

Centrality determination in light-ion collisions

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Thanks to Anthony Timmins, Wilke van der Schee, Andreas Kirchner, Rupam Samanta

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LHC Heavy-Ion Working Group

lpcc.web.cern.ch/content/lhc-hi-wg

On-going task:
Documentation of centrality determination
across LHC experiments

February meeting indico.cern.ch/event/1639600/

- Anthony Robert Timmins
- Peter Alan Steinberg
- Constantinos Loizides
- Óscar Boente García
- Wilke Van Der Schee

Conveners:

- ALICE: Alice Ohlson and Alexander Kalweit
- ATLAS: Qipeng Hu and Martin Rybar
- CMS: Austin Baty and Andre Stahl
- LHCb: Giulia Manca and Saverio Mariani
- Theory: Liliana Apolinario and Aleksas Mazeliauskas
- LPCC contact: Pier Monni
- Reach all through lhc-hiwg-admin@cern.ch

Community input needed:

What is most relevant information for cross-experiment and theory comparison?

Why centrality is harder in light ions

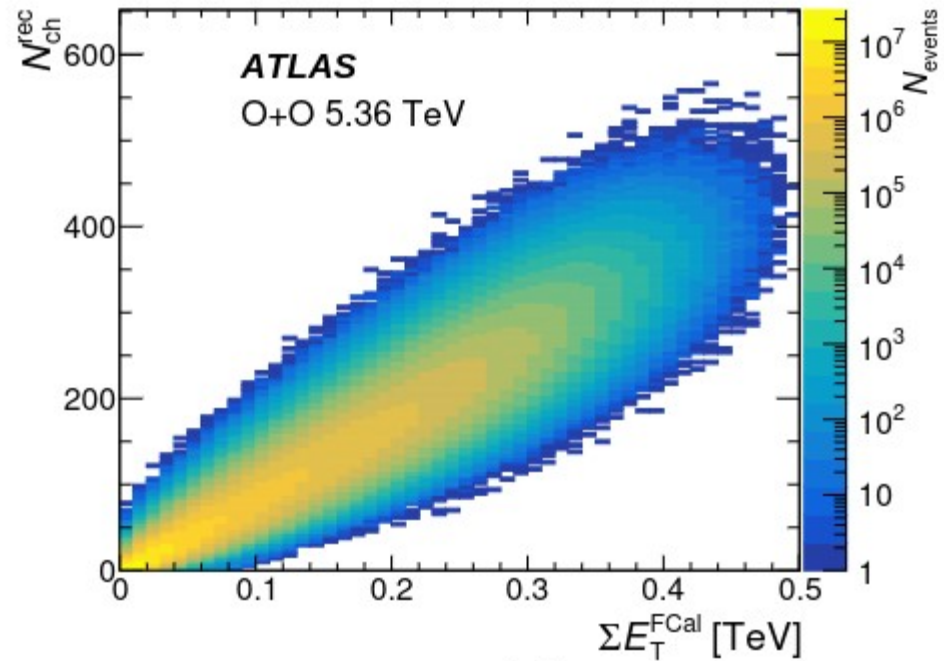
● Geometry gets blurred

- The dynamic range in N_{part} between central and peripheral O+O is only a factor of a few, and fluctuations at fixed geometry are large.
- The same percentile averages over a broader spread of geometries than in Pb–Pb.

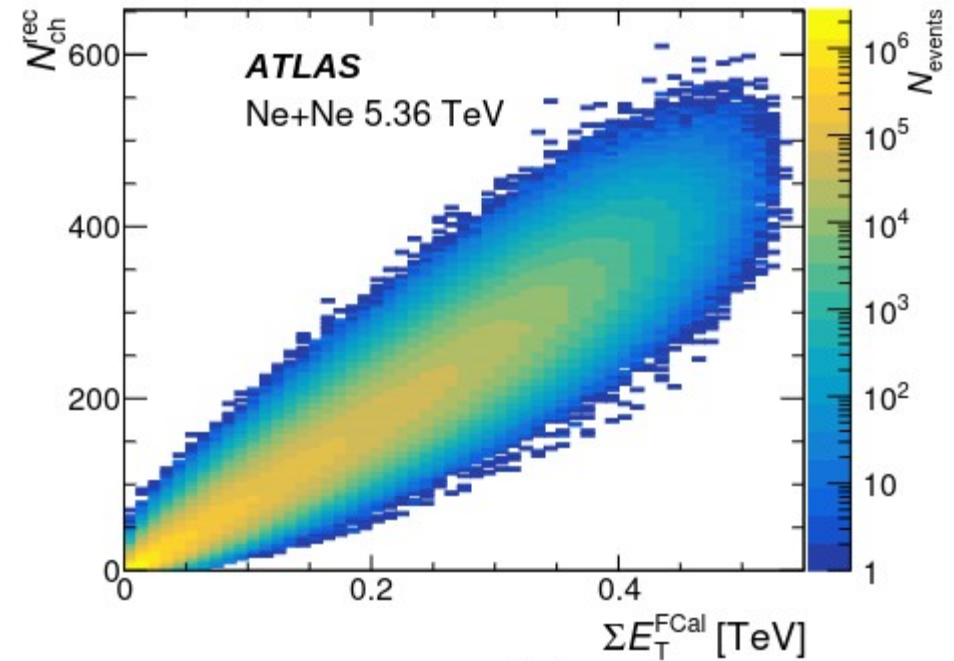
● Nuclear structure shapes the multiplicity

- α -clustering and deformation in ^{16}O and ^{20}Ne change the nucleon density, and so change the estimator distribution itself.

Multiplicity correlation with centrality estimator



(a)



(b)

ATLAS, arXiv:2509.05171

Four quantities to keep apart

● Estimator

One number per event, measured away from mid-rapidity so that it does not autocorrelate with the observable. Events are ordered by it and cut into percentiles of the inelastic hadronic cross section.

ALICE: FT0C amplitude

CMS, ATLAS: ΣE_T

● Anchor point

The estimator value at which the event selection is fully efficient and background is negligible. The percentile scale is fixed relative to it; below it the distribution is either corrected or discarded.

