Two topics on event anisotropies: hard parton contribution and event shape sorting

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Giardini Naxos, 1.9.2015

Anisotropic expansion

(only nuclear collisions and assume non-flow effects under control)

- generic effect: blue-shift
  $\Rightarrow$ more particles and higher p_t in direction of stronger transverse flow
- link between the observable spectrum and the expansion of the fireball
- expansion results from the pressure gradients
- anisotropic expansion $\Leftarrow$ anisotropic pressure gradients in initial conditions
- initial conditions evolved into final distribution—nothing added

Mapping of ε_n's and v_n'n

- spatial anisotropy

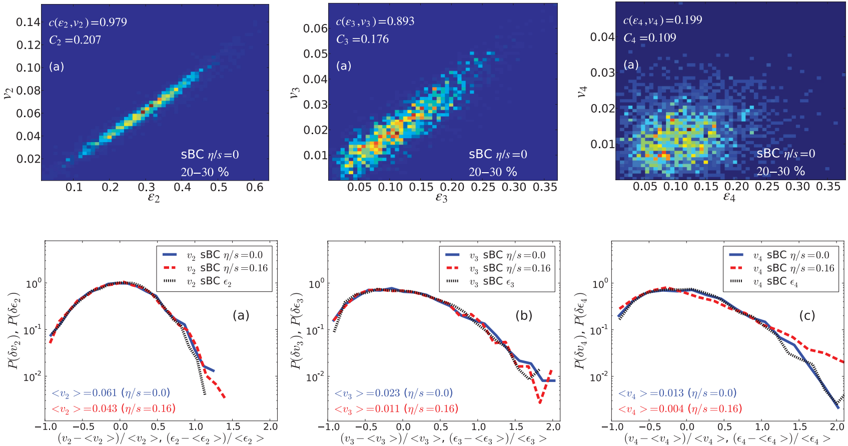
$$\varepsilon_{m,n} e^{in\Psi_{m,n}} = \int r\, dr\, d\phi\, r^m e^{in\phi}\, \rho(r, \phi)$$

use $\varepsilon_n = \varepsilon_{n,n}$

- to a very good extent $\langle v_n \rangle = k \langle \varepsilon_n \rangle$
  [F.G. Gardim *et al.*, Phys. Rev. C **85** (2012) 024908]

- also mapping between the values in individual events and between probability distributions
  valid for various initial conditions and ideal as well as viscous hydro
  [H. Niemi *et al.*, Phys. Rev. C **87** (2013) 54901]

Mapping of ε_n's and v_n'n – cont'd



[H. Niemi *et al.*, Phys. Rev. C **87** (2013) 054901]

One question and one answer

Question

Does the hydrodynamical evolution really not contribute to the fluctuations of flow anisotropies?

Answer

We demonstrate such a mechanism based on deposition of *momentum* from a number of hard partons into the fluid.

Momentum deposition 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.

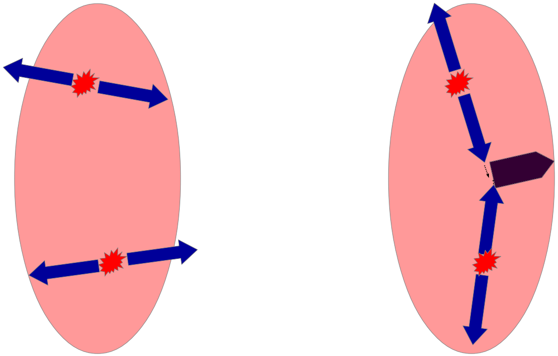
Anisotropic flow from isotropic hard partons

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

$\Rightarrow$ less contribution to flow out of plane

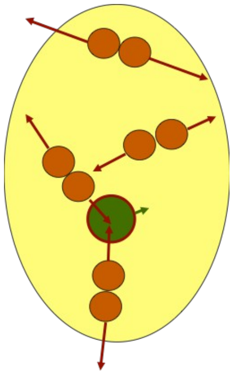
$\Rightarrow$ enhance v_2 correlated with the reaction plane

