Observables of the non-equilibrium phase transition

Boris Tomášik

Univerzita Mateja Bela, Banská Bystrica, Slovakia
and České vysoké učení technické, FNSPE, Praha, Czech Republic

boris.tomasik@umb.sk

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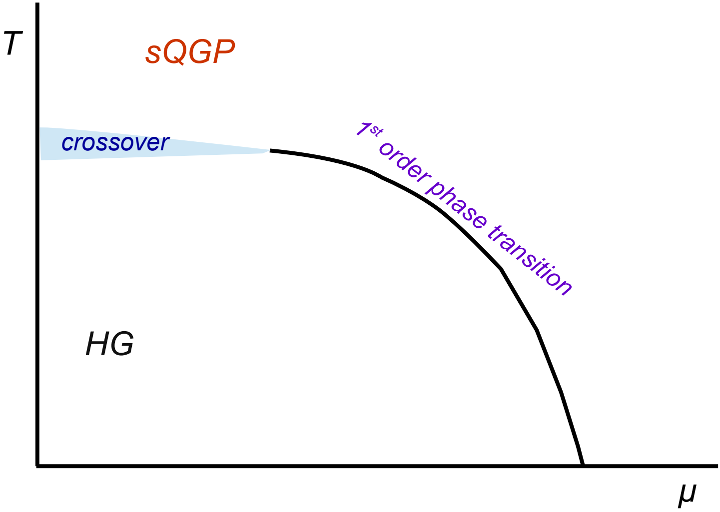
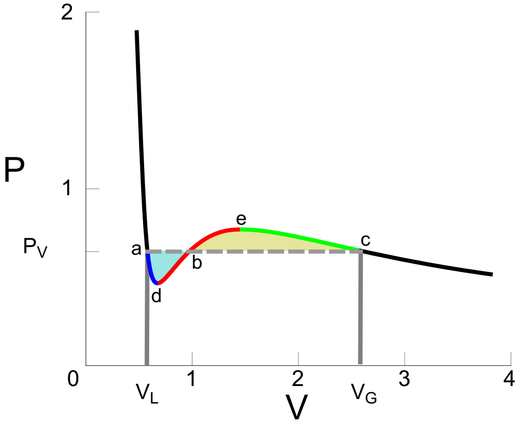
The phase diagram of strongly interacting matter



1st order phase transition

- phase coexistence for *slow* transitions
- spinodal fragmentation for fast processes



Spinodal fragmentation in liquid/gas nuclear phase transition

P. Chomaz, M. Colonna, J. Randrup, Phys. Rept. **384** (2004) 263-440

Size of the fragments

the size decreases with expansion rate H

$$R = \left(\frac{5\gamma}{\Delta E\, H^2} \right)^{1/3}$$

ΔE is latent heat, H is Hubble constant, γ is surface tension

I.N.Mishustin, Phys. Rev. Lett. **82** (1999) 4779

Simulations

J. Randrup, J. Steinheimer: PRL 109 212301, PRC 87 054903, PRC 89 034901 (with V. Koch)

Equation of State is augmented by the surface term
Enhancement of the baryon density fluctuations

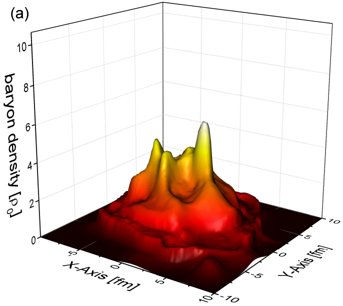
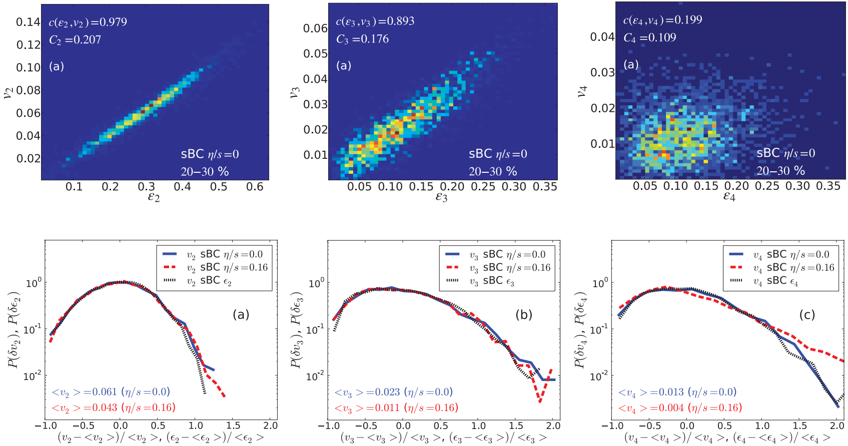


