Probing Quark-Gluon Plasma in Light-Ion Collisions with ATLAS

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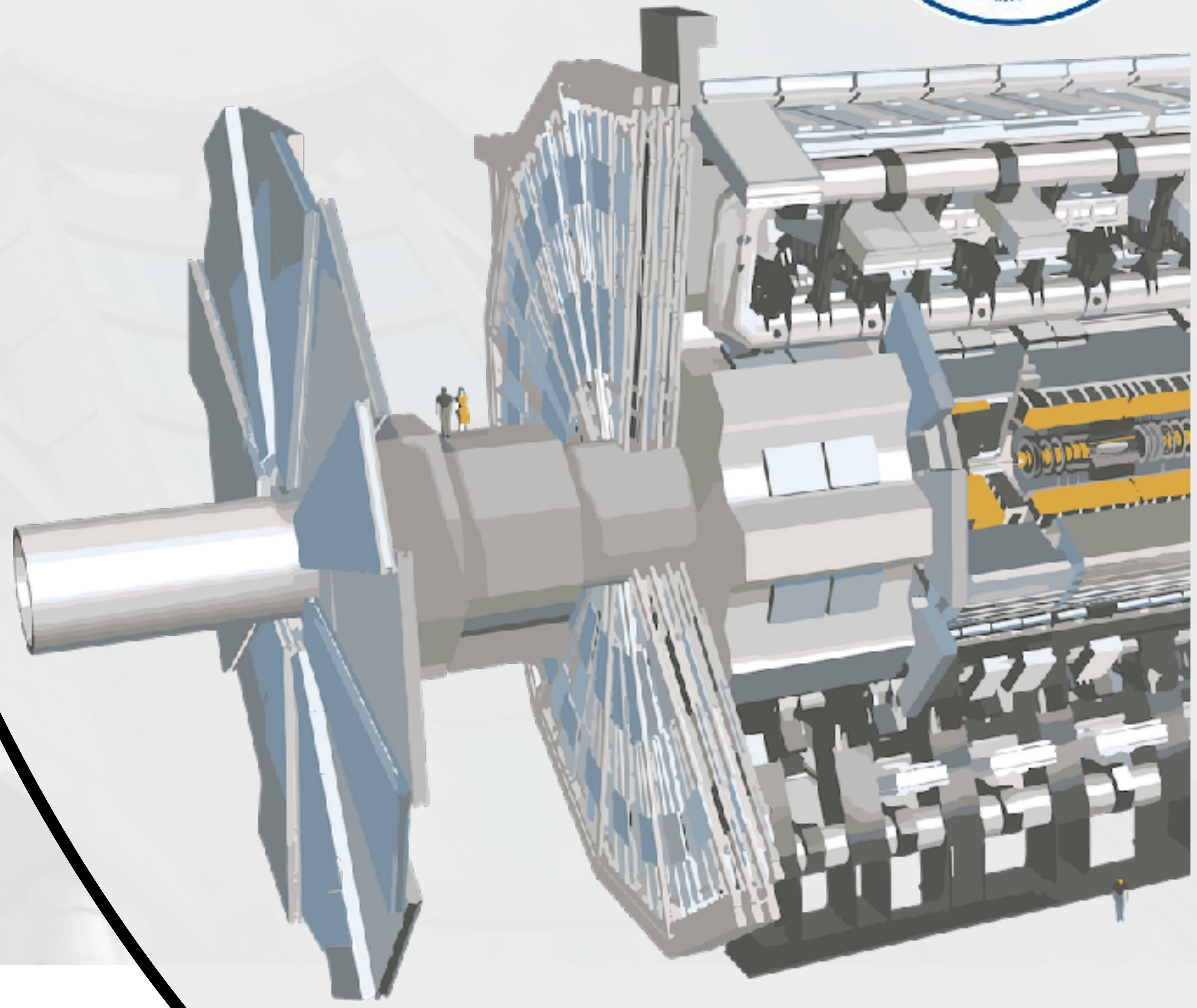
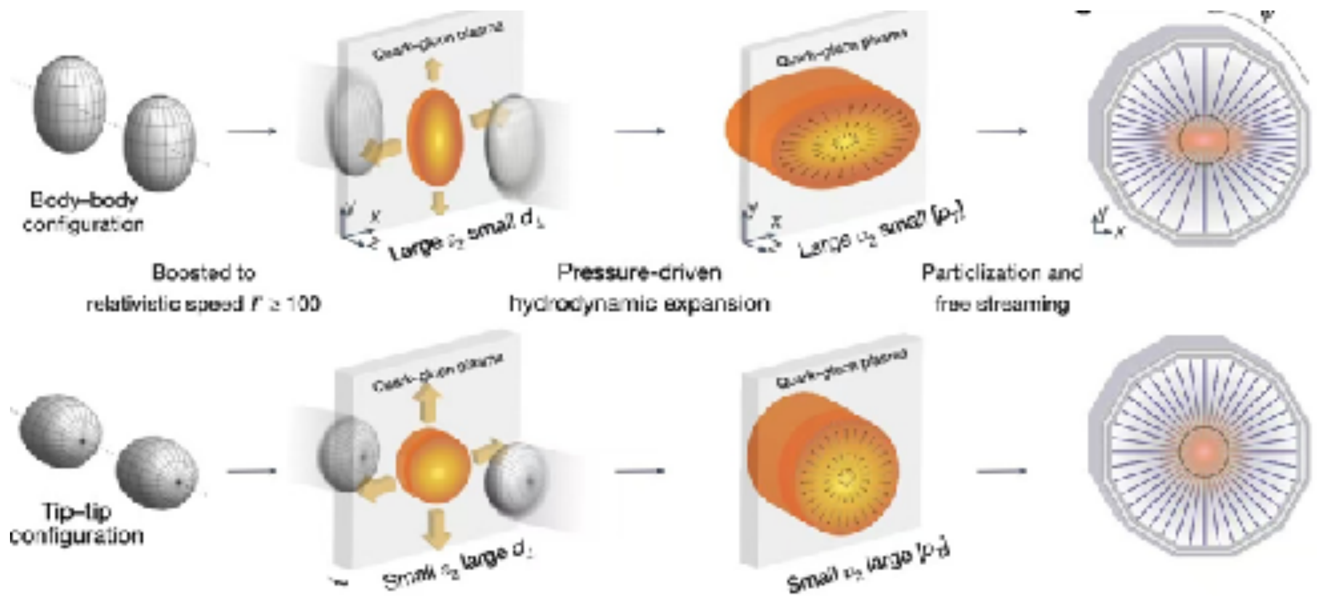
September 20, Wuhan





跨能标核物理眼前学术研讨会

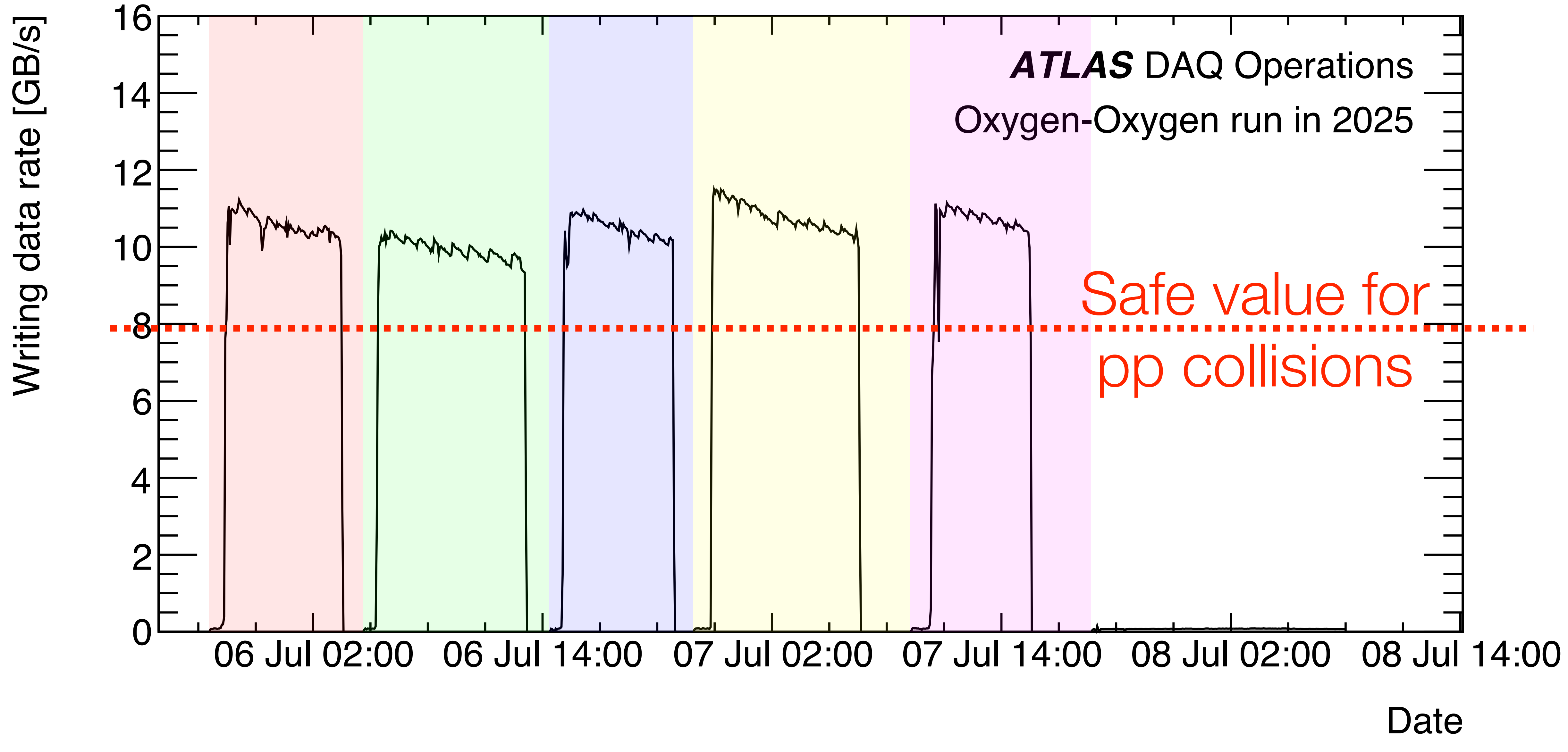
Nuclear Physics Across Energy Scales

2025 LHC light ion run preparation

Thanks to the dedicated efforts of the CERN TH and LHC Injector teams, O+O and Ne+Ne collisions were placed on CERN management's agenda after Light Ion workshop

Intensive experimental preparations began in spring 2025

- Worked hard to convince the HEP community that ~0.5 nb^{-1} of O+O data would yield impactful physics
- Spent weeks anticipating "what if" scenarios and planning for possible challenges
- Insisted the choice of 5.36 TeV to match with pp
- Delivered prompt estimates of impact of beam transmutation
- ……

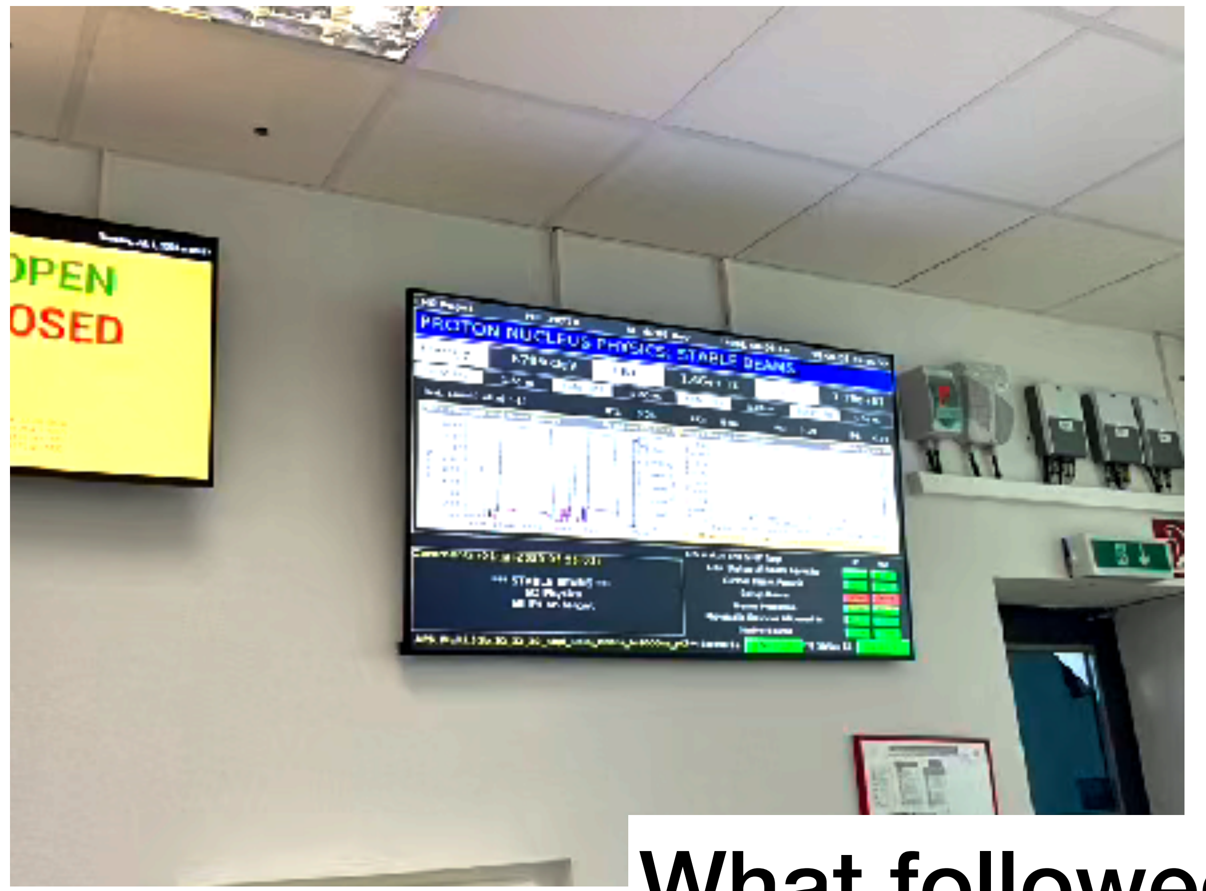


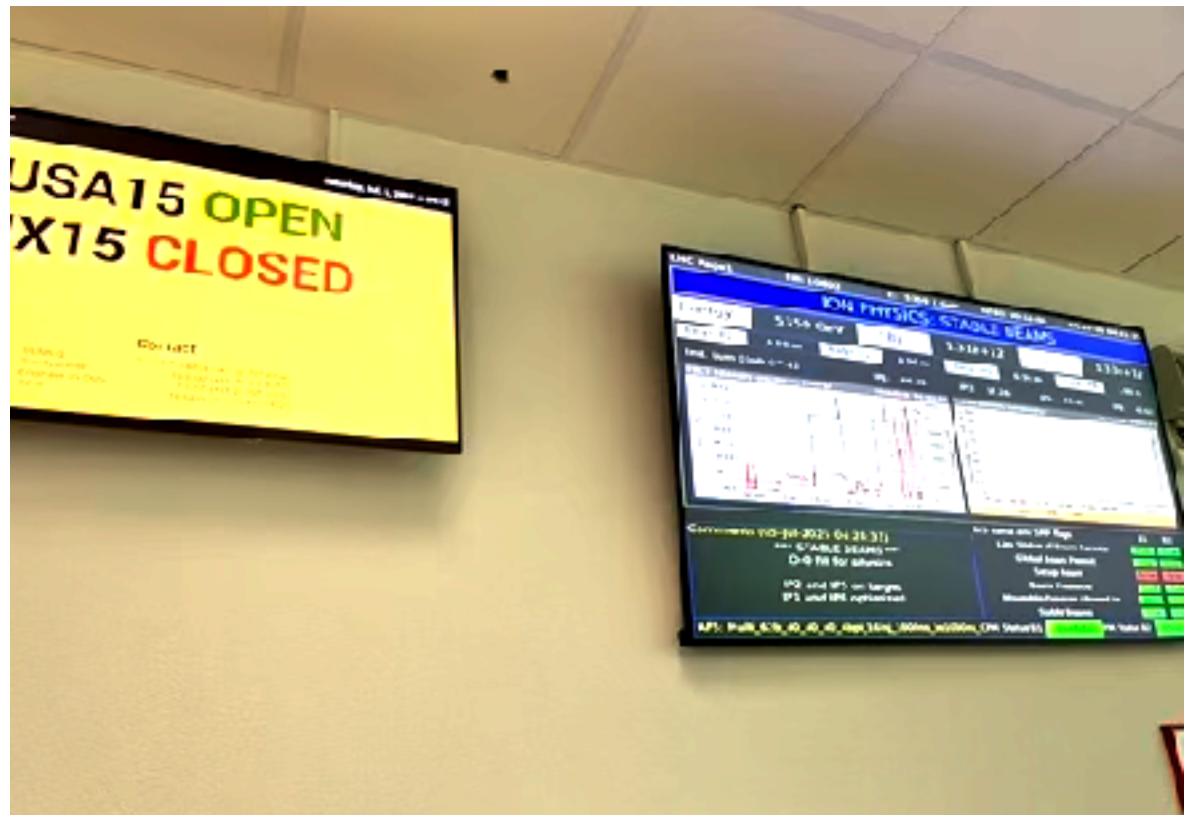
Most complicated runs I ever experienced

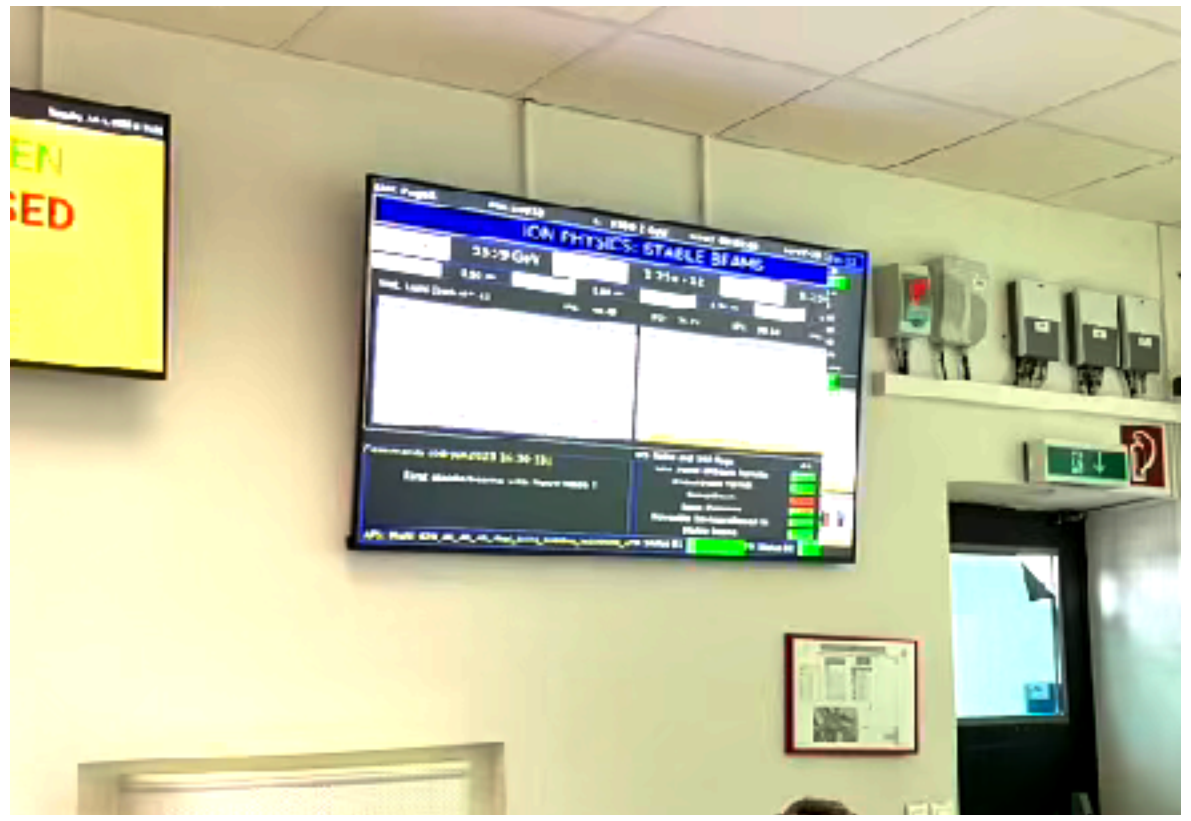
First stable p+O: ~5:50 am

First stable O+O: ~4:20 am

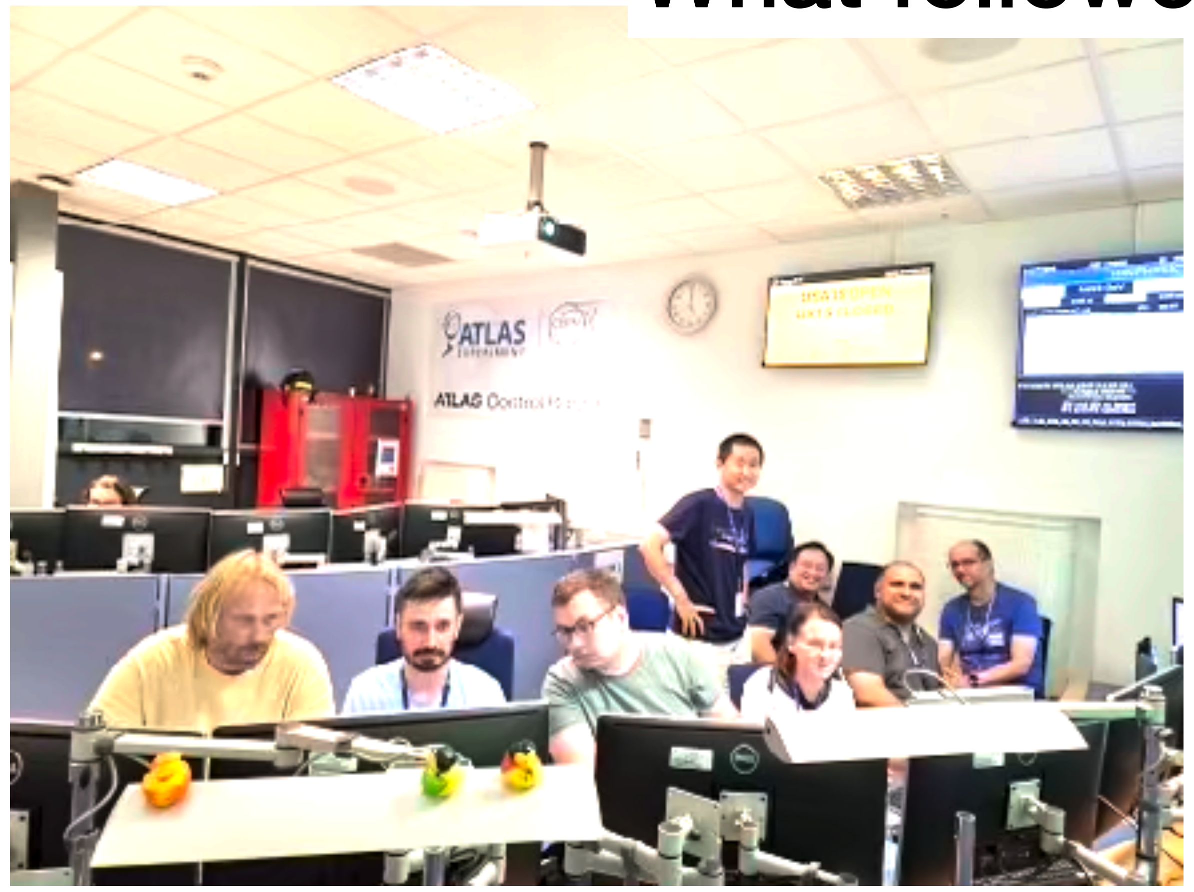
First stable Ne+Ne: ~4:20 pm

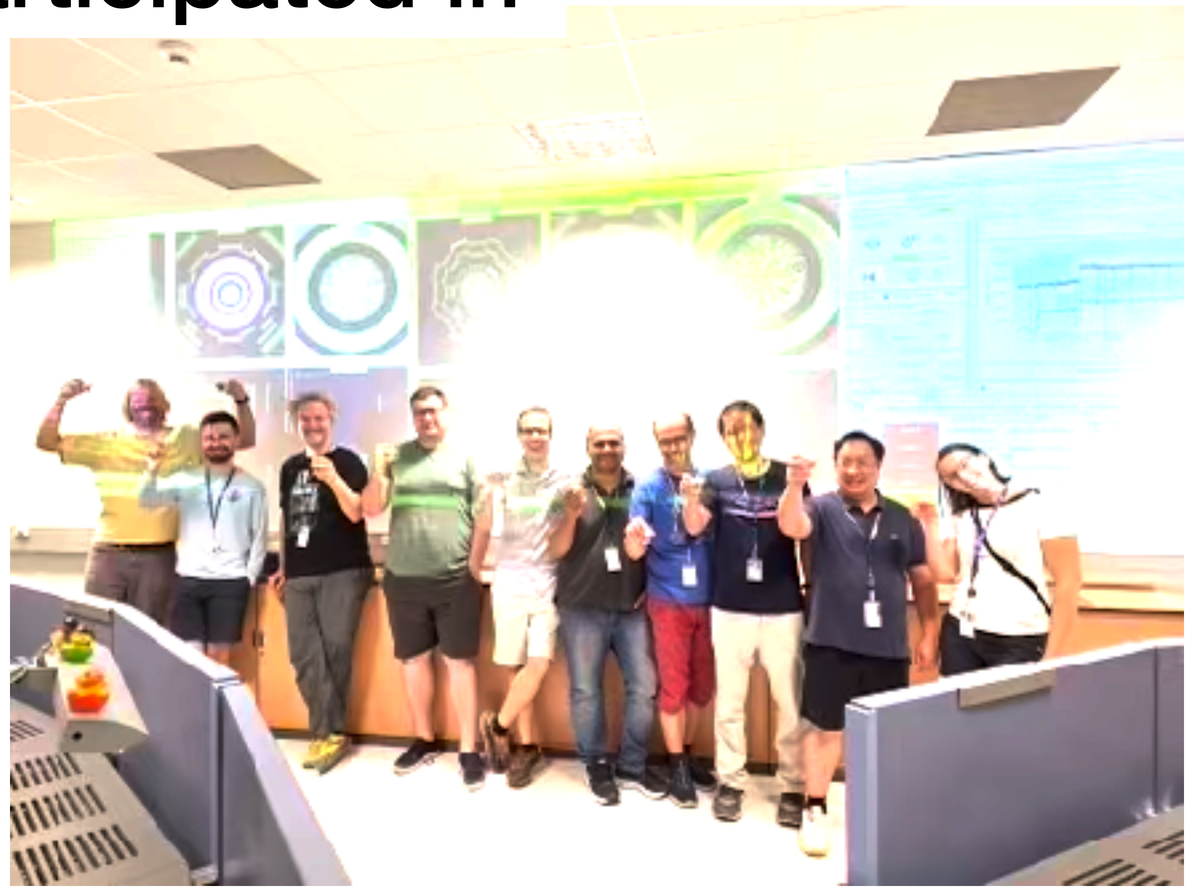




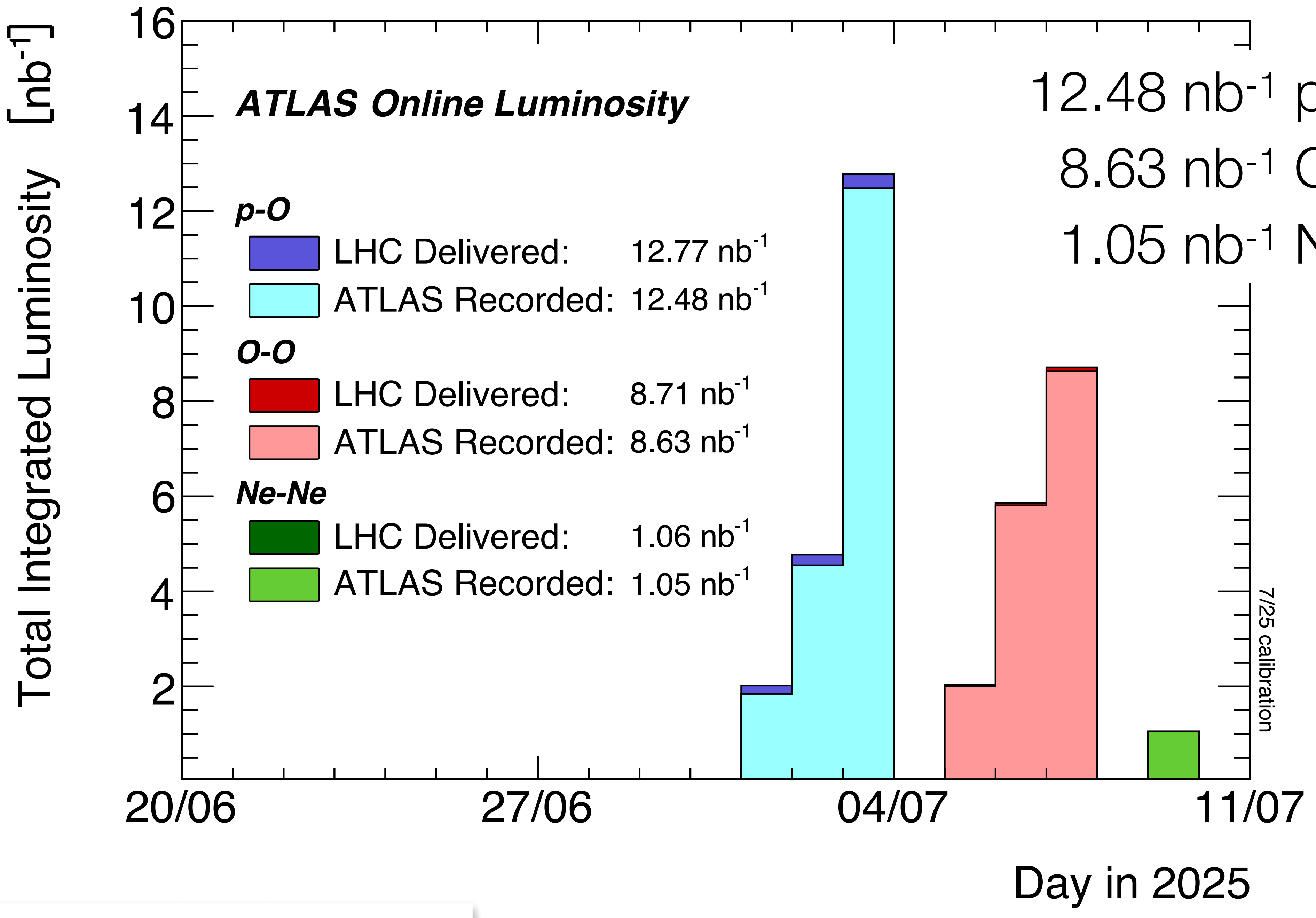


What followed was the most intricate heavy-ion operation I had ever participated in





