Nontrivial subleading two-particle correlations in heavy-ion collisions

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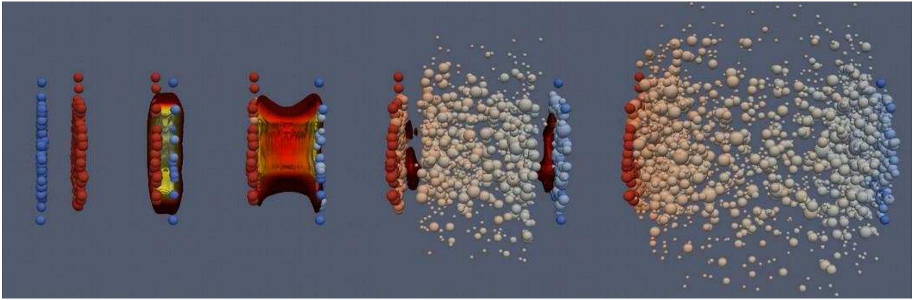
Introduction

- In **heavy-ion collisions**, a lot remains to be known about the **initial stages** of the system.
- Hydrodynamic expansion converts **initial geometry** to momentum-space **correlations**.
- **Principal Component Analysis** (PCA):
  Ultimate tool for characterizing **momentum-dependent** two-particle **correlations**.
- **PCA** analysis reveals **subleading** modes of **anisotropic flow**.

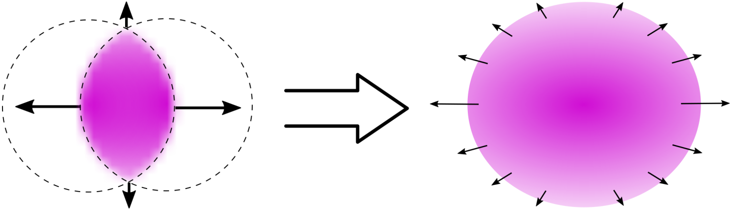
Heavy Ion Collisions



- Early stages, **expansion**, particlization, hadron dynamics.
- Pressure gradients ⇒ anisotropic flow ⇒ final-state correlations.

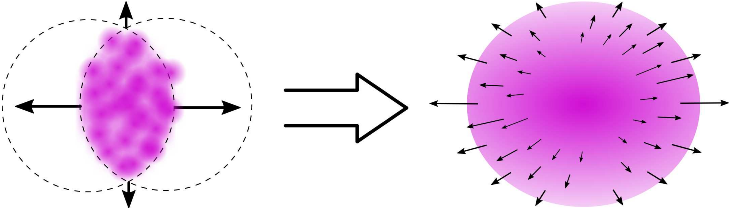
See G. Denicol's and J. Takahashi's talks.
Fig.: MADAI collaboration, H. Petersen, J. Bernhard.

Anisotropic flow



- Conversion of **initial geometry** to **momentum anisotropy**.
- Initial-state **fluctuations** $\Rightarrow$ azimuthal **correlations**.

Anisotropic flow



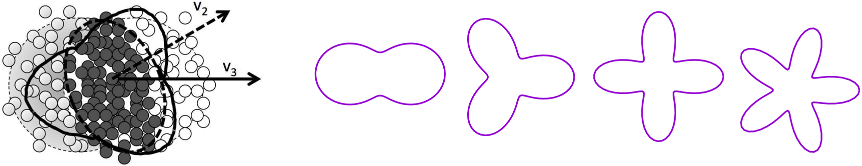
- Conversion of **initial geometry** to **momentum anisotropy**.
- Initial-state **fluctuations** ⇒ azimuthal **correlations**.
- **Small-scale** fluctuations ⇒ **momentum-dependent** correlations.

F. G. Gardim, F. Grassi, P. Ishida, M. Luzum, P. S. Magalhães and J. Noronha-Hostler, PRC **97** (2018)

Flow harmonics

Azimuthal distribution of particles in each event (momentum space):

$$\frac{dN}{p_T\, dp_T\, d\eta\, d\varphi} = \frac{1}{2\,\pi} \frac{dN}{p_T\, dp_T\, d\eta} \sum_{n=-\infty}^{\infty} V_n(p_T, \eta)\, e^{-in\varphi}\,. \qquad (1)$$



- Characterized by the **Fourier** coefficients, or flow **harmonics**.
- We are interested in $V_n(p_T)$ correlations.