figure: J. Steinheimer, J. Randrup: PoS (CPOD 2013) 016

N.B. fluctuations at high energies

There is a commonly accepted paradigm, that the azimuthal anisotropies observed at RHIC and LHC are caused only by anisotropies in initial state

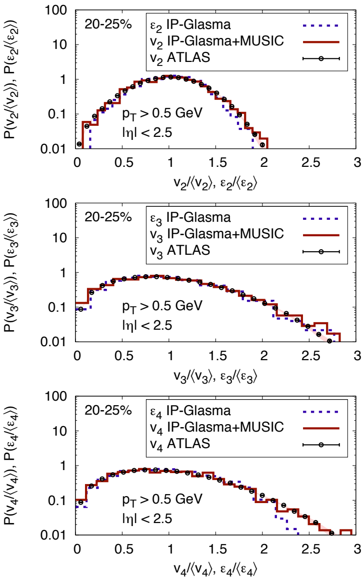


[H. Niemi *et al.*, Phys. Rev. C **87** (2013) 054901]

Fluctuating initial conditions

- Use the fluctuations of v_n's to get the access to initial conditions.
- fluctuations of v_n's seem to follow those of spatial anisotropies ε_n's

[Ch. Gale et al.: Phys. Rev. Lett. **110** (2013) 012302]

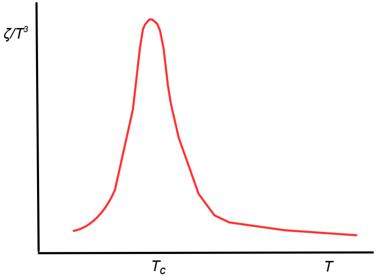


Fragmentation (cavitation) due to bulk viscosity

rate of energy density decrease with bulk viscosity

$$\frac{u^\mu \partial_\mu \varepsilon}{\varepsilon} = \frac{\varepsilon + p - \zeta \partial_\rho u^\rho}{\varepsilon} \partial_\mu u^\mu$$

effective decrease of the pressure due to bulk viscosity



fragment size estimate in Bjorken scenario

$$L^2 = \frac{24\zeta_c}{\varepsilon_c \partial_\mu u^\mu|_{\tau=\tau_c}}$$

G. Torrieri, B. Tomášik, I.N. Mishustin, Phys. Rev. C **77** (2008) 034903

Rapidity correlations

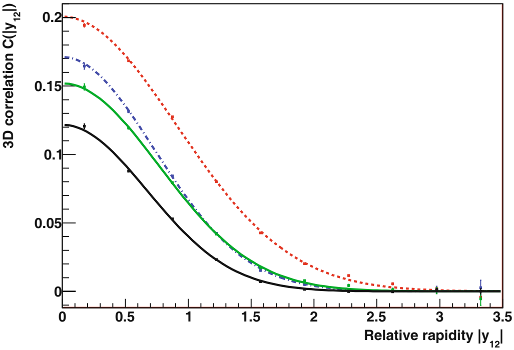
- If the fireball fragments, hadrons will be correlated
- choose protons: heavy (less thermal smearing) and still abundant (good statistics)
- correlation functions in 3D rapidity differences:

$$
\begin{aligned}
y_{12} &= \ln\left[\gamma_{12} + \sqrt{\gamma 12 - 1}\right] \\
\gamma_{12} &= \frac{p_1 \cdot p_2}{m_1 m_2}
\end{aligned}
$$

