Longitudinal fluctuations and decorrelations of anisotropic flows

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Based on arXiv:1805.03762

Outline

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- (3+1)-dimensionsal ideal hydrodynamics model

Numerical Results

- Longitudinal decorrelations of flows
- Collision energy and centrality dependences
- Linearity of flow decorrelations & 4-η-bin observables

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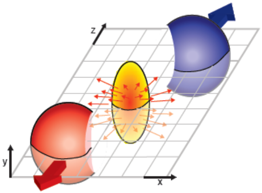
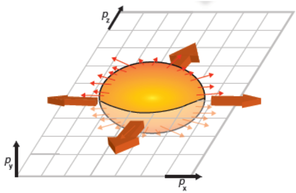
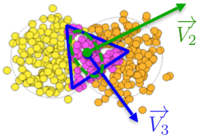
Introduction





The event-by-event fluctuations of the initial state density and geometry lead to anisotropic momentum distributions for the final state soft hardons.



Probe the initial conditions and the transport properties of QGP

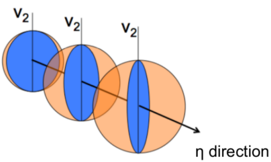
Many flow observables:

- higher-order anisotropic flows
- event plane correlation
- symmetric cummulants
- nonlinear respones

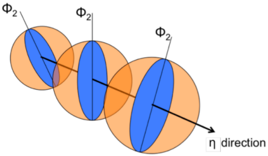
focus on fluctuations in the transverse plane.

Longitudinal fluctuations

Anisotropic flows $\mathbf{V}_n(\eta) = v_n(\eta)e^{in\Psi_n(\eta)} = \frac{\int \exp(in\phi)\frac{dN}{d\eta dp_T d\phi}dp_T d\phi}{\int \frac{dN}{d\eta dp_T d\phi}dp_T d\phi}$



(a) $v_2(\eta) \neq v_2(-\eta)$



(b) $\Psi_2(\eta) \neq \Psi_2(-\eta)$

Longitudinal fluctuations can lead to:

- rapidity dependent anisotropic flows
  [Denicol, Gabriel et al. Phys.Rev.Lett. 116 (2016)]
  [ALICE Collaboration (Adam, Jaroslav et al.)Phys.Lett.B762(2016)]
- decorrelation of anisotropic flows
  [L.G.Pang, et al, Eur.Phys.J.A52,97(2016)]
  [P.Bozek and W.Broniowski,(2017),arXiv:1711.03325.]
  [J,Jia and P.Huo, Phys. Rev. C90, 034905 (2014)]

Our work:
Systematic study for the longitudinal decorrelations of anisotropic flows for different collision energy & centrality, using different observables(flow vector, magnitude, orientations,3-η-bin,4-η-bin)

Model Setup

CLVisc (IDEAL) (3+1)-dimensionsal hydrodynamics model

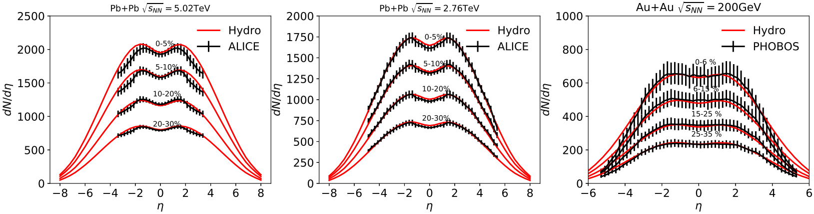
[L. Pang, Q. Wang, and X.-N. Wang, Phys. Rev. C86,024911 (2012), Pang,Long-Gang et al. arXiv:1802.04449]

- initial state: A-Multi-Phase-Transport (AMPT) model
  [Z.W. Lin, C. M. Ko, B.A. Li, B. Zhang, and S. Pal,Phys. Rev. C72, 064901 (2005)]
  local energy-momentum tensor $T^{\mu\nu}$ at the inital proper time:

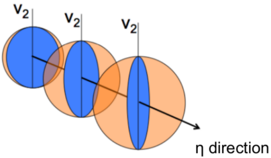
$$T^{\mu\nu}(\tau_0, x, y, \eta_s) = K \sum_i \frac{p_i^\mu p_i^\nu}{p_i^\tau} \frac{1}{\tau_0\sqrt{2\pi\sigma_{\eta s}^2}} \frac{1}{2\pi\sigma_r^2} \times \exp\left[-\frac{(x-x_i)^2+(y-y_i)^2}{2\sigma_r^2} - \frac{(\eta_s-\eta_{si})^2}{2\sigma_{\eta s}^2}\right] \quad (1)$$

