



Longitudinal fluctuations and decorrelations of anisotropic flows

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Based on arXiv:1805.03762



Introduction

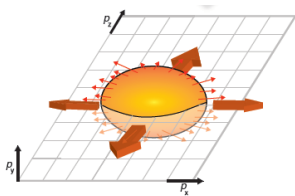
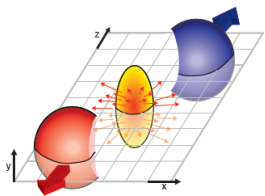
Model Setup

- (3+1)-dimensional ideal hydrodynamics model

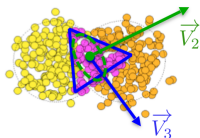
Numerical Results

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

Conclusion



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



Probe the initial conditions and the transport properties of QGP

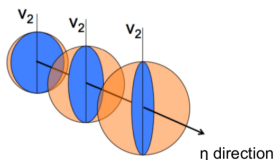
Many flow observables:

- ▶ higher-order anisotropic flows
- ▶ event plane correlation
- ▶ symmetric cumulants
- ▶ nonlinear responses

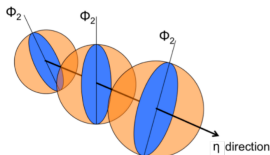
focus on fluctuations in the transverse plane.

Longitudinal fluctuations

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



(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)

CLVisc (IDEAL) (3+1)-dimensional 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)]

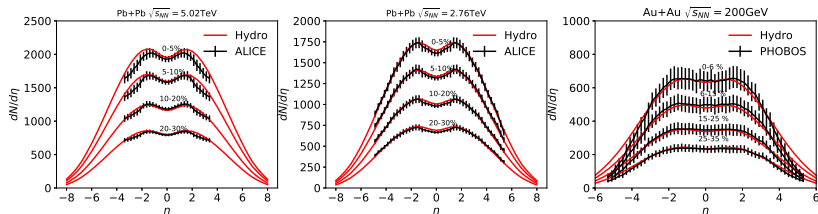
local energy-momentum tensor $T^{\mu\nu}$ at the initial proper time:

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

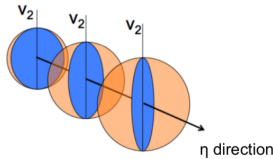
$\tau_0 = 0.2$ fm for LHC, 0.4fm for RHIC, $\sigma_r = 0.6$ fm $\sigma_{\eta_S} = 0.6$

- ▶ evolution: ideal hydrodynamics $\partial_\mu T^{\mu\nu} = 0$
- ▶ freeze-out: Cooper-Frye Formula ($T_f = 137$ MeV)

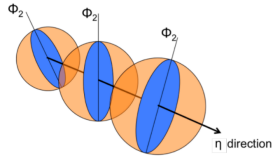
$$E \frac{dN_h}{d^3p} = \frac{g_h}{(2\pi)^3} \int_\Sigma p^\mu d^3\sigma_\mu f(p) \quad (2)$$



Longitudinal decorrelation observables

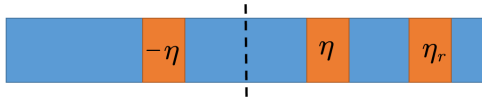


(c) $q_2(\eta) \neq q_2(-\eta)$



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

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



Longitudinal observables
(3- η -bin observables)

Effects

$$r[n, k](\eta) = \frac{\langle \mathbf{Q}_n^k(-\eta) \mathbf{Q}_n^{*k}(\eta_r) \rangle}{\langle \mathbf{Q}_n^k(\eta) \mathbf{Q}_n^{*k}(\eta_r) \rangle}$$

