Collective effects in small collision systems from a hybrid approach

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in collaboration with

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arxiv:2509.05613

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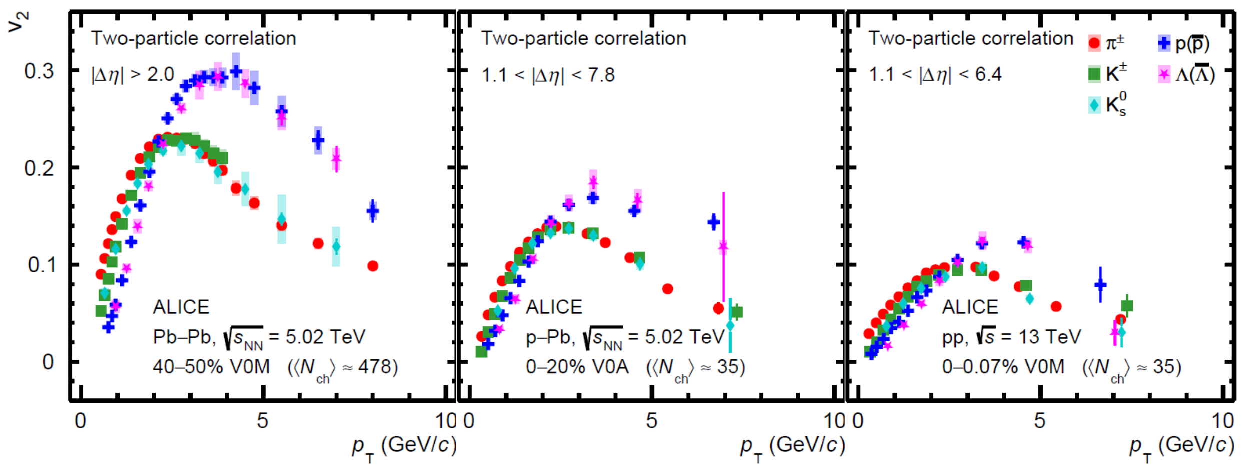
Initial Stages 2025

September 9th

CRC–TR 211 Strong-interaction matter under extreme conditions

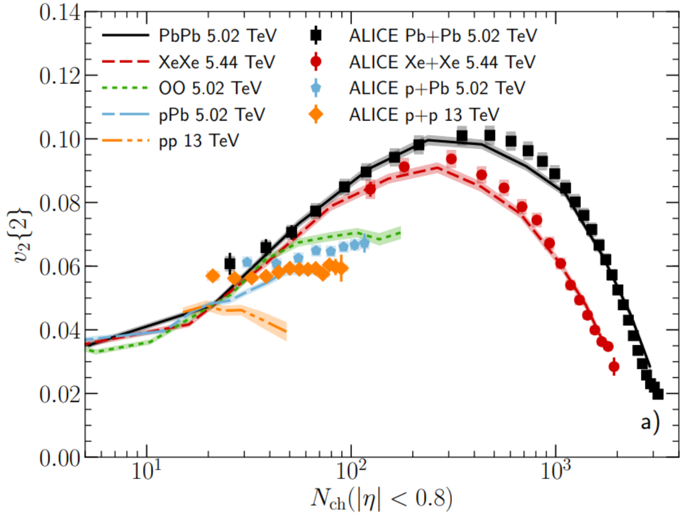
Motivation

- Anisotropic flow in p-p and p-Pb, but no jet-quenching

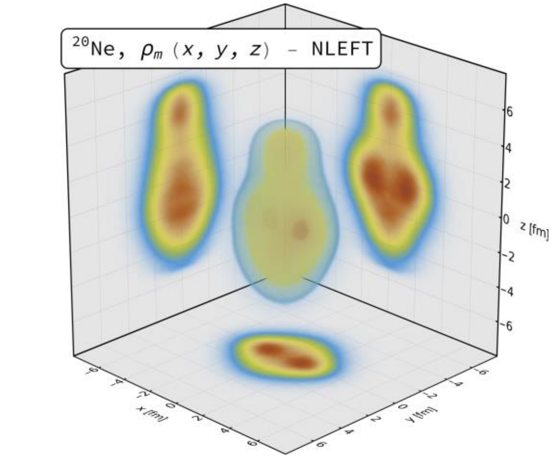


ALICE Collaboration arXiv:2411.09323

→What about intermediate small systems like O-O and Ne-Ne?

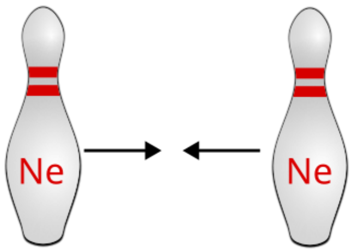


Schenke et. al. *Phys.Rev.C* 102 (2020) 4, 044905



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

Nuclear Structure



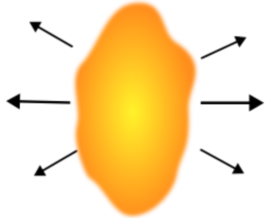
NLEFT

Spatial Anisotropy

Eccentricity

Hydro?

