Event-shape sorting as seen by femtoscopy

Jakub Cimerman

28.9.2018

Motivation

- In heavy-ion collisions each event evolves from different initial conditions
- Some information may get lost if we average hadron distributions over events with fluctuating anisotropies
- If events are aligned acording to second or third-order event plane, only that order of anisotropies is seen in correlation radii
- What if we select pairs of particles from events which are similar and were likely to undergo similar evolution?

Emission function

- Emission function is the Wigner phase-space density
- It describes the probability, that a particle with 4-momentum p is emitted from spacetime point x
- By integrating emission function through the volume of fireball we get the spectrum

$$P(p_t, \phi) = \frac{\mathrm{d}^3 N}{p_t \mathrm{d} p_t \mathrm{d} Y \mathrm{d}\phi} = \int S(x, p) \mathrm{d}^4 x$$

- We can decompose spectrum in azimuthal angle into Fourier series, where Fourier coefficients can be expressed as

$$v_n(p_t) = \frac{\int_0^{2\pi} P(p_t, \phi) \cos(n(\phi - \theta_n)) \mathrm{d}\phi}{\int_0^{2\pi} P(p_t, \phi) \mathrm{d}\phi}$$

Two-particle correlation function

- Correlation femtoscopy gives us information about structure of fireball
- Correlation function is defined as ratio of two-particle spectrum and the product of one-particle spectra
- We use correlation function in form

$$C(q,K) - 1 \approx \frac{|\int \mathrm{d}^4 x S(x,K) \exp(iqx)|^2}{\left(\int \mathrm{d}^4 x S(x,K)\right)^2}$$

  - $K = \frac{1}{2}(p_1 + p_2)$, $q = p_1 - p_2$
- Correlation function can be approximated by Gauss distribution

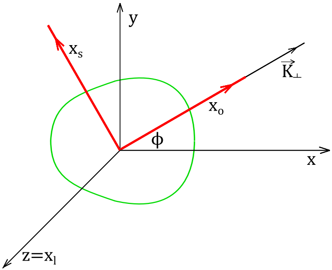
$$\begin{aligned} C(q,K) - 1 &\approx \exp\left(-q^\mu q^\nu \langle \tilde{x}_\mu \tilde{x}_\nu \rangle\right) \\ &= \exp\left(-R_o^2 q_o^2 - R_s^2 q_s^2 - R_l^2 q_l^2 - 2R_{os}^2 q_o q_s - 2R_{ol}^2 q_o q_l - 2R_{sl}^2 q_s q_l\right) \end{aligned}$$

  - where we used $q_0 = \vec{q} \cdot \vec{K} / K_0$

HBT radii

- HBT radii R_i give us information about size of homogeneity regions within the fireball

$$
\begin{aligned}
R_o^2(K) &= \left\langle \left(\tilde{x}_o - \beta_o \tilde{t}\right)^2 \right\rangle (K) \\
R_s^2(K) &= \left\langle \tilde{x}_s^2 \right\rangle (K) \\
R_l^2(K) &= \left\langle \left(\tilde{x}_l - \beta_l \tilde{t}\right)^2 \right\rangle (K) \\
R_{os}^2(K) &= \left\langle \left(\tilde{x}_o - \beta_o \tilde{t}\right) \tilde{x}_s \right\rangle (K) \\
R_{ol}^2(K) &= \left\langle \left(\tilde{x}_o - \beta_o \tilde{t}\right) \left(\tilde{x}_l - \beta_l \tilde{t}\right) \right\rangle (K) \\
R_{sl}^2(K) &= \left\langle \left(\tilde{x}_l - \beta_l \tilde{t}\right) \tilde{x}_s \right\rangle (K).
\end{aligned}
$$



- $\langle ... \rangle$ means averaging over emission function

Femtoscopy with similar events

- We generate events with
  - **DRAGON** (DRoplet and hAdron GeneratOr for Nuclear collisions)
  - **AMPT** (A Multi-Phase Transport)

Femtoscopy with similar events

- We generate events with
  - **DRAGON** (DRoplet and hAdron GeneratOr for Nuclear collisions)
  - **AMPT** (A Multi-Phase Transport)
- We sort events by its shape with Event Shape Sorting

Femtoscopy with similar events

- We generate events with
  - **DRAGON** (DRoplet and hAdron GeneratOr for Nuclear collisions)
  - **AMPT** (A Multi-Phase Transport)
- We sort events by its shape with Event Shape Sorting
- We calculate correlation function with CRAB (CoRrelation After Burner)

  [S. Pratt]