Principal Component Analysis (PCA)

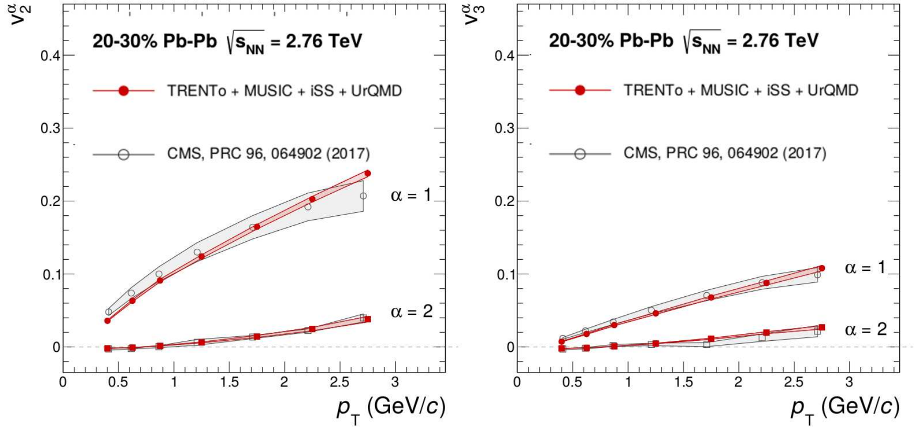
- General method to **isolate** uncorrelated **fluctuation modes**.
- **Spectral decomposition** of flow covariance matrix:

$$V_{n\Delta}(\mathbf{p}_1, \mathbf{p}_2) = \langle V_n(\mathbf{p}_1)\, V_n^*(\mathbf{p}_2) \rangle \simeq \sum_{\alpha=1}^{k} V_n^{(\alpha)}(\mathbf{p}_1) V_n^{(\alpha)}(\mathbf{p}_2)\,.$$

- Eigenvalues are **strongly ordered** $\Rightarrow$ truncation.
- Reveals **subleading** fluctuation **modes** for $\alpha > 1$.

R. S. Bhalerao, J. Y. Ollitrault, S. Pal and D. Teaney, PRL **114** (2015).

PCA modes for V_2 and V_3



T. Nunes da Silva, D. D. Chinellato, R. Derradi De Souza, MH, M. Luzum, J. Noronha and J. Takahashi, arXiv:1811.05048
A. M. Sirunyan *et al.* [CMS Collaboration], PRC **96** (2017).

Original PCA Proposal

- In practice, spectral decomposition of

$$V^N_{n\Delta}(\mathbf{p}_1, \mathbf{p}_2) = \langle N(\mathbf{p}_1)\, N(\mathbf{p}_2)\, V_n(\mathbf{p}_1)\, V_n^*(\mathbf{p}_2)\rangle\,. \quad (2)$$

- Only $\langle N(\mathbf{p}_1)\rangle\langle N(\mathbf{p}_2)\rangle$ is compensated by definition of $V_n^{N(\alpha)}$:

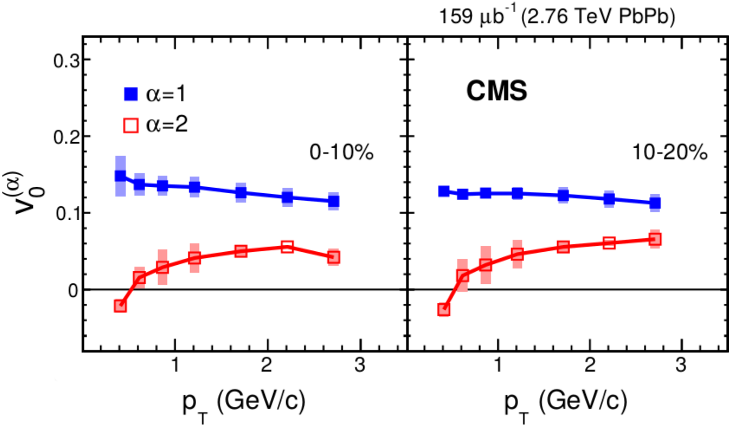
$$V^N_{n\Delta}(\mathbf{p}_1, \mathbf{p}_2) \simeq \sum_{\alpha=1}^{k} \langle N(\mathbf{p}_1)\rangle\langle N(\mathbf{p}_2)\rangle\, V_n^{N(\alpha)}(\mathbf{p}_1) V_n^{N(\alpha)}(\mathbf{p}_2) \quad (3)$$

