

# Collective effects in small collision systems from a hybrid approach

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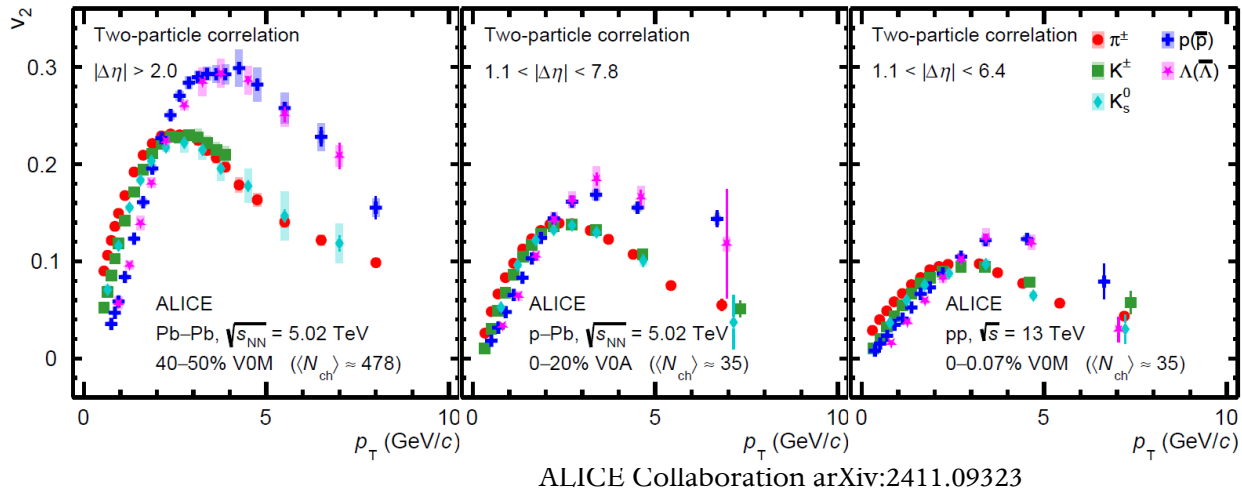
in collaboration with

Niklas Götz, Carl B. Rosenkvist and Hannah Elfner

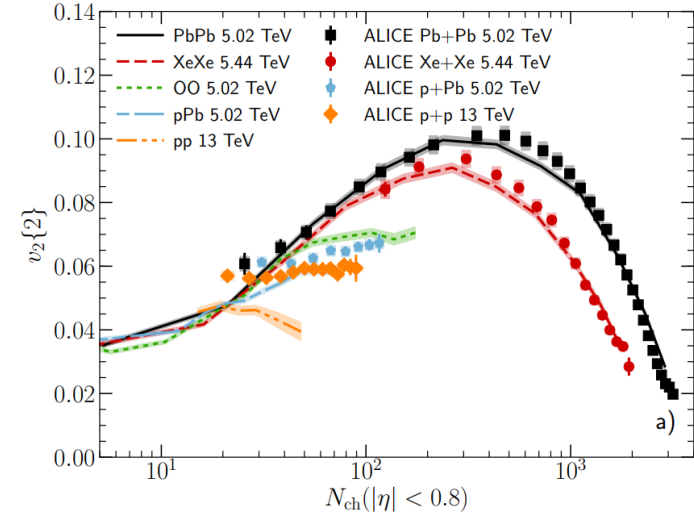
arxiv:2509.XXXX

# Motivation

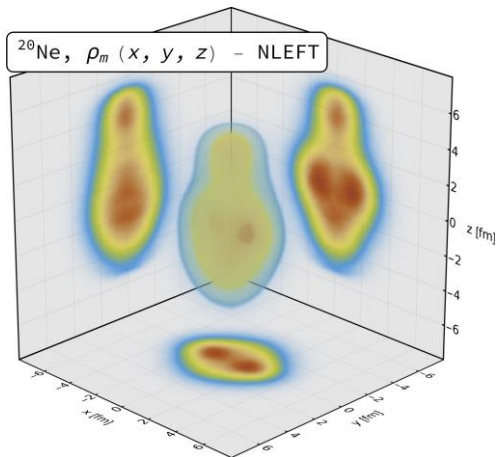
- Anisotropic flow in p-p and p-Pb, but no jet-quenching



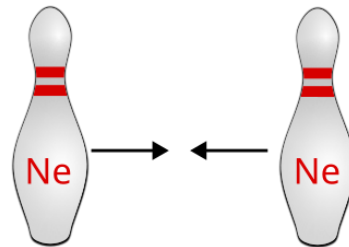
→ What about intermediate small systems like O-O and Ne-Ne?



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



Nuclear Structure



NLEFT

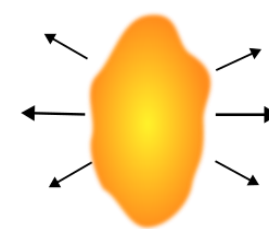
Spatial Anisotropy



Eccentricity

Hydro?