CMS: anchored at 80% of σ_{had}

ALICE: fit matched over the top 90%

● ϵ_{had} — an efficiency

The fraction of hadronic events the experiment actually records. A property of trigger and event selection; the goal is for it to be as close to unity as possible.

$$\epsilon_{had} = N_{ev}(\text{observed}) / N_{ev}(\text{total}) = \sigma_{AA}(\text{vis}) / \sigma_{AA}(\text{tot})$$

● f_{MC} — a fiducial fraction

The fraction of the Glauber cross section lying above a deliberately chosen minimum estimator value.

$$f_{MC} = \sigma(\Sigma E_T > \Sigma E_T^{min}) / \sigma_{AA}(\text{inel})$$

Two ways to normalise the distribution

Method 1 — fit

ALICE · ATLAS

- Fit the measured estimator distribution with a Glauber-based production model.
- The model supplies the unobserved part of the distribution.
- Normalisation and geometry come from the same fit.

Method 2 — correct

CMS

- Correct the measured distribution for event loss and background using generators folded with the detector response.
- The corrected distribution is the reference.
- Percentiles are fixed first; the Glauber fit comes afterwards.

Estimator and normalisation

	ALICE	CMS	ATLAS
Detector	FT0-C, Fast Interaction Trigger	HF, steel and quartz-fibre	FCal, forward calorimeters
Acceptance	$-3.3 < \eta < -2.1$	extends coverage to $2.9 < \eta < 5.2$	$3.2 < \eta < 4.9$
Quantity	Raw amplitude $\propto$ number of charged particles	Scalar ΣE_T , $E_T = E / \cosh \eta$	ΣE_T^{FCal}
Method	Fit — NBD–Glauber	Correct, then fit	Fit — Glauber above a minimum ΣE_T
Anchor point	Fit matched over the top 90% of the hadronic cross section	80% of the hadronic cross section, where the selection efficiency is unity; position known to ~10%	Minimum ΣE_T^{FCal} threshold; results published over 0–80%

Mapping to geometry

$$N_{\text{sources}} = f \cdot N_{\text{part}} + (1 - f) \cdot N_{\text{coll}} \quad \text{convolved with a per-source fluctuation kernel}$$

	ALICE	CMS	ATLAS
Production model	Two-component, $N_{\text{sources}} = f \cdot N_{\text{part}} + (1-f) \cdot N_{\text{coll}}$	Two-component: soft $\propto N_{\text{part}}$, hard $\propto N_{\text{coll}}$, combined into effective sources	Glauber-model fit to the ΣE_T^{FCal} distribution; two-component picture *
Fluctuation kernel	Negative binomial, parameters μ and k ($k = 1.5$ by default)	Gamma distribution per source	Gamma function for the effective NN collision
Nuclear density	— not specified for ^{16}O / ^{20}Ne	MC Glauber; $\sigma_{\text{NN}} = 68.0 \pm 1.2$ mb, $\omega = 0.3 \pm 0.3$; N_{part} uncertainty from the spread of oxygen density profiles	PGCM and NLEFT densities as implemented in Trajectum (TR_OXYGEN_V15, TR_NEON_V14, $\omega = 0.3$) — α -clustering explicit

* Not named in the ATLAS paper; the two-component picture with a gamma kernel was stated in the February 2026 LPCC discussion.

Questions

1

Is the difference real?

To what extent does a percentile still track collision geometry in O+O and Ne+Ne — and can the same percentile be taken to select equivalent event populations across experiments?

2

Can the estimators be cross-calibrated?

Can a multiplicity-type and an energy-type estimator be calibrated against each other within one experiment, so that the cross-experiment comparison runs through that calibration?

3

What do theorists need?

What must be published for a calculation to reproduce the experimental event selection — the estimator and its acceptance, the production model and its parameters, or a measured quantity such as N_{ch} distribution?

