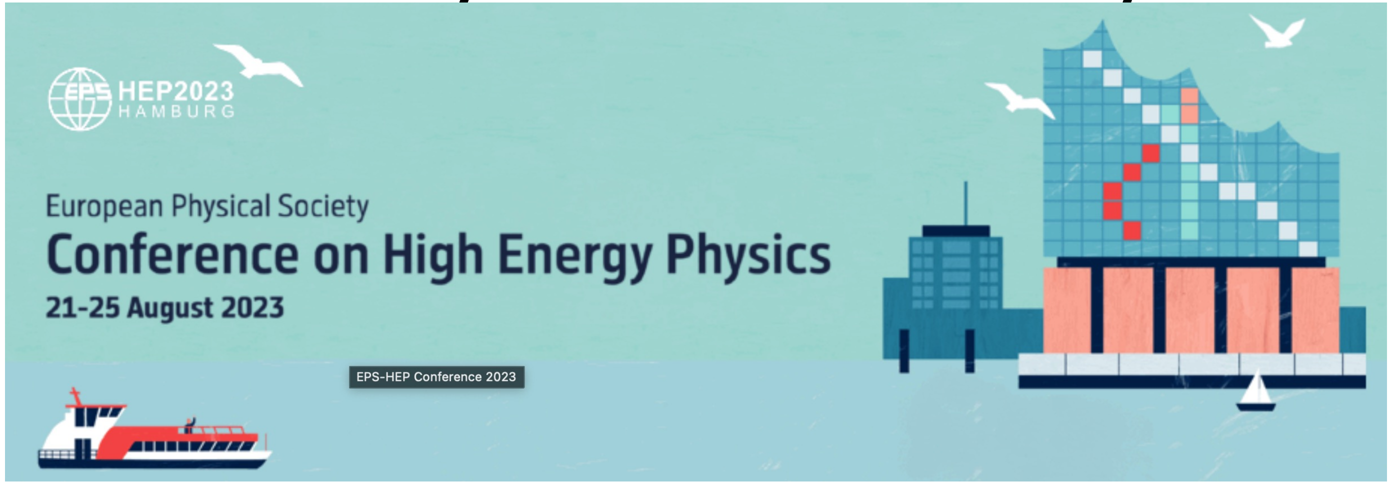
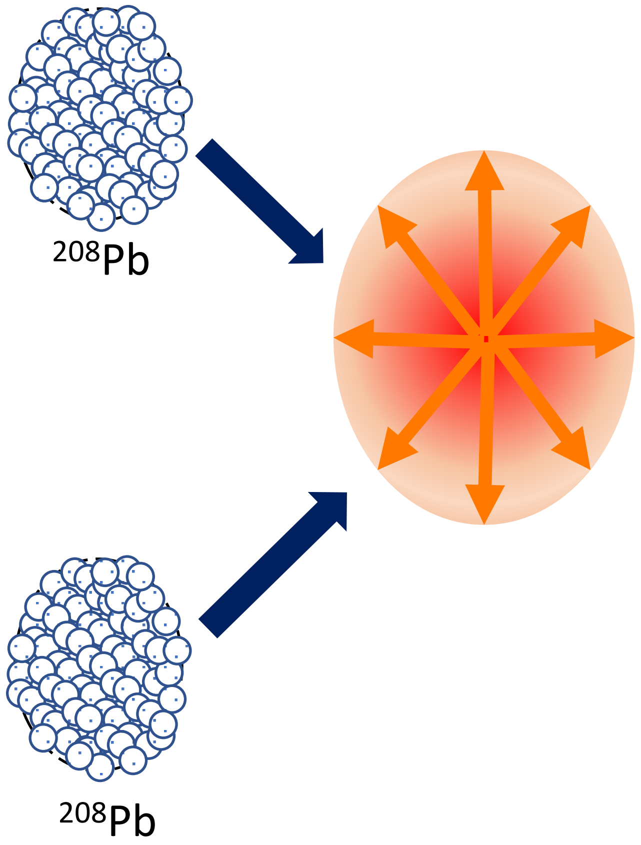
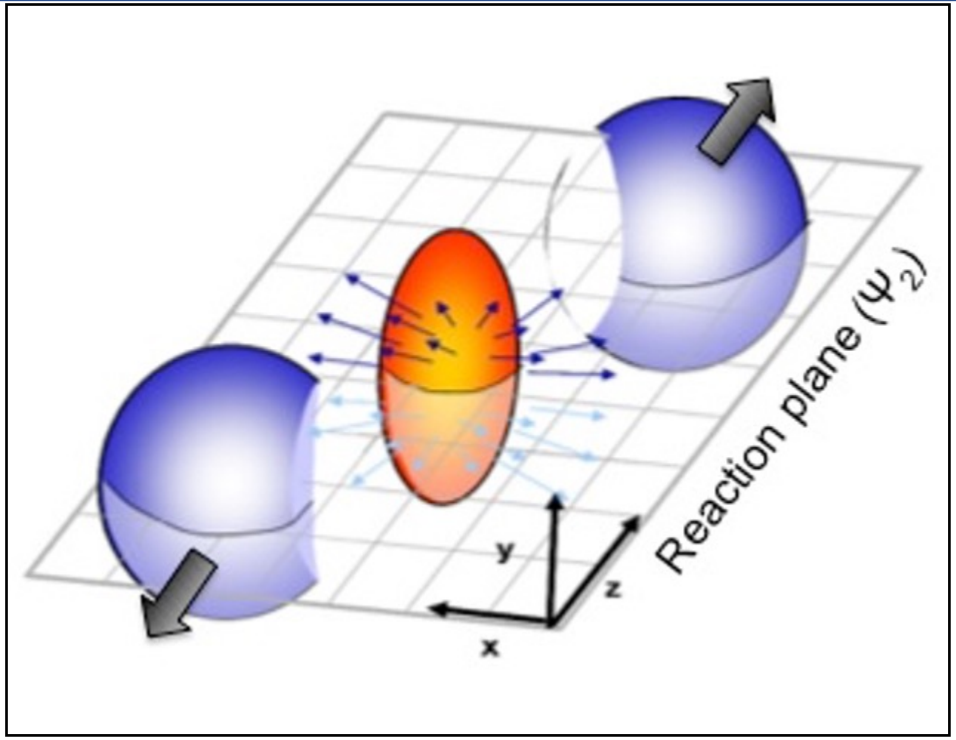
Measurement of collective dynamics in small and large systems with the ATLAS detector

Somadutta Bhatta for the ATLAS Collaboration
Stony Brook University

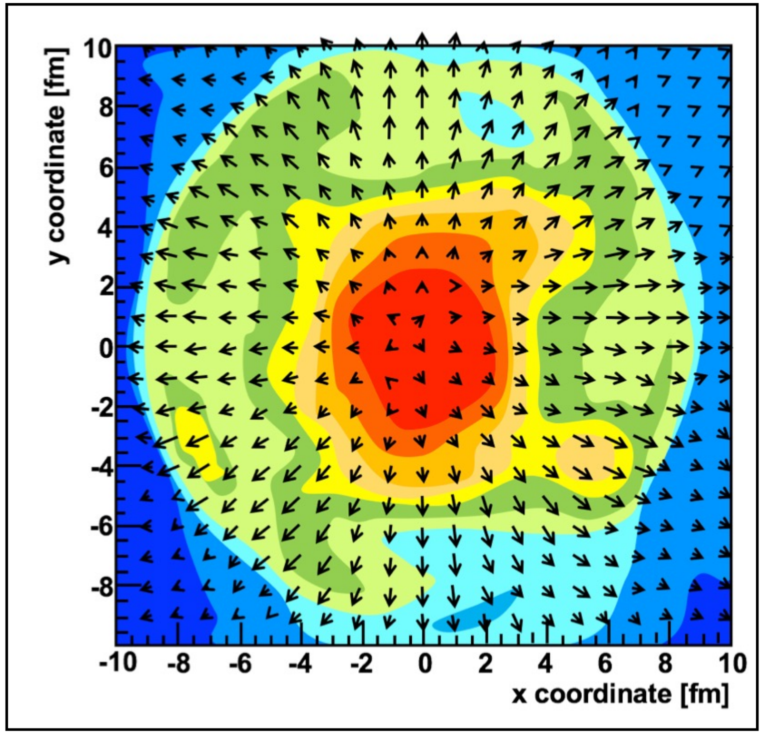


Collectivity in Heavy Ion Collisions





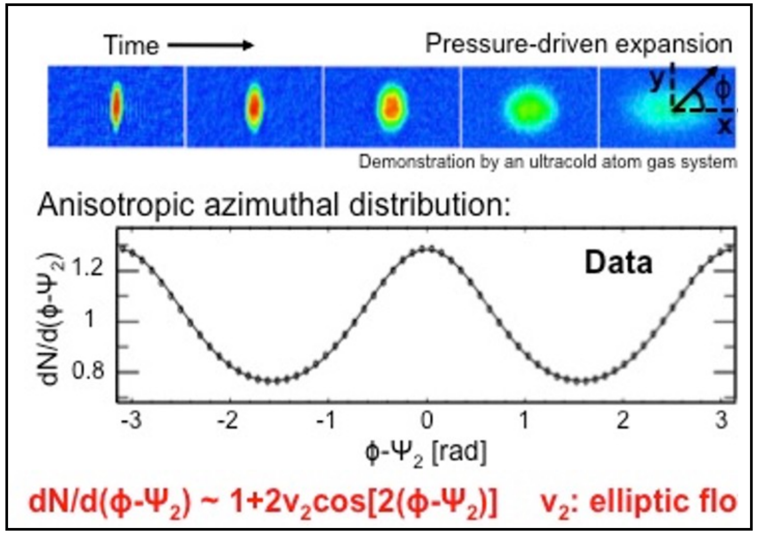
Geometrically anisotropic initial collision region

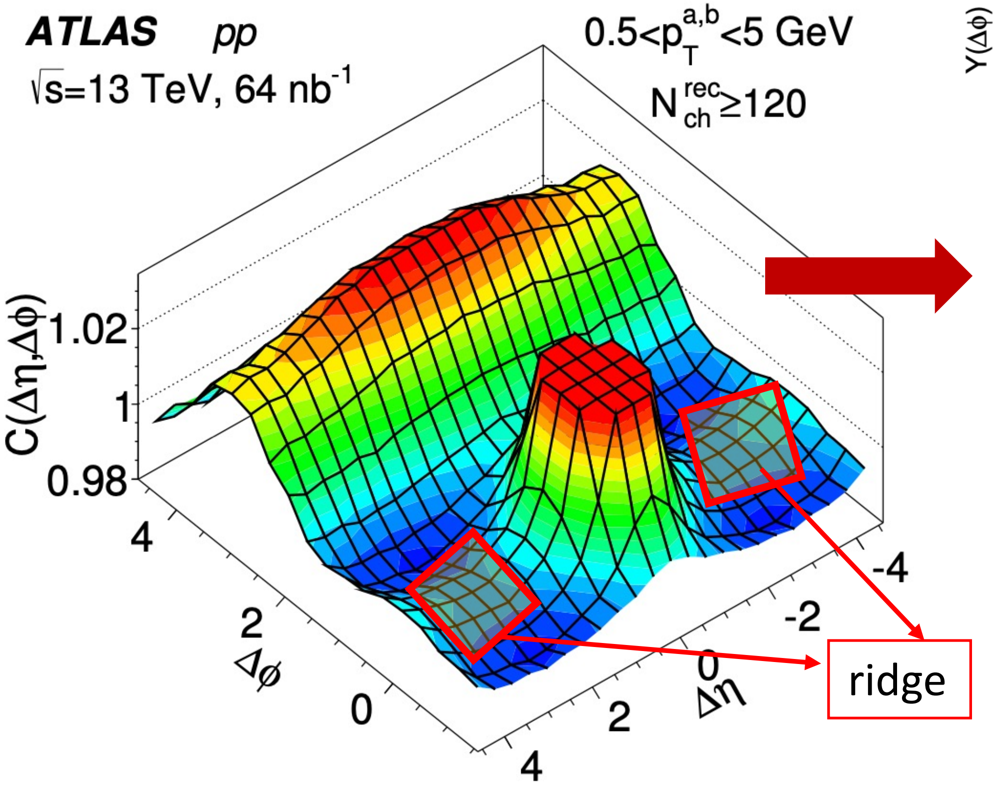


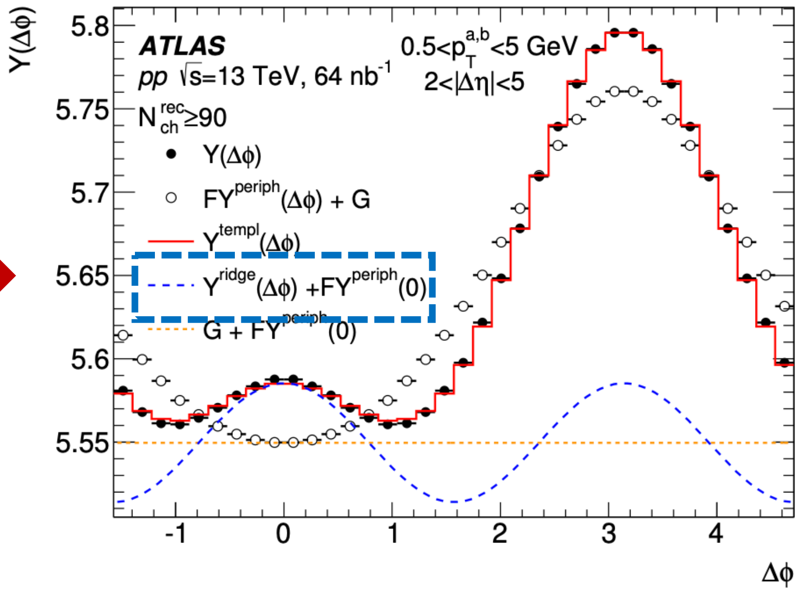
Temperature and flow profile of an A + A collision from a hydrodynamic model.

- Heavy Ion collisions produce a deconfined state of matter: Quark Gluon Plasma.
- Collectivity: characterized by Large Collective transverse emission of particles: Flow (contrast to random thermal motion).
- In HIC, Collective flow arises from both Geometrical effects and interactions between particles.