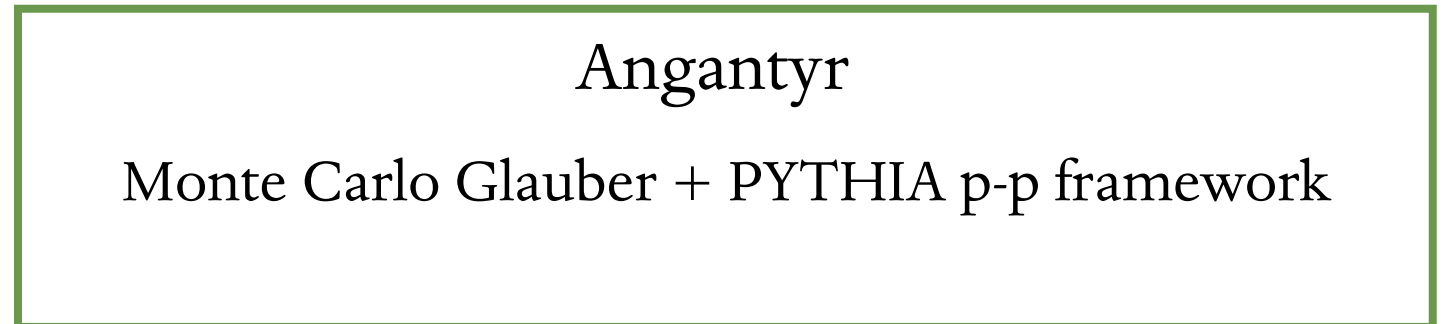
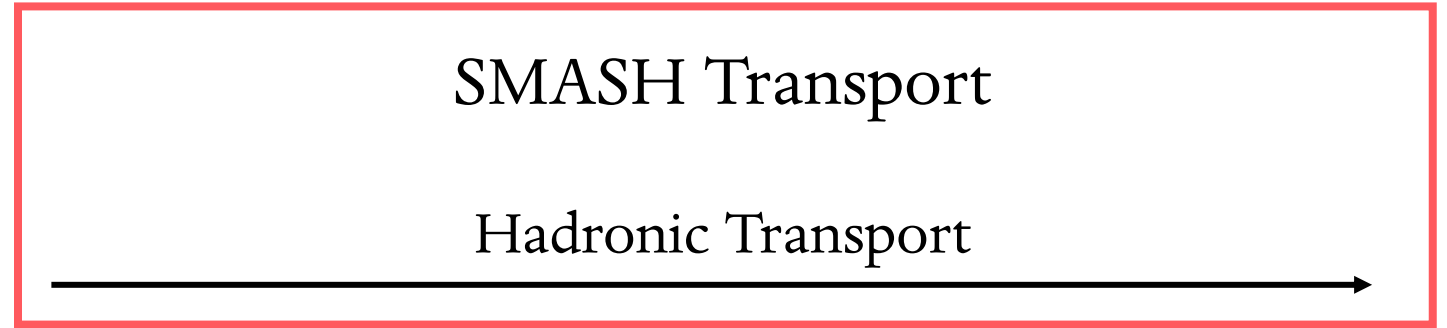
Momentum Anisotropy