  τ_0 = 0.2 fm for LHC , 0.4fm for RHIC, σ_r =0.6 fm $\sigma_{\eta s}$=0.6
- evolution: ideal hydrodynamics $\partial_\mu T^{\mu\nu} = 0$
- freeze-out: Cooper-Frye Formula (T_f=137 MeV)

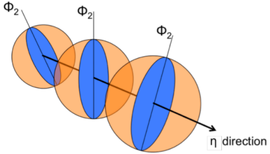
$$E\frac{dN_h}{d^3p} = \frac{g_h}{(2\pi)^3}\int_\Sigma p^\mu d^3\sigma_\mu f(p) \quad (2)$$



Longitudinal decorrelation observables

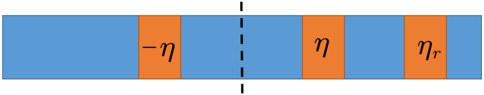


(c) $q_2(\eta) \neq q_2(-\eta)$



(d) $\Psi_2(\eta) \neq \Psi_2(-\eta)$

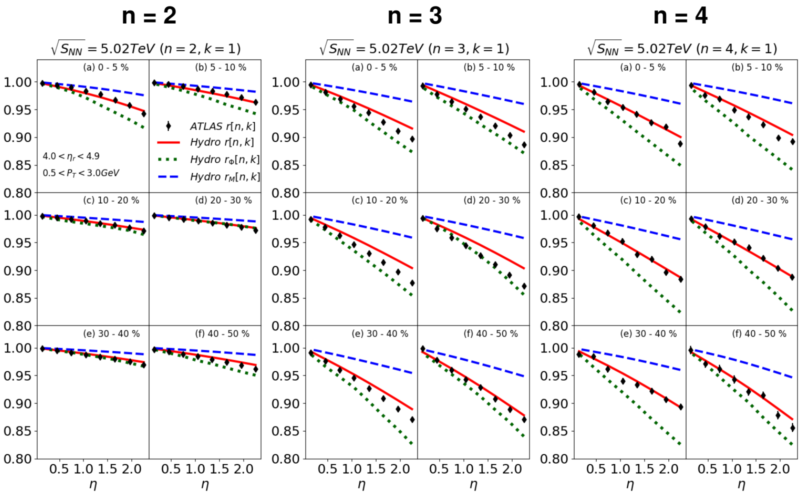
We use Q-vector method: $\mathbf{Q}_n(\eta) = q_n(\eta)\hat{Q}_n(\eta) = q_n(\eta)e^{in\Psi_n(\eta)} = \frac{1}{N}\sum_{i=1}^{N} e^{in\phi_i}$



Longitudinal observables (3-η-bin observables)	Effects
$r[n,k](\eta) = \frac{\langle \mathbf{Q}_n^k(-\eta)\mathbf{Q}_n^{*k}(\eta_{\mathrm{r}})\rangle}{\langle \mathbf{Q}_n^k(\eta)\mathbf{Q}_n^{*k}(\eta_{\mathrm{r}})\rangle}$	Decorrelation of flow vector[1,2]
$r_M[n,k](\eta) = \frac{\langle q_n^k(-\eta)q_n^k(\eta_{\mathrm{r}})\rangle}{\langle q_n^k(\eta)q_n^k(\eta_{\mathrm{r}})\rangle}$	Decorrelation of flow magnitude[3]
$r_\Phi[n,k](\eta) = \frac{\langle \hat{Q}_n^k(-\eta)\hat{Q}_n^{*k}(\eta_{\mathrm{r}})\rangle}{\langle \hat{Q}_n^k(\eta)\hat{Q}_n^{*k}(\eta_{\mathrm{r}})\rangle}$	Decorrelation of flow orientations[3]