Momentum Anisotropy



Elliptic Flow

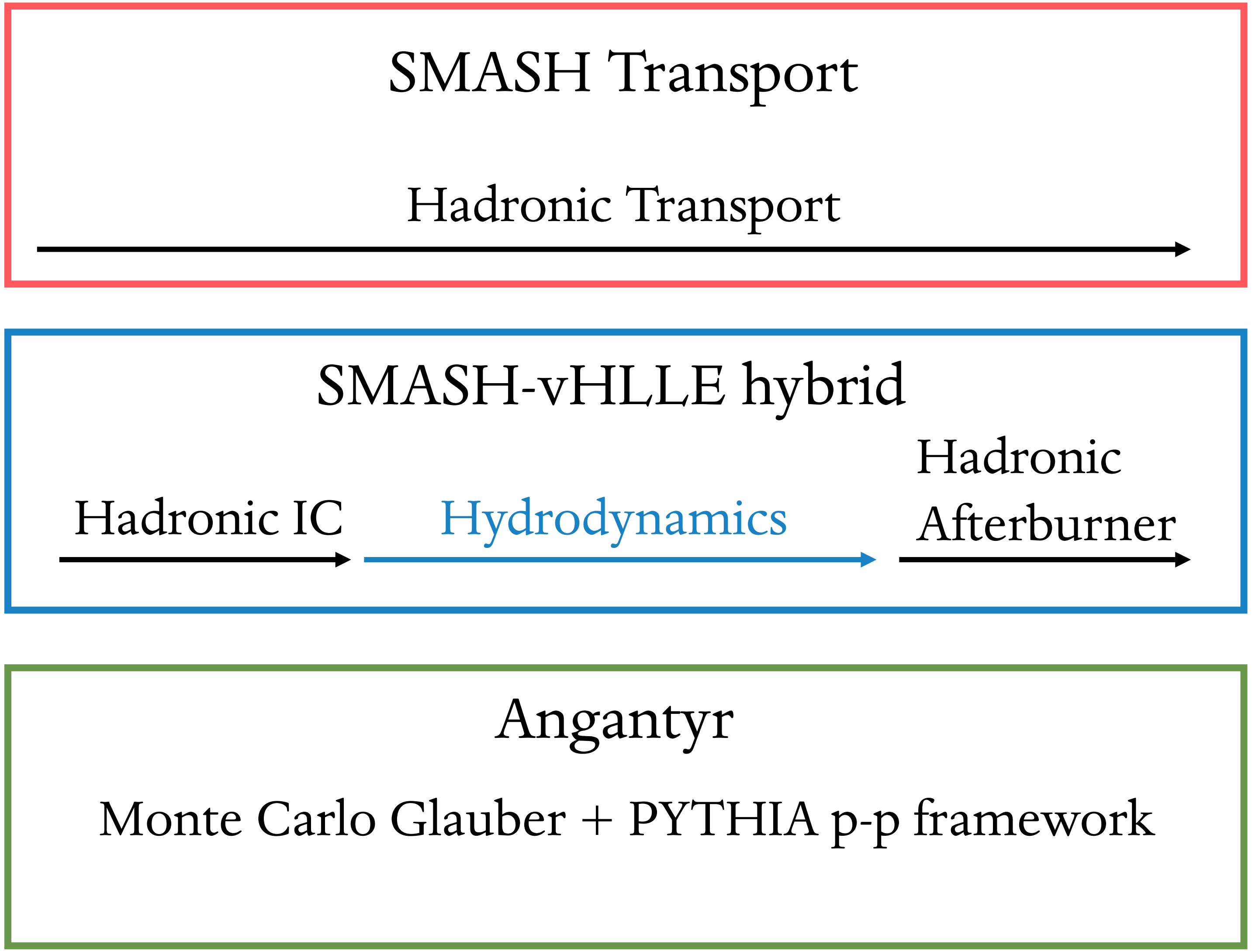
Triangular Flow

Plan of this work

- Compare models with and without hydrodynamic evolution <u>on equal basis</u>

- Angantyr serves as baseline for no collective effects

→ Analyze observables for collectivity like R_{AA} and anisotropic flow



The SMASH-vHLLE hybrid

SMASH Initial Conditions

- Boltzmann equation

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

- PYTHIA for string excitations
- Particles are removed from evolution upon crossing a τ-hypersurface

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

vHLLE

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

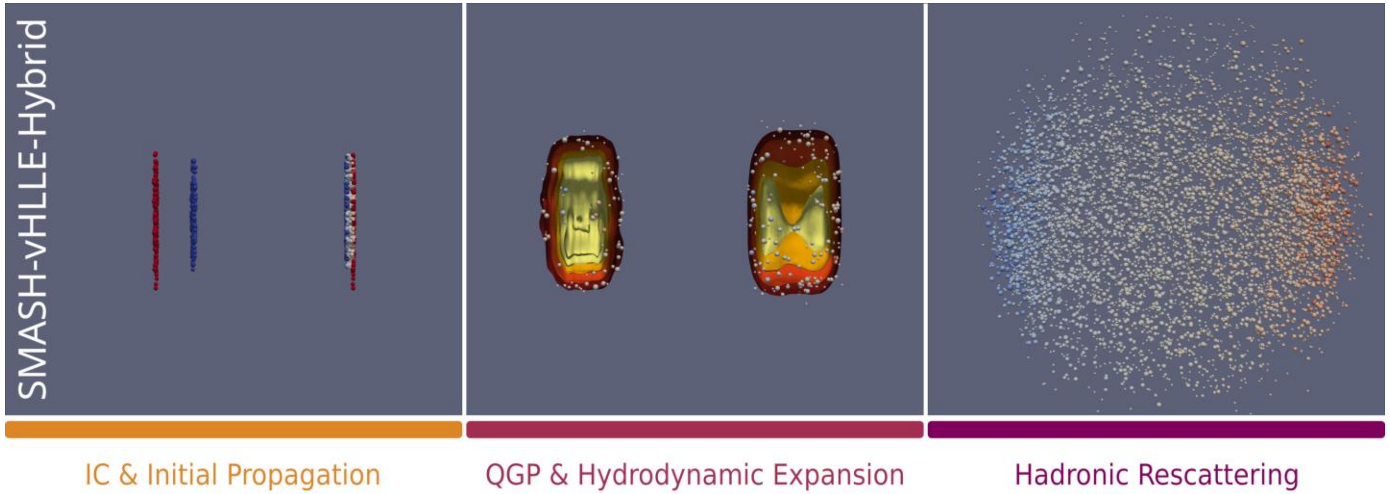
$$\Delta K = \exp\left(-\frac{\Delta x^2+\Delta y^2}{R_\perp^2} - \frac{\Delta\eta^2}{R_\eta^2}\gamma_\eta^2\tau_0^2\right)$$

$R_\perp = 0.65$ fm $\quad R_\eta = 1.66$ fm

Particlization & Afterburner

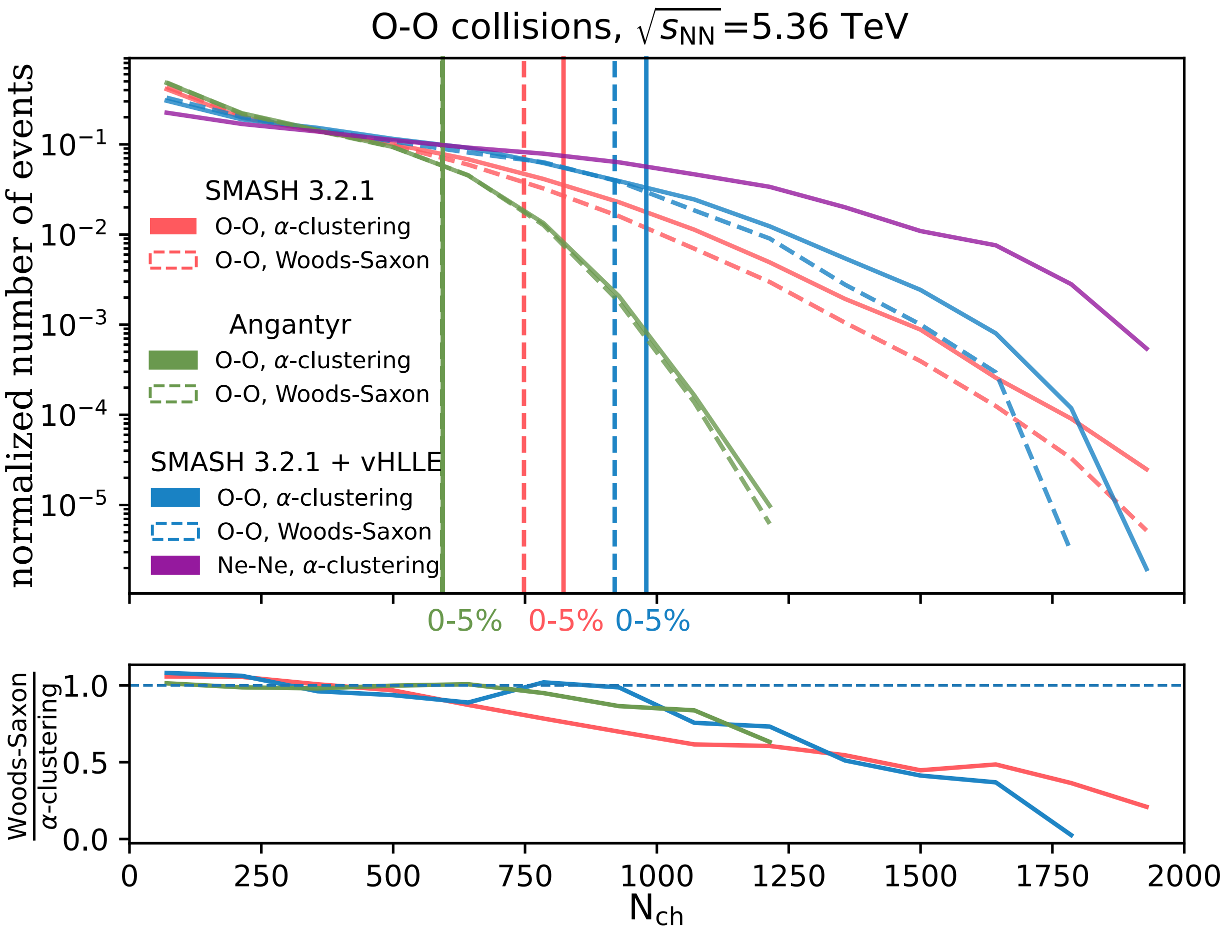
- Cooper-Frye sampling at hypersurface of constant energy density ε_{switch}
- Hadronic transport for rescatterings