Elliptic Flow  
Triangular Flow

# 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 anisotropic flow



# The SMASH-vHLL E 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  $\tau$ -hypersurface

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

## vHLL E

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

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

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

## Particlization & Afterburner

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

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



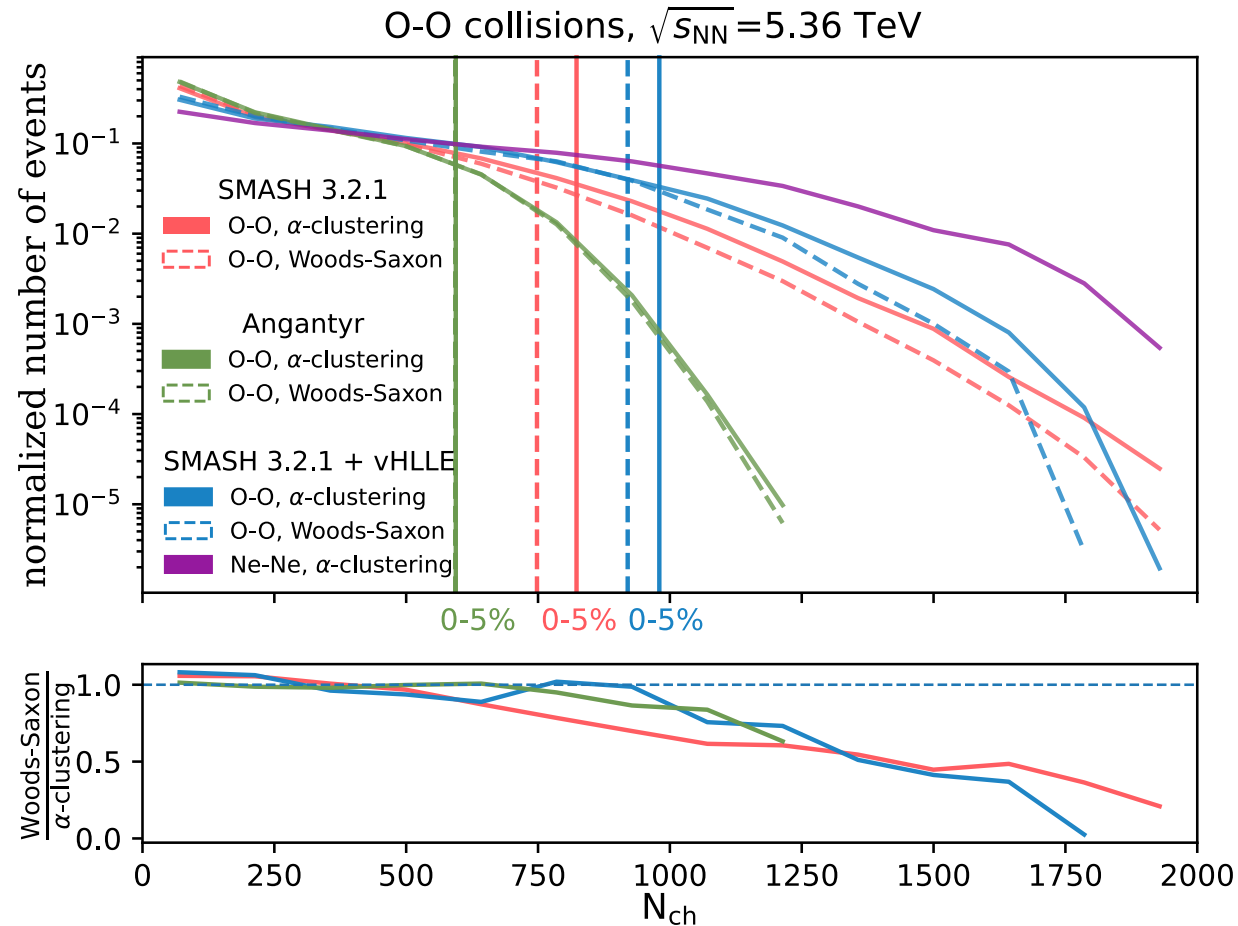
IC & Initial Propagation

QGP & Hydrodynamic Expansion

Hadronic Rescattering

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

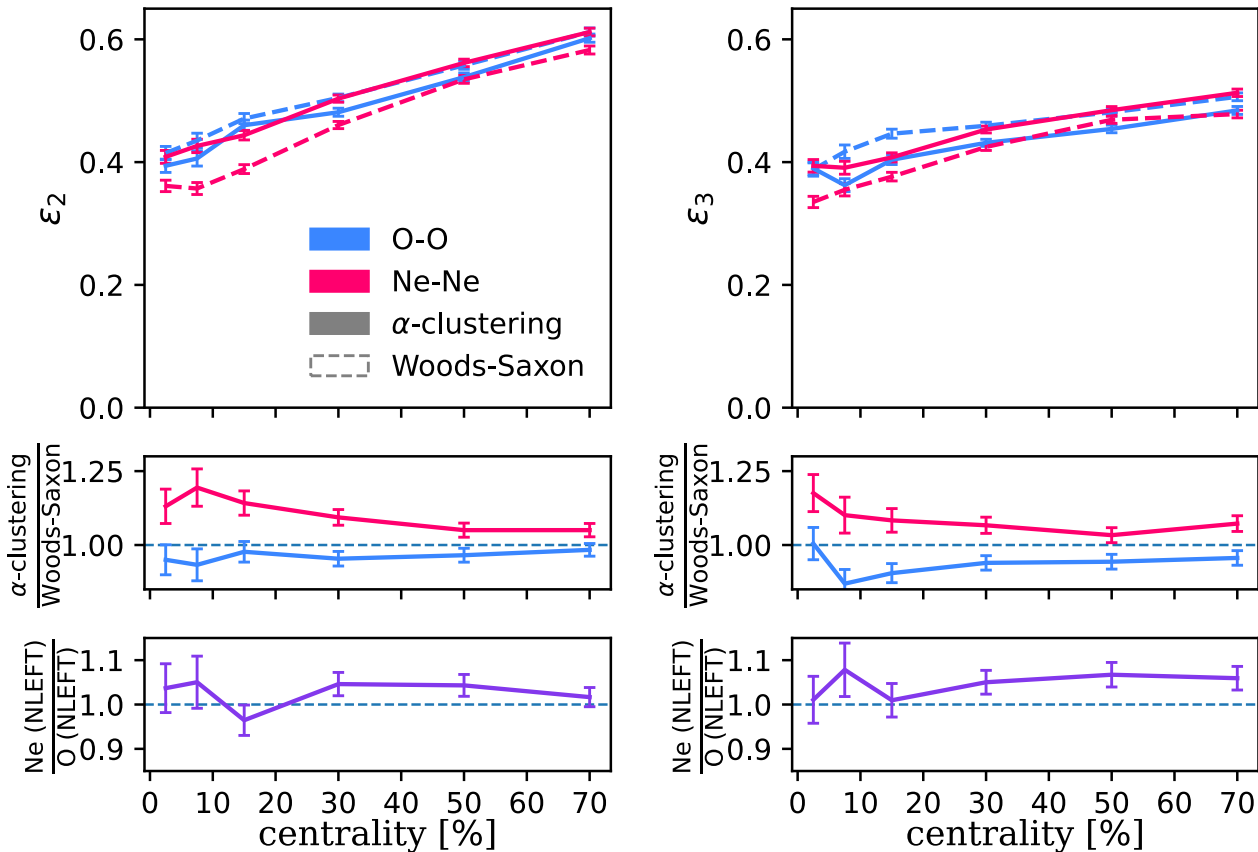
# Centrality Selection



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

# Eccentricity

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



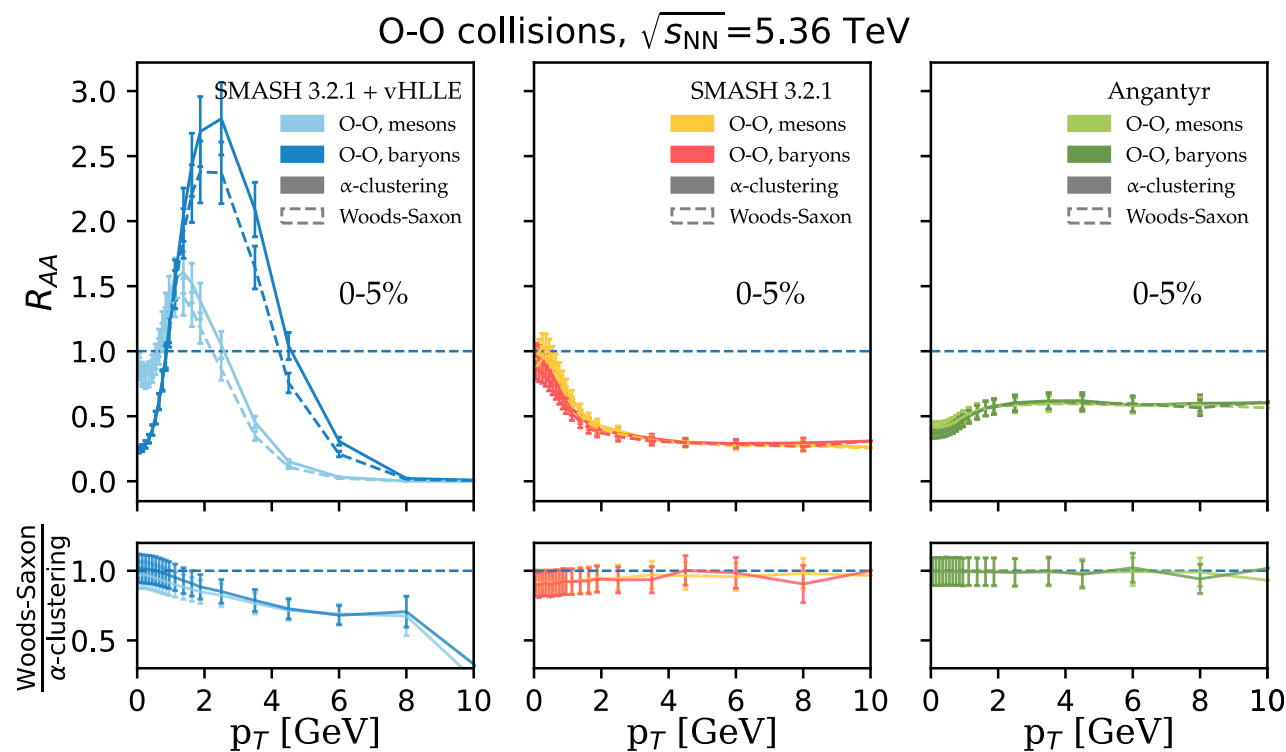
$$|\epsilon_n| = \frac{\sqrt{\langle r^n \sin(n\varphi) \rangle^2 + \langle r^n \cos(n\varphi) \rangle^2}}{\langle r^n \rangle}$$