- Multiplicity fluctuations can be retrieved from $n = 0$:

$$V^N_{0\Delta}(\mathbf{p}_1, \mathbf{p}_2) = \langle \Delta N(\mathbf{p}_1)\, \Delta N(\mathbf{p}_2)\rangle\,. \quad (4)$$

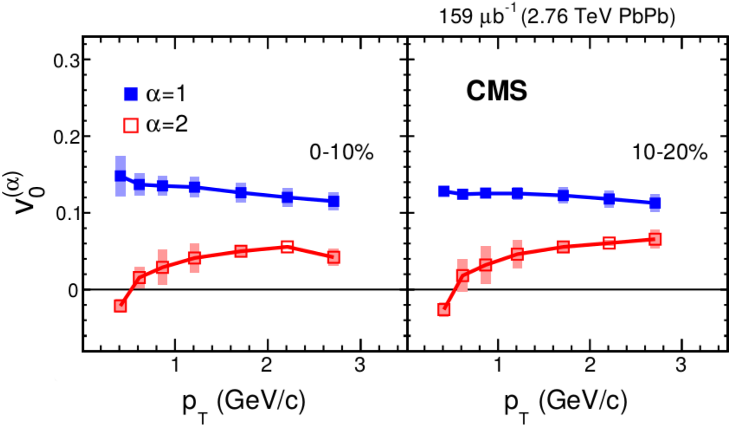
R. S. Bhalerao, J. Y. Ollitrault, S. Pal and D. Teaney, PRL **114** (2015).

Particle-number fluctuations



A. M. Sirunyan *et al.* [CMS Collaboration], PRC **96** (2017).
F. Gardim, F. Grassi, P. Ishida, M. Luzum and J. Y. Ollitrault, arXiv:1906.03045.

Particle-number fluctuations



Problem: particle-number fluctuations enter the other PCA modes.

Effects from multiplicity fluctuations

- Because of particle-number fluctuations,

$$V^N_{n\Delta}(\mathbf{p}_1, \mathbf{p}_2) \neq V_{n\Delta}(\mathbf{p}_1, \mathbf{p}_2) \tag{5}$$

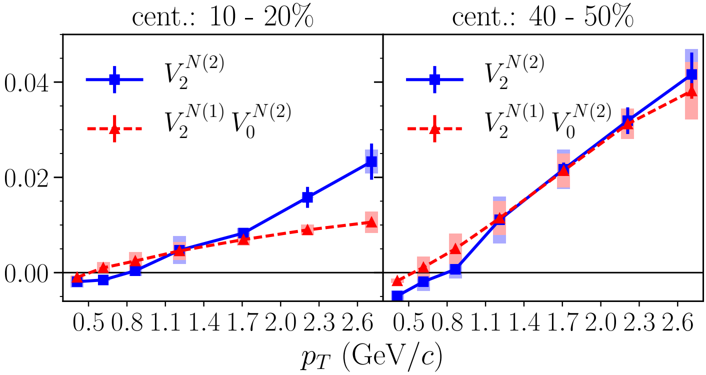
- Assuming multiplicity fluctuations factorize,

$$\begin{aligned} V^N_{n\Delta}(\mathbf{p}_1, \mathbf{p}_2) &= \langle N(\mathbf{p}_1)\, N(\mathbf{p}_2)\, V_n(\mathbf{p}_1)\, V_n^*(\mathbf{p}_2) \rangle \\ &\simeq \langle N(\mathbf{p}_1)\, N(\mathbf{p}_2) \rangle\, V_{n\Delta}(\mathbf{p}_1, \mathbf{p}_2) \end{aligned} \tag{6}$$