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



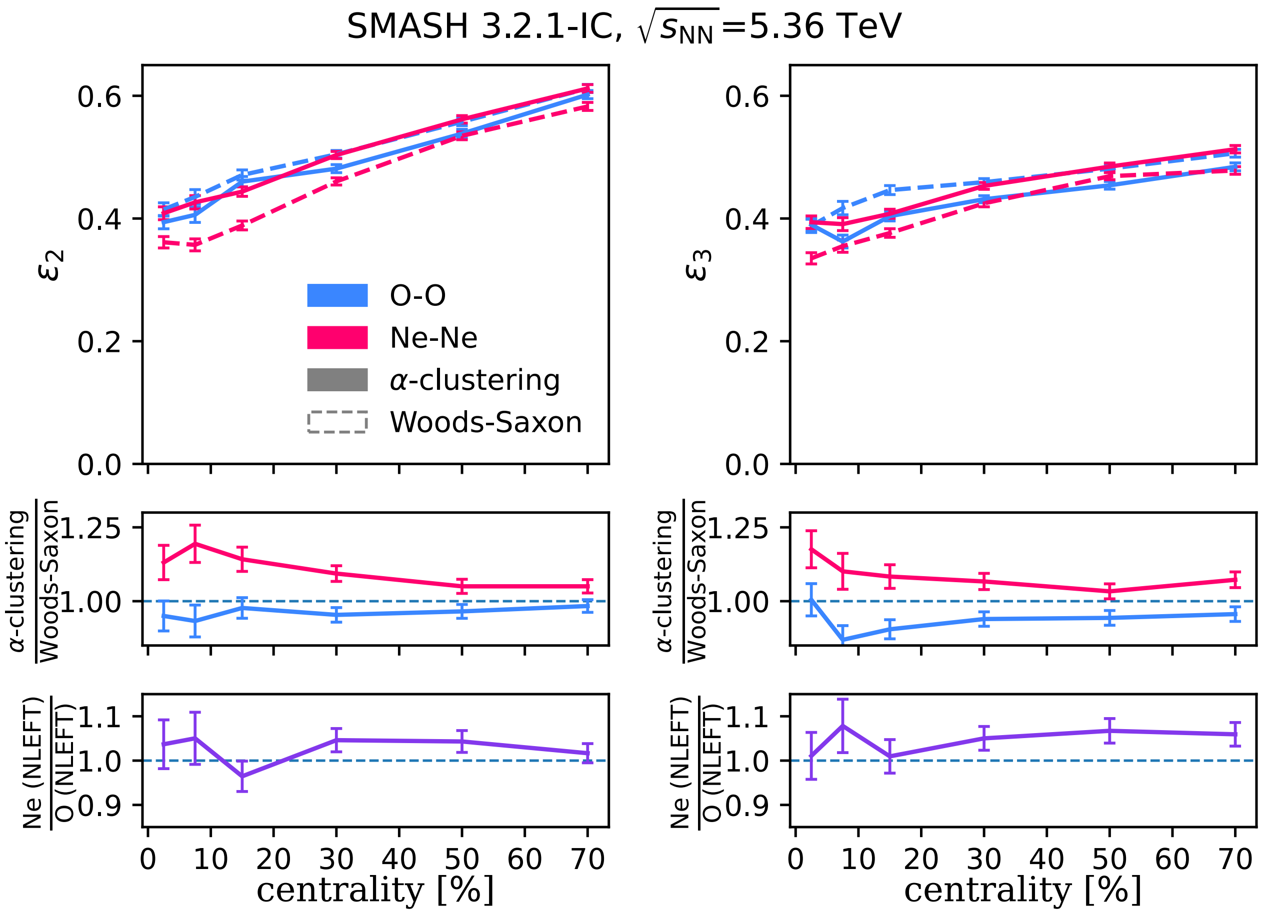
Bayesian analysis by N. Götz et. al.
Phys.Rev.C 112 (2025) 1, 014910

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?