Femtoscopy with similar events

- We generate events with
  - **DRAGON** (DRoplet and hAdron GeneratOr for Nuclear collisions)
  - **AMPT** (A Multi-Phase Transport)
- We sort events by its shape with Event Shape Sorting
- We calculate correlation function with CRAB (CoRrelation After Burner)

  [S. Pratt]
- By fitting correlation function we get correlation radii, so we can study their azimuthal dependence

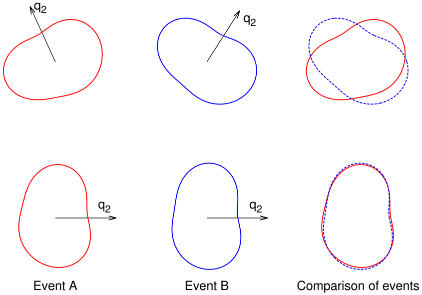
Event samples

- We generated 3 samples of events:
  - *DRAGON:* (blast-wave Monte Carlo with resonances) 150 000 events by DRAGON with anisotropies $a_2, \rho_2 \in (-0.1; 0.1)$, $a_3, \rho_3 \in (-0.03; 0.03)$
  - *AMPT-RHIC:* 10 000 events by AMPT in AuAu collisions with energy $\sqrt{s_{NN}} = 200$ GeV, impact parameter $7 - 10$ fm
  - *AMPT-LHC:* 10 000 events by AMPT in PbPb collisions with energy $\sqrt{s_{NN}} = 2760$ GeV, impact parameter $7 - 10$ fm

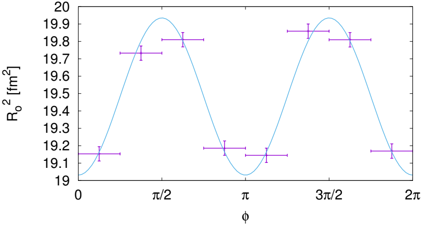
Event rotations

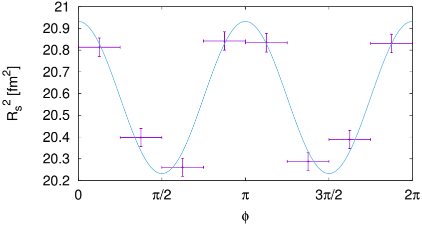
- Events may be similar, even if they do not seem at first glance
- We rotate all events to have the same direction of the vector

$$\vec{q_2} = \left(\sum \cos(2\phi_i), \sum \sin(2\phi_i)\right)$$



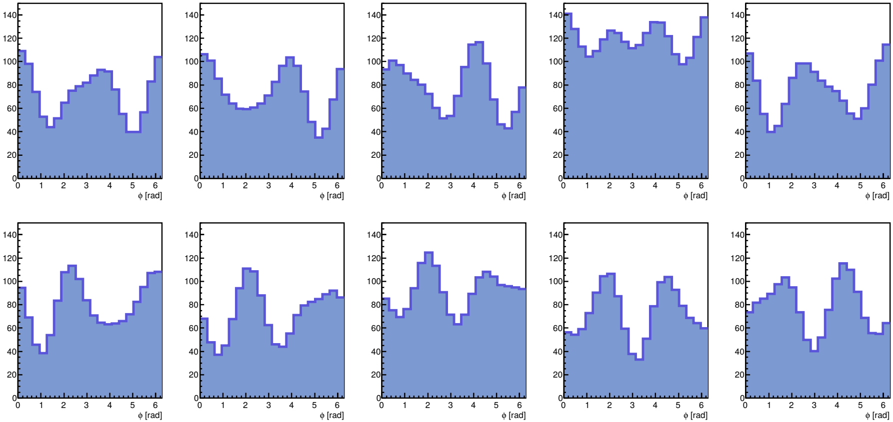
- Once we have rotated all events in one direction, second order anisotropy will sum up, while third order will be averaged out
- We can observe this in the resulting azimuthal dependence of correlation radii
- Correlation functions in these plots were integrated over p_t



