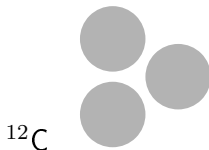


Nuclear structure effects in the initial state

Wojciech Broniowski

Jan Kochanowski U., Kielce, and
Institute of Nuclear Physics PAN, Cracow

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



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

Instead of outline

Two phenomena are related:

α clustering in light nuclei



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 ${}^8\text{Be}$, ${}^{12}\text{C}$, ${}^{16}\text{O}$... were composed of α -particles

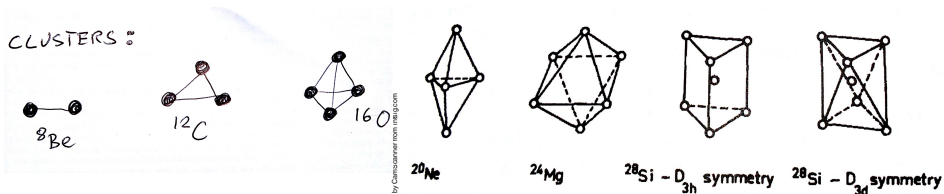
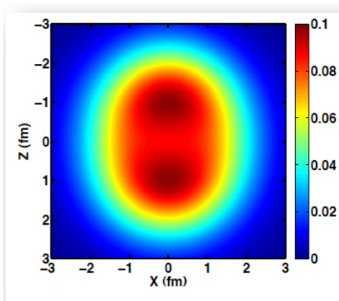


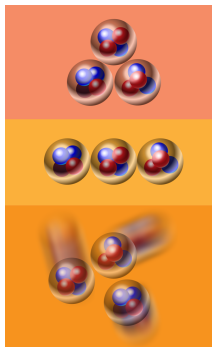
Fig. 1. Alpha-particle configuration for some $4N$ nuclei.

Generated by CamScanner from intsig.com

α clusters in light nuclei



${}^9\text{Be}$



${}^{12}\text{C}$

ground

Hoyle 0^+

other excited, 2^+ ...

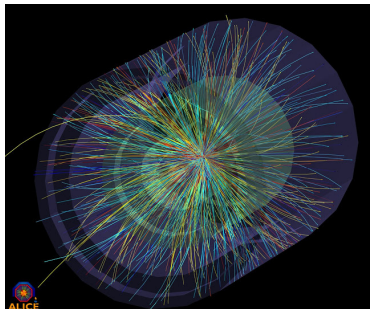
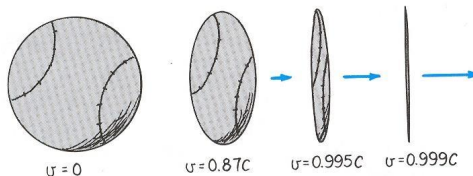
How can we detect the α clusters in the ground state?
What is their spatial arrangement?
Assessment of n-body correlations (one-body not enough)

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

Flow

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

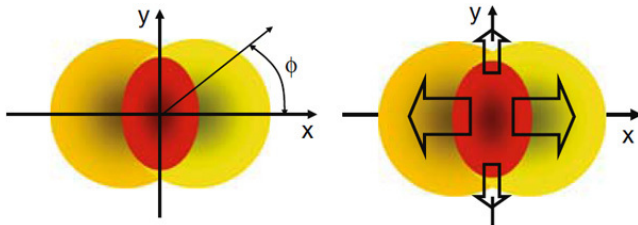
- Lorentz contraction
- Collision: essentially instantaneous passage, frozen configuration
- Reduction of the **ground-state** wave function of the nucleus (like measurement)



- “Development”: detection of particles in the transverse direction

Phenomenon of flow

Quark-gluon plasma is formed!



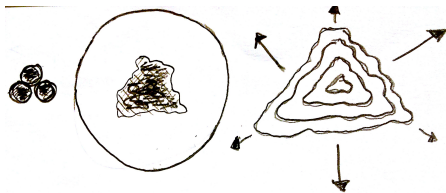
“Initial shape – final flow” transmutation detectable in the asymmetry of the momentum distribution of detected particles – follows from collectivity

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

[WB & ERA, PRL 112 (2014) 112501]

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



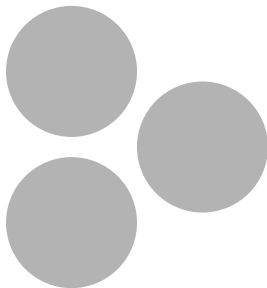
nuclear triangular geometry \rightarrow fireball triangular geometry \rightarrow triangular flow

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

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

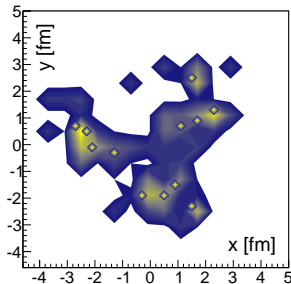
Our making ^{12}C

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)



Why ultra-relativistic?