Collectivity in Heavy Ion Collisions



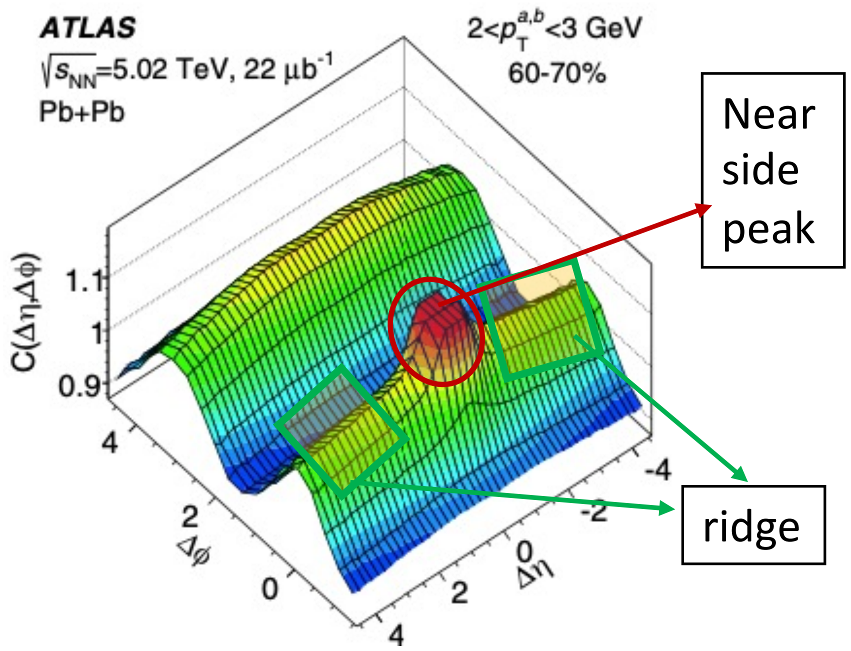




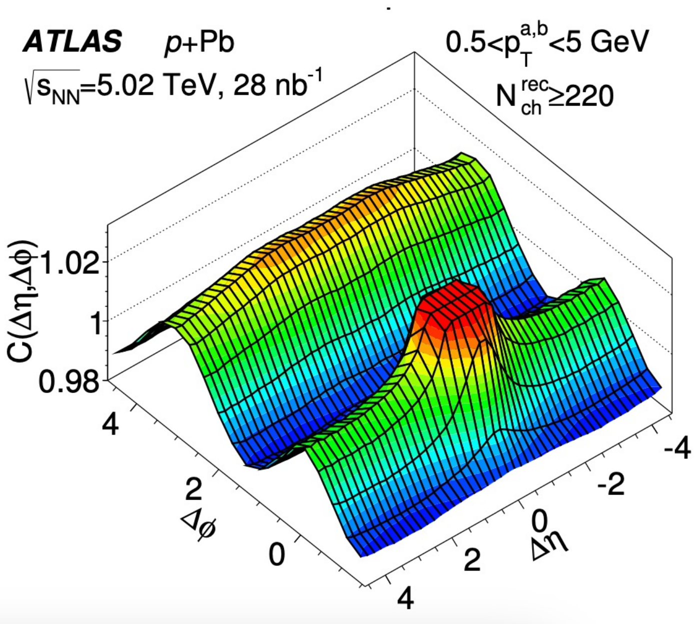
ATLAS, PRC 96 (2017) 024908

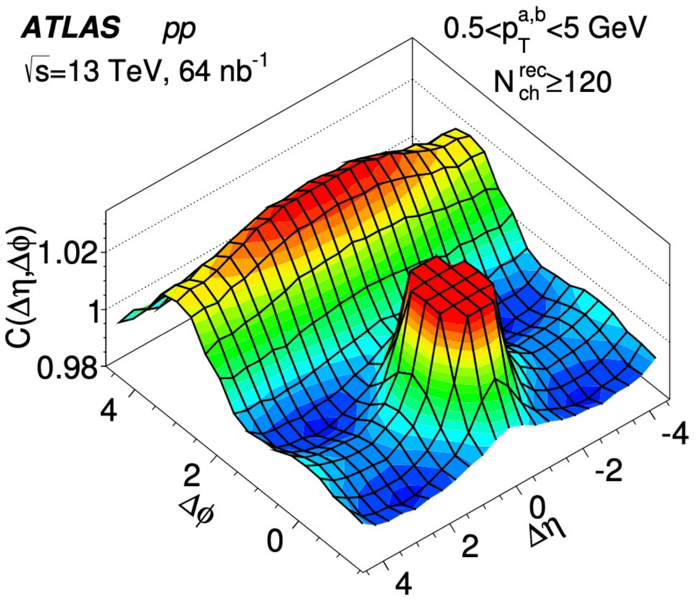
- Flow characterized by Fourier decomposition of azimuthal distribution: 0^{th} order: radial flow and 2^{nd} order coefficient: elliptic flow.
- Azimuthal projection of 2-dimensional $\Delta\eta - \Delta\phi$ is used to extract flow coefficients: Y_{ridge}
- The presence of ridge indicates the long-range behavior of flow: Global property

I. Correlation in small collision systems



ATLAS, EPJ.C (2018) 78:997





ATLAS, PRC 96 (2017) 024908

- Ridge is observed in Large as well as small systems like pp and p+Pb collisions.
- Question: in small systems like pp, what is the origin of the collective behavior?

Is it collective dynamics from early time or is it from semi-hard processes?

➢ CGC model suggests: hard/semi-hard processes from early times could describe the ridge in pp collisions. Dumitru et. al PLB697:21-25,2011

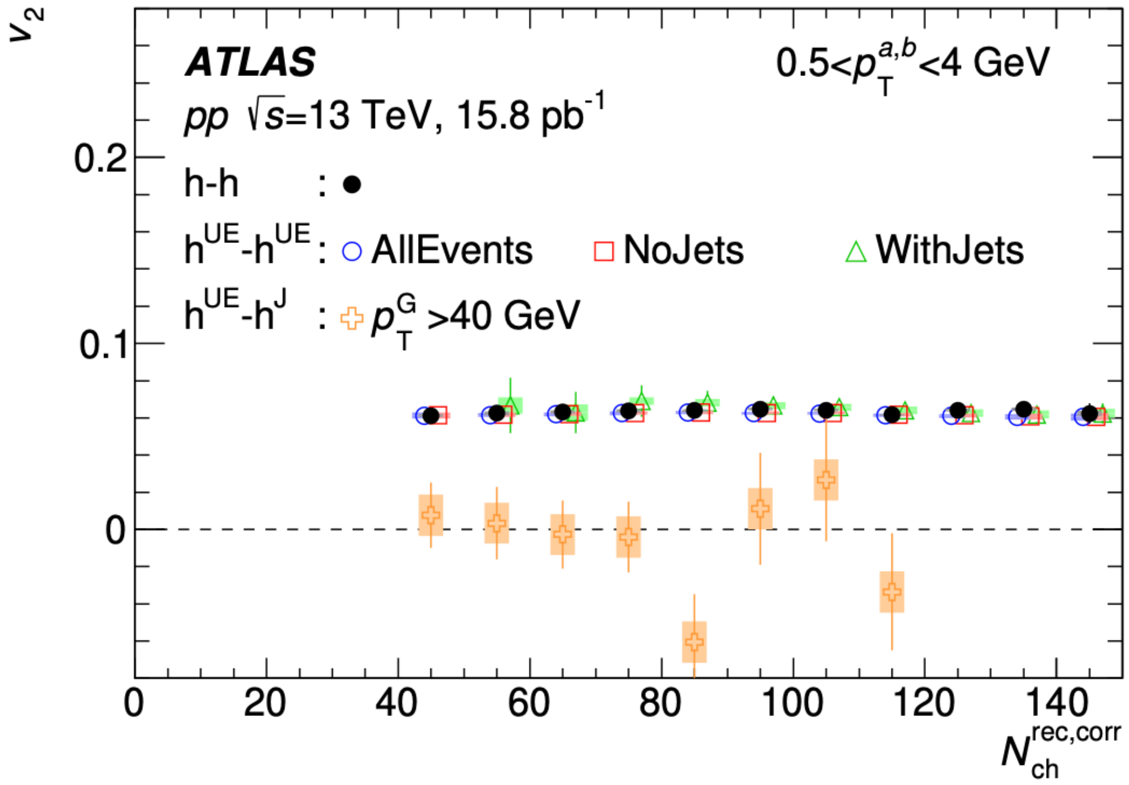
I. Sensitivity of flow to hard-scatterings

CERN-EP-2023-036, 2303.17357

- ATLAS has measured effect of hard/semi-hard processes (Jets) in flow measurement in pp@13 TeV.

- First, 5 types of correlation measures are defined:

1. **Inclusive (h-h):** Usual 2PC with all particles.
2. **AllEvents:** Remove tracks within $|\eta| < 1$ from jet above $p_T \geq 10$ GeV.
3. **WithJet:** Events with at least 1 jet above chosen threshold.
4. **NoJet:** Events with No jet above chosen threshold.
5. **h^{UE} - h^{J}:** Correlation between one particle from Jet, another from underlying event.



- Measured v_2 is insensitive to presence or absence of jets in an event.

- v_2 for **h^{UE} - h^{J} is consistent with zero:** particles from hard scattering processes with p_T <4 GeV do not contribute significantly to the long-range correlation in pp collisions.

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CERN-EP-2023-036, 2303.17357

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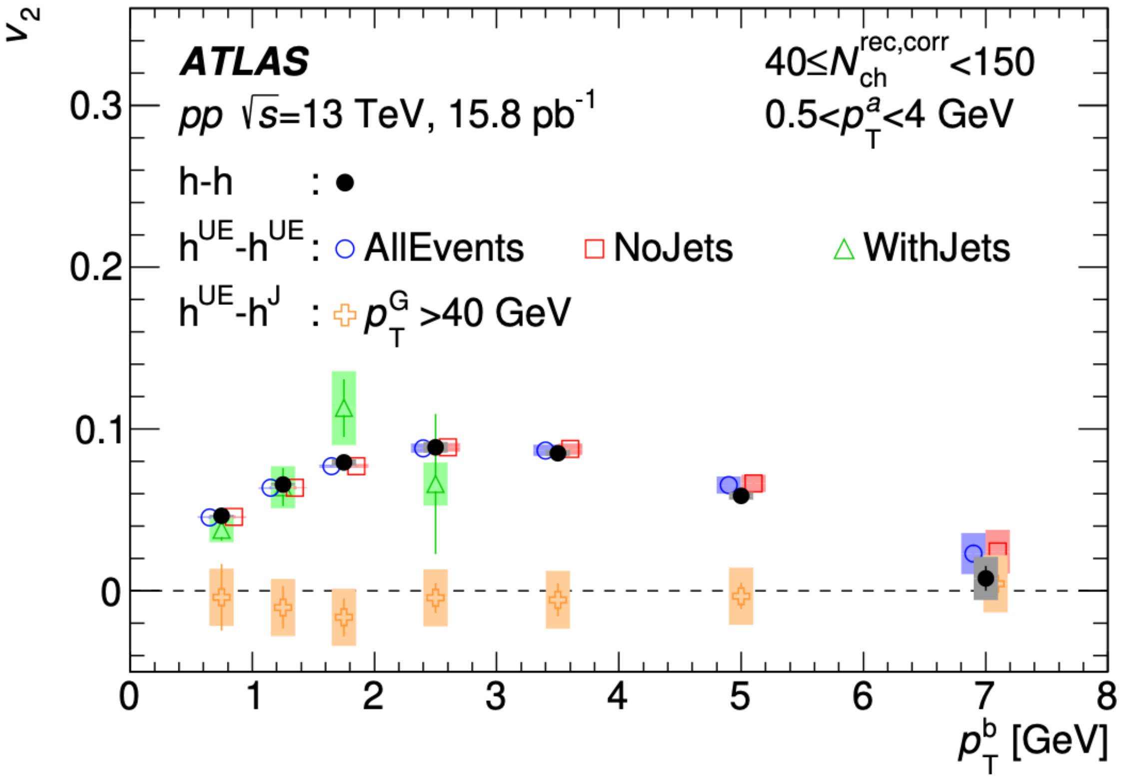

❖ Differential $v_2(p_T)$ is insensitive to presence or absence of jets in an event.

❖ $v_2(p_T)$ for **h^{UE} - h^{J} is consistent with zero:** particles from hard scattering processes with p_T <4 GeV do not contribute significantly to the long-range correlation in *pp* collisions.

