α clusters from hydrodynamic flow

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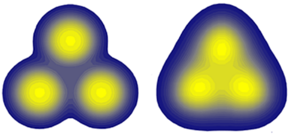


UJ, 9.06.2014

[research with Enrique Ruiz Arriola, *arXiv:1312.0289*, PRL 112 (2014) 112501]

Instead of outline

Two phenomena are related:

α clustering in light nuclei

$\updownarrow$

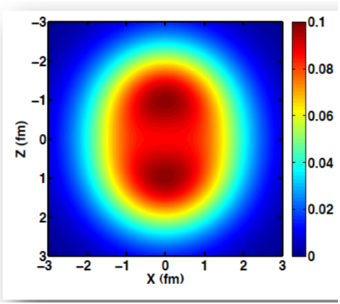
harmonic flow in ultra-relativistic nuclear collisions

Surprising link:

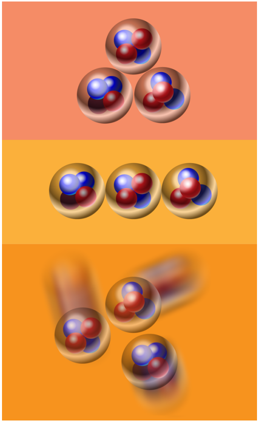
lowest-energy ground-state structure $\longleftrightarrow$ highest energy reactions

α clusters

α clusters expected in light nuclei



^{9}Be



ground

Hoyle 0^+

other excited, 2^+ ...

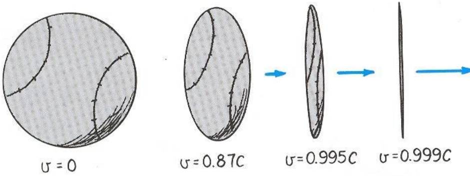
^{12}C

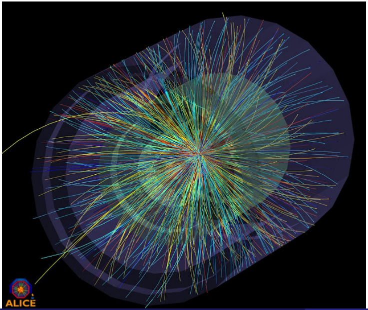
How can we detect the α clusters in the ground state?
What is their spatial arrangement?
Assessment of n-body correlations (one-body not enough)

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)

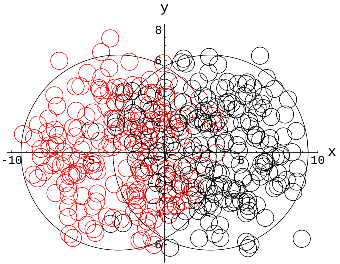




- detection of particles (mostly pions) in the transverse direction (mid-rapidity)

Soft ($p_T < 2$ GeV) particle production

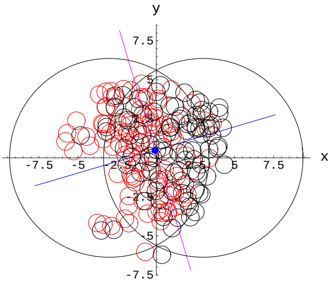
Glauber-Czyż-Maximon model – particle production from independent NN collisions (wounded nucleon model of Białas, Błeszyński, and Czyż)



Au+Au collision at RHIC

Soft ($p_T < 2$ GeV) particle production

Glauber-Czyż-Maximon model – particle production from independent NN collisions (wounded nucleon model)



Au+Au collision at RHIC

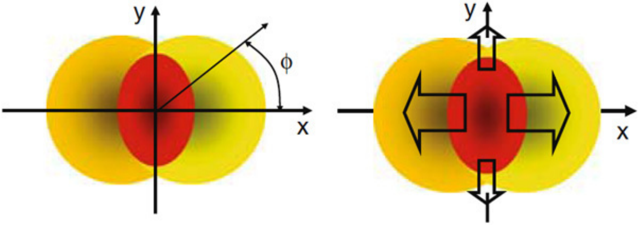
- QCD partons produced in the initial phase → sQGP

Subsequent phases:

- expansion
- freezeout
- hadrons (mostly pions) streaming to detectors

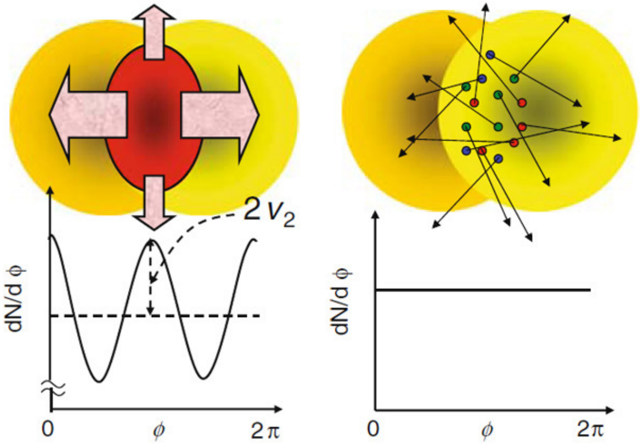
Phenomenon of flow

Quark-gluon plasma is formed!



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

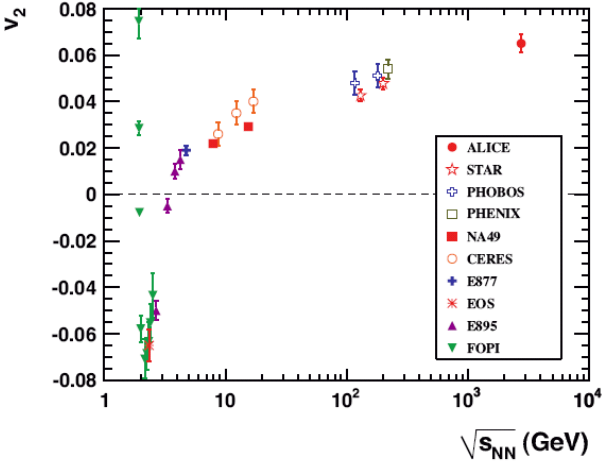
Elliptic flow



[ALICE]

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

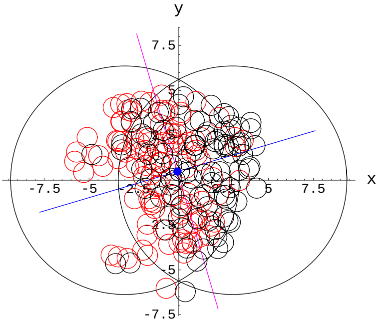
Major observation in HIC – signature of QGP



[ALICE]

Harmonic flow

Wounded nucleons – experienced at least one inelastic collision



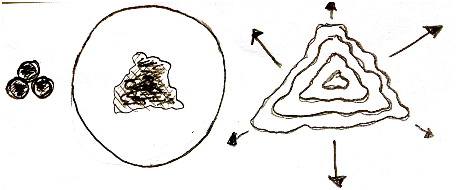
- Initial fireball is asymmetric in the transverse plane from
  1) geometry 2) fluctuations
- collectivity! – **flow generated**
- Strong elliptic flow, triangular flow (in Au+Au entirely from fluctuations), higher-order harmonic flow

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

From α clusters to flow in relativistic collisions

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

(^{12}C as example)



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

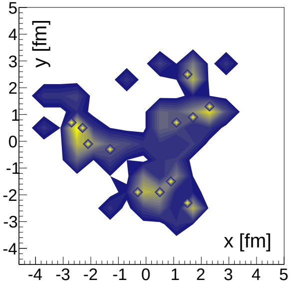
What are the signatures, chances of detection?
(some blurring by fluctuations)

Related idea: triton/^{3}He–Au at RHIC in 2015
The case of ^{12}C is more promising, as it leads to more abundant fireballs

^{12}C-^{208}Pb – single event

Why ultrarelativistic?

