Light ion overview ATLAS soft physics

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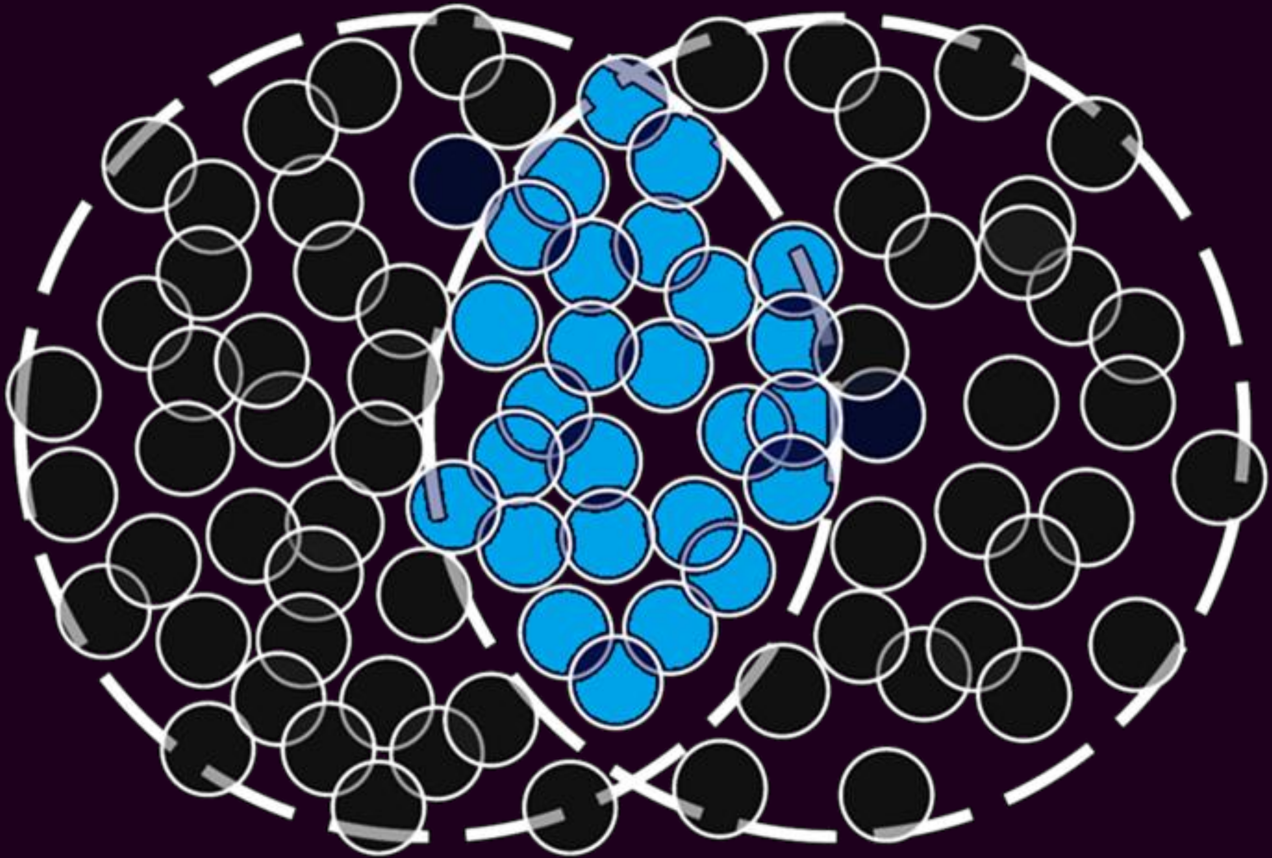
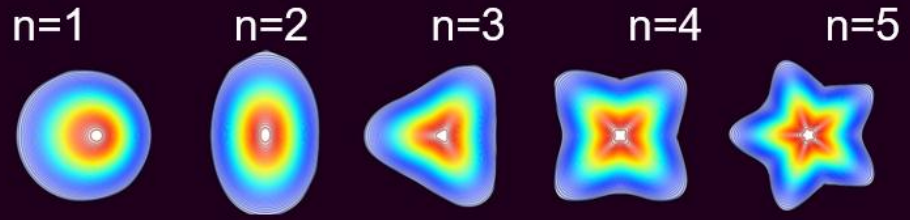
Initial state of heavy ion collisions

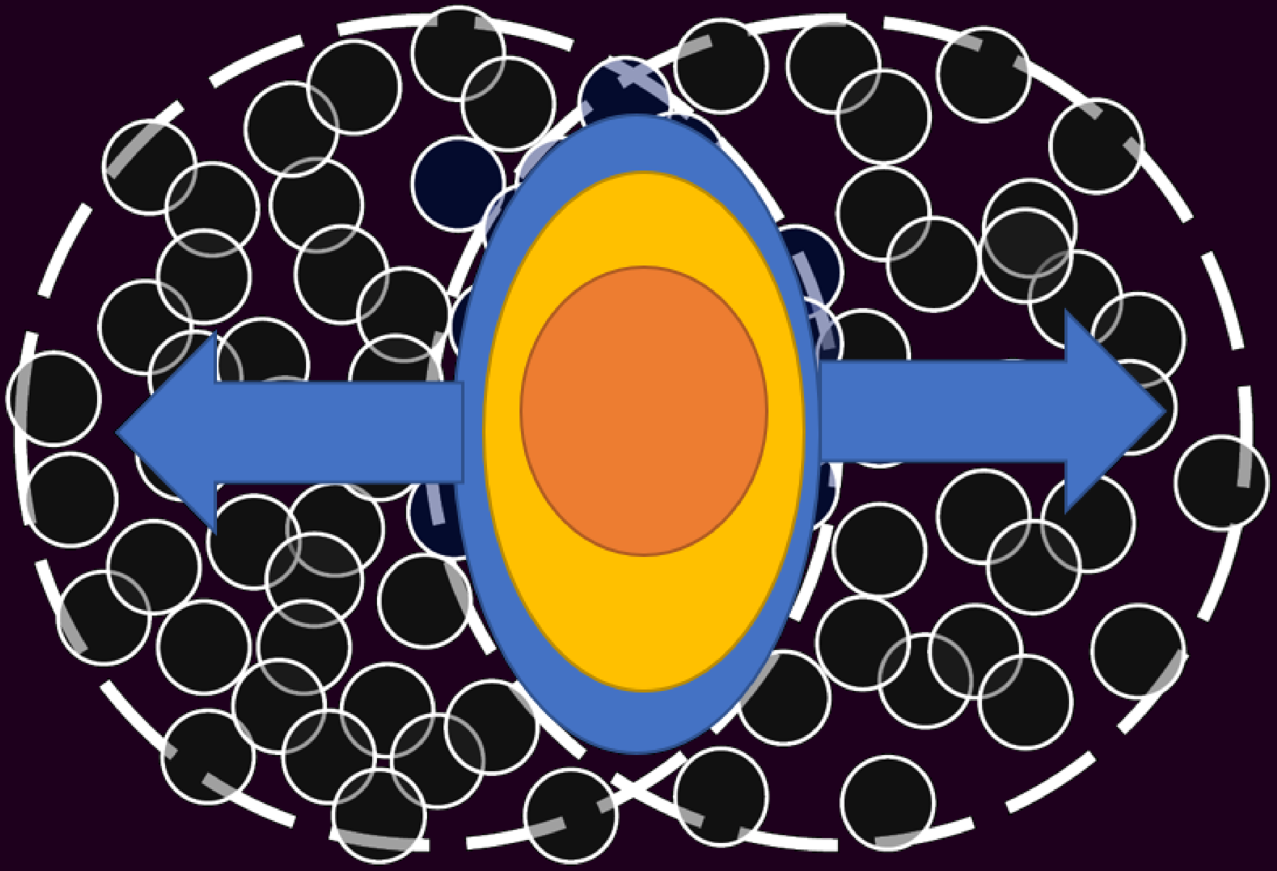


Parametrize spatial anisotropy

Geometric eccentricity

$$\varepsilon_n = \frac{\sqrt{\langle r_i^n \cos(n\varphi_i)\rangle^2 + \langle r_i^n \sin(n\varphi_i)\rangle^2}}{\langle r_i^n \rangle}$$





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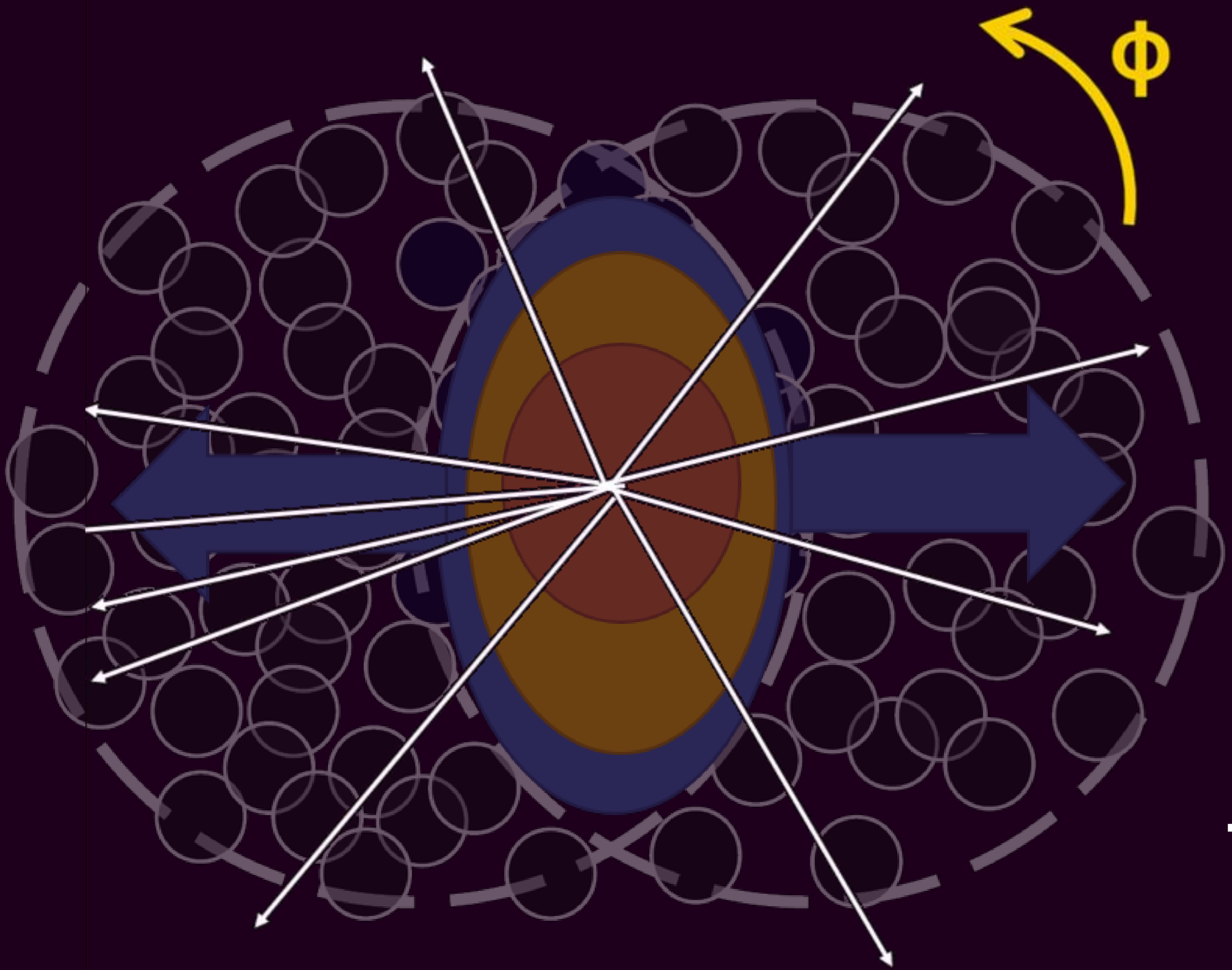
Viscous Hydrodynamics

