The 259th HENPIC Seminar
Small-System Mini-Series · 2026

QGP in Small Volumes:

Insights from ATLAS Light-Ion Measurements

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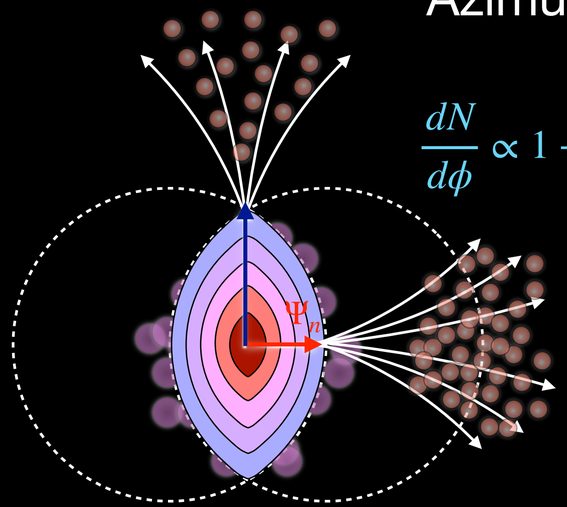
Large systems: collectivity and energy loss

The “perfect fluid” paradigm in heavy-ion collisions (large system)

Bulk particles: pressure gradients convert spatial anisotropy into momentum anisotropy

Azimuthal anisotropy

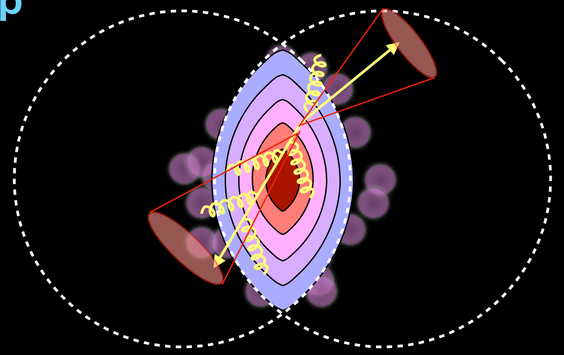
$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_n))$$



Hard probes: interactions with the medium modify energetic partons

Jet quenching

$$R_{\mathrm{AA}} = \frac{\textbf{Yields per A+A}}{< N_{\mathrm{coll}} > \textbf{Yields per pp}}$$

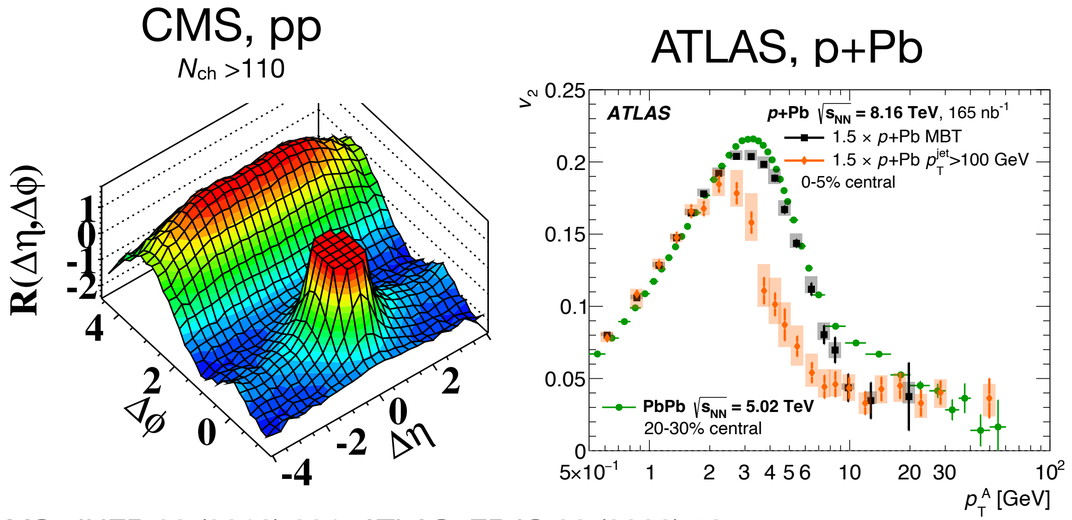


Traditional reference — small systems:

- ***pp*** — hard-scattering and fragmentation
- ***p*+Pb** — cold nuclear matter effects

The pp and p+Pb puzzle

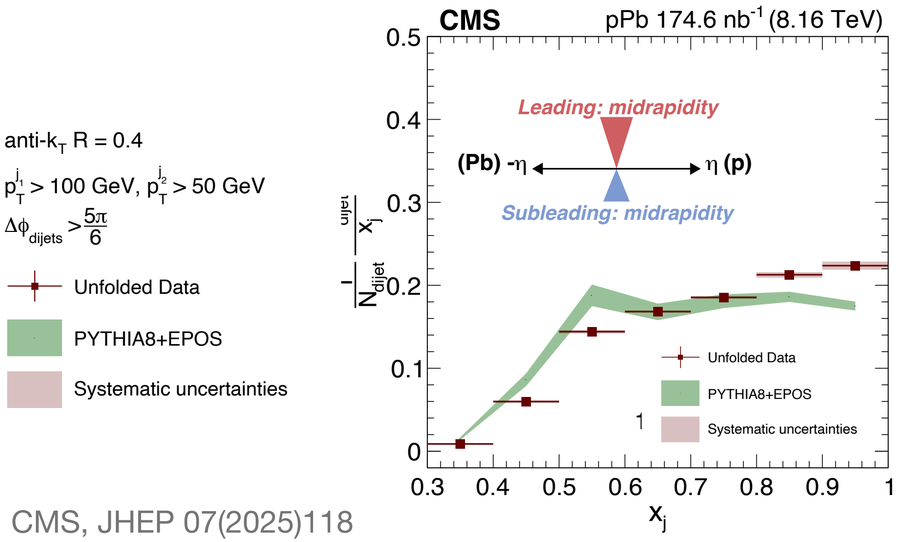
Collectivity in pp and p+Pb



CMS, JHEP 09 (2010) 091; ATLAS, EPJC 80 (2020) 73

Long-range azimuthal correlations in high-multiplicity events

Strong constraints on quenching in p+Pb



CMS, JHEP 07(2025)118

Dijet balance broadly follows a reference without quenching

Can a common description explain collectivity and hard-probe constraints?

