Fluctuating shapes of the fireballs in heavy-ion collisions

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Results shown here are worked out by
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Motivation

- Standard paradigm: Anisotropies in azimuthal hadron distribution – response of QCD matter to initial conditions – the response depends on the properties of the matter
- Properties of QCD matter: Equation of State, transport coefficients
- Problem: initial conditions are beyond control in experiments

- **Part 1: Energy and momentum deposition from hard partons modifies the anisotropies and is not included in the initial conditions. This modifies the Standard paradigm. (Relevant mainly for LHC experiments.)**

- **Part 2: Event Shape Sorting**
  Proposal for more exclusive analysis by selecting events with similar final state.

Part 1: Bulk anisotropic flow from hard partons

- At the LHC there is copious production of hard partons – may have more than one pair in single event.
- Their momentum is deposited into medium over some time span $\Rightarrow$ collective flow, wakes, streams
- Anisotropic flow – event by event
- Elliptic flow after summation over all events.

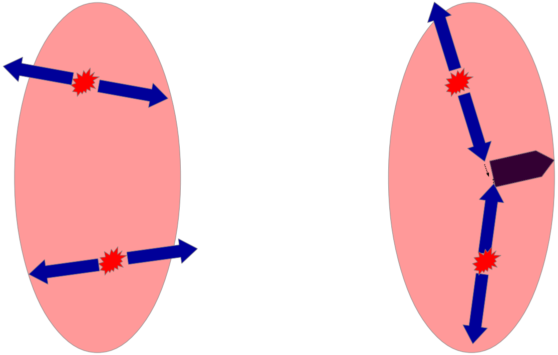
Anisotropic flow from isotropic jets

Streams are more likely to merge if they are directed out of reaction plane

$\Rightarrow$ less contribution to flow out of plane

$\Rightarrow$ enhance v_2 correlated with the reaction plane

$\Rightarrow$ also contribute to v_3



Hydrodynamic simulations of nuclear collisions

- 3+1D ideal hydrodynamics
- EoS from P. Petreczky, P. Huovinen: Nucl. Phys. A **897** (2010) 26
- smooth initial energy density scaled with

$$W(x,y;b) = (1-\alpha)n_w(x,y;b) + \alpha n_{\mathrm{bin}}(x,y;b)$$

  with $\alpha = 0.16$, $\varepsilon(0,0,0) = 60$ GeV/fm^3 at $\tau_0 = 0.55$ fm/c
  rapidity plateau over 10 units of rapidity
- $$\frac{dE}{dx} = \left.\frac{dE}{dx}\right|_0 \frac{s}{s_0}$$
- fluctuating number of jet pairs

Generation of hard partons

- p_t according to

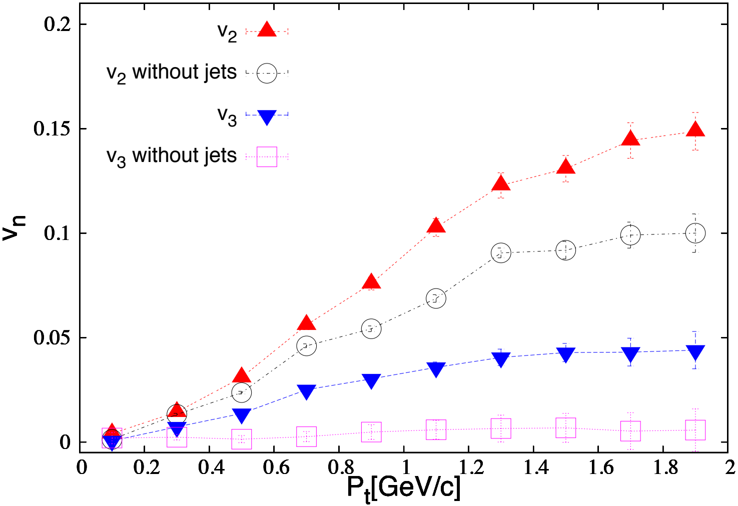
$$\frac{1}{2\pi}\frac{d\sigma_{NN}}{p_t dp_t\, dy} = \frac{B}{(1+p_t/p_0)^n}$$

$B = 14.7$ mb/GeV^2, $p_0 = 6$ GeV, $n = 9.5$

- back-to-back in p_t

- spatial distribution according to Glauber model for binary collisions

Results from 30–40% centrality



Results from ultra-central collisions

Anisotropy coefficients

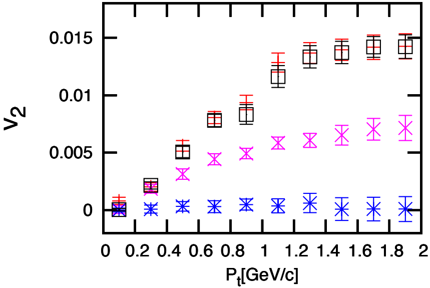
compare:

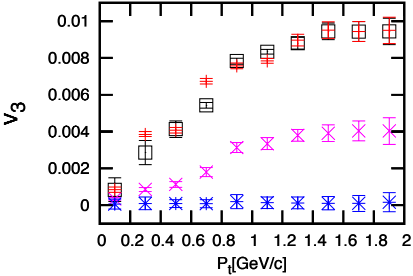
$dE/dx = 7$ GeV/fm

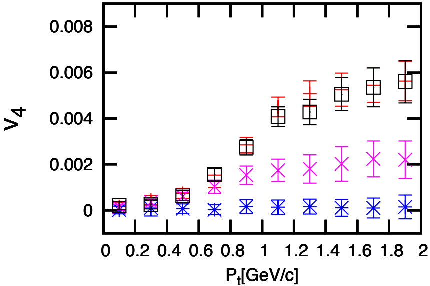
$dE/dx = 4$ GeV/fm

hot spots

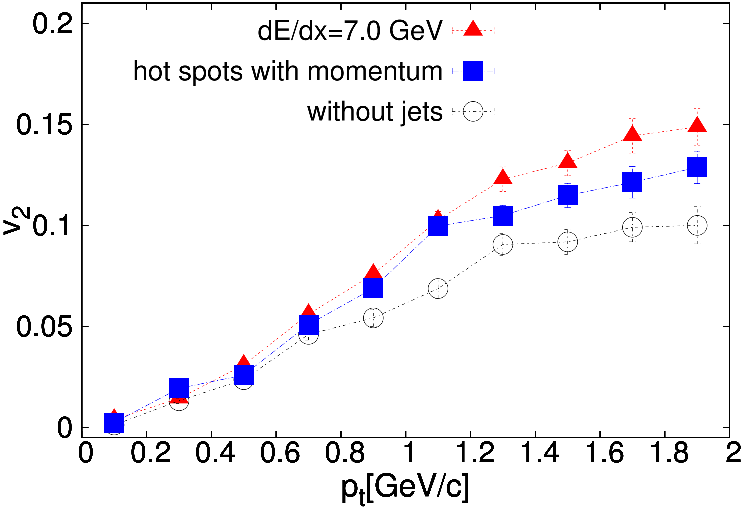
smooth initial conditions







This cannot be included into initial conditions



Summary of Part 1

- Momentum deposition from hard partons gives large contribution to anisotropic flow
  $\Rightarrow$ must be included in simulations

- This mechanism breaks the linear relation between initial and final anisotropy

References:
M. Schulc and B. Tomášik, J. Phys. G **40** (2013) 125104
M. Schulc and B. Tomášik, Phys. Rev. C **90** (2014) 064910
M. Schulc and B. Tomášik, J. Phys. G **43** (2016) 125106

Part 2: Event Shape Sorting

- try to avoid extensive averaging over very different events by identifying events with similar distribution of final state hadrons and taking averages over them only
- useful for data analyses of observables which depend on fireball shape
    - jet quenching
    - jet shapes
    - anisotropic flow of heavy flavors
    - azimuthal dependence of correlation radii
    - ...
- useful for the comparison with theoretical simulations
    - hydrodynamic simulations with specific geometry
    - identification of rare events

Event Shape Sorting

- iteratively sorts events in such a way, that events with similar histograms (in azimuthal angle, e.g.) end up close to each other
- divides the totality of events into (customarily 10) event bins
- no need to specify a sorting variable, unlike Event Shape Engineering [J. Schukraft, A. Timmins, S. A. Voloshin, Phys. Lett. B 719 (2013) 394-398]

Algorithm based on:

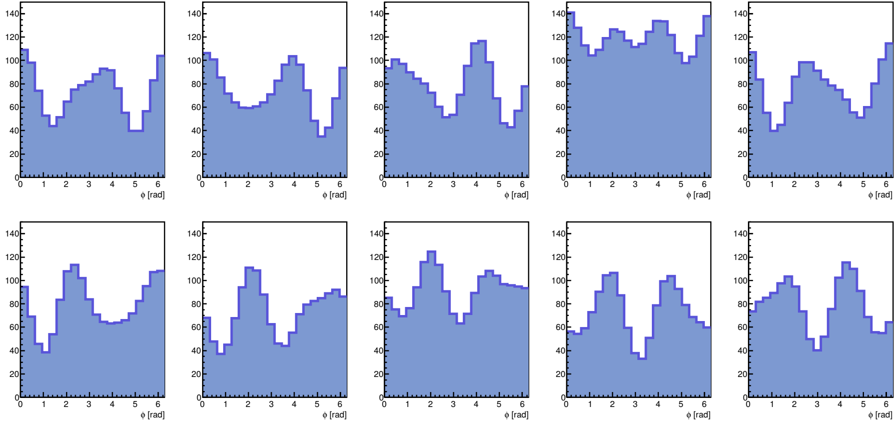
S. Lehmann, A.D. Jackson, B. Lautrup, arXiv:physics/0512238

S. Lehmann, A. D. Jackson and B. E. Lautrup, Scientometrics **76** (2008) 369 [physics/0701311 [physics.soc-ph]]

Published in

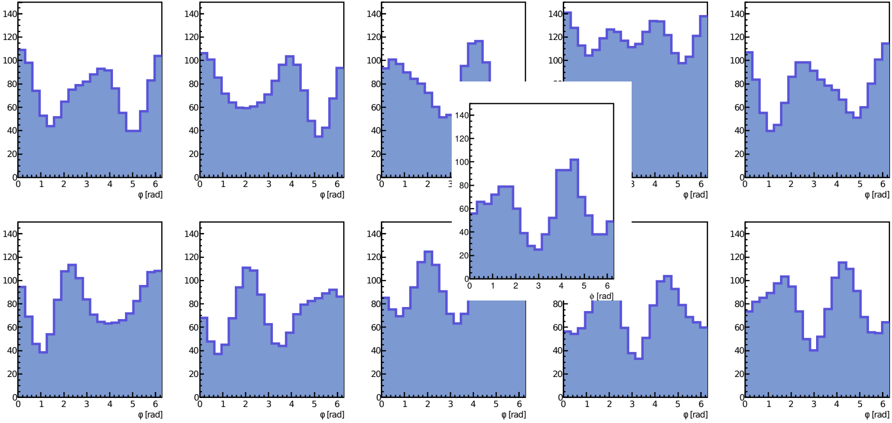
R. Kopečná, B. Tomášik: Eur. Phys. J. A **52** (2016) 115.