$$T^{\mu\nu} = \epsilon u^\mu u^\nu + P[\epsilon]\Delta^{\mu\nu} - \eta[\epsilon]\sigma^{\mu\nu} - \zeta[\epsilon]\Delta^{\mu\nu}\nabla^\perp_\lambda u^\lambda$$

Equation of state
transport coefficients $P[\epsilon]$ $\eta[\epsilon]$ $\zeta[\epsilon]$

Initial state → **Pre-equilibrium dynamics** → **Hydrodynamic expansion** → **Momentum anisotropy**



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Equation of state
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Azimuthal Momentum anisotropy

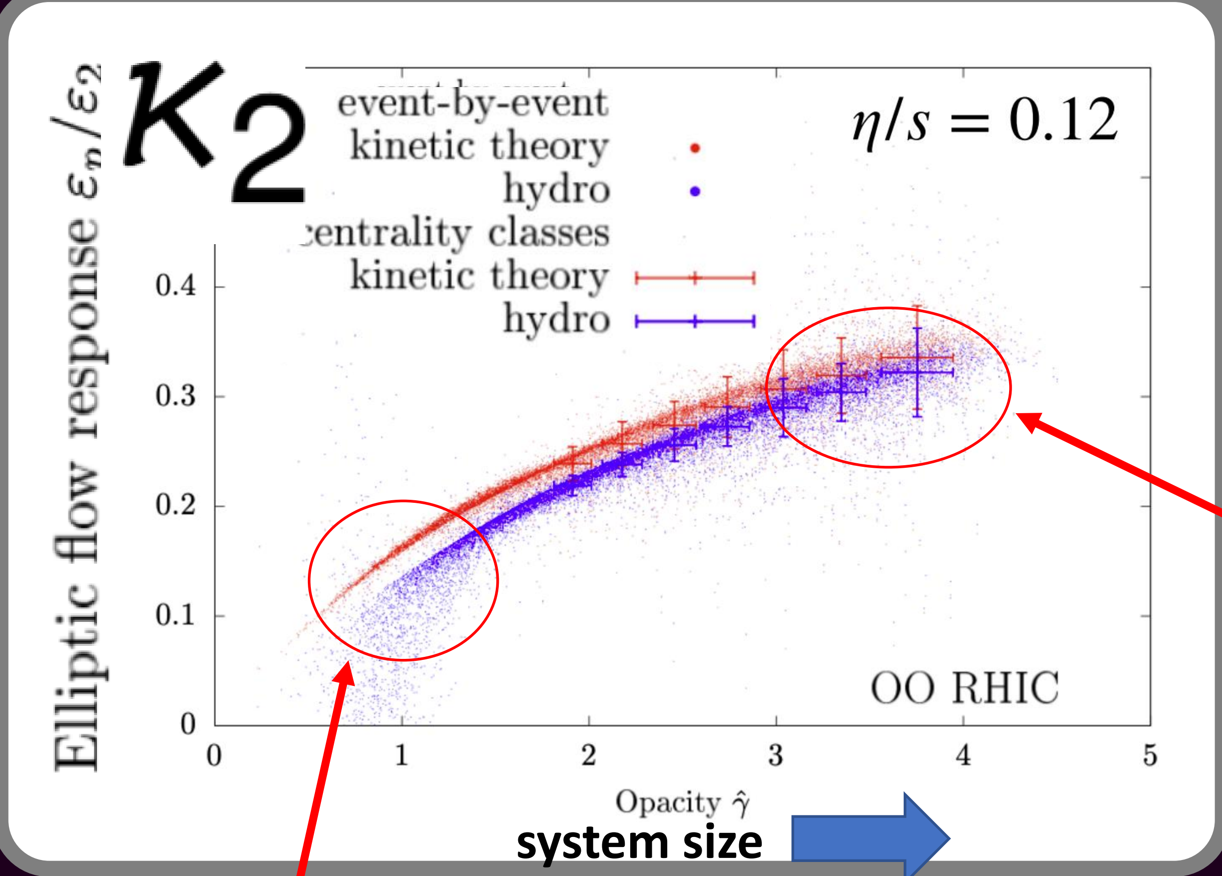
$$\frac{dN}{d\varphi} \propto 1 + 2\boldsymbol{v_1}\cos(\phi) + 2\boldsymbol{v_2}\cos(2\phi) + 2\boldsymbol{v_3}\cos(3\phi) + \ldots$$

Initial state ε_n → **Pre-equilibrium dynamics** → **Hydrodynamic expansion** → **Momentum anisotropy** V_n

$$V_n \simeq \kappa_n \varepsilon_n$$

Break down of hydrodynamics in small systems

Schlichting, Werthmann



Azimuthal anisotropy is a response to geometry

$$v_n \simeq \kappa_n \varepsilon_n$$

Event by event calculation of kappa for **hydrodynamics** and **kinetic theory**

The two models converge at large system size

Break down of hydro at small system size

Explore hot QCD

Can we gain experimental sensitivity to far-from-equilibrium dynamics

Need precise control of geometry

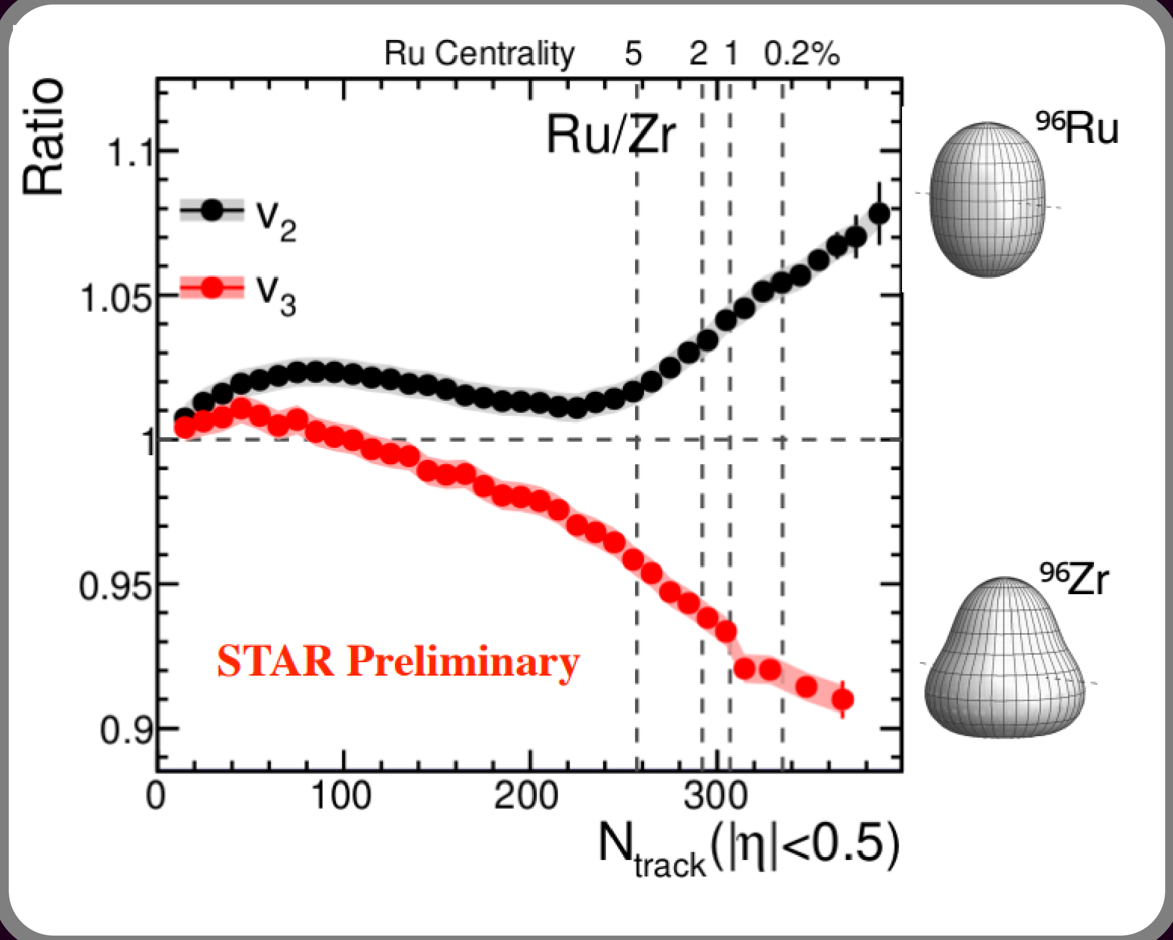
Can we obtain precise control of initial-state geometry

Test: similar size system with drastically different geometry

This control has been achieved in large systems, like Ru+Ru & Zr+Zr

Geometric effect most pronounced in the top **5%** or **ultracentral collisions UCCs**

