Measurements of flow correlations in PbPb at $\sqrt{s_{NN}}$=2.76 and 5.02TeV with ATLAS detector

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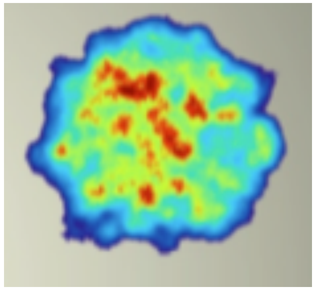
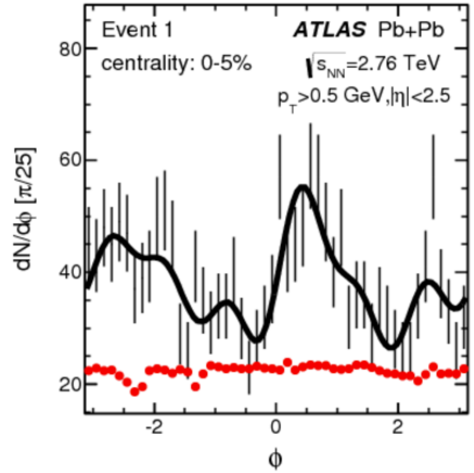
ATLAS-CONF-2017-003

Flow observables

A little bang

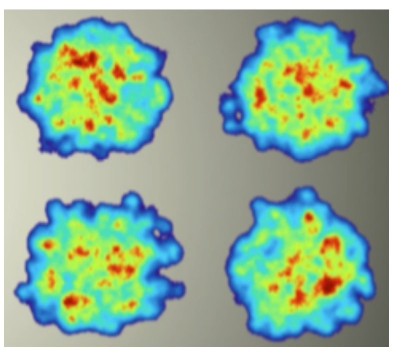




$$\frac{dN}{d\phi} \sim 1 + 2\sum_{n=1} v_n \cos\left(n(\phi - \Phi_n)\right)$$

$$v_n = \langle\cos(n(\phi - \Phi_n))\rangle, \quad \boldsymbol{v}_n = v_n e^{in\Phi_n}$$

Many little bangs



Joint p.d.f. of v_n and Φ_n

$$p(v_n, v_m, ..., \Phi_n, \Phi_m, ...) = \frac{1}{N_{\rm evts}} \frac{dN_{\rm evts}}{dv_n dv_m ... d\Phi_n d\Phi_m ...}$$

Flow observables

J.Jia, *arxiv*: 1407.6057

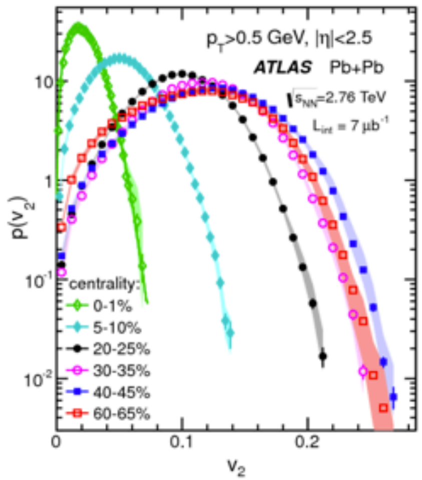
	pdfs	cumulants
Flow-amplitudes	$p(v_n)$	$v_n\{2k\}$, $k = 1,2,...$
	$p(v_n, v_m)$	$\langle v_n^2 v_m^2\rangle - \langle v_n^2\rangle\langle v_m^2\rangle$, $n \neq m$ ...
	$p(v_n, v_m, v_l)$	$\langle v_n^2 v_m^2 v_l^2\rangle + 2\langle v_n^2\rangle\langle v_m^2\rangle\langle v_l^2\rangle -$ $\langle v_n^2 v_m^2\rangle\langle v_l^2\rangle - \langle v_m^2 v_l^2\rangle\langle v_n^2\rangle - \langle v_l^2 v_n^2\rangle\langle v_m^2\rangle$ $n \neq m \neq l$ ...
	...	Obtained recursively as above
EP-correlation	$p(\Phi_n, \Phi_m, ...)$	$\langle v_n^{\lvert c_n\rvert} v_m^{\lvert c_m\rvert} ... \cos(c_n n\Phi_n + c_m m\Phi_m + ...)\rangle$ $\sum_k kc_k = 0$
Mixed-correlation	$p(v_l, \Phi_n, \Phi_m, ...)$	$\langle v_l^2 v_n^{\lvert c_n\rvert} v_m^{\lvert c_m\rvert} ... \cos(c_n n\Phi_n + c_m m\Phi_m + ...)\rangle -$ $\langle v_l^2\rangle\langle v_n^{\lvert c_n\rvert} v_m^{\lvert c_m\rvert} ... \cos(c_n n\Phi_n + c_m m\Phi_m + ...)\rangle$ $\sum_k kc_k = 0$, $n \neq m \neq l ...$

Correlations and fluctuations in transverse plane

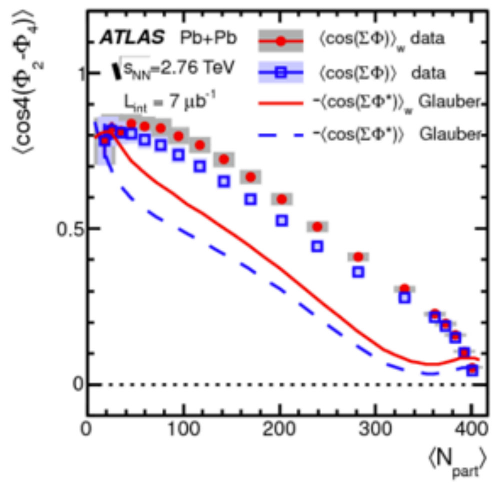
- Transverse dynamics has been well explored both in experiments and theory

Experiment

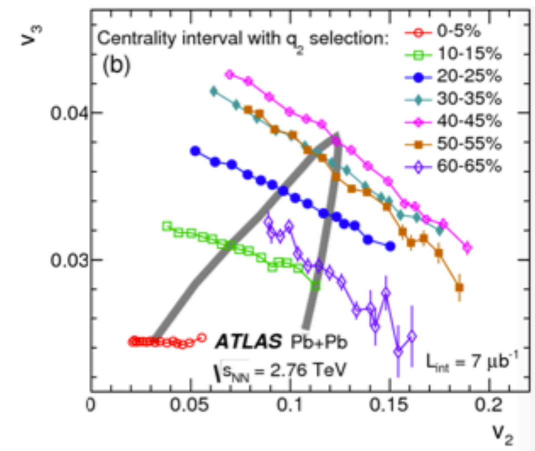
E-by-E flow distribution



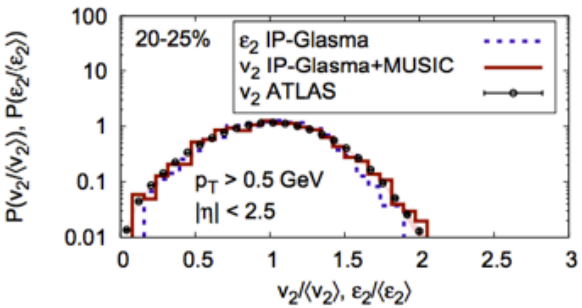
Event-plane correlation



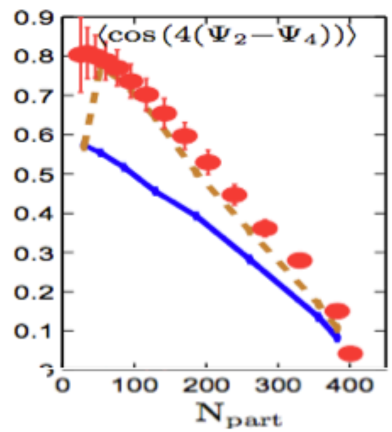
v_3-v_2 amplitude correlation



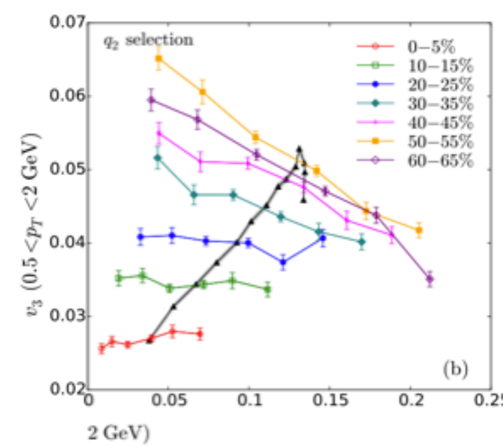
Theory



PRL 110.012302



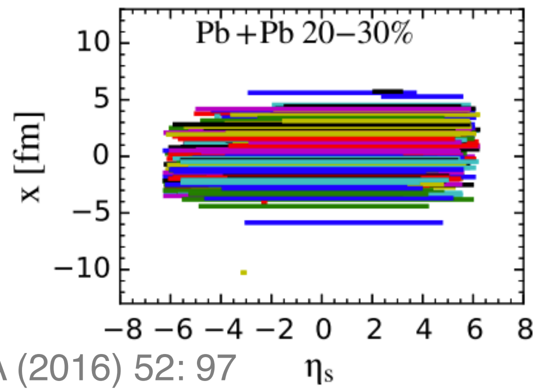
PLB 717, 261 (2012)



PRC 94, 024910 (2016)

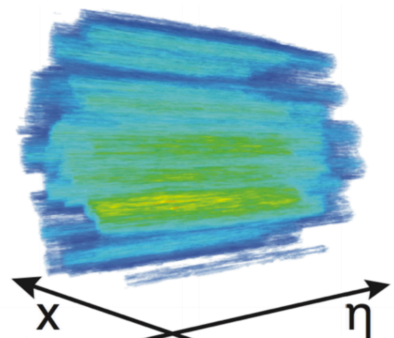
3D initial conditions

- Longitudinal dynamics hasn't been fully explored yet
  - AMPT: HIJING with string melting
    - ➢ Soft string length fluctuation



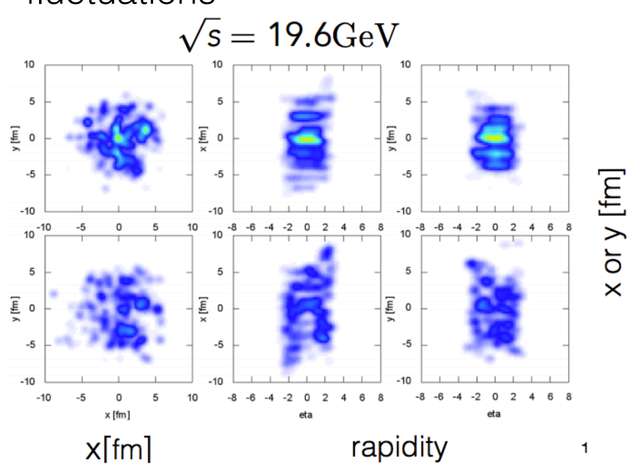
EPJA (2016) 52: 97

  - 3D-Glasma: JIMWLK+IP Glasma



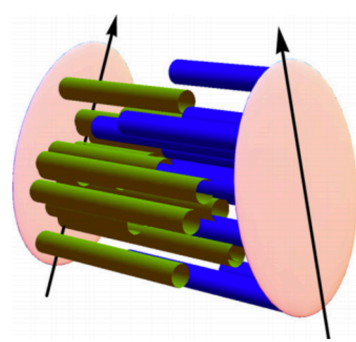
PRC.94.044907

  - Quark 3DMC-Glauber
    - ➢ Lexus model for the longitudinal fluctuations



PLB 752, 317-321

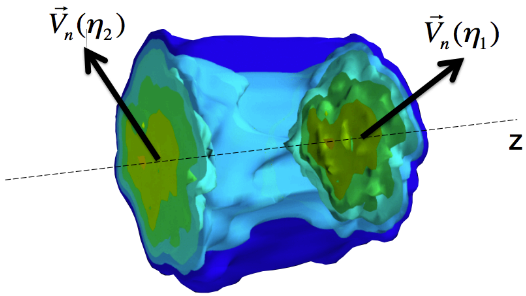
- ➢ Strings of random longitudinal length



PLB 752(2016)206-211

3+1D QGP evolution

- Longitudinal dynamics hasn't been fully explored yet



$$\boldsymbol{v}_n(\eta) = v_n(\eta)e^{in\Phi_n(\eta)}$$

Q: what is the influence of longitudinal dynamics on these transverse observables

	pdfs	cumulants
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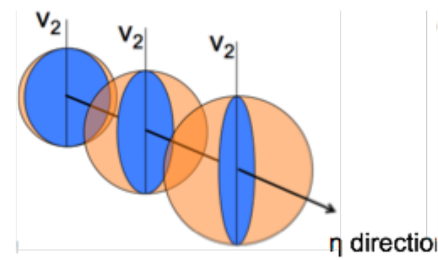
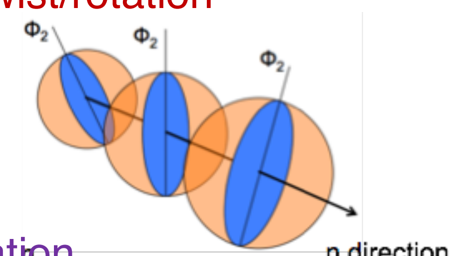
J.Jia, arxiv: 1407.6057

- Amplitude asymmetry
  $v_n(\eta)$



- Event plane twist/rotation
  $\Phi_n(\eta)$



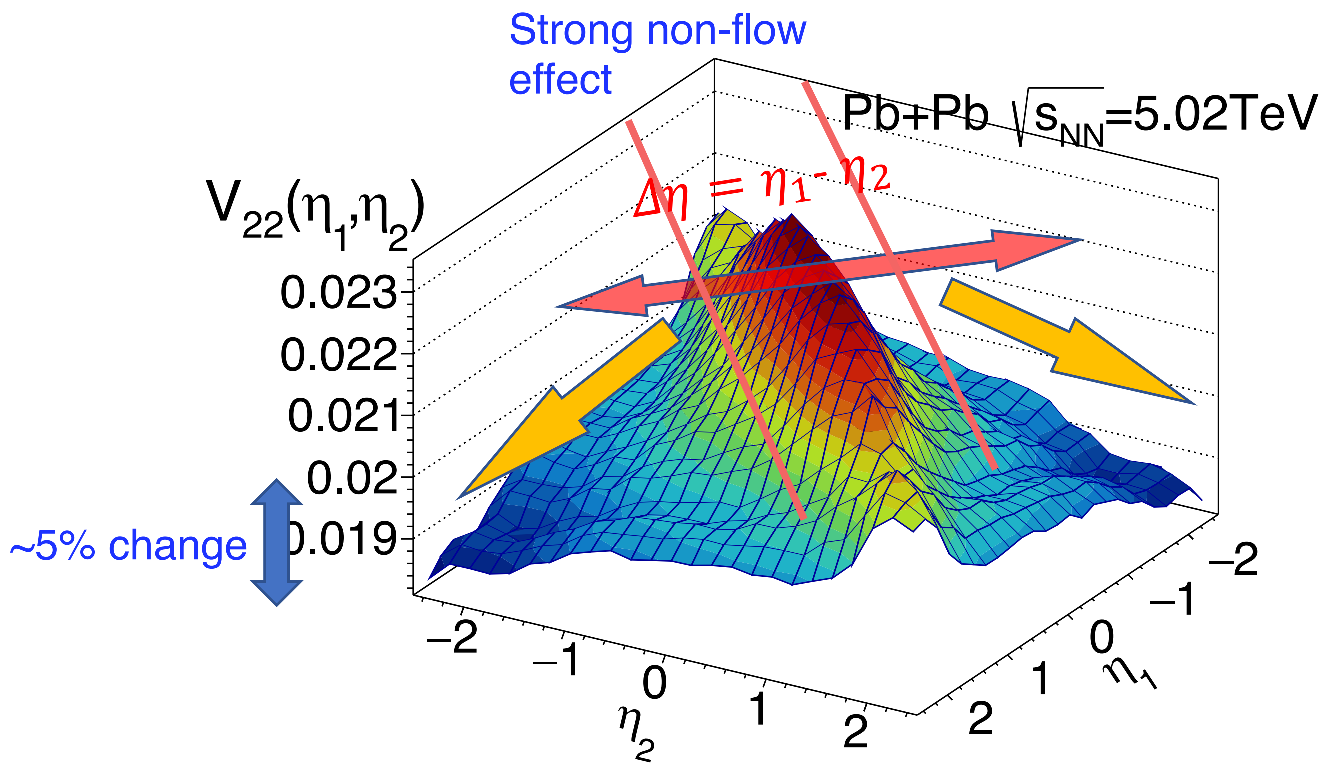
- Mixed-correlation
  $\mathbf{v}_n - \mathbf{v}_n$, $\mathbf{v}_n - \mathbf{v}_m$
- Higher order moments

