IS2021

The VI[th] International Conference on the
INITIAL STAGES
OF HIGH-ENERGY NUCLEAR
COLLISIONS

v_n and $[p_T]$ correlations in Pb+Pb and Xe+Xe collisions with ATLAS

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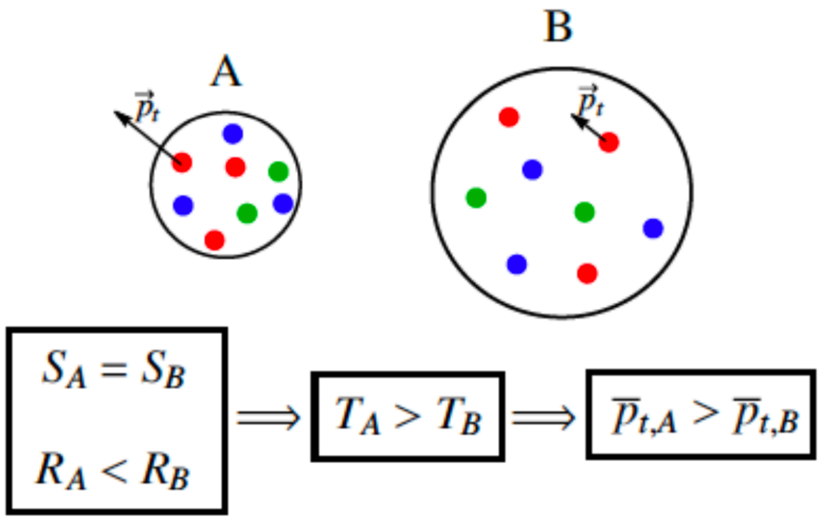
Conf Note: CONF-HION-2021-001

Motivation



In Boltzmann statistics with massless ideal gas: $p \simeq E = 3T$

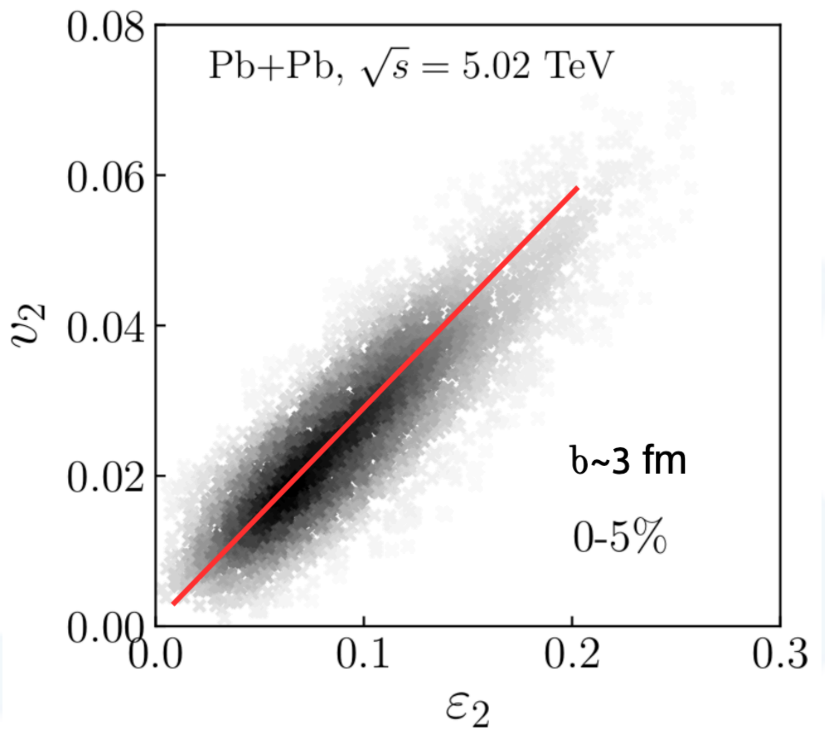
In Heavy Ion Collisions: $\langle p_T \rangle \simeq 3T$

In the limit of Small Fluctuations: $\frac{d\langle p_T \rangle}{\langle\langle p_t \rangle\rangle} = -3c_s^2 \frac{dR}{\langle R \rangle}$

PRC 102, 024901 (2020)

$$1/R \longrightarrow [p_T]$$

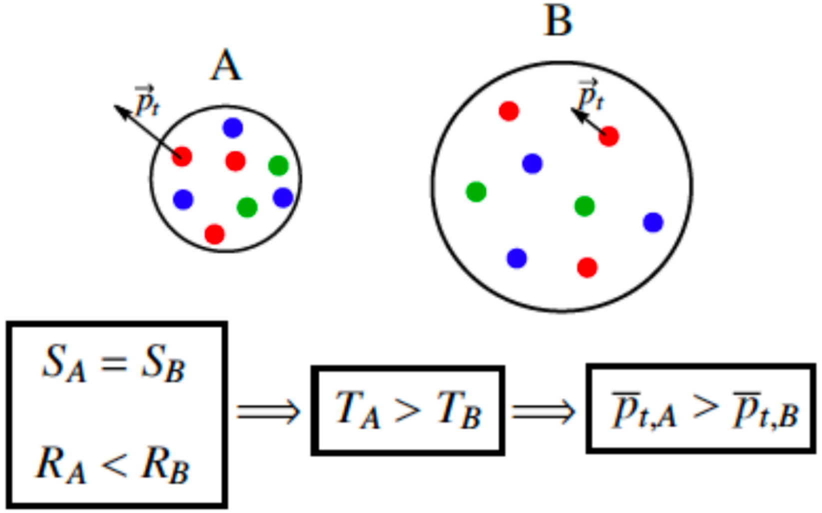
- Similar total energy, smaller transverse size in the initial state creates stronger radial expansion or larger $[p_T]$.



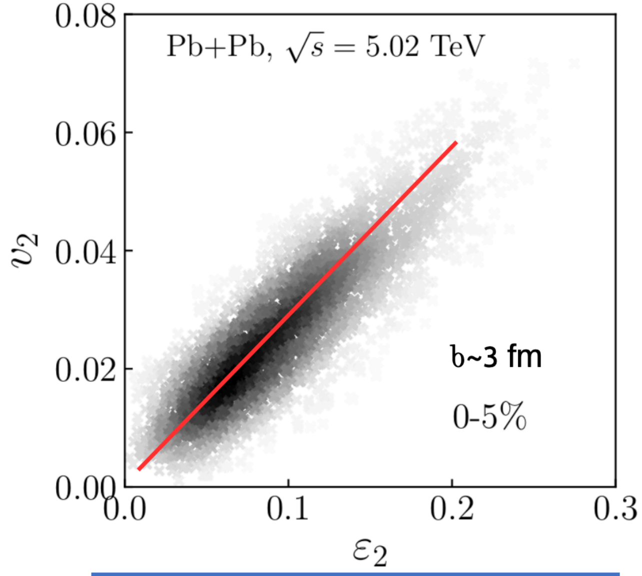
$$\epsilon_n \longrightarrow v_n$$

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

$v_n - [p_T]$ correlation



$$1/R \longrightarrow [p_T]$$



$$\epsilon_n \longrightarrow v_n$$

Eur. Phys. J. C 79 (2019) 985

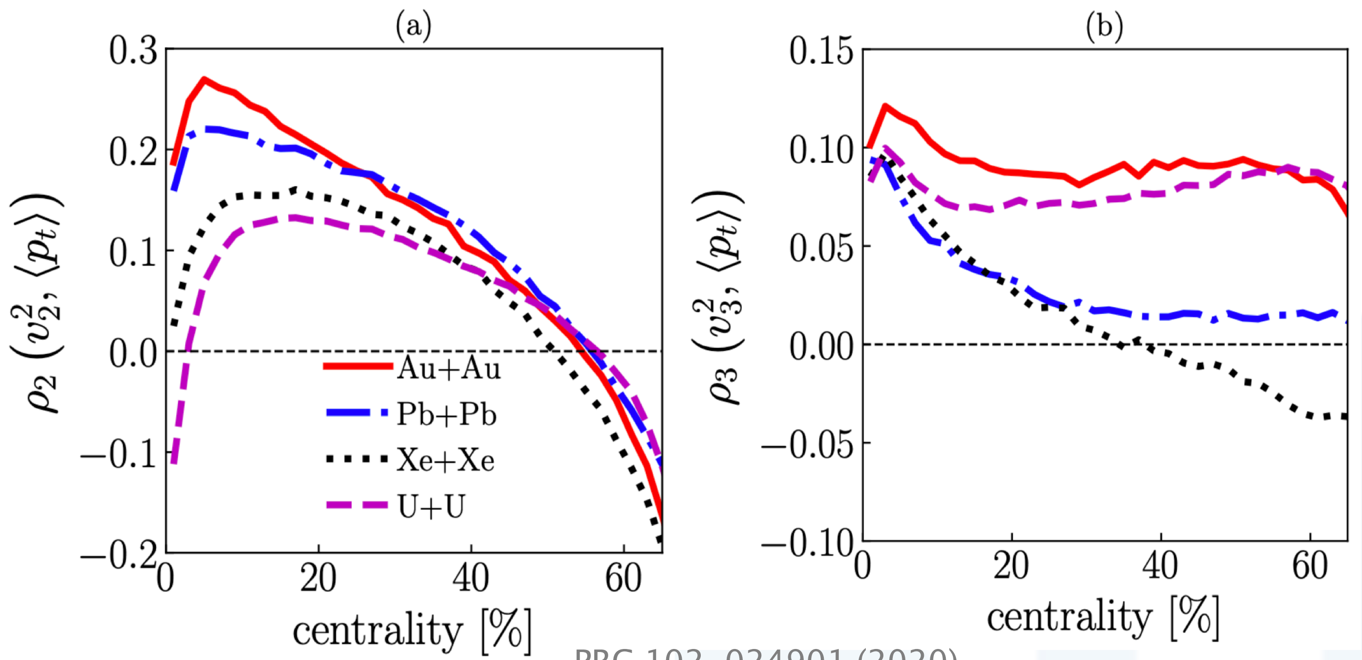
Phys. Rev. C 93, 044908 (2016)