Comparable size, different geometries

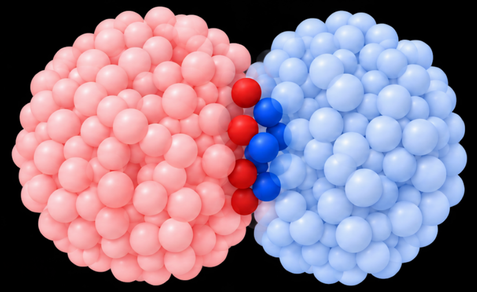
Comparable $\langle N_{\mathrm{part}} \rangle$ can correspond to different spatial profiles

- Collective response depends on gradients and expansion
- Hard probes depend on production points and paths through the evolving medium

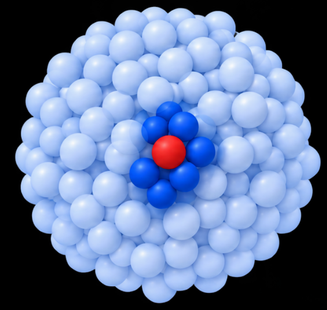
70–80% Pb+Pb

Participants drawn from the edges of two large nuclei

Strong sensitivity to surface geometry, production fluctuations and selection biases



Comparable $\langle N_{\mathrm{part}} \rangle$



0–5% p+Pb

One proton interacting with several Pb nucleons

Strong sensitivity to production fluctuations and proton configurations

Matching N_{part} / N_{coll} / multiplicity does not determine the energy-density profile, fluctuations, or paths traversed by hard partons

Event selection changes the hard-probe baseline

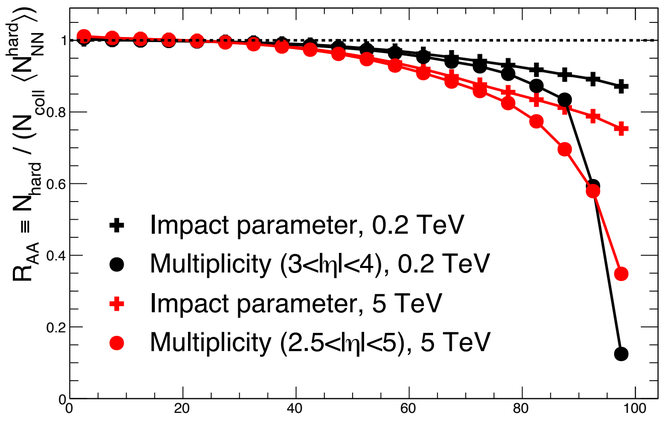
Event selection bias

- Geometry bias: selected NN encounters differ from minimum-bias pp encounters
- Activity-selection bias: soft activity correlates with hard-process probability

Hard-process selection bias

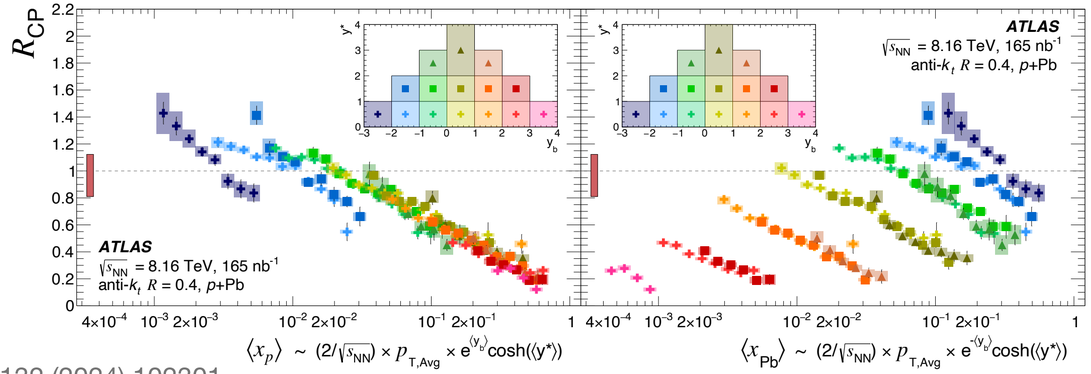
- **Proton x dependence:** color transparency effects etc.

Calculation without jet quenching



Constantin Loizides et al, PLB 773 (2017) 408-411

HG-Pythia: geometry and event selection can produce apparent peripheral suppression



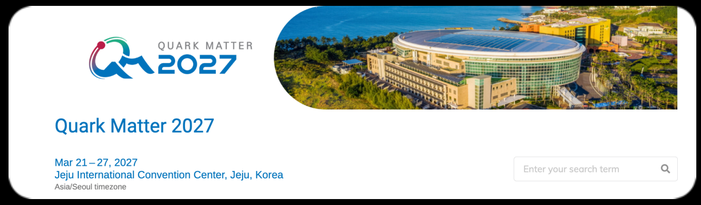
PRL 132 (2024) 102301

Suppression of dijet in central p+Pb is strongly correlated with x_p

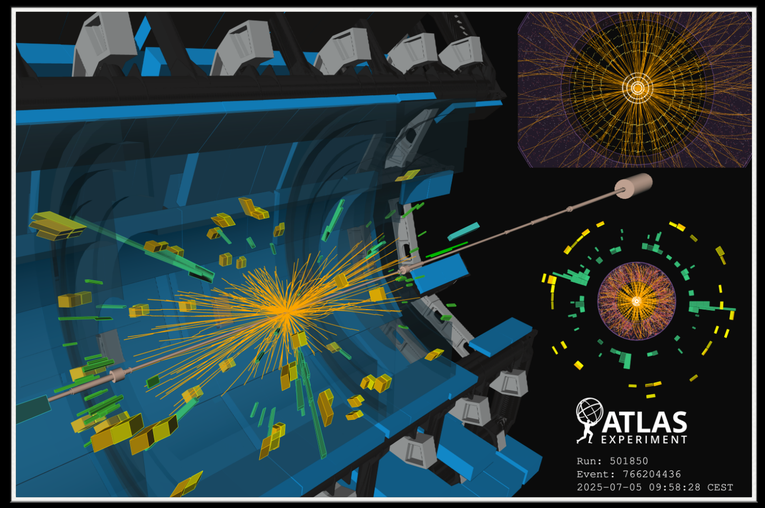
Why add O+O and Ne+Ne?

