# Longitudinal fluctuations and decorrelations of anisotropic flows

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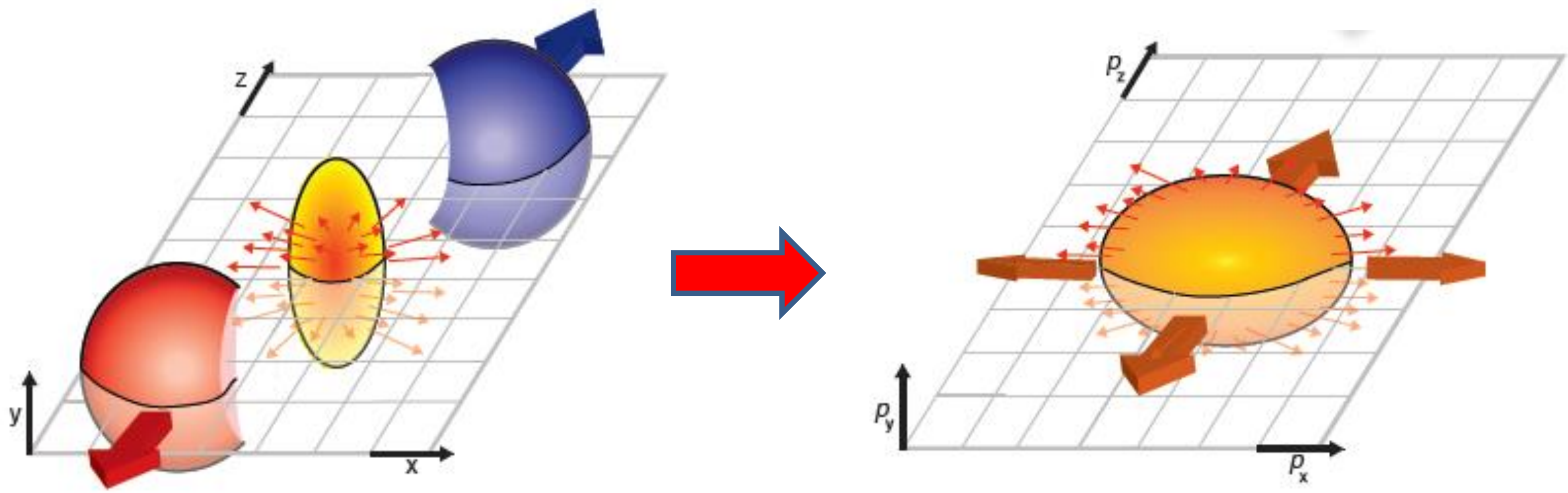
Based on Wu, Pang, GYQ, Wang, PRC 2018; etc.

# Outline

- Introduction
  - Initial state fluctuations and final anisotropic flows
- Model
  - (3+1)-dimensional viscous (ideal) hydrodynamics (CLVisc)
- Numerical results
  - Longitudinal decorrelations of $v_n$
  - Collision energy and centrality dependences
  - Longitudinal structures in the initial states
  - Small collision systems
- Summary

# Flow and sQGP

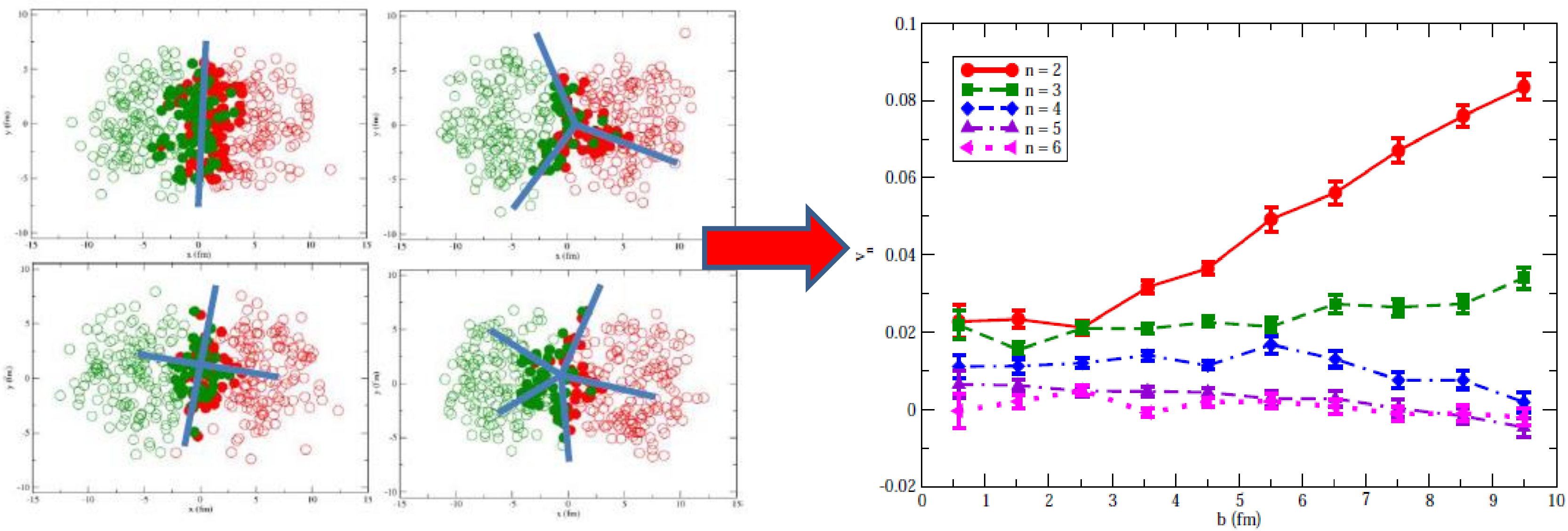
- The interaction among QGP constituents translates initial state geometric anisotropy to final state momentum anisotropy.




