Throwing triangles against the wall:

ultrarelativistic heavy-ion collisions detecting shape of light nuclei

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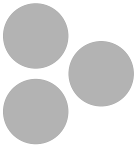
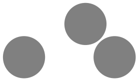
^{12}C



^{3}He



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

Instead of outline

Details may be found in:

^{12}C: WB & E.Ruiz Arriola, PRL 112 (2014) 112501 (News and Commentary in Physics, *An Untested Window into Nuclear Structure*, `http://journals.aps.org/prl/`)

^{3}He: Piotr Bożek & WB, arXiv:1409.2160

Two phenomena are related:

α clustering in light nuclei

$\updownarrow$

harmonic flow in ultra-relativistic nuclear collisions

Surprising link:

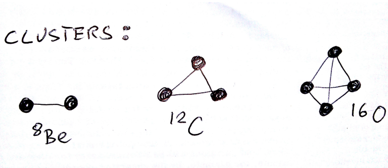
lowest-energy ground-state structure $\longleftrightarrow$ highest energy reactions

- 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*



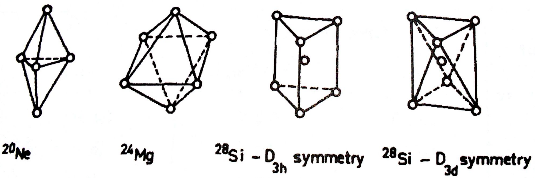
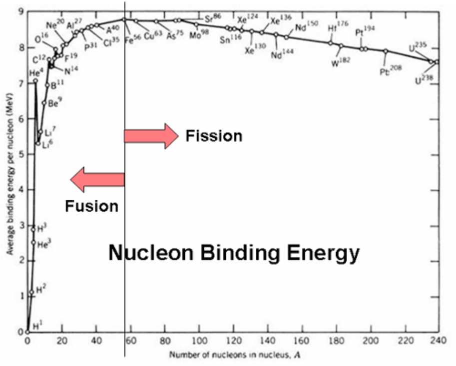


Fig. 1. Alpha-particle configuration for some $4N$ nuclei.

Binding

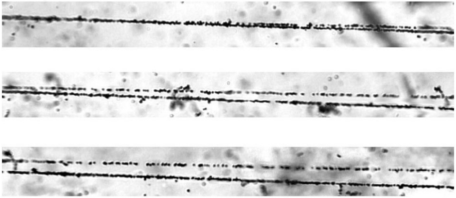


α very tightly bound

Fragmentation

Evidence from dissociation in nuclear track emulsions

[Zarubin 2013 (BECQUEREL)]



Example: dissociation of ^{7}Be (energy of a few A GeV)

(neutrons not specified)

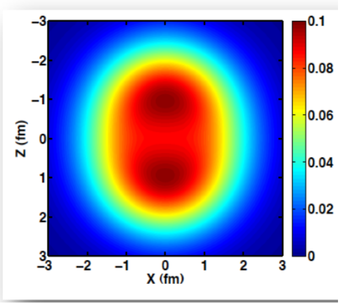
channel	^{4}He+^{3}He	^{3}He+^{3}He	^{4}He+2p	^{4}He+d+p	^{3}He+2p	^{3}He+d+p	^{3}He+2d	^{3}He+t+p	3p+d	^{6}Li+p
N	30	11	13	10	9	8	1	1	2	9
%	31	12	14	11	10	9	1	1	2	10

Numerous ongoing experiments (GANIL, Osaka, ...)

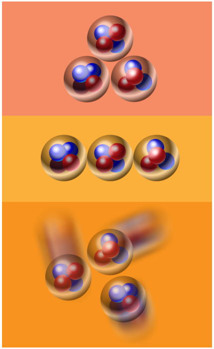
Was the cluster there or is it created at break-up?