Two open questions:

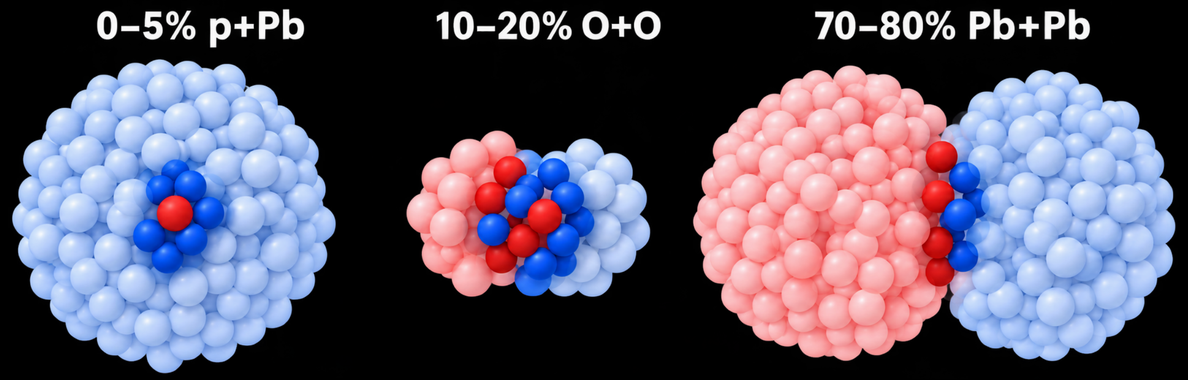
- Under what conditions do collectivity and partonic energy loss coexist?
- How do collision geometry and medium evolution affect these observables?



density.)
- **Small Systems** (Strongly interacting matter in proton and light-ion collisions.)



An O+O collision recorded by ATLAS in 2025



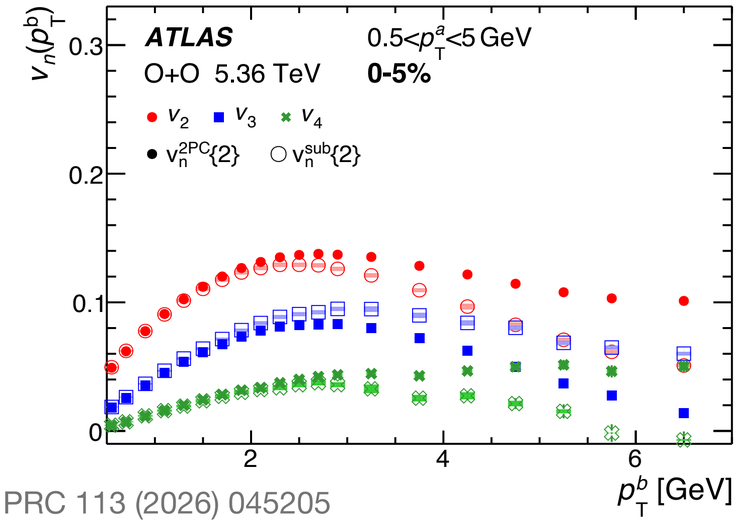
O+O: a new small nuclear overlap geometry

Ne+Ne vs. O+O: an additional variation of nuclear structure and particle production

Can the same initial conditions and medium evolution describe both **collectivity** and **hard probes**?

