

Mapping the longitudinal structure of collective dynamics in O+O and Ne+Ne collisions at the LHC

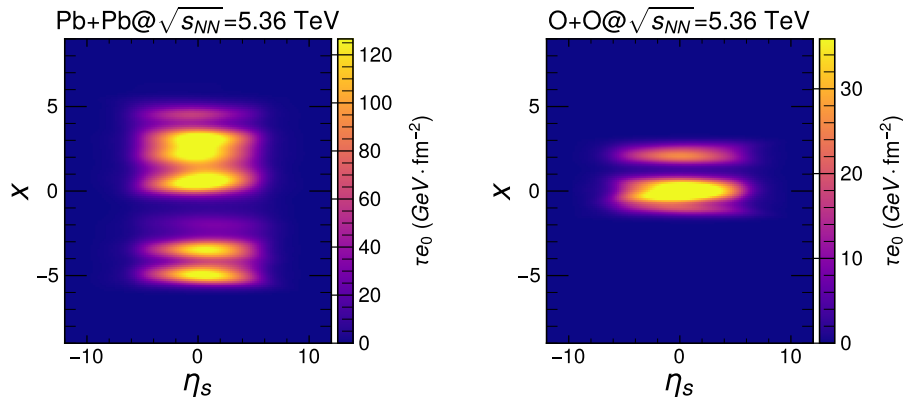
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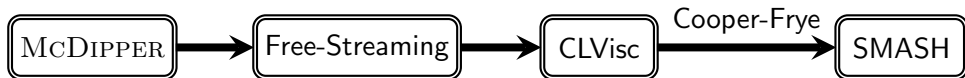
Light-Ion Collisions 2026 · Heidelberg



- 1 Motivation
- 2 (3+1)D hybrid modeling of light ion collisions
- 3 Results and discussions
 - Longitudinal structure in O+O and Ne+Ne
 - Sensitivity to pre-equilibrium dynamics
- 4 Summary and outlook



- ▶ Recent O+O/ Ne+Ne measurements show sizable collectivity and a clear sensitivity to nuclear geometry.
- ▶ Most current constraints come from midrapidity observables, yet the initial state is far from boost invariant.
- ▶ **Longitudinal structures of final observables remain unexplored**, e.g. rapidity dependence of flow and longitudinal decorrelation may be affected by initial geometry.



- **McDipper:** saturation-based 3D initial model. [PRC 109, 044916 \(2024\)](#)

PGCM-clustered configurations used. [PRL 135, 012302 \(2025\)](#)

$$(\tau e)_0 = \int d^2\mathbf{p} |\mathbf{p}| \left[K_g \frac{dN_g}{d^2\mathbf{x} d^2\mathbf{p} dy} + \sum_{f, \bar{f}} \frac{dN_{qf}}{d^2\mathbf{x} d^2\mathbf{p} dy} \right]_{y=\eta_s}.$$

- **Free-Streaming:** $T^{\mu\nu}(\tau_{fs}, \mathbf{x}_\perp, \eta_s) = \frac{1}{\tau_{fs}} \int_0^{2\pi} \frac{d\phi}{2\pi} \hat{p}^\mu \hat{p}^\nu (\tau e)_0(\mathbf{x}_\perp - \Delta\tau \hat{\mathbf{p}}_\perp, \eta_s)$

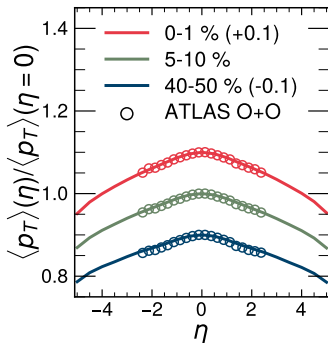
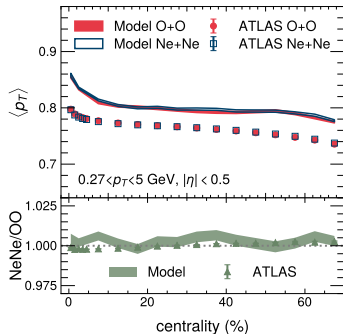
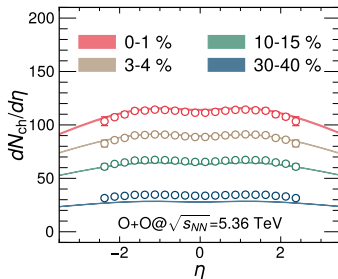
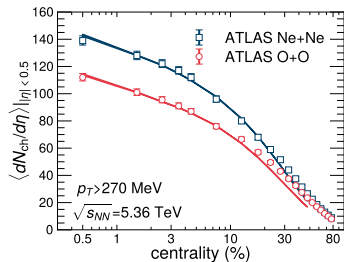
[PRC 103 \(2021\) 5, 054909,](#) $\hat{p}^\mu = (1, v_{fs} \cos \phi, v_{fs} \sin \phi, 0), \tau_{fs}=0.6 \text{ fm}, v_{fs}=0.6.$

