Some thoughts about flow anisotropy

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ULtra-RelatIvistiCH HEavy IoNZ 2016
CERN, 19.7.2019

Motivation

- (transverse) flow is the response to pressure gradients
- inhomogeneities in the initial state are translated into anisotropies in flow and hadron distribution
- the response of the system depends on the properties of the matter: Equation of State and transport properties

Momentum deposition from jets

- 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.

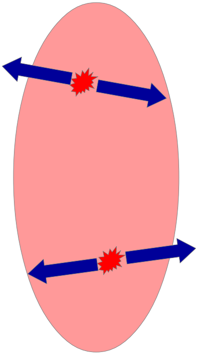
Anisotropic flow from isotropic jets

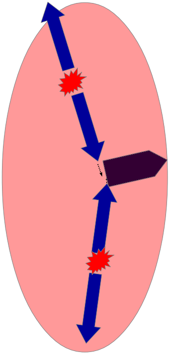
Streams are more likely to merge if they are directed out of reaction plane

$\Rightarrow$ 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

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

  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

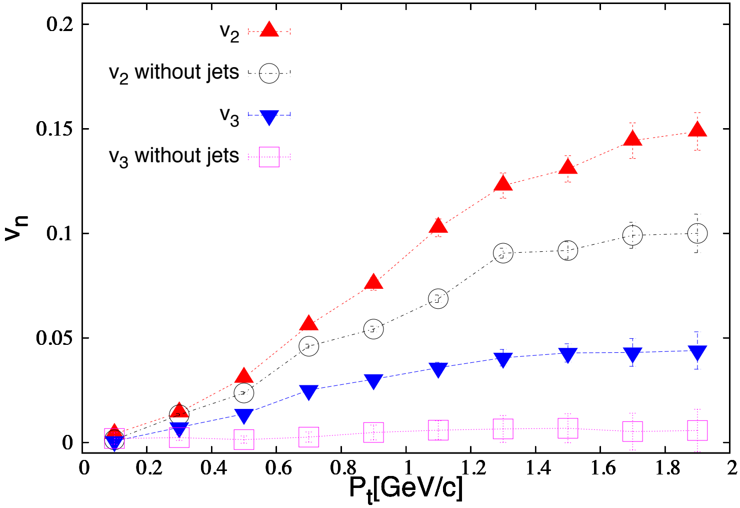
Generation of hard partons

- p_t according to
$$\frac{1}{2\pi}\frac{d\sigma_{NN}}{p_t dp_t\, dy} = \frac{B}{(1+p_t/p_0)^n}$$
$B = 14.7\ \mathrm{mb/GeV}^2$, $p_0 = 6\ \mathrm{GeV}$, $n = 9.5$

- back-to-back in p_t

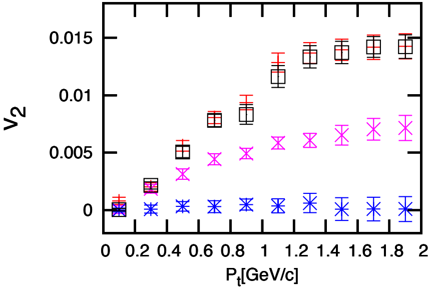
- spatial distribution according to Glauber model for binary collisions

