The unexpected uses of a bowling pin

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

Govert Nijs



September 22, 2025

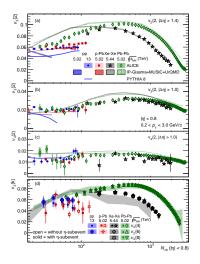
Based on:

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



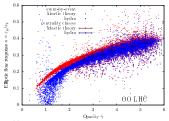


One fluid to rule them all?

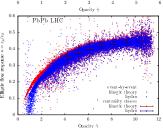


- Collective flow is one of the main characteristics of AA collisions.
 - We interpret this as the hydrodynamic expansion of a QGP formed in the collision.
 - Our understanding is quantitative, and models describe the data with ever-improving precision.
- Collective flow has also been seen in smaller systems:
 - High multiplicity pPb,
 - High multiplicity pp,
 - Inside high multiplicity jets.
- Does a QGP form in these systems?
- Are small systems hydrodynamic in nature?



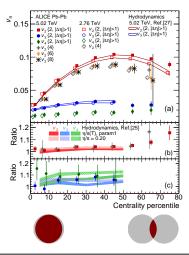


Collectivity in small systems acanaáa



- Binary yes/no is not really the right question.
- All 'hydro' models used in AA collisions have non-hydro aspects:
 - Initial state.
 - Prehydrodynamic stage,
 - Non-hydrodynamic modes,
- Example: compare kinetic theory to Israel-Stewart hydrodynamics.
 - Hydro aspects are chosen to be the same.
 - OO results differ more than PbPb.
- Better questions about small systems:
 - What is the relative importance of hydrodynamic aspects?
 - What is the nature of the non-hydrodynamic aspects?





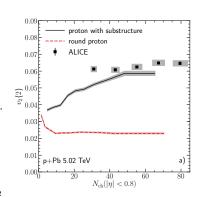
- Not just the presence of $v_n\{k\}$.
- We understand where the $v_n\{k\}$ come from!
 - Hydrodynamics converts initial state anisotropic geometry into final state momentum anisotropy.
 - We can control the initial geometry by binning in centrality.
- For pPb this is not the case.
 - We do not understand the initial geometry.
 - No clear connection between initial state and final state.
- Why is the geometry of *p*Pb so hard to control?



Reason 1: substructure

Collectivity in small systems ററാക്കറ്റ

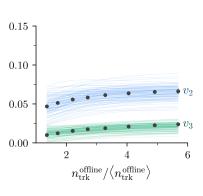
- In a pPb collision, one of the projectiles is a single proton.
- Proton geometry at low x is largely unknown.
- In models, substructure is usually modelled as a proton consisting of several constituents.
- With substructure, the collision geometry becomes significantly less round.
- This has a large effect on the v_2 .
 - We can describe the data...
 - ... but only when making the 'right' choice for proton substructure.





Fitting the substructure

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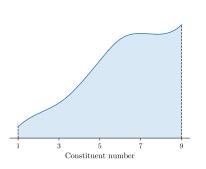


- Bayesian fits give a similar picture.
- Combined fits to PbPb and pPb are able to describe experimental data.
 - Non-trivial result: there are choices for the proton substructure for which a hydro model works
 - Constituent width is tightly constrained.
- But...
 - Uncertainties are relatively large.
 - This approach assumes a hydro model when making the fit.
 - This does not get the geometry under control in the way that we need.
 - We need to look at a system where proton substructure is not important.



Fitting the substructure

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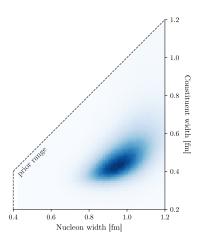


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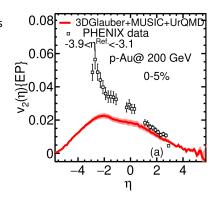


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Collectivity in small systems

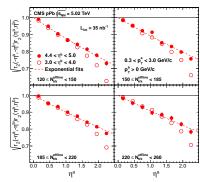
- In pPb, $v_2(\eta)$ is not flat at midrapidity.
- Also, the flow decorrelates across rapidities more than in PbPb.
- Describing this properly requires a good description of the longitudinal structure of the initial conditions.
 - This is an active area of study.
 - Can probably be overcome in the future with better tuned models.
 - However, current descriptions are not precise enough to reliably control this aspect.
- Looking at systems for which boost invariance is a good approximation avoids this problem.