Decorrelation of **flow vector**^{1,2}

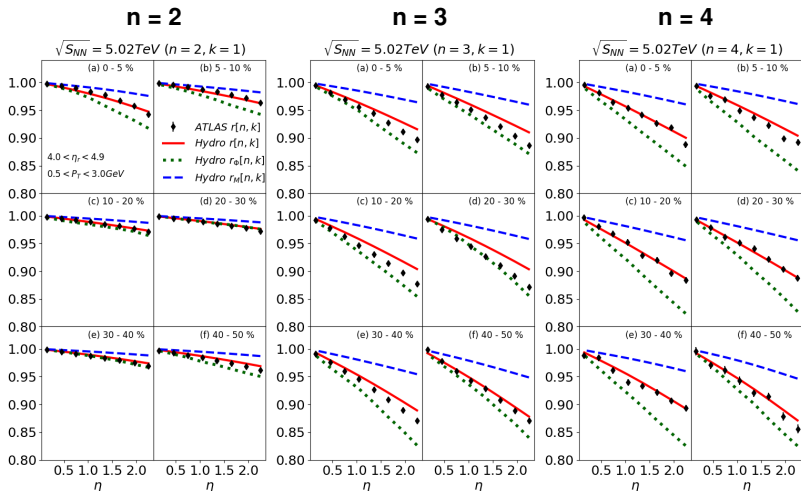
$$r_M[n, k](\eta) = \frac{\langle q_n^k(-\eta) q_n^k(\eta_r) \rangle}{\langle q_n^k(\eta) q_n^k(\eta_r) \rangle}$$

Decorrelation of **flow magnitude**³

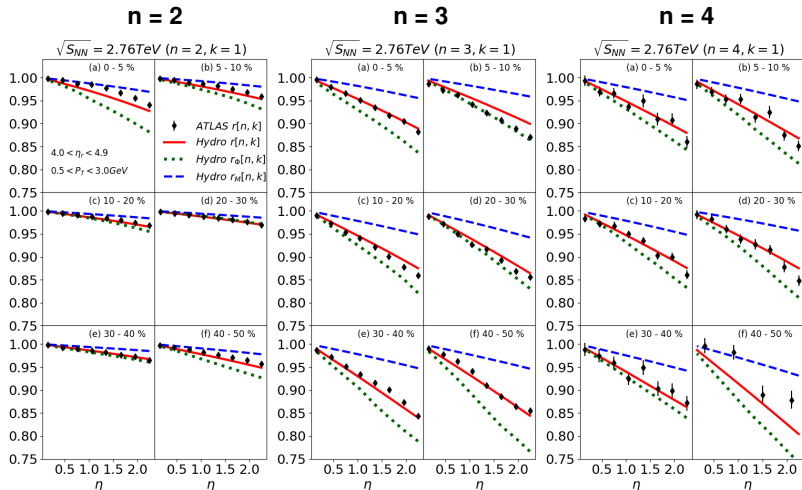
$$r_\Phi[n, k](\eta) = \frac{\langle \hat{\mathbf{Q}}_n^k(-\eta) \hat{\mathbf{Q}}_n^{*k}(\eta_r) \rangle}{\langle \hat{\mathbf{Q}}_n^k(\eta) \hat{\mathbf{Q}}_n^{*k}(\eta_r) \rangle}$$

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.]



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



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- $r_\phi[n, k] < r[n, k] < r_M[n, k]$
- Decorrelation effects ($5.02A \text{ TeV} < 2.76A \text{ TeV}$)

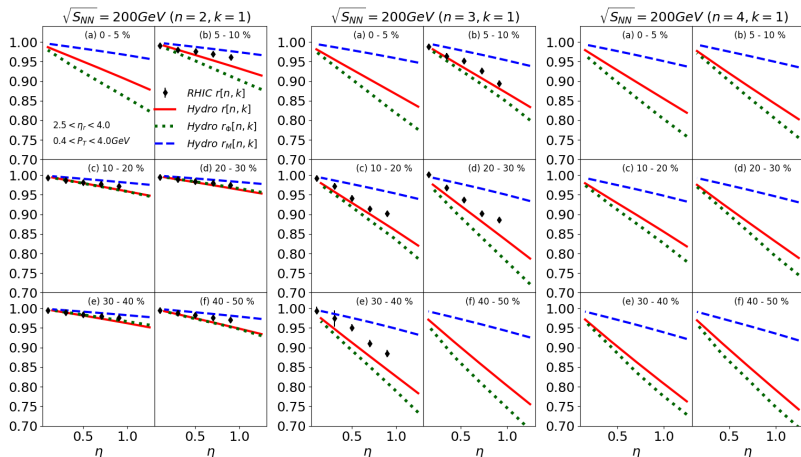
Longitudinal decorrelations in AuAu collisions at 200A GeV



n = 2

n = 3

n = 4



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



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:

