Nuclear structure effects in the initial state

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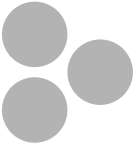
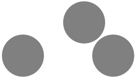
Ab initio approaches in many-body QCD confront HI experiments
EMMI Workshop, Heidelberg, 15-17 Dec. 2014

^{12}C


^{3}He


[research with **Enrique Ruiz Arriola, Piotr Bożek, Maciej Rybczyński**]

Instead of outline

Nuclear structure affects the initial conditions e-by-e

Two phenomena are related:

α clustering in light nuclei

$\updownarrow$

harmonic flow in ultra-relativistic nuclear collisions

Surprising link:

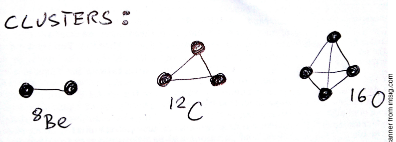
lowest-energy ground-state structure $\longleftrightarrow$ highest energy reactions

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

α clusters

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*



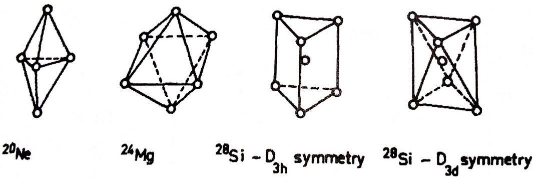
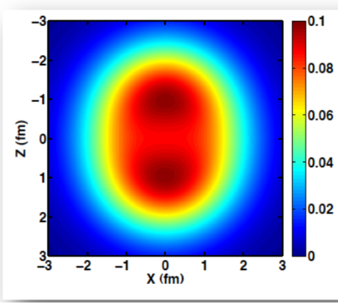
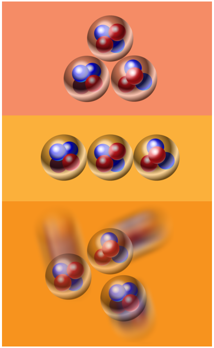


Fig. 1. Alpha-particle configuration for some 4N nuclei.

α clusters in light nuclei



^{9}Be



^{12}C

ground

Hoyle 0^{+}

other excited, 2^{+} ...

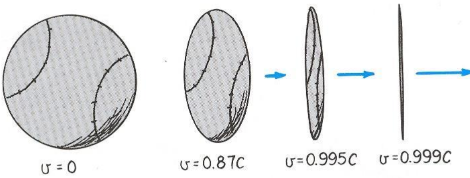
How can we detect the α clusters in the ground state?
What is their spatial arrangement?
Assessment of n-body correlations (one-body not enough)

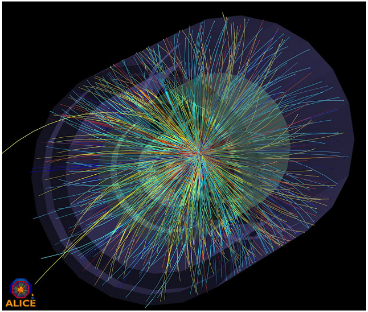
[Recent status: SOTANCP3 Conference, Yokohama, May 2014]

Flow

Ultra-relativistic A+A collisions (LHC, RHIC, SPS)

- Lorentz contraction
- Collision: essentially instantaneous passage, frozen configuration
- Reduction of the ground-state wave function of the nucleus in the transverse plane **(acts as measurement)**

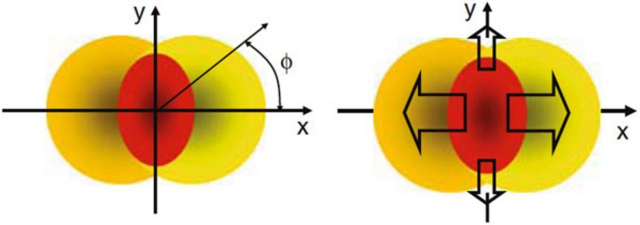




- "Development": detection of particles in the transverse direction

Phenomenon of flow

Quark-gluon plasma is formed!