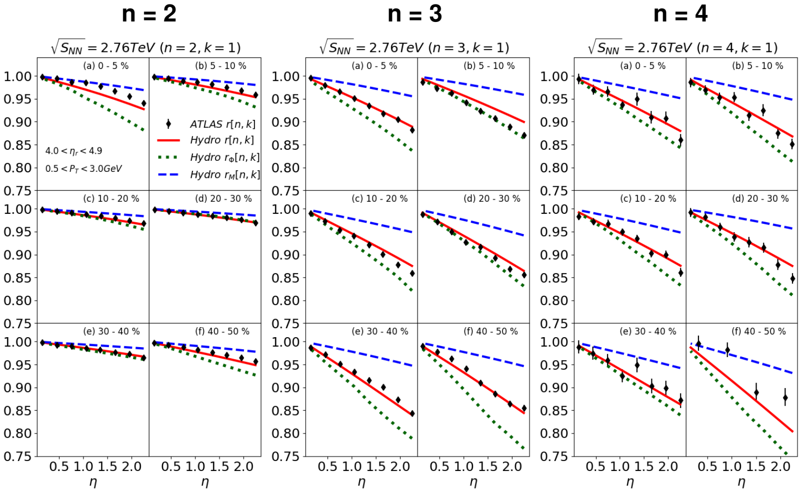
[1][CMS Collaboration (Khachatryan, Vardan et al.) Phys.Rev. C92 (2015)] [2][ATLAS Collaboration (Aaboud, Morad et al.) Eur.Phys.J. C78 (2018)]
[3][P.Bozek and W.Broniowski,(2017),arXiv:1711.03325.]

Longitudinal decorrelations in PbPb collisions at 5.02A TeV



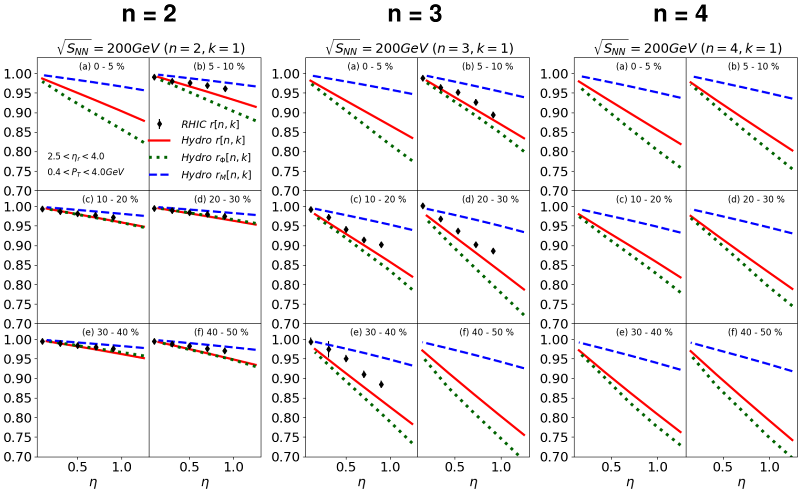
- The decorrelation functions are linear in η directions around midrapidity
- $r_\Phi[n,k] < r[n,k] < r_M[n,k]$

Longitudinal decorrelations in PbPb collisions at 2.76A TeV



- The decorrelation functions are linear in η directions around midrapidity
- $r_\Phi[n,k] < r[n,k] < r_M[n,k]$
- Decorrelation effects (5.02A TeV $<$ 2.76A TeV)

Longitudinal decorrelations in AuAu collisions at 200A GeV



- The decorrelation functions are linear in η directions around midrapidity
- $r_{\Phi}[n, k] < r[n, k] < r_M[n, k]$
- Decorrelation effects (5.02A TeV $<$ 2.76A TeV $<$ 200A GeV)

Slope parameters for longitudinal decorrelations

Since $r[n,k](\eta)$, $r_\Phi[n,k](\eta)$ and $r_M[n,k](\eta)$ are almost linear in η, they can be parameterized as follows:

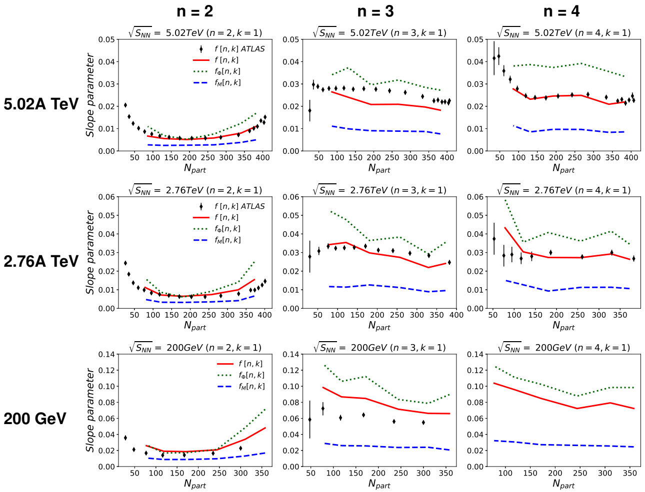
$$\begin{aligned} r[n,k](\eta) &\approx 1 - 2f[n,k]\eta \\ r_M[n,k](\eta) &\approx 1 - 2f_M[n,k]\eta \\ r_\Phi[n,k](\eta) &\approx 1 - 2f_\Phi[n,k]\eta \end{aligned} \tag{3}$$

where $f[n,k]$, $f_M[n,k]$, $f_\Phi[n,k]$ are called slope parameters. They can be measured via:

$$f[n,k] = \frac{\sum_i \{1 - r[n,k](\eta_i)\}\,\eta_i}{2\sum_i \eta_i^2} \tag{4}$$