2D map of flow correlation in η

- 2-particle correlator: correlate flow $\mathbf{v}_n$ between η_1 and η_2

$$V_{nn}(\eta_1,\eta_2) = \langle \boldsymbol{v}_n(\eta_2)\, \boldsymbol{v}_n^*(\eta_1) \rangle$$

$$= \langle v_n(\eta_1)\, v_n(\eta_2) \cos n \left(\Psi_n(\eta_1) - \Psi_n(\eta_2)\right) \rangle$$



✓ V_{22} decreases at large $\Delta\eta = |\eta_1 - \eta_2|$: decorrelation in correlation

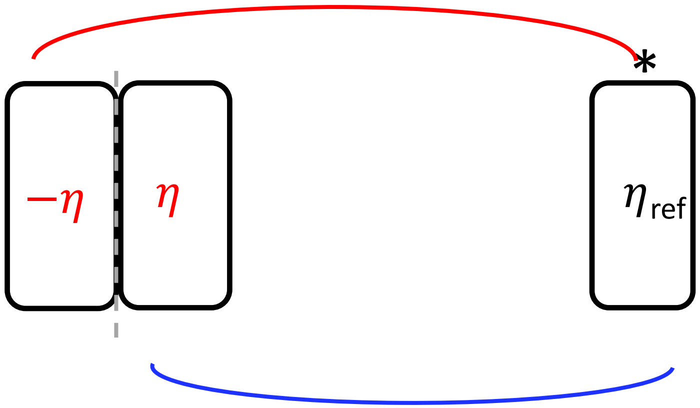
✓ V_{22} has small variation

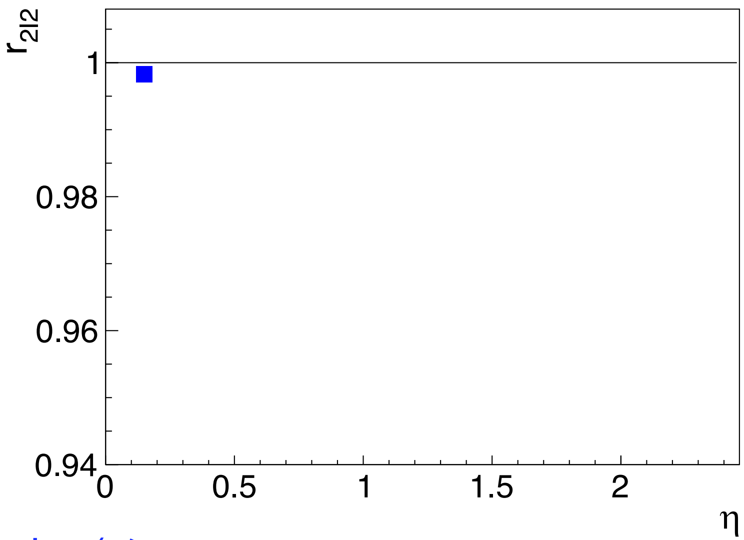
How to measure flow decorrelation

- Factorization ratio $r_{n|n}$ is constructed to measure flow decorrelation

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

CMS PRC.92.034911





- $r_{n|n}$ is measures relative variance of between $\mathbf{v}_n(-\eta)$ and $\mathbf{v}_n(\eta)$

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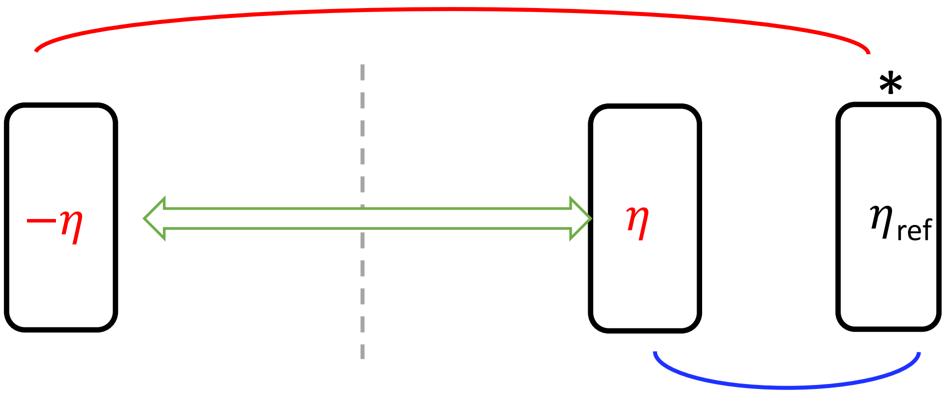
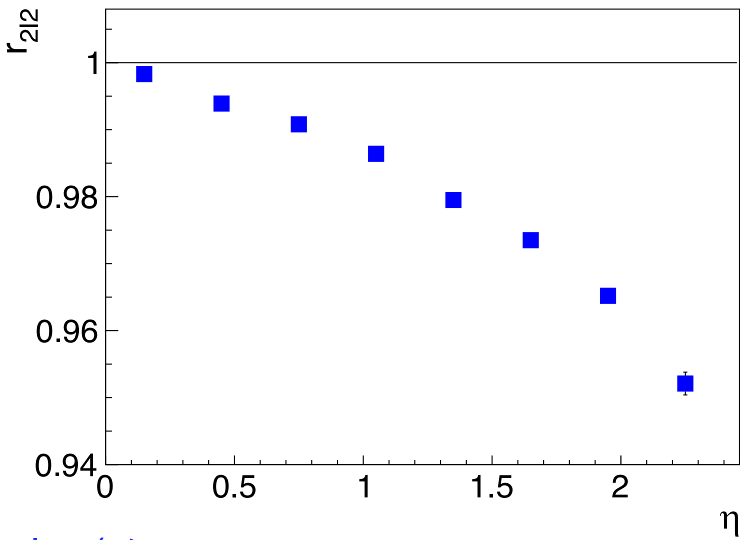
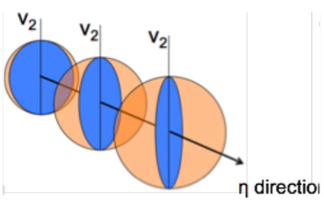


$v_n(-\eta)e^{in\Phi_n(-\eta)}$

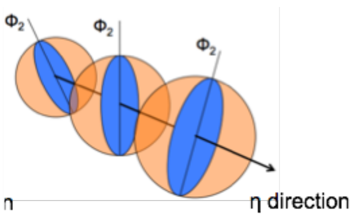


- $r_{n|n}$ is measures relative variance of between $\mathbf{v}_n(-\eta)$ and $\mathbf{v}_n(\eta)$

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



FB magnitude asymmetry

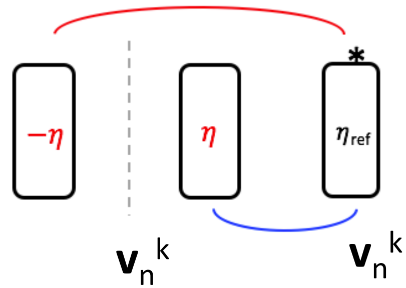


Event Plane (EP) twist

New observables in ATLAS

- **Decorrelation of $[\boldsymbol{v}_n(\eta)]^k$**

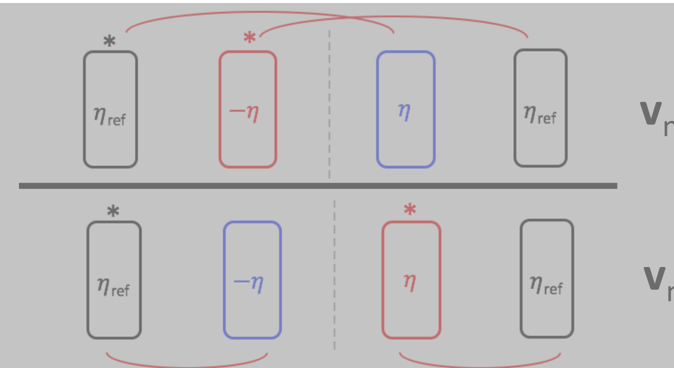
$$r_{n|n;k} = \frac{\langle \boldsymbol{v}_n(-\eta)^k \boldsymbol{v}_n^*(\eta_{\rm ref})^k \rangle}{\langle \boldsymbol{v}_n(\eta)^k \boldsymbol{v}_n^*(\eta_{\rm ref})^k \rangle}$$



Sensitive to how η-dependent decorrelation fluctuates EbyE

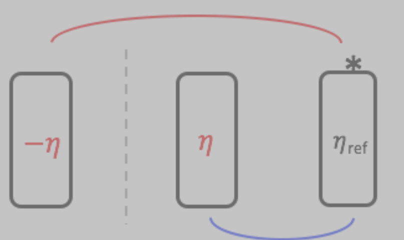
- **4-particle correlator**

$$R_{n|n;2}(\eta) = \frac{\langle \boldsymbol{v}_n^*(-\eta_{\rm ref}) \boldsymbol{v}_n^*(-\eta) \boldsymbol{v}_n(\eta) \boldsymbol{v}_n(\eta_{\rm ref}) \rangle}{\langle \boldsymbol{v}_n^*(-\eta_{\rm ref}) \boldsymbol{v}_n(-\eta) \boldsymbol{v}_n^*(\eta) \boldsymbol{v}_n(\eta_{\rm ref}) \rangle} =$$



Minimize v_n fluct. and single out EP twist

- **Mixed harmonics decorrelation**



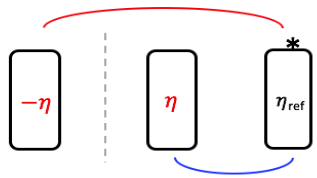
$\mathbf{v}_2\mathbf{v}_3$	$\mathbf{v}_2\mathbf{v}_3$
$\mathbf{v}_2^2$	$\mathbf{v}_4$
$\mathbf{v}_2\mathbf{v}_3$	$\mathbf{v}_5$

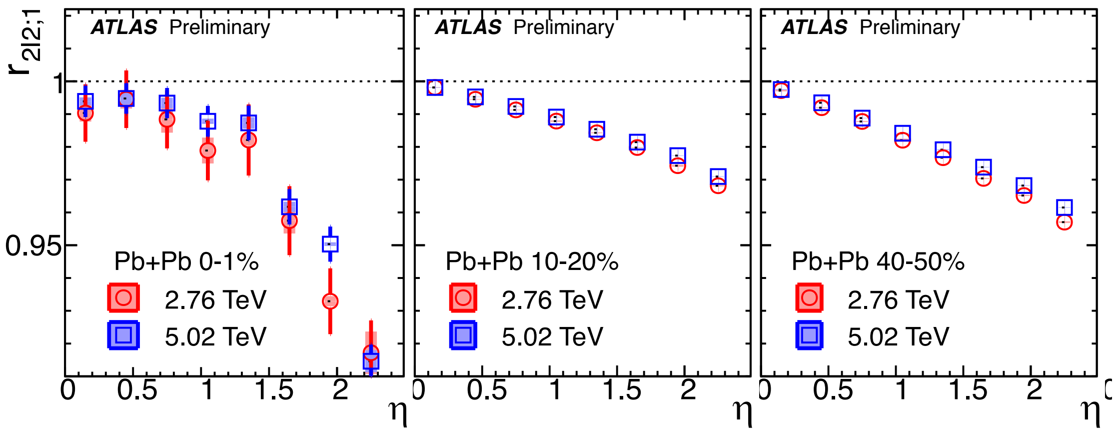
Are the decorrelation of different harmonics correlated?

