Flow and transverse momentum fluctuations in Pb+Pb and Xe+Xe collisions with ATLAS: assessing the initial condition of the QGP

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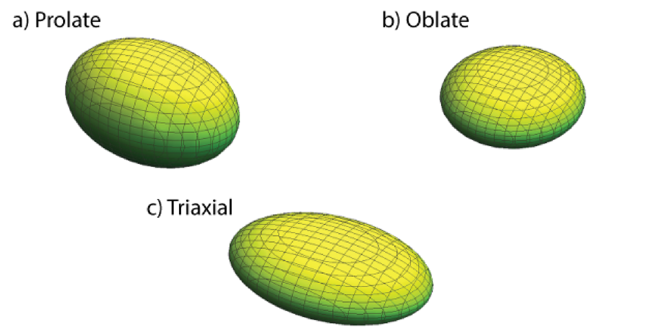
Physics Motivations



1. **Correlations** between **flow harmonics v_n** for n=2,3,4 and **mean transverse momentum p_T** in ^{129}Xe+^{129}Xe and ^{208}Pb+^{208}Pb collisions at $\sqrt{s_{NN}}$=5.44 TeV and 5.02 TeV are potentially sensitive to the **shape** and **size** of the **initial geometry**, **nuclear deformation** and **initial momentum anisotropy**.
2. **v_n-p_T correlations** show strong dependencies on **centrality**, **harmonic number n**, **p_T** and **pseudorapidity range**.
3. **Current models** qualitatively describe the overall centrality and system-dependent trends but **fail** to quantitatively reproduce all features of the data: therefore a correlator is a good observable to investigate the available models.
4. In central collisions, where models generally show good agreement, the **v_2-p_T correlations** are **sensitive** to the **triaxiality of the quadruple deformation**. This work shows strong evidence for a triaxial deformation of the ^{129}Xe nucleus from high-energy heavy-ion collisions.

The ρ_n Correlator

$$\rho_n = \frac{cov_n}{\sqrt{var(v_n^2)}\,c_k}$$

$$cov_n = \langle\langle v_n^2 \,\partial p_T\rangle\rangle$$

$$var(v_n^2) = \langle v_n^4\rangle - \langle v_n^2\rangle^2$$

$$c_k = \langle\langle \partial p_T \,\partial p_T\rangle\rangle$$

Origin of v_n-p_T Correlations

In Relativistic Viscous Hydrodynamics the rapid expansion converts **spatial anisotropy in the initial state** into **momentum anisotropy in the final state**; therefore eccentricity vectors ϵ_n show good correlation with n-order azimuthal flow vectors V_n. [Int. J. Mod. Phys. A 28 (2013) 1340011], [Phys. Rev. C 85 (2012) 024908]

The size of the overlap region also leads to fluctuations in the **radial flow**, reflected by the average transverse momentum of particles in each event.
Smaller transverse size in the initial state are expected to have a stronger radial expansion and therefore a larger p_T. [Phys. Rev. C 85 (2012) 044910],[Phys. Rev. C 85 (2012) 044910]

⇒ Dynamical Correlations between v_n and p_T in the final state are expected.

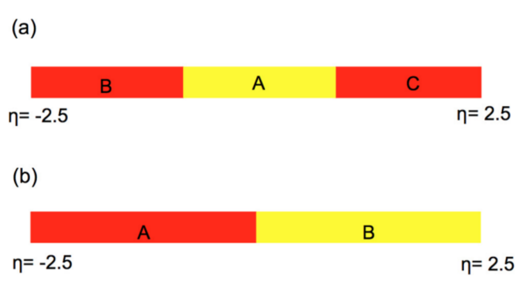
Triaxiality

Nuclei with density distribution as $R(\Theta,\Phi) = R_0(1+\beta[\cos\gamma Y_{2,0} + \sin\gamma Y_{2,2}])$ are less deformed. β: magnitude of deformation, γ=(0, 60, 30) angle for prolate, oblate and max triaxiality ($2r_2$=r_1+r_3) cases. [Atom. Data Nucl. Data Tabl. 109-110 (2016) 1]
For Even-even nuclei (^{208}Pb) shape is measured by low energy spectroscopy while for odd nuclei like ^{129}Xe models are applied; in addition, the ρ_n measurement allows to study their deformation.

