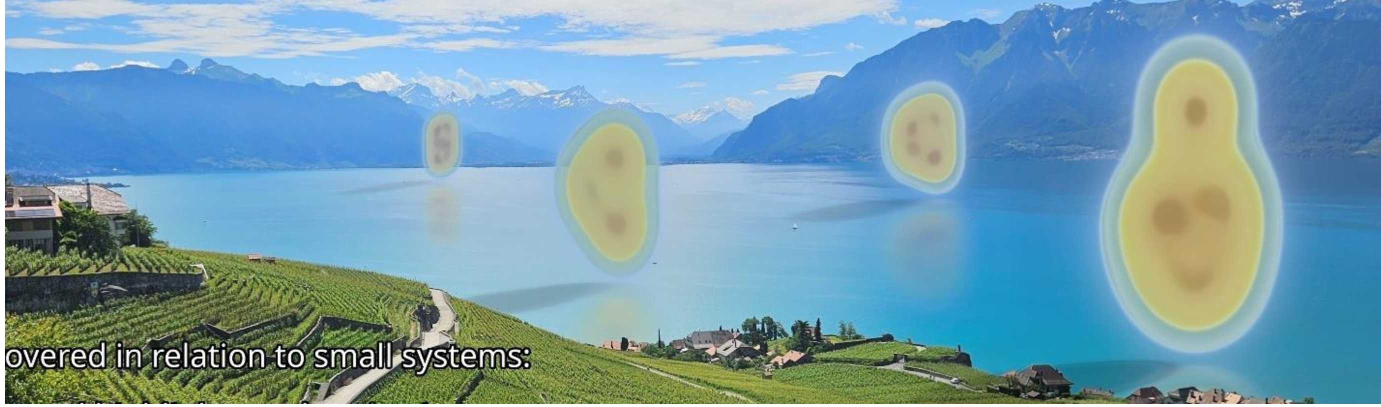
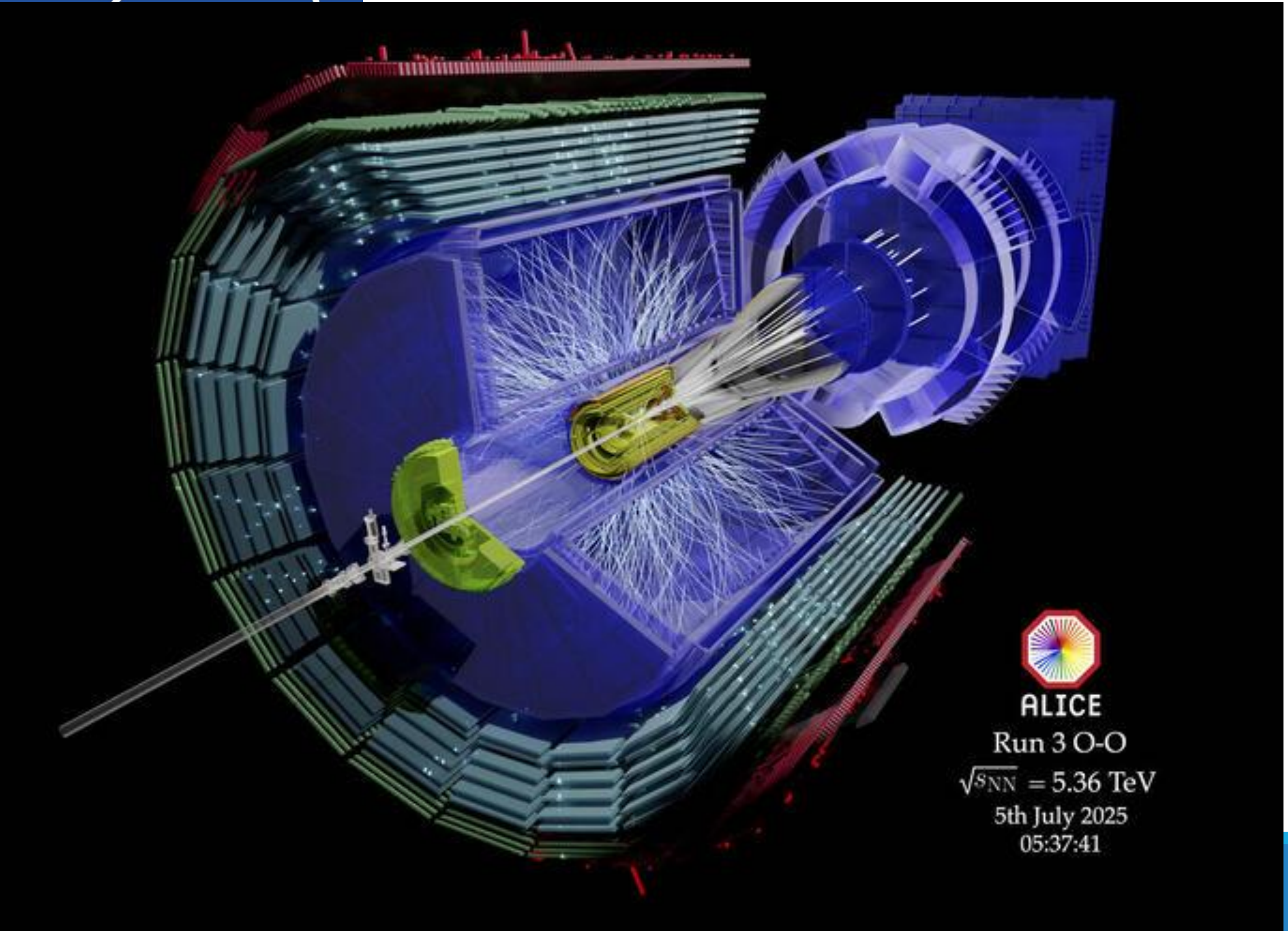
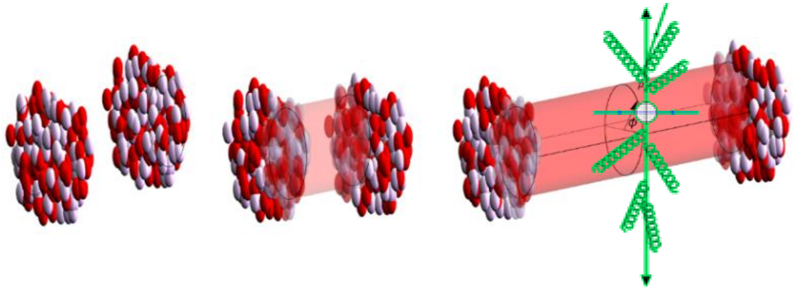




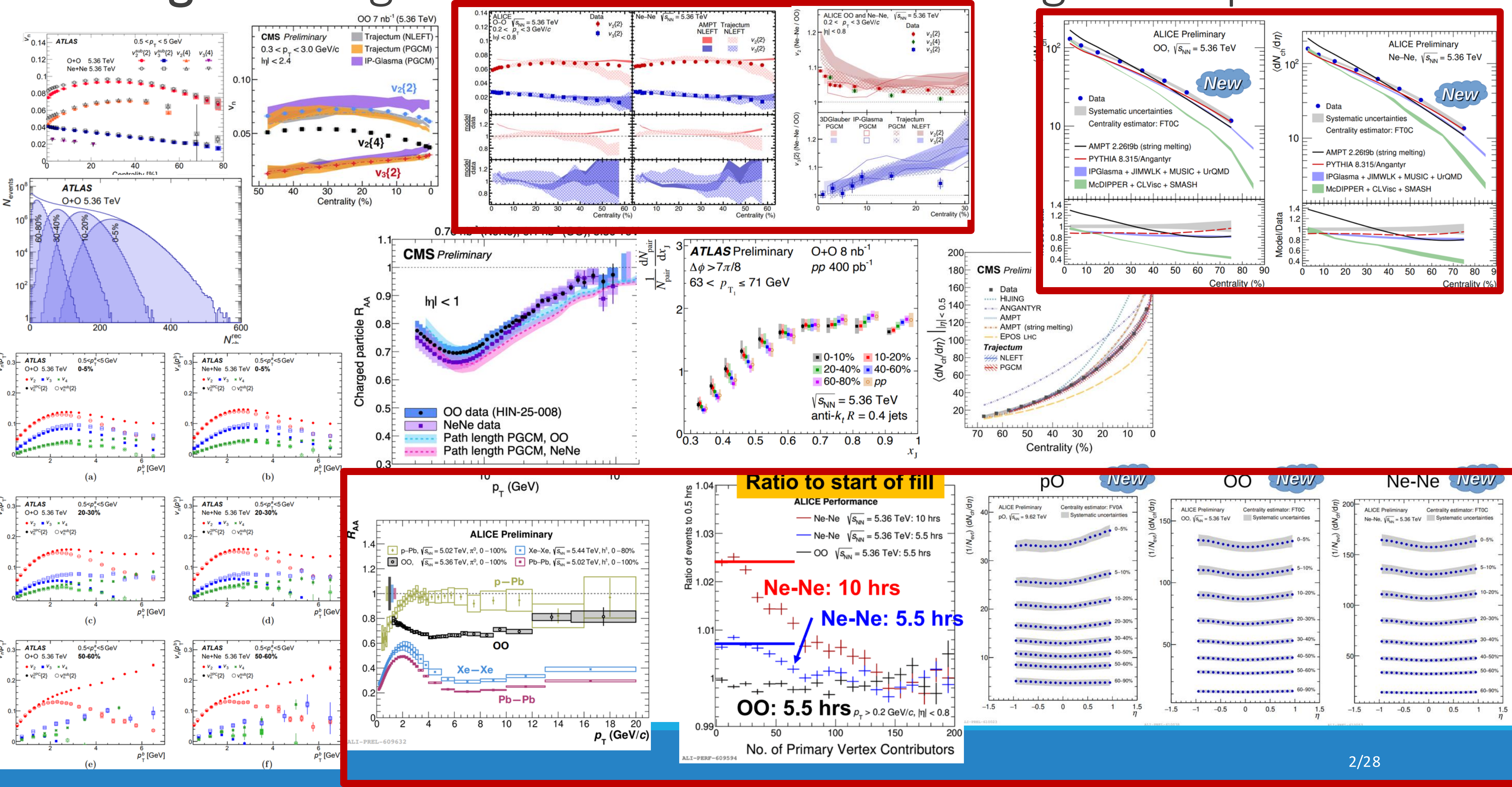


Trajectum framework applied to light ion collisions

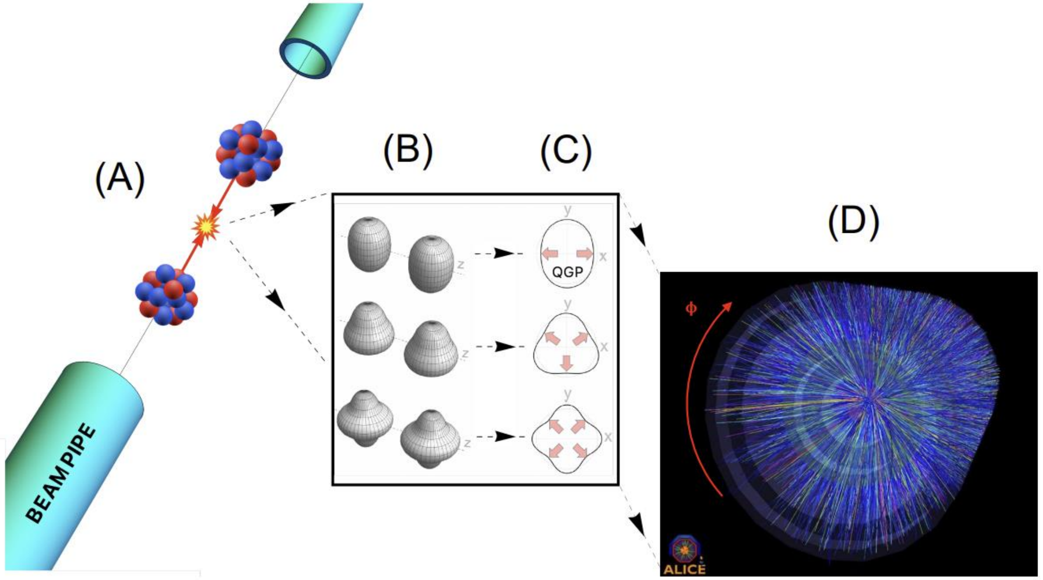
Work mostly with Govert Nijs and Giuliano Giacalone

Wilke van der Schee
ALICE Week
03 November 2025

Exciting times: light ion collisions allow(ed?) for genuine predictions



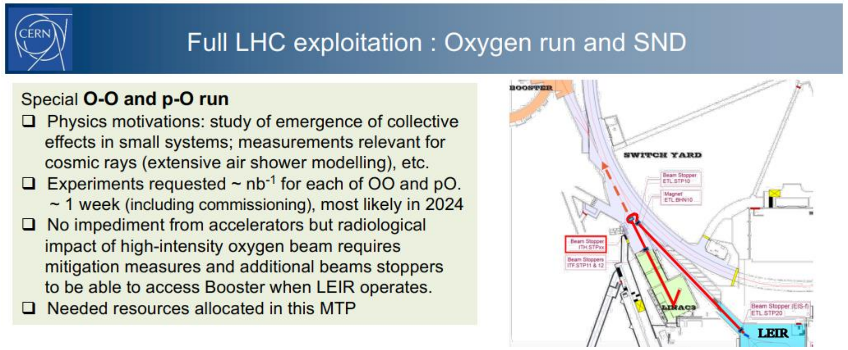
The shape of nuclei



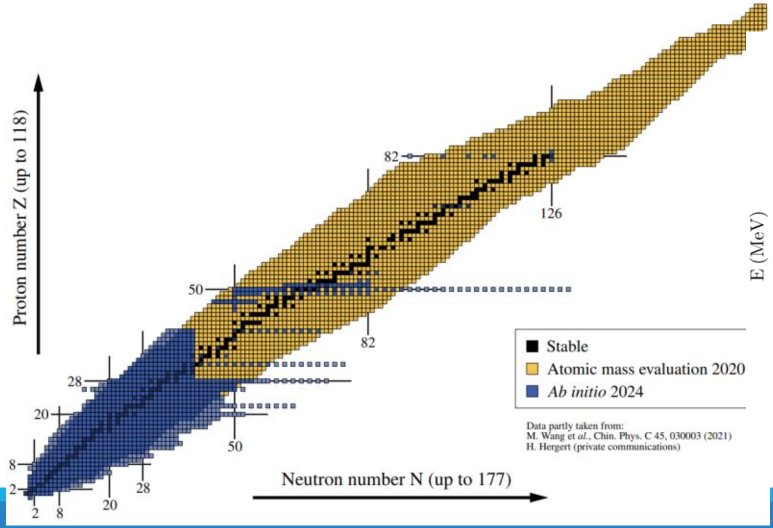
Hydrodynamics converts position space anisotropy into momentum space anisotropy

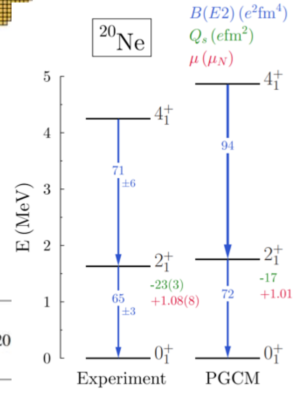
Synergy between HIC and nuclear structure

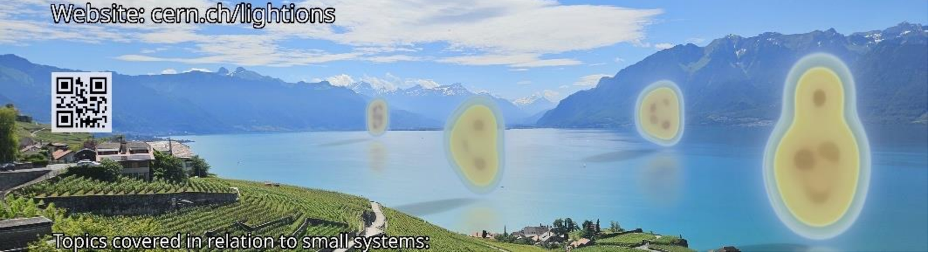
1. LHC seems like an expensive machine to determine the shapes of nuclei
    - Ion collisions are unique: yoctosecond imaging of the ground state
    - Much like a collapse of the wave function (nucleon positions)
    - Thickness function: two-dimensional projection / random orientation
    - Very complementary to `standard' nuclear structure:
        - Charge profile, excitation energies, isospin density (PREX)