1st moment of decorrelation: $r_{n|n;1}$

- Decorrelation of $v_2(\eta)$

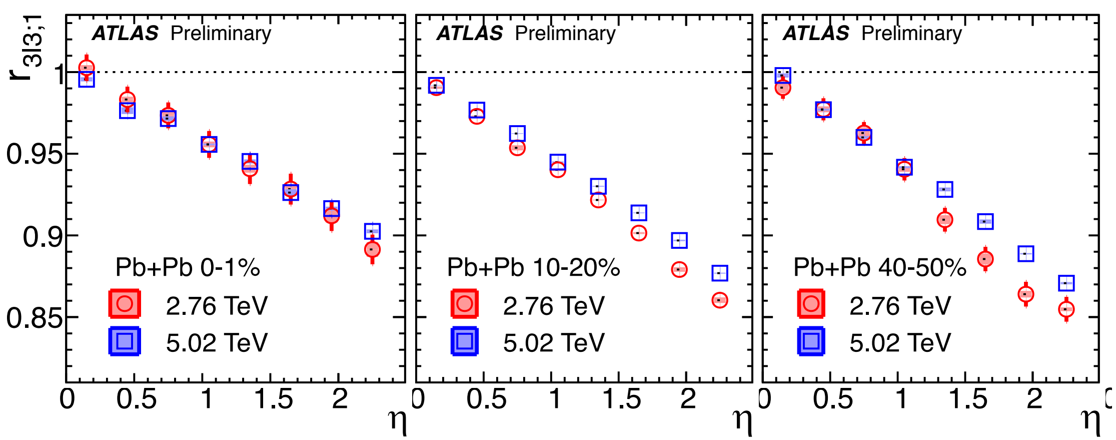
$$r_{2|2;1} = \frac{\langle v_2(-\eta) v_2^*(\eta_{\rm ref})\rangle}{\langle v_2(\eta) v_2^*(\eta_{\rm ref})\rangle}$$





- ❖ linear decreasing along η
- ❖ smallest decorrelation in mid-central
- ❖ stronger decorrelation at lower energy

- Decorrelation of $v_3(\eta)$



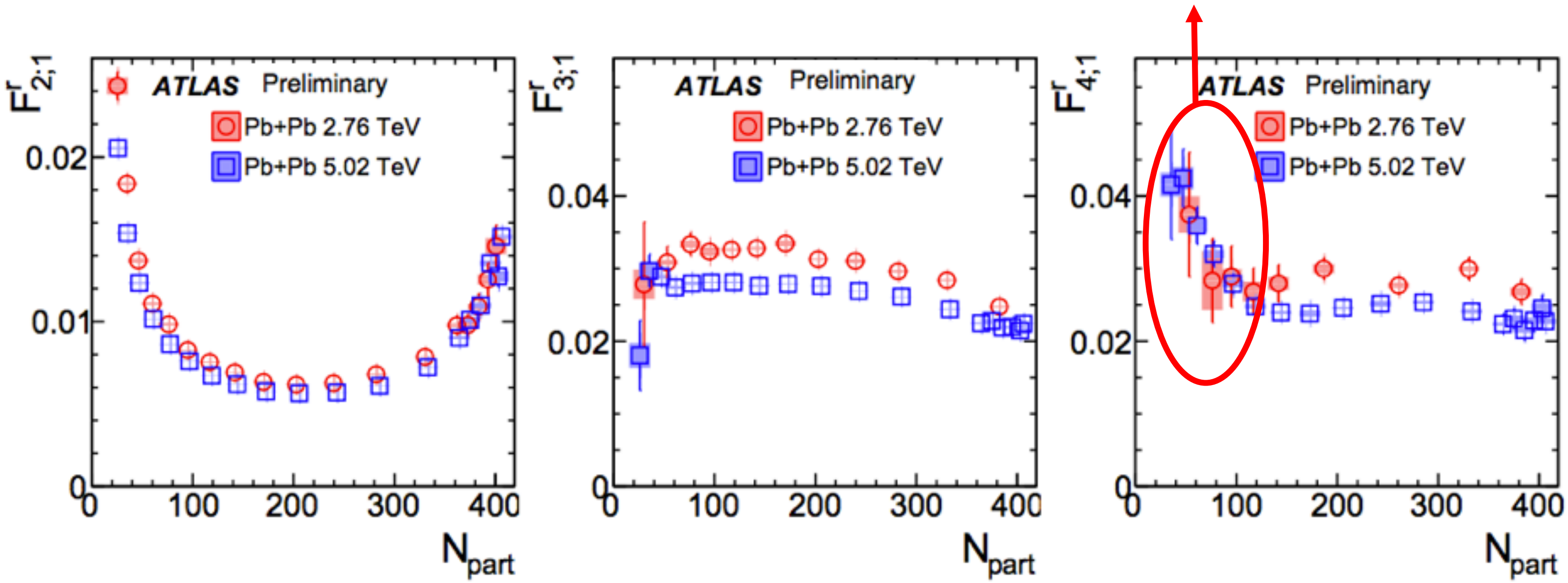
- ❖ linear decreasing along η
- ❖ weak centrality dependence
- ❖ stronger decorrelation at lower energy

Quantify decorrelation using linear fitting

- $r_{n|n;1}$ is parameterized with linear function

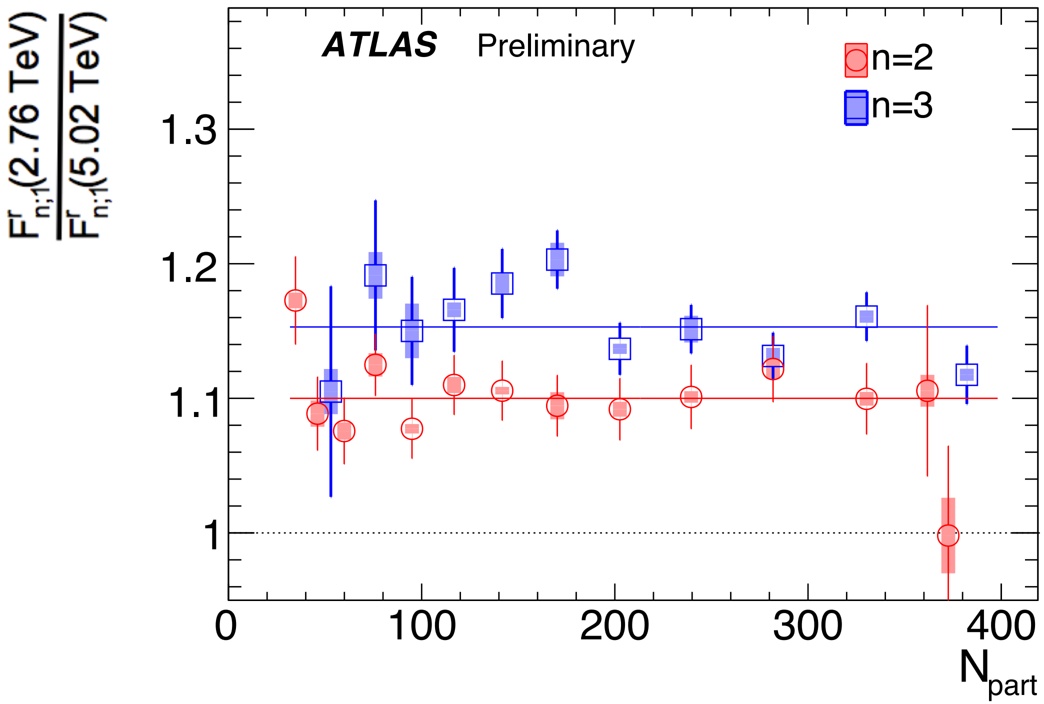
$$r_{n|n;1} = 1 - 2F^{r}_{n;1}\eta$$

From increasing contribution of v_2^2



- For n=2,
  - Slope is minimum in mid-central events
  - Magnitude of slope is quite small
- For higher order harmonics
  - Slope significantly larger
  - Weak centrality dependence trends are seen

The Energy dependence of slope



	$n = 2$	$n = 3$
$F^{r}_{n;1}(2.76\ \mathrm{TeV})/F^{r}_{n;1}(5.02\ \mathrm{TeV})$	1.100 ± 0.010	1.152 ± 0.011

- For n=2, ratios are independent of centrality.
- For n=2 decorrelation is 10% stronger at 2.76 TeV than at 5.02 TeV
- For n=3 decorrelation is 15% stronger
- Stronger decorrelation effect should be expected at RHIC

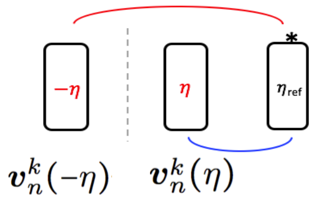
Higher order decorrelation: $(\mathbf{v}_2)^k$

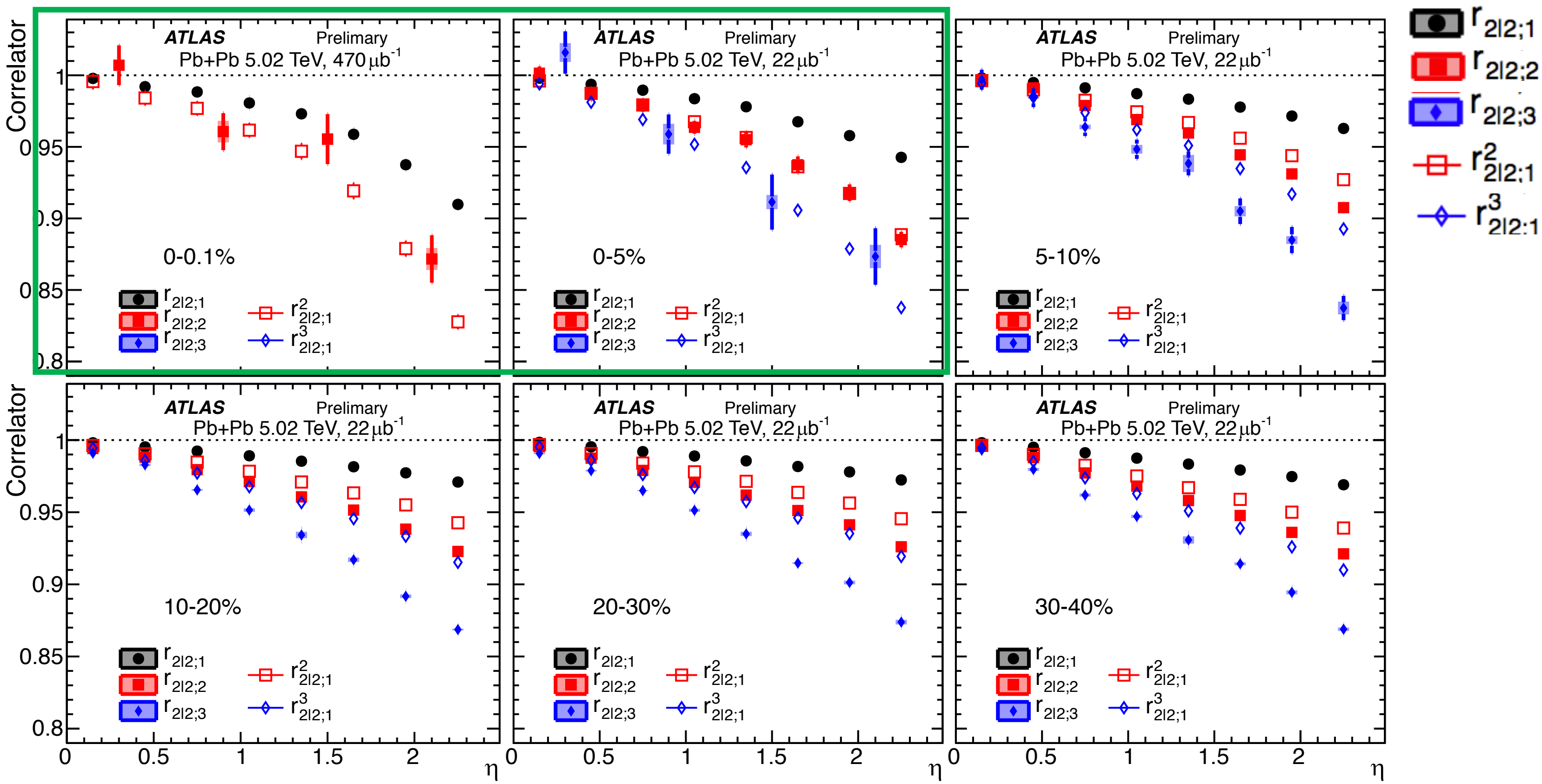
- Higher order moments $\langle A^k \rangle$ provide more constrains on *P(A)*
  - $r_{2|2;k}$ measures decorrerlation of $(\mathbf{v}_2)^k$, stronger decorrelation is expected
  - In general $\langle v_n^k v_n^{*k} \rangle \neq \langle v_n v_n^* \rangle^k$

$$r_{n|n;k} = \frac{\langle v_n(-\eta)^k v_n^*(\eta_{\rm ref})^k \rangle}{\langle v_n(\eta)^k v_n^*(\eta_{\rm ref})^k \rangle} \stackrel{?}{=} \frac{\langle (v_n(-\eta) v_n^*(\eta_{\rm ref})) \rangle^k}{\langle (v_n(\eta) v_n^*(\eta_{\rm ref})) \rangle^k} \equiv r_{n|n;1}^k$$

  - Central: $r_{2|2;k} \approx r^k_{2|2;1}$; Non-central: $r_{2|2;k} > r^k_{2|2;1}$

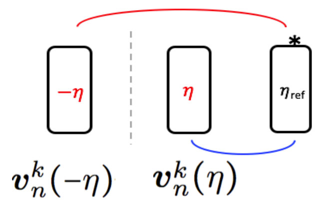
$$r_{n|n;k} = \frac{\langle v_n(-\eta)^k v_n^*(\eta_{\rm ref})^k \rangle}{\langle v_n(\eta)^k v_n^*(\eta_{\rm ref})^k \rangle}$$