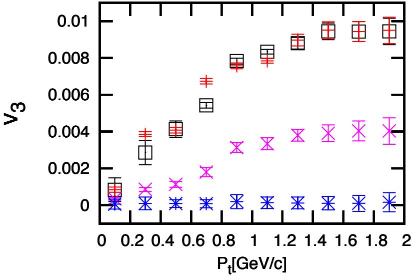
Results from 30–40% centrality

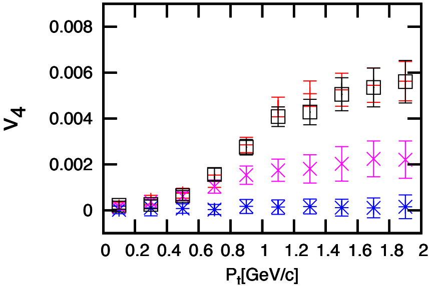


Results from ultra-central collisions

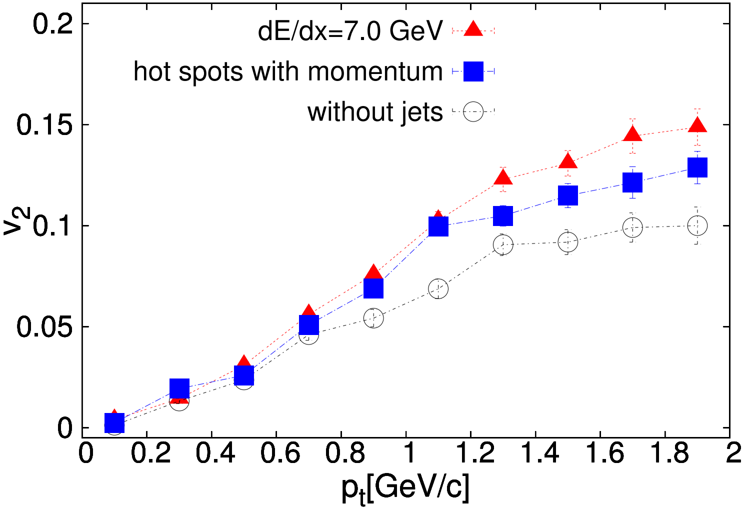
Anisotropy coefficients
compare:
$dE/dx = 7$ GeV/fm
$dE/dx = 4$ GeV/fm
hot spots
smooth initial conditions







This cannot be included into initial conditions



Similar approaches

- Y. Tachibana, T. Hirano: Phys. Rev. C **90** (2014) 021902
  reponse of medium to only one dijet
- R.P.G. Andrade, J. Noronha, G. Denicol:
  Phys. Rev. C **90** (2014) 024914
  one dijet, 2+1D hydrodynamics
- S. Floerchinger and K. Zapp: Eur. Phys. J. C **74** (2014) 3189
  1+1D hydrodynamics

Summary 1 and questions to be looked at. . .

- 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
- How the response to jets changes in viscous hydrodynamics?
- How does one distinguish initial state generated anisotropies from those generated on the way (from jets or dynamical fluctuations)?

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, arXiv:1512.06215 [nucl-th]

How to distinguish the sources of anisotropy?

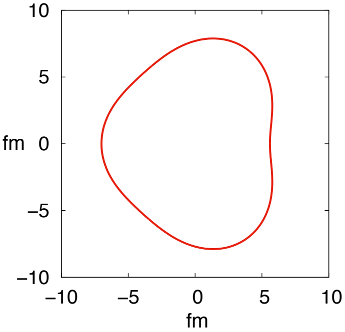
We do not know, yet. Possible ways include:

- evolution of modes (à la Wiedemann & Floerchinger)
- correlation of Fourier amplitudes
- resolving spatial and flow anisotropies with AS-femtoscopy

The v_n's provide ambiguous information about the system!

Anisotropy of hadron distribution can be caused by:

Spatial anisotropy



Flow anisotropy

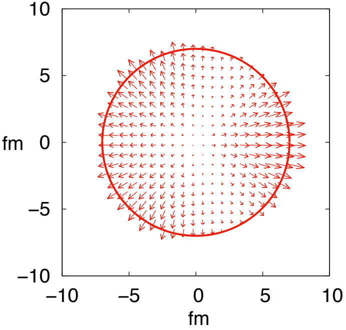


Illustration with extended BW model: Jakub Cimerman

Example: ambiguity in second-order anisotropies

v_2 calculated in the extended Blast-Wave model

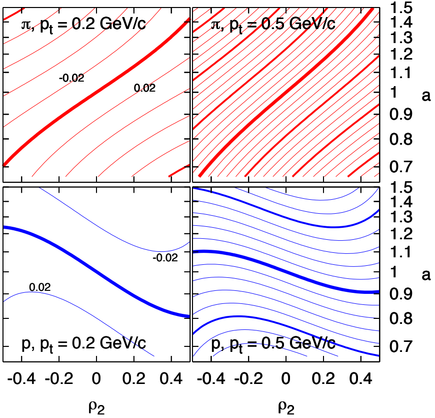
Spatial anisotropy: ratio of radii in out-of-plane/in-plane directions