These studies cannot reveal the geometry (cluster arrangement)

α clusters in light nuclei – theoretical calculations



^{9}Be



^{12}C

ground

Hoyle 0^+

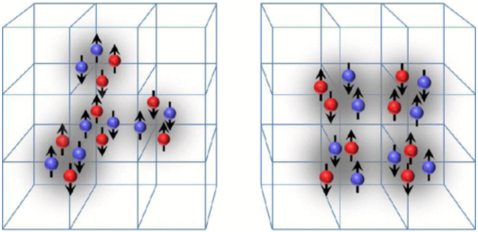
other excited, 2^+ . . .

[Fynbo+Freer: Physics 4 (2011) 94]

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]

Ab initio calculations of ^{16}O with chiral NN force
$\rightarrow$ strong α clusterization [Bochum-Jülich, PRL 112 (2014) 102501]



(a) Initial state "A", 8 equivalent orientations.

(b) Initial states "B" and "C", 3 equivalent orientations.

ground state | excited

Computational techniques

Funaki et al.: *certain states in self-conjugated nuclei ... can be described as product states of* α *particles, all in the lowest* $0S$ *state. We define a state of condensed* α *particles in nuclei as a bosonic product state in good approximation, in which all bosons occupy the lowest quantum state of the corresponding bosonic mean-field potential* (αBEC)

Another approach: Fermionic Molecular Dynamics (FMD)

Quantum Variational Monte Carlo (with 2- and 3-body forces) for A=2-12 [R. Wiringa et al.,]

All approaches $\rightarrow$ **light nuclei have clusters**

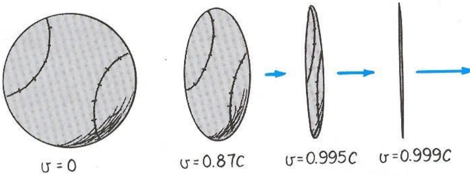
Goal (not yet accurately reached):

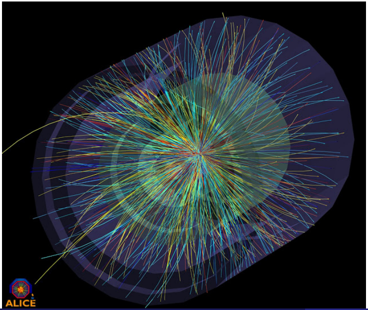
reproduce ground-state energy, excitation spectrum, EM form factor, ...

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 **(like measurement)**

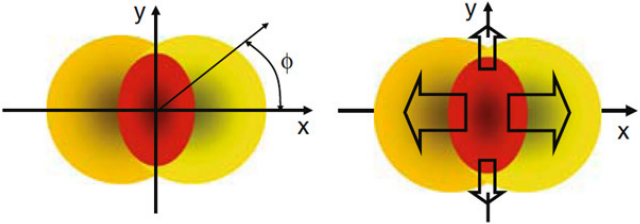




- "Development": detection of particles in the transverse direction

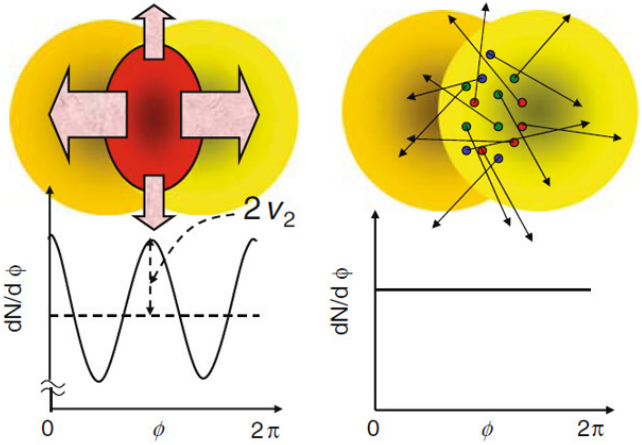
Phenomenon of flow

Quark-gluon plasma is formed!