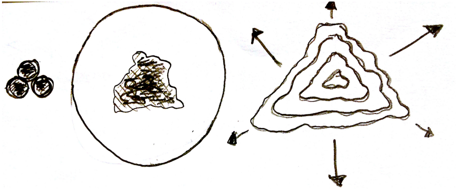
"Initial shape – final flow" transmutation detectable in the asymmetry of the momentum distribution of detected particles – follows from collectivity

Merge the two ideas (α's and flow) $\rightarrow$

[WB & Ruiz Arriola, PRL 112 (2014) 112501] [Bożek, WB, Ruiz Arriola & Rybczyński, PRC 90 (2014) 064902]

From α clusters to flow in relativistic collisions

α clusters $\to$ asymmetry of shape $\to$ asymmetry of initial fireball $\to$
$\to$ hydro or transport $\to$ collective harmonic flow



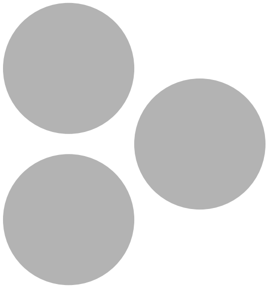
nuclear triangular geometry $\to$ fireball triangular geometry $\to$ triangular flow

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

Described later: ^{3}He–Au at RHIC [PHENIX proposal, 2013]
The case of ^{12}C promising, as it leads to more abundant fireballs

Our making ^{12}C

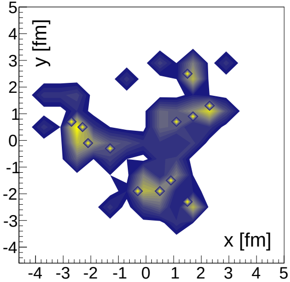
Three α's in a triangular arrangement, generate nucleon positions with Monte Carlo, parameters (size of the cluster, distance between clusters) properly adjusted (fit one-body radial distributions from other calculations, fit EM form factor)



^{12}C-^{208}Pb – single event

Why ultra-relativistic?

Reaction time is much shorter than time scales of the structure
$\rightarrow$ a frozen "snapshot" of the nuclear configuration



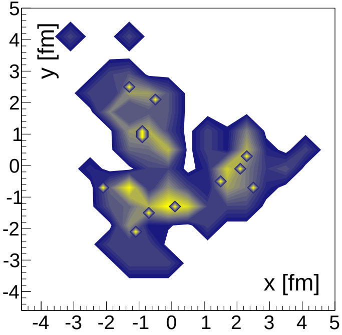
wounding range determined by $\sigma_{\rm NN}^{\rm inel}$

Here $N_w > 70$ - flat-on orientation (for the moment)

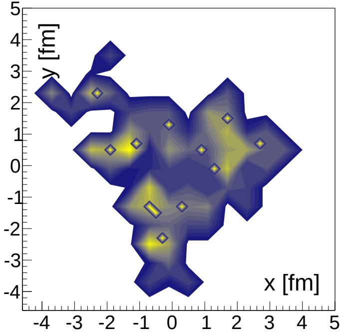
Imprints of the three α clusters clearly visible

Simulations with GLISSANDO 2

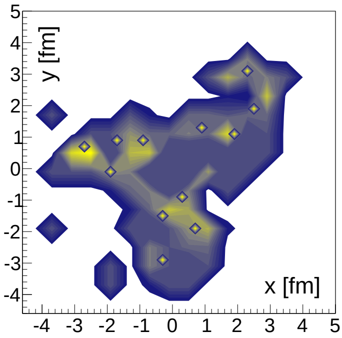
… more events



… more events



… more events



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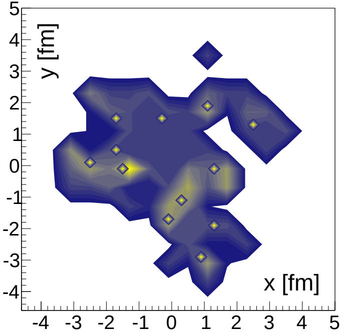

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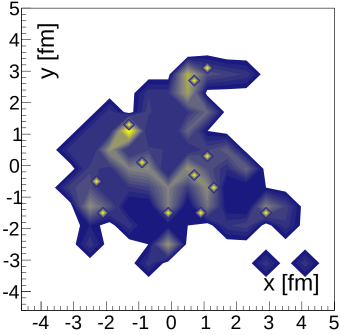
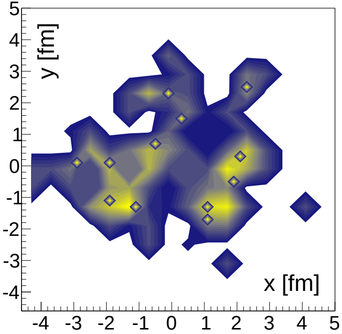