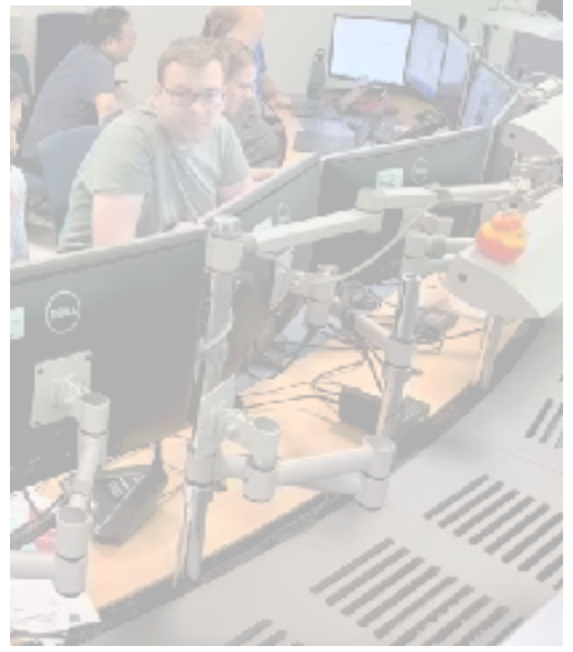
Best runs I ever experienced



$12.48\ nb^{-1}$ p+O data

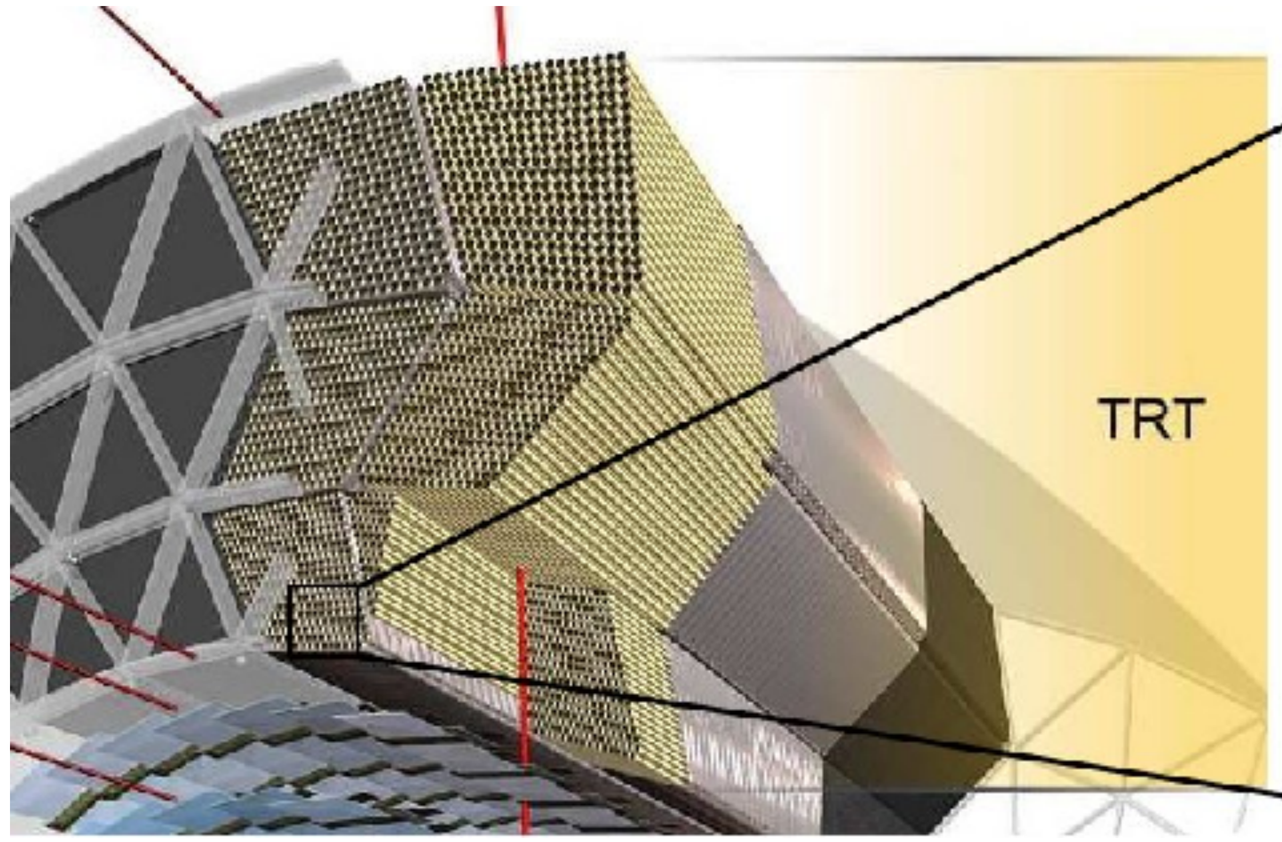
$8.63\ nb^{-1}$ O+O data

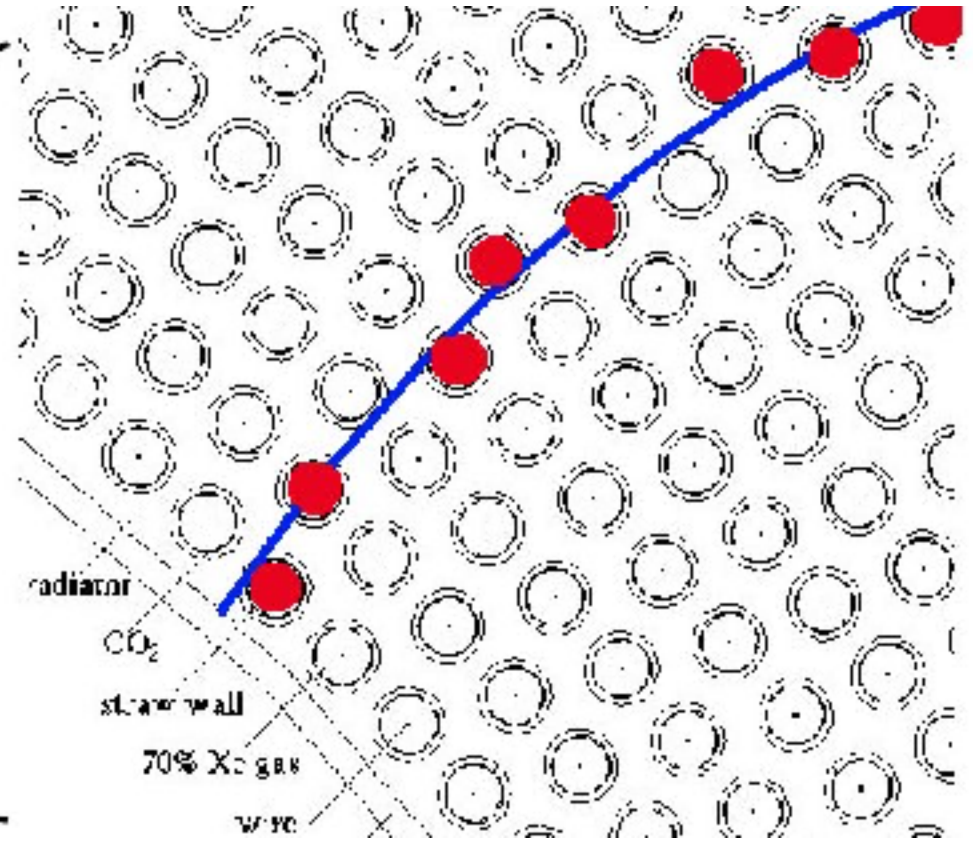
$1.05\ nb^{-1}$ Ne+Ne data

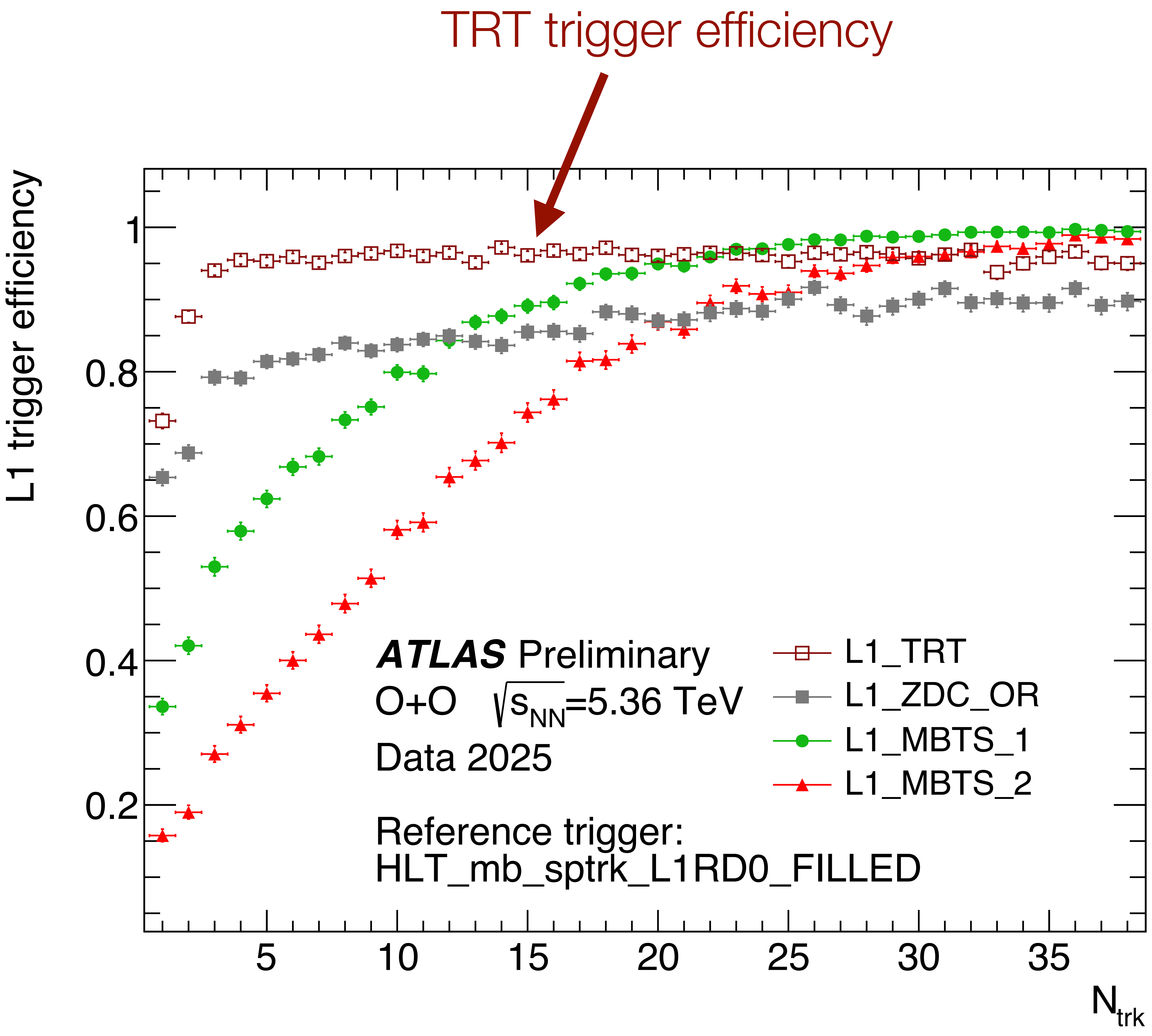


- **Excellent machine performance throughout the run**
- **High detector availability and reliability**
- **Grateful to the many colleagues who worked tirelessly, often overnight**

ATLAS trigger strategy



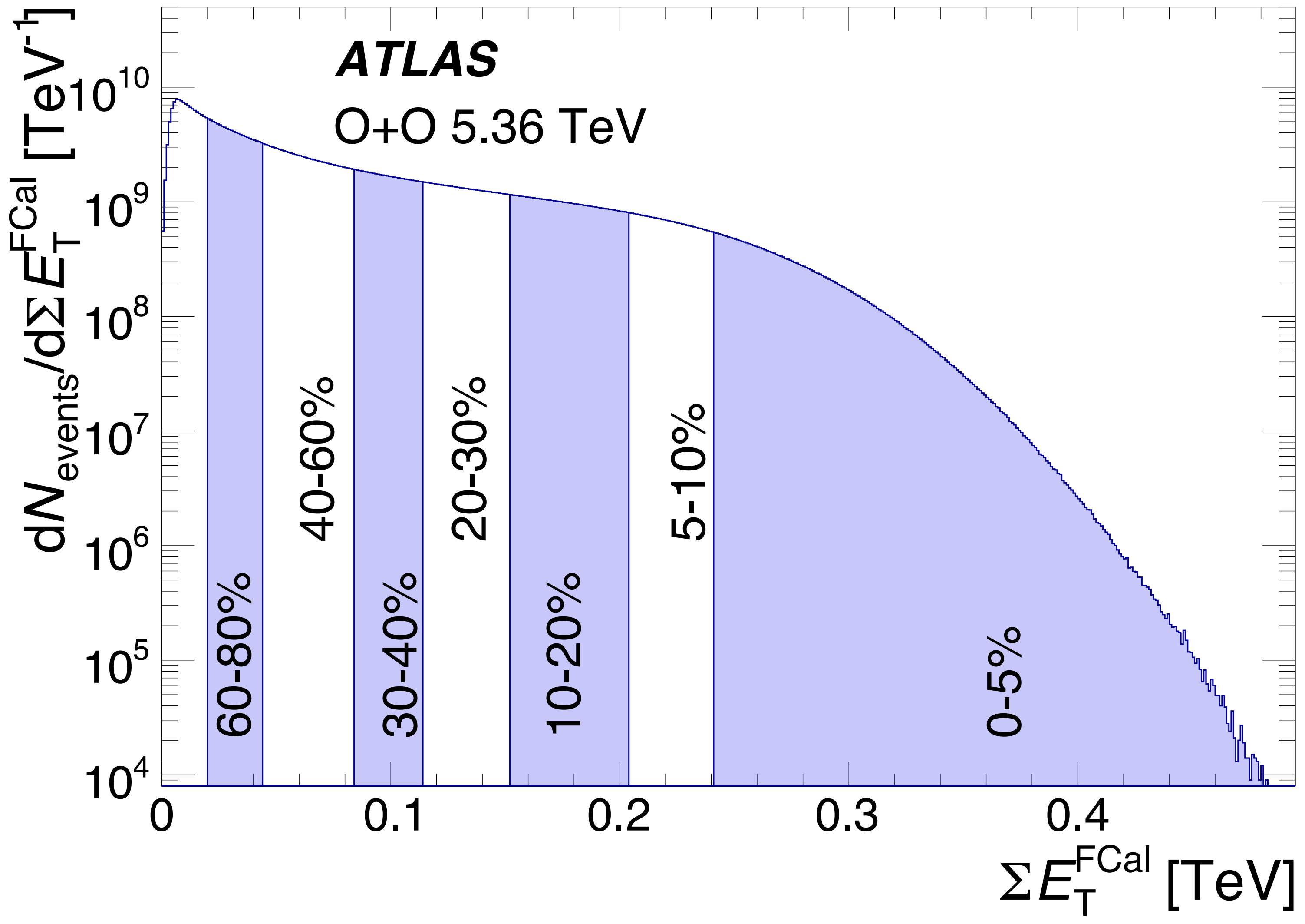




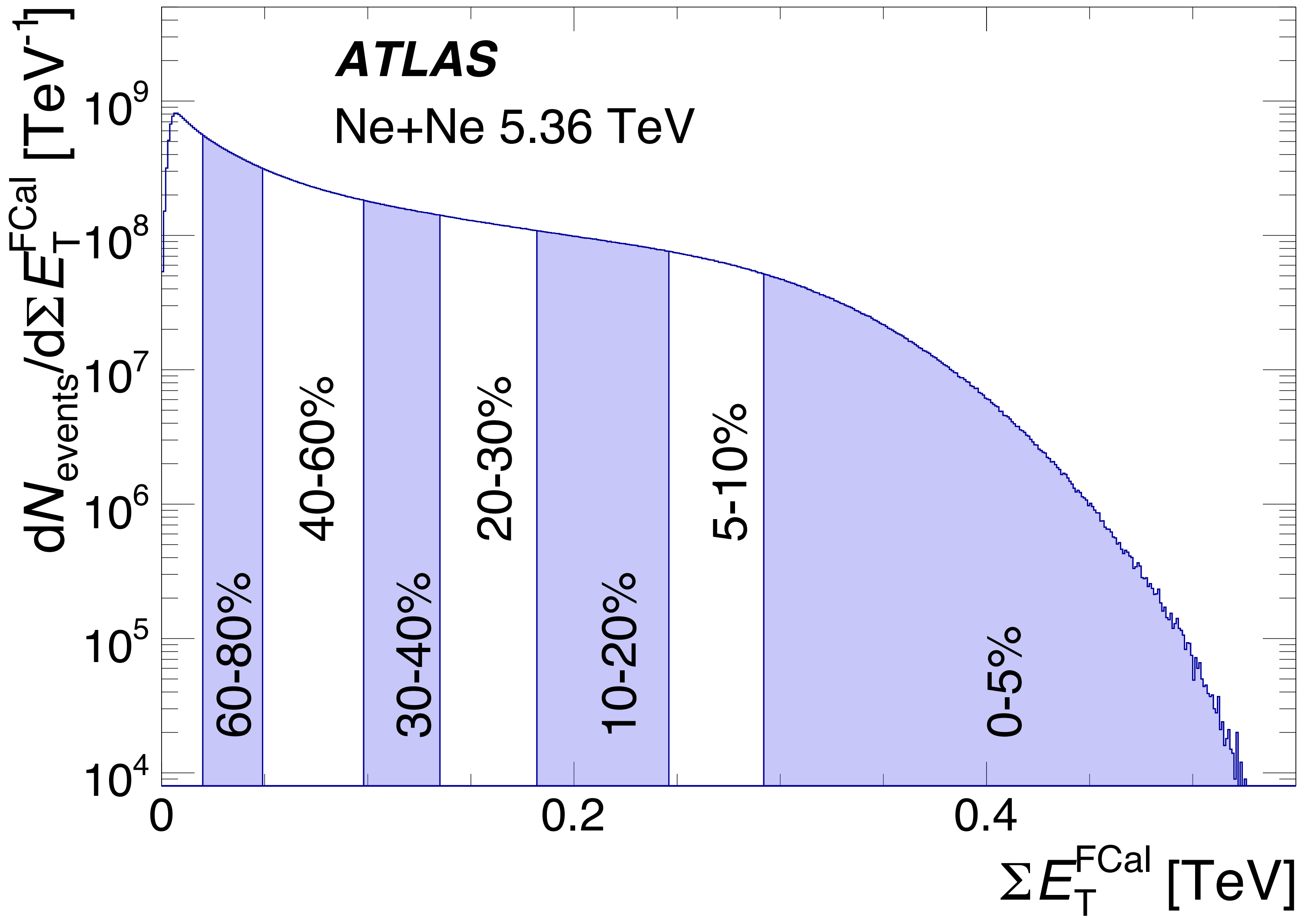
- Minimum-bias event triggering with TRT
- Unbiased down to very low multiplicities
- Significantly better performance than other ATLAS minimum-bias triggers (MBTS, ZDC, etc.)

O+O and Ne+Ne Centrality

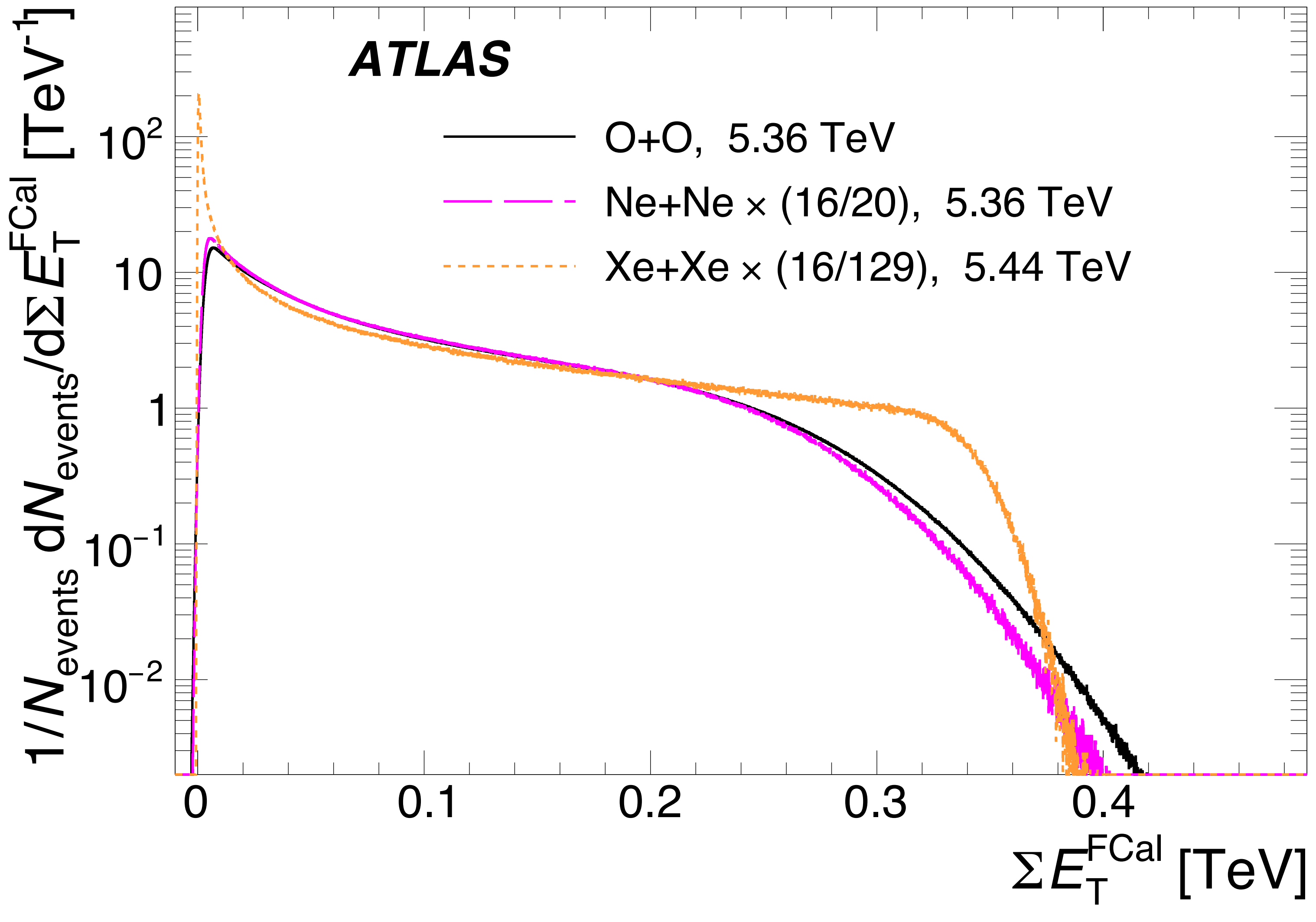
O+O



Ne+Ne



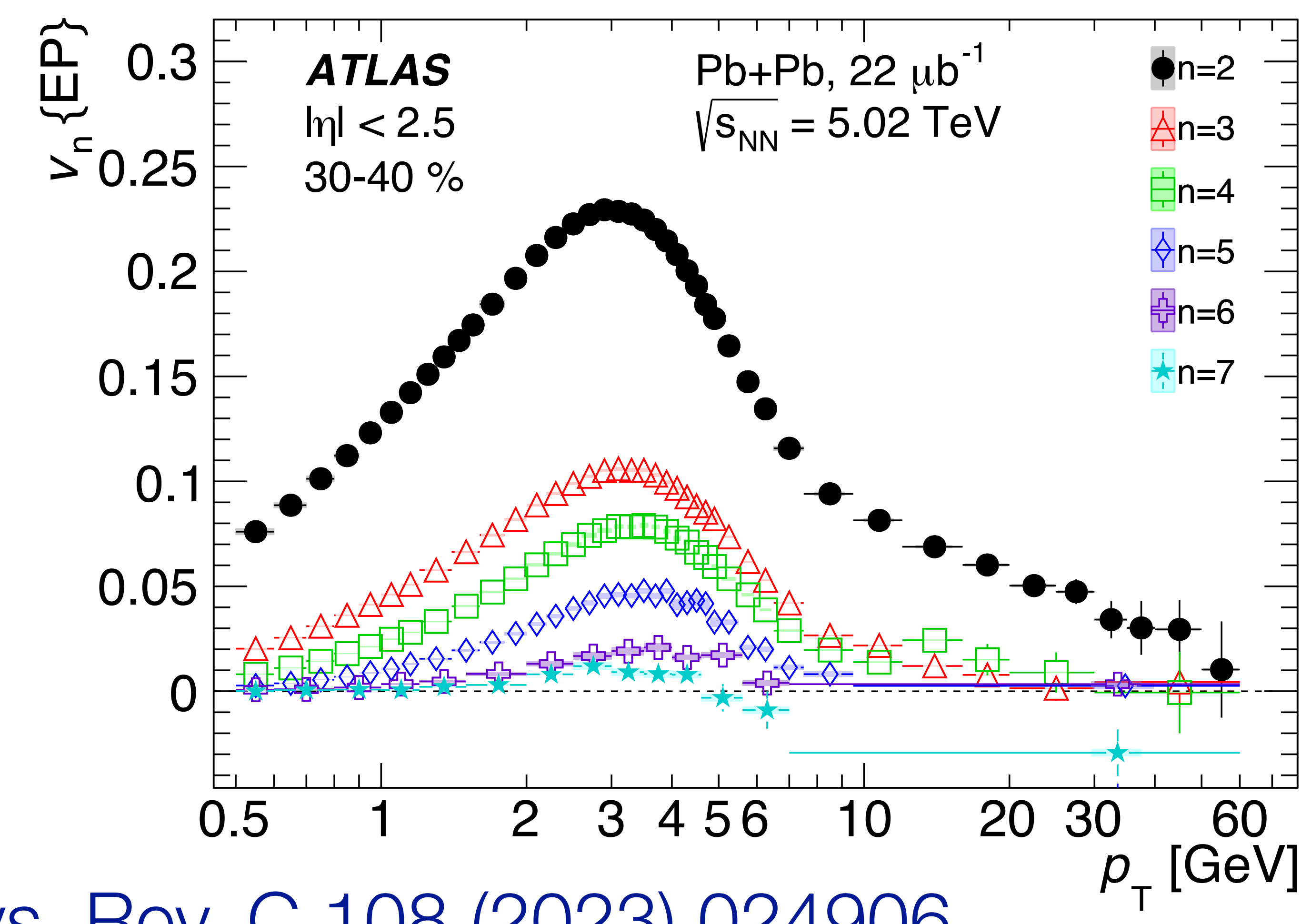
"A-scaled" light ion vs heavy ion



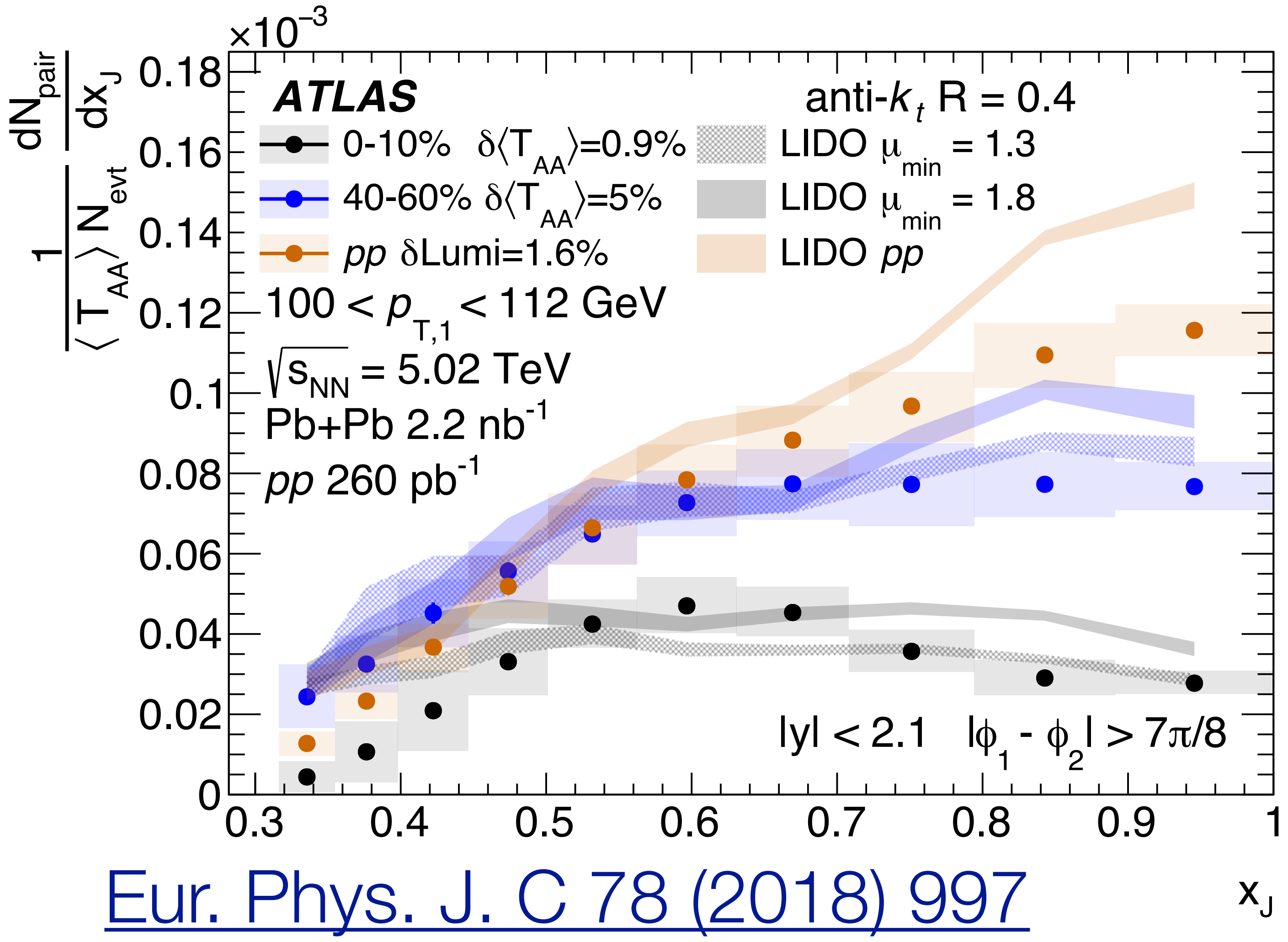
- Centrality from Forward Calorimeter energy sum (0–80%)
- Glauber analysis with improved light-ion geometry and fluctuations (Loizides, arXiv:2507.05853)
- Event-by-event fluctuations play a larger role in light-ion collisions in most central collisions (long tails)