$$\rho(v_n^2\{2\},[p_T]) = \frac{cov(v_n^2\{2\},[p_T])}{var(\sqrt{v_n^2\{2\}_{dyn}}\sqrt{c_k})}$$

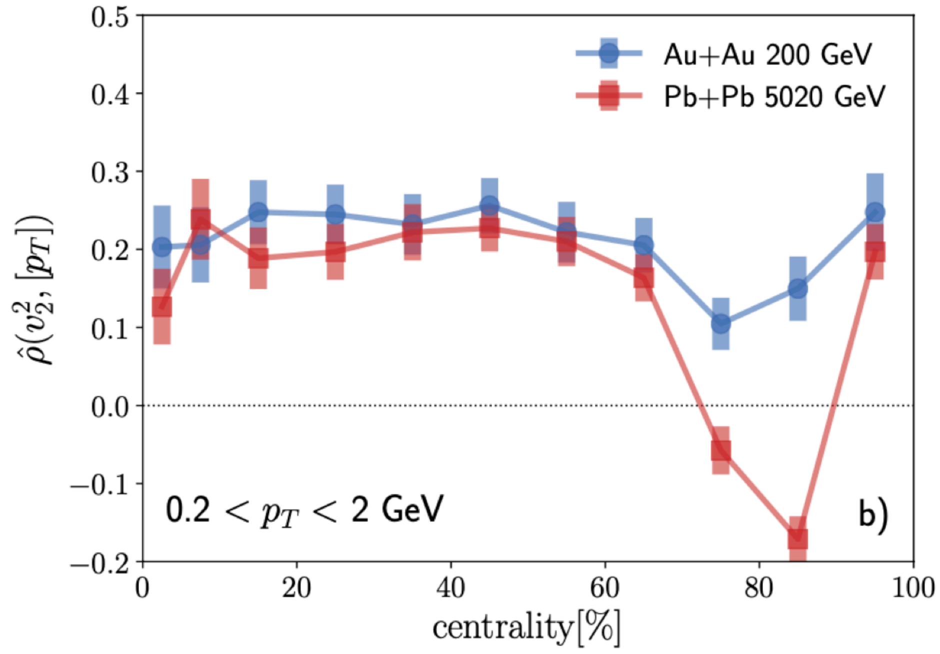
Modified Person's Correlation Coefficient between v_n and $[p_T]$

- Correlations between the $[p_T]$ and v_n sheds light on:
  1. Correlation in the initial state between the size and the eccentricities.
  2. Correlations of the strength of the hydrodynamic response with the Flow coefficients.
- Pearson's correlator measures correlation b/w two observables up to linear order.
- The modification is introduction of dynamic variances which which are more sensitive to intrinsic initial-state fluctuations.

Theoretical predictions



PRC 102, 024901 (2020)



PRL. 125, 192301 (2020)

TRENTo model predictions

1. ρ_2(Pb+Pb) $>$ ρ_2(Xe+Xe)
2. ρ_2(Xe+Xe) and ρ_2(Pb+Pb) turns -ve towards peripheral centralities.
3. ρ_3 shows milder dependence on centrality (fluctuations driven)
4. ρ_3(Xe+Xe) turns –ve towards peripheral centralities.

IP-Glasma+MUSIC+URQMD predictions

1. Sign change observed in PbPb collisions at 5.02 TeV is not seen in AuAu collisions at 200 GeV.

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

Method

- Cumulant in subevent framework used.
- Standard calculations: $-2.5 \leq \eta \leq 2.5$
- 2 SE calculations: subevent A and C.
- 3 SE calculations: subevent A, B and C.

- ρ_n calculated by combination of the covariance and variance terms calculated independently.
- Combined subevent method: Final results are average of two- and three subevent methods.

Full-Event method

$-2.5 \leq \eta \leq 2.5$

Subevent A	Subevent B	Subevent C
$-2.5 \leq \eta \leq -0.75$	$\lvert\eta\rvert \leq 0.5$	$0.75 \leq \eta \leq 2.5$

$$cov(v_n\{2\}^2, [p_T]) = \left\langle \frac{\sum_{i\neq j\neq k} w_i w_j w_k e^{in(\phi_i-\phi_j)} (p_{T,k} - \langle[p_T]\rangle)}{\sum_{i\neq j\neq k} w_i w_j w_k} \right\rangle$$

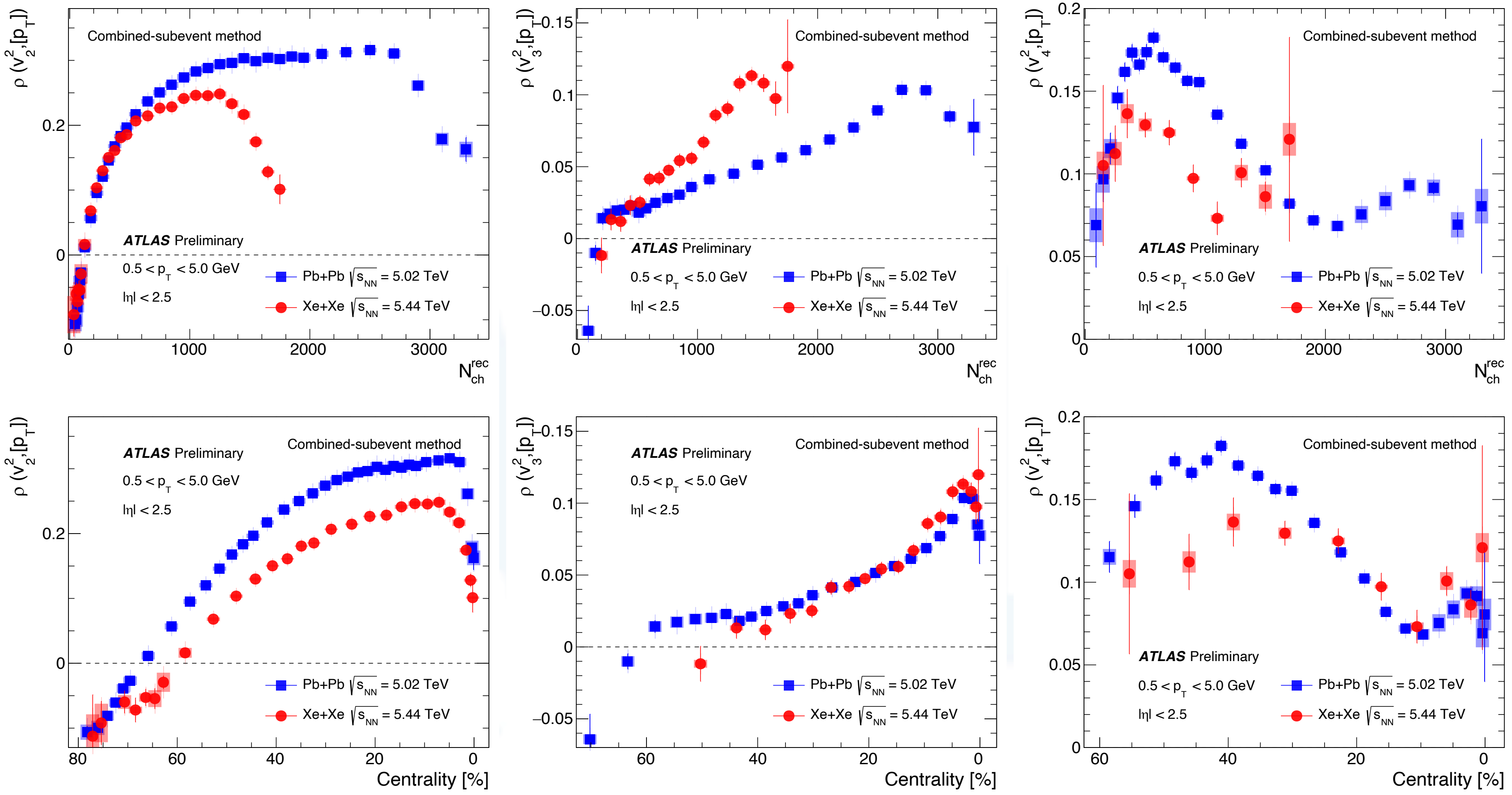
$$\rho(v_n^2\{2\}, [p_T]) = \frac{cov(v_n^2\{2\}, [p_T])}{\sqrt{var(v_n^2), c_k}} =$$

$$\sqrt{c_k = \left\langle \frac{\sum_{i\neq j} w_i w_j (p_{T,i} - \langle p_T\rangle)(p_{T,j} - \langle p_T\rangle)}{\sum_{i\neq j} w_i w_j} \right\rangle \quad var(v_n^2\{2\})_{dyn} = c_n\{4\}_{std} + c_n\{2\}^2_{two-sub}}$$

