Measurement of longitudinal flow decorrelation in Pb+Pb collisions at $\sqrt{s_{NN}}$ =2.76 and 5.02 TeV with the ATLAS detector

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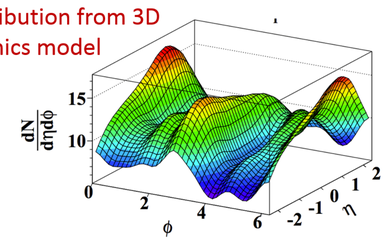
1. Motivation

- Both **longitudinal** & **transverse fluctuation** exist in event-by-event particle distribution in (η, ϕ). The goal of this analysis is to study the longitudinal flow fluctuation.

Particle distribution from 3D hydrodynamics model



For harmonic flow $\boldsymbol{v_n} = v_n(\eta)e^{i\Psi_n(\eta)}$ longitudinal flow fluctuation could manifest as:

- Event plane twist
  $\Psi_n(\eta_1) \neq \Psi_n(\eta_2)$
- Forward-backward (FB) magnitude asymmetry
  $v_n(\eta_1) \neq v_n(\eta_2)$

2. Methods & Observables

- Estimate flow using q-vector $\boldsymbol{q}_n \equiv \frac{\sum_i w_i e^{in\phi_i}}{\sum_i w_i} \equiv q_n\, e^{in\Psi_n}$
- Correlate flow from different sub-detectors

$$\langle \boldsymbol{q}_n^k(\eta_1)\boldsymbol{q}_n^{*k}(\eta_2)\rangle = \langle \boldsymbol{v}_n^k(\eta_1)\boldsymbol{v}_n^{*k}(\eta_2)\rangle = \left\langle [v_n(\eta_1)v_n(\eta_2)]^k \cos kn(\Phi_n(\eta_1)-\Phi_n(\eta_2))\right\rangle$$

- Define factorization ratio $r_{n|n;k}$

$$r_{n|n;k}(\eta) = \frac{\langle \boldsymbol{q}_n^k(-\eta)\boldsymbol{q}_n^{*k}(\eta_{\rm ref})\rangle}{\langle \boldsymbol{q}_n^k(\eta)\boldsymbol{q}_n^{*k}(\eta_{\rm ref})\rangle} = \frac{\left\langle [v_n(-\eta)v_n(\eta_{\rm ref})]^k \cos kn(\Phi_n(-\eta)-\Phi_n(\eta_{\rm ref}))\right\rangle}{\left\langle [v_n(\eta)v_n(\eta_{\rm ref})]^k \cos kn(\Phi_n(\eta)-\Phi_n(\eta_{\rm ref}))\right\rangle}$$

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- quantify flow decorrelation: FB asymmetry + event plane twist
- higher-order moments capture statistics of fluctuation
- 1st-order = CMS measurements r_n *PRC.* 92, 034911 (2015)
- A linear trend predicted from the Glauber model

$$r_{n|n;k}(\eta) \approx 1 - 2kF^{\rm r}_{n;k}\eta, \quad F^{\rm r}_{n;k} = F^{\rm asy}_{n;k} + F^{\rm twi}_{n;k}$$

- Define factorization ratio $R_{n,n|n,n}$

$$R_{n,n|n,n}(\eta) = \frac{\langle \boldsymbol{q}_n^*(-\eta_{\rm ref})\boldsymbol{q}_n^*(-\eta)\boldsymbol{q}_n(\eta)\boldsymbol{q}_n(\eta_{\rm ref})\rangle}{\langle \boldsymbol{q}_n^*(-\eta_{\rm ref})\boldsymbol{q}_n(-\eta)\boldsymbol{q}_n^*(\eta)\boldsymbol{q}_n(\eta_{\rm ref})\rangle} = \frac{\langle \cancel{v_n(-\eta_{\rm ref})}\cancel{v_n(-\eta)}\cancel{v_n(\eta_{\rm ref})}\cancel{v_n(\eta)}e^{in[\Phi_n(\eta_{\rm ref})-\Phi_n(-\eta_{\rm ref})+\Phi_n(\eta)-\Phi_n(-\eta)]}\rangle}{\langle \cancel{v_n(-\eta_{\rm ref})}\cancel{v_n(-\eta)}\cancel{v_n(\eta_{\rm ref})}\cancel{v_n(\eta)}e^{in[\Phi_n(\eta_{\rm ref})-\Phi_n(-\eta_{\rm ref})-(\Phi_n(\eta)-\Phi_n(-\eta))]}\rangle}$$

- mostly sensitive to EP twist
- together with $r_{n|n;2}$, can separate twist + asymmetry

$$R_{n,n|n,n} = 1 - 4F^{twi}_{n;2}\eta\,; \qquad r_{n|n;2} = 1 - 4F^{twi}_{n;2}\eta - 4F^{asy}_{n;2}\eta$$