Can we achieve it in light ions



Need precise control of geometry

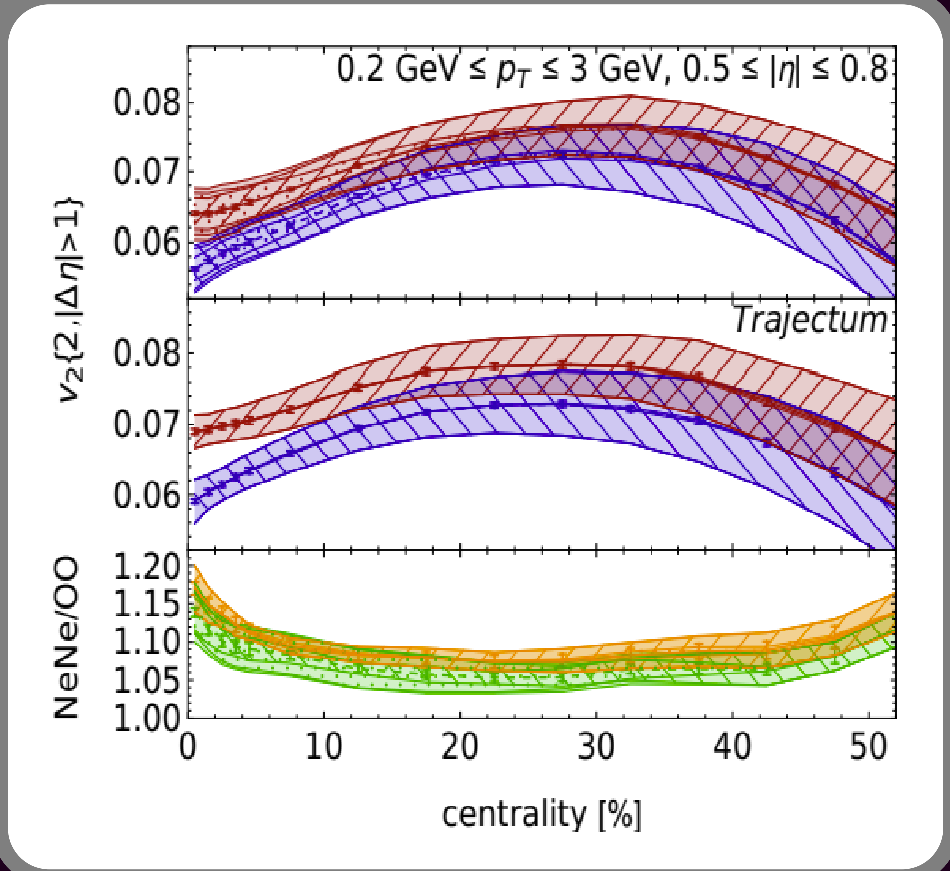
<u>Test</u>: similar size system with drastically different geometry

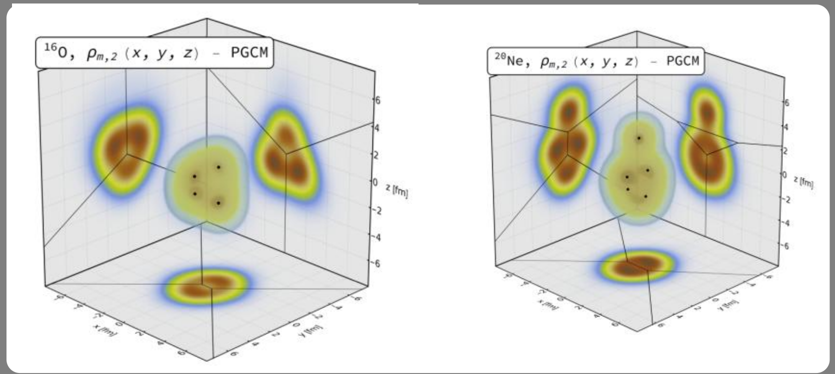
$^{20}Ne+^{20}Ne$ & $^{16}O+^{16}O$ @ 5.36 TeV

Ab initio nuclear structure calculations in light ions

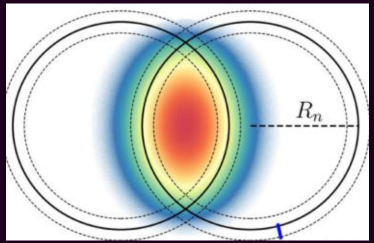
Ab initio calculations:
NLEFT & PGCM

arXiv:2402.05995





+ TRENTo

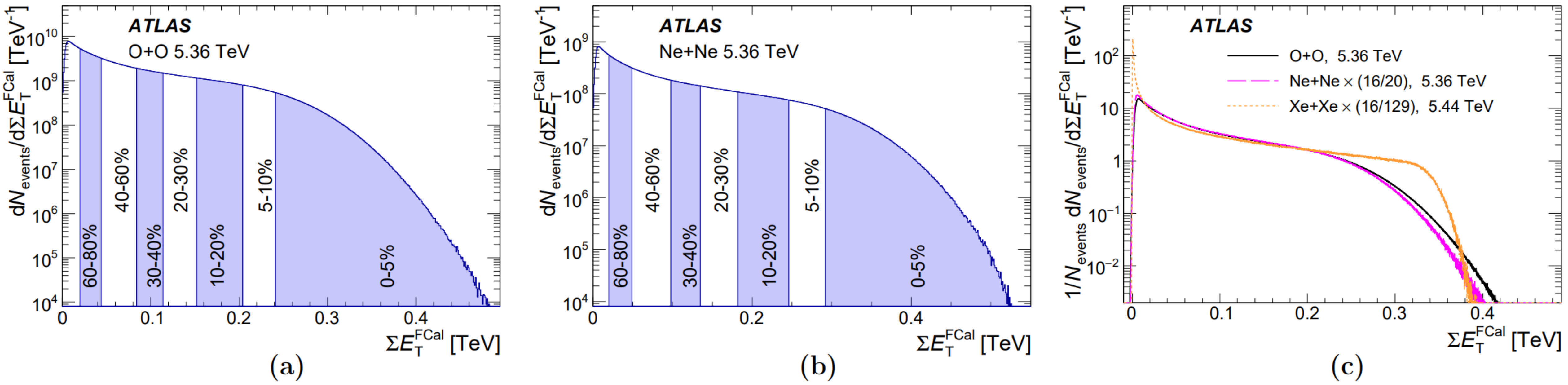


+ Hydro…

Centrality and particle production

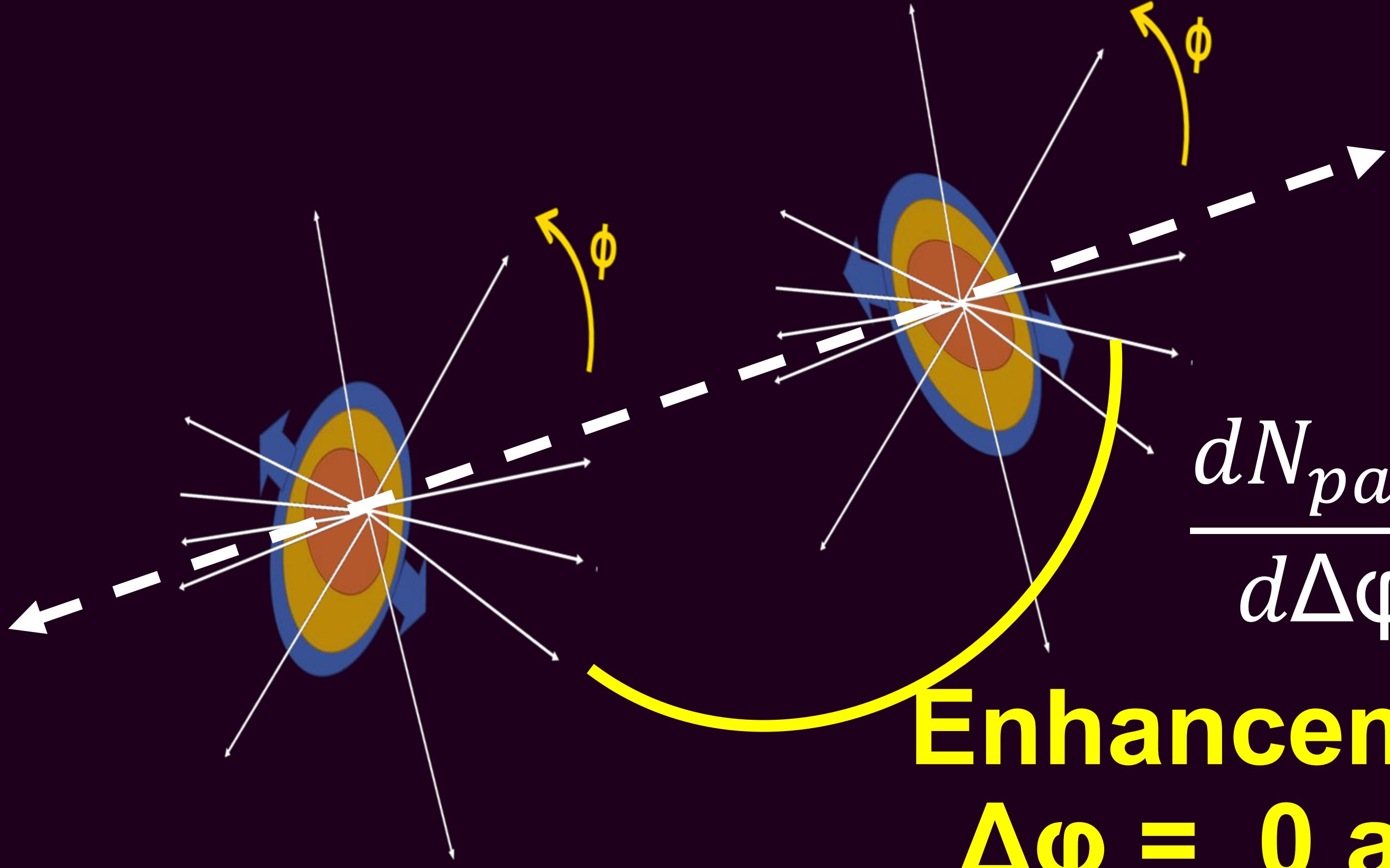
- Event energy in the forward calorimeter ($3.2 < |\eta| < 4.9$) ΣE_T^{FCal}
- Glauber-based fit with contributions from N_{coll} and N_{part}
- Centrality percentiles are defined for 80% or greater
- Right: ΣE_T^{FCal} roughly scales with **A**

arXiv:2509.05171



(a) (b) (c)

Two-particle correlations



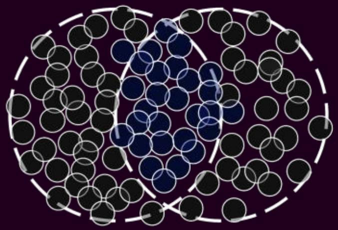
$$\frac{dN_{pair}}{d\Delta\varphi} \alpha\ 1 + 2v_{2,2}\cos(2\Delta\varphi) + \ .$$

