The unexpected uses of a bowling pin

Exploiting ^{20}Ne isotopes for precision characterizations of collectivity in small systems

Govert Nijs

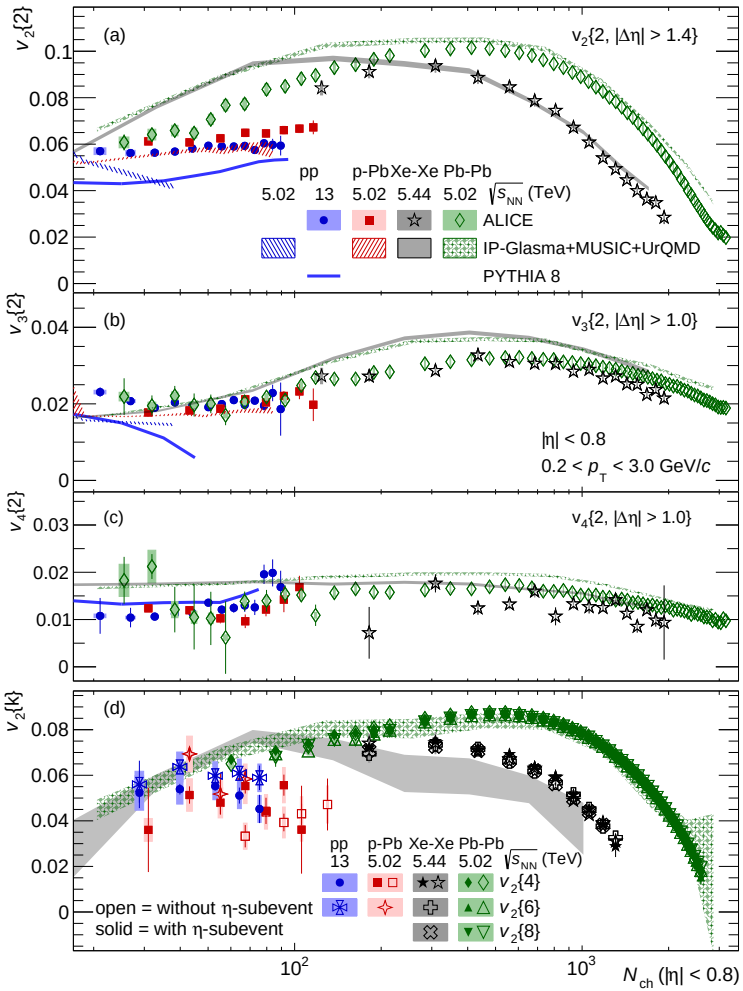
November 11, 2024

Based on:

- Giacalone, Bally, GN, Shen, Duguet, Ebran, Elhatisari, Frosini, Lähde, Lee, Lu, Ma, Meißner, Noronha-Hostler, Plumberg, Rodríguez, Roth, van der Schee, Somà, 2402.05995