J. Randrup, Heavy Ion Physics **22** (2005) 69

Rapidity difference correlation function for protons

- all hadrons emitted from droplets
- at FAIR/NICA expect bigger droplets
- lines color coding:
  FAIR/NICA,
  RHIC 130,
  RHIC 130 no resonances
  LHC



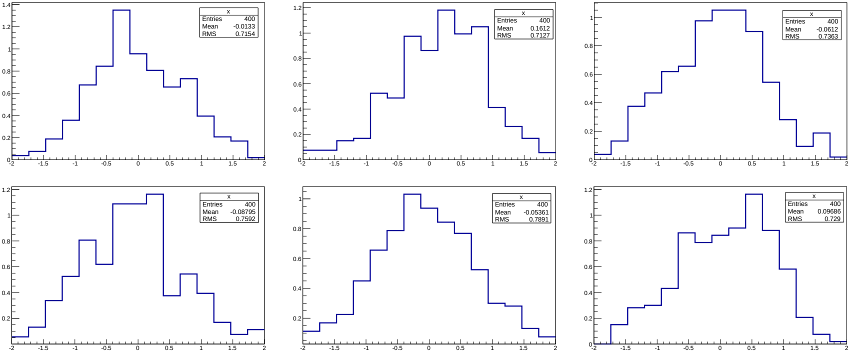
- Signal weaker if only a fraction of all hadrons from droplets
- here neglected Fermi-Dirac statistics and strong interaction: expect effect at 25 MeV (small relative rapidity)

M. Schulc, B. Tomášik, Eur. Phys. J. A **45** (2010) 91

Comparison of rapidity distribution

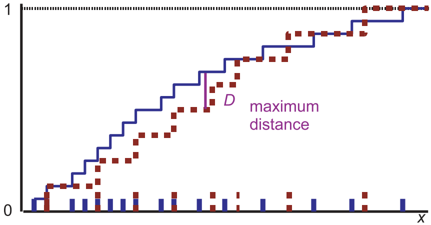
- If there are fluctuations, each event (from the same centrality class) will have a different rapidity distribution.
- Spinodal fragmentation will lead to droplets which will emit hadrons.
- How do we recognise a non-statistical difference between two empirical distributions?

Are these realisations of the same distribution?



The Kolmogorov-Smirnov test

Are two empirical distributions generated by the same probability density?
Construct *distance* D between two emipirical distributions (event rapidity distributions) for all event pairs



Take away the effect of multiplicity

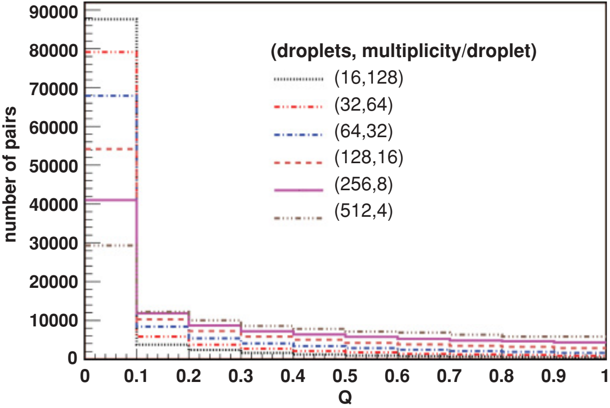
$$d = \sqrt{\frac{n_1 n_2}{n_1 + n_2}} D$$

Use the probability $Q(d)$: probability, that randomly selected pair of events generated by the same distribution will have their distance bigger than d.

Events from the same distribution will lead to uniform Q-distribution.
Non-statistically different events will show a peak at small Q.
(There are formulas to calculate $Q(d)$.)