I. Sensitivity of flow to hard-scatterings

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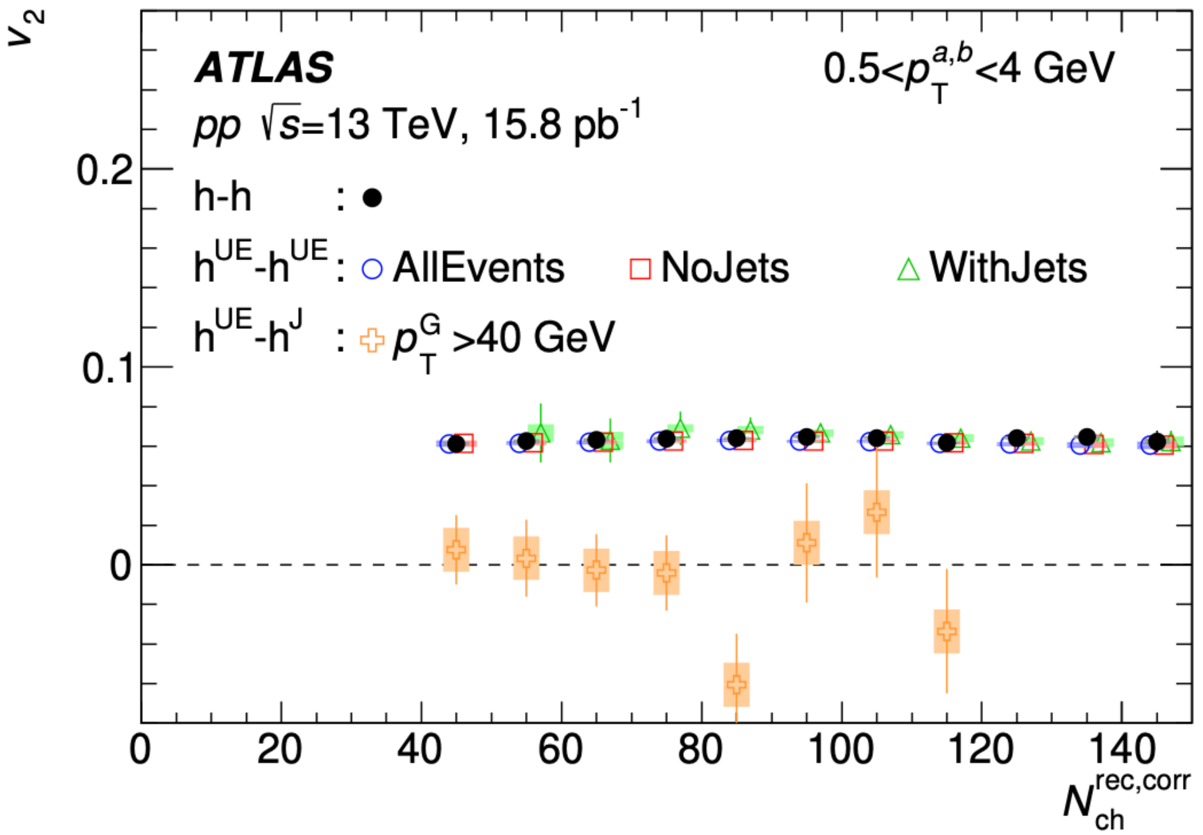
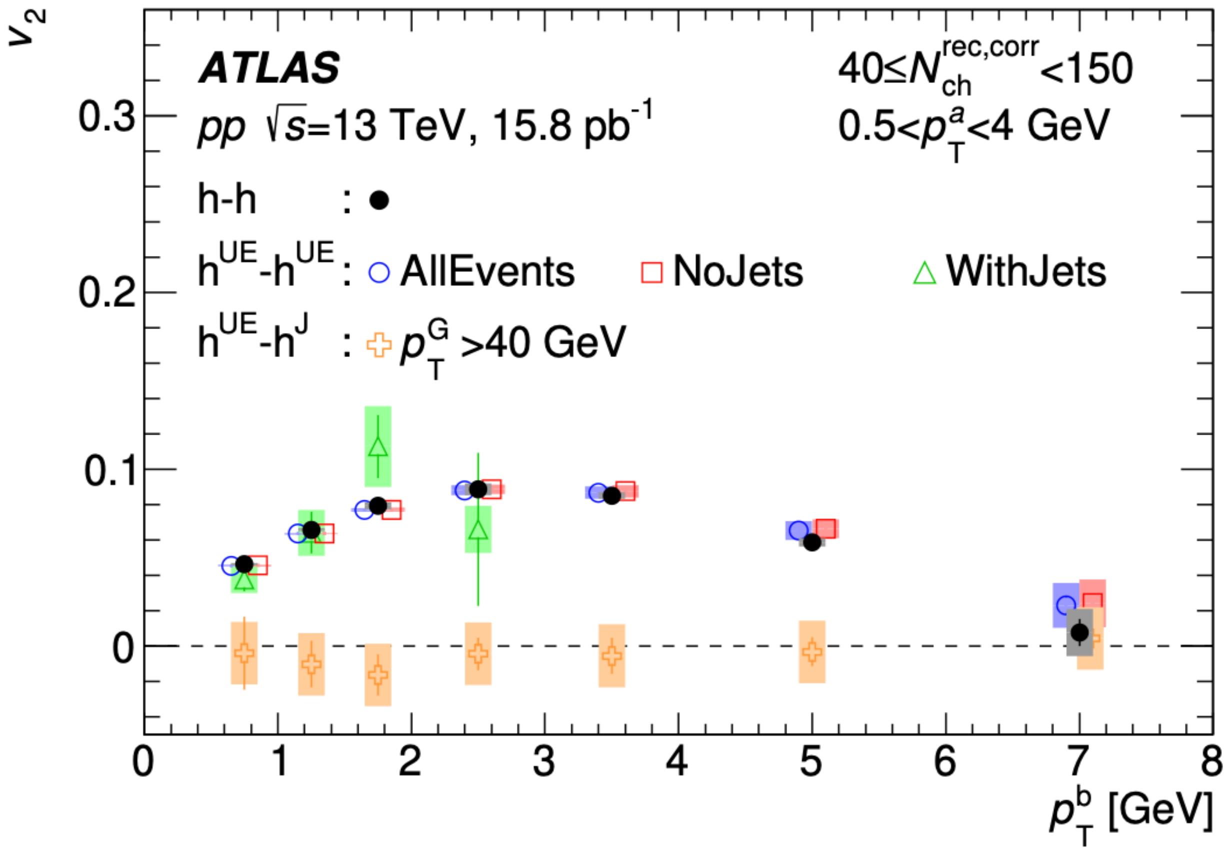
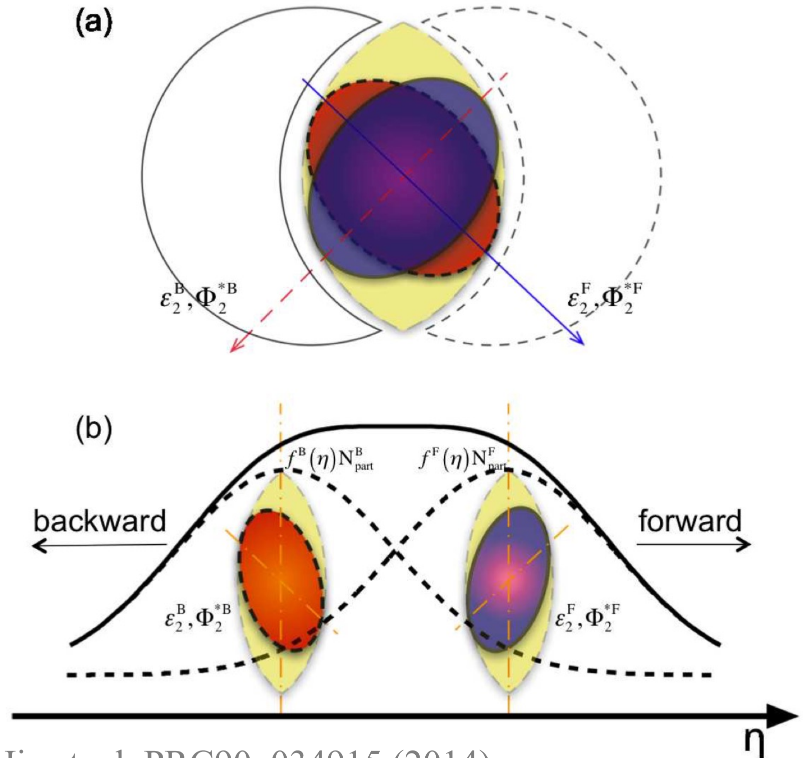




CONCLUSION: Hard scattering does not contribute to the long-range correlations
This measurement rules out hard processes contributing to the ridge.

II. Sensitivity of flow to sub-nucleonic fluctuations

- Owing to initial state fluctuations, deposited energy and transverse shape of the fireball is not boost invariant,



Jia et. al, PRC90, 034915 (2014)

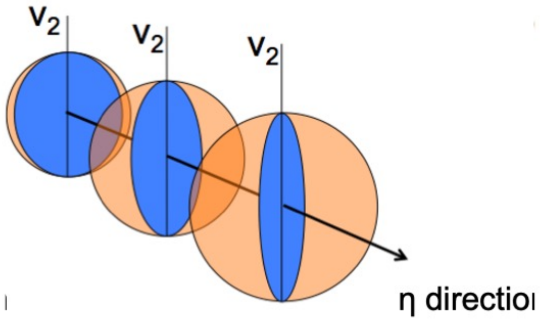
- Forward moving nucleons produce particles preferably in the forward direction, lead to an event- by-event torqued fireball.

Bozek et. al, PRC83:034911,2011

- Shape of overlap region is driven by eccentricities of Forward and Backward going participants.

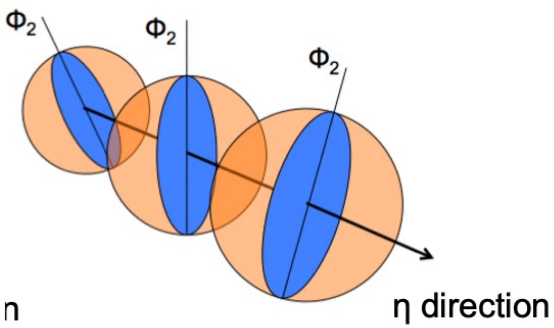
Jia et. al, PRC90, 034915 (2014)

Asymmetry of flow magnitude



$$v_n(\eta_1) \neq v_n(\eta_2)$$

Torque/twist of event plane



$$\Psi_n(\eta_1) \neq \Psi_n(\eta_2)$$

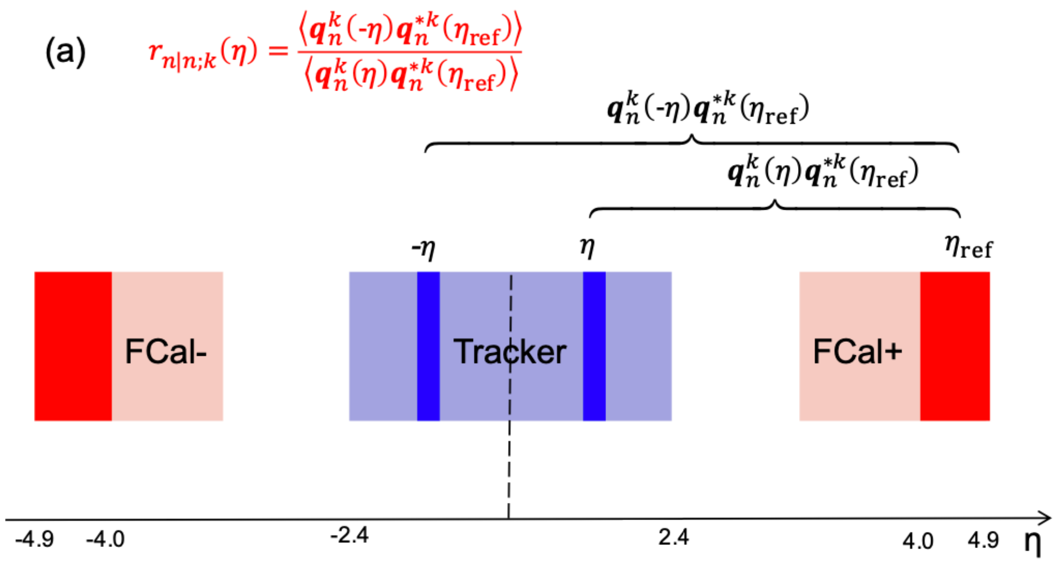
- Experimentally measured by correlating flow in widely separated η.

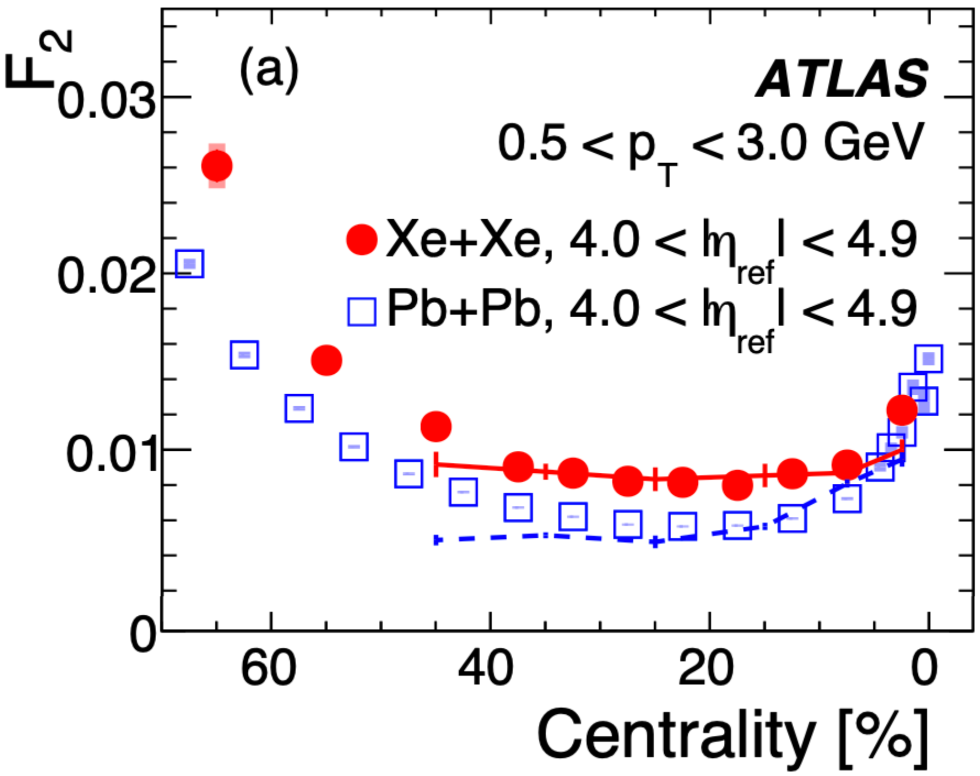
II. Sensitivity of flow to sub-nucleonic fluctuations

ATLAS-CONF-2022-020

$$r_{n|n}(\eta) = \frac{\langle \boldsymbol{v}_n(-\eta)\boldsymbol{v}_n^*(\eta_{\mathrm{ref}})\rangle}{\langle \boldsymbol{v}_n(\eta)\boldsymbol{v}_n^*(\eta_{\mathrm{ref}})\rangle}$$

$$r_{n|n}(\eta) = 1 - 2F_n\eta$$





ATLAS, PRL. **126** (2021) 122301

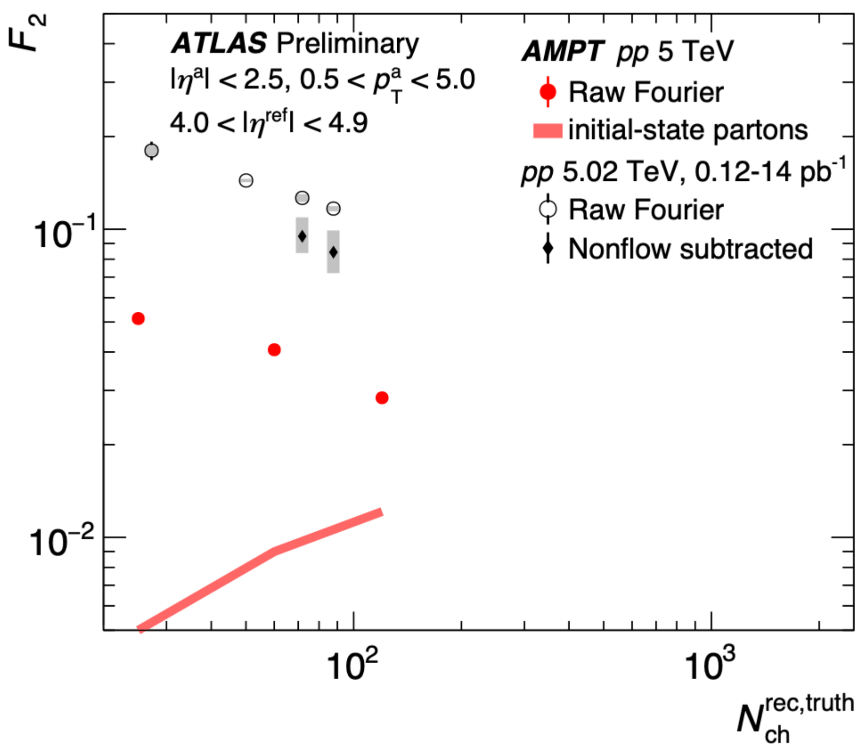
- Previous ATLAS measurement of decorrelation shows that state-of-art Hydro models fail to describe longitudinal structure of initial energy deposition.