- **CLVisc:** (3+1)D viscous hydrodynamic model with viscosity from Duke group.

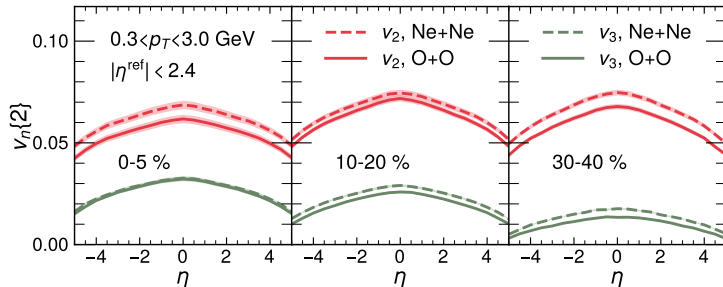
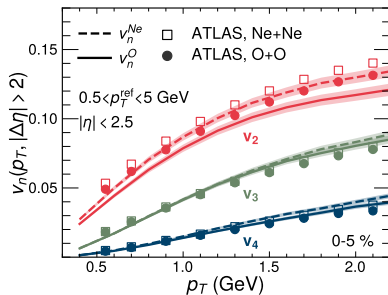
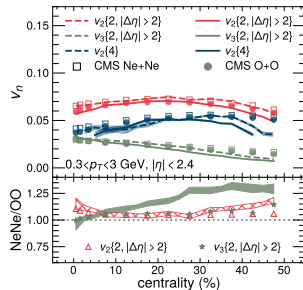
[PRC 97, 064918 \(2018\); PRC 105, 034909 \(2022\); PRC 94, 024907 \(2016\)](#)

$$\partial_\mu T^{\mu\nu} = 0, \quad \tau_\Pi D\Pi + \Pi = -\zeta\theta + \dots, \quad \tau_\pi \Delta_{\alpha\beta}^{\mu\nu} D\pi^{\alpha\beta} + \pi^{\mu\nu} = \eta_v \sigma^{\mu\nu} + \dots,$$

- **Cooper-Frye + SMASH:** particlization on the hypersurface with $e_{\text{frz}} = 0.4 \text{ GeV/fm}^3$, oversampled 1000 times per event, followed by hadronic transport. [PRC 94, 054905 \(2016\)](#)

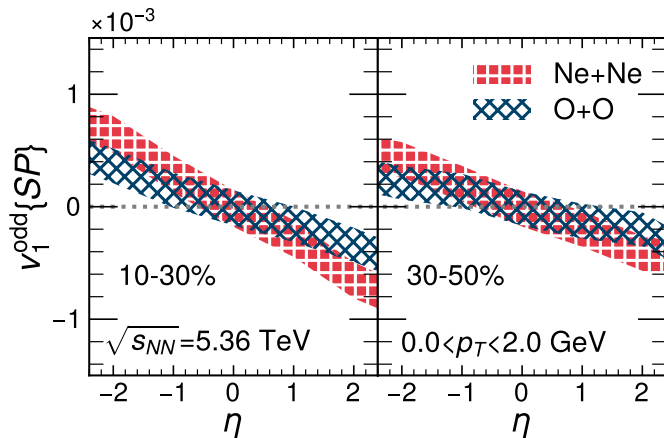


- Centrality definition:
 $\sum E_T$ in $3 < |\eta| < 5$.
- 20,000 minimum-bias events.
- $K_g = 2.5$, fitted to ATLAS $dN/d\eta|_{|\eta| < 0.5}$ data in 5–10%.
- Multiplicity and its rapidity dependence: well reproduced.
- $\langle p_T \rangle$: $\sim 10\%$ too high, but rapidity dependence and Ne/O ratio reproduced.



