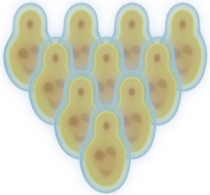
The unexpected uses of a bowling pin

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

Govert Nijs

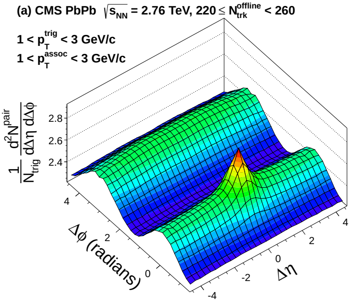


July 1, 2026

Based on:

- Giacalone, GN, van der Schee, 2606.03993
- 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 *p*Pb,
  - High multiplicity *pp*,
  - Inside high multiplicity jets,
  - ...
- Does a QGP form in these systems?
- Are small systems hydrodynamic in nature?

[CMS, 1009.4122; CMS, 1305.0609; ALICE, 1903.01790]

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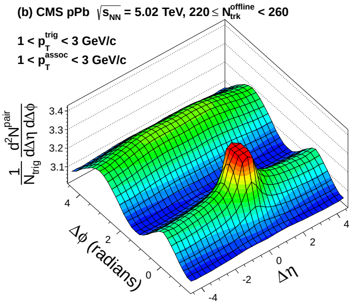

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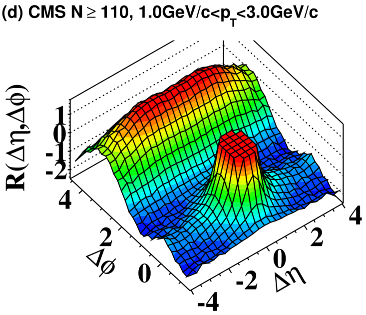

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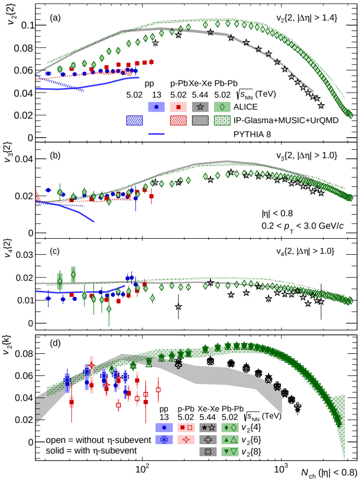

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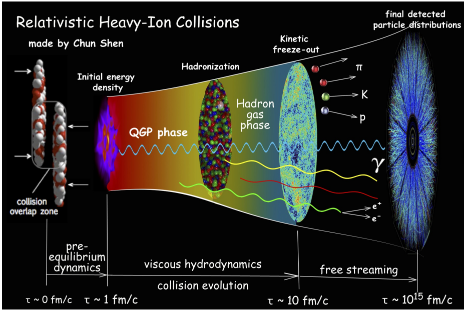
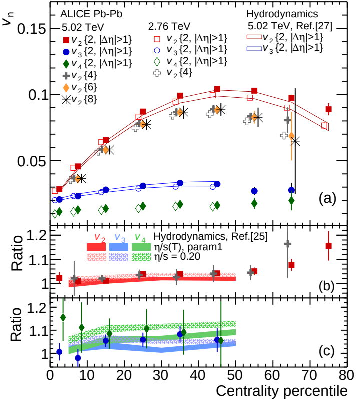
A broad picture of heavy ion collisions

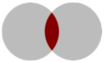


- A heavy ion collision proceeds in several stages:
  - An initial collision.
  - The approach to local equilibrium.
  - Hydrodynamic expansion.
  - Freeze-out as the fluid cools and falls out of equilibrium.
- The first two stages are the least understood.
- If small systems follow this paradigm, they spend relatively more time in these early stages!

[Sorensen, Shen, 1304.3634]

Recap: why do we believe PbPb is hydrodynamic?