v_2 and ρ_2 follow the parametric form $v_2^2 \simeq a + b\beta^2$ and $\rho_2 \simeq a' + b'\cos(3\gamma)\beta^3$, where **a, a'** are the **lowest at high centrality** and b and b' represent the deformation (together with β) and they do not depend on centrality. Therefore in **central collision** are expected the **strongest effects of deformation** on flows.[Phys. Lett. B 784 (2018) 82],[Phys. Rev. C 100 (2019) 044902]

The Subevent Method

The event is divided into **three rapidity ranges**, a, b, and c. **4-particle correlators** are constructed by choosing two particles from a and one particle each from b and c.
Dijets contributions are **suppressed**, since they can only produce particles in two subevents.
Cumulants can be based on two subevents as well. In this case, two particles each are chosen from b and c, which effectively suppresses contributions from intrajet correlations, but not from interjet correlations.

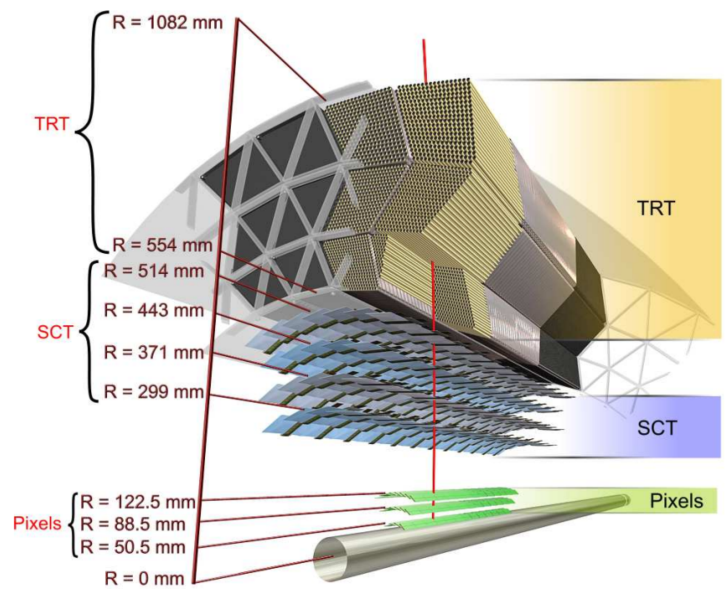


The HI ATLAS detector and triggers

The trigger system: level-1 (L1) + high-level trigger (HLT)

- **Inner Detector (ID)**⇒ charged particles at |η| < 2.5 [Si Pixel, Si Microstrip (SCT), straw-tube transition-radiation tracker (2 T axial field)]
- **Forward Calorimeters (FCal)**⇒ 3 layers, longitudinal in shower depth, at 3.2 < |η| < 4.9
- **Zero-Degree Calorimeters (ZDC)**⇒ ±140 m from IP, neutrons and photons at |η| > 8.3

The experimental centrality definition based on the final-state particle multiplicity N_{rec} is smeared by fluctuations in the particle production process.
A **better centrality estimator** is the **total transverse energy ΣE_T** in FCal at 3.2 < |η| < 4.9.
Nrec is applied at mid rapidity η < 2.5 but is less performing



Data set and Event/Track Selection

ATLAS datasets and Track Reconstruction:

- **Xe+Xe**: **3 μb^{-1}** of minimum-bias at $\sqrt{s_{NN}}$[=5.44 TeV (2017) (**p_T > 0.3 GeV** and **|η| < 2.5**)
- **Pb+Pb**: **22 μb^{-1}** min. bias + **470 μb^{-1}** ultracentral at $\sqrt{s_{NN}}$=5.02 TeV (2015) (**p_T > 0.5 GeV** and **|η| < 2.5**)

Further requirements:

- primary **vertex at |z|<100 mm** + closest **track to vertex < 2.5 mm**
- Pb+Pb pile up suppression: neutrons in ZDC and correlation with N_{rec}
- Centrality using ΣE_T (>42 GeV in Pb+Pb and >30 GeV in Xe+Xe)

Analysis Procedure and Subevents η ranges

cov_n, $var(v_n^2)$ and **c_k** measurement is done in 3 steps:

1. calculated in each event as the **average over all combinations** among particles in ranges of η and a p_T
2. **averaged over events** with comparable multiplicity ΣE_T
3. **recombined** in broader multiplicity ranges of the event ensemble to obtain statistically more precise results