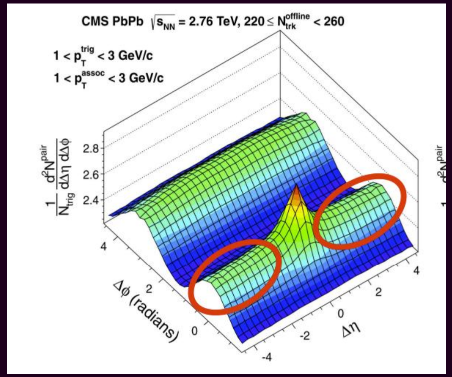
Enhancement at
Δφ = 0 and π

$v_n\{2\}$

System size

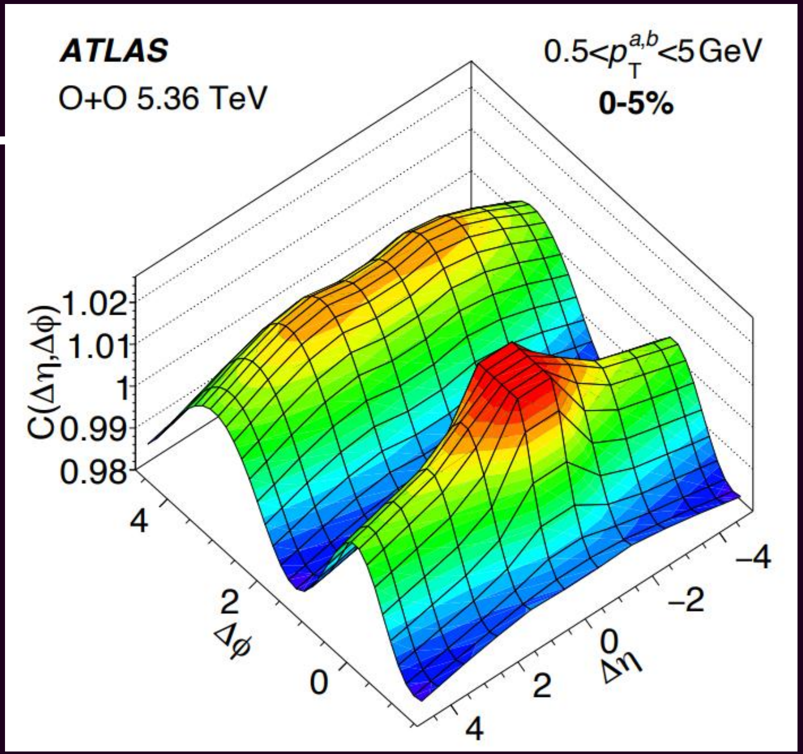
Pb+Pb



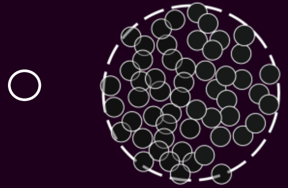


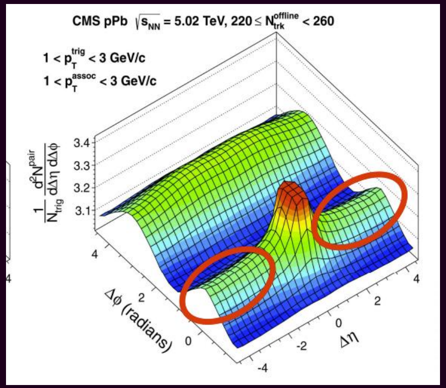
^{16}O

+ ^{16}O

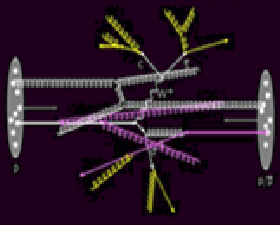


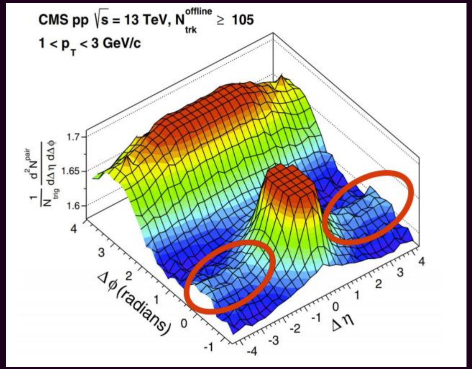
p+Pb





pp



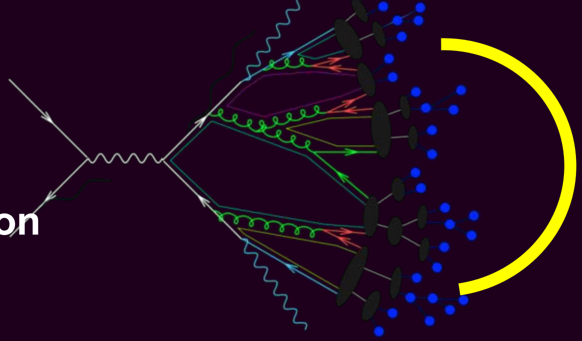


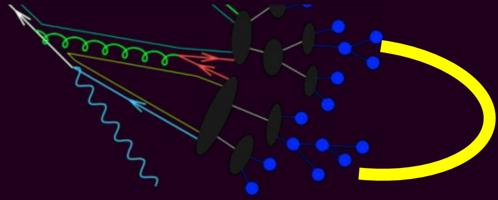
Momentum conservation

Jets & particle decays

Termed “nonflow”

Not collective phenomenon





$\Delta\varphi < 2$

$\Delta\eta < 2$

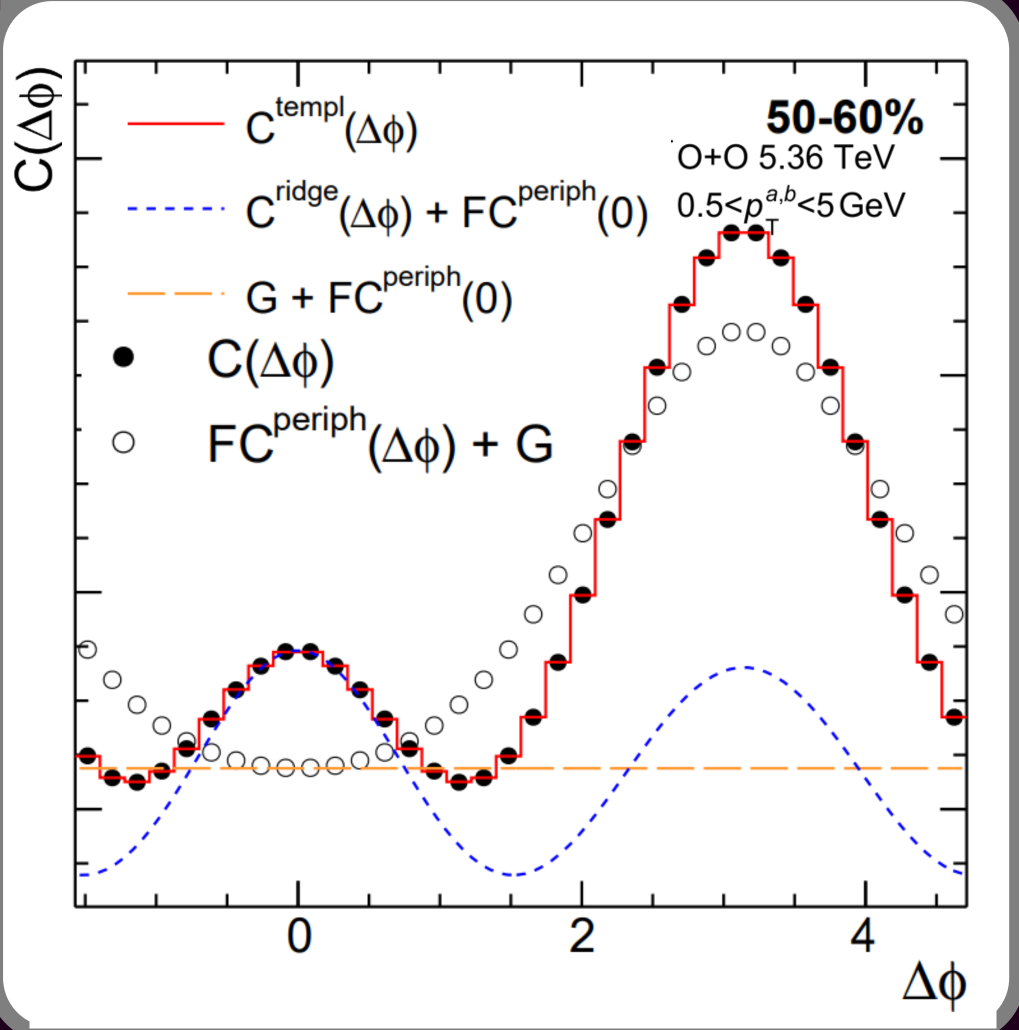
Removing non-flow effects in 2PC

arXiv:2509.05171

Fit correlation with a superposition of flow terms and nonflow template (peripheral collisions)

<u>Nonflow subtraction</u>

- High multiplicity (HM) fit with peripheral (LM) data and flow coef.
- HM and LM assumed to have same nonflow shape
- Different LM selections leads to similar results



$$C(\Delta\phi) = FC^{\text{periph}}(\Delta\phi) + G\left[1 + 2\sum_{n=2}^{5} v_{n,n}(p_T^a, p_T^b)\cos(n\Delta\phi)\right]$$