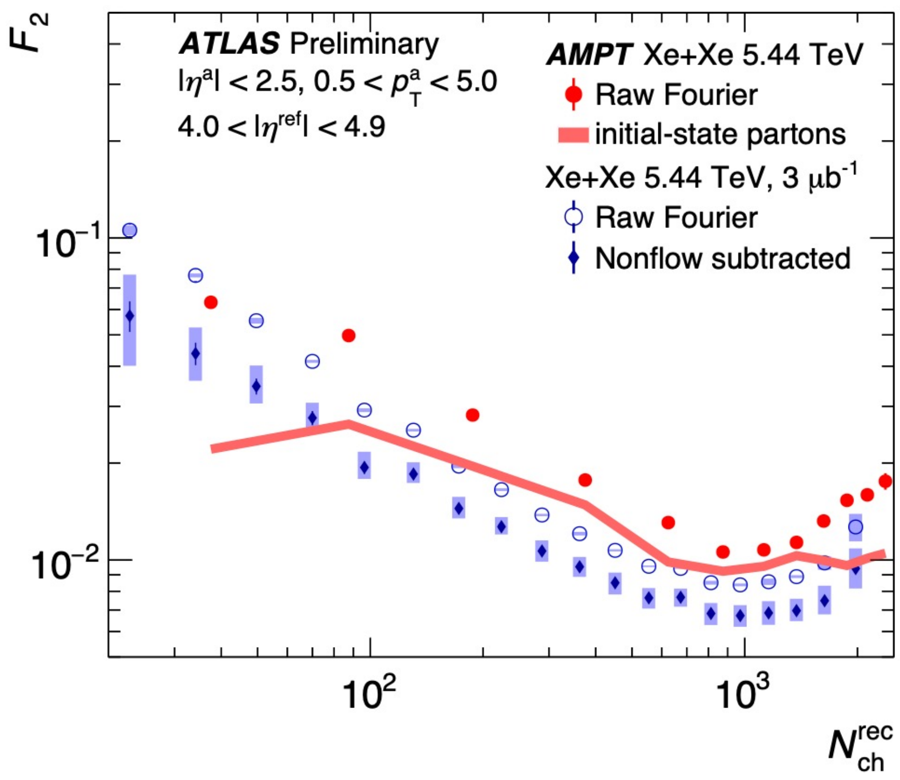
➢ Small systems are simpler to try to understand longitudinal structure:: pp collisions.

II. Sensitivity of flow to sub-nucleonic fluctuations

ATLAS-CONF-2022-020

- To probe role of sub-nucleonic fluctuations on collectivity, ATLAS measured the de-correlation of flow in pp and Xe+Xe collisions in the low multiplicity region.

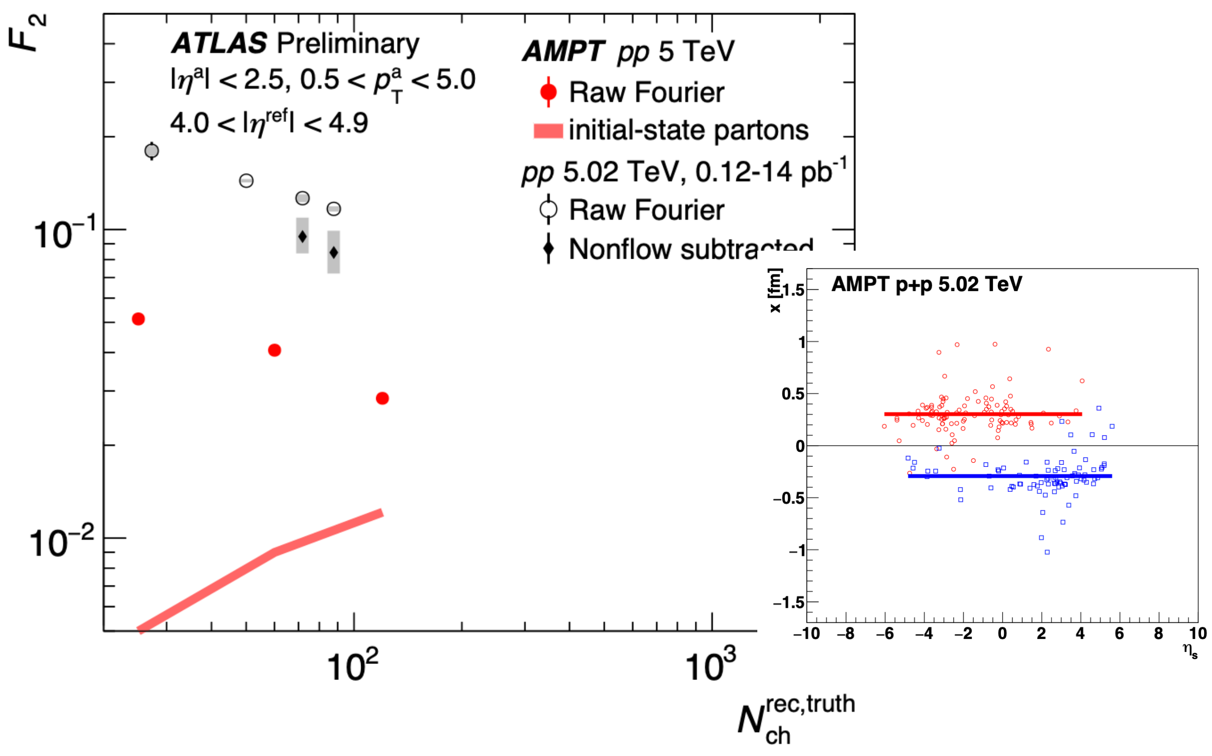


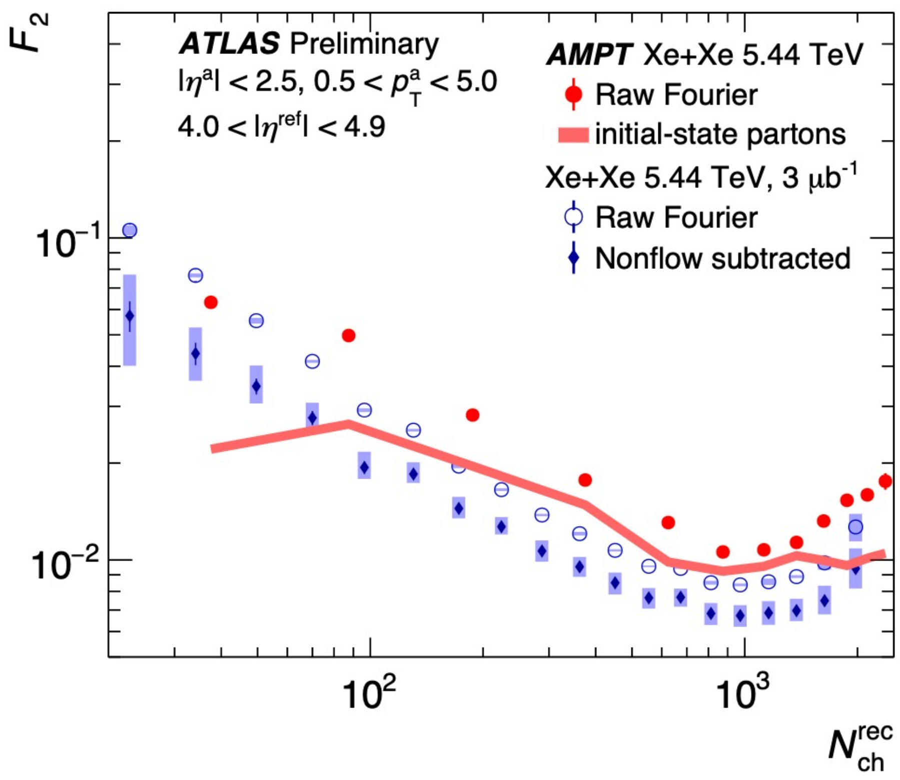


- ➢ At the lowest multiplicities, pp shows similar decorrelations(F_2) as Xe+Xe collisions.
- Events are dominated by single nucleon- nucleon configurations.
- ➢ At larger multiplicities, the F_2 values smaller in XeXe collisions.
- Mechanism of additional particle production is different in the two systems.

II. Sensitivity of flow to sub-nucleonic fluctuations

ATLAS-CONF-2022-020

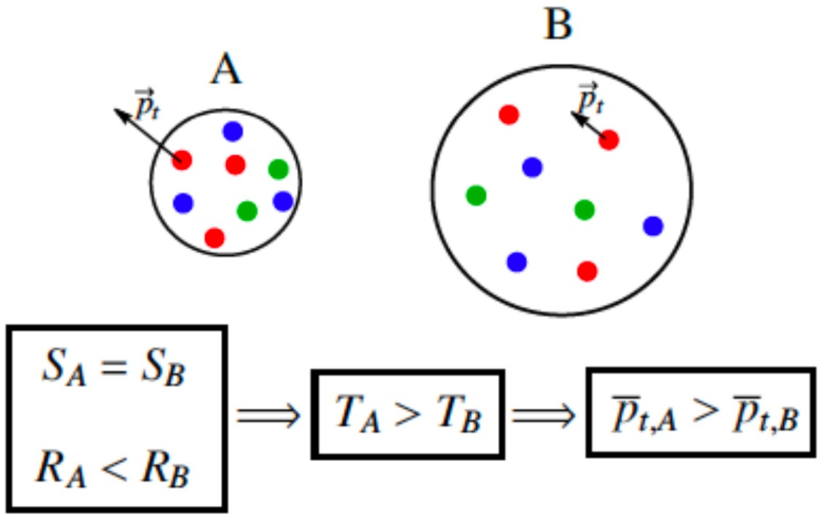




➢ Conclusion: Correlation between the initial-state geometry and overall particle production is different at sub-nucleonic scales than at nucleonic scales.

- AMPT picture of two-color strings spanning a large longitudinal extent in pp is highly disfavored by the data. For Xe+Xe, AMPT only shows a qualitative agreement.

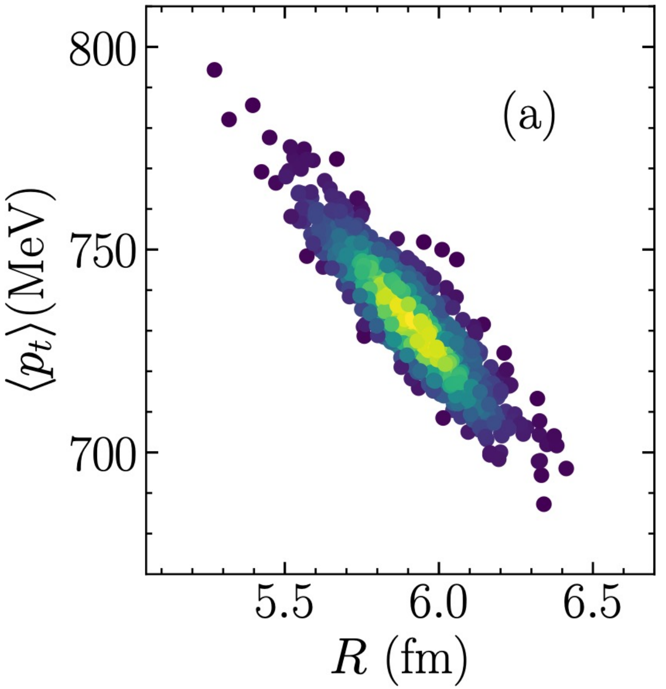
III. Probing role of initial state towards collectivity



In the limit of Small Fluctuations:

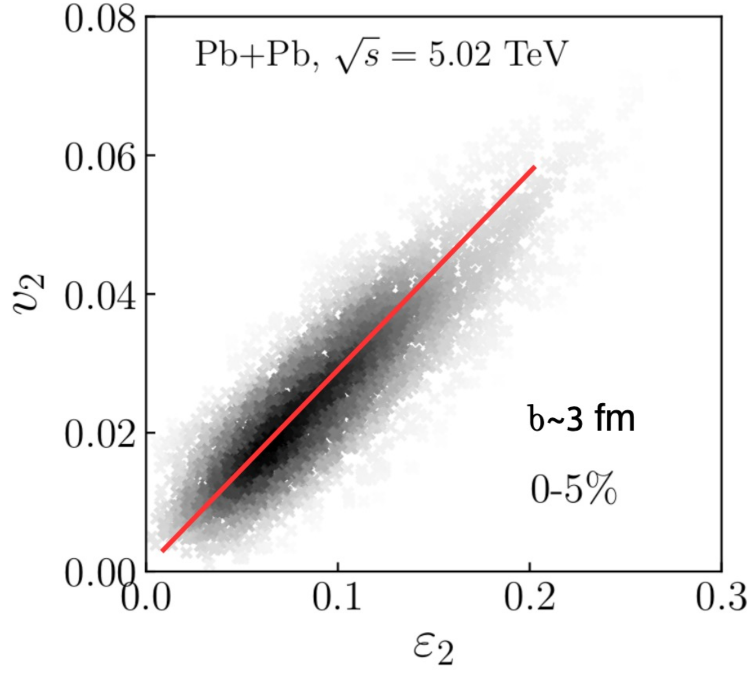
$$\frac{d\langle p_T\rangle}{\langle\langle p_t\rangle\rangle} = -3c_s^2 \frac{dR}{\langle R\rangle}$$

Giacalone et. al, PRC 103, 024909 (2021)



$$\delta[p_\mathrm{T}] \propto -\delta R$$

Giacalone, PhD thesis 2101.00168



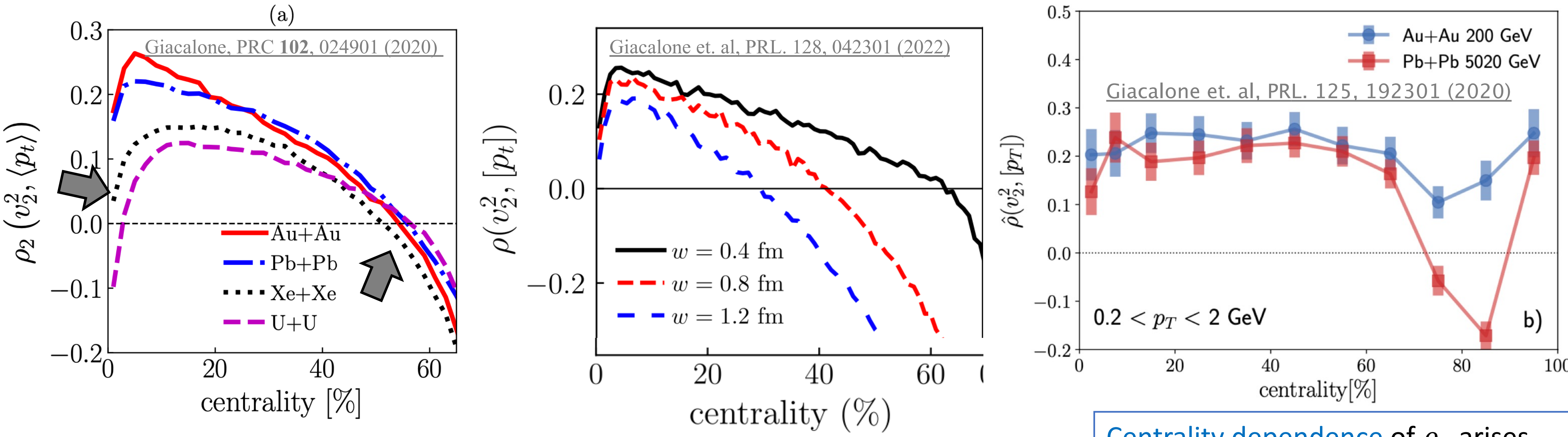
$$\epsilon_n \longrightarrow v_n$$

- Similar total energy, smaller transverse size in the initial state creates stronger radial expansion or larger $[p_T]$.