Assigning event to event bin



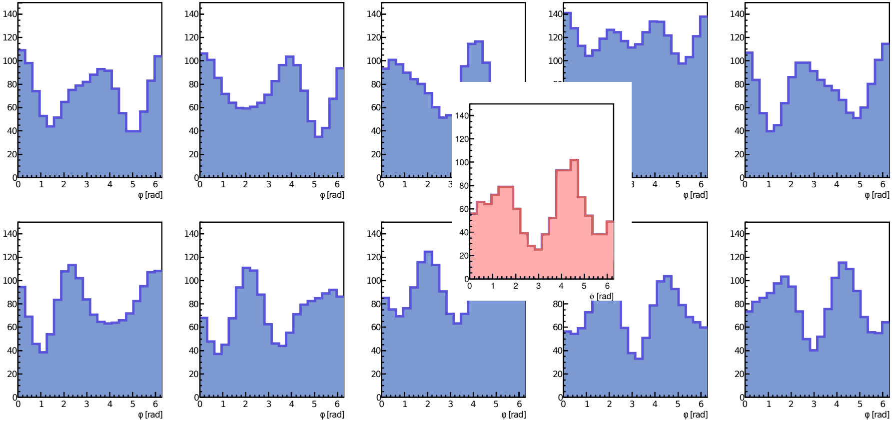
Assigning event to event bin

To which event bin is this event similar?