- Relativistic hydrodynamics has been very successful in describing medium evolution and collective flows. => strongly-coupled QGP

# IS fluctuations and FS flows

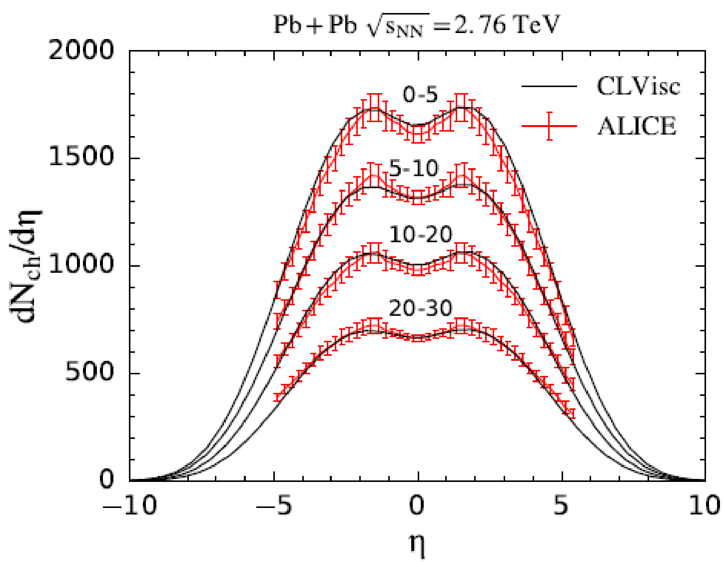
- **Event-by-event initial state density and geometry fluctuations play an important role in understanding final state anisotropic flows.**

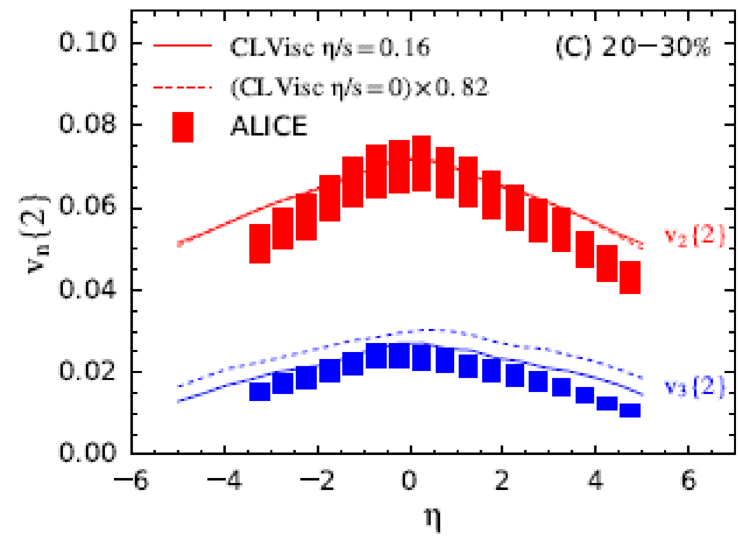



- **Many flow observables (high-order $v_n$, $v_n$ fluctuations, $v_n$ & $\Phi_n$ correlations, symmetric cumulants, non-linear response, etc) focus on the fluctuations in the transverse directions.**

# Longitudinal fluctuations

- The initial states are fluctuating also in longitudinal (rapidity) directions



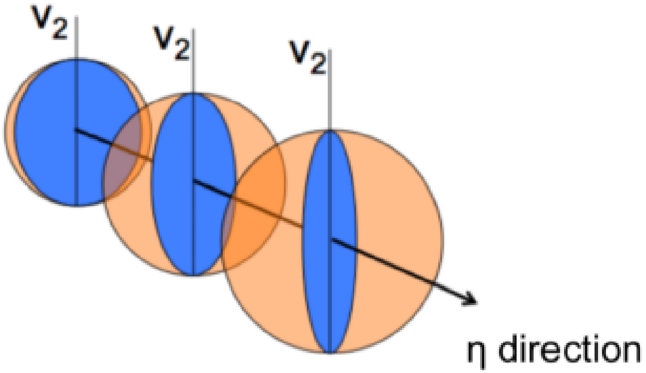




- Longitudinal fluctuations can lead to rapidity-dependent particle yield and $v_n$
- The rapidity dependence of $v_n$ may be used to probe the QGP properties

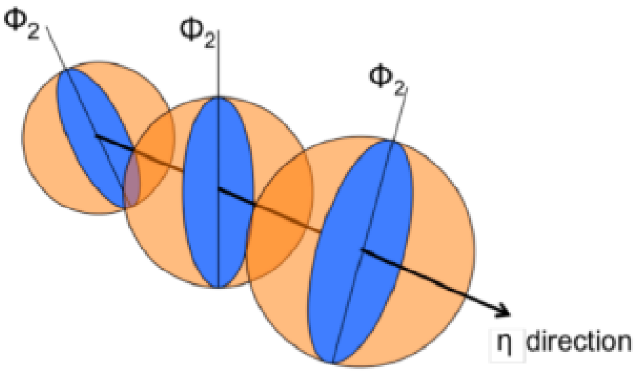
Gabriel et al. PRL 2016; Pang, Petersen, Wang PRC 2018

# Longitudinal fluctuations

- **Longitudinal fluctuations can also cause rapidity decorrelations (asymmetry) of $v_n$**




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




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

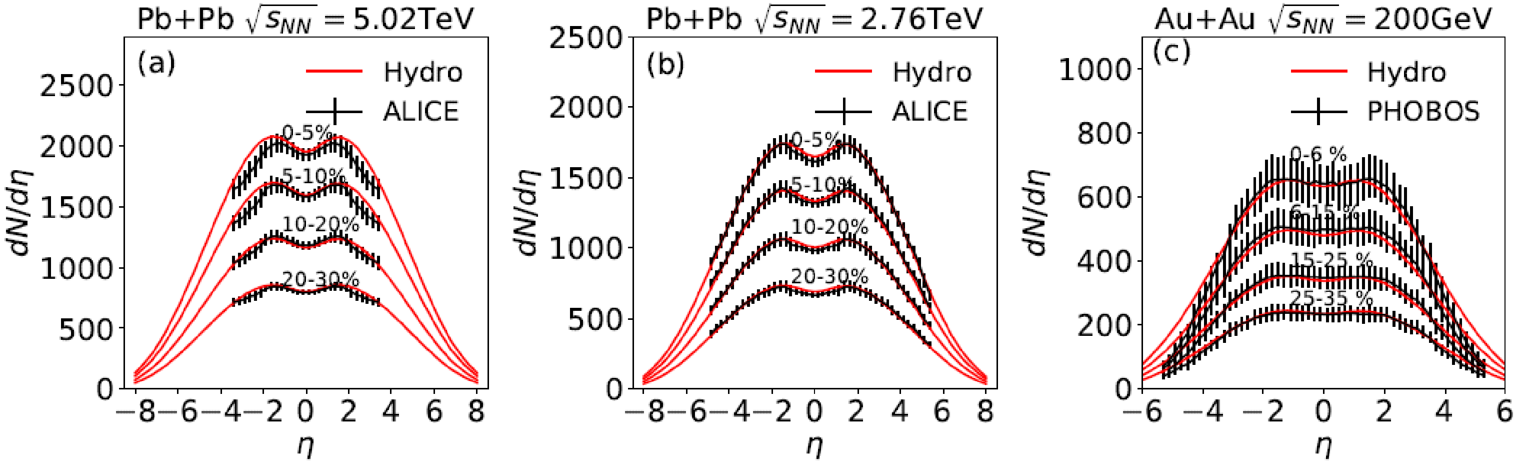
- **Our study: longitudinal decorrelations of anisotropic flows for different collision energy, centrality & systems, with different observables (flow vector, magnitude, orientations/angles)**