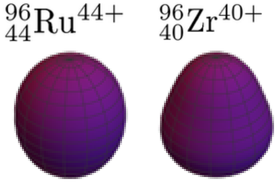


2. Two-way transfer:
   heavy ion community needs to know the structure accurately
    - Fluctuations are enormous
    - Unlikely to learn much without full control of the shape

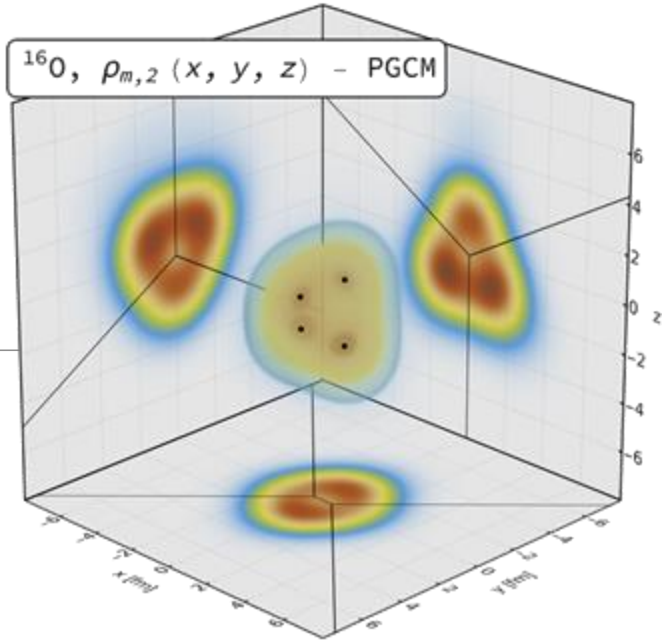








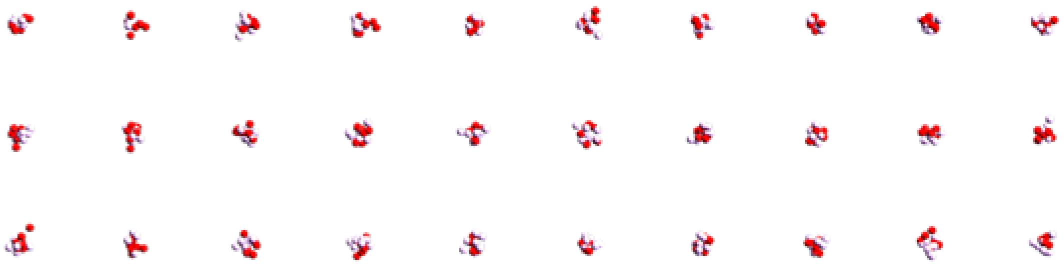
^{16}Oxygen and ^{20}Neon nuclear structure

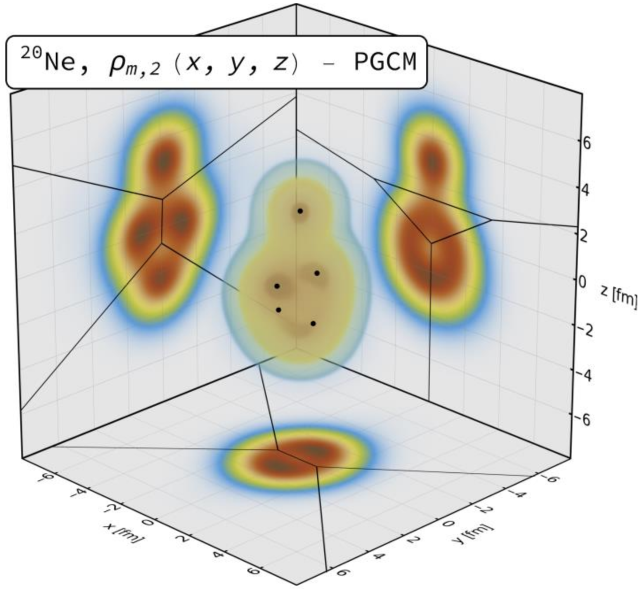


Studied using two complementary nuclear structure methods:

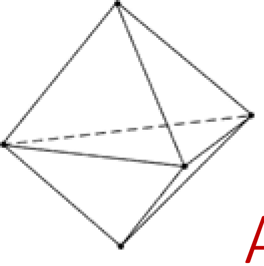
1. State-of-the-art Projected Generator Coordinate Method (PGCM)
   - N^3LO chiral EFT with Hartree-Fock-Bogoliubov constrained states
   - We sample 4 nucleons in Voronoi regions determined by 4 or 5 local maxima

2. \`Pinhole' configurations from Nuclear Lattice Effective Field Theory (NLEFT)
   - Minimal pionless EFT Hamiltonian, lattice of eight sites (spacing = 1.315fm)
   - Output is directly nucleon positions (!) (but note negative weights for 1/3 configs ☹)
   - We still cluster the nucleons to optimise the breaking of periodic lattice





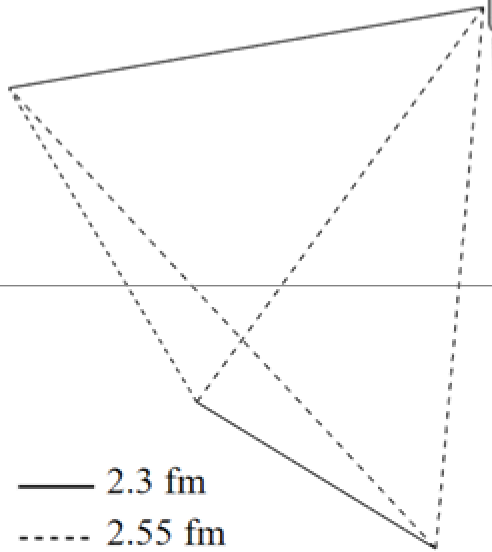
Giuliano Giacalone, Benjamin Bally, Govert Nijs, Shihang Shen et al, The unexpected uses of a bowling pin: exploiting 20Ne isotopes for precision characterizations of collectivity in small systems (2024)

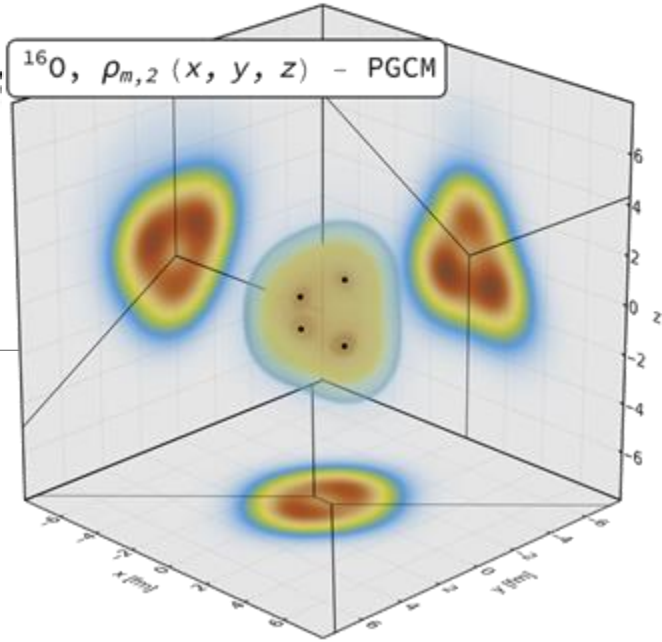


Alphas from nuclear structure

Two big surprises (at least to me ☺)

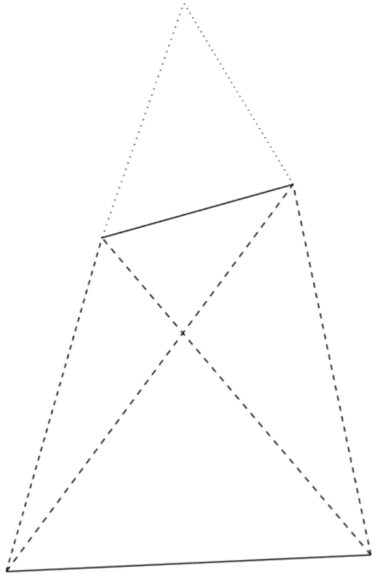
1. ^{16}O alphas do not form a regular tetrahedron (!)
   → more like two coupled rods
   Similar results in NLEFT

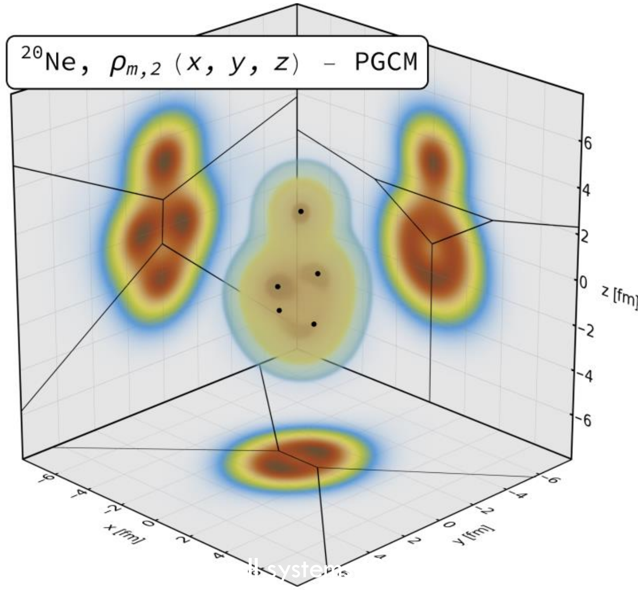




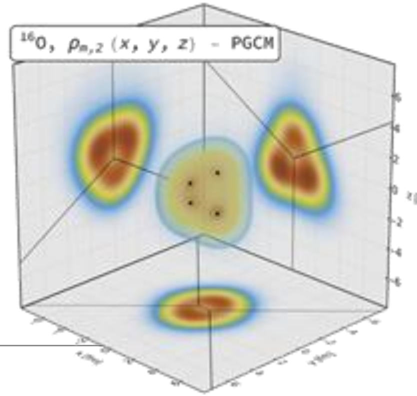
2. ^{20}Ne alphas do not form a bipyramid (!)
   → seemingly randomly placed on top…
   (was a challenge to find due to breaking of symmetry, credit to Benjamin Bally)

3. Of course the intuition of alphas as point particles with interaction energy is really quite naïve…



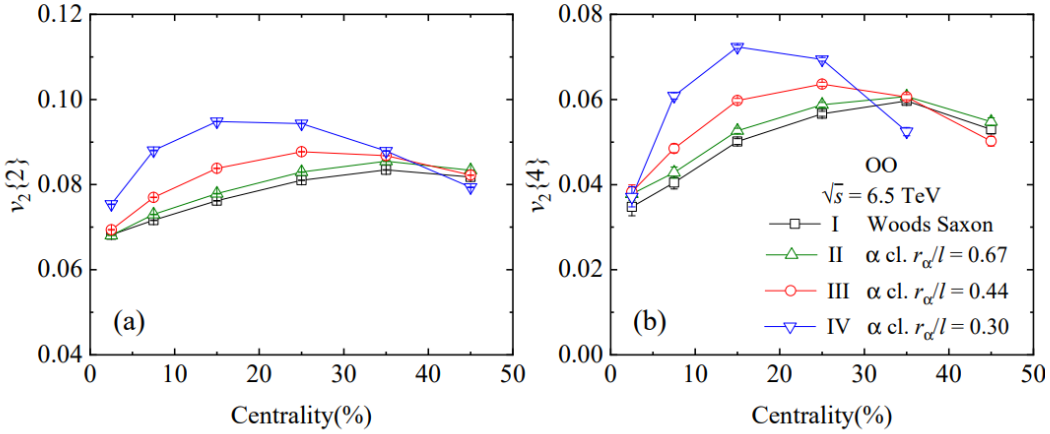


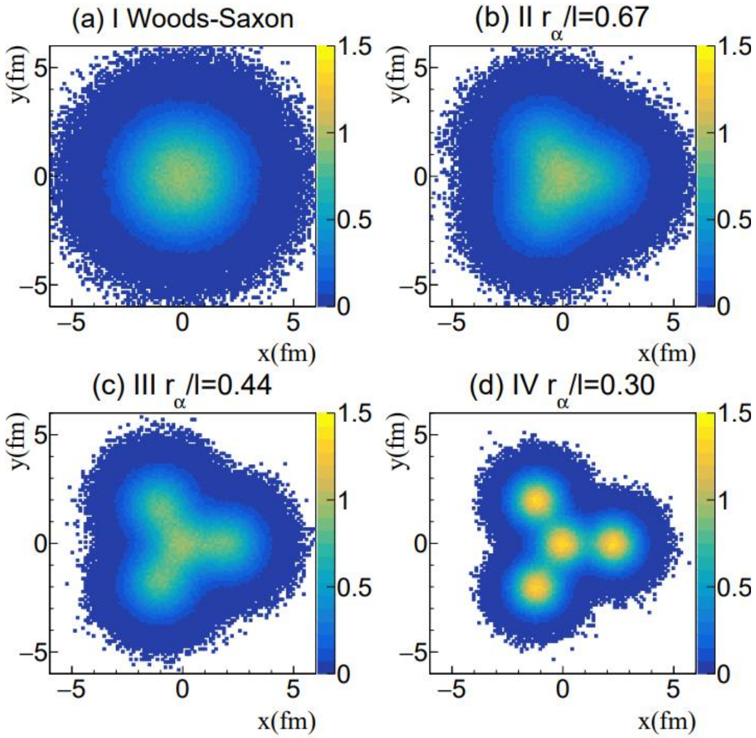
How do we see α-clustering?



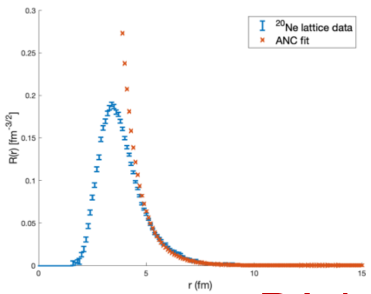
The first obvious try: compare Woods-Saxon with alpha clustered shape

1. Significantly different flow
2. PGCM ab initio close to case II (green, not very different from WS)
3. But how to correct for systematic uncertainty due to viscosity etc etc?

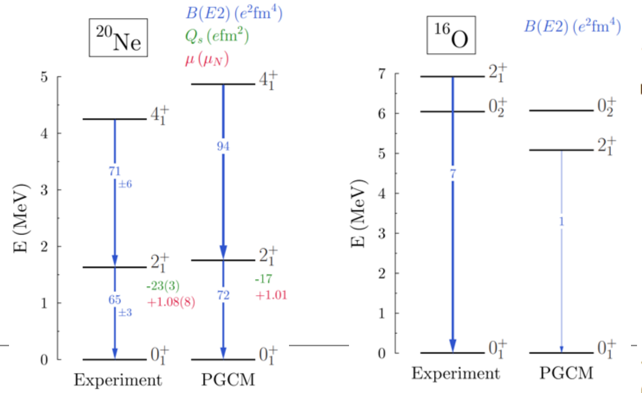


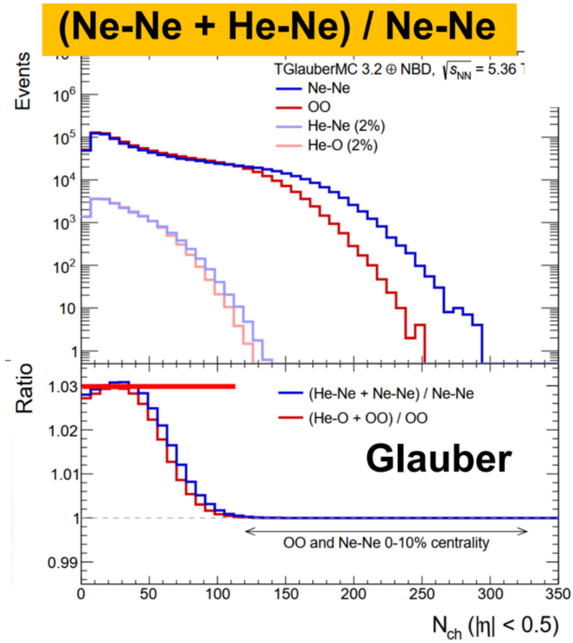


Nicholas Summerfield, Bing-Nan Lu, Christopher Plumberg, Dean Lee, Jacquelyn Noronha-Hostler and Anthony Timmins, 16O16O at RHIC and the LHC comparing α clustering vs substructure (2021)
Yuanyuan Wang, Shujun Zhao, Boxing Cao, Ho-jie Xu and Huichao Song, Exploring the compactness of α cluster in 16O nuclei with relativistic 16O+16O Collisions (2024)



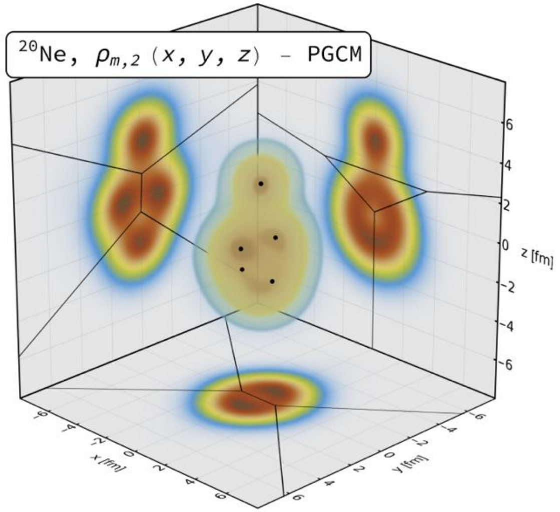
Did we see α – clustering? (I think yes)

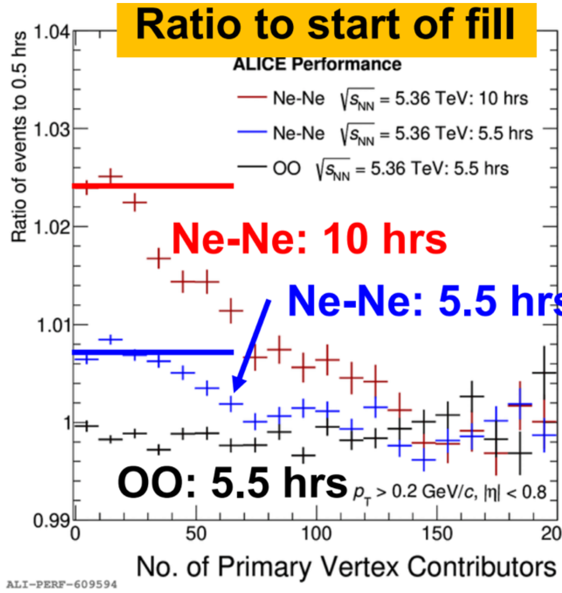




1. After 10 hours convincingly 2% ^{20}Ne – ^{4}He collisions in ALICE
    - Not seen in Oxygen collisions (!)
    - Not yet seen in other experiments (pile-up, different bunches?)