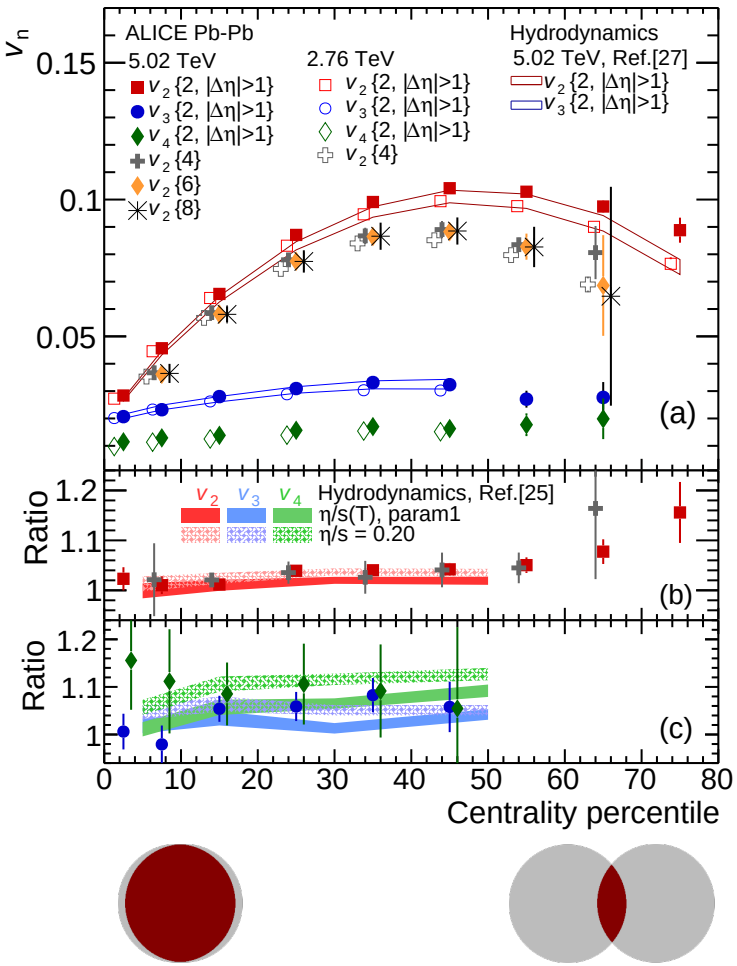
CERN

One fluid to rule them all?



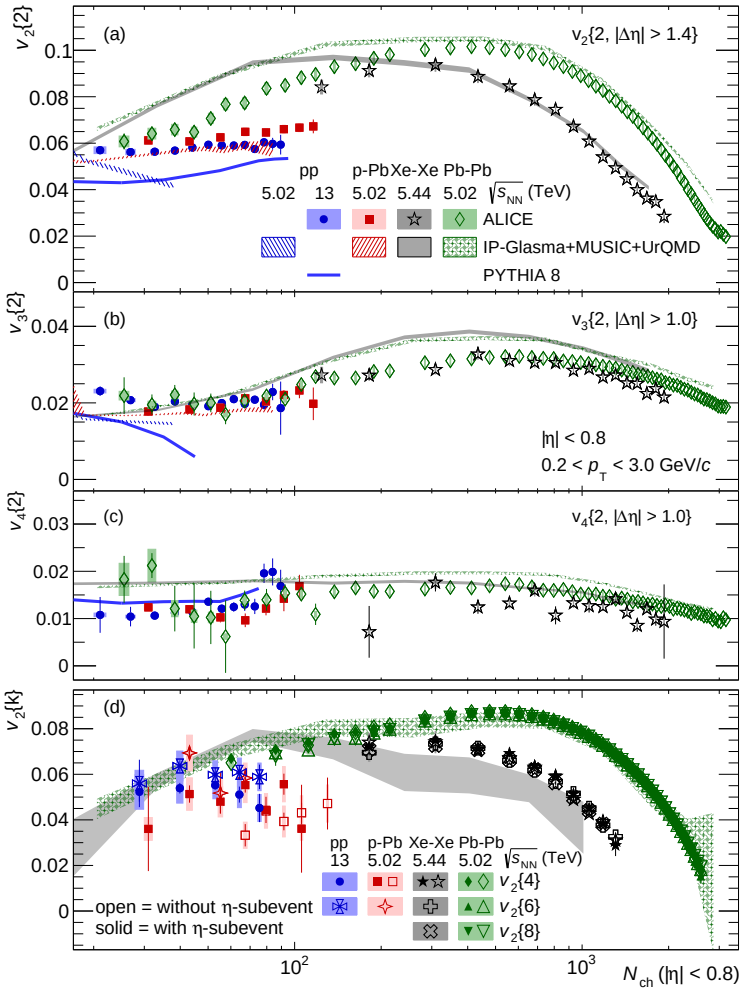
- Anisotropic flow is present in a great range of system sizes:
  - PbPb,
  - High multiplicity *p*Pb,
  - High multiplicity *pp*,
  - . . .
- Is this a sign of hydrodynamics?
  - Hydrodynamical simulations seem to work reasonably well.
  - But can a system that small really behave hydrodynamically?
  - Initial state geometry is poorly understood.
- We need a precision test of hydrodynamics in small systems.

Recap: why do we believe PbPb is hydrodynamic?



- Not just the presence of $v_n\{k\}$.
- We understand where the $v_n\{k\}$ come from!
  - Hydrodynamics converts initial state anisotropic geometry into final state momentum anisotropy.
  - We understand very well what the initial geometry looks like!
- For pPb this is not the case.
  - There is $v_n\{k\}$ measured.
  - But we do not understand the initial geometry.
  - No clear interpretation of experimental results.