$$a = \frac{R_x}{R_y}$$

Flow anisotropy: 2nd order variation of transverse rapidity ρ (with $R_0 = \sqrt{R_x R_y}$)

$$\rho = \frac{r}{R_0}\rho_0(1 + \rho_2 \cos(2\phi_s))$$

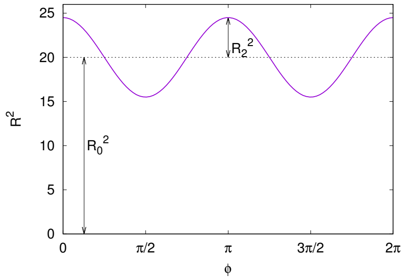
Contours of constant v_2

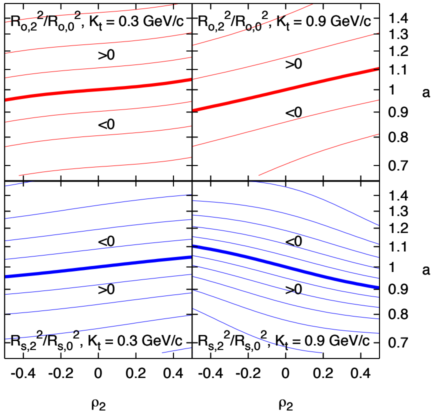


Boris Tomášik: Acta Physica Polonica **36** (2005) 2087

Oscillation of HBT radii

Scaled amplitude of azimuthal dependence



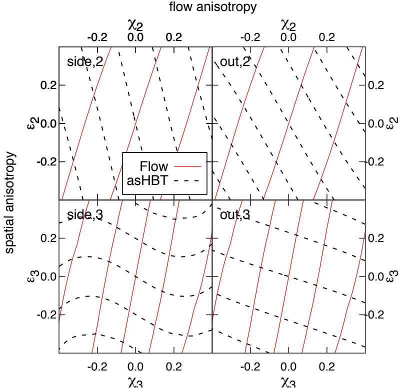


- Depends on spatial and flow anisotropy differently than v_2
- Here: blast-wave model

Resolving spatial and flow anisotropy

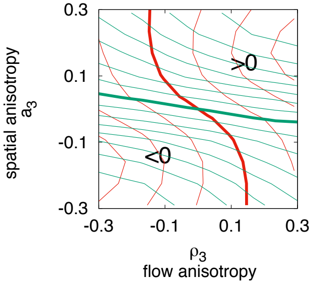
Look at both v_n and correlation radii oscillation
Worked out for 2nd and 3rd order

Buda-Lund model



Blast-Wave model

colour coding:
3rd order anisotropy of R_o^2, v_3



Summary 2

When studying the anisotropy of the fireball, look also at correlation radii.
Their azimuthal dependence can provide additional information.

References:
Blast-Wave 2nd order: B. Tomášik, Acta Phys. Polonica **36** (2005) 2087
Buda-Lund 2nd order: M. Csanád, B. Tomášik, T. Csörgő, Eur. Phys. J. A **37** (2008) 111
Buda-Lund 2nd and 3rd order: S. Lökös, M. Csanád, T. Csörgő, B. Tomášik, arXiv:1604.07470 [nucl-th]
Blast-Wave 2nd and 3rd order: J. Cimerman, B. Tomášik, M. Csanád, *in preparation*

A more exclusive selection of events?

Looking at the shape of the events,

there is always averaging over others but the selected order event plane.

Various event shapes are averaged out!

Can we see non-averaged events?

