Hydrodynamics in small and medium systems

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1. p-Pb (research with P. Bożek)
2. α-clustered nucleus-A (research with E. Ruiz Arriola and M. Rybczyński)

Collectivity in small and medium systems

Main questions:

What is the nature of the initial state and correlations therein?
What are the limits/conditions on applicability of hydrodynamics?

What is the ground state of light nuclei?

Other analyses of collectivity in small systems:

Romatschke, Luzum, arXiv:0901.4588, Prasad et al., arXiv:0910.4844,
Bozek, arXiv:0911.2393, Werner et al., arXiv:1010.0400,
Deng, Xu, Greiner, arXiv:1112.0470, Yan et al., arXiv: 0912.3342,
Bozek, arXiv:1112.0912 Shuryak, Zahed, arXiv:1301.4470,
Bzdak et al.,arXiv:1304.3403, Qin, Müller, arXiv:1306.3439,
Werner et al., arXiv:1307.4379

Method

Flow develops

3-stage approach

Our three-phase approach ("Standard Model of heavy-ion collisions"):

initial → hydro → statistical hadronization

(successful in description of A+A collisions)

- **Initial phase** - Glauber model `GLISSANDO`
- **Hydrodynamics** - 3+1 D viscous event-by-event
- **Statistical hadronization** - `THERMINATOR`

Hydrodynamics [Bożek 2011]

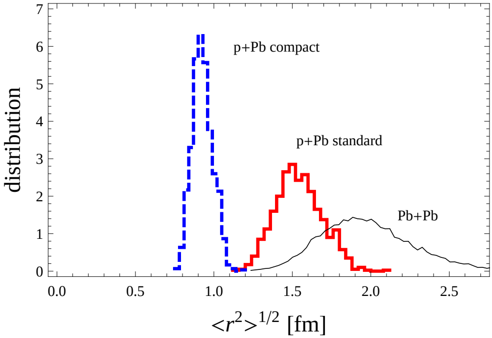
3+1 D viscous Israel-Stewart event-by-event hydrodynamics (viscous corrections essential due to large gradients)

- $\tau_{\text{init}} = 0.6$ fm/c, $\eta/s = 0.08$ (**shear**), $\zeta/s = 0.04$ (**bulk**)
- Gaussian smearing of the sources, $r = 0.4$ fm – physical effect
- average initial temperature in the center of the fireball adjusted to fit the multiplicity
- realistic equation of state (lattice + hadron gas [based on Chojnacki, Florkowski 2007])
- freezeout at $T_f = 150$ MeV
- lattice spacing of 0.15 fm (**thousands of CPU hours for one reaction**)

Highlights of p-Pb

Size in p-Pb vs Pb-Pb

fixed $N_{\text{part}} = 19$



smaller size in p-Pb → larger entropy density → more rapid expansion

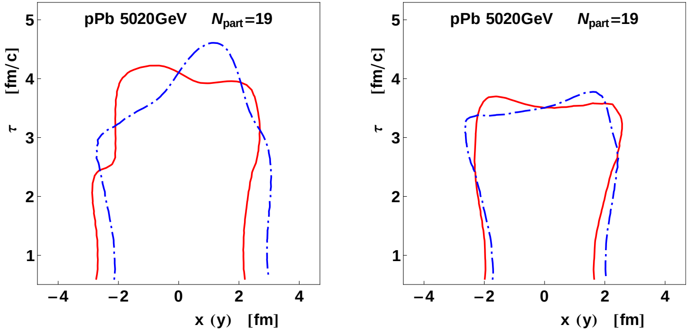
standard - source positioned at the center of the nucleons

compact - source at the CM of the colliding pair

[see also Bzdak, Schenke, Tribedy, Venugopalan, arXiv:1304.3403]

All in all, initial conditions in most central p-Pb not very far from those in peripheral Pb-Pb