Similarly for the slope parameters $f_M[n,k]$ and $f_\Phi[n,k]$.

Slope parameters for longitudinal decorrelations

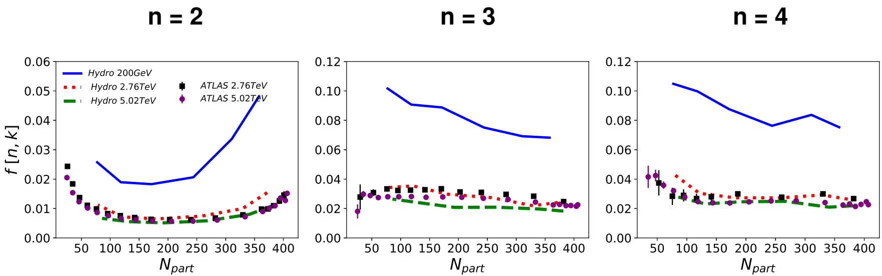


- $f_\Phi[n,k] > f[n,k] > f_M[n,k]$
- Decorrelation effects (5.02A TeV $<$ 2.76A TeV $<$ 200A GeV)
- Centrality denpendence:

For v_2, non-monotonic, strong dependence on initial collision geometry

For v_3 & v_4, weakly centrality dependence(fluctuations dominate), slight increase from central to peripheral collisions.

Collision energy and centrality dependences



The longitudinal decorrelation effects for anisotropic flows:

Energy dependence:

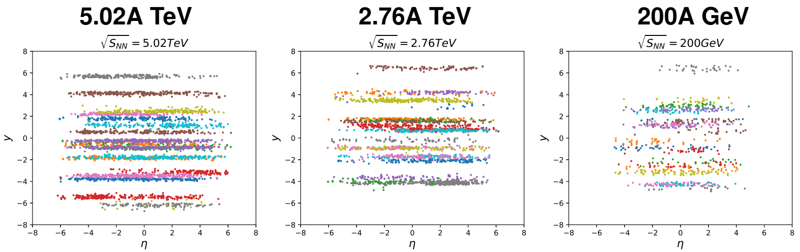
- f (5.02A TeV) $<$ f (2.76A TeV) $\ll$ f (200A GeV)

Centrality denpendence:

- for v_2, slope parameters strong dependence on initial geometry.
- for v_3, v_4, slope parameters slight decrease with N_{part}.

How do we understand these dependences?

Longitudinal structure of initial states

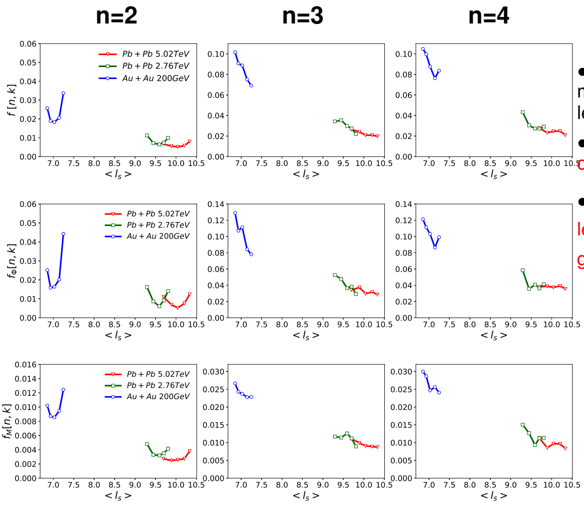


- Divide the initial partons into different clusters in transverse plane
- Arrange partons in the same cluster in the longitudinal direction to form a 'string'
- The length of each string is obtained from difference between the maximum and minimum rapidities of the initial patrons in the same cluster.

