



Longitudinal decorrelations of anisotropic flow and γ -Jet induced rapidity even direct flow

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The 4th China LHC Physics Workshop

Outline

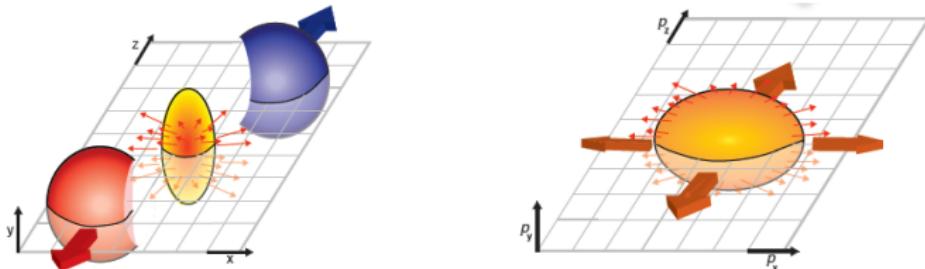


- Introduction
- Longitudinal decorrelations of anisotropic flows
- γ -Jet induced rapidity even direct flow
- Conclusion

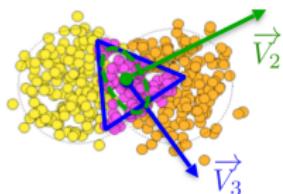


Longitudinal decorrelations of anisotropic flows

In collaboration with: Long-Gang Pang Guang-You Qin Xin-Nian Wang
Based on PhysRevC.98.024913



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

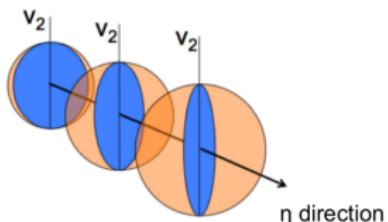
Many flow observables:

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

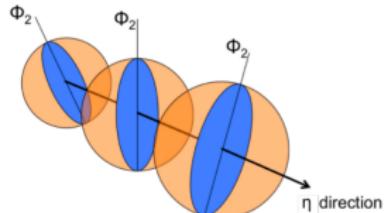
focus on fluctuations in the transverse plane.

Longitudinal fluctuations

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



(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)

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)]

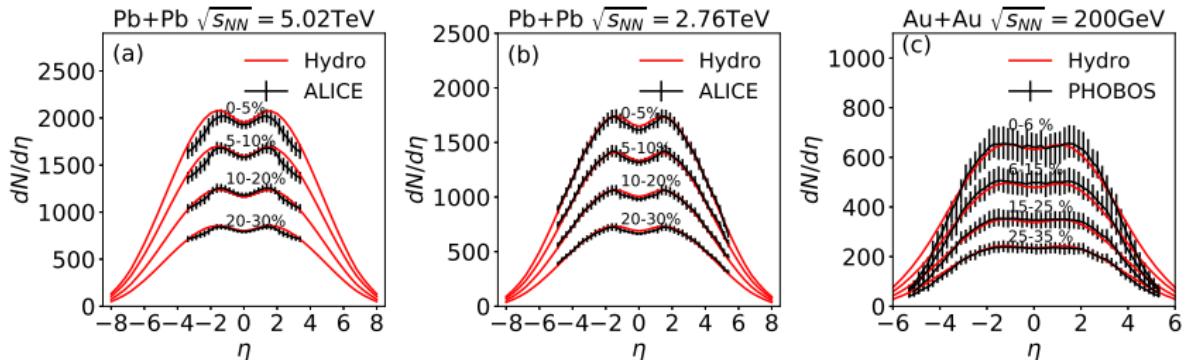
local energy-momentum tensor $T^{\mu\nu}$ at the initial proper time:

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

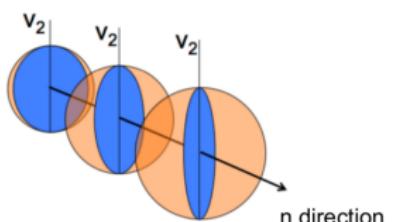
$\tau_0 = 0.2$ fm for LHC , 0.4fm for RHIC, $\sigma_r = 0.6$ fm $\sigma_{\eta_s} = 0.6$

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

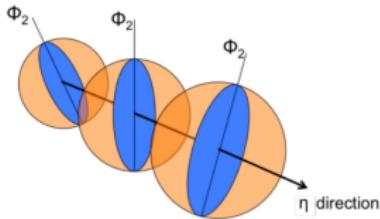
$$E \frac{dN_h}{d^3p} = \frac{g_h}{(2\pi)^3} \int_{\Sigma} p^\mu d^3\sigma_\mu f(p) \quad (2)$$