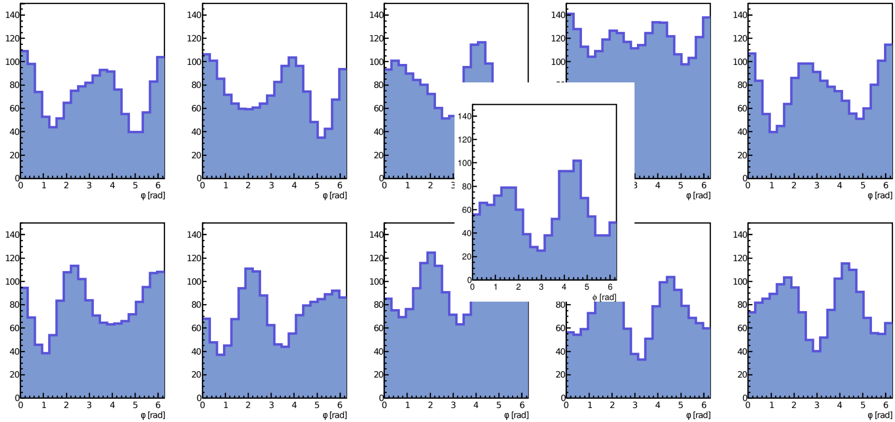


- Sample *DRAGON*

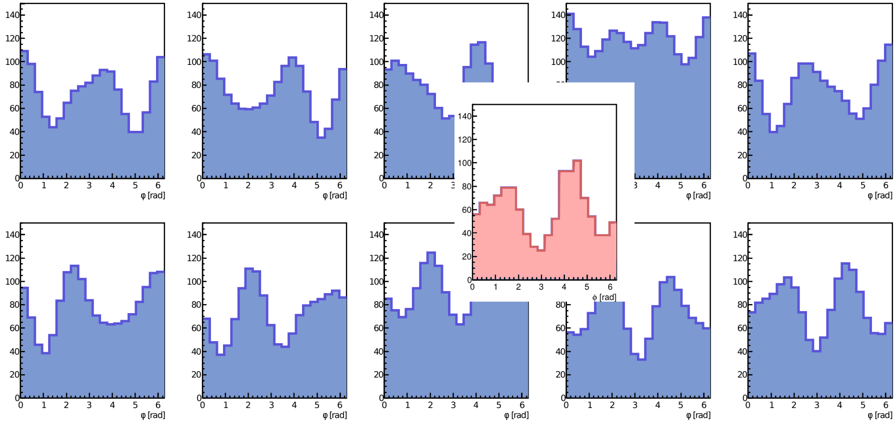
Event Shape Sorting algorithm



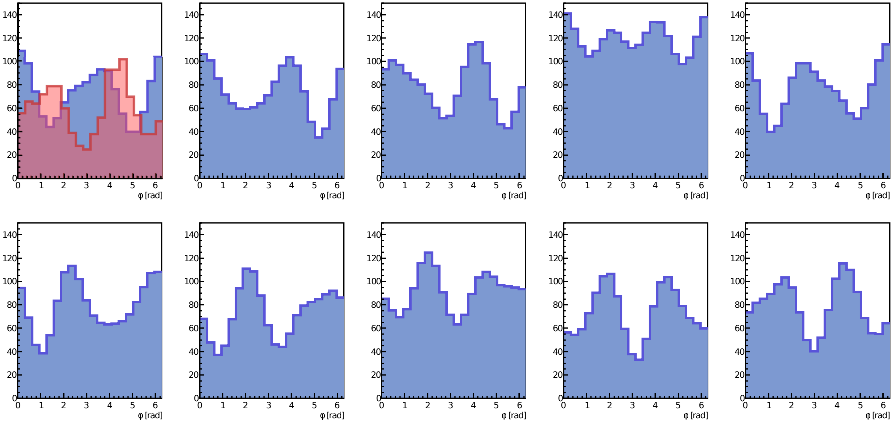
Event Shape Sorting algorithm



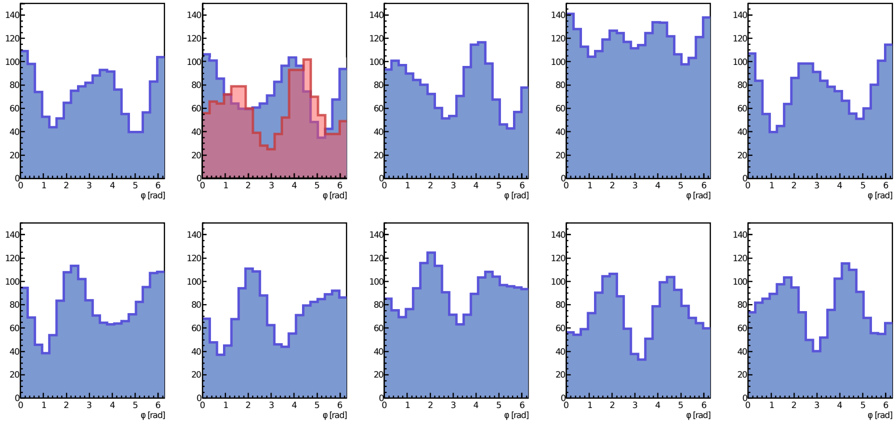