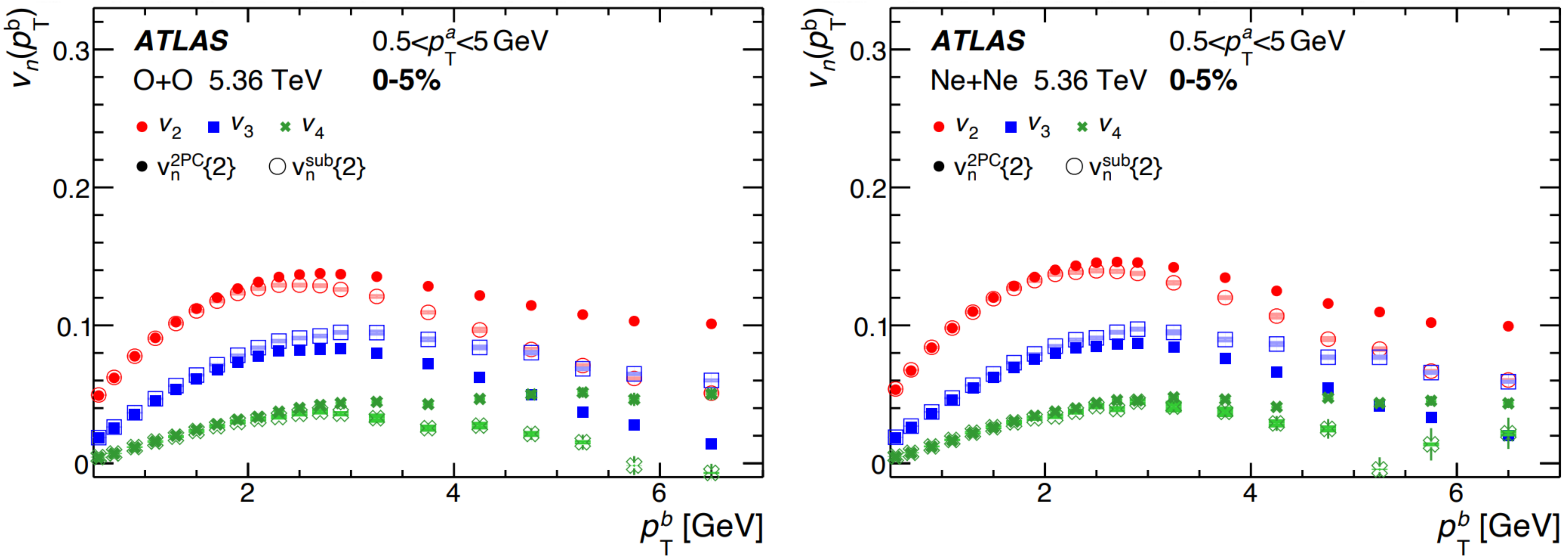
For $v_n(p_T)$ results

$$v_n(p_T^b) = \frac{v_{n,n}(p_T^a, p_T^b)}{v_n(p_T^a)} = \frac{v_{n,n}(p_T^a, p_T^b)}{\sqrt{v_{n,n}(p_T^a, p_T^a)}},$$

Non-negligible effects from non-flow

2PC $v_n\{2\}$

arXiv:2509.05171



Clear hierarchy between flow harmonics: $\mathbf{v_2 > v_3 > v_4}$

Strong influence of non-flow beyond 3 GeV

Qualitatively similar to observations from large systems

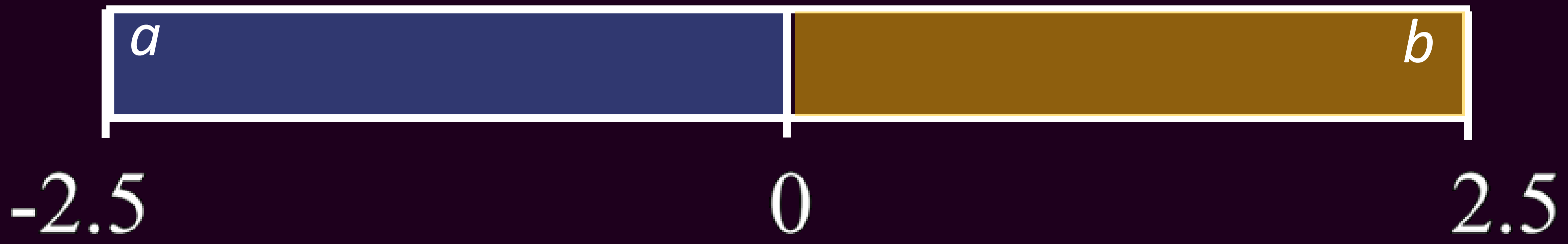
4-particle cumulant measurement

- Four-particle correlations are sensitive to the event-by-event v_n fluctuations in a different way than two-particle correlations

$$v_n\{4\}^2 = \bar{x}_n^2, \qquad \text{where: } \bar{x}_n \equiv \text{Geometric Component}$$

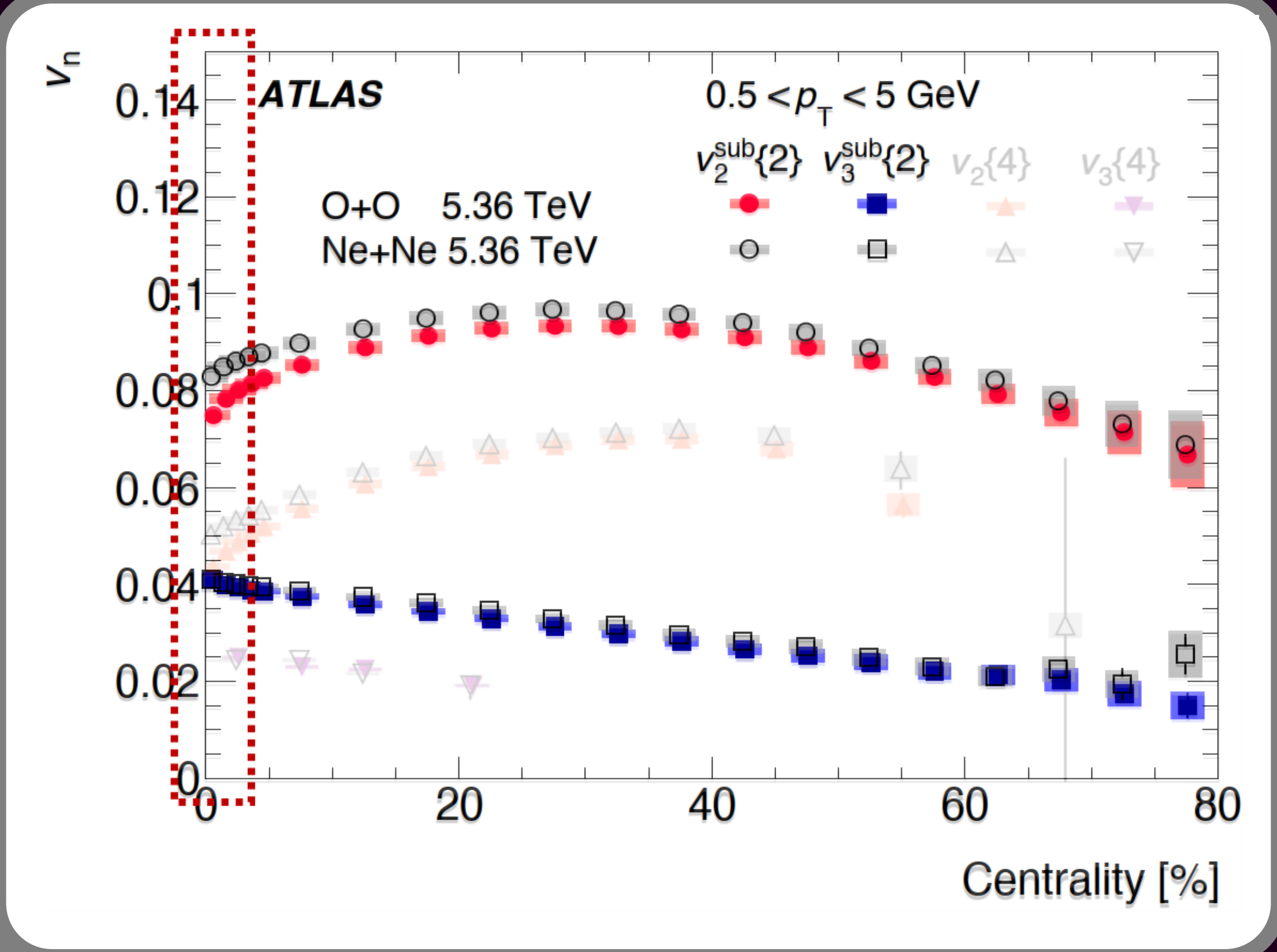
$$v_n^{\text{sub}}\{2\}^2 = \bar{x}_n^2 + \Delta_n^2 \qquad \Delta_n \equiv \text{Fluctuation Component}$$

- Use sub-events to suppress nonflow
  - Tracks are selected from different regions in η to suppress short-range correlations
  - Shown, two-subevent result (checked 3 and 4 subevents, non-flow suppressed well with 2 subevents)



Measure $v_n\{4\}$ as well, for deeper look at geometry

Centrality differential $v_n\{k\}$ results



arXiv:2509.05171

- $v_2\{2\}$ is larger for NeNe than OO
- $v_3\{2\}$ is also larger at fixed centrality

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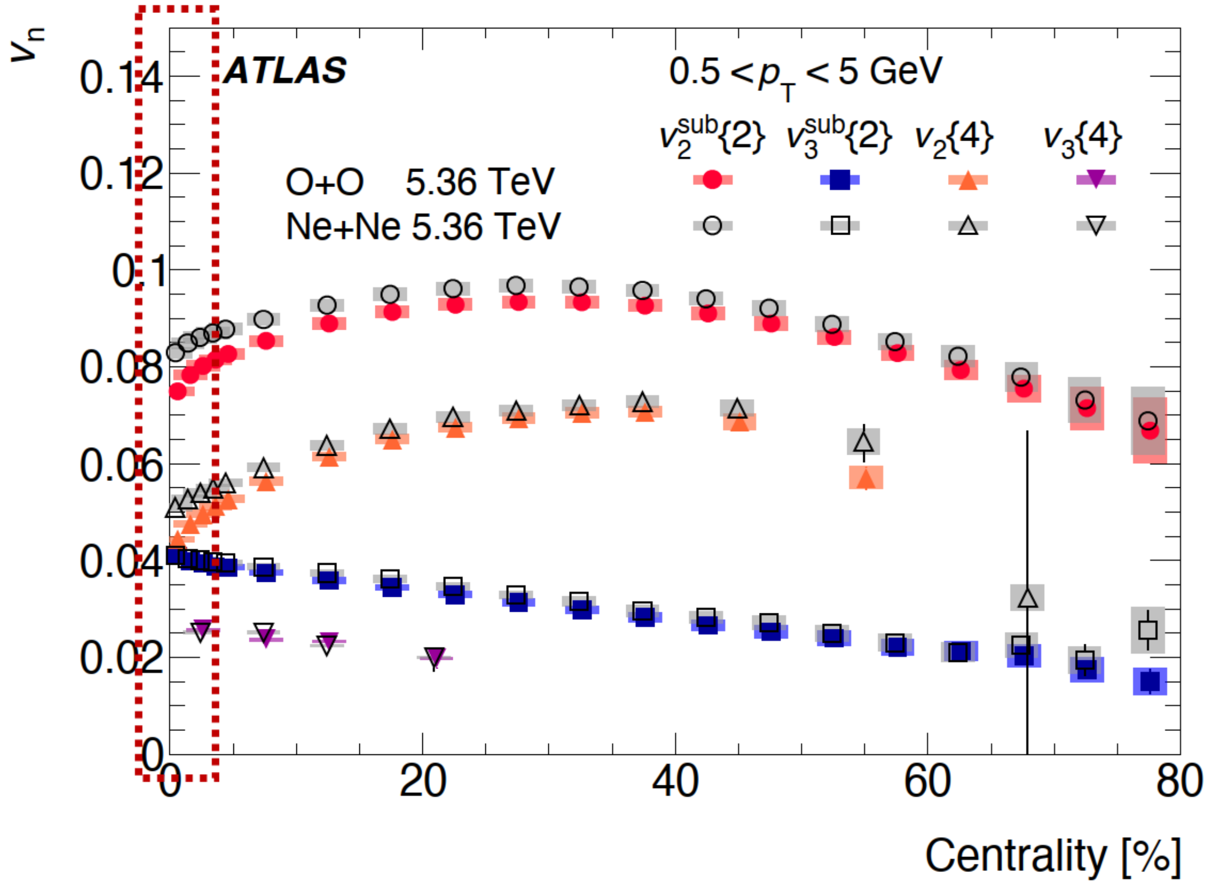