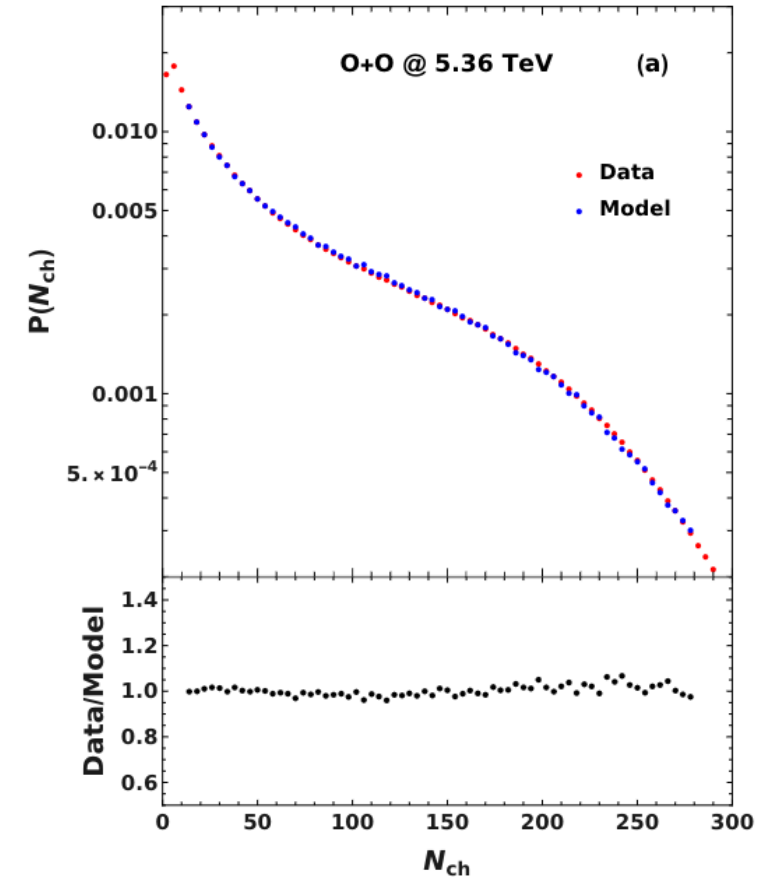
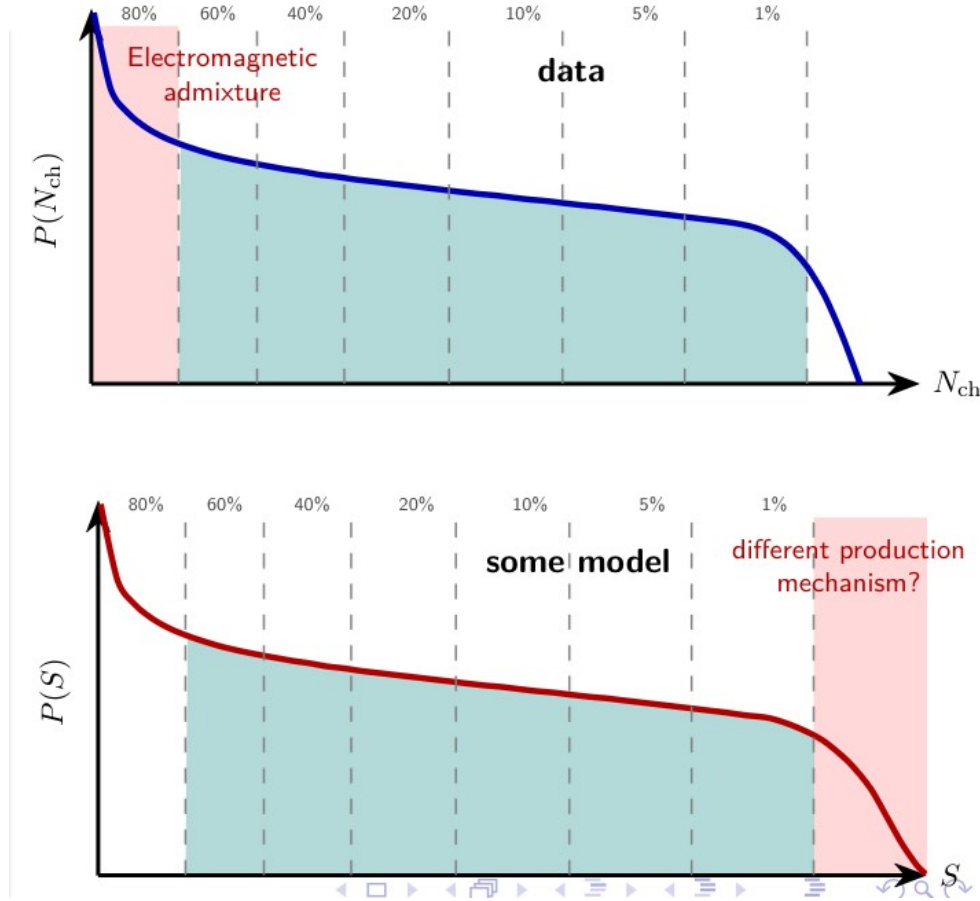
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Is the centrality bias for hard probes correctable?

If it is irreducible, does that bias centrality-integrated observables for the jet-quenching onset?

