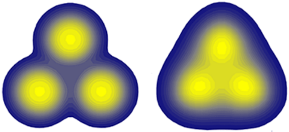
Nowe okno na strukturę lekkich jąder: klastry α a ultrarelatywistyczne zderzenia jądrowe

Wojciech Broniowski

IFJ PAN



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[szczegóły w WB& E. Ruiz Arriola, *arXiv:1312.0289*, PRL 112, 112501]

Instead of outline

Two phenomena are related:

α clustering in light nuclei

$\updownarrow$

harmonic flow in ultra-relativistic A+B collisions

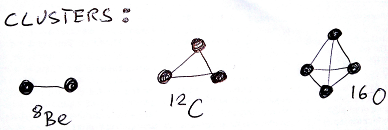
Surprising link:

low-energy structure $\longleftrightarrow$ highest energy reactions

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*



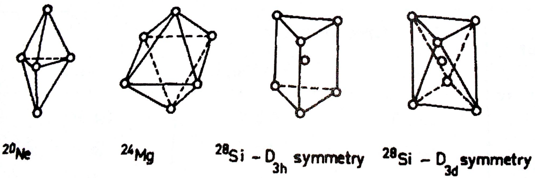
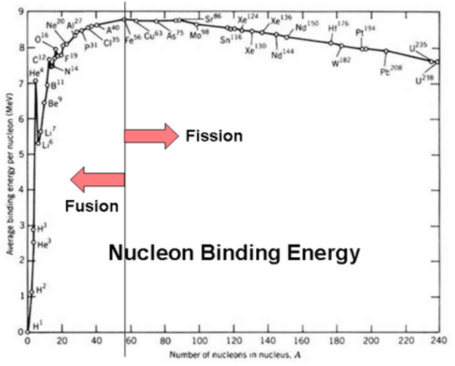


Fig. 1. Alpha-particle configuration for some $4N$ nuclei.

Binding



α very tightly bound

Shell model (and its problems)

Eugene Wigner, Maria Goeppert-Mayer, Hans Jensen, Nobel in 1963

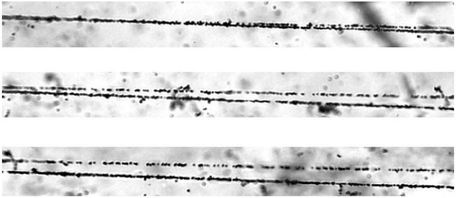
Michael P. Carpenter: *However, in the 1960s, excited states in nuclei that comprise equal numbers of protons and neutrons, (e.g., ^{12}C and ^{16}O) were identified that could not be described by the shell model, and it was suggested by Ikeda and others that these states could be associated with configurations composed of α particles*

Also: problems with α decay of ^{212}Po
shell model predicts a way too small decay width
spectroscopy: $^{212}\text{Po} = {}^{208}\text{Pb}+\alpha$ [Astier et al. 2014]

Fragmentation

Evidence from dissociation in nuclear track emulsions

[Zarubin 2013 (BECQUEREL)]



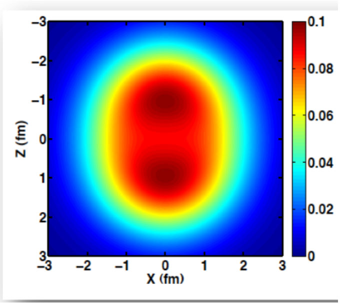
Example: dissociation of ^{7}Be (energy of a few A GeV)

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

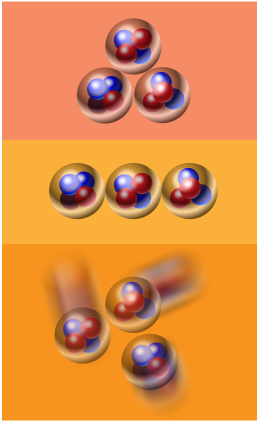
Numerous ongoing experiments (GANIL, Osaka, ...)