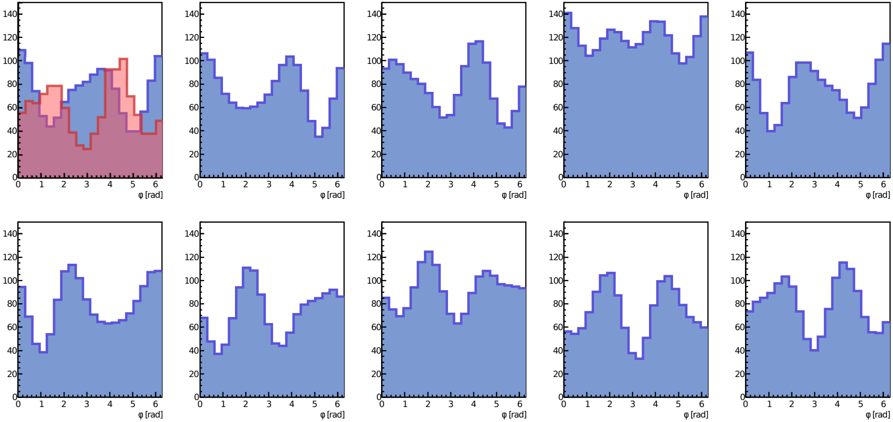
Assigning event to event bin

Calculate Bayesian probability that the event belong to each event bin



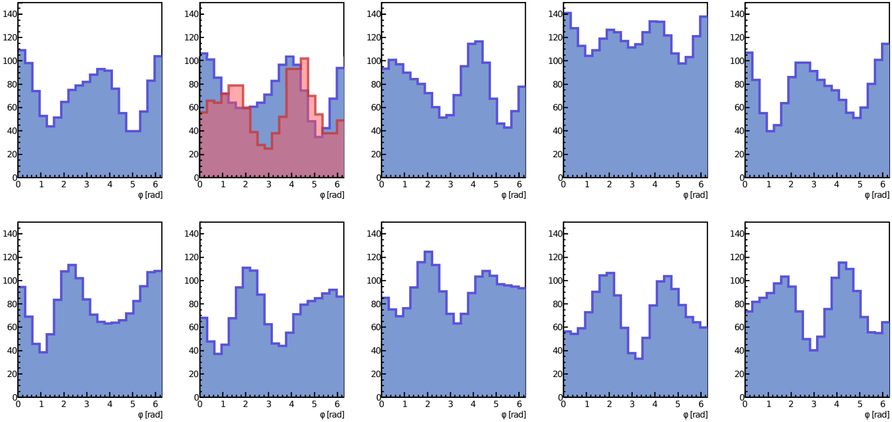
Assigning event to event bin

Calculate Bayesian probability that the event belong to event bin 1



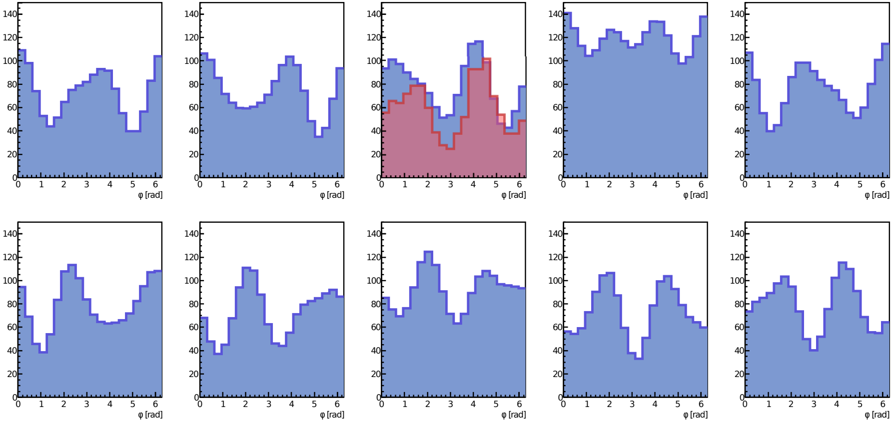
Assigning event to event bin

Calculate Bayesian probability that the event belong to event bin 2



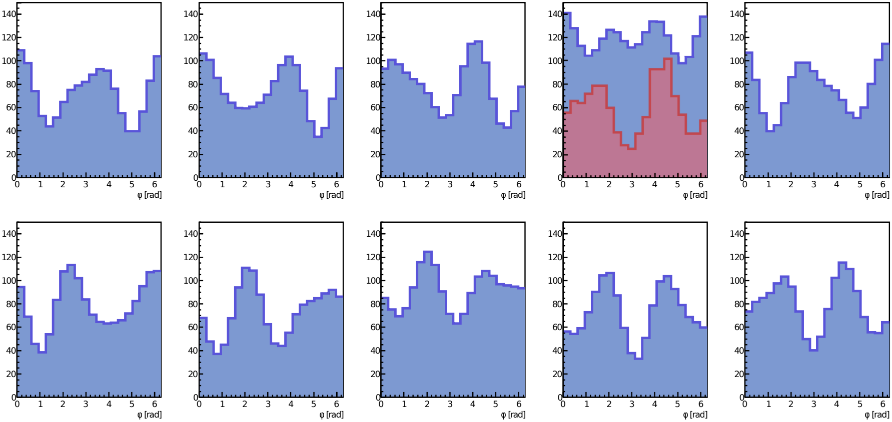
Assigning event to event bin

Calculate Bayesian probability that the event belong to event bin 3



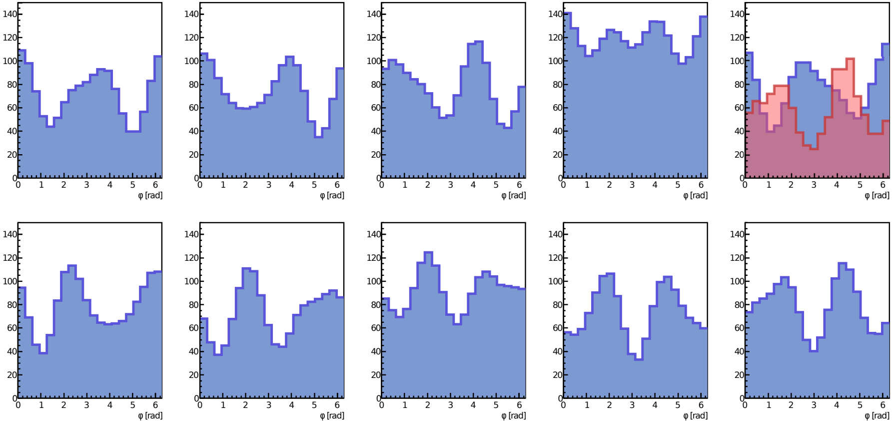
Assigning event to event bin

Calculate Bayesian probability that the event belong to event bin 4



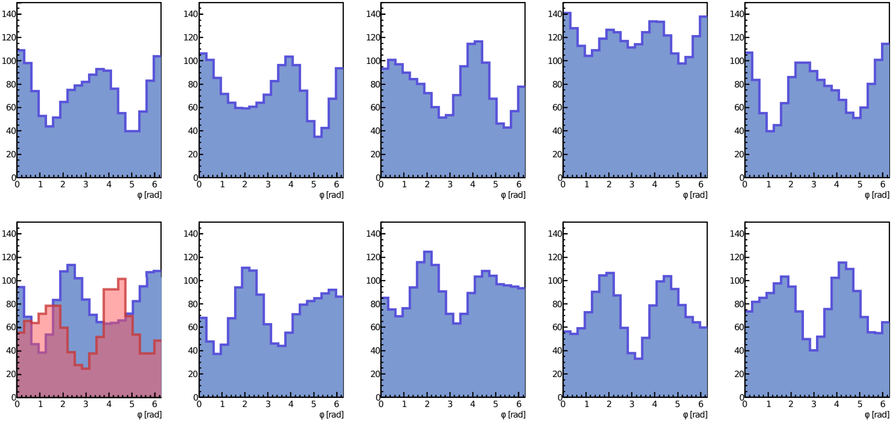
Assigning event to event bin

Calculate Bayesian probability that the event belong to event bin 5