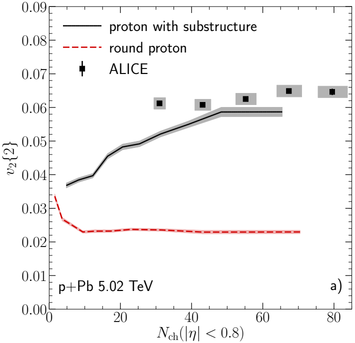


- Not just the presence of $v_n\{k\}$.
- We understand where the $v_n\{k\}$ come from!
  - Hydrodynamics converts initial state anisotropic geometry into final state momentum anisotropy.
  - We can control the initial geometry by binning in centrality.
- For pPb this is not the case.
  - We do not understand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

[ALICE, 1602.01119]

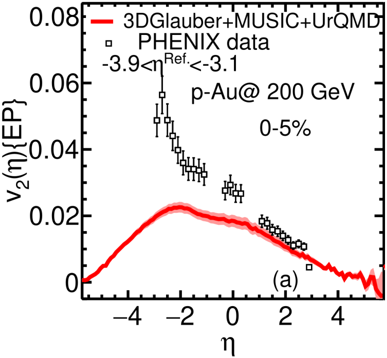
Reason 1: substructure

- In a *p*Pb 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.
- We expect better theoretical control if none of the projectiles are a proton.



Reason 2: longitudinal structure

- In pPb, $v_2(\eta)$ is not flat at midrapidity.
- Also, the flow decorrelates across rapidities more than in PbPb.
- This violates the assumption of boost invariance present in most models.
  - Dropping this assumption 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.
- Symmetric systems avoid this problem.



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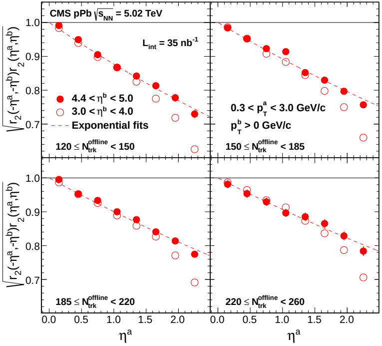
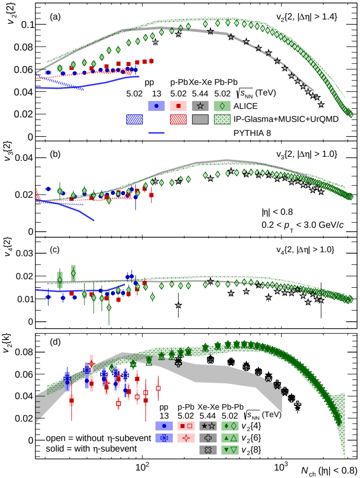


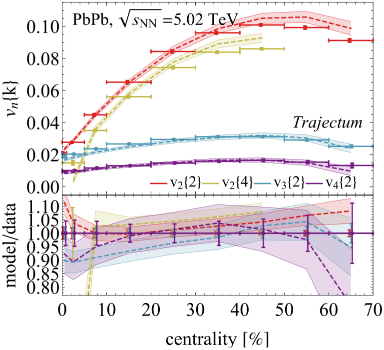
Posing a precise question



- 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.
  - $v_2\{2\}$ is shown as an example.
- The resulting posterior distribution allows us to predict observables, *including systematic theory uncertainties*.
  - The ultracentral $\langle p_T \rangle$ is shown as an example.



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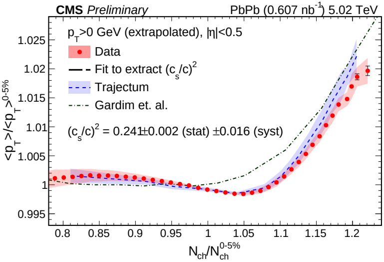
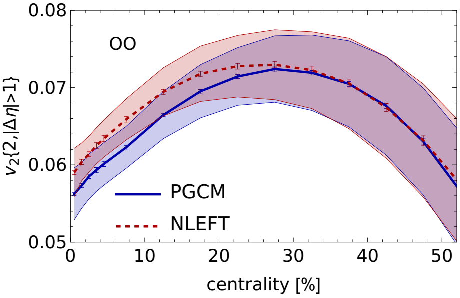