- Initial state correlation between eccentricity and transverse size generates final state $v_n - [p_T]$ correlations.

III. Probing role of initial state towards collectivity

$$\rho(\epsilon_n^2, \delta R) = \frac{cov(\epsilon_n^2, \delta R)}{\sqrt{var(\epsilon_n^2)var(\delta R)}} \Rightarrow \rho_n \equiv \rho(v_n^2, \delta p_T) = \frac{cov(v_n^2, \delta p_T)}{\sqrt{var(v_n^2)var(\delta p_T)}}$$



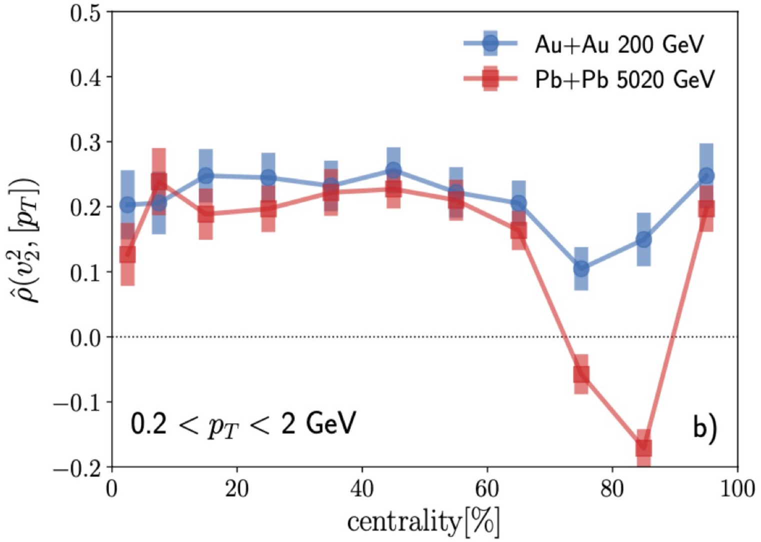
- $\rho_2(Xe) < \rho_2(Pb)$.
  Early sign change for smaller system in peripheral centrality.

- Large or fat nucleon reduces ρ_2 : stronger sign-change.

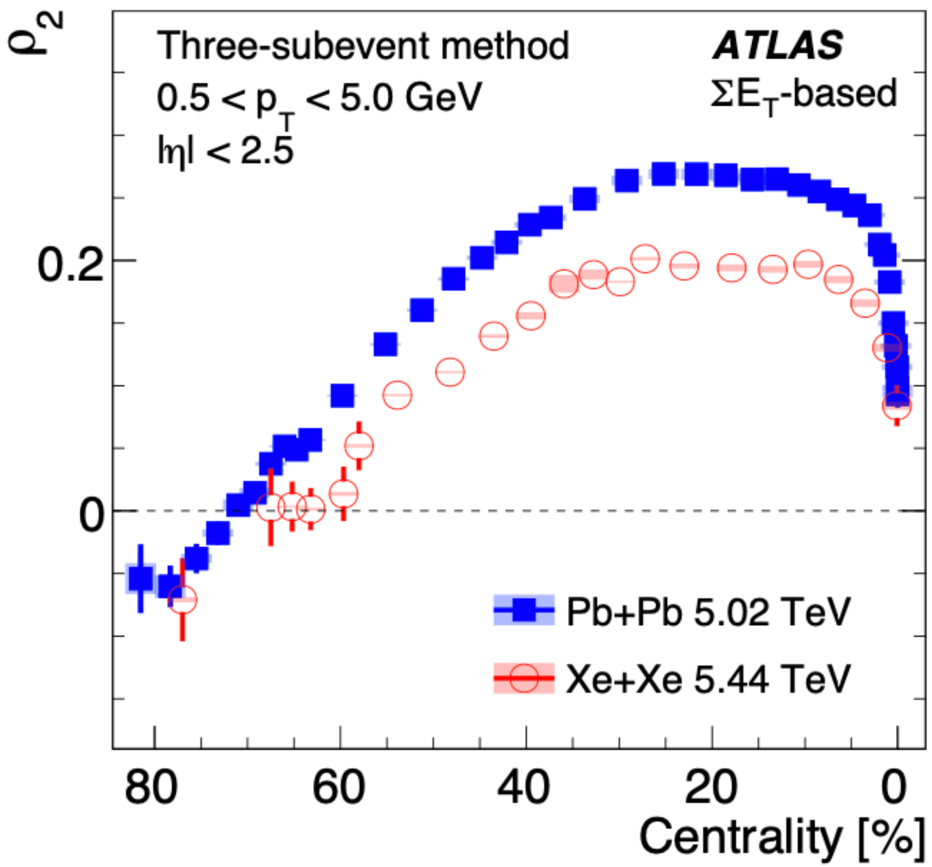
Centrality dependence of ρ_2 arises from: geometry dominance of v_2 in central and
initial p_T anisotropy dominance in peripheral events.

III. Probing role of initial state towards collectivity

ATLAS, PRC 107, 054910 (2023)



Giacalone et. al, PRL. 125, 192301 (2020)

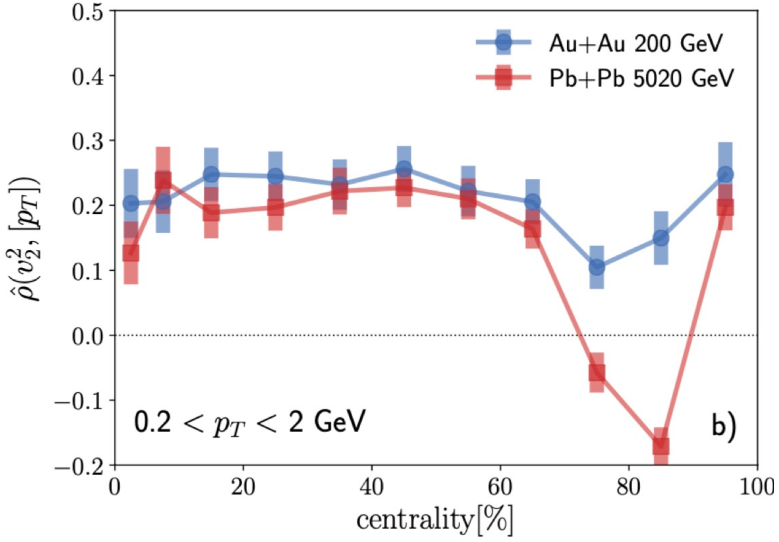


Flow-mean p_T correlation are different between PbPb and XeXe.

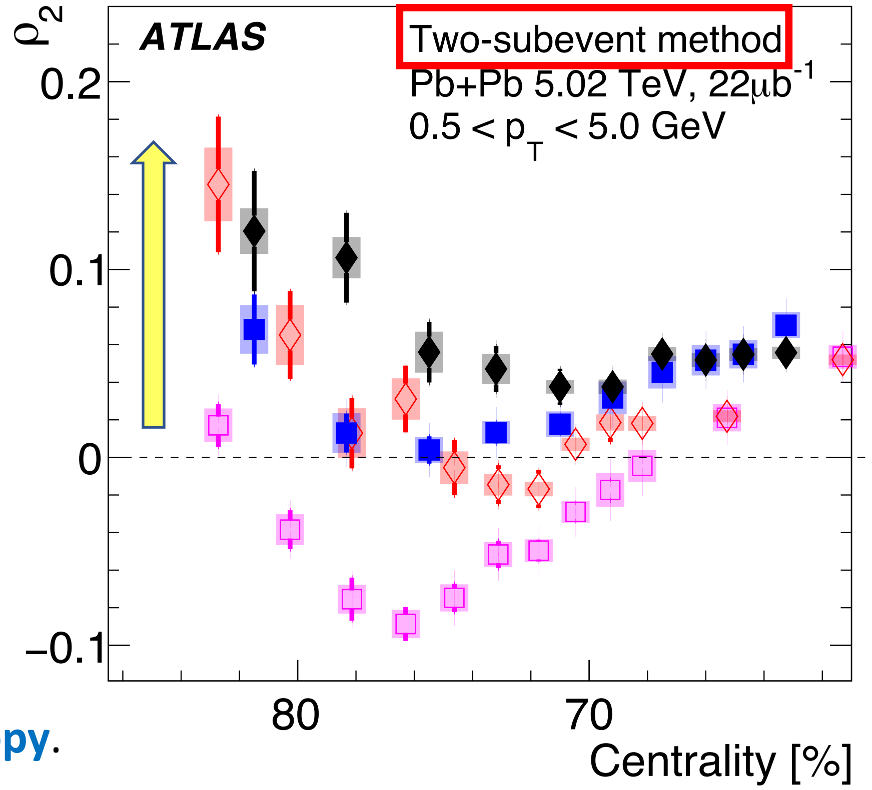
At same Centrality: smaller magnitude for all ρ_n for smaller system.

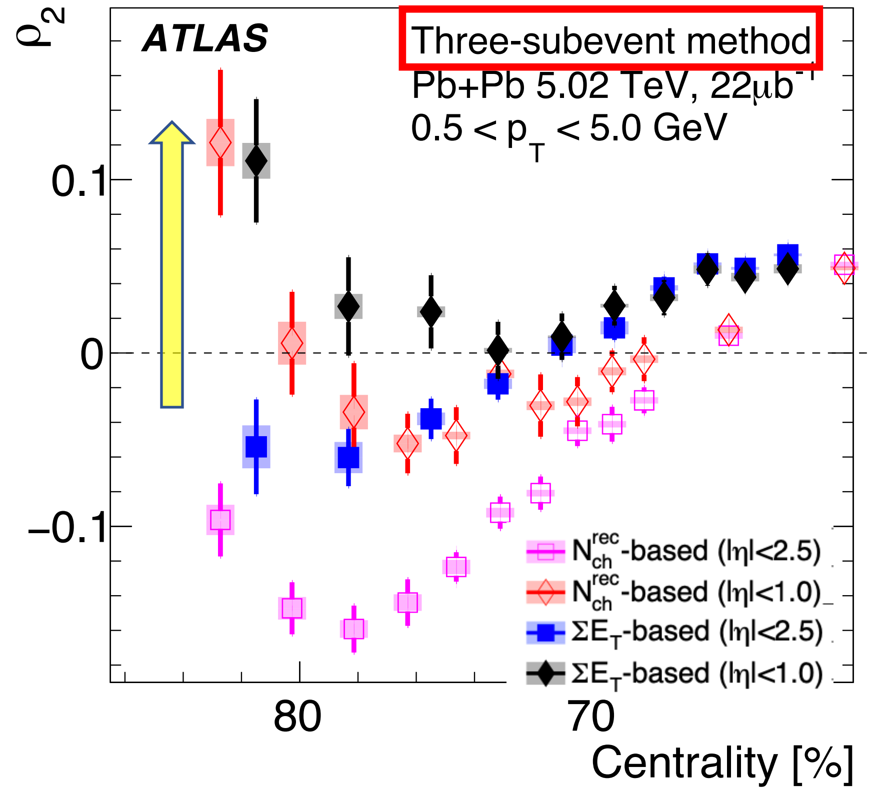
III. Probing role of initial state towards collectivity

ATLAS, PRC 107, 054910 (2023)



Giacalone et. al, PRL. 125, 192301 (2020)





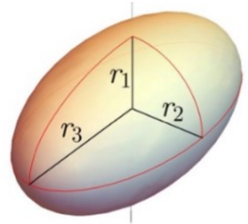
- ρ_2 double sign change in peripheral centralities at 5 TeV: **Strong evidence of initial p_T anisotropy**.

- Two important factors:
  1) Non-Flow: Larger ρ_2 for $|\eta| < 1$ than $|\eta| < 2.5$.
  2) Centrality Fluctuations : Differences between N_{ch}^{rec} and $\sum E_T$ large for both η ranges.