Eccentricity



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

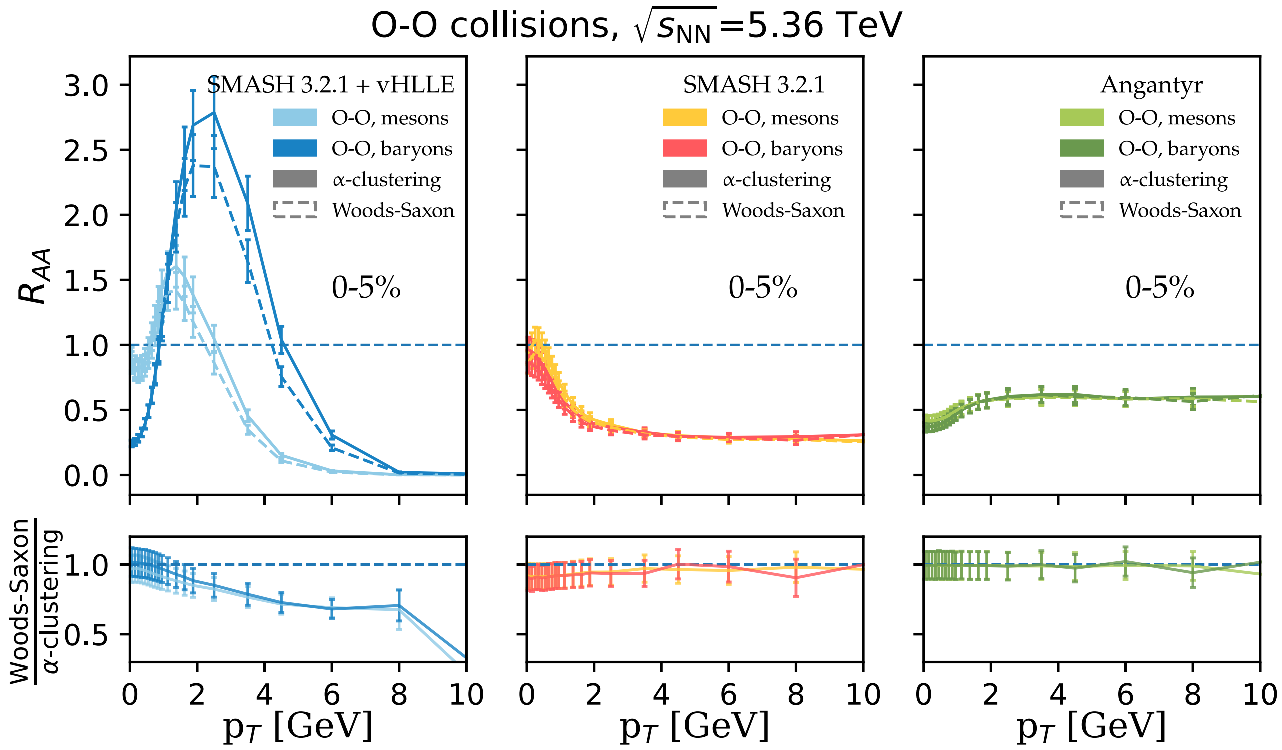
- Already high ε_n in very central collisions
  → Dominated by event-by-event fluctuations

- α-clustering enhances ε_n in Ne-Ne but decreases ε_n in O-O

- Fluctuations, geometry and centrality selection are difficult to disentangle

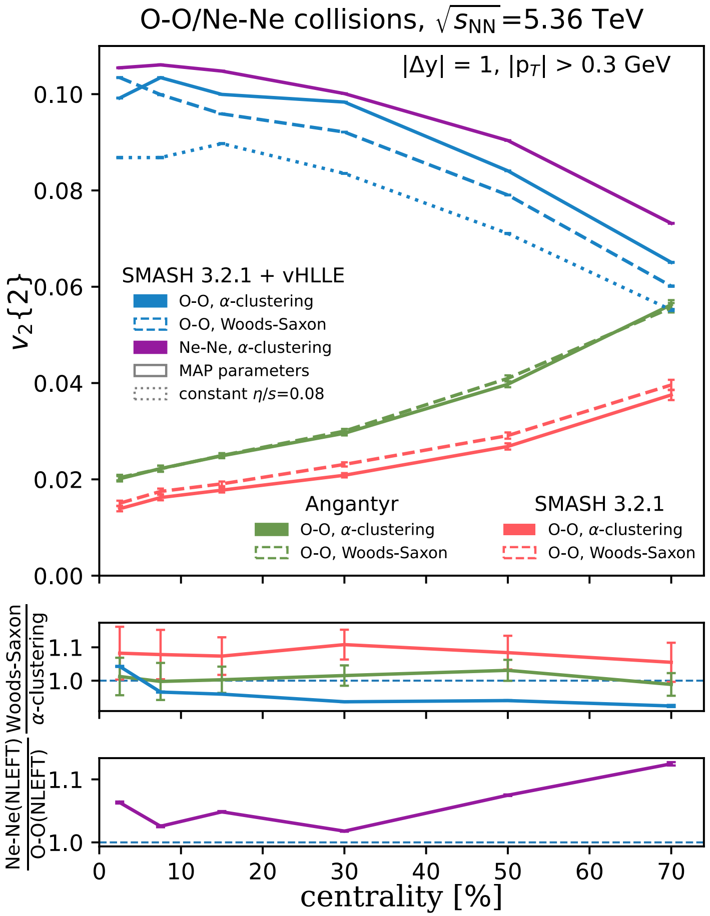
Nuclear Modification Factor

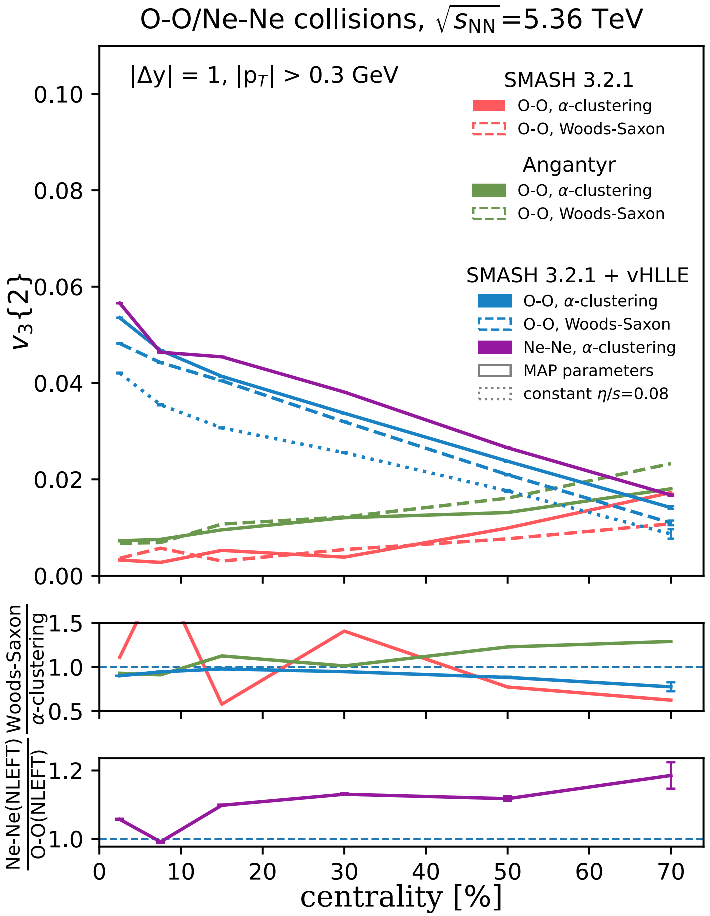
$$R_{\mathrm{AA}}(p_T) = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{\mathrm{d}^2 N_{\mathrm{AA}}/\mathrm{d}p_T \mathrm{d}y}{\mathrm{d}^2 N_{\mathrm{pp}}/\mathrm{d}p_T \mathrm{d}y}\Bigg|_{y=0}$$