- Thus, for suppressed subleading modes of $V_{n\Delta}$, one still has

$$V_n^{N(2)}(p_T) \sim V_0^{N(2)}(p_T)\, V_n^{N(1)}(p_T)\,. \tag{7}$$

A test with published CMS data



MH, D. Dobrigkeit Chinellato, M. Luzum, J. Noronha, T. Nunes da Silva and J. Takahashi, arXiv:1906.08915

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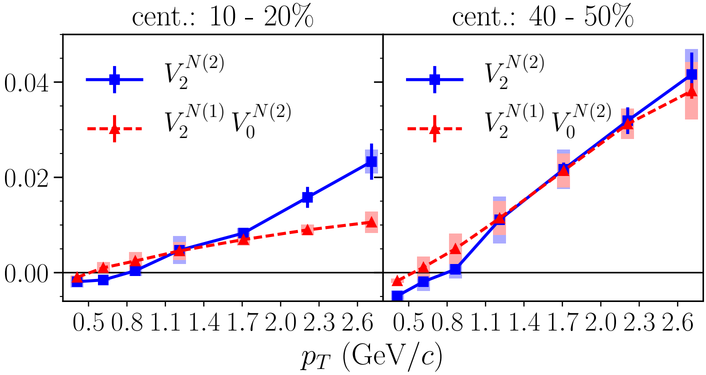


- Original $V_2^{N(2)}$ mode **dominated** by particle-number fluctuations.

MH, D. Dobrigkeit Chinellato, M. Luzum, J. Noronha, T. Nunes da Silva and J. Takahashi, arXiv:1906.08915

Redefined Principal Component Analysis

- **Remove** large contribution from **multiplicity fluctuations**.
- Ideally, diagonalizing "normalized" $V_{n\Delta} = \langle V_n(\mathbf{p}_1)\, V_n^*(\mathbf{p}_2)\rangle$.
- Alternatively, use **redefined** covariance **matrix**:

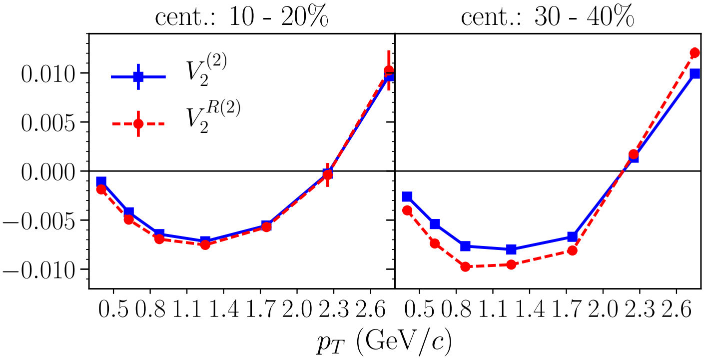
$$V_{n\Delta}^R \equiv \frac{\langle N(\mathbf{p}_1)\, N(\mathbf{p}_2)\, V_n(\mathbf{p}_1)\, V_n^*(\mathbf{p}_2)\rangle}{\langle N(\mathbf{p_1})\mathbf{N}(\mathbf{p_2})\rangle} \simeq \langle V_n(\mathbf{p}_1)\, V_n^*(\mathbf{p}_2)\rangle\,. \tag{8}$$

- Redefined PCA $\Rightarrow$ **anisotropic fluctuations only**.

MH, D. Dobrigkeit Chinellato, M. Luzum, J. Noronha,
T. Nunes da Silva and J. Takahashi, arXiv:1906.08915

Redefined PCA observables

Simulations with T$_{\text{R}}$ENTO + MUSIC + ISS + UrQMD for $Pb + Pb$ at $\sqrt{s_{NN}} = 2.76$ TeV.



MH, D. Dobrigkeit Chinellato, M. Luzum, J. Noronha, T. Nunes da Silva and J. Takahashi, arXiv:1906.08915

Conclusion

- **New PCA** observables isolate **subleading modes** of anisotropic flow.
- Their measurement might **uncover** new features of **quantum fluctuations in the initial stages** of heavy-ion collisions
- Will enable **new comparisons to theoretical calculations**, helping to extract the **properties of the quark-gluon plasma**.
- **Predictions** from realistic **hydrodynamic** simulations.

Acknowledgements

FAPESP

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