- Flow signals reproduced in central and mid-central collisions, underestimated towards peripheral.
- Ne/O ratio well described for v_2 , overestimated for v_3 in mid-central and peripheral collisions.
- Longitudinal structures of $v_2\{2\}$ and $v_3\{2\}$ show similar patterns in Ne+Ne and O+O.

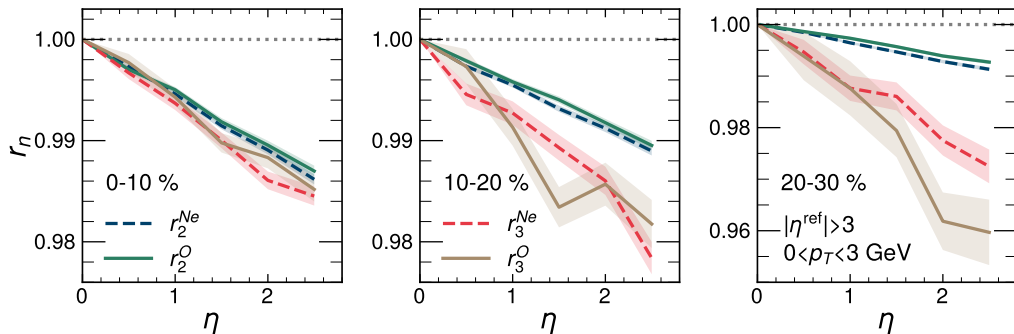
- $v_1^{\text{odd}}\{SP\}$ is calculated with respect to spectator nucleons.



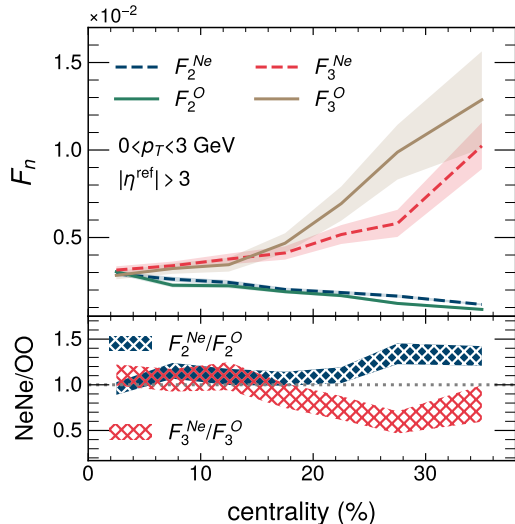
- Steeper slope in Ne+Ne: stronger initial tilt and weaker damping in the larger system.

K. Nayak, V. Bairathi, [arXiv:2609.12096](https://arxiv.org/abs/2609.12096)

$$r_n(\eta) \equiv \frac{V_{n\Delta}(-\eta, \eta^{\text{ref}}) + V_{n\Delta}(\eta, -\eta^{\text{ref}})}{V_{n\Delta}(\eta, \eta^{\text{ref}}) + V_{n\Delta}(-\eta, -\eta^{\text{ref}})}, \quad V_{n\Delta}(\eta_1, \eta_2) \equiv \text{Re} \langle Q_n(\eta_1) Q_n^*(\eta_2) \rangle.$$



- In central collisions, the difference in decorrelation between Ne+Ne and O+O collisions is marginal.
- In mid-central collisions, we find
 - slightly larger elliptic flow decorrelation in Ne+Ne collisions,
 - but larger triangular flow decorrelation in O+O collisions.