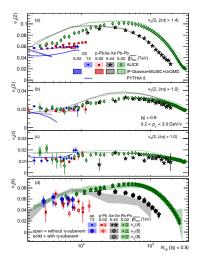
Collectivity in small systems ററററര്റ

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Posing a precise question

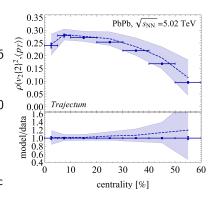


- Can we describe a small system using a hydrodynamical model which also describes PbPb?
 - Hydro model used should describe a wide range of PbPb observables.
 - We want to use the remaining freedom in the model after demanding agreement with PbPb data as an uncertainty.
- Can we find a quantity to predict which does not suffer from huge theoretical uncertainties? Wishlist:
 - Small sensitivity to proton substructure.
 - No longitudinal structure issues.
 - Quantifiable and small theory uncertainty.



Interlude: Bayesian analysis & systematic uncertainties

- We use the *Trajectum* model, and apply Bayesian analysis to fit to PbPb observables.
- We fit to 670 individual data points at 2.76 and 5.02 TeV.
 - $\rho(v_2\{2\}^2, \langle p_T \rangle)$ is shown as an example.
- From the posterior distribution, we draw 20 parameter sets.
 - This ensemble represents the remaining uncertainty in the parameters.
 - For each observable, the ensemble of predictions encodes the theory systematic uncertainty.
 - The ultracentral $\langle p_T \rangle$ is shown as an example.

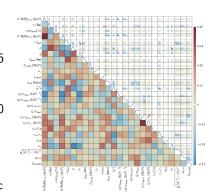




Interlude: Bayesian analysis & systematic uncertainties

OO collisions

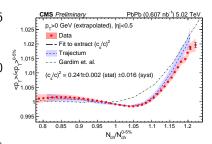
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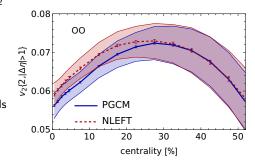
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Predictions for ¹⁶O¹⁶O at the LHC

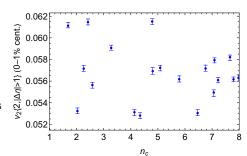
- Using the parameters obtained by Bayesian analysis, we predict the v_2 of $^{16}O^{16}O$ collisions at LHC energies.
 - The bands represent the systematic uncertainty.
 - Uncertainty varies between 4% and 14%.
 - Different nuclear structure models give slightly different but consistent answers.
- Virtually no dependence on proton substructure.
- Longitudinal decorrelation is much less of an issue compared to pPb.





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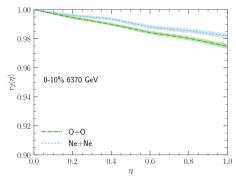
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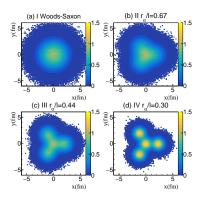


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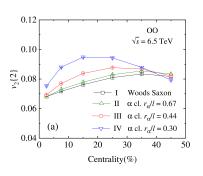




- We removed the dependence on nucleon substructure.
 - ¹⁶O nucleus is much larger than a single proton.
 - Makes sense that proton substructure becomes subleading.
- But we also introduced dependence on nuclear structure.
 - lacksquare Presence of lpha-clusters matters.
 - Size of α -clusters matters.
 - Placement of α -clusters matters.
- Are we just exchanging one problem for another?
- No. Nuclear structure can be reliably computed for small nuclei.

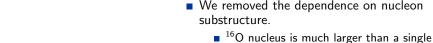


Dependence on nucleon substructure nuclear structure



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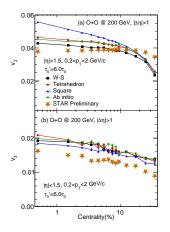


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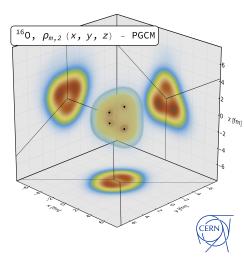


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Ab initio nuclear structure models

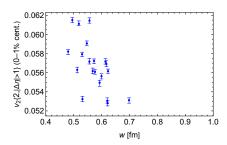
OO collisions

- PGCM and NLEFT are both state-of-the-art nuclear structure computations.
 - PGCM provides a nucleon density.
 - NLEFT provides configurations.
- Both frameworks yield results that are largely consistent with each other.
- ¹⁶O consists of 4 α -clusters.
- The α -clusters are arranged in an irregular tetrahedron.