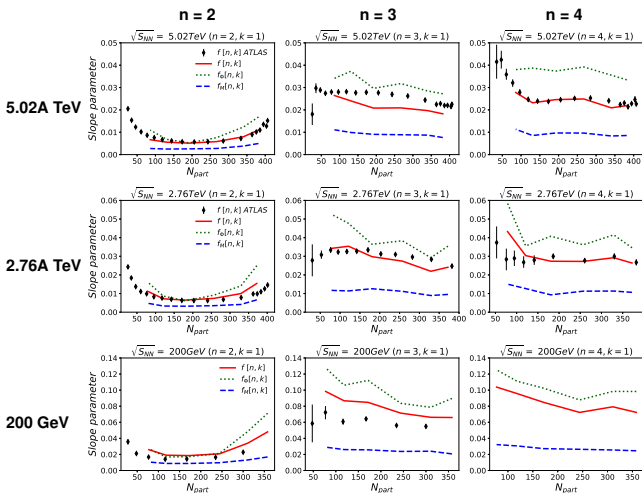
$$\begin{aligned}r[n, k](\eta) &\approx 1 - 2f[n, k]\eta \\r_M[n, k](\eta) &\approx 1 - 2f_M[n, k]\eta \\r_\phi[n, k](\eta) &\approx 1 - 2f_\phi[n, k]\eta\end{aligned}\tag{3}$$

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



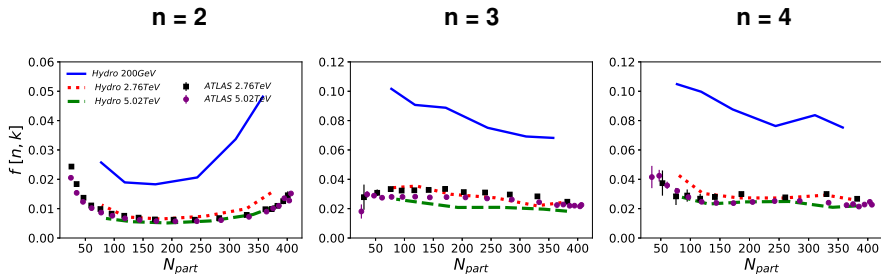
- $f_\phi[n, k] > f[n, k] > f_M[n, k]$

- Decorrelation effects (5.02A TeV < 2.76A TeV < 200A GeV)

- Centrality dependence:

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.



The longitudinal decorrelation effects for anisotropic flows:

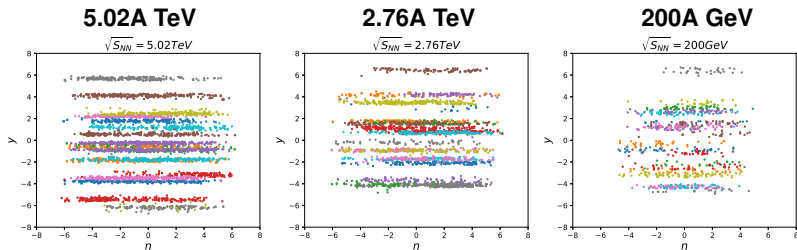
Energy dependence:

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

Centrality dependence:

- 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?

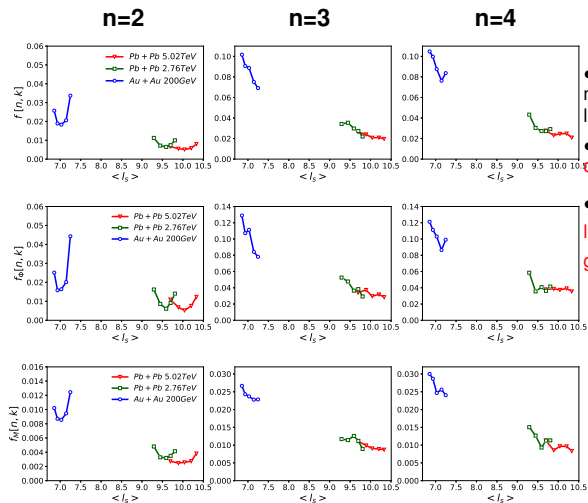


- ▶ Divide the initial partons into different clusters in transverse plane
- ▶ Arrange partons in the same cluster in the longitudinal direction to form a 'string'
- ▶ The length of each string is obtained from difference between the maximum and minimum rapidities of the initial partons in the same cluster.

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

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

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**.