Why light ions at LHC — QGP physics

Heavy Ions:
Pb+Pb, Xe+Xe



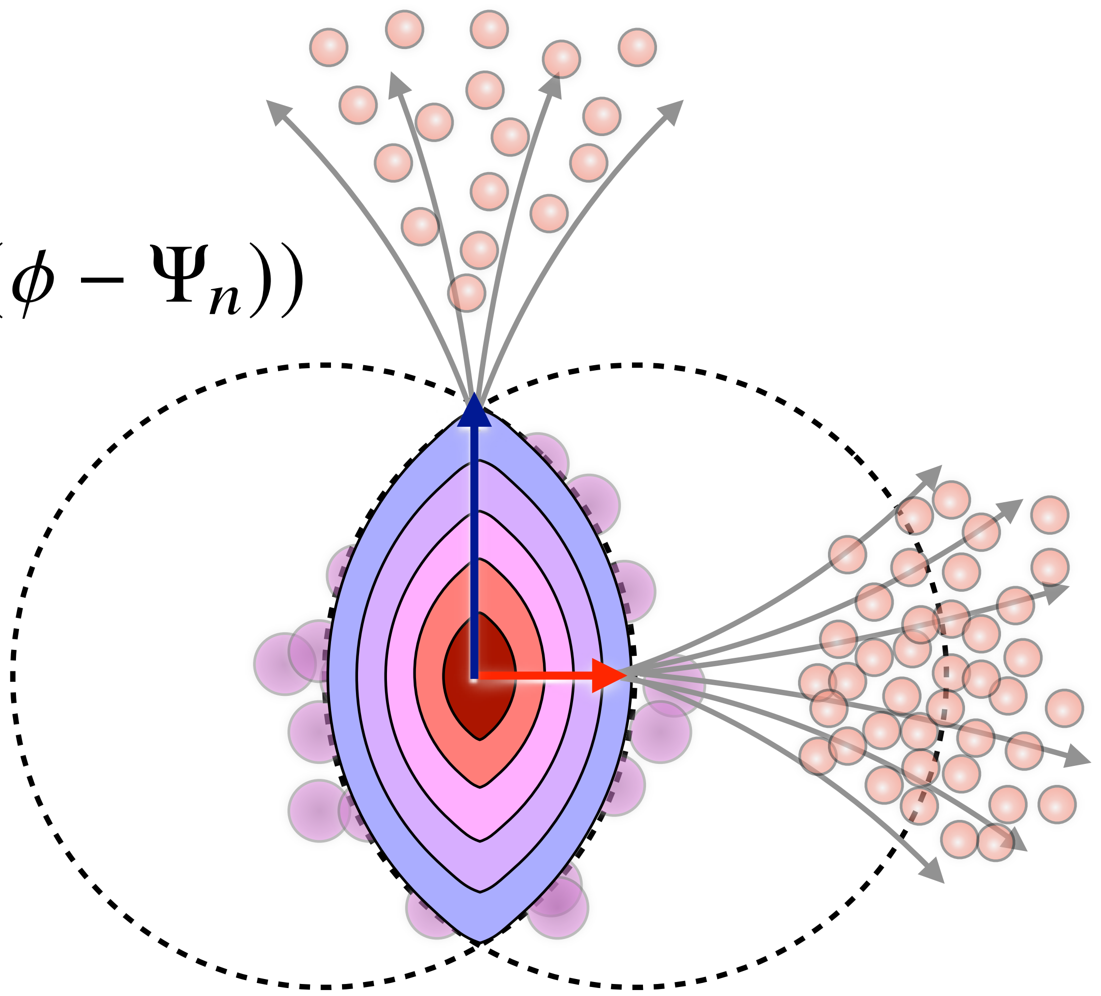
Phys. Rev. C 108 (2023) 024906

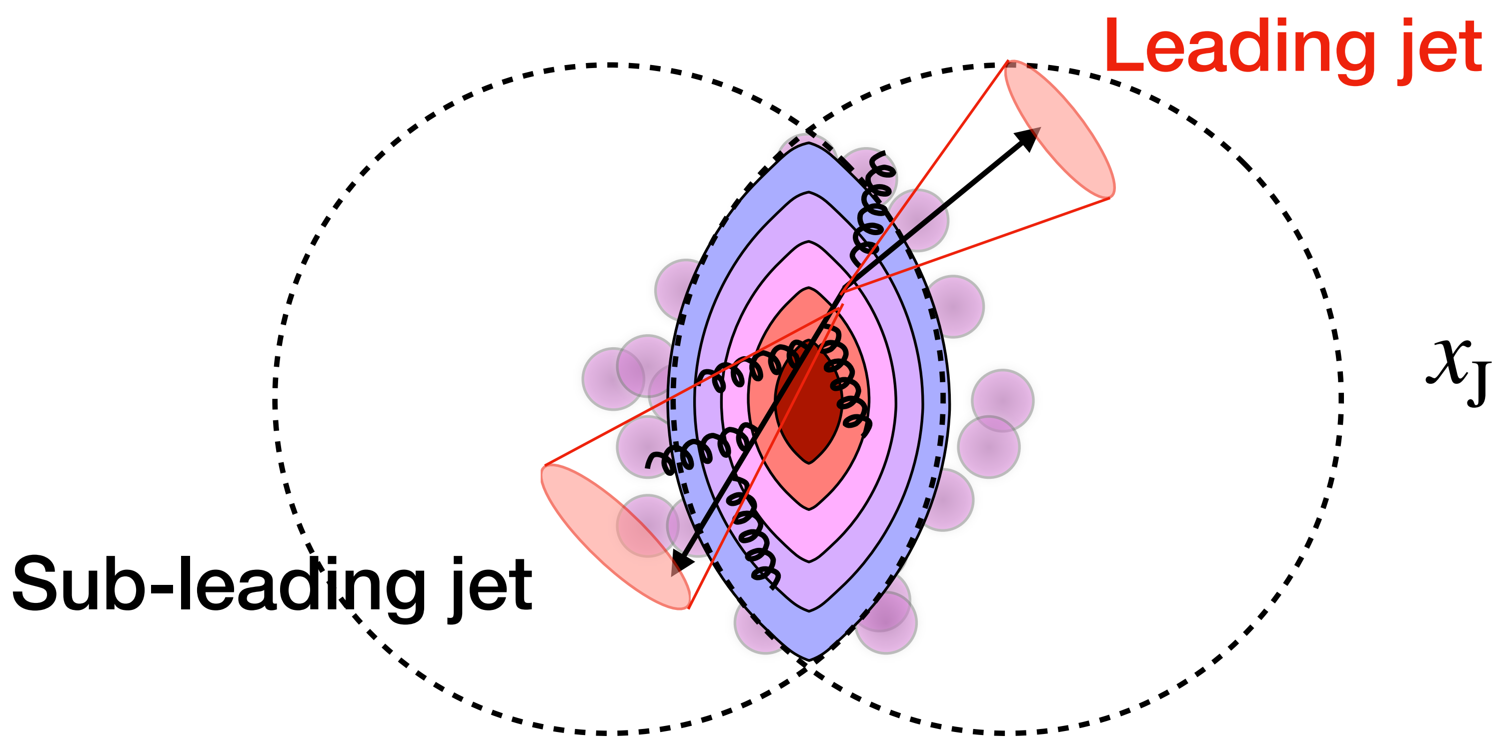


Eur. Phys. J. C 78 (2018) 997

Two key signatures of the QGP: azimuthal anisotropy and jet quenching

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

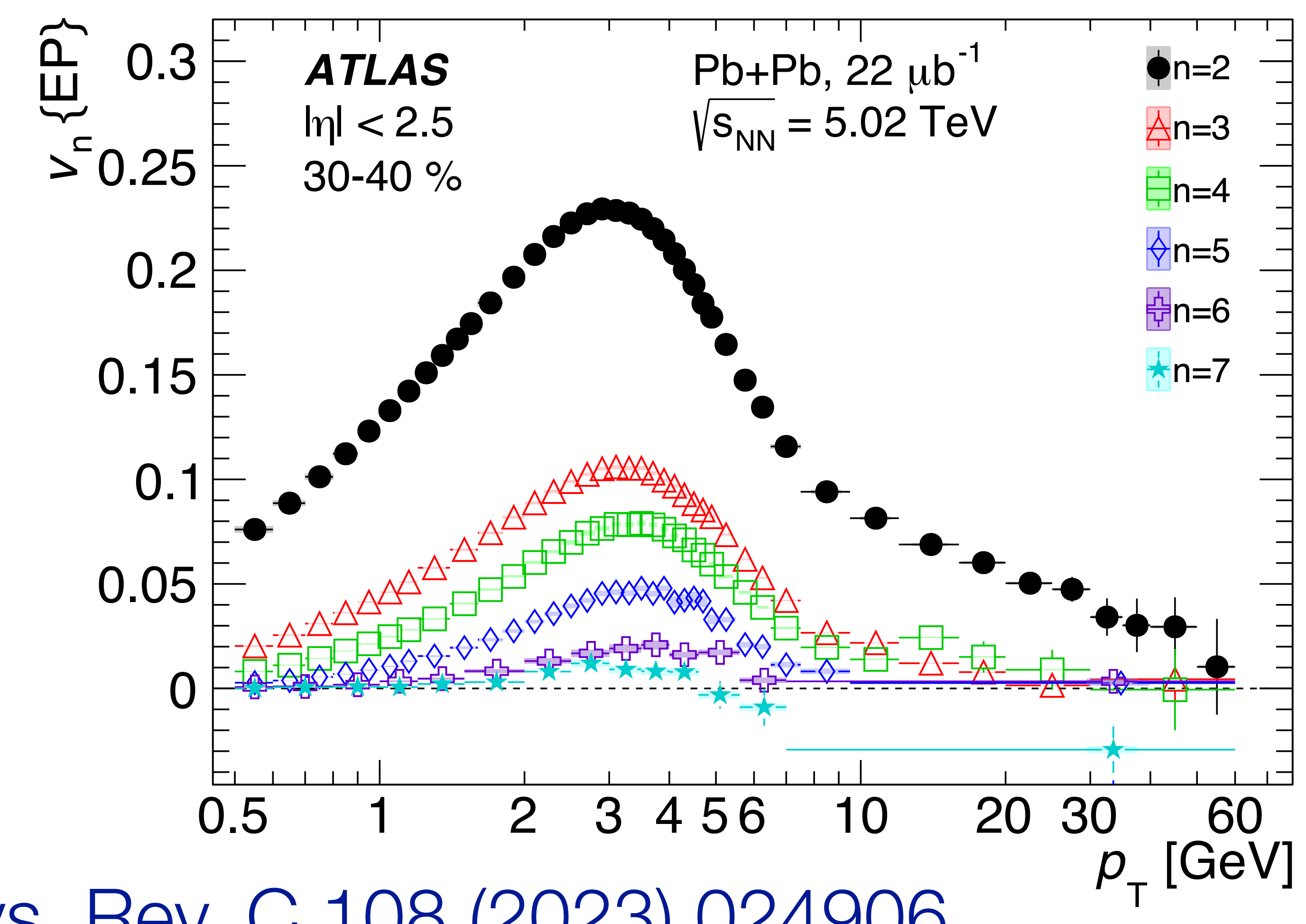




$$x_J = \frac{p_T^{\text{subleading}}}{p_T^{\text{leading}}}$$

Why light ions at LHC — QGP physics

Heavy Ions:
Pb+Pb, Xe+Xe



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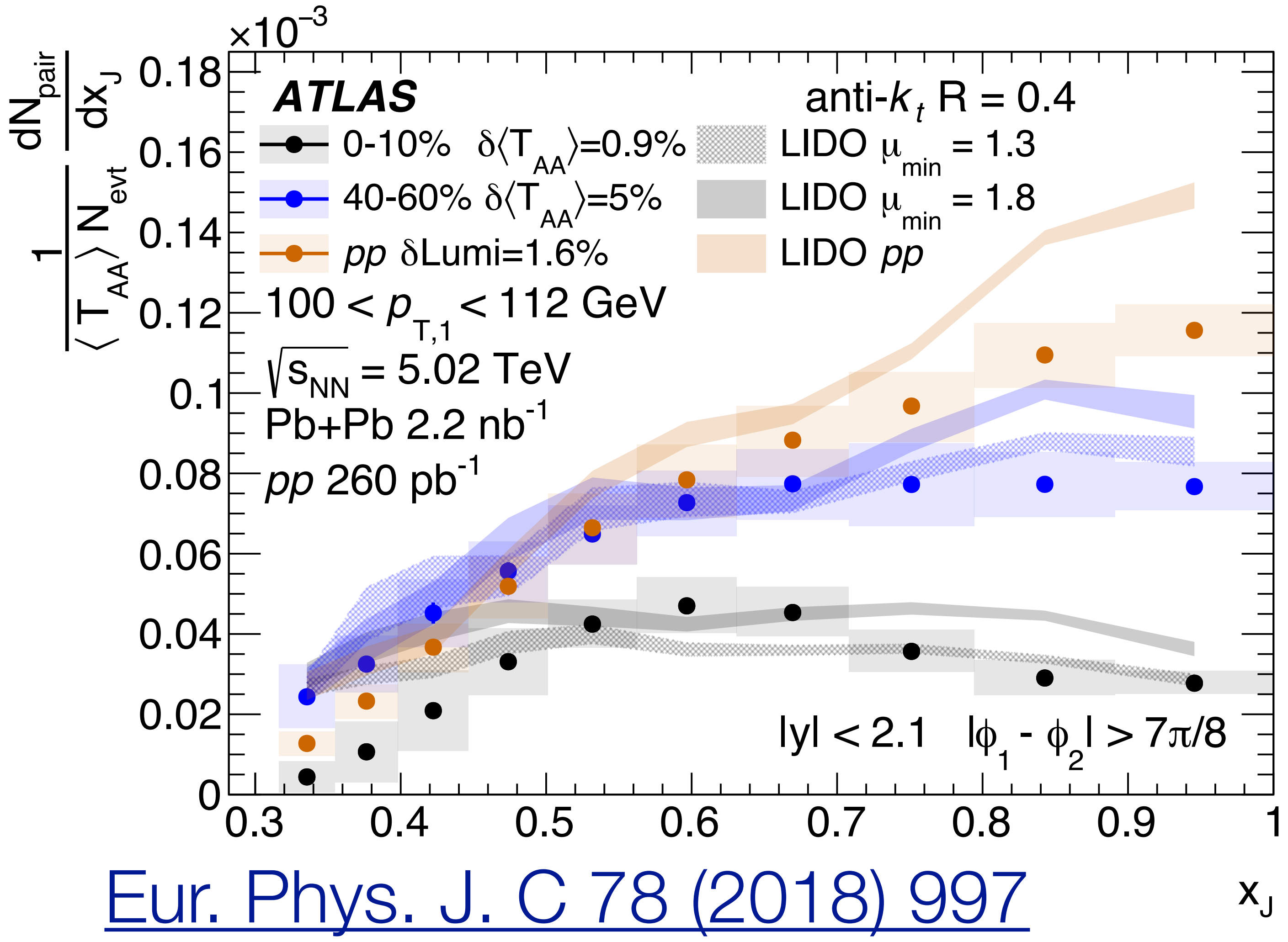

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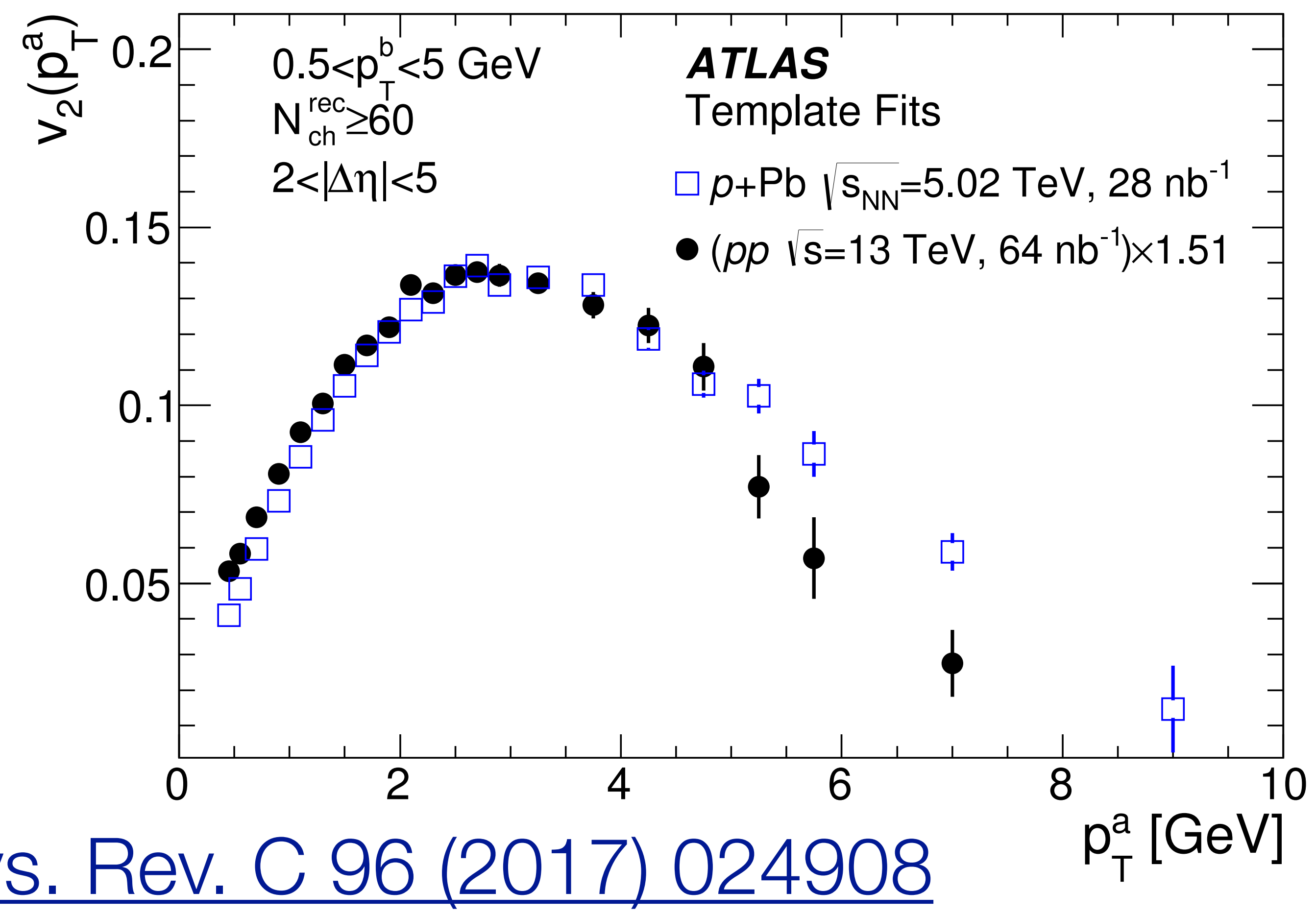
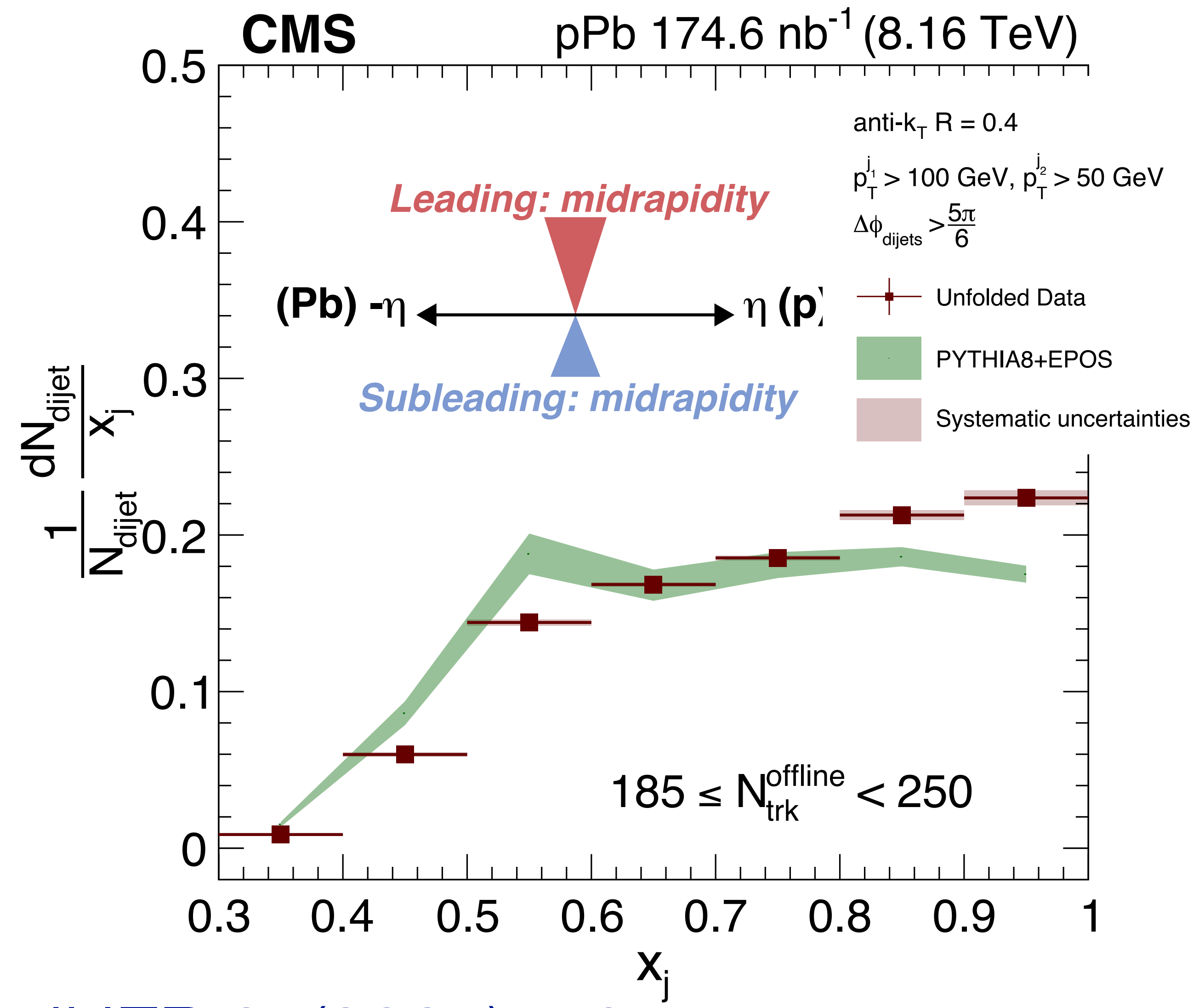
Small system:
p+Pb, p+p