- ▶ The magnitude of decorrelation can be quantified by the slope parameter, F_n .

$$r_n(\eta) \simeq 1 - 2F_n\eta,$$

$$F_n = \frac{\sum_i [1 - r_n(\eta_i)] \eta_i}{2 \sum_i \eta_i^2}.$$

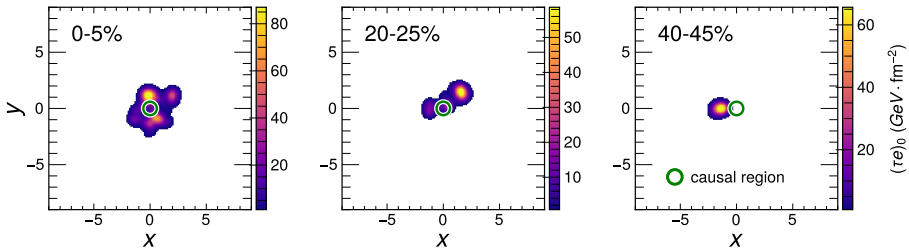
- ▶ F_2 decreases while F_3 increases towards mid-central collisions.
- ▶ The NeNe/OO ratios make the system difference visible, and it goes in opposite directions:

F_2 larger in Ne+Ne, F_3 larger in O+O.

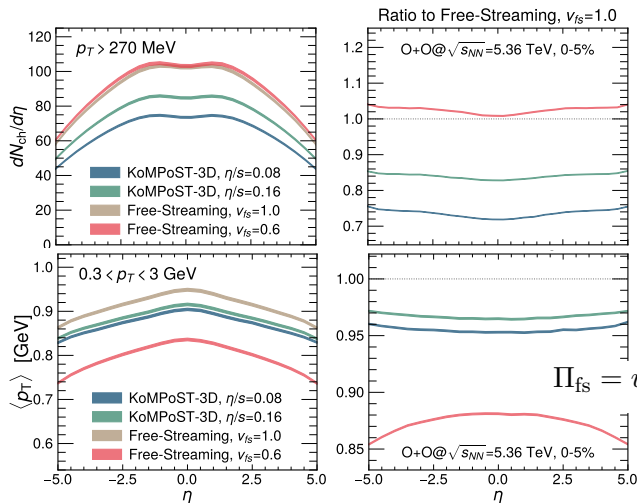
The initial geometry leaves its imprint on the longitudinal decorrelation.



- ▶ Test prehydro effects with 200 events from 0-5% O+O collisions.
- ▶ Compare K ϕ MP ϕ ST-3D ($\eta/s=0.08$ or 0.16) to Free-streaming ($v_{fs}=1.0$ or 0.6).

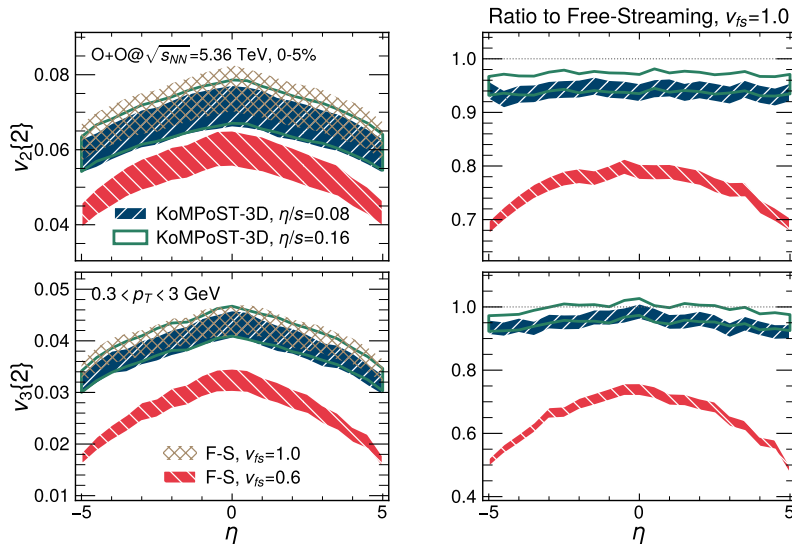


- ▶ K ϕ MP ϕ ST assumes the causal region is much smaller than the system size, then $T^{\mu\nu}(\tau, \mathbf{x})$ of the system can be expressed as a sum of the evolved background and the response to the initial out-of-equilibrium perturbations,
 - The non-equilibrium background ($\bar{T}^{\mu\nu}$) evolution is described by a universal function $\mathcal{E}\left[x = \frac{\tau T_{\text{id.}}}{\eta/s}\right]$ derived from the scaling behavior of kinetic evolution.
 - Perturbations around the background can be described by **linear response theory** derived from RTA kinetics. [PRD 102 \(2020\) 5, 056003](#), [PRD 113 \(2026\) 9, 096009](#)