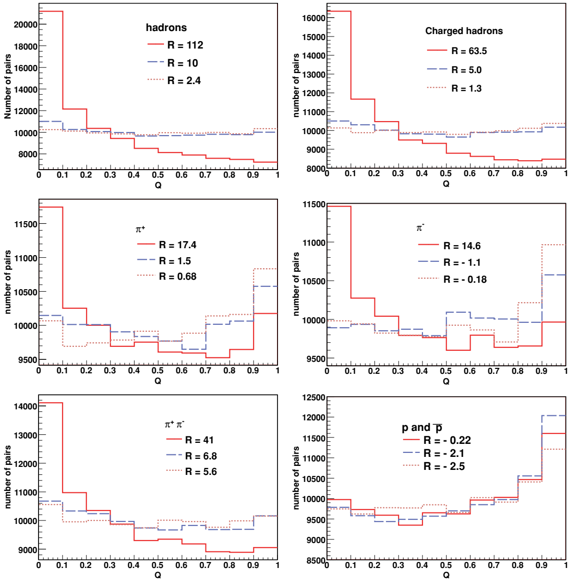
Convolution of droplets which emit pions

- uniformly distributed Gaussian sources with the width 0.707
- always the same total multiplicity



Application to Monte-Carlo-generated data

- DRAGON:
  Blast-wave model with possible droplet production
- lines color coding:
  RHIC with droplets,
  RHIC no droplets,
  FAIR no droplets

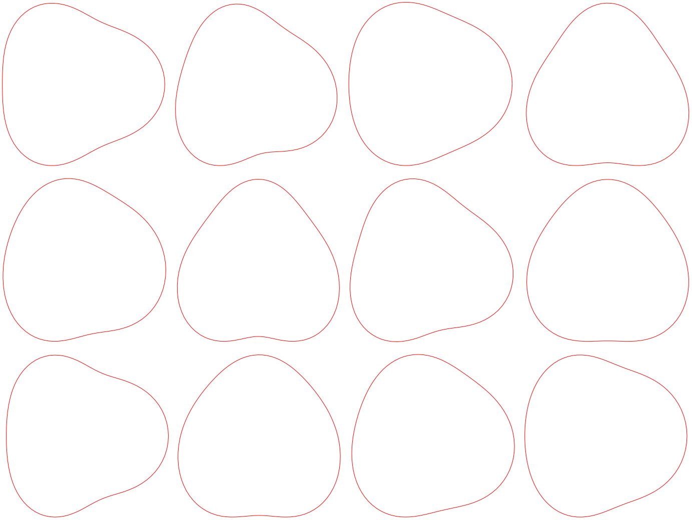


Kolmogorov-Smirnov test is a powerful tool to check if there are droplets/clusters observed in the observed events.

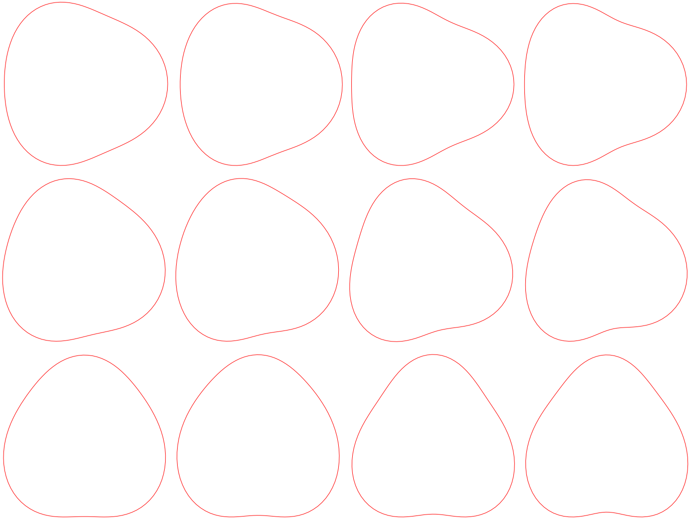
I. Melo *et al.*, Phys. Rev. C. **80** (2009) 024904