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



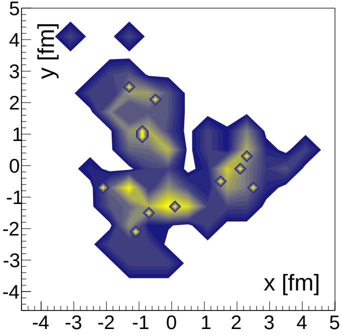
wounding range determined by $\sigma_{\rm NN}^{\rm inel}$

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

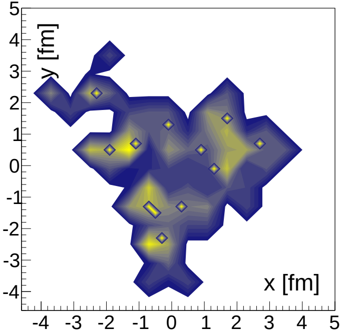
Imprints of the three α clusters clearly visible

Simulations with GLISSANDO 2 – implementation of the Glauber model

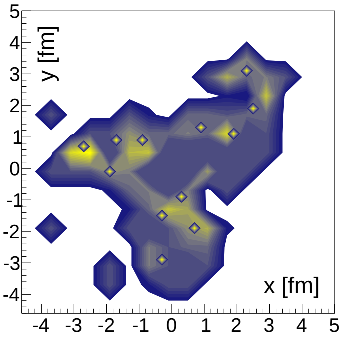
… more events



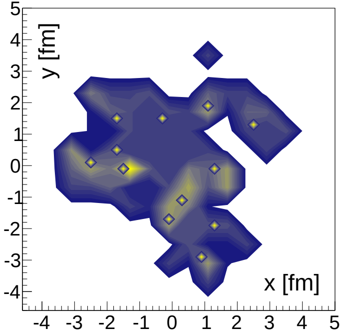
… more events



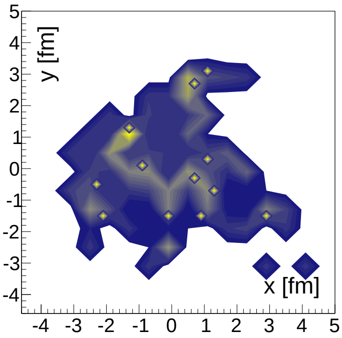
... more events



... more events



... more events



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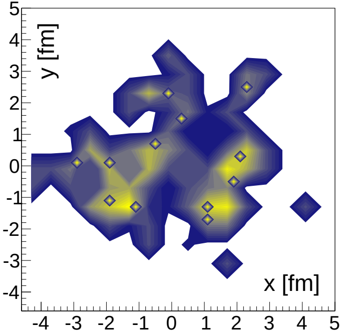

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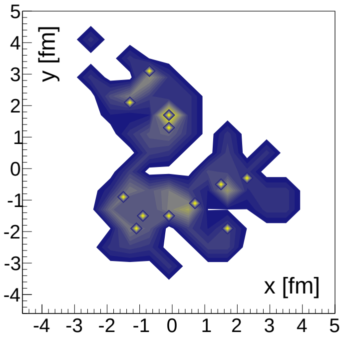
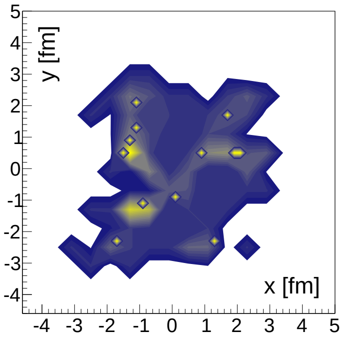



y [fm]
x [fm]
5
4
3
2
1
0
-1
-2
-3
-4
-4 -3 -2 -1 0 1 2 3 4 5

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:

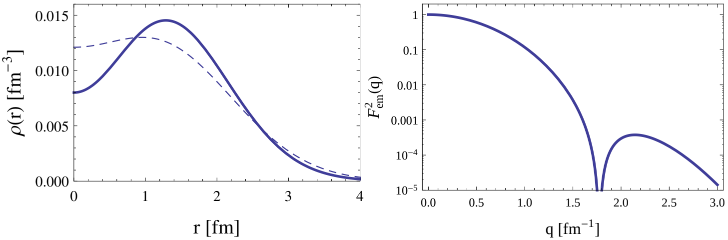
$$|\Psi_{0^+}(x_1,\ldots,x_N)\rangle = \frac{1}{4\pi}\int d\Omega \Psi_{\rm intr}(x_1,\ldots,x_N;\Omega)$$