An example:

- $R_o^2(\phi)$ for a fireball with both 2nd and 3rd order flow anisotropy
- varying angles between 2nd and 3rd event plane

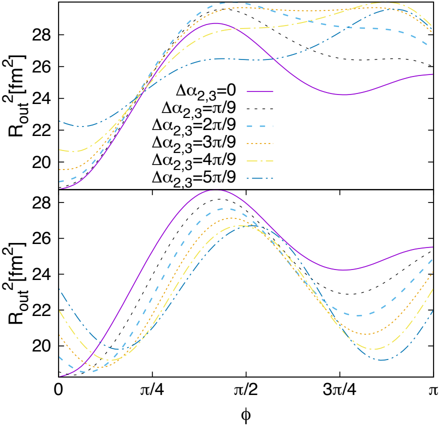


Figure: Sándor Lökös

Event Shape Sorting

- 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, like in Event Shape Engineering
  [J. Schukraft, A. Timmins, S. A. Voloshin, Phys. Lett. B 719 (2013) 394-398]

Algorithm based on:

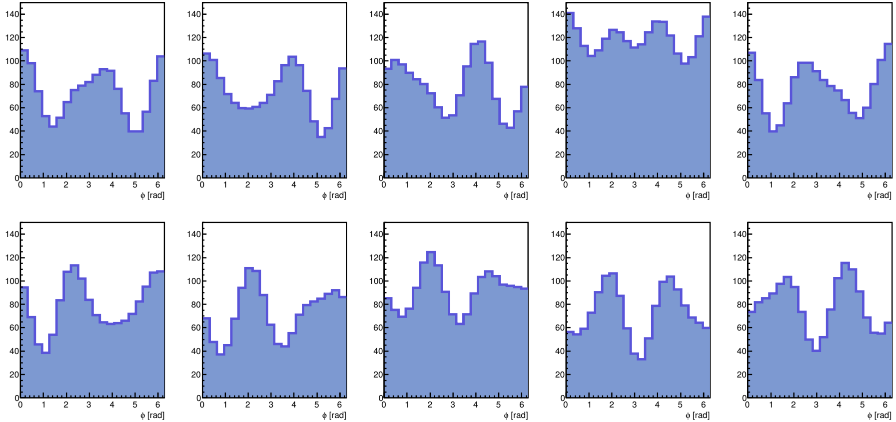
S. Lehmann, A.D. Jackson, B. Lautrup, arXiv:physics/0512238

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

Published in

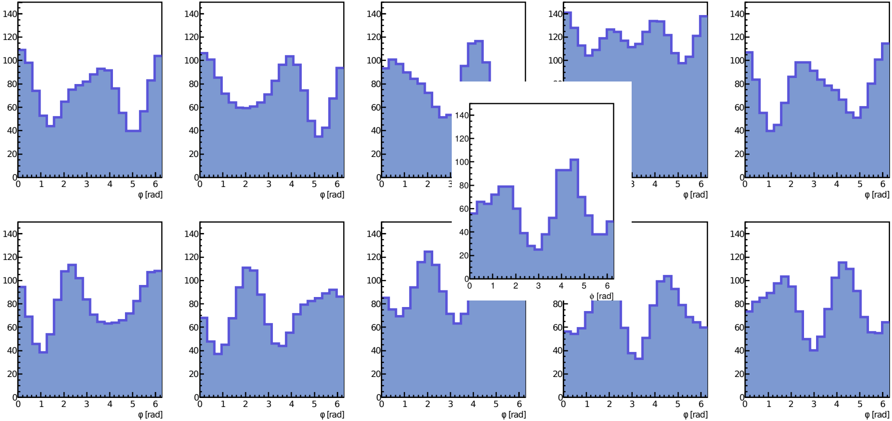
R. Kopečná, B. Tomášik: Eur. Phys. J. A **52** (2016) 115.

Assigning event to event bin



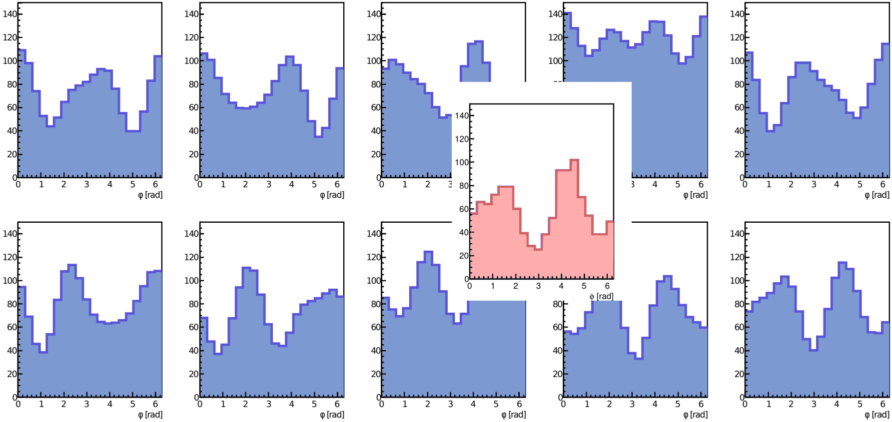
Assigning event to event bin

To which event bin is this event similar?