2. The (only?) convincing argument why this happens:
    - Neon top α breaks off
    - Related: First excited state Neon much lower energy
    - Much more convincing than flow measurements





3. Unexpected benefit: first time asymmetric nuclear collisions at top LHC energy (!)
    - Especially mean p_T will be interesting to verify size and hydrodynamic paradigm
    - Possible to distinguish E-by-E? V0A versus V0C, ZDC asymmetry, mean p_T?

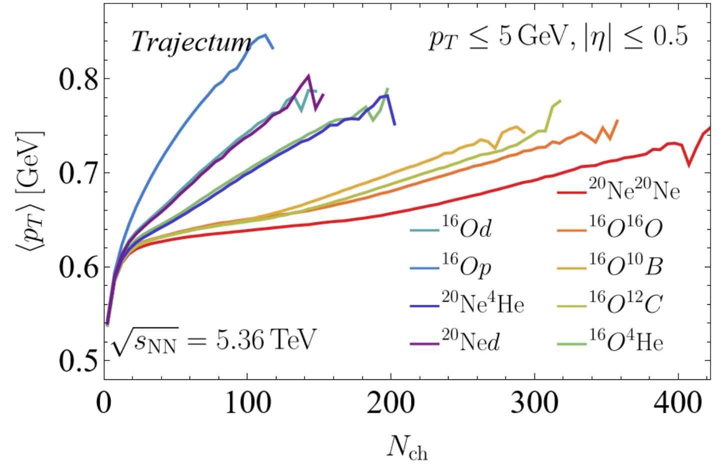
E. Harris et al, Quantifying α clustering in the ground states of ^{16}O and ^{20}Ne (2025)

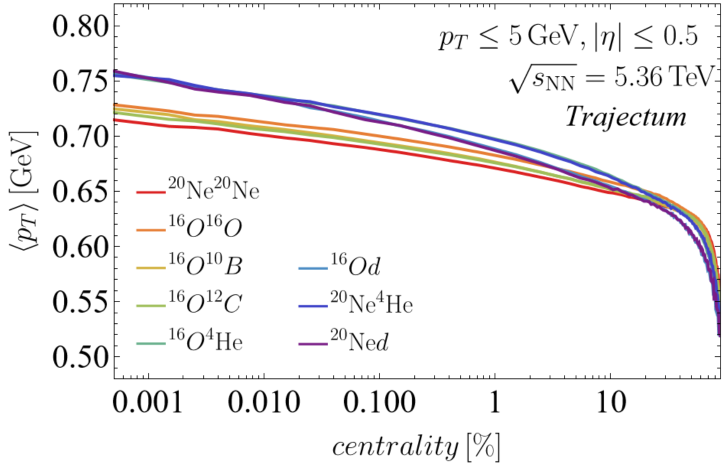
Govert Nijs and WS, Transmutation of 16O and 20Ne at the Large Hadron Collider (2025)

https://indico.cern.ch/event/1436085/contributions/6107509/attachments/2966206/5218662/talk_bally_cern_13112024.pdf

https://indico.cern.ch/event/1479384/contributions/6631982/attachments/3130687/5553818/JFGO8p.pdf

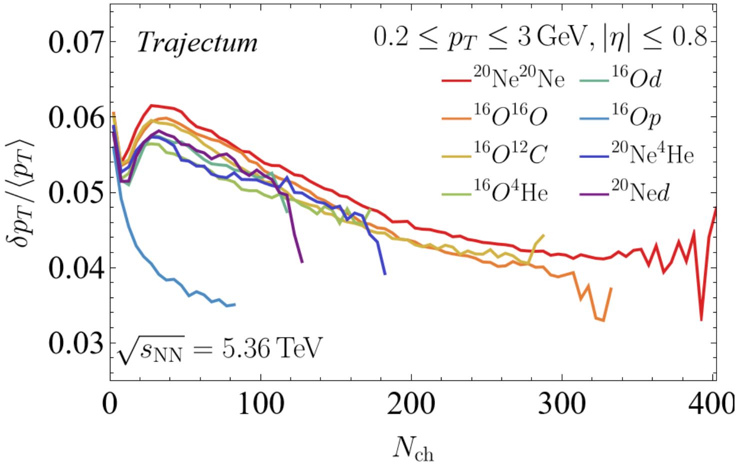
Transmutation: a prediction





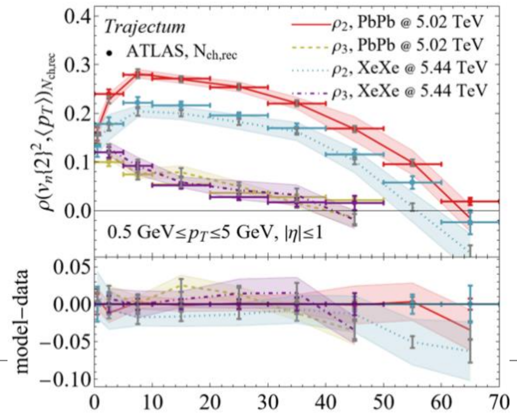
The mean transverse momentum of Ne-He will be measured and large

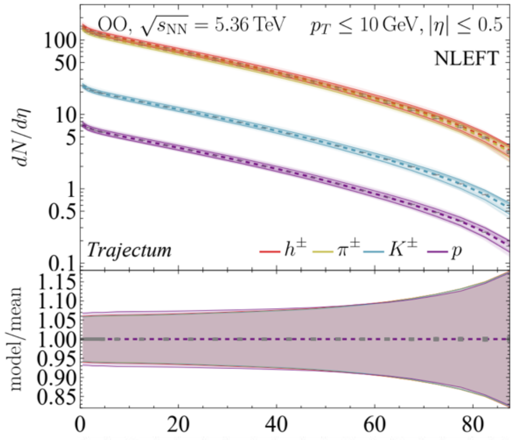
- Close analogy with `speed of sound’, or ultracentral PbPb
- But in much smaller system (!)
- pO also interesting mean pt fluctuations

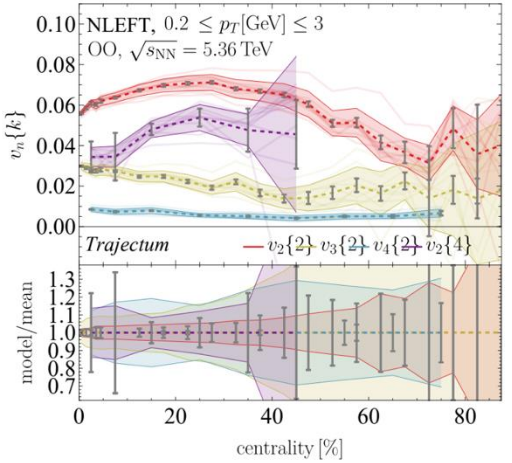


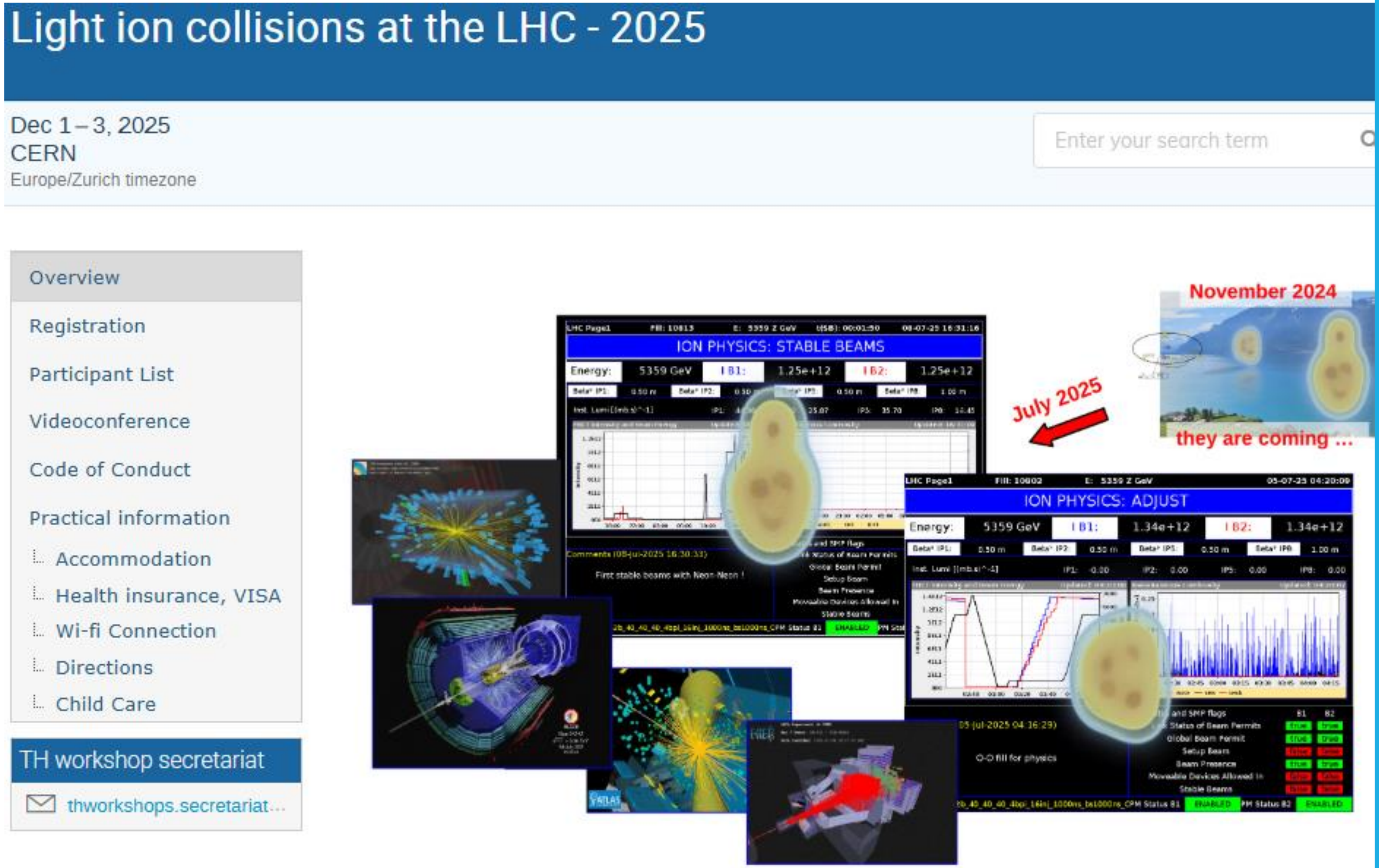
Exciting times:
heavy ions is now a precision science

1. Systematic uncertainties, also in theoretical estimates
   - Uncertainty comes from Bayesian posterior
   - Full correlations among datapoints is included
2. Uncertainties can be small
   - ~6% for multiplicity in OO
   - ~2-5% for anisotropic flow (except $v_2\{4\}$: statistics dominate)
3. Corollaries:
   - We need to understand the shapes of colliding nuclei precisely
   - We need to have the full model of heavy ion collisions under control
   - This is necessary to understand \`**the details**’ such as:
     - Hydrodynamisation
     - Extreme hydrodynamics: when gradients are large
     - First and second order viscous gradient corrections, during hydro and freeze-out





