Recent results on anisotropic flow and related phenomena in ALICE

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Outline

- Introduction
- Anisotropic flow in small systems?
- Correlation techniques in a nutshell
- First flow results from Run 2
The transfer of initial anisotropy in coordinate space into the final anisotropy in momentum space via interactions between the constituents is the anisotropic flow phenomenon.
Transfer of anisotropy

- Two conceptually different notions of anisotropy:
  - **Coordinate space anisotropy:** Is the volume containing the interacting particles which are produced in heavy-ion collision anisotropic or not?
  - **Momentum space anisotropy:** Is the final-state azimuthal distribution of resulting particles which are recorded in the detector anisotropic or not?

- **A priori**, these two anisotropies are **unrelated**

made by Mike Lisa
How to quantify flow?

- S. Voloshin and Y. Zhang, Z.Phys.C70:665-672,1996: **Fourier series**

\[
E \frac{d^3N}{d^3 \vec{p}} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left( 1 + \sum_{n=1}^{\infty} 2\nu_n \cos \left( n(\phi - \Psi_{RP}) \right) \right)
\]

\[
\nu_n = \langle \cos(n(\phi - \Psi_{RP})) \rangle
\]

- Harmonics \( \nu_n \) quantify anisotropic flow
  - \( \nu_1 \) is directed flow, \( \nu_2 \) is elliptic flow, \( \nu_3 \) is triangular flow, etc.
Correlation techniques

- Statistical independence of emitted particles:

\[
\left\langle e^{in(\phi_1 - \phi_2)} \rightangle = \left\langle e^{in(\phi_1 - \Psi_{RP} - (\phi_2 - \Psi_{RP}))} \rightangle = \left\langle e^{in(\phi_1 - \Psi_{RP})} \rightangle \left\langle e^{-in(\phi_2 - \Psi_{RP})} \rightangle = \langle \nu_n^2 \rangle
\]

- Behind the scene: Factorization of joint multivariate p.d.f.

\[
f(\phi_1, \ldots, \phi_n) = f_{\phi_1}(\phi_1) \cdots f_{\phi_n}(\phi_n)
\]

- If the measured azimuthal correlators have contribution only from collective flow correlations, factorization works exactly to all orders
Breakdown of factorization can be overcome (to certain degree) with cumulants:

\[ \sqrt{c_n\{2\}} = \sqrt{\langle \langle 2 \rangle \rangle} = v_n, \]
\[ \sqrt[4]{-c_n\{4\}} = \sqrt[4]{-\langle \langle 4 \rangle \rangle + 2 \cdot \langle \langle 2 \rangle \rangle^2} = \sqrt[4]{-v_n^4 + 2v_n^4} = v_n \]

Cumulants suppress unwanted few particle correlations
- Reliable estimators of collective flow correlations for large multiplicities

Specific observables:

\[ v_n\{2\} \equiv \sqrt{c_n\{2\}}, \]
\[ v_n\{4\} \equiv \sqrt[4]{-c_n\{4\}} \]
Anisotropic flow in small systems?
**p-Pb controversy**

- **Executive summary:** When measured with correlation techniques, anisotropic flow results in p-Pb exhibit **similar trends** as the ones in Pb-Pb.
  - The similar magnitude of flow results is hard to comprehend...

ALICE, Phys. Rev. C 90, 054901 (2014)
Executive summary: When measured with correlation techniques, anisotropic flow results in p-Pb exhibit similar trends as the ones in Pb-Pb.

The similar magnitude of flow results is hard to comprehend...