Was the cluster there or is it created at break-up?
These studies cannot reveal the geometry (cluster arrangement)

Present theory status



^{9}Be



^{12}C

ground

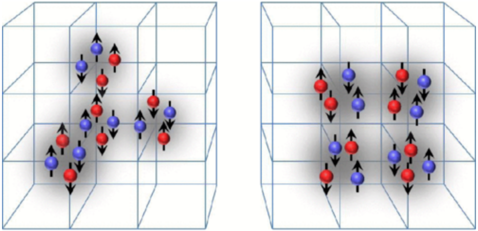
Hoyle 0^+

other excited, 2^+ . . .

[M. Freer: WPCF13, H. Fynbo+Freer: Physics 4 (2011) 94]

^{16}O

Ab initio calculations of ^{16}O with chiral NN force (Juelich 2014)
$\rightarrow$ strong α clusterization



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

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

ground state

excited

Computational techniques

(massive effort)

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., `http://www.phy.anl.gov/theory/research/density/`]

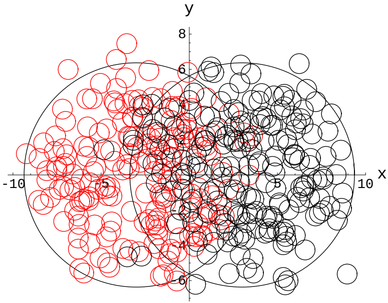
All approaches to light nuclei give clusters

Goal (not yet accurately reached):

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

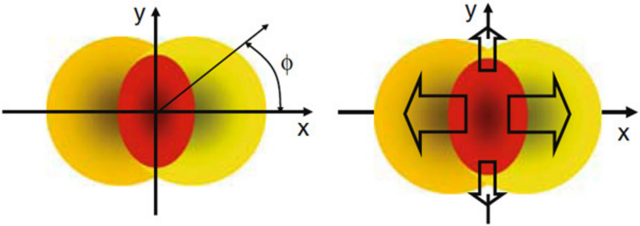
Flow

A+A collisions



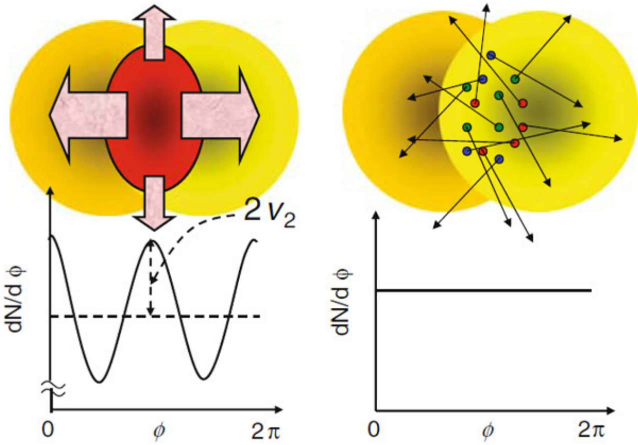
Au+Au collision at RHIC

Idea of flow



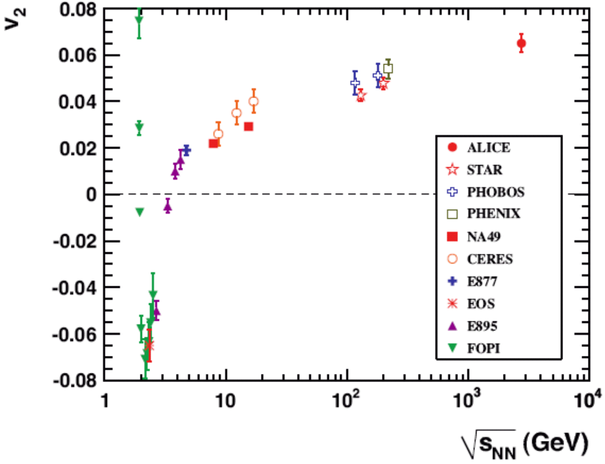
"Initial shape – final flow" transmutation detectable in the asymmetry of the momentum distribution of detected particles