The higher the collision energy, the longer the initial strings length

$$l_s(5.02A\ TeV) > l_s(2.76A\ TeV) > l_s(200A\ GeV) \quad (5)$$

Collision energy and centrality dependences



- Given collision energy, more central collisions, longer lengths of the string.
- v_3, v_4 depend on the length of the strings
- v_2 depends on the string length and initial collision geometry.

Test of the linearity of flow decorrelations

Parameterization for the **Q**-vector:

$$\mathbf{Q}_n(\eta) \approx \mathbf{Q}_n(0)(1+\alpha_n\eta)e^{i\beta_n\eta} \tag{6}$$
$$\mathbf{Q}_n^k(0)\mathbf{Q}_n^{*k}(\eta_\mathrm{r}) = A_{n,k}(\eta_\mathrm{r})e^{-i\delta_{n,k}(\eta_\mathrm{r})} = X_{n,k}(\eta_\mathrm{r}) + iY_{n,k}(\eta_\mathrm{r})$$

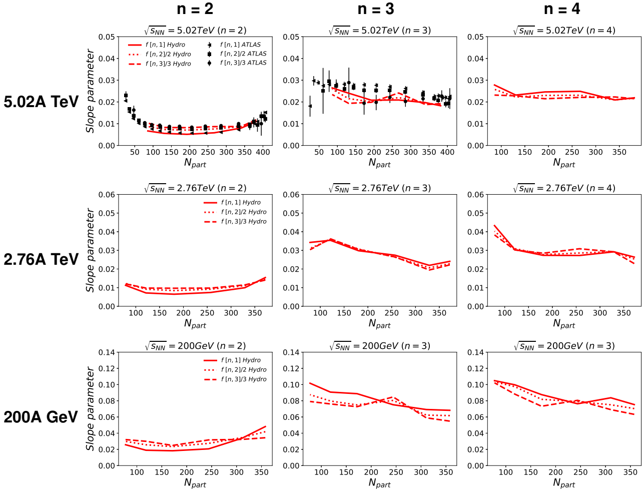
α_n : The forward-backward asymmetry
β_n : The rotation of the flow orientation
The decorreltion function can be approximated as:

$$r[n,k](\eta) \approx 1-2f[n,k]\eta \qquad f[n,k] = k\left(\frac{\langle\alpha_n X_{n,k}\rangle}{\langle X_{n,k}\rangle} + \frac{\langle\beta_n Y_{n,k}\rangle}{\langle X_{n,k}\rangle}\right)$$
$$r_M[n,k](\eta) \approx 1-2f_M[n,k]\eta \qquad f_M[n,k] = k\frac{\langle\alpha_n A_{n,k}\rangle}{\langle A_{n,k}\rangle}$$
$$r_\Phi[n,k] \approx 1-2f_\Phi[n,k]\eta \qquad f_\Phi[n,k] = k\frac{\langle\beta_n \sin(\delta_{n,k})\rangle}{\langle\cos(\delta_{n,k})\rangle}$$

Simple approximate relations between the slope parameters with different k:

$$\begin{aligned} f[n,k]/k &\approx f[n,1] \\ f_M[n,k]/k &\approx f_M[n,1] \\ f_\Phi[n,k]/k &\approx f_\Phi[n,1] \end{aligned} \tag{7}$$

Test of linearity of flow decorrelations

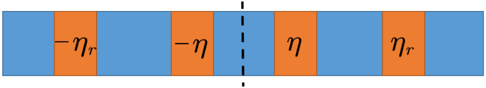


- Linear approximation works well at two LHC energy
- More breaking at RHIC energy than at LHC energy

$f[n,k]/k \approx f[n,1]$

Four-rapidity-bin decorrelation obervables

3-rapidity-bin decorrelation	Slope parameter
$r[n,k](\eta) = \frac{\langle \mathbf{Q}_n^k(-\eta)\mathbf{Q}_n^{*k}(\eta_r)\rangle}{\langle \mathbf{Q}_n^k(\eta)\mathbf{Q}_n^{*k}(\eta_r)\rangle}$	$f[n,k] = k\left(\frac{\langle \alpha_n X_{n,k}\rangle}{\langle X_{n,k}\rangle} + \frac{\langle \beta_n Y_{n,k}\rangle}{\langle X_{n,k}\rangle}\right)$
$r_M[n,k](\eta) = \frac{\langle q_n^k(-\eta) q_n^k(\eta_r)\rangle}{\langle q_n^k(\eta) q_n^k(\eta_r)\rangle}$	$f_M[n,k] = k\frac{\langle \alpha_n A_{n,k}\rangle}{\langle A_{n,k}\rangle}$
$r_\Phi[n,k](\eta) = \frac{\langle \hat{Q}_n^k(-\eta)\hat{Q}_n^{*k}(\eta_r)\rangle}{\langle \hat{Q}_n^k(\eta)\hat{Q}_n^{*k}(\eta_r)\rangle}$	$f_\Phi[n,k] = k\frac{\langle \beta_n \sin(\delta_{n,k})\rangle}{\langle \cos(\delta_{n,k})\rangle}$