➢ **Requires further investigation in small systems to disentangle effect of initial momentum anisotropy.**

IV. Constraining nuclear structure using collectivity

- Nuclear deformation parameters are generally estimated from spectroscopic methods:



$$\rho(r) = \frac{\rho_0}{[1 + exp(r - R(\theta,\phi))/a]}$$

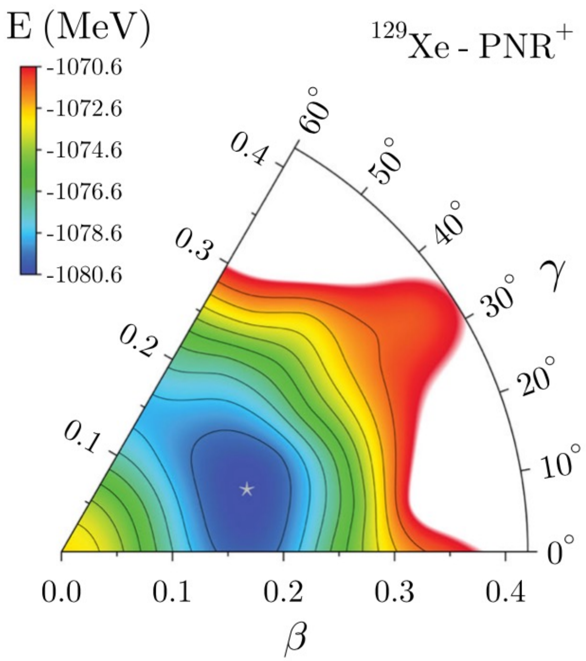
Nuclear geometry: Woods-Saxon

$$R(\theta,\phi) = R_0(1 + \beta(cos\gamma Y_{20}(\theta,\phi) + sin\gamma Y_{22}(\theta,\phi)))$$

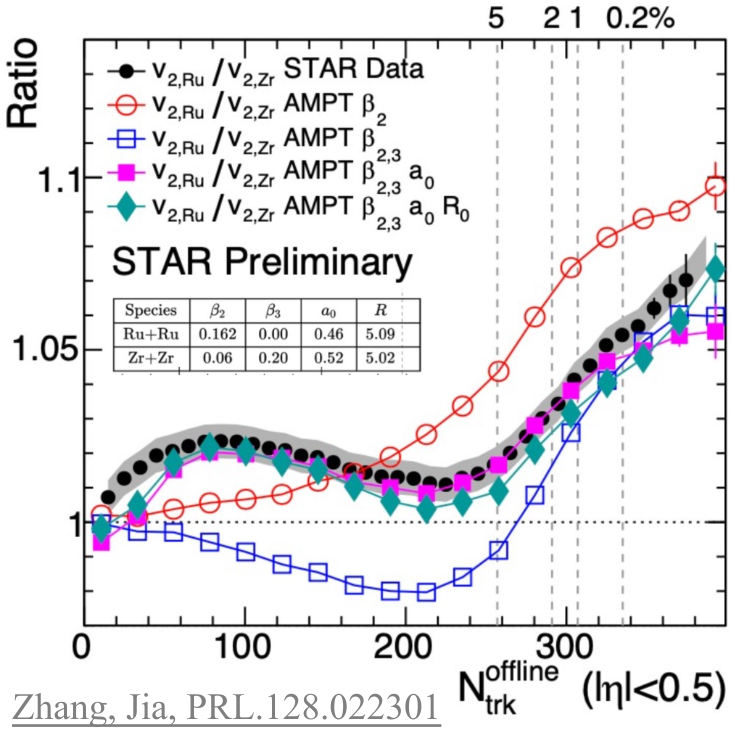
Parametrization of deformation

$$\beta = \frac{4\pi}{3ZeR_0^2}\sqrt{B(E2)\uparrow}$$

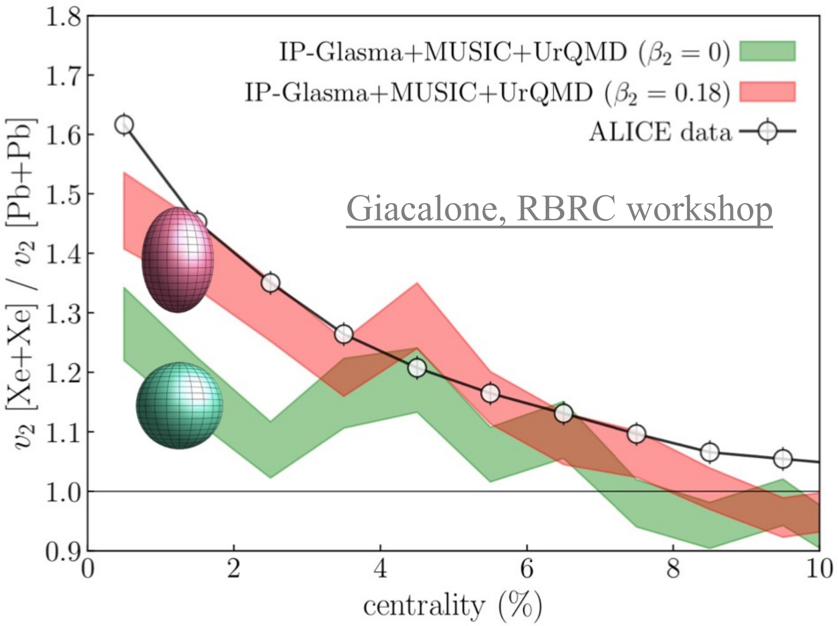
Estimation of deformation



Bally et.al, EPJA 58, 187 (2022)



Zhang, Jia, PRL.128.022301



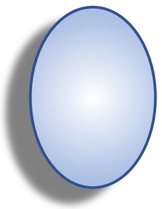
MeV 200 GeV 5 TeV

IV. Constraining nuclear structure using collectivity

- How does nuclear deformation affect initial state Pearson correlation $\rho(\varepsilon_2^2, {}^{\delta d_\perp}/_{d_\perp})$?

$$R(\theta,\phi) = R_0(1 + \beta(\cos\gamma Y_{20}(\theta,\phi) + \sin\gamma Y_{22}(\theta,\phi)))$$

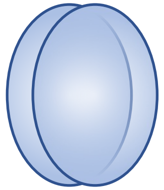
Nucleus Geometry



β>0, γ<30^0

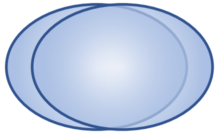
Prolate

Central Collision configurations



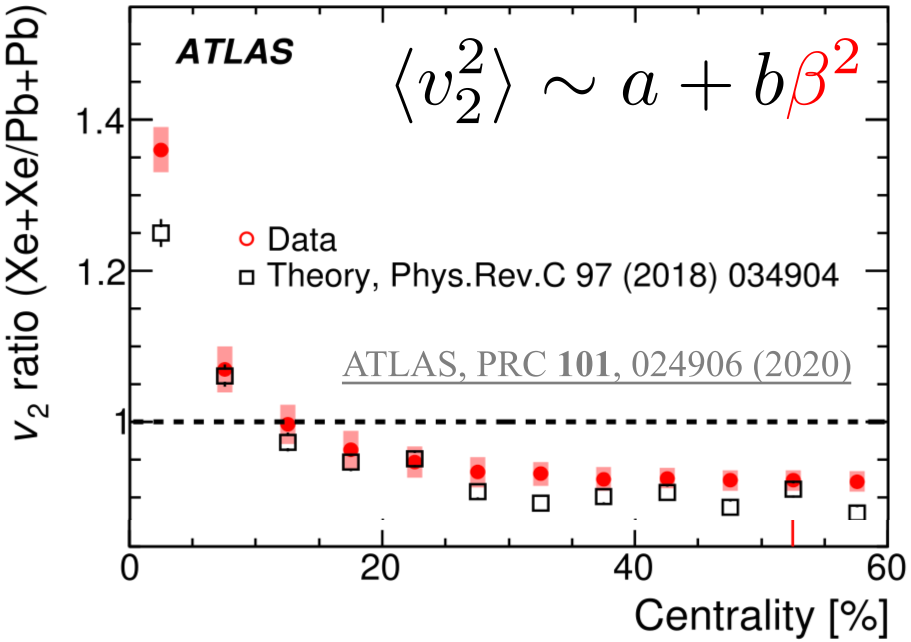
Body-body

ε_2 ↑, $d_\perp$ ↑

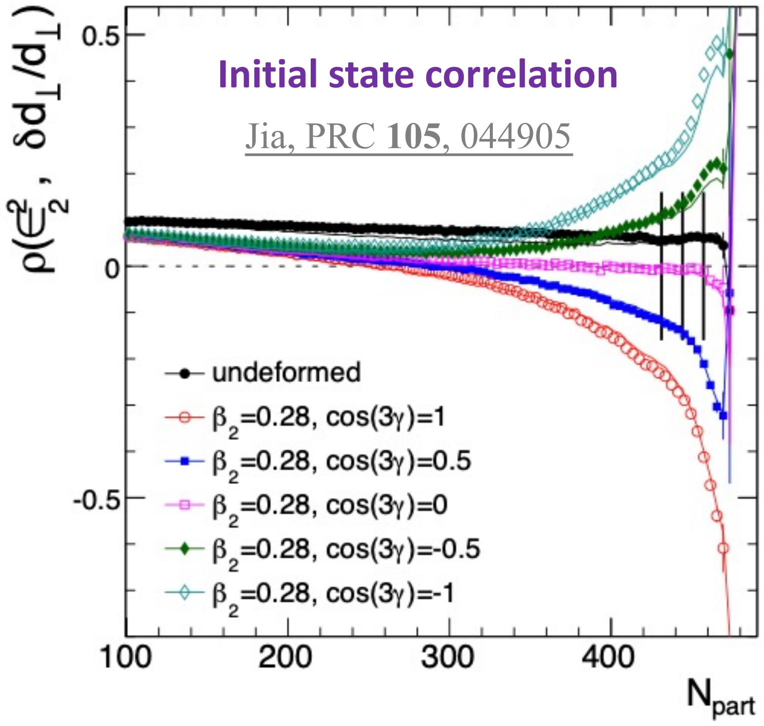


Tip-tip

ε_2 ↓, $d_\perp$ ↓



Nuclear deformation plays an important role in final state flow measurements.



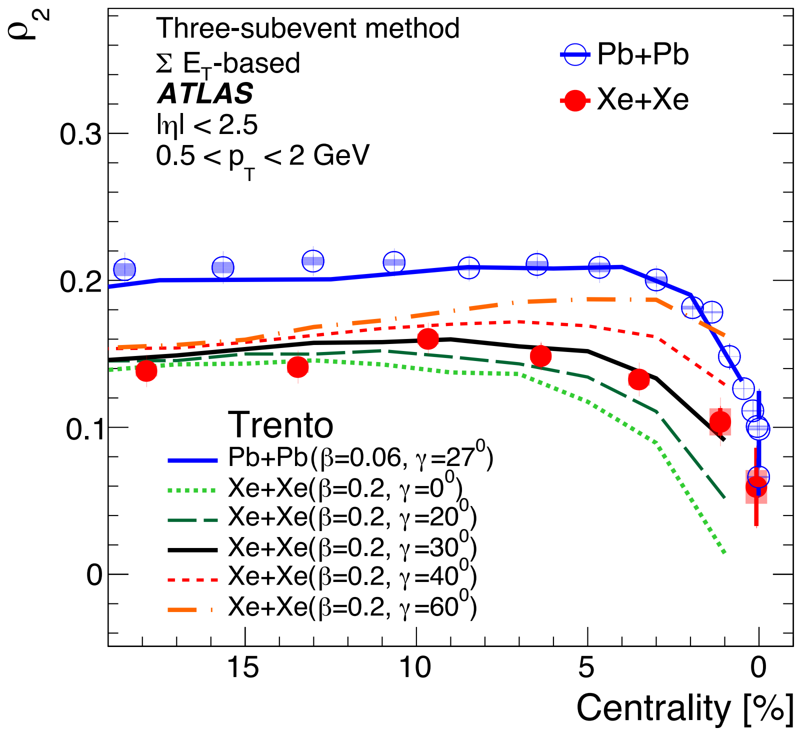
$$\langle v_2^2 \delta p_T \rangle \sim a - b\langle \beta^3 \cos(3\gamma) \rangle$$

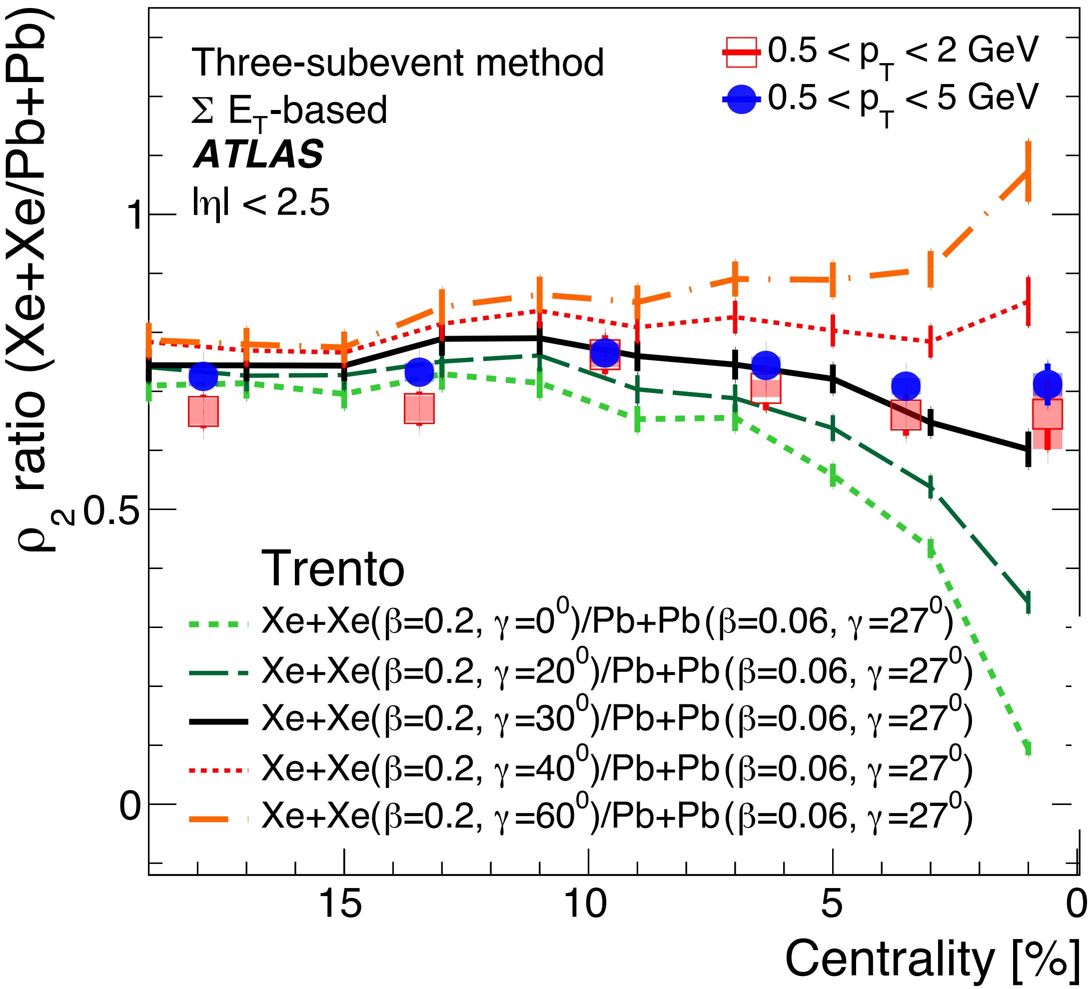
IV. Constraining nuclear structure using collectivity

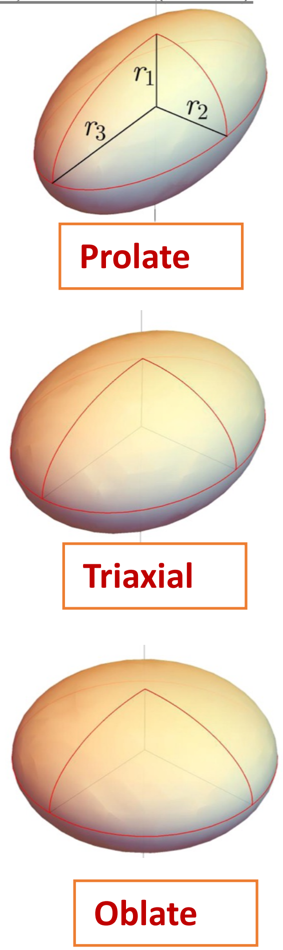
ATLAS, PRC 107, 054910 (2023)

Bally et.al, PRL 128, 082301 (2022)

$$\langle v_2^2 \delta p_T \rangle \sim a - b\langle \beta^3 \cos(3\gamma) \rangle$$







- $\rho(v_2^2, [p_T])$ shows large sensitivity to triaxiality of deformed nuclei in central collision events.