- Mixed-harmonics correlation can help test nonlinear contribution in $\boldsymbol{v_4}$ and $\boldsymbol{v_5}$

$$\boldsymbol{v}_4 = \boldsymbol{v}_{4L} + \beta_{2,2}(\boldsymbol{v}_2)^2, \quad \boldsymbol{v}_5 = \boldsymbol{v}_{5L} + \beta_{2,3}\boldsymbol{v}_2\boldsymbol{v}_3$$

$$r_{2,3|2,3}(\eta) = \frac{\langle \boldsymbol{q}_2(-\eta)\boldsymbol{q}_3(-\eta)\boldsymbol{q}_2^*(\eta_{\rm ref})\boldsymbol{q}_3^*(\eta_{\rm ref})\rangle}{\langle \boldsymbol{q}_2(\eta)\boldsymbol{q}_3(\eta)\boldsymbol{q}_2^*(\eta_{\rm ref})\boldsymbol{q}_3^*(\eta_{\rm ref})\rangle}$$

✓ If weak correlation between v_2 and v_3, then we expect $r_{2,3|2,3} \approx r_{2|2;1} \times r_{3|3;1}$

$$r_{2,2|4}(\eta) = \frac{\langle \boldsymbol{q}_2^2(-\eta)\boldsymbol{q}_4^*(\eta_{\rm ref})\rangle}{\langle \boldsymbol{q}_2^2(\eta)\boldsymbol{q}_4^*(\eta_{\rm ref})\rangle} = \frac{\langle \boldsymbol{q}_2^2(-\eta)\boldsymbol{q}_{4L}^*(\eta_{\rm ref})\rangle + \beta_{2,2}\langle \boldsymbol{q}_2^2(-\eta)\boldsymbol{q}_2^{*2}(\eta_{\rm ref})\rangle}{\langle \boldsymbol{q}_2^2(\eta)\boldsymbol{q}_{4L}^*(\eta_{\rm ref})\rangle + \beta_{2,2}\langle \boldsymbol{q}_2^2(\eta)\boldsymbol{q}_2^{*2}(\eta_{\rm ref})\rangle}$$

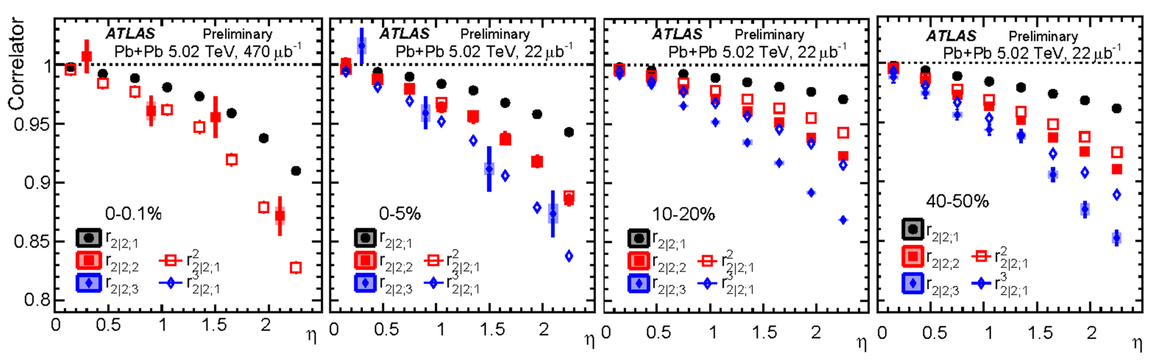
$$r_{2,3|5}(\eta) = \frac{\langle \boldsymbol{q}_2(-\eta)\boldsymbol{q}_3(-\eta)\boldsymbol{q}_5^*(\eta_{\rm ref})\rangle}{\langle \boldsymbol{q}_2(\eta)\boldsymbol{q}_3(\eta)\boldsymbol{q}_5^*(\eta_{\rm ref})\rangle} = \frac{\langle \boldsymbol{q}_2(-\eta)\boldsymbol{q}_3(-\eta)\boldsymbol{q}_{5L}^*(\eta_{\rm ref})\rangle + \beta_{2,3}\langle \boldsymbol{q}_2(-\eta)\boldsymbol{q}_3(-\eta)\boldsymbol{q}_2^*(\eta_{\rm ref})\boldsymbol{q}_3^*(\eta_{\rm ref})\rangle}{\langle \boldsymbol{q}_2(\eta)\boldsymbol{q}_3(\eta)\boldsymbol{q}_{5L}^*(\eta_{\rm ref})\rangle + \beta_{2,3}\langle \boldsymbol{q}_2(\eta)\boldsymbol{q}_3(\eta)\boldsymbol{q}_2^*(\eta_{\rm ref})\boldsymbol{q}_3^*(\eta_{\rm ref})\rangle}$$