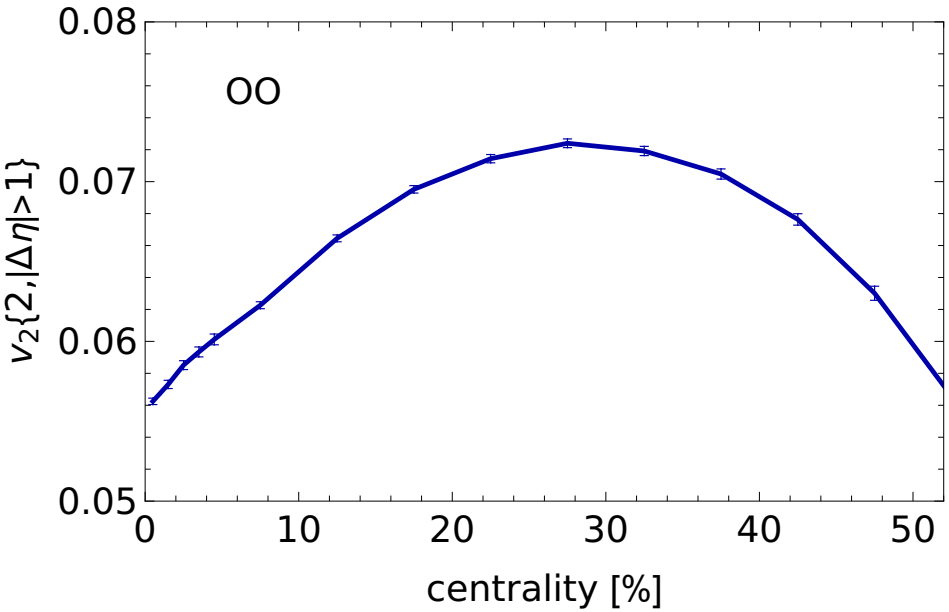
Posing a precise question



- Can we describe PbPb and a small system in a hydrodynamical model *with the same settings*?
  - Hydro model used should describe a wide range of PbPb observables.
- Can we find a quantity to predict which does not suffer from huge theoretical uncertainties? Wishlist:
  - Initial geometry under control.
  - Small sensitivity to proton substructure.
  - No longitudinal structure issues.
  - Quantifiable and small theory uncertainty.

Can $^{16}O^{16}O$ collisions help?

- $^{16}O^{16}O$ collisions are planned at the LHC for 2025.
- Shape of the proton and longitudinal structure are not an issue, but...



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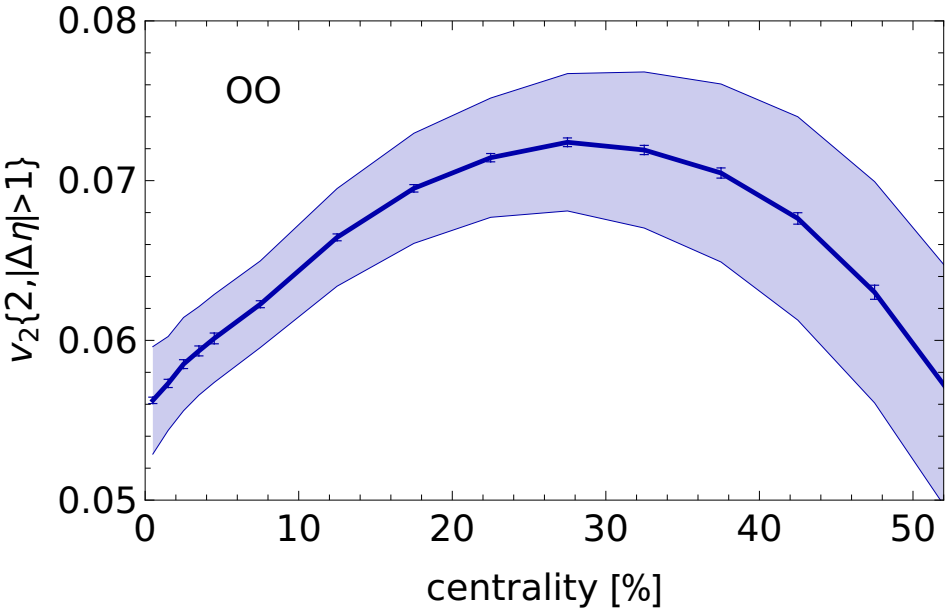