Parameterization for the \mathbf{Q} -vector:

$$\mathbf{Q}_n(\eta) \approx \mathbf{Q}_n(0)(1 + \alpha_n \eta) e^{i\beta_n \eta} \quad (6)$$

$$\mathbf{Q}_n^k(0) \mathbf{Q}_n^{*k}(\eta_r) = A_{n,k}(\eta_r) e^{-i\delta_{n,k}(\eta_r)} = X_{n,k}(\eta_r) + iY_{n,k}(\eta_r)$$

α_n : The forward-backward **asymmetry**

β_n : The **rotation** of the flow orientation

The decorrelation function can be approximated as:

$$r[n, k](\eta) \approx 1 - 2f[n, k]\eta \quad f[n, k] = k \left(\frac{\langle \alpha_n X_{n,k} \rangle}{\langle X_{n,k} \rangle} + \frac{\langle \beta_n Y_{n,k} \rangle}{\langle X_{n,k} \rangle} \right)$$

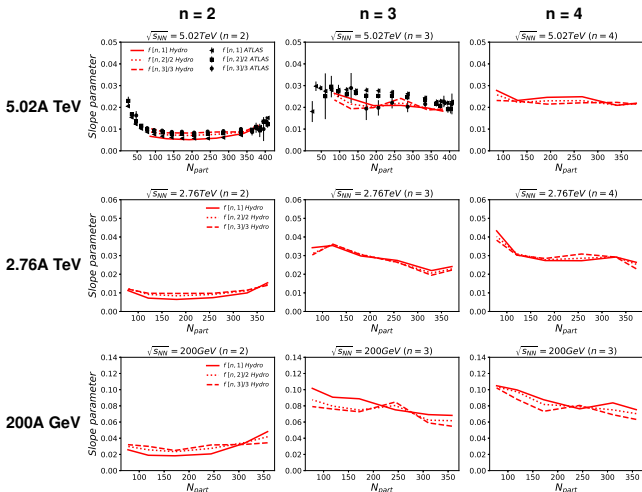
$$r_M[n, k](\eta) \approx 1 - 2f_M[n, k]\eta \quad f_M[n, k] = k \frac{\langle \alpha_n A_{n,k} \rangle}{\langle A_{n,k} \rangle}$$

$$r_\Phi[n, k] \approx 1 - 2f_\Phi[n, k]\eta \quad f_\Phi[n, k] = k \frac{\langle \beta_n \sin(\delta_{n,k}) \rangle}{\langle \cos(\delta_{n,k}) \rangle}$$

Simple approximate relations between the slope parameters with different k :

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

Test of linearity of flow decorrelations



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

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

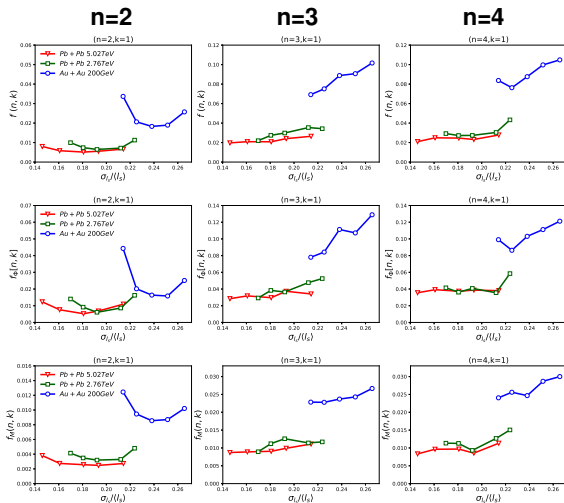


- ▶ We have performed a detailed analysis for longitudinal decorrelation of v_2, v_3, v_4 for the LHC & RHIC energies.
- ▶ We find:
 - $f_\phi[n, k] > f[n, k] > f_M[n, k]$
 - $f(5.02A \text{ TeV}) < f(2.76A \text{ TeV}) < f(200A \text{ GeV})$
- ▶ Centrality dependence:
 - v_2 decorrelation has a strong 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:
 $I_s(5.02A \text{ TeV}) > I_s(2.76A \text{ TeV}) > I_s(200A \text{ GeV})$.