Reaction time is much shorter than time scales of the structure
→ a frozen “snapshot” of the nuclear configuration



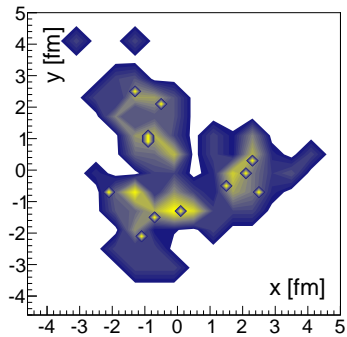
wounding range determined by $\sigma_{\text{NN}}^{\text{inel}}$

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

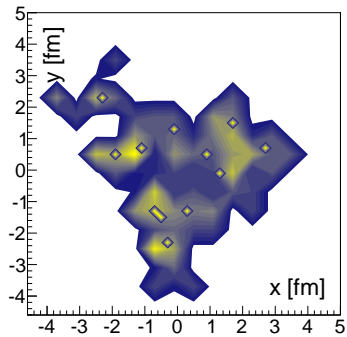
Imprints of the three α clusters clearly visible

Simulations with GLISSANDO 2

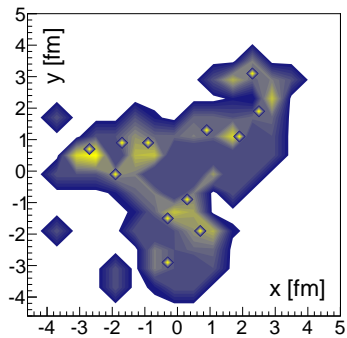
... more events



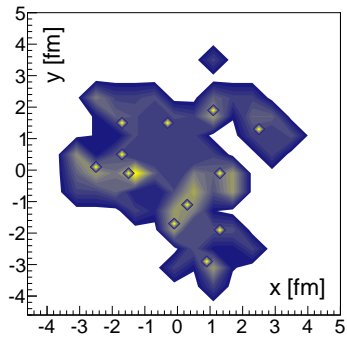
... more events



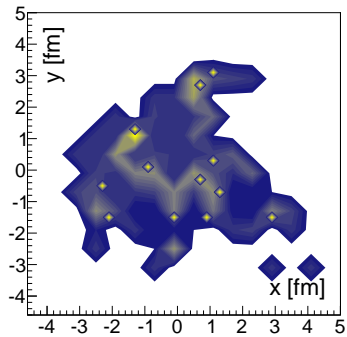
... more events



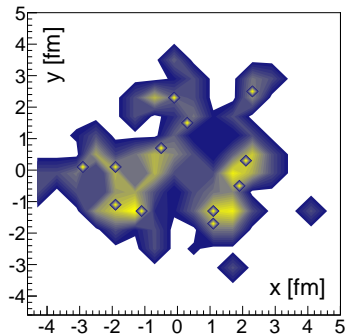
... more events



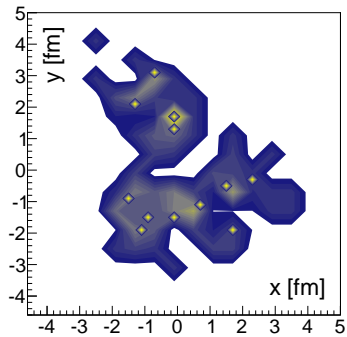
... more events



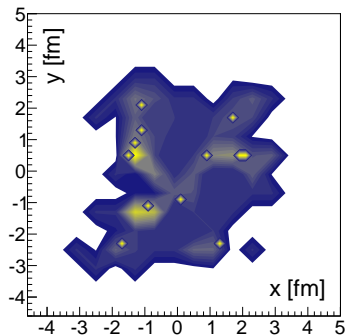
... more events



... more events

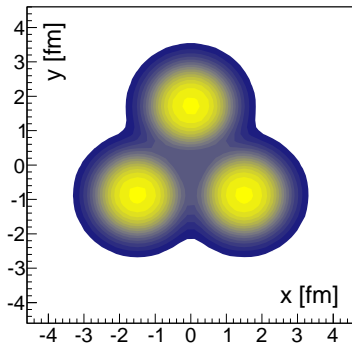


... more events



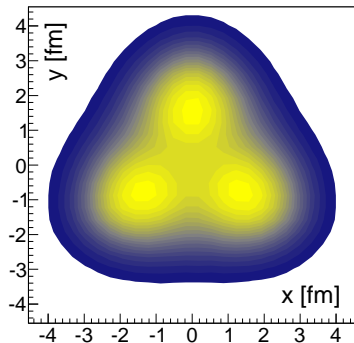
Geometry of nucleus \rightarrow geometry of fireball