Typical evolution in p-Pb

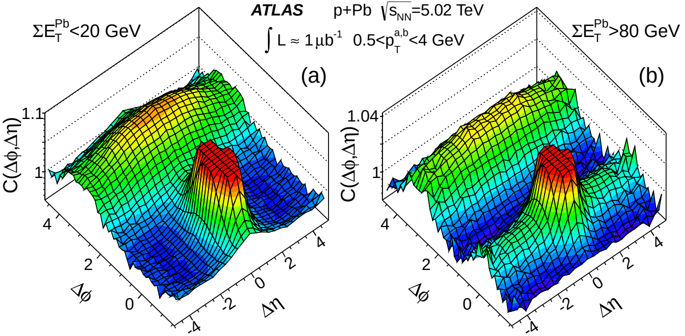

standard

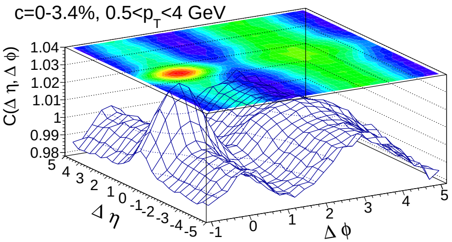
compact

isotherms at freeze-out $T_f = 150$ MeV for two sections in the transverse plane

evolution lasts about 4 fm/c - shorter but more rapid than in A+A

Ridge in p-Pb, ATLAS

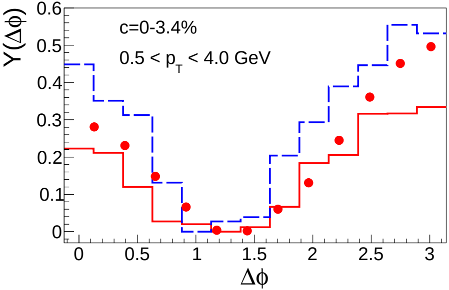




Projection on $2 \leq |\Delta\eta| \leq 5$, ATLAS

$$Y(\Delta\phi) = \frac{\int B(\Delta\phi)d(\Delta\phi)}{N} C(\Delta\phi) - b_{\mathrm{ZYAM}}$$

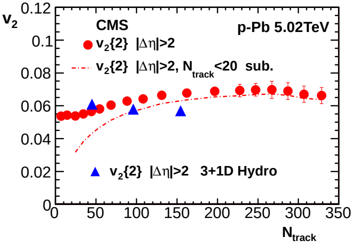
The near-side ridge from our model:

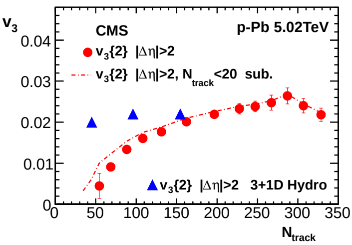


red - standard, blue - compact

[CGC: Dusling, Venugopalan, arXiv:1210.3890, 1211.3701, 1302.7018]

