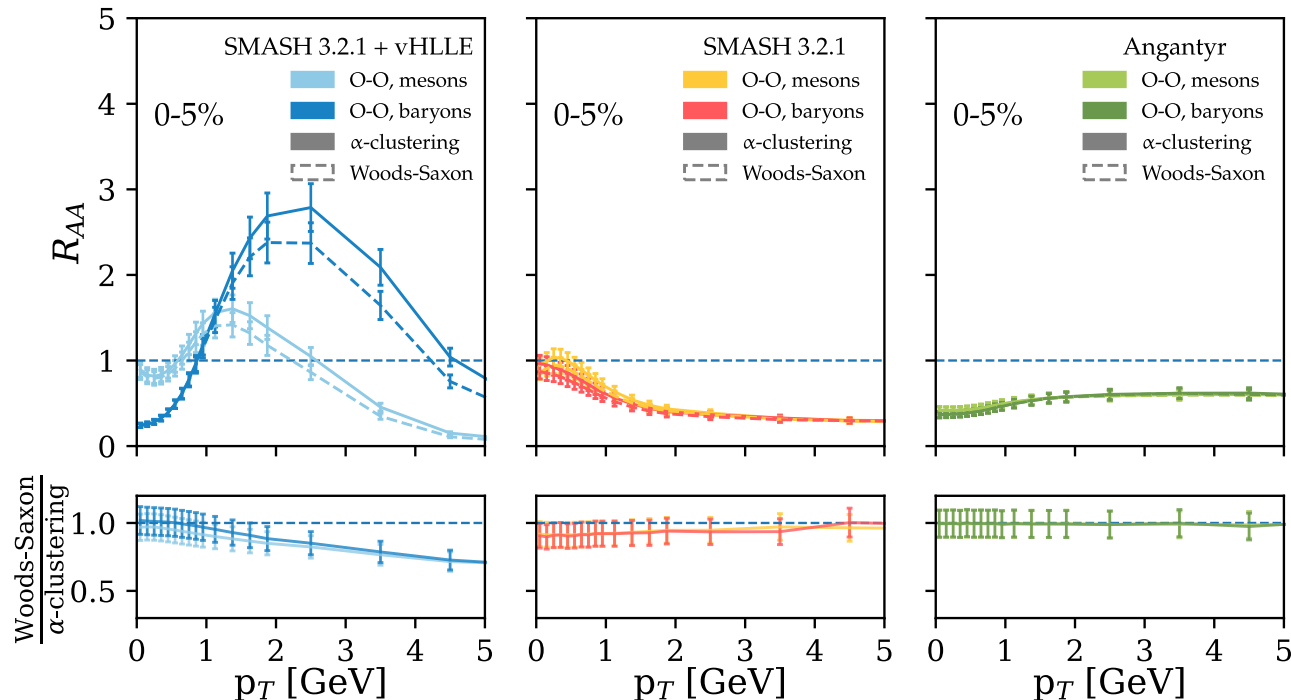


- Multiplicities affect anisotropic flow observables
- Results reflect entropy production in the 3 models
 - Hybrid has viscous effects
 - Angantyr with hadronic rescatterings off
- α -clustered configuration leads to higher multiplicities
 - Hint at a denser medium?

Nuclear Modification Factor

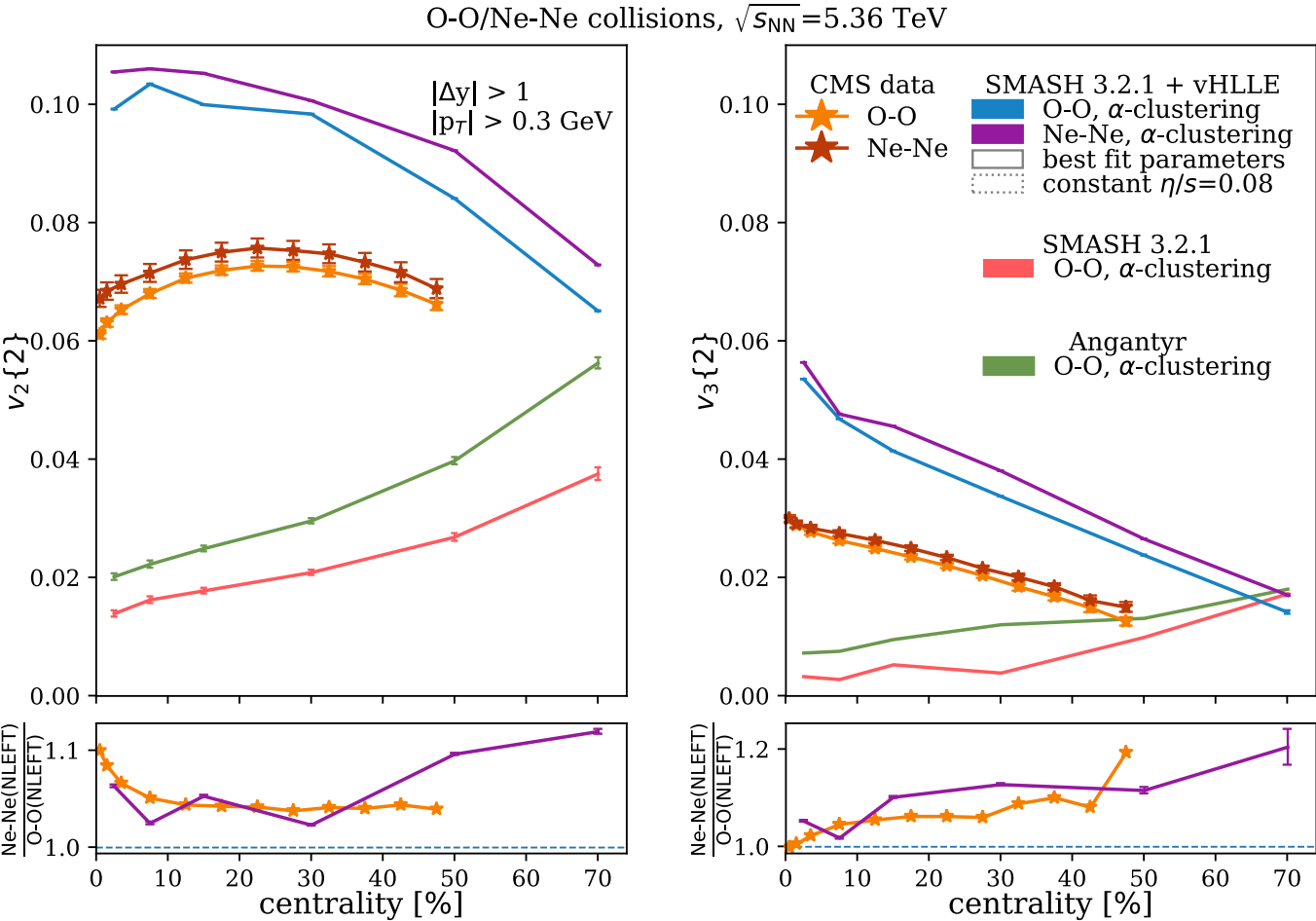
$$R_{AA}(p_T) = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{d^2 N_{AA}/dp_T dy}{d^2 N_{pp}/dp_T dy} \Big|_{y=0}$$