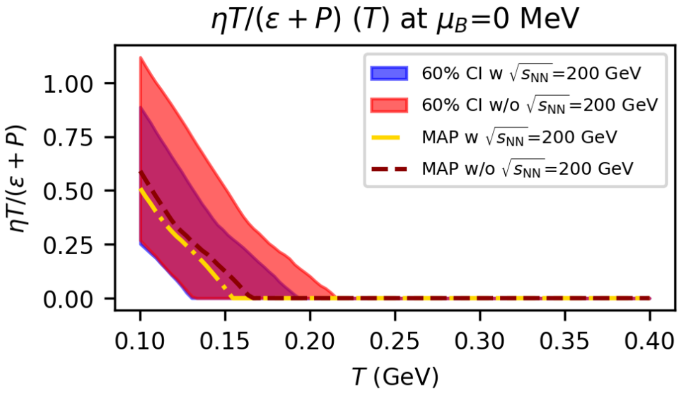
- Hybrid: expected result for thermal over vacuum spectra
  - → Mass ordering clear sign of radial flow
- SMASH: enhancement at low p_T
  - → Stopping from hadronic medium
- Angantyr: almost constant
- Only hybrid shows difference between nuclear configurations

2-Particle Anisotropic Flow





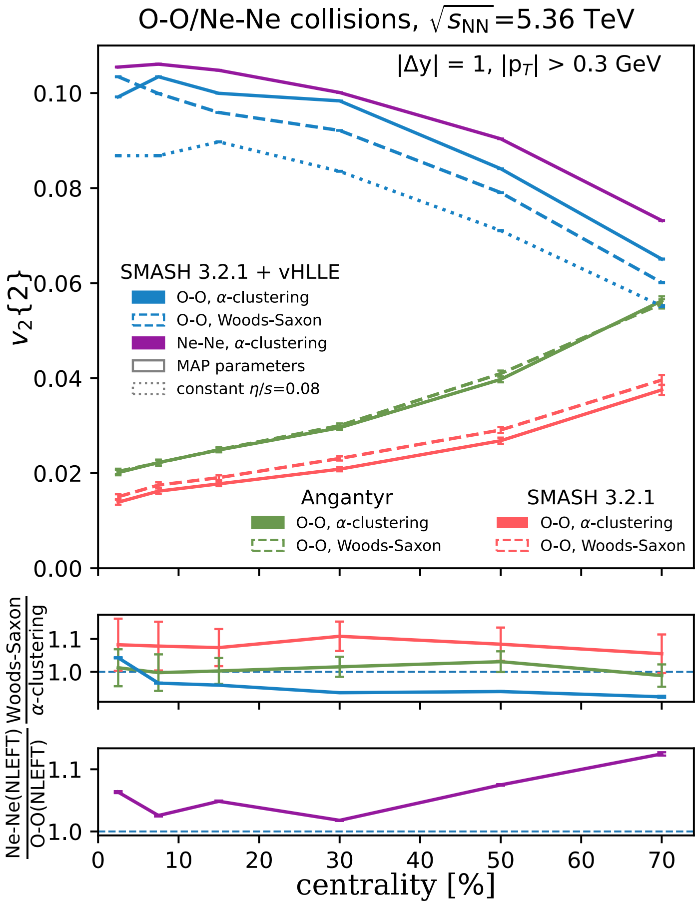
- Opposite behavior between collective and non-collective models
- Increase in SMASH and Angantyr with centrality due to non-flow
- Angantyr shows no difference between nuclear configurations

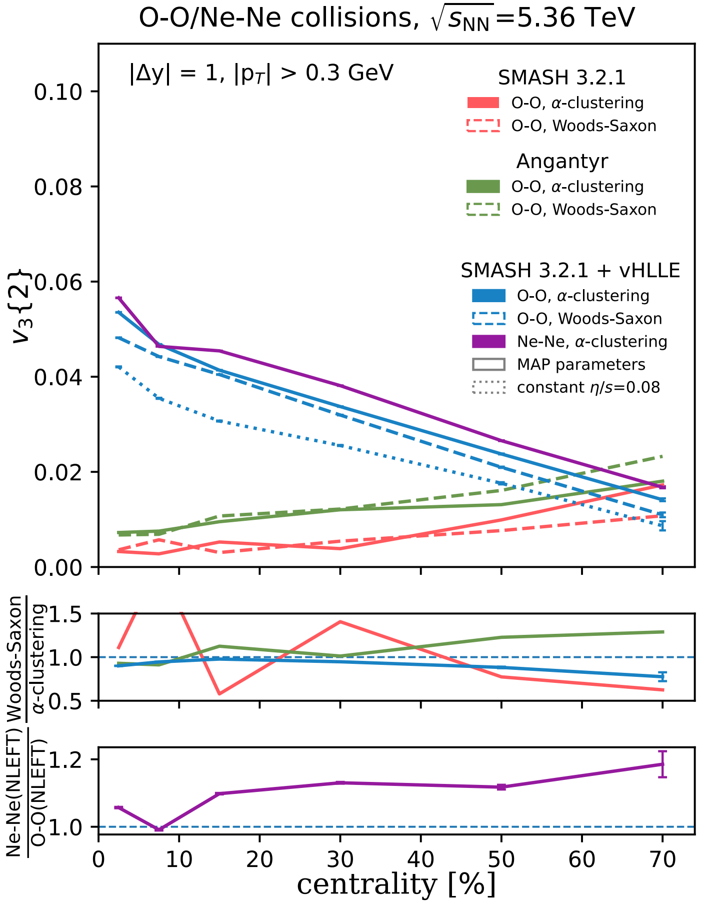


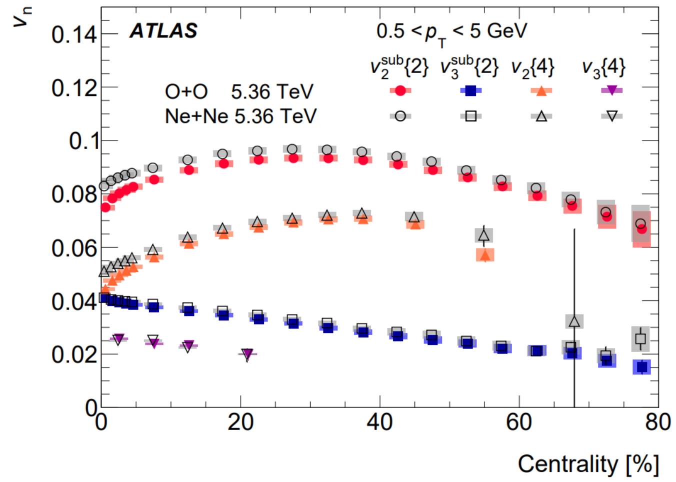
N. Götz et. al. *Phys.Rev.C* 112 (2025) 1, 014910