4-rapidity-bin decorrelation	Slope parameter
$R[n,2](\eta) = \frac{\langle \mathbf{Q}_n(-\eta_r)\mathbf{Q}_n(-\eta)\mathbf{Q}_n^*(\eta)\mathbf{Q}_n^*(\eta_r)\rangle}{\langle \mathbf{Q}_n(-\eta_r)\mathbf{Q}_n^*(-\eta)\mathbf{Q}_n(\eta)\mathbf{Q}_n^*(\eta_r)\rangle}$	$F[n,2] = 2\frac{\langle \beta_n Y_{n,2}\rangle}{\langle X_{n,2}\rangle}$ (defined by ALTAS[1])
$R_\Phi[n,2](\eta) = \frac{\langle \hat{Q}_n(-\eta_r)\hat{Q}_n(-\eta)\hat{Q}_n^*(\eta)\hat{Q}_n^*(\eta_r)\rangle}{\langle \hat{Q}_n(-\eta_r)\hat{Q}_n^*(-\eta)\hat{Q}_n(\eta)\hat{Q}_n^*(\eta_r)\rangle}$	$F_\Phi[n,2] = 2\frac{\langle \beta_n \sin(\delta_{n,2})\rangle}{\langle \cos(\delta_{n,2})\rangle}$

α_n : The forward-backward asymmetry

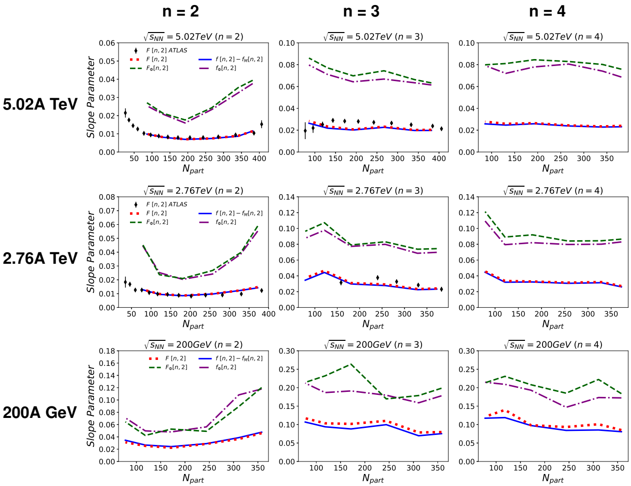
β_n : The rotation of the flow orientation

The relation between 4-η-bin & 3-η-bin slope parameters:

$$\begin{aligned} F[n,2] &\approx f[n,2] - f_M[n,2] \\ F_\Phi[n,2] &\approx f_\Phi[n,2] \end{aligned} \quad (8)$$

[1][ATLAS Collaboration (Aaboud, Morad et al.) Eur.Phys.J. C78 (2018)]

Four-rapidity-bin decorrelation obervables



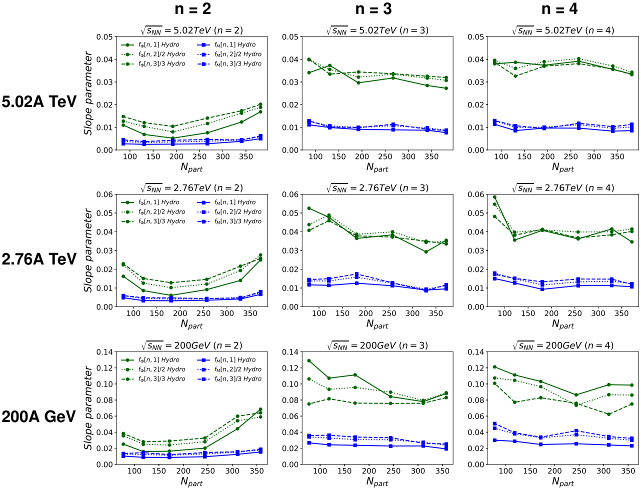
- $F[n,2] \approx f[n,2] - f_M[n,2]$ holds pretty well for PbPb collision at two LHC energy, a slight violation for AuAu collision at RHIC energy
- $F_\Phi[n,2] \approx f_\Phi[n,2]$ has a sizble violation due to the larger decorrelation effects for pure flow orientations
- Violation is larger at the RHIC than at the LHC