Predictions for $^{16}O^{16}O$ at the LHC

- 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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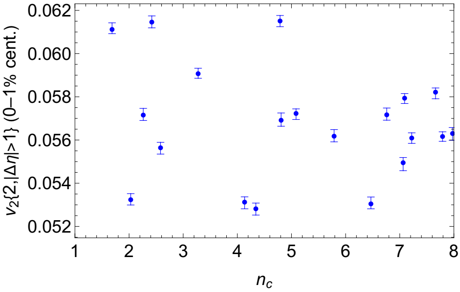

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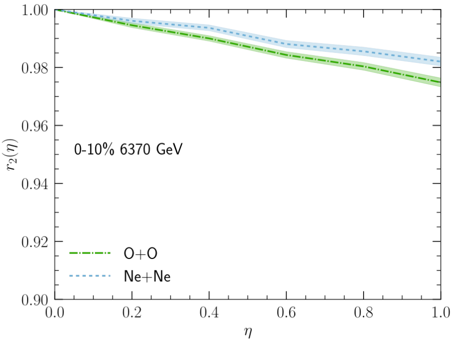
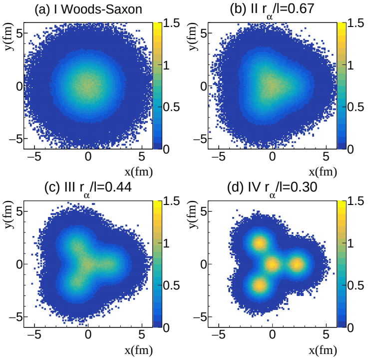


[Giacalone, Bally, GN, Shen et al., 2402.05995; Shen, in preparation]

Dependence on ~~nucleon substructure~~ nuclear structure



- We removed the dependence on nucleon substructure.
  - ^{16}O nucleus is much larger than a single proton.
  - Makes sense that proton substructure becomes subleading.
- But we also introduced dependence on nuclear structure.
  - Presence of α-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.

[Wang, Zhao, Cao, Xu, Song, 2401.15723; Zhao, Ma, Zhou, Lin, Zhang, 2404.09780]

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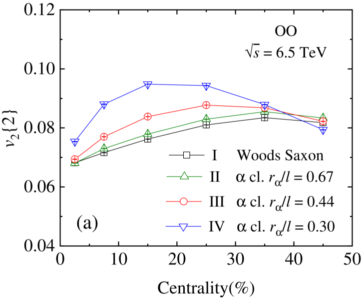

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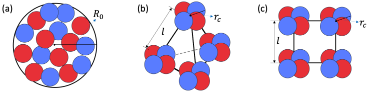

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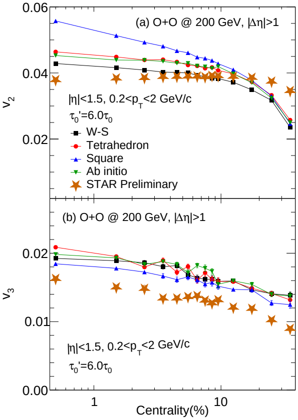

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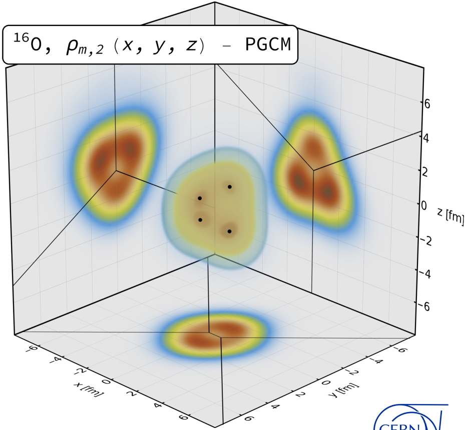
Ab initio nuclear structure models

- 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.
- ^{16}O consists of 4 α-clusters.
- The α-clusters are arranged in an irregular tetrahedron.



Revisiting the wishlist

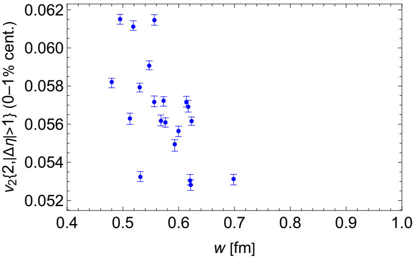
$v_n\{k\}$ in	pPb	OO
Small sensitivity to proton substructure	✗	✓
No longitudinal structure issues	✗	✓
Quantifiable theory uncertainty	✗	✓
Small theory uncertainty	✗	$\geq 4\%$

- Theory has a much better handle on ^{16}O^{16}O compared to pPb.
- Uncertainties are still substantial.
  - This limits our ability to test theory models.
- Can we do better?