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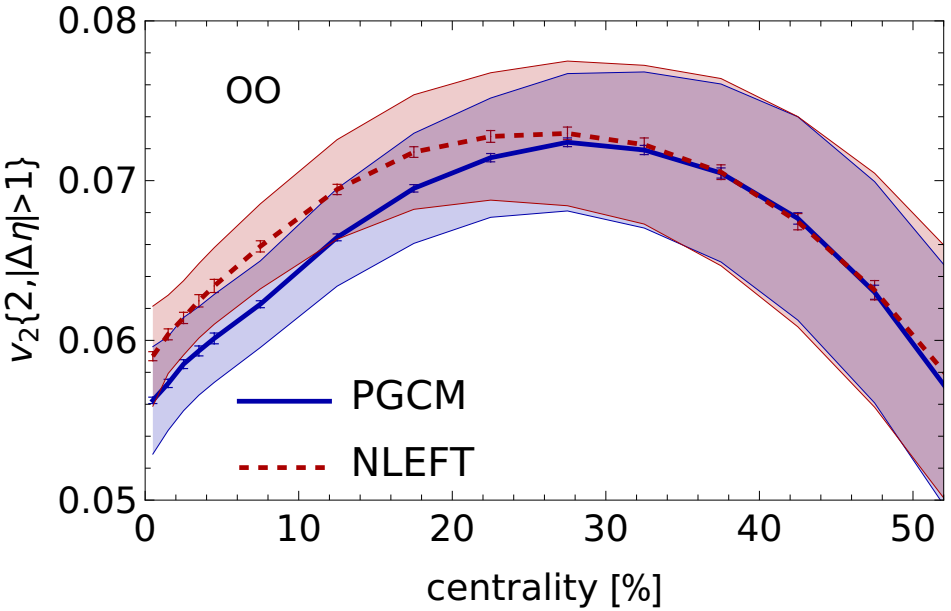
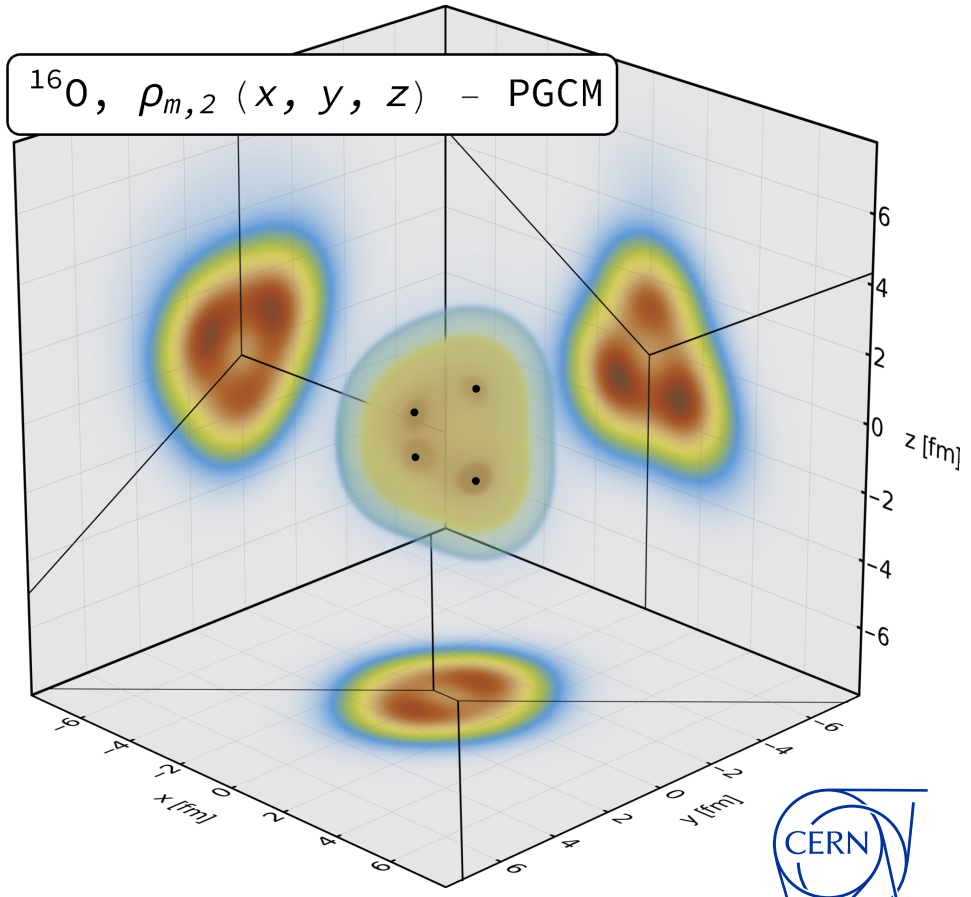
- $^{16}O^{16}O$ collisions are planned at the LHC for 2025.
- Shape of the proton and longitudinal structure are not an issue, but...
- Magnitude of fluctuations in the initial state is poorly constrained.
- Different nuclear structure calculations give different answers!
- We have a handle on systematics, but errors are substantial.