Results-I: Comparison of ρ_n between Xe and Pb

N_{ch}

FCal E_T

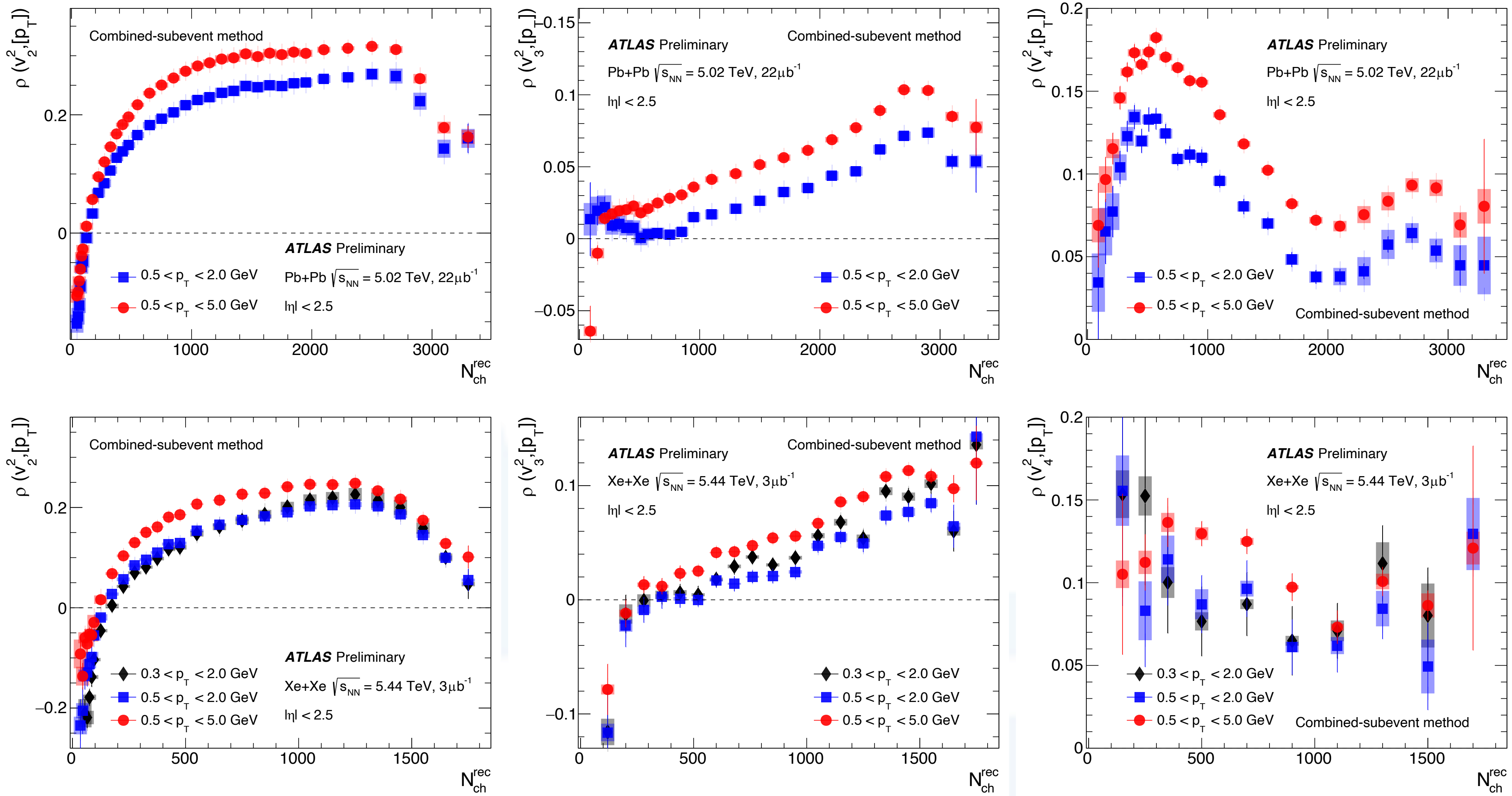


Size

Shape

- Both Xe+Xe and Pb+Pb go -ve in very low Nch for n=2.
- Smaller magnitude in Xe+Xe for n=2 & n=4.
- Larger magnitude in Xe+Xe for n=3 due to larger fluctuations in smaller system.
- As a function of centrality, ρ_2 is smaller in Xe+Xe but ρ_3 and ρ_4 are comparable.

Results-II: Dependence on pT range



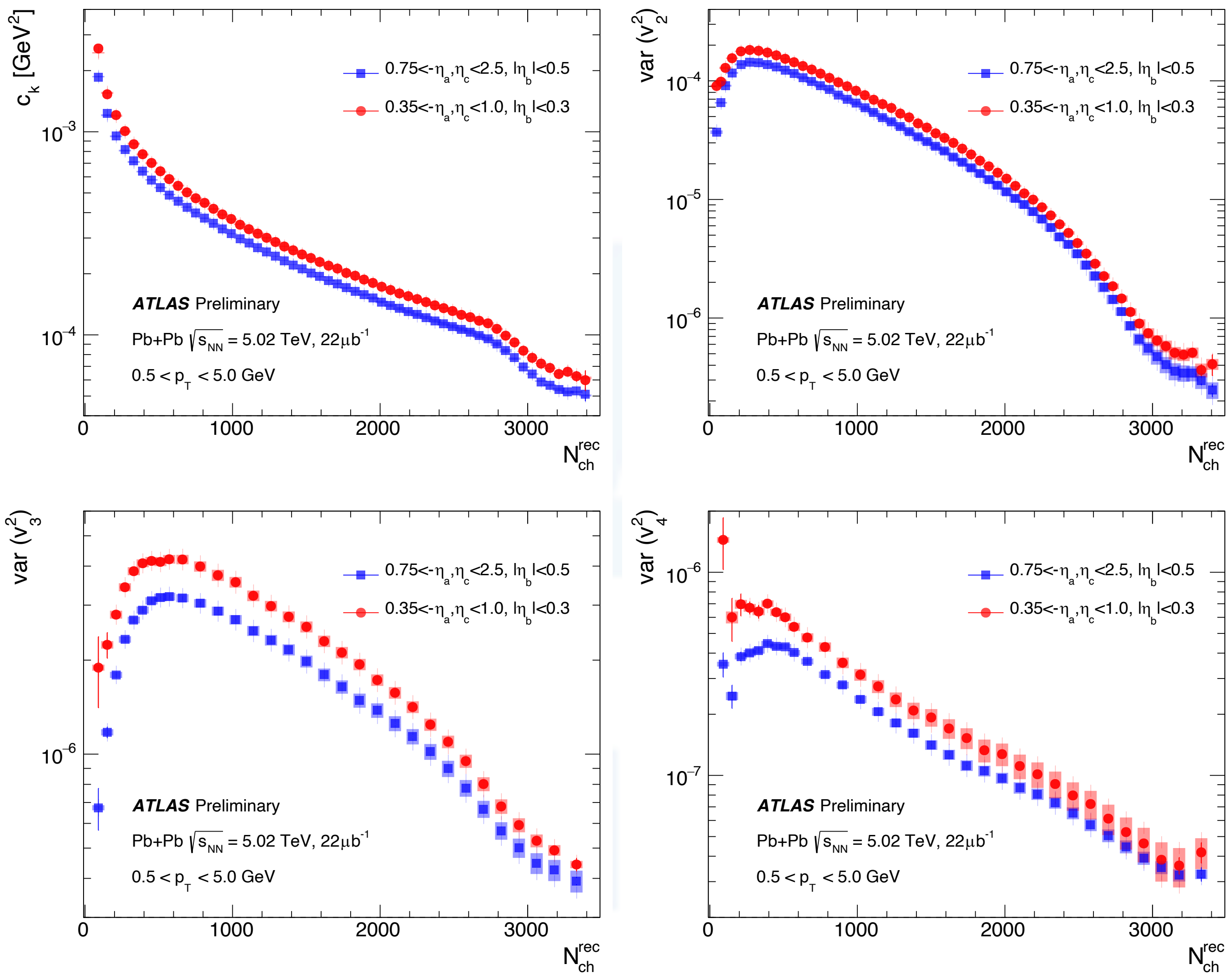
- In both systems ρ is smaller for 0.5< p_T <2.0 GeV than 0.5< p_T <5.0 GeV.
- In Xe+Xe : ρ is comparable for 0.5< p_T <2.0 GeV and 0.3< p_T <2.0 GeV.
- Collective behavior not sensitive to change in lower limit - Low p_T region well described by hydrodynamics