Jia, Huo, PRC 2014; CMS, PRC 2015; L.G. Pang et al, EPJA 2016; Jia et al, JPG 2017; ATLAS EPJC 2018; Bozek, Broniowski, PRC 2018

# Hydrodynamics model

- **CLVisc (ideal) (3+1)-D hydrodynamics model**
- **Initial condition: AMPT model**

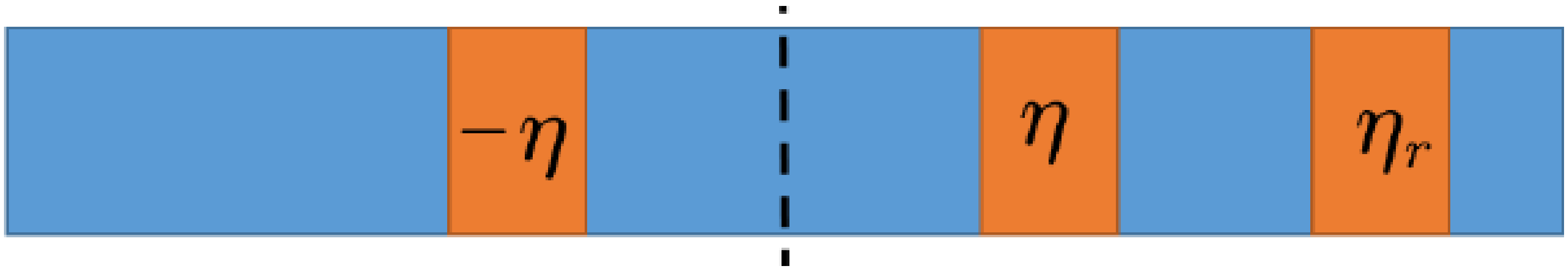
$$T^{\mu\nu}(\tau_0, x, y, \eta_s) = K \sum_i \frac{p_i^\mu p_i^\nu}{p_i^\tau} \frac{1}{\tau_0\sqrt{2\pi\sigma_{\eta_s}^2}} \frac{1}{2\pi\sigma_r^2} \times \exp\left[-\frac{(x-x_i)^2+(y-y_i)^2}{2\sigma_r^2} - \frac{(\eta_s-\eta_{si})^2}{2\sigma_{\eta_s}^2}\right]$$




- **$\tau_0$ (LHC) = 0.2fm/c, $\tau_0$ (RHIC) = 0.4fm, $\sigma_r$ = 0.6fm, $\sigma_\eta$ = 0.6, $T_f$ = 137MeV**

Pang, Wang, Wang, PRC 2012; Pang, Petersen, Wang PRC 2018;
Lin, Ko, Li, Zhang, Pal, PRC 2005

# Longitudinal decorrelations



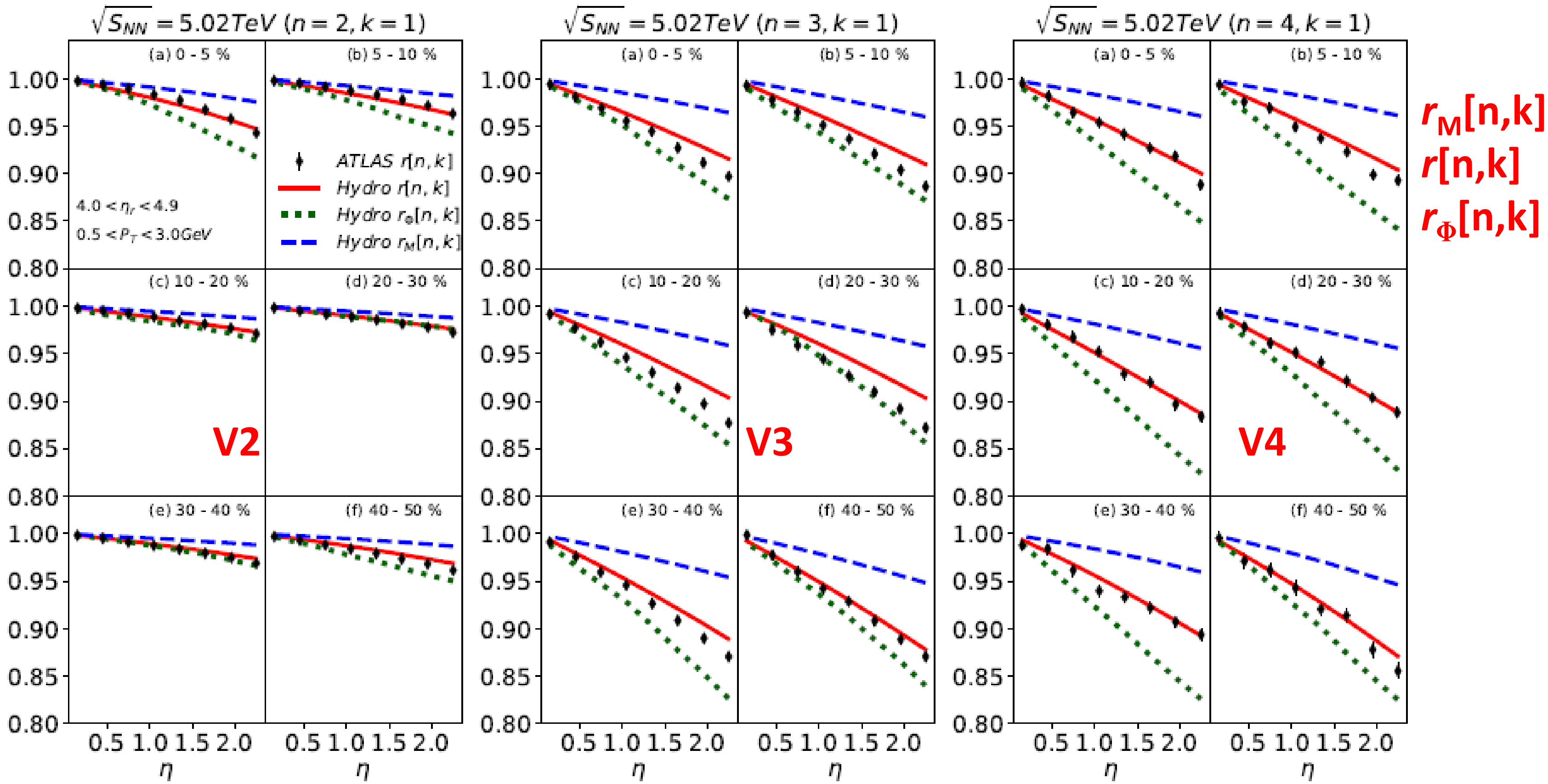

$$r[n,k](\eta) = \frac{\langle \mathbf{Q}_n^k(-\eta)\mathbf{Q}_n^{*k}(\eta_\mathrm{r})\rangle}{\langle \mathbf{Q}_n^k(\eta)\mathbf{Q}_n^{*k}(\eta_\mathrm{r})\rangle}$$