Method	Default η selection	Alternative η selection
Standard	$\lvert\eta\rvert < 2.5$	$\lvert\eta\rvert < 1$
Two-subevent	$0.75 < -\eta_a, \eta_c < 2.5$	$0.35 < -\eta_a, \eta_c < 1$
Three-subevent	$0.75 < -\eta_a, \eta_c < 2.5$, $\lvert\eta_b\rvert < 0.5$	$0.35 < -\eta_a, \eta_c < 1$, $\lvert\eta_b\rvert < 0.3$
Combined-subevent	average of two-subevent and three-subevent results	

p_T selection for Xe+Xe	p_T selection for Pb+Pb
$0.3 < p_T < 2$ GeV, $0.5 < p_T < 5$ GeV, $0.5 < p_T < 2$ GeV	$0.5 < p_T < 5$ GeV, $0.5 < p_T < 2$ GeV

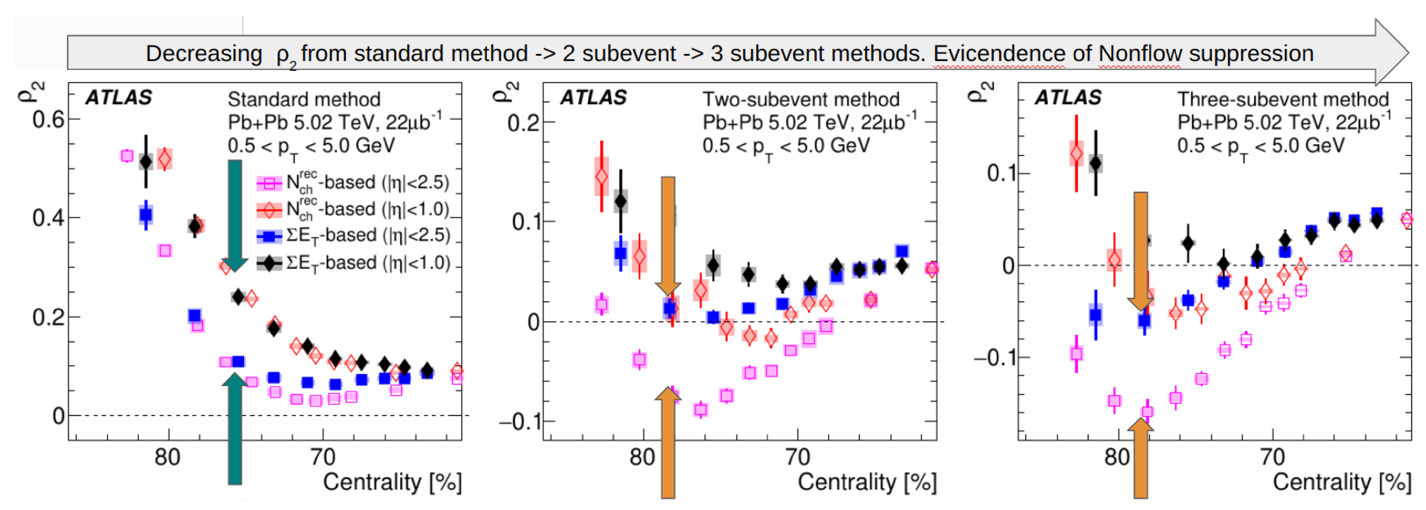
Event weights $w(\eta,\Phi,p_T) = d(\Phi,\eta)/\epsilon(\eta,p_T)$: d accounts for nonuniformities in the azimuthal acceptance.