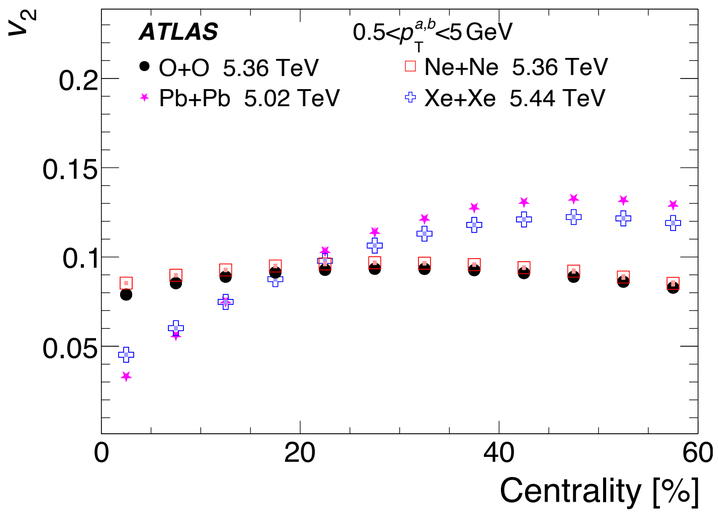
Light ion flow

O+O v_n vs p_T

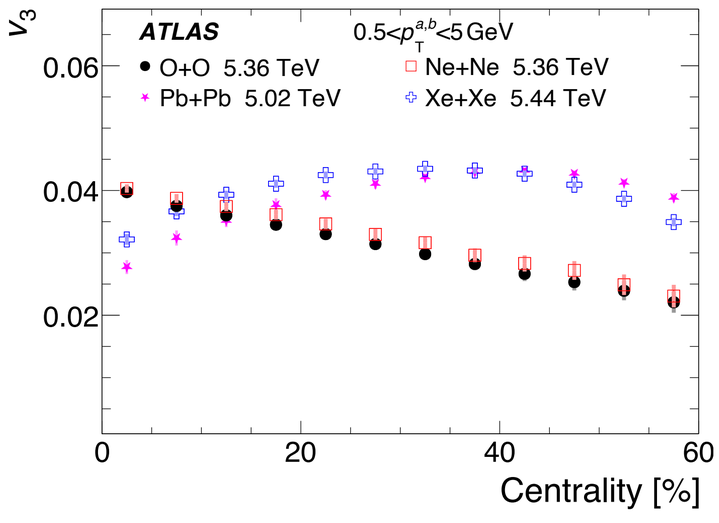


PRC 113 (2026) 045205

O+O / Ne+Ne v_2 vs Centrality



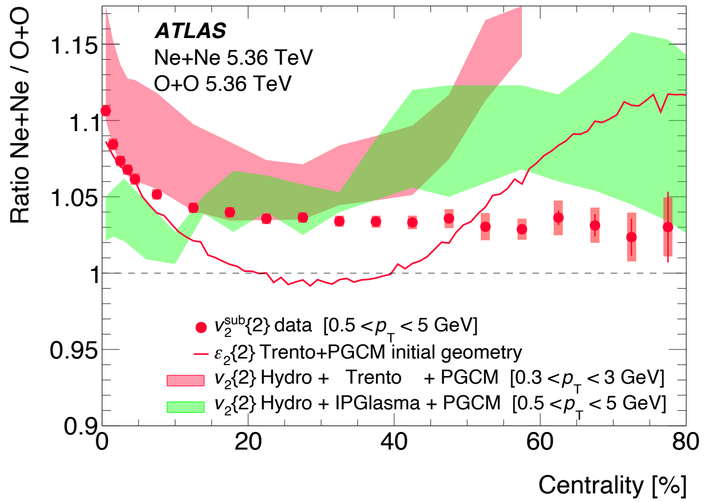
O+O / Ne+Ne v_3 vs Centrality



- Significant collective flow in O+O and Ne+Ne collisions, measured p_T dependence in light-ion collisions resemble those seen in heavy-ion collisions
- Light-ion v_2 varies much less with centrality than in Pb+Pb and Xe+Xe; Light-ion v_3 decreases toward peripheral; emphasizing fluctuations and medium response

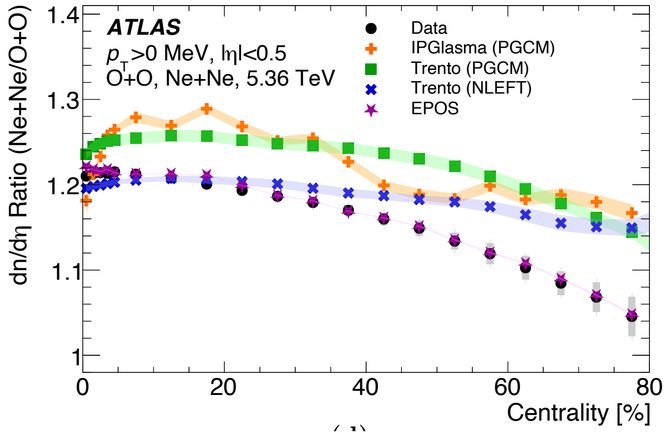
Ne+Ne/O+O comparison

v_2 ratio



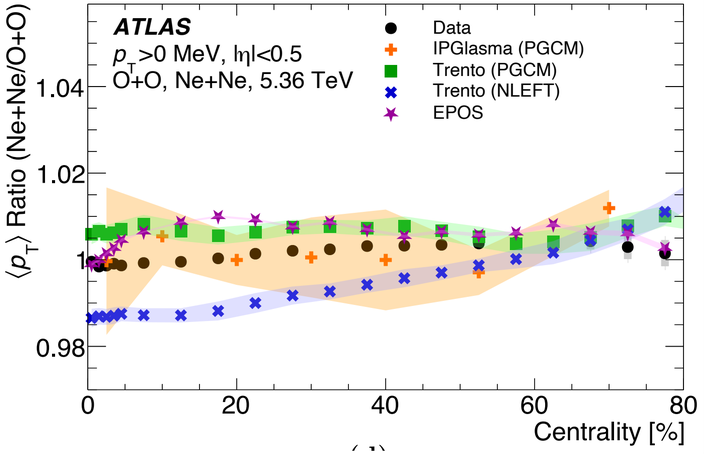
PRC 113 (2026) 045205

dn/dη ratio



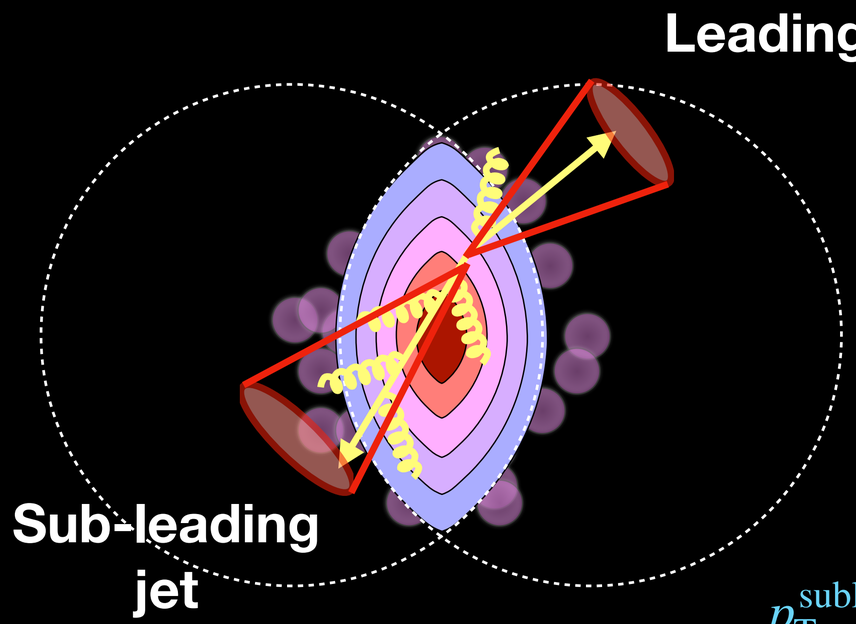
2606.20257

Mean p_T ratio

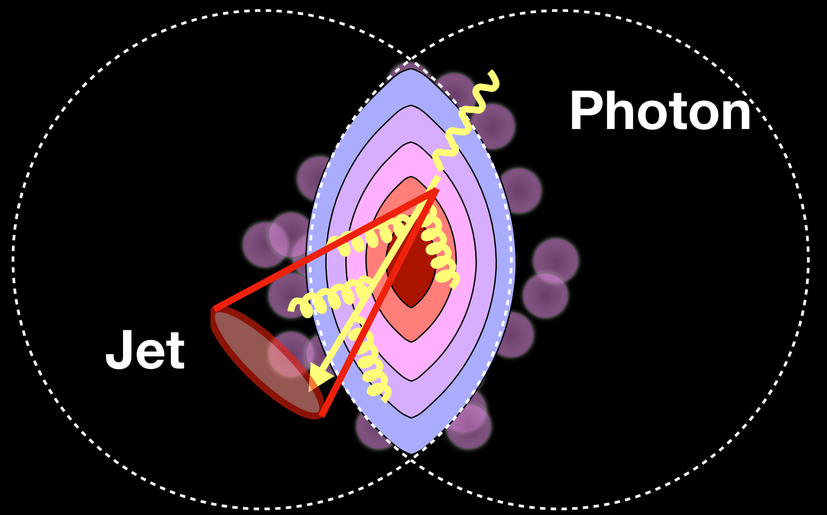


- The additional enhancement of elliptic flow in the most central neon events is consistent with its deformed nuclear structure
- At matched centrality, Ne+Ne produces 5–20% more particles, while mean p_T differs by 1%
- Trento+PGCM better captures the central v_2 enhancement, but both PGCM-based calculations overestimate the multiplicity ratio