... more events



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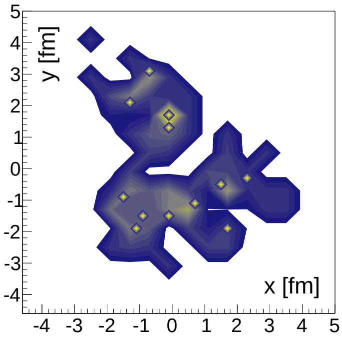
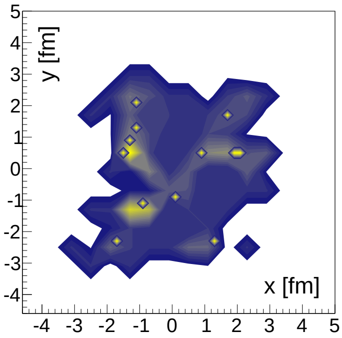


... more events



Eccentricity parameters (event-by-event)

Eccentricity parameters ϵ_n (Fourier analysis)

$$\epsilon_n = \frac{\left|\sum_j \rho_j^n e^{in\phi_j}\right|}{\sum_j \rho_j^n}$$

describe the shape of each event (j labels the sources in the event, n=rank)
$n = 2$ – ellipticity, $n = 3$ – triangularity, ...

Two components:

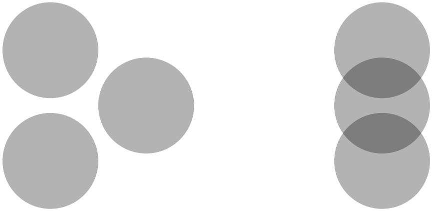
- intrinsic (from existent mean deformation of the fireball)
- from fluctuations

(Gaussian smearing of sources, $\sigma = 0.4$ fm)

Geometry vs multiplicity correlations in ^{12}C-Pb

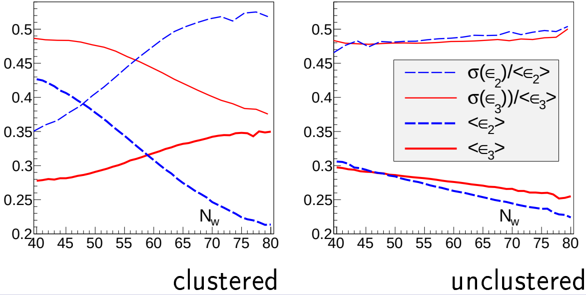
Two extreme cases of angular orientation

cluster plane parallel or perpendicular to the transverse plane:



flat-on	sidewise
higher multiplicity	lower multiplicity
higher triangularity	lower triangularity
lower ellipticity	higher ellipticity

Ellipticity and triangularity vs multiplicity



Clusters: (qualitative signal!)

When $N_w \nearrow$ then $\langle\epsilon_3\rangle \nearrow$ and $\langle\epsilon_2\rangle \searrow$

and $\langle\sigma(\epsilon_3)/\epsilon_3\rangle \searrow$, $\langle\sigma(\epsilon_2)/\epsilon_2\rangle \nearrow$

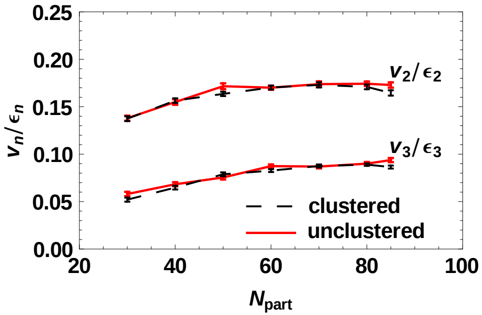
No clusters:

similar behavior for $n = 2$ and $n = 3$

Shape-flow transmutation

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

$v_n \sim \epsilon_n$, response grows with multiplicity



[wounded nucleon model + Bożek's 3+1 viscous hydro ($\eta/s = 0.08$, $\tau_0 = 0.6$ fm) + THERMINATOR ($T_f = 150$ MeV)]

Hydro without hydro

We have to a very good approximation

$$v_n = \kappa_n \epsilon_n, \quad n = 2, 3, \ldots$$

(κ_n depends on multiplicity and hydro details)

Cumulant moments: $\epsilon_n\{2\}^2 = \langle \epsilon_n^2 \rangle$, $\epsilon_n\{4\}^4 = 2\langle \epsilon_n^2 \rangle - \langle \epsilon_n^4 \rangle$

Ratio's insensitive to response:

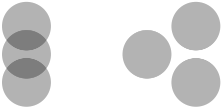
$$\frac{v_n\{m\}}{v_n\{2\}} = \frac{\epsilon_n\{m\}}{\epsilon_n\{2\}}, \quad m = 4, 6, \ldots$$

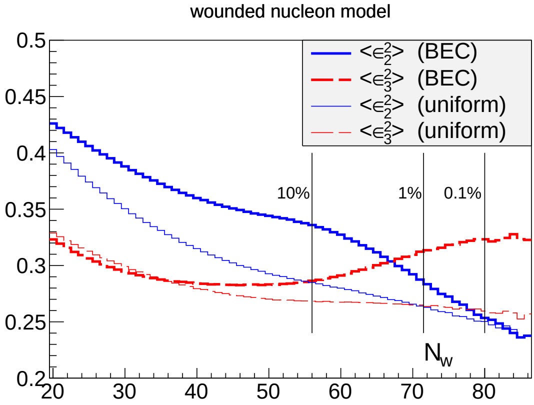
(infer info on flow from just the eccentricities, no hydro!)