O-O collisions, $\sqrt{s_{NN}} = 5.36$ TeV



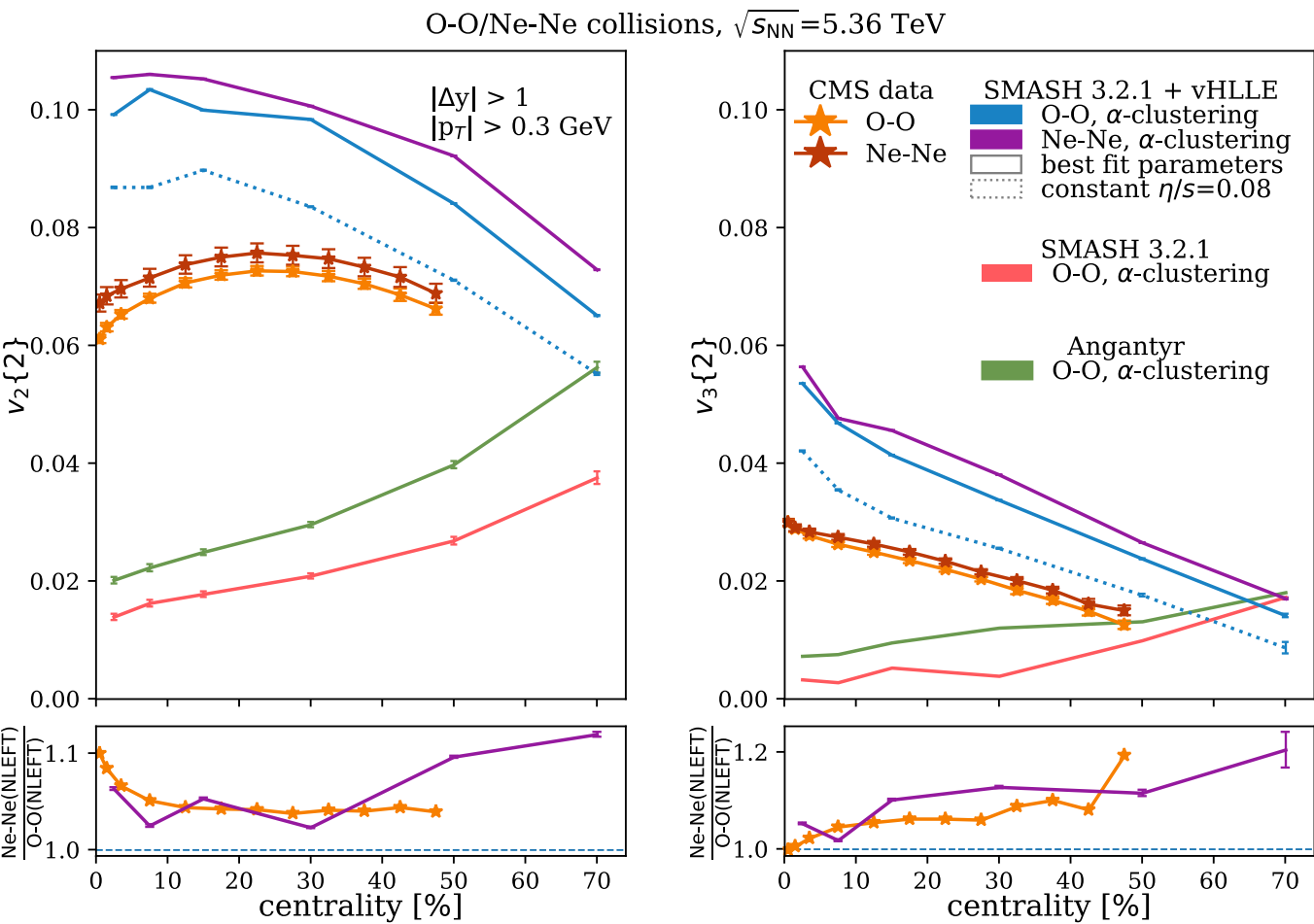
- Hybrid: expected result for thermal over vacuum spectra
→ Mass ordering from radial flow
- SMASH: enhancement at low p_T
→ Stopping from hadronic medium
- Angantyr: almost constant
- Only hybrid shows difference between nuclear configurations

2-Particle Anisotropic Flow



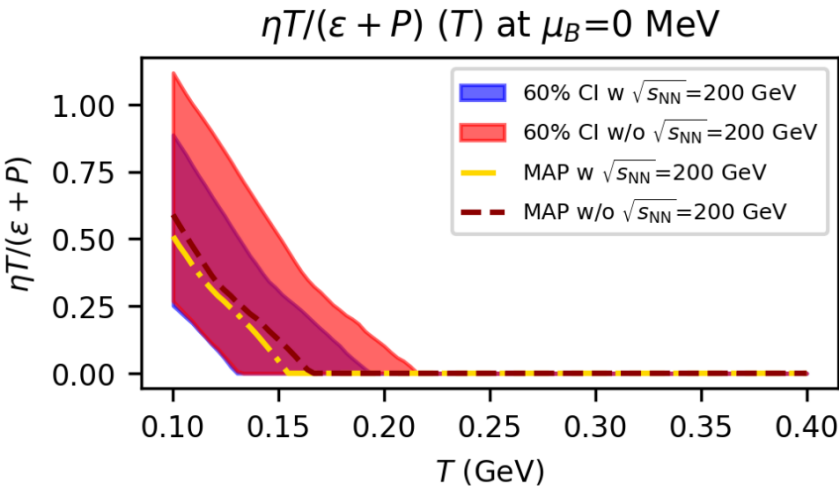
- Opposite behavior between collective and non-collective models
- Increase in SMASH and Angantyr with centrality due to non-flow