$$\mathbf{Q}_n(\eta) = q_n(\eta)\hat{Q}_n(\eta) = q_n(\eta)e^{in\Psi_n(\eta)} = \frac{1}{N}\sum_{i=1}^{N} e^{in\phi_i}$$

$$r_M[n,k](\eta) = \frac{\langle q_n^k(-\eta)q_n^k(\eta_\mathrm{r})\rangle}{\langle q_n^k(\eta)q_n^k(\eta_\mathrm{r})\rangle} \qquad r_\Phi[n,k](\eta) = \frac{\langle \hat{Q}_n^k(-\eta)\hat{Q}_n^{*k}(\eta_\mathrm{r})\rangle}{\langle \hat{Q}_n^k(\eta)\hat{Q}_n^{*k}(\eta_\mathrm{r})\rangle}$$

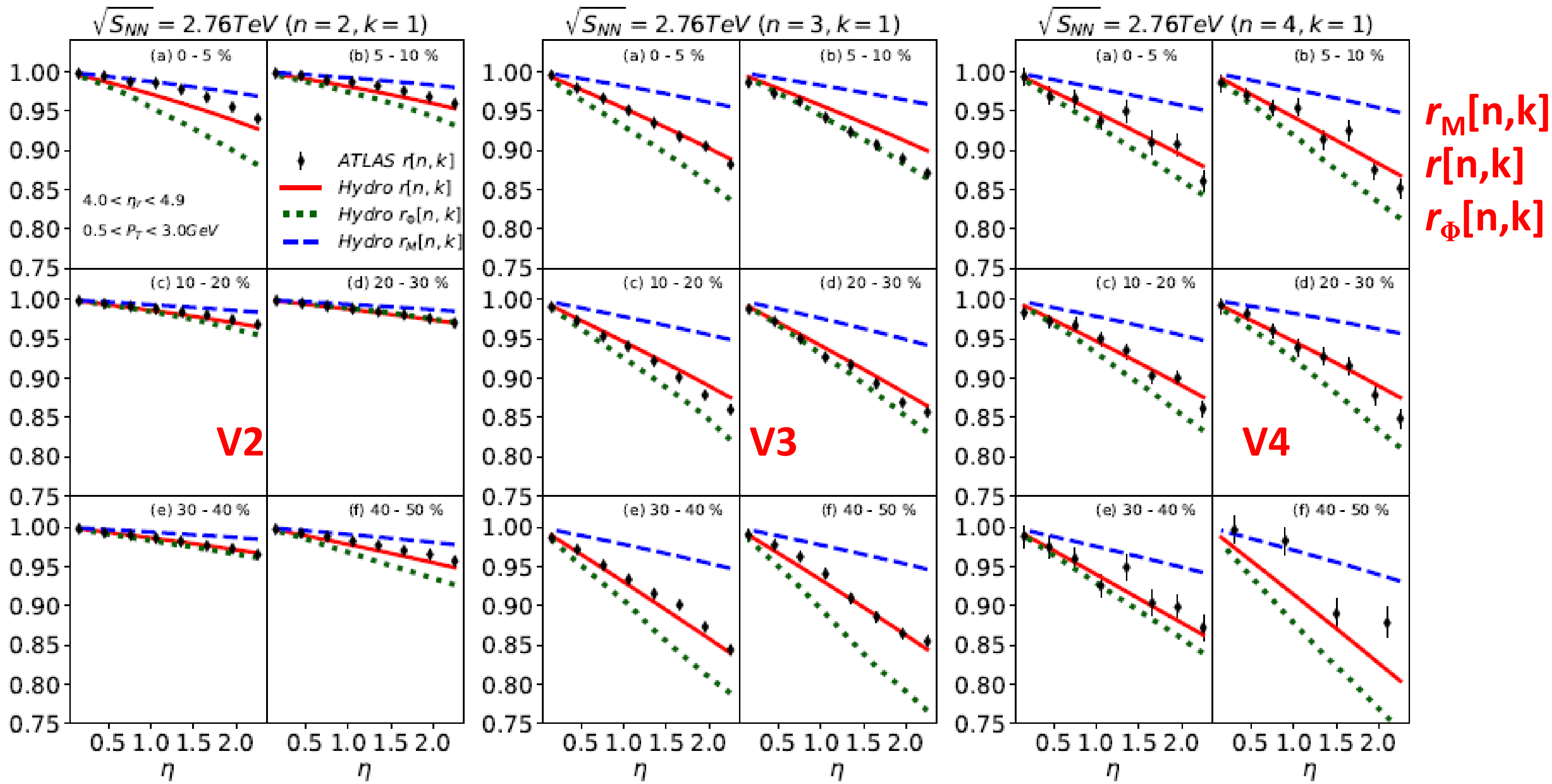
Jia, Huo, PRC 2014; CMS, PRC 2015; Jia et al, JPG 2017; ATLAS EPJC 2018; Bozek, Broniowski, PRC 2018