Elliptic flow



[ALICE]

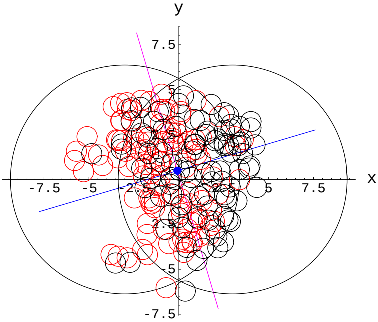
Major observation in HIC – signature of QGP



[ALICE]

Harmonic flow

Participants:

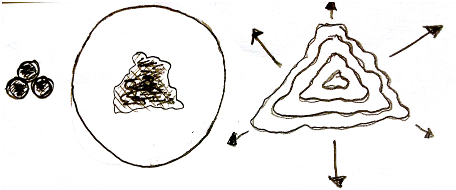


- initial fireball is asymmetric in the transverse plane from 1) geometry 2) fluctuations
- collectivity! – **flow generated**
- strong elliptic flow, triangular flow from fluctuations, higher-order flow

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

From α clusters to flow in relativistic collisions

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



nuclear triangular geometry $\rightarrow$ fireball triangular geometry $\rightarrow$ triangular flow

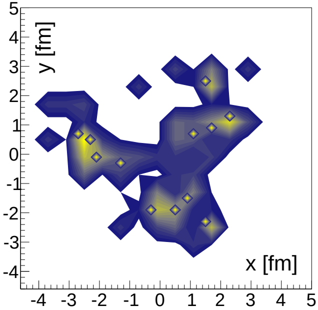
What are the signatures, chances of detection?

Related idea: triton/^{3}He–Au at RHIC in 2015 [Sickles (PHENIX) 2013]
The case of light nuclei is more promising, as it leads to abundant fireballs

^{12}C-^{208}Pb – single event

why ultrarelativistic?

reaction time is much shorter than time scales of the structure
→ a frozen "snapshot" of the nuclear configuration

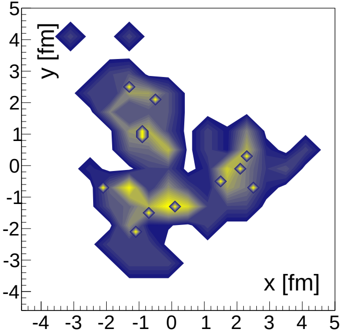


($N_w > 70$ - flat-on orientation)

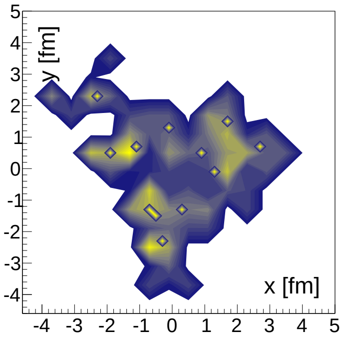
Imprints of the three α clusters clearly visible

[simulations with GLISSANDO 2]

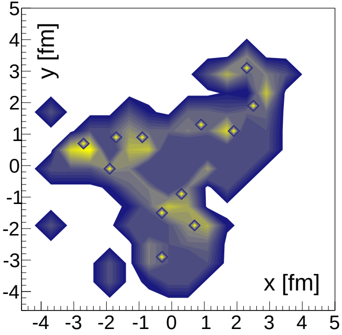
... more events



... more events



... more events



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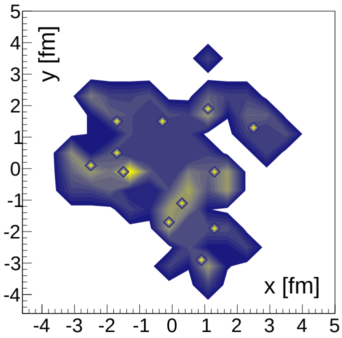