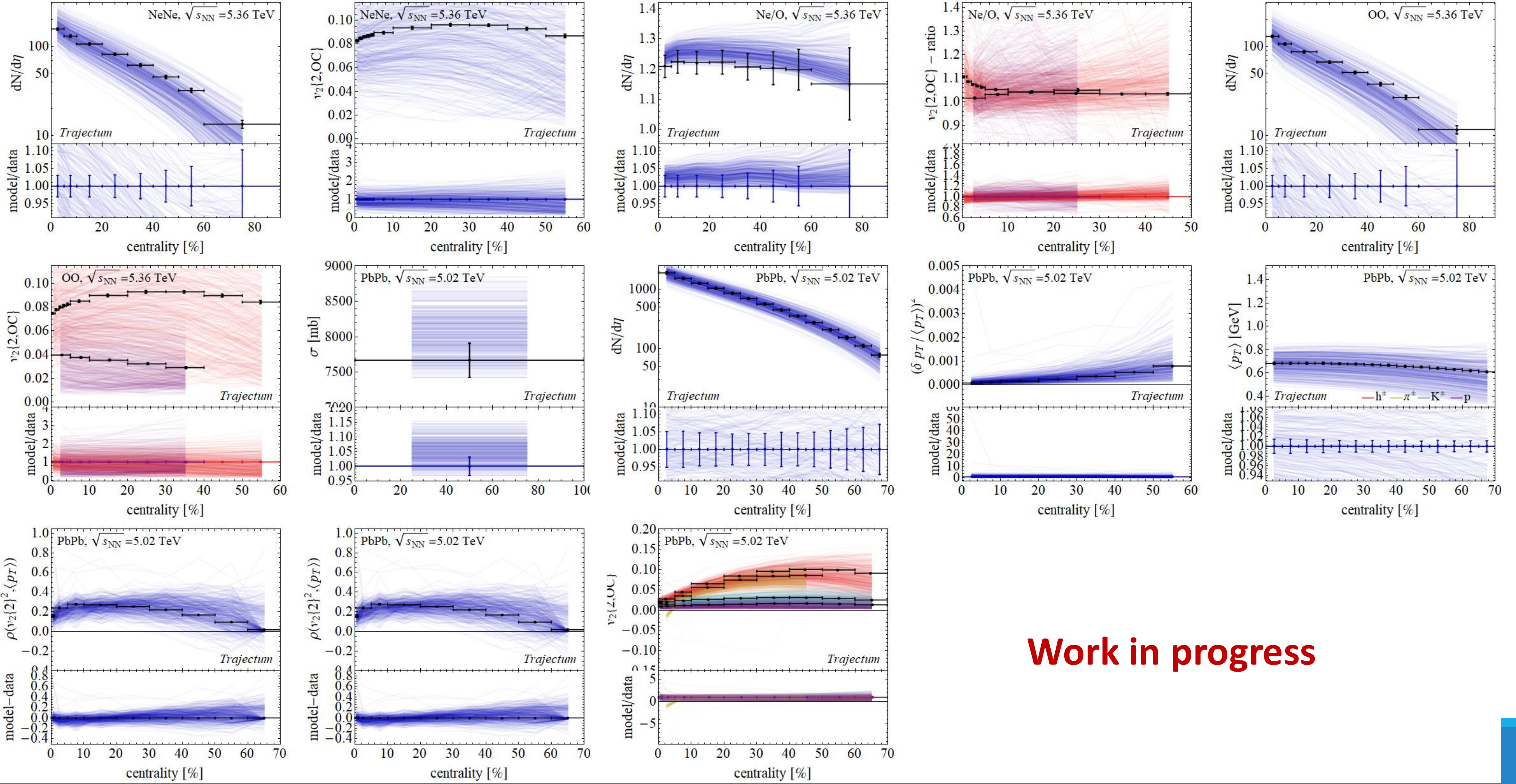




Light ions at the LHC – the sequel

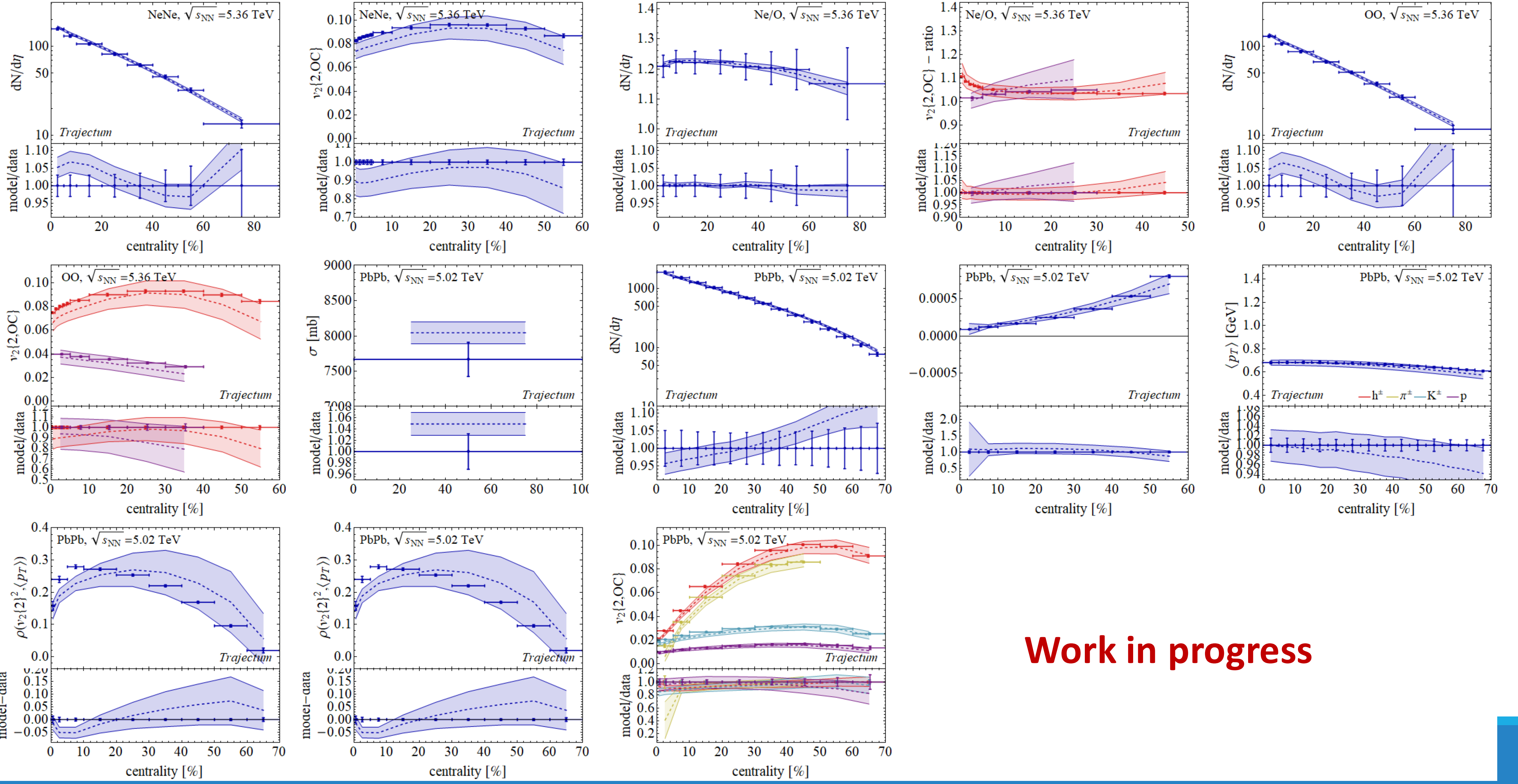
CERN.CH/LIGHTIONS2025

Refit parameters based on current data



Work in progress

Refit parameters based on current data



Work in progress

Multiplicity

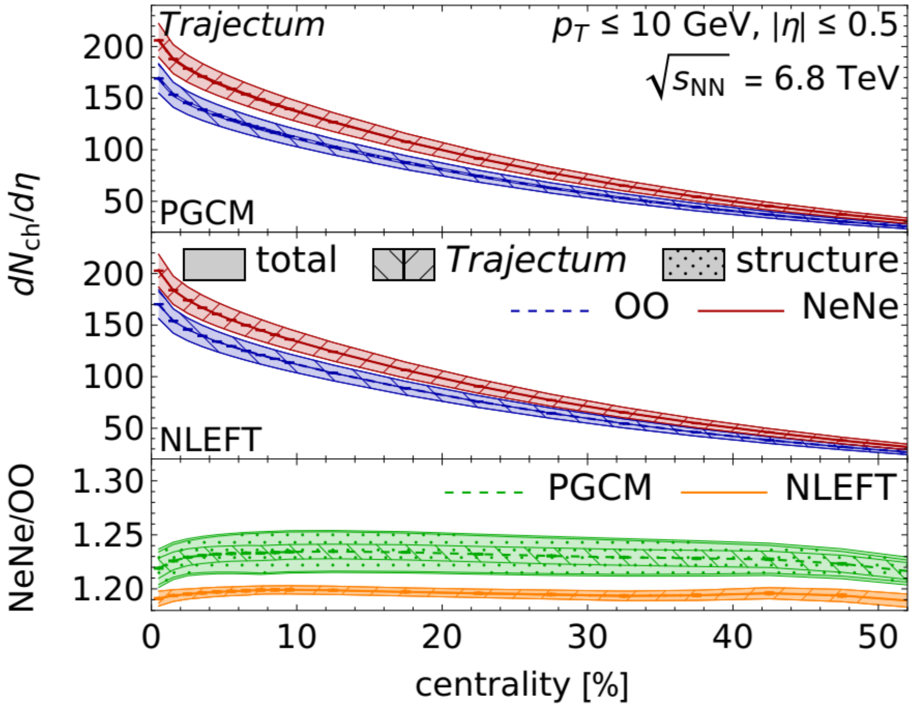
Exciting times:
light ion collisions allow(ed?) for genuine predictions

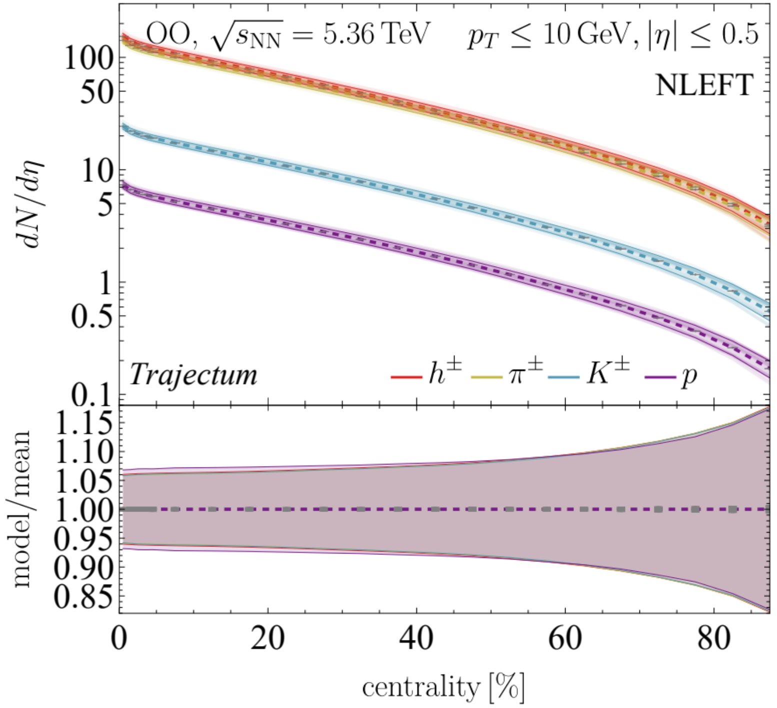
Hydrodynamic predictions for light ion collisions

All the way to dN/dη ~ 10; hydro at its limits?

Model is (only!) fitted to PbPb data

Difference PGCM/NLEFT is understood due to size differences

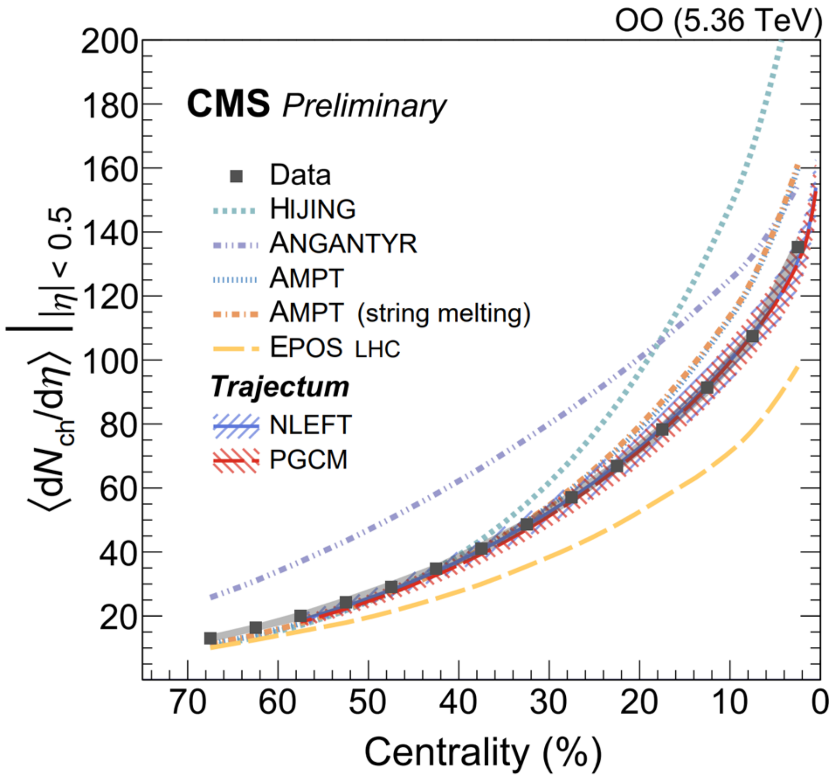


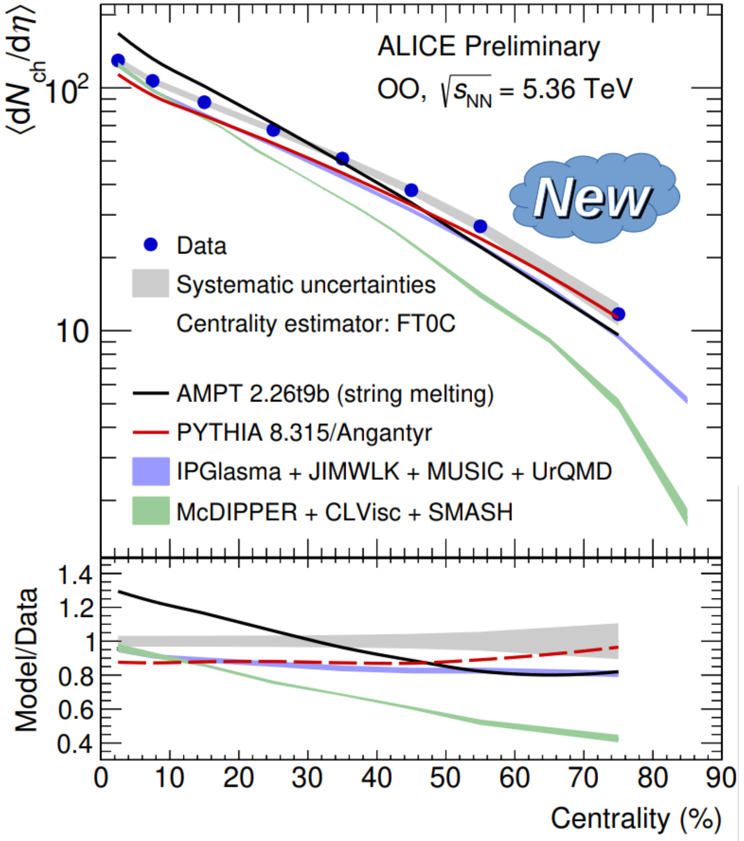


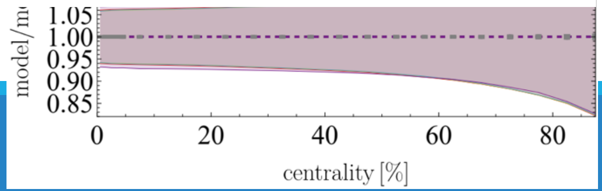
Exciting times:
comparison with CMS and ALICE

Agreement almost too good to be true?

Also: non-hydro models tend to be off
(but notice lack of syst uncertainty)

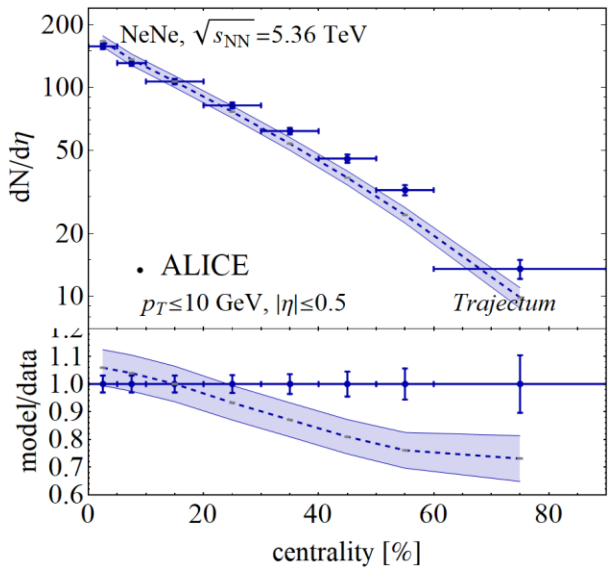


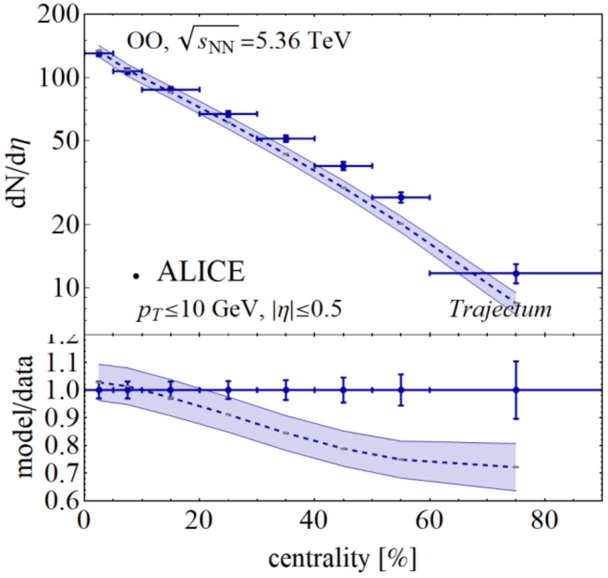


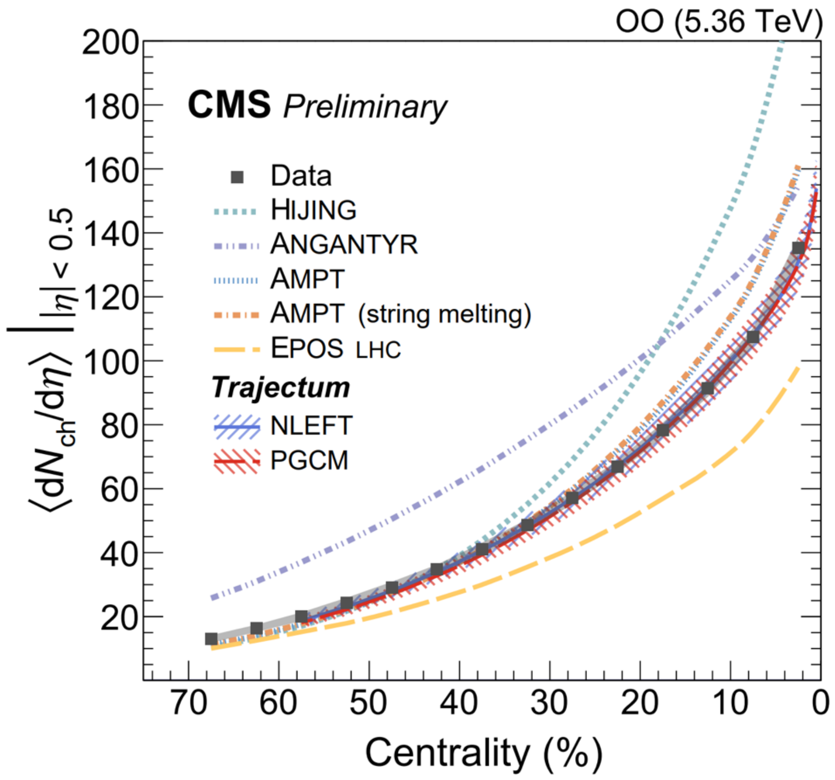


Giuliano Giacalone et al, The unexpected uses of a bowling pin: exploiting 20Ne isotopes for precision characterizations of collectivity in small systems (2024)
CMS, First measurement of pseudorapidity distributions of charged hadrons in oxygen-oxygen collisions at $\sqrt{s_{NN}}$= 5.36 TeV (2025)
https://indico.cern.ch/event/1479384/contributions/6663047/attachments/3131557/5555439/IS_mult_v3.pdf

Exciting times:
comparison with CMS and ALICE







Agreement almost too good to be true?
Maybe true: fits CMS much better than ALICE..