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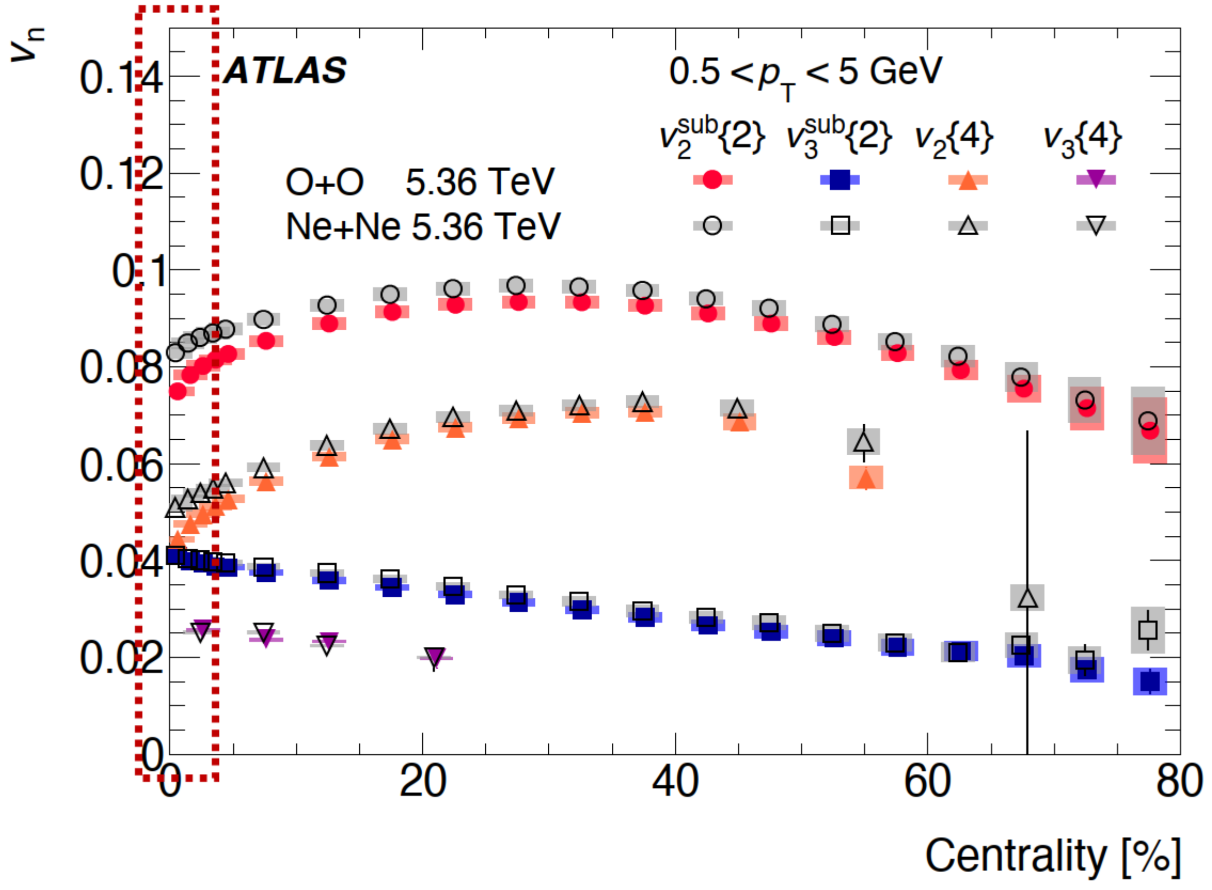
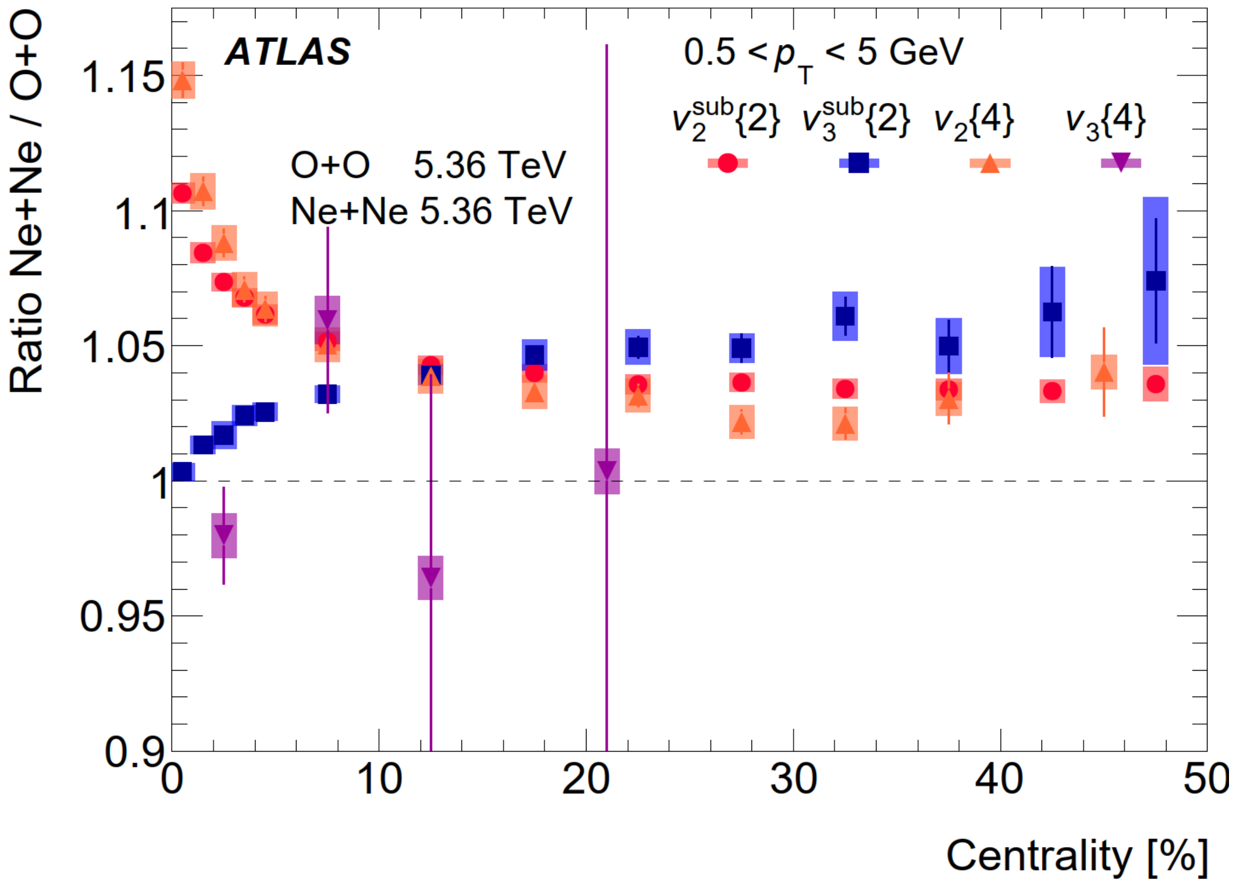
- $v_2\{2\}$ is larger for NeNe than OO
- $v_3\{2\}$ is also larger at fixed centrality
- $v_n\{4\}$ lower than $v_n\{2\}$ due to large fluctuation component in v_n