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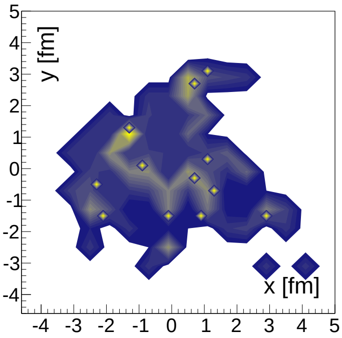
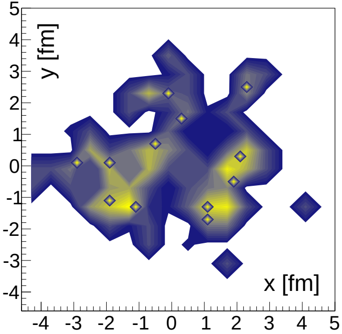


... more events



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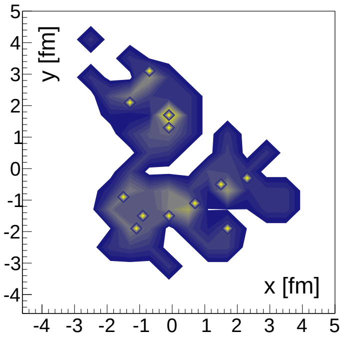
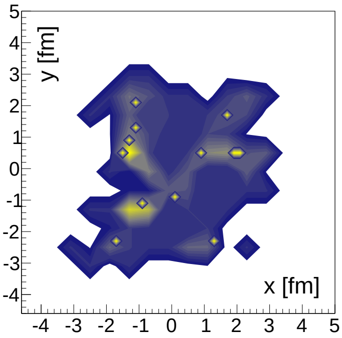


... more events



The meaning of *intrinsic*

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

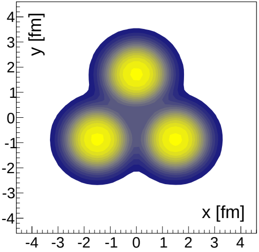
Superposition over orientations:

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

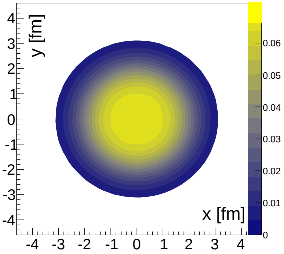
The *intrinsic* density of sources of rank n is defined as the average over events, where the distributions in each event have aligned principal axes: $f_n^{\rm intr}(\vec{x}) = \langle f(R(-\Phi_n)\vec{x})\rangle$. Brackets indicate averaging over events and $R(-\Phi_n)$ is the inverse rotation by the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

Back to ^{12}C – intrinsic density

Intrinsic distributions in ^{12}C: three α's in a triangular arrangement

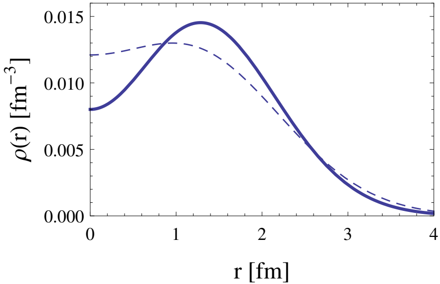


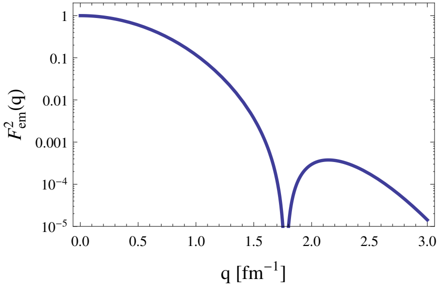
clustered



unclustered

Constraints on ^{12}C from EM form factor

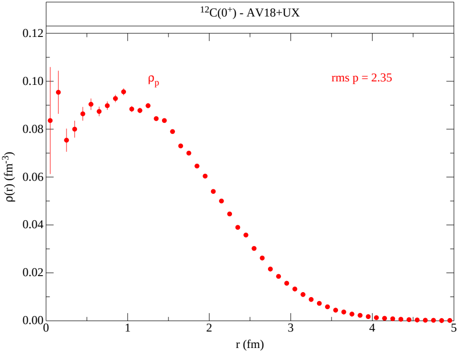




Electric charge density (dashed line) and the corresponding distribution of the centers of protons (solid line) in ^{12}C for the data plotted against the radius, for the **BEC** calculation – agrees with the experimental data for the charge form factor