0-5% class: CMS has 135.3, ALICE has 130.3 (4.0 uncertainty)
50-60% class: CMS has 22.5, ALICE has 27.0 (1.5 uncertainty)

[different cuts means CMS should be approximately 1% lower]

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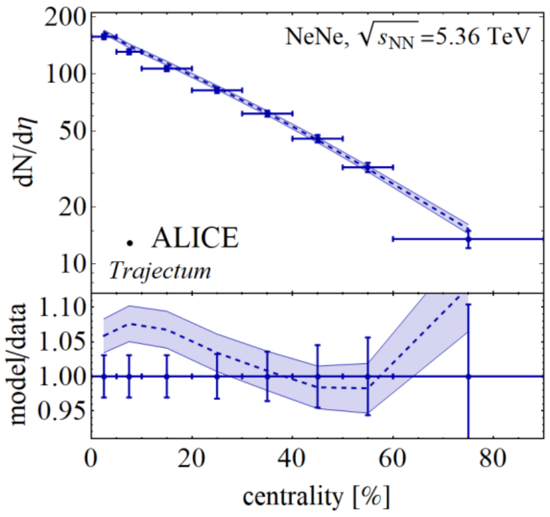
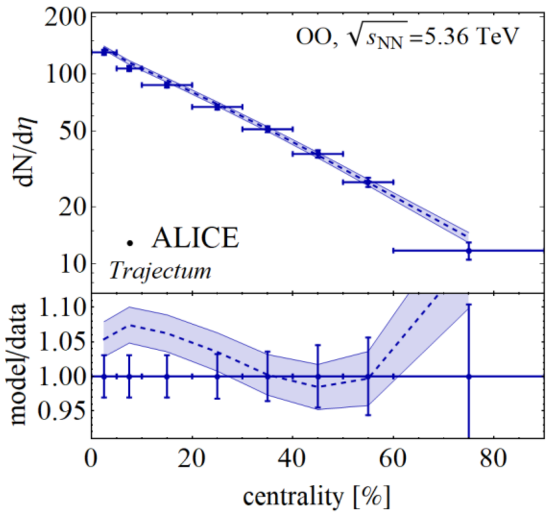
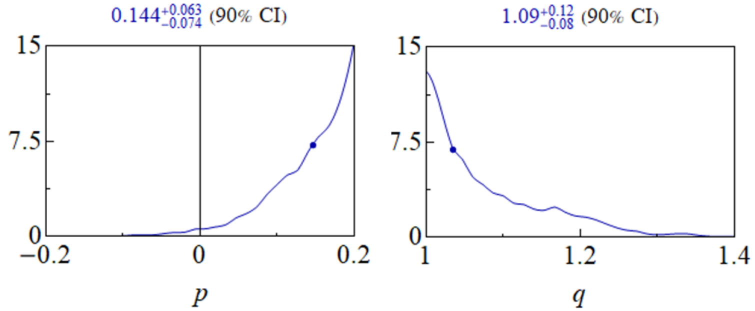
Exciting times:
Fitting new ALICE data

Work in progress (no smash or lattice spacing correction)







Fit seems to work OK; but slightly strange Trento parameters

Giuliano Giacalone et al, The unexpected uses of a bowling pin: exploiting 20Ne isotopes for precision characterizations of collectivity in small systems (2024)
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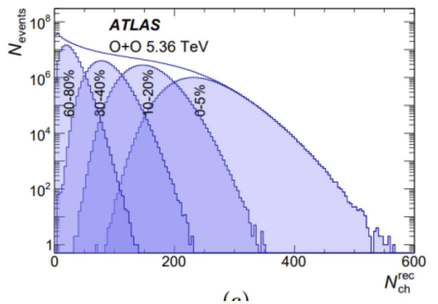
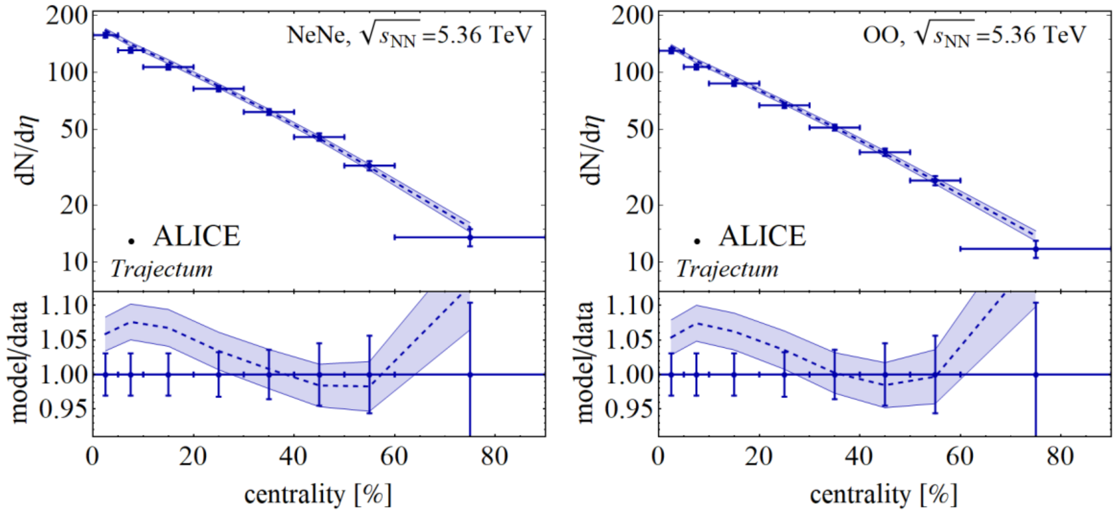
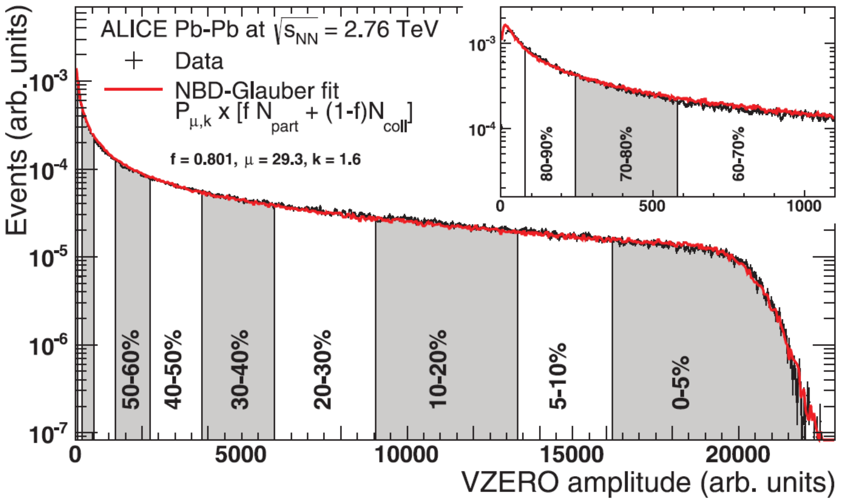


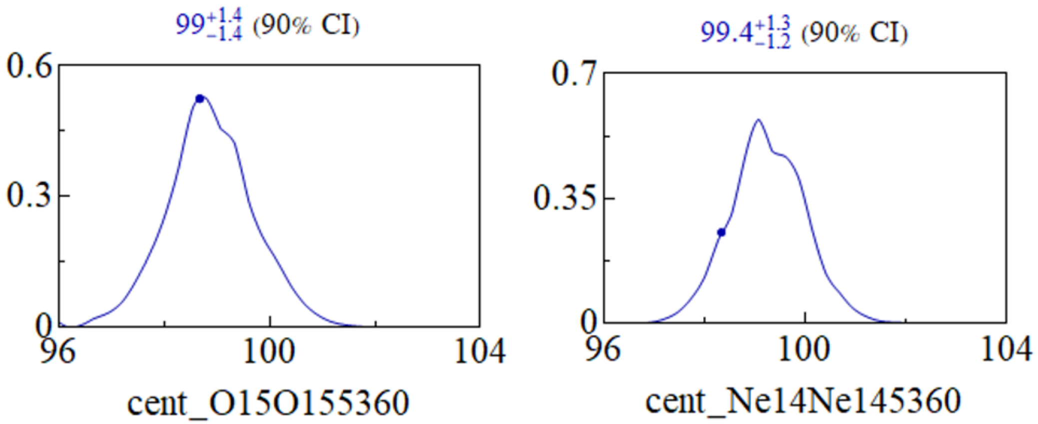




How is the centrality determination done? Usually NBD-Glauber; perhaps a bit outdated?

Nevertheless, preliminary Trajectum results (varying the 100% anchor point) suggest results consistent with 100% (slight preference for 99%).

This is done with ALICE dN/deta, but ATLAS vnk [we don't vary centrality normalisation per experiment]



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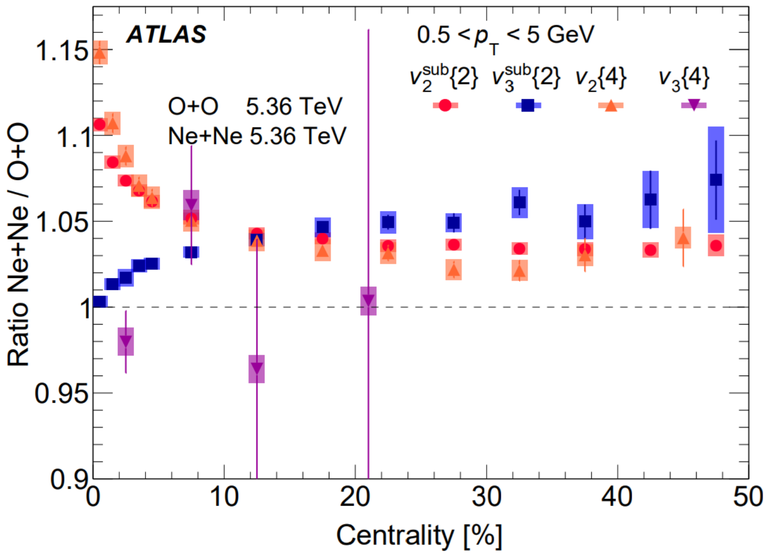
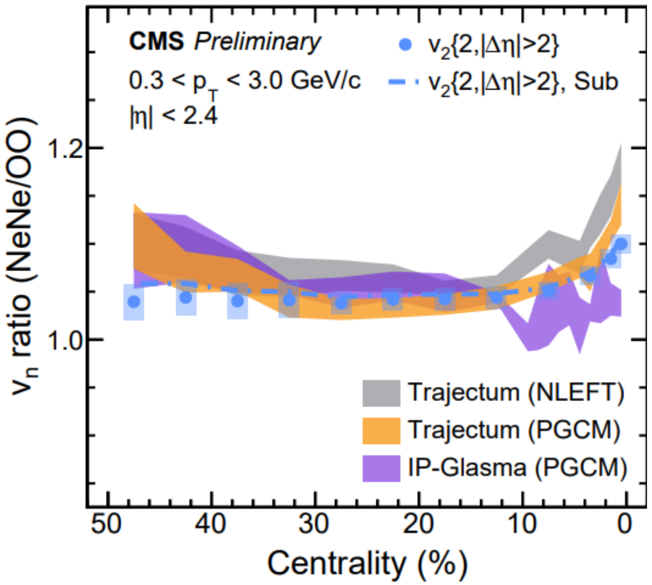
Flow

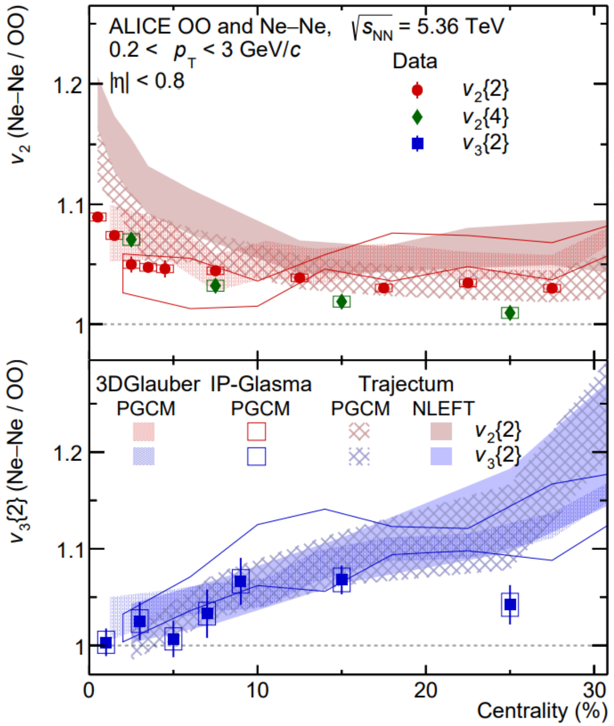
Anisotropic flow --- ratio

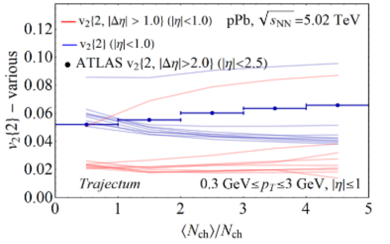
0-1% elliptic flow ratio significantly overestimated

- But: uncertainty is only one standard deviation (treat uncertainty seriously)
- Also: PGCM significantly closer
- Not clear if ATLAS and ALICE are consistent