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

# Nuclear Modification Factor

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

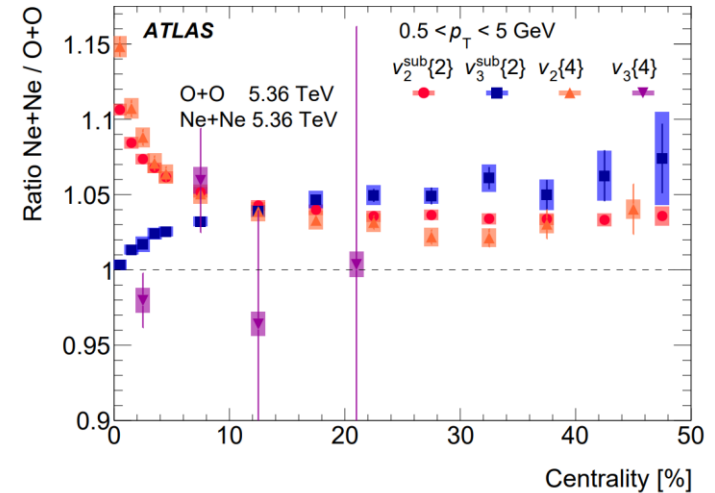
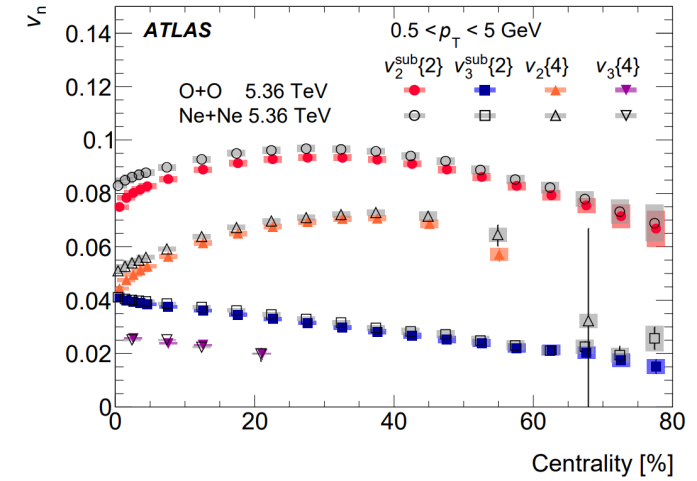
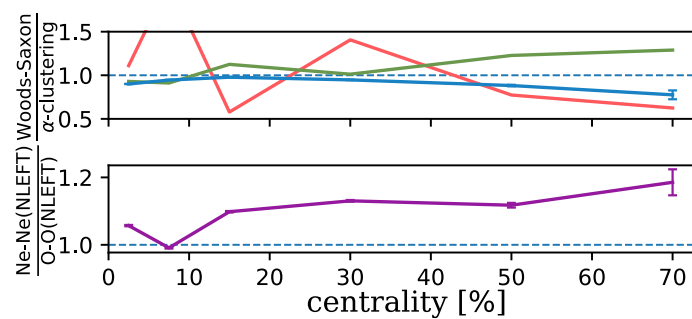
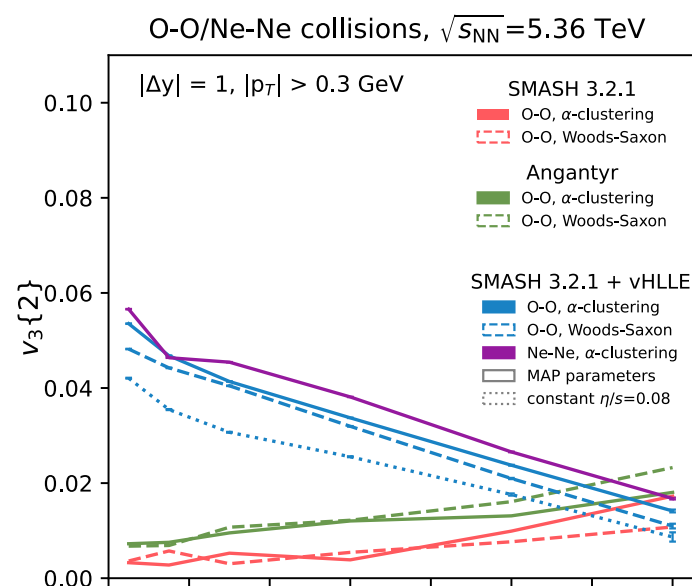
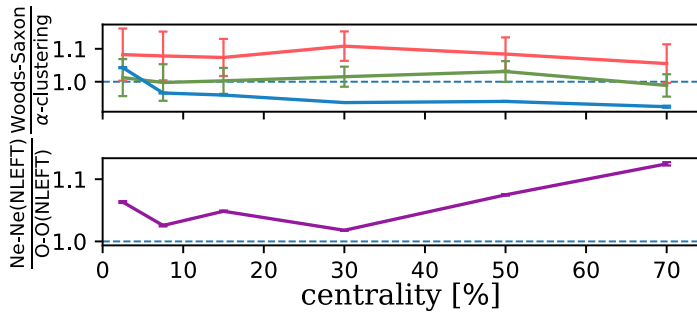
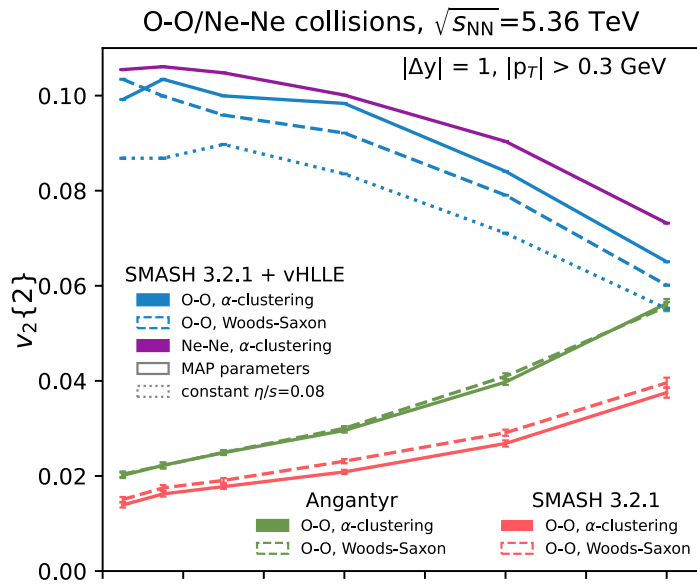
- Hybrid: expected result for thermal over vacuum spectra  
→ Mass ordering clear sign of radial flow



- SMASH: enhancement at low  $p_T$   
→ Stopping from hadronic medium
- Angantyr: almost constant
- Only hybrid shows difference between nuclear configurations