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

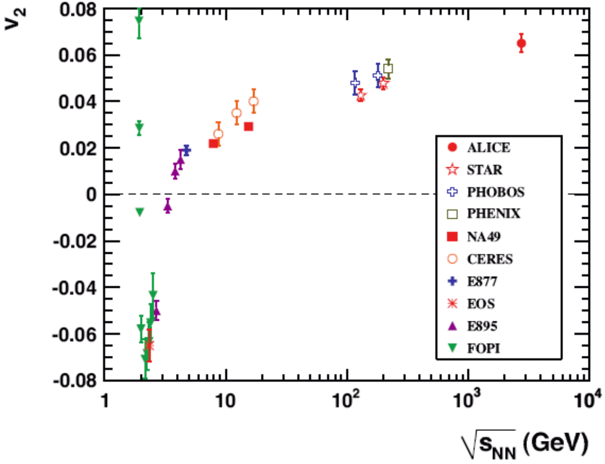
Elliptic flow



[ALICE]

$$dN/d\phi = A\left(1 + 2\sum_n v_n \cos[n(\phi - \Psi_n)]\right)$$

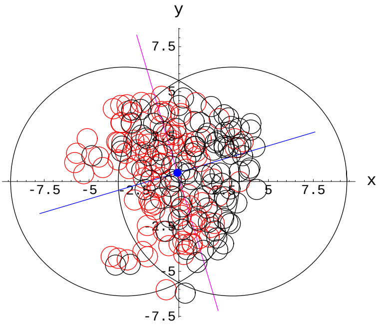
Major observation in HIC – signature of QGP



[ALICE]

Harmonic flow

Wounded nucleons – experienced at least one inelastic collision [Białas, Błeszyński & Czyż]

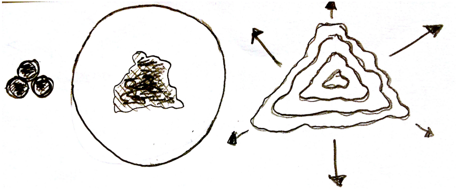


- Initial fireball is asymmetric in the transverse plane from 1) geometry 2) fluctuations
- collectivity! – **flow generated**
- Strong elliptic flow, triangular flow (in Au+Au entirely from fluctuations), higher-order harmonic flow

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

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



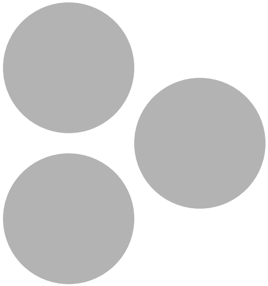
nuclear triangular geometry $\to$ fireball triangular geometry $\to$ triangular flow

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 is more promising, as it leads to more abundant fireballs

Our making ^{12}C

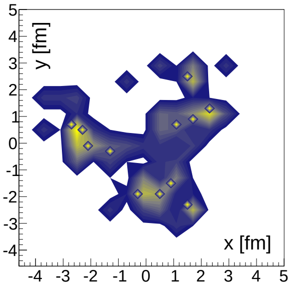
Three α's in a triangular arrangement, generate nucleon positions with Monte Carlo, parameters (size of the cluster, distance between clusters) properly adjusted (fit one-body radial distributions from other calculations, fit EM form factor)



^{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



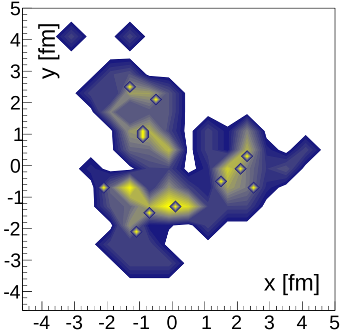
wounding range determined by $\sigma_{\rm NN}^{\rm inel}$