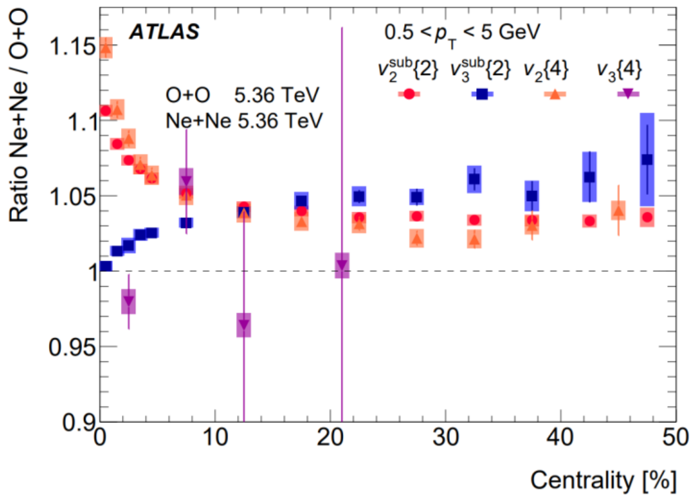
→ Values are sensitive to parameters, but the qualitative behavior stays the same

Experimental Data





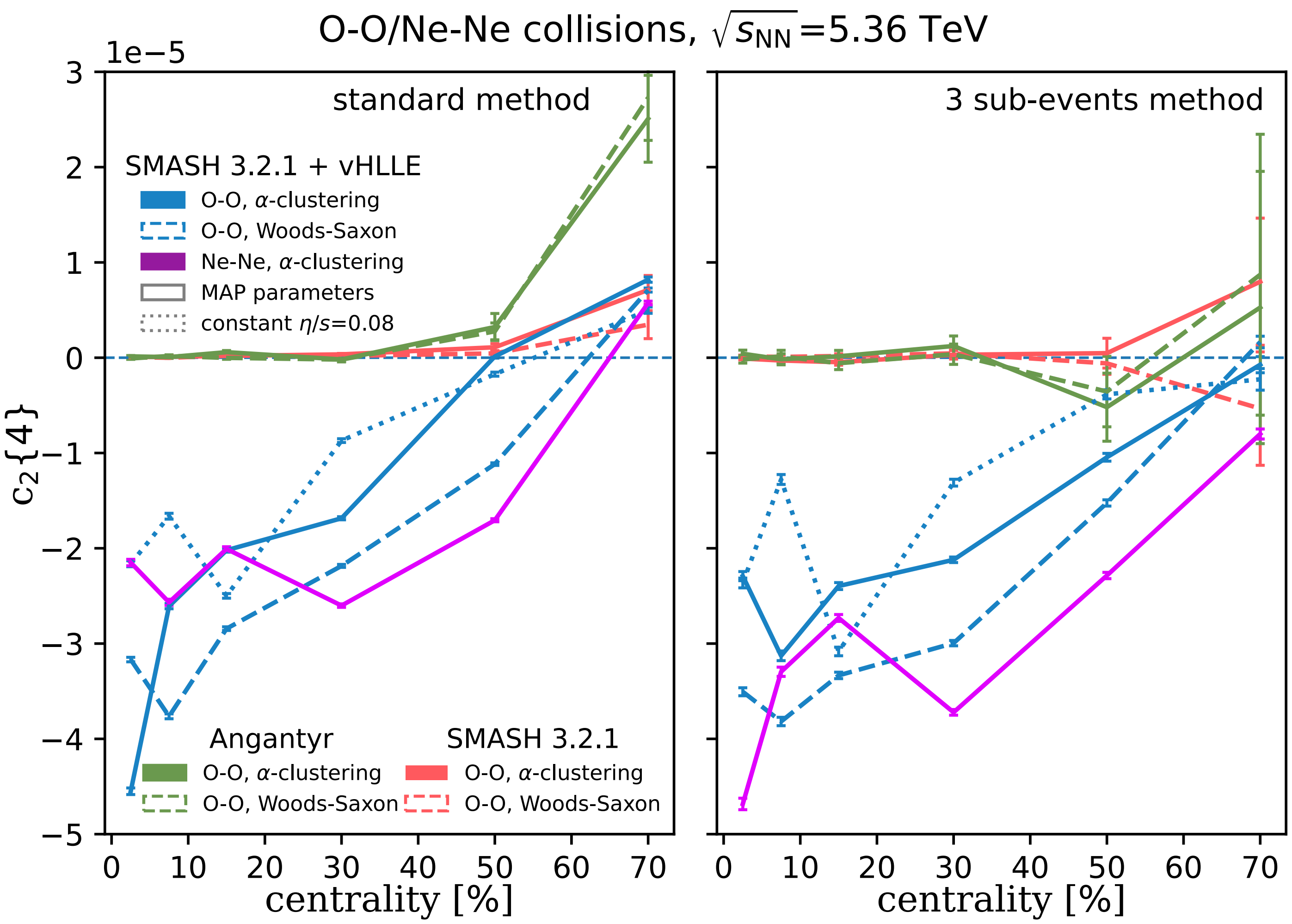


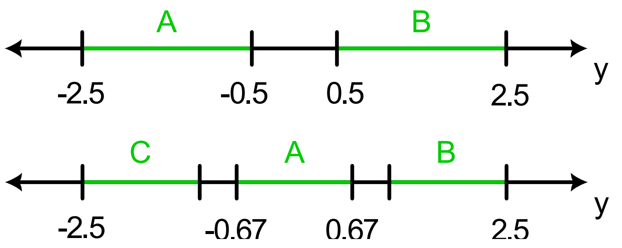


- Hybrid with constant η/s in good agreement with data!