v_2, v_3 vs CMS

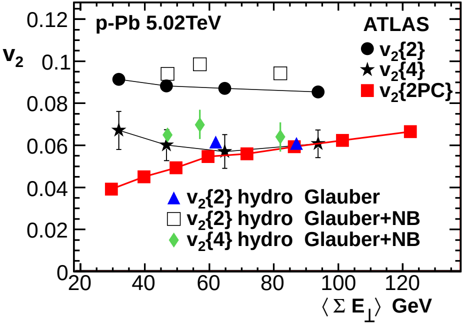




v_3 somewhat too large for lower-multiplicity collisions

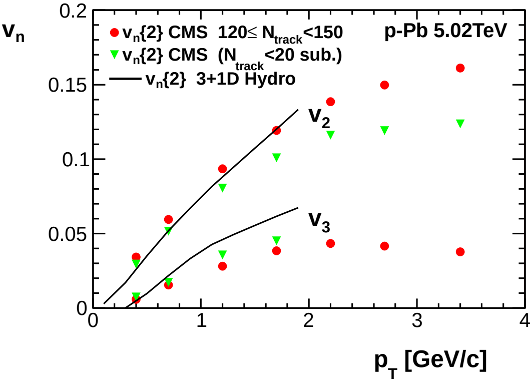
→ limit of validity of the model

LHC: v_2 vs ATLAS



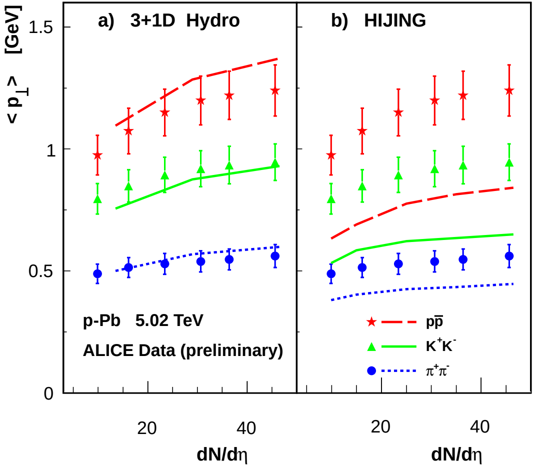
(NB – additional fluctuations of the strength of the sources, adjusted in such a way that the experimental multiplicity distribution is reproduced)

v_2, v_3 vs p_T

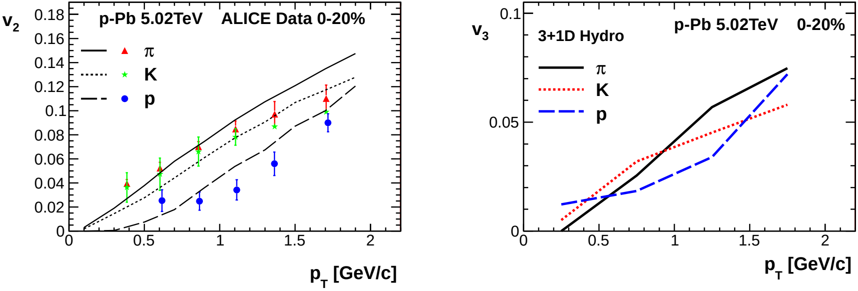

v_n
0.2
0.15
0.1
0.05
0
0
1
2
3
4
p_T [GeV/c]
● v_n{2} CMS 120≤ N_track<150
▼ v_n{2} CMS (N_track<20 sub.)
v_n{2} 3+1D Hydro
p-Pb 5.02TeV
v_2
v_3

Identified $\langle p_T \rangle$

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



Identified v_2 and v_3

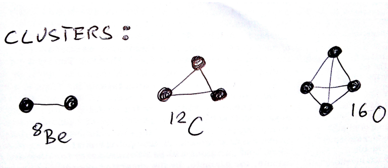


Resonance decays affect the mass ordering in v_3

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*



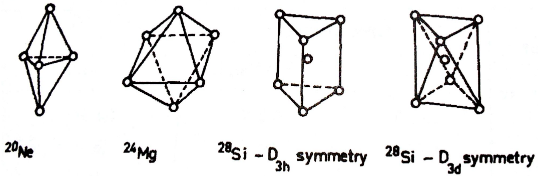


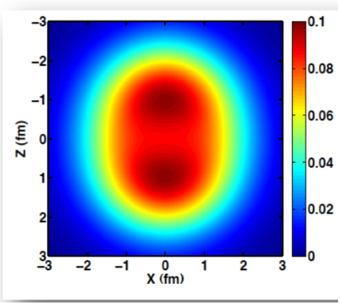
Fig. 1. Alpha-particle configuration for some $4N$ nuclei.

Shell model (and its problems)

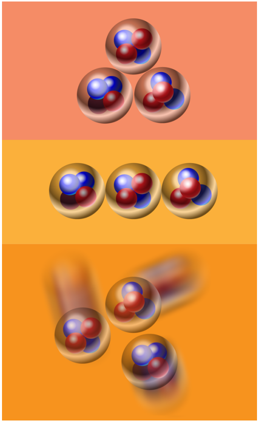
Eugene Wigner, Maria Goeppert-Mayer, Hans Jensen, Nobel in 1963

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*

Present theory status



^{9}Be



ground

Hoyle 0^+

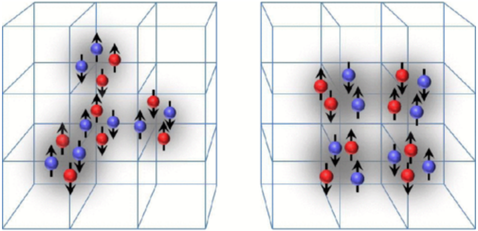
other excited, 2^+ . . .