Fluctuations only: ratio drops with N_w ($\sim N_w^{1/m-1/2}$)

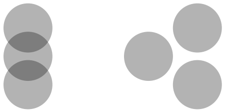
Geometry: ratio tends to 1 from below as $N_w \to \infty$

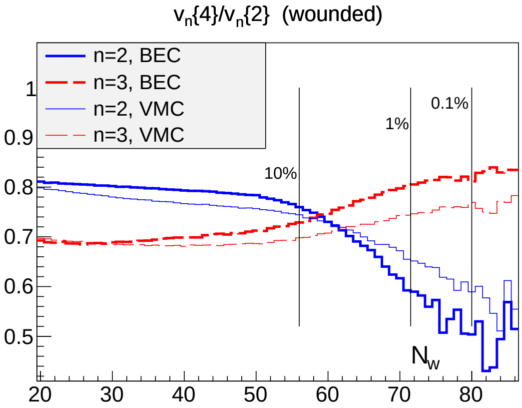
Cumulant moments





Ratios of cumulant moments





^{3}He-Au

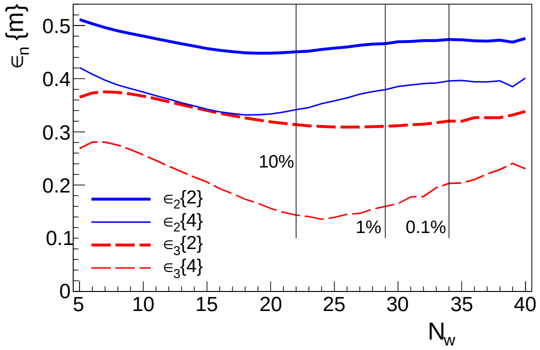
^{3}He-Au

(being presently analyzed at RHIC)

[hydro: J. Nagle et al., PRL 113 (2014) 112301]

[hydro without hydro: Piotr Bożek and WB, PLB 739 (2014) 308]

Sampling from ab initio MC Green's function method [Carlsson & Schiavilla 1998]



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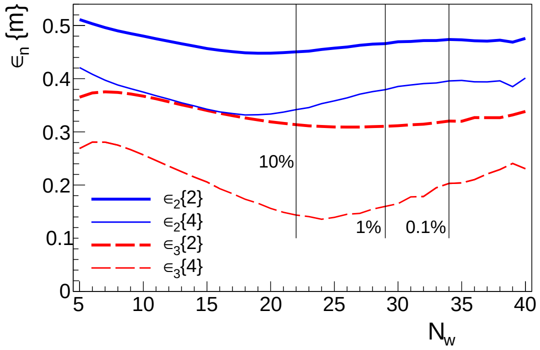
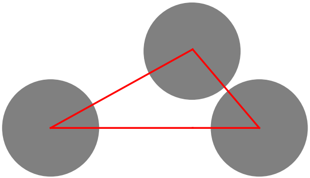
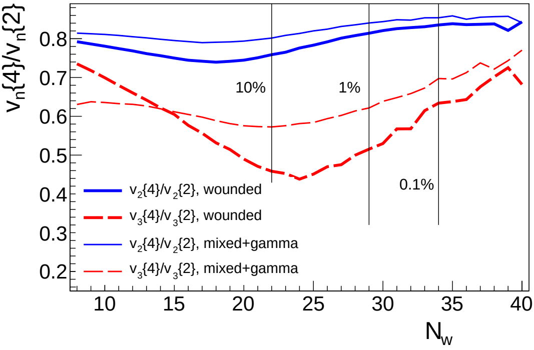




(Not equilateral! Side-wise: $\epsilon_2 \sim 1$, $\epsilon_3 \sim 3/5$)

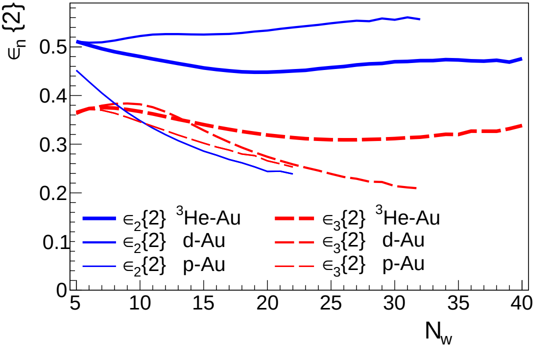
Ratio for ^{3}He-Au



Large-N_w behavior should exhibit geometric triangularity as well as ellipticity!