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

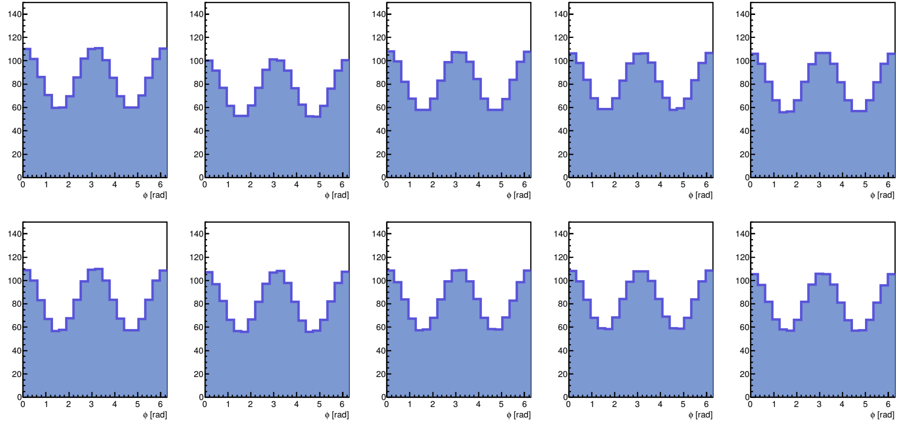
We will sort events according to their histograms in azimuthal angle.

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]]

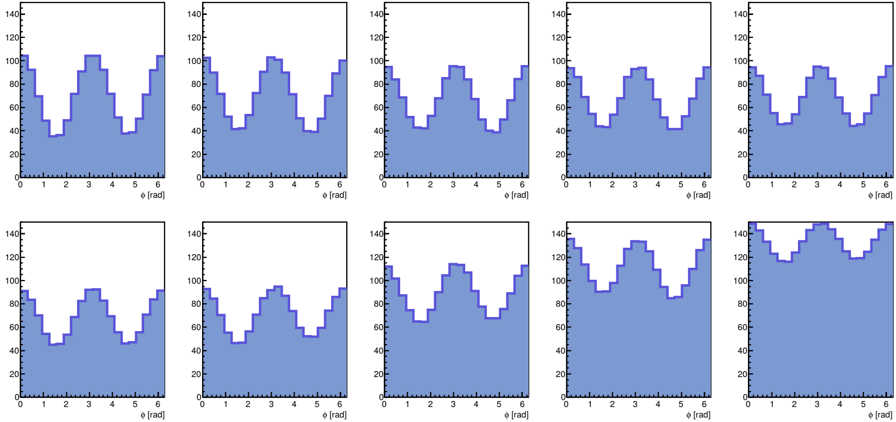
Average histograms for random sorting 'before'

Only fluctuating v_2



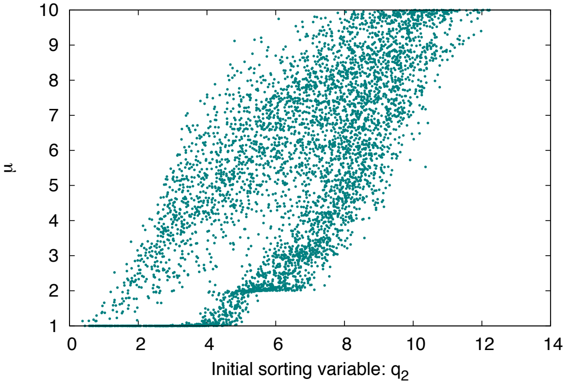
Average histograms for random sorting 'after'