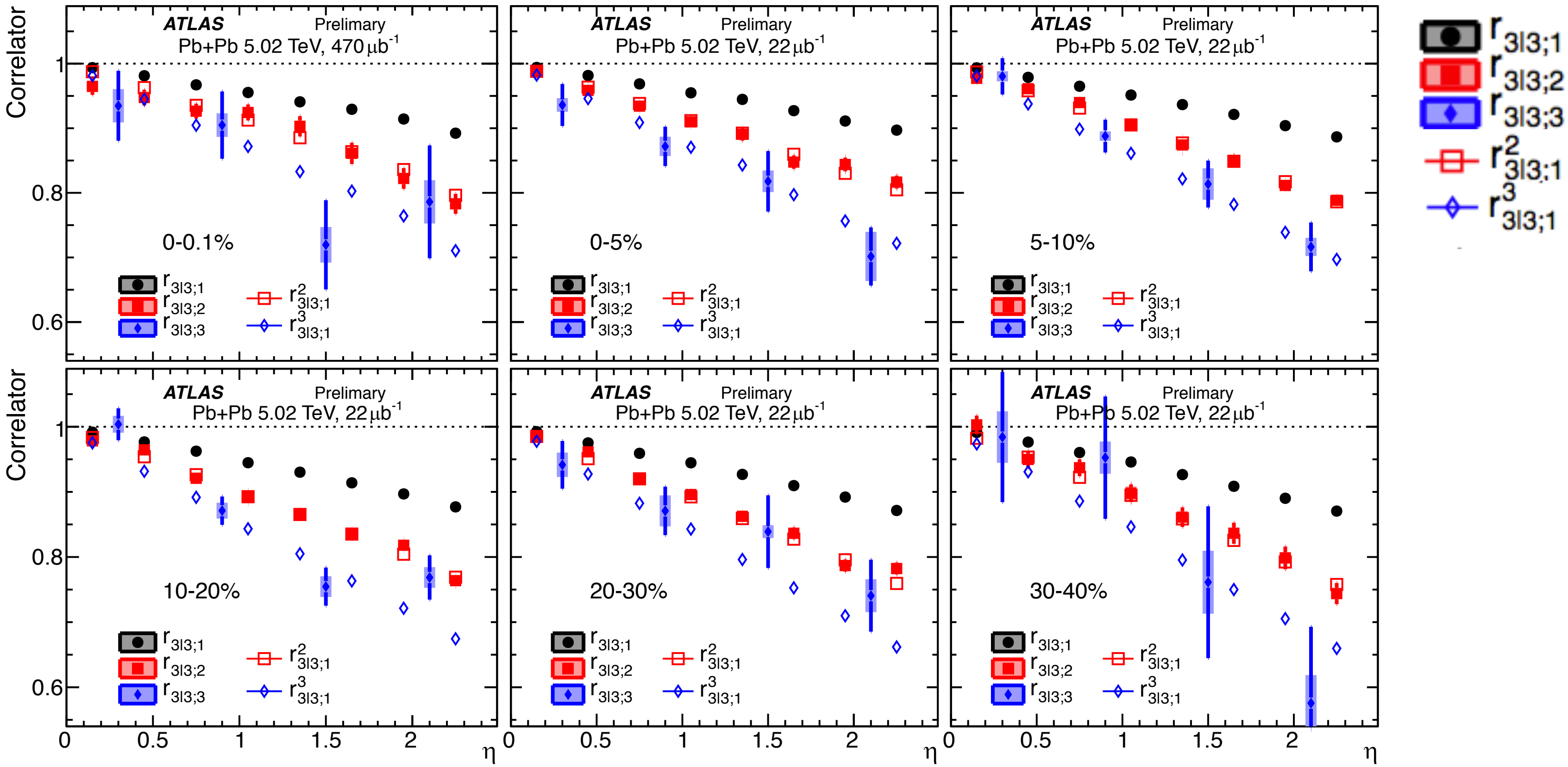


Higher order decorrelation: $(\mathbf{v}_3)^k$

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



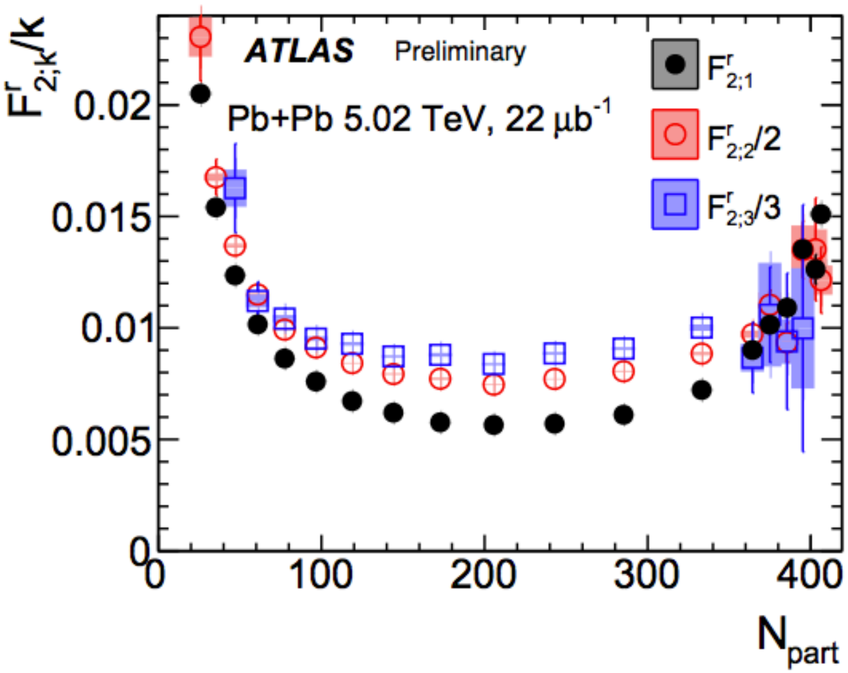
- $r_{3|3;k}$: v_3 is fluctuation driven
  - ➢ k-th moment has stronger decorrelation
  - ➢ $r_{3|3;k} \approx r^k_{3|3;1}$ in all centrality intervals
  - ➢ The relationship maybe related to fluctuation driven nature of v_3

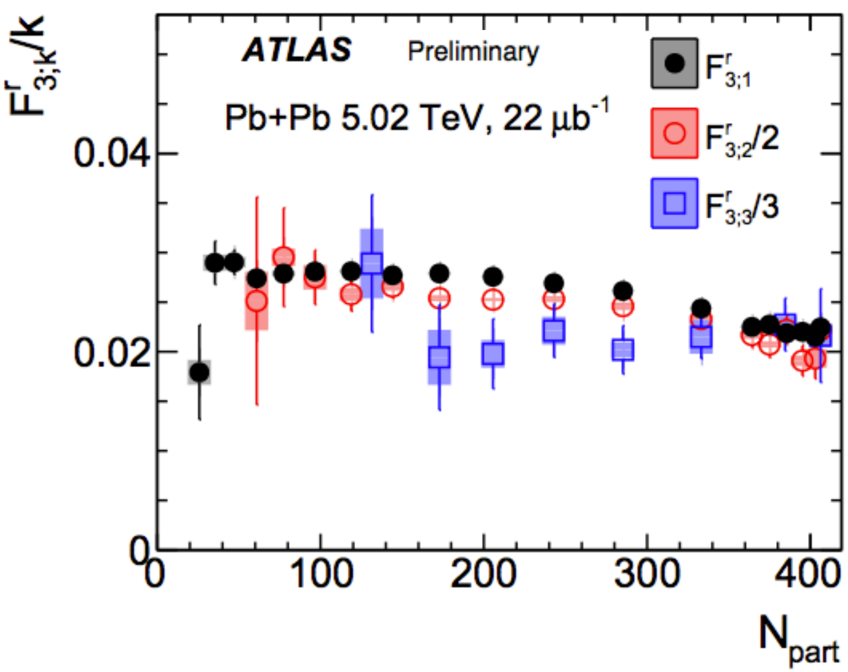


Scaling relationship $F_{n;k}{}^{r}/k = F_{n;1}{}^{r}$

- $r_{n|n;k}$ are parameterized with linear functions

$$r_{n|n;k} = 1 - 2F^{r}_{n;k}\eta \qquad (r_{n|n;1})^{k} \approx 1 - 2kF^{r}_{n;1}\eta$$



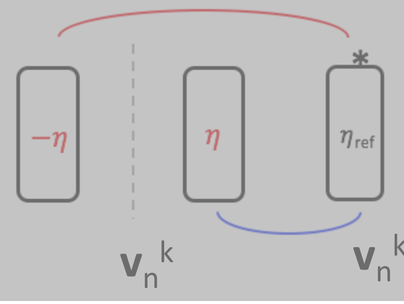


- $F_{2;3}{}^{r}/3 > F_{2;2}{}^{r}/2 > F_{2;1}{}^{r}$ except in most central
- Slightly opposite trend $F_{3;k}{}^{r}/k \leq F_{3;1}{}^{r}$ holds in all centrality

New observables in ATLAS

- Decorrelation of $[\boldsymbol{v}_n(\eta)]^k$

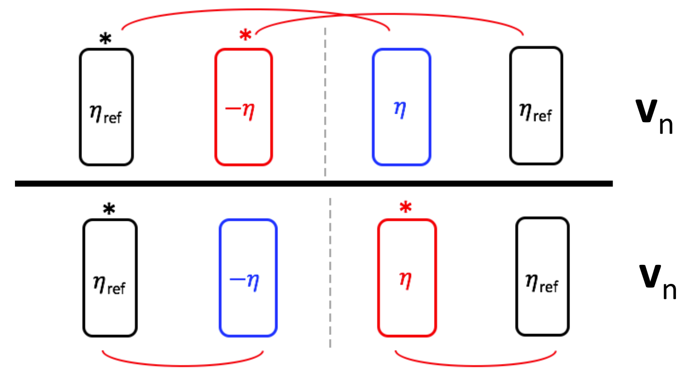
$$r_{n|n;k} = \frac{\langle v_n(-\eta)^k v_n^*(\eta_{\mathrm{ref}})^k \rangle}{\langle v_n(\eta)^k v_n^*(\eta_{\mathrm{ref}})^k \rangle}$$



Sensitive to how η-dependence decorrelation fluctuates EbyE

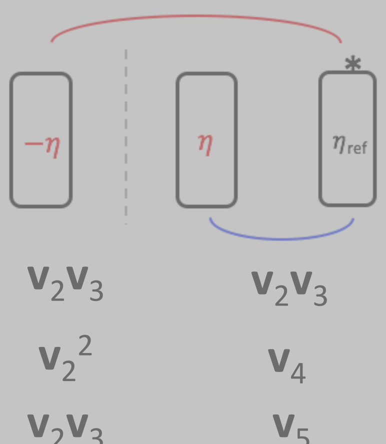
- 4-particle correlator

$$R_{n|n;2}(\eta) = \frac{\langle v_n^*(-\eta_{\mathrm{ref}}) v_n^*(-\eta) v_n(\eta) v_n(\eta_{\mathrm{ref}}) \rangle}{\langle v_n^*(-\eta_{\mathrm{ref}}) v_n(-\eta) v_n^*(\eta) v_n(\eta_{\mathrm{ref}}) \rangle} =$$



Minimize v_n fluct. and single out EP twist

- Mixed harmonics decorrelation

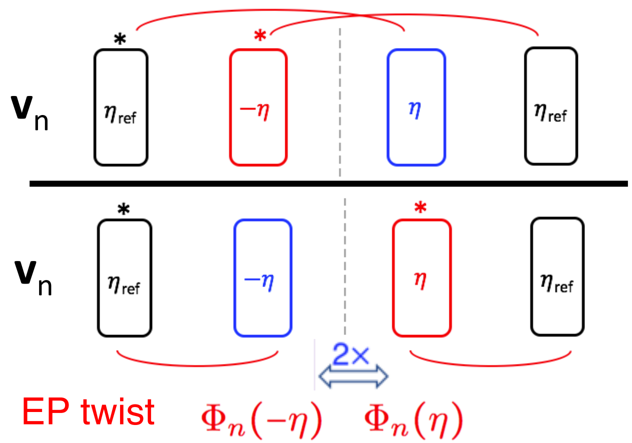


Are the decorrelation of different harmonics correlated?

$R_{n|n;2}$ at 2.76TeV & 5.02TeV

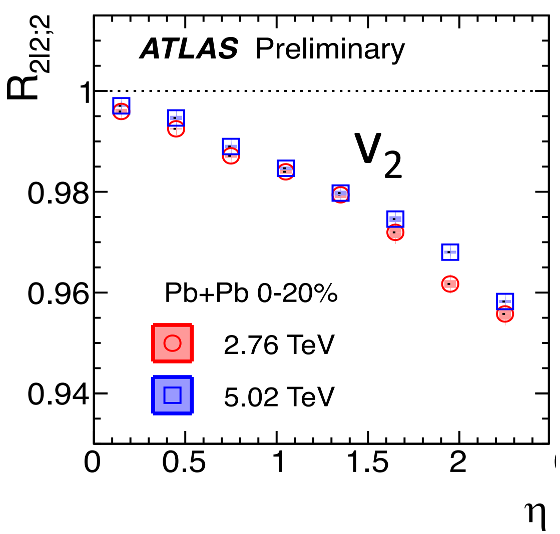
- $R_{n|n;2}$: mostly sensitive to EP twist

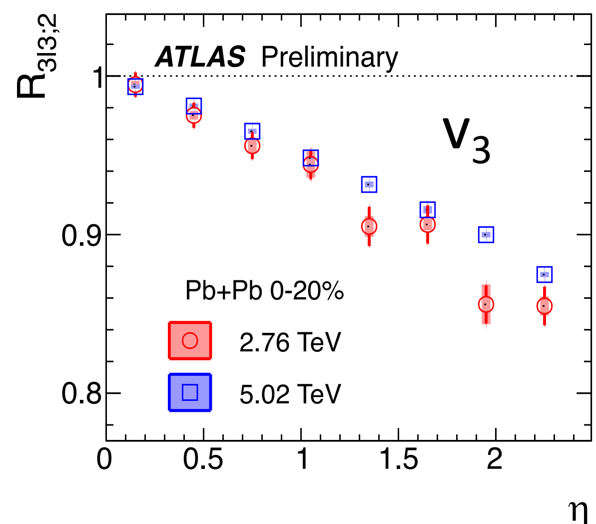
$$R_{n|n;2}(\eta) = \frac{\langle \boldsymbol{v}_n^*(-\eta_{\mathrm{ref}})\boldsymbol{v}_n^*(-\eta)\boldsymbol{v}_n(\eta)\boldsymbol{v}_n(\eta_{\mathrm{ref}})\rangle}{\langle \boldsymbol{v}_n^*(-\eta_{\mathrm{ref}})\boldsymbol{v}_n(-\eta)\boldsymbol{v}_n^*(\eta)\boldsymbol{v}_n(\eta_{\mathrm{ref}})\rangle} =$$



$$= \frac{\langle v_n(-\eta_{\mathrm{ref}})v_n(-\eta)v_n(\eta_{\mathrm{ref}})v_n(\eta)\cos(n[\Phi_n(\eta_{\mathrm{ref}})-\Phi_n(-\eta_{\mathrm{ref}})+(\Phi_n(\eta)-\Phi_n(-\eta))])\rangle}{\langle v_n(-\eta_{\mathrm{ref}})v_n(-\eta)v_n(\eta_{\mathrm{ref}})v_n(\eta)\cos(n[\Phi_n(\eta_{\mathrm{ref}})-\Phi_n(-\eta_{\mathrm{ref}})-(\Phi_n(\eta)-\Phi_n(-\eta))])\rangle}$$

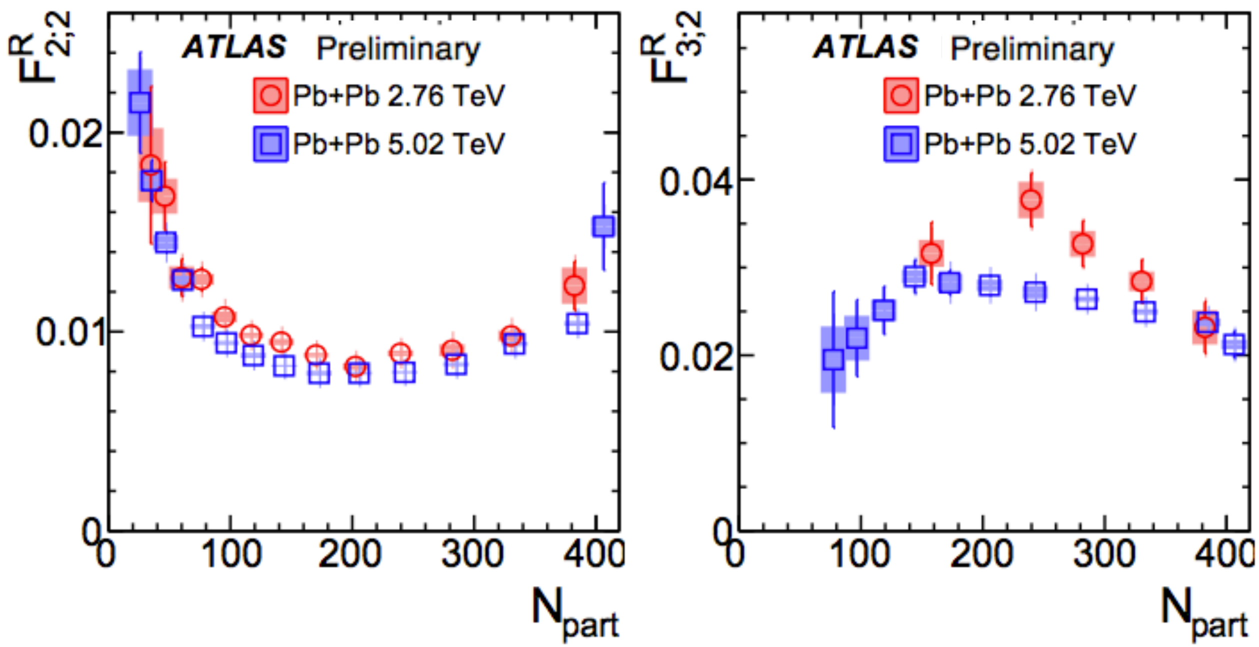
- ❖ $R_{n|n;2}$ decrease linearly along η
- ❖ Stronger decorrelation at lower energy