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

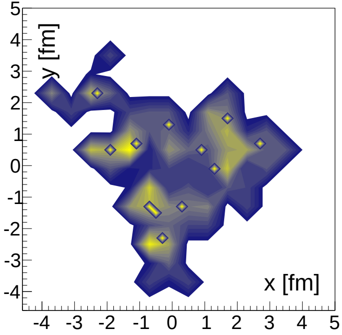
Imprints of the three α clusters clearly visible

Simulations with GLISSANDO 2

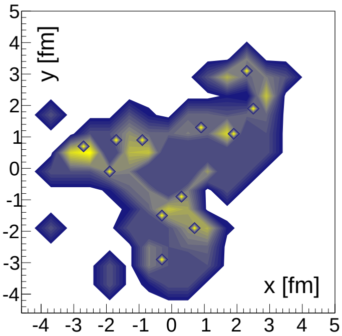
... more events

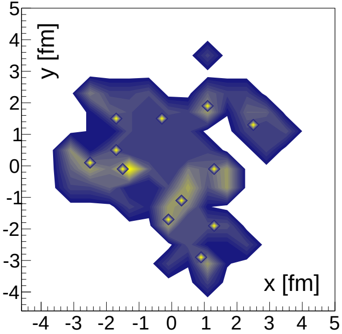


... more events

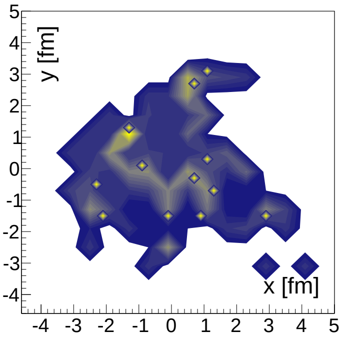


… more events

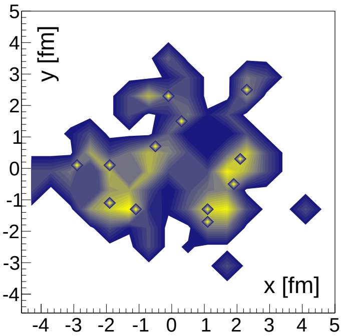


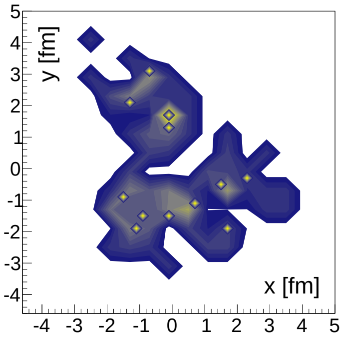

y [fm]
x [fm]
5
4
3
2
1
0
-1
-2
-3
-4
-4 -3 -2 -1 0 1 2 3 4 5

… more events



… more events




y [fm]
x [fm]
5
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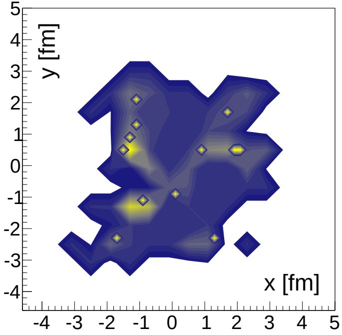
-4 -3 -2 -1 0 1 2 3 4 5

… more events



Eccentricity parameters (event-by-event)

We need quantitative measures of deformation (heavily used in heavy-ion analyses)

Eccentricity parameters ϵ_n (Fourier analysis)

$$\epsilon_n e^{in\Phi_n} = \frac{\int dxdy\, \rho(x,y)\rho^n e^{in\phi}}{\int dxdy\, \rho(x,y)\rho^n}$$

$n = 2$ – ellipticity, $n = 3$ – triangularity, ...
Φ_n – angle of the principal axes
$\rho = \sqrt{x^2 + y^2}$, $\tan\phi = y/x$
$\rho(x,y)$ – fireball density