> ➢ **Pb corresponds to $\beta \sim 0.06$ and $\gamma \sim 27^0$** ***(near spherical)*** **;**
> **Xe corresponds to $\beta \sim 0.21$ and $\gamma \sim 27^0$** ***(highly deformed triaxial nucleus).***

IV. Constraining nuclear structure using collectivity

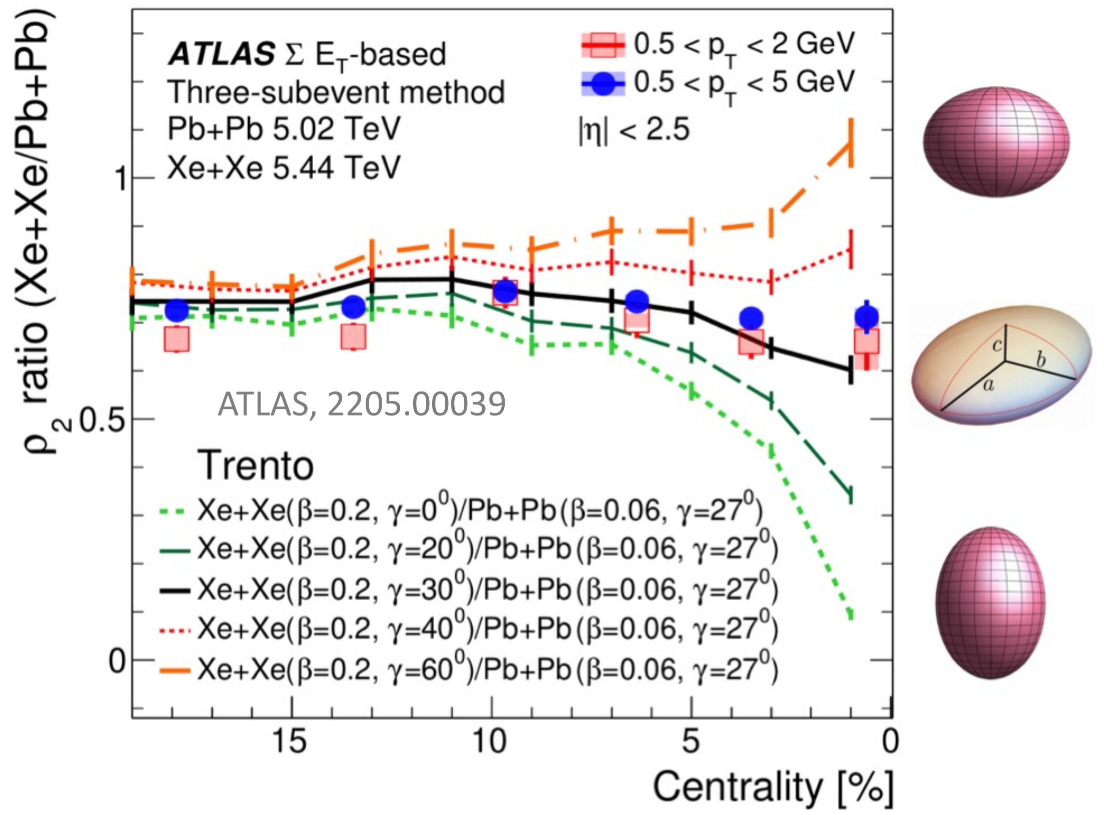
ATLAS, PRC 107, 054910 (2023)

PHYSICAL REVIEW LETTERS 128, 082301 (2022)

Evidence of the Triaxial Structure of ^{129}Xe at the Large Hadron Collider

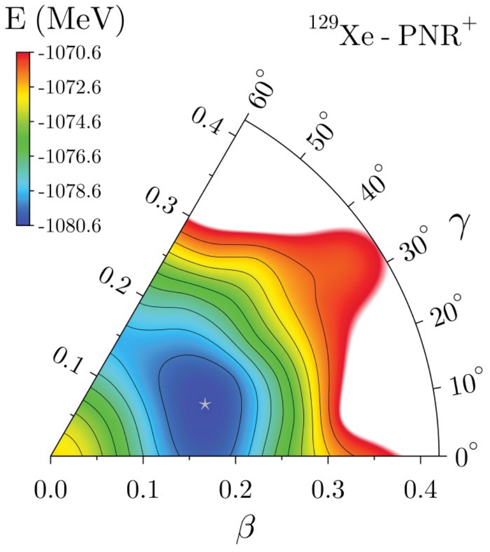
Benjamin Bally,[1] Michael Bender,[2] Giuliano Giacalone,[3] and Vittorio Somà[4]

- Consistent descriptions between Low energy predictions and observations at LHC energy.

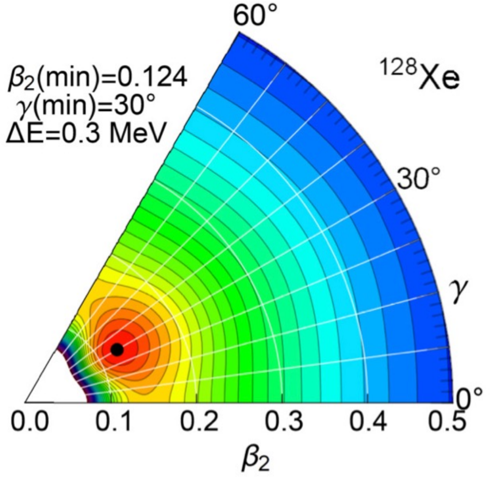


IV. Constraining nuclear structure using collectivity (caveat: Role of shape fluctuations)

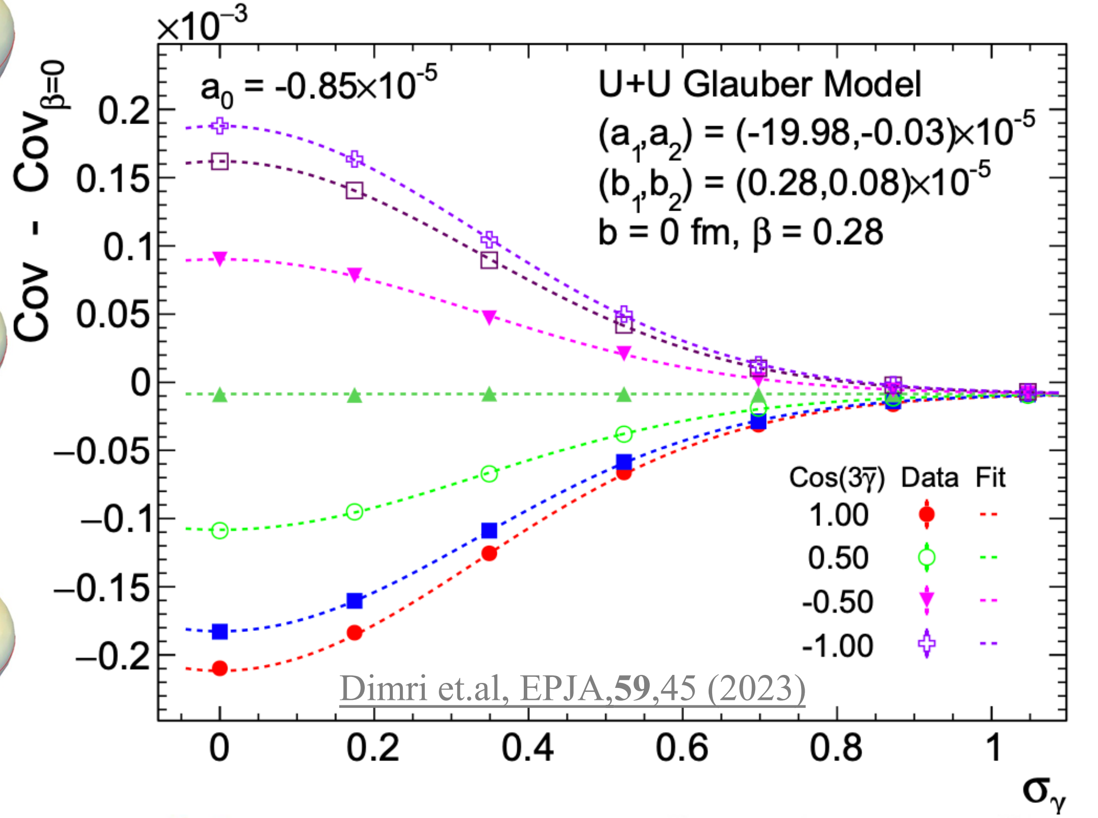
$$\langle v_2^2 \delta p_T \rangle \sim a - b\langle \beta^3 \cos(3\gamma) \rangle$$



Bally et. al, EPJA 58, 187 (2022)



Budaca, Budaca, PRC **101**, 064318 (2020)



Dimri et.al, EPJA,**59**,45 (2023)

$$\langle \cos(3\gamma) \rangle \approx \exp\left(-9\sigma_\gamma^2/2\right)\cos(3\bar{\gamma}) \qquad \sigma_\gamma^2 = \langle (\gamma - \bar{\gamma})^2 \rangle$$

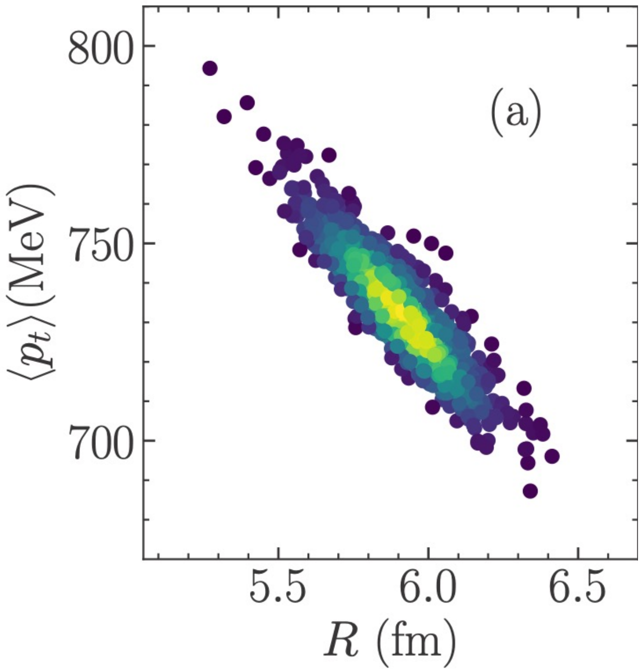
- Fluctuations in γ washes out difference between prolate and oblate shapes, all results approach Triaxial case

➢ $\rho_{2,Xe}/\rho_{2,Pb}$ ratio supports triaxial shape of ^{129}Xe: Only if fluctuations in γ_{Xe} not large.

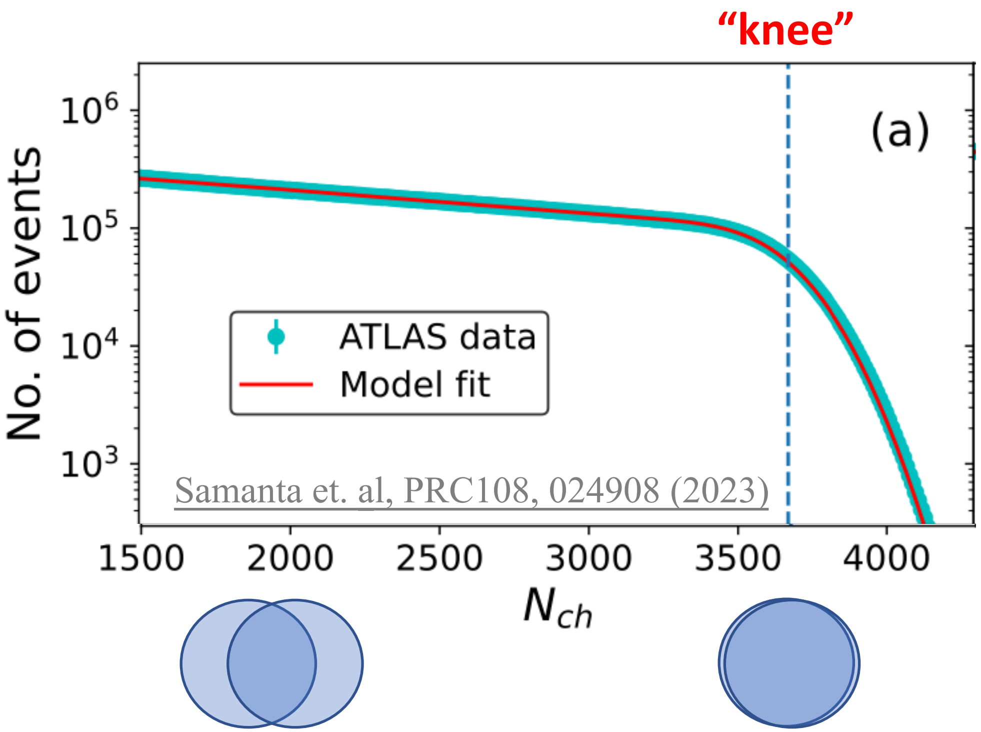
V. Impact of collision geometry on $[p_T]$ fluctuations

- Model assumption: At fixed N_{ch} and b, $[p_T]$ fluctuation is Gaussian

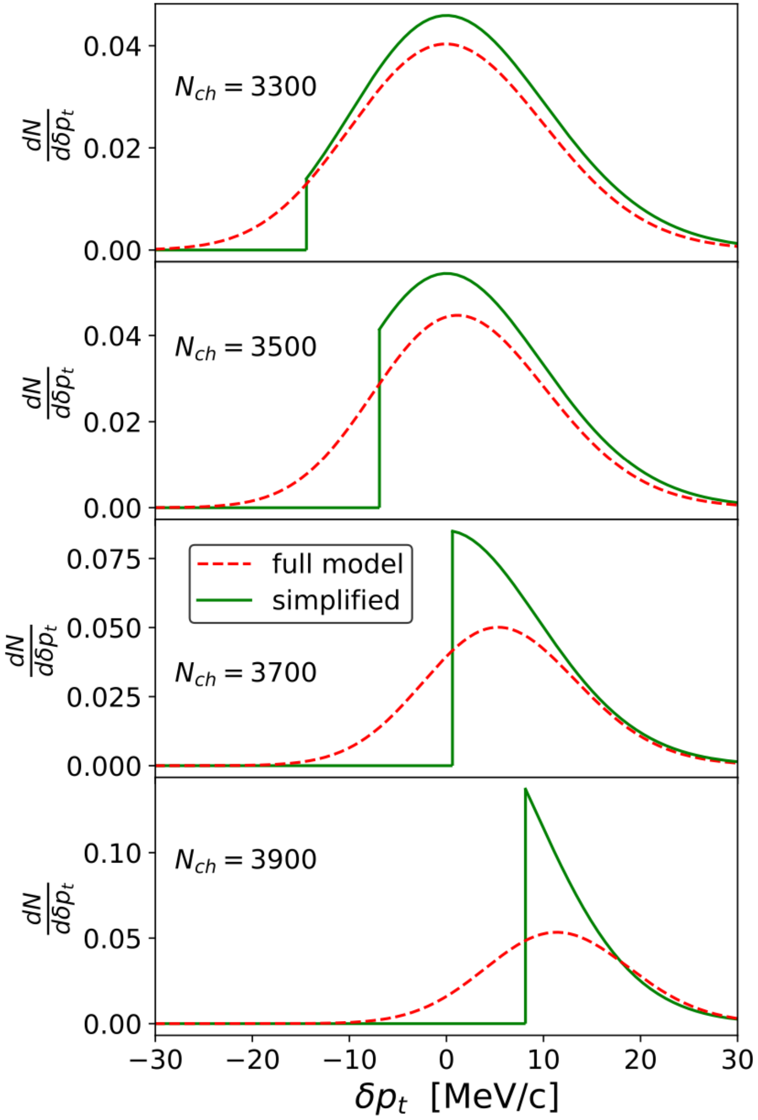
$$\delta[p_\mathrm{T}] \propto -\delta R$$