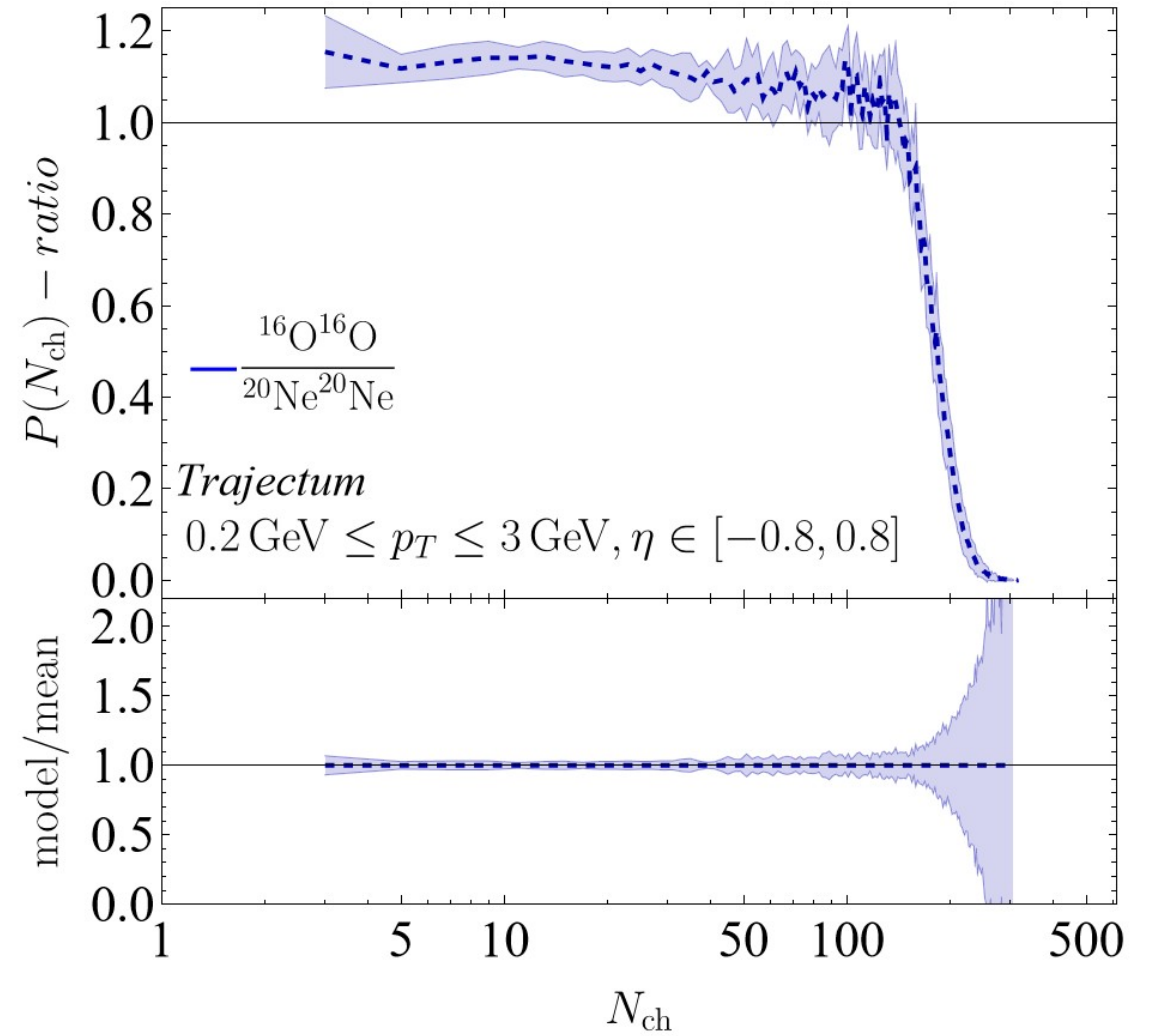
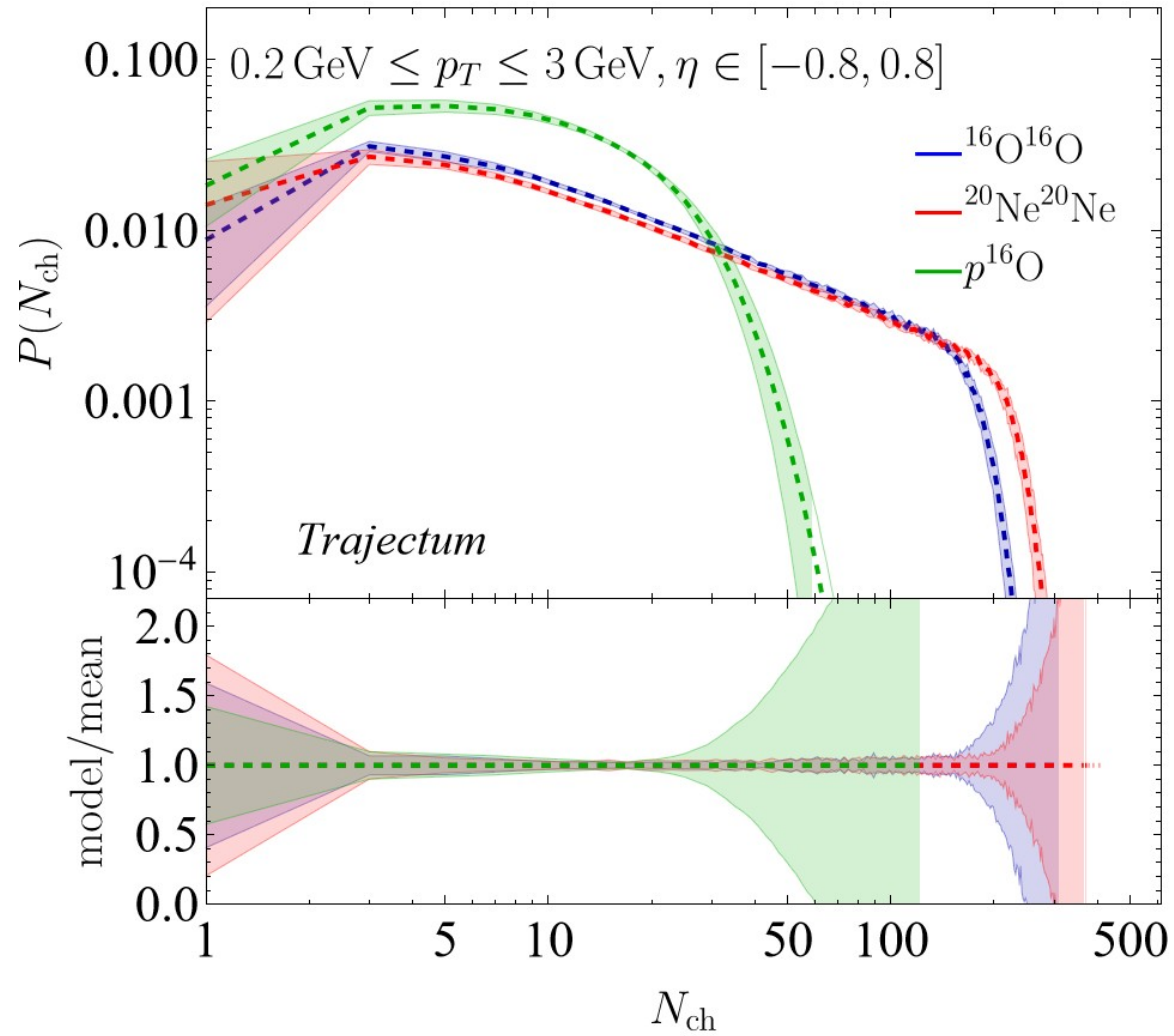
Proposal: fitting the multiplicity distribution

