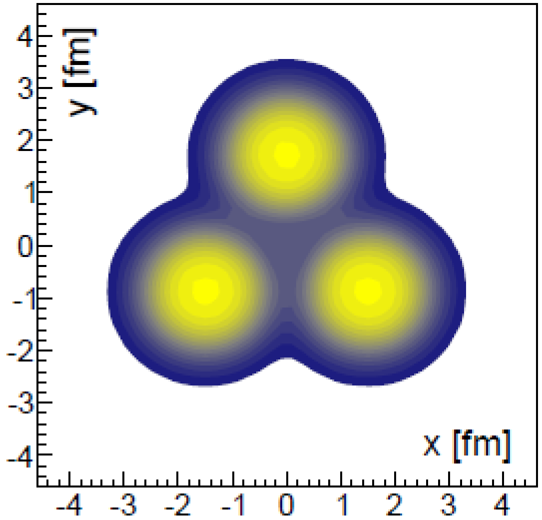
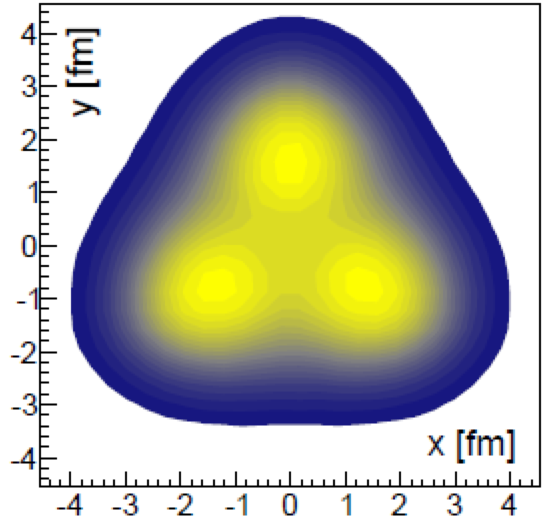
α clusters
in ultra-relativistic light-ion + Pb collisions

Maciej Rybczyński

Institute of Physics, Jan Kochanowski University, Kielce





Based on
W. Broniowski, E. R. Arriola, Phys. Rev. Lett. **112**, 112501 and
P. Bozek, W. Broniowski, E. R. Arriola, MR, Phys. Rev. **C90**, 064902
MR, M.Piotrowska, W.Broniowski, arXiv: **1711.00438**

Outline

Two phenomena are related:

α clustering in light nuclei
and
harmonic flow in ultra-relativistic nuclear collisions

- ✓ New method of investigating many-particle nuclear correlations
- ✓ Another test of collective dynamics/harmonic flow

Some history

David Brink: *After Gamow's theory of α-decay it was natural to investigate a model in which nuclei are composed of α-particles. Gamow developed a rather detailed theory of properties in his book "Constitution of Nuclei" published in 1931 before the discovery of the neutron in 1932. He supposed that 4n-nuclei like ^{8}Be, ^{12}C, ^{16}O ... were composed of α-particles.*

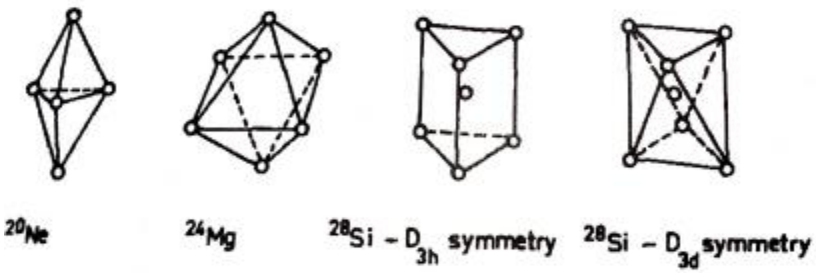
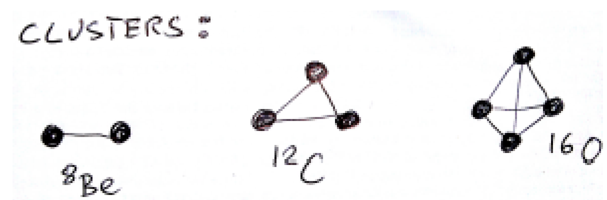
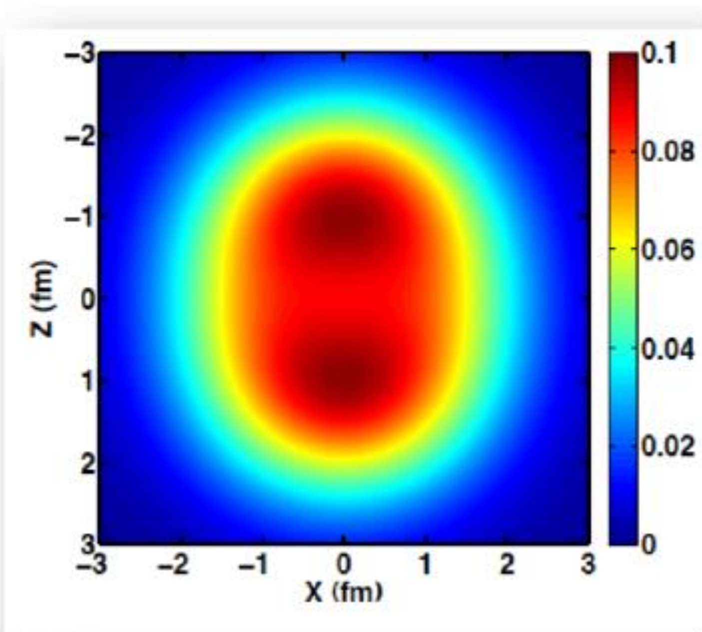


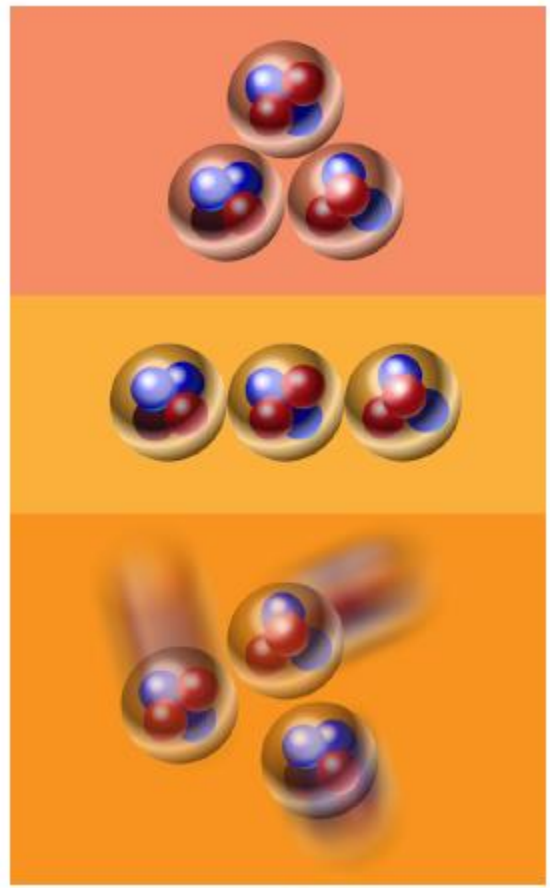
Fig. 1. Alpha-particle configuration for some 4*N* nuclei.



α clusters in light nuclei



^{9}Be



ground

Hoyle 0^{+}

other excited, 2^{+} ...