Event Shape Sorting algorithm



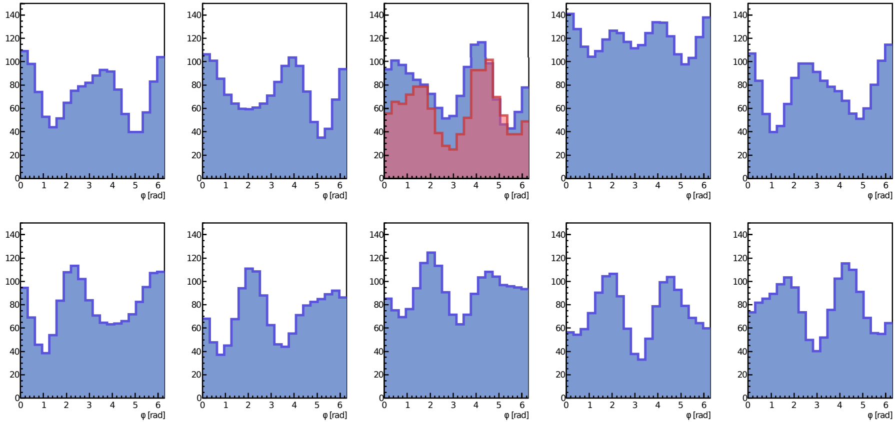
Event Shape Sorting algorithm



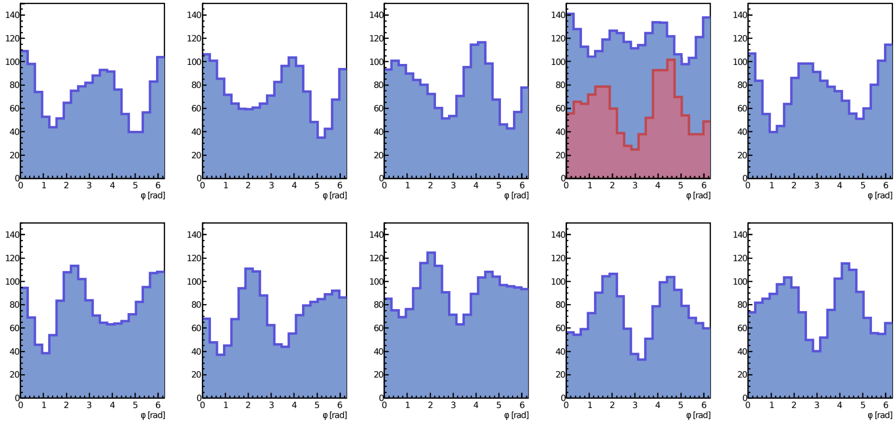
Event Shape Sorting algorithm



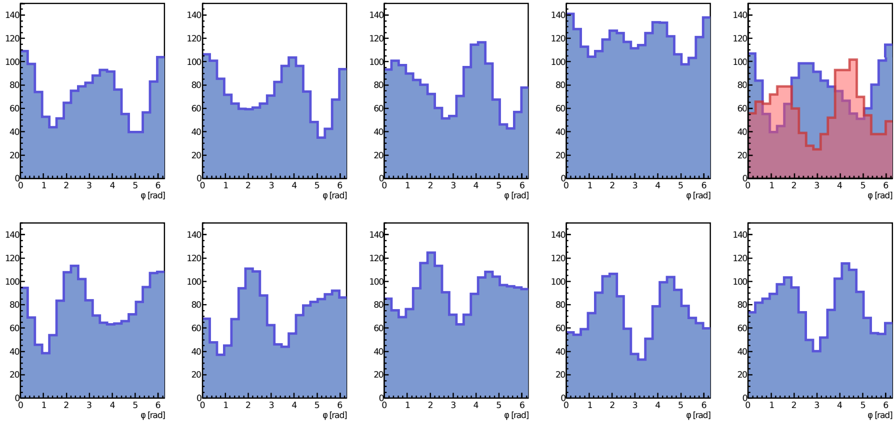
Event Shape Sorting algorithm



