Eccentricities in collisions with 16O and 12C

Wojciech Broniowski

Opportunities of OO and pO collisions at the LHC

4-10 February 2021

Outline

- Development of eccentricities in light-heavy collisions
- A way to look at correlations and cluster structure in nuclear distributions (new)
- Glossary of Glauber model results for collisions with ^{16}O (O-A, O-O, p-O)

Based on research with **Maciej Rybczyński, Piotr Bożek, Enrique Ruiz Arriola**:

WB, ERA, Phys.Rev.Lett. 112 (2014) 112501
PB, WB, ERA, MR, Phys.Rev. C90 (2014) 064902
MR, M. Piotrowska, WB, Phys.Rev. C97 (2018) 034912
MR, WB, PRC 100 (2019) 6, 064912

All simulations from `GLISSANDO`, wounded + admixture of binary collisions

Development of eccentricities

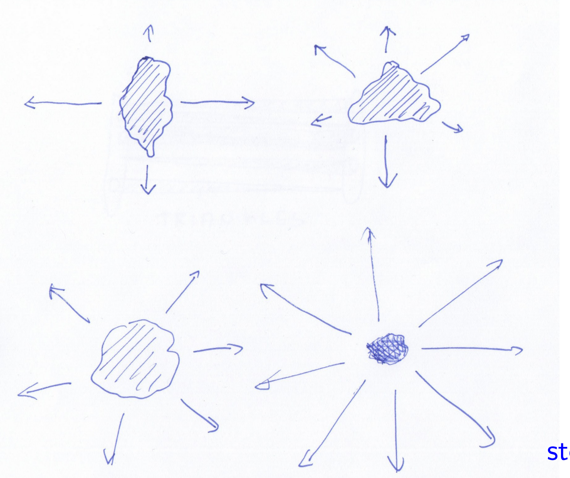
Development of eccentricities in light-heavy collisions

"wall" of A + intrinsically deformed ^{12}C → deformed fireball → shape-flow transmutation

(same is true, e.g, for d-A or ^{3}He-A collisions)

Shape-flow transmutation