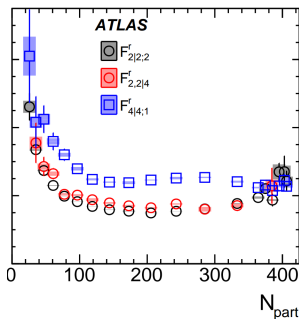
Back Up

Collision energy and centrality dependences



- Lower collision energy, larger variance-to-mean ratio of the string.
- Given collision energy, more central collisions, smaller variance-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 $\sigma_{I_S} / \langle I_S \rangle$

The decorrelation functions with shear viscosity at 2.76A TeV



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

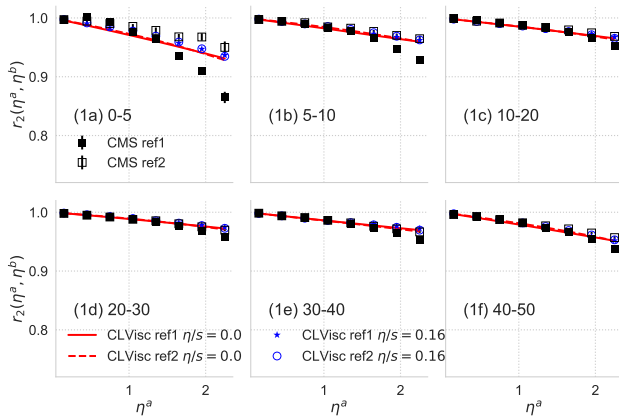
$$\approx \frac{\langle \vec{Q}_2^2(-\eta) \vec{Q}_2^{*2}(\eta_{ref}) \rangle}{\langle \vec{Q}_2^2(\eta) \vec{Q}_2^{*2}(\eta_{ref}) \rangle} = r_{2,2|2}$$

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

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 functions with shear viscosity at 2.76A TeV

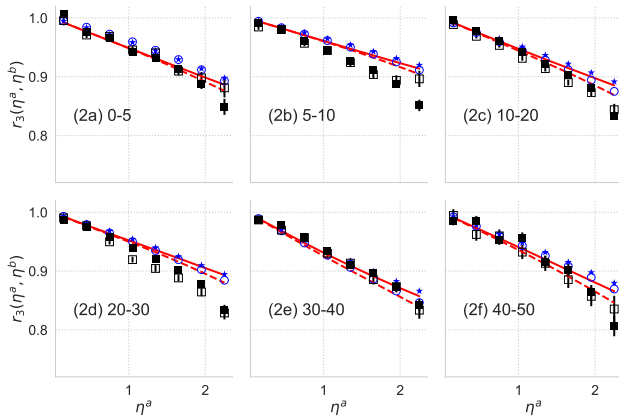


ref1: $3.0 < \eta < 4.0$ ref2: $4.4 < \eta < 5.0$

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 functions with shear viscosity at 2.76A TeV

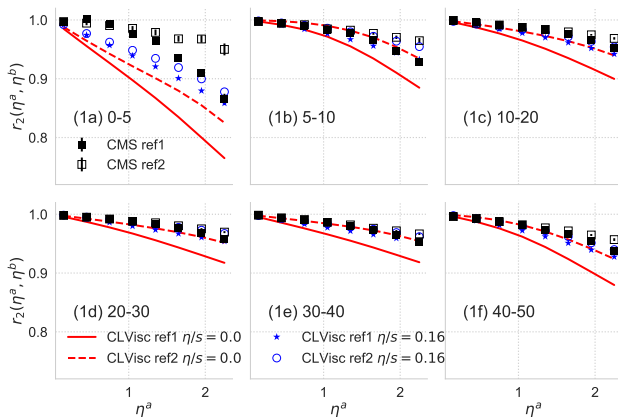


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The decorrelation functions with flow velocity at 2.76A TeV

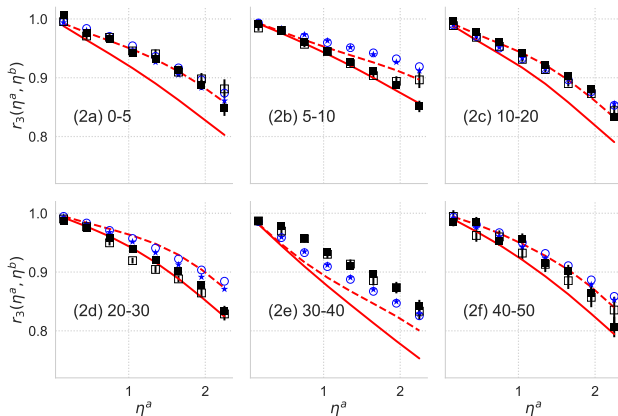


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For decorrelation functions $r[2,1]$, the decorrelation effects become larger due to the stronger short range correlations when the initial velocity is computed.

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