arXiv:2607.16485



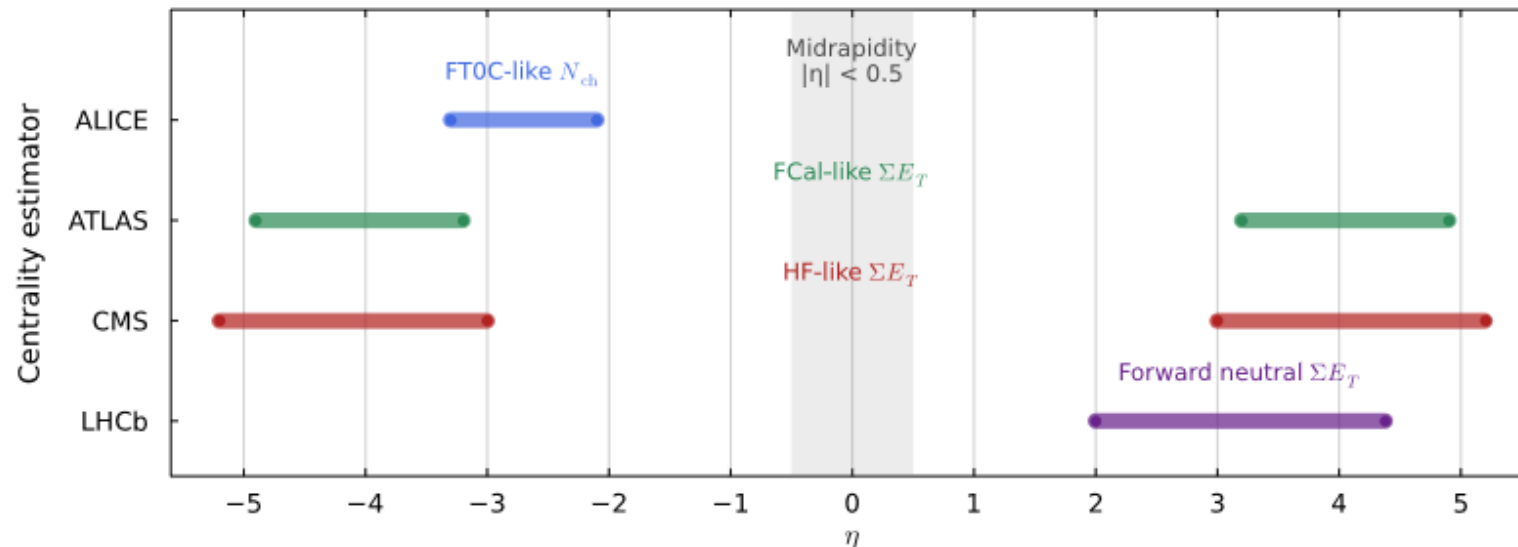
Need experiments to publish distributions.

Trajectum N_{ch} distribution (thanks Wilke)

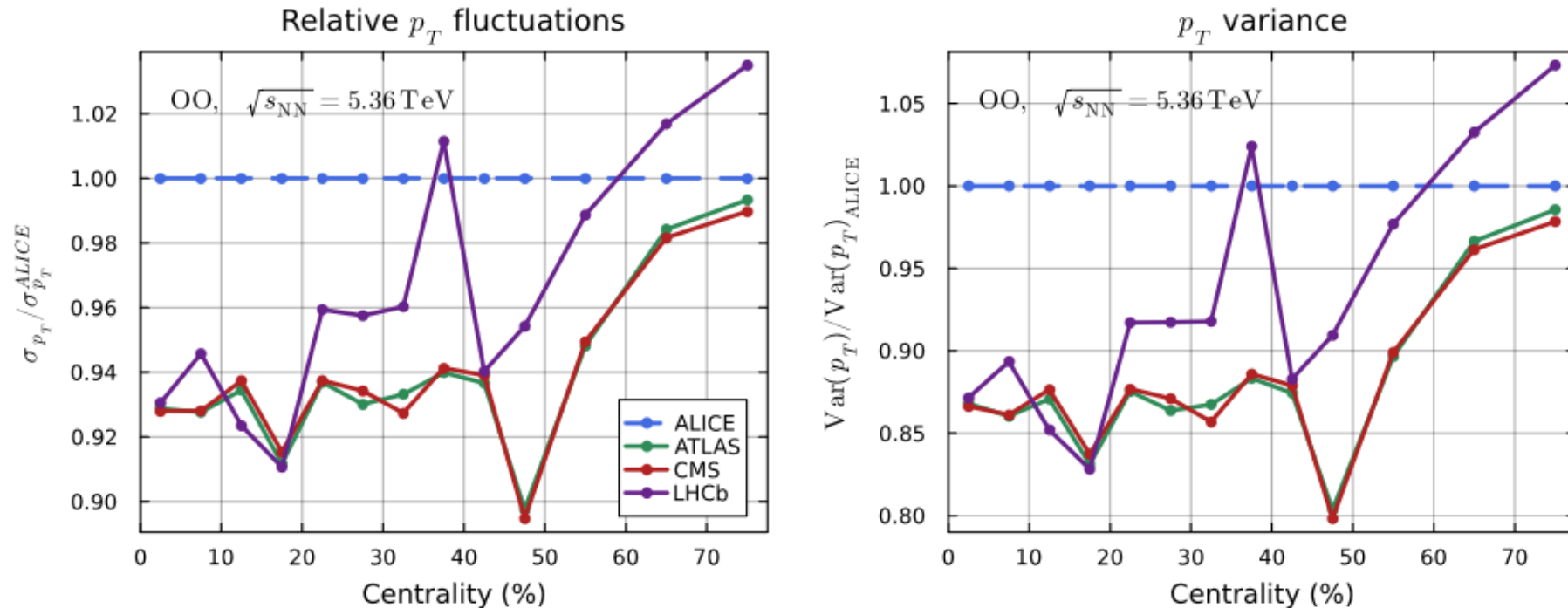


Centrality selection

- **ALICE**: FT0C-like N_{ch} for $-3.3 < \eta < -2.1$
- **ATLAS**: FCal-like ΣE_T of PID for $3.2 < |\eta| < 4.9$
- **CMS**: HF-like ΣE_T of PID for $3.0 < |\eta| < 5.2$
- **LHCb**: Forward neutral ΣE_T for $2.0 < \eta < 4.38$