Phys. Rev. C 96 (2017) 024908

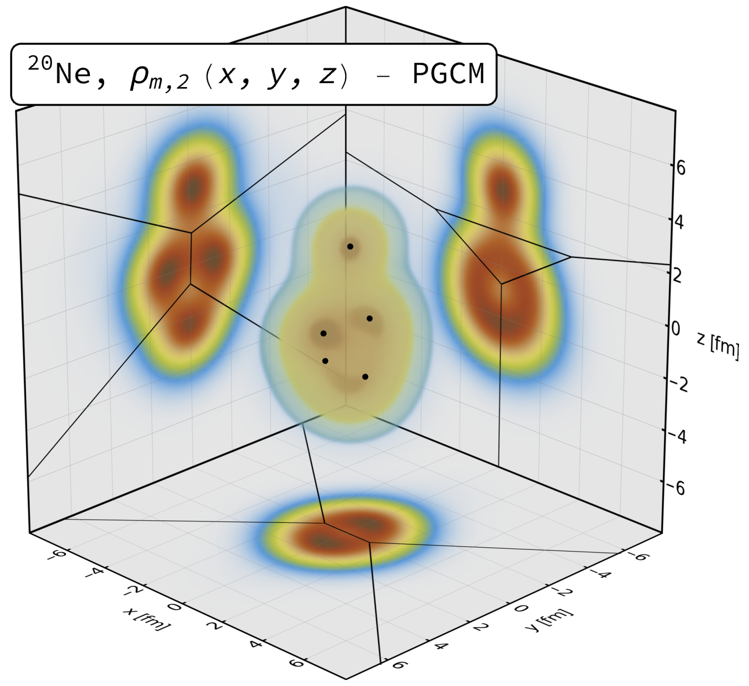


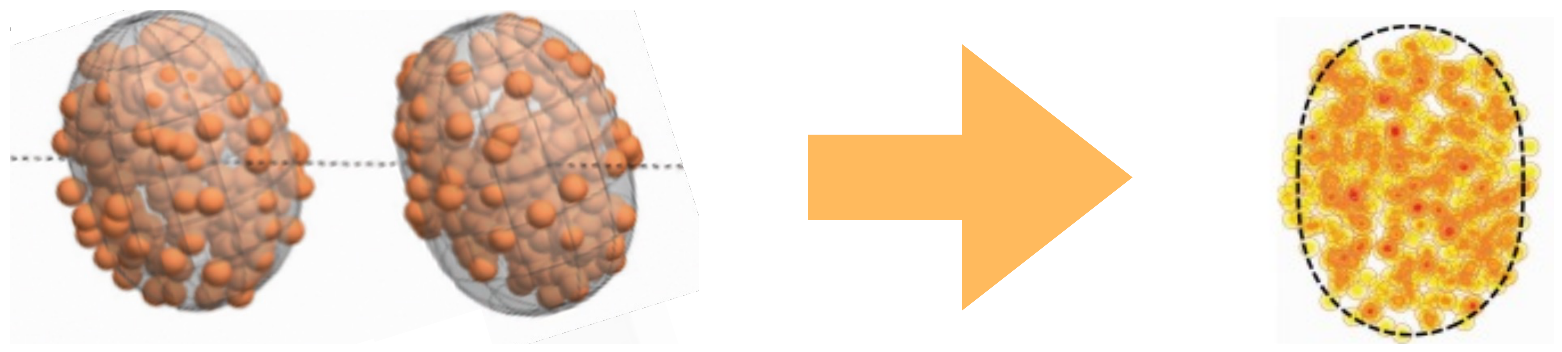
JHEP 07(2025)118

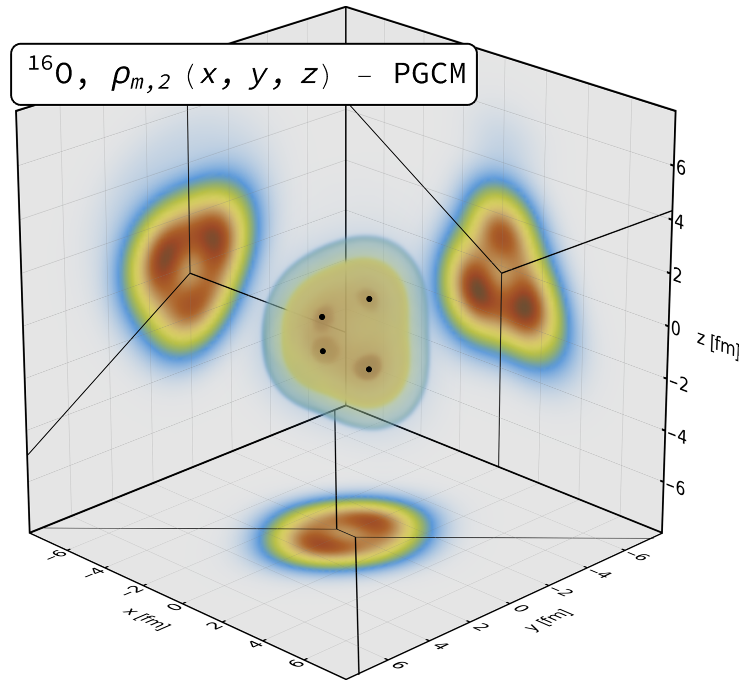
- p+Pb remains inconclusive for QGP formation, with no evidence of jet quenching
- Light-ion collisions offer new opportunities to gain insight
- Help explore the boundary conditions for QGP formation

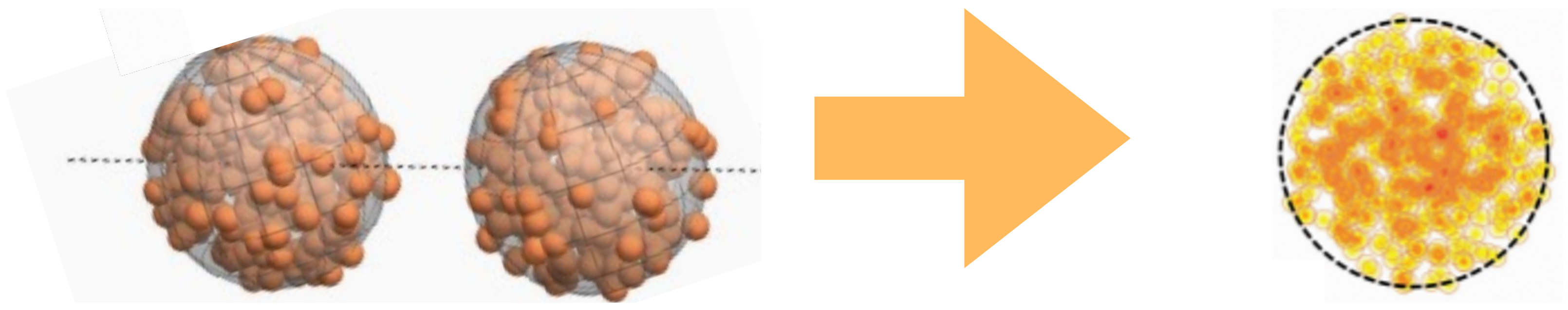
Why light ions at LHC — Probing nuclear structure

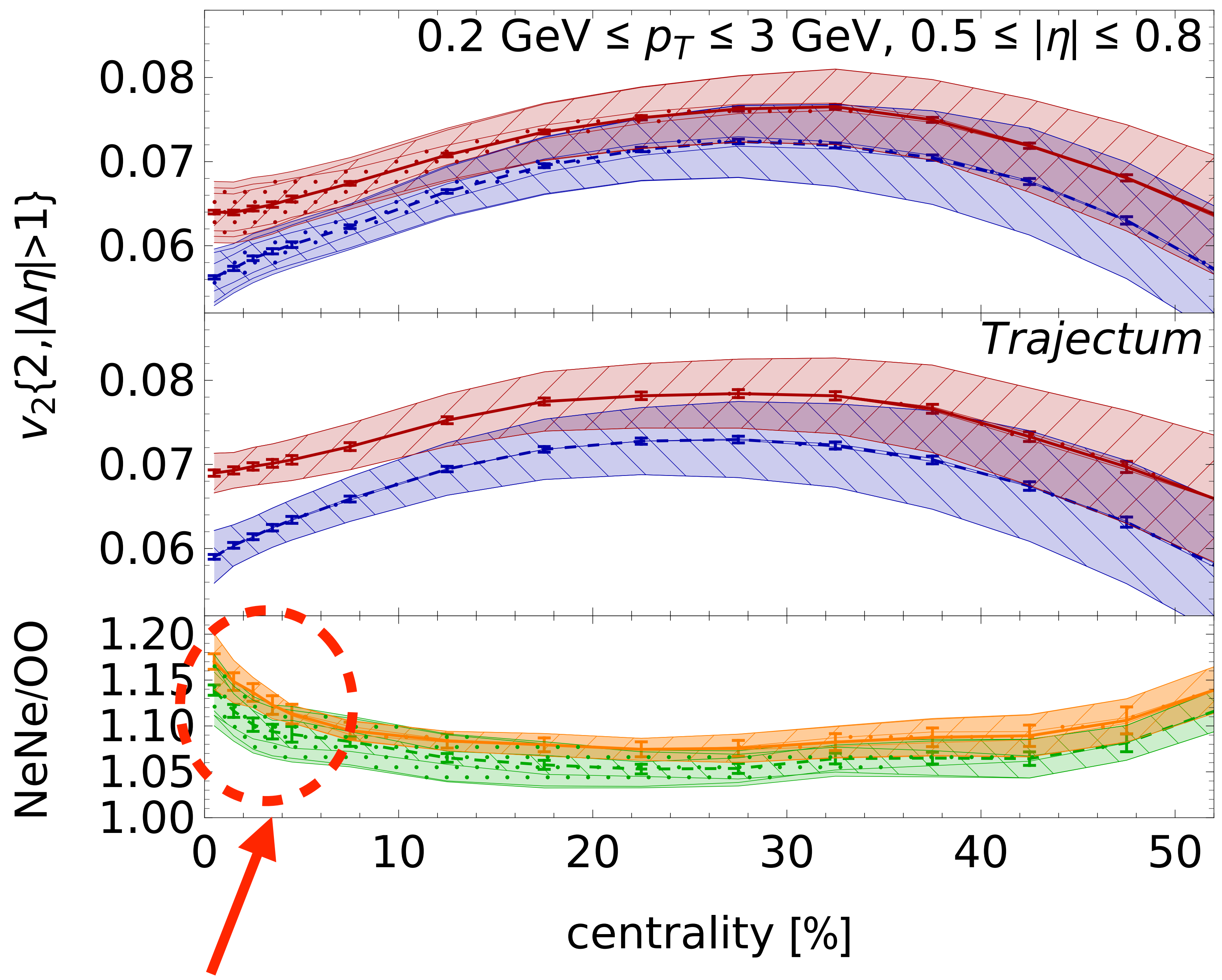
Structure | **Geometry (Transverse)** | **Exp. Observable**









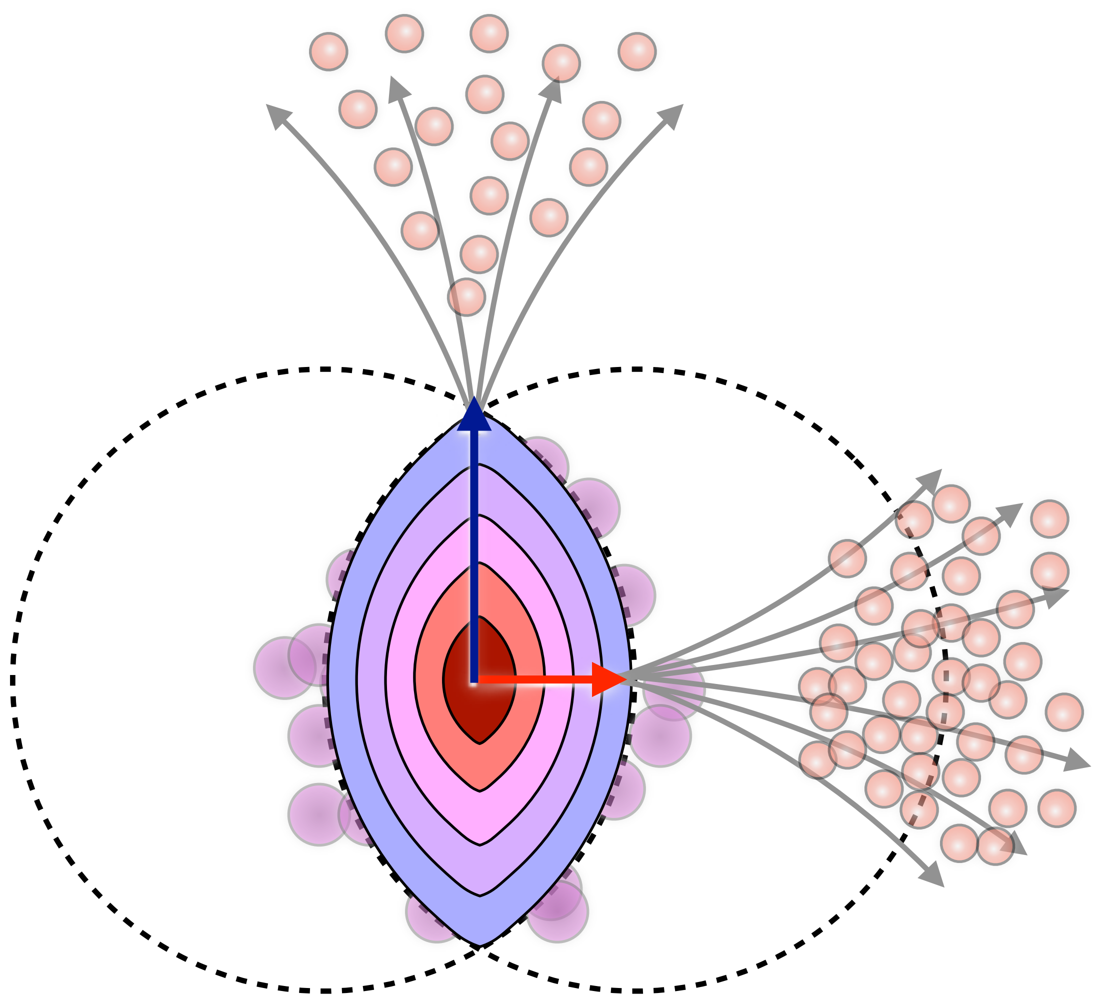


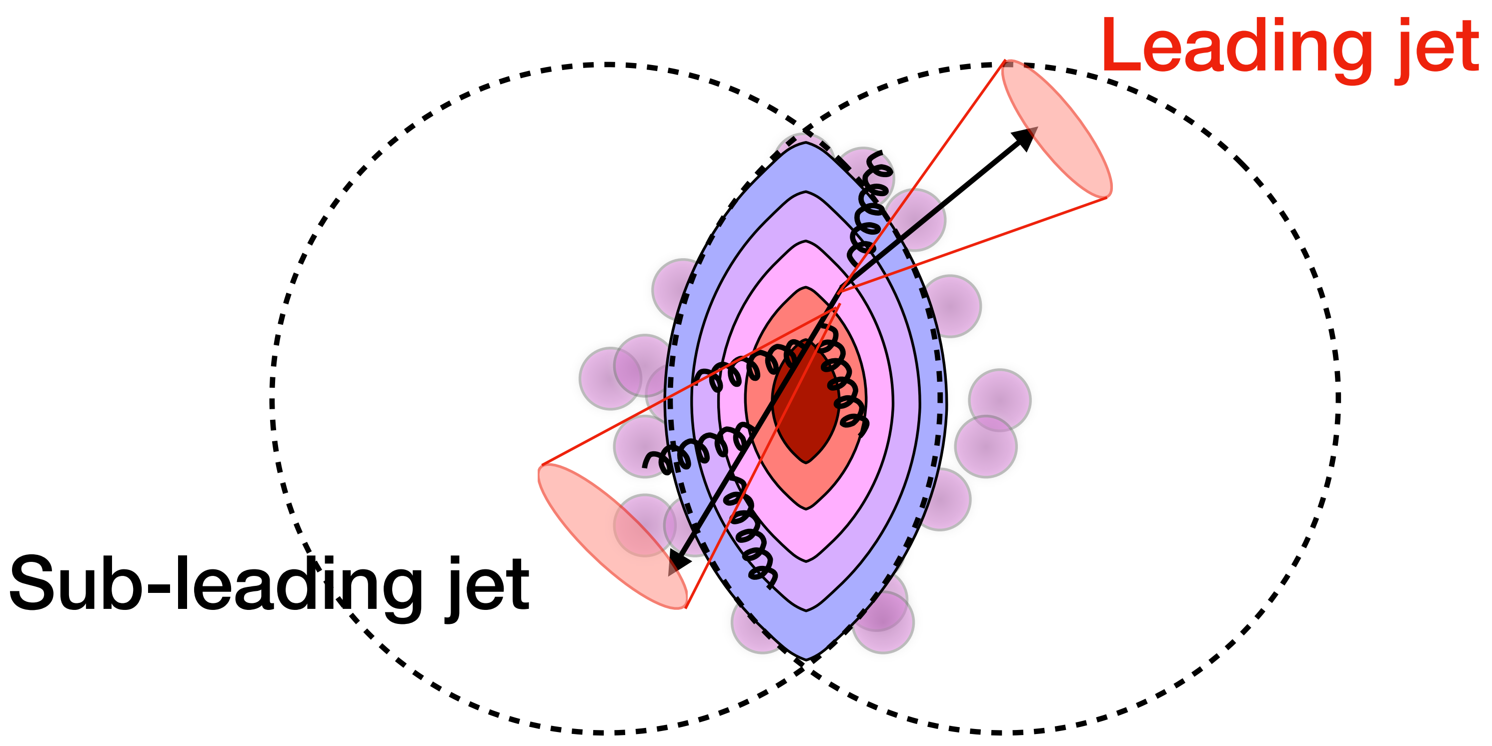
Most-central events are sensitive to non-spherical structure (bowling-pin shape of ^{20}Ne)

- Assuming QGP formed, most central events can be used to probe deformed nuclear structure

Giuliano Giacalone et al. PRL 135 (2025) 012302
Jiangyong Jia, arXiv:2501.16071

First sets of ATLAS measurements in O+O and Ne+Ne

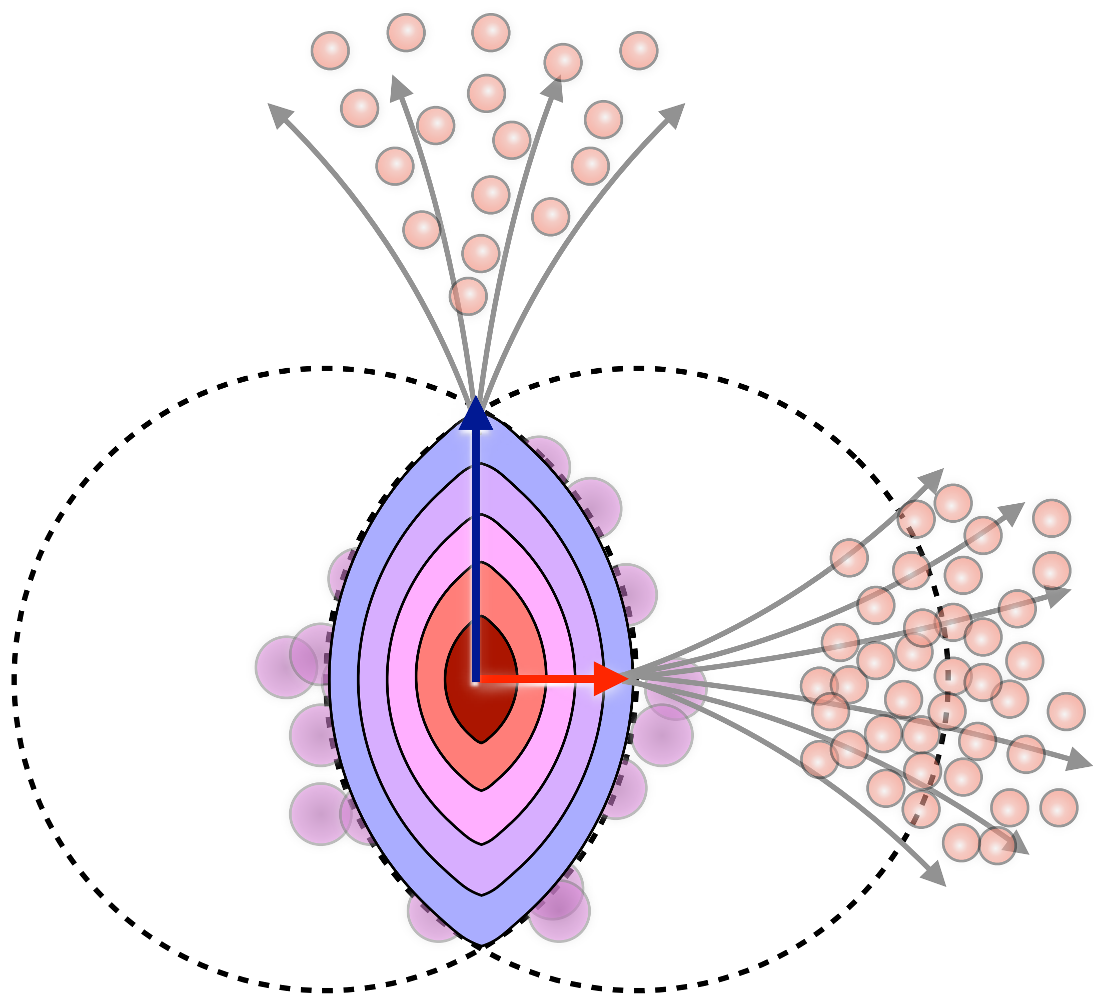




arXiv:2509.05171

ATLAS-CONF-2025-010

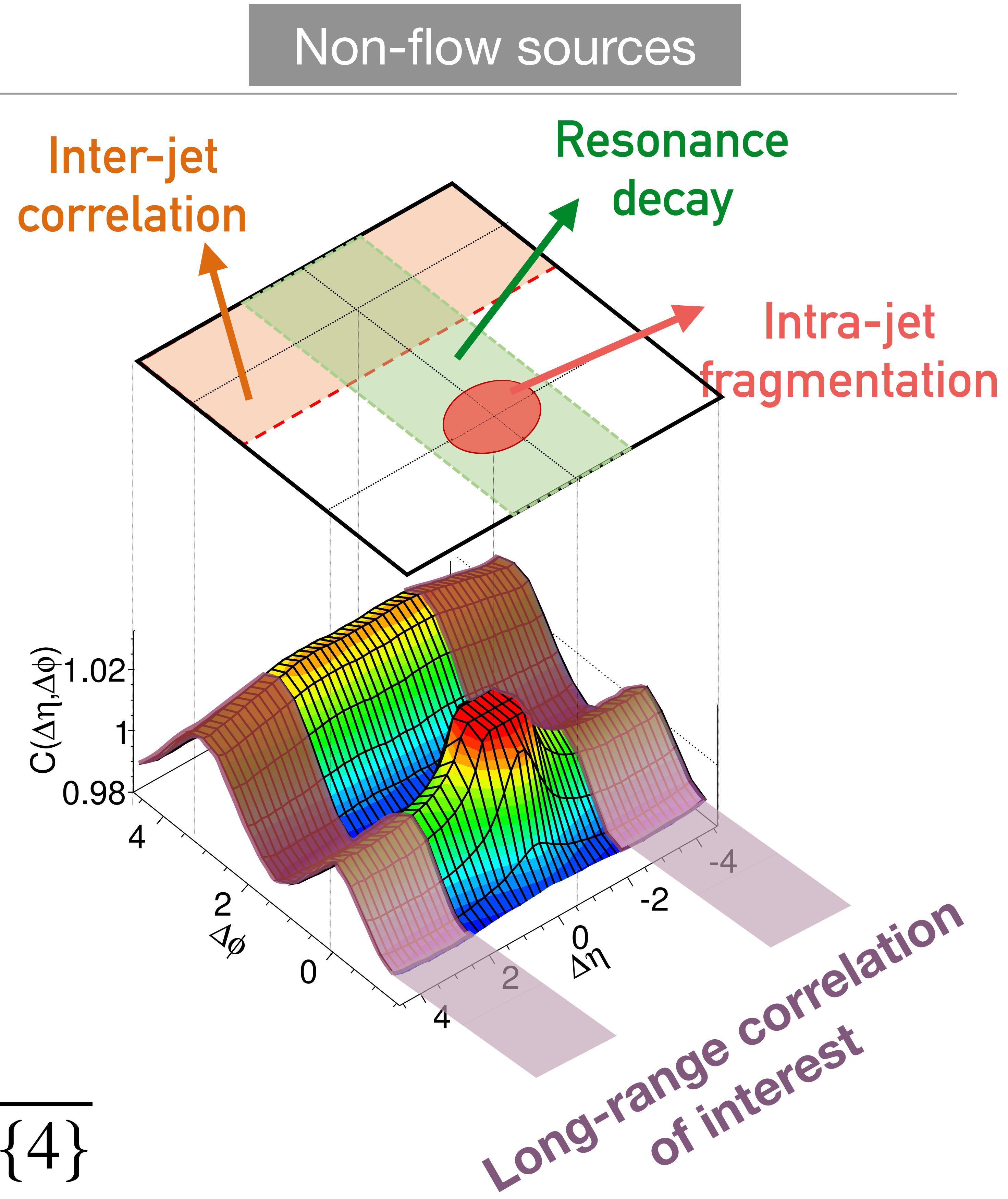
Flow harmonics in O+O and Ne+Ne



Standard 2-particle correlation analysis with $\Delta\eta$ gap:

$$C(\Delta\phi) = C_0\left(1 + 2\Sigma_{n=1}^{\infty} v_{n,n}(p_T^a, p_T^b)\cos(n\Delta\phi)\right)$$

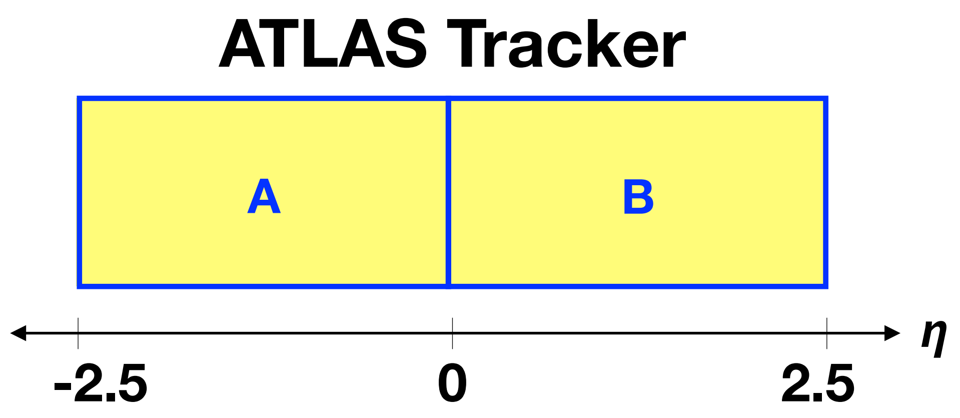
$$v_n(p_T^b) = \frac{v_{n,n}(p_T^a, p_T^b)}{v_n(p_T^a)} = \frac{v_{n,n}(p_T^a, p_T^b)}{\sqrt{v_{n,n}(p_T^a, p_T^a)}}$$



Standard 4-particle cumulant analysis with 2 subevents:

$$c_n\{2\} = \langle\langle\{2\}_n\rangle\rangle,$$
$$c_n\{4\} = \langle\langle\{4\}_n\rangle\rangle - 2\langle\langle\{2\}_n\rangle\rangle^2$$

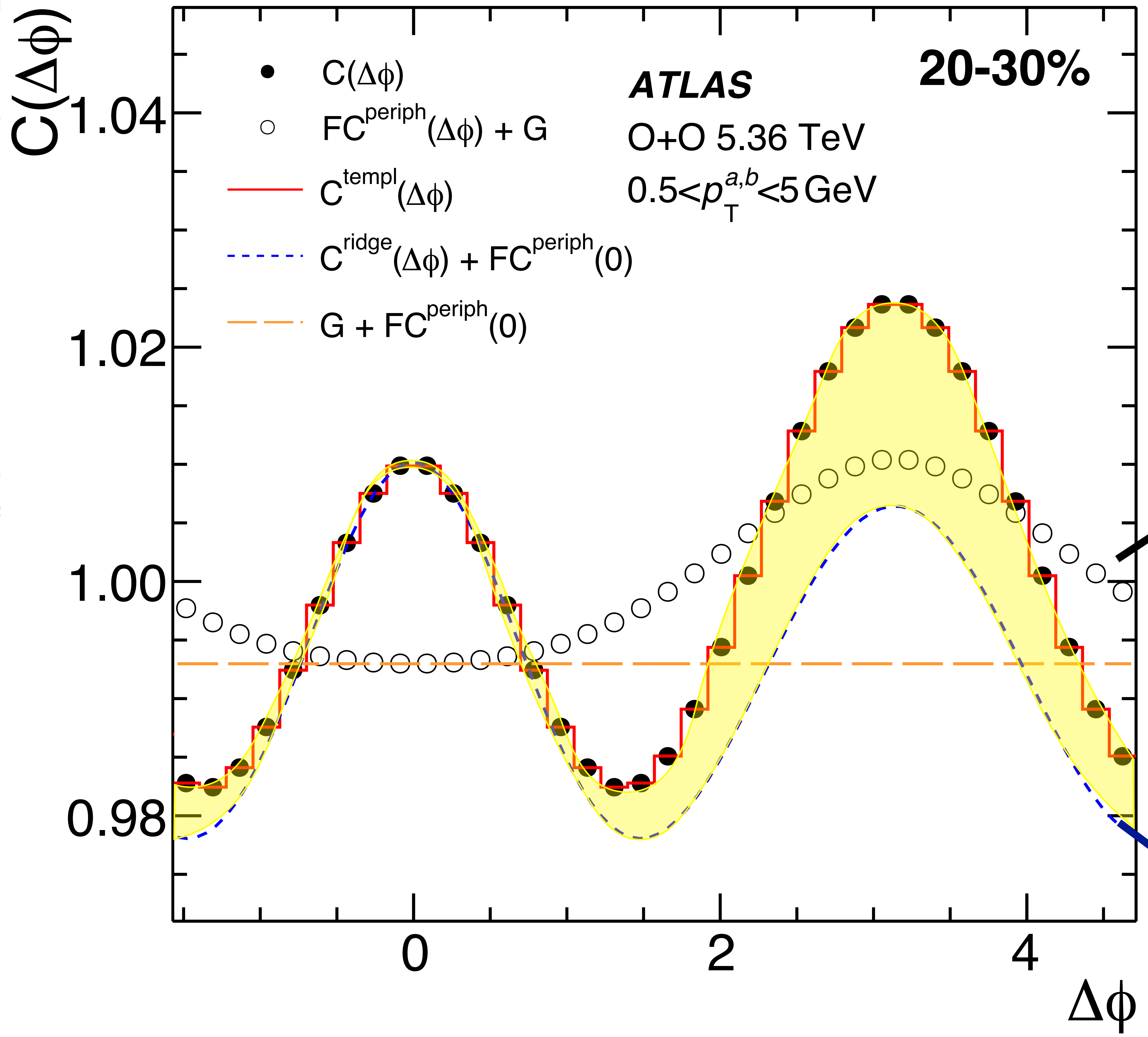
$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$