2-Particle Anisotropic Flow



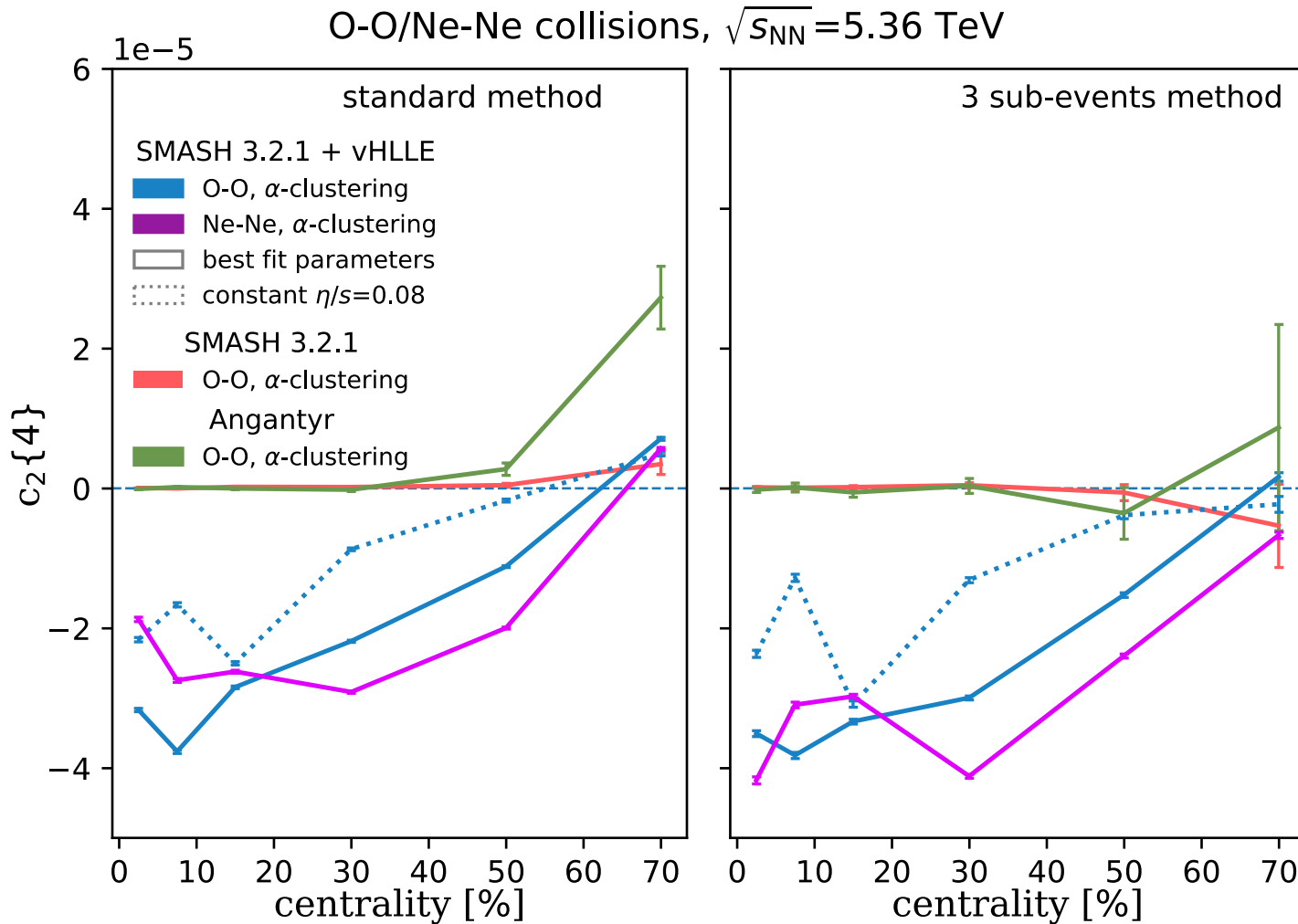
- Values are sensitive to parameters, but the qualitative behavior stays the same
- Experimental Data suggests hydro-like behavior

- Opposite behavior between collective and non-collective models
- Increase in SMASH and Angantyr with centrality due to non-flow



N. Götz et. al. *Phys.Rev.C* 112 (2025) 1, 014910

4-Particle Cumulants



- $c_2\{4\} \approx 0$ in SMASH and Angantyr confirms they are dominated by non-flow
- Correct sign (-) from hybrid allows calculation of $v_2\{4\}$