Longitudinal decorrelation observables

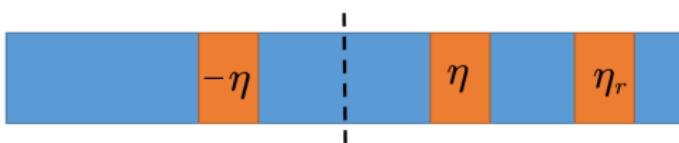


$$(c) q_2(\eta) \neq q_2(-\eta)$$



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

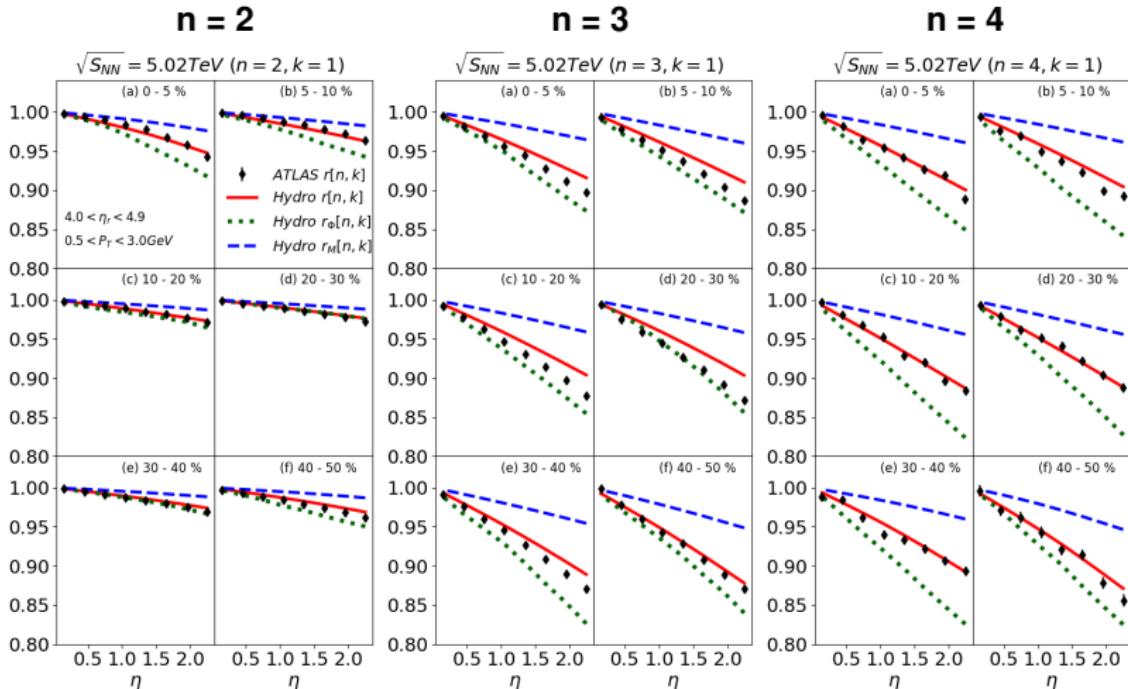
We use Q-vector method: $\mathbf{Q}_n(\eta) = q_n(\eta)\hat{Q}_n(\eta) = q_n(\eta)e^{in\Psi_n(\eta)} = \frac{1}{N} \sum_{i=1}^N e^{in\phi_i}$



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
$r_\Phi[n, k](\eta) = \frac{\langle \hat{Q}_n^k(-\eta) \hat{Q}_n^{*k}(\eta_r) \rangle}{\langle \hat{Q}_n^k(\eta) \hat{Q}_n^{*k}(\eta_r) \rangle}$	Decorrelation of flow orientations ³

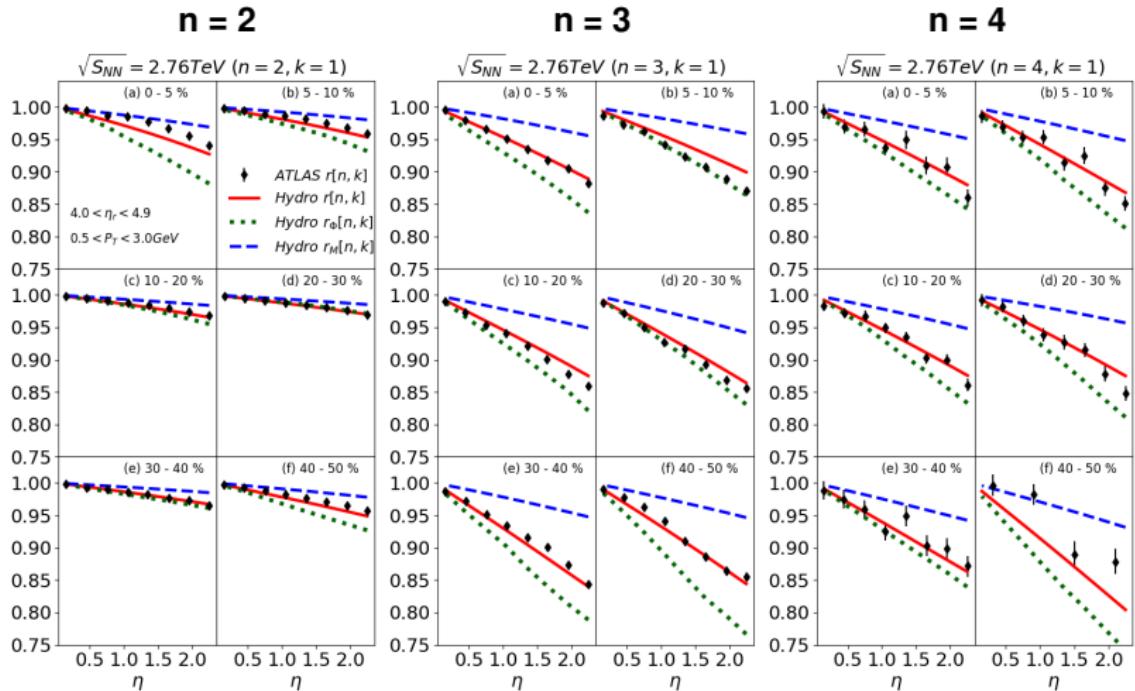
[1][CMS Collaboration (Khachatryan, Vardan et al.) Phys.Rev. C92 (2015)] [2][ATLAS Collaboration (Aaboud, Morad et al.) Eur.Phys.J. C78 (2018)]
[3][P.Bozek and W.Broniowski,(2017),arXiv:1711.03325.]