- Detector effects are corrected in constructing the observables
- Residual non-flow effects are further subtracted or investigated

Non-flow in two-particle correlations — template fit

$$C(\Delta\phi) = FC^{\rm periph}(\Delta\phi) + G\left\{1 + 2\sum_{n=2}^{5} v_{n,n}(p_{\rm T}^{\rm a}, p_{\rm T}^{\rm b})\cos(n\Delta\phi)\right\}$$
$$= FC^{\rm periph}(\Delta\phi) + Y^{\rm ridge}(\Delta\phi).$$



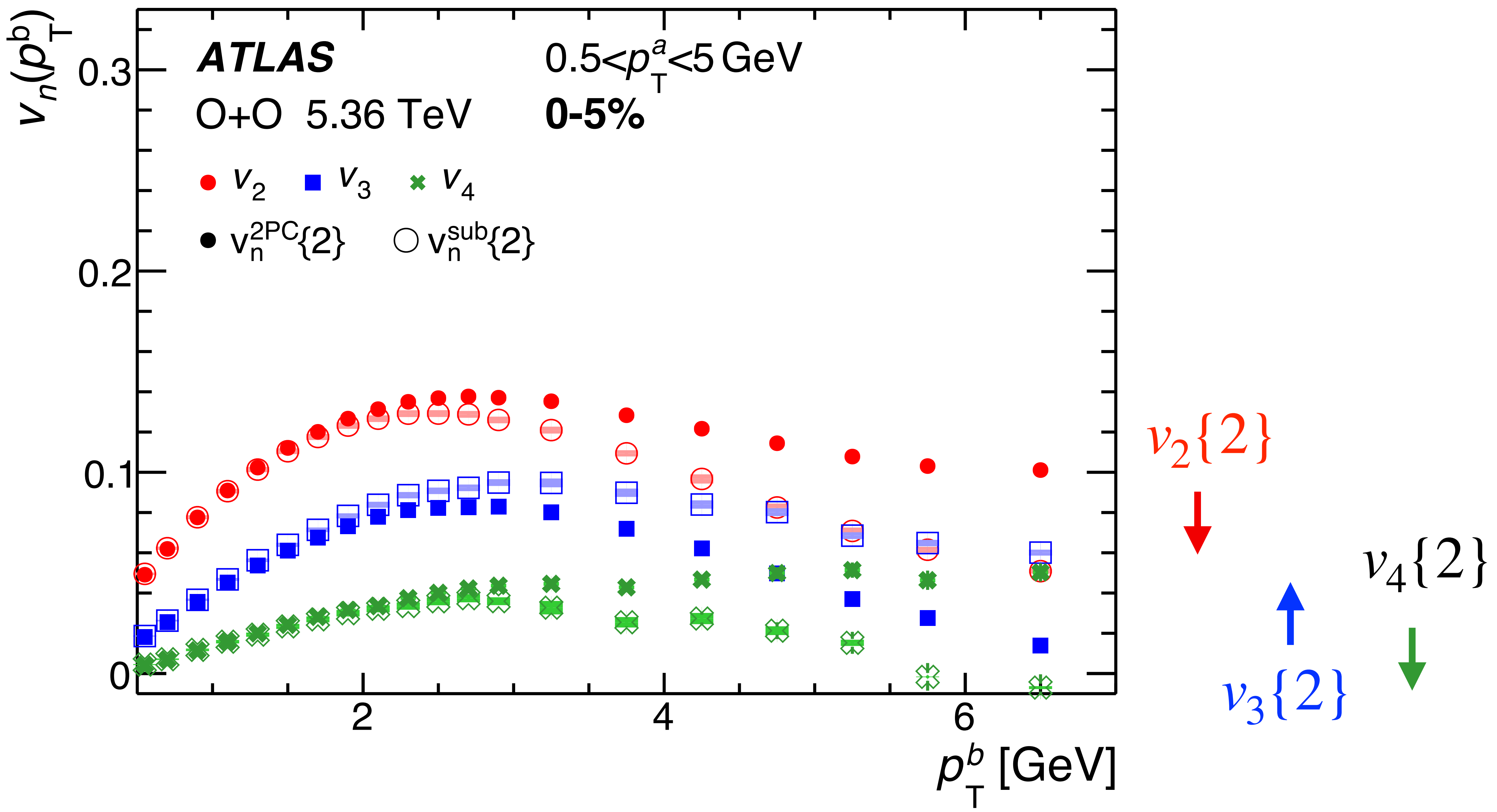
Shifted peripheral reference (>80%) for visibility

Remaining non-flow from inter-jet correlation

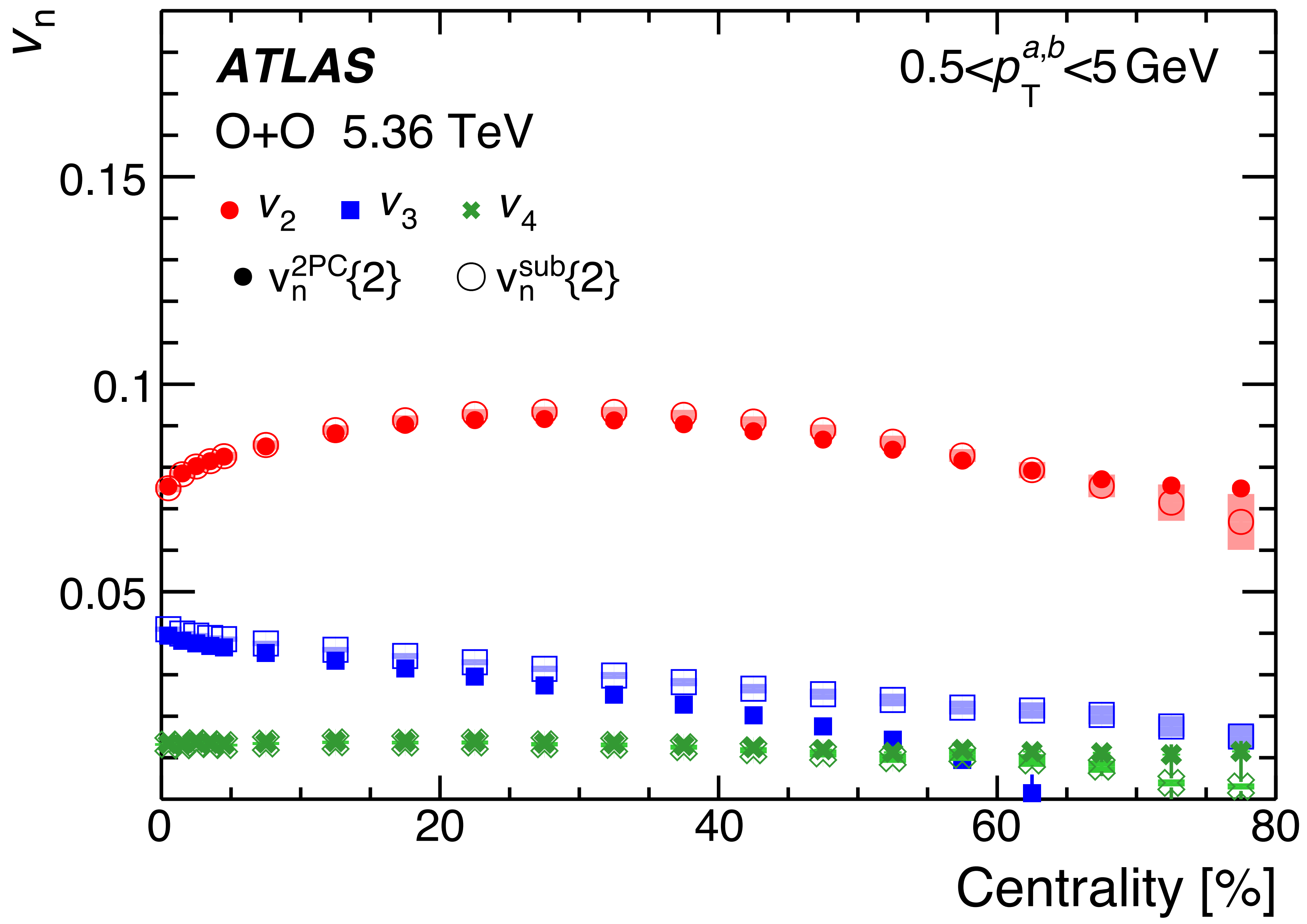
Flow modulation around pedestal

Impact of non-flow subtraction

p_T dependence



Centrality dependence



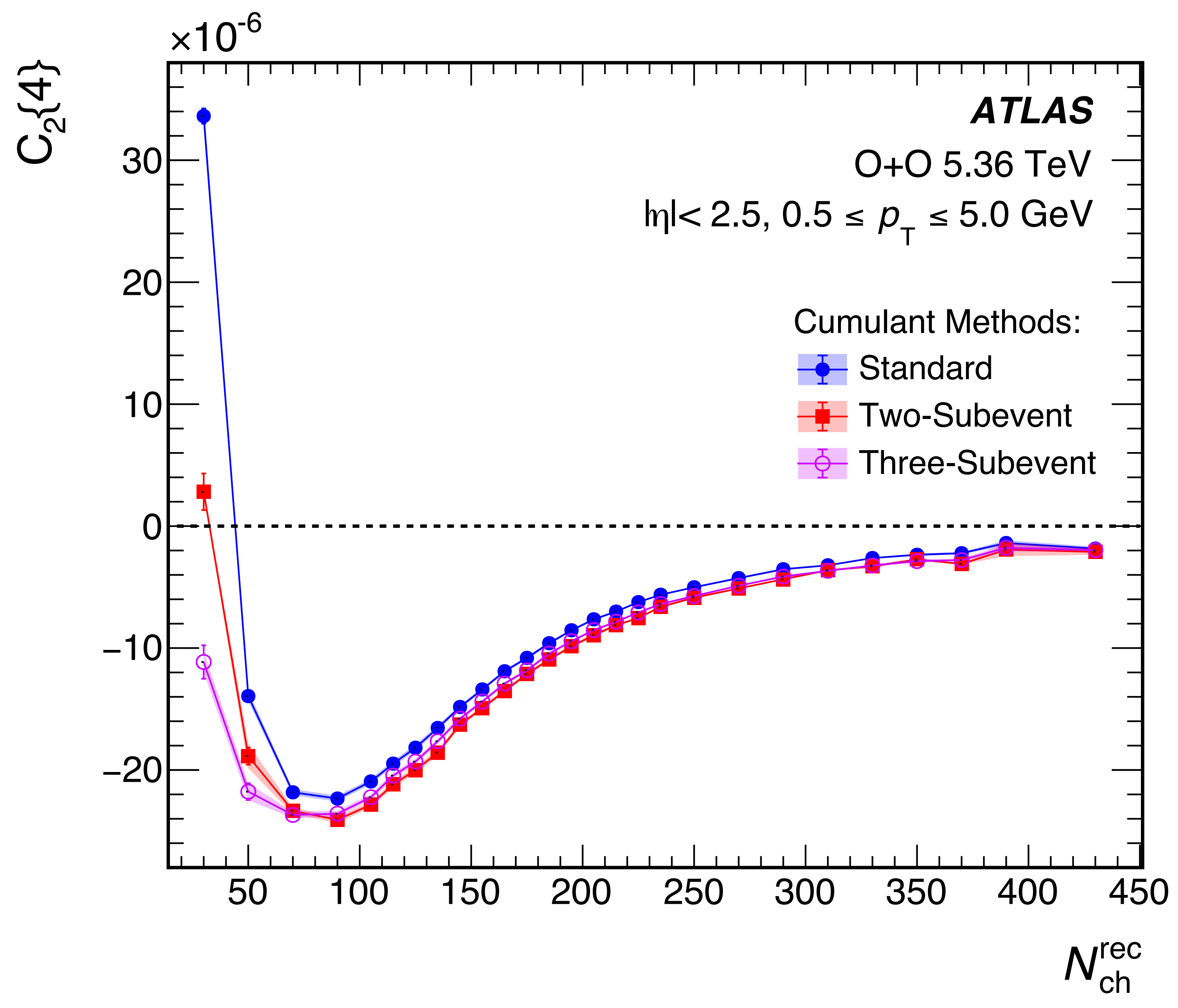
- Direct Fourier decomposition: $v_n^{2PC}\{2\}$
- Template fit: $v_n^{sub}\{2\}$

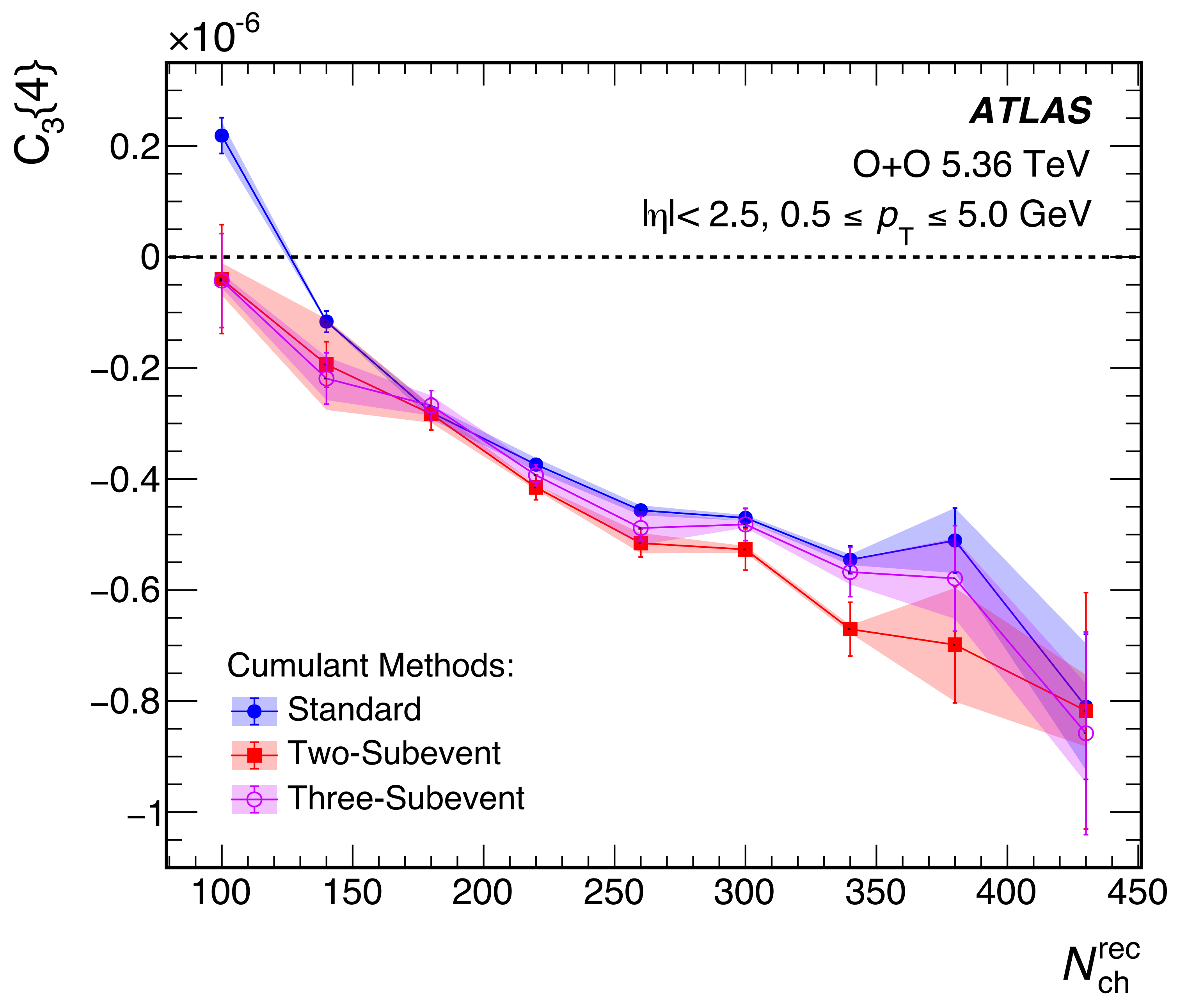
Effect of subtraction (strongly p_T dependent):

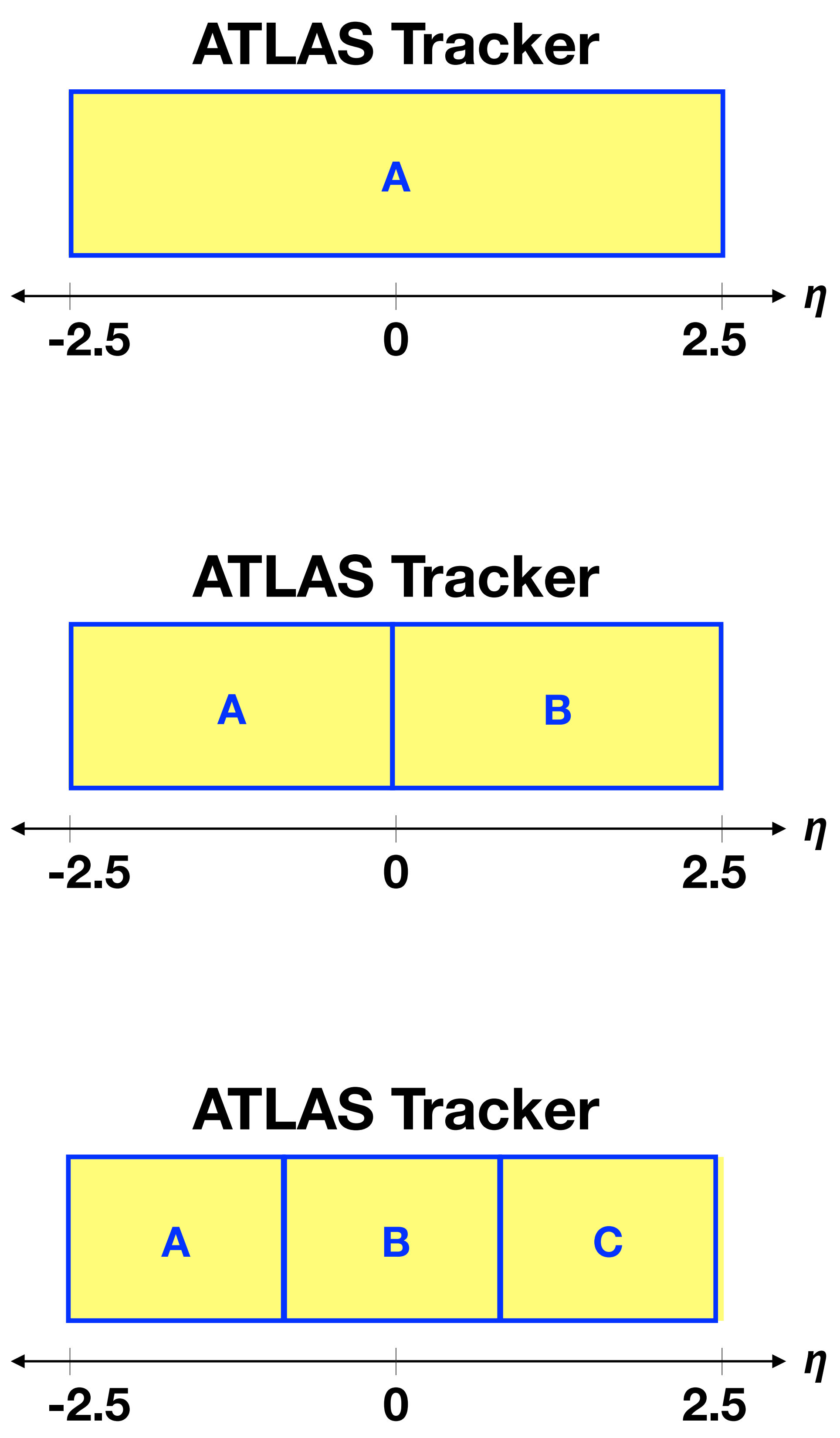
$v_2\{2\}\downarrow$, $v_3\{2\}\uparrow$, $v_4\{2\}\downarrow$

- $v_n^{sub}\{2\}$ is chosen as the central results
- When integrated over wide p_T range (0.5 ~ 5 GeV), the impact of non-flow is small

Non-flow in 4 particle cumulant — subevent method

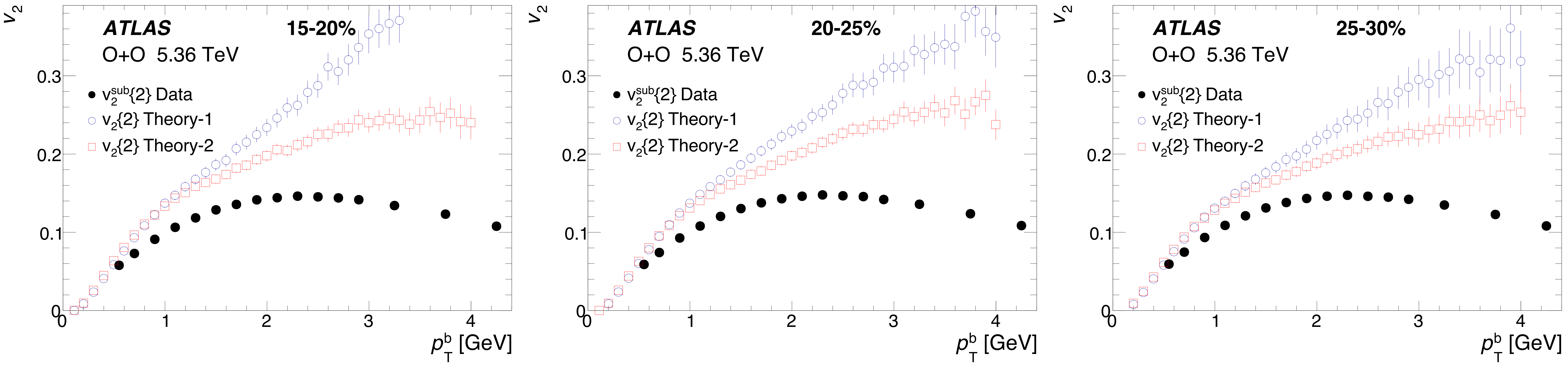






- Additional event division further reduce non-flow, but with only small impact for p_T-integrated results
- Two subevent results are taken as nominal

Non-flow at high p_T

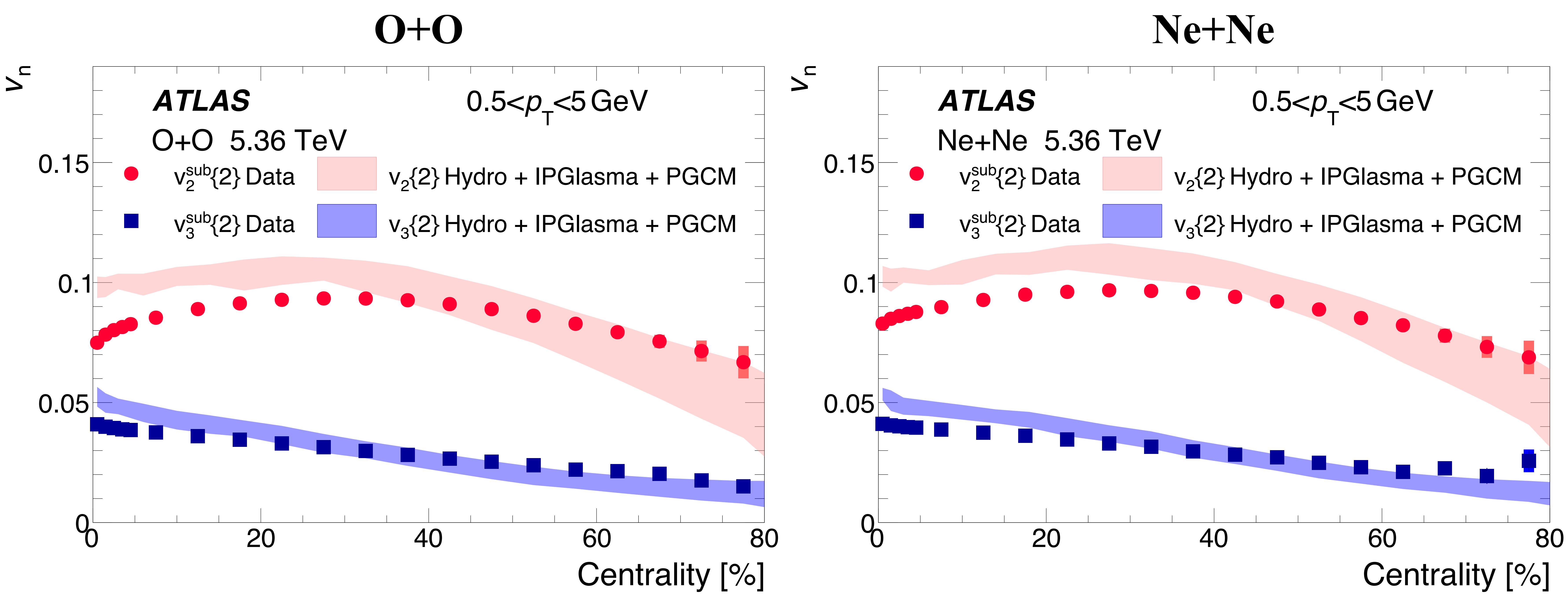


IPGlasma+Hydro+PGCM: (Heikki Mantysaari et al, PRL135 (2025) 022302)

- “Theory-1” vs “Theory-2” correspond to how much anisotropy from the glasma stage is retained in the hydro initialization
- ATLAS data provide input to further improve models

Other aux figures of the paper can be found at https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HION-2025-02/

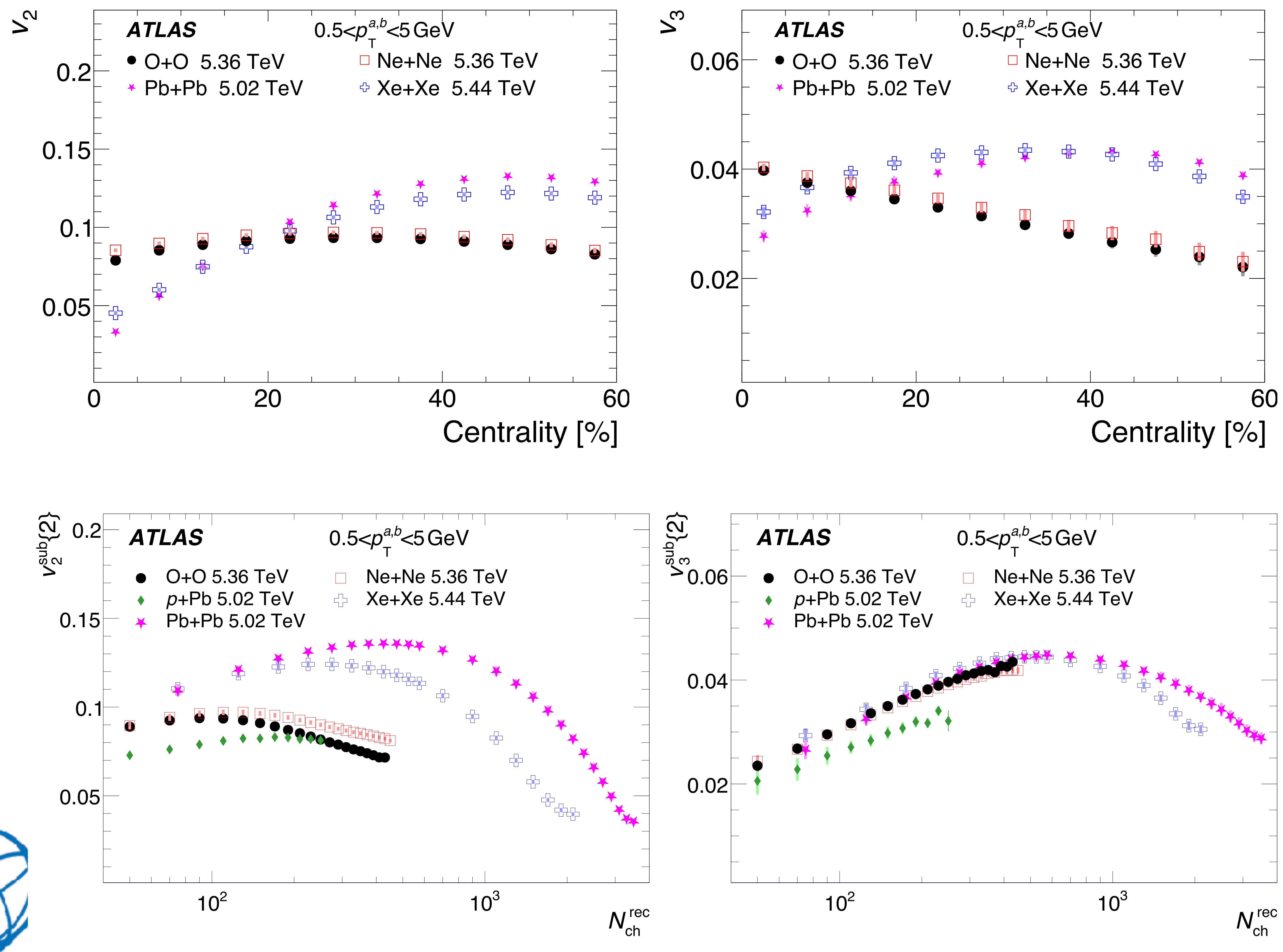
Measured v_n vs. model



- Flow signals in O+O and Ne+Ne resemble those seen in heavy-ion collisions
- Characteristic ordering observed: $v_2 > v_3 > v_4$
- Comparison with **Hydro+IPGlasma+PGCM** models clearly indicates a collective (hydrodynamical) response