[Giacalone, Bally, GN, Shen et al., 2402.05995]

Where are these uncertainties coming from?

- There are still substantial geometric uncertainties in the $^{16}O^{16}O$ 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 $^{16}O^{16}O$ should share these dependencies.
  - Can we exploit this?



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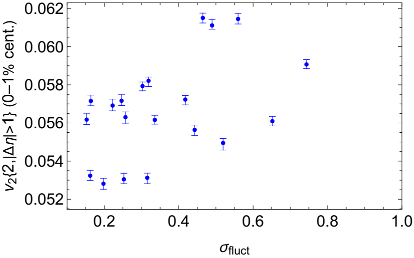
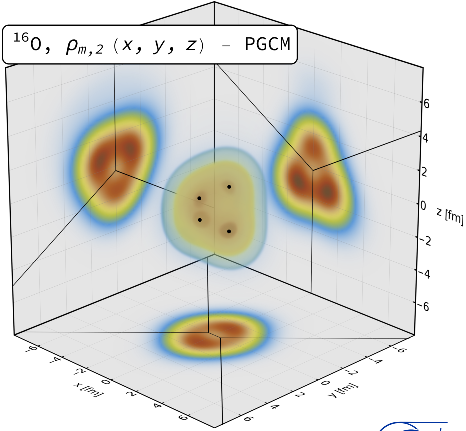


The nuclear bowling pin: ^{20}Ne

- 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.
- ^{20}Ne is close in size to ^{16}O.
  - Remaining geometric uncertainties should largely cancel.
- ^{20}Ne looks like ^{16}O, but with an extra α-cluster on top.
  - Whereas ^{16}O is close to spherical, ^{20}Ne is the most deformed nucleus in the Segrè chart.
  - Central v_2 ratio NeNe/OO should have a large signal.



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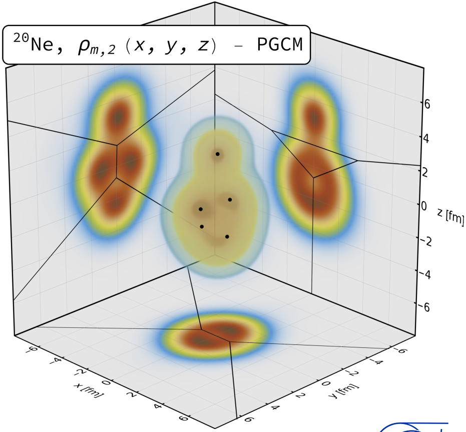
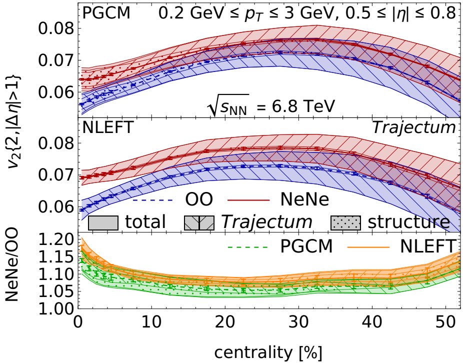


Comparing ^{20}Ne to ^{16}O significantly reduces errors!

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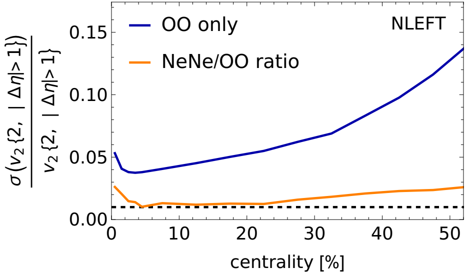