✓ If Linear contribution is weak and can be neglected, then we expect

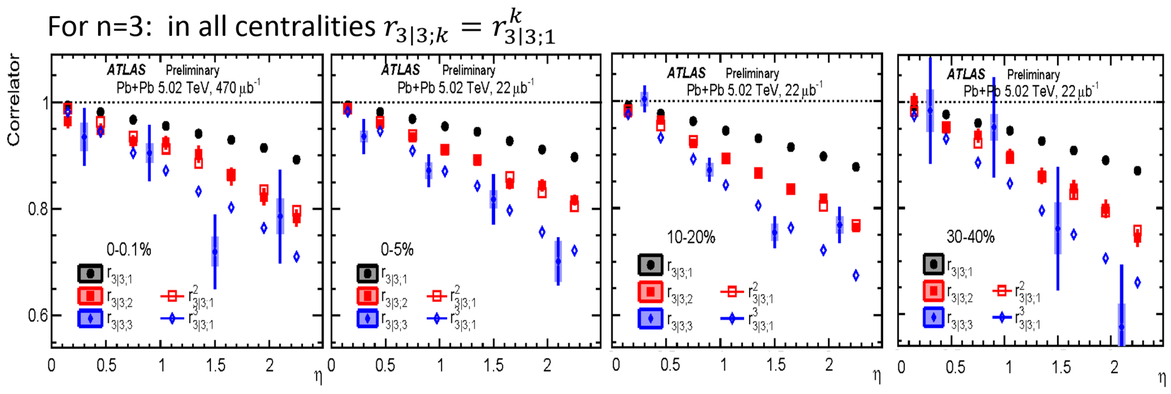
$$r_{2,2|4} \approx r_{2|2;2}, r_{2,3|5} \approx r_{2,3|2,3}$$

3. Higher order moments at 5.02TeV

- For n=2 and k=2,3 :
  in central events: $r_{2|2;k} = r^k_{2|2;1}$; in non-central collision $r_{2|2;k} > r^k_{2|2;1}$

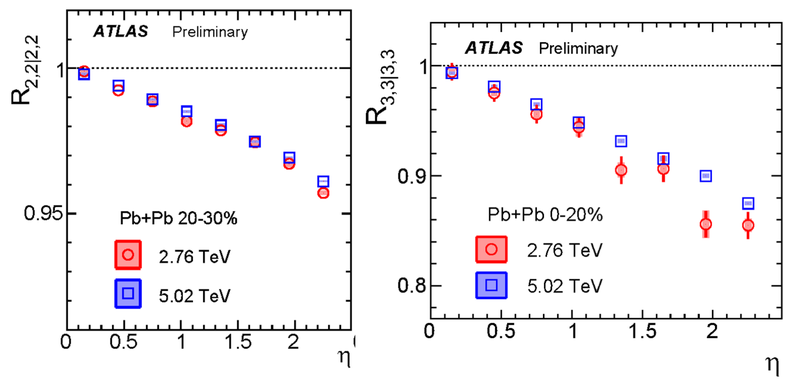


- For n=3: in all centralities $r_{3|3;k} = r^k_{3|3;1}$



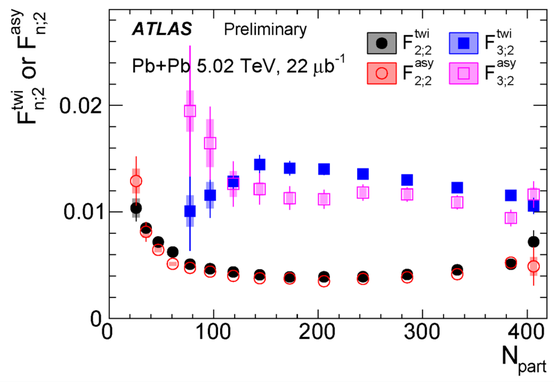
4. $R_{n,n|n,n}$ at 2.76TeV and 5.02TeV

For n=2 and 3 ,
a linear trend is observed in all centralities



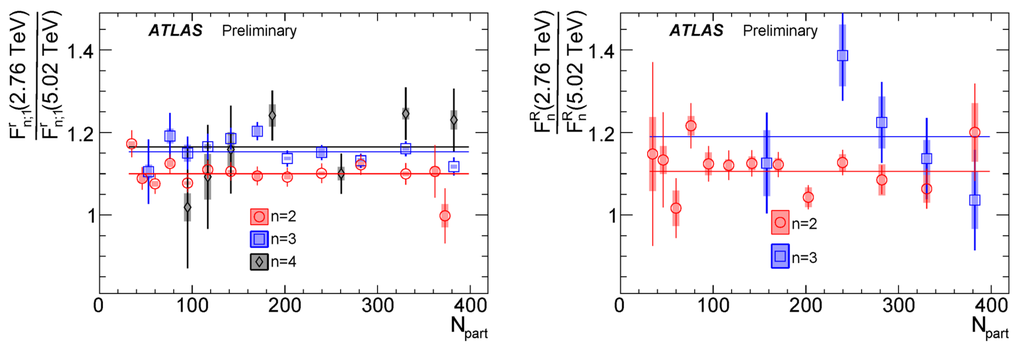
5. Extract EP twist + FB magnitude asymmetry at 5.02TeV