Can we do better?

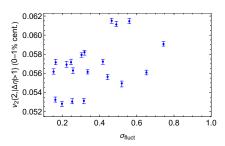
- There are still substantial geometric uncertainties in the ¹⁶O¹⁶O prediction for v_2 :
 - Increasing the nucleon size w decreases v_2 .
 - Increasing initial state fluctuations σ_{fluct} increases v_2 .
- Systems close in size to ¹⁶O¹⁶O should share these dependencies.
 - Can we exploit this?





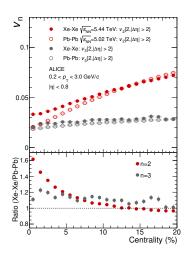
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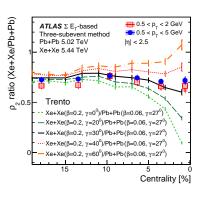


Nuclear shapes



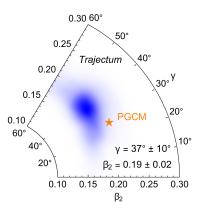
- We can model the shape of large deformed nuclei with a quadrupole deformation β_2 and triaxiality γ .
 - Central v_2 is sensitive to β_2 .
 - Central $\rho(v_2\{2\}^2, \langle p_T \rangle)$ is sensitive to β_2 and γ .
- By fitting to ¹²⁹Xe to ²⁰⁸Pb observable ratios/differences, we can extract β_2 and γ .
 - Reasonable agreement (1.8σ) with PGCM calculations.
- Experimental data was obtained during just an 8 hour run!

Nuclear shapes



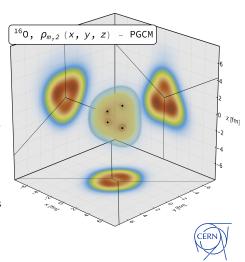
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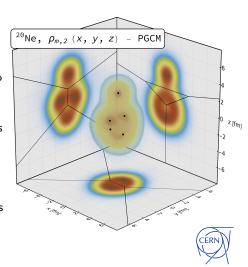


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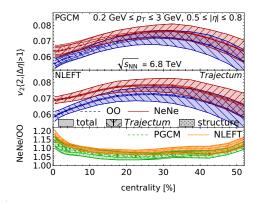
- We now turn around the argument.
 - Using ratios of observables to extract the difference in shape.
 - Using a known shape difference to predict ratios of observables.
- Ne is close in size to ¹⁶O.
 - Remaining geometric uncertainties should largely cancel.
- ²⁰Ne looks like ¹⁶O, but with an extra α -cluster on top.
 - Whereas ¹⁶O is close to spherical, ²⁰Ne is the most deformed nucleus in the Segrè chart.
 - Central v₂ ratio NeNe/OO should have a large signal.



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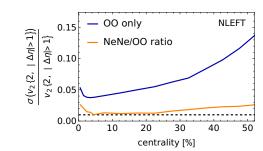
- Central NeNe/OO v₂ ratio has a large enhancement.
 - Ratio of $v_2\{2\}$ reaches percent level precision from 5% to 20% centrality!
 - Geometric uncertainties indeed largely cancel.
- Difference of $\rho(v_2\{2\}^2, \langle p_T \rangle)$ has uncertainty reduced by up to a factor 5!



0-1%	$v_2\{2\}_{\text{NeNe}}/v_2\{2\}_{\text{OO}}$	$ ho_{2,NeNe}- ho_{2,OO}$
NLEFT	$1.174(8)_{\text{stat.}}(31)_{\text{syst.}}^{Traj.}(4)_{\text{syst.}}^{\text{str.}}$	$-0.124(14)_{\text{stat.}}(10)_{\text{syst.}}^{Traj.}(7)_{\text{syst.}}^{\text{str.}}$
PGCM	1.139(6) _{stat.} (27) ^{Traj.} _{syst.} (28) ^{str.} _{syst.}	$-0.124(10)_{\text{stat.}}(10)_{\text{syst.}}^{\text{Traj.}}(29)_{\text{syst.}}^{\text{str.}}$



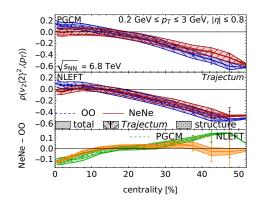
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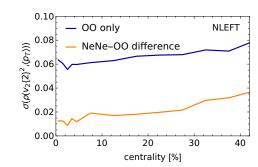
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Revisiting the wishlist