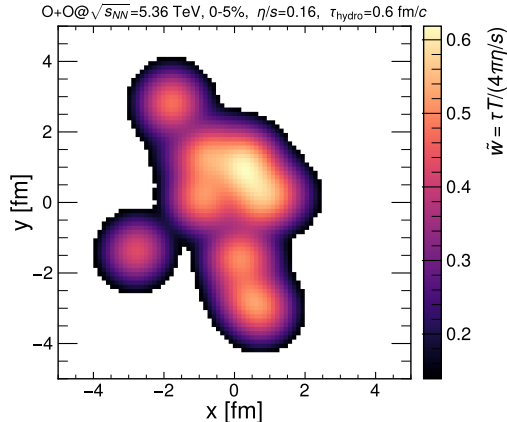
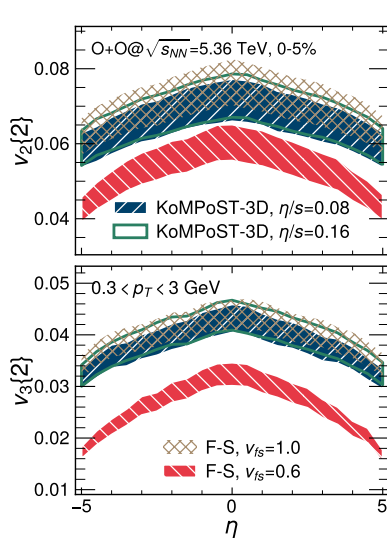


$$\Pi_{fs} = v_{fs}^2 e/3 - P_{QCD}(e) < 0$$

- Interactions drive down both the particle production and the radial expansion, through the work done by the longitudinal pressure.
- The effective free-streaming velocity leaves the particle production untouched but suppresses the radial flow strongly, because the interface gives a negative bulk pressure.



- Interactions only suppress the anisotropic flow slightly.
- The effective free-streaming velocity reduces the anisotropic flow significantly.



► The system is still far from hydro:

$$\tilde{w} \lesssim 0.6, P_L/P_T \simeq 0.24.$$

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- The effective free-streaming velocity reduces the anisotropic flow significantly.

Summary

- ▶ With the MCDIPPER+Free-Streaming+CLVisc+SMASH framework we reproduce the multiplicity and the anisotropic flow, and deliver predictions for their longitudinal structure: $v_1^{\text{odd}}, v_n\{2\}(\eta)$ and the decorrelation slopes F_n .
- ▶ The pre-equilibrium stage shifts the multiplicity and the radial flow, but leaves $v_n(\eta)$ nearly unchanged.

Outlook

- ▶ Better initial modeling, including transverse-gradient corrections that generate initial momentum anisotropy and shear stress. [\[see talks by Oscar on Thursday\]](#)
- ▶ In light ions, KØMPØST-3D is squeezed from both sides: hydrodynamization calls for a later τ_{hydro} and the causal circle for an earlier one, so going beyond linear response may be helpful.

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Thank you for your attention!

Appendix

Multi-particle cumulant method [PRC 64, 054901 (2001), PRC 63, 054906 (2001), PRC 83, 044913 (2011)]:

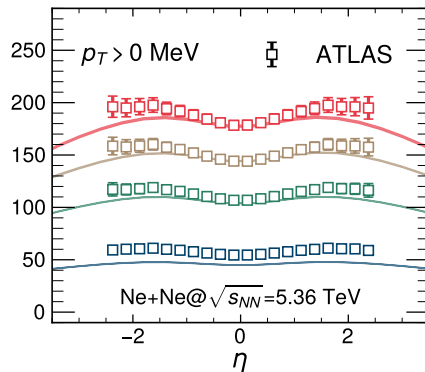
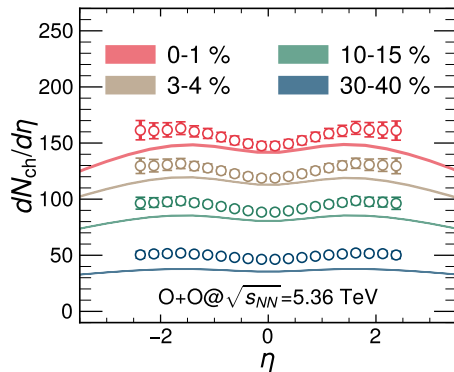
$$v'_n\{2\} = \frac{d_n\{2\}}{\sqrt{c_n\{2\}}} = \frac{\langle\langle 2' \rangle\rangle}{\sqrt{\langle\langle 2 \rangle\rangle}} \quad (1)$$