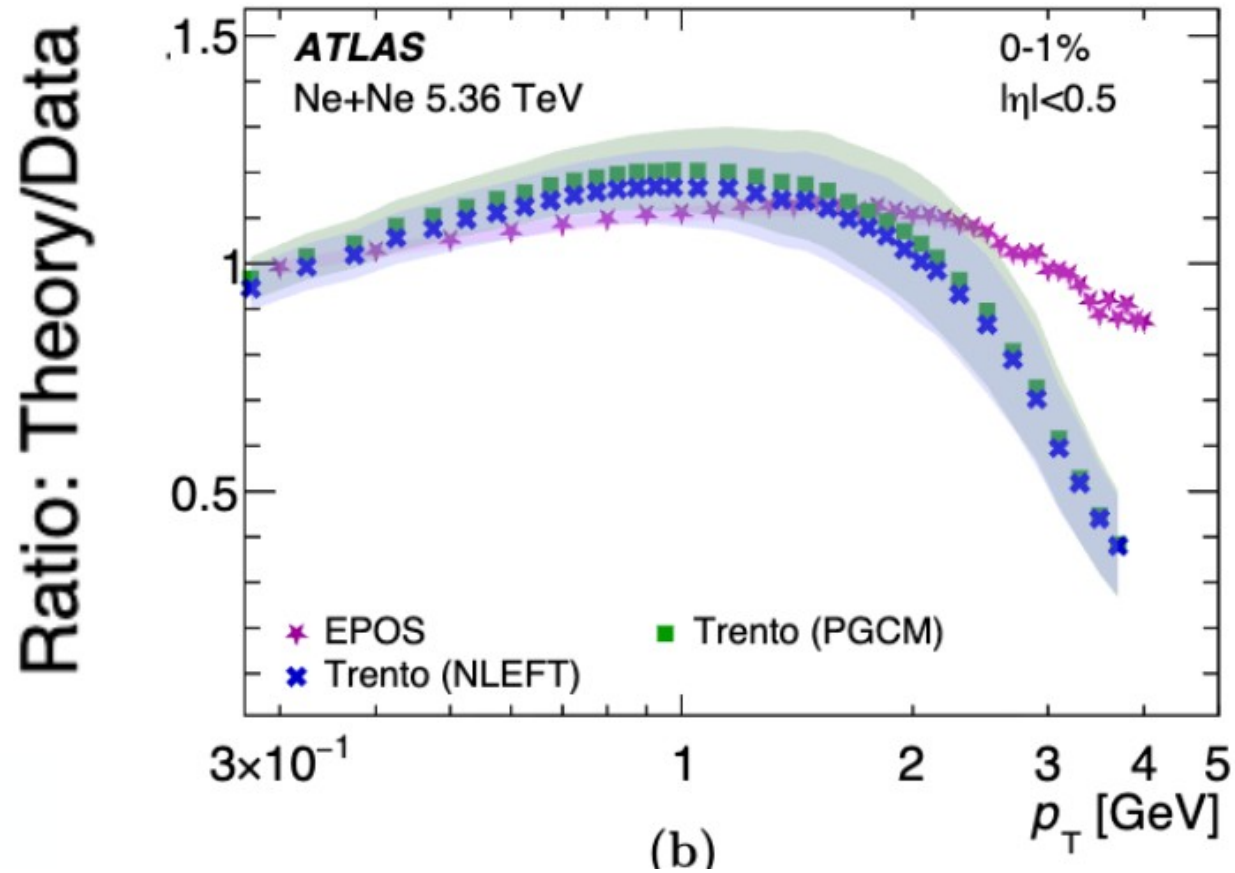


Which observables are sensitive to centrality selection?