Results-III: Dependence on eta range

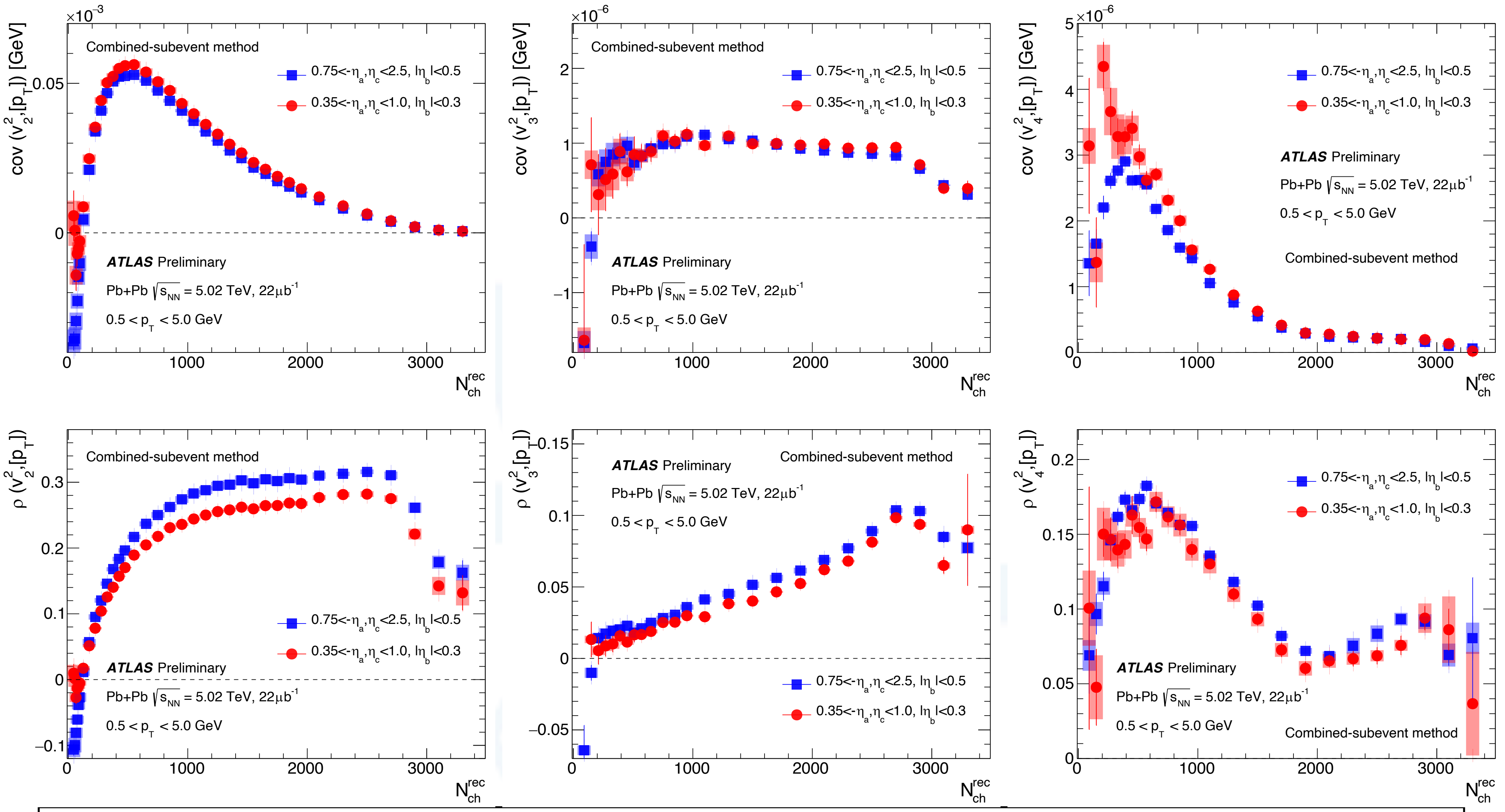
- Two eta ranges used $|\eta| < 2.5$ $|\eta| < 1.0$
- 3-subevents also used in the new case

$\eta < -0.35$	$|\eta| < 0.3$	$\eta > 0.35$

- C_k is larger by 10% for $|\eta| < 1$.
- Var(v_n) is larger by 10-20% for $|\eta| < 1$.
- The v_n and $[p_T]$ magnitudes are smaller at larger η.
- Possible decorrelation in v_n and $[p_T]$