$\Rightarrow$ also contribute to v_3



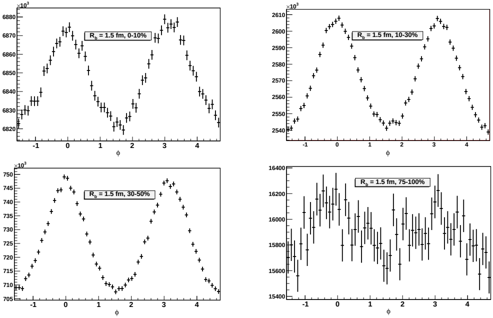
Check the idea with a toy model

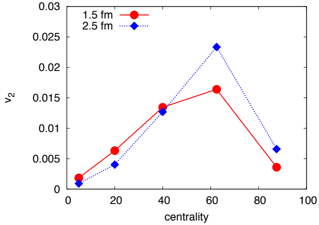
- Streams represented by drops
- Pairs of drops back-to-back (with some k_t smearing)
- Drops merge after they meet
- Size of the drop represents the radius of the stream
- Pions evaporate from droplets ($T = 175$ MeV)



Toy model – results

Azimuthal distribution of hadrons





[B. Tomášik, P. Lévai: J.Phys.G **38** (2011) 095101]

Hydrodynamic implementation

[B. Betz et al.: Phys. Rev. C **79** (2009) 034902]

Ideal hydrodynamics with source term

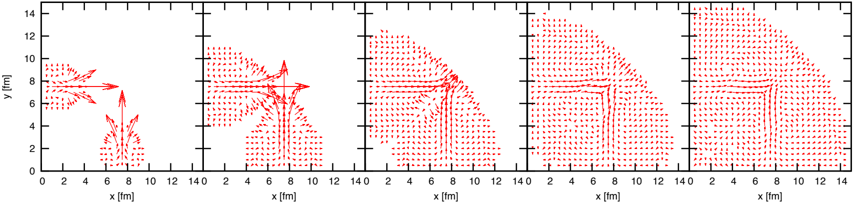
$$\partial_\mu T^{\mu\nu} = J^\nu$$

$$J^\nu = \sum_i \frac{1}{(2\,\pi\,\sigma_i^2)^{3/2}} \exp\left(-\frac{\left(\vec{x}-\vec{x}_{\mathrm{jet},i}\right)^2}{2\,\sigma_i^2}\right) \left(\frac{dE_i}{dt}, \frac{d\vec{P}_i}{dt}\right)$$

with $\sigma = 0.3$ fm

Test of the concept: static medium

The stream includes about 90% of hard parton momentum
Two streams meet perpendicularly
Plot momentum density



[M. Schulc, B. Tomášik: J. Phys. G **40** (2013) 125104]

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 $\alpha = 0.16$, $\varepsilon(0,0,0) = 60\ \mathrm{GeV/fm}^3$ at $\tau_0 = 0.55\ \mathrm{fm}/c$
  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, $n = 9.5$

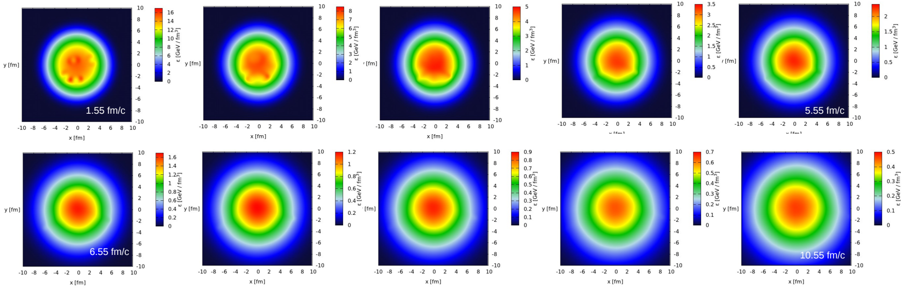
- back-to-back in p_t

- spatial distribution according to Glauber model for binary collisions

Illustration: evolution of energy density

Evolution of an event with four pairs of jets at the beginning.

frames follow with time delay 1fm$/c$



Results from ultra-central collisions

Anisotropy coefficients

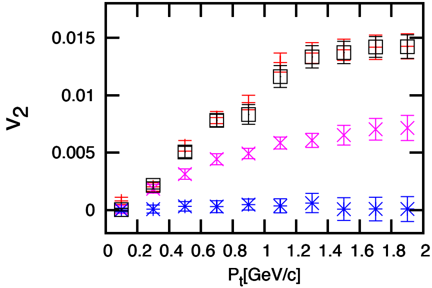
compare:

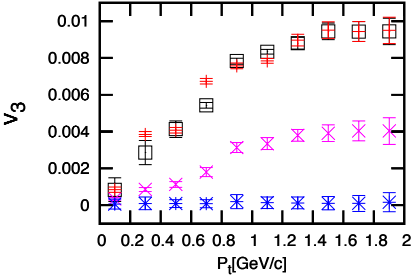
$dE/dx = 7$ GeV/fm

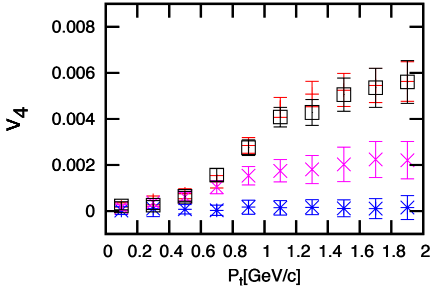
$dE/dx = 4$ GeV/fm

hot spots

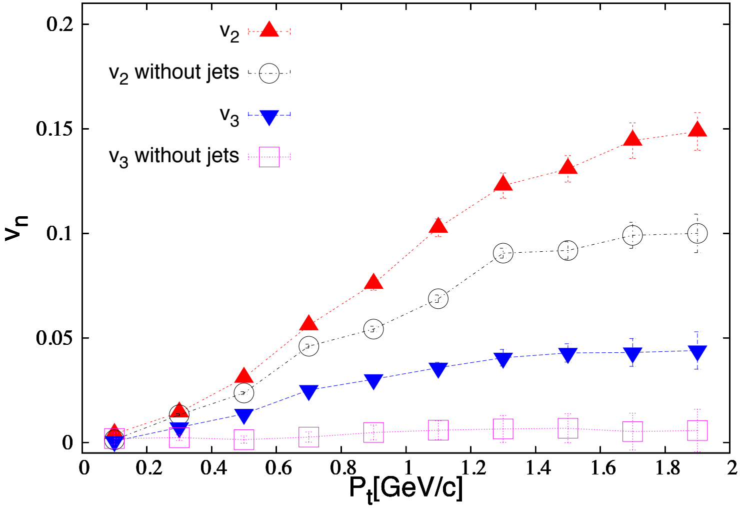
smooth initial conditions







Results from 30–40% centrality



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

Questions to be looked at...

- How does one distinguish initial state generated anisotropies from those generated on the way (from jets or dynamical fluctuations)?
  Get v_2 with different methods...
  Correlations of various v_n's...

- How much anisotropy can one produce during evolution in order not to produce too much entropy?

- How the response to jets changes in viscous hydrodynamics?

Preliminary summary

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

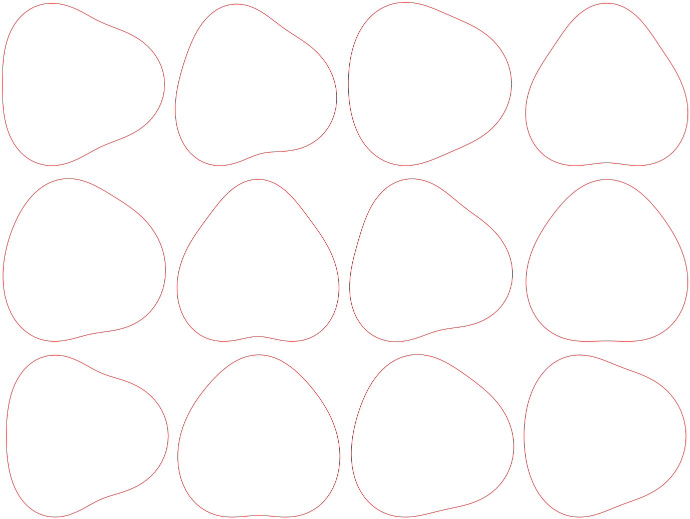
- The interplay of many induced streams is important

- Outlook: simulations with viscous hydrodynamics and fluctuating initial conditions

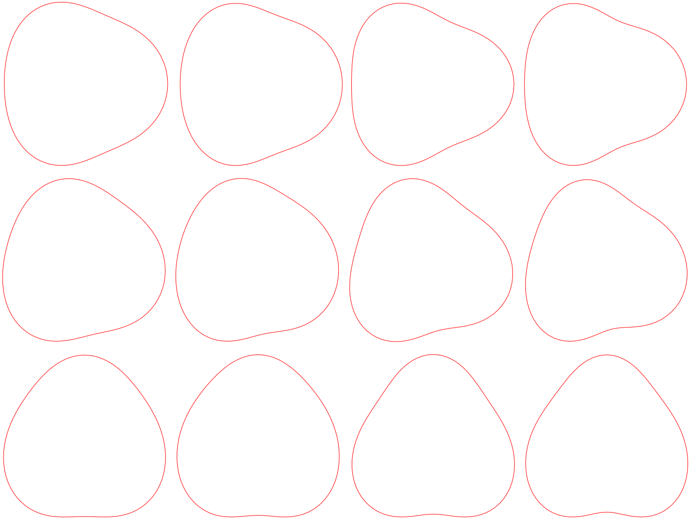
M. Schulc, B. Tomášik: Phys. Rev. C **90** (2014) 064910
[arxiv:1409.6116]

Event shapes

How to do Event Shape Engineering among these shapes. . . ?