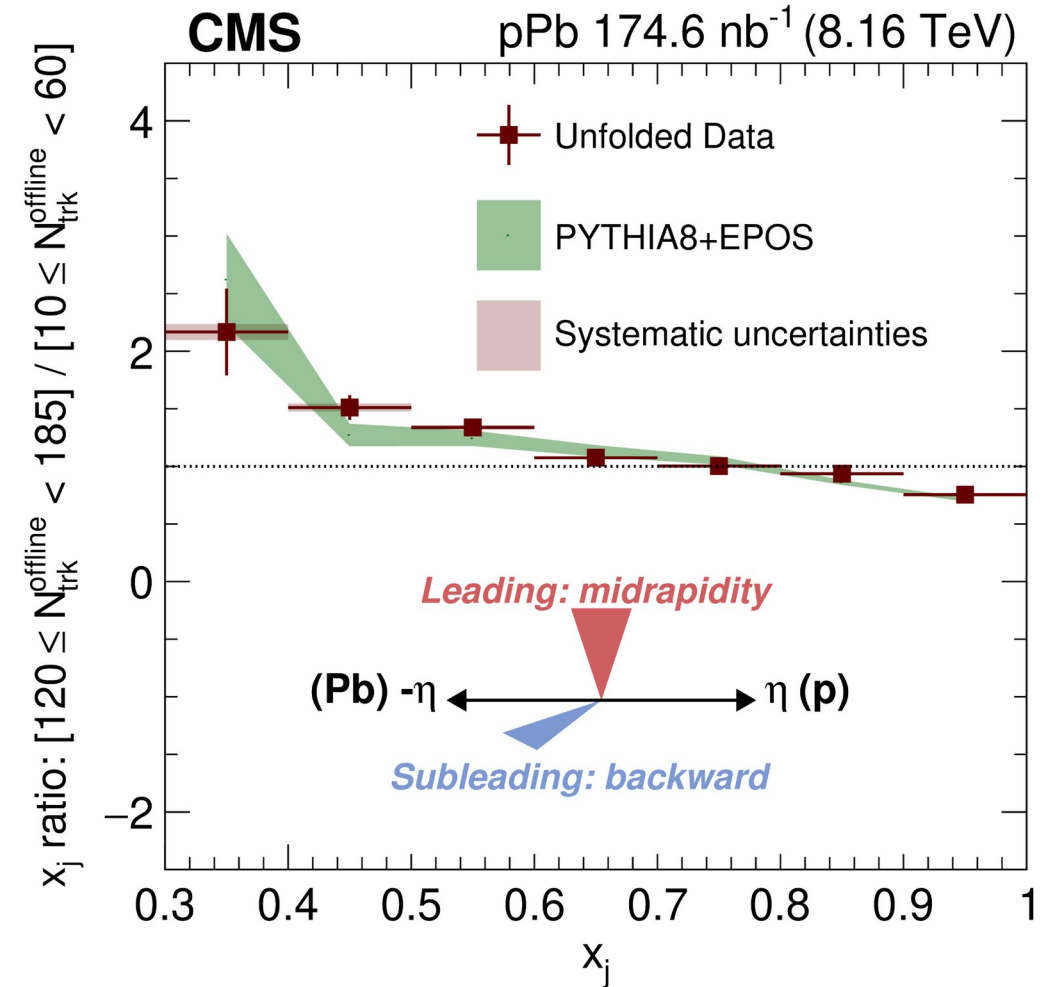
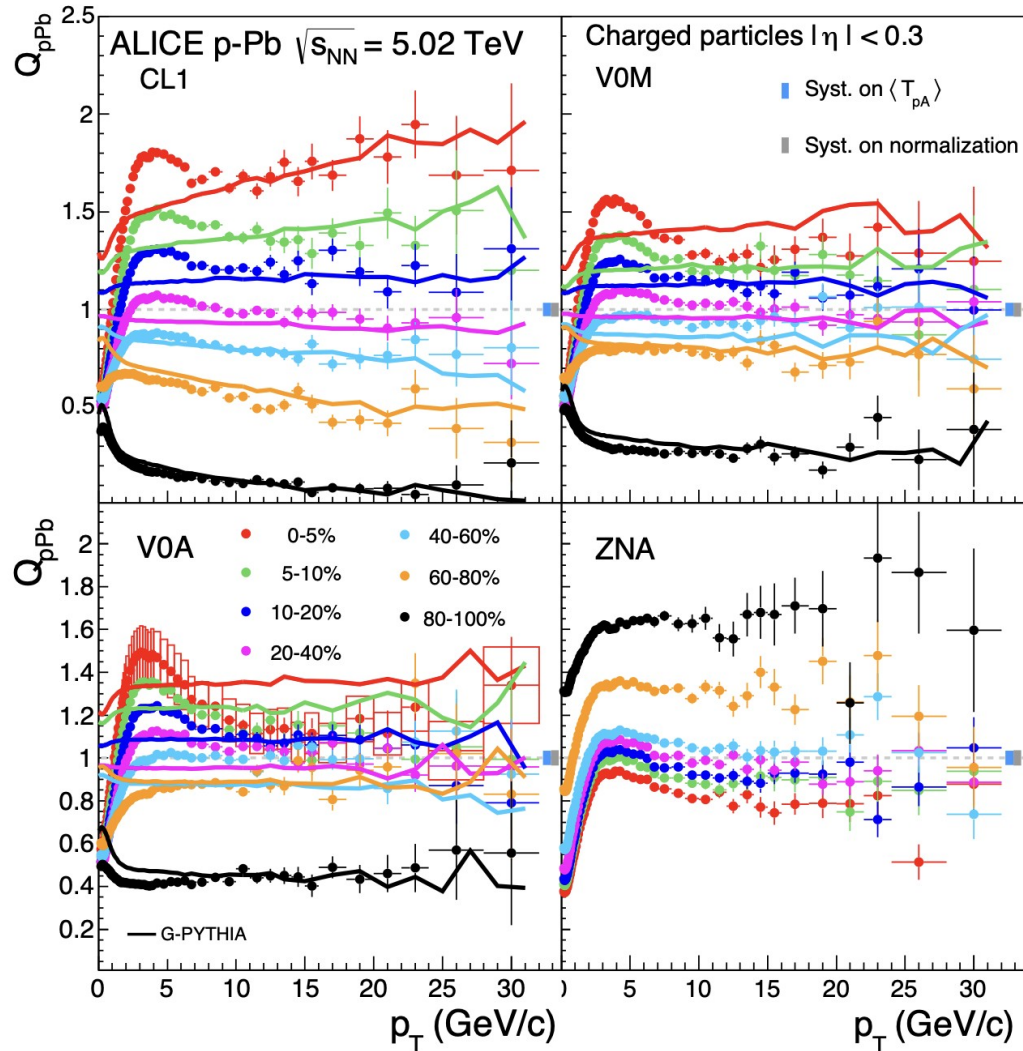
Higher order and **fluctuation** related observables are **very sensitive** to centrality selection and show differences up to 20%

p_T distribution in ultra-central light-ion collisions



From the talk of Tomasz Bold

Mid-rapidity event activity vs. hard observables in p-Pb





Backup



ALICE

O+O and Ne+Ne, $\sqrt{s_{NN}} = 5.36$ TeV · arXiv:2509.06428, with the calibration written out in the Pb–Pb paper arXiv:2504.02505

ESTIMATOR AND EVENT SELECTION

- Centrality from the amplitude measured in FT0-C, $-3.3 < \eta < -2.1$.
- Minimum-bias trigger: at least one hit in both FT0A and FT0C in the nominal time window; vertex within 10 cm of the nominal interaction point.
- Bunch-crossing and pileup rejection cuts applied to optimise the centrality estimation.

GEOMETRY

- $\langle N_{part} \rangle$ obtained from the Glauber model with the same cuts applied to the simulated FT0-C response.
- Pb density: 2pF Woods–Saxon, $R = 6.62 \pm 0.06$ fm, $a = 0.546 \pm 0.010$ fm, $w = 0$; $\sigma_{INEL} = 68.2 \pm 0.6$ mb.

CALIBRATION (PB-PB PAPER)

- Raw FT0-C amplitude fitted with a Glauber model coupled to a two-component model, $N_{sources} = f \cdot N_{part} + (1-f) \cdot N_{coll}$.
- Particles per source from a negative binomial distribution with parameters μ and k ; k fixed to 1.5 by default.
- The fit describes the amplitude over the top 90% of the hadronic cross section.

WHAT THE LIGHT-ION PAPERS DO NOT STATE

- No ^{16}O or ^{20}Ne nuclear density is quoted.
- No numerical $\langle N_{part} \rangle$ values are published for O+O or Ne+Ne; they appear only as a figure abscissa in the proceedings arXiv:2604.07184.

[ALICE — Evidence of nuclear geometry-driven anisotropic flow in OO and Ne–Ne at 5.36 TeV, arXiv:2509.06428](#)

[ALICE — Centrality dependence of \$dN_{ch}/d\eta\$ at midrapidity in Pb–Pb at 5.36 TeV, arXiv:2504.02505](#)

[A. Modak \(ALICE\) — Recent ALICE results from light-ion collision systems, arXiv:2604.07184](#)



CMS

O+O, $\sqrt{s_{NN}} = 5.36$ TeV · arXiv:2606.02285

ESTIMATOR AND EVENT SELECTION

- Centrality from the scalar sum of transverse energy in the HF calorimeters, which extend the coverage to $|\eta| < 5.2$.
- Trigger: HF signal above noise on at least one side, in coincidence with both BPTX detectors.
- Offline: ≥ 2 deposits above 4 GeV in each HF and one vertex within $|v_z| < 15$ cm; events with more than one vertex rejected.
- ~ 2 million events from $\sim 2 \mu\text{b}^{-1}$.