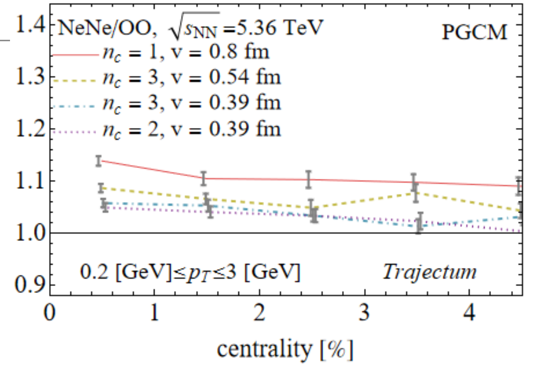






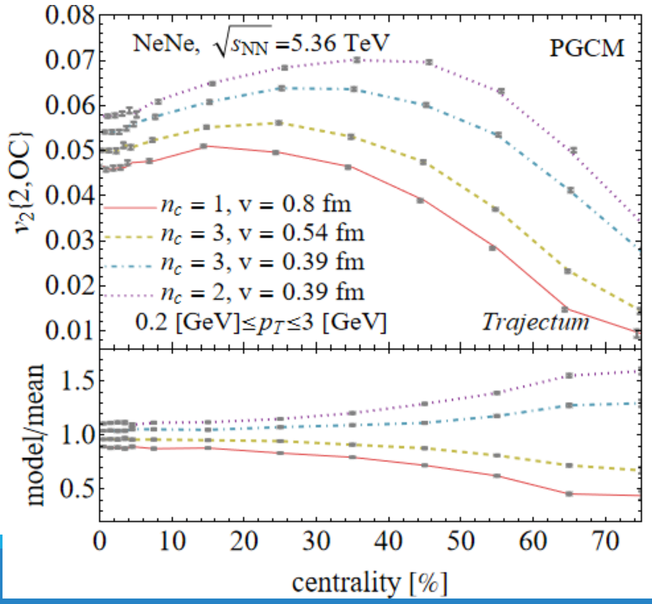


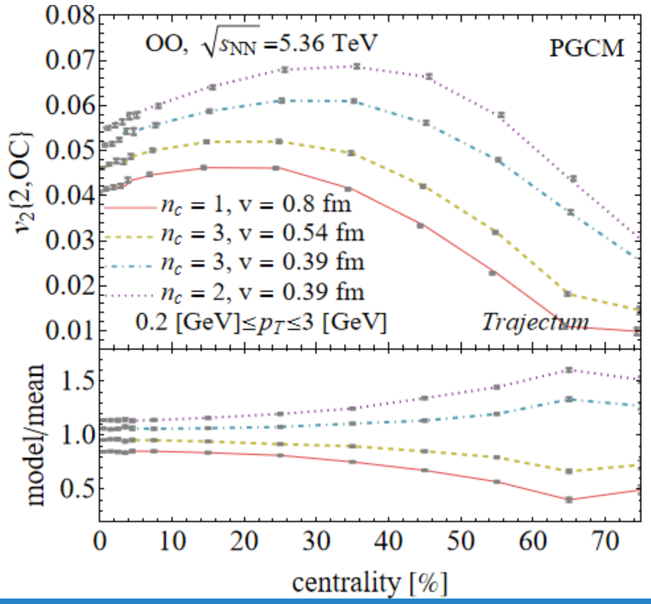
Anisotropic flow --- ratio: subnucleonic structure

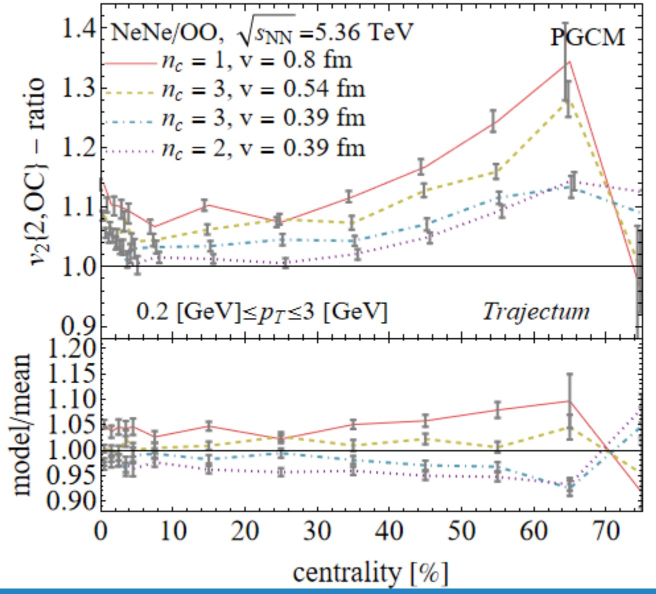


1. Actually: not all uncertainties cancel in the ratio
   - Subnucleonic structure affects oxygen significantly more than neon
   - Reducing 0-1% ratio by up to 10%
   - Potentially even making NLEFT viable as a structure
   - Consistent with IP-Glasma?

→ Seeing first hints about how we can learn about hydro, small systems, initial stage, nuclear structure etc etc

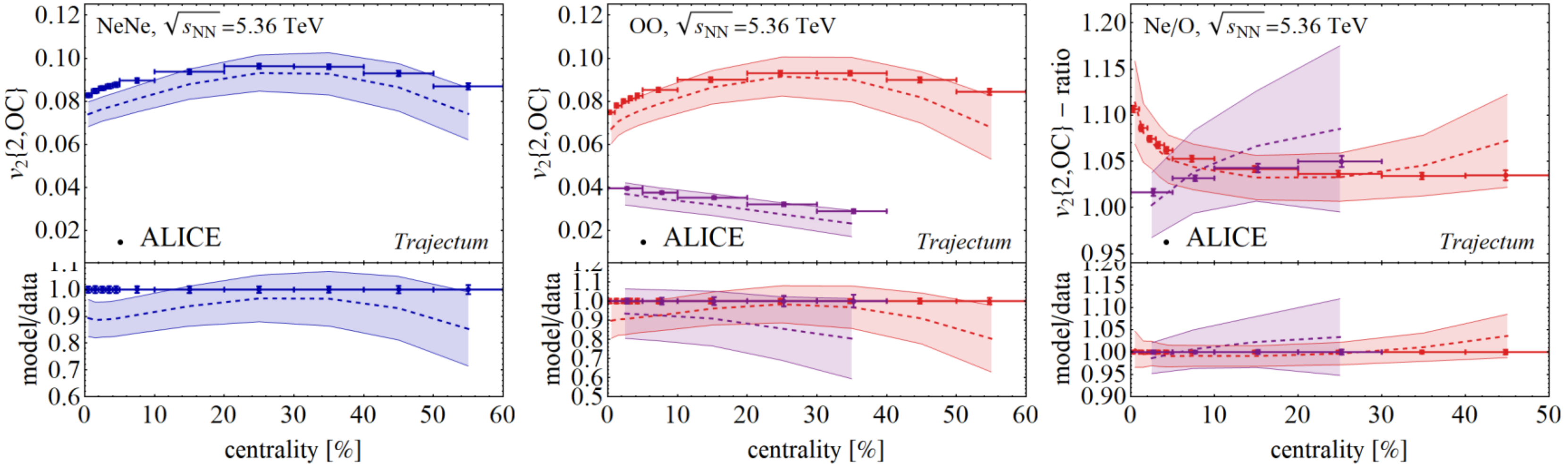






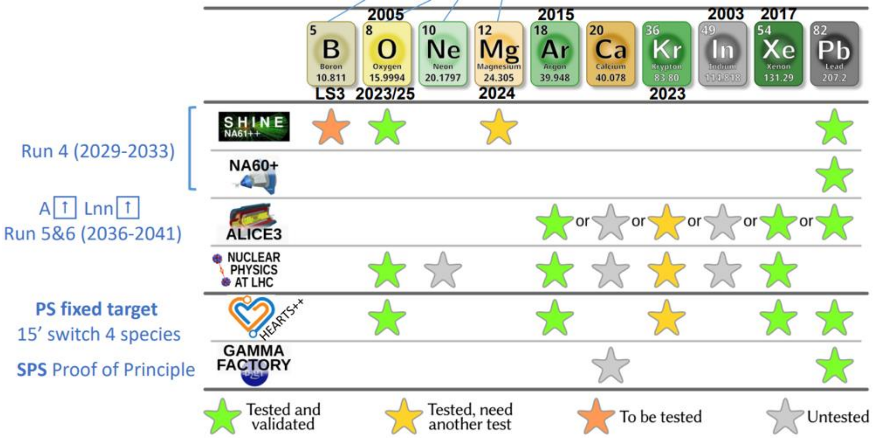
Exciting times:
Fitting new ALICE data

Work in progress (no smash or lattice spacing correction)



Fit seems to work OK; but slightly strange Trento parameters

Giuliano Giacalone et al, The unexpected uses of a bowling pin: exploiting 20Ne isotopes for precision characterizations of collectivity in small systems (2024)
CMS, First measurement of pseudorapidity distributions of charged hadrons in oxygen-oxygen collisions at $\sqrt{s_{NN}}$= 5.36 TeV (2025)
https://indico.cern.ch/event/1479384/contributions/6663047/attachments/3131557/5555439/IS_mult_v3.pdf



What's next?

New systems such as OO and NeNe have shown clear advantages; should be considered already before run 5?

^{40}Ca or ^{48}Ca

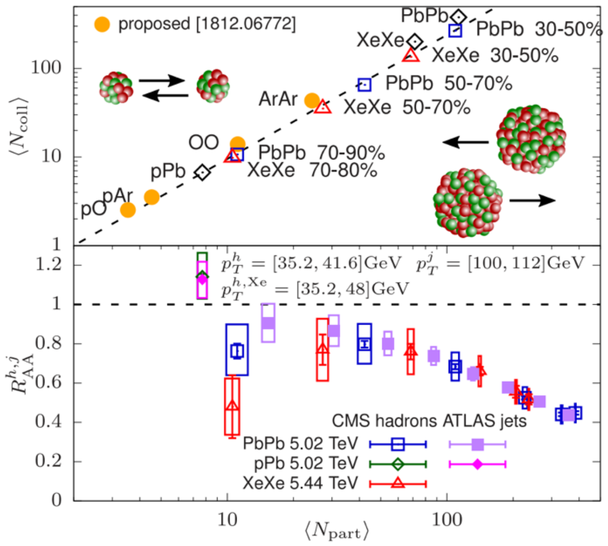
- Nice spherical nuclei; interesting for the neutron skin, synergy with neutron stars

^{76}Ge and/or ^{76}Se

- Relevant for neutrinoless double beta decay; in between Neon and Xenon sizewise

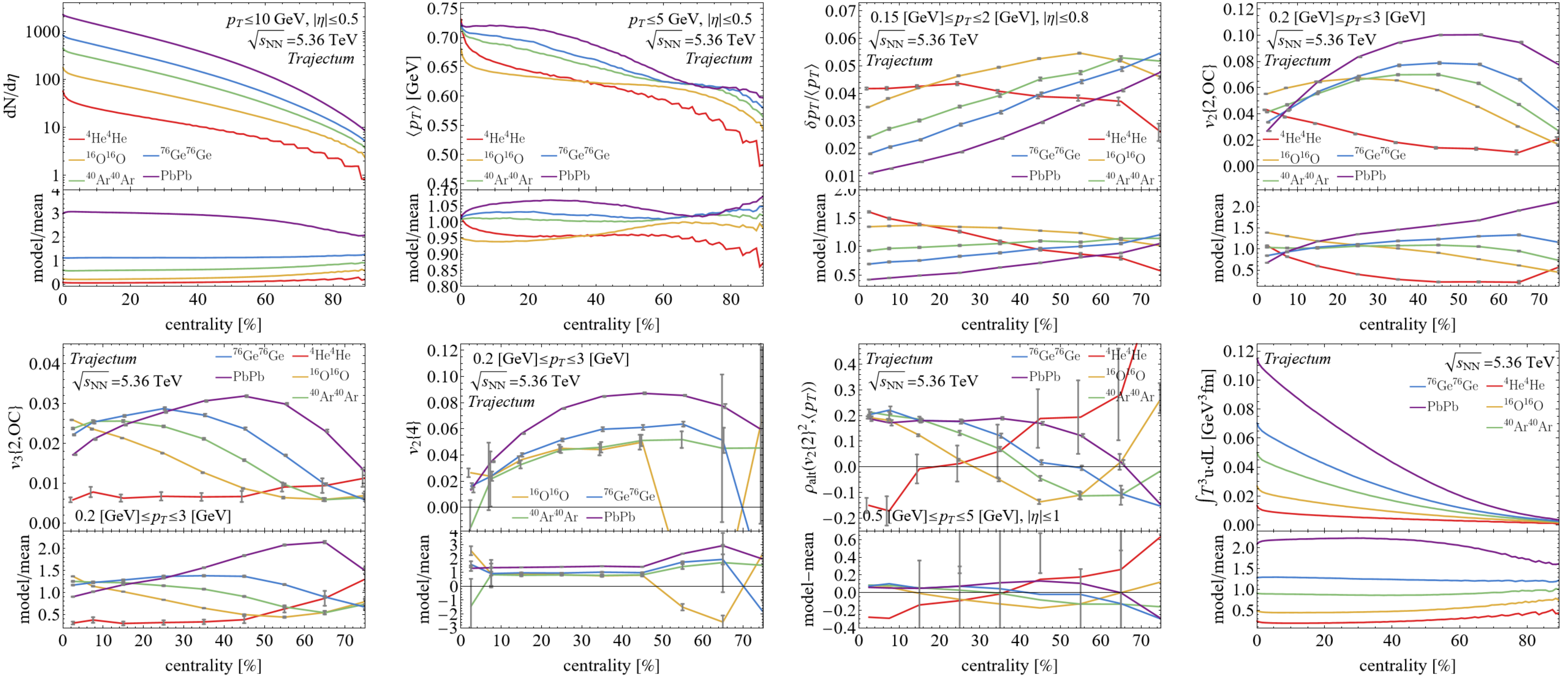
^{84}Kr

- Synergy with injector/HEARTS++



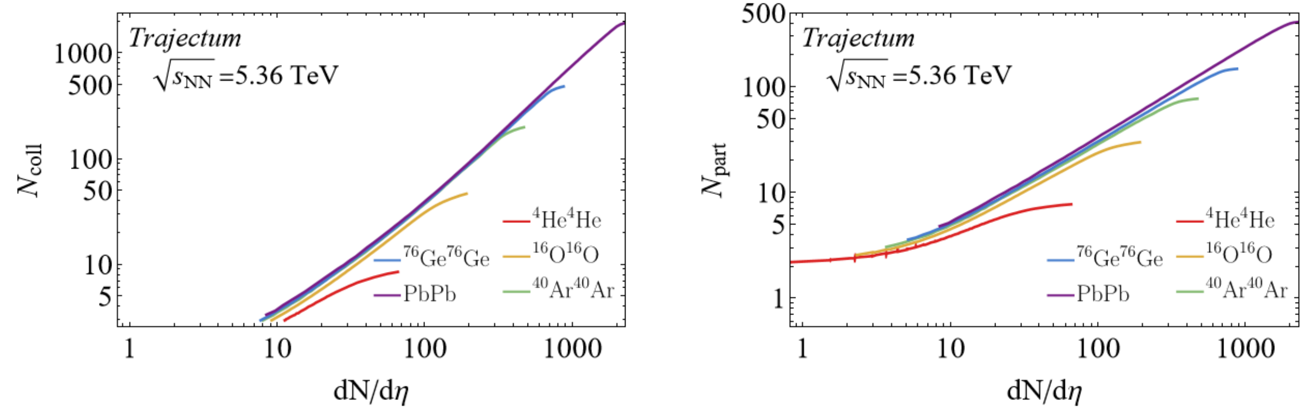
Might yield the physics goals of PbPb + much more?
Need at least high nucleon-nucleon lumi, and sizeable QGP?

What's next?

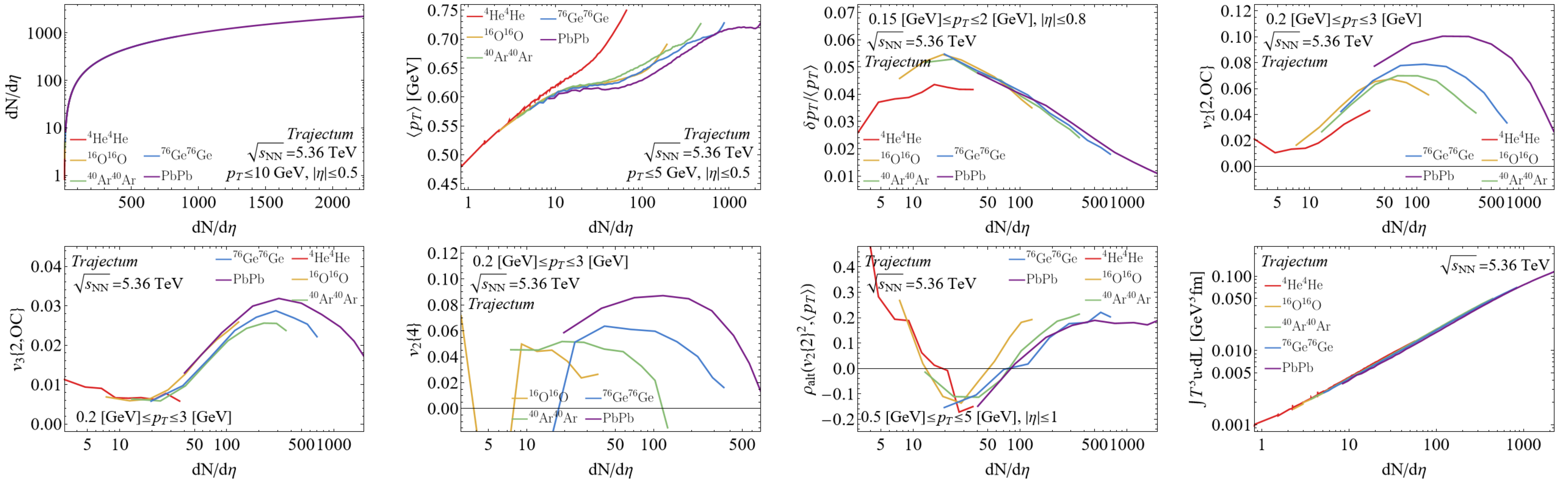


pT≤10 GeV, |η|≤0.5
√sNN =5.36 TeV
Trajectum
dN/dη
model/mean
centrality [%]
4He4He
16O16O
76Ge76Ge
40Ar40Ar
PbPb
pT≤5 GeV, |η|≤0.5
⟨pT⟩ [GeV]
0.15 [GeV]≤pT≤2 [GeV], |η|≤0.8
δpT/⟨pT⟩
0.2 [GeV]≤pT≤3 [GeV]
v2{2,OC}
v3{2,OC}
v2{4}
ρalt(v2{2}2,⟨pT⟩)
0.5 [GeV]≤pT≤5 [GeV], |η|≤1
model−mean
∫T3u·dL [GeV3fm]

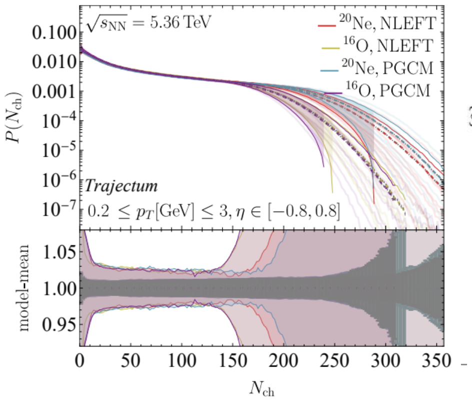
What’s next?