Observables for small energy-loss effects



$$x_{\mathrm{J}} = \frac{p_{\mathrm{T}}^{\mathrm{subleading}}}{p_{\mathrm{T}}^{\mathrm{leading}}}$$



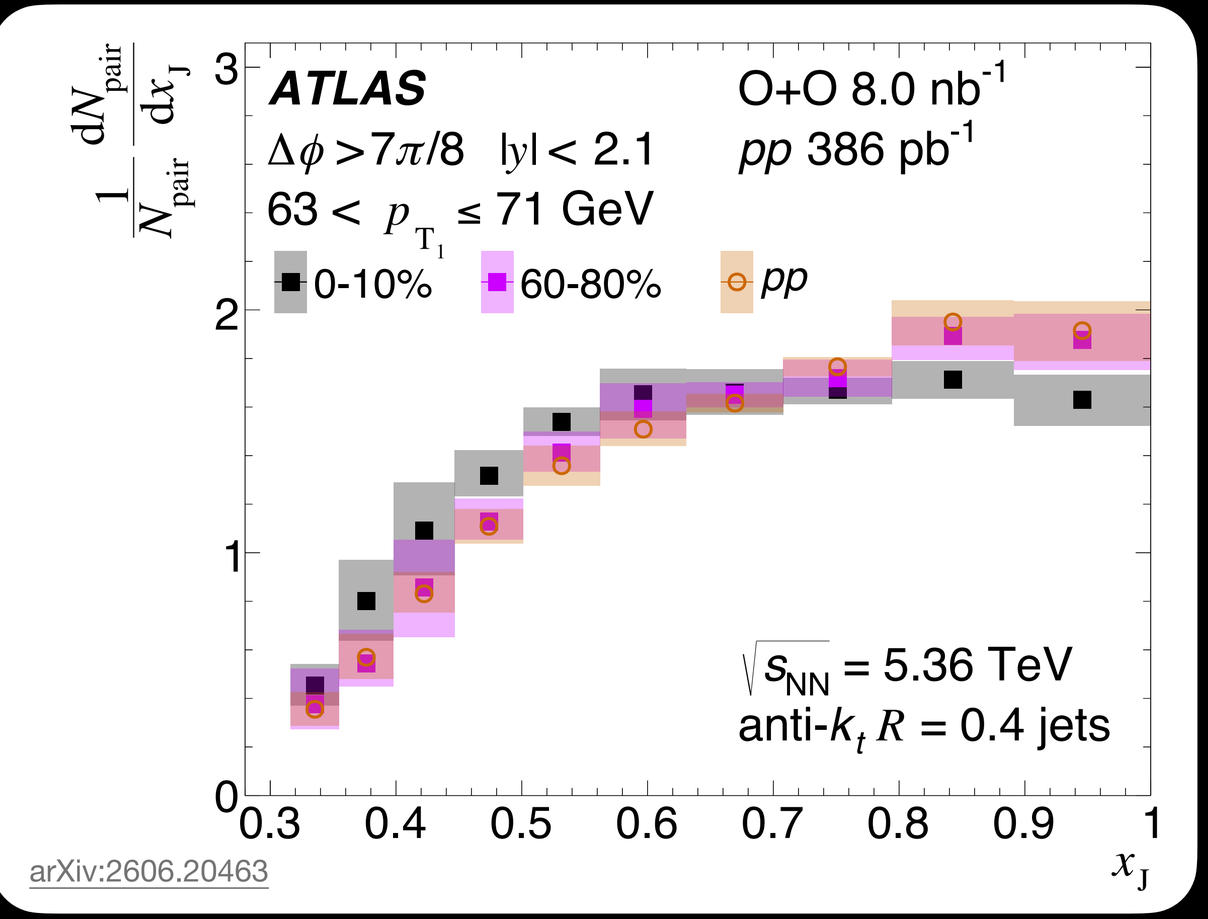
$$I_{\mathrm{OO}} = \frac{\mathrm{d}N_{\mathrm{ch}}(p_{\mathrm{T}}^{\mathrm{ch}})/N_{\gamma}|_{\mathrm{O+O}}}{\mathrm{d}N_{\mathrm{ch}}(p_{\mathrm{T}}^{\mathrm{ch}})/N_{\gamma}|_{\mathrm{pp}}}$$

- Dijet balance probes the relative momentum of the two reconstructed jets
- Photon–hadron correlations measure recoil yields per photon without selecting a recoil jet