$R_{nln;2}$ at 2.76TeV & 5.02TeV

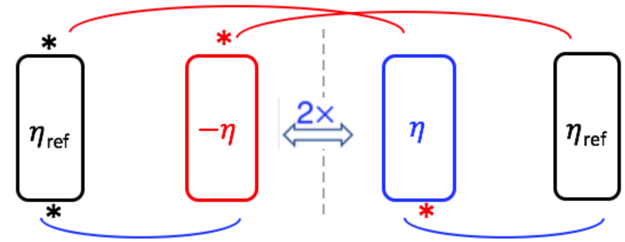
- Fit $R_{nln;2}$ using linear function $R_{n|n;2} = 1 - 2F^{R}_{n;2}\,\eta$



❖ Lower energy shows stronger decorrelation

How to separate twist and asymmetry

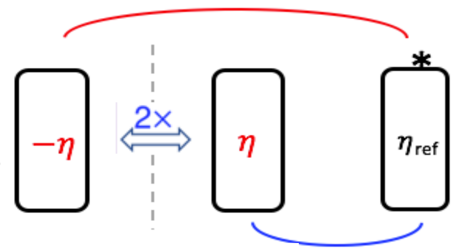
$$R_{n|n;2}(\eta) = \frac{\langle \boldsymbol{v}_n^*(-\eta_{\mathrm{ref}})\boldsymbol{v}_n^*(-\eta)\boldsymbol{v}_n(\eta)\boldsymbol{v}_n(\eta_{\mathrm{ref}})\rangle}{\langle \boldsymbol{v}_n^*(-\eta_{\mathrm{ref}})\boldsymbol{v}_n(-\eta)\boldsymbol{v}_n^*(\eta)\boldsymbol{v}_n(\eta_{\mathrm{ref}})\rangle}$$



EP twist $\Phi_n(-\eta)$ $\Phi_n(\eta)$

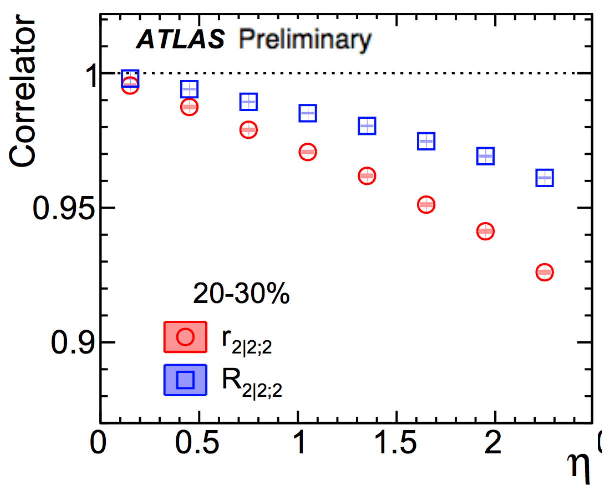
$$r_{n|n;2}(\eta) = \frac{\langle(\boldsymbol{v}_n(-\eta)\boldsymbol{v}_n^*(\eta_{\mathrm{ref}}))^2\rangle}{\langle(\boldsymbol{v}_n(\eta)\boldsymbol{v}_n^*(\eta_{\mathrm{ref}}))^2\rangle}$$

$$= \frac{\langle v_n(-\eta)v_n(-\eta)v_n(-\eta_{\mathrm{ref}})v_n(\eta_{\mathrm{ref}})\cos(2n[(\Phi_n(-\eta)-\Phi_n(\eta_{\mathrm{ref}})])\rangle}{\langle v_n(\eta)v_n(\eta)v_n(-\eta_{\mathrm{ref}})v_n(\eta_{\mathrm{ref}})\cos(2n[(\Phi_n(\eta)-\Phi_n(\eta_{\mathrm{ref}})])\rangle}$$



Asymmetry: $v_n(-\eta)$ $v_n(\eta)$

EP twist: $\Phi_n(-\eta)$ $\Phi_n(\eta)$

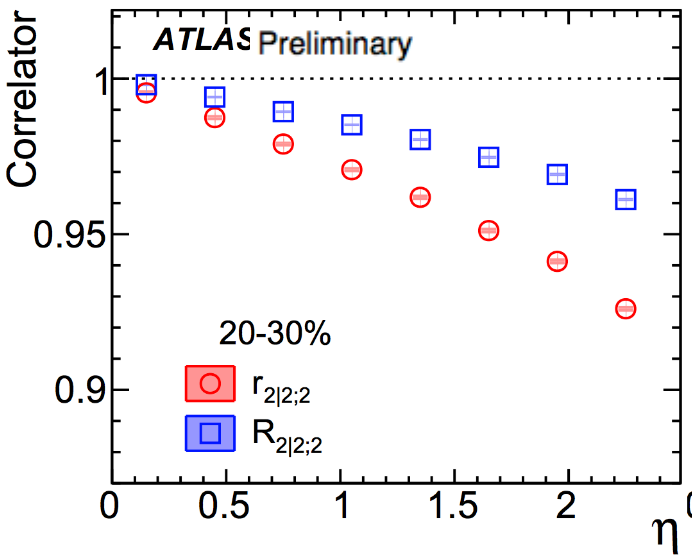


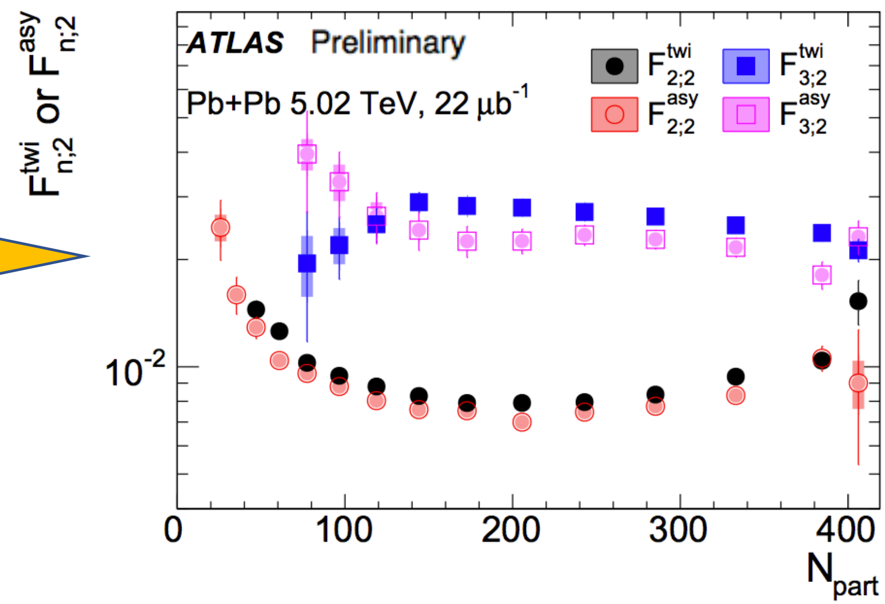
❖ Same EP twist in $R_{n|n;2}$ and $r_{n|n;2}$, the difference indicates non-trivial asymmetry component

Separating asymmetry and twist contributions

$$R_{n|n;2}(\eta) = \frac{\langle \boldsymbol{v}_n^*(-\eta_{\rm ref})\boldsymbol{v}_n^*(-\eta)\boldsymbol{v}_n(\eta)\boldsymbol{v}_n(\eta_{\rm ref})\rangle}{\langle \boldsymbol{v}_n^*(-\eta_{\rm ref})\boldsymbol{v}_n(-\eta)\boldsymbol{v}_n^*(\eta)\boldsymbol{v}_n(\eta_{\rm ref})\rangle} \qquad R_{n|n;2} \approx 1 - 2F_{n;2}^{\rm twi}\eta$$

$$r_{n|n;k} = \frac{\langle \boldsymbol{v}_n(-\eta)^k \boldsymbol{v}_n^*(\eta_{\rm ref})^k\rangle}{\langle \boldsymbol{v}_n(\eta)^k \boldsymbol{v}_n^*(\eta_{\rm ref})^k\rangle} \qquad r_{n|n;k}(\eta) \approx 1 - 2F_{n;k}^{\rm r}\eta, \quad F_{n;k}^{\rm r} = F_{n;k}^{\rm asy} + F_{n;k}^{\rm twi}$$



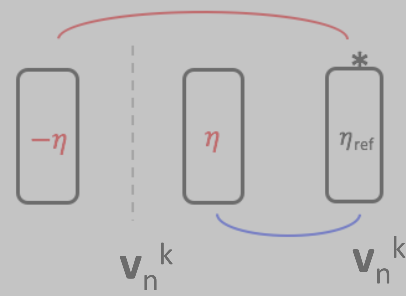


- For v_2,v_3, twist is slightly larger than asymmetry

New observables in ATLAS

- Decorrelation of $[\boldsymbol{v}_n(\eta)]^k$

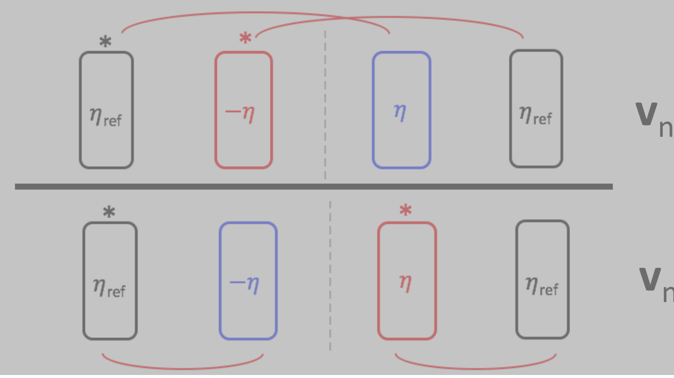
$$r_{n|n;k} = \frac{\langle \boldsymbol{v}_n(-\eta)^k \boldsymbol{v}_n^*(\eta_{\mathrm{ref}})^k \rangle}{\langle \boldsymbol{v}_n(\eta)^k \boldsymbol{v}_n^*(\eta_{\mathrm{ref}})^k \rangle}$$



Sensitive to how η-dependence decorrelation fluctuates EbyE

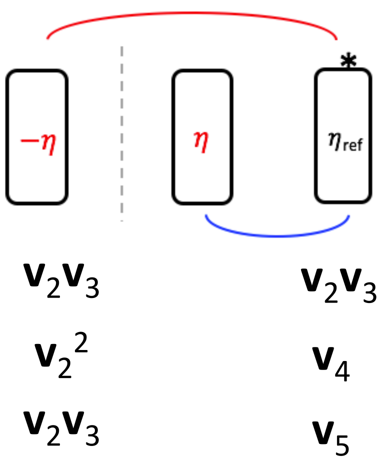
- 4-particle correlator

$$R_{n|n;2}(\eta) = \frac{\langle \boldsymbol{v}_n^*(-\eta_{\mathrm{ref}}) \boldsymbol{v}_n^*(-\eta) \boldsymbol{v}_n(\eta) \boldsymbol{v}_n(\eta_{\mathrm{ref}}) \rangle}{\langle \boldsymbol{v}_n^*(-\eta_{\mathrm{ref}}) \boldsymbol{v}_n(-\eta) \boldsymbol{v}_n^*(\eta) \boldsymbol{v}_n(\eta_{\mathrm{ref}}) \rangle} =$$



Minimize v_n fluct. and single out EP twist

- Mixed harmonics decorrelation

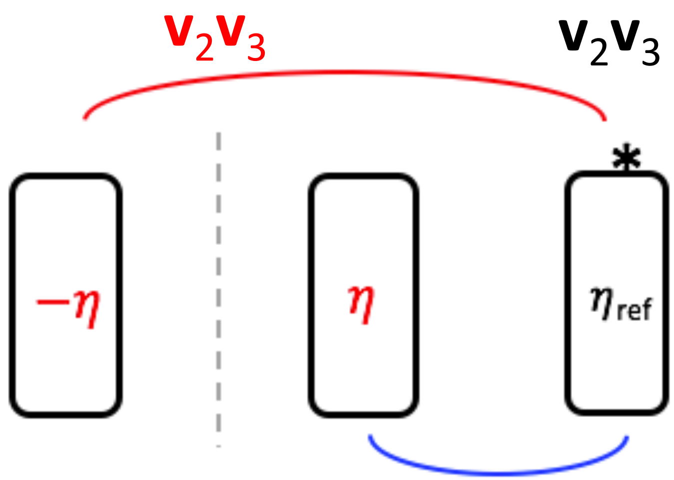


Are the decorrelation of different harmonics correlated?

Decorrelation of ($\mathbf{v}_2\mathbf{v}_3$): $r_{2,3|2,3}$

- Decorrelation of ($\mathbf{v}_2\mathbf{v}_3$)