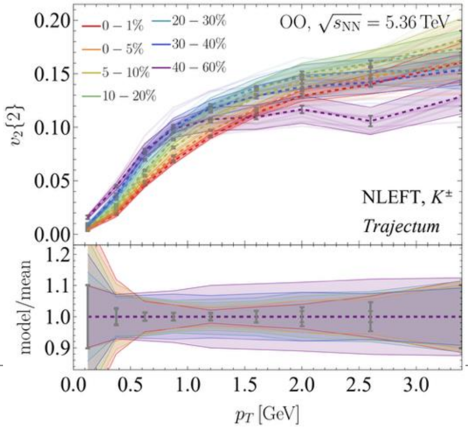


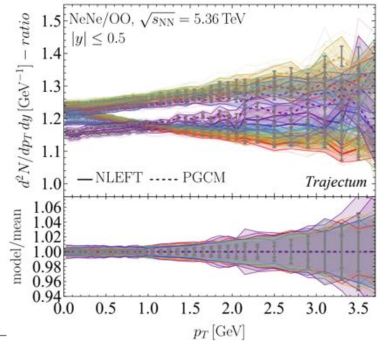
Trajectum
$\sqrt{s_{NN}}$ =5.36 TeV
N_{coll}
N_{part}
dN/dη
^{4}He^{4}He
^{16}O^{16}O
^{76}Ge^{76}Ge
^{40}Ar^{40}Ar
PbPb



Trajectum
$\sqrt{s_{NN}}$ =5.36 TeV
p_T≤10 GeV, |η|≤0.5
p_T≤5 GeV, |η|≤0.5
0.15 [GeV]≤p_T≤2 [GeV], |η|≤0.8
0.2 [GeV]≤p_T≤3 [GeV]
0.5 [GeV]≤p_T≤5 [GeV], |η|≤1
dN/dη
⟨p_T⟩ [GeV]
$\delta p_T/\langle p_T\rangle$
v_2{2,OC}
v_3{2,OC}
v_2{4}
$\rho_{alt}(v_2\{2\}^2,\langle p_T\rangle)$
∫T³u·dL [GeV³fm]
^{4}He^{4}He
^{16}O^{16}O
^{76}Ge^{76}Ge
^{40}Ar^{40}Ar
PbPb



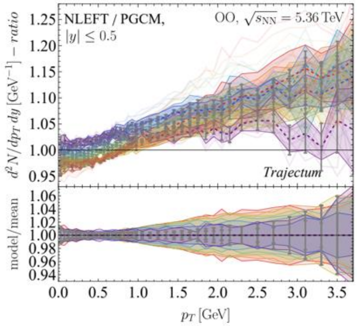


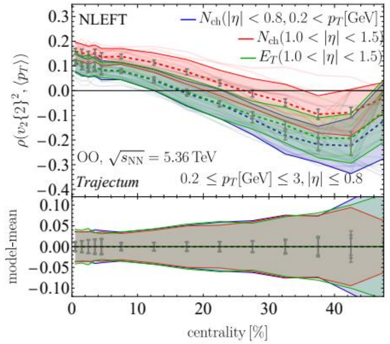


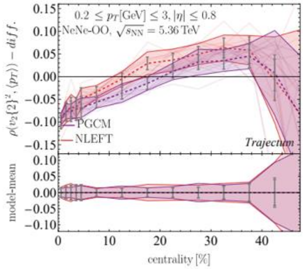
Exciting times!

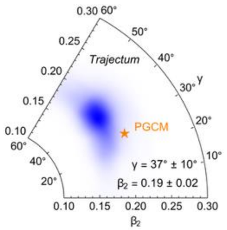
Many more measurements will follow

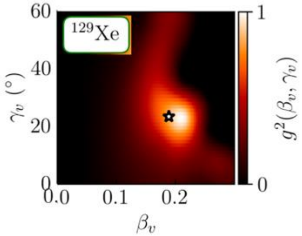
- Mean p_T, higher order correlations like ρ_2, ultracentral fluctuations, spectra, jets
- Much better understanding of the shape
- Hydrodynamics at its limits!
- Energy loss in small systems
- Ne-He collisions

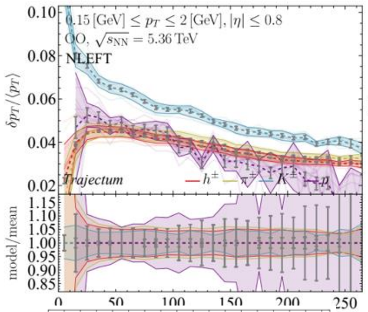


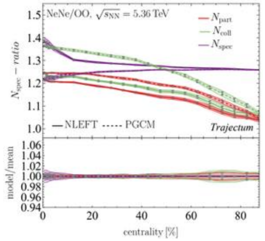


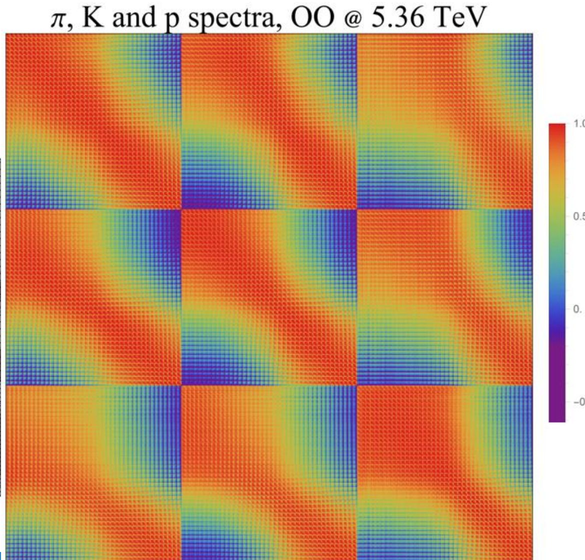


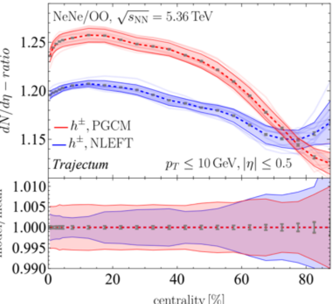


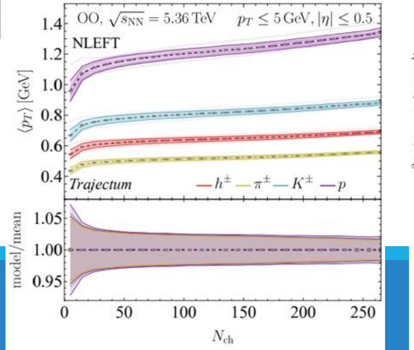


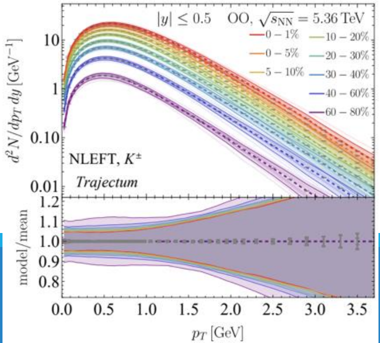


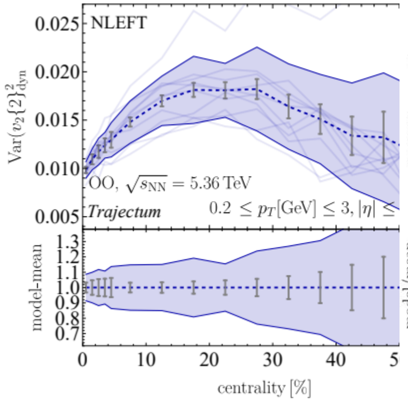


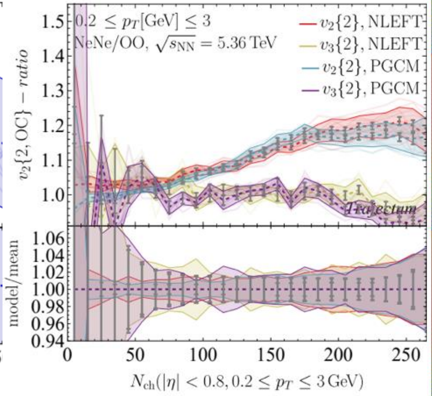


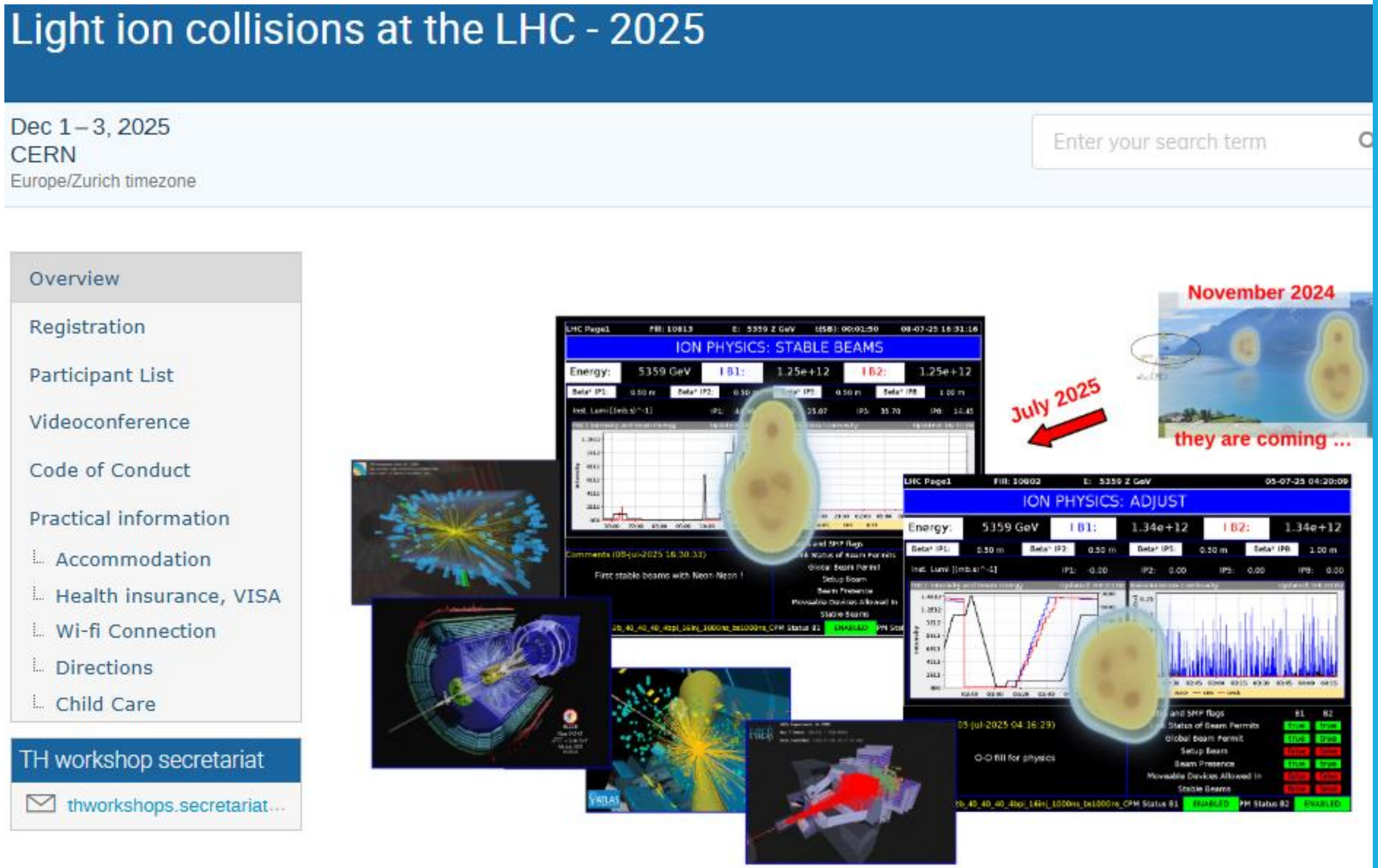








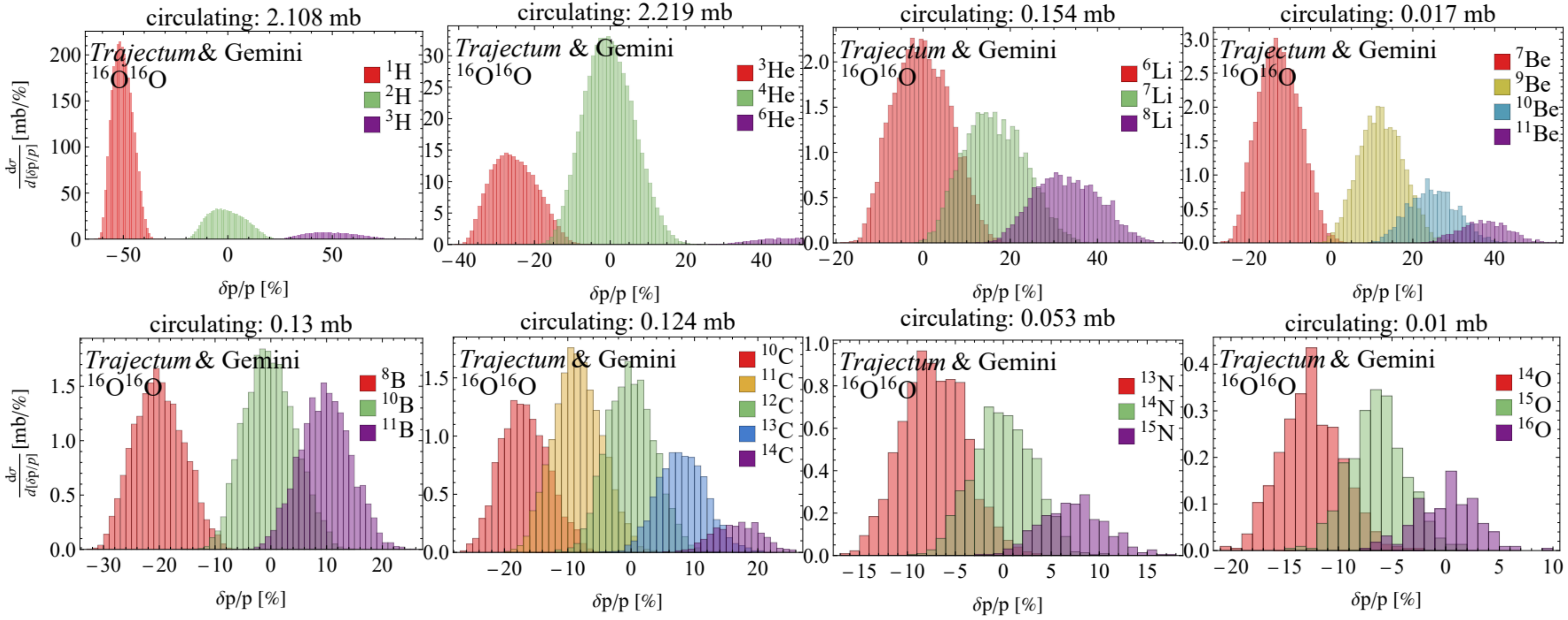




Light ions at the LHC – the sequel

[CERN.CH/LIGHTIONS2025](https://cern.ch/lightions2025)