Analysis of Results and Discussion

Centrality and Nonflow suppression

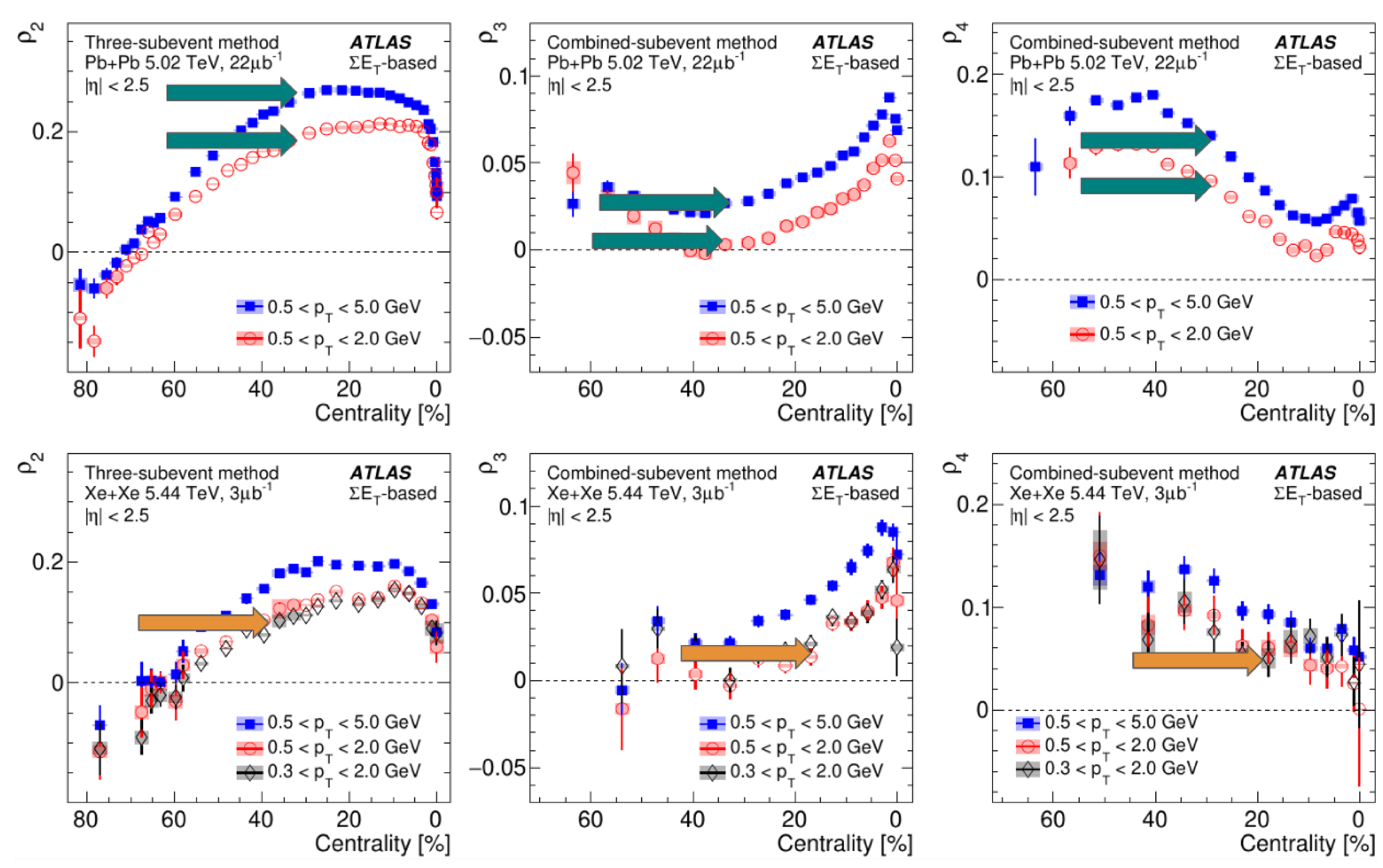
Reduction of ρ_2 from standard method in left panel, to the two-subevent method in middle and to three-subevent method in right is a robust proof of suppression of the nonflow correlations.
In middle and right plots:

1. ρ_2 values for the narrow |η|<1 range are much larger (red and black) than for |η|<2.5, therefore |η|<1 still have significant nonflow contributions;
2. differences between the ρ_2 values from the two event-activity estimators are large for both η ranges, reflecting the impact of centrality fluctuations;
3. No clear evidence for initial-state momentum anisotropy emerged.