^{12}C

[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):

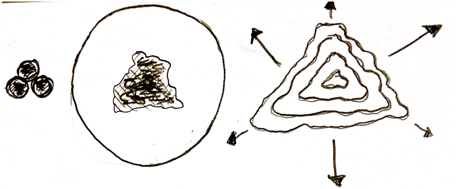
reproduce ground-state energy, excitation spectrum, EM form factor, ...

Merge the two ideas: α's and flow

From α clusters to flow in relativistic collisions

[WB, Ruiz Arriola, PRL 112 (2014) 112501]

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



nuclear triangular geometry → fireball triangular geometry → triangular flow

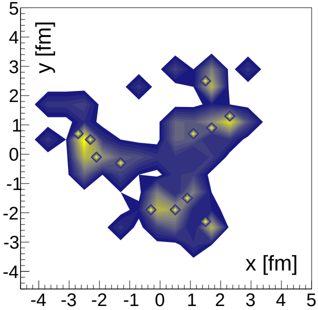
What are the signatures, chances of detection?

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

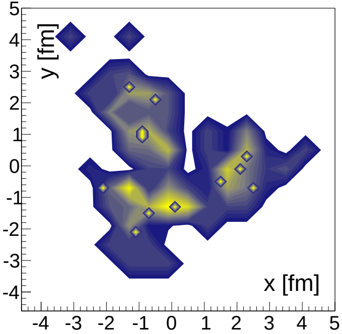


($N_w > 70$ - flat-on orientation)

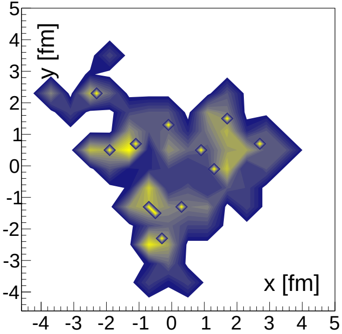
Imprints of the three α clusters clearly visible

[simulations with GLISSANDO 2]