Both avoid explicit T_{AA} normalization

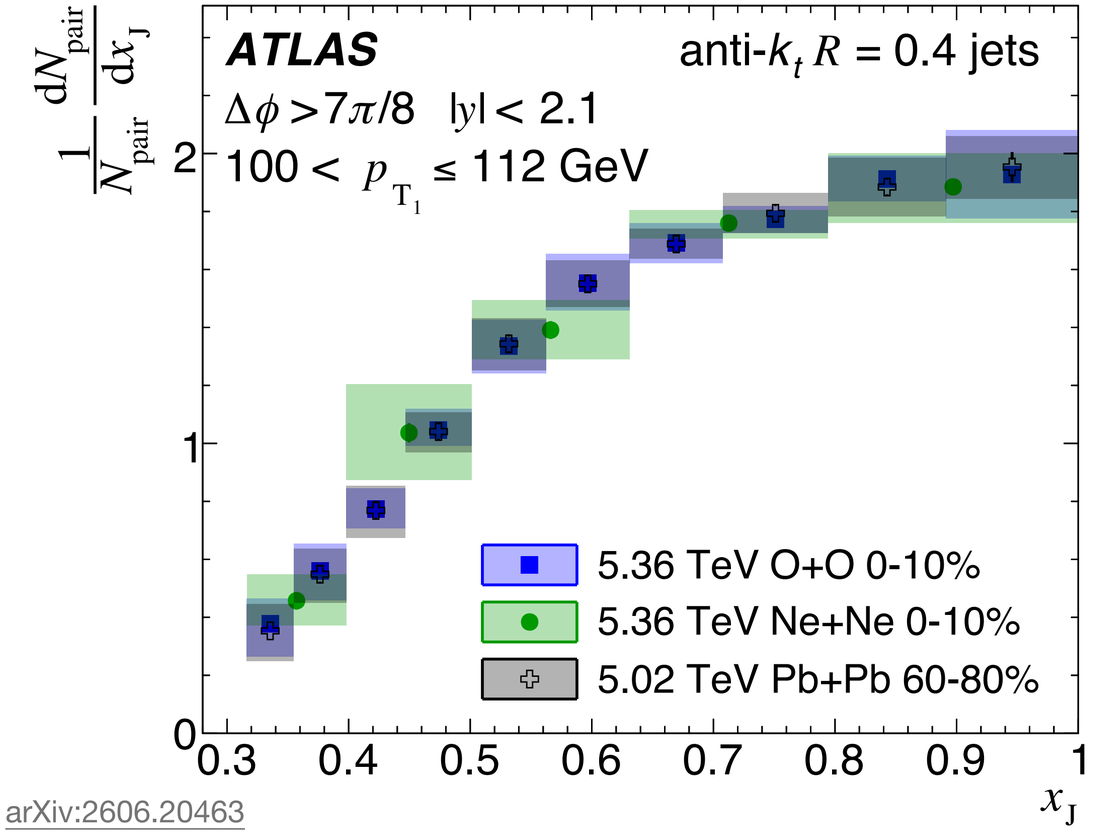
Central O+O shifts dijet momentum balance

- pp and peripheral O+O (60–80%) show similar distributions
- Central O+O (0–10%) events exhibit clear differences compared to pp and peripheral O+O ~ **jet quenching signature**



Dijet balance at comparable forward activity

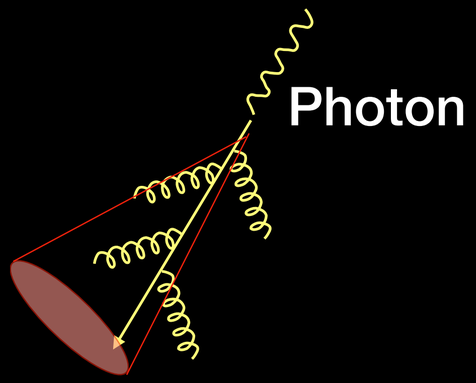
- Central O+O and Ne+Ne have similar x_J distributions to 60–80% Pb+Pb at comparable forward activity
- Comparable activity does not establish identical density, lifetime or path lengths
- This tests descriptions across different collision geometries



arXiv:2606.20463

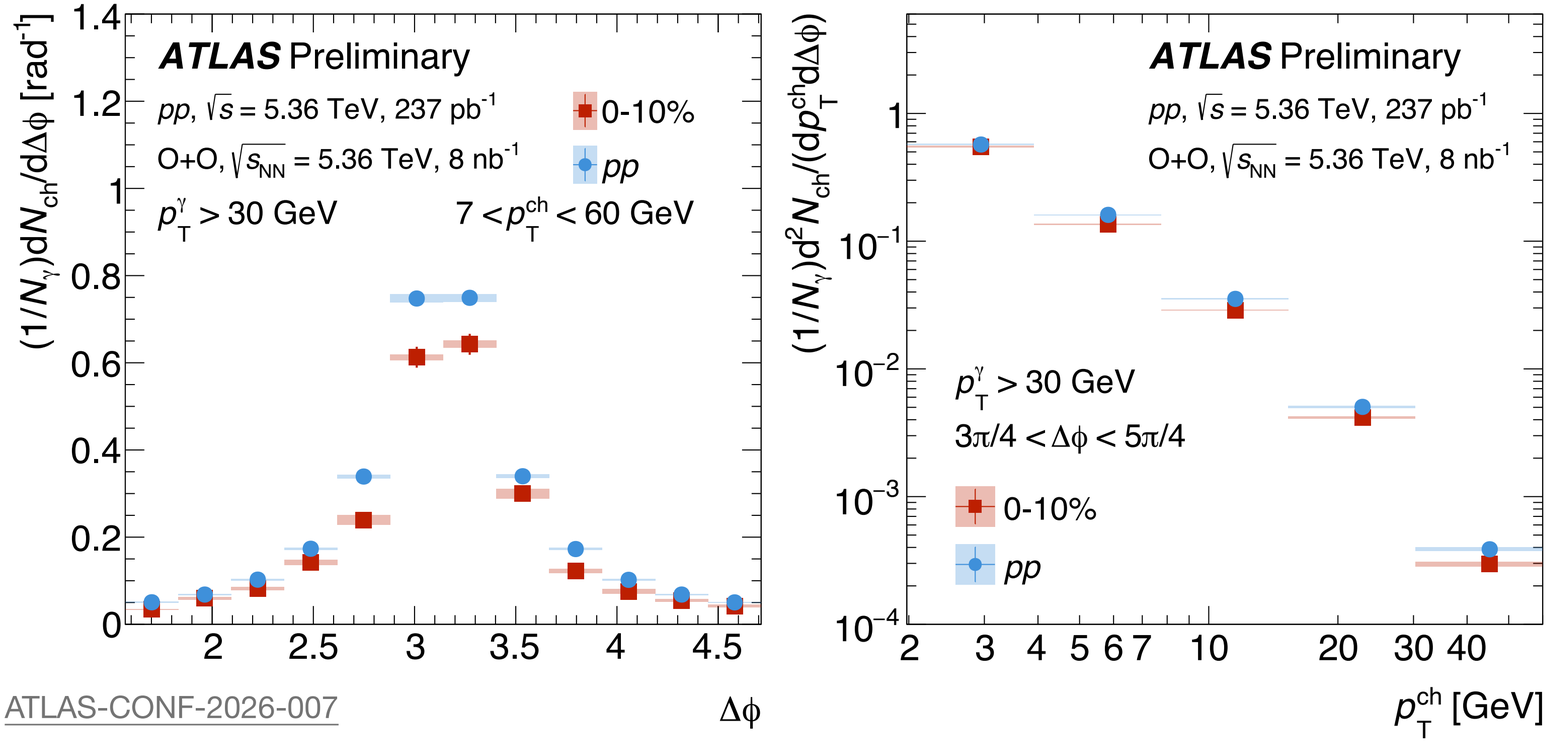
A photon reference reveals recoil modification