ATLAS Collaboration, arXiv:2509.05171

4-Particle Cumulants





- $c_2\{4\}$ 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

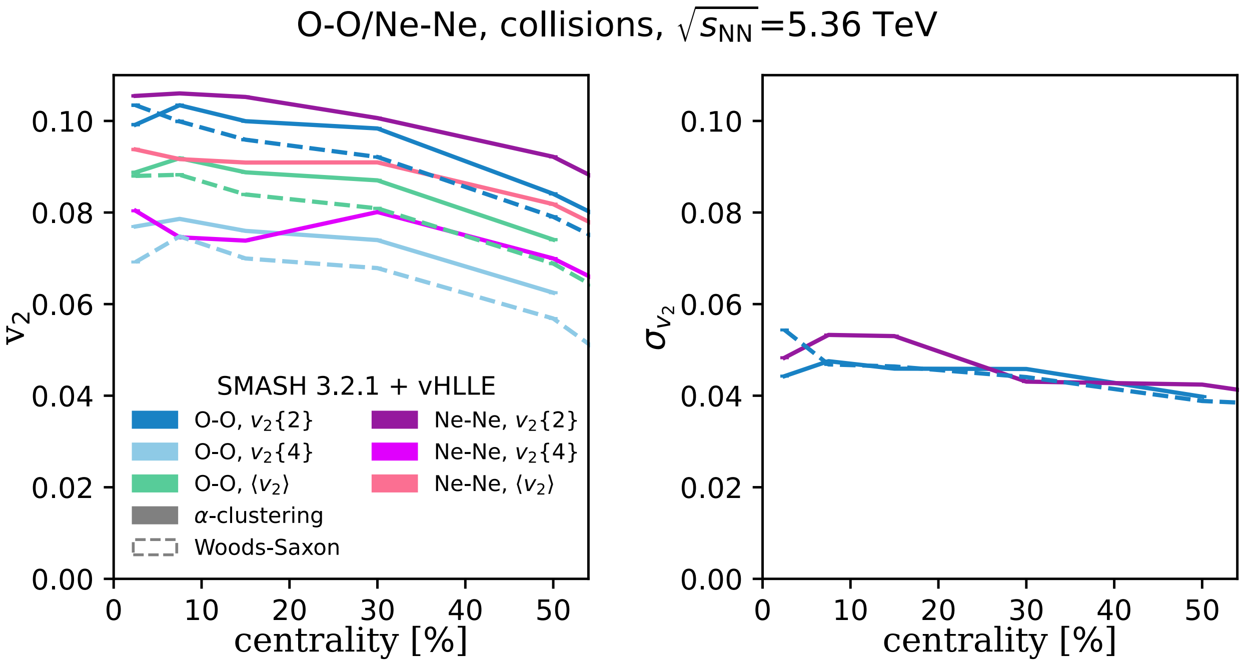
- Cumulant method gives estimates for flow coefficients raised to the 2^{nd} / 4^{th} power

→ Systematically biased by flow fluctuations

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

Unbiased flow coefficients:

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

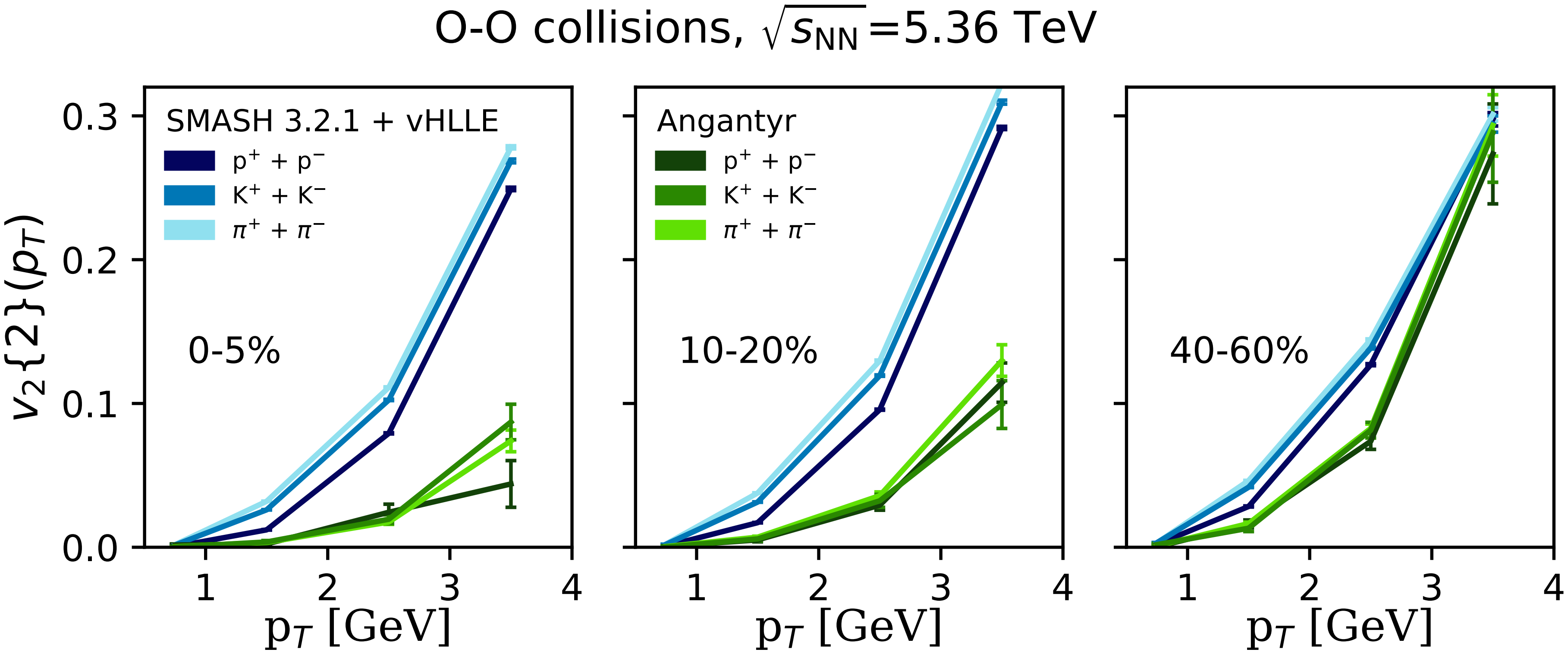


- Fluctuations constant in centrality

→ Trend stays the same

Jean-Yves Ollitrault et. al., *Phys.Rev.C* 80 (2009) 014904

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

Summary and Outlook

- Qualitative predictions for collective effects in light ion collisions from a hybrid approach

- We observe clear difference between collective and non-collective models
  →Opposite trend in v_n , mass ordering

- Differences between nuclear configurations only emerge in collective models
  →Giveaway for collectivity when comparing O-O and Ne-Ne in experiment