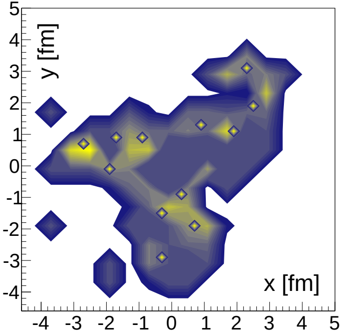
... more events



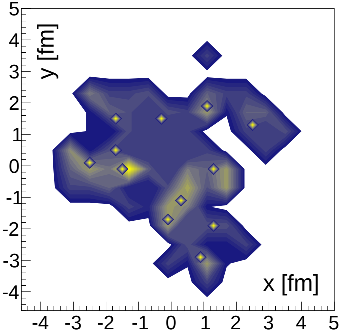
… more events



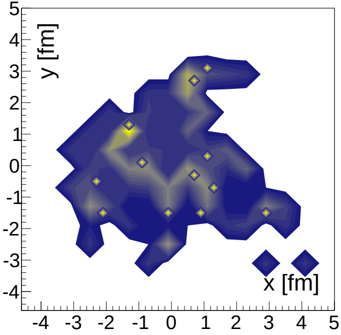
… more events



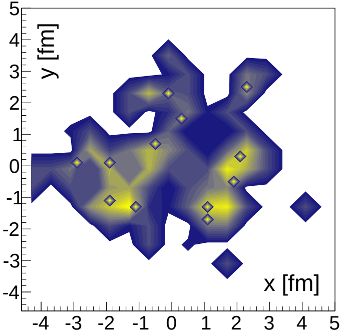
... more events



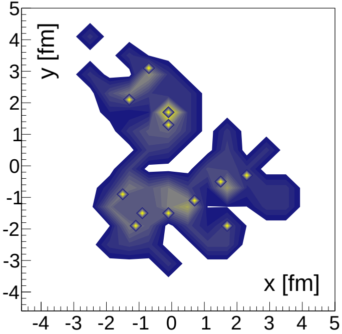
… more events



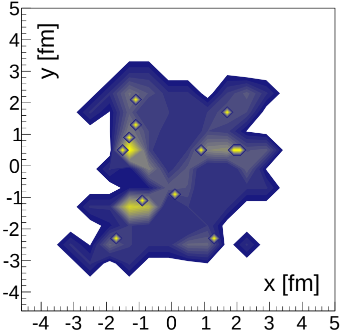
… more events



... more events



… 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

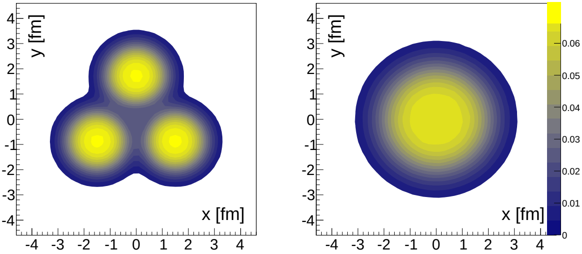
Superposition over orientations:

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

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

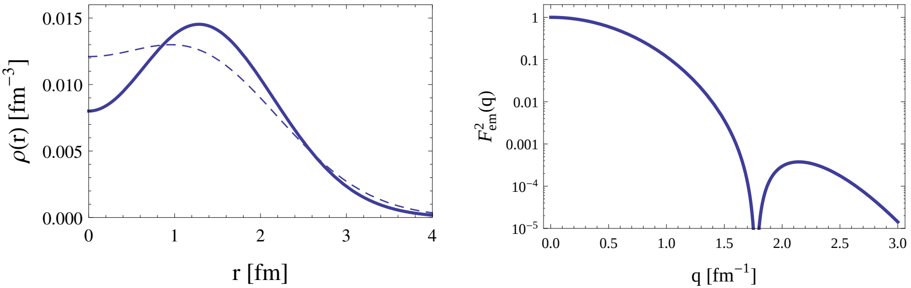
Intrinsic distributions in ^{12}C: three α's in a triangular arrangement



clustered

unclustered

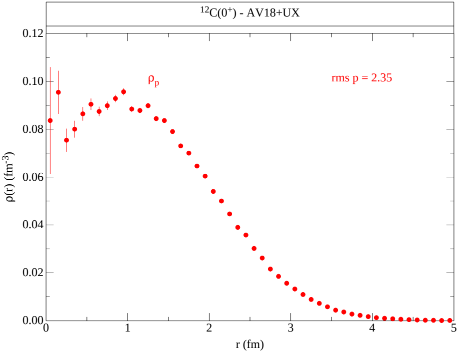
Constraints on ^{12}C from EM form factor



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

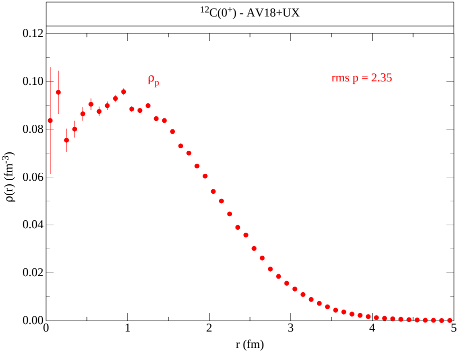
^{12}C from Wiringa's MC



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

smaller central depletion

^{12}C from Wiringa's MC



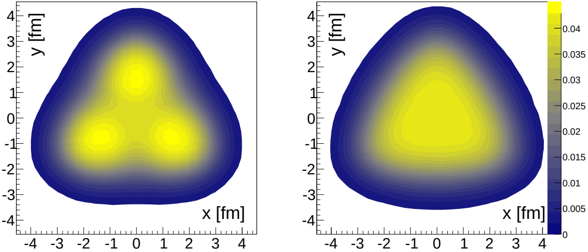
Distribution of the centers of protons = neutrons in ^{12}C

smaller central depletion

GLISSANDO implements these clustered distributions
→ carry out detailed simulations