- Isolated photons provide a reference for the hard-scattering scale
- Away-side charged-particle yields are measured per photon, without a recoil-jet requirement



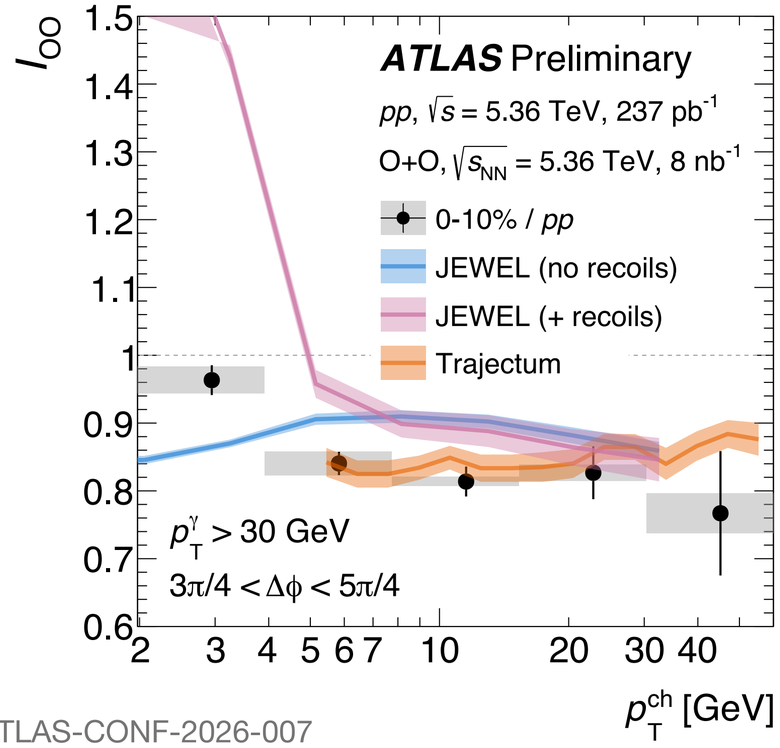
Central vs. pp

$\mathrm{d}N_{\mathrm{ch}}(p_{\mathrm{T}}^{\mathrm{ch}})/N_{\gamma}$



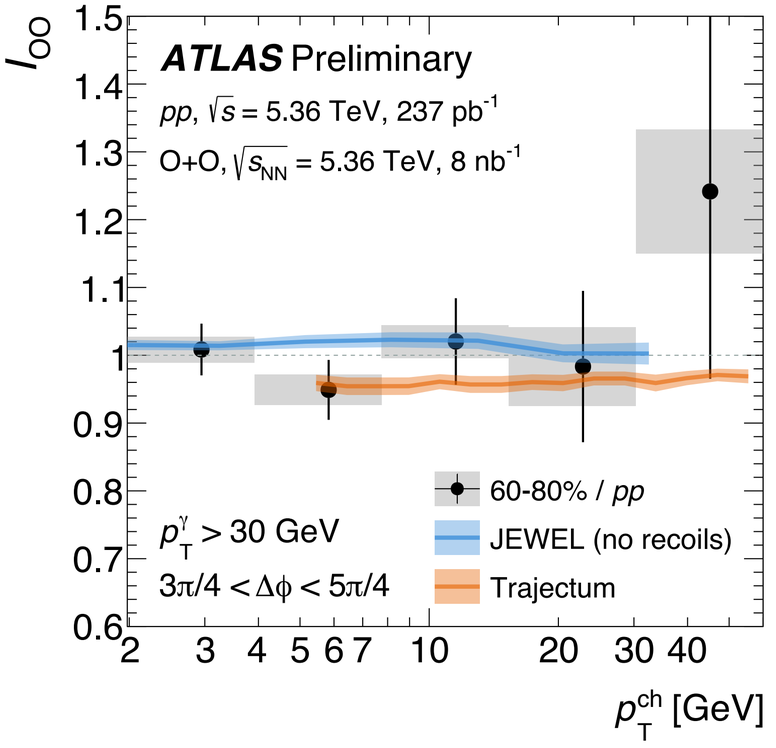
Photon–hadron modification across centrality

Central O+O



ATLAS-CONF-2026-007

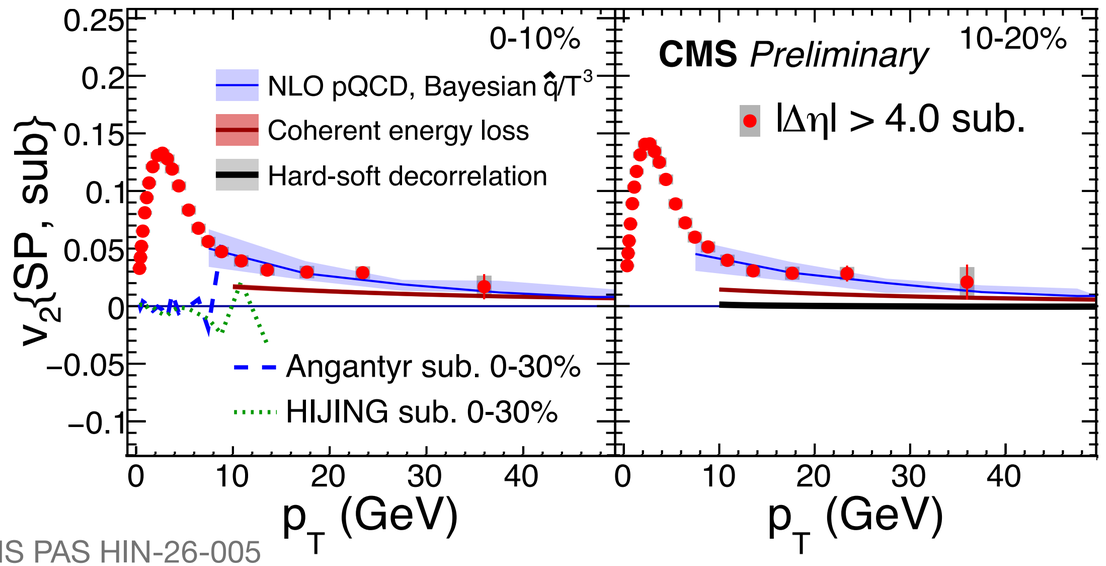
Peripheral O+O



- Central O+O recoil yields are suppressed by 15–20% over a broad particle pT range
- Peripheral O+O is broadly compatible with the pp reference