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



- If longitudinal dynamics of $\mathbf{v}_2$, $\mathbf{v}_3$ are independent

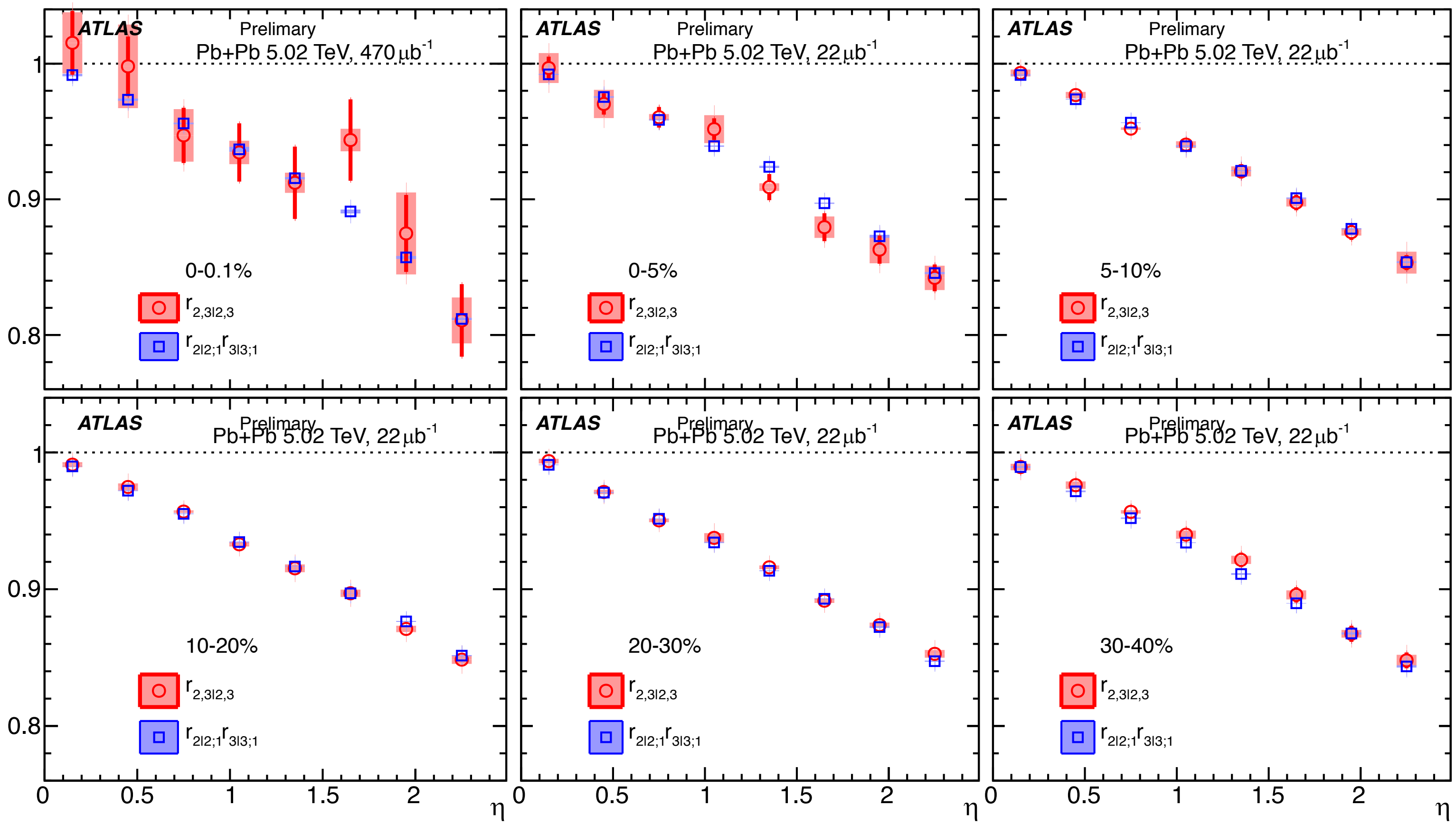
$$\langle \boldsymbol{v}_2(-\eta)\boldsymbol{v}_2^*(\eta_{\rm ref})\boldsymbol{v}_3(-\eta)\boldsymbol{v}_3^*(\eta_{\rm ref})\rangle \longrightarrow \langle \boldsymbol{v}_2(-\eta)\boldsymbol{v}_2^*(\eta_{\rm ref})\rangle \times \langle \boldsymbol{v}_3(-\eta)\boldsymbol{v}_3^*(\eta_{\rm ref})\rangle$$

$$r_{2,3|2,3} = \frac{\langle \boldsymbol{v}_2(-\eta)\boldsymbol{v}_2^*(\eta_{\rm ref})\boldsymbol{v}_3(-\eta)\boldsymbol{v}_3^*(\eta_{\rm ref})\rangle}{\langle \boldsymbol{v}_2(\eta)\boldsymbol{v}_2^*(\eta_{\rm ref})\boldsymbol{v}_3(\eta)\boldsymbol{v}_3^*(\eta_{\rm ref})\rangle} = \frac{\langle \boldsymbol{v}_2(-\eta)\boldsymbol{v}_2^*(\eta_{\rm ref})\rangle \times \langle \boldsymbol{v}_3(-\eta)\boldsymbol{v}_3^*(\eta_{\rm ref})\rangle}{\langle \boldsymbol{v}_2(\eta)\boldsymbol{v}_2^*(\eta_{\rm ref})\rangle \times \langle \boldsymbol{v}_3(\eta)\boldsymbol{v}_3^*(\eta_{\rm ref})\rangle} = r_{2|2;1} \times r_{3|3;1}$$

$r_{2,3|2,3}$ and $r_{2|2} \times r_{3|3}$

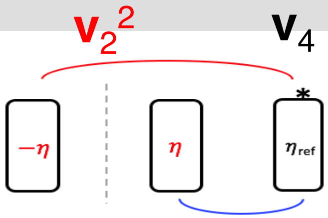
- $r_{2,3|2,3} = r_{2|2} \times r_{3|3}$ indicates the decorrelation of $\mathbf{v}_2$, $\mathbf{v}_3$ are independent

$$r_{2,3|2,3} = \frac{\langle \boldsymbol{v}_2(-\eta)\boldsymbol{v}_2^*(\eta_{\rm ref})\boldsymbol{v}_3(-\eta)\boldsymbol{v}_3^*(\eta_{\rm ref})\rangle}{\langle \boldsymbol{v}_2(\eta)\boldsymbol{v}_2^*(\eta_{\rm ref})\boldsymbol{v}_3(\eta)\boldsymbol{v}_3^*(\eta_{\rm ref})\rangle} = \frac{\langle \boldsymbol{v}_2(-\eta)\boldsymbol{v}_2^*(\eta_{\rm ref})\rangle \times \langle \boldsymbol{v}_3(-\eta)\boldsymbol{v}_3^*(\eta_{\rm ref})\rangle}{\langle \boldsymbol{v}_2(\eta)\boldsymbol{v}_2^*(\eta_{\rm ref})\rangle \times \langle \boldsymbol{v}_3(\eta)\boldsymbol{v}_3^*(\eta_{\rm ref})\rangle} = r_{2|2;1} \times r_{3|3;1}$$



$r_{2,2|4}$ and $r_{4|4;1}$

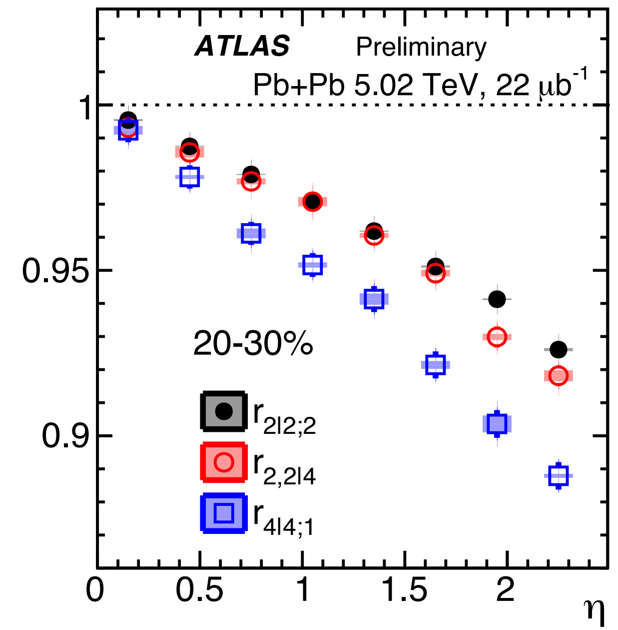
- **Flow correlations can be extended between $\mathbf{v}_4$ and $\mathbf{v}_2^2$**



Since $v_4 = v_{4L} + \beta_{2,2} v_2^2$

$$\langle v_{4L} v_2^{2*} \rangle \propto \langle \epsilon_4 \epsilon_2^{2*} \rangle \approx 0 \longrightarrow \langle v_4 v_2^{2*} \rangle = \cancel{\langle v_{4L} v_2^{2*} \rangle} + \beta_{2,2} \langle v_2^2 v_2^{2*} \rangle$$

$$r_{2,2|4} = \frac{\langle v_2^2(-\eta) v_4^*(\eta_{\rm ref}) \rangle}{\langle v_2^2(\eta) v_4^*(\eta_{\rm ref}) \rangle} \approx \frac{\langle v_2^2(-\eta) v_2^{2*}(\eta_{\rm ref}) \rangle}{\langle v_2^2(\eta) v_2^{2*}(\eta_{\rm ref}) \rangle} \equiv r_{2|2;2}$$



- ❖ v_4 is dominated by the non-linear contribution associated with v_2^2

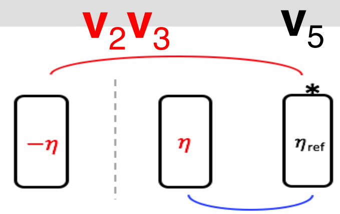
- $r_{4|4;1}$ can be approximated by

$$r_{4|4;1}(\eta) \approx \frac{\langle v_{4L}(-\eta) v_{4L}^*(\eta_{\rm ref}) \rangle + \beta_{2,2}^2 \langle v_2^2(-\eta) v_2^{*2}(\eta_{\rm ref}) \rangle}{\langle v_{4L}(\eta) v_{4L}^*(\eta_{\rm ref}) \rangle + \beta_{2,2}^2 \langle v_2^2(\eta) v_2^{*2}(\eta_{\rm ref}) \rangle}$$

- ❖ $r_{4|4;1}$ shows stronger decorrelation
- ❖ suggesting stronger decorrelation of $\mathbf{v}_{4L}$ than $\mathbf{v}_2^2$

$r_{2,3|5}$ and $r_{2,3|2,3}$

- Decorrelation between $\mathbf{v}_5$ and $\mathbf{v}_2\mathbf{v}_3$

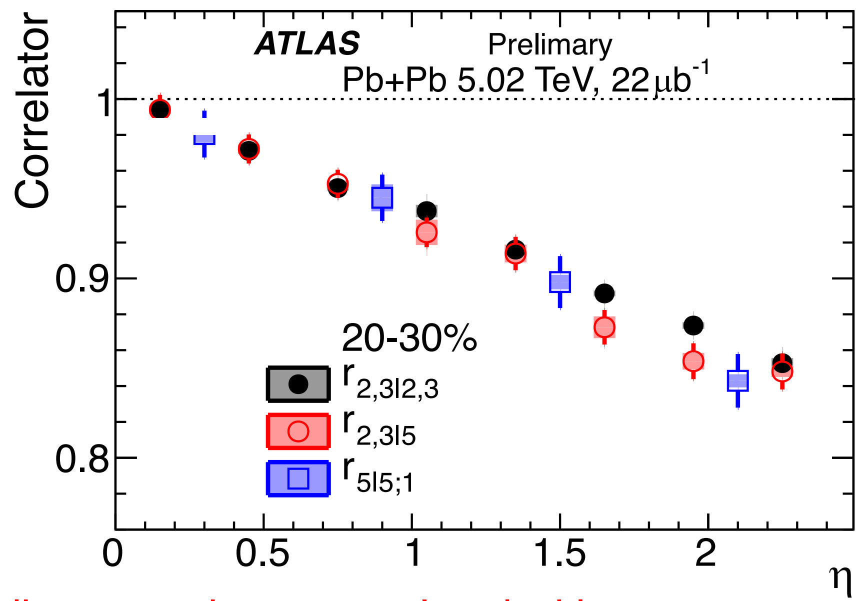


For $v_5 = v_{5L} + \beta_{2,3} v_2 v_3$

$$\langle v_{5L} v_2^* v_3^* \rangle \propto \langle \epsilon_5 \epsilon_2^* \epsilon_3^* \rangle \approx 0 \longrightarrow \langle v_5 v_2^* v_3^* \rangle = \langle v_{5L} v_2^* v_3^* \rangle + \beta_{2,3} \langle v_2 v_3 v_2^* v_3^* \rangle$$

$$r_{2,3|5}(\eta) = \frac{\langle v_2(-\eta) v_3(-\eta) v_5^*(\eta_{\rm ref}) \rangle}{\langle v_2(\eta) v_3(\eta) v_5^*(\eta_{\rm ref}) \rangle} \approx \frac{\langle v_2(-\eta) v_3(-\eta) v_2^*(\eta_{\rm ref}) v_3^*(\eta_{\rm ref}) \rangle}{\langle v_2(\eta) v_3(\eta) v_2^*(\eta_{\rm ref}) v_3^*(\eta_{\rm ref}) \rangle} = r_{2,3|2,3}(\eta)$$

$$r_{5|5;1}(\eta) \approx \frac{\langle v_{5L}(-\eta) v_{5L}^*(\eta_{\rm ref}) \rangle + \beta_{2,3}^2 \langle v_2(-\eta) v_2^*(\eta_{\rm ref}) v_3(-\eta) v_3^*(\eta_{\rm ref}) \rangle}{\langle v_{5L}(\eta) v_{5L}^*(\eta_{\rm ref}) \rangle + \beta_{2,3}^2 \langle v_2(\eta) v_2^*(\eta_{\rm ref}) v_3(\eta) v_3^*(\eta_{\rm ref}) \rangle}$$



- $r_{2,3|5} \approx r_{2,3|2,3}$ indicates v_{5L} is not correlated with v_2v_3
- $r_{2,3|5} \approx r_{2,3|2,3} \approx r_{5|5;1}$ indicates $\mathbf{v}_{5L}$ has same decorrelation effect with $\mathbf{v}_2\mathbf{v}_3$

Thoughts on future experimental measurements

- A+A system: Correction on η-dependent v_n measurements

CMS HIN-15-008

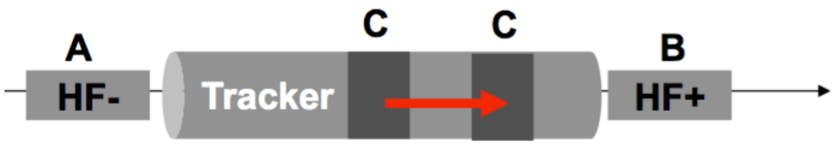
$$v_2\{EP\} = \frac{\langle \cos(n\phi_c - \Psi_n^A) \rangle}{R_A^{obs}} = \frac{v_n^{True} \times R_A^{True} \times \cos(\Delta\Psi_{AC})}{R_A^{True} \times \cos(\Delta\Psi_{AC})}$$

$$R_A^{obs} = \sqrt{\frac{\langle \cos[n(\Psi_n^A - \Psi_n^B)] \rangle \langle \cos[n(\Psi_n^A - \Psi_n^C)] \rangle}{\langle \cos[n(\Psi_n^B - \Psi_n^C)] \rangle}}$$

$$= R_A^{True} \times \sqrt{\frac{\cos(\Delta\Psi_{AB})\cos(\Delta\Psi_{AC})}{\cos(\Delta\Psi_{BC})}} = R_A^{True} \times \cos(\Delta\Psi_{AC})$$

since EP twist is linear dependent on |Δη|

CMS HIN-15-008



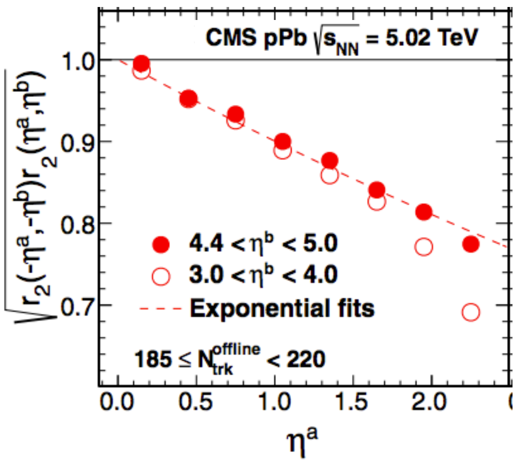
A,B are fixed

C is the same detector where v_n is measured

- LHC p+Pb: stronger decorrelation ~ 20%
  - r3, r4……also for pp?
  - How to understand sub-event cumulant where Δη is applied between a, b

$c_n^{a,a|b,b}\{4\} \equiv \langle\langle 4 \rangle\rangle_{a,a|b,b} - 2\,\langle\langle 2 \rangle\rangle_{a|b}^2$ J.Jia etc. *arxiv*: 1701.03830

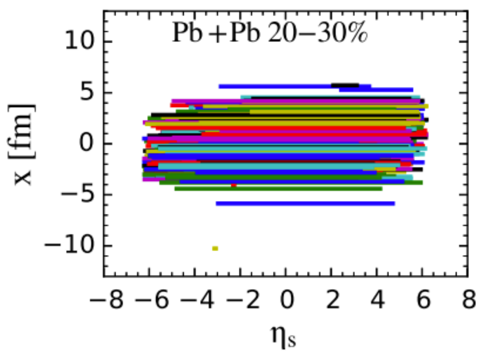
CMS PRC.92.034911

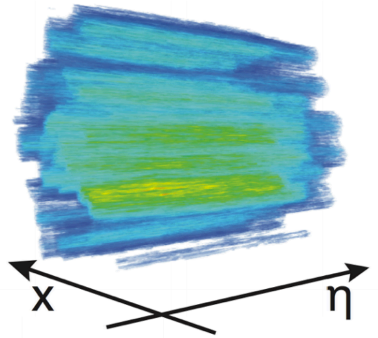


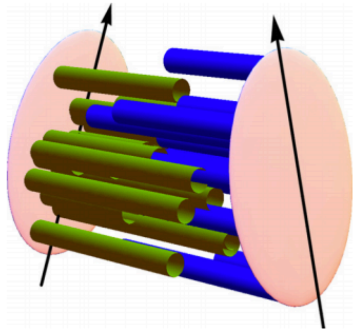
- Stronger decorrelation expected at RHIC! How stronger, will this affect the BES result?