# Experimental Data

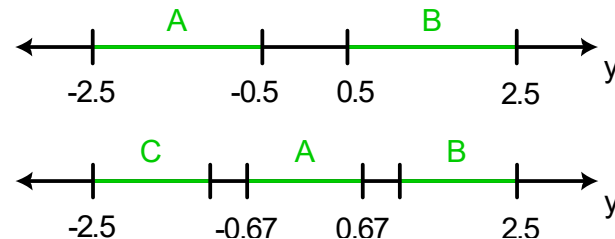
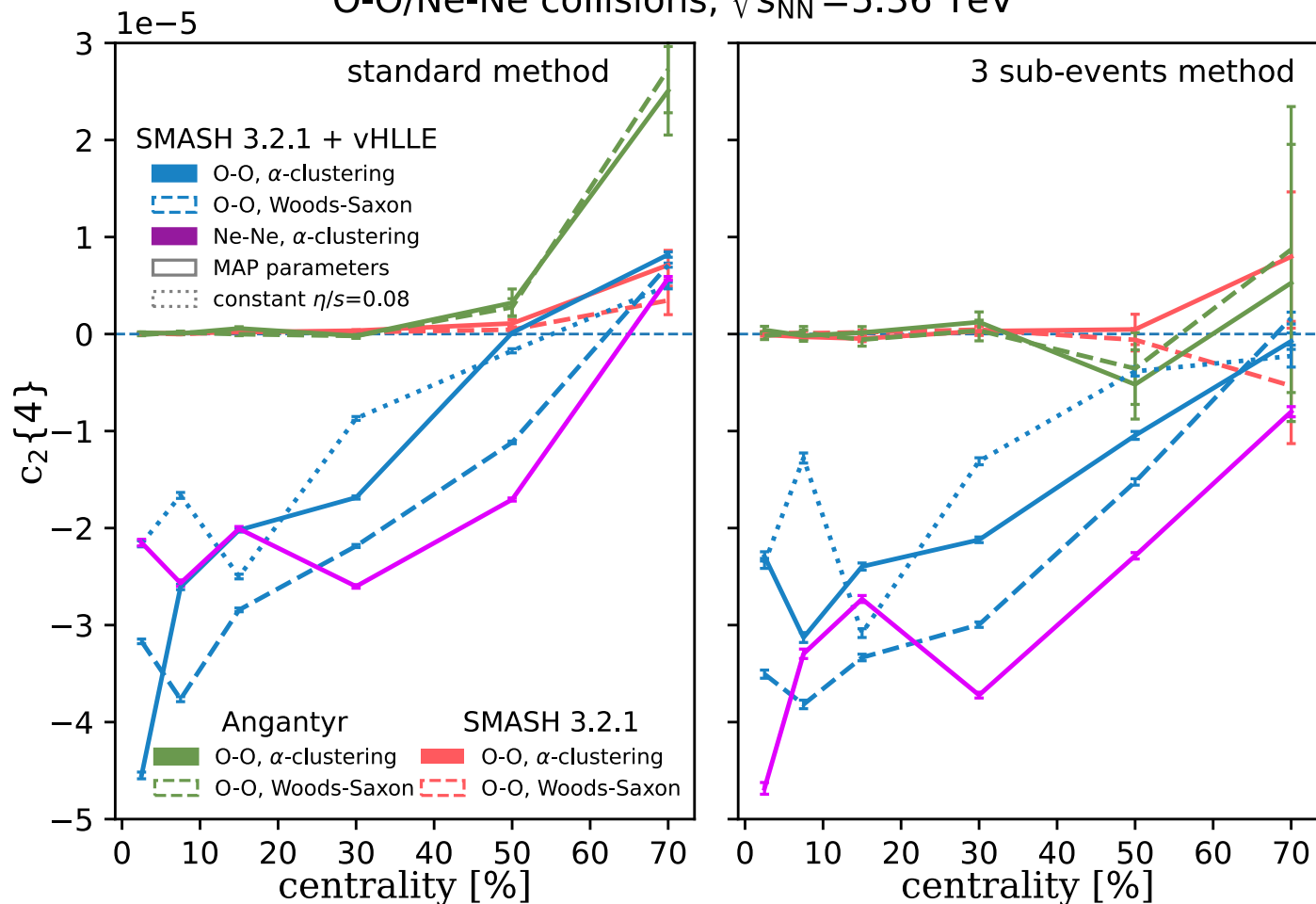


- Hybrid with constant  $\eta/s$  in good agreement with data!

ATLAS Collaboration, arXiv:2509.05171

# 4-Particle Cumulants

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



- $c_2\{4\}$  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<sup>nd</sup> / 4<sup>th</sup> power

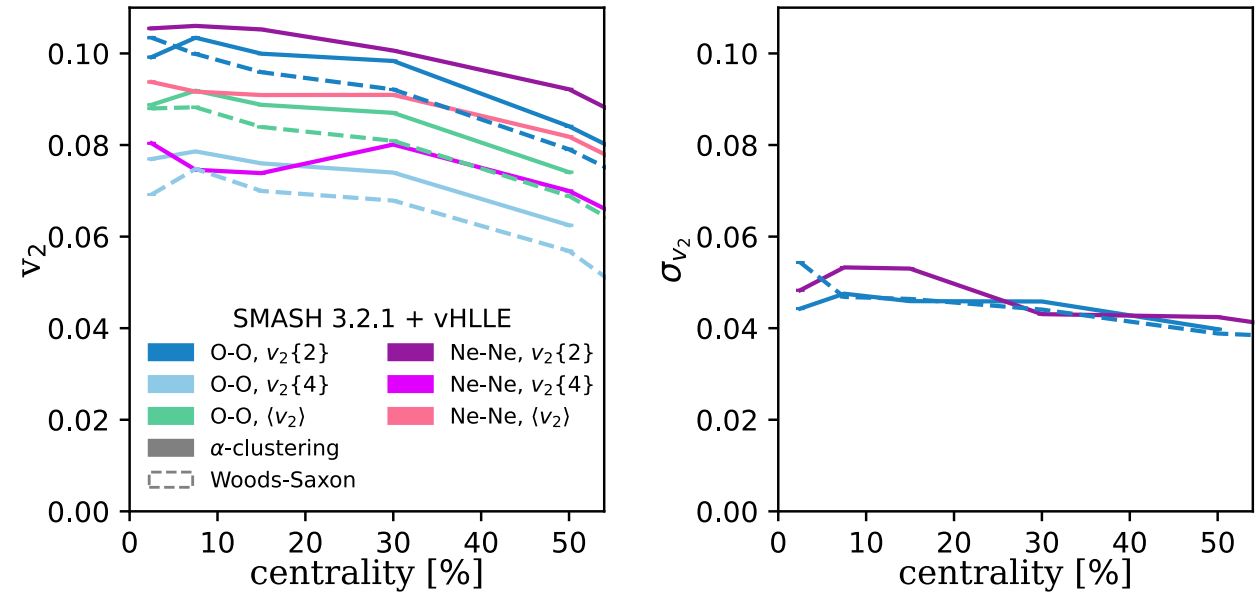
→ Systematically biased by flow fluctuations