- By fitting $R_{n,n|n,n}$ and $r_{n|n;2}$, we can separate the twist and asymmetry component
  - Two effects are comparable
  - Higher order flow harmonics have stronger decorrelation



6. Energy dependence: 2.76TeV vs 5.02TeV

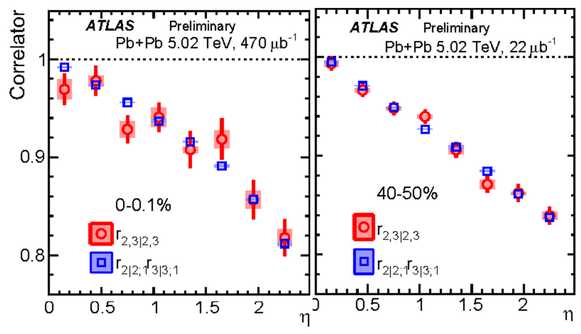
- Compare the ratio of linear decreasing trend
  $r_{n|n;1} = 1 - 2F^r_{n;1}\eta$ and $R_{n,n|n,n} = 1 - 2F^R_n\eta$



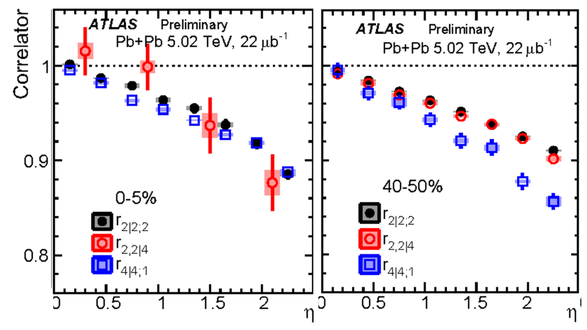
- Lower energy shows stronger decorrelation for $r_{n|n}$ and $R_{n,n|n,n}$

7. Mixed-harmonics correlation at 5.02TeV

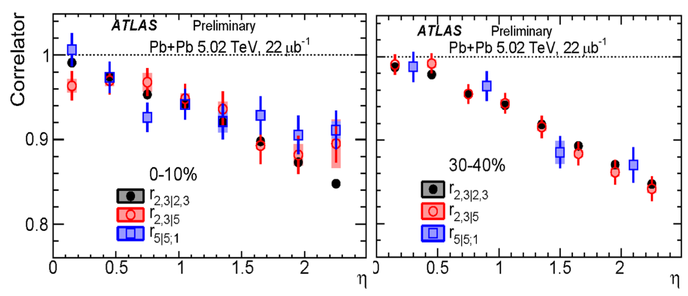
- In all centrality intervals:
  $r_{2,3|2,3} \approx r_{2|2;1} \times r_{3|3;1}$
  Indicates $\boldsymbol{v}_2$ and $\boldsymbol{v}_3$ are weakly correlated



- For $r_{2,2|4}$:
  in all centrality intervals: $r_{2,2|4} \approx r_{2|2;2}$
  Indicates longitudinal fluctuation of $\boldsymbol{v}_4$ is driven from $(\boldsymbol{v}_2)^2$
  in non-central collision: $r_{2,2|4} < r_{4|4;1}$



- In all centrality interval:
  $r_{2,3|5} \approx r_{2,3|2,3} \approx r_{5|5;1}$
  Indicates longitudinal fluctuation of $\boldsymbol{v}_5$ is driven from $\boldsymbol{v}_2\boldsymbol{v}_3$



Summary

A comprehensive study of flow decorrelation in Pb+Pb is shown at ATLAS experiment:

- $\boldsymbol{v}_n$ (n>2) has stronger decorrelation than $\boldsymbol{v}_2$
- Moments result shows $r_{n|n;k} = r^k_{n|n;1}$ holds for n=3 but not in central collision for n=2.
- Mixed-harmonics results show non-linear component carries most of the flow decorrelation of $\boldsymbol{v}_4$ ($\boldsymbol{v}_5$)
- 2.76TeV data shows stronger decorrelation than 5.02TeV data.

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