$$v'_n\{4\} = -\frac{d_n\{4\}}{(-c_n\{4\})^{3/4}} = -\frac{\langle\langle 4' \rangle\rangle - 2 \cdot \langle\langle 2' \rangle\rangle \langle\langle 2 \rangle\rangle}{(2 \cdot \langle\langle 2 \rangle\rangle^2 - \langle\langle 4 \rangle\rangle)^{3/4}} \quad (2)$$

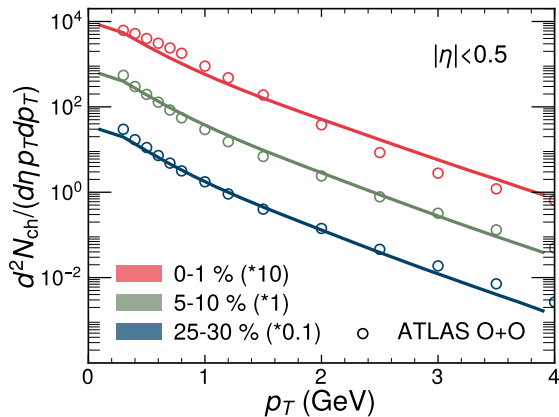
where the 2(4)-particle differential and integrated correlators are defined as

$$\langle 2 \rangle \equiv \left\langle e^{in(\phi_1 - \phi_2)} \right\rangle, \quad \langle 4 \rangle \equiv \left\langle e^{in(\phi_1 + \phi_2 - \phi_3 - \phi_4)} \right\rangle \quad (3)$$

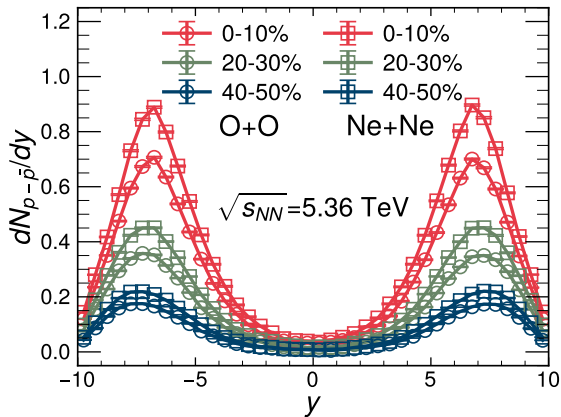
$$\langle 2' \rangle \equiv \left\langle e^{in(\psi_1 - \phi_2)} \right\rangle, \quad \langle 4' \rangle \equiv \left\langle e^{in(\psi_1 + \phi_2 - \phi_3 - \phi_4)} \right\rangle \quad (4)$$

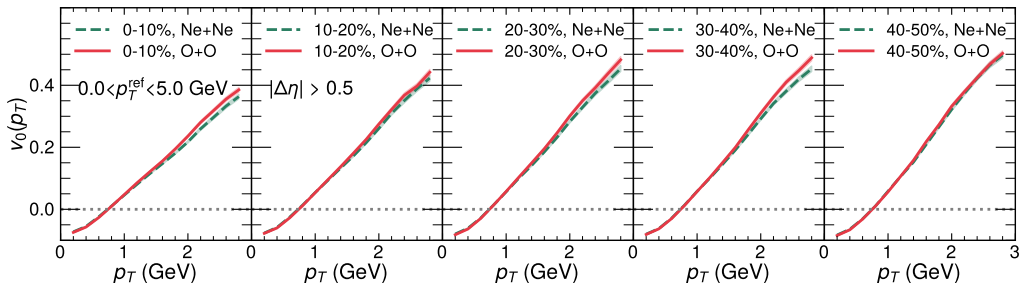


- Underestimate the particle production when including lower p_T particles.



- Flatter p_T spectra compared to ATLAS data.





- Larger radial flow fluctuation in O+O collisions.