. . . ordered



Similar events

- in *similar events* the evolution is likely to be similar
- analyse samples of similar events!
- How to select similar events?

Event Shape Sorting: the algorithm

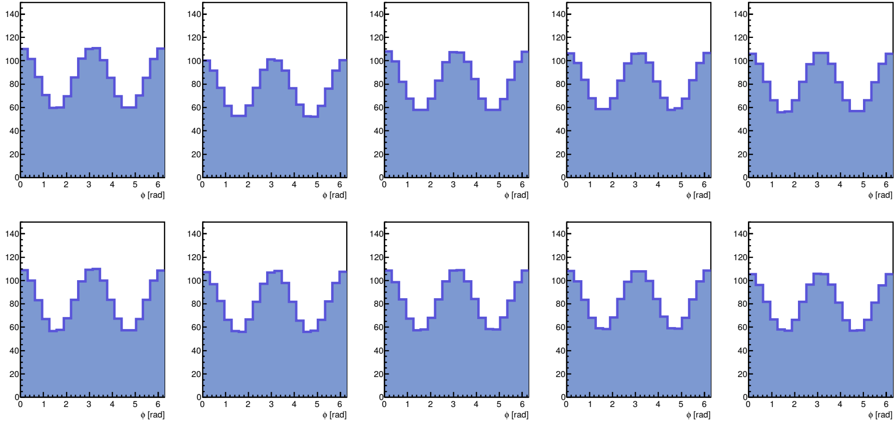
We will sort events according to their histograms in azimuthal angle.

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]]

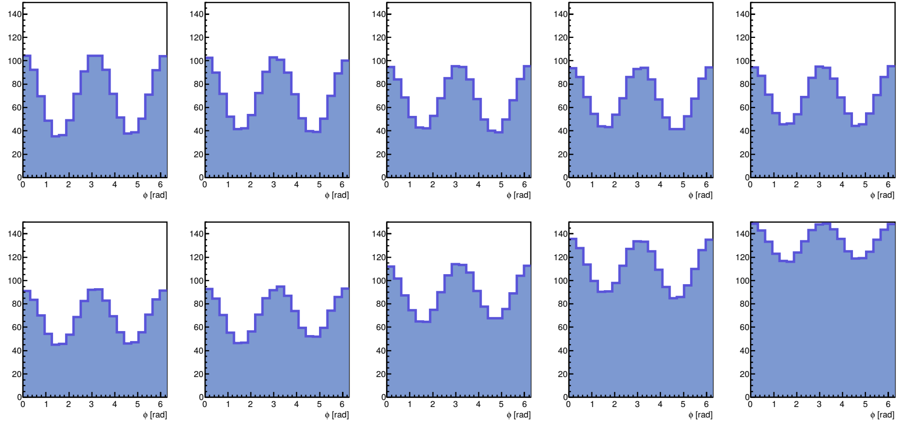
Average histograms for random sorting 'before'

Only fluctuating v_2



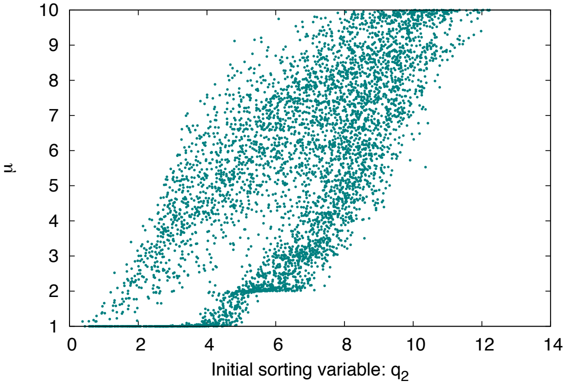
Average histograms for random sorting 'after'