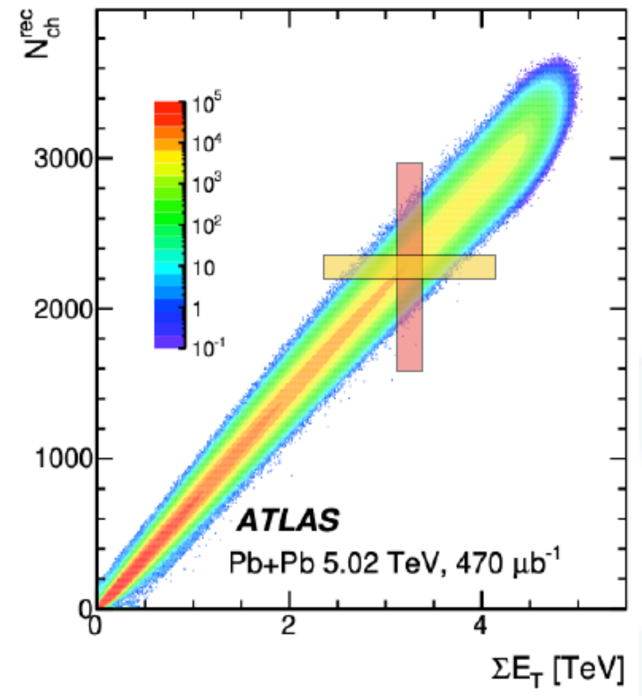


Results-IV: Dependence on eta range

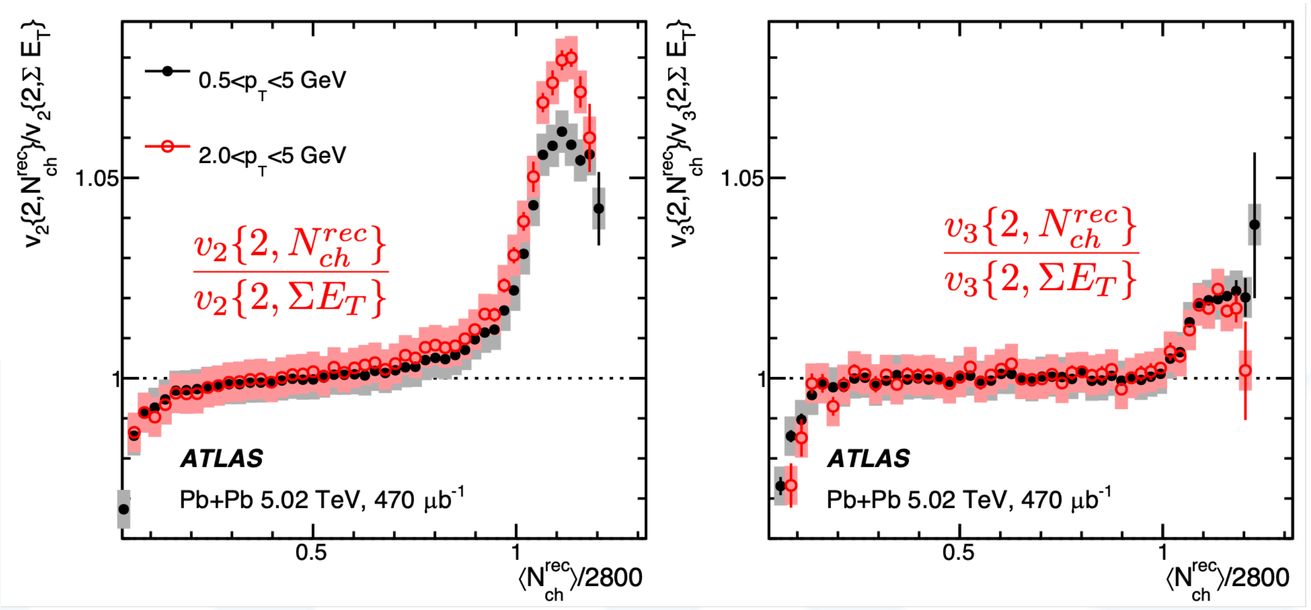


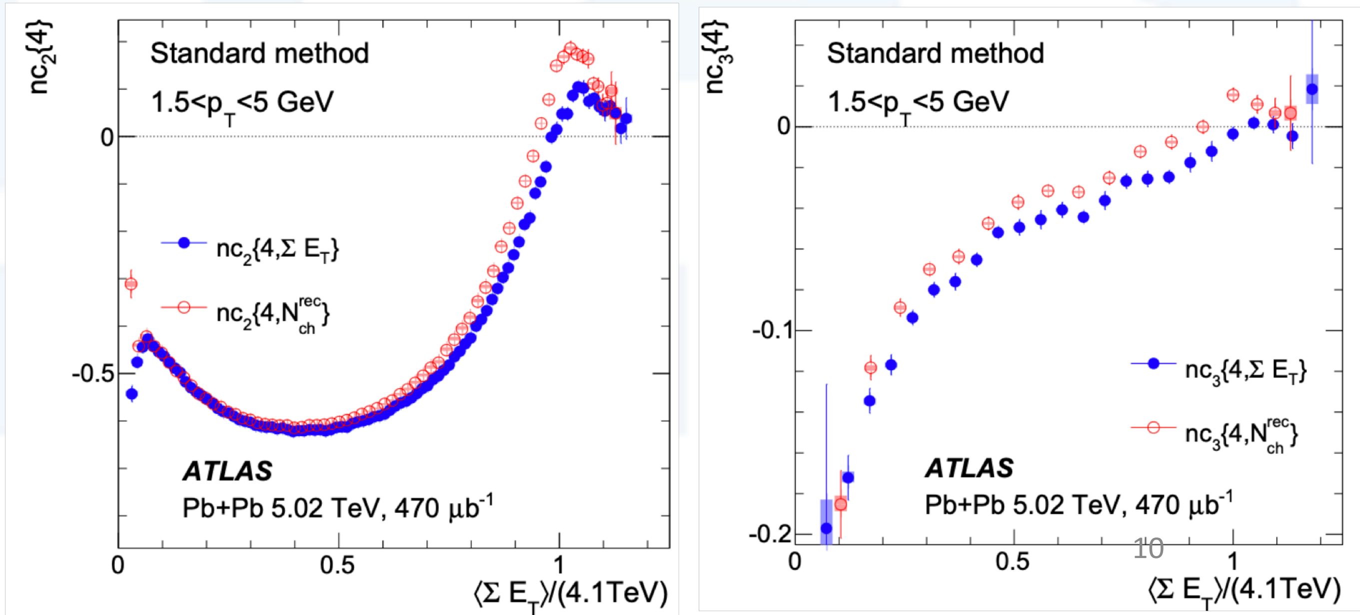
- Covariances show good agreement between eta-ranges except for n=4 at low N_{ch}.
- ρ is systematically smaller for $|\eta| < 2.5$ due to smaller c_k and var(v_n).

Results-V: Centrality Fluctuations



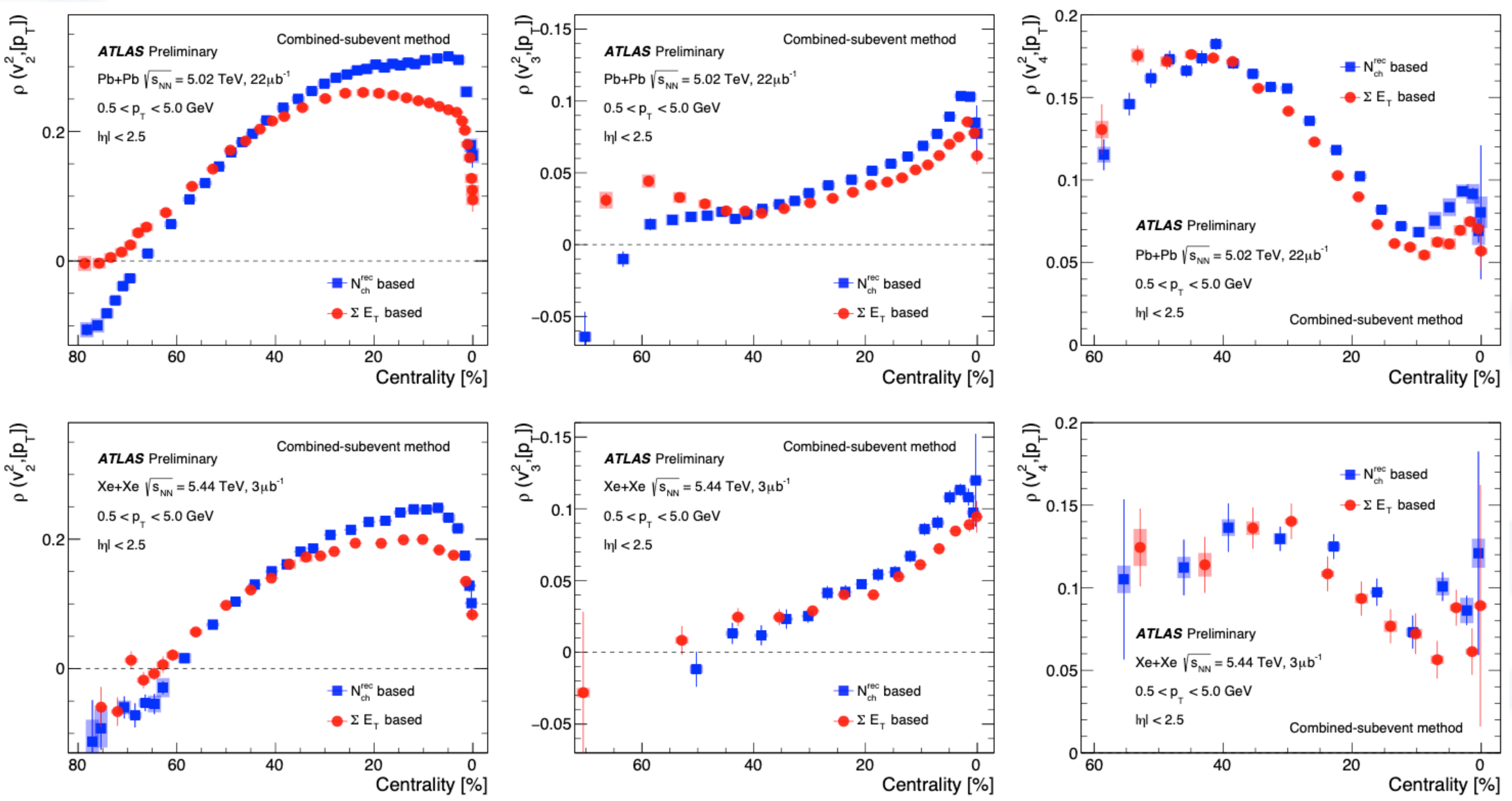
JHEP 01 (2020) 51





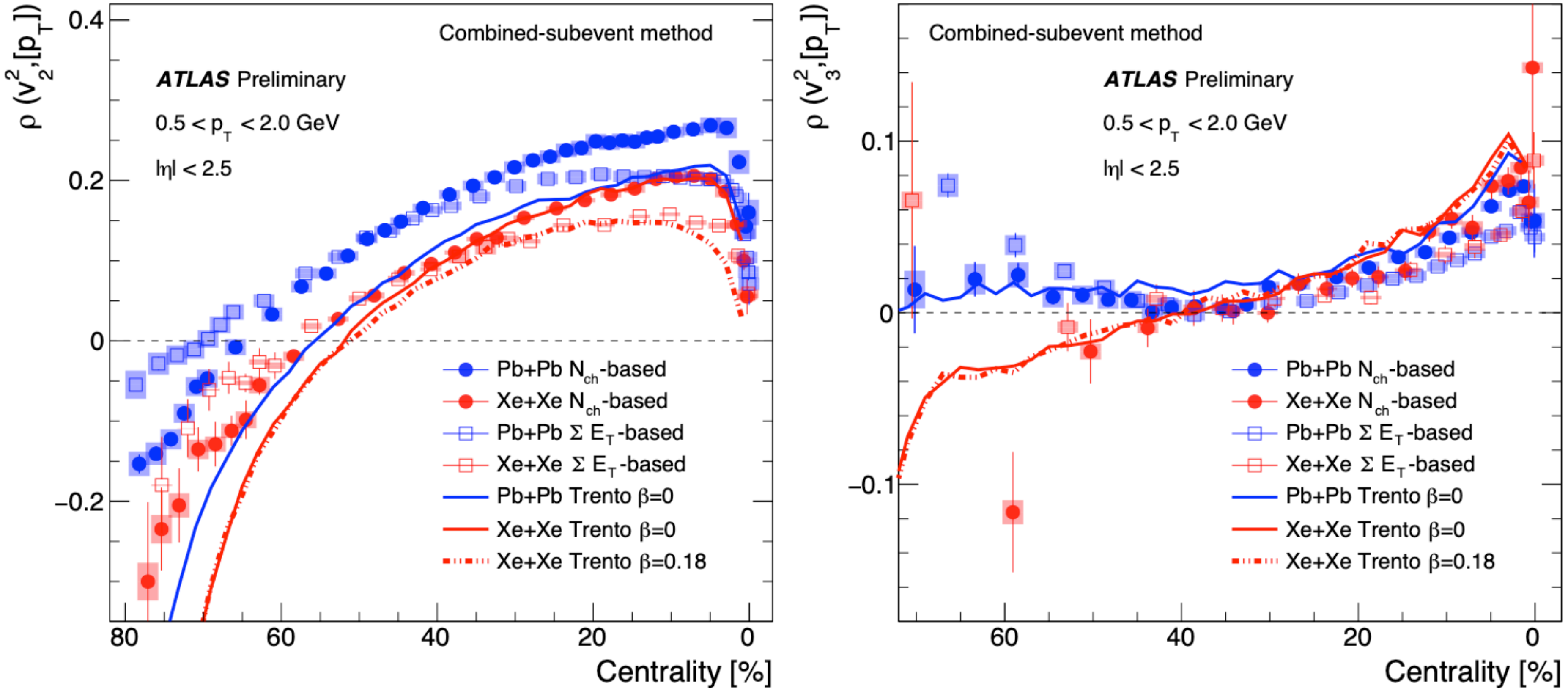
- Event averaging in Nch and FCal-Et bins - Centrality fluctuations.
- Larger centrality fluctuation effect for higher particle-cumulants
- Effect present in much broader centrality range for both n=2 and n=3.