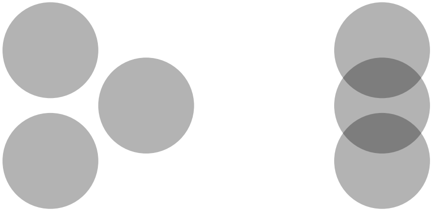
Two components:

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

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

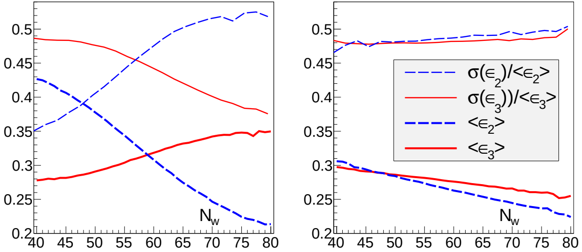
Two extreme cases of angular orientation

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



clustered unclustered

Clusters: (qualitative signal!)

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

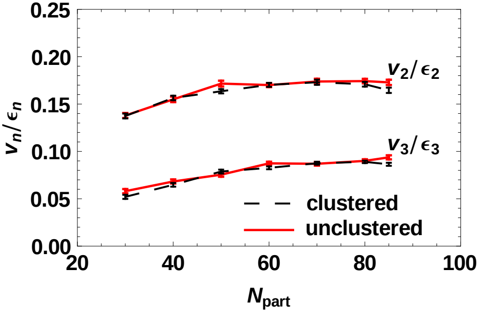
and $\sigma(\epsilon_3)/\langle\epsilon_3\rangle = \sigma(v_3)/\langle v_3\rangle \searrow$, $\sigma(\epsilon_2)/\langle\epsilon_2\rangle = \sigma(v_2)/\langle v_2\rangle \nearrow$

No clusters:

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

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" – linear response to fluctuations

We have to a very good approximation

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

(κ_n depends on mutiplicity and hydro details)

Equality of scale-independent ratios, e.g., $\sigma(\epsilon_n)/\langle\epsilon_n\rangle = \sigma(v_n)/\langle v_n\rangle$

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

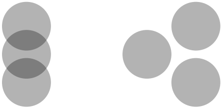
Ratio's insensitive to response:

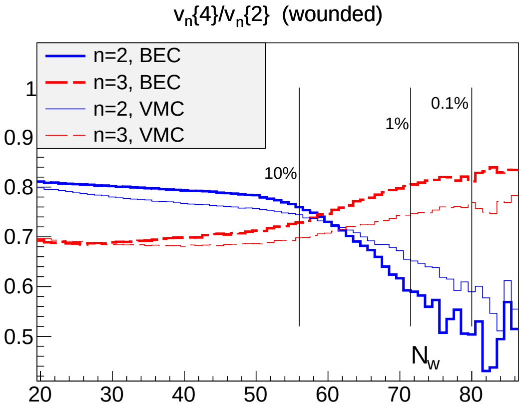
$$\frac{v_n\{m\}}{v_n\{2\}} = \frac{\epsilon_n\{m\}}{\epsilon_n\{2\}}, \quad m = 4, 6, \ldots$$

(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 $N_w \to \infty$

Ratios of cumulant moments





^{3}He-Au

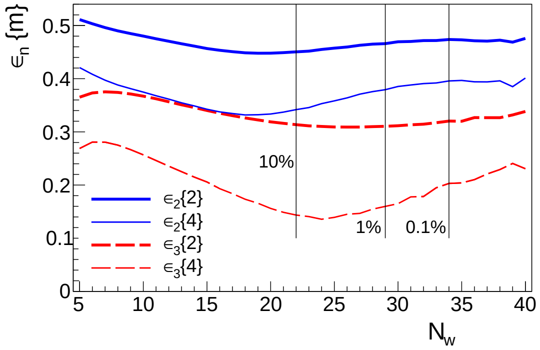
^{3}He-Au

(being presently analyzed by PHENIX)

[hydro: J. Nagle et al., arXiv:1312.4565]