The nuclear bowling pin: ^{20}Ne

- We use both the PGCM and NLEFT frameworks for our nuclear structure input.
  - PGCM computes the average deformed densities.
  - NLEFT simulates an effective theory on a lattice.
- ^{16}O is shaped like an irregular tetrahedron.
- ^{20}Ne is close in size, but has the most extreme shape in the Segrè chart.
- Can we take a ratio between systems to cancel the uncertainties?



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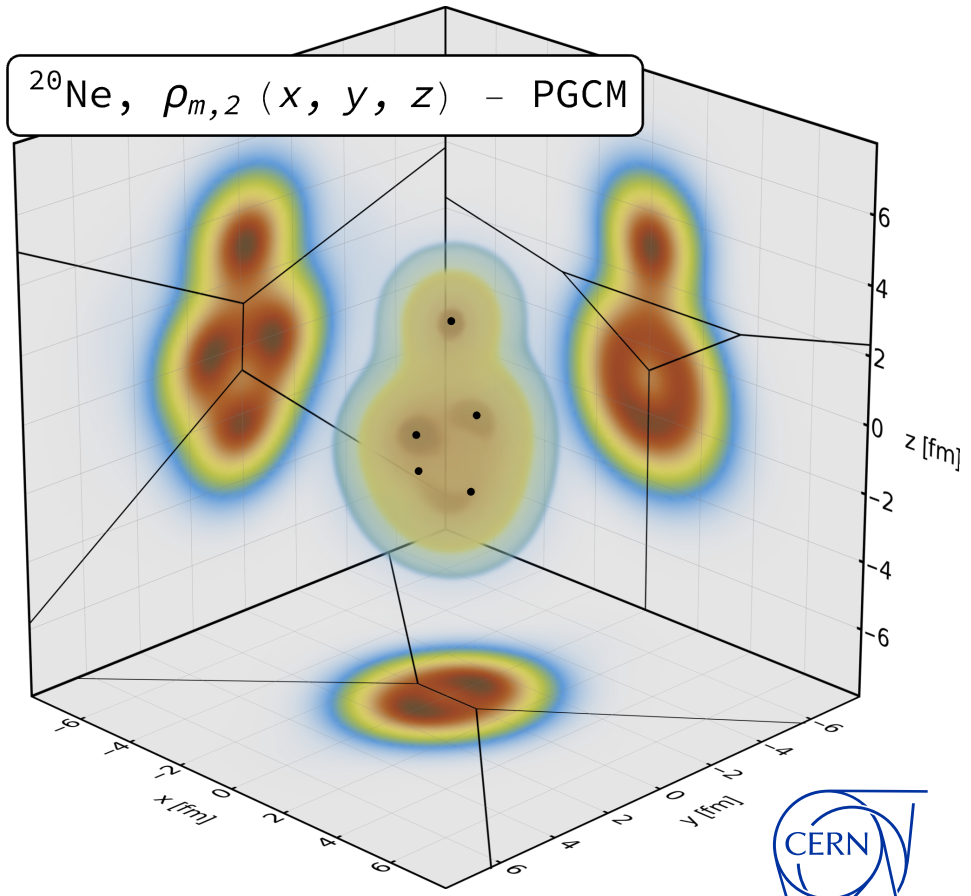
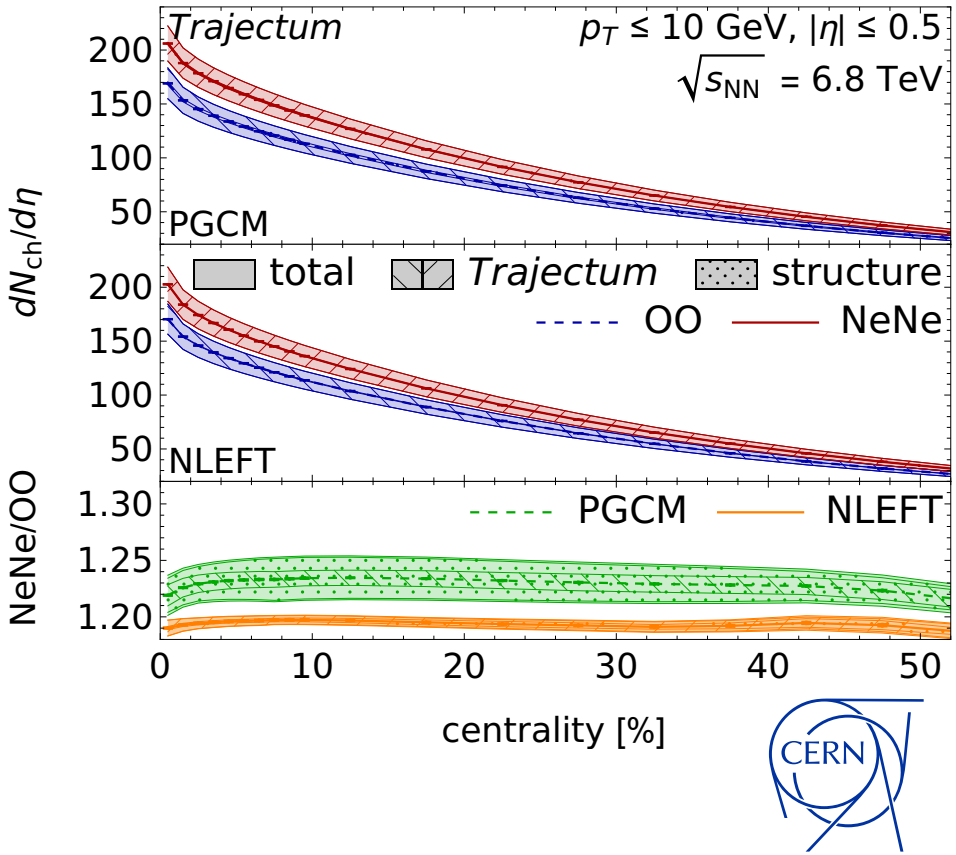