# Decorrelations in PbPb collisions @ 5.02TeV



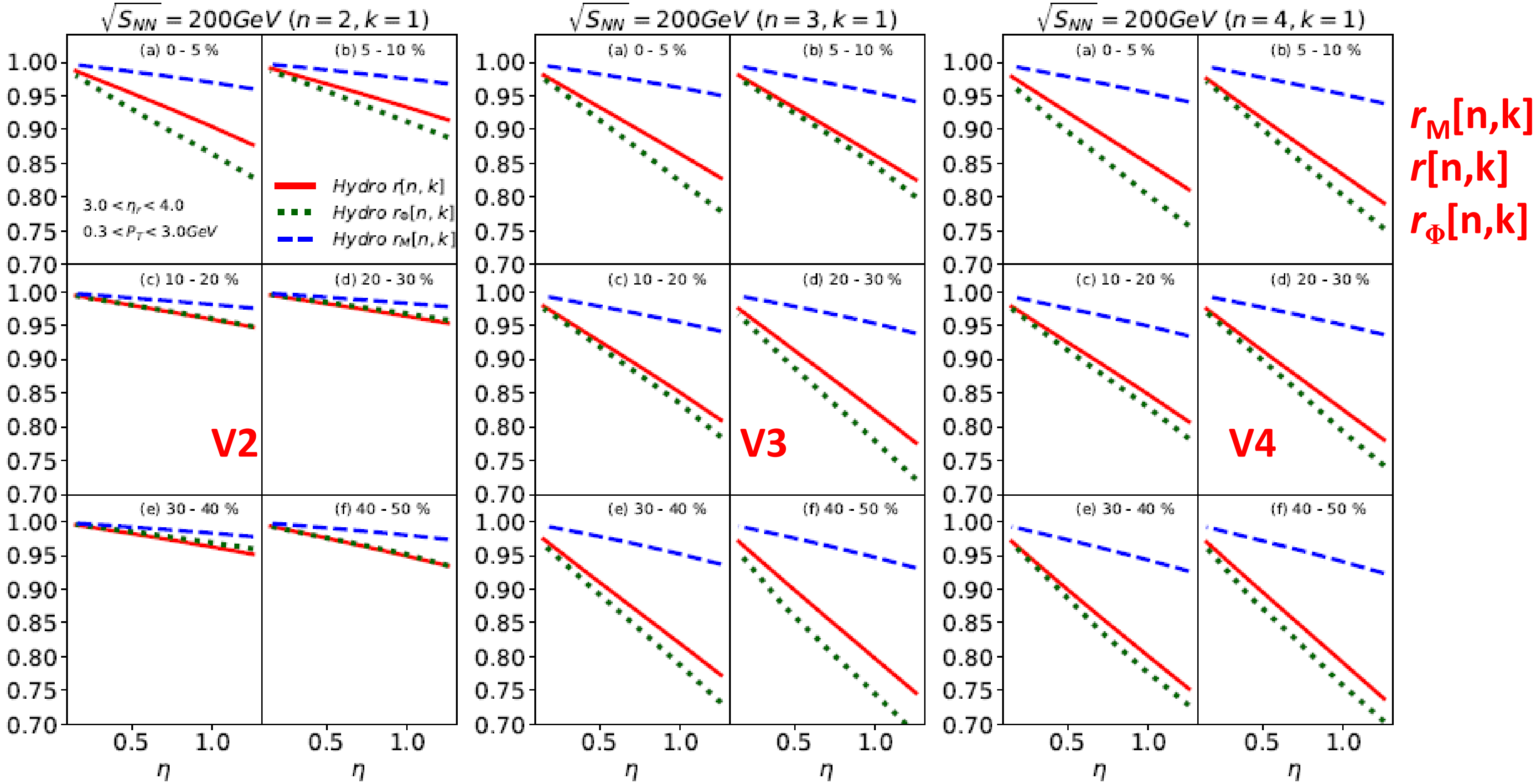

- **$r_{\Phi}$[n,k] < $r$[n,k] < $r_M$[n,k] (larger decorrelation effects for flow angles than flow magnitudes)**
- **Decorrelation funcitons are linear along $\eta$ around $\eta$ = 0**

# Decorrelations in PbPb collisions @ 2.76TeV




- $r_{\Phi}$[n,k] < $r$[n,k] < $r_M$[n,k] (larger decorrelation effects for flow angles than flow magnitudes)
- Decorrelation funcitons are linear along $\eta$ around $\eta$ = 0
- Decorrelation effects: [2.76TeV] > [5.02TeV]

# Decorrelations in AuAu collisions @ 200GeV




- $r_\Phi$[n,k] < $r$[n,k] < $r_M$[n,k] (larger decorrelation effects for flow angles than flow magnitudes)
- Decorrelation funcitons are linear along $\eta$ around $\eta$ = 0
- Decorrelation effects: [200GeV] > [2.76TeV] > [5.02TeV] (larger decorrelations for smaller energies)

# Slope parameters for longitudinal decorrelations

- **Linear parameterizations of decorrelation functions around $\eta$ = 0:**

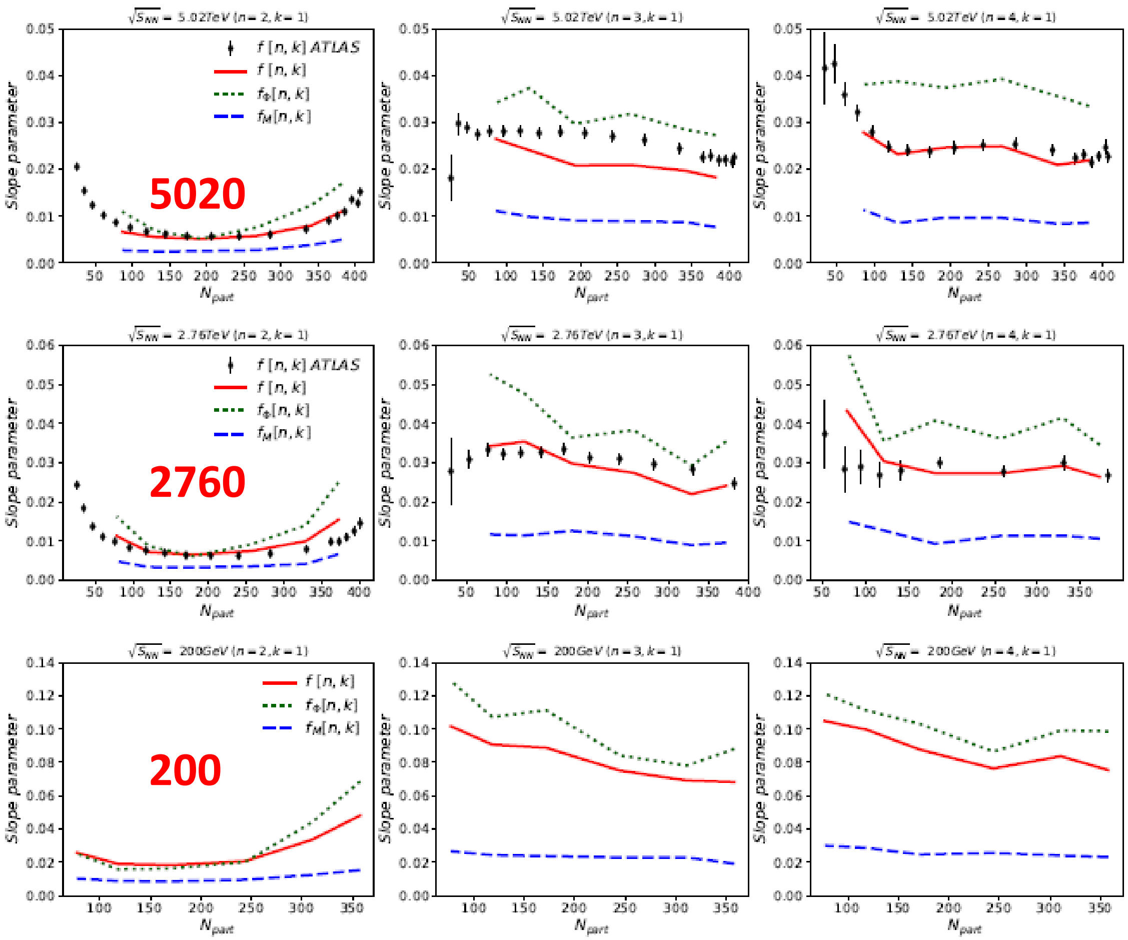
$$r[n,k](\eta) \approx 1 - 2f[n,k]\eta$$
$$r_M[n,k](\eta) \approx 1 - 2f_M[n,k]\eta$$
$$r_\Phi[n,k](\eta) \approx 1 - 2f_\Phi[n,k]\eta$$