Triangular nucleus causes triangular "damage"!



intrinsic density of ^{12}C

\rightarrow



geometry of the fireball
(flat-on collision)

Eccentricity parameters (event-by-event)

(yesterday's talk by J.-Y. Ollitrault)

We need quantitative measures of deformation

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, $n=\text{rank}$)
 $n = 2$ – ellipticity, $n = 3$ – triangularity, ...

Two components:

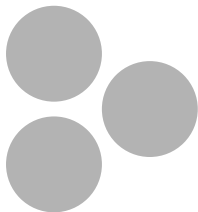
- **intrinsic** (from existent mean deformation of the fireball)
- **from fluctuations**

(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

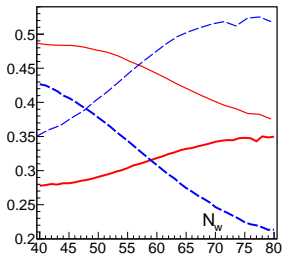
higher multiplicity
higher triangularity
lower ellipticity



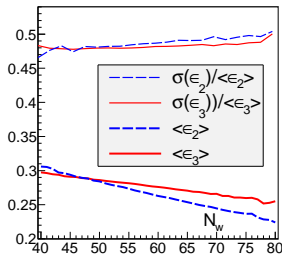
sidewise

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:

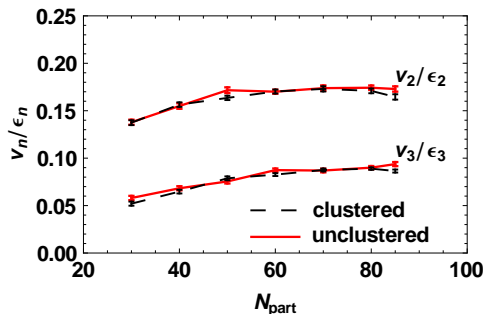
similar behavior for $n = 2$ and $n = 3$

Shape-flow transmutation

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

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

(recall yesterday's talk by J.-Y. Ollitrault)

We have to a very good approximation

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

(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:

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

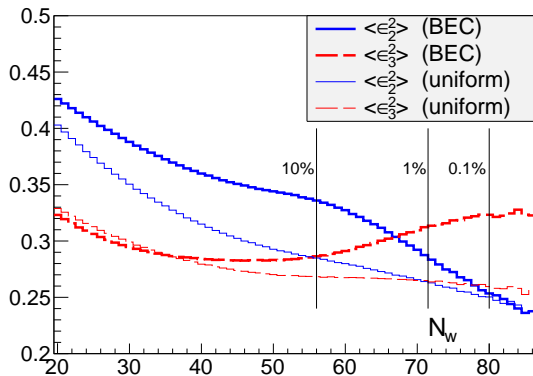
(infer info on flow from just the eccentricities, no hydro!)

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

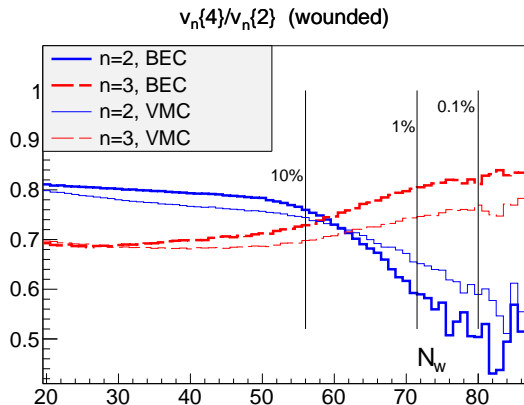
Geometry: ratio tends to 1 from below as $N_w \rightarrow \infty$