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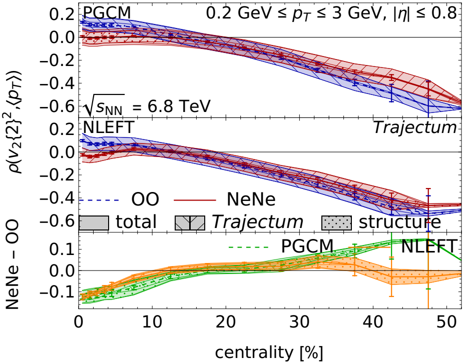

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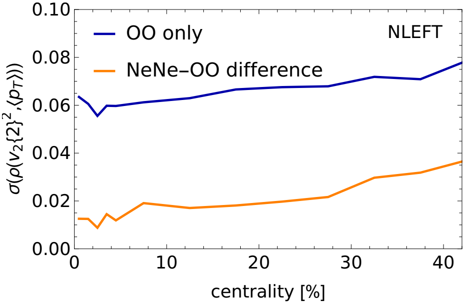

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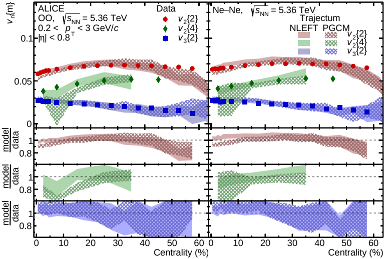
Revisiting the wishlist again

$v_n\{k\}$ in	pPb	OO	NeNe/OO
Small sensitivity to proton substructure	✗	✓	✓
No longitudinal structure 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 further by supplementing ^{16}O^{16}O collisions with ^{20}Ne^{20}Ne collisions.
  - We can bring the initial geometry under control to the percent level!
  - 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 describe OO (see ATLAS results).
  - No model describes all the data!
  - Without NeNe data, there would not be enough precision to see these tensions.

[Giacalone, Bally, GN, Shen et al., 2402.05995; ALICE, CERN-EP-2025-203]

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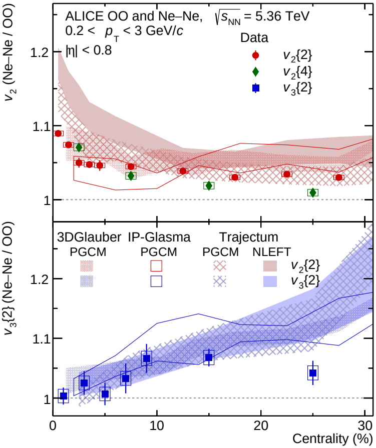

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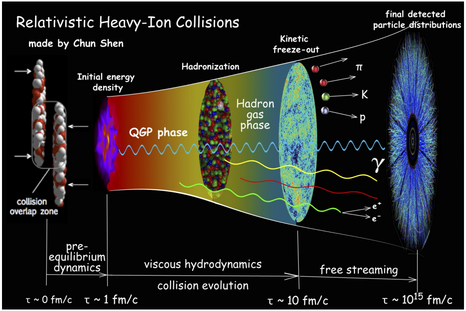
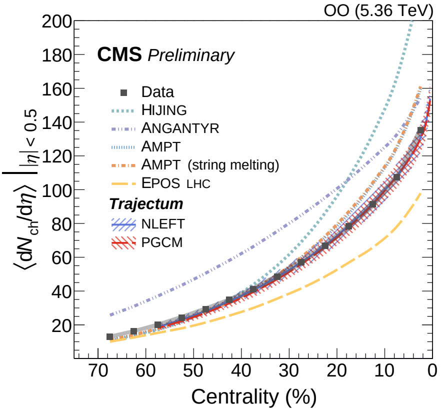
Where do these models differ?



- Details of the initial state and pre-hydrodynamic stage matter!
- Opportunity to learn about the stages we understand least!
- We can fit to the new data, with the aim of revealing precisely these aspects.

[Sorensen, Shen, 1304.3634]

We got lots of other results too!