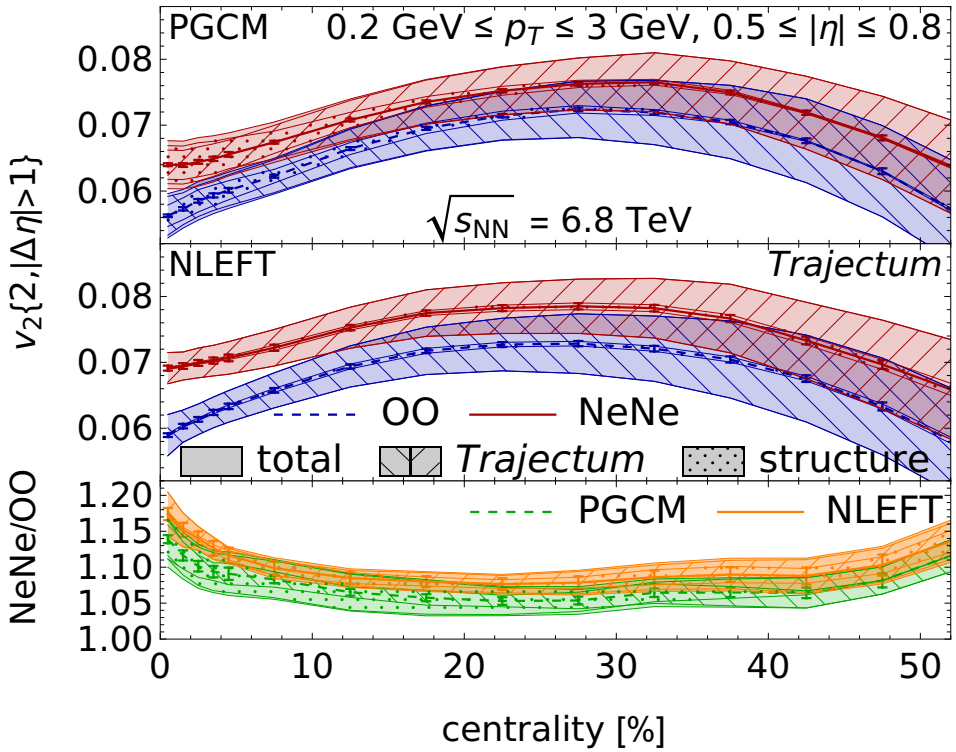
A careful look at uncertainties

- *Trajectum* systematic uncertainty contains contributions from:
  - Uncertainties in parameters.
  - Extrapolation to zero grid spacing.
- PGCM systematic uncertainty contains contributions from:
  - Sampling method: how to convert a density into a configuration.
  - Constraint application: order of operations in the PGCM computation.
- NLEFT systematic uncertainty contains contributions from:
  - Resolution of ambiguities from periodicity of the lattice.
  - Nuclear Hamiltonian parameters.