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

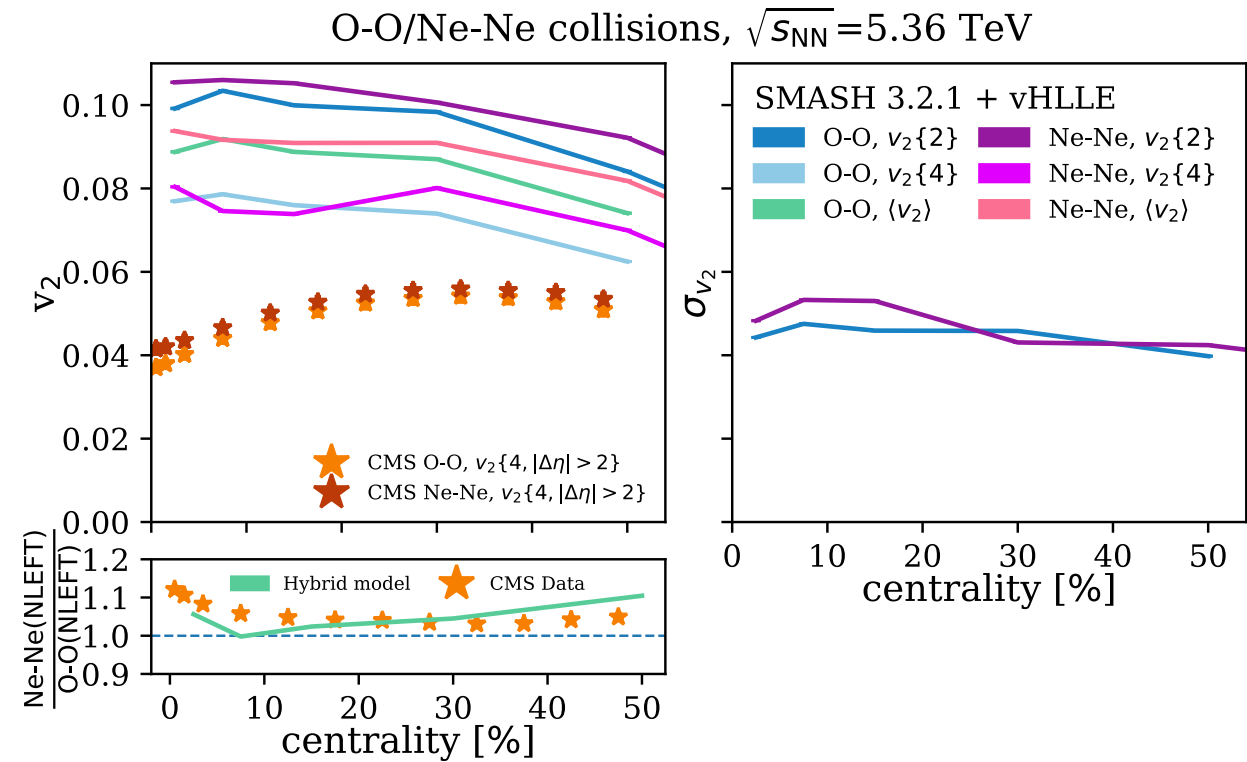
Flow Fluctuations

- Cumulant method gives estimates for flow coefficients raised to the $2^{nd} / 4^{th}$ power
- Systematically biased by flow fluctuations

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

Fluctuations:

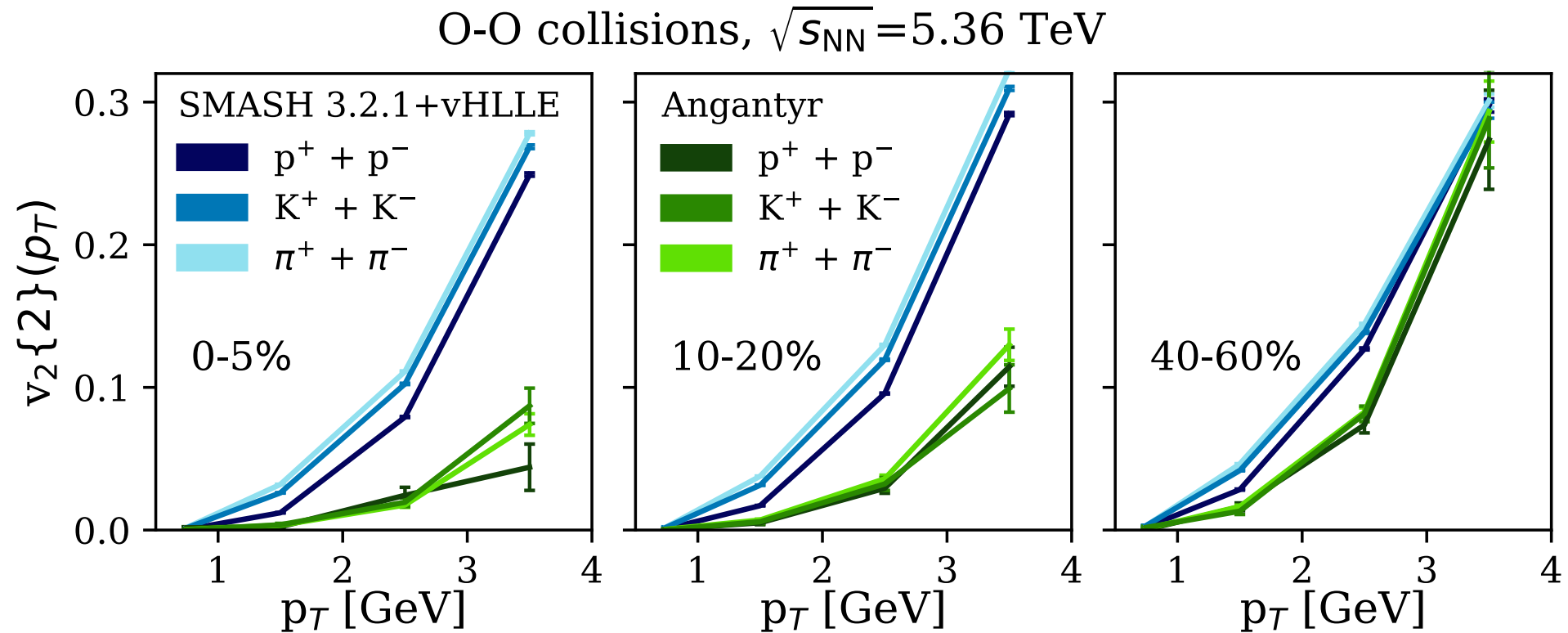
$$\langle v_n \rangle = \sqrt{\frac{v_n^2\{2\} + v_n^2\{4\}}{2}} \quad \sigma_{v_n} = \sqrt{\frac{v_n^2\{2\} - v_n^2\{4\}}{2}}$$