Only fluctuating v_2



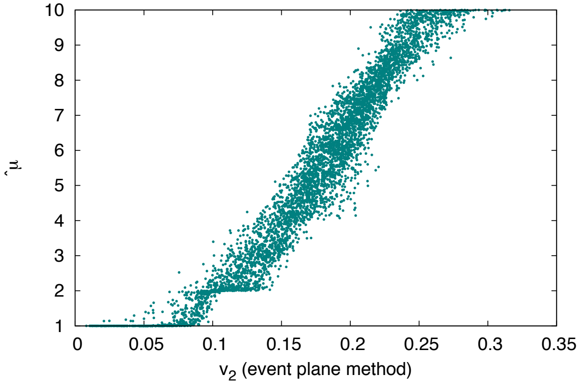
Toy Model: q_2 sorting

- Generated 5000 events up to v_2, $v_2 = aM^2 + bM + c$
- $M \in (300, 3000)$
- Initial rotation: Ψ_2
- Sort: q_2



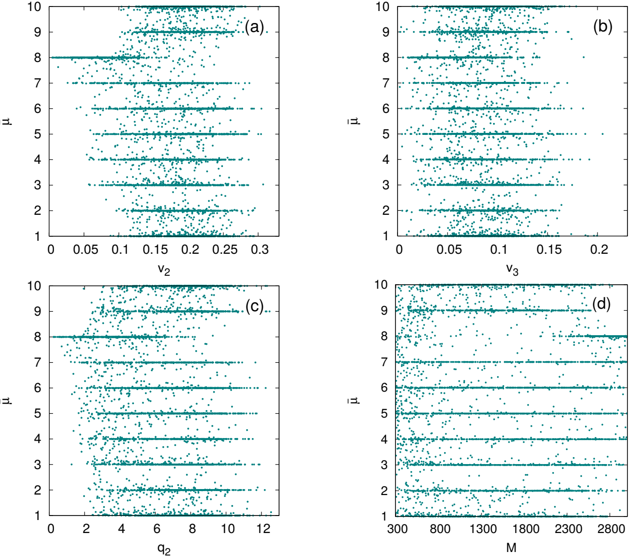
Elliptic flow for q_2 sorting

- Correlation v_2 and μ: 0.959
- Obvious linear dependence
- v_2 might be a better measure than q_2

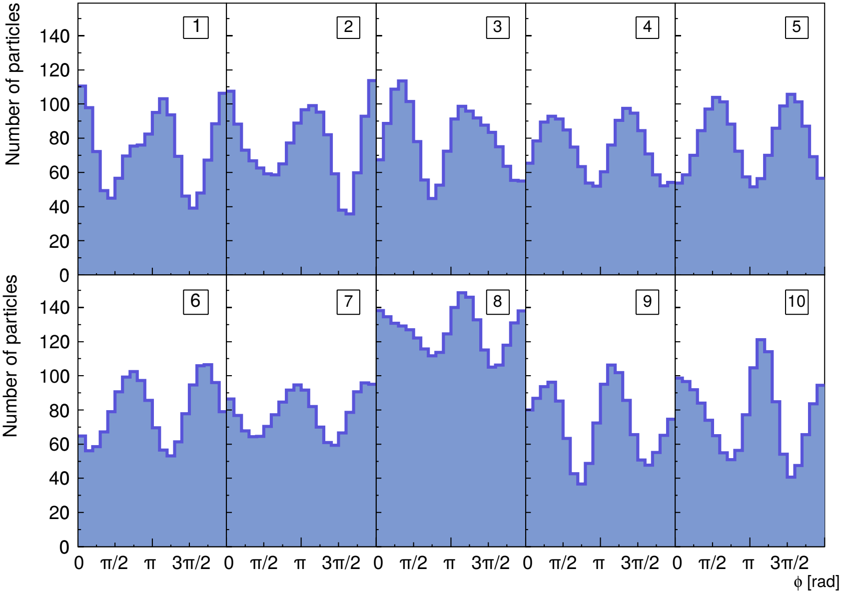


More realistic: all orders of anisotropy

No correlation with any of the conventional measures



More realistic anisotropy: sorting



Summary

- Event Shape is determined in more complicated way than single variable can characterize
- Try Event Shape Sorting (ESS)
- ESS might be useful for Single Event Femtoscopy
- Hard parton momentum deposition may give important contribution to flow anisotropies. This will be important to account for when extracting transport properties.

R. Kopečná, B. Tomášik: arxiv:1507.XXXXX
M. Schulc, B. Tomášik: Phys. Rev. C **90** (2014) 064910 [arxiv:1409.6116]