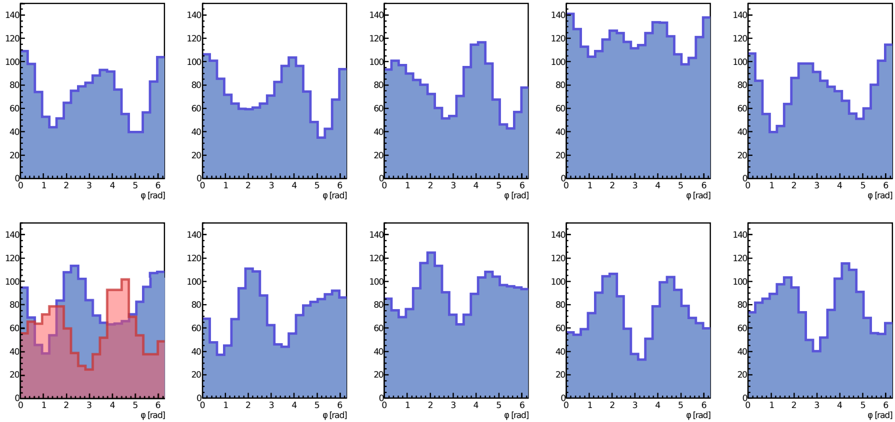
Event Shape Sorting algorithm

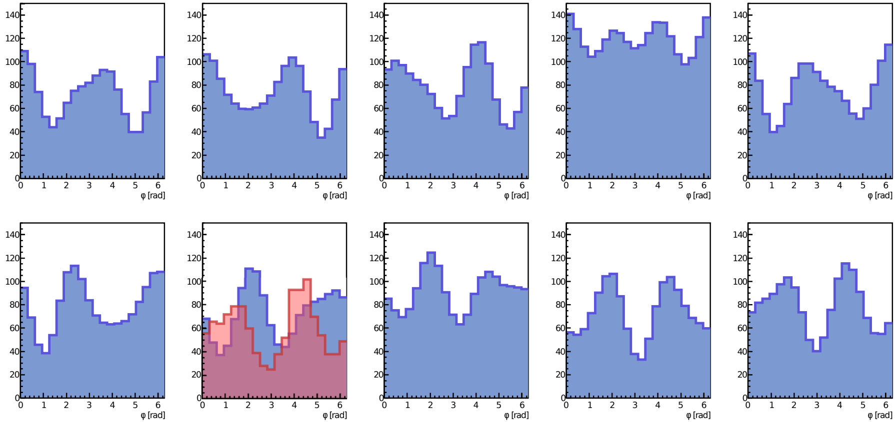


Event Shape Sorting algorithm

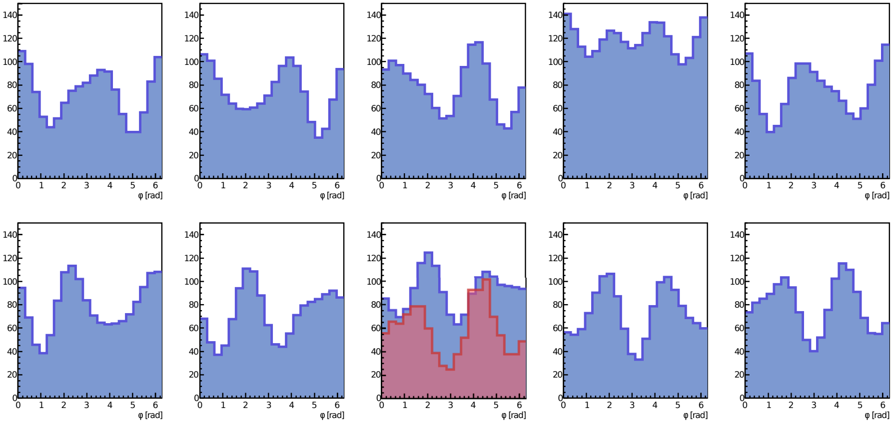


Event Shape Sorting algorithm

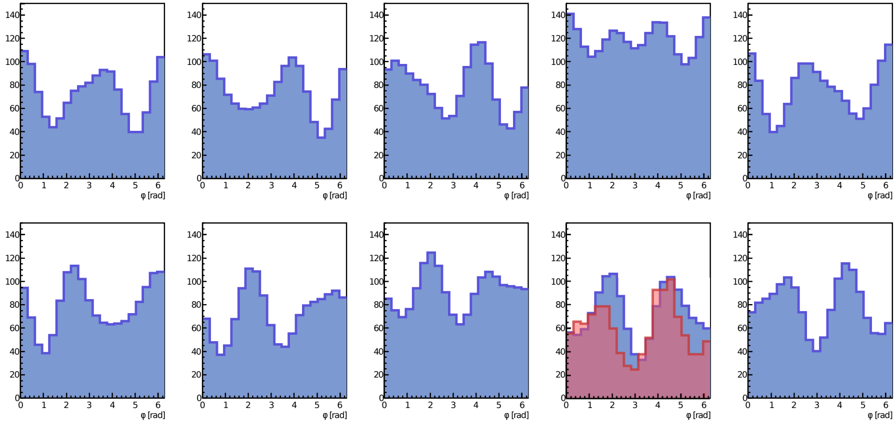



φ [rad]