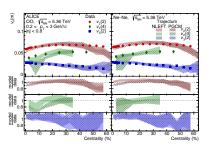
$v_n\{k\}$ in		00	NeNe/OO
Small sensitivity to proton substructure		√	✓
No longitudinal structure issues		1	✓
Quantifiable theory uncertainty		1	✓
Small theory uncertainty	X	≥ 4%	$\geq 1\%$

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- Theory has a much better handle on $^{16}O^{16}O$ compared to pPb.
- Theory uncertainties can be substantially reduced further by supplementing ¹⁶O¹⁶O collisions with ²⁰Ne²⁰Ne collisions.
 - We can bring the initial geometry under control to the percent level!
 - Models with different non-hydro parts give different answers.
 - We can use this as a probe for non-hydro contribution to collectivity!

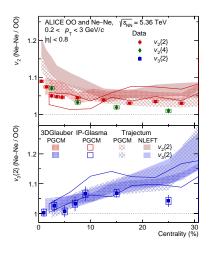


How do these predictions hold up?

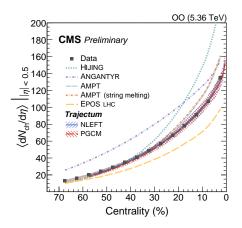


- We answer some questions...
 - Hydro agrees broadly with data.
- ...and we also got new questions!
 - NLEFT *Trajectum* describes OO, but has tensions in the ratio
 - PGCM *Trajectum* describes the ratio better, but has tensions in OO.
 - IP-Glasma is compatible with the ratio, but does not have the central enhancement and does not desribe OO (see ATLAS results).
 - Details of the initial state and pre-hydrodynamic stage matter!
 - Opportunity to learn!

How do these predictions hold up?



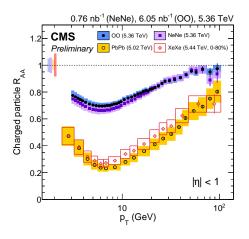
- We answer some questions...
 - Hydro agrees broadly with data.
- ...and we also got new questions!
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- Multiplicity agrees very well with Trajectum, and shows large differences between models!
- R_{AA} shows a difference between NeNe and OO.
 - Surprisingly well described by a path length based scaling of the PbPb R_{AA}.



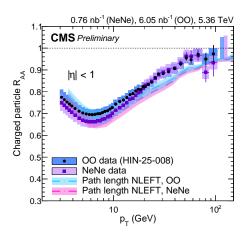
We got lots of other results too!



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The power of short runs

- The ¹²⁹Xe run took just 6h of data.
 - We can quantitatively extract its shape.
 - Proof of concept for similar future studies with big physics impact.
- The ²⁰Ne run took 12h.
 - Broad agreement with hydro.
 - Tensions provide new questions.
 - Would be interesting to compare $\rho(v_2\{2\}^2, \langle p_T \rangle)$ too.
 - Should we next go smaller? Larger?
- What can we learn from future short runs?
 - ⁷⁶Ge and ⁷⁶Se?
 - 48 Ca and 40 Ca?
 - 4He?
 - ²⁴Mg?
- A big thanks to everyone who made this happen!



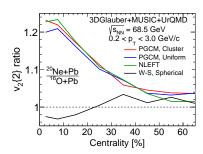
Backup

Backup



Opportunities at LHCb

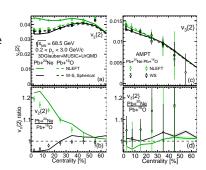
- The SMOG2 system at LHCb is able to inject gas into the beampipe.
 - This allows to perform collisions at $\sqrt{s} = 68.5 \, \text{GeV}$.
- Similar to the NeNe/OO ratio, one can take a NePb/OPb v₂ ratio.
 - A large signal is predicted by multiple models.
- Challenges:
 - Injected Ne gas is not isotopically pure.
 - Injecting O has not been approved.
- ¹⁶O and ²⁰Ne beams would allow for several new collision systems:
 - ¹⁶O¹⁶O (if O is approved for SMOG2),
 - ¹⁶O²⁰Ne.
 - ²⁰Ne²⁰Ne.





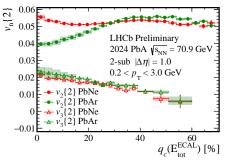
Opportunities at LHCb

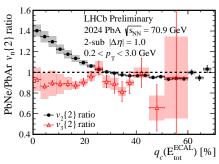
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How do predictions hold up?





 \blacksquare Measured v_2 , v_3 ratios between NeNe and OO agree well with model predictions.