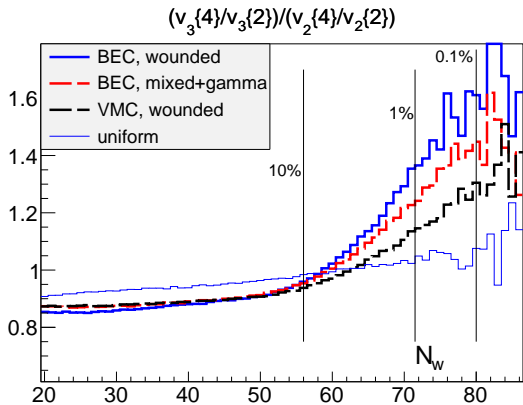
wounded nucleon model



Ratios of cumulant moments



Double ratio of cumulant moments



Test the wave function and the early production model

$^3\text{He-Au}$

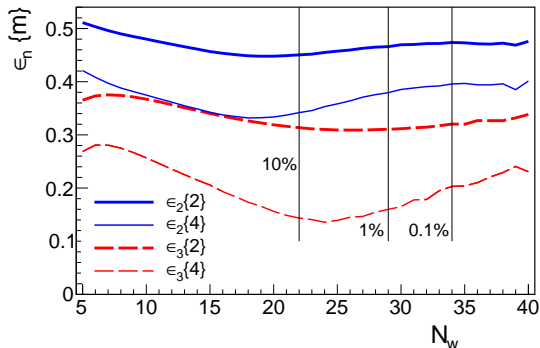
PB & WB, arXiv:1409.2160

(being presently analyzed by PHENIX)

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

[hydro without hydro: Piotr Bożek and WB, arXiv:1409.2160]

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

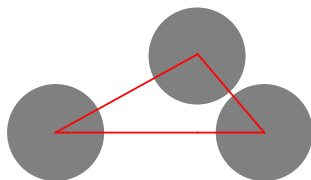
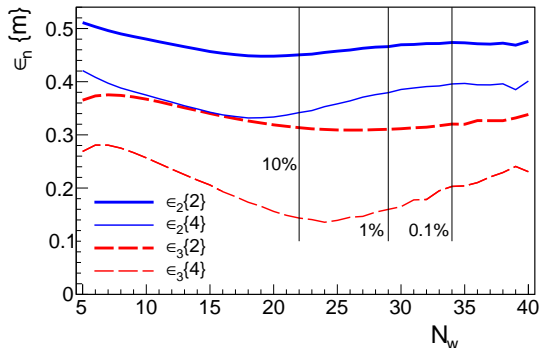


(being presently analyzed by PHENIX)

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

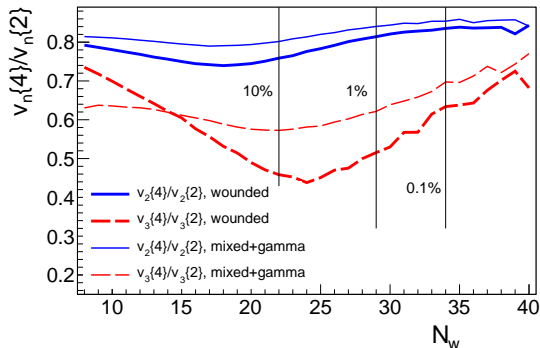
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Sampling from ab initio MC Green's function method [Carlsson & Schiavilla 1998]

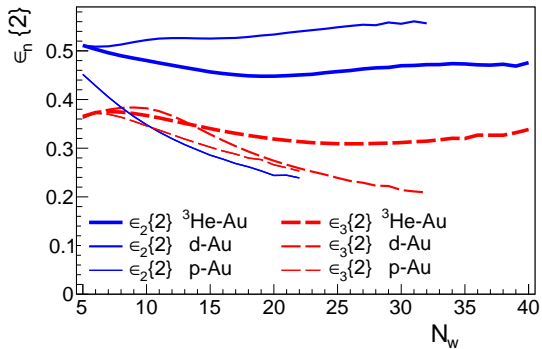


(Not equilateral! Sidewise: $\epsilon_2 \sim 1$, $\epsilon_3 \sim 3/5$)

Ratio for ${}^3\text{He}\text{-Au}$



Large- N_w behavior exhibits both geometric triangularity and ellipticity!
(to be confirmed by the experiment!)