- Fluctuations constant in centrality

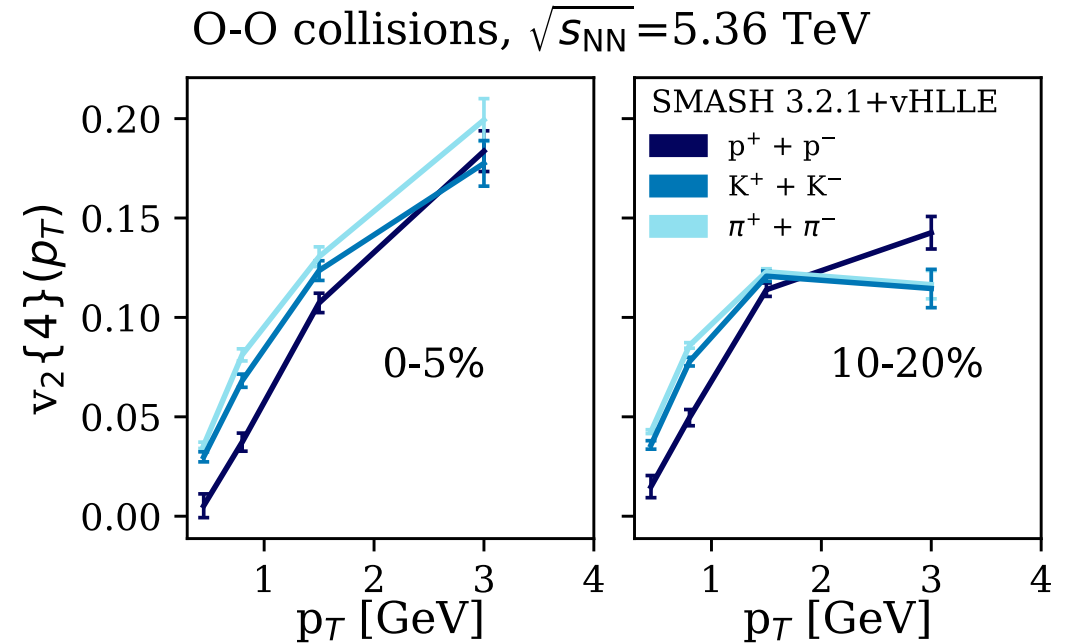
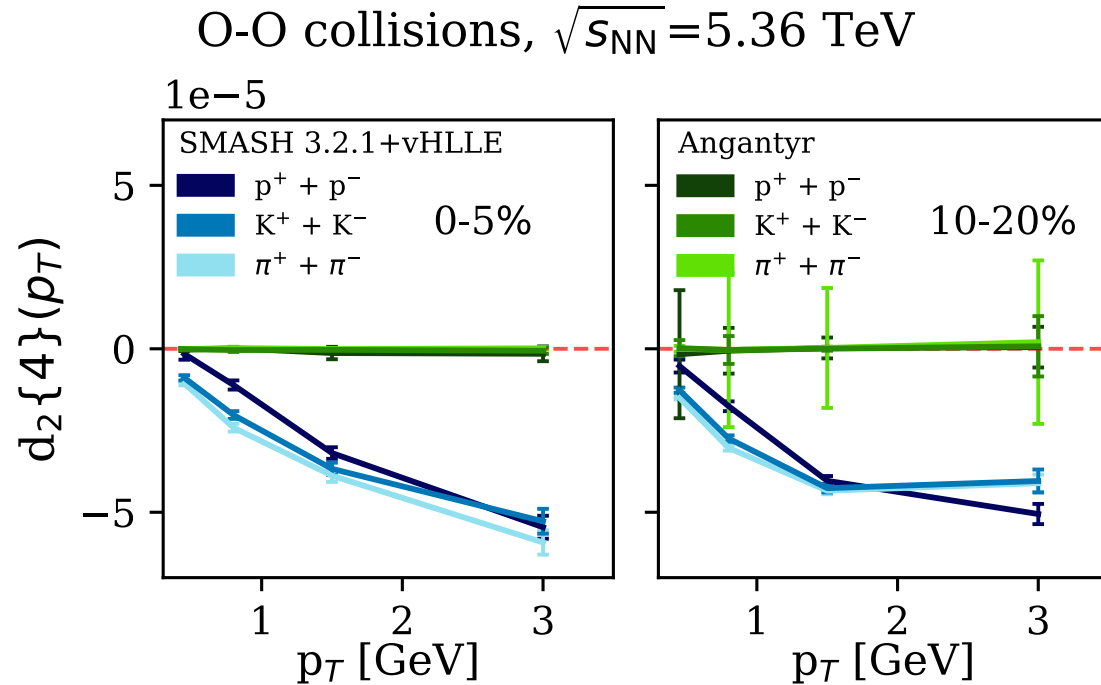
→ Trend stays the same

Differential Flow



- Hybrid shows clear mass ordering, but no baryon-meson splitting
- Angantyr shows that non-flow plays a big role at higher p_T