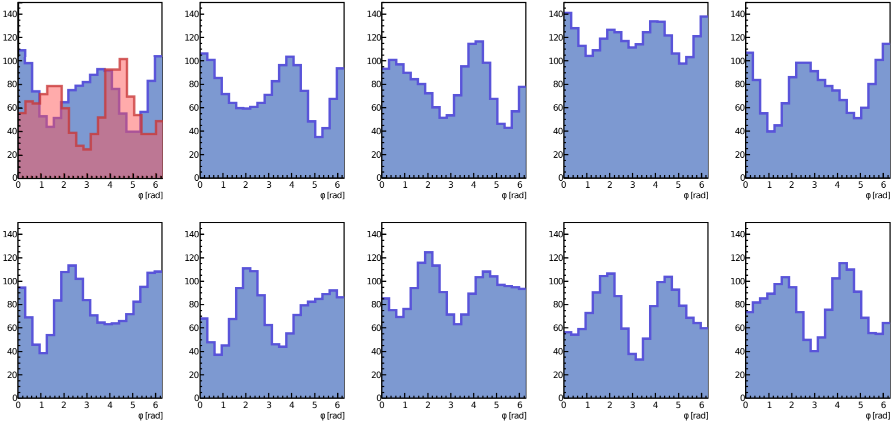
Assigning event to event bin

Calculate Bayesian probability that the event belong to each event bin



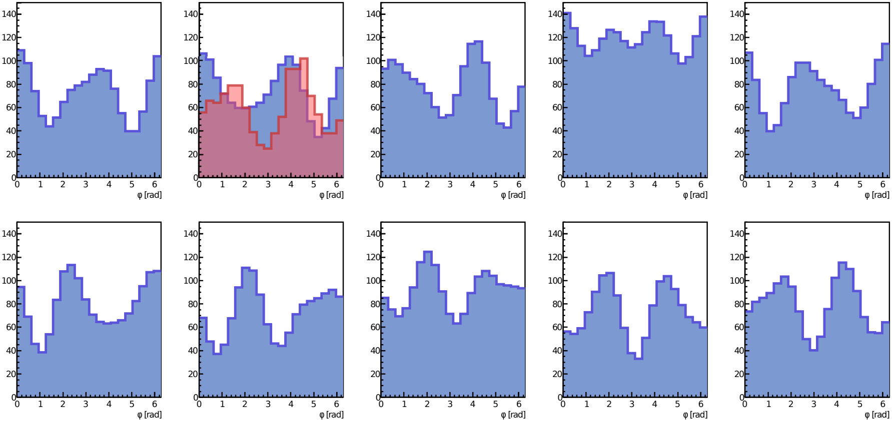
Assigning event to event bin

Calculate Bayesian probability that the event belong to event bin 1



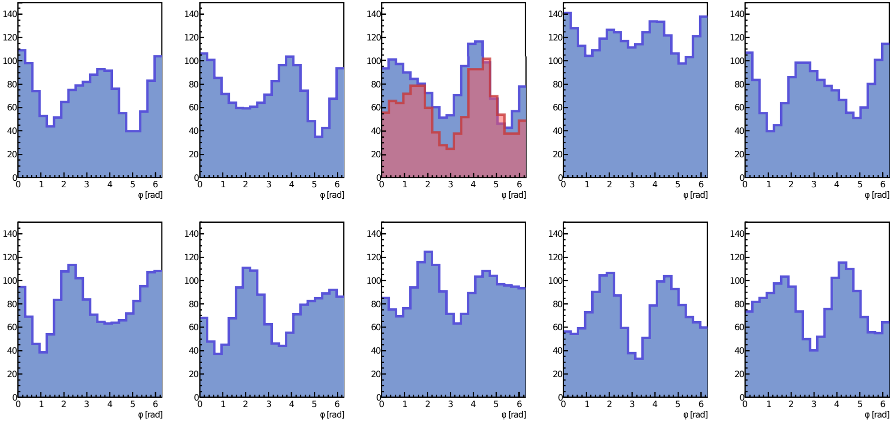
Assigning event to event bin

Calculate Bayesian probability that the event belong to event bin 2



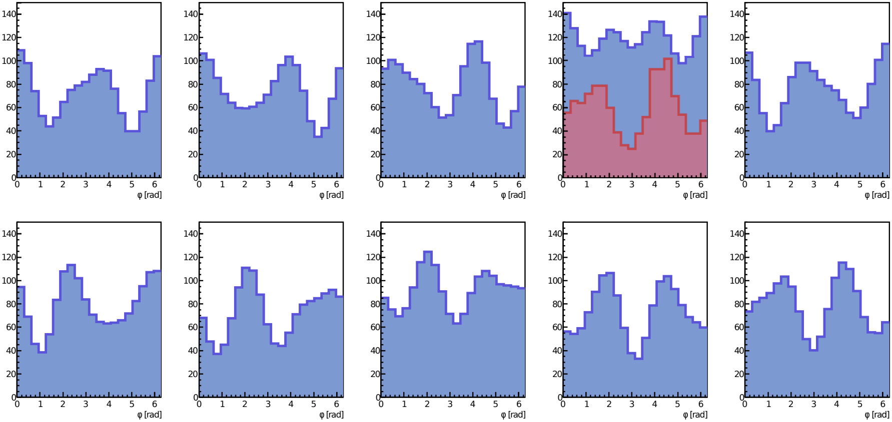
Assigning event to event bin

Calculate Bayesian probability that the event belong to event bin 3



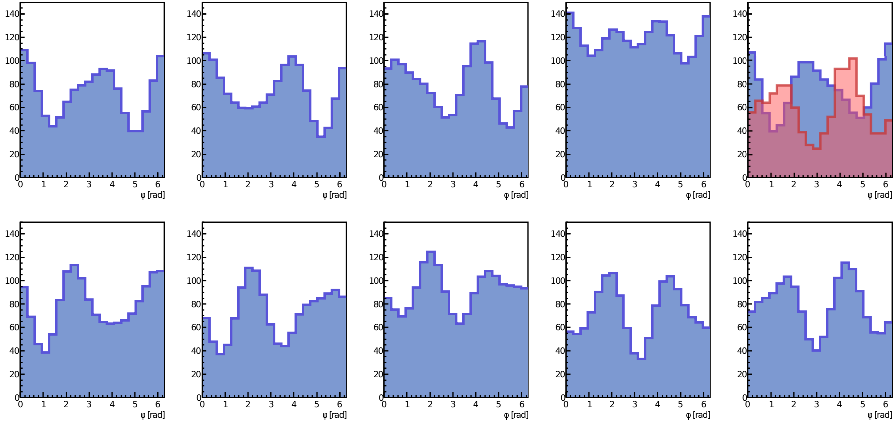
Assigning event to event bin