GLAUBER FIT

- Two-component ansatz: soft $\propto N_{\text{part}}$, hard $\propto N_{\text{coll}}$, combined into effective sources and convolved with a gamma distribution.
- The fit is constrained so that the model reproduces the 80% reference point of the data.
- $\sigma_{NN}(\text{inel}) = 68.0 \pm 1.2$ mb, $\omega = 0.3 \pm 0.3$.

NORMALISATION

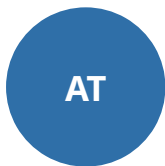
- Selection inefficiency corrected in bins of tracklet multiplicity using HIJING 1.383.
- Diffractive and non-hadronic contributions estimated with EPOS LHC and STARLIGHT+DPMJET and subtracted in bins of E_T and tracklet multiplicity.
- The corrected E_T spectrum is divided into percentiles, anchored at the E_T value corresponding to 80% of the hadronic cross section, where the efficiency is unity and EM contamination negligible. The anchor position is known to $\sim 10\%$.

UNCERTAINTIES AND OUTPUT

- $\langle N_{\text{part}} \rangle$ uncertainty from the spread of available oxygen density profiles and from varying the fit range between 60% and 94%.
- $\langle N_{\text{part}} \rangle$ published in 5%-wide intervals over 0–70%, plus the 0–100% value (10.9 ± 0.4).
- Centrality-calibration systematic on $dN_{\text{ch}}/d\eta$: 0.5–8%, dominant in peripheral collisions.

[CMS — Centrality dependence of charged-hadron pseudorapidity distributions in OO at 5.36 TeV, arXiv:2606.02285](#)

[C. Loizides, J. Kamin, D. d'Enterria — Improved Monte Carlo Glauber predictions, arXiv:1710.07098](#)



ESTIMATOR AND EVENT SELECTION

- Events categorised into centrality percentiles from $\Sigma E_{\text{T}}^{\text{FCal}}$, the transverse energy in the forward calorimeters, $3.2 < |\eta| < 4.9$.
- Primary vertex within 10 cm of the centre of ATLAS.
- Inclusive photonuclear (γ +A) background rejected by requiring at least one topocluster with $p_{\text{T}} > 400 \text{ MeV}$ within the acceptance of each FCal.
- Pileup suppressed by requiring exactly one high-quality vertex and by the FCal-ZDC correlation.

EFFECT OF THE CLUSTERED DENSITIES

- Relative to the earlier ATLAS flow measurement, the $\Sigma E_{\text{T}}^{\text{FCal}}$ values at the centrality-interval boundaries changed by less than 1% in the most central collisions and by as much as 5% in the most peripheral.

GLAUBER FIT

- A Glauber fit gives the fraction of events above a minimum $\Sigma E_{\text{T}}^{\text{FCal}}$ threshold and its systematic uncertainty, and $\langle N_{\text{part}} \rangle$ per centrality interval.
- Nucleon densities from the PGCM and NLEFT initial-state models as implemented in Trajectum (TR_OXYGEN_V15, TR_NEON_V14, $\omega = 0.3$), explicitly accounting for α -particle clustering in ^{16}O and ^{20}Ne .
- The paper names neither the production model nor the kernel; ATLAS states in the Feb 2026 comments a two-component picture with a gamma function, and no Trento.

OUTPUT AND UNCERTAINTIES

- Results in 5%-wide intervals over 5–80% and 1%-wide intervals over 0–5%; $\langle N_{\text{part}} \rangle$ tabulated in the Appendix.
- The centrality-definition uncertainty is evaluated by repeating the analysis with alternative thresholds; smallest centrally, growing monotonically towards peripheral.



LHCb

O+O and Ne+Ne in collider mode, plus the SMOG2 fixed-target programme · no light-ion publication yet

ESTIMATOR

- Total ECAL energy, $2 < \eta < 4.36$ — a neutral energy estimator, kept from Run 2 for continuity.
- Single-arm forward spectrometer; in fixed-target mode the same detector covers roughly $-2.5 < \eta_{\text{cms}} < 0.5$.

RESOLUTION

- $\sigma(N_{\text{coll}})/\langle N_{\text{coll}} \rangle \approx 50\%$ in the 100–90% class and $\approx 15\%$ in the 10–0% class for fixed-target PbNe — the only quantitative statement of centrality resolution in the set.

CALIBRATION

- $N_{\text{anc}} = f \cdot N_{\text{part}} + (1-f) \cdot N_{\text{coll}}$ followed by NBD sampling, with k fixed to 1.5.
- TGlauberMC v3.2 moving to v3.3; the fit is restricted to the range where electromagnetic contamination stays below 5%.

RUN 3

- The upgraded VELO gives a segmented acceptance, which would allow the probe–estimator correlation to be measured rather than assumed.
- Centrality uncertainties for Run 3 are still being determined.

Sources

Light-ion papers

[ALICE — flow in OO and Ne-Ne, arXiv:2509.06428](#)

[ALICE \(Modak\) — light-ion results, arXiv:2604.07184](#)

[CMS — \$dN_{ch}/d\eta\$ in OO, arXiv:2606.02285](#)

[ATLAS — \$dn/d\eta\$ and \$\langle p_T \rangle\$ in O+O, Ne+Ne, arXiv:2606.20257](#)

Reference and meetings

[ALICE — \$dN_{ch}/d\eta\$ in Pb-Pb, arXiv:2504.02505](#)

[Loizides, Kamin, d'Enterria — MC Glauber, arXiv:1710.07098](#)

[LPCC HI WG — Centrality in light ions, 5 Feb 2026](#)

[Light-ion collisions at the LHC workshop, Dec 2025](#)

Tables and backup slides use the published papers; the LHCb slide uses the 5 February 2026 LPCC presentation.