Results-V: Effect of centrality fluctuations



- E_T and N_{ch} are mapped to centrality (based on E_T cuts)
- Large influences of centrality fluctuations for all harmonics
- Trends similar in Pb+Pb and Xe+Xe

Results-VI: Theoretical predictions

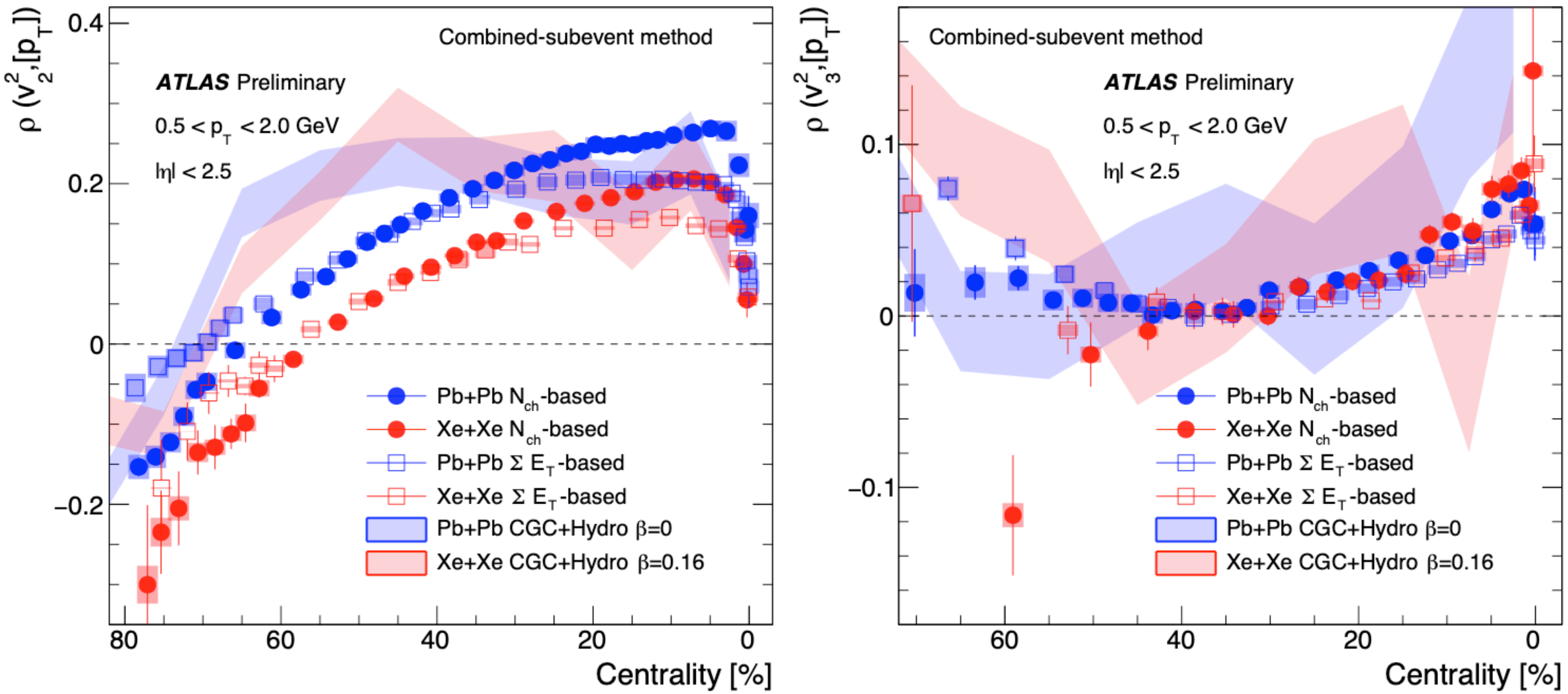


arXiv:2004.14463

➢ **Trento :**

- Deformation strongly affects n=2 but not n=3
- Can explain some qualitative trends in data but not quantitatively
- Scaling for n=3 seen both in data and model.
- Due to centrality fluctuation - any conclusion on deformation effect is not clear in Xe+Xe

Results-VI: Theoretical predictions



- **IP-Glasma+MUSIC+URQMD calculations:**

- have larger uncertainties than Trento model
- CGC+Hydro cannot reproduce the ordering between Xe+Xe and Pb+Pb
- Cannot explain data qualitatively or quantitatively.

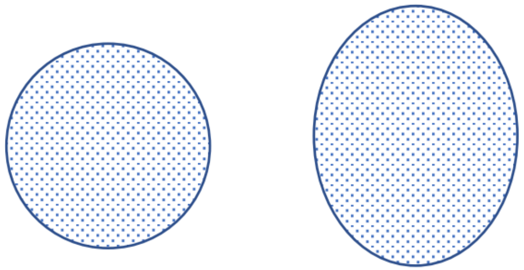
arXiv:2006.15721
arXiv:2004.00690

CONCLUSION

- Flow and mean-momentum correlations show strong system-size dependence
  - Smaller magnitude of ρ_n in XeXe for n=2 and n=4
  - Larger magnitude in XeXe for n=3
- Significant dependence on p_T and η ranges
  - Larger variances for smaller eta range of |eta|<1
  - much smaller difference in covariance
- Centrality fluctuations
  - N_{ch} vs FCal-E_T binnings - significant differences
  - Nature similar for different pT ranges in both Pb+Pb and Xe+Xe
- Theory comparison with observed trends on data
  - Trento model captures qualitative trends in data
  - Models do not explain the measurements quantitatively
  - Quantitative inferences from theory should address centrality fluctuation

Thank You

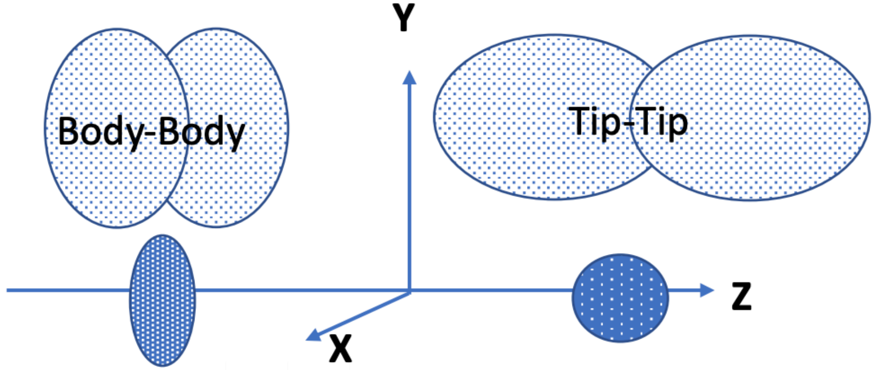
Effect of Nuclear Deformation on $v_n - [p_T]$ correlation

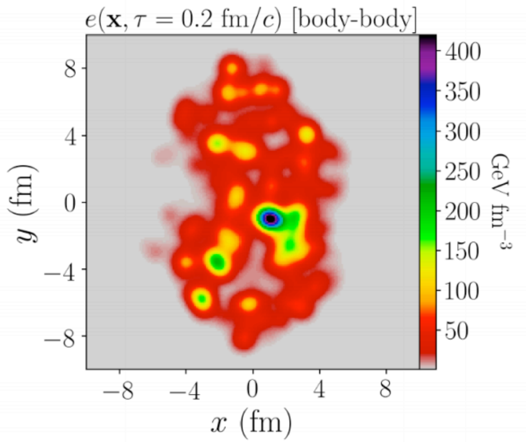


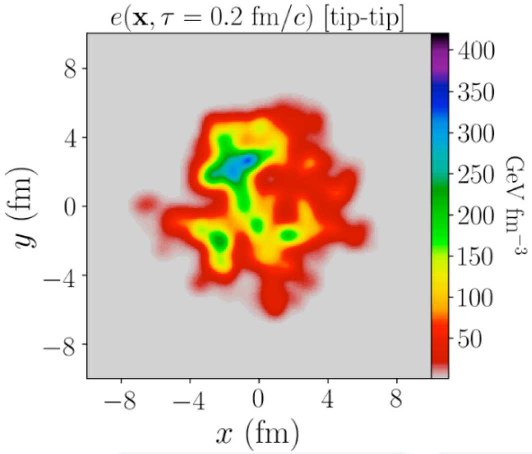
Spherical
(eg: ^{208}Pb)

