p_T-dependent particle number fluctuations from PCA

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Based on: arXiv:1906.03045, to appear in Phys. Rev. C.

Objective

- Various methods to analyze flow devised before importance of event-by-event fluctuations was realized.
- New specific method: Principal Component Analysis.
  - Used in many fields of science.
  - Taylored to study fluctuations.
  - Bhalerao, Ollitrault, Pal & Teaney PRL 114 (2015) 152301.
- Here: compare hydro predictions with data.

Principal Component Analysis: $\rightarrow$ Covariance matrix

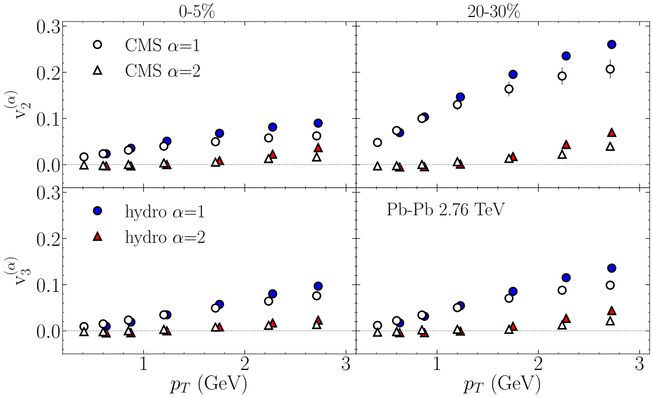
- Expand
  $\frac{dN}{dy dp_T d\phi} = \sum_{n=-\infty}^{+\infty} \mathcal{V}_n(p_T) e^{-in\phi}$
  $\mathcal{V}_n(p_T)$ Fourier coefficient (without the usual normalization by multiplicity)
- Construct, diagonilize and order (larger eigenvalue to smaller):
  $$\mathcal{V}_{n\Delta}(p_T^a, p_T^b) \equiv \langle \mathcal{V}_n(p_T^a) \mathcal{V}_n^*(p_T^b) \rangle - \langle \mathcal{V}_n(p_T^a) \rangle \langle \mathcal{V}_n^*(p_T^b) \rangle$$
  $$= \sum_\alpha \mathcal{V}_n^{(\alpha)}(p_T^a) \mathcal{V}_n^{(\alpha)}(p_T^b)$$
- Two to three principal components provide a good approximation.

Comparison hydro vs. data

- Hydro: NeXSPheRIO vs. Data: CMS in PRC96 (2017) 064902
- $v_n^{(\alpha)}(p_T) \equiv \frac{\mathcal{V}_n^{(\alpha)}(p_T)}{\langle \mathcal{V}_0(p_T) \rangle}$ scaled principal component

  $\alpha = 1 \rightarrow$ usual anisotropic flow

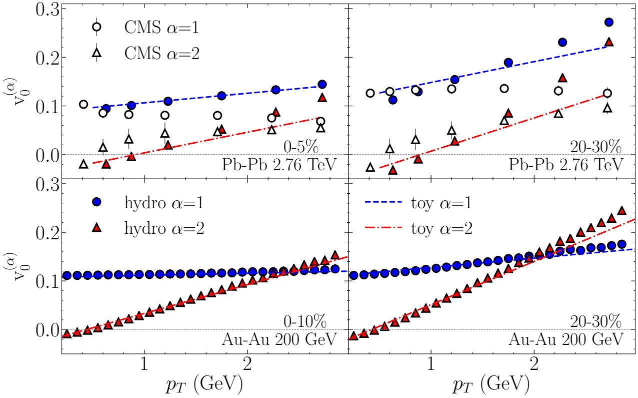
  $\alpha \geq 2 \rightarrow$ momentum dependence of flow fluctuations.
- n=2,3: good agreement (improved w/viscosity)



Comparison hydro vs. data/cont'd.

- n=0
- Leading component is independent of p_T in data but increases in simulation

  Leading component is also predicted to increase at RHIC (but less)



- Other hydro simulations have the same problem
- Such <u>qualitative</u> disagreement hydro-data is not commun

  Can we understand this?