Giacalone, PRC103 2, 024909 (2021)



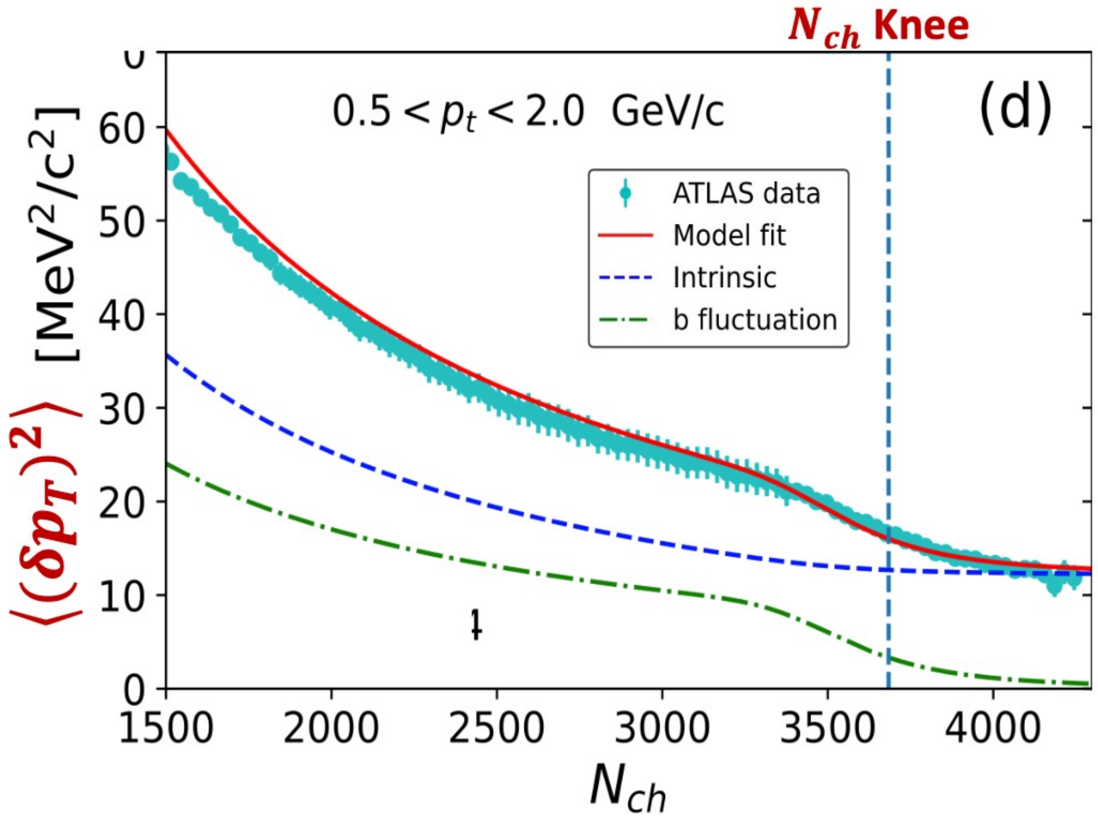
Samanta et. al, PRC108, 024908 (2023)



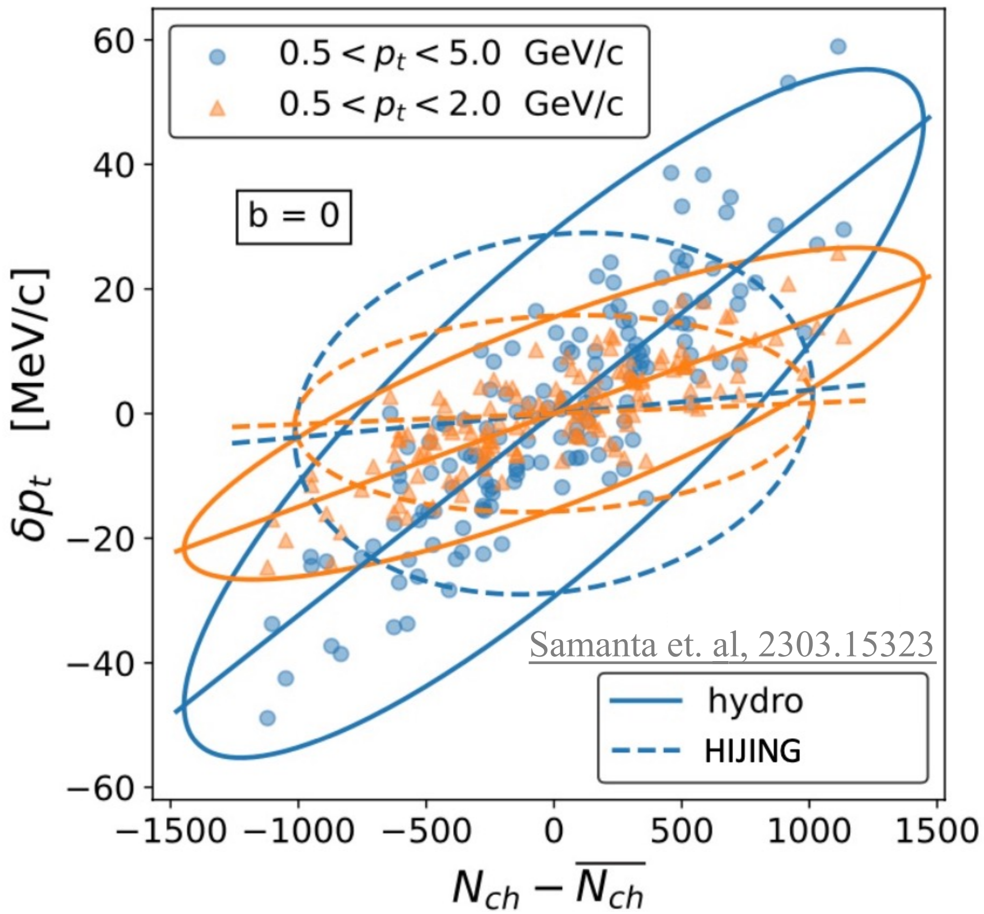
Samanta et. al, PRC108, 024908 (2023)

- A lower limit on impact parameter sets lower limit on $[p_T]$.
- Beyond knee, the variance of $\delta[p_T]$becomes progressively smaller due to truncation from the lower limit.

V. Impact of collision geometry on $[p_T]$ fluctuations

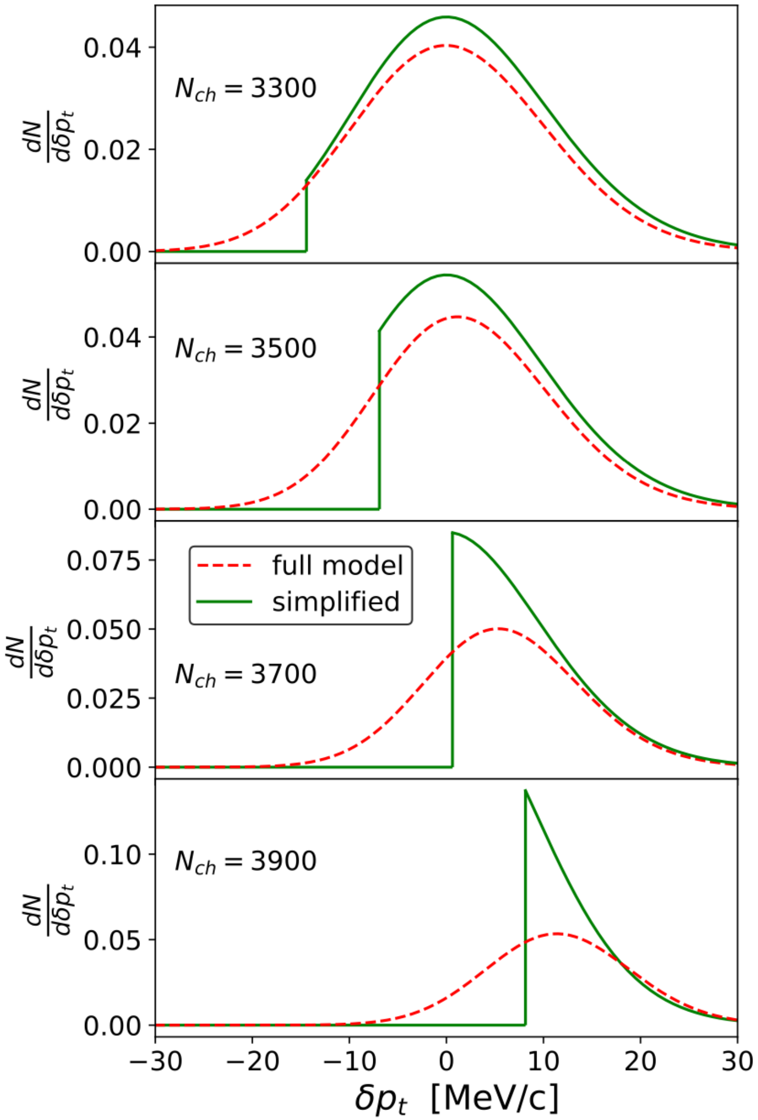


Samanta et. al, PRC108, 024908 (2023)
Samanta et. al, 2303.15323
ATLAS, PRC 107 (2023) 054910

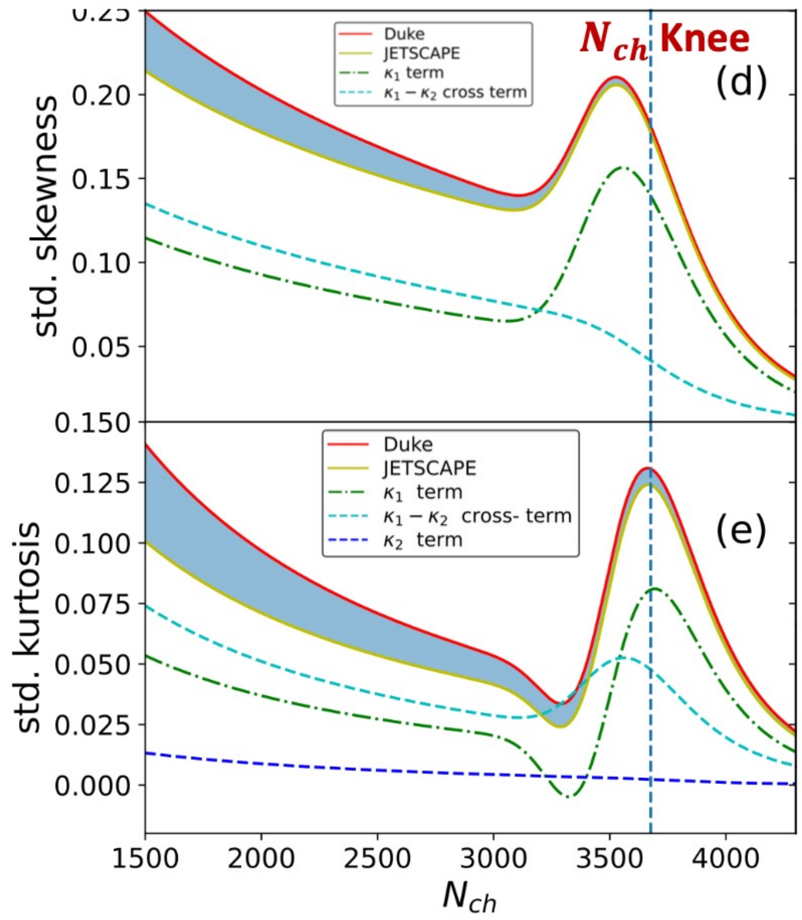


- Reducing contribution from 'b' fluctuations: **Sharp drop in $(\delta[p_T])^2$ in Ultra central collisions.**
- Prediction: Increase in $[p_T]$ with increasing N_{ch}: **Evidence of thermalization.**

V. Impact of collision geometry on $[p_T]$ fluctuations



Samanta et. al, PRC108, 024908 (2023)



Samanta et. al, PRC108, 024908 (2023)

- Future measurements of higher order $[p_T]$ fluctuations will help further establish influence of maximal overlap area in ultra-central collisions.

Conclusion

PART 1: **Sensitivity of Flow to hard-scatterings** in pp collisions at $\sqrt{s_{NN}}$ = 13 TeV:

Hard scattering does not contribute to the long-range correlations.

PART 2: **Sensitivity of flow to sub-nucleonic fluctuations:**

Decorrelation in XeXe at $\sqrt{s_{NN}}$ = 5.44 TeV and pp collisions at $\sqrt{s_{NN}}$ = 5 TeV :

1. Correlation between the initial-state geometry and overall particle production is different at sub-nucleonic scales than at nucleonic scales.
2. Current models fail to describe decorrelation signal entirely in pp collisions.

PART 3 & 4 : **Probing role of initial state towards collectivity using $\rho(v_n^2, \delta p_T)$**

in XeXe collisions at $\sqrt{s_{NN}}$ = 5.44 TeV and PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV:

1. *In peripheral collisions:* measurement has good precision, can be used to constrain the initial momentum anisotropy. Further model calculations are needed.
2. *Central collisions: Experimental constraint* on nuclear deformation parameters (esp. triaxiality) from Heavy-Ion collisions, consistent with low-energy measurements.

Conclusion

PART 5: Impact of collision geometry on $[p_T]$ fluctuations in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV:

1. Fluctuations of $[p_T]$ provide important detail on initial state variations leading to final state observed fluctuations.
2. $[p_T]$ measurement in UCC provide important information on thermalization of formed medium.

STAY TUNED!!

MANY MORE INTERESTING MEASUREMENTS FROM ATLAS IN UPCOMING QUARK MATTER 2023