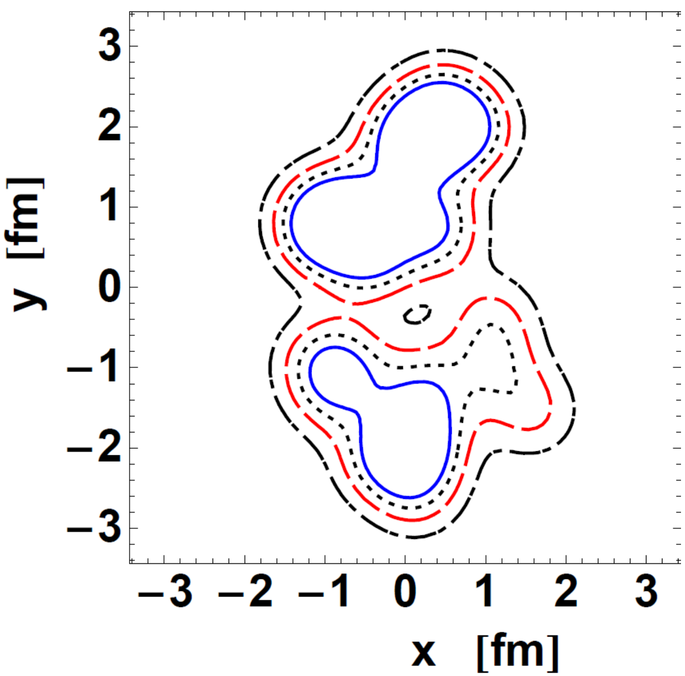
^{12}C

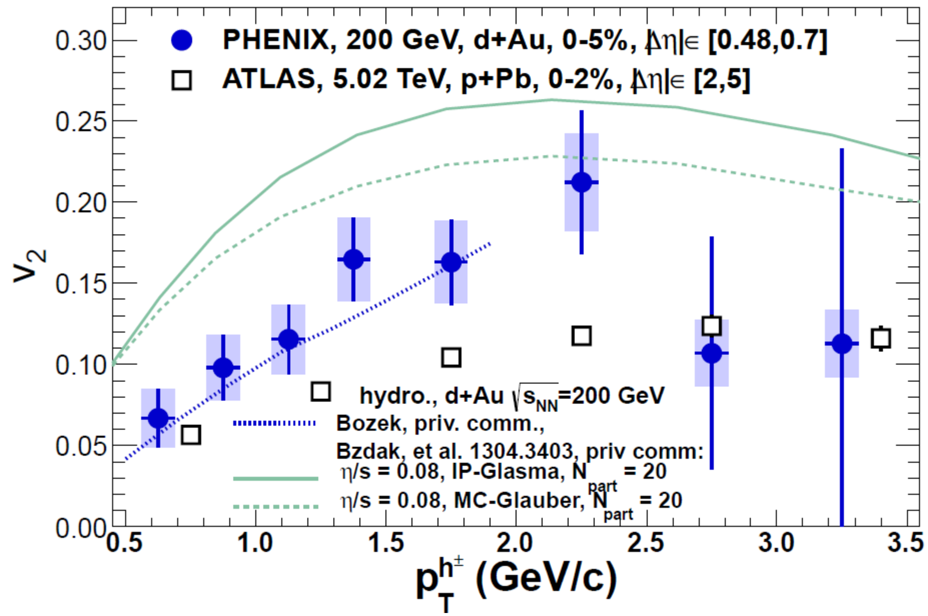
How can we detect the α clusters in the ground state?
What is their spatial arrangement?
Assessment of n-body correlations (one-body not enough)

Precursor: d+Au by Bożek

The deuteron has an intrinsic dumbbell shape with very large deformation: rms ≈ 2 fm

Initial entropy density in a d+Au collision with N_{part} = 24



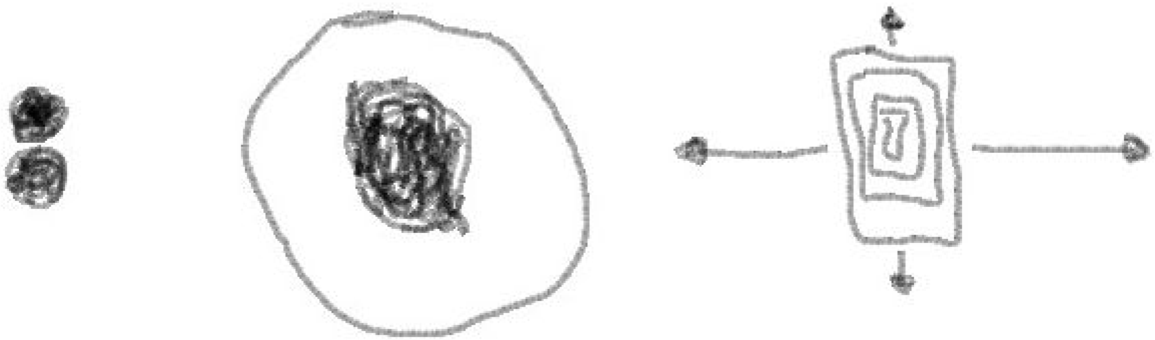


Resulting large elliptic flow confirmed with the later RHIC analysis

Details:
P. Bożek, Phys. Rev. **C85**, 014911

From α clusters to flow in relativistic collisions

α clusters → asymmetry of shape → asymmetry of initial fireball → hydro or transport → collective harmonic flow

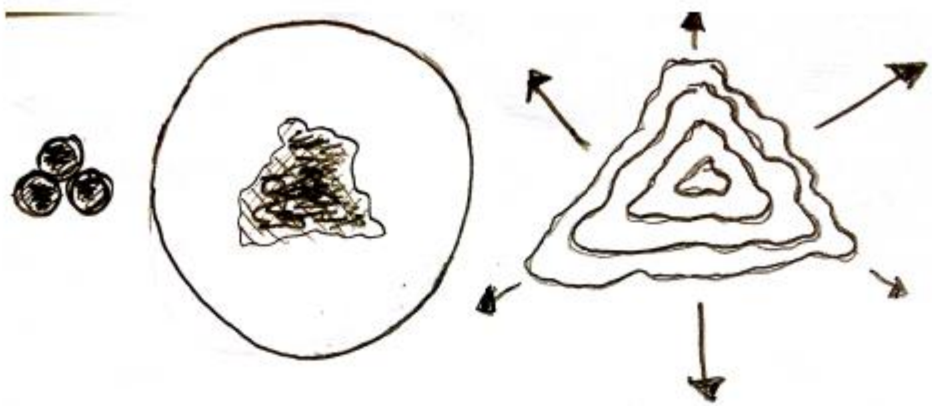


nuclear elliptic geometry → fireball elliptic geometry → elliptic flow

What are the signatures, chances of detection?
(some blurring by fluctuations)
„Easy snap-shot but difficult development”

From α clusters to flow in relativistic collisions

α clusters → asymmetry of shape → asymmetry of initial fireball →
hydro or transport → collective harmonic flow

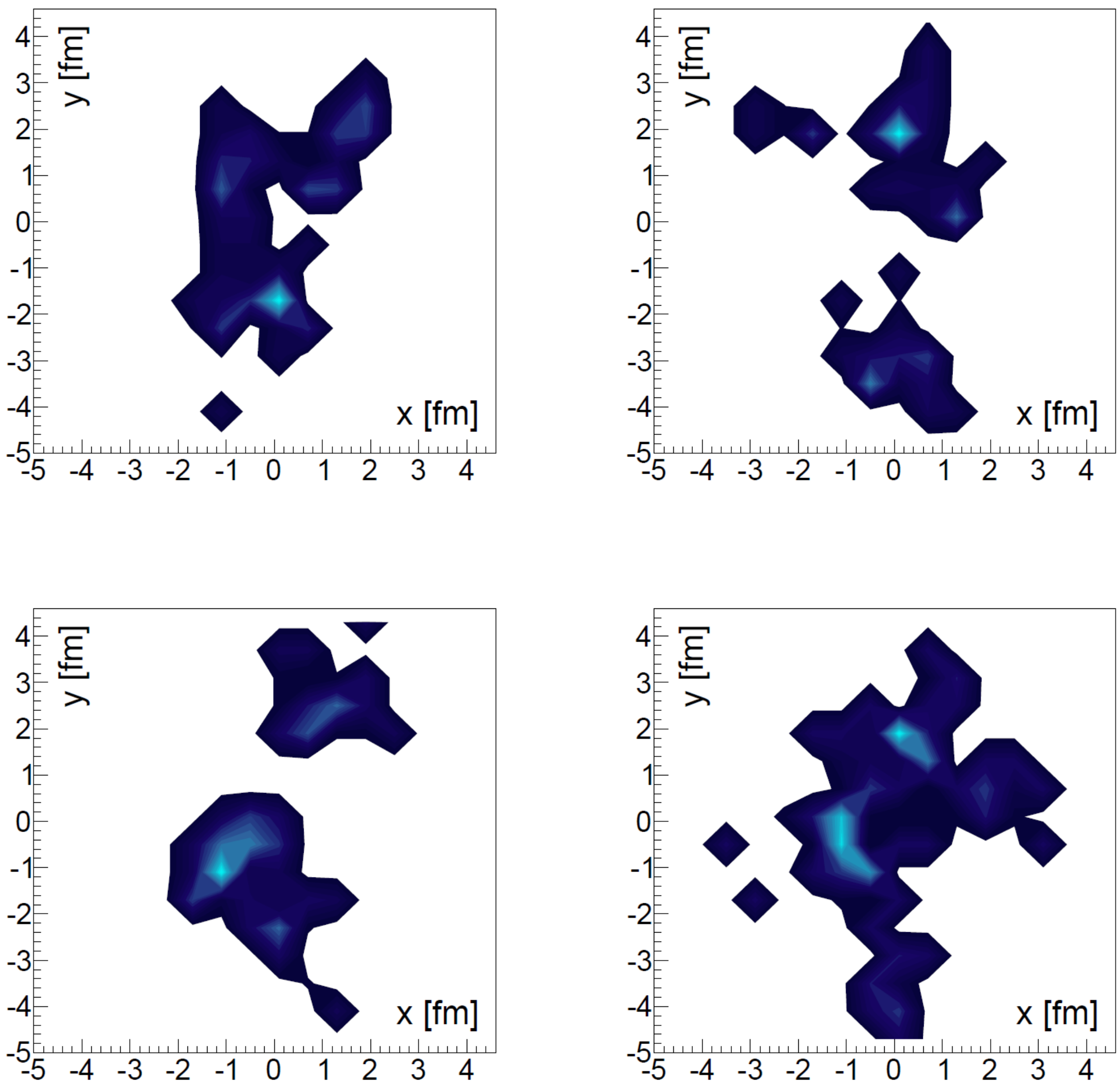


nuclear triangular geometry → fireball triangular geometry → triangular flow

What are the signatures, chances of detection?
(some blurring by fluctuations)
„Easy snap-shot but difficult development"

The reaction time at ultra-relativistic energies is much shorter that any typical nuclear-dynamics time!