Toy model for n=0 PCA

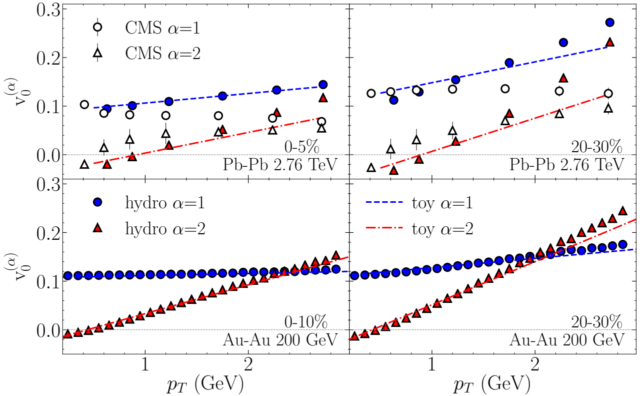
- Assume
  $\frac{1}{2\pi}\frac{dN}{dy dp_T} = \mathcal{V}_0(p_T) = \frac{2 p_T N}{\pi \bar{p}_T^2} e^{-\frac{2 p_T}{\bar{p}_T}}$
- Do
  $N = \langle N \rangle + \delta N$ and $\bar{p}_T = \langle \bar{p}_T \rangle + \delta \bar{p}_T$
- Covariance matrix can be diagonalized analytically

Toy model for n=0 PCA/cont'd

$$v_0^{(1)}(p_T) \simeq \frac{\sigma_N}{\langle N\rangle} + \left[\frac{-\left(\frac{\sigma_{p_T}}{\langle \bar{p}_T\rangle}\right)^2 + 2\frac{\langle \delta N \delta \bar{p}_T\rangle}{\langle N\rangle\langle \bar{p}_T\rangle}}{\left(\frac{\sigma_N}{\langle N\rangle}\right)}\right]\frac{p_T}{\langle \bar{p}_T\rangle}$$

$$v_0^{(2)}(p_T) \simeq -\frac{3}{2}\frac{\sigma_{p_T}}{\langle \bar{p}_T\rangle}\left(1-\frac{4}{3}\frac{p_T}{\langle \bar{p}_T\rangle}\right).$$

$\rightarrow$ Works well [values $\sigma_N/\langle N\rangle$, $\sigma_{p_T}/\langle \bar{p}_T\rangle$, $\langle \delta N \delta \bar{p}_T\rangle/(\langle N\rangle\langle \bar{p}_T\rangle)$ from hydro]



Toy model for n=0 PCA/cont'd

What we learn:

- $v_0^{(1)}(0) \simeq \frac{\sigma_N}{\langle N \rangle}$ well reproduced $\rightarrow$ mult. fluctuations correct in hydro
- $v_0^{(2)}(p_T)$ crossing independent of centrality in agreement with data
- $v_0^{(2)}(p_T) \propto \sigma_{p_T}/\langle \bar{p}_T \rangle$ (cf. Mazeliauskas & Teaney PRC 93 (2016) 024913)
- $v_0^{(1)}(p_T)$ increases in hydro $\rightarrow$ $N - p_T$ covariance too large $\rightarrow$ p_T fluctuations too large (see also Bozek & Broniowski PRC 85 (2012) 044910)
- Double-check: extract variances and covariance from CMS data and compare with hydro's

energy	centrality		$\frac{\sigma_N}{\langle N \rangle}$	$\frac{\sigma_{p_T}}{\langle \bar{p}_T \rangle}$	$\sqrt{\frac{\langle \delta N \delta \bar{p}_T \rangle}{\langle N \rangle \langle \bar{p}_T \rangle}}$
2.76 TeV	0-5 %	hydro	0.12	0.026	0.041
		CMS	*0.09*	*0.010*	*0.*
	20-30 %	hydro	0.16	0.041	0.070
		CMS	*0.13*	*0.019*	*0.020*
200 GeV	0-10 %	hydro	0.11	0.017	0.017
	20-30%	hydro	0.12	0.025	0.031

Indeed, CMS has smaller covariance and p_T variance.
PHENIX/STAR variances $\sim$ similar to hydro $\rightarrow$ n=0 PCA predictions good.

Summary and conclusion

- Hydro compared to CMS data:
  - $v_{2,3}^{(\alpha)}(p_T)$ reasonable
  - $v_0^{(1)}(p_T)$ incorrect: increases in hydro, $\sim$ constant in data
- Toy model:
  - reproduces well n=0 PCA from hydro
  - indicates $v_0^{(1)}(p_T)$ increase in hydro due to too large $N - p_T$ covariance and p_T fluctuations.
- Fluctuations in N and p_T have been studied in the past:
  - related QCD phase transition, geometry fluctuations
  - n=0 PCA may help.