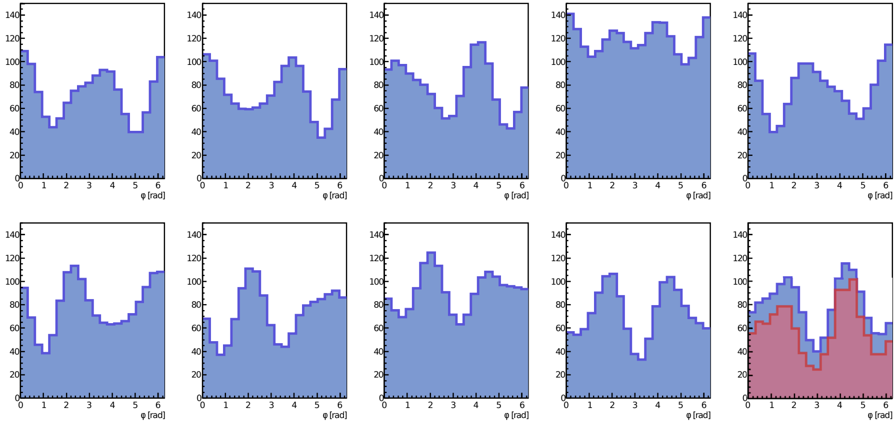
Event Shape Sorting algorithm



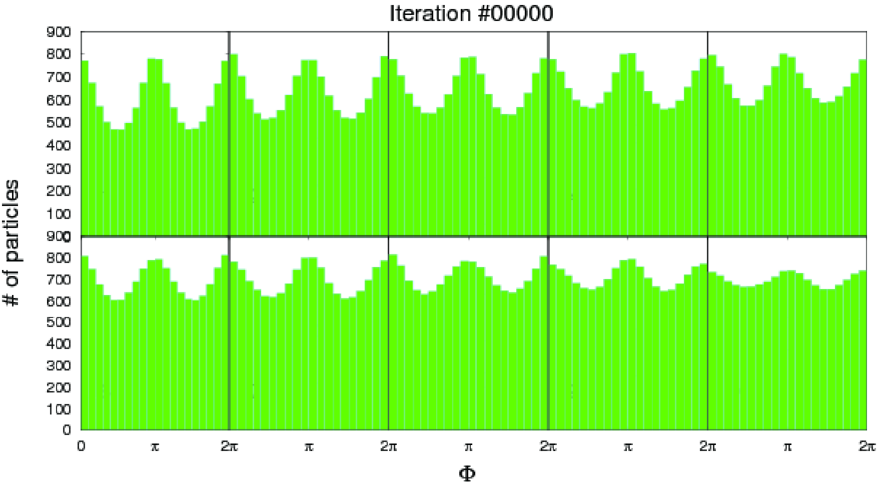
Event Shape Sorting algorithm



Event Shape Sorting algorithm



Animation of Event Shape Sorting

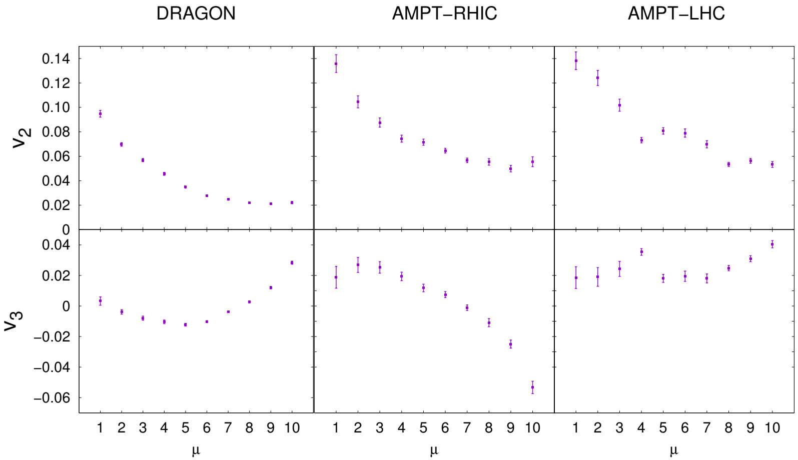


Anisotropic flow in similar events

- After sorting events we split them into 10 classes
- We can calculate v_2 and v_3 from the azimuthal distribution of particles for each class
- Evolution of these coefficients across classes shows us, how the average shape is changing