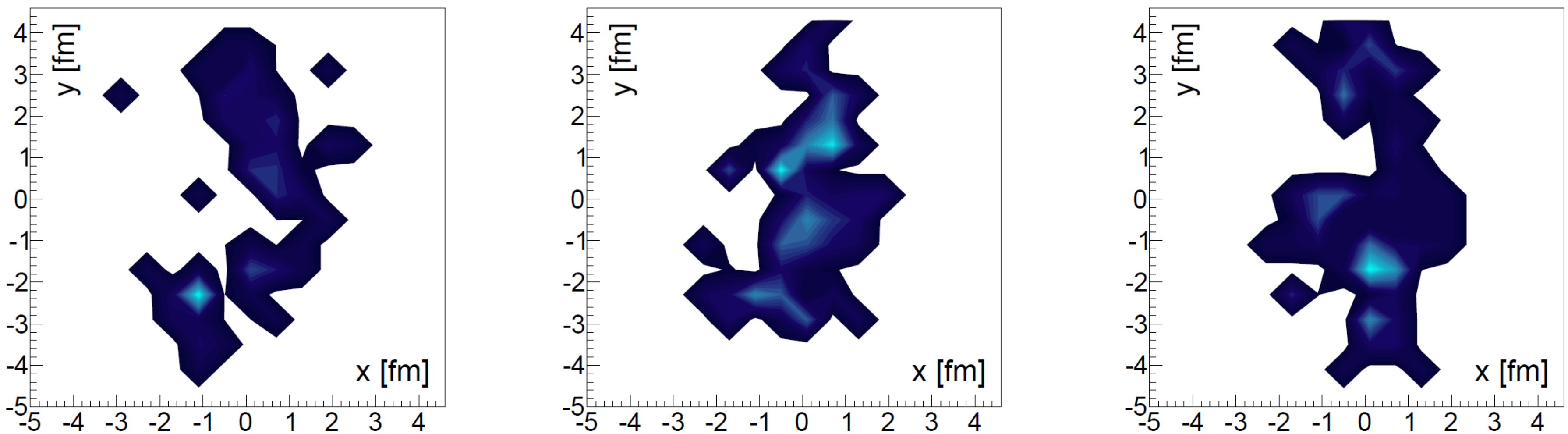
$^{7}Be+^{208}Pb$ - single events

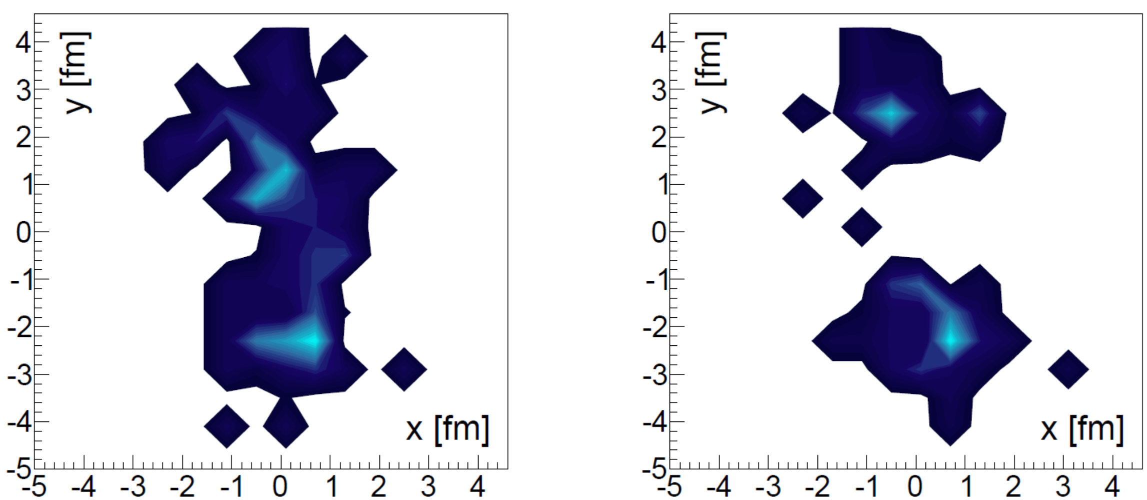


$\sqrt{s_{NN}}$=11 GeV
most central (b=0 fm) collisions

All simulations with GLISSANDO 2

$^{9}Be+^{208}Pb$ - single events

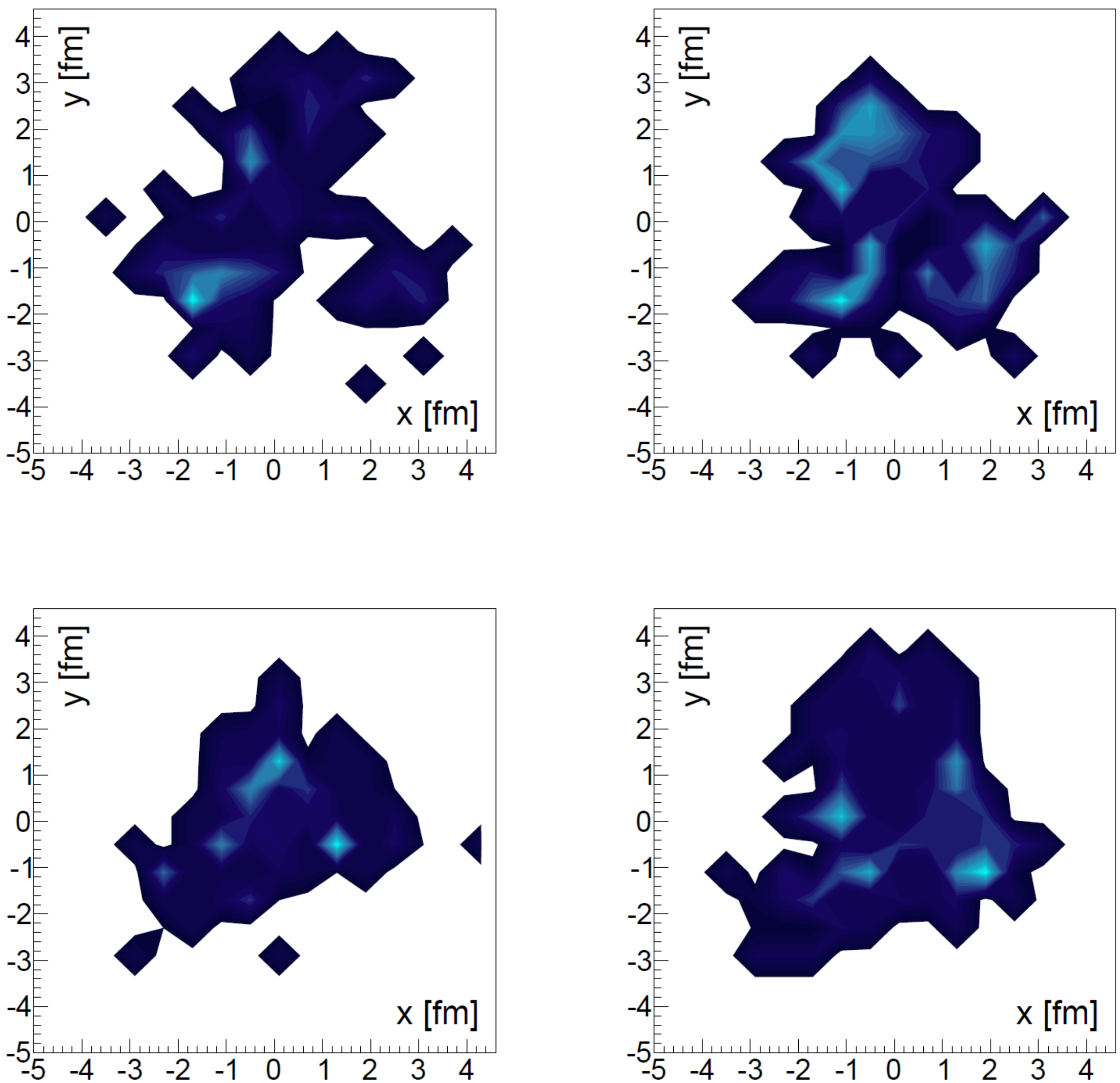




$\sqrt{s_{NN}}$=11 GeV
most central (b=0 fm) collisions

All simulations with GLISSANDO 2

$^{12}C+^{208}Pb$ - single events



$\sqrt{s_{NN}}$=11 GeV
most central (b=0 fm) collisions

All simulations with GLISSANDO 2

Eccentricity parameters

We need some quantitative measures of deformation (heavily used in heavy-ion analyses). Eccentricity parameters:

$$\epsilon_n \exp(in\Phi_n) = \frac{\sum_j r_j^n \exp(in\phi_j)}{\sum_j r_j^n}$$

describe the shape of each event.
j labels the sources in the event, *n*=rank, Φ_n is the principal axis angle, $r = \sqrt{x^2 + y^2}$, $\tan(\phi) = \frac{y}{x}$

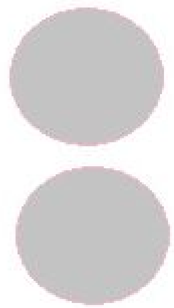
n = 2 – ellipticity, *n* = 3 – triangularity, . . .

Two components:

- ✓intrinsic (from existent mean deformation of the fireball)
- ✓from fluctuations (due to finite number of nucleons)

Geometry vs multiplicity correlations in $^{7,9}Be + ^{208}Pb$ collisions

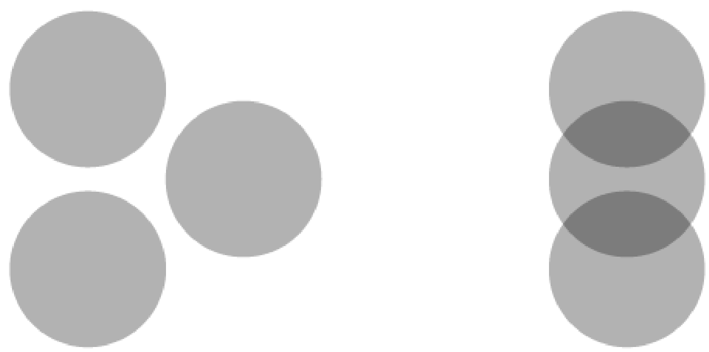
Two cases of angular orientation
cluster plane parallel or perpendicular to the transverse plane



higher multiplicity	lower multiplicity
higher ellipticity	lower (no) ellipticity

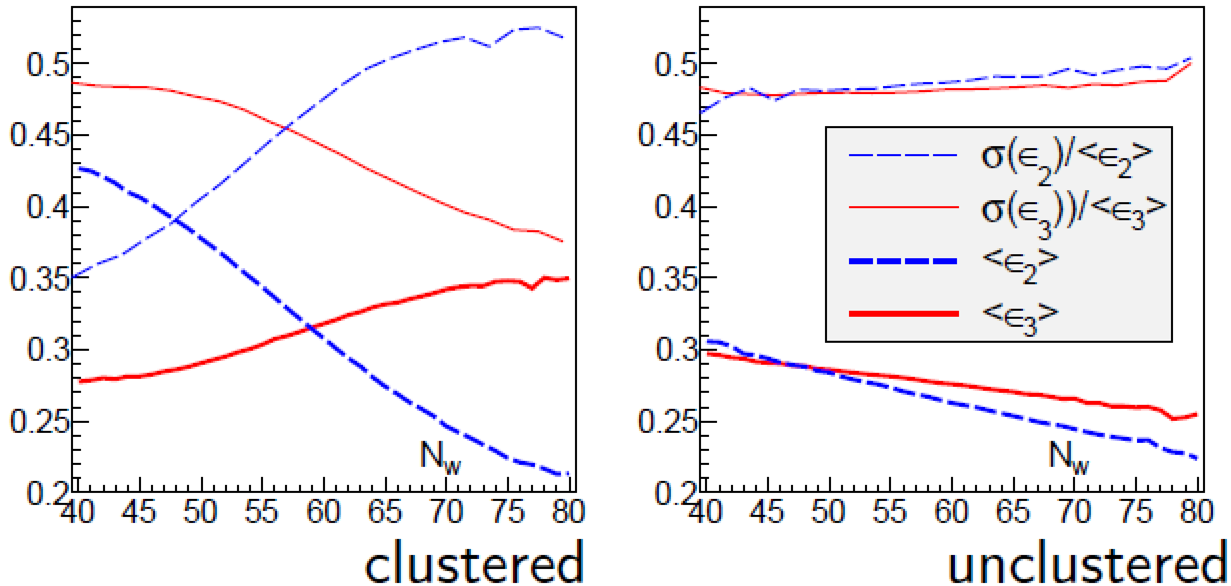
Geometry vs multiplicity correlations in $^{12}C+^{208}Pb$ collisions

Two cases of angular orientation
cluster plane parallel or perpendicular to the transverse plane



higher multiplicity	lower multiplicity
higher triangularity	lower triangularity
lower ellipticity	higher ellipticity

Ellipticity and triangularity vs multiplicity in $^{12}C+^{208}Pb$ collisions



Clusters: (qualitative signal!)

When N_w ↗ then $\langle\varepsilon_3\rangle$↗ , $\langle\varepsilon_2\rangle$↘, $\sigma(\varepsilon_3)/\langle\varepsilon_3\rangle$ ↘ and $\sigma(\varepsilon_2)/\langle\varepsilon_2\rangle$ ↗

No clusters:

similar behavior for n = 2 and n = 3

Details:

W. Broniowski, E. R. Arriola, Phys. Rev. Lett. **112**, 112501

P. Bozek, W. Broniowski, E. R. Arriola, M. Rybczyński, Phys. Rev. **C90**, 064902

Cumulants, moments and its ratios

$$v_n = \kappa_n \epsilon_n$$

$$v_n\{m\} = \kappa_n \epsilon_n\{m\} \quad n = 2,3,\ldots \quad m = 2,4,6,\ldots$$

$$\frac{v_n\{m\}}{v_n\{2\}} = \frac{\epsilon_n\{m\}}{\epsilon_n\{2\}}$$

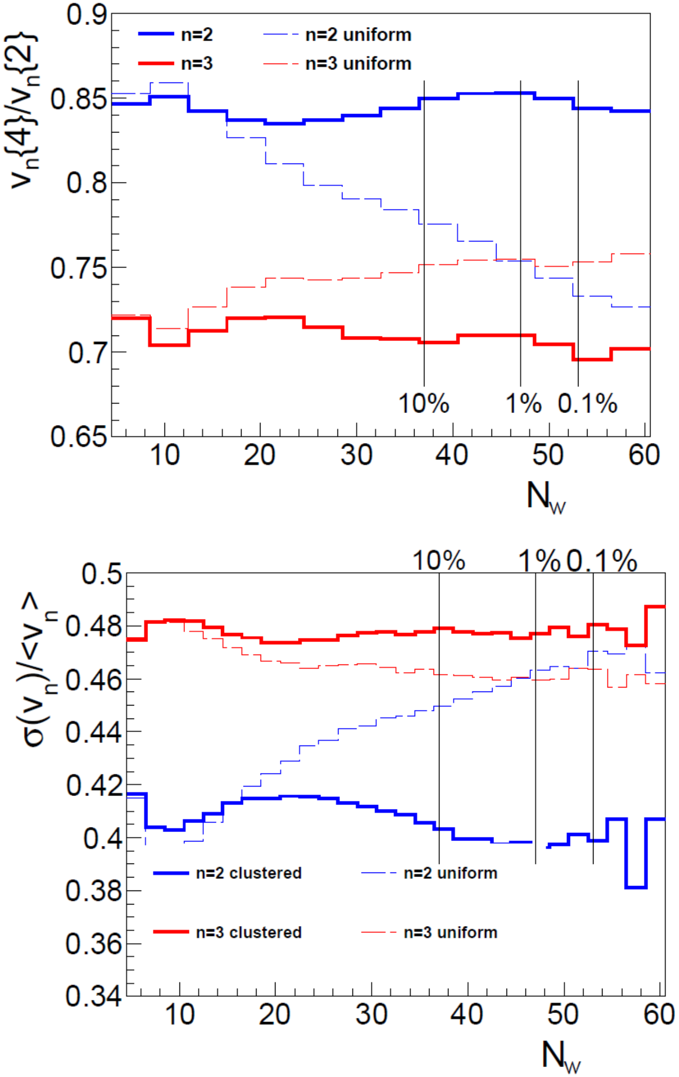
$$\frac{\sigma(v_n)}{\langle v_n \rangle} = \frac{\sigma(\epsilon_n)}{\langle \epsilon_n \rangle}$$