CMS, Phys. Rev. Lett. 115 (1) (2015) 012301
Agreement between higher order cumulants is often cited as a strong proof of collectivity, but seen also in:

- Pythia $e^+e^-$

C. Loizides, arXiv:1602.09138
Why we are here?

- Citation from conference website:
  
  ... we make a special effort to bring together theorists and experimenters. THEORETICAL TALKS SHOULD BE PREPARED WITH EXPERIMENTERS IN THE AUDIENCE IN MIND, AND EXPERIMENTAL TALKS SHOULD LIKELY BE AIMED AT THEORISTS.
  
  http://moriond.in2p3.fr/QCD/2016/Contributions.html

- Okay...
Correlation techniques in a nutshell
Correlation techniques

- We have to correlate different particles in all multi-particle correlators:

\[ \langle 2 \rangle \equiv \langle \cos n(\phi_1 - \phi_2) \rangle , \quad \phi_1 \neq \phi_2 \]

\[ \langle 4 \rangle \equiv \langle \cos n(\phi_1 + \phi_2 - \phi_3 - \phi_4) \rangle , \quad \phi_1 \neq \phi_2 \neq \phi_3 \neq \phi_4 \]

- \( Q \)-vector in harmonic \( n \)

\[ Q_n \equiv \sum_{k=1}^{M} e^{in\varphi_k} \]

- Example correlation expressed in terms of \( Q \)-vectors:

\[ \langle 4 \rangle = \frac{|Q_n|^4 + |Q_{2n}|^2 - 2 \cdot \text{Re}[Q_{2n}Q_n^*Q_n^*] - 4(M - 2) \cdot |Q_n|^2}{M(M - 1)(M - 2)(M - 3)} + \frac{2}{(M - 1)(M - 2)} \]
Characteristic functions (inverse Fourier transform of p.d.f.) of $Q$-vectors seem to exhibit purely mathematical attractor!!

$$\phi_{\text{Re}Q_m}(k) = \left[ J_0(k) + 2 \sum_{p=1}^{\infty} (-1)^p \left[ c_{2p,m}J_{2p}(k) - ic(2p-1),mJ_{2p-1}(k) \right] \right]^M$$

$$\phi_{\text{Im}Q_m}(k) = \left[ J_0(k) + 2 \sum_{p=1}^{\infty} \left[ c_{2p,m}J_{2p}(k) + is(2p-1),mJ_{2p-1}(k) \right] \right]^M$$

- The above two expressions are dominated by the first term, which is present also for the random walk case.
- Reincarnation of central limit theorem?
- Challenge to theorists: Analogous characteristic functions for correlations are still out of reach.
If correlation techniques exhibit an attractor, then the two results below in Pb-Pb and p-Pb couldn’t be more different when it comes to physics.

CMS, Phys. Rev. Lett. 115 (1) (2015) 012301

Most likely, the devil is in the detail (as always...
First results from Run 2
Energy dependence

- J. Auvinen and H. Petersen, J. Phys. Conf. Ser. 503 (2014) 012025, arXiv:1310.7751

The relative importance of various stages in the system evolution as a function of collision energy can vary for each flow coefficient.
Energy dependence

- J. Noronha-Hostler, M. Luzum, and J.-Y. Ollitrault, arXiv:1511.06289

- Compared to the Run 1 LHC measurements, it is predicted that the mean transverse momentum will increase between 2.5%-3.5%

- $v_2$ and $v_3$ will see the largest increases in peripheral collisions, while in central collisions they will see little change

- Flow saturation in central collisions
Contribution to $v_2$ from out-of-plane flow!

- C. Shen and U. Heinz, Phys. Rev. C85 (2012) 054902, arXiv:1202.6620

At higher collision energy the system lives longer and has actually enough time to become elongated along the reaction plane, instead of its original elongation perpendicular to it.

Such contribution comes with the negative signature, the overall flow might decrease at Run 2!
Study of temperature dependence of transport coefficients has just begun

H. Niemi, K. J. Eskola, R. Paatelainen, Phys. Rev. C 93, 024907 (2016)

This state-of-the-art model quantitatively describes the Run 1 data
Compared to the Run 1 LHC measurements, higher harmonics will show bigger and non-trivial increase as a function of centrality.
Run 2 collisions
The anisotropic flow coefficients $v_2$, $v_3$ and $v_4$ are found to increase by $(3.0 \pm 0.6)\%$, $(4.3 \pm 1.4)\%$ and $(10.2 \pm 3.8)\%$, respectively, in the centrality range 0-50%.