4-Particle Differential Flow



$$v_2\{4\}(p_T) = - \frac{d_2\{4\}(p_T)}{(-c_2\{4\})^{3/4}}$$

4-particle cumulant in a specific p_T bin
 Integrated 4-particle cumulant

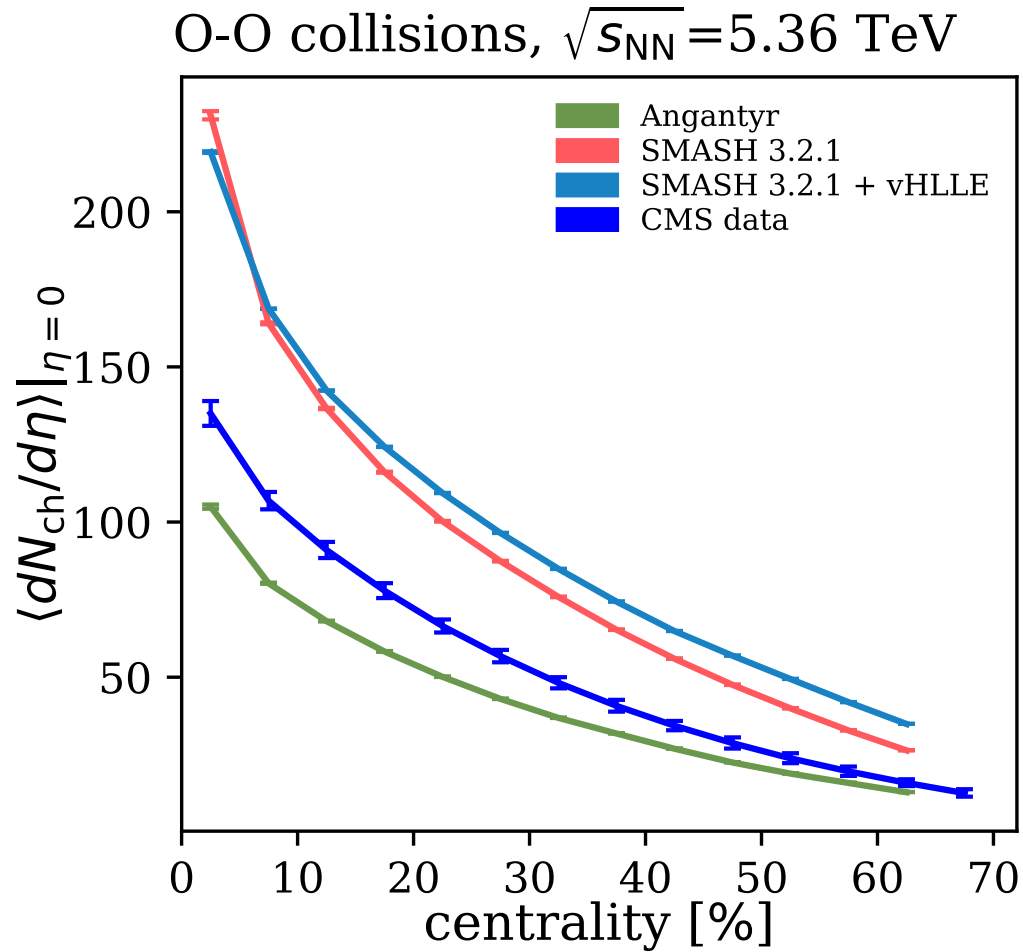
- 4-particle cumulants drastically reduce non-flow contributions at „higher“ p_T

Summary

- We made a qualitative comparison for collective effects in light-ion collisions from a hybrid approach
- We observe clear differences between collective and non-collective models
 - Opposite trend in v_n , mass ordering
- Differences between nuclear configurations only emerge in collective models
 - Neon to Oxygen ratio from hybrid model agrees well with experimental data
- Trend in data rules out pure transport description and suggests hydro-like behavior is necessary

Backup

Disclaimer!



- Bayesian analysis for the used parameters was performed at BES collision energies (7.7 – 200 GeV)

N. Götz et. al. *Phys.Rev.C* 112 (2025) 1, 014910

- Secondary interactions in SMASH under investigation:

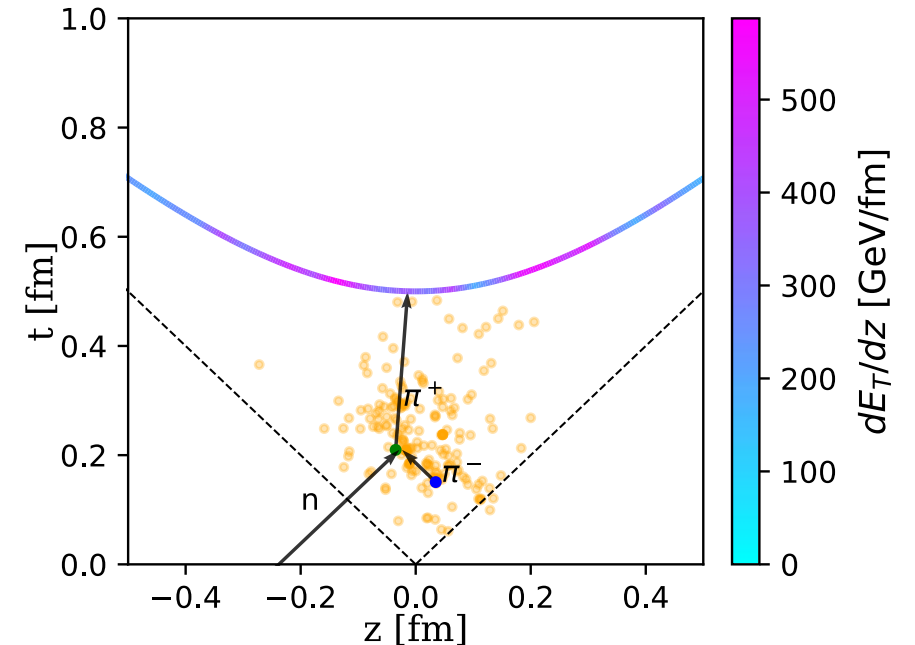
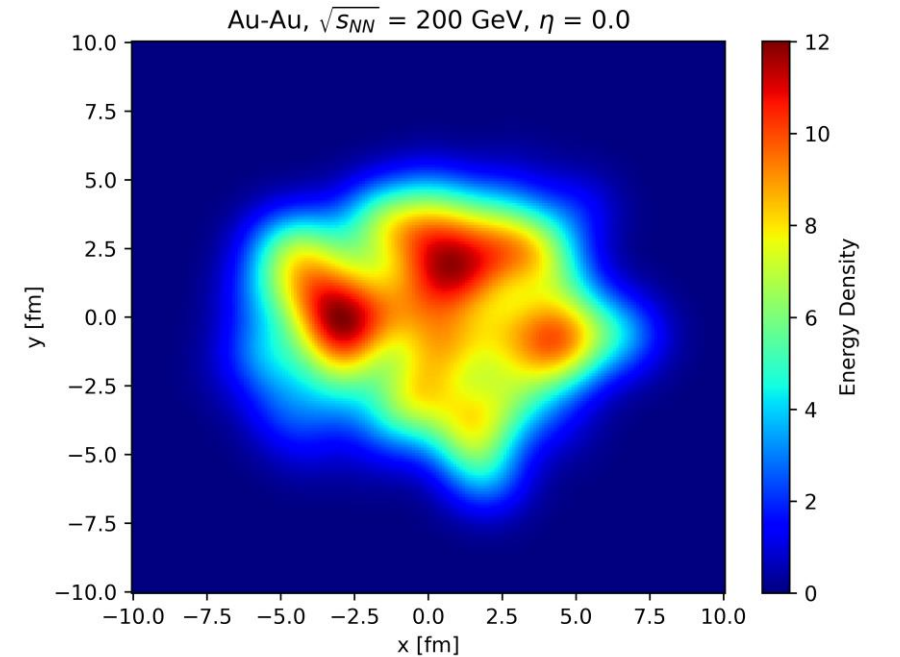
see [arxiv:2605.16914](https://arxiv.org/abs/2605.16914)