$$\epsilon_n\{2\}^2 = \langle \epsilon_n^2 \rangle$$

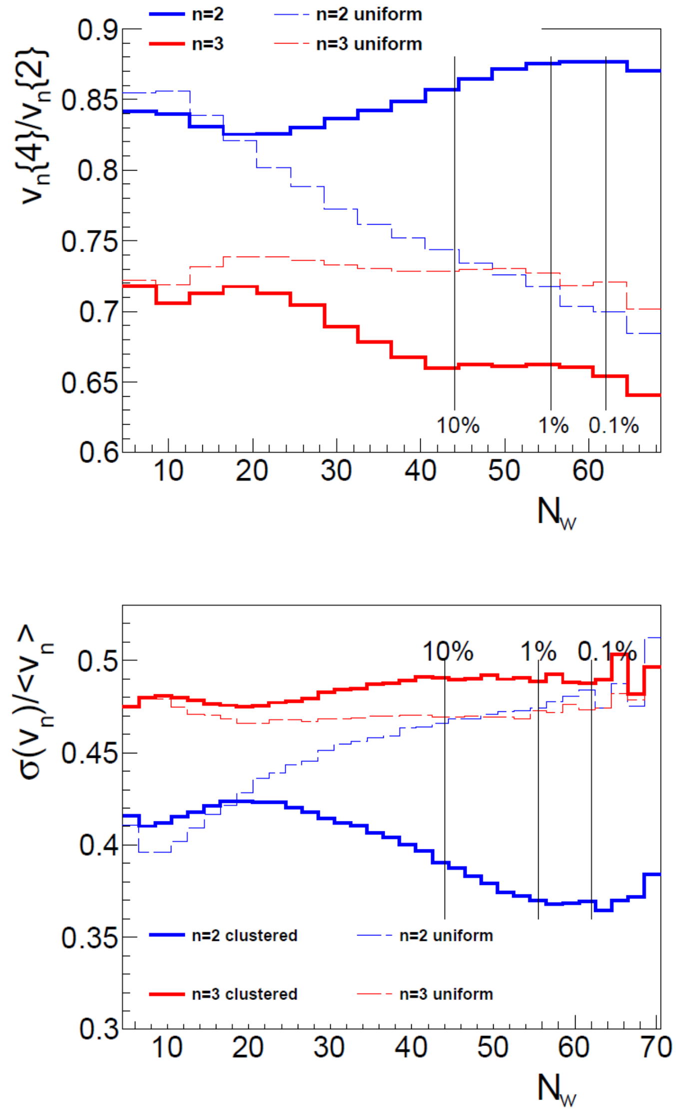
$$\epsilon_n\{4\}^4 = 2\langle \epsilon_n^2 \rangle - \langle \epsilon_n^4 \rangle$$