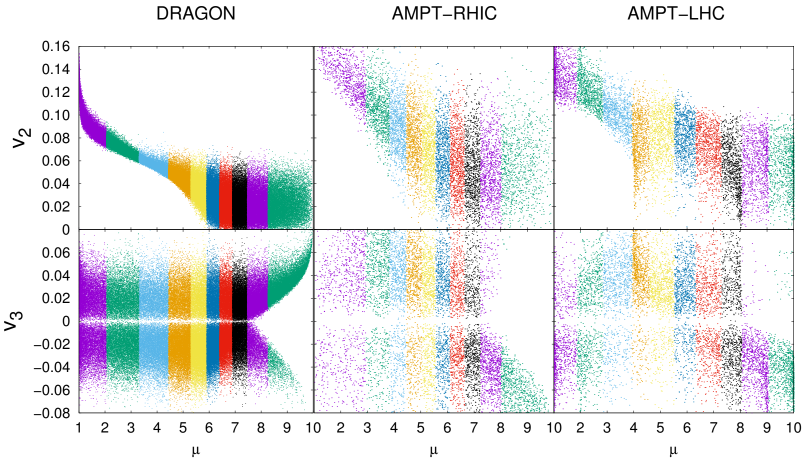
Anisotropic flow in similar events

- *DRAGON*: $a_2, \rho_2 \in (-0.1; 0.1)$, $a_3, \rho_3 \in (-0.03; 0.03)$
- other samples: $b \in (7; 10)$ fm $\Rightarrow$ centrality $\sim 20 - 40\%$



Anisotropic flow in similar events

- *DRAGON*: $a_2, \rho_2 \in (-0.1; 0.1)$, $a_3, \rho_3 \in (-0.03; 0.03)$
- other samples: $b \in (7; 10)$ fm $\Rightarrow$ centrality $\sim 20 - 40\%$

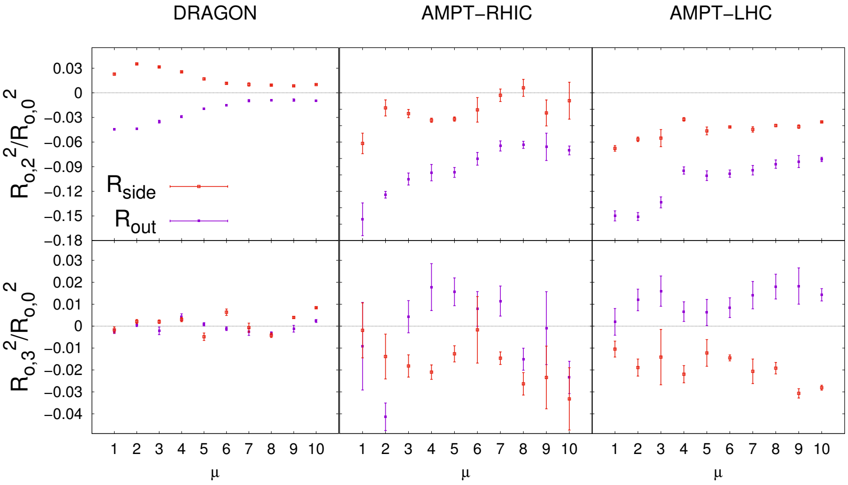


- In each class we can also obtain azimuthal dependence of correlation radii
- We can then see both second and third order anisotropies at the same time
- We can also see, how average shape evolves between classes
- We decomposed R_o^2 and R_s^2 into Fourier series and calculated series' coefficients

$$R_\mu^2 = (R_\mu^2)_0 + \sum_{n=2}^{\infty} (R_\mu^2)_n \cos(n(\phi - \delta_n))$$

- To avoid scaling by absolute value of correlation radii, we use relative Fourier coefficients $(R_\mu^2)_n/(R_\mu^2)_0$

Correlation radii R_o nad R_s of similar events



Summary

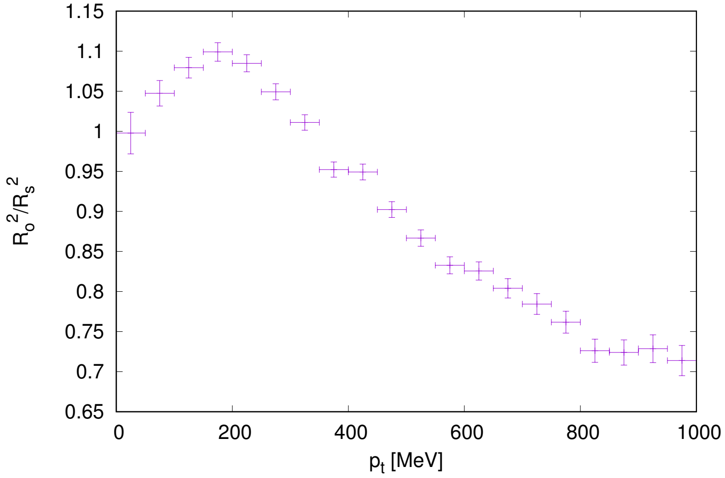
- Event shape sorting can help to select events with similar shapes. Thanks to ESS we can calculate correlation functions of similar events, because events, over which we take averages, are chosen more exclusively.
- In classes of similar events we can observe both second and third order anisotropies of correlation radii at the same time.
- The sorting program is now available at

  github.com/jakubcimerman/nESSie

Backup slides

Dependence of ratio R_o/R_s on p_t

- Here is the reason, why $R_o < R_S$ for $DRAGON$ sample - we integrate over p_t