- **The slope parameters can be measured via the following:**

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

- **The slope parameters probe similar information to decorelation functions: the larger values for f[n,k], larger decorrelation effects.**

# Slope parameters for longitudinal decorrelations




**Decorrelation functions:**

**$r_\Phi$[n,k] < $r$[n,k] < $r_M$[n,k]**

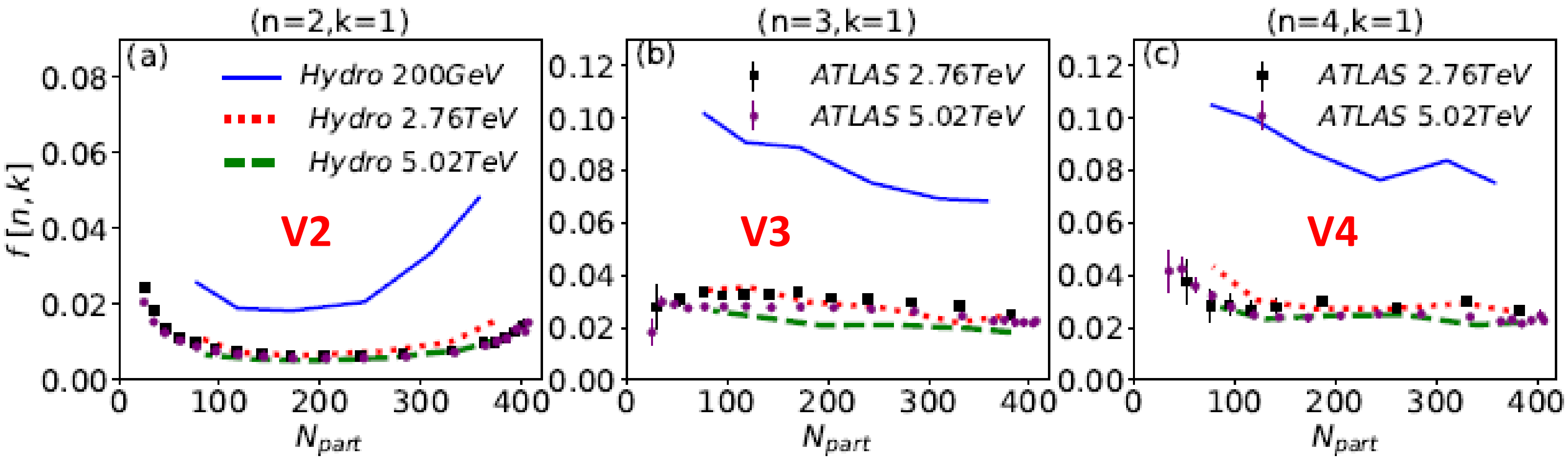
**Decorrelation effects:**

**f[200GeV] > f[2.76TeV] > f[5.02TeV]**

**For $v_2$, non-monotontic centrality dependence due to initial collision geometry**

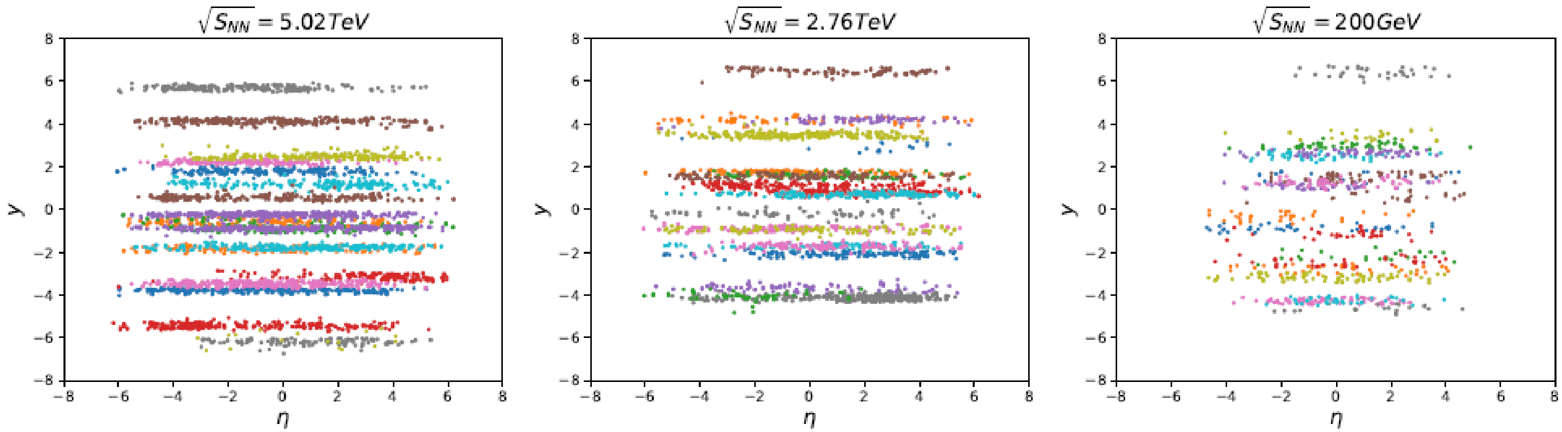
**For $v_3$ & $v_4$, weak centrality dependence, slight increase of decorrelation effects from central to peripheral collisions**