SMASH Initial Conditions

- Switching time corresponds to passing time of the two nuclei

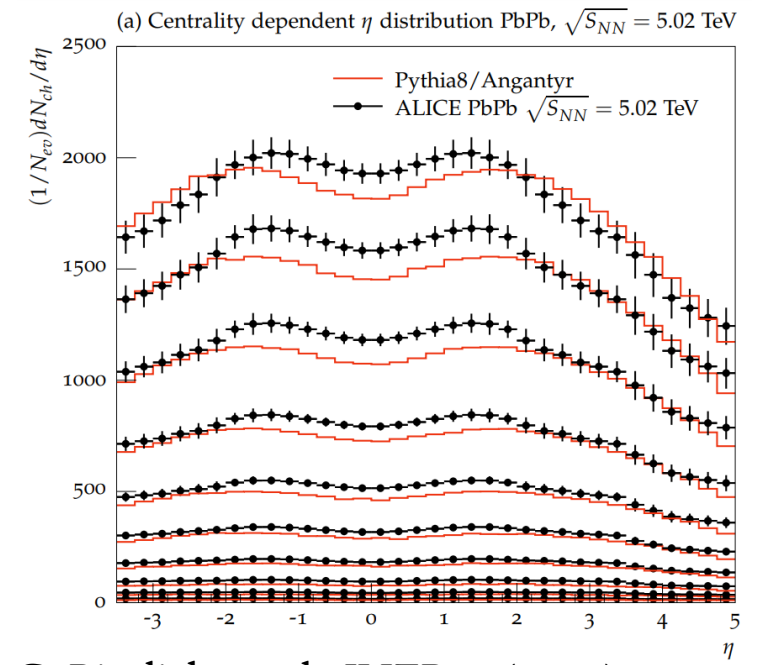
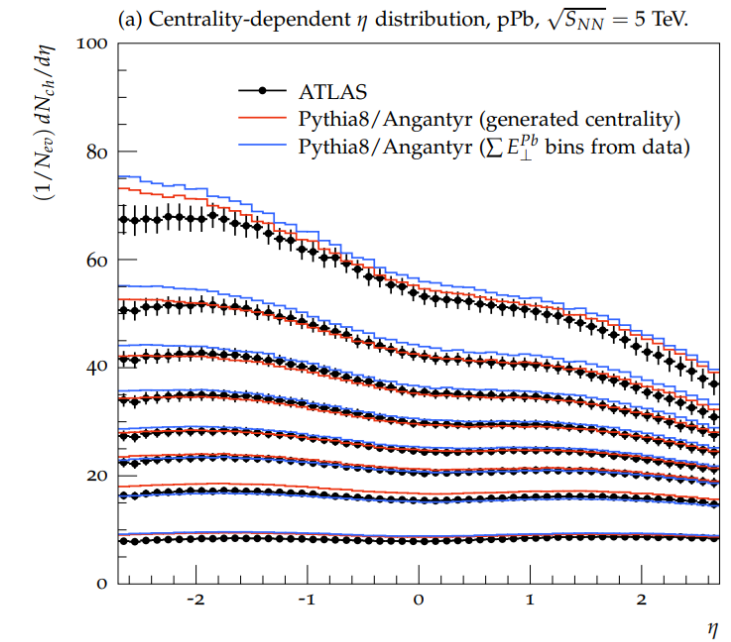
$$\tau_{\text{switch}} = \frac{R_p + R_t}{\sqrt{\left(\frac{\sqrt{s_{NN}}}{2m_N}\right)^2 - 1}}$$

- String interactions are handled in PYTHIA
- Fragmented hadrons free stream for the duration of a formation time
- Particles that cross the hypersurface get removed from the evolution



Angantyr

- Extrapolation of PYTHIA p-p events to full HIC
- Monte-Carlo Glauber model determines wounded nucleons
 - Nucleons can have primary and secondary interactions
- Sub-collisions are combined to obtain full heavy-ion event
 - Baseline for no collective effects
 - Fitted to p-p collisions and applicable to large range of system sizes



Applicability of Hydrodynamics

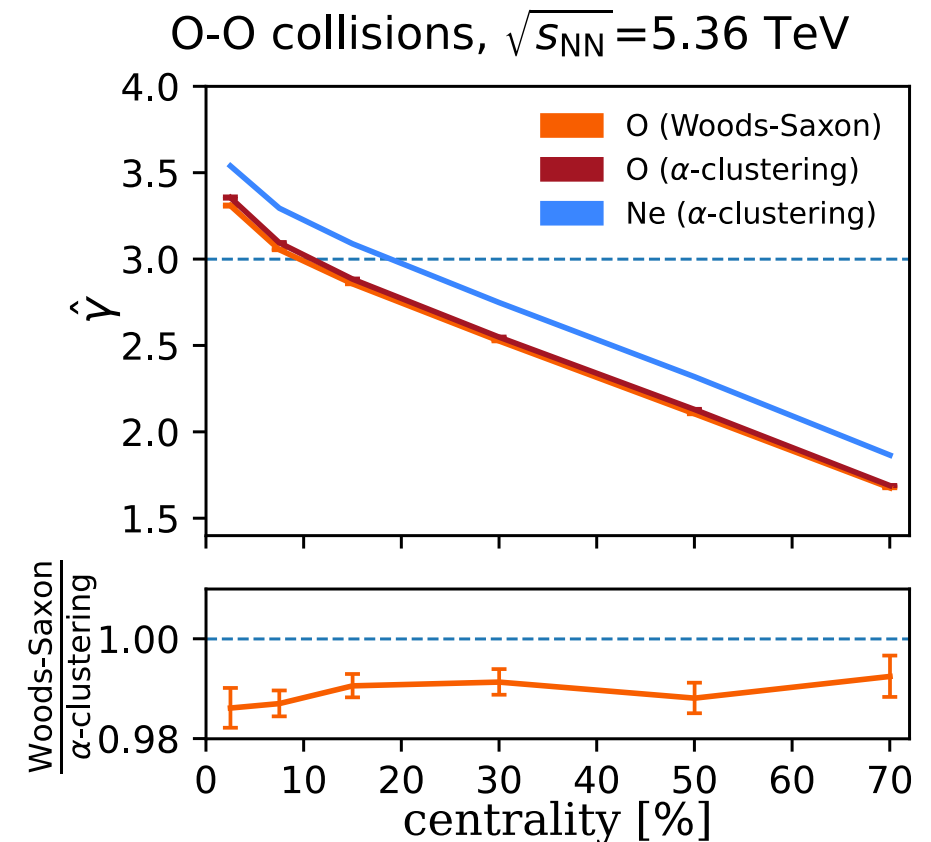
- Assumption of local thermal equilibrium not necessarily true - especially in small systems!