- Multiplicity agrees very well with *Trajectum*, and shows large differences between models!
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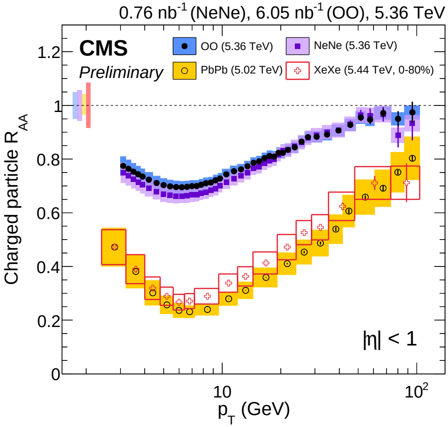

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[CMS, CMS-PAS-HIN-25-010, CMS-PAS-HIN-25-014; Giacalone, Bally, GN, Shen et al., 2402.05995; van der Schee, Kolbé, GN et al., 2509.04299]

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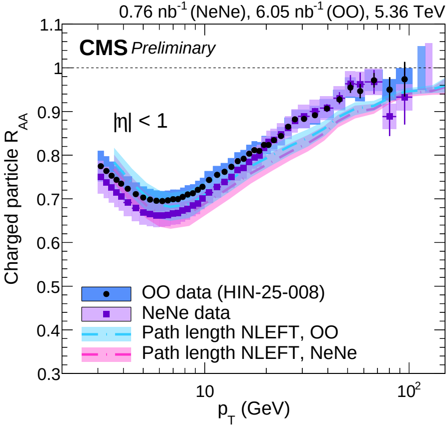

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The deformation of ^{129}Xe

- We describe ^{129}Xe with a *deformed* Woods-Saxon distribution:

$$\rho_{\mathrm{WS}}(r) \propto \frac{1}{1+\exp\left(\frac{r-R(\theta,\phi)}{a}\right)},$$

$$R(\theta,\phi) = R\left(1+\beta_2\cos\gamma\, Y_2^0 + \beta_2\sin\gamma\, Y_2^2\right),$$

with Y_l^m spherical harmonics.

  - We do not distinguish protons and neutrons.
- Observables in the central region are sensitive to β_2 and γ:
  - v_2 is sensitive to β_2.
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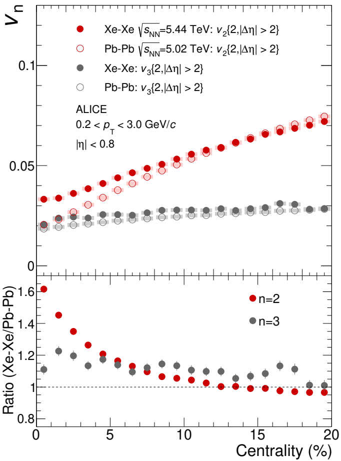

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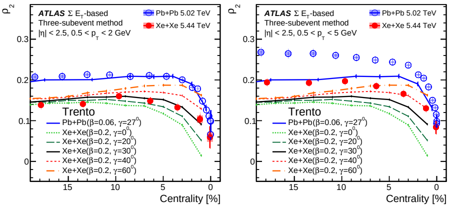
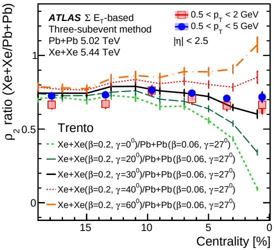
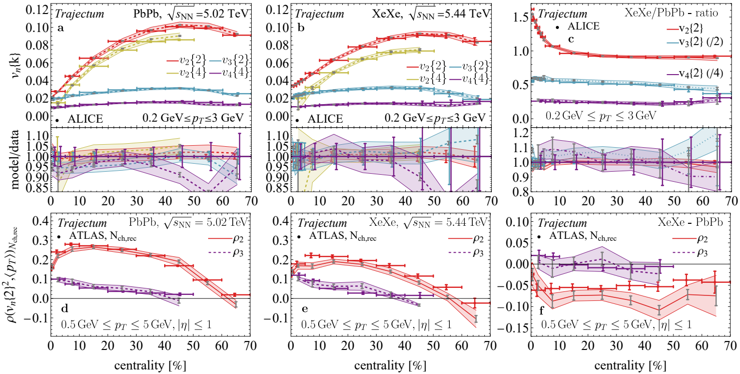




[Giacalone, GN, van der Schee, 2606.03993; ALICE, 1805.01832; ATLAS, 2205.00039]