Longitudinal decorrelations in PbPb collisions at 5.02A TeV



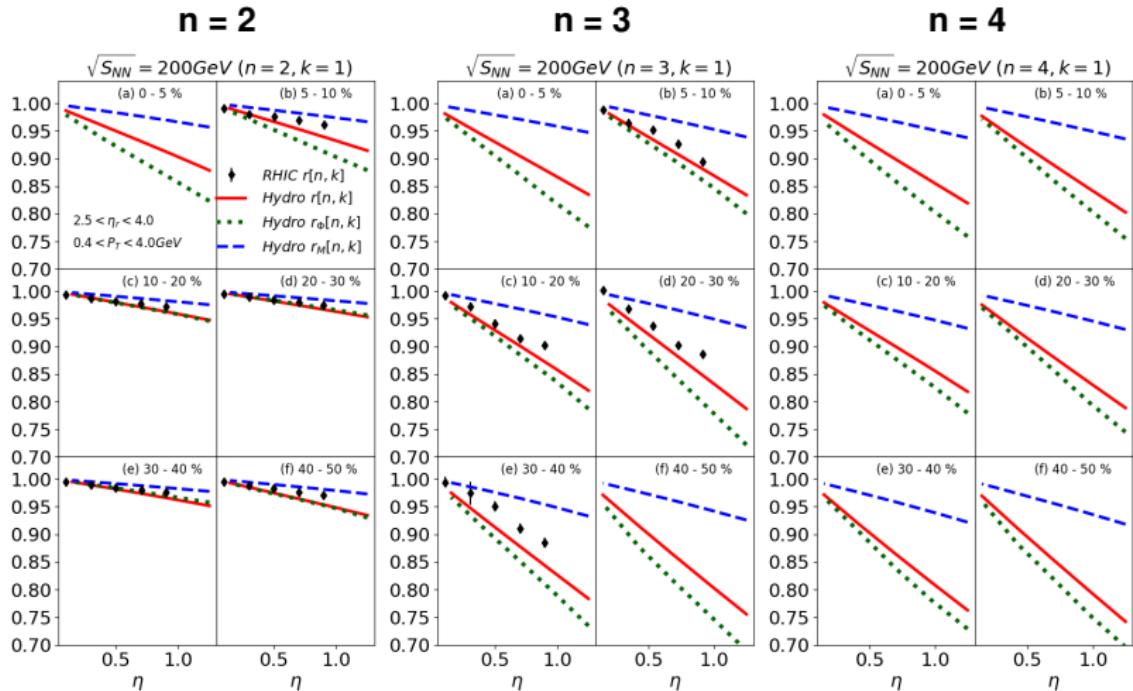
- The decorrelation functions are linear in η directions around midrapidity
- $r_\Phi[n, k] < r[n, k] < r_M[n, k]$

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 ($5.02\text{A TeV} < 2.76\text{A TeV}$)

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



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:

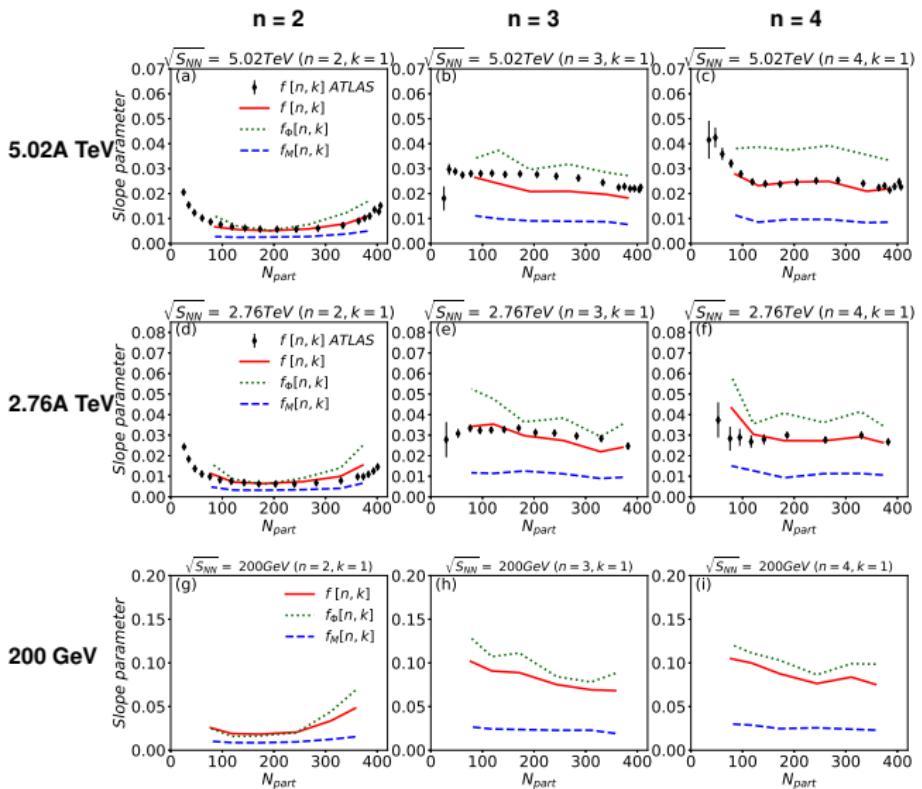
$$\begin{aligned} r[n, k](\eta) &\approx 1 - 2f[n, k]\eta \\ r_M[n, k](\eta) &\approx 1 - 2f_M[n, k]\eta \\ r_\Phi[n, k](\eta) &\approx 1 - 2f_\Phi[n, k]\eta \end{aligned} \tag{3}$$

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



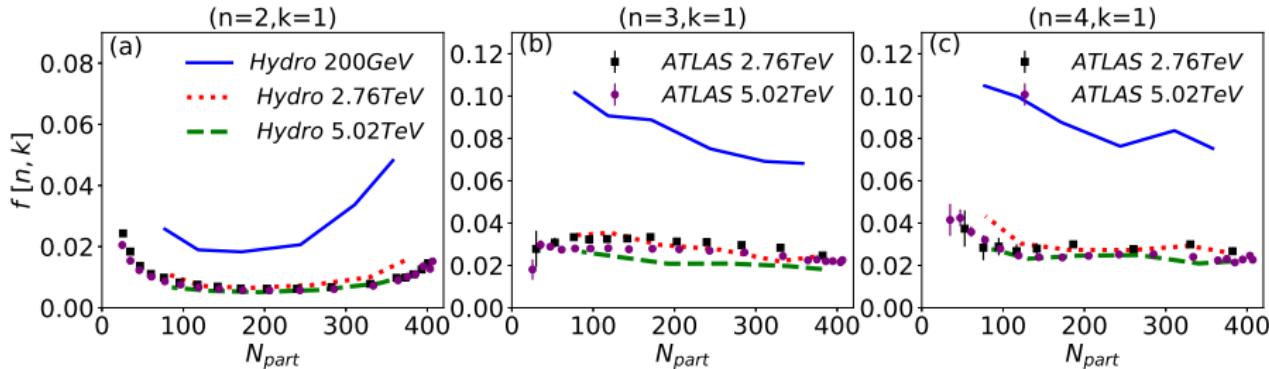
- $f_\Phi[n, k] > f[n, k] > f_M[n, k]$

- Decorrelation effects ($5.02\text{A TeV} < 2.76\text{A TeV} < 200\text{A GeV}$)

- 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:

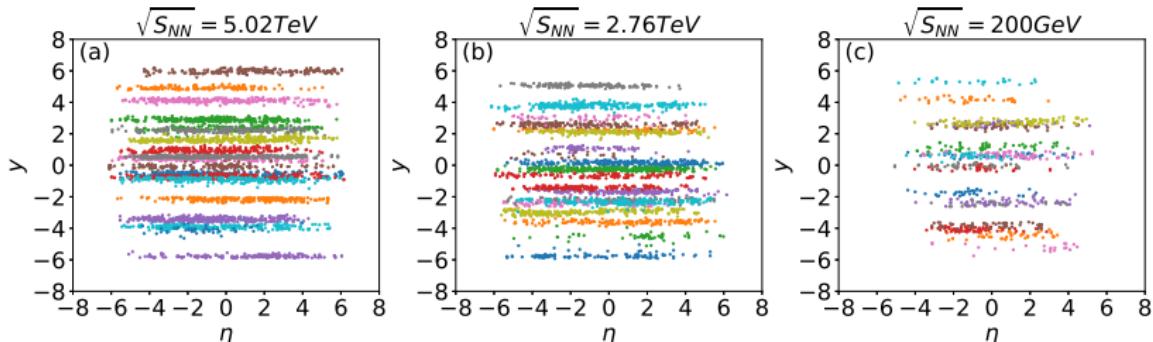
- $f(5.02\text{A TeV}) < f(2.76\text{A TeV}) \ll f(200\text{A GeV})$

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?

Longitudinal structure of initial states

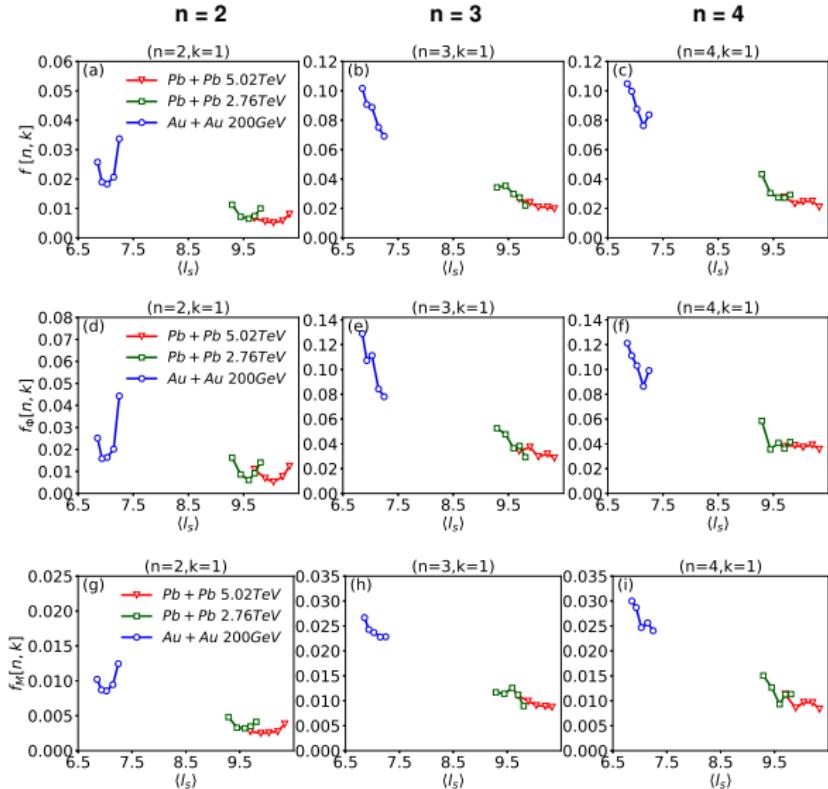


- ▶ Divide the initial partons into different clusters in transverse plane
- ▶ Arrange partons in the same cluster in the longitudinal direction to form a 'string'
- ▶ The length of each string is obtained from difference between the maximum and minimum rapidities of the initial partons in the same cluster.

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.



γ -Jet induced rapidity even direct flow

(CoLBT-hydro model)

In collaboration with: Wei Chen Long-Gang Pang Guang-You Qin Xin-Nian Wang

γ -Jet induced rapidity even direct flow

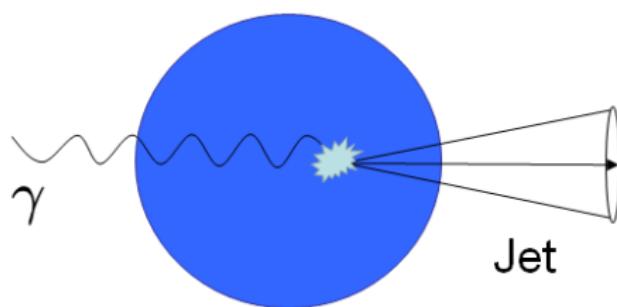
Directed flow^[1]: $\vec{v}_1 = \vec{v}_1^{odd} + \vec{v}_1^{even}$

\vec{v}_1^{odd} develops along the impact parameter direction, depends on rapidity

\vec{v}_1^{even} created by fluctuations in the initial geometry(dipole-like), weakly depends on rapidity

Event plane method: $v_1(p_t) = \langle \cos(\phi - \Psi_{EP}) \rangle$, $\Psi_{EP} = \tan^{-1} \frac{\sum_{|\eta|<1} w_i \sin \phi_i}{\sum_{|\eta|<1} w_i \cos \phi_i}$

Where weight^[2]: $w_i(p_t) = p_t - \frac{\langle p_t^2 \rangle}{\langle p_t \rangle}$



$$x_{j\gamma} = \frac{p_{T_{Jet}}}{p_{T_\gamma}}$$

quantify the γ -jets imbalance due to the Jet energy loss^[3,4]

How does γ -jet affects rapidity even direct flow?