[hydro without hydro: Bożek & WB, arXiv:1409.2160]

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



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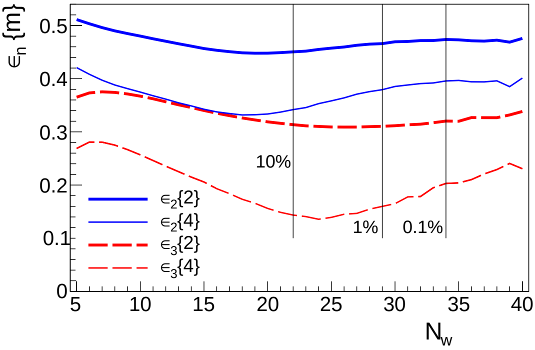
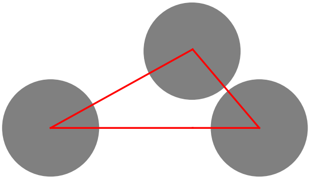
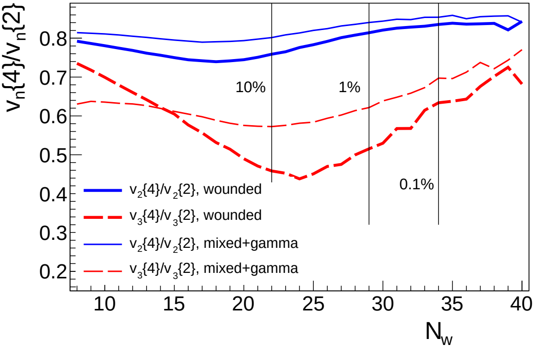




(Not equilateral! Sidewise: $\epsilon_2 \sim 1$, $\epsilon_3 \sim 3/5$)

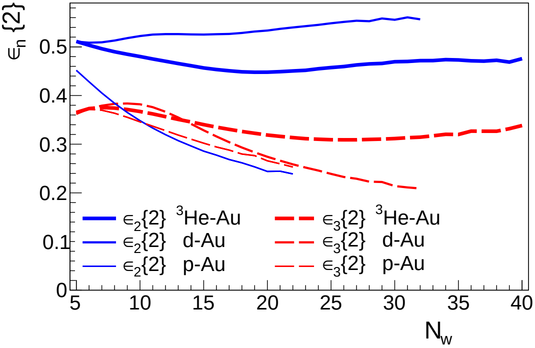
Ratio for ^{3}He-Au



Large-N_w behavior exhibits both geometric triangularity and ellipticity!

(to be confirmed by the experiment!)

p, d, ^{3}He



$\epsilon_n\{2\}$
0.5
0.4
0.3
0.2
0.1
0
5
10
15
20
25
30
35
40
N_w
$\epsilon_2\{2\}$ ^{3}He-Au
$\epsilon_2\{2\}$ d-Au
$\epsilon_2\{2\}$ p-Au
$\epsilon_3\{2\}$ ^{3}He-Au
$\epsilon_3\{2\}$ d-Au
$\epsilon_3\{2\}$ 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-^{208}Pb collisions

- Increase of triangularity with multiplicity for the highest multiplicity events
- Anticorrelation of ellipticity and triangularity
- Very clear signals from event-by-event scaled standard deviation or ratios of cumulant moments
- Effect persists in forward and backward rapidities
- ^{12}C lead to larger/more collective fireball than ^{3}He

Extensions: ^{7,9}Be, ^{16}O

Experiments needed!