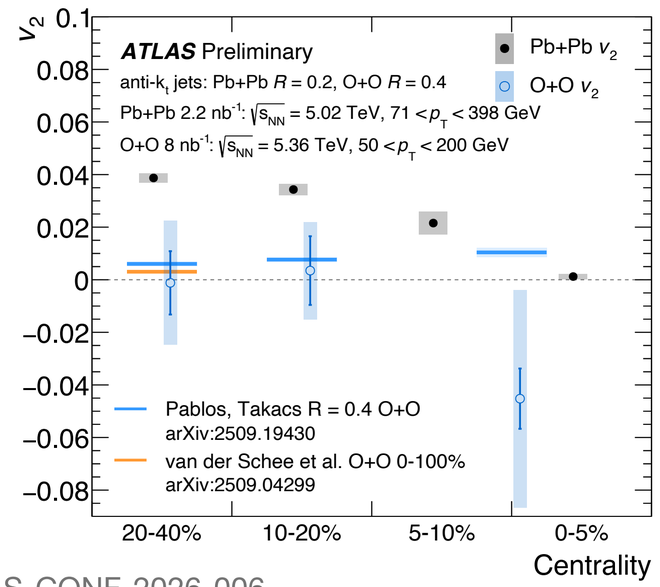
High-p_T anisotropy in O+O

CMS, hadron v_2



CMS PAS HIN-26-005

ATLAS, jet v_2

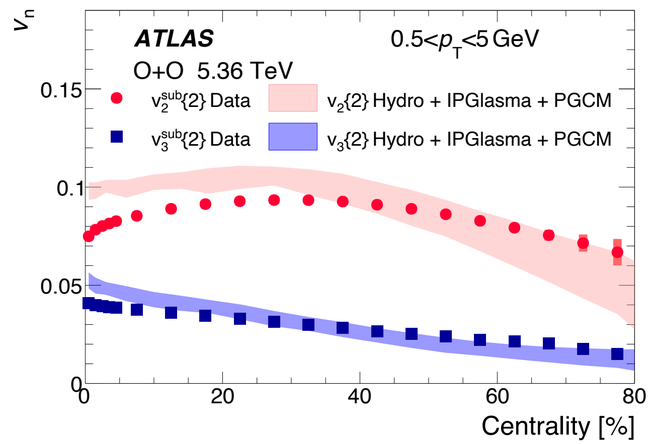


ATLAS-CONF-2026-006

- CMS observes positive high-p_T charged-particle v_2 after non-flow subtraction
- ATLAS jet v_2 remains uncertainty limited in O+O
- Particle and jet anisotropy probe different parent energies and energy recovery

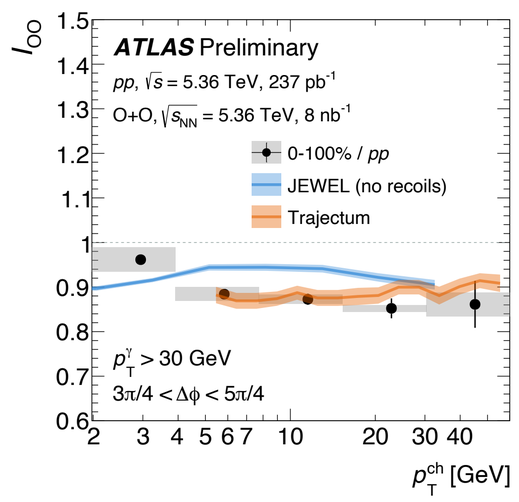
Joint constraints from soft and hard probes

Bulk response



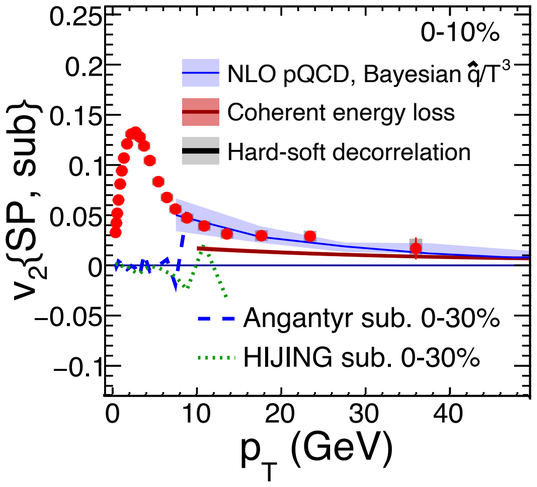
Initial geometry and collective response

Parton modification



Interactions along energetic-parton trajectories

Hard-soft correlation



Correlation of energetic particles with the bulk geometry

- Bulk response: IPGlasma+PGCM overpredicts flow in central collisions
- Recoil modification: Trajectum broadly describes I_{OO}; JEWEL predicts too little suppression
- Hard–soft correlation: Models must reproduce both suppression and positive high-p_T anisotropy

What light ions have added

- **QGP in small volumes:** consistent evidence from both collectivity and hard-probe modification in light-ion collisions
- **Nuclear structure:** Ne+Ne/O+O comparisons add sensitivity through flow and particle production
- **A common description:** connect Pb+Pb, light ions and p+Pb with consistent initial conditions and medium evolution
- **Open questions:** how do density, geometry and interaction time control the observed behavior?
- **Future runs:** He+He, O+Pb? Identify priorities and build community support for the next measurements