Only fluctuating v_2



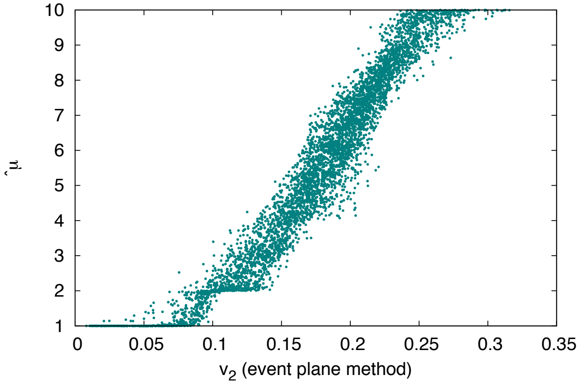
Toy Model: q_2 sorting

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



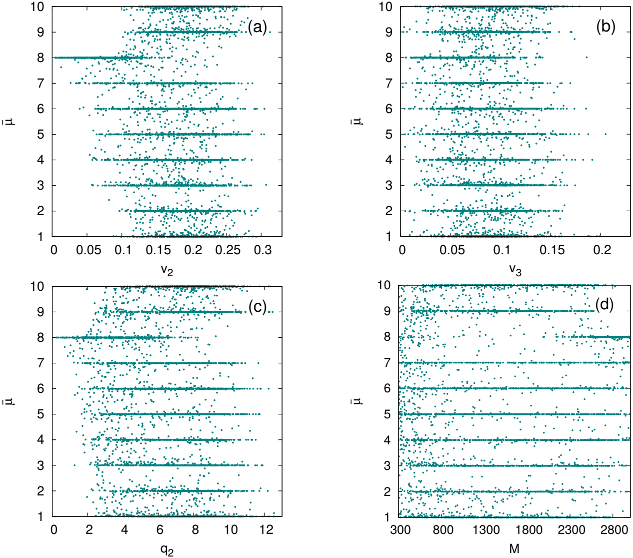
Elliptic flow for q_2 sorting

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

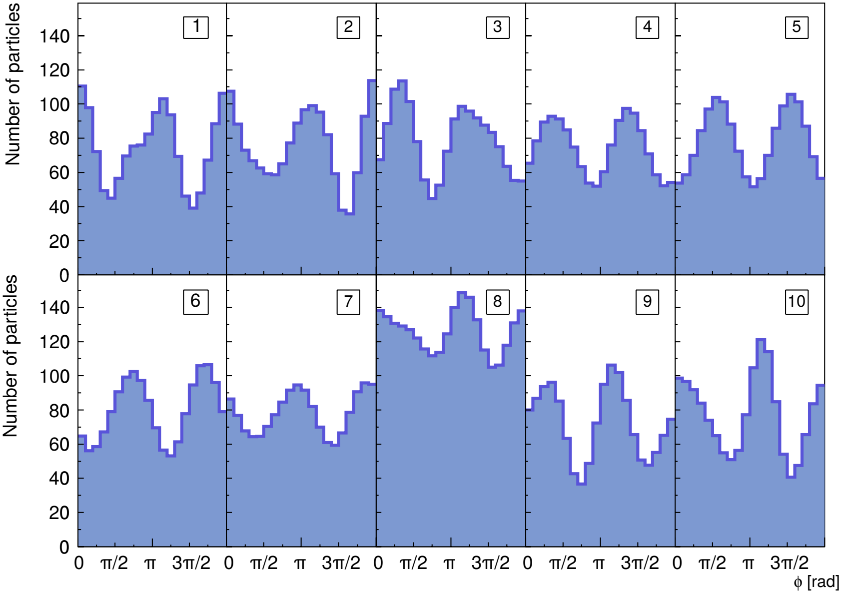


More realistic: all orders of anisotropy

No correlation with any of the conventional measures



More realistic anisotropy: sorting



Event Shape Sorting

- The same method can be applied on rapidity distributions or even on 2D histograms

- Event Shape is determined in more complicated way than single variable can characterize

- ESS might be useful (necessary?) for building mixed events samples in the construction of correlation functions

- ESS might be useful for Single Event Femtoscopy

R. Kopečná, B. Tomášik: arxiv:1506.06776

Summary

- spinodal fragmentation at the first-order phase transition
- first-order phase transition would lead to baryon number/density fuctuations ad correlations (correlation function, Kolmogorov-Smirnov test)
- there could be fragmentation also at higher collision energies due to bulk viscosity peak—what would be the unique signal of critical point
- Event Shape Sorting - look at events with similar shapes