Central depletion naturally explained with the hole between the clusters

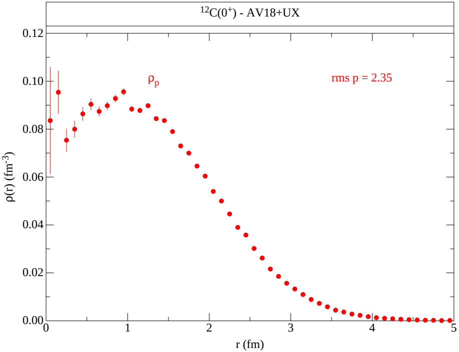
^{12}C from Wiringa's MC



Distribution of the centers of protons = neutrons in ^{12}C

smaller central depletion

^{12}C from Wiringa's MC



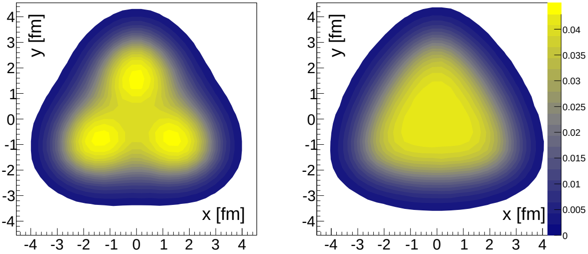
Distribution of the centers of protons = neutrons in ^{12}C

smaller central depletion

GLISSANDO implements these clustered distributions
→ carry out detailed simulations

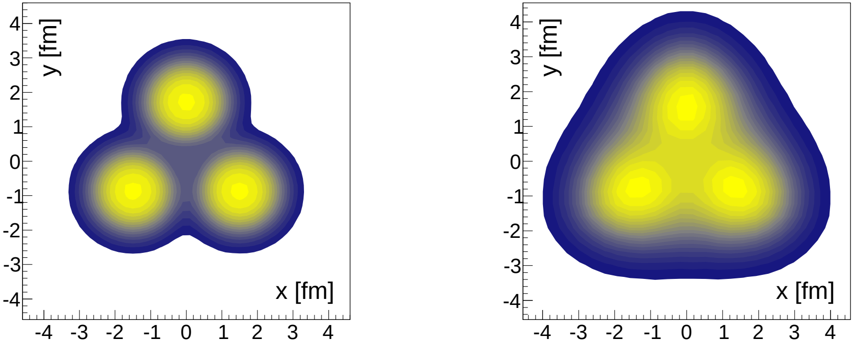
^{12}C–^{208}Pb collision

Intrinsic distributions in the *transverse plane* of the fireball (here with $N_w > 70$ – large multiplicity enforcing the flat-on collision)



clustered unclustered

Geometry of nucleus → geometry of fireball



intrinsic density of ^{12}C → geometry of the fireball

Eccentricity parameters

Eccentricity parameters ϵ_n (Fourier analysis)

$$\epsilon_n e^{in\Phi_n} = \frac{\sum_j \rho_j^n e^{in\phi_j}}{\sum_j \rho_j^n}$$

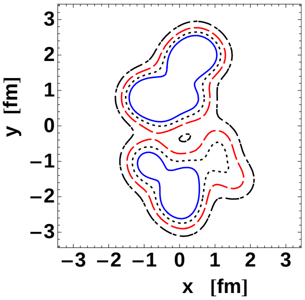
describe the shape of each event (j labels the sources in the event, n=rank, Φ_n is the principal axis angle)

Two components:

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

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]