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

Our poor-man's ^{12}C

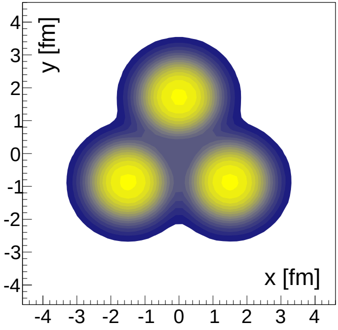
[Could use actual distributions from theoretical calculations]

Three α's in a triangular arrangement, generate nucleon positions with Monte Carlo, parameters (size of the cluster, distance between clusters) chosen such that the EM form factor is reproduced



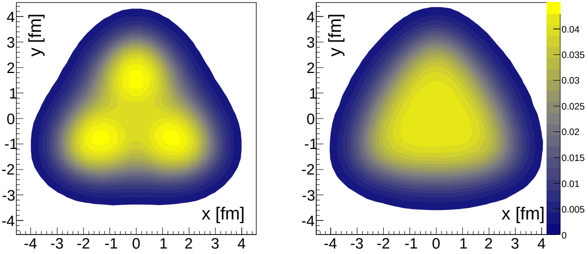
Electric charge density (dashed line) and the corresponding distribution of the centers of protons (solid line) in ^{12}C for the data (i.e., after unfolding the proton charge form factor), plotted against the radius

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



^{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)

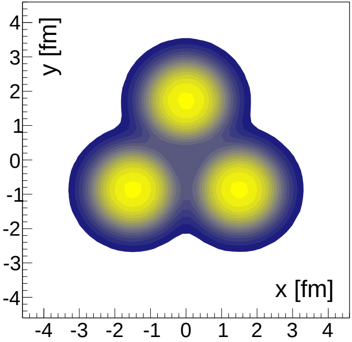


clustered unclustered

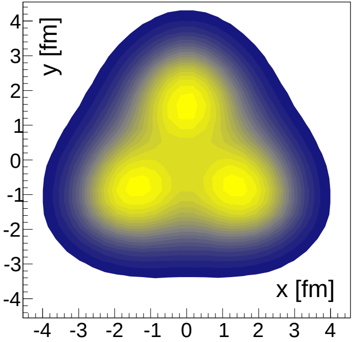
Some triangularity in the unclustered case follows from the fluctuations

Geometry of nucleus $\rightarrow$ geometry of fireball

Triangular nucleus causes triangular "damage"!



intrinsic density of ^{12}C $\rightarrow$



geometry of the fireball

Eccentricity parameters

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

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)
$n = 2$ – ellipticity, $n = 3$ – triangularity, ...

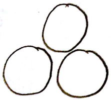
Two components:

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

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

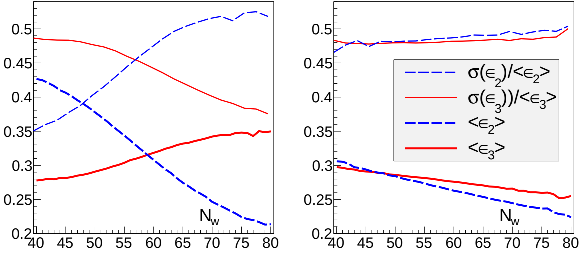
Specific feature of the ^{12}C collisions:

The cluster plane parallel or perpendicular to the transverse plane:



higher multiplicity higher triangularity lower ellipticity	lower multiplicity lower triangularity 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 $\langle\sigma(\epsilon_3)/\epsilon_3\rangle \searrow$, $\langle\sigma(\epsilon_2)/\epsilon_2\rangle \nearrow$

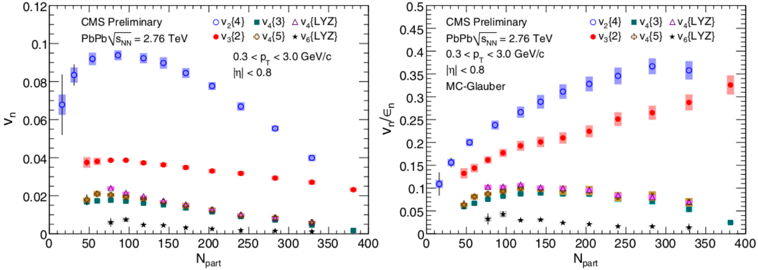
No clusters:

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
It has been found that

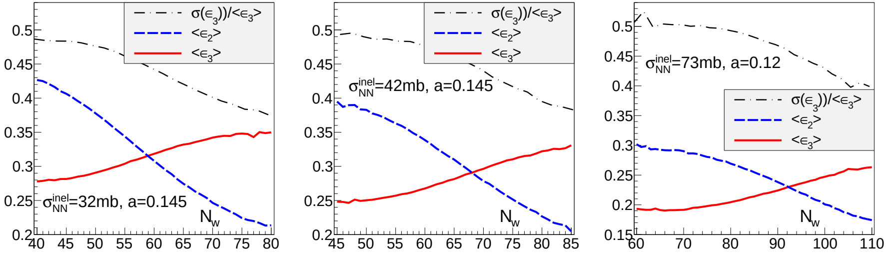
$\langle v_n \rangle$ grows with $\langle \epsilon_n \rangle$



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

[detailed modeling of v_3 under way, research with Piotr Bożek]

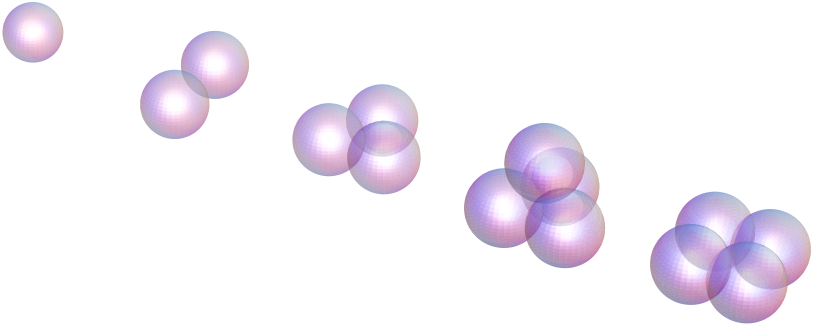
Dependence on the collision energy



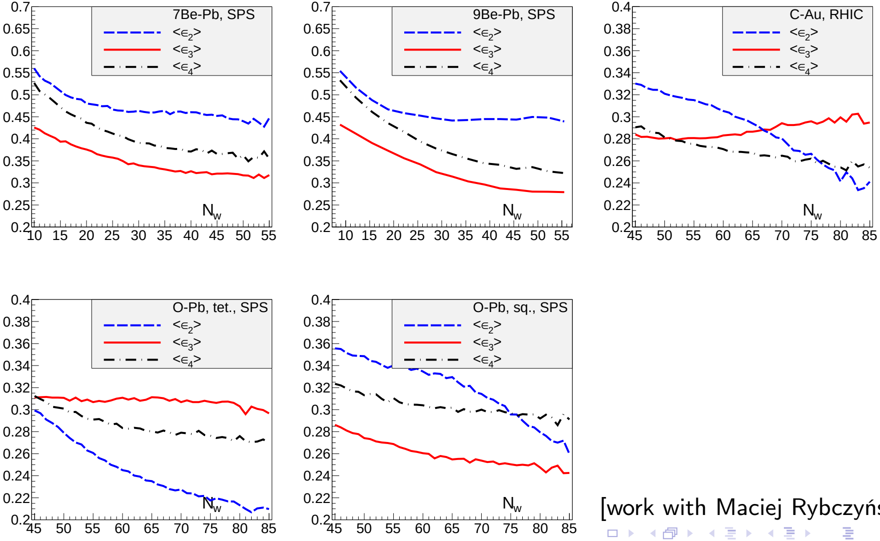
$\sigma_{\rm NN}^{\rm inel}$ =32mb (SPS) 42mb (RHIC) 72mb (LHC)

Qualitative conclusions hold from SPS to the LHC

Other systems



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



[work with Maciej Rybczyński]

Conclusions

Nuclear structure from ultra-fast heavy ion collisions

Snapshots of the ground-state wave function

Spatial deformation of the ground state $\rightarrow$ harmonic flow

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

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

Extensions

- Other systems (e.g., in ^{7,9}Be growth of v_2 with multiplicity)
- More detailed modeling involving event-by-even hydrodynamics (in-progress) needed

Possible data (NA61@SPS, RHIC) 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