None of the ratios $5.02 \, \text{TeV}/2.76 \, \text{TeV}$ of flow harmonics exhibit a significant centrality dependence in the centrality range 0–50%.

arXiv:1602.01119 (accepted by PRL)
Comparable results to Run 1 results, increase in integrated flow can be attributed to the increase in mean transverse momentum.
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- The $v_2\{4\}$ decreases from mid-central to central collisions over the entire $p_T$ range

arXiv:1602.01119 (accepted by PRL)
Our mark in history

- ALICE has measured the largest hydro-like flow ever!
Thanks!
Backup slides
Executive summary

- Theoretical expectations for the transition from 2.76 TeV to 5.02 TeV:
  - Increase/decrease of initial spatial eccentricities?
  - Flow saturation?
  - Hydrodynamic flow out-of-plane?
  - Pinning down temperature dependence of $\eta/s$?
  - Elliptic flow increases for light and decreases for heavy particles at low $p_T$?
  - Different change in relative contributions of various stages of system evolution for different harmonics?
Symmetry planes at Run 2

- H. Niemi, K. J. Eskola, R. Paatelainen, and K. Tuominen, Phys. Rev. C 93, 014912 (2016) arXiv:1511.04296 [hep-ph]
Energy dependence

- J. Noronha-Hostler, M. Luzum, and J.-Y. Ollitrault, arXiv:1511.06289

- Initial state models: MC-Glauber, MC-KLN, MCrcBK and Trento

- Each of these models uses the measured nucleon-nucleon inelastic cross-section as input: 64 mb at Run 1 and 70 mb at Run 2 (extrapolation)

- Predict both increase and decrease of eccentricities
Flow saturation

- C. Shen and U. Heinz, Phys. Rev. C85 (2012) 054902, arXiv:1202.6620

In viscous hydro the "saturation" of elliptic flow is shifted to higher collision energies by shear viscous effects.
Flow saturation

- C. Shen and U. Heinz, Phys. Rev. C85 (2012) 054902, arXiv:1202.6620

Interplay between radial and elliptic flow leads to a subtle cancellation between increasing contributions from light and decreasing contributions from heavy particles!
Only at LHC energies we see the difference in behavior between two models of initial conditions
Negative $v_2$

- ‘Squeeze-out’ a.k.a. elliptic flow ‘out-of-plane’
  - Can be both trivial (shadowing) and non-trivial (hydro)

\[ \sqrt{s_{NN}} \sim 2-4 \text{ GeV} \]
There is no a single centrality for which a given parametrization describe both SC(3,2) and SC(4,2)!
As a function of time anisotropy in coordinate space decreases, while the anisotropy in momentum space increases.

P.F. Kolb and U. Heinz, in Quark Gluon Plasma, nucl-th/0305084
Centrality

- (Almost) exclusively the heavy-ion concept

- $N_{\text{part}}$ or $N_{\text{wounded}}$: number of nucleons which suffered at least one inelastic nucleon-nucleon collision

- $N_{\text{coll}}$ or $N_{\text{bin}}$: number of inelastic nucleon-nucleon collisions
Can we estimate the amplitudes $v_n$ without the explicit knowledge of symmetry planes?

\[ v_n = \langle \cos(n(\phi - \Psi_{RP})) \rangle \]

The ‘flow principle’: Correlations among produced particles are induced solely by correlation of each particle to the reaction plane.
Analogy with gravity

- Falling bodies appear to be correlated in gravitational field due to correlation of each body with the common center of gravity.

- Geometry of massive body: gravitational field
- Geometry of heavy-ion collision: the pressure gradients
  - Particle trajectories are the same whether they would be emitted simultaneously or one-by-one: statistical independence.