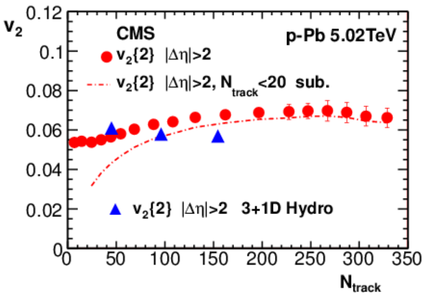


Resulting large elliptic flow confirmed with the later RHIC analysis

Digression 2: collectivity in small systems

Active research:

hydro in p-A, d-A collisions, pioneered by Bożek

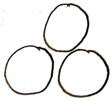


[Bożek+WB+Torrieri PRL 111 (2013) 172303]

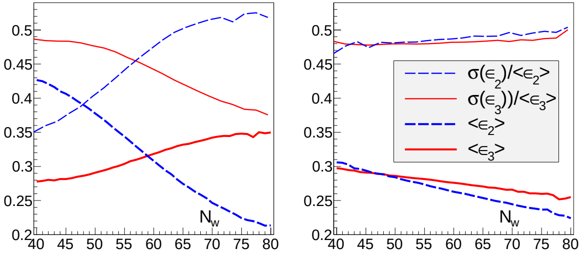
Geometry vs multiplicity correlations in ^{12}C-Pb

Specific feature of the ^{12}C collisions:

The cluster plane parallel or perpendicular to the transverse plane:



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



clustered unclustered

Clusters:

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

and $\langle\sigma(\epsilon_3)/\epsilon_3\rangle \searrow$, $\langle\sigma(\epsilon_2)/\epsilon_2\rangle \nearrow$ tending to $\sqrt{4/\pi - 1} \sim 0.52$

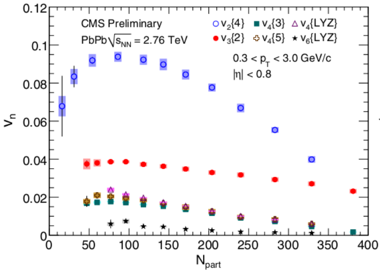
No clusters:

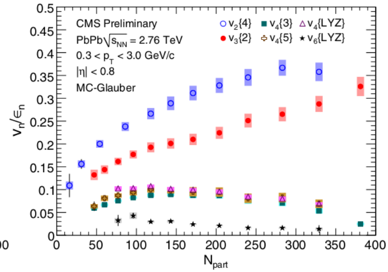
similar behavior for $n = 2$ and $n = 3$

Shape-flow transmutation

The eccentricity parameters are transformed (in all models based on collective dynamics) into asymmetry of the transverse-momentum flow
It has been found that

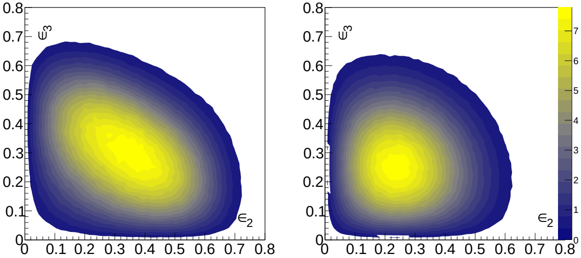
$\langle v_n \rangle$ grows with $\langle \epsilon_n \rangle$





$\rightarrow$ for ^{12}C collisions v_3 will grow with multiplicity even stronger than ϵ_3

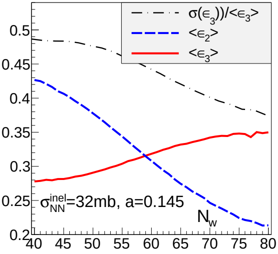
Triangularity vs ellipticity



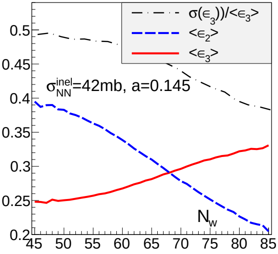
clustered   unclustered

Clusters:

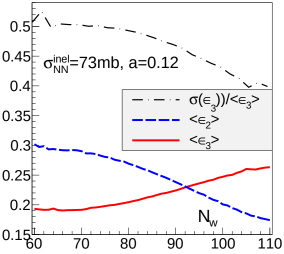
Anticorrelation: $\rho(\epsilon_2, \epsilon_3) \simeq -0.3$