(to be confirmed by the experiment!)

p, d, ^{3}He



ϵn{2}
0.5
0.4
0.3
0.2
0.1
0
5
10
15
20
25
30
35
40
Nw
ϵ2{2} 3He-Au
ϵ2{2} d-Au
ϵ2{2} p-Au
ϵ3{2} 3He-Au
ϵ3{2} d-Au
ϵ3{2} p-Au

Conclusions

Nuclear structure from ultra-relativistic heavy ion collisions

Snapshots of the ground-state wave function
Spatial correlations in the ground state → geometric harmonic flow
Signatures in clustered ^{12}C-A collisions

- Increase of triangularity with multiplicity for the highest multiplicity events
- Anticorrelation of ellipticity and triangularity
- Very clear signals from ratios of cumulant moments
- Ratios depend on the nuclear wave function and the initial-state model, but not on hydro
- Effect qualitatively similar at other collision energies
- ... and in ^{12}C or ^{197} hemispheres
- ^{12}C leads to larger/more collective fireball than ^{3}He

Extensions: ^{7,9}Be, ^{16}O (in progress)

Data (RHIC, NA61@SPS) would allow to place constrains on the spatial structure of the light projectiles and verify the fireball formation models

Back-up

Intrinsic distributions

Ground state of ^{12}C is a 0^+ state (rotationally symmetric wave function). The meaning of *deformation* concerns multiparticle correlations between the nucleons

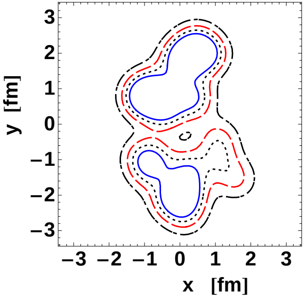
Superposition over orientations:

$$|\Psi_{0^+}(x_1,\ldots,x_N)\rangle = \frac{1}{4\pi}\int d\Omega \Psi_{\rm intr}(x_1,\ldots,x_N;\Omega)$$

The *intrinsic* density of sources of rank n is defined as the average over events, where the distributions in each event have aligned principal axes: $f_n^{\rm intr}(\vec{x}) = \langle f(R(-\Phi_n)\vec{x})\rangle$. Brackets indicate averaging over events and $R(-\Phi_n)$ is the inverse rotation by the principal-axis angle in each event

The deuteron has an intrinsic dumbbell shape with very large deformation: rms $\simeq 2$ fm

Initial entropy density in a d-Pb collision with $N_{\mathrm{part}} = 24$ [Bożek 2012]



Digression: d-A by Bożek

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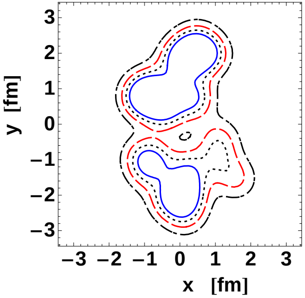
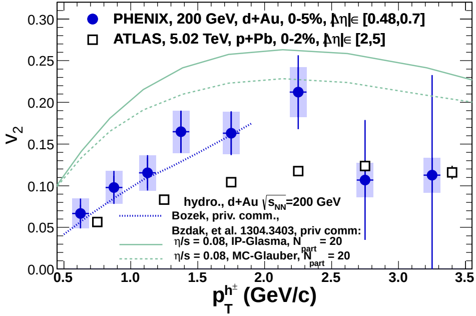
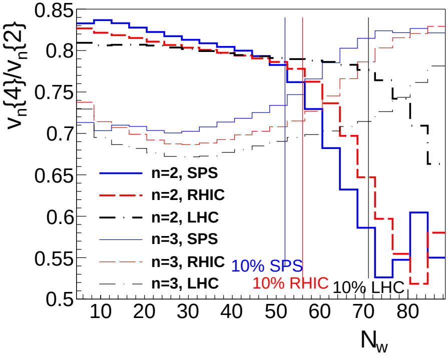




Resulting large elliptic flow confirmed with the later RHIC analysis

Dependence on the collision energy



Qualitative conclusions hold from SPS to the LHC

Other systems
(distributions matched to Wiringa's et al. radial densities)