Prolate ($\beta = 0.18$)
(eg: ^{129}Xe)

$$\beta_2 \sim \frac{\langle Y_2^0(\Theta,\Phi) r^2 \rho(r)\rangle}{\langle r^2\rangle}$$

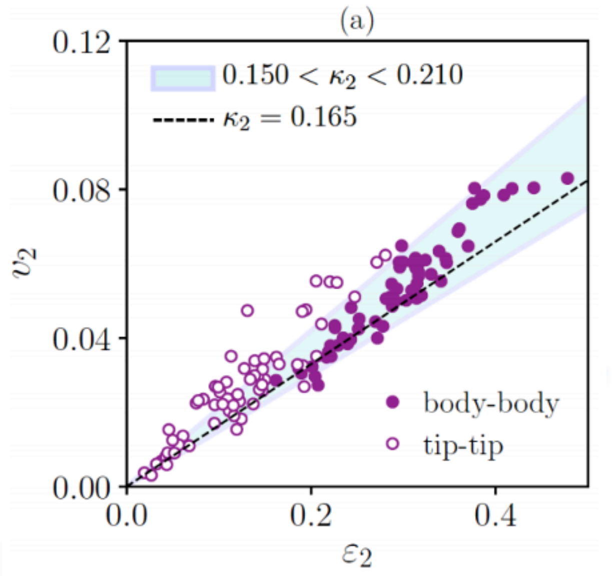


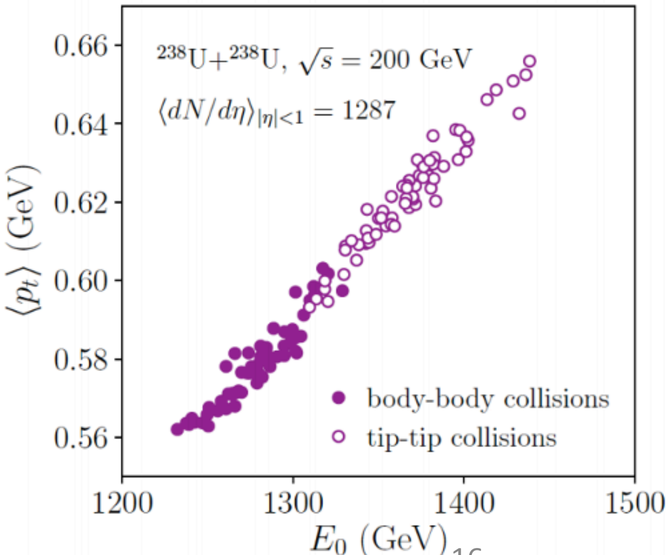




Has lower $< p_T >$

Has higher E_0, lower ε_2





- Thus, $v_n - [p_T]$ correlation is expected to be different for spherical and deformed nuclei, especially in central collisions.

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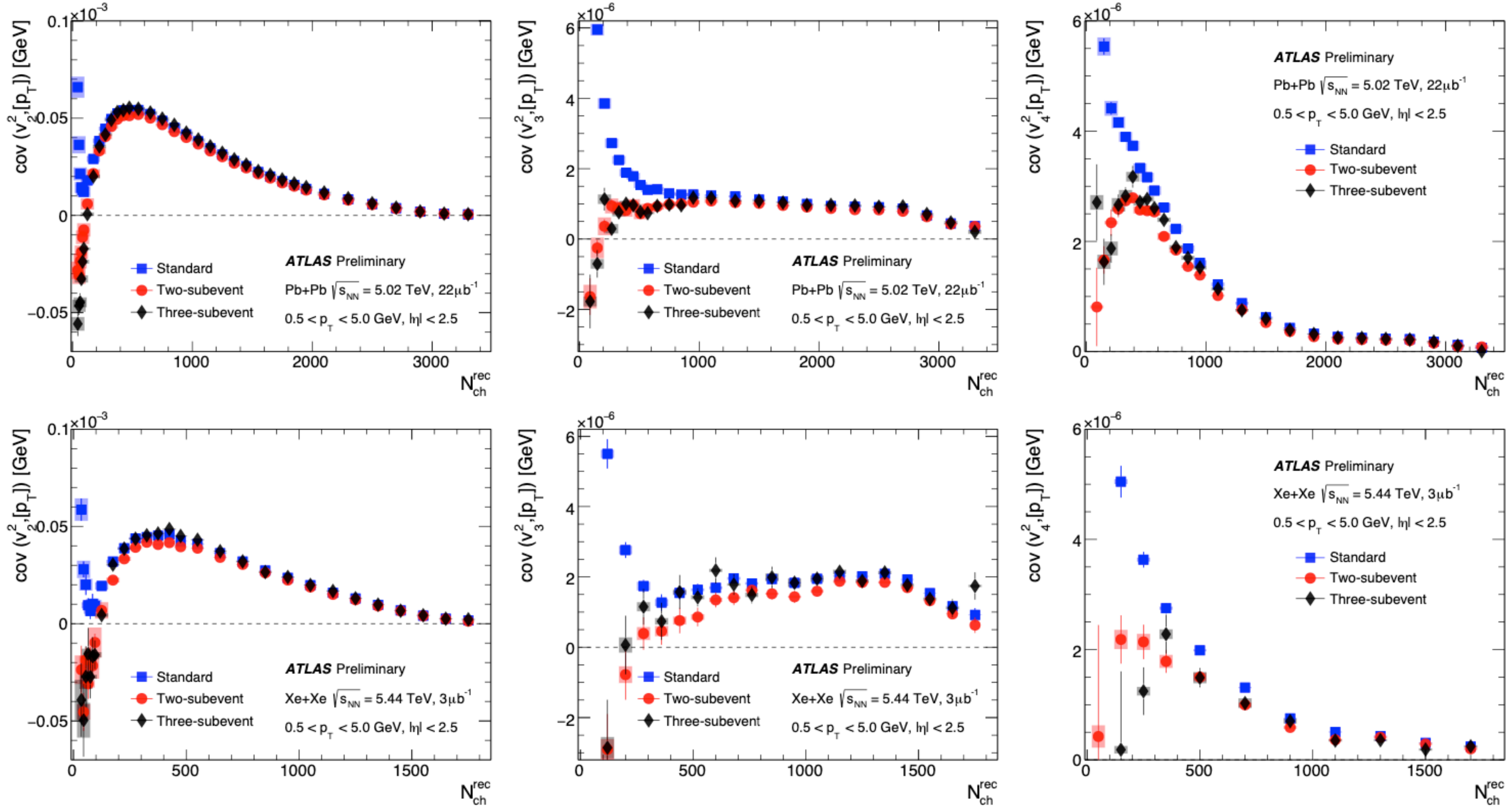
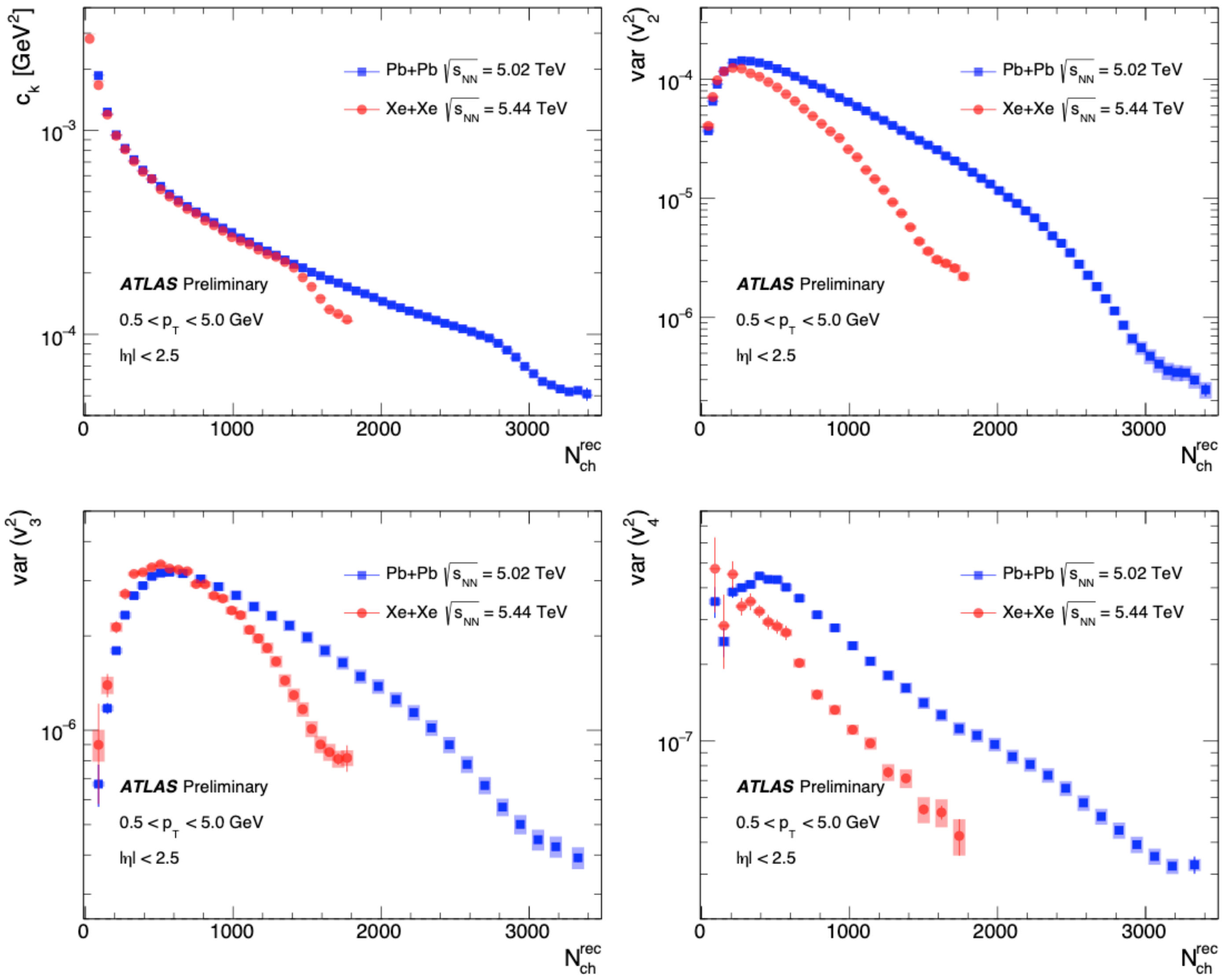
Backup-I: Covariance comparison between subevent methods