# Collision energy and centrality dependences



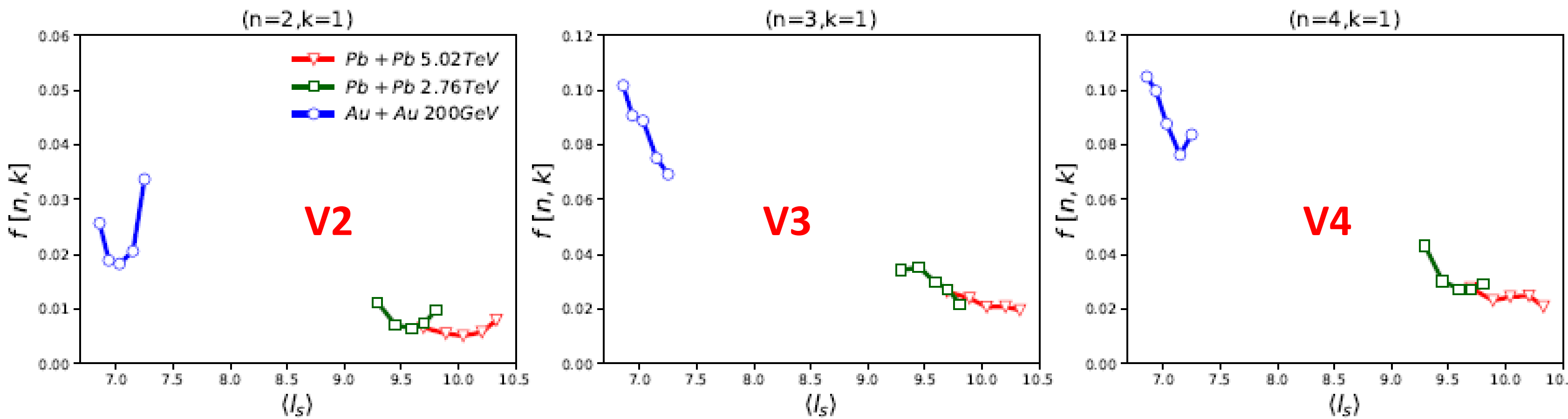

- Decorrelation effects: f[200GeV] > f[2.76TeV] > f[5.02TeV]
- For $v_2$, non-monotontic centrality dependence due to initial collision geometry.
- For $v_3$ & $v_4$, weak centrality dependence, slight increase of decorrelation effects from central to peripheral collisions.
- Where do these interesting patterns come from?

# Longitudinal fluctuations in initial states



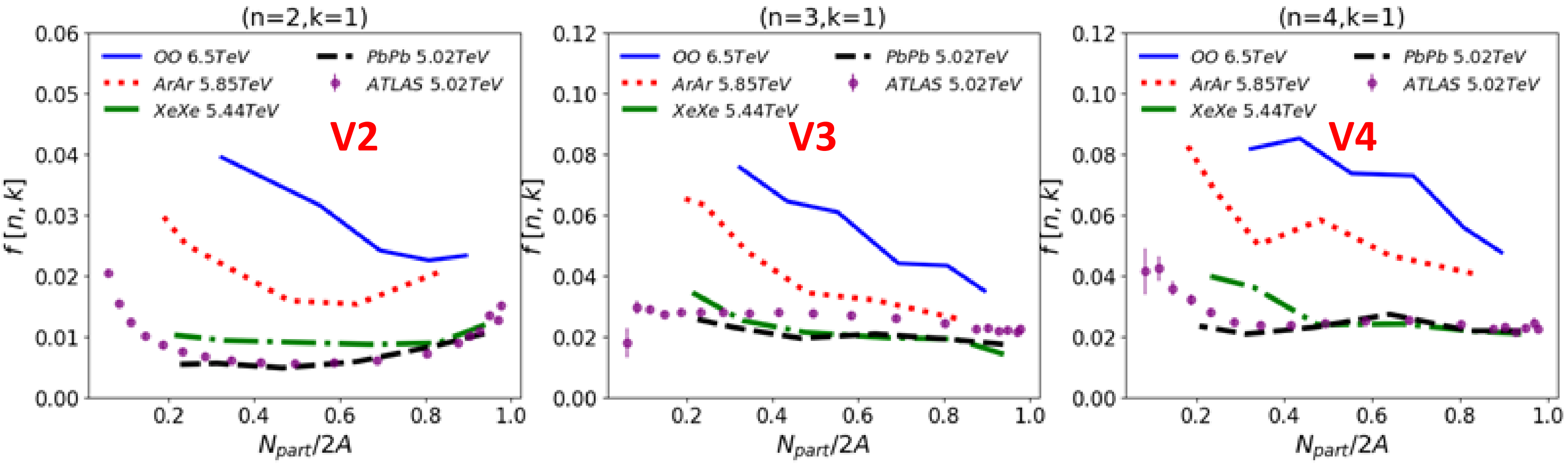

- **Divide initial partons into clusters according to their transverse positions.**
- **Partons in the same cluster are arranged in longitudinal direction according to their rapidities to form a string-like object.**
- **The length of each string is estimated using the difference between maximum & minimum rapidities of initial patrons in the same cluster.**
- $L_s$**[200GeV] <** $L_s$**[2.76TeV] <** $L_s$**[5.02TeV]**

# Dependence on collision energy, collision centrality and initial string lengths




- **f[200GeV] > f[2.76TeV] > f[5.02TeV]**
- **$L_s$[200GeV] < $L_s$[2.76TeV] < $L_s$[5.02TeV]**
- **Given collision energy, the string lengths are longer for more central collisions.**
- **$v_2$ decorrelation depends on both string lengths and collision geometry.**
- **$v_3$ & $v_4$ decorrelations depend mainly on string lengths.**