Thoughts on theory

- 3D initial conditions







- With these ATLAS measurements

  They can help to distinguish / constrain these models

  ✓ Simultaneously fit decorrelation of different harmonics n

  ✓ Describe energy dependence

  ✓ Fit A+A and p+A

  ……

Summary

- Decorrelation of $[\boldsymbol{v}_n(\eta)]^k$

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

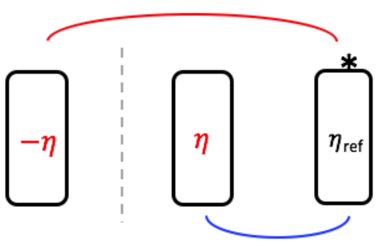
  - ➢ Flow decorrelation contains: twist + asymmetry
  - ➢ Stronger decorrelation at lower energy

- 4-particle correlator

$$R_{n|n;2}(\eta) = \frac{\langle \boldsymbol{v}_n^*(-\eta_{\mathrm{ref}}) \boldsymbol{v}_n^*(-\eta) \boldsymbol{v}_n(\eta) \boldsymbol{v}_n(\eta_{\mathrm{ref}}) \rangle}{\langle \boldsymbol{v}_n^*(-\eta_{\mathrm{ref}}) \boldsymbol{v}_n(-\eta) \boldsymbol{v}_n^*(\eta) \boldsymbol{v}_n(\eta_{\mathrm{ref}}) \rangle}$$

  - ➢ EP twist and asymmetry are separated

- Mixed harmonics decorrelation

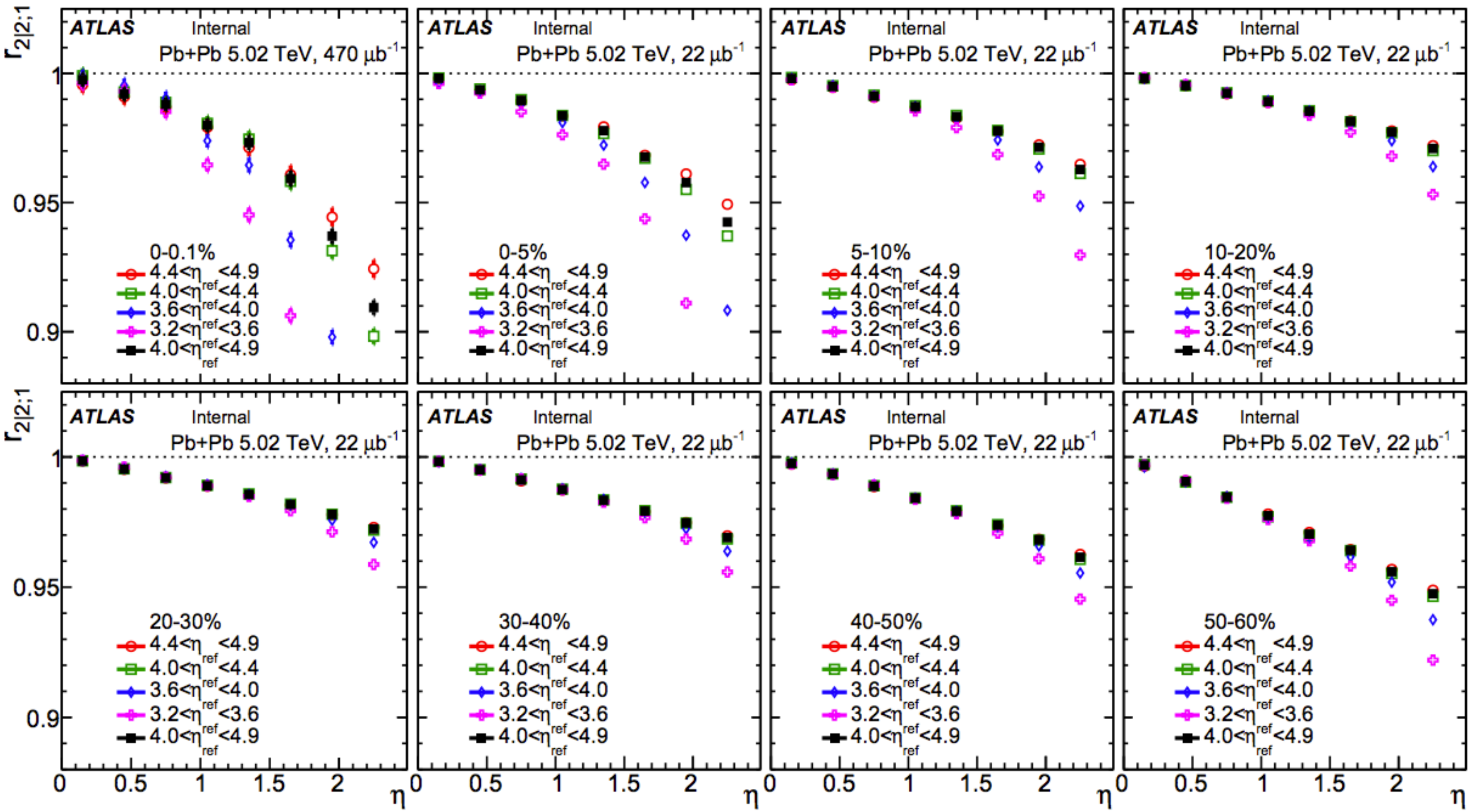


v_2v_3	v_2v_3
v_2^2	v_4
v_2v_3	v_5

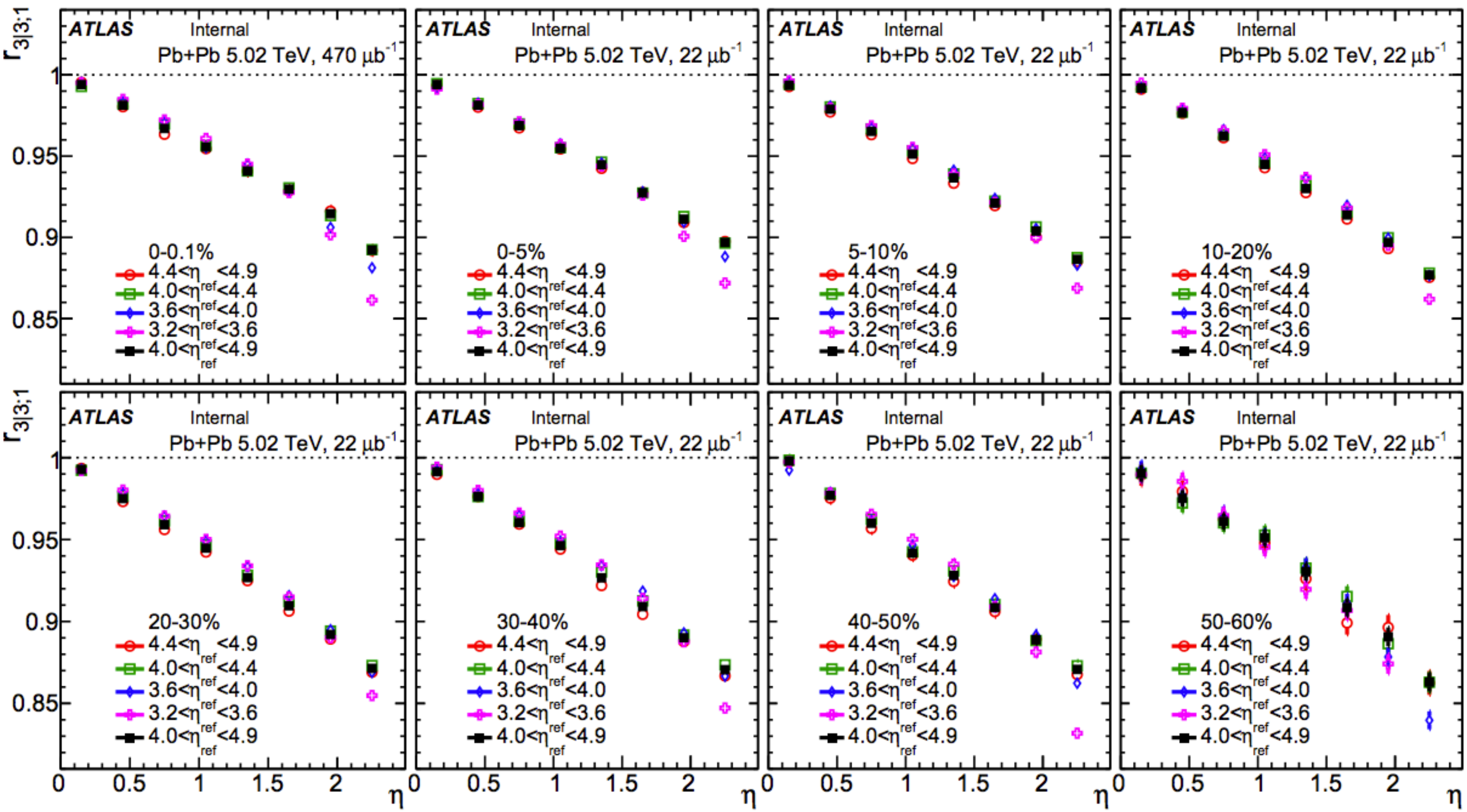
  - ➢ Mode-mixing effect are tested in the longitudinal direction

Back Up

η_{ref} dependence of $r_{2|2;1}$

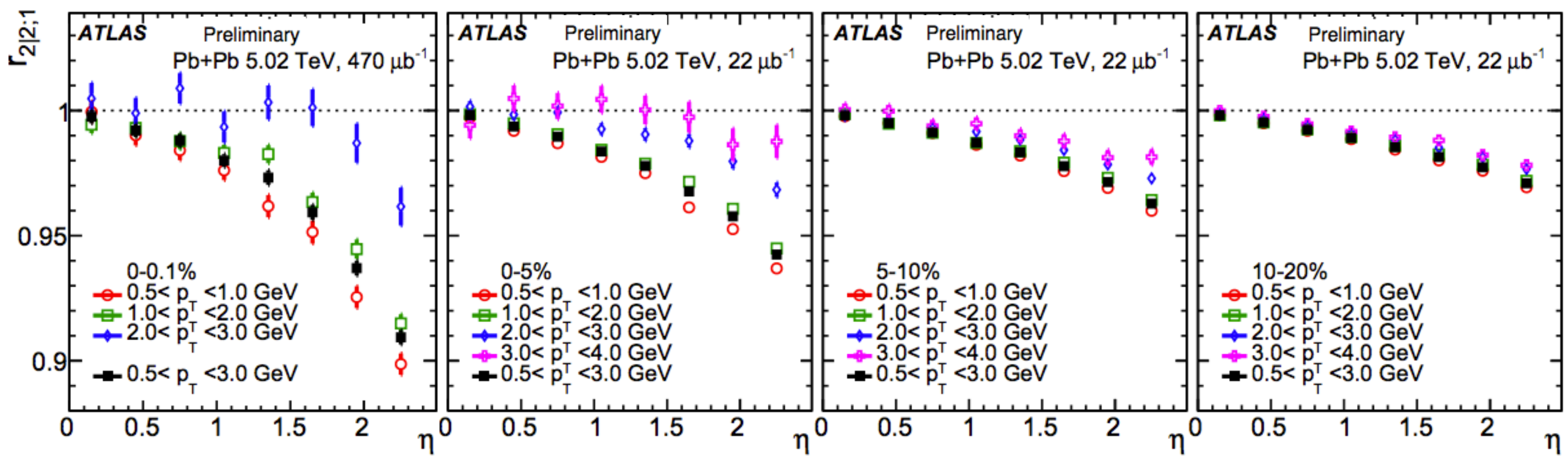


η_{ref} dependence of $r_{3|3;1}$

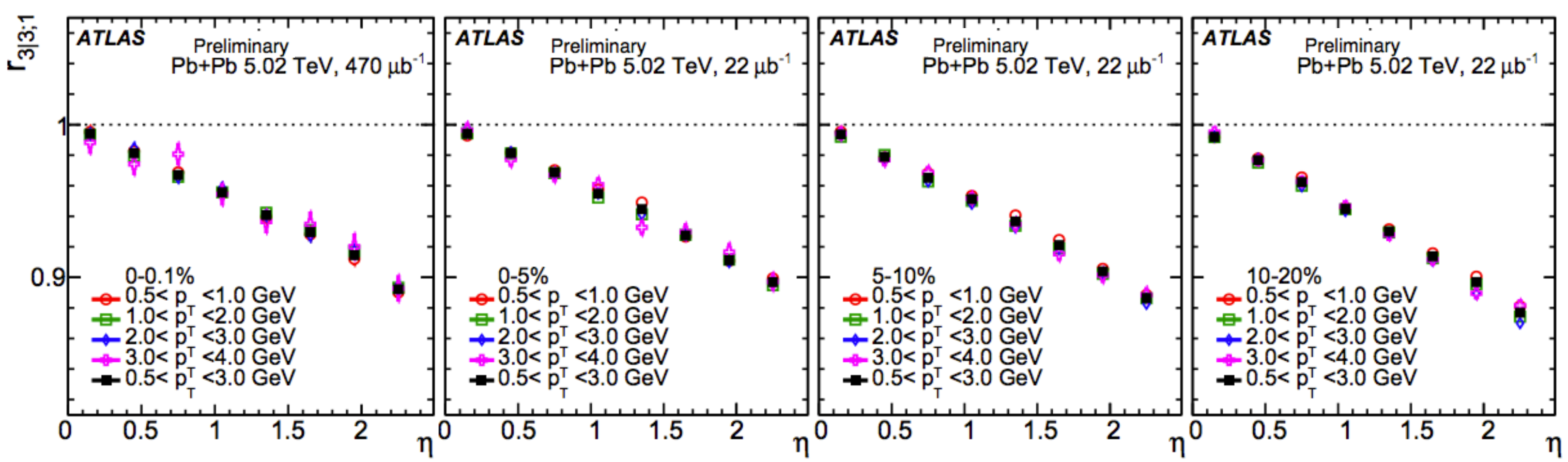


pT dependence of $r_{n|n;1}$

- $r_{2|2;1}$: pT dependence in central



- $r_{3|3;1}$: no pT dependence



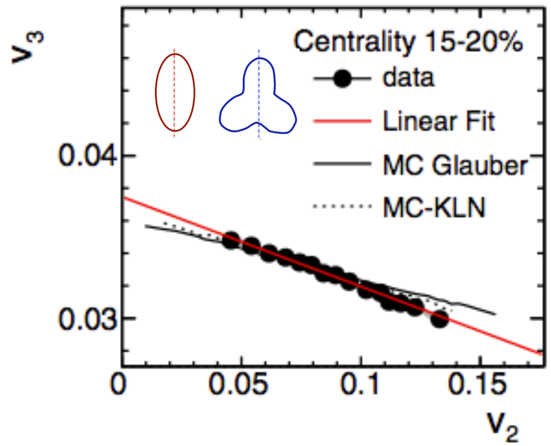
Linear and non-linear hydro. response

- From hydro. calculation: v_2 (v_3) $\propto \epsilon_2$ (ϵ_3)

  linear hydro. response

$$v_2 e^{i2\Phi_2} \propto \epsilon_2 e^{i2\Phi_2^*}, \quad v_3 e^{i3\Phi_3} \propto \epsilon_3 e^{i3\Phi_3^*}$$