Comparing ^{20}Ne to ^{16}O significantly reduces errors!

- NLEFT and PGCM are consistent within uncertainties.
- Ratio of $v_2\{2\}$ reaches percent level precision from 5% to 20% centrality!
- Difference of $\rho(v_2\{2\}^2, \langle p_T \rangle)$ has uncertainty reduced by up to a factor 5!
- Larger PGCM uncertainty is mostly due to ambiguity in how to generate configurations from densities.



0–1%	$v_2\{2\}_{\mathrm{NeNe}}/v_2\{2\}_{\mathrm{OO}}$	$\rho_{2,\mathrm{NeNe}} - \rho_{2,\mathrm{OO}}$
NLEFT	$1.174(8)_{\mathrm{stat.}}(31)^{\mathit{Traj.}}_{\mathrm{syst.}}(4)^{\mathrm{str.}}_{\mathrm{syst.}}$	$-0.124(14)_{\mathrm{stat.}}(10)^{\mathit{Traj.}}_{\mathrm{syst.}}(7)^{\mathrm{str.}}_{\mathrm{syst.}}$
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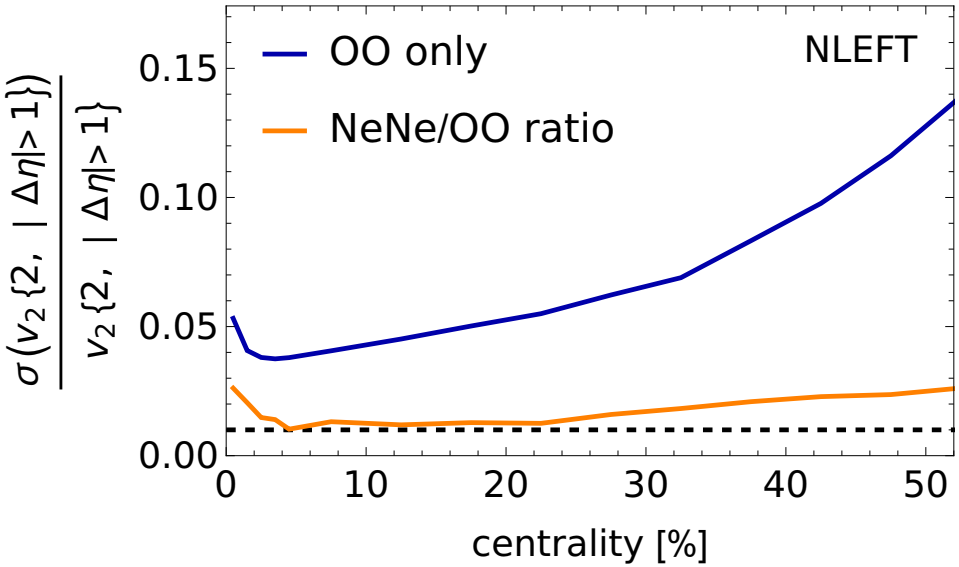