- Experimental data presented this week agrees well with the hybrid approach

All of the software is public! SMASH Transport SMASH-vHLLE hybrid PYTHIA 8

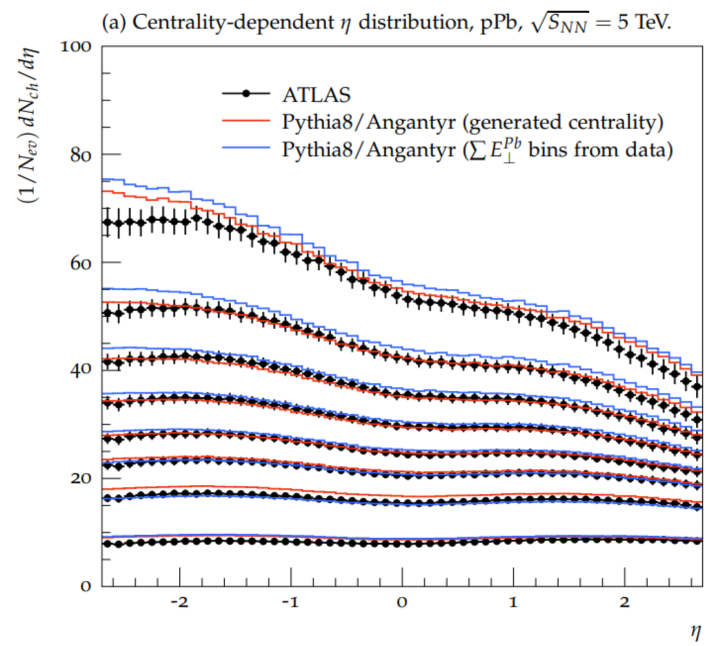
Backup

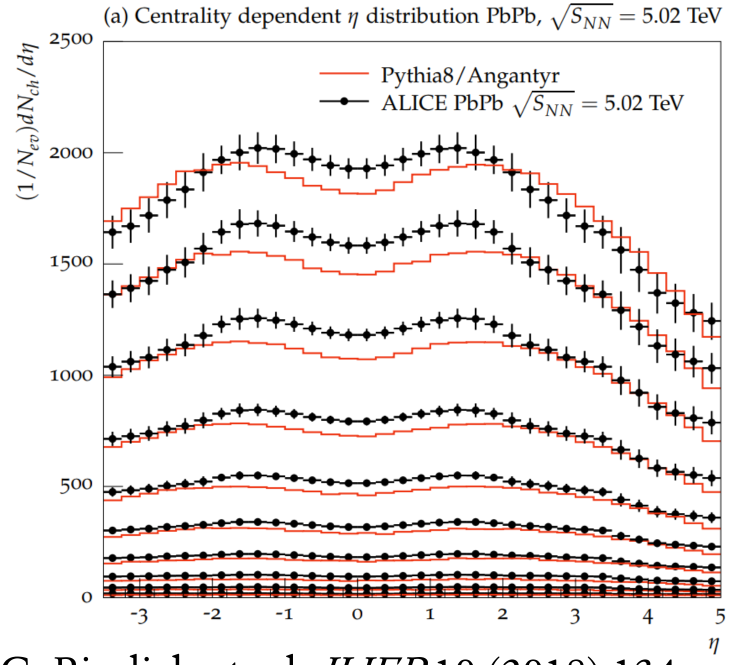
Angantyr

- 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





C. Bierlich et. al. *JHEP* 10 (2018) 134

Applicability of Hydrodynamics

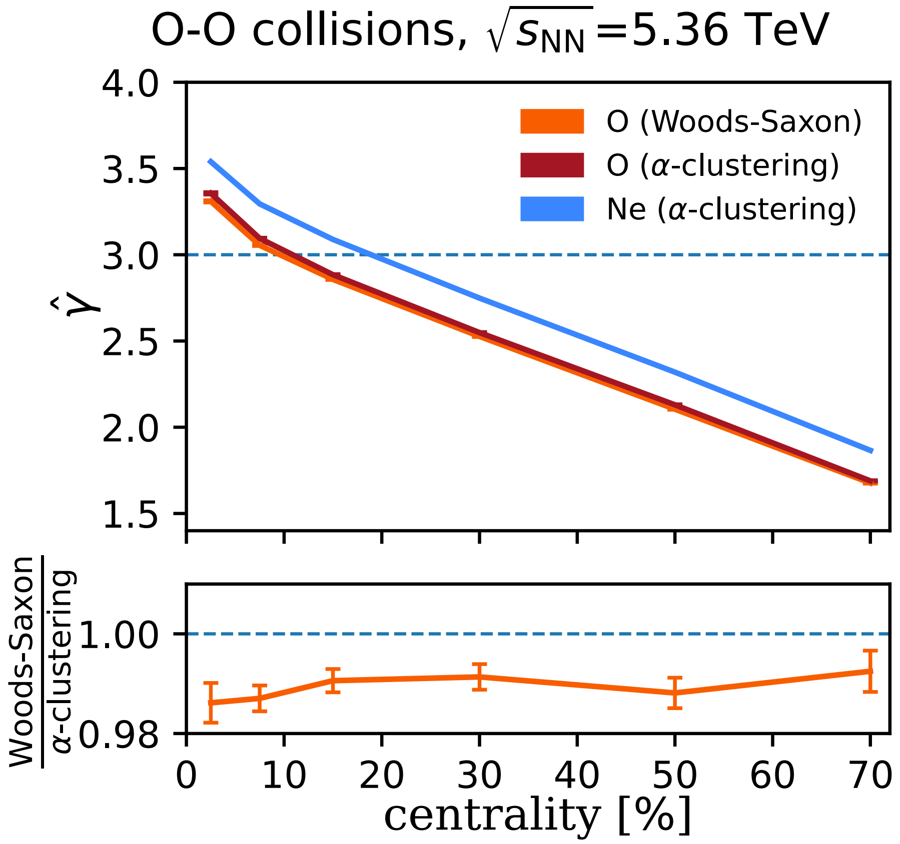
- Assumption of local thermal equilibrium not necessarily true - especially in small systems!

→Assess the accuracy of hydrodynamics:

Opacity

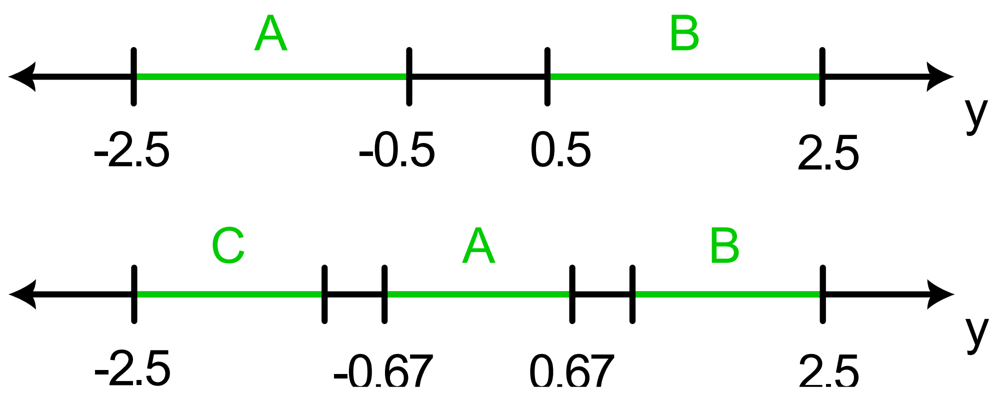
$$\hat{\gamma} = (5\eta/s)^{-1} \left(\frac{1}{a\pi} R \frac{dE_T}{d\eta_s} \right)^{\frac{1}{4}}$$

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



V. E. Ambrus, S. Schlichting and C. Werthmann, *Phys. Rev. D* 107 (2023) 094013

3-sub-event Method



Q-Vector

$$Q_n = \sum_i^M = e^{in\phi_i},$$

4-particle correlation:

$$\langle 4 \rangle_{a,a|b,c} = \frac{(Q_{n,a}^2 - Q_{2n,a})Q_{n,b}^* Q_{n,c}^*}{M_a(M_a - 1)M_b M_c}$$

4-particle cumulant:

$$c_n^{a,a|b,c}\{4\} = \langle\langle 4 \rangle\rangle_{a,a|b,c} - 2 \langle\langle 2 \rangle\rangle_{a|b} \langle\langle 2 \rangle\rangle_{a|c} .$$

→ 2-particle correlations are subtracted

→ Only contains genuine 4-particle correlations