Event Shape Sorting algorithm

- 1. Split particles in each event into k azimuthal angle bins
- 2. Initial sorting according to $|\vec{q}_2|$
- 3. Calculate $P(i|\mu)$ for each angle bin in each class

$$P(i|\mu) = \frac{\sum_{\text{events in } \mu\text{-th class}} (n_i)_j}{\sum_{\text{events in } \mu\text{-th class}} N_j}$$

- 4. Calculate $P(\mu| \{n_i\}_j)$ for each event

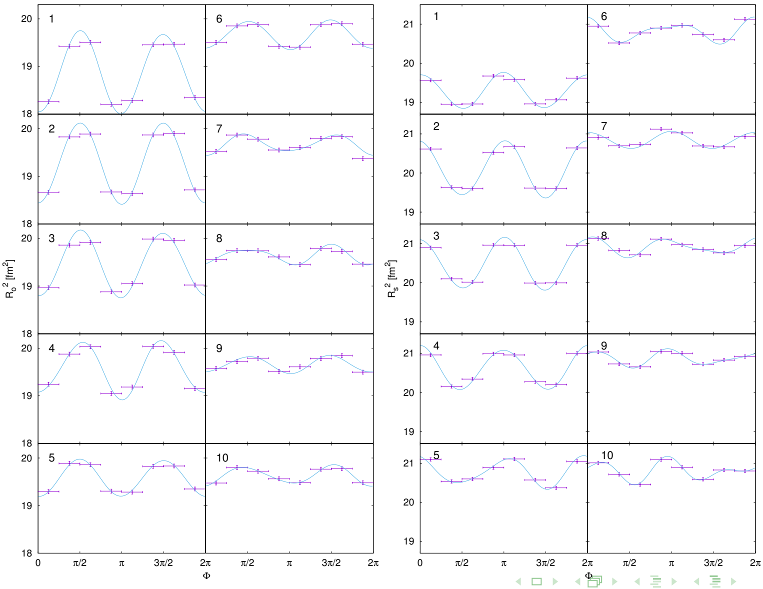
$$P(\mu| \{n_i\}_j) = \frac{\prod_{i=1}^{k} P(i|\mu)^{(n_i)_j}}{\sum_{\mu'=1}^{\omega} \prod_{i=1}^{k} P(i|\mu')^{(n_i)_j}}$$

- 5. Calculate mean class number $\overline{\mu}$

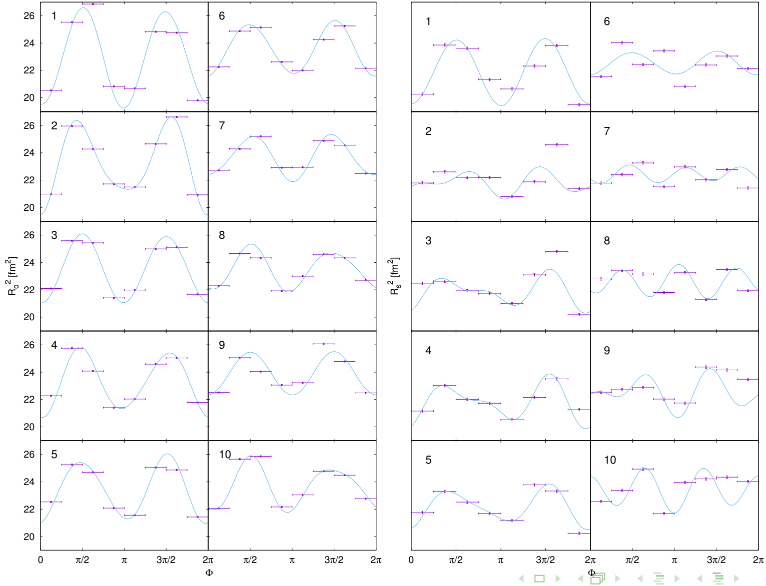
$$\overline{\mu} = \sum_{\mu=1}^{\omega} \mu P(\mu| \{n_i\}_j)$$

- 6. Sort events according to $\overline{\mu}$
- 7. Repeat from step 3, until order of events stay unchanged

Correlation radii for *DRAGON* sample



Correlation radii for *AMPT-RHIC* sample



Correlation radii for *AMPT-LHC* sample