$v_n\{k\}$ NeNe / OO ratios





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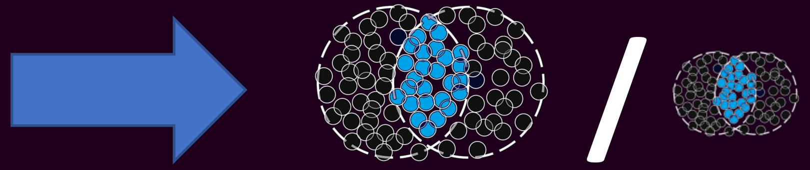
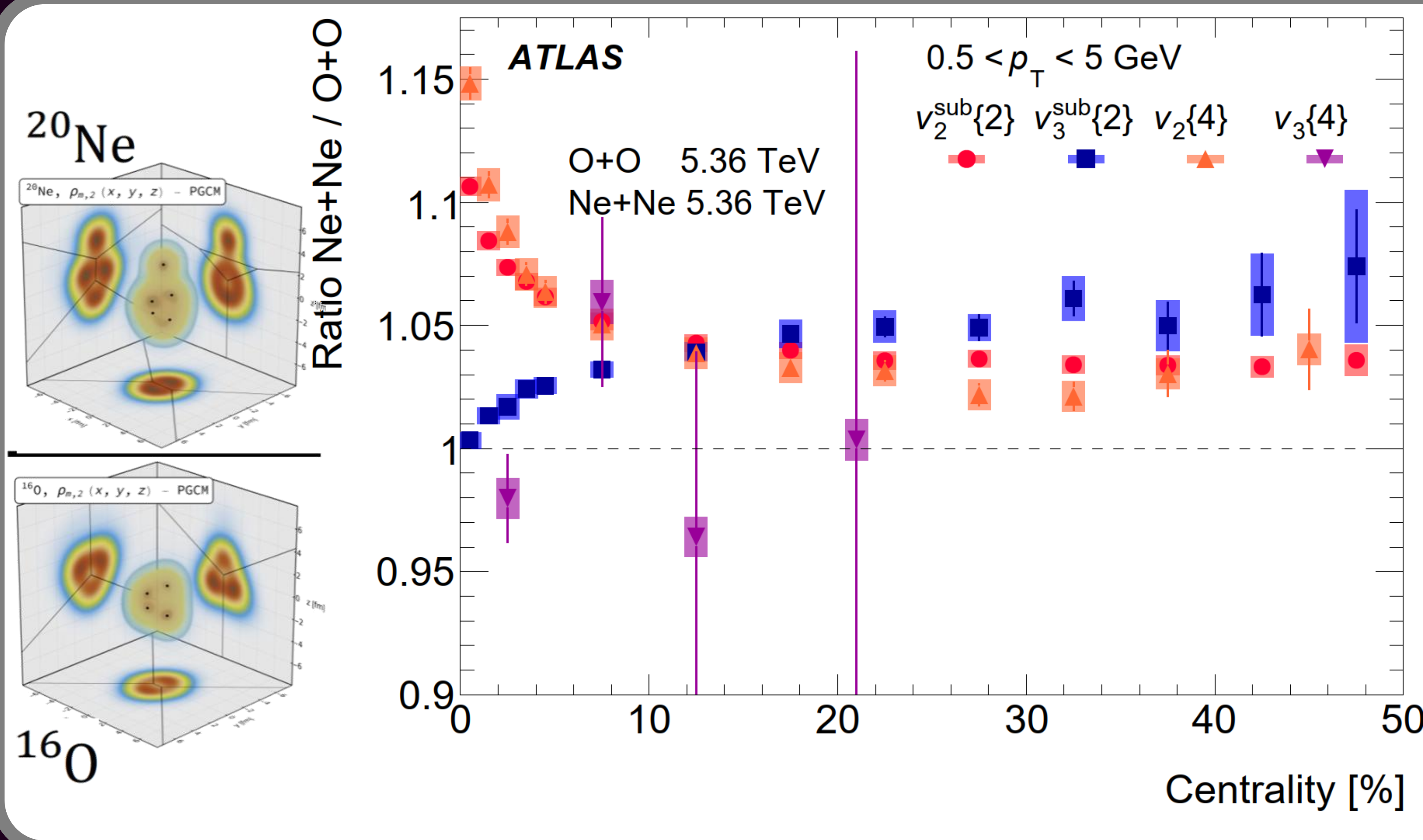
Ratio
Ne+Ne / O+O



$v_n\{k\}$ NeNe / OO ratios

- $v_2\{k\}$ enhancement in NeNe → elongated shape
- $v_2\{4\}$ ratio 15% enhanced in UCC!
- $v_3\{k\}$ ratio suppressed in central collisions → larger triangular fluctuations in OO?
- **Very precise:** ~0.5% uncertainties on $v_{2,3}\{2\}$!



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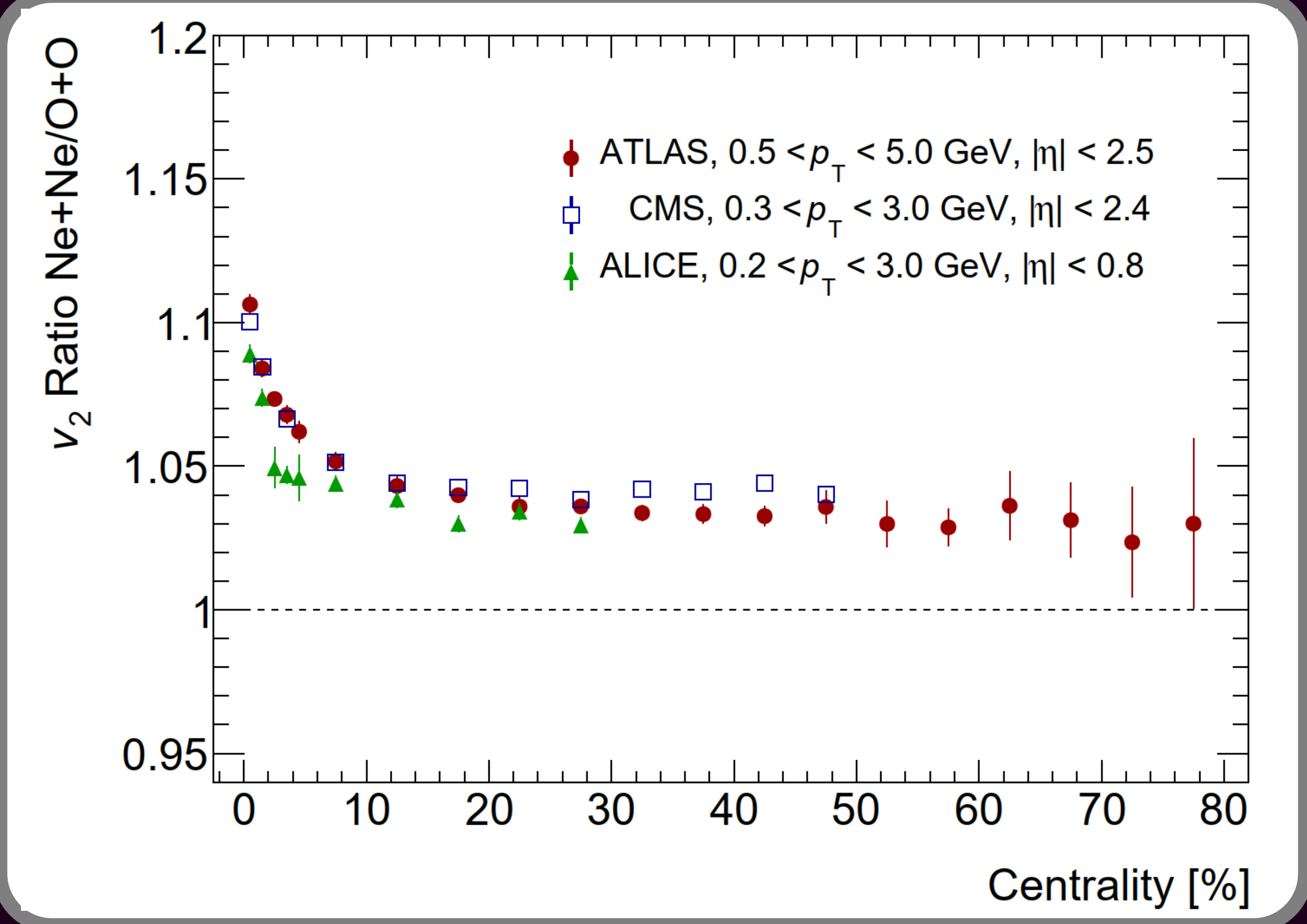
Evidence of elongated shape of neon

Comparison of experimental results



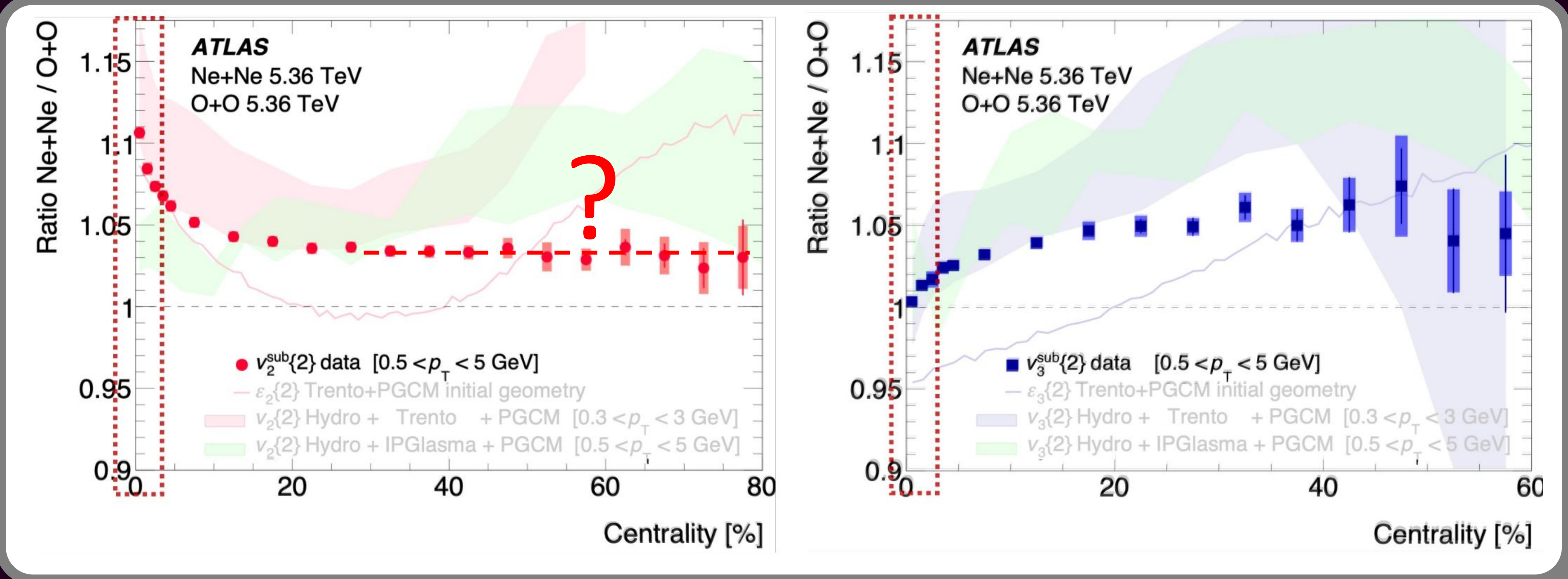
**overlapping p_T intervals, but not identical*

**CMS preliminary*

Very similar results (<1% deviation) between CMS and ATLAS

~1% on average difference between ALICE and ATLAS/CMS. Decorrelation?