^{12}C–^{208}Pb collision

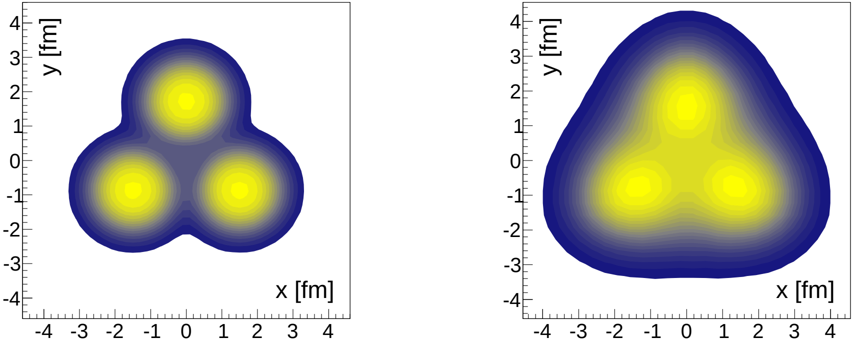
Intrinsic distributions in the *transverse plane* of the fireball (here with $N_w > 70$ – large multiplicity enforcing the flat-on collision)



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)

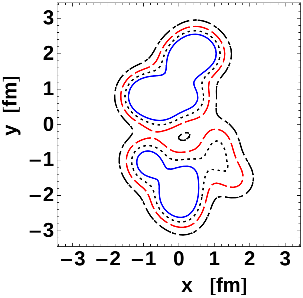
Two components:

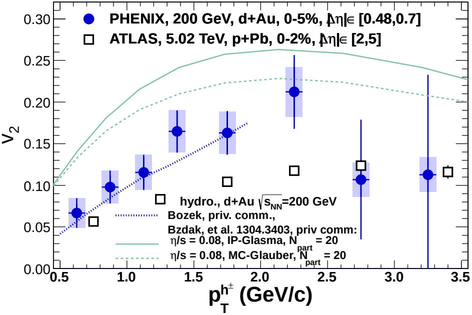
- internal (from existent mean deformation of the fireball)
- from fluctuations

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]





Resulting large elliptic flow confirmed with the later RHIC analysis

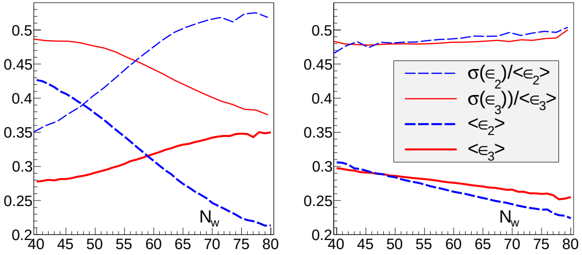
Geometry vs multiplicity correlations in ^{12}C-Pb

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

Ellipticity and triangularity vs multiplicity



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 $\sqrt{4/\pi - 1} \sim 0.52$

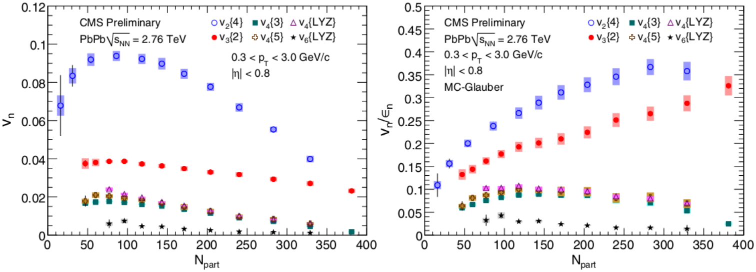
No clusters:

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

Shape-flow transmutation

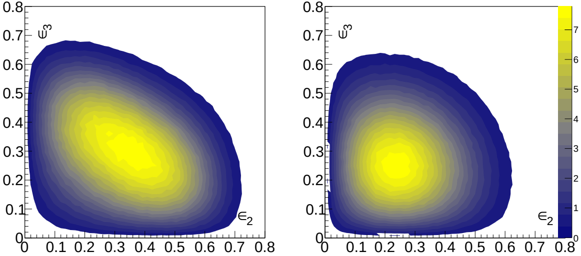
The eccentricity parameters are transformed (in all models based on collective dynamics) into asymmetry of the transverse-momentum flow
It has been found that