√s_{NN}=11 GeV, central rapidity

$^{7}Be+^{208}Pb$

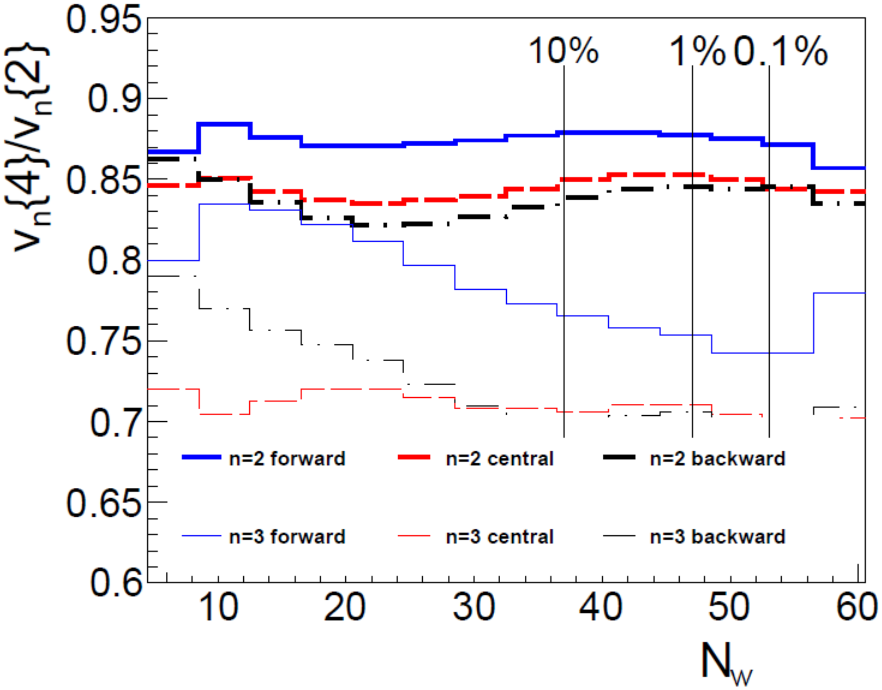


$^{9}Be+^{208}Pb$

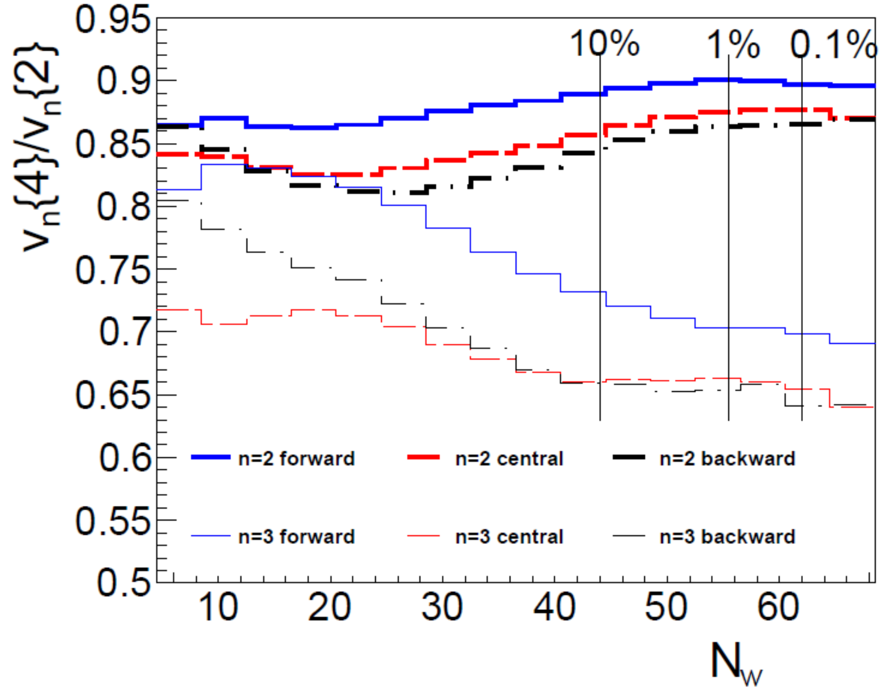


$\sqrt{s_{NN}}$=11 GeV

$^{7}Be+^{208}Pb$

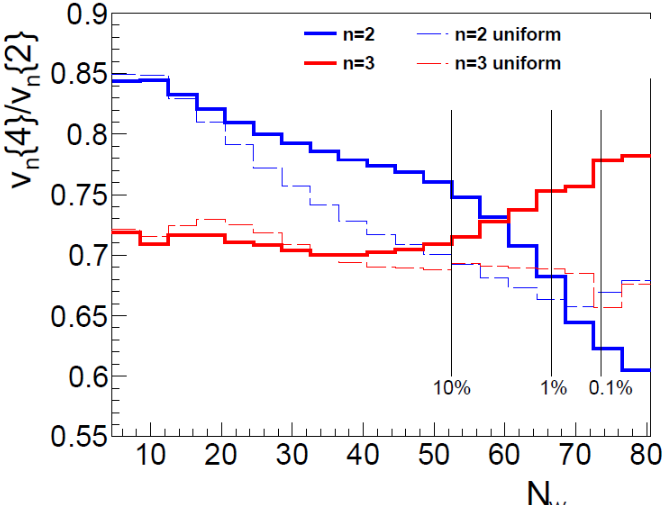


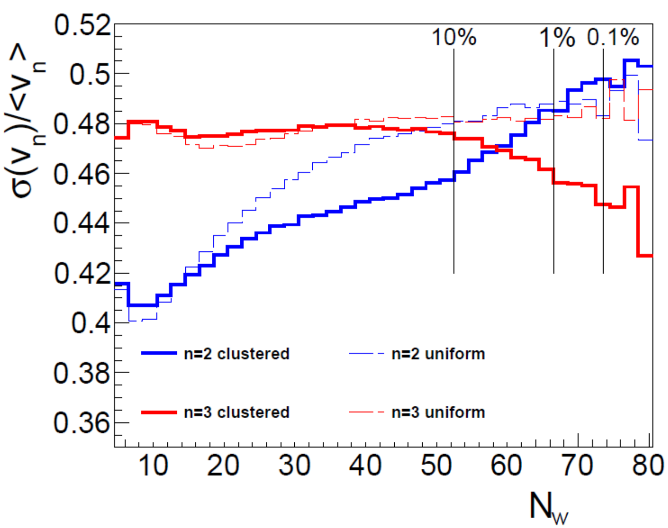
$^{9}Be+^{208}Pb$



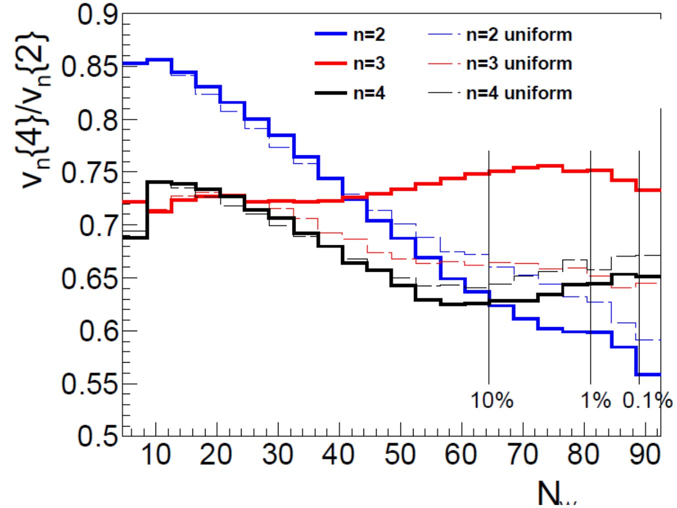
$\sqrt{s_{NN}}$=11 GeV, central rapidity

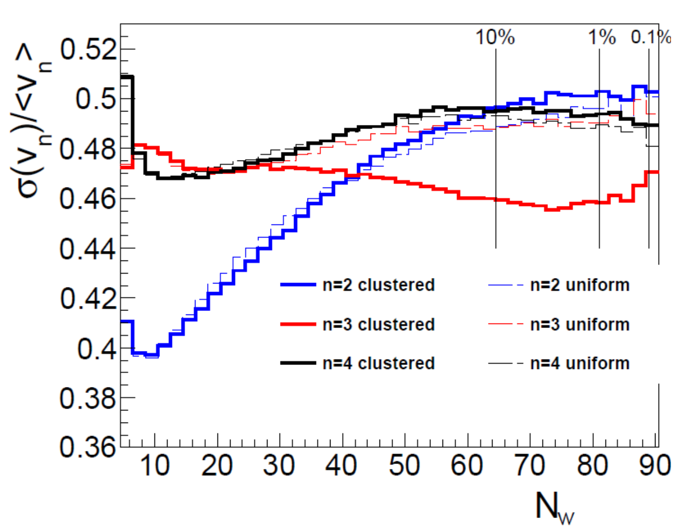
$^{12}C+^{208}Pb$



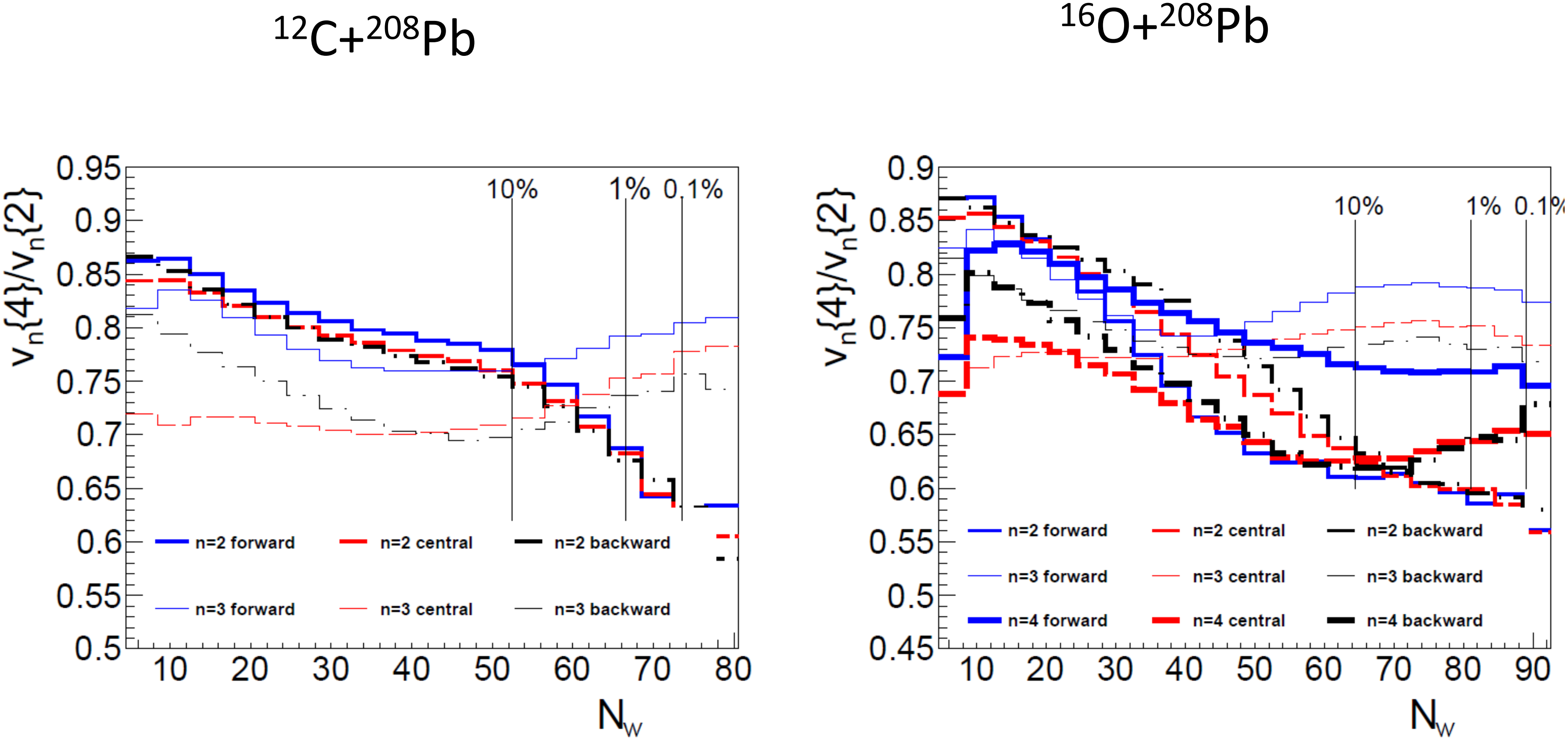


$^{16}O+^{208}Pb$





$\sqrt{s_{NN}}$=11 GeV



Summary

Nuclear structure from ultra-relativistic heavy ion collisions

Snapshots of the ground-state wave function
Spatial correlations in the ground state → harmonic flow

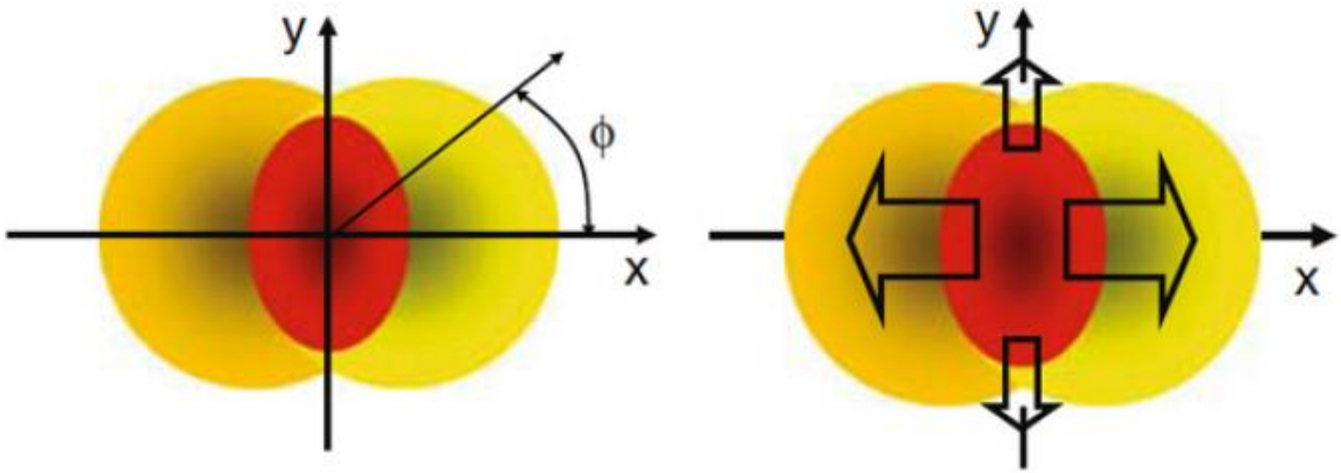
Possible data (MPD@NICA) in conjunction with a detailed knowledge of the evolution of the fireball would allow to place constrains on the α-cluster structure of the colliding nuclei.