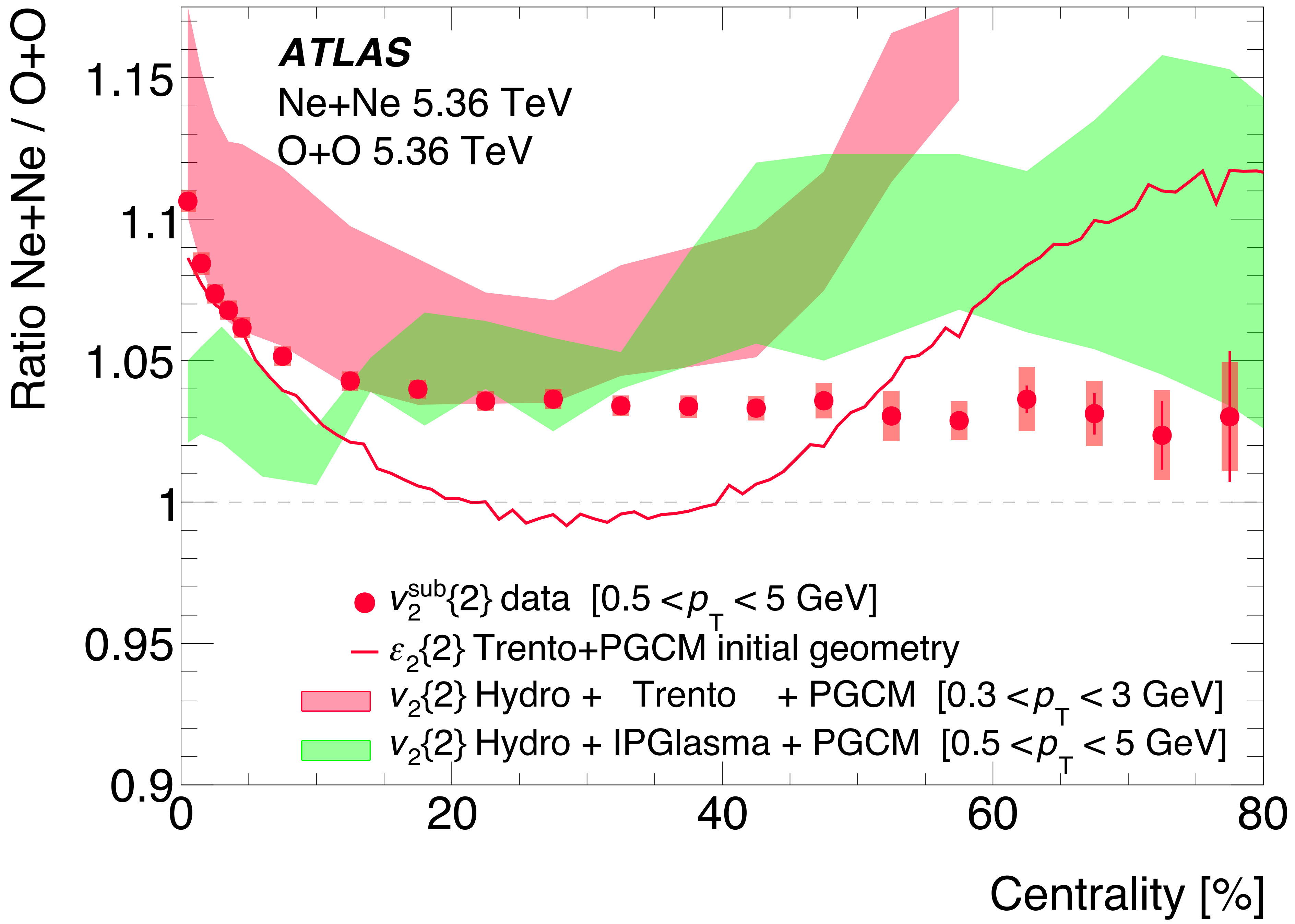
Heikki Mantysaari et al, PRL135 (2025) 022302

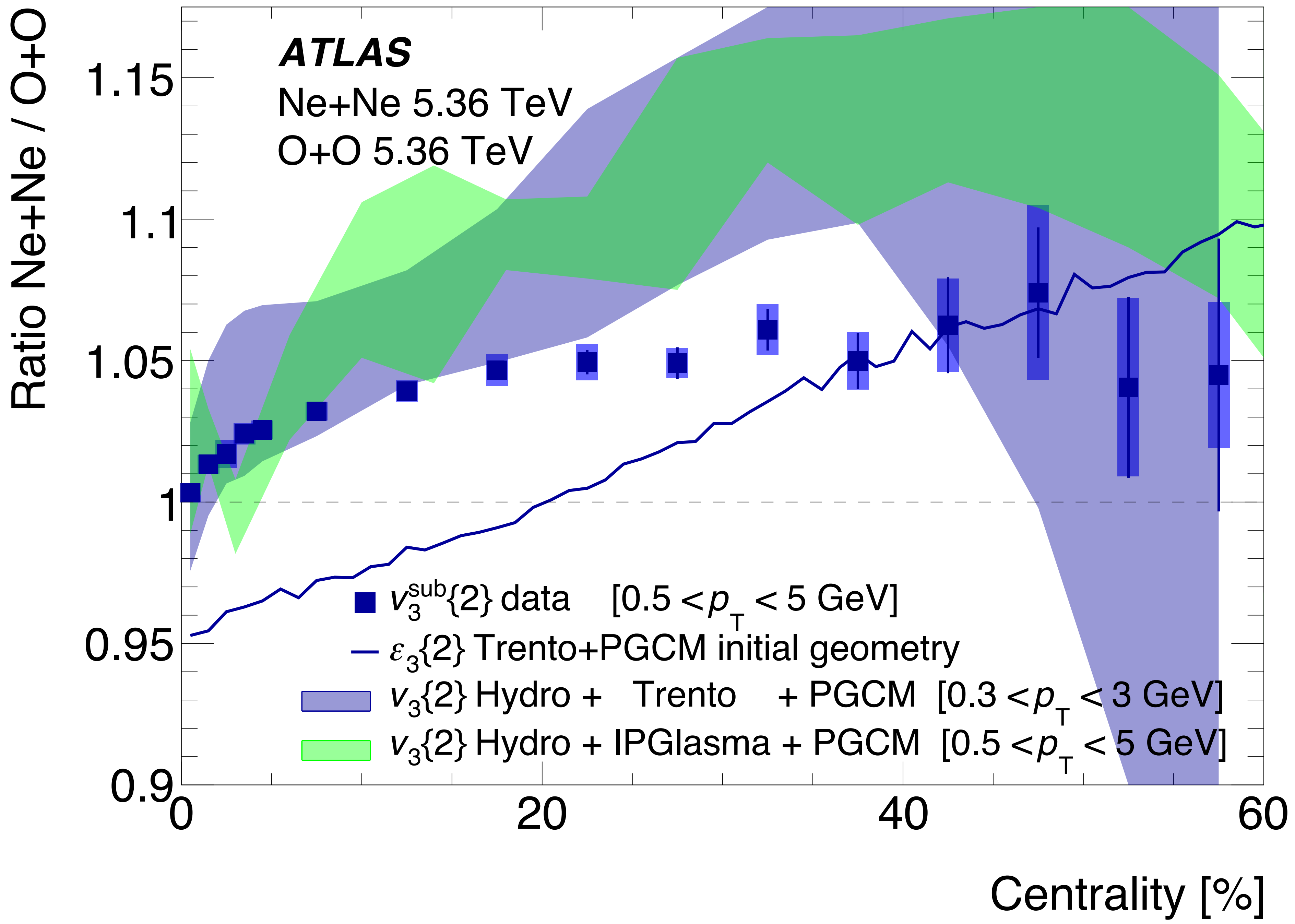
Comparison of different ion collisions



- Flow in Ne+Ne consistently larger than in O+O
- Light ions vs. heavy ions in centralities:
  - Light ion v_2 is much flatter
  - Light ion v_3 decreases from central to peripheral
  - Stronger fluctuation contributions in light ions
- Light ions vs. heavy ions in multiplicities:
  - O+O v_2 converges with p+Pb
  - Light ion v_3 align with heavy ion

Ne+Ne/O+O vs. model calculations



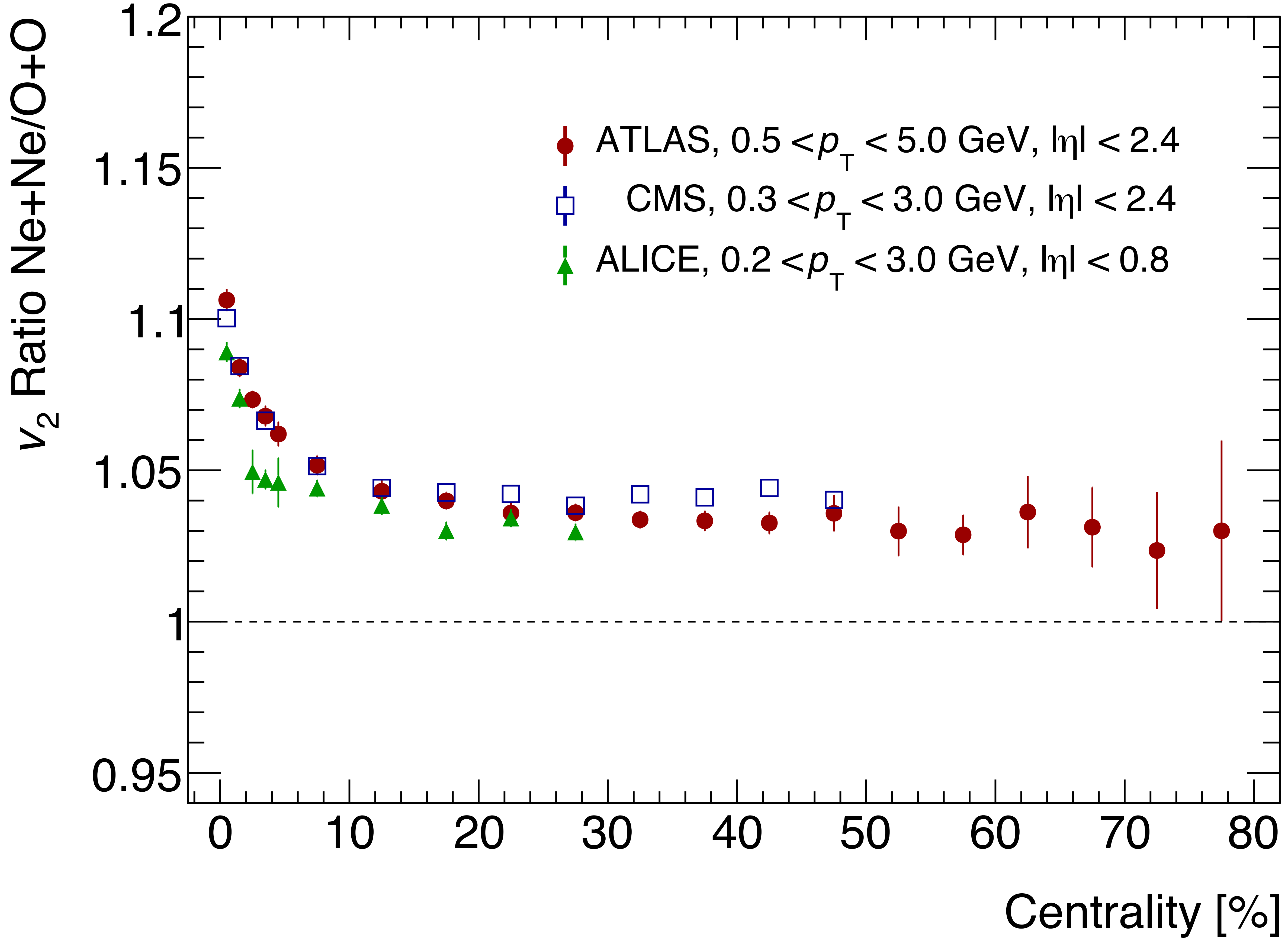


Compare to PGCM + hydro + different hydro initial conditions:

- **Trento:** provides a better description of centrality dependence in central events
- **IPGlasma:** fails to reproduce the observed central-event trend

Giacolone et al, PRL 135 (2025) 012302
Mantysaari et al, PRL 135 (2025) 022302

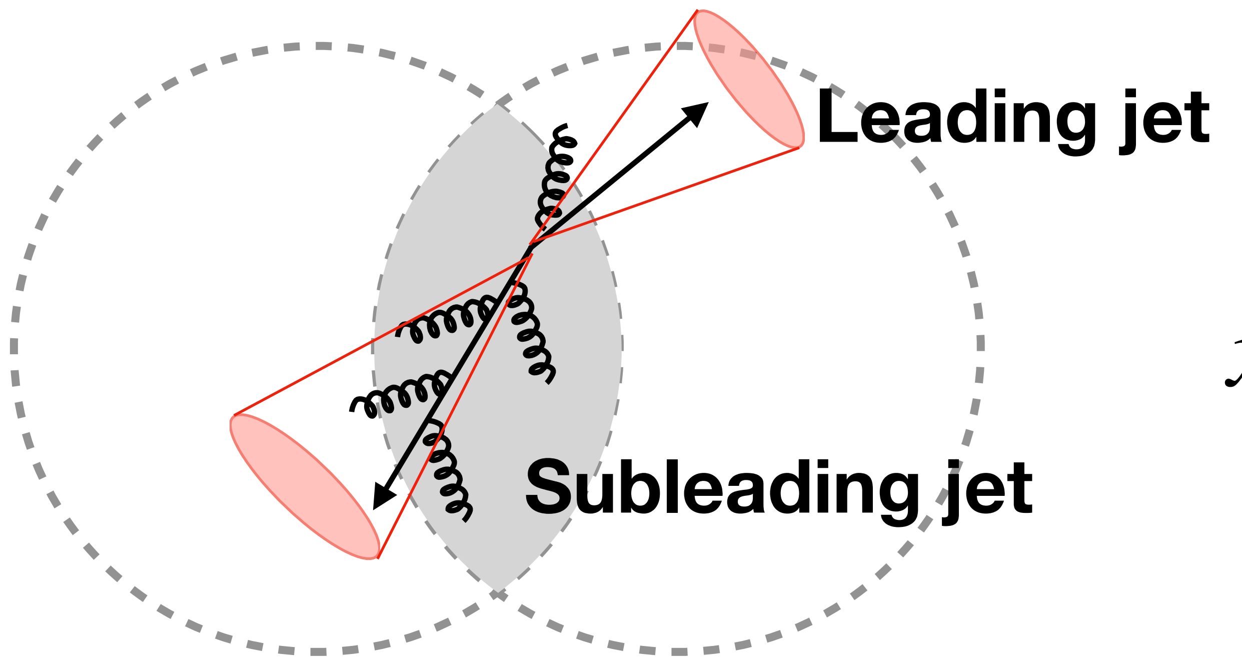
Comparison of different experiments



- Overall good consistency across experiments
- Small difference between experiments could arise from different selections

ATLAS: arXiv:2509.05171
ALICE: arXiv:2509.06428
CMS: PAS HIN-25-009

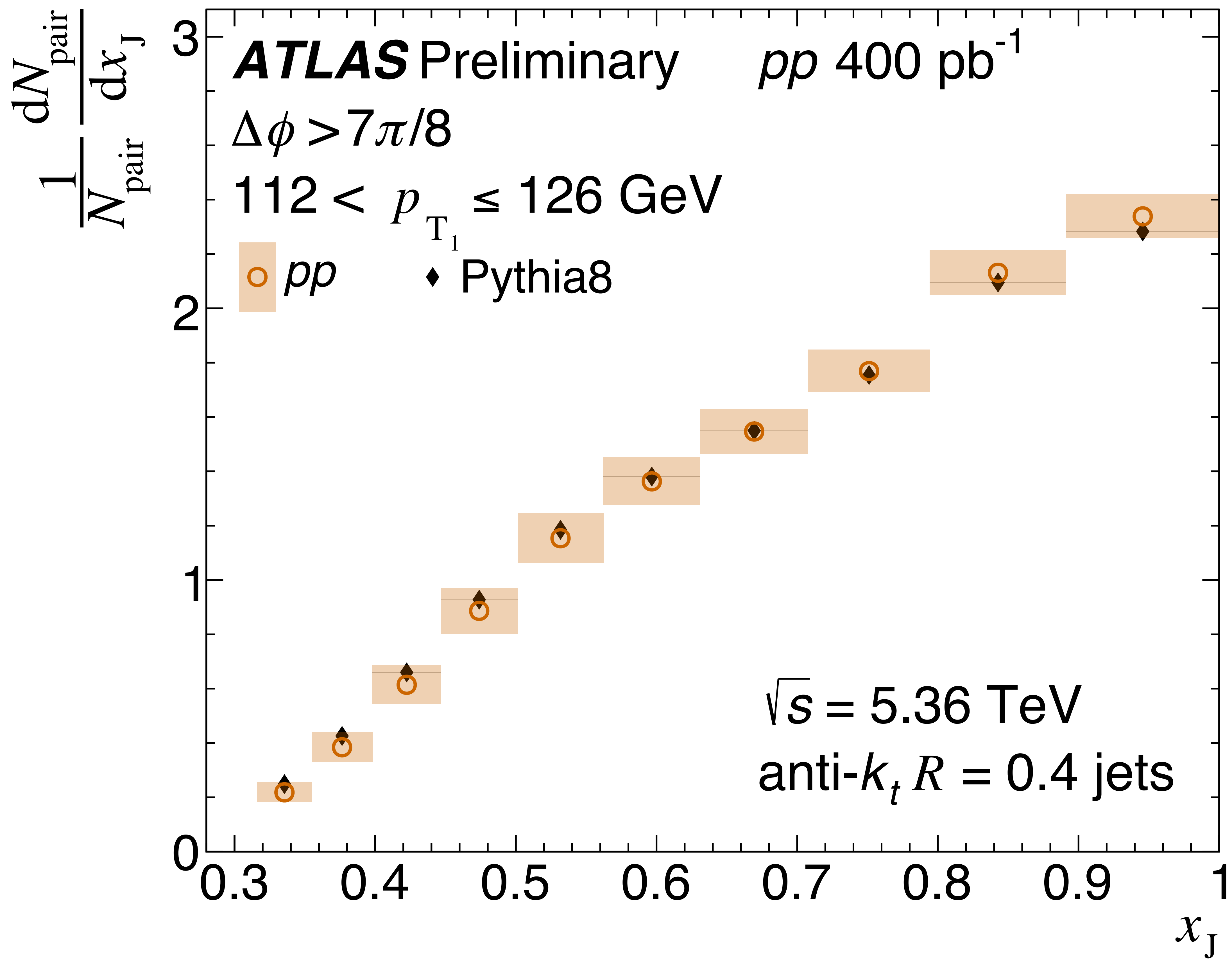
Dijet momentum balance in O+O collisions



$$x_J = \frac{p_T^{\text{subleading}}}{p_T^{\text{leading}}}$$

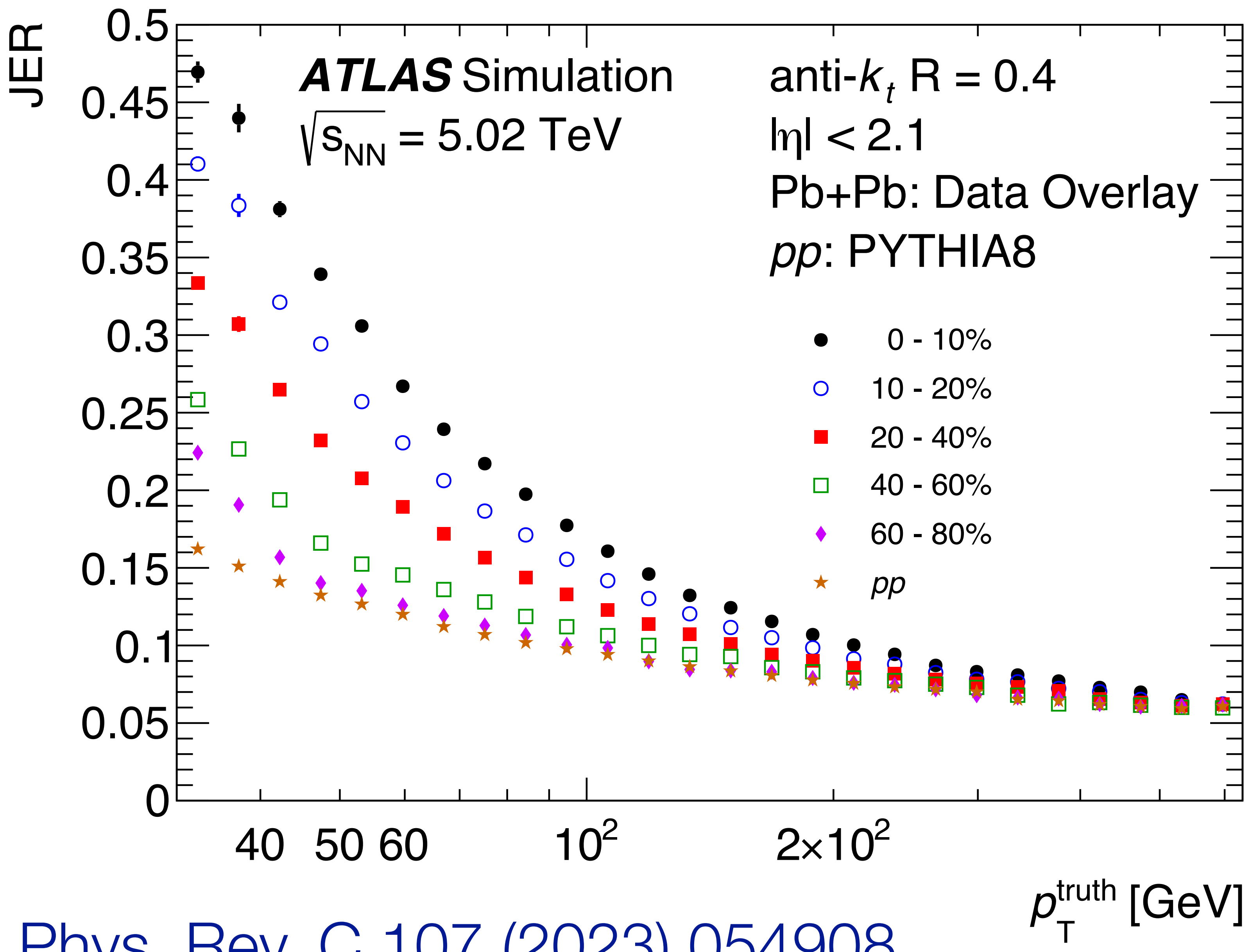
- Leading jet: $63 < p_T < 251$ GeV
- Sub-leading jet: $p_T > 20$ GeV
- Jet rapidities: $|y| < 2.1$
- dijet alignment: $|\Delta\phi| > 7\pi/8$
- Unfolded in (p_T^1, p_T^2) to remove detector effects

x_J in pp



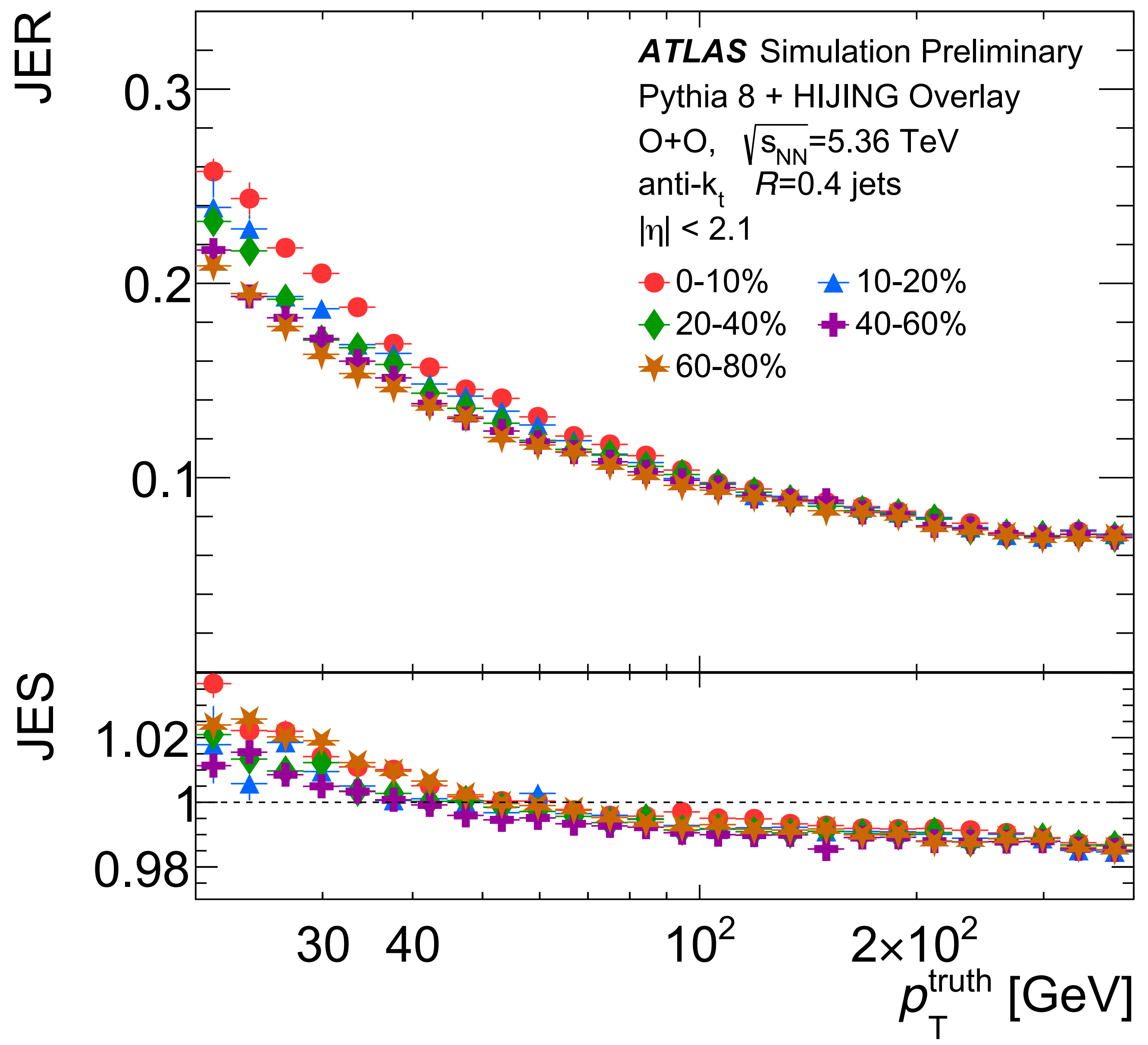
Jet reconstruction in O+O

Pb+Pb



Phys. Rev. C 107 (2023) 054908

O+O



- Jet energy resolution (JER) dominated by underlying-event (UE) energy density
- Much smaller UE in O+O enabled jet measurements down to 20 GeV