- Non-flow significant in standard method at low N_{ch}, at larger N_{ch} difference is ~ constant, due to decorrelation or $v_n(\eta)$.
- Difference between subevent methods are expected, flow/non-flow signal may not be the same for all triplets even in each method.
- For n=2: not limited by statistics, so we choose the 3-subevent as default method.
- For n=3 and 4: limited by statistics, especially low p_T, choose the average of 2- and 3 subevent as default method.

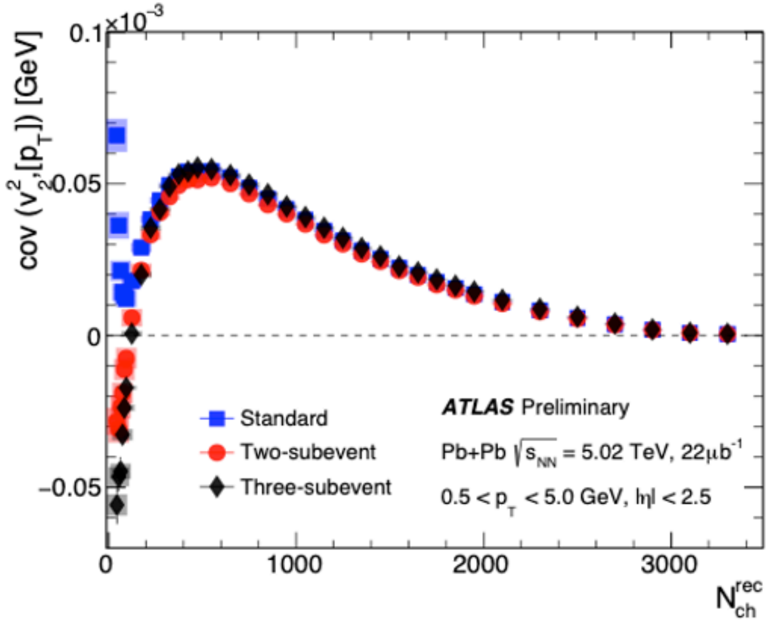
Backup-II: Comparison of Variances of v_n and $[p_T]$

- c_k is consistent in Xe+Xe and Pb+Pb and follows a power-law dependence
- Departure from power-law in ultra central region - also seen in STAR and ALICE.
- Reduced $[p_T]$ fluctuations - due to upper boundary effect in UCC.
- Var(v_n) follows similar N_{ch} dependence in both system
- The ordering and trends are similar to $v_n\{2\}$.



Backup-III: Covariance of v_n^2 and $[p_T]$

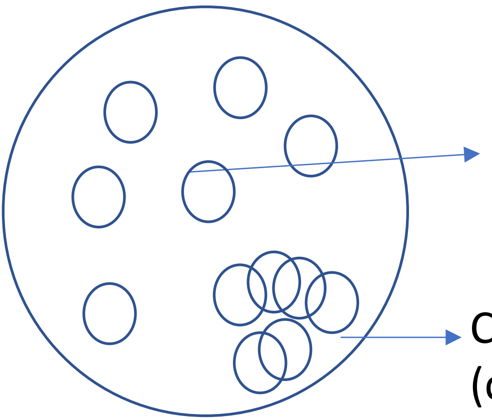
[ref] arXiv:2004.00690v1 [nucl-th]



❖ $\mathrm{Cov}((v_2\{2\})^2, [p_T])$ is –ve in peripheral events.
Explanation: This sign change is a geometrical effect coming from the correlation between S/A and ε_2 at fixed Multiplicity.

1. Compact Source Model: possible explanation for –ve correlation for peripheral events
2. In Mid-central region, impact parameter fluctuation leads to a rise in initial state fluctuations lead to rise of covariance in mid-Centrality [ref].

PERIPHERAL EVENTS

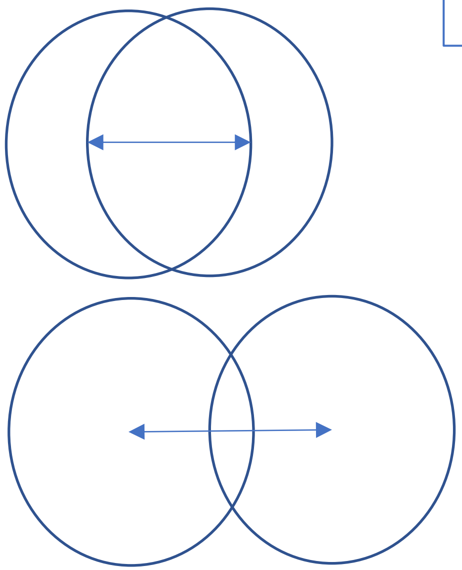


Patchy energy deposition

Can lead to clustering (compact source)

Smaller area and small eccentricity (-ve correlation)

MID-CENTRAL EVENTS



At same multiplicity, increase in b(from increasing fluctuations) can give rise to smaller area and increasing eccentricity. increasing correlation.

Analysis Procedure

$\rho(v_n^2, p_T)$
is measured from 3 quantities

$$cov(v_n\{2\}^2, [p_T]) = \left\langle \frac{\sum_{i\neq j\neq k} w_i w_j w_k e^{in(\phi_i - \phi_j)} (p_{T,k} - \langle [p_T] \rangle)}{\sum_{i\neq j\neq k} w_i w_j w_k} \right\rangle$$

$$var(v_n^2\{2\})_{dyn} = c_n\{4\}_{std} + c_n\{2\}^2_{two-sub}$$

$$c_k = \left\langle \frac{\sum_{i\neq j} w_i w_j (p_{T,i} - \langle p_T \rangle)(p_{T,j} - \langle p_T \rangle)}{\sum_{i\neq j} w_i w_j} \right\rangle$$

- Expand the nested-loop into polynomials of flow vectors and scalars, including

$$\mathbf{q}_{n;k} = \frac{\sum_i w_i^k e^{in\phi_i}}{\sum_i w_i^k}, \quad p_{m;k} = \frac{\sum_i w_i^k (p_{\mathrm{T},i} - \langle [p_{\mathrm{T}}] \rangle)^m}{\sum_i w_i^k}, \quad [p_{\mathrm{T}}] = \frac{\sum_i w_i p_{\mathrm{T},i}}{\sum_i w_i}$$

- Detector effects enters via particle weights, includes efficiency and flattening $w_i(\phi, \eta, p_{\mathrm{T}}) = d(\phi, \eta)/\epsilon(\eta, p_{\mathrm{T}})$
- Correct for residual offsets in flow vectors $\mathbf{q}_{n;k} - \langle \mathbf{q}_{n;k} \rangle_{\mathrm{evts}}$
- Repeat for each systematic check