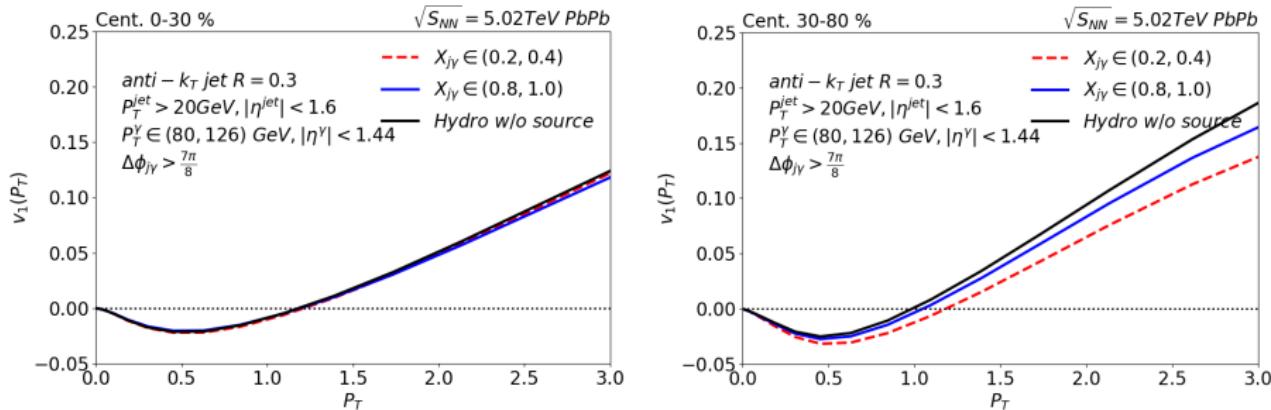
[1][STAR Collaboration (Adam, J. et al.) Phys.Lett. B784 (2018) 26-32 arXiv:1804.08647 [nucl-ex]]

[2][Gardim, Fernando G. et al. Phys.Rev. C83 (2011) 064901 arXiv:1103.4605 [nucl-th]]

[3][Phys.Lett. B785 (2018) 14-39 arXiv:1711.09738 [nucl-ex]]

[4][Chen, Wei et al. Phys.Lett. B777 (2018) 86-90 arXiv:1704.03648 [nucl-th]]

Rapidity even directed flow both $x_{j\gamma}$ and centrality dependence



- ▶ Central collision: γ -jets induced v_1^{even} is almost same, medium dominated
- ▶ Peripheral collision: γ -jets induced v_1^{even} has larger cross point, jet energy loss become more important



Conclusion

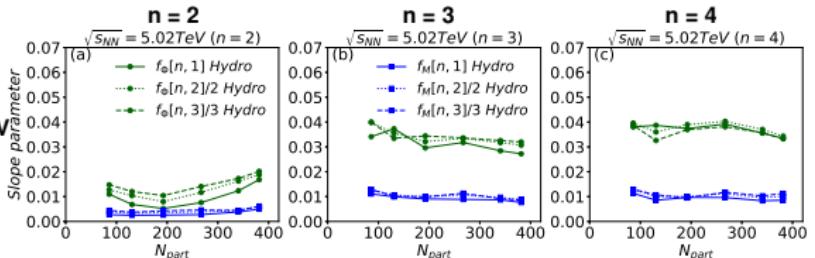
- ▶ We have performed detailed analysis for longitudinal decorrelation of v_2, v_3, v_4 for the LHC & RHIC energies.
- ▶ We find:
 - $f_\Phi[n, k] > f[n, k] > f_M[n, k]$
 - $f(5.02A \text{ TeV}) < f(2.76A \text{ TeV}) < f(200A \text{ GeV})$
- ▶ Centrality dependence:
 - v_2 decorrelation has a strong 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:
 $I_s(5.02A \text{ TeV}) > I_s(2.76A \text{ TeV}) > I_s(200A \text{ GeV})$.
- ▶ We have a brief study about γ -Jet induced even direct flow.
 - For **peripheral** collision, the jet energy loss will lead to **larger** even direct flow v_1



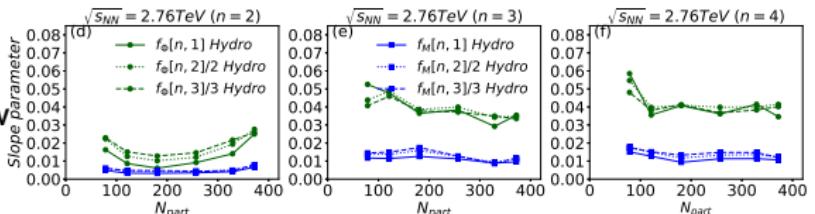
Back Up

Test of linearity of flow decorrelations

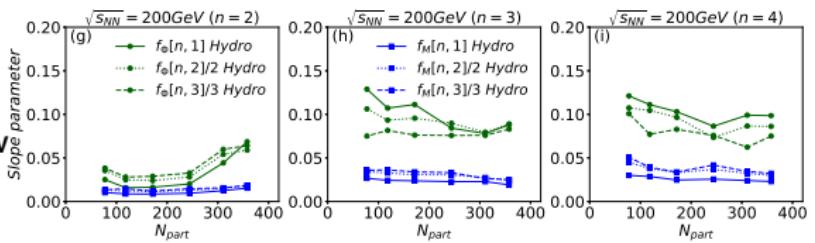
5.02A TeV



2.76A TeV



200A GeV

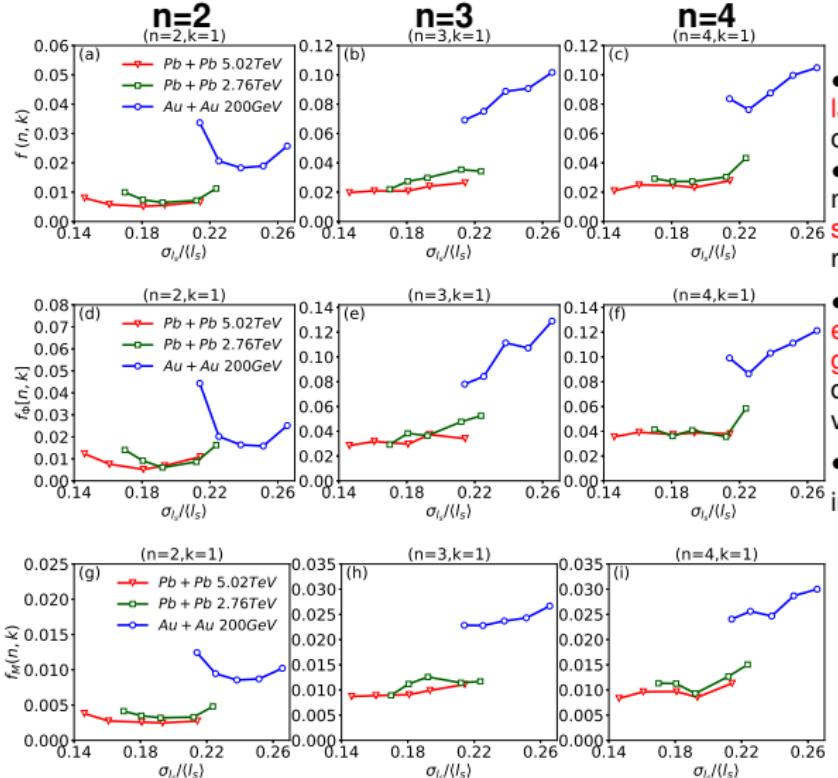


- Linear approximation works well at two LHC energy
- More breaking at RHIC energy than at LHC energy
- Linear approximation works better for flow magnitudes
- More breaking for flow orientations