A selection of posterior observables

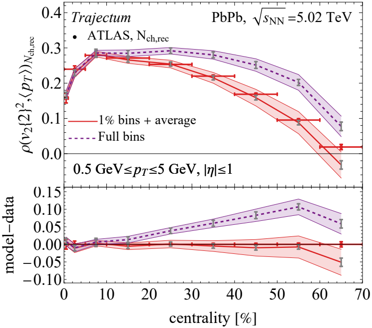


- Precise description of $v_n\{k\}$ and ρ_2.
  - We fit PbPb as well as XeXe data.
  - For ρ_2 we also fit to the difference of XeXe compared to PbPb, for $v_n\{k\}$ we fit to the ratio.

[Giacalone, GN, van der Schee, 2606.03993]

Details are important!

- Some observables, such as ρ_2, depend sensitively on the measurement details.
- Bin size matters:
  - Measurement of ρ is done in small centrality bins.
  - Should compute in small bins, then average.
- Definition of centrality:
  - Different definitions give different answers.
  - In this case, many definitions are available.
  - Should compare to a measurement which uses a definition that our model can reliably compute.
- Ignoring these details can result in biased answers!



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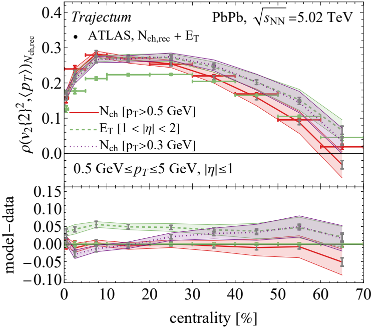
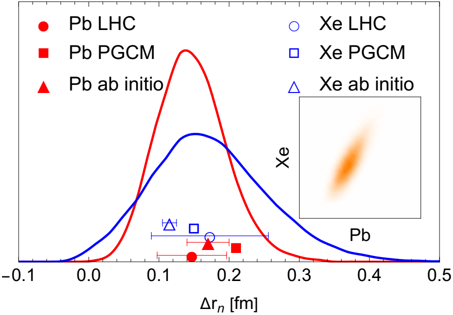


Bayesian analysis result using LHC data

- We are able to extract the skin depth a.
    - Using the known charge radius, we can convert to neutron skin.
    - First experimental measurement of the neutron skin of ^{129}Xe.
    - The neutron skins of ^{208}Pb and ^{129}Xe are correlated.
- The deformation parameters β_2 and γ are well constrained.
- ^{129}Xe is truly triaxial, shaped like a kiwi.
- Potential applications to $0\nu\beta\beta$ decay.



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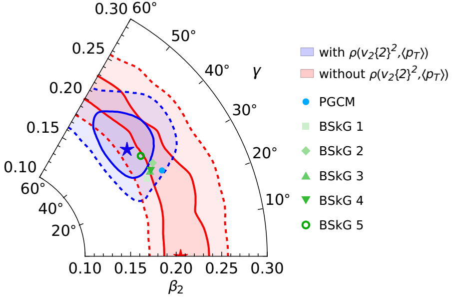
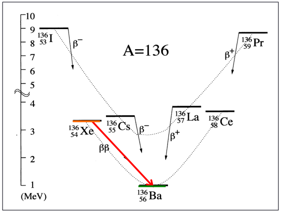


Neutrinoless double beta decay

- For certain nuclei, single beta decay is kinematically forbidden, but double beta decay is allowed.
- If the neutrino is a Majorana particle, then the two neutrinos can annihilate: neutrinoless double beta decay.
    - In the spectrum for the electrons, this would show up as a peak at the end.
- The decay rate is given by:

$$\Gamma \propto |M|^2 m_{\beta\beta}^2.$$



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- $|M|$ is a *nuclear matrix element* for this decay.
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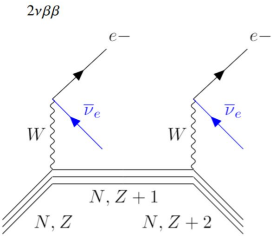

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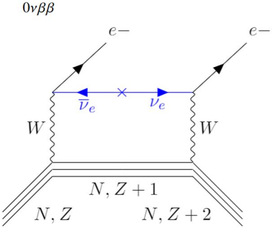