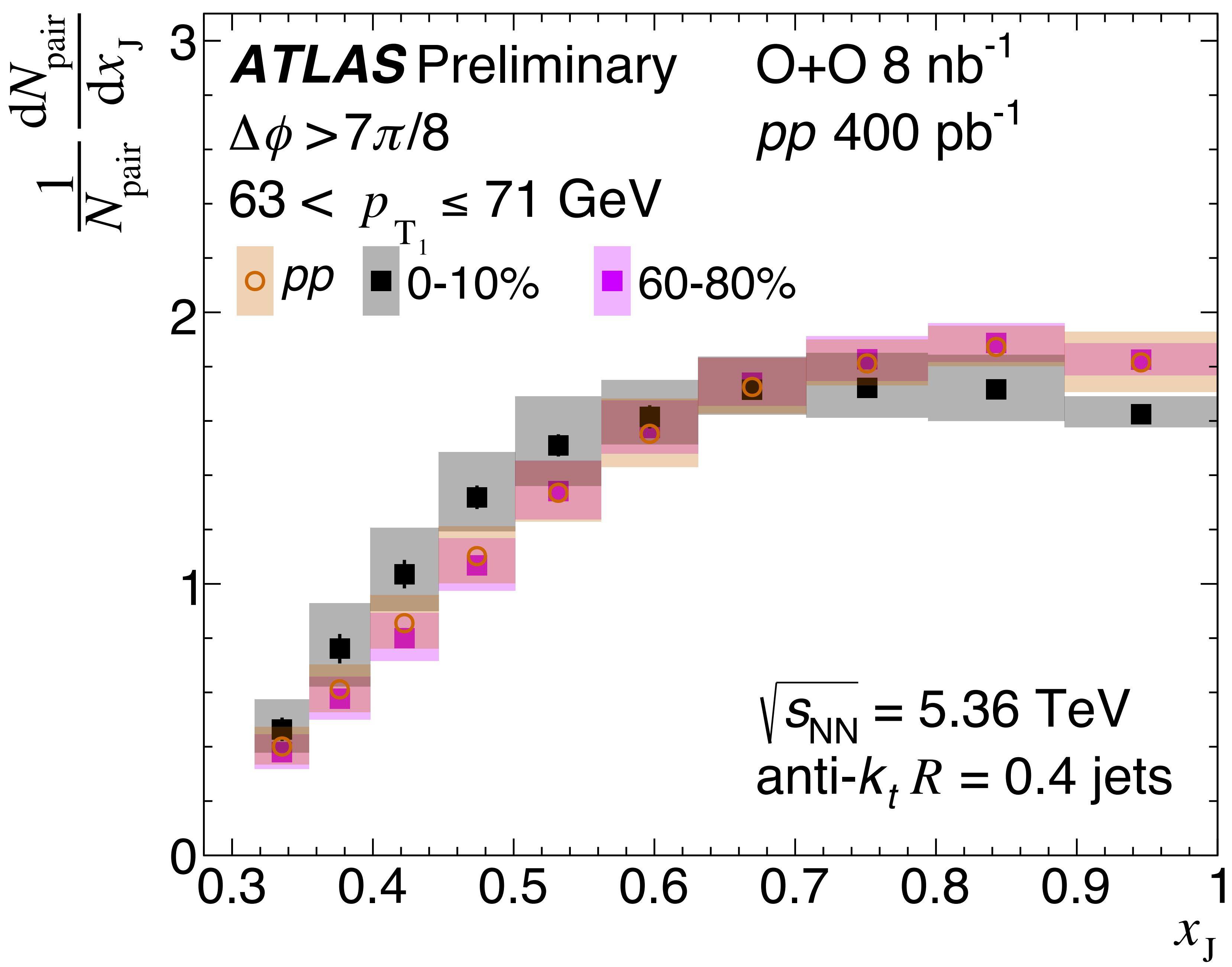
Central Pb+Pb at 40 GeV: 0.45

Central O+O at 40 GeV: 0.16

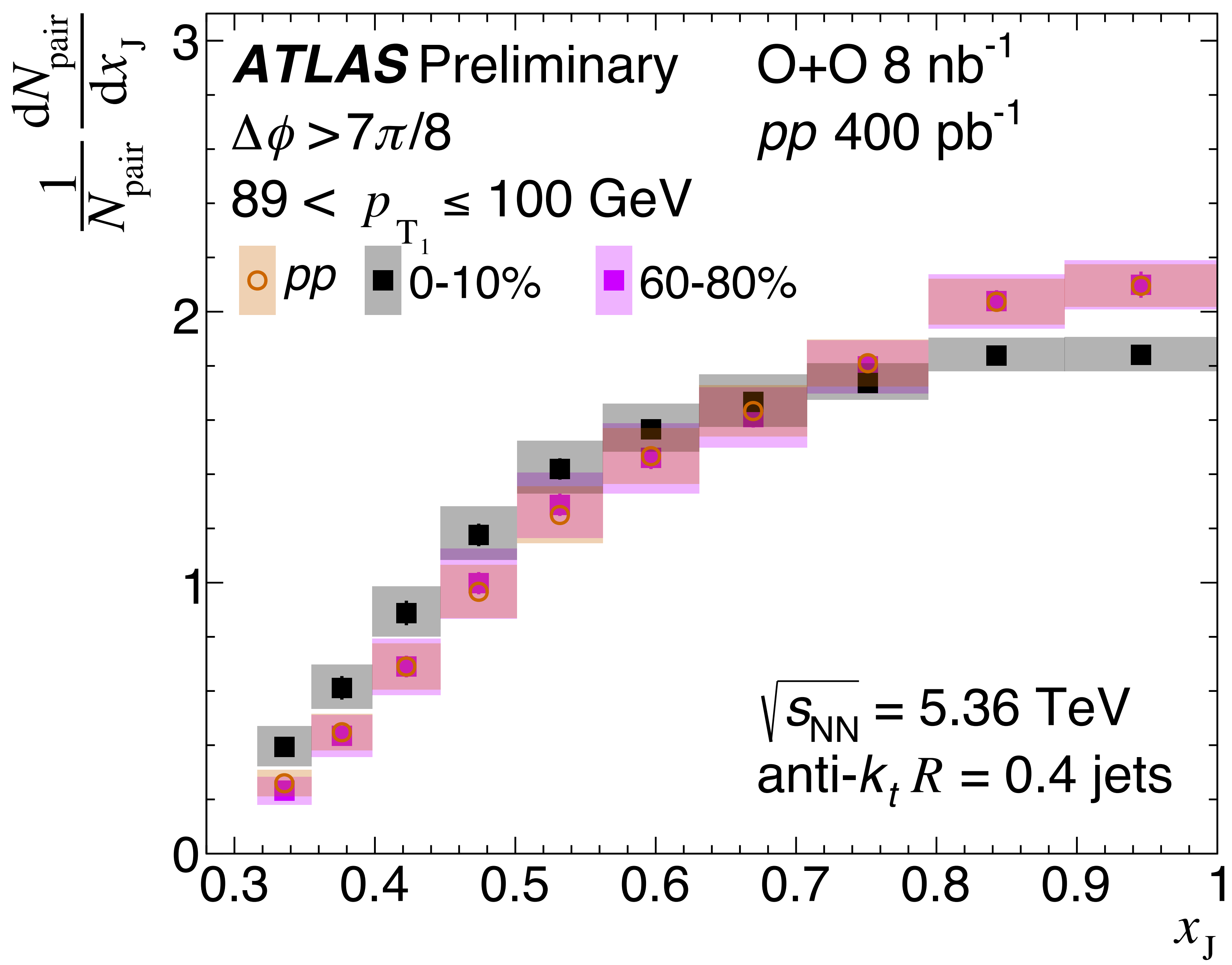
pp at 40 GeV: 0.15

Adding 0-10% O+O distributions

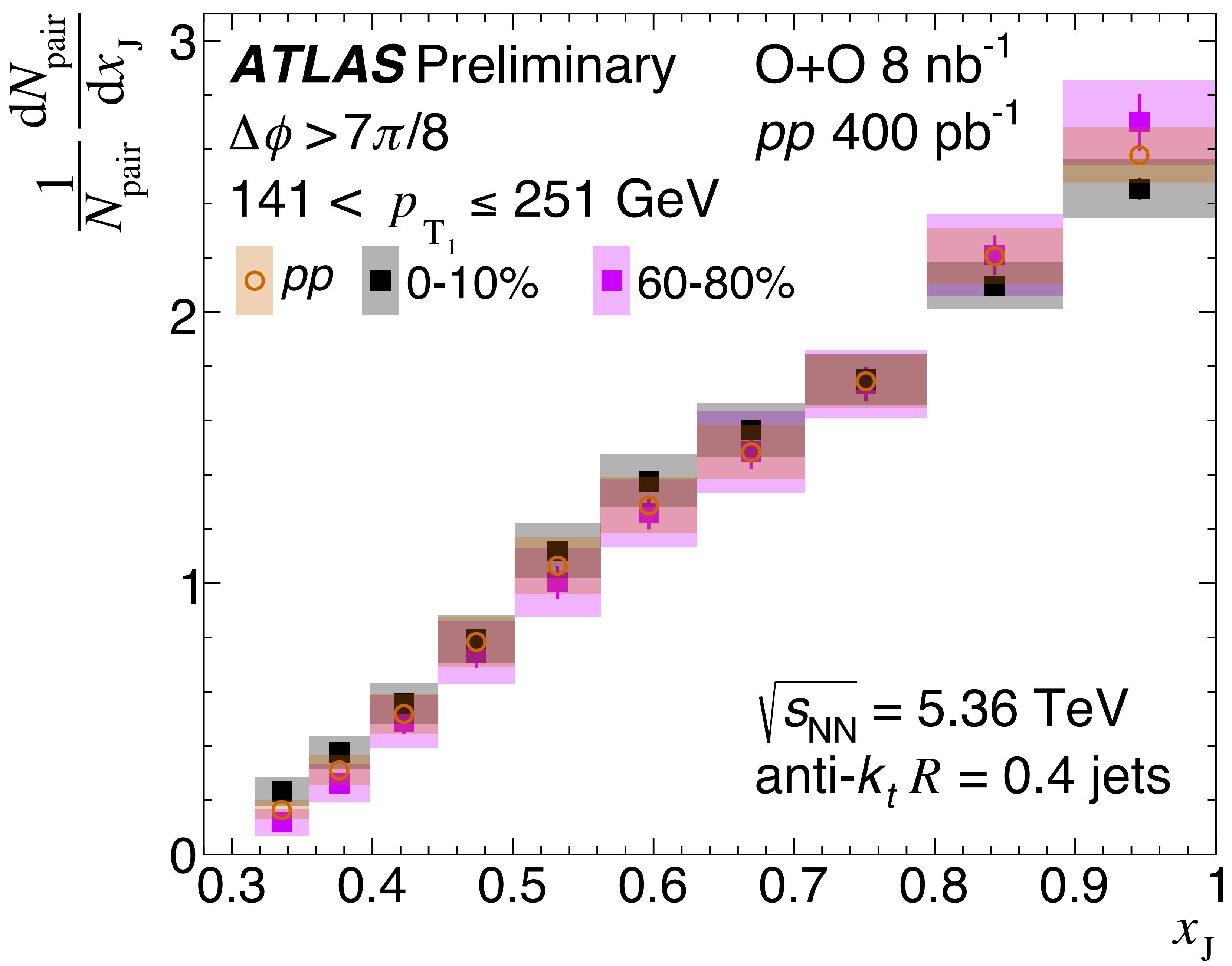
Lowest leading p_T



Intermediate leading p_T

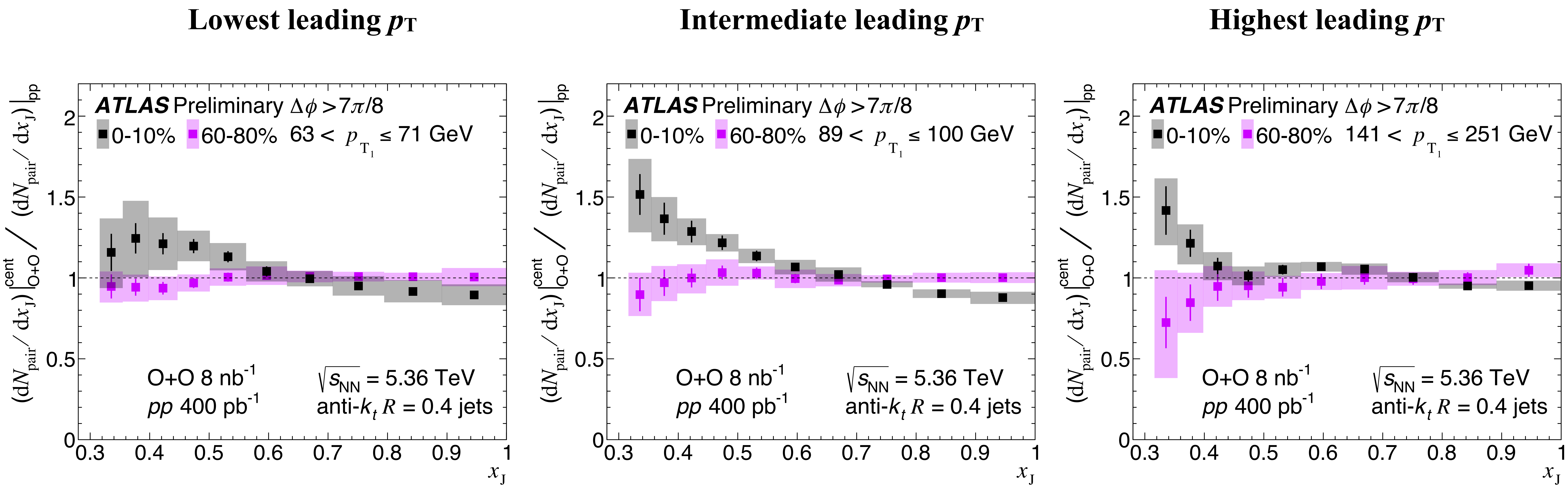


Highest leading p_T



- 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

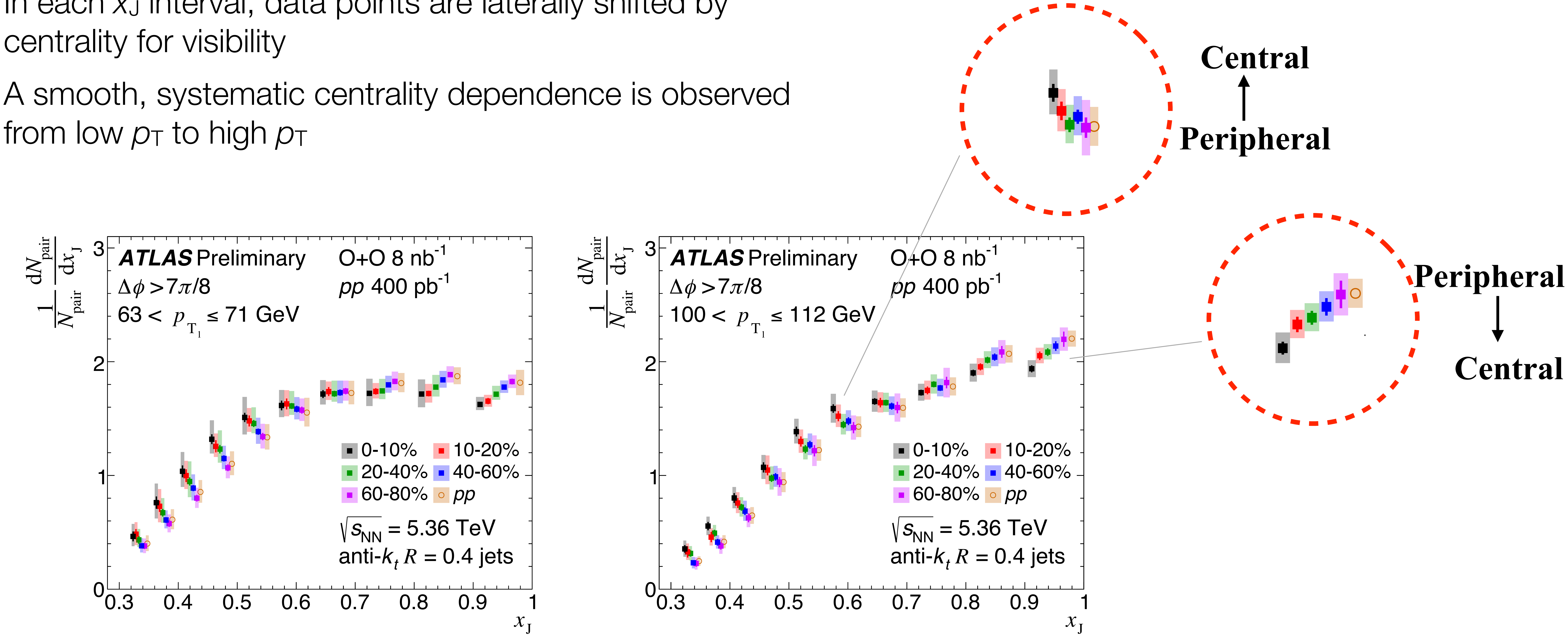
Adding 0-10% O+O distributions



- Ratios make the difference more visible
- pp ~ peripheral O+O within uncertainties
- Central O+O shows clear relative suppression of subleading jets, similar to heavy ion collisions

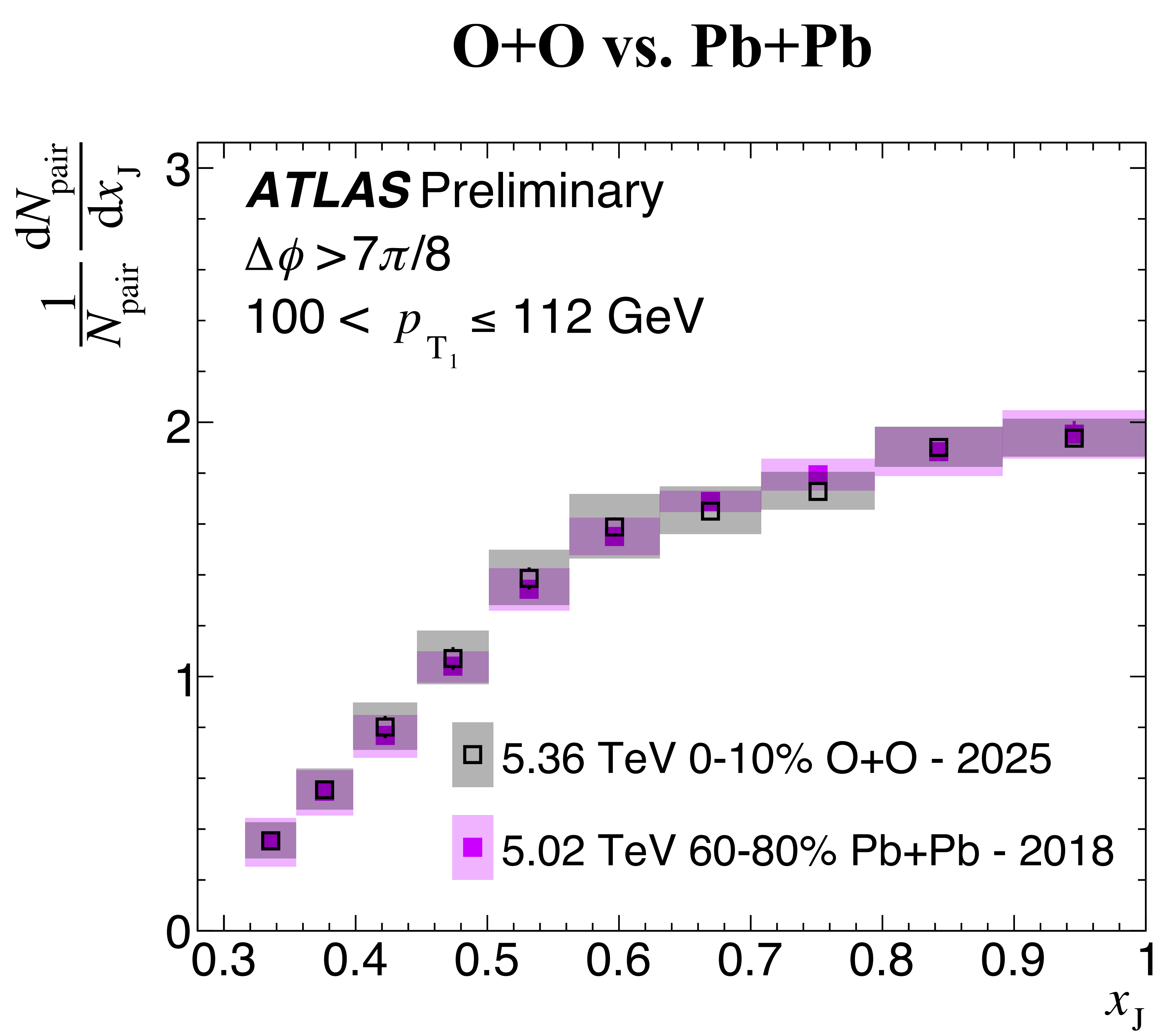
Centrality dependence

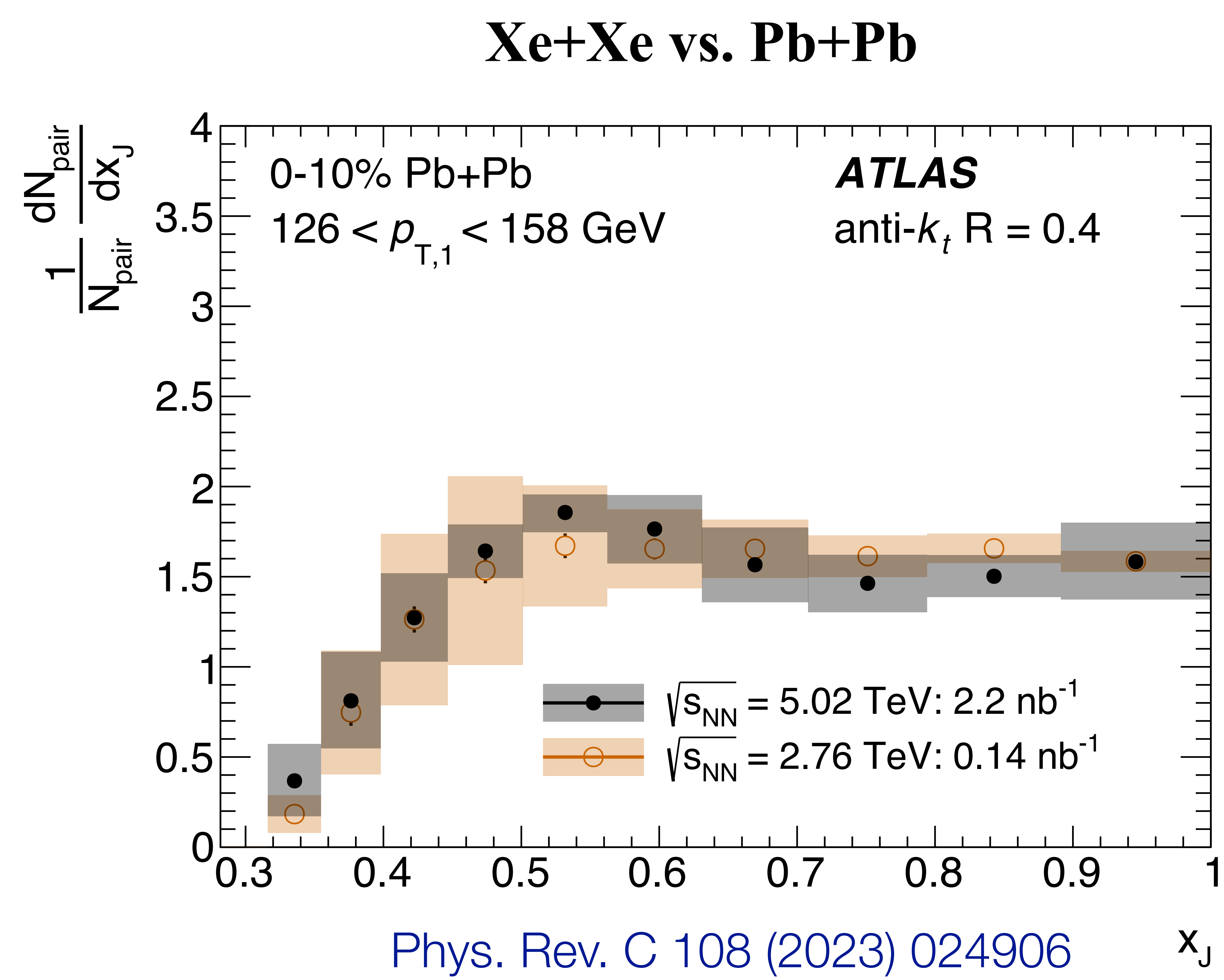
- In each x_J interval, data points are laterally shifted by centrality for visibility
- A smooth, systematic centrality dependence is observed from low p_T to high p_T



Low leading p_T **High leading p_T**

Light and heavy ions with matched event activity





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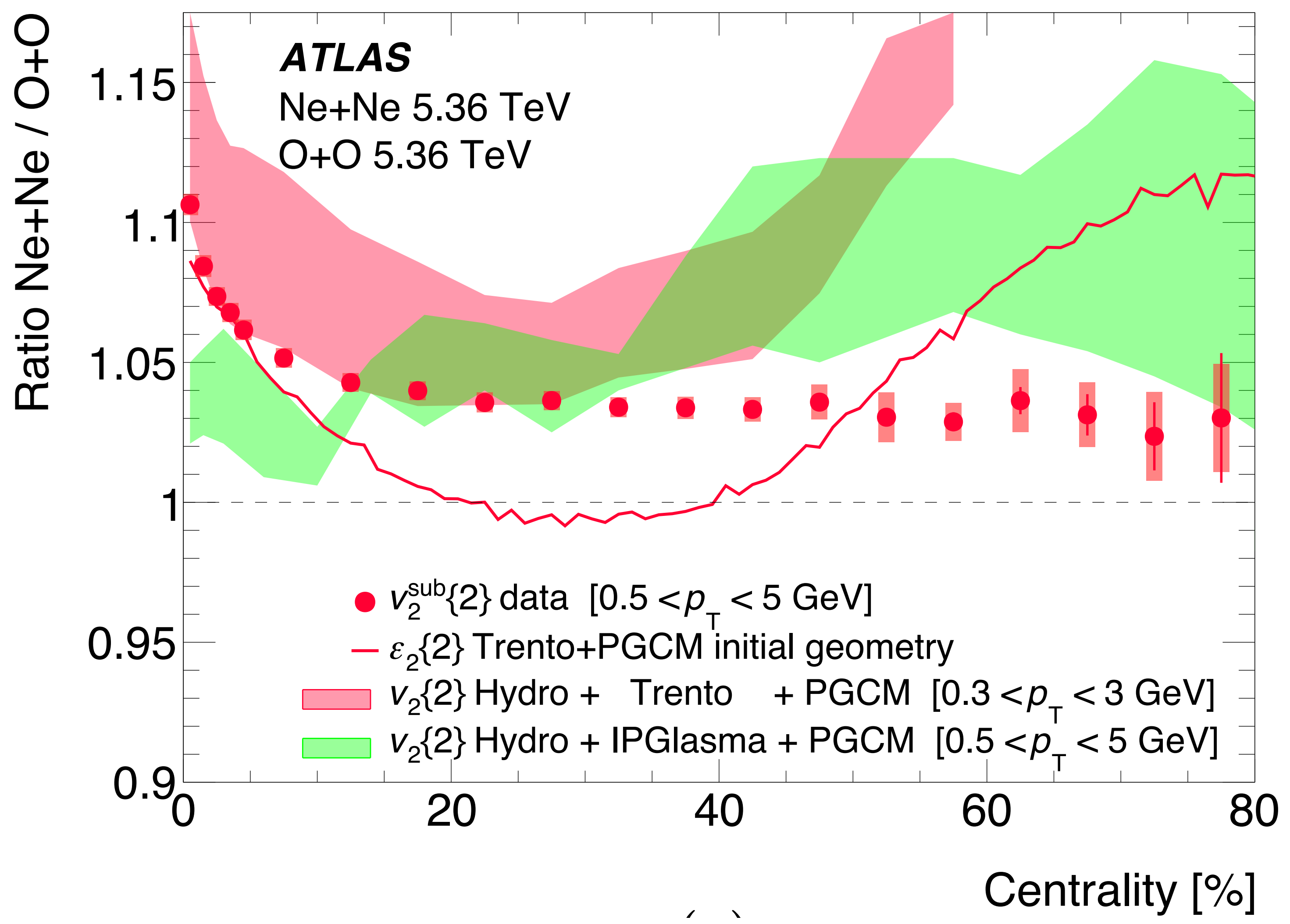
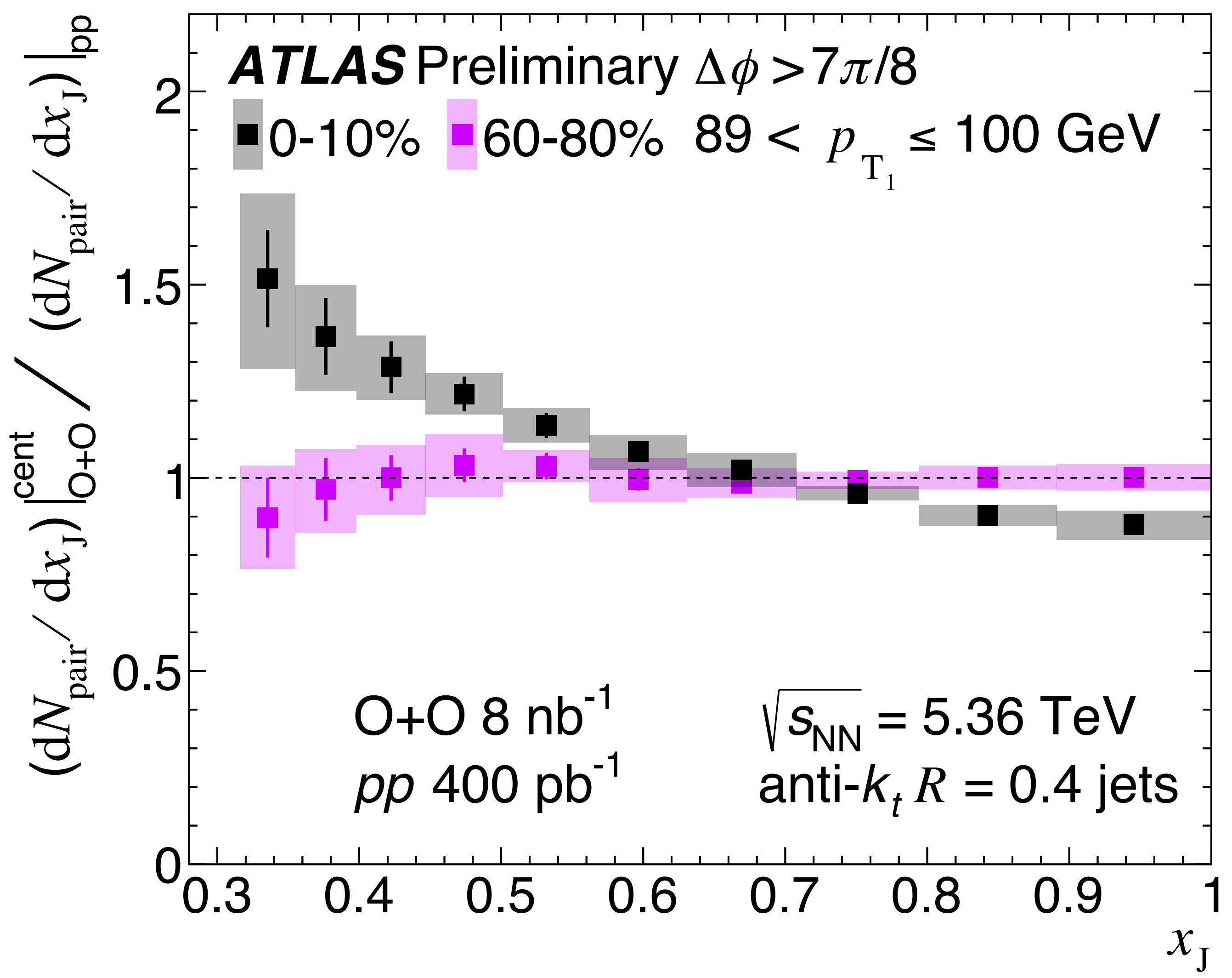
- Across different collision systems, dijets experience a similar medium once event activity (forward energy) is matched — independent of nuclear size or geometry