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

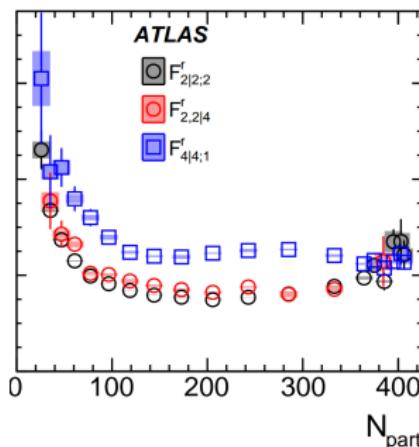
$$f_M[n, k]/k \approx f_M[n, 1]$$

Collision energy and centrality dependences



- Lower collision energy, larger 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 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

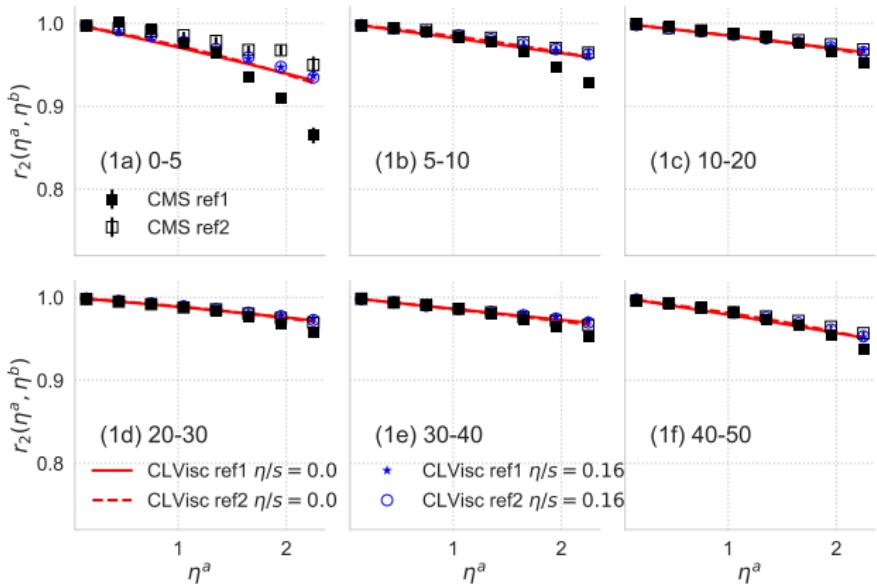


$$\begin{aligned}
 r_{2,2|4} &\approx \frac{\langle \vec{Q}_2^2(-\eta) \beta_{2,2} \vec{Q}_2^{*2}(\eta_{ref}) \rangle + \langle \vec{Q}_2^2(\eta_{ref}) \beta_{2,2} \vec{Q}_2^{*2}(-\eta) \rangle}{\langle \vec{Q}_2^2(\eta) \beta_{2,2} \vec{Q}_2^{*2}(\eta_{ref}) \rangle + \langle \vec{Q}_2^2(\eta_{ref})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

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

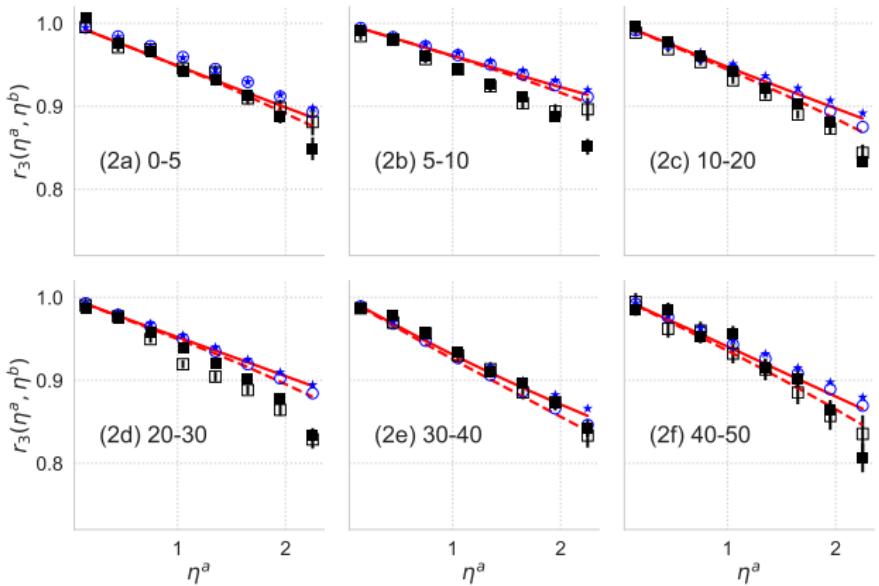


ref1: $3.0 < \eta < 4.0$ ref2: $4.4 < \eta < 5.0$

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]

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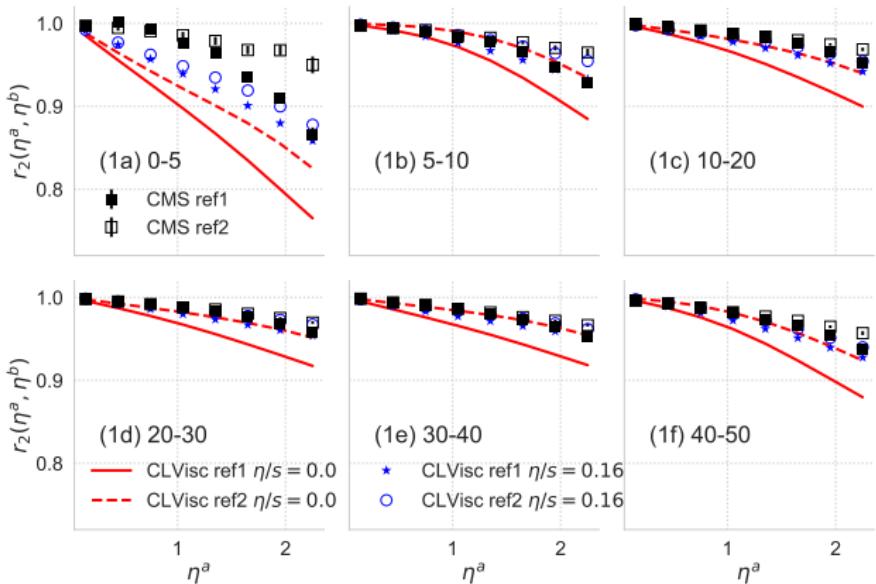