Conversely, the knowledge of the clustered nuclear distributions helps to verify the fireball evolution models

Additional slides

Phenomenon of flow

Quark-gluon plasma is formed!

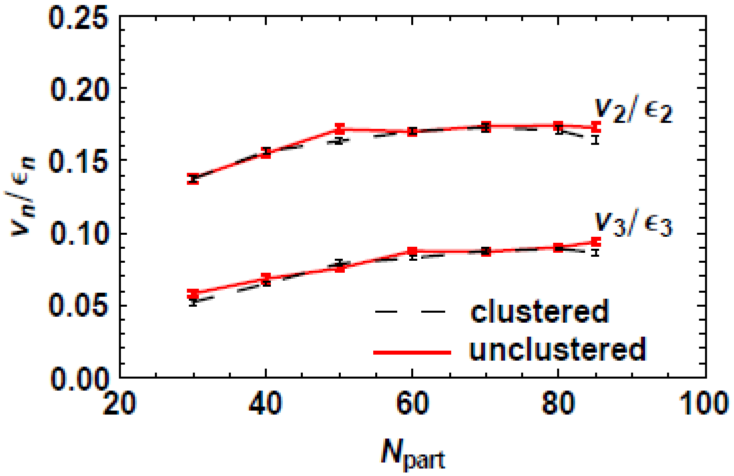


“Initial shape – final flow” transmutation detectable in the asymmetry
of the momentum distribution of detected particles – follows from collectivity

Shape-flow transmutation

The eccentricity parameters are transformed (in all models based on collective dynamics) into asymmetry of the transverse-momentum flow.
Linear response:

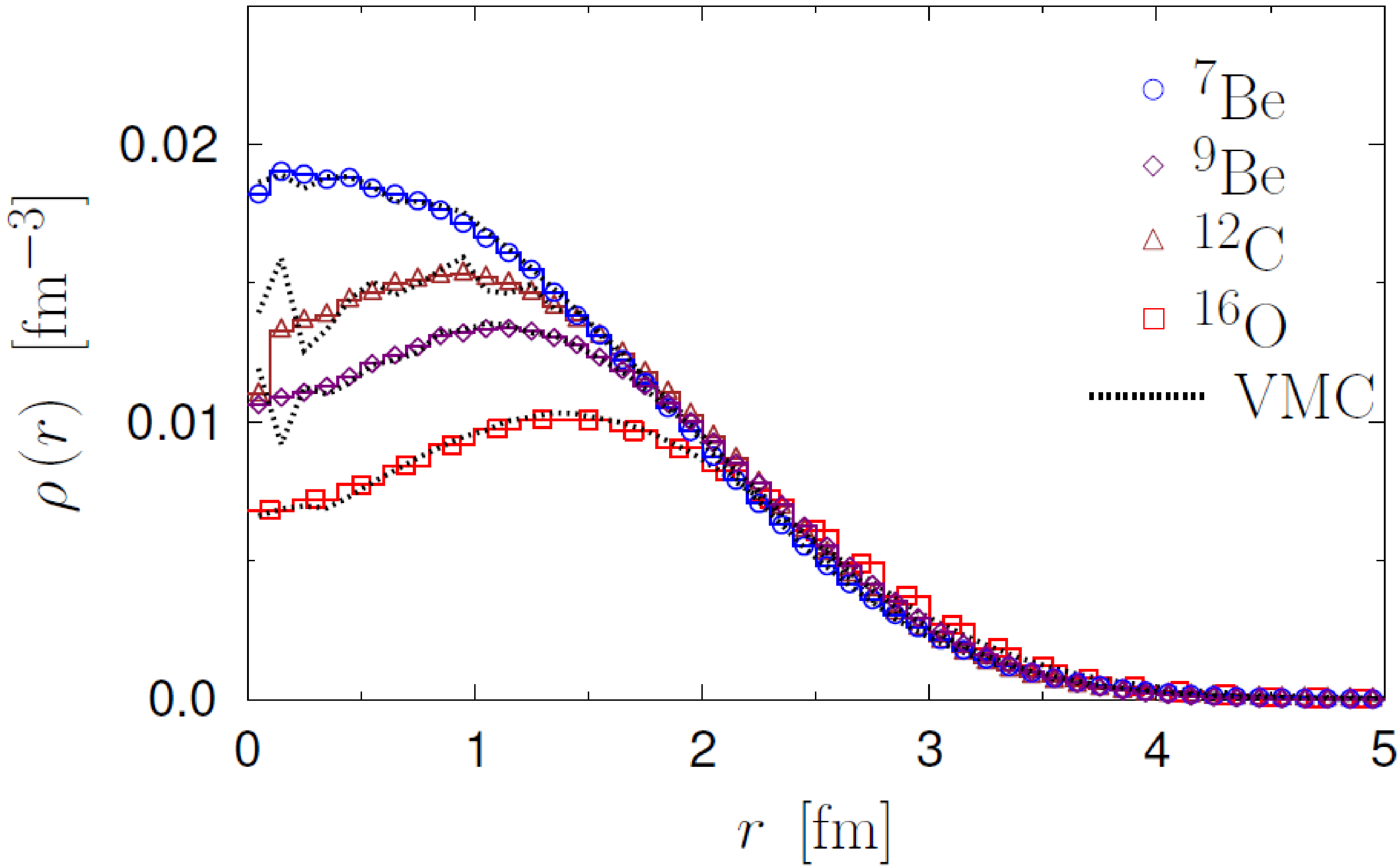
v_n grows with ϵ_n



[Bożek 3+1 viscous hydro + THERMINATOR]

Our modeling

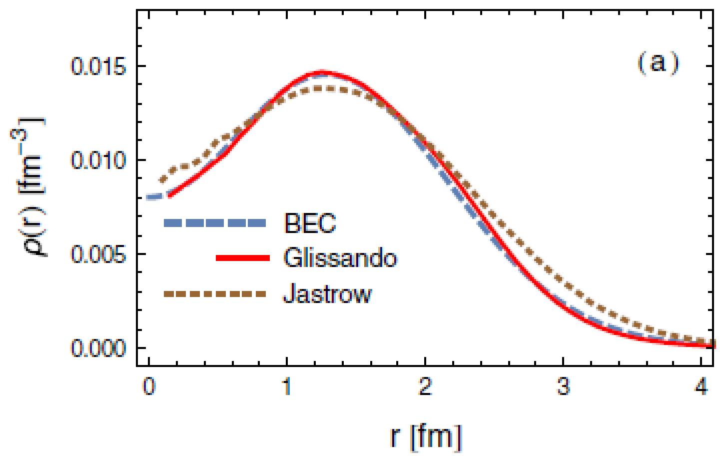
Generate nucleon positions with Monte Carlo, parameters (size of the cluster, distance between clusters) properly adjusted



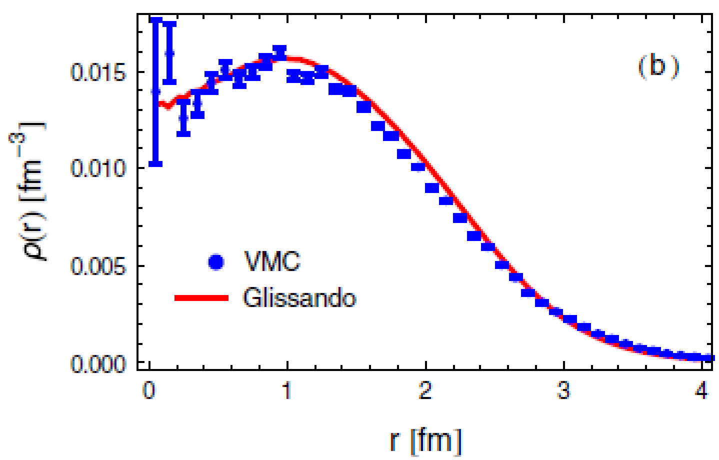
All simulations with GLISSANDO 2

Our modeling (^{12}C)