Data (RHIC, NA61@SPS) will allow to place constrains on the spatially deformed structure of the light projectiles and/or 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:

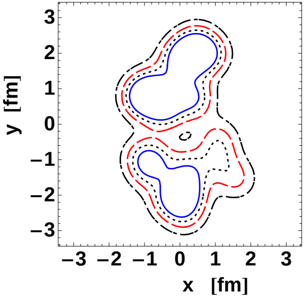
$$|\Psi_{0^+}(x_1,\ldots,x_N)\rangle = \frac{1}{4\pi}\int d\Omega \Psi_{\rm intr}(x_1,\ldots,x_N;\Omega)$$

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

Digression: d-A by Bożek

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

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



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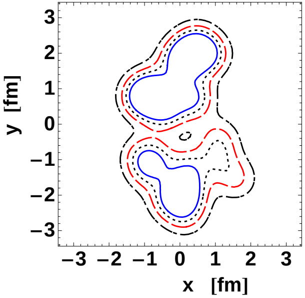
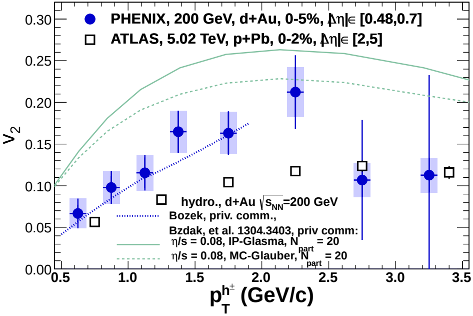
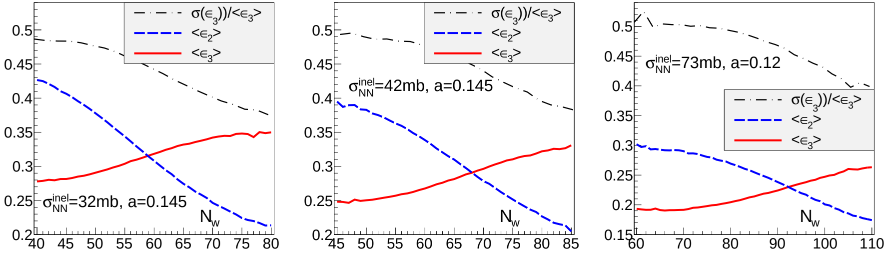




Resulting large elliptic flow confirmed with the later RHIC analysis

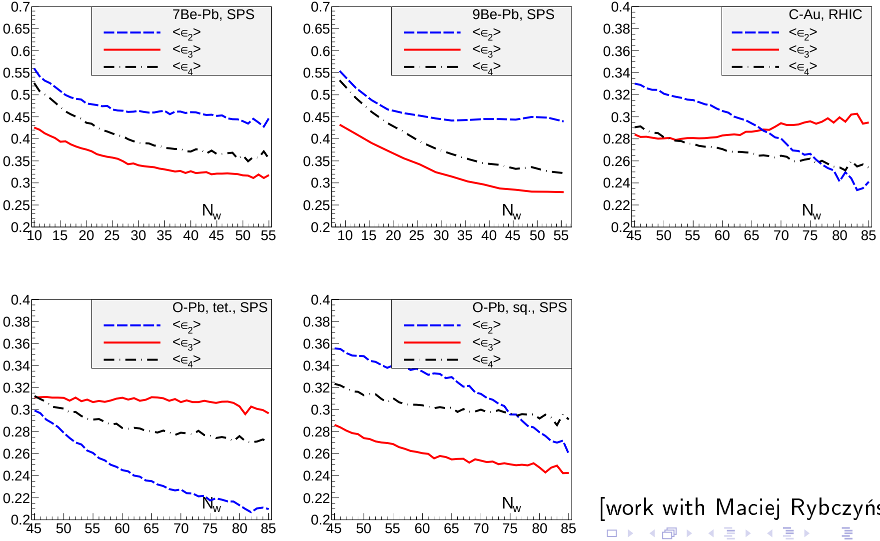
Dependence on the collision energy



$\sigma_{\rm NN}^{\rm inel}$ =32mb (SPS) 42mb (RHIC) 72mb (LHC)

Qualitative conclusions hold from SPS to the LHC

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



[work with Maciej Rybczyński]