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



→ for ^{12}C collisions v_3 should grow with multiplicity even stronger than ϵ_3

Triangularity vs ellipticity

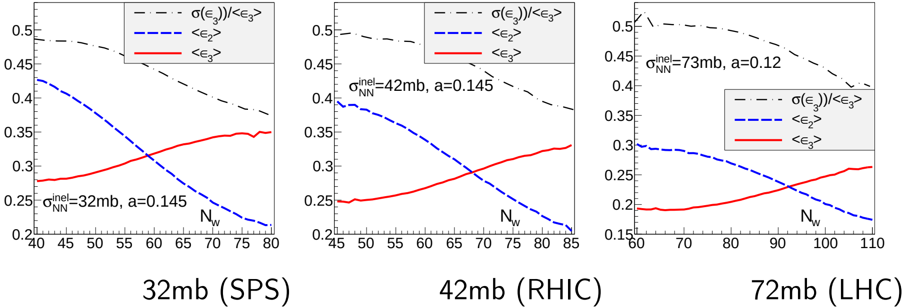


clustered unclustered

Clusters:

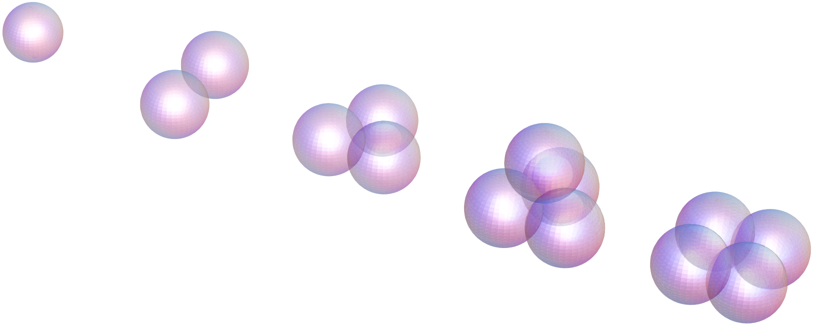
Anticorrelation of ϵ_2 and ϵ_3

Dependence on the collision energy

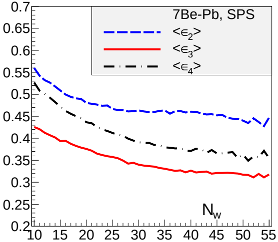


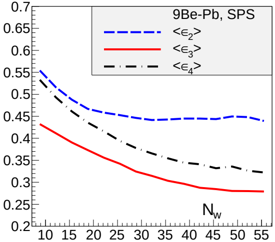
Qualitative conclusions hold from SPS to the LHC

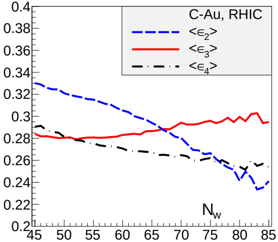
Other systems

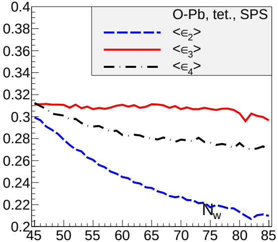


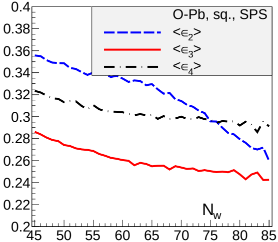
Other systems (Wiringa's distributions)











[work with Maciej Rybczyński]

Conclusions

Is there collectivity in p-Pb?

Collective dynamics is compatible with the high-multiplicity soft LHC data for p-Pb

- Large v_2 and v_3 coefficients measured in p-Pb reasonably reproduced, including the p_T dependence
- Model 2D correlations exhibit the two ridges, in particular the near-side ridge
- Mass ordering in $\langle p_T \rangle$ and flow coefficients reproduced

- Numerous effects should still be incorporated (jets, core-corona, ...) – more important for the lower-multiplicity events

α clusters

Clustered geometry of the ground state → harmonic flow

Best signatures of ^{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, more detailed modeling involving e-by-e hydro

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