Conclusion

- We have a performed detailed analysis for longitudinal decorrelation of v_2, v_3, v_4 for the LHC & RHIC energies.
- We find:
  - $f_\Phi[n,k] > f[n,k] > f_M[n,k]$
  - $f(5.02A\ TeV) < f(2.76A\ TeV) < f(200A\ GeV)$
- Centrality dependence:
  - v_2 decorrelation has a strong dependence on initial collision geometry
  - v_3, v_4 decorrelations slightly increase for smaller N_{part}
- The collision energy dependence of flow decorrelation can be traced back to the longitudinal structure(fluctuations) of initial states: $l_s(5.02A\ TeV) > l_s(2.76A\ TeV) > l_s(200A\ GeV)$.

Back Up

Test of linearity of flow decorrelations

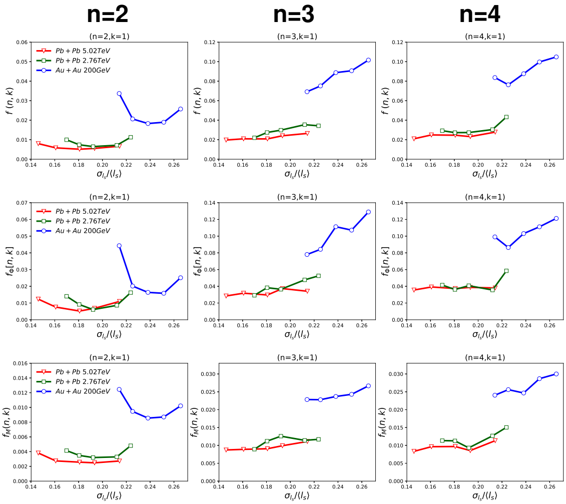


- Linear approximation works well at two LHC energy
- More breaking at RHIC energy than at LHC energy
- Linear approximation works better for flow magnitudes
- More breaking for flow orientaions

$$f_\Phi[n,k]/k \approx f_\Phi[n,1]$$

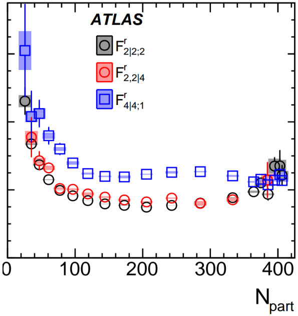
$$f_M[n,k]/k \approx f_M[n,1]$$

Collision energy and centrality dependences



- Lower collision energy, larger varience-to-mean ratio of the string.
- Given collision energy, more central collisions, smaller varience-to-mean ratio of the string.
- v_2 depends on the collision energy and initial collision geometry, complex dependence on the the variance of the string lengths.
- v_3, v_4 increase with increasing the $\sigma_{l_s}/\langle l_s\rangle$

The decorrelation fuctions with shear viscosity at 2.76A TeV



$$r_{2,2|4} \approx \frac{\langle \vec{Q}_2^2(-\eta)\beta_{2,2}\vec{Q}_2^{*2}(\eta_{ref})\rangle + \langle \vec{Q}_2^2(\eta_{ref})\beta_{2,2}\vec{Q}_2^{*2}(-\eta)\rangle}{\langle \vec{Q}_2^2(\eta)\beta_{2,2}\vec{Q}_2^{*2}(\eta_{ref})\rangle + \langle \vec{Q}_2^2(\eta_{ref})\beta_{2,2}\vec{Q}_2^{*2}(\eta)\rangle}$$

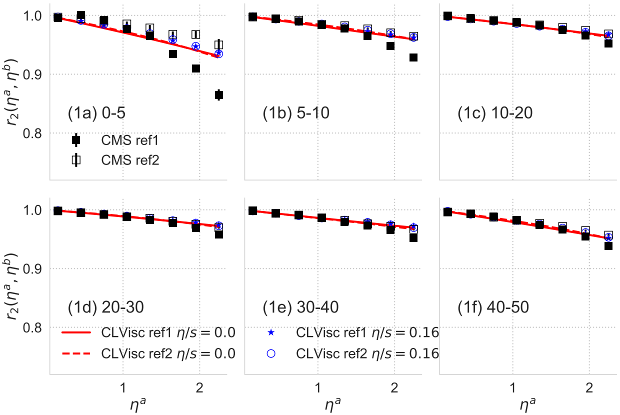
$$\approx \frac{\langle \vec{Q}_2^2(-\eta)\vec{Q}_2^{*2}(\eta_{ref})\rangle}{\langle \vec{Q}_2^2(\eta)\vec{Q}_2^{*2}(\eta_{ref})\rangle} = r_{2,2|2}$$