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

Unbiased flow coefficients:

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

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

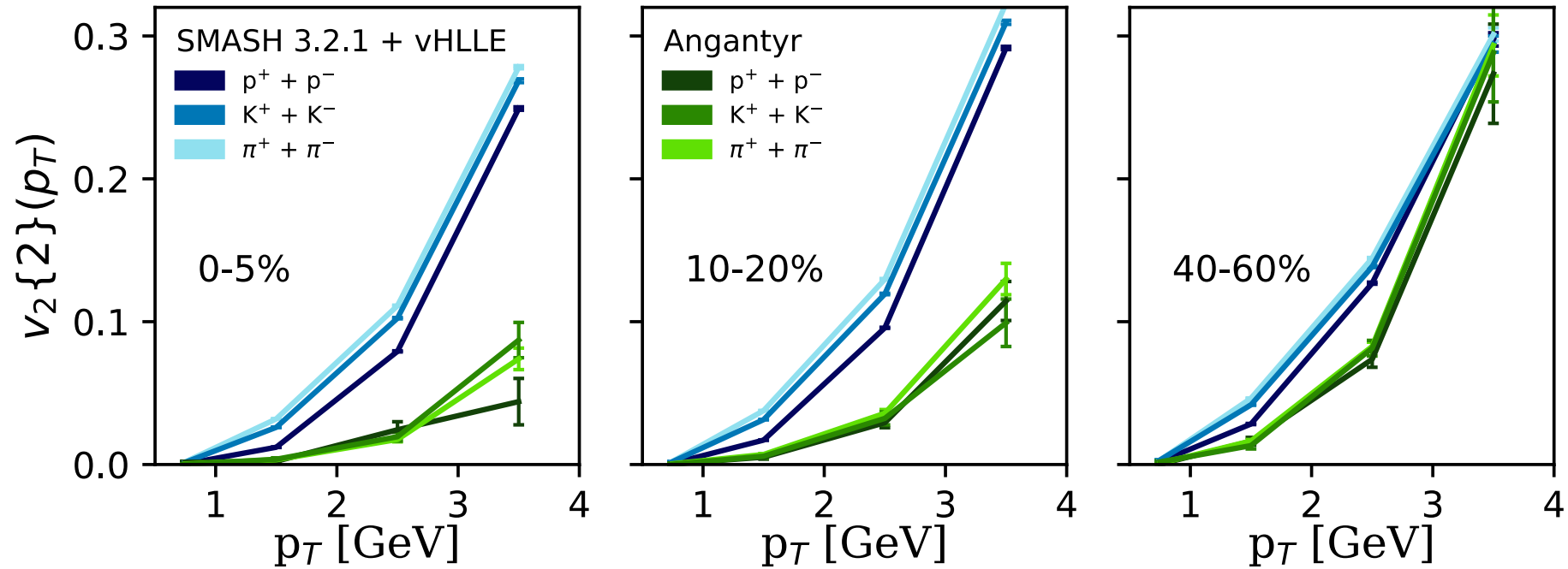


- Fluctuations constant in centrality

→ Trend stays the same

# Differential Flow

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



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

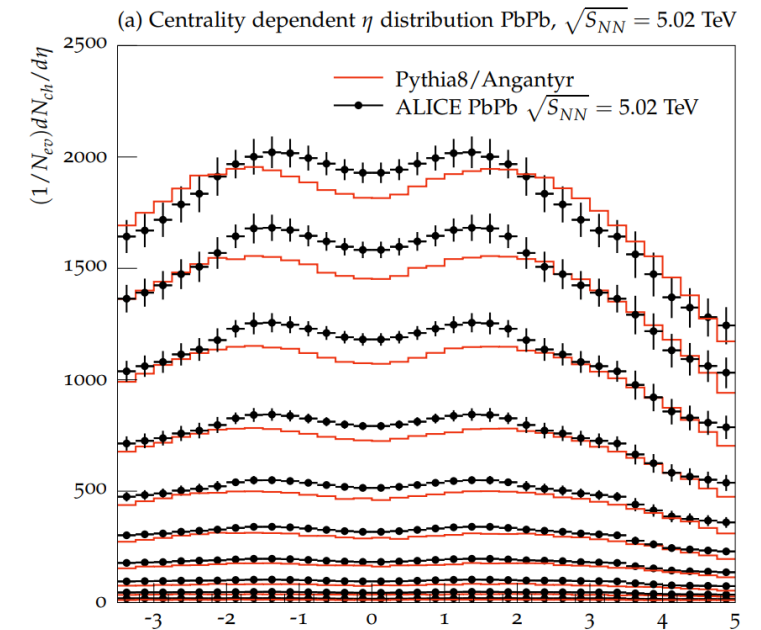
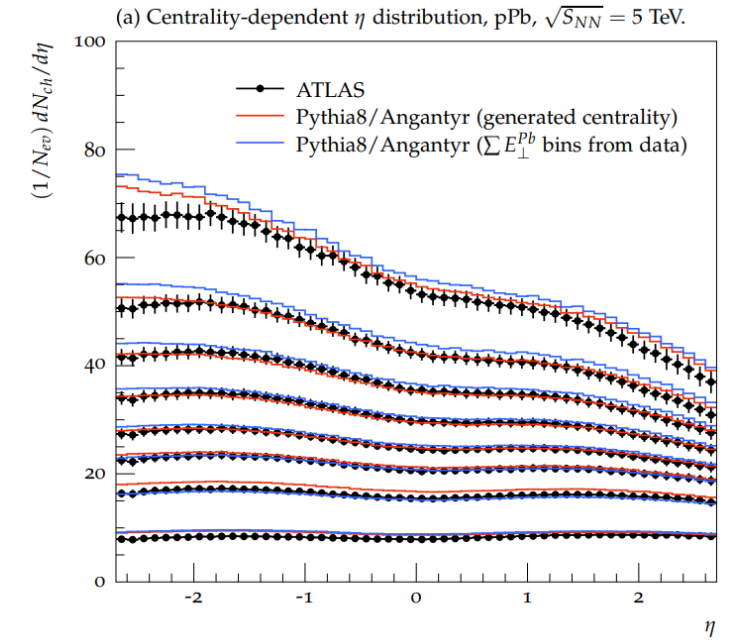
# Summary and Outlook