Calculate Bayesian probability that the event belong to event bin 4



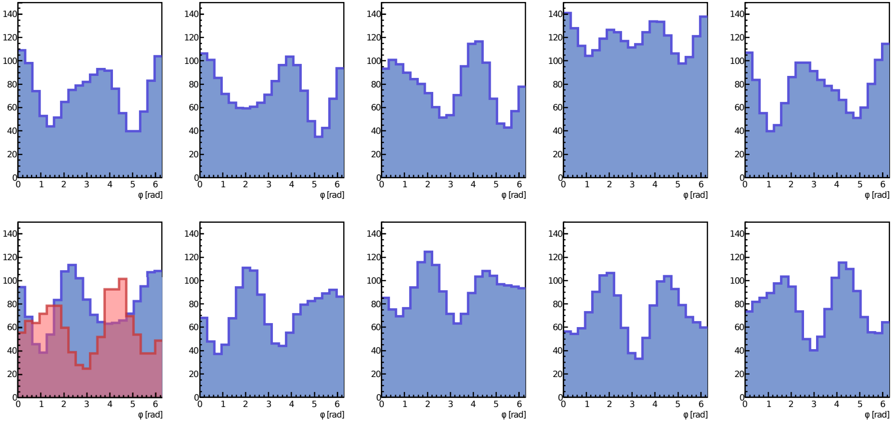
Assigning event to event bin

Calculate Bayesian probability that the event belong to event bin 5



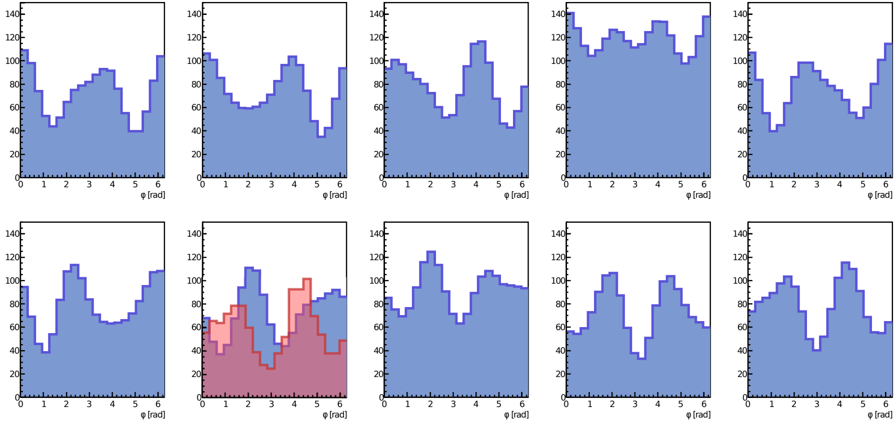
Assigning event to event bin

Calculate Bayesian probability that the event belong to event bin 6



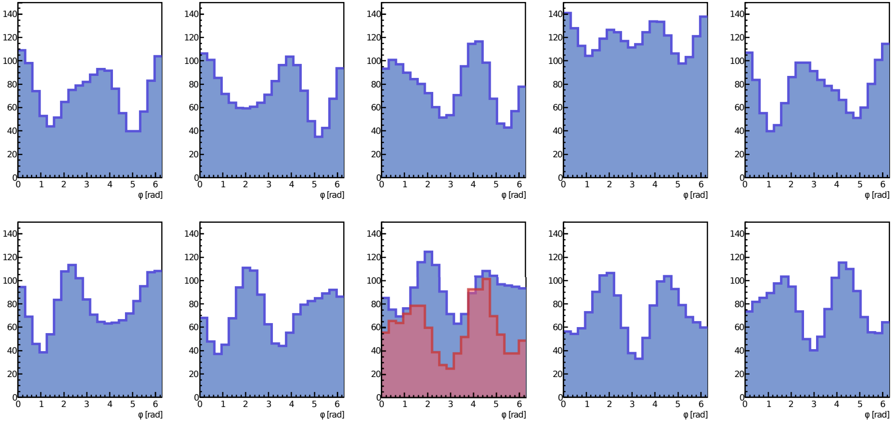
Assigning event to event bin

Calculate Bayesian probability that the event belong to event bin 7



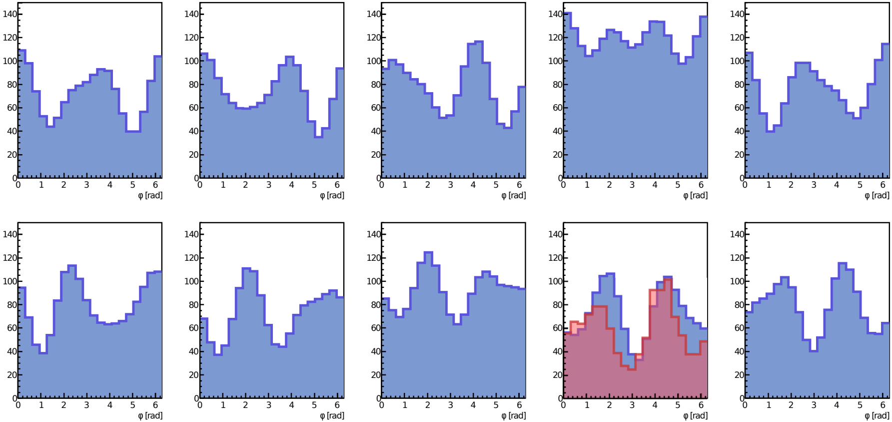
Assigning event to event bin

Calculate Bayesian probability that the event belong to event bin 8



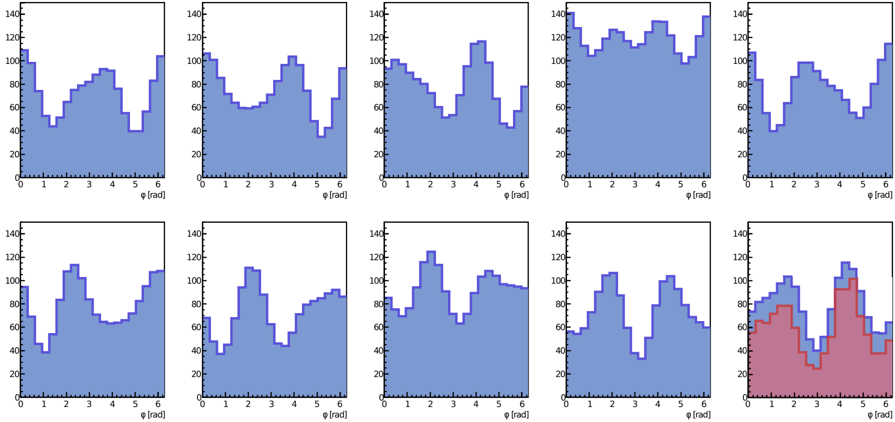