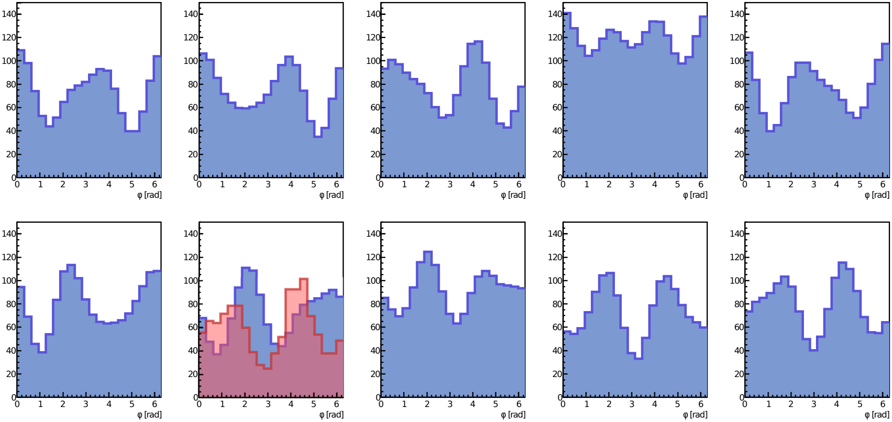
Assigning event to event bin

Calculate Bayesian probability that the event belong to event bin 6



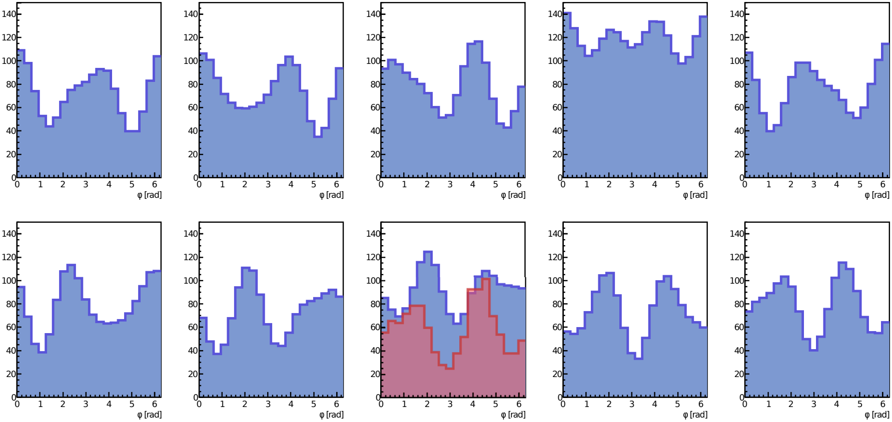
Assigning event to event bin

Calculate Bayesian probability that the event belong to event bin 7



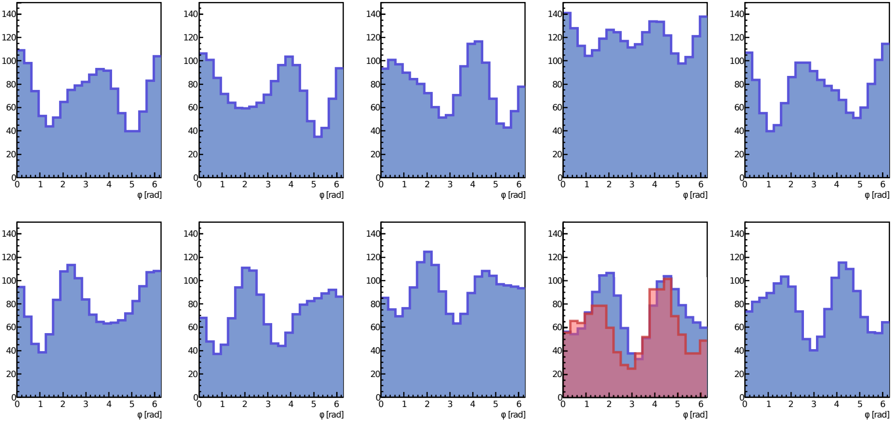
Assigning event to event bin

Calculate Bayesian probability that the event belong to event bin 8



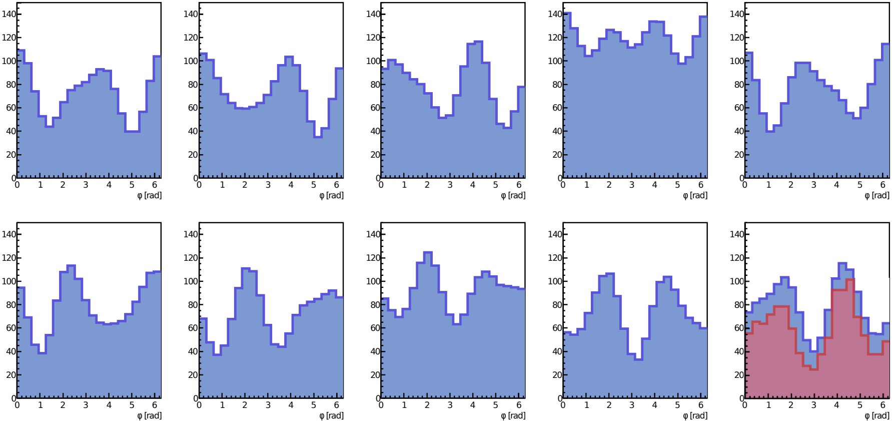
Assigning event to event bin

Calculate Bayesian probability that the event belong to event bin 9

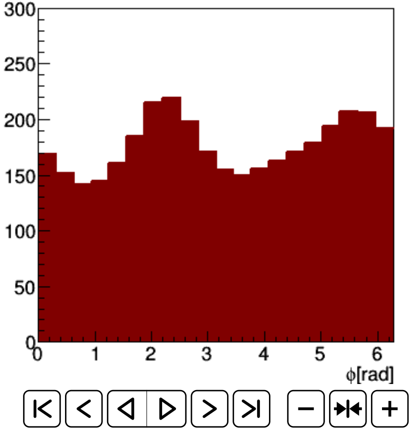


Assigning event to event bin

Calculate Bayesian probability that the event belong to event bin 10



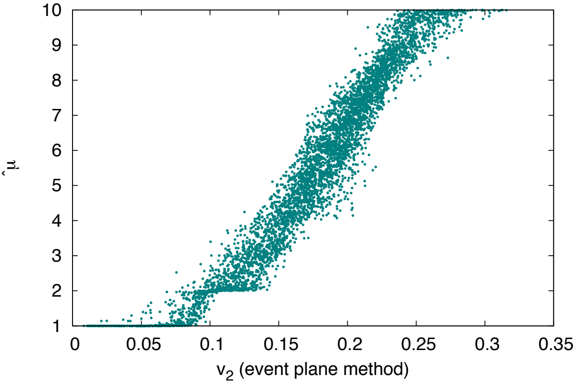
Sorted events: Gradual change of event shape



- 2000 events, AMPT centrality 0–20%, $\sqrt{s_{NN}} = 2.76$ TeV
- each frame averaged over 50 events and shifted by 10 events wrt previous frame
- change of colour = change of event bin

Toy model: only elliptic flow

- in the toy model, azimuthal distribution of pions with only elliptic flow is generated
- correlation between v_2 and μ: 0.959
- v_2 is good sorting variable



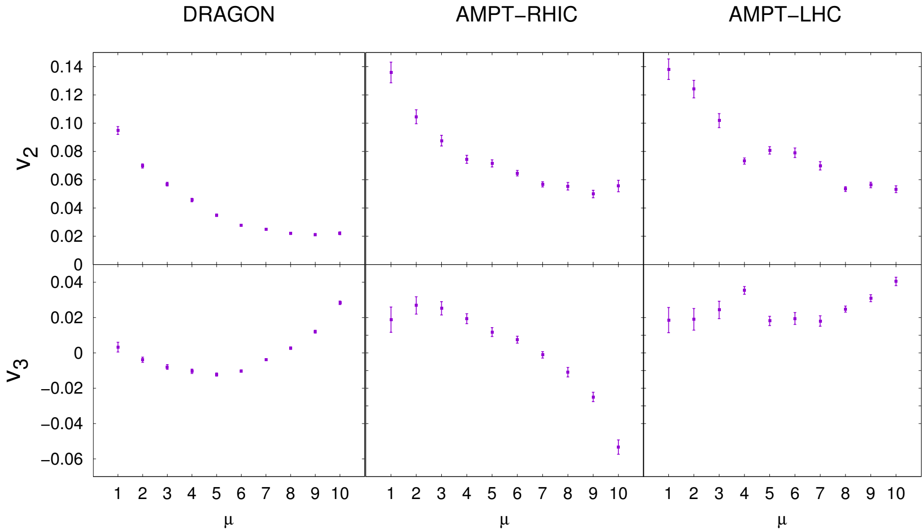
Models which will be compared

DRAGON 150 000 events by DRAGON with anisotropies $a_2, \rho_2 \in (-0.1; 0.1)$, $a_3, \rho_3 \in (-0.03; 0.03)$ (DRAGON is MC final state generator based on blast-wave model with included resonances)

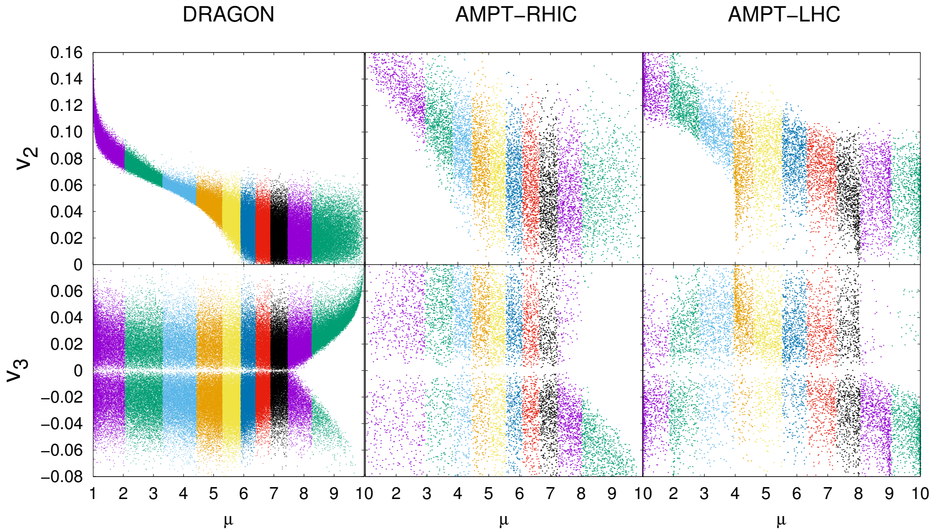
AMPT-RHIC 10 000 events by AMPT in AuAu collisions with energy $\sqrt{s_{NN}} = 200$ GeV, impact parameter $7 - 10$ fm

AMPT-LHC 10 000 events by AMPT in PbPb collisions with energy $\sqrt{s_{NN}} = 2760$ GeV, impact parameter $7 - 10$ fm

Anisotropic flow in similar events



Anisotropic flow in similar events



Femtoscopy: trivia

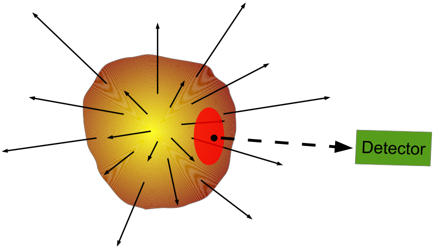
Correlation radii are parameters of the measured correlation function:

$$C(q,K) - 1 = \exp\left(-R_o^2(K)q_o^2 - R_s^2(K)q_s^2 - R_l^2(K)q_l^2\right)$$

- K: average pair momentum, q: relative pair momentum
- no cross terms at midrapidity at high energies
- out-side-long coordinate frame

out	perpendicular to beam, along K_t
long	beam direction
side	perpendicular to out and long

The correlation radii measure the sizes of the homogeneity regions



Azimuthal dependence of correlation radii

Correlation radii are customarily decomposed into Fourier series

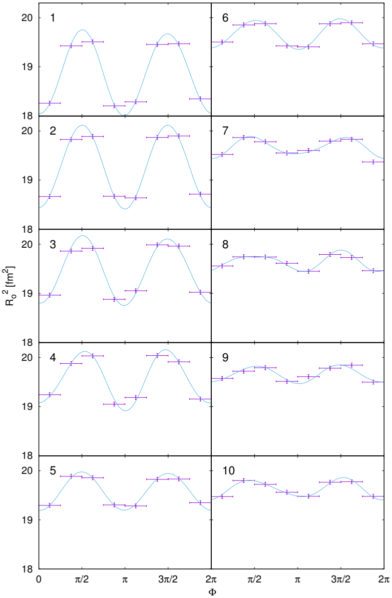
$$R_i^2(\phi) = R_{i,0}^2 + \sum_{n=1}^{\infty} R_{i,n}^2 \cos\left(n(\phi - \phi_n)\right)$$

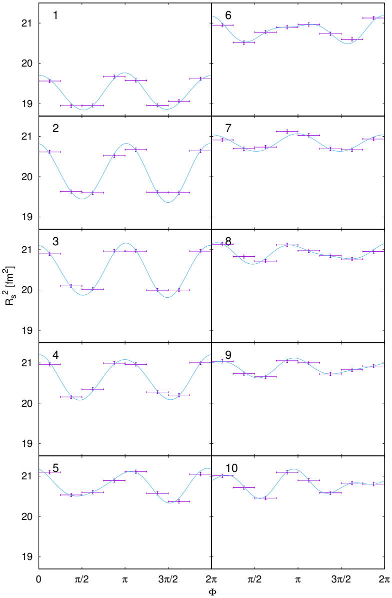
where $i = o, s, l$.

Real effect of oscillations: amplitudes divided by 0th term allow to scale out the absolute sizes

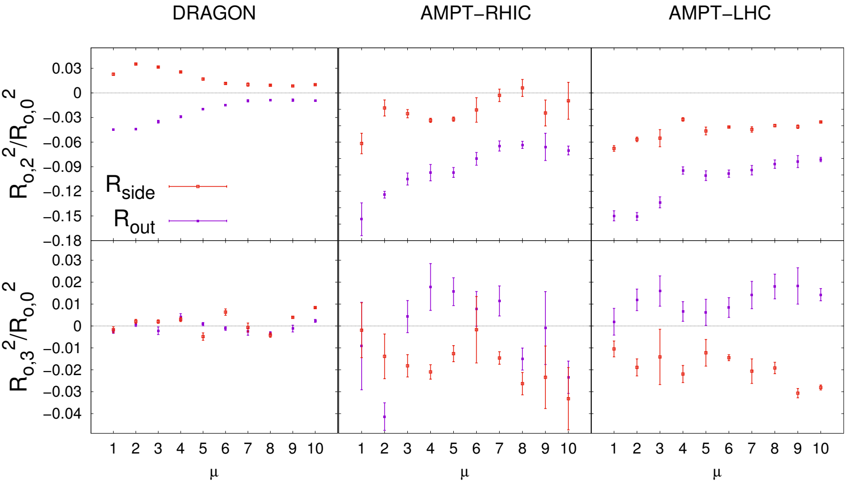
$$R_i^2(\phi) = R_{i,0}^2 \left(1 + \sum_{n=1}^{\infty} \frac{R_{i,n}^2}{R_{i,0}^2} \cos\left(n(\phi - \phi_n)\right)\right)$$

Correlation radii from DRAGON in different event bins





Oscillation amplitudes for R_s^2



What is it good for?

- More selective comparison of data to theory.
- Better insight into the dynamics of evolution and freeze-out.
- Looking for and selecting rare events.
- Construction of mixed-events background for correlation functions.
- Better selection of the environment for other processes, e.g. jet quenching.
- . . .

Published in
R. Kopečná, B. Tomášik: Eur. Phys. J. A **52** (2016) 115.
J. Cimerman, B. Tomášik: in preparation.

Summary

Momentum deposition from hard partons must be included in simulations which aim at extracting transport coefficients from the comparison with data.

Event Shape Sorting allows more exclusively select events with similar distribution of particles.
Such events are likely to have undergone similar evolution.

Sorting algorithm available:

https://github.com/jakubcimerman/nESSie

BACKUP SLIDES

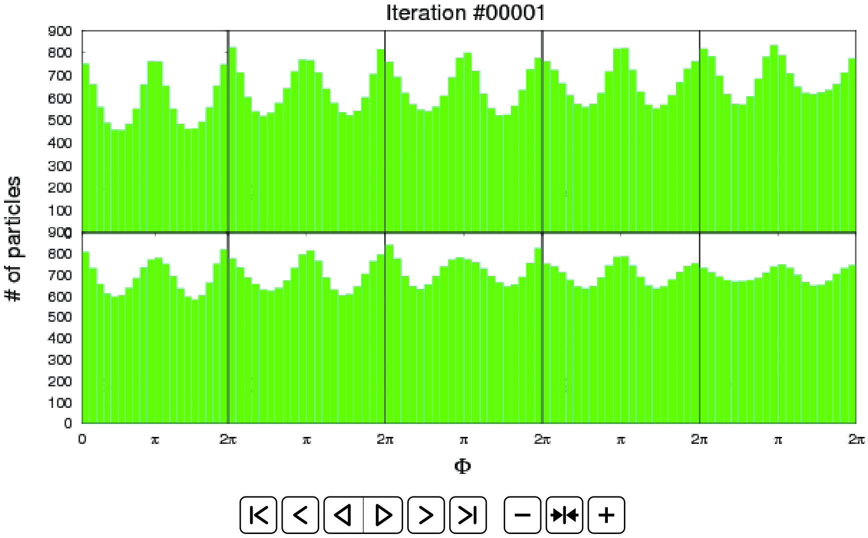
Event Shape Sorting: the algorithm

We will sort events according to their histograms in azimuthal angle.

1. (Rotate the events appropriately)
2. Sort your events as you wish
3. Divide sorted events into quantiles (we'll do deciles)
4. Determine average histograms in each quantiles
5. For each event i calculate Bayesian probability $P(i|\mu)$ that it belongs to quantile μ
6. For each event calculate average $\bar{\mu} = \sum_\mu \mu P(i|\mu)$
7. Sort events according to their values of $\bar{\mu}$
8. If order of events changed, return to 3. Otherwise sorting converged.

S. Lehmann, A.D. Jackson, B. Lautrup, arXiv:physics/0512238
S. Lehmann, A. D. Jackson and B. E. Lautrup, Scientometrics **76** (2008) 369 [physics/0701311 [physics.soc-ph]]

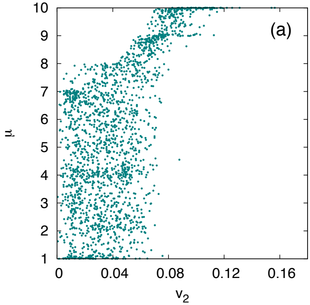
Iterations of event bins

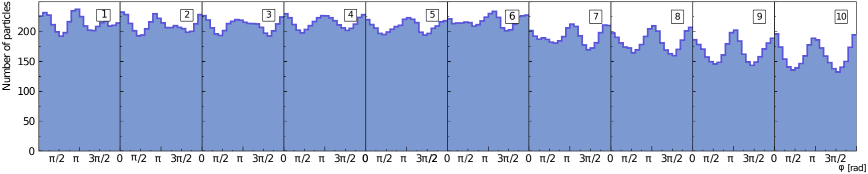


Sorted AMPT central events (LHC energy)

Event shape sorting goes beyond characterisation of events according to single variable (e.g. v_2 or q_2)

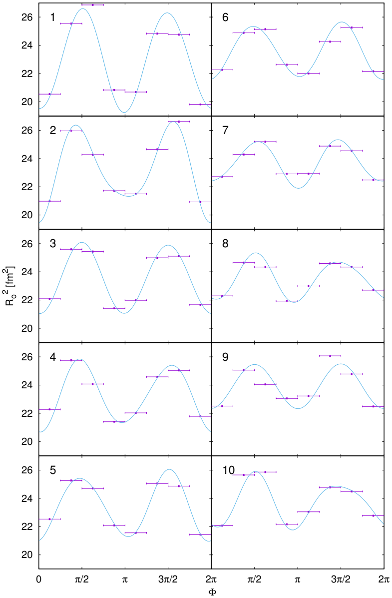
- simulated 2000 central 0–20% events from AMPT for $\sqrt{s_{NN}} = 2.76$ TeV
- correlation between sorting variable μ and elliptic flow v_2

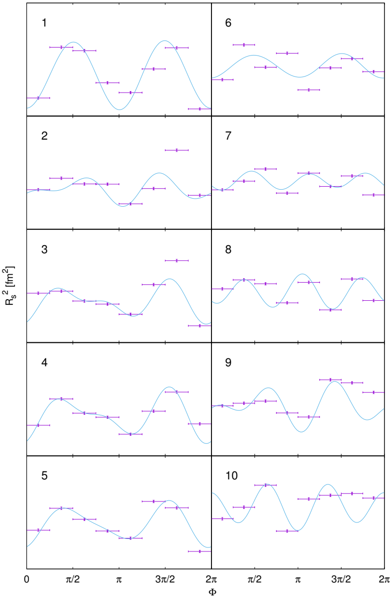




R. Kopečná, B. Tomášik: Eur. Phys. J. A **52** (2016) 115.

Correlation radii from AMPT-RHIC in different event bins





Correlation radii from AMPT-LHC in different event bins