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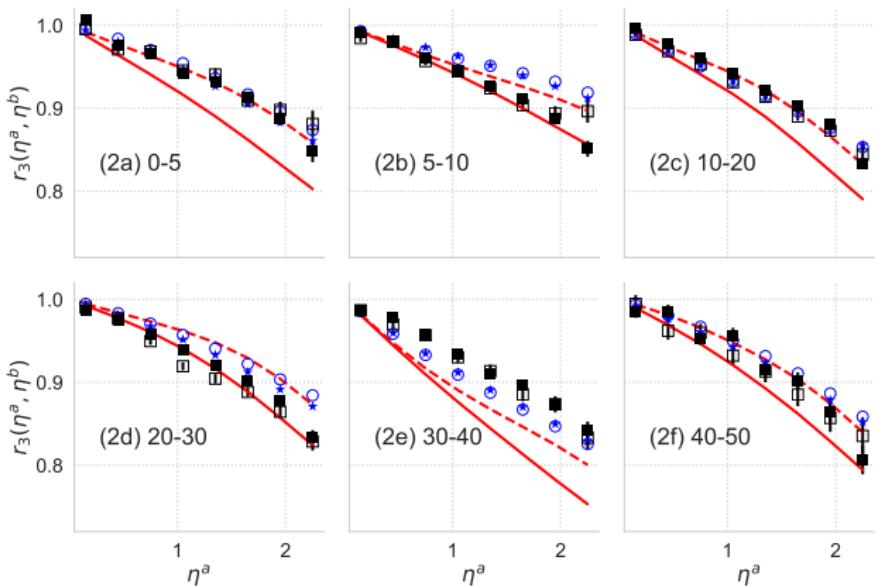


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For decorrelation functions $r[2,1]$, the decorrelation effects become larger due to the stronger short range correlations when the initial velocity is computed.

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

The decorrelation fuctions with flow velocity at 2.76A TeV



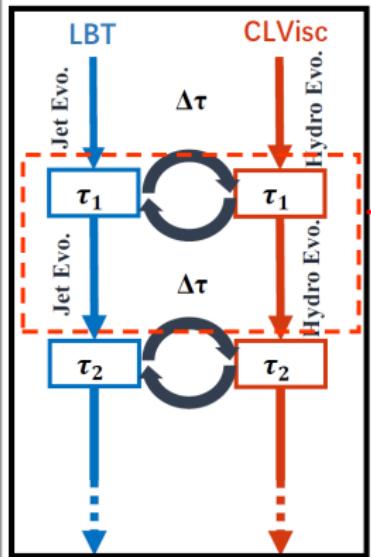
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CoLBT-hydro model



CoLBT-hydro model

Linear Boltzmann Transport model + 3+1D hydrodynamic model
(LBT) (CLVisc)

- ✓ formulated in Milne coordinates (τ, x_\perp, η_s)
- ✓ simulated in sync with each other

- ① provide medium info (T, u) to jet partons
- ② carry out jet shower partons' transport according to medium info.
- ③ soft($p \cdot u < p_{cut}^0$) and 'negative'($p \cdot u < 0$) partons deposited into medium as source term
- ④ hard($p \cdot u \geq p_{cut}^0$) partons propagate in LBT frame
- ⑤ update the medium info through solving
$$\partial_\mu T^{\mu\nu} = j^\nu$$

9



Hydrodynamic equations with source term

Assumption: Instantaneous local thermalization of deposited energy and momentum

Hydrodynamic equation with source term

$$\partial_\mu T_{QGP}^{\mu\nu}(x) = j_{jet}^\nu(x)$$

Energy-momentum
tensor of QGP fluid

Energy and momentum
deposited from jet

source term:

$$j_{jet}^\nu(x) = \sum_i \frac{\theta(p_{cut}^0 - p_i \cdot u) p_i^\nu}{\Delta\tau} \delta^3(\vec{x} - \vec{x}_i)$$

soft partons
($p \cdot u < p_{cut}^0$)

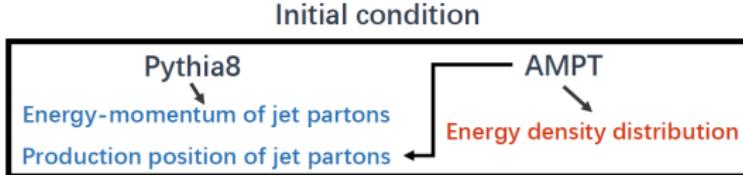
negative partons
($p \cdot u < 0$)

$$\text{Gaussian approximation: } \frac{\delta^3(\vec{x} - \vec{x}_i)}{\Delta\tau} \rightarrow \frac{1}{\tau \Delta\tau (2\pi)^{3/2} \sigma_r^2 \sigma_{\eta_s}^2} \exp\left[-\frac{(\vec{x}_\perp - \vec{x}_{\perp i})^2}{2\sigma_r^2} - \frac{(\eta_s - \eta_{si})^2}{2\sigma_{\eta_s}^2}\right]$$

10



Initial condition



AMPT:

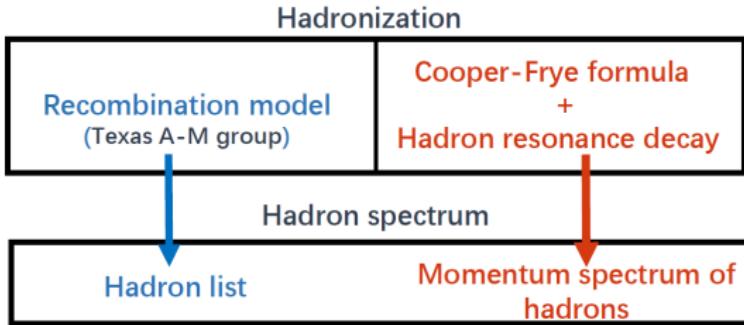
- ✓ Energy density distribution includes transverse and longitudinal fluctuation.
- ✓ Production positions of jet partons: sampled from spatial distribution of binary hard processes.