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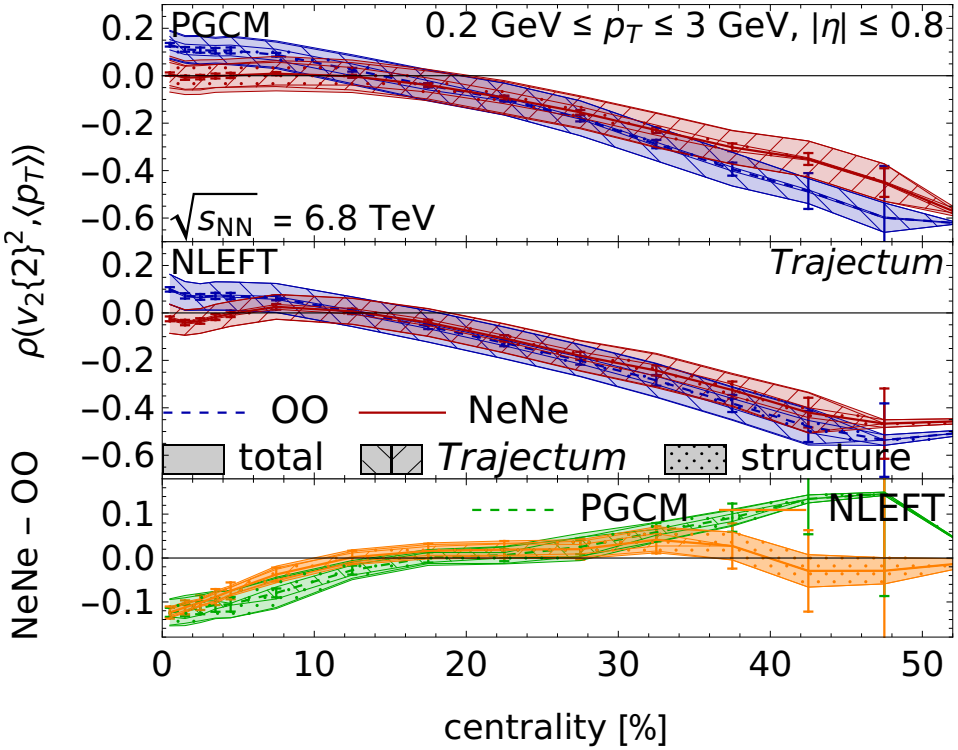

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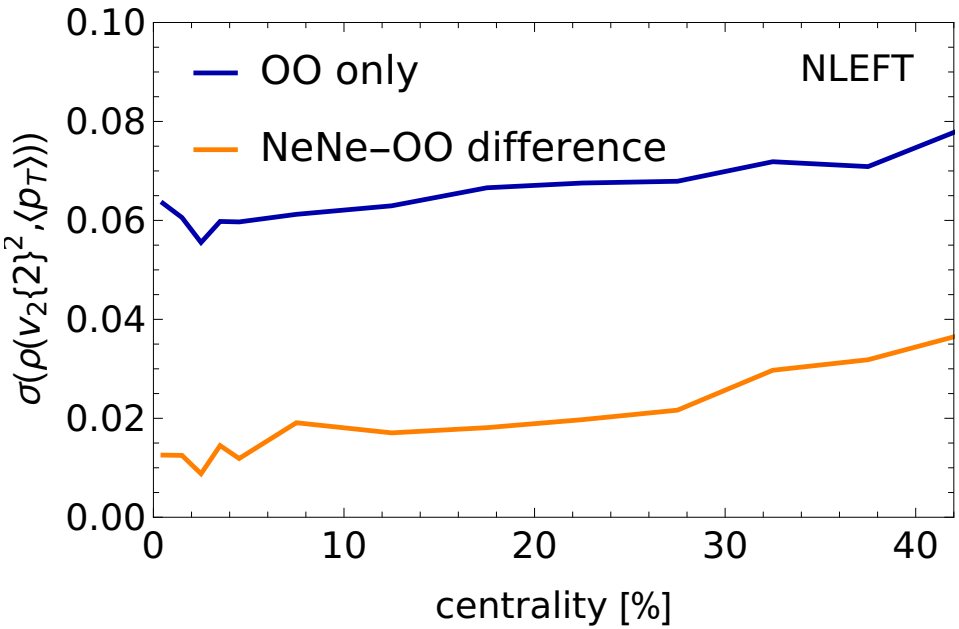

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Revisiting the wishlist

$v_n\{k\}$ in	pPb	OO	NeNe/OO
Initial geometry under control	✗	✓	✓
Small sensitivity to proton substructure	✗	✓	✓
No longitudinal decorrelation issues	✗	✓	✓
Quantifiable theory uncertainty	✗	✓	✓
Small theory uncertainty	✗	$\geq 4\%$	$\geq 1\%$

- Theory has a much better handle on ^{16}O^{16}O compared to pPb.
- Theory uncertainties can be substantially reduced by supplementing ^{16}O^{16}O collisions with ^{20}Ne^{20}Ne collisions.
  - $v_2\{2\}$ ratio can be predicted to 1% precision between 5% and 20% centrality.
  - Different nuclear structure calculations give consistent results.