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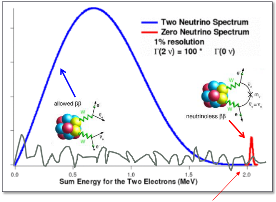

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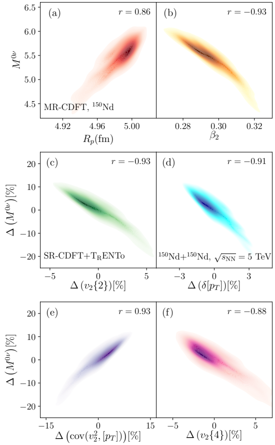
Nuclear matrix elements from heavy ion collisions



- Nuclear matrix elements are very correlated with the *difference* in shape of the nuclei.
  - This leaves imprints in heavy ion collisions of these nuclei.
  - The nuclei involved are isobar pairs, making extracting the difference in shape easier.
  - The ‘shape’ can be made well-defined using multinucleon correlators.
- We are currently expanding on this, and will conduct a sensitivity study for $^{76}\mathrm{Ge} \mapsto {}^{76}\mathrm{Se}$.

[Li, Zhang, Giacalone, Yao, 2502.08027]

The power of short runs

- The ^{129}Xe run took just 6h of data.
  - We can quantitatively extract its shape.
  - Proof of concept for similar future studies with big physics impact.
- The ^{20}Ne run took 12h.
  - Broad agreement with hydro.
  - Tensions provide new questions.
  - Should we next go smaller? Larger?
- What can we learn from future short runs?
  - ^{76}Ge and ^{76}Se?
  - ^{48}Ca and ^{40}Ca?
  - ^{4}He?
  - ^{24}Mg?
- We have the opportunity to shape the future of the LHC ion program!

Backup

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Opportunities at LHCb

- The SMOG2 system at LHCb is able to inject gas into the beampipe.
  - This allows to perform collisions at $\sqrt{s} = 68.5\,\mathrm{GeV}$.
- Similar to the NeNe/OO ratio, one can take a NePb/OPb v_2 ratio.
  - A large signal is predicted by multiple models.
- Challenges:
  - Injected Ne gas is not isotopically pure.
  - Injecting O has not been approved.
- ^{16}O and ^{20}Ne beams would allow for several new collision systems:
  - ^{16}O^{16}O (if O is approved for SMOG2),
  - ^{16}O^{20}Ne,
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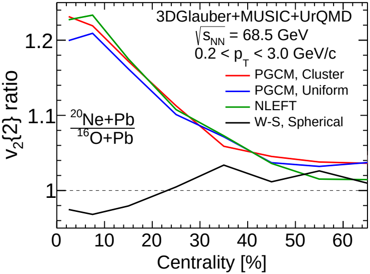

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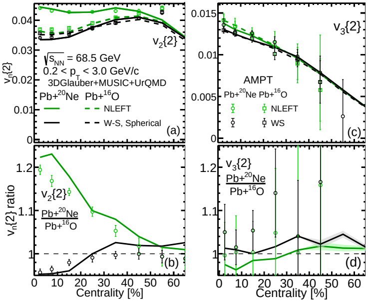
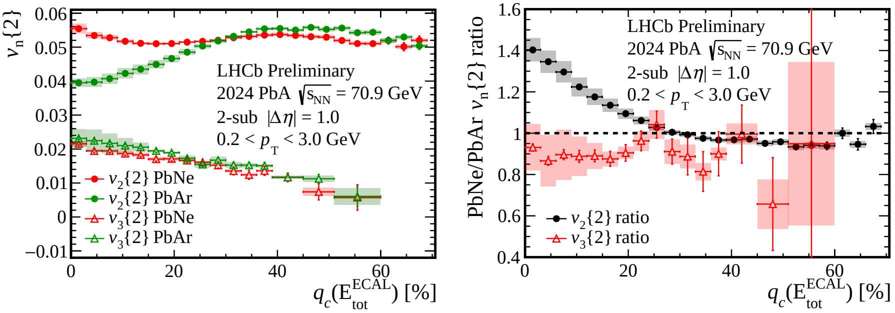


How do predictions hold up?



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