Three α's in a triangular arrangement, generate nucleon positions with Monte Carlo, parameters (size of the cluster, distance between clusters) properly adjusted



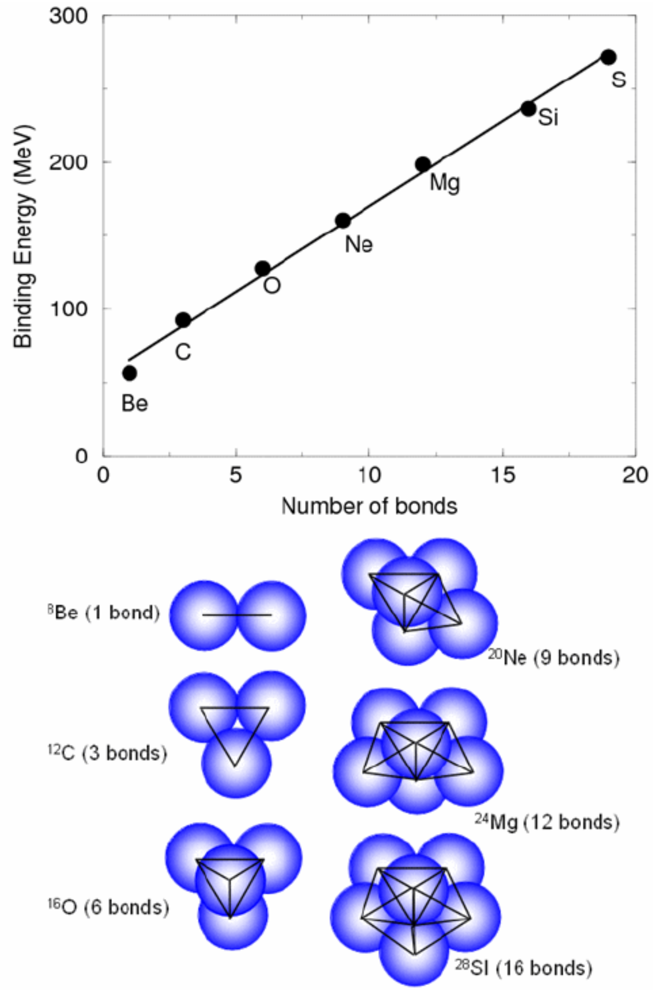
a)
dashed: data from charge form factor → BEC,
solid - our BEC,
dotted - Jastrow (Buendia et al.)



b)
points - variational MC (Wiringa et al.),
line - our VMC

All simulations with GLISSANDO 2

α clusters in light nuclei



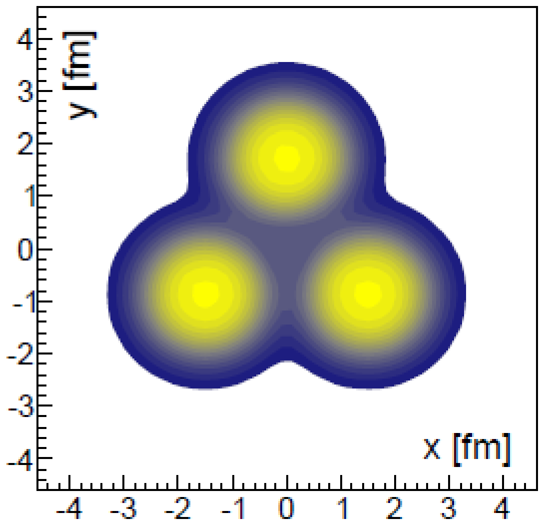
- small overlap
- specific excitation spectra
- fragmentation experiments

^{7}Be = ^{4}He + ^{3}He
^{9}Be = ^{4}He + ^{4}He + n
^{12}C = ^{4}He + ^{4}He + ^{4}He

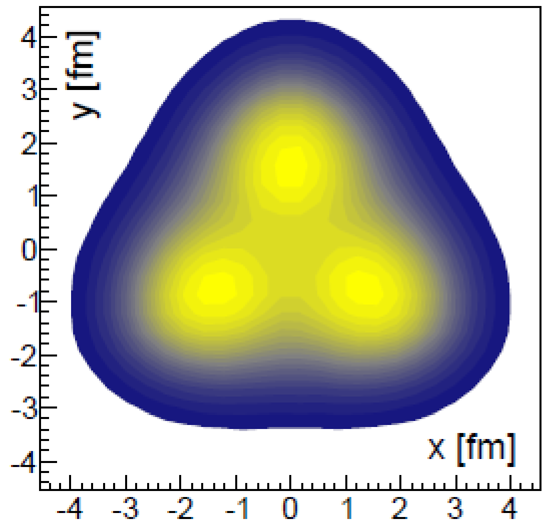
[see C. Beck ed., Clusters in Nuclei, Lecture Notes in Physics 818, 848, 875, Springer (2010, 2012, 2014)]

Geometry of nucleus → geometry of fireball

Triangular nucleus causes triangular ”damage”!

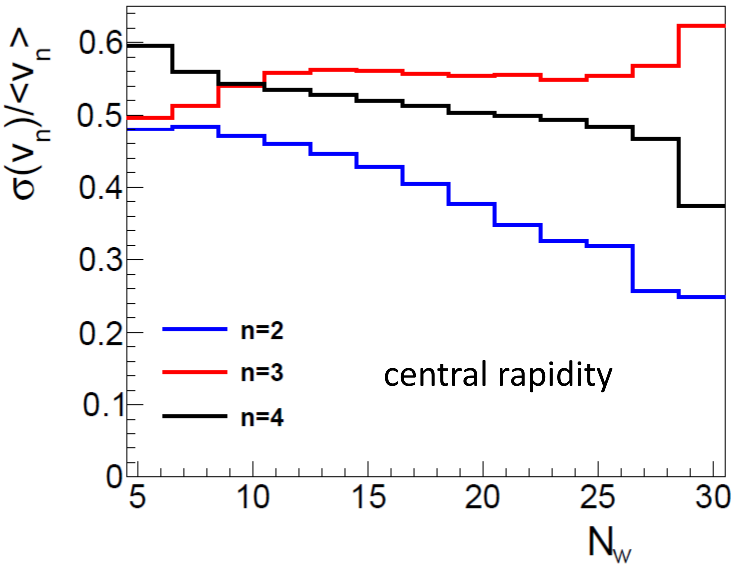


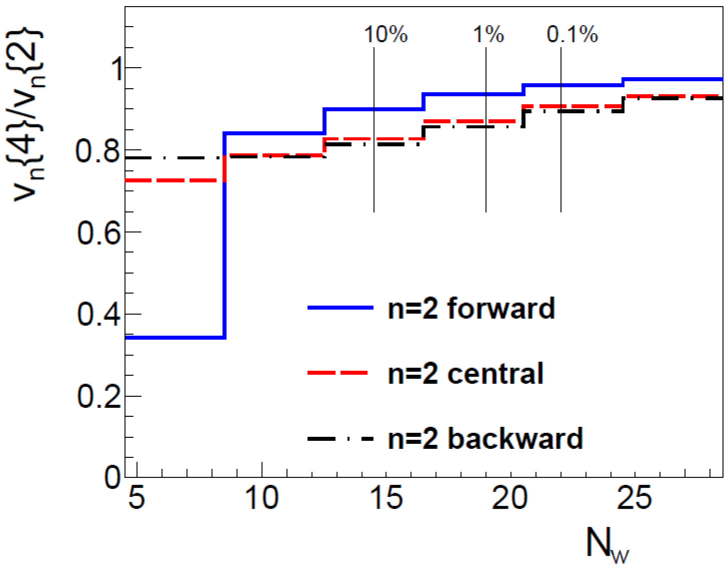
intrinsic density of ^{12}C



geometry of the fireball

$^{2}H+^{208}Pb$ @ $\sqrt{s_{NN}}=11$ GeV





Isotopes of beryllium

symbol	Z	N	lifetime	decay	J^P
^{7}Be	4	3	53 days	e capture	$3/2^-$
^{8}Be	4	4	7×10^{-17} s	α	0^+
^{9}Be	4	5	stable		$3/2^-$