→ Assess the accuracy of hydrodynamics:

Opacity

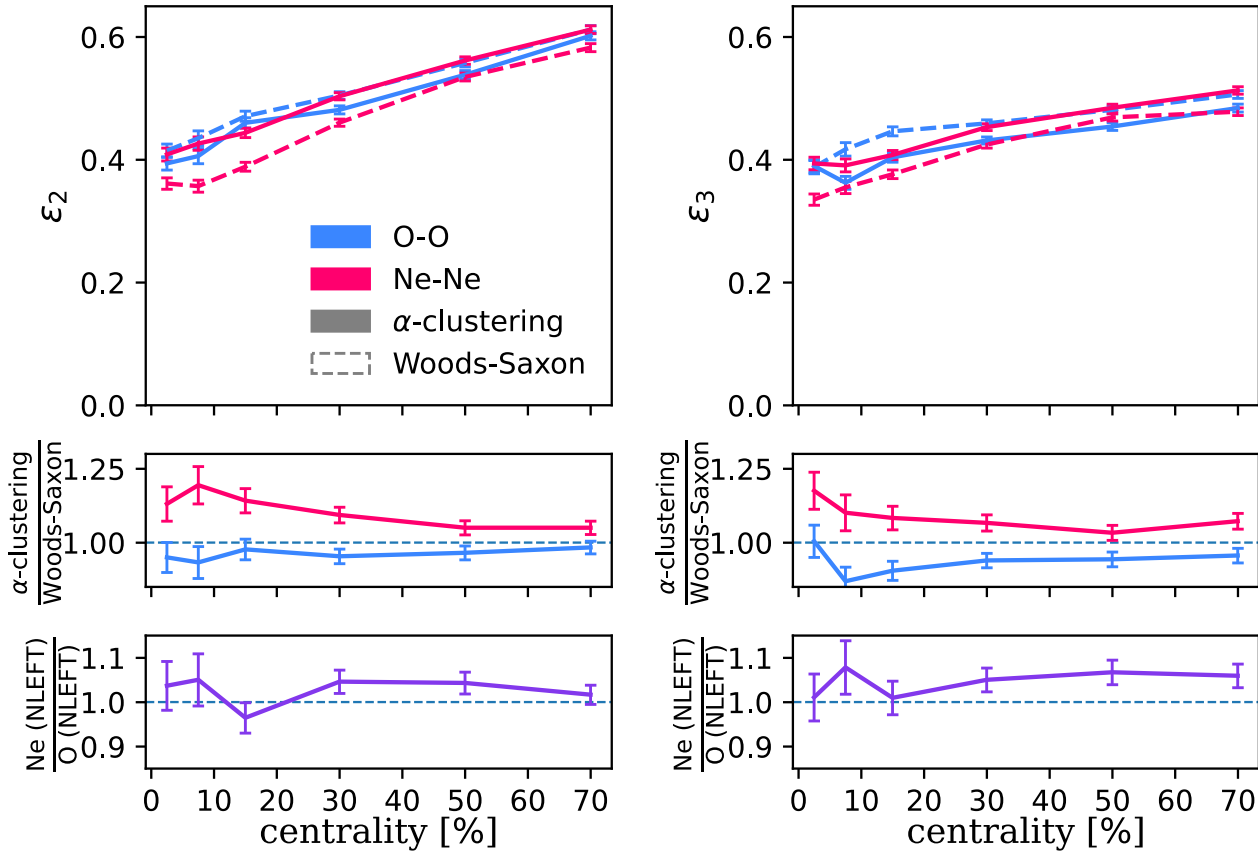
$$\hat{\gamma} = (5\eta/s)^{-1} \left(\frac{1}{a\pi} R \frac{dE_T}{d\eta_s} \right)^{\frac{1}{4}}$$

- Measure for the interaction rate
- Hydrodynamics found to be accurate to kinetic theory if $\hat{\gamma} > 3-4$



Eccentricity

SMASH 3.2.1-IC, $\sqrt{s_{NN}}=5.36$ TeV



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

- Already high ϵ_n in very central collisions
→ Dominated by event-by-event fluctuations
- α -clustering enhances ϵ_n in Ne-Ne but decreases ϵ_n in O-O
- Fluctuations, geometry and centrality selection are difficult to disentangle

How to calculate flow coefficients?

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

Cumulant Method

- Based on multi-particle correlations
- Cumulants capture genuinely correlated part of a distribution function

$$c_n\{2\} = \left\langle \left\langle e^{in(\phi_1 - \phi_2)} \right\rangle \right\rangle$$

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

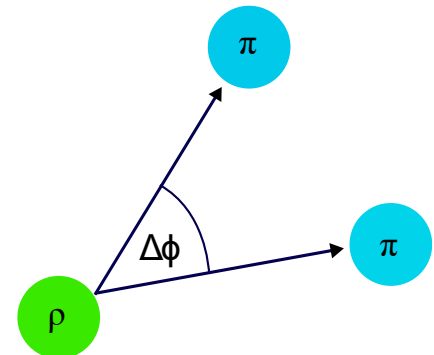
$$v_n\{2\} = \sqrt{c_n\{2\}}$$

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

→ K-particle cumulant does not contain contributions from lower order particle correlation

Problem: Non-Flow

- Correlations that do not originate from collective flow
- Sources: Momentum Conservation, particle decays, back-to-back jets
- Scaling with $\frac{1}{N-1}$
- Close in phase space
→ Only take particles far in rapidity



Transverse Momentum Spectra