Conclusions

Nuclear structure from ultra-relativistic heavy ion collisions

Snapshots of the ground-state wave function

Spatial correlations in the ground state \rightarrow 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 ratios of cumulant moments
- Stronger effect at lower $\sigma_{NN}^{\text{inel}}$ (i.e., at lower collision energies)
- Even stronger effect on the ^{12}C side in rapidity
- ^{12}C lead to larger/more collective fireball than ^3He
- Ratios depend on the nuclear wave function and the initial-state model, but not on hydro

Extensions: $^{7,9}\text{Be}$, ^{16}O

Data (RHIC, NA61@SPS) would allow to place constraints 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:

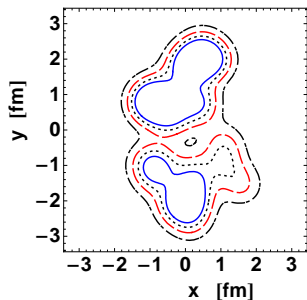
$$|\Psi_{0^+}(x_1, \dots, x_N)\rangle = \frac{1}{4\pi} \int d\Omega \Psi_{\text{intr}}(x_1, \dots, x_N; \Omega)$$

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:
 $f_n^{\text{intr}}(\vec{x}) = \langle f(R(-\Phi_n)\vec{x}) \rangle$. 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: $r_{\text{rms}} \simeq 2$ fm

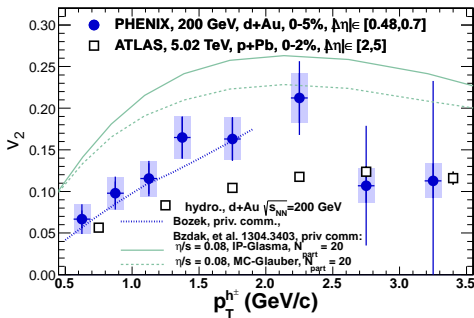
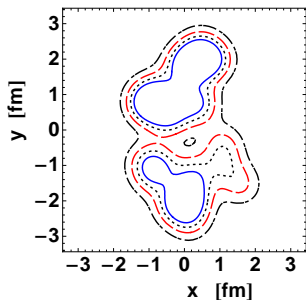
Initial entropy density in a d-Pb collision with $N_{\text{part}} = 24$ [Bożek 2012]



Digression: d-A by Bożek

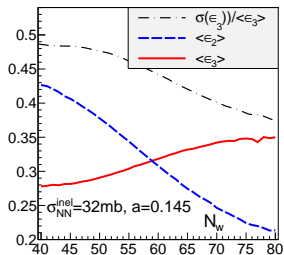
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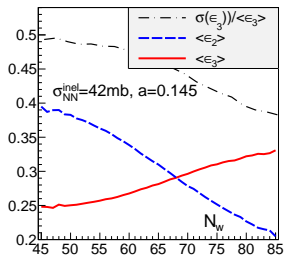


Resulting large elliptic flow confirmed with the later RHIC analysis

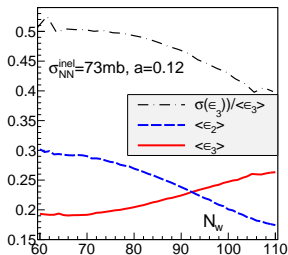
Dependence on the collision energy



$\sigma_{NN}^{inel} = 32\text{mb}$ (SPS)



42mb (RHIC)

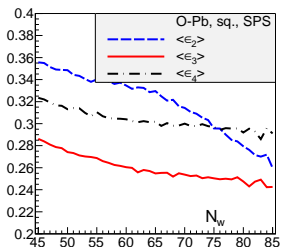
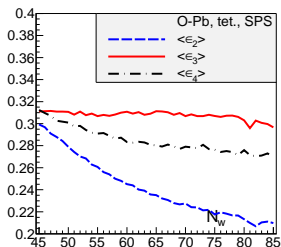
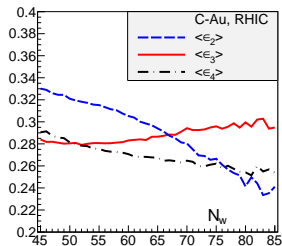
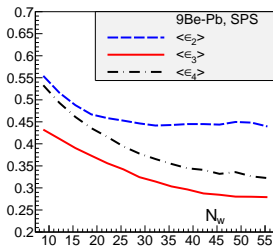
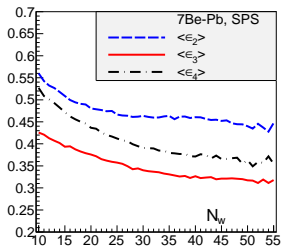


72mb (LHC)

Qualitative conclusions hold from SPS to the LHC

Other systems

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



[work with Maciej Rybczyński]