Summary of ATLAS results

- **Flow results**: qualitatively consistent with hydrodynamical response; v_n ratios reveal sensitivity to nuclear geometry (^{20}Ne vs ^{16}O)
- **Dijet results**: direct evidence of quenching in smallest symmetric ion system to date; systematics to be further reduced in final publication. Single jet, gamma-tagged jet results forthcoming

While we cannot yet conclude that QGP is definitively formed in O+O and Ne+Ne collisions, the medium produced in these light ion systems exhibits behavior strikingly similar to that in heavy ion collisions





Light Ions, Big Impact

Start of **2025 O+O** data taken: **July 4**, 2025

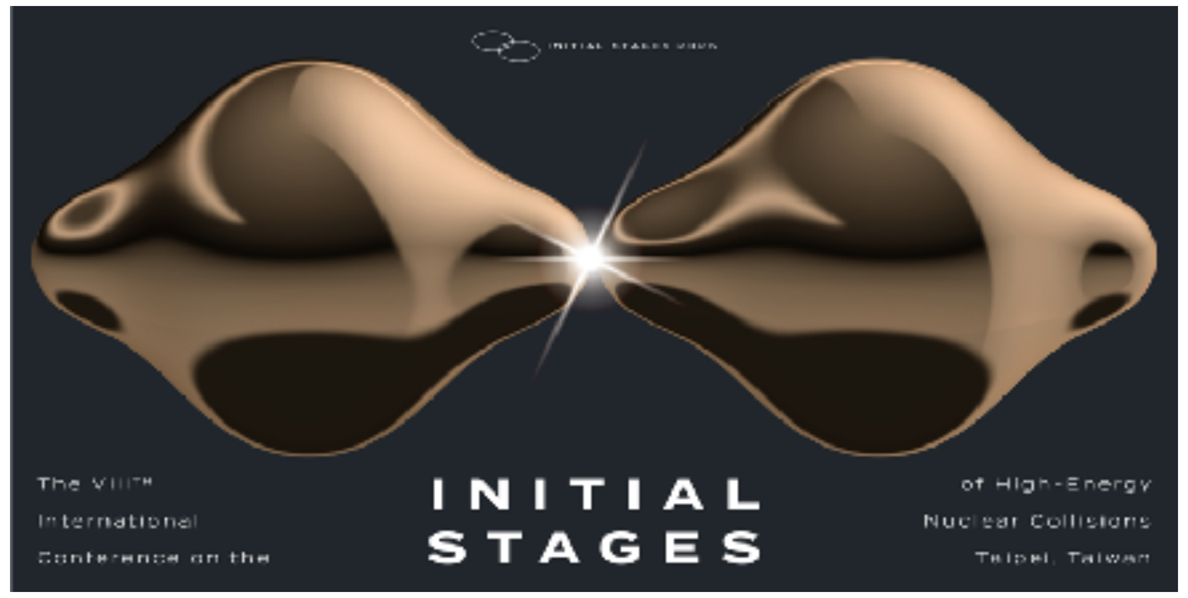
First flow results:

- ATLAS paper submitted — Sep 8, 2025
- CMS preliminary — Sep 8, 2025
- ALICE paper submitted — Sep 9, 2025

2010 Pb+Pb data taken: **Nov 7** - Dec 6

First results released:

- ALICE flow submitted: Nov 11, 2010
- ALICE multiplicity submitted: Nov 11, 2010
- ATLAS dijet submitted: Nov 29, 2010
- CMS dijet submitted: Feb 9, 2011

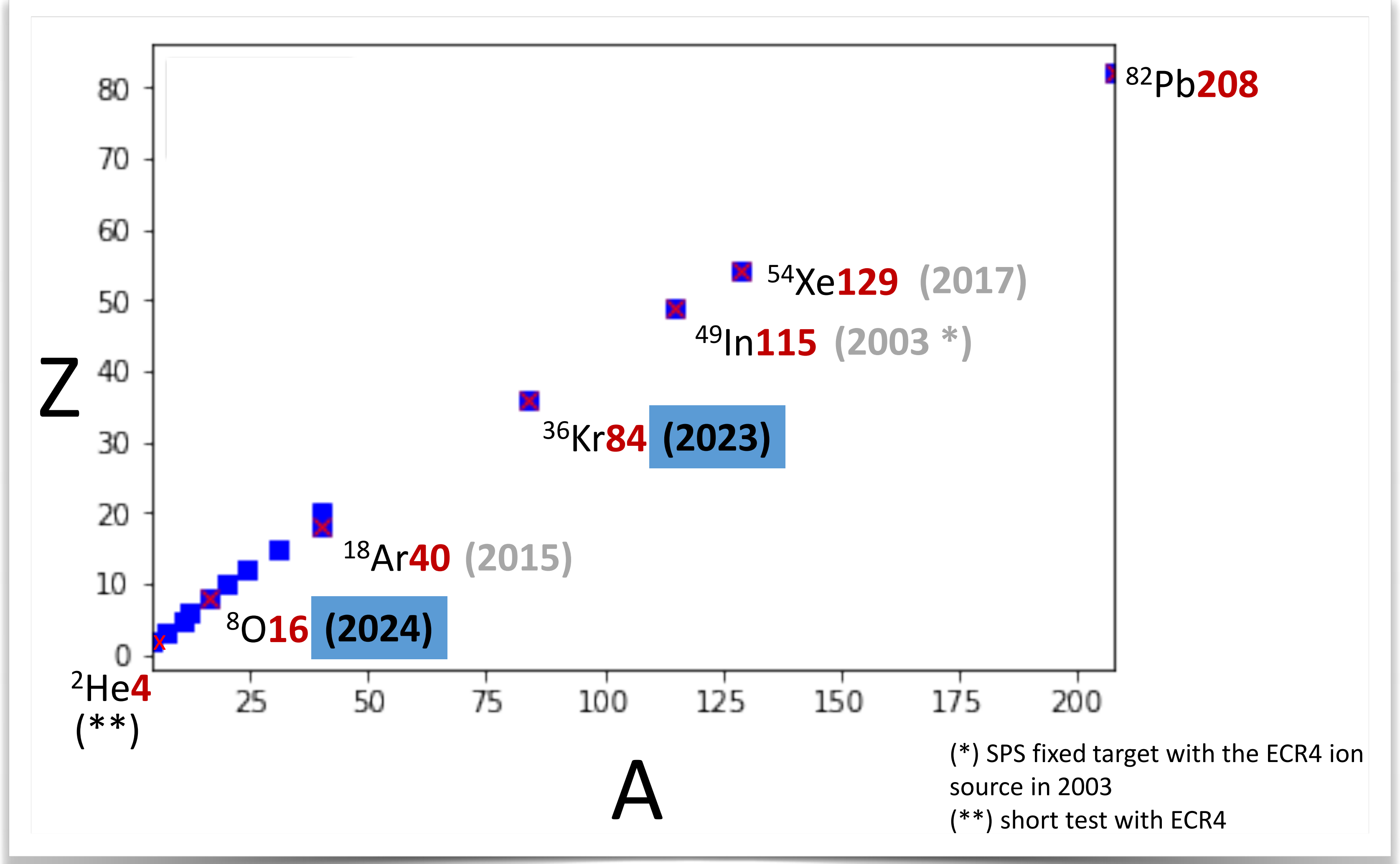


- Light-ion results set the stage for an exciting IS2025
- The momentum carried forward into a dedicated CERN Jamboree event
- The last time with such excitement was after the very first Pb+Pb collisions

Keep the momentum

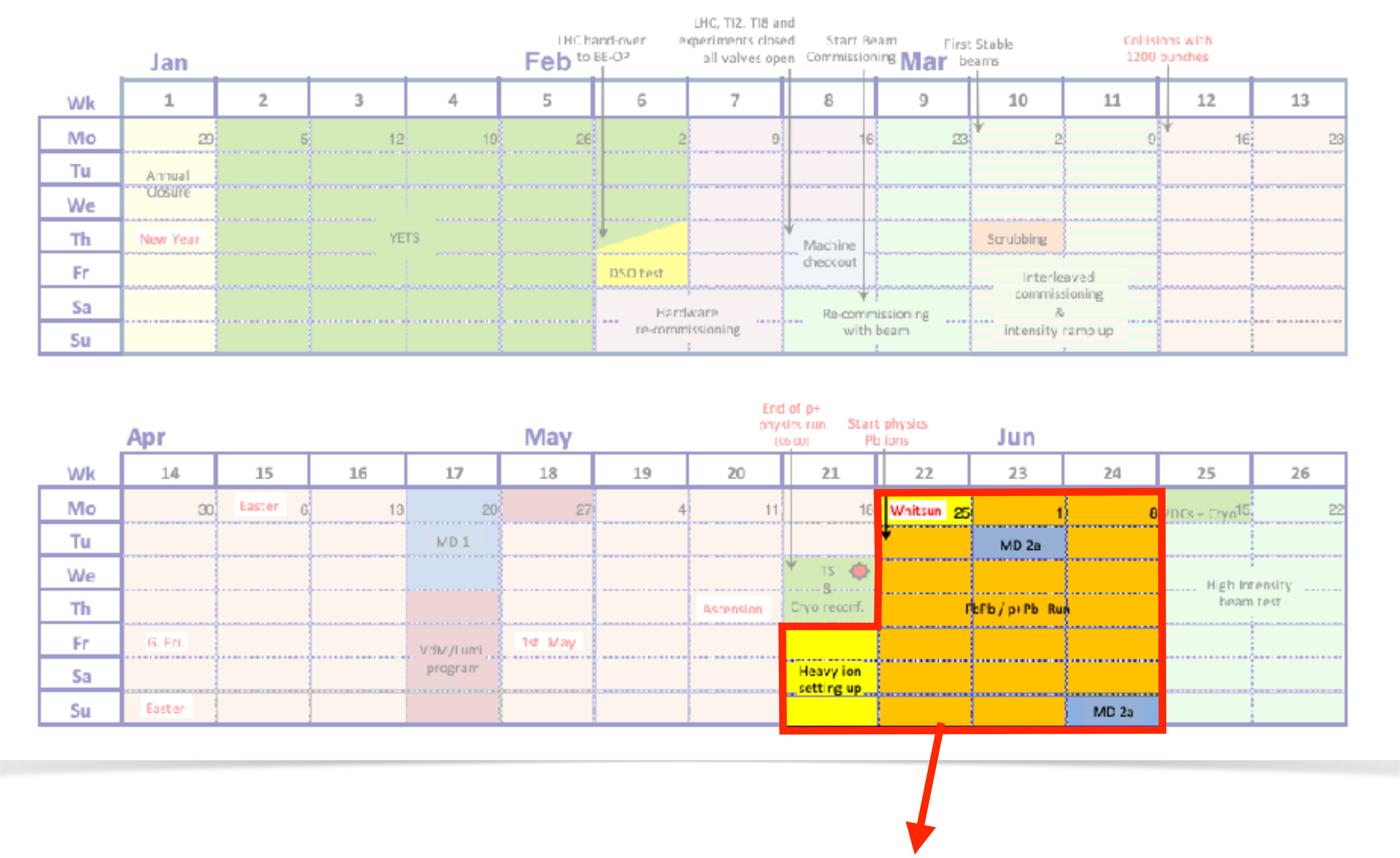
Starting to wonder if Pb+Pb or p+Pb still the best option for 2026

- Wouldn't it be **good** to have another light ion run with species lighter or heavier than ^{16}O?
- Perhaps even **better**: a run with two ion species — one lighter and one heavier than ^{16}O?



Light ion workshop
Reyes Fernandez, 11.11.2024

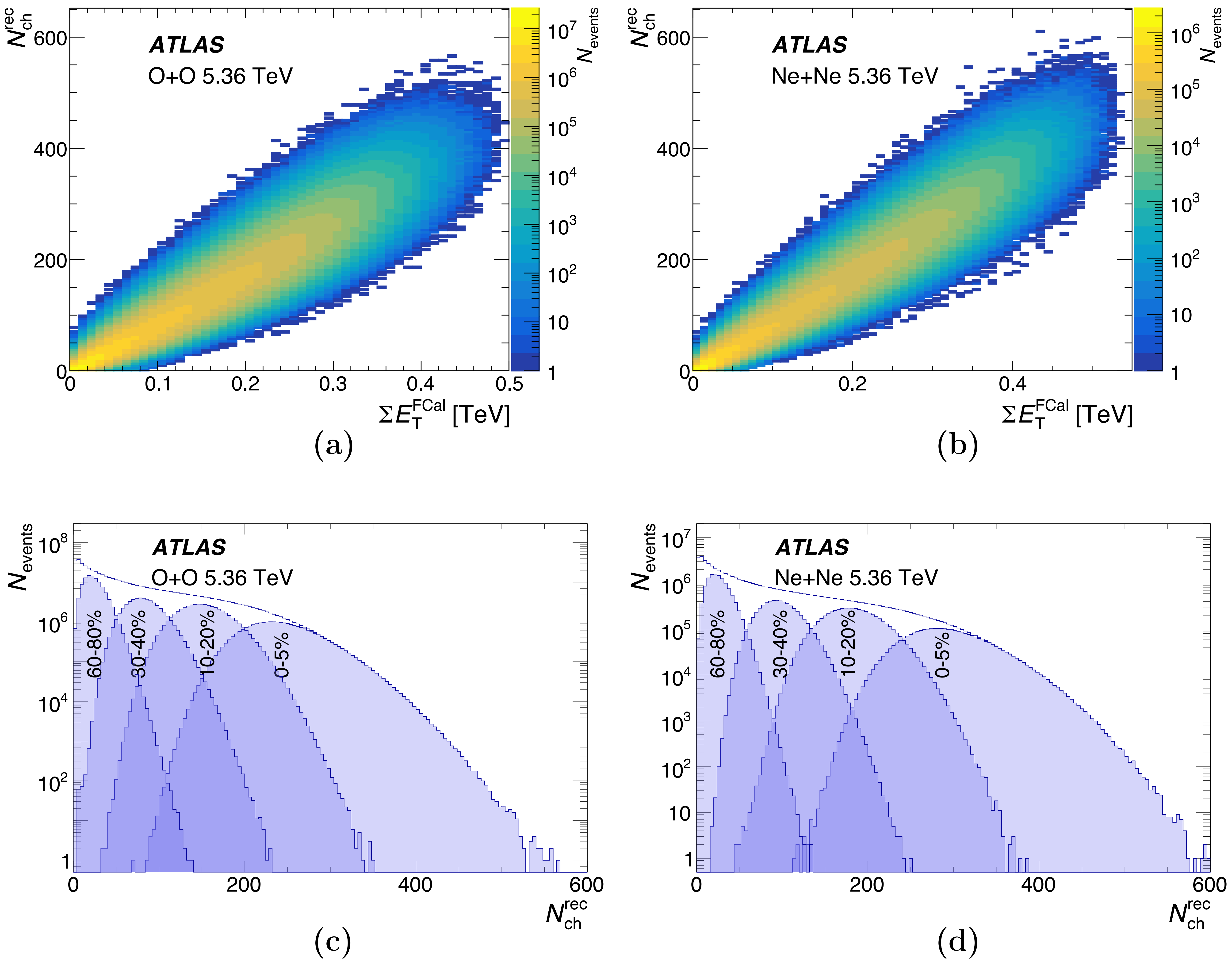
2026-LHC-v0.5



Another heavy ion run (~3 weeks) at LHC scheduled in summer 2026 Pb+Pb or p+Pb

Backup Slides

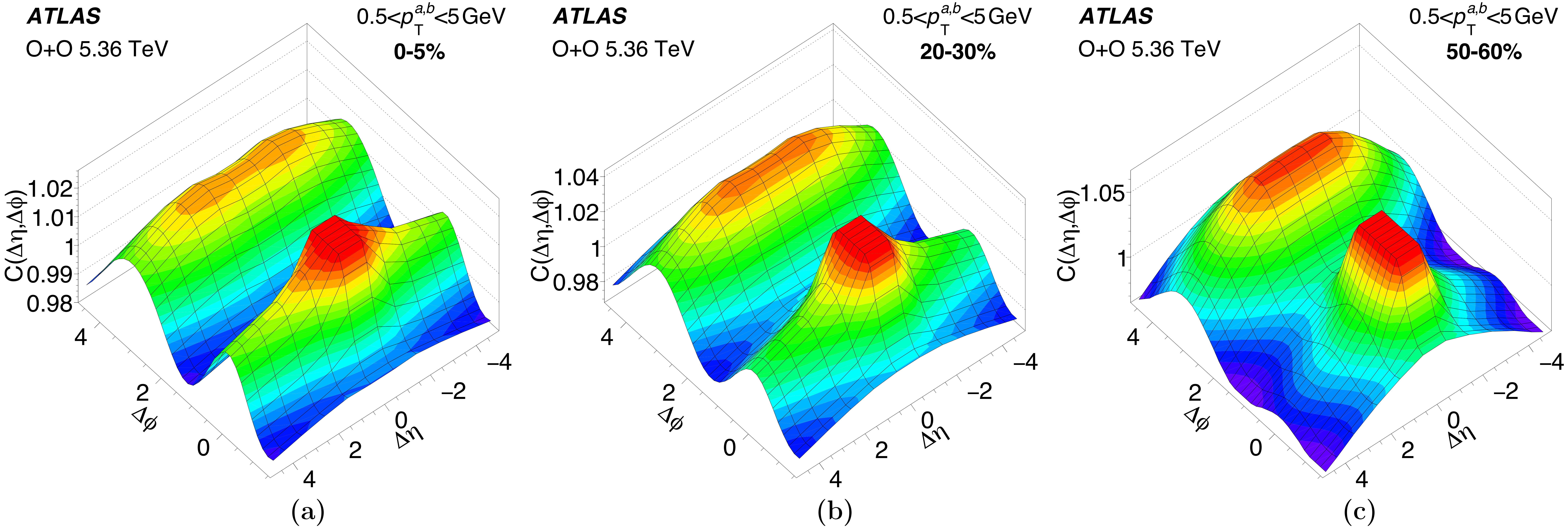
Centrality vs. multiplicity



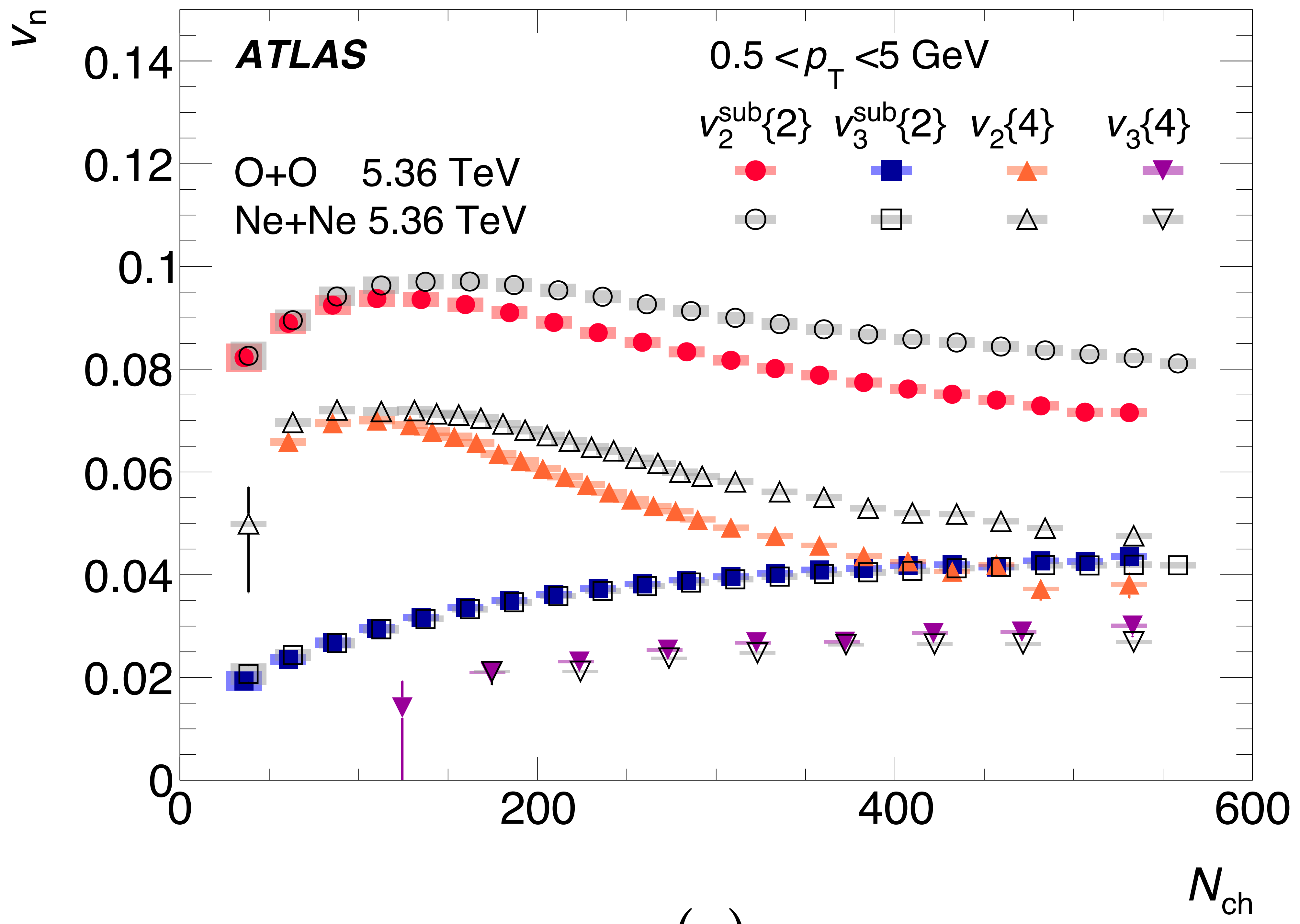
(a) (b) (c) (d)

Correlation between

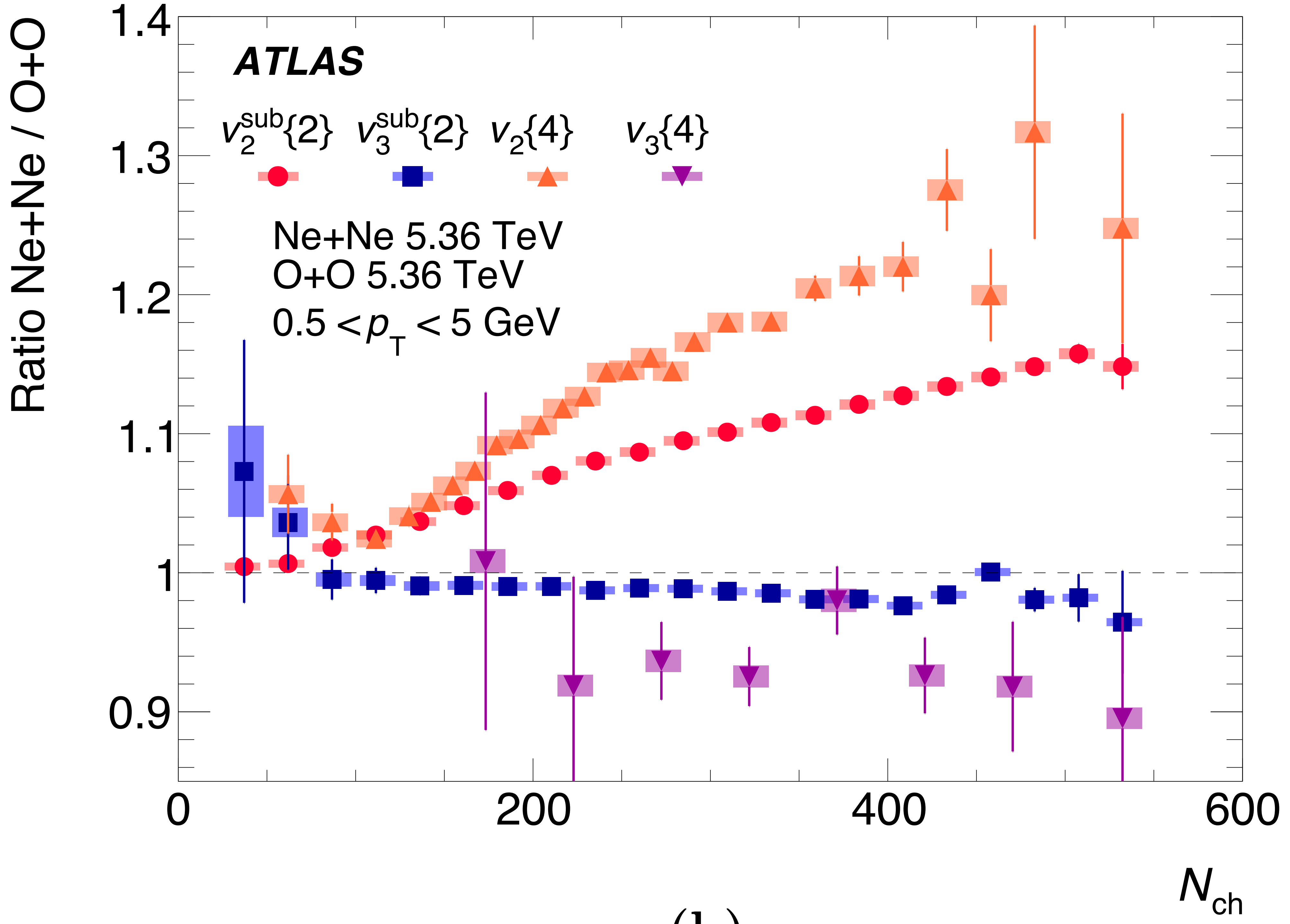
Two particle correlation



Two particle correlation vs. four particle cumulant



(a)



(b)

Flow systematics

Source	harmonic order	0–40% [%]	40–70% [%]
1. MC closure	v_2–v_4	1	1
2. Track selection	v_2	0.5	0.5
	v_3	0.75	0.75
	v_4	1.5	1.5
3. Tracking efficiency	v_2–v_4	0.25	0.25
4. Centrality definition	v_2	0.2	0.2–0.6
	v_3	0.2–1.0	1–2
	v_4	0.2	0.2–0.6
5. Residual pileup	v_2–v_4	0.2	0.2
6. Event-mixing	v_2	0.25	0.25
	v_3	0.5	0.5
	v_4	1	1
7. Peripheral reference	v_2	0.5	0.5–3
	v_3	0.75–3.5	3.5–12
	v_4	1.0–4.5	4.5–20
8. Flattening procedure	v_2–v_3	0.25	0.25

Dijet momentum balance systematics