- 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

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



# Applicability of Hydrodynamics

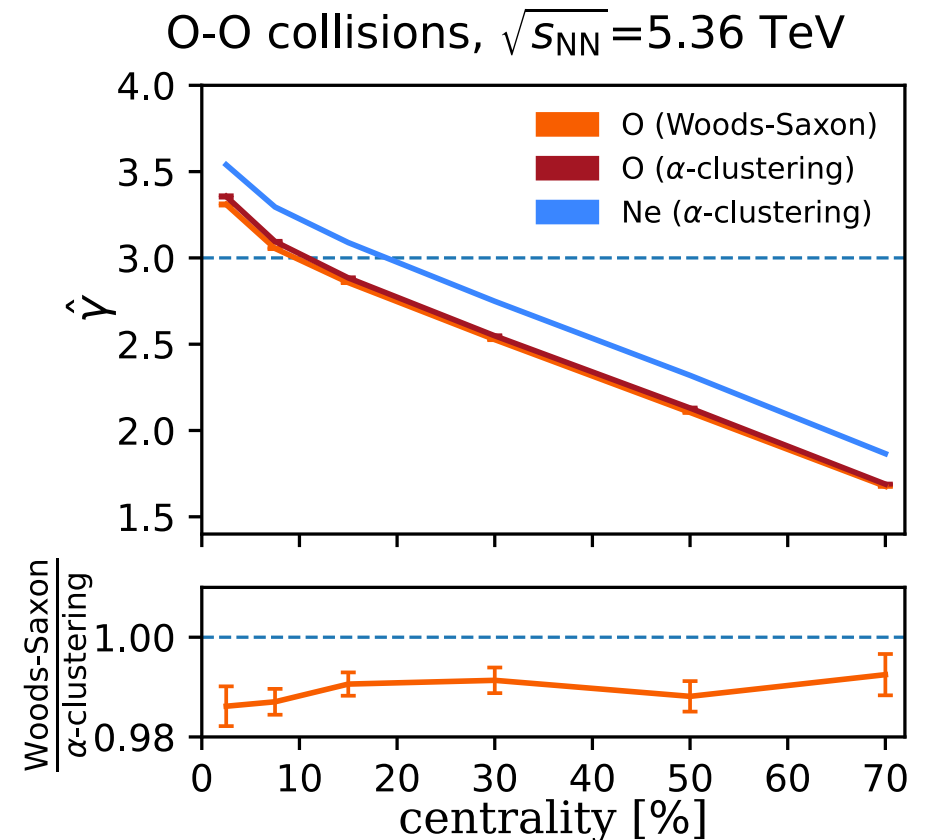
- Assumption of local thermal equilibrium not necessarily true - especially in small systems!

→ Assess the accuracy of hydrodynamics:

Opacity

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

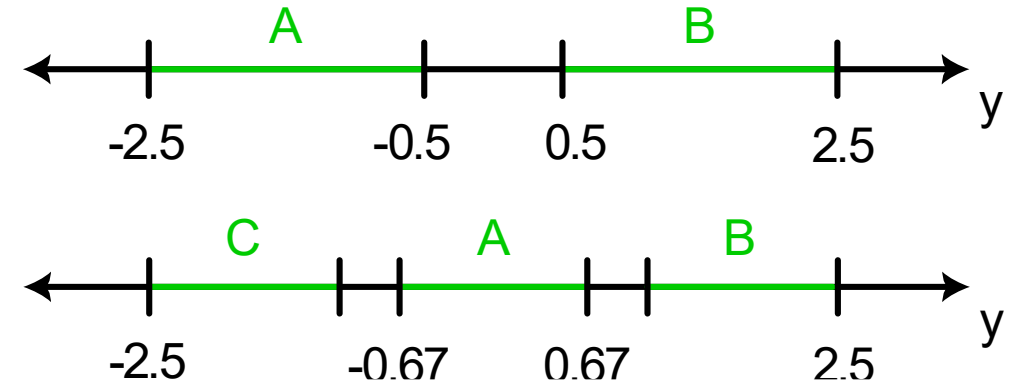
- Measure for the interaction rate
- Hydrodynamics found to be accurate to kinetic theory if  $\hat{\gamma} > 3-4$



# 3-sub-event Method

Q-Vector

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



4-particle correlation:

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

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