# Small collision systems

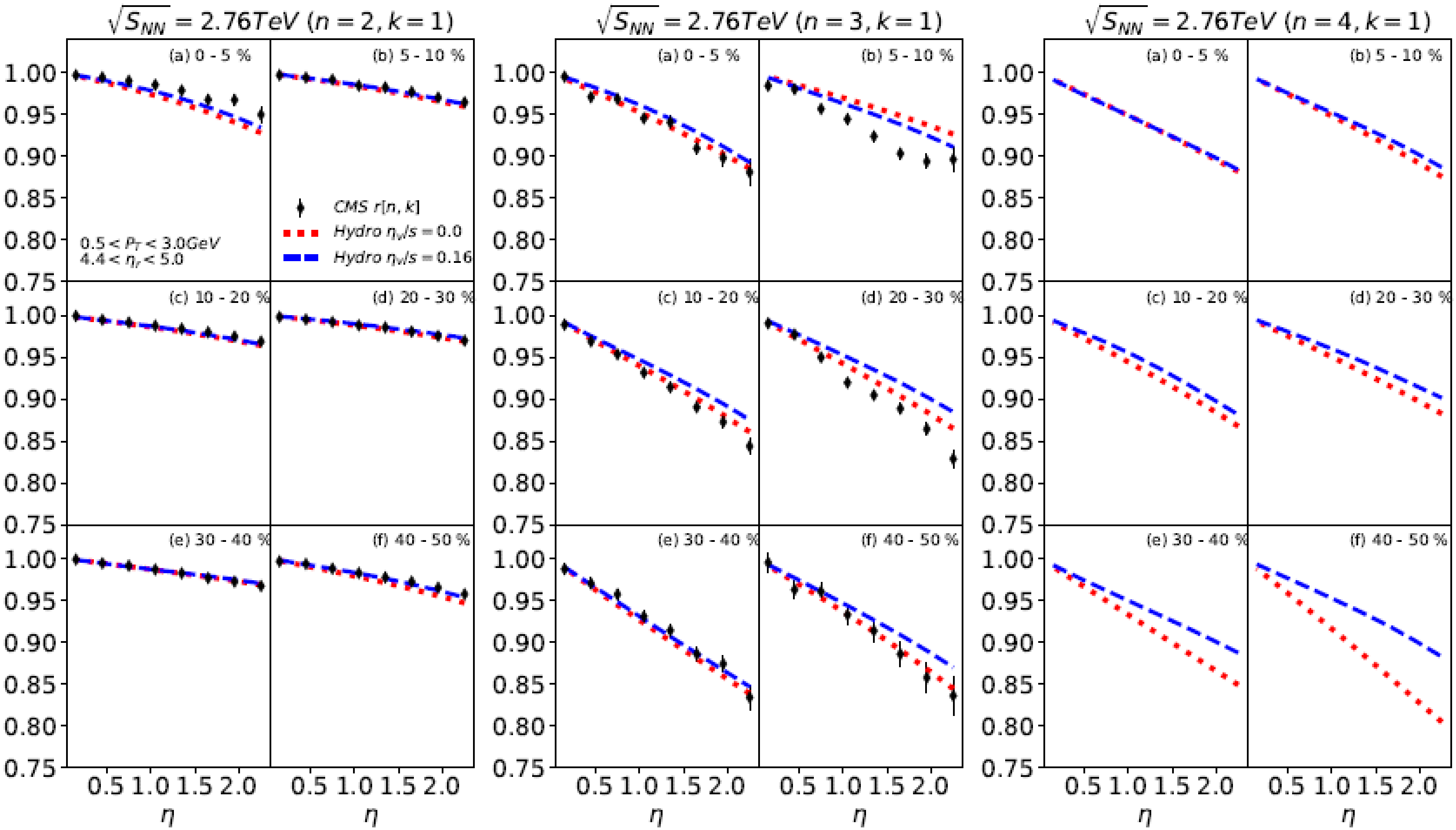



- The decorrelation effects are larger for smaller collision systems
- f[OO] > f[ArAr] > f[XeXe] > f[PbPb]
- The decorrelation effects are typically larger for more peripheral collisions
- $v_2$ decorrelation has some dependence on initial collision geometry

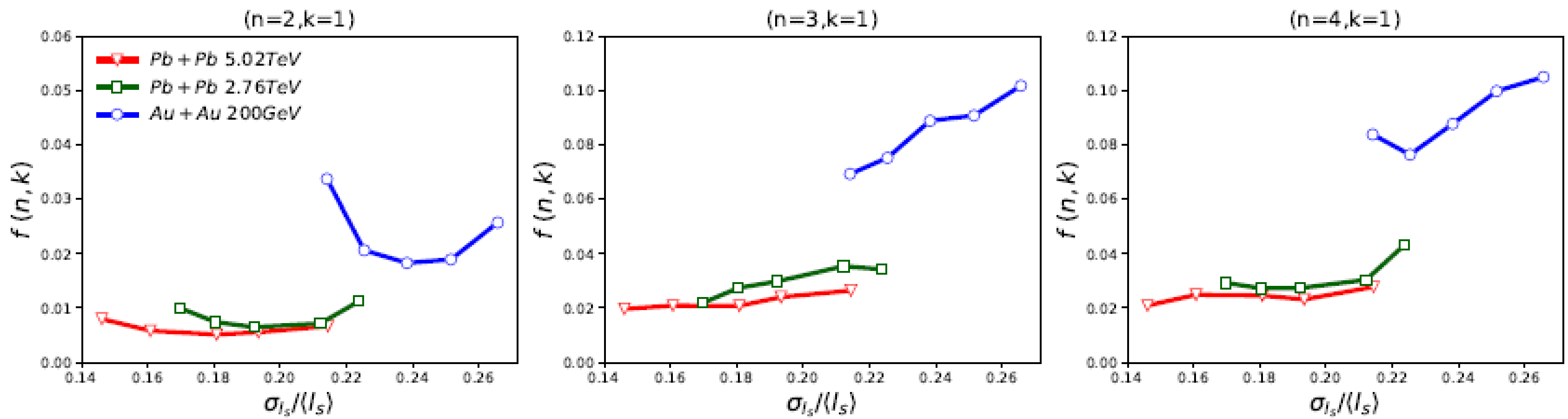
# Conclusions

- **Detailed analysis on longitudinal decorrelations of $v_n$ at RHIC & LHC**
  - **Decorrelation funtions: $r_\Phi$[n,k] < $r$[n,k] < $r_M$[n,k]**
  - **Slope parameters (decorrelation effects): f[200GeV] > f[2.76TeV] > f[5.02TeV]**
  - **For $v_2$, non-monotontic centrality dependence due to collision geometry**
  - **For $v_3$ & $v_4$, weak centrality dependence, slight increase of decorrelation effects from central to peripheral collisions**
- **The collision energy dependence of $v_n$ decorrelations can be traced back to the longitudinal structures of initial states (string lengths in AMPT)**
  - **$L_s$[200GeV] < $L_s$[2.76TeV] < $L_s$[5.02TeV]**
  - **f[200GeV] > f[2.76TeV] > f[5.02TeV]**
- **Larger longitudinal fluctuations for smaller collision systems**
  - **f[OO] > f[ArAr] > f[XeXe] > f[PbPb]**

# Viscous effect on longitudinal decorrelations



# Dependence on collision energy, collision centrality and initial string length fluctuations




- **The variance-to-mean-ratio of the string lengths is typically larger for lower collision energies and more peripheral collisions.**
- **For given collision energy, $v_2$, $v_3$ and $v_4$ decorreatlions typically increase with increasing variance-to-mean-ratio of the string lengths, but the pattern is more complex for $v_2$ decorrelation due to its dependence on collision centrality.**