Pythia8:

- ✓ Energy-momentum of jet partons different in each event.



Hadronization



Not consider:

- ✓ Recombination between jet shower partons and thermal partons
- ✓ hadron cascade

12



Test of the linearity of flow decorrelations

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:

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

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

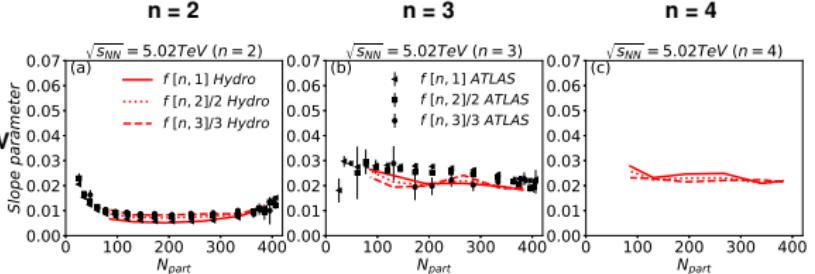
$$r_\Phi[n, k] \approx 1 - 2f_\Phi[n, k]\eta \quad f_\Phi[n, k] = k \frac{\langle \beta_n \sin(\delta_{n,k}) \rangle}{\langle \cos(\delta_{n,k}) \rangle}$$

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

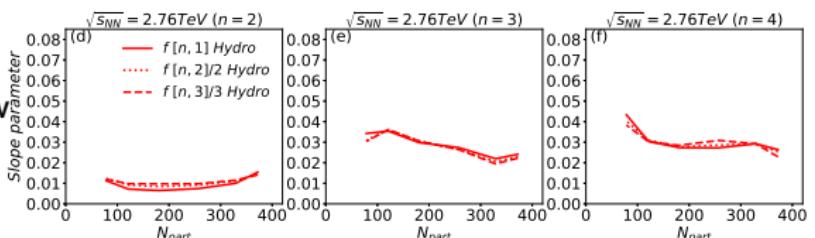
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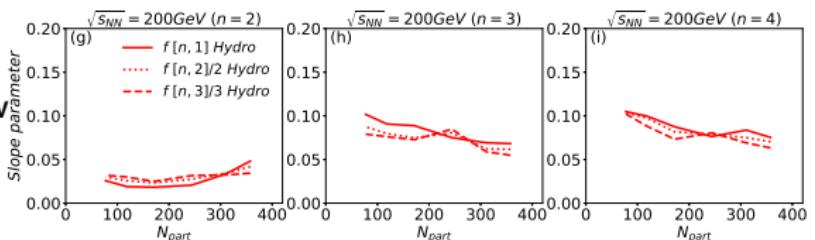
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- More breaking at RHIC energy than at LHC energy

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

2.76A TeV



200A GeV

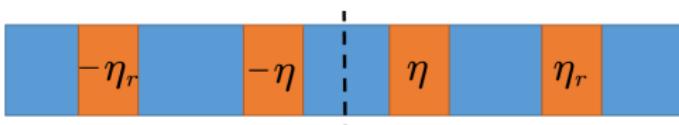


Four-rapidity-bin decorrelation observables

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 ATLAS 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**

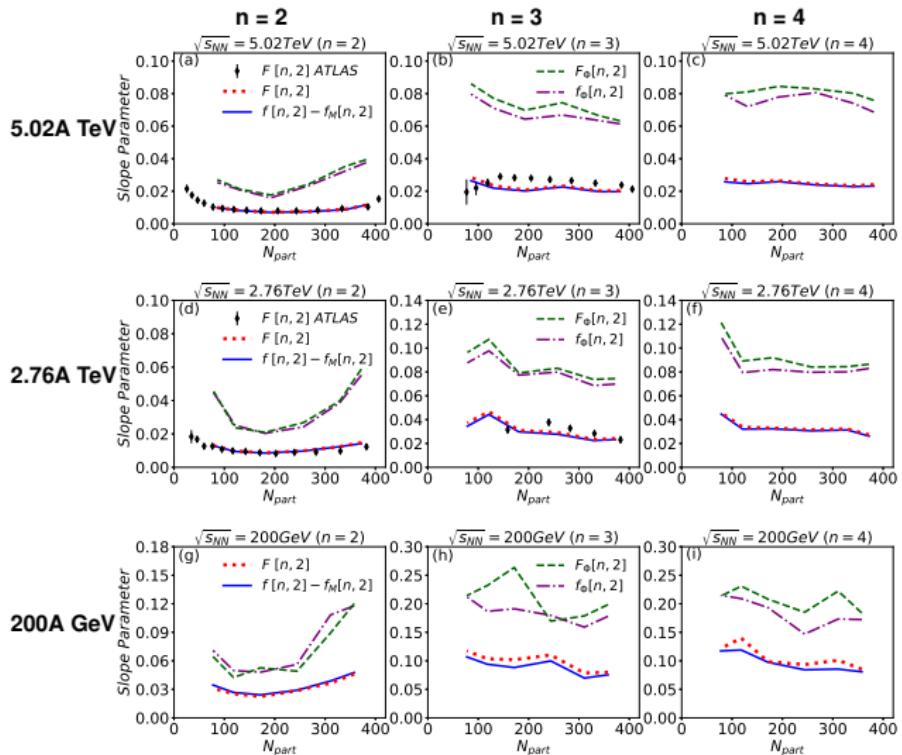
β_n : The **rotation** of the flow orientation

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

$$F[n, 2] \approx f[n, 2] - f_M[n, 2]$$

$$F_\Phi[n, 2] \approx f_\Phi[n, 2]$$

Four-rapidity-bin decorrelation observables



- $F[n, 2] \approx f[n, 2] - f_M[n, 2]$ 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 sizable violation due to the larger decorrelation effects for pure flow orientations
- Violation is larger at the RHIC than at the LHC