Back-up

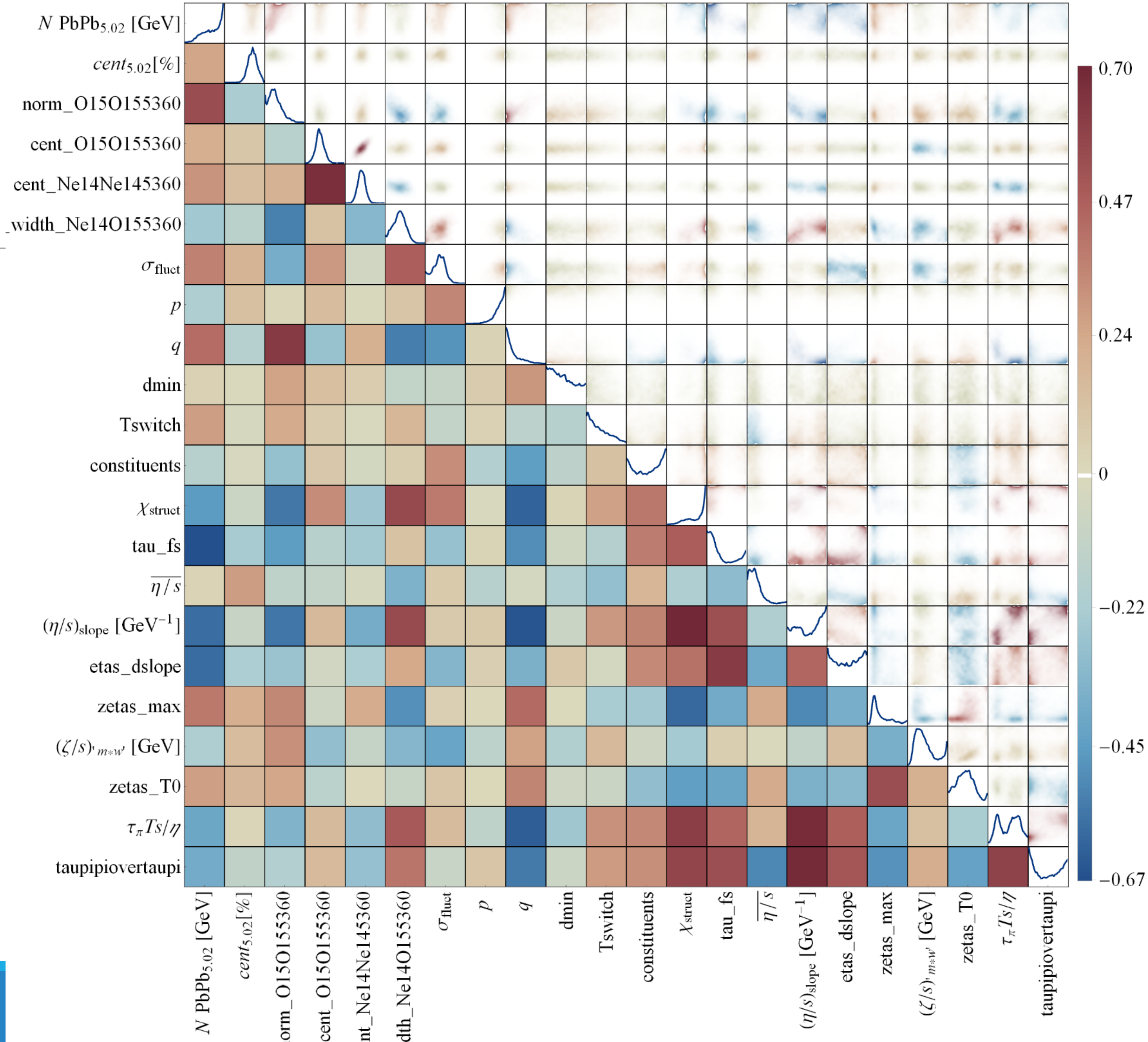


Transmutation: **results**

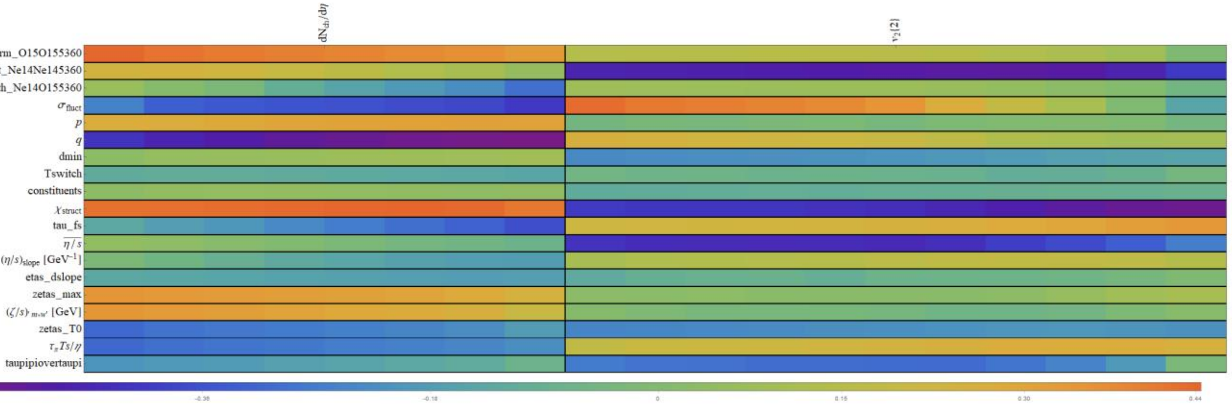
Lots of elements, but with 0.034% momentum cut not much \`survives' (compare total hadronic cross section: 1.42b)

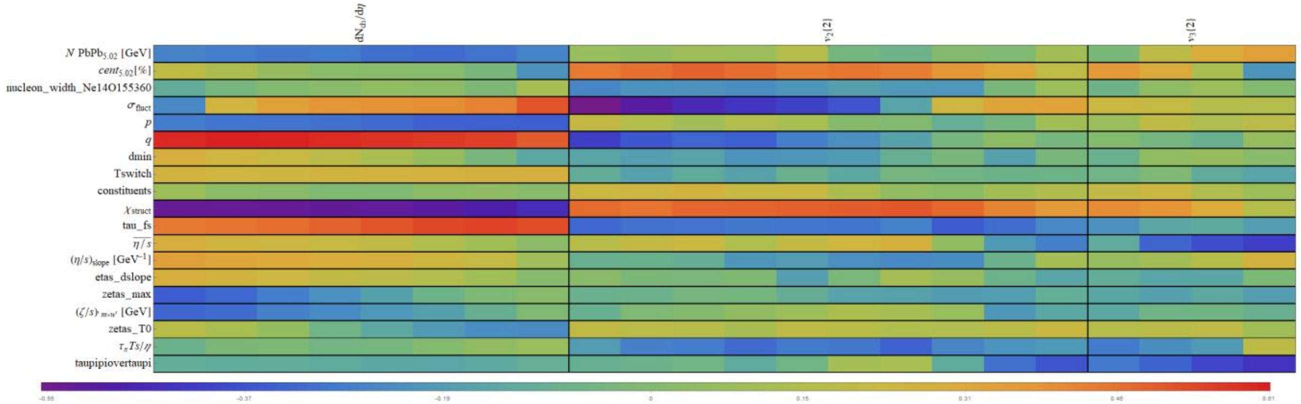
- Dominant are deuteron and Helium-4
- Quite crucially depends on momentum distribution; large systematic uncertainty since nucleons are not really \`free'

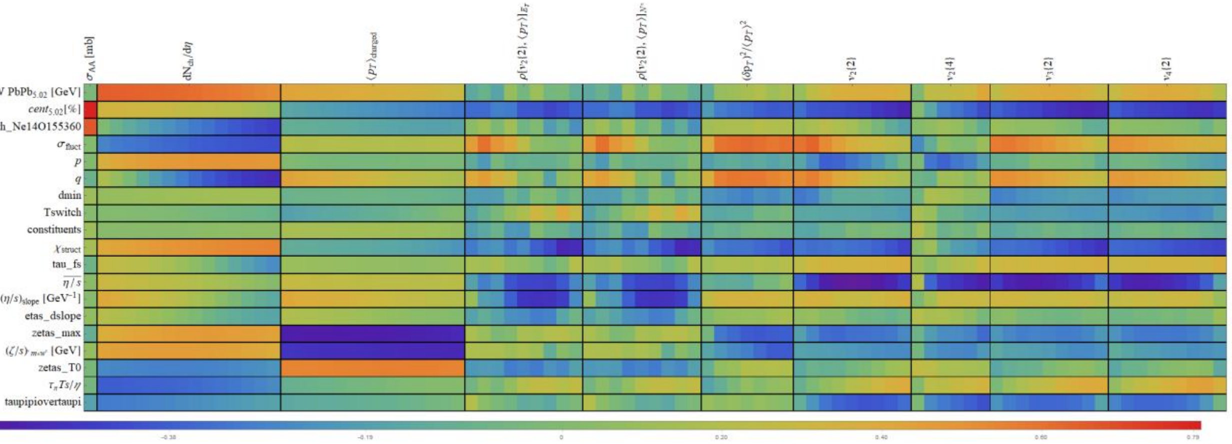
Posterior with light ions
work in progress

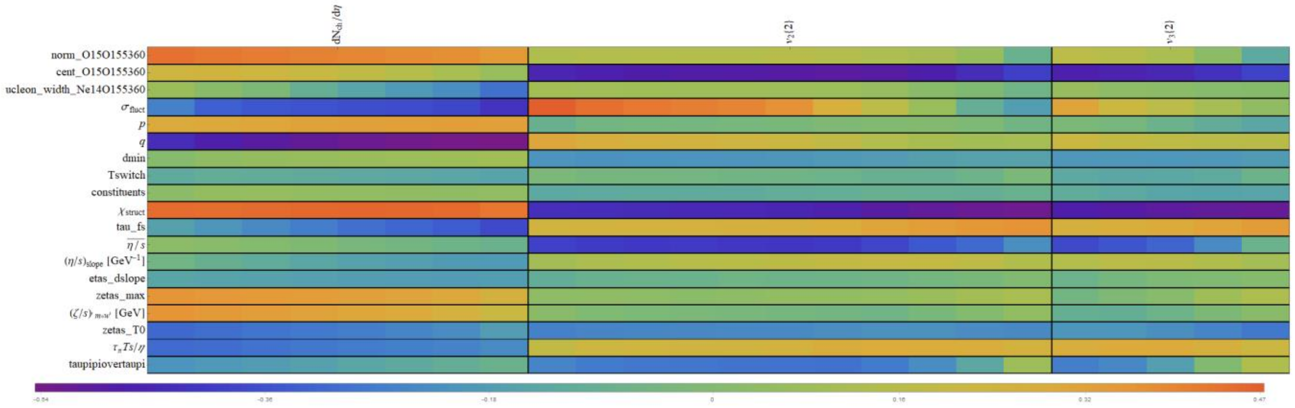


Prior with light ions
work in progress

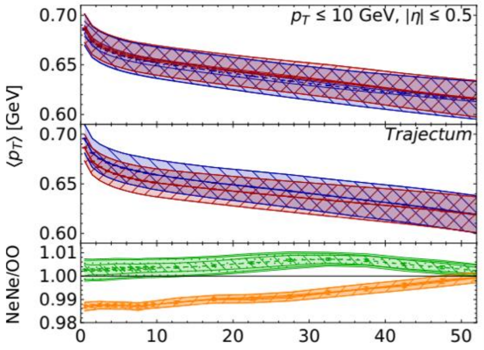








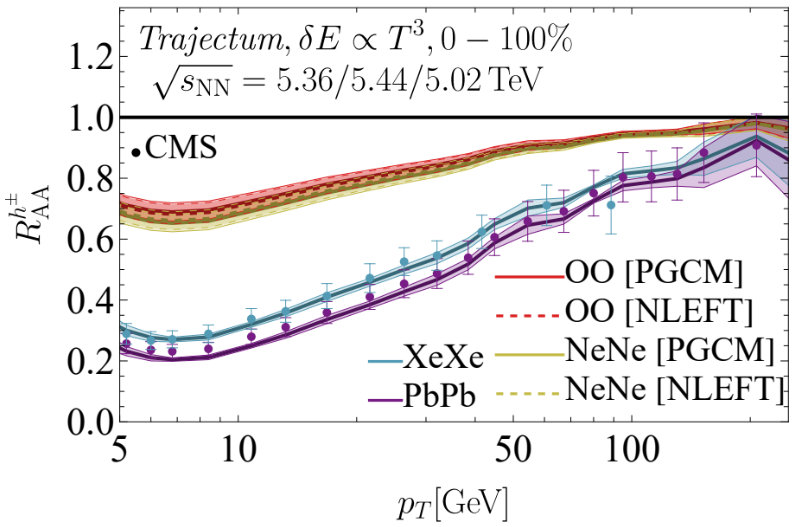
$$R_{AA} = \sigma_{pp}(p_T + \delta e(p_T))/\sigma_{pp}(p_T),$$
$$\delta e(p_T) = \kappa(p_T) \int T^3 \mathbf{u} \cdot \mathbf{dL},$$

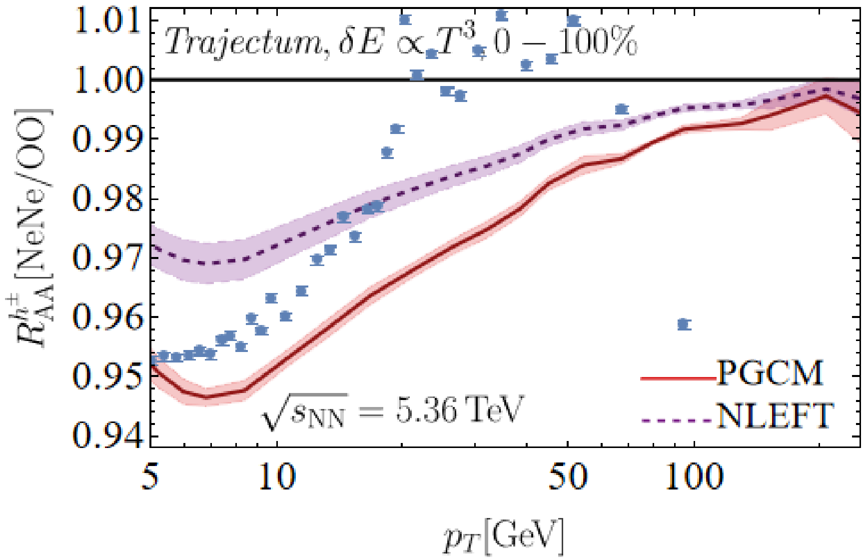


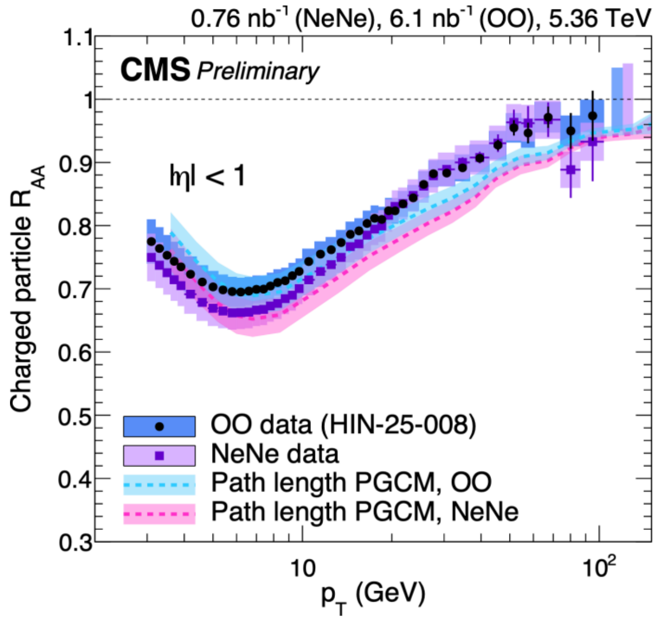
The mean transverse momentum – an **interplay with hard probes**

A path-length approach to energy loss: assume energy loss ~ T^3 and extrapolate from (central) PbPb

- Also significant difference between PGCM and NLEFT
- CMS data somewhere in the middle? (no uncertainties available though…)







Anisotropic flow --- SMOG2

Fixed target mode LHCb

- Lower energy, asymmetric 3+1D hydro
- Very accurate predictions from NLEFT + Chun Shen QM25, including v_3