$v_n\{2\}$ NeNe/OO theory comparisons



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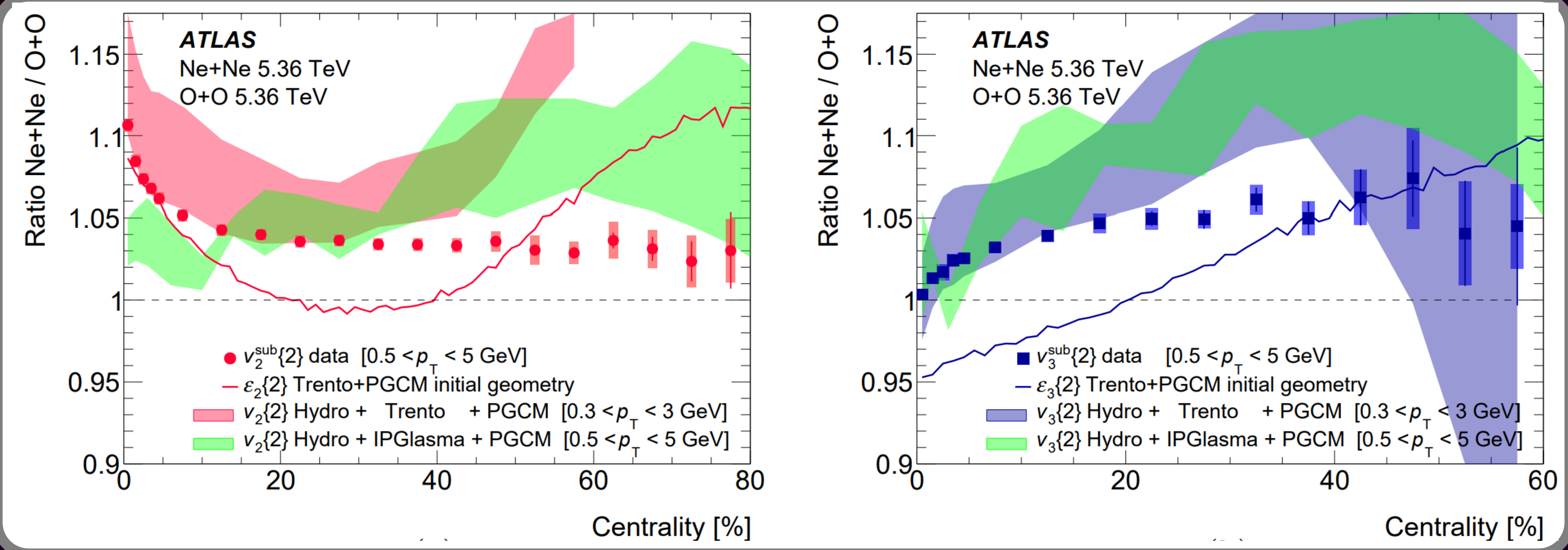
- Flat v_2 ratio from 30-80% (!) unexpected from geometry predictions

$v_n\{2\}$ NeNe/OO theory comparison

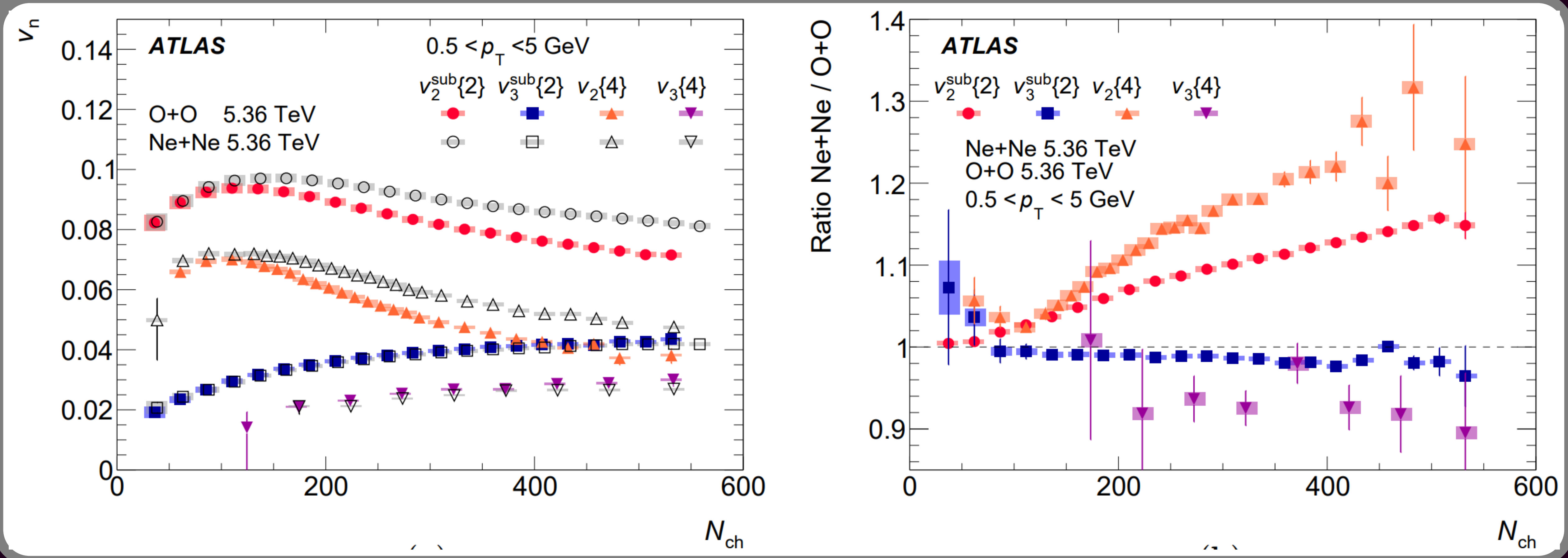


arXiv:2509.05171

- Hydro+IPGlasma+PGCM
  - IPGLASMA with JIMWLK evolution has enhanced multiplicity fluctuations, leading to a reduced correlation between the final-state centrality measure and geometry
- Hydro+Trento+PGCM: reproduces UCC rise, but over-predicts peripheral

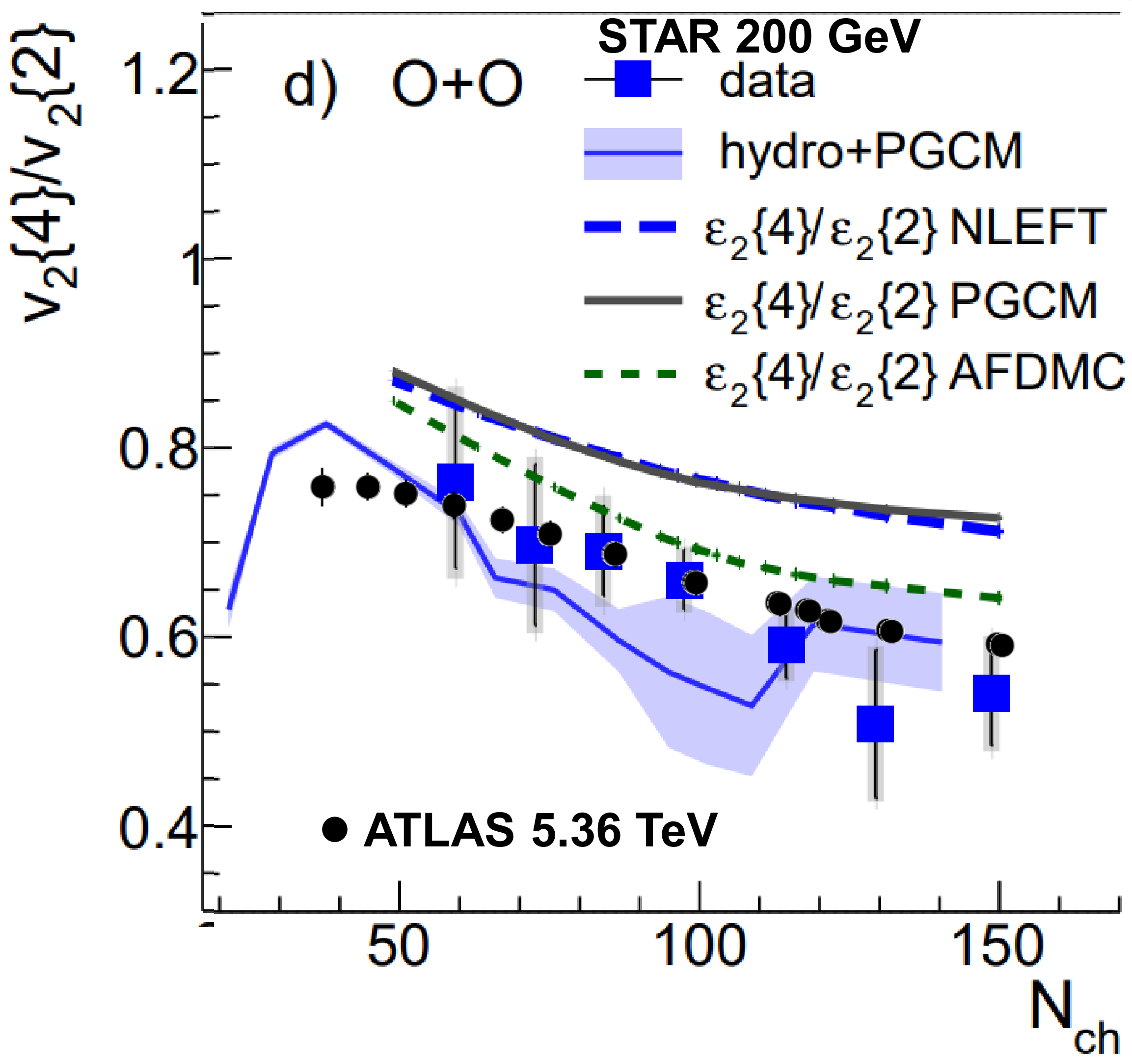
$v_n\{k\}$ as a function of N_{ch}

arXiv:2509.05171



- Neon's geometric UCC enhancement of v_2 grows throughout the majority of the N_{ch} distribution
- Very similar v_3 → fluctuation driven and transport grows with N_{ch}

Compare geometry across collision energy



arXiv:2510.19645

- Final state effects largely cancel – linear hydro approximation
- Geometry should be similar for 200 GeV and 5.36 TeV O+O
- Use STAR centrality → $<N_{ch}>$, to map ATLAS on to STAR N_{ch}
- STAR & ATLAS agree within uncertainties

Summary

- First measurement of azimuthal anisotropy in light-ion $^{16}O+^{16}O$ and $^{20}Ne+^{20}Ne$ collisions

- p_T differential v_n with non-flow subtraction
  - Qualitatively similar to large systems, indicative of QGP formation

- Centrality differential 2- and 4-particle correlations
  - Evidence of elongated (bowling pin) shape of neon

- Comparisons to theory show,
  - Preference for models with strong correlation between particle production and impact parameter
  - Discrepancies in mid-central and peripheral collisions

- N_{ch} differential results as well, good for full theory comparisons

Backup

Light ion event characteristics

arXiv:2509.05171