$$r_{4|4;1} \approx \frac{\langle \vec{Q}_{4L}(-\eta)\vec{Q}_{4L}^{*}(\eta_{ref})\rangle + \beta_{2,2}^2\langle \vec{Q}_2^2(-\eta)\vec{Q}_2^{*2}(\eta_{ref})\rangle}{\langle \vec{Q}_{4L}(\eta)\vec{Q}_{4L}^{*}(\eta_{ref})\rangle + \beta_{2,2}^2\langle \vec{Q}_2^2(\eta)\vec{Q}_2^{*2}(\eta_{ref})\rangle}$$

The decorrelation effects are stronger for the linear component of v_4 than for the nonlinear component.

[ATLAS Collaboration (Aaboud, Morad et al.) Eur.Phys.J. C78 (2018)]

The decorrelation fuctions with shear viscosity at 2.76A TeV

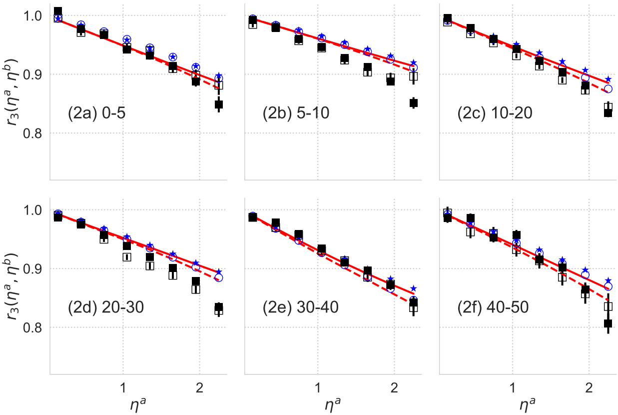


ref1: $3.0 < \eta < 4.0$ ref2: $4.4 < \eta < 5.0$

For decorrelation functions r[2,1], the effect of shear viscosity is very small for zero-flow velocity.

[Pang,Long-Gang et al. arXiv:1802.04449]

The decorrelation fuctions with shear viscosity at 2.76A TeV



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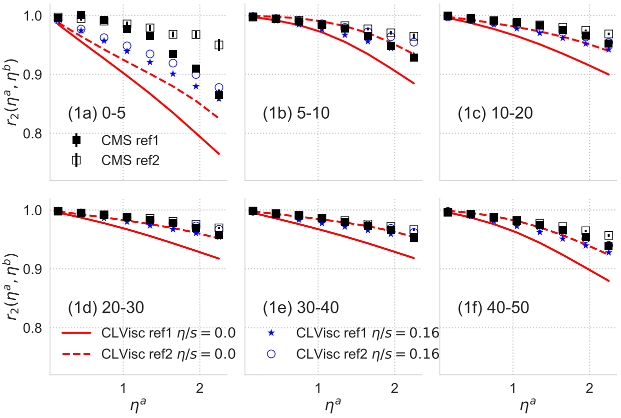
The decorrelation fuctions with flow velocity at 2.76A TeV



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For decorrelation functions r[2,1], the decorrelation effects become larger due to the stronger short range correlations when the initial velocity is computed.

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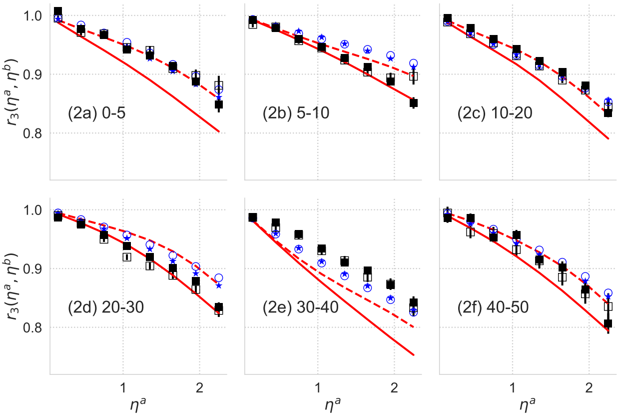
The decorrelation fuctions with flow velocity at 2.76A TeV



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