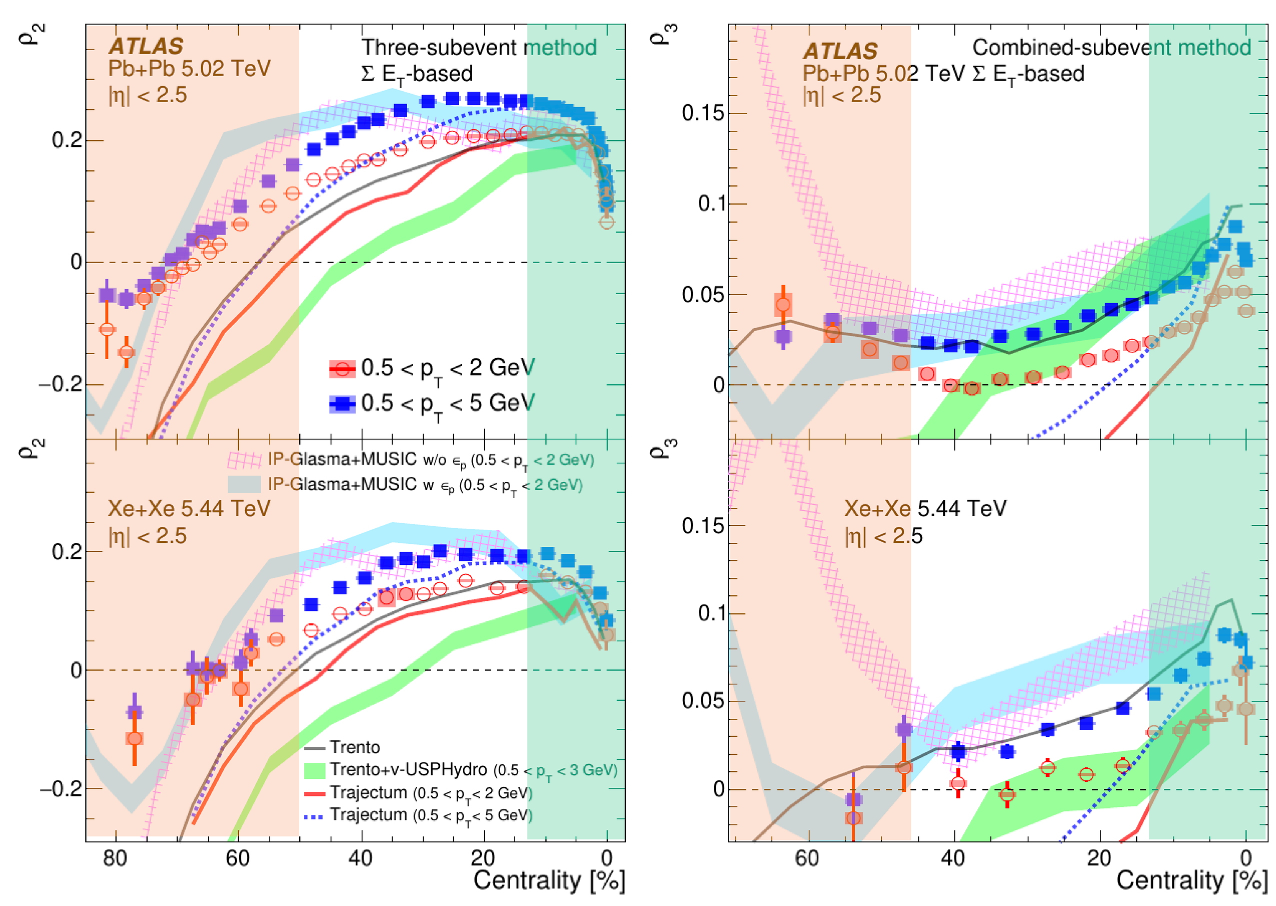
P_T-correlated effects

For both Pb+Pb and Xe+Xe the correlators are higher for wider P_T ranges (0.5-5 GeV/c^2).
In Xe+Xe, a lower P_T limit to 0.3 GeV/c^2 do not alter the correlations (black and red points). This is because bulk particles (low Pt) follows mainly hydrodinamics behaviour, without bringing new effects to the overall ρ_n definition.



Testing Models

At high centrality the nuclear deformations are important and all models show agreement with data.
In noncentral collisions, they show significant differences. Trento underestimates ρ_2 in all p_T ranges and overestimate ρ_3.
v-USPhydro and Trajectum underestimate both ρ_2 and ρ_3 values in noncentral collisions. IP-Glasma+MUSIC does not reproduce the experimental data.



^{129}Xe Triaxiality

Due to the large ^{129}Xe quadrupole deformation, β_{Xe} ~0.2, the ρ_2 is sensitive to the triaxiality γ_{Xe}. This is confirmed in Trento model by ρ_2 differences as a function of centrality for different γ_{Xe}. However p_T dependence is absent in Trento model.
To cancel out the p_T dependence, Xe+Xe and Pb+Pb ρ_2 ratios are compared with Trento model.
At high centrality, where the predicted ρ_2 show triaxiality dependence, the γ_{Xe} ~30 is favored (black line).
Therefore, flow measurements in central collisions can constrain the nucleus quadrupole deformation.