ATLAS PRC 92, 034903



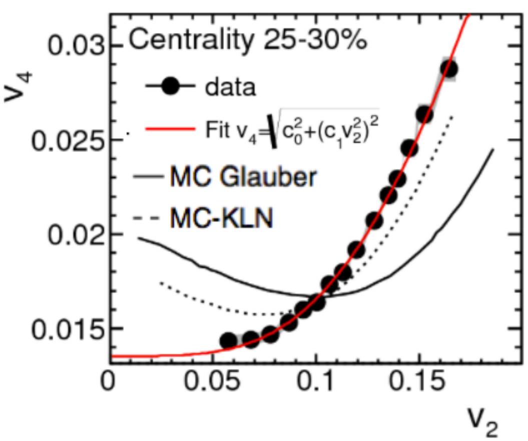
- Higher-order (n > 3) harmonics:

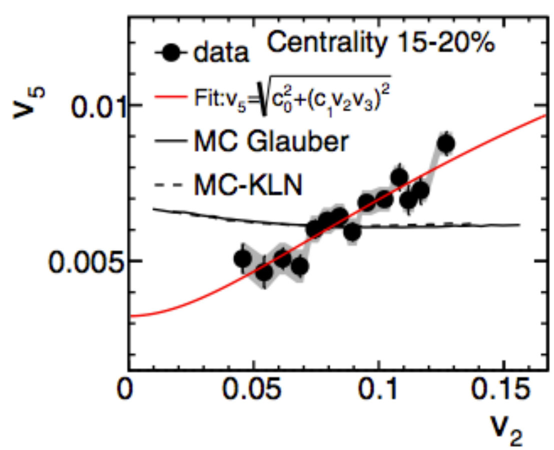
  linear response from ϵ_n + nonlinear mixing of lower-orders

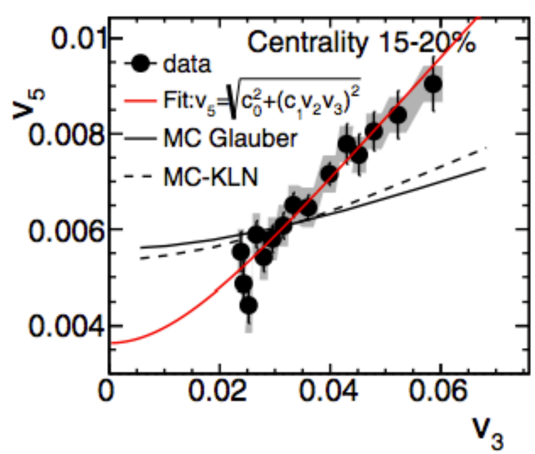
$$v_4 e^{i4\Phi_4} = a_0\, \varepsilon_4 e^{i4\Phi_4^*} + a_1 \left(\varepsilon_2 e^{i2\Phi_2^*}\right)^2 + \ldots = c_0\, e^{i4\Phi_4^*} + c_1 v_2^2 e^{i4\Phi_2} + \ldots,$$

$$v_5 e^{i5\Phi_5} = a_0 \varepsilon_5 e^{i5\Phi_5^*} + a_1 \varepsilon_2 e^{i2\Phi_2^*} \varepsilon_3 e^{i3\Phi_3^*} + \ldots = c_0 e^{i5\Phi_5^*} + c_1 v_2 v_3 e^{i(2\Phi_2+3\Phi_3)} + \ldots,$$

D.Teaney, L,Yan
PRC 83, 064904 (2011)
PRC 86, 044908 (2012)

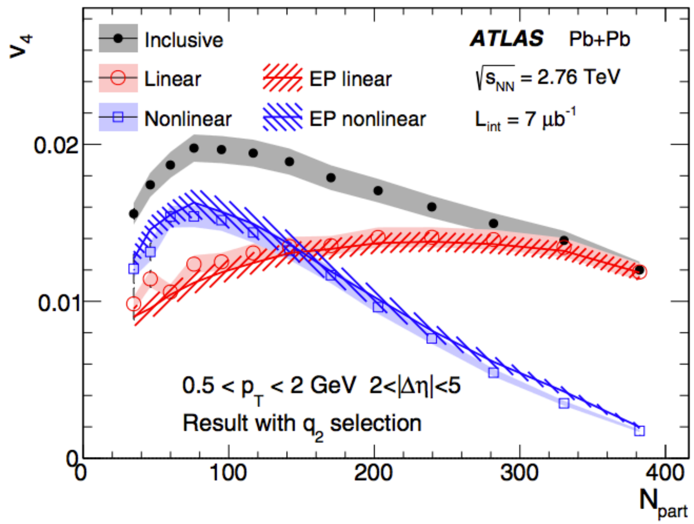


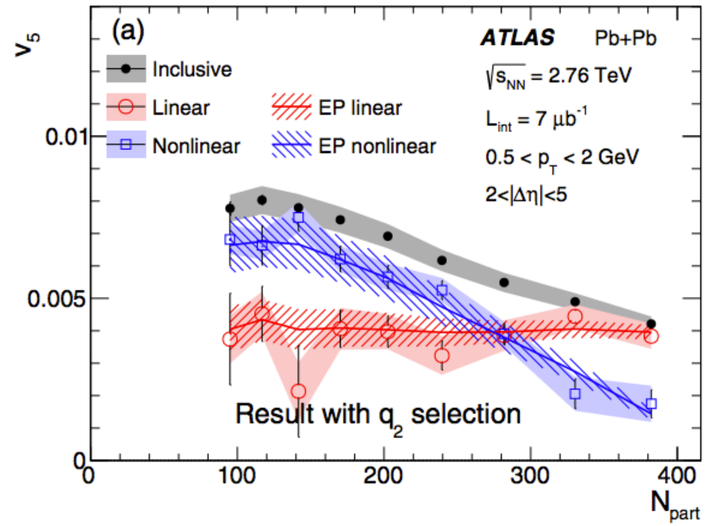




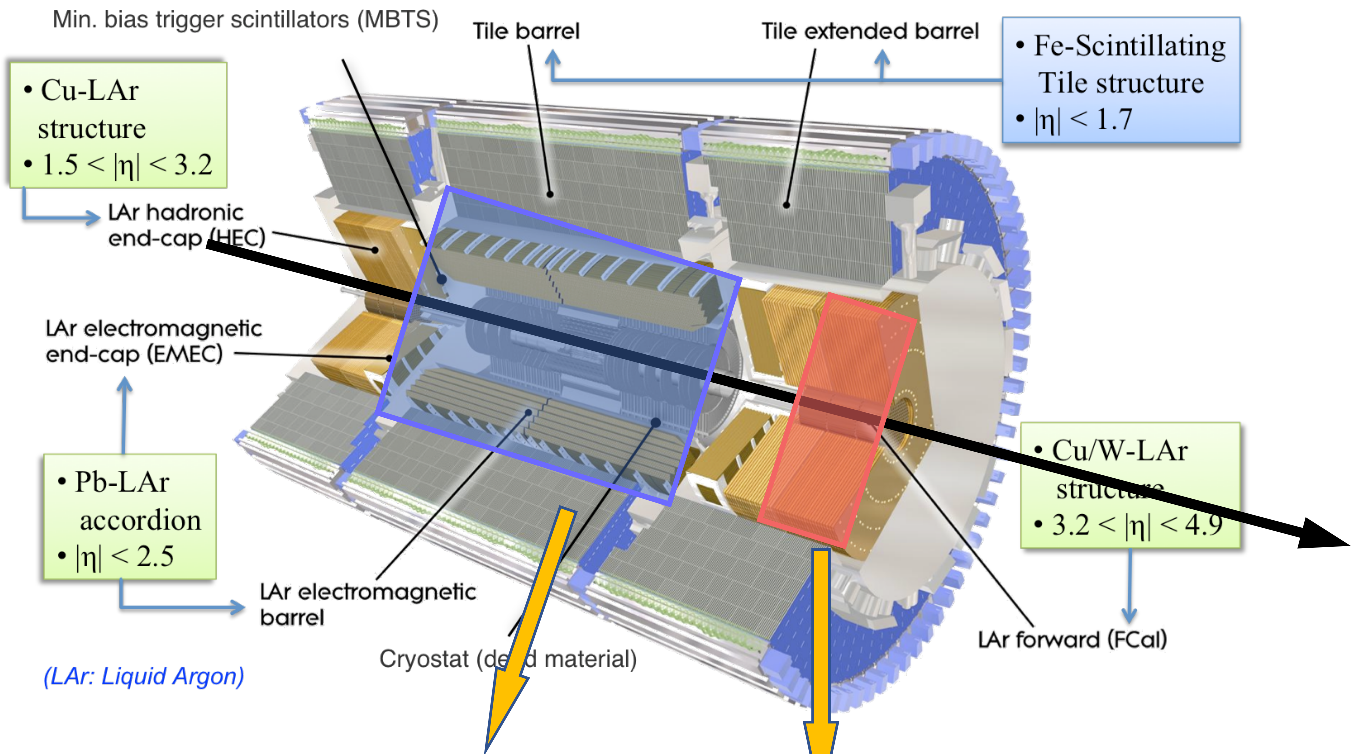
Linear and NL contribution

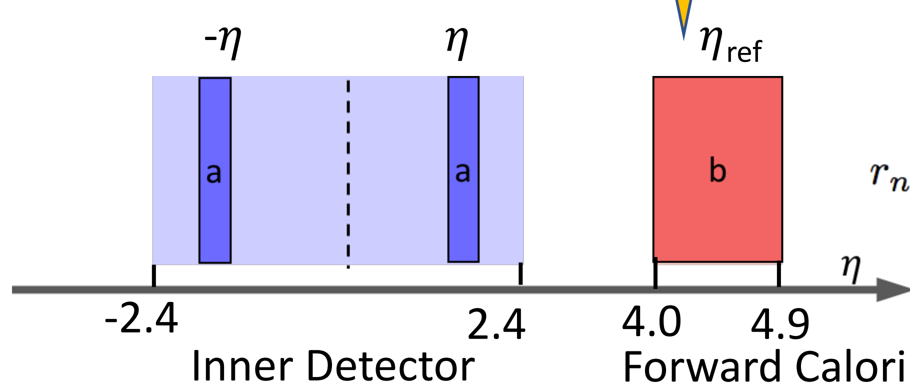
- Linear term is dominant in central collision and NL term dominates in other centrality intervals





ATLAS experiment





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

Why linear decrease

- Assuming v_n in each event slowly varying around $\eta \sim 0$

$$v_n(\eta) \approx v_n(0)\,(1+\alpha_n\eta)\,e^{i\beta_n\eta},\quad v_n^{\mathrm{k}}(0)v_n^{*\mathrm{k}}(\eta_{\mathrm{ref}}) = X_{n;k}(\eta^{\mathrm{ref}}) - iY_{n;k}(\eta^{\mathrm{ref}})$$

Then the two particle correlator $\left\langle q_n^k(\eta_1) q_n^{*k}(\eta_{\mathrm{ref}})\right\rangle$ can be expanded

$$\begin{aligned}\left\langle q_n^k(\eta_1) q_n^{*k}(\eta_{\mathrm{ref}})\right\rangle &\approx \langle (1+k\eta\alpha_n)\,(X_{n;k}+k\beta_n Y_{n;k})\rangle \\ &\approx \langle X_{n;k} + k\eta\alpha_n X_{n;k} + k\eta\beta_n Y_{n;k}\rangle \\ &\approx \langle X_{n;k}\rangle \left(1 + \frac{\langle k\eta\alpha_n X_{n;k}\rangle}{\langle X_{n;k}\rangle} + \frac{\langle k\eta\beta_n Y_{n;k}\rangle}{\langle X_{n;k}\rangle}\right)\end{aligned}$$

With this format then $r_{n£n;k}$ can be approximated by:

$$r_{n|n;k}(\eta) = 1 - 2F_{n,k}^{r}\eta,\ F_{n,k}^{r} \approx F_{n,k}^{\mathrm{asy}} + F_{n,k}^{\mathrm{twi}},\ F_{n,k}^{\mathrm{asy}} = \frac{\langle \alpha_n k X_{n;k}(\eta^{\mathrm{ref}})\rangle}{\langle X_{n;k}(\eta^{\mathrm{ref}})\rangle},\ F_{n,k}^{\mathrm{twi}} = \frac{\langle \beta_n k Y_{n;k}(\eta^{\mathrm{ref}})\rangle}{\langle Y_{n;k}(\eta^{\mathrm{ref}})\rangle}$$

- If twist and asymmetry doesn't depend on k, then expect $F_{n;k}^{r}/k = F_{n;1}^{r}$

$$R_{n|n;2} \approx 1 - 2F_{n;2}^{R}\eta = 1 - 4\eta\frac{\langle \beta_n Y_{n;2}(\eta^{\mathrm{ref}})\rangle}{\langle Y_{n;2}(\eta^{\mathrm{ref}})\rangle},\qquad F_{n;2}^{R} = F_{n;2}^{\mathrm{twi}}$$

- $R_{n|n;2}$ and $r_{n|n;2}$ together can help separate twist and asymmetry

$$r_{n|n;2} \approx 1 - 2F_{n;2}^{\mathrm{r}}\eta = 1 - 2F_{n,2}^{\mathrm{twi}}\eta - 2F_{n,2}^{\mathrm{asy}}\eta$$