32mb (SPS)



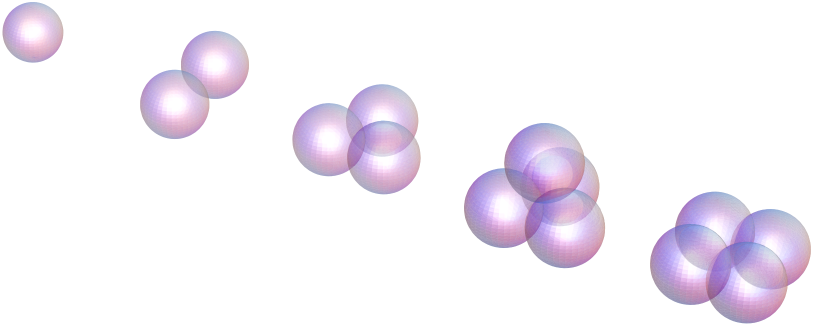
42mb (RHIC)



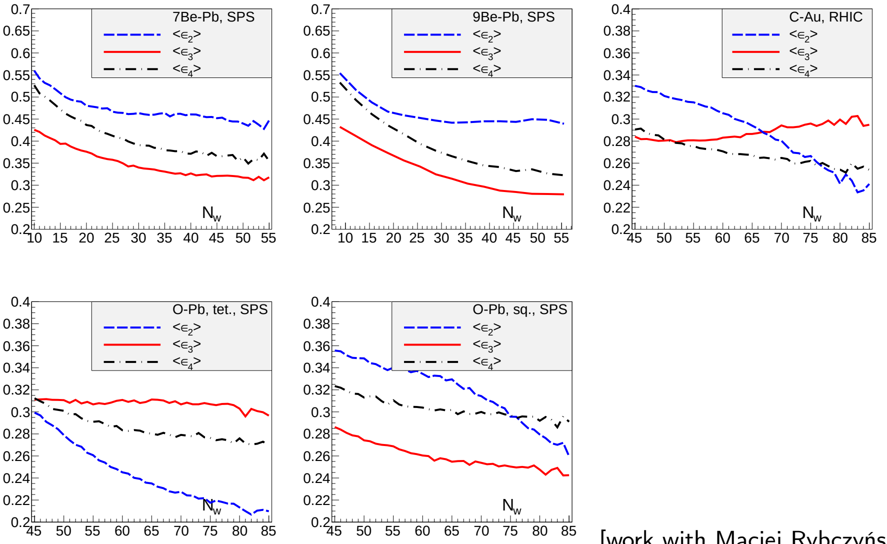
72mb (LHC)

Qualitative conclusions hold from SPS to the LHC

Other systems



Other systems (Wiringa's distributions)



[work with Maciej Rybczyński]

Conclusions

Why small on big?

small on big

small nucleus $\rightarrow$ large deformation from clusters
big nucleus $\rightarrow$ large fireball, collectivity

small on small

more difficult evolution / particle production, other signatures

big on big

(U+U, Cu+Au) $\rightarrow$ possible signatures of nuclear deformation (but not clustering) [Filip, Voloshin 2010, Rybczyński, WB, Stefanek 2011]

ultrarelativistic $\rightarrow$ snapshots

New method: nuclear structure from ultra-fast heavy ion collisions / Geometry of the ground state → flow

Signatures (qualitative and quantitative) of clustered ^{12}C-^{208}Pb collisions

- Increase of triangularity with multiplicity for the highest multiplicity events
- Decrease of scaled variance of triangularity with multiplicity for the highest multiplicity events
- Anticorrelation of ellipticity and triangularity

Extensions (in progress)

- Other systems and other possible signatures
- More detailed modeling involving hydrodynamics

Possible future data (NA61, RHIC?) in conjunction with a detailed knowledge of the dynamics 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 may help to verify the fireball evolution models