Assigning event to event bin

Calculate Bayesian probability that the event belong to event bin 9

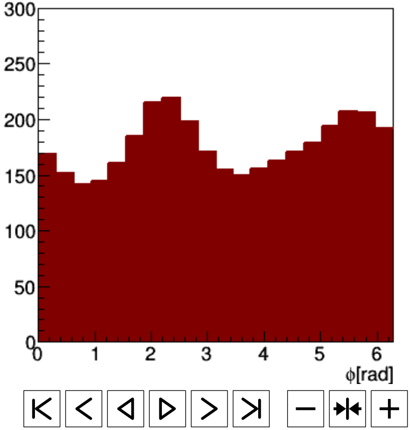


Assigning event to event bin

Calculate Bayesian probability that the event belong to event bin 10



Sorted events: Gradual change of event shape

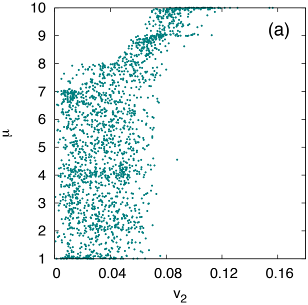


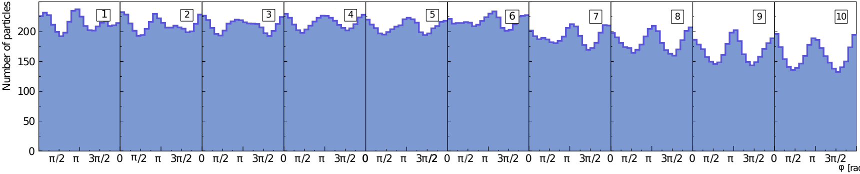
- 2000 events, AMPT centrality 0–20%, $\sqrt{s_{NN}} = 2.76$ TeV
- each frame averaged over 50 events and shifted by 10 events wrt previous frame
- change of colour = change of event bin

Sorted AMPT events

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.

Summary 3

Event shape sorting can help to select events with similar shapes for more exclusive studies.

Applications:

- More dedicated theory vs. experiment comparison
- Better background for correlation functions
- "Single-event femtoscopy"?
- . . .

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

Summary

- Include into realistic hydrodynamic simulations momentum deposition from hard partons. It can influence the anisotropies.
- Look at azimuthal dependence of correlation radii to get complementary information on the fireball.
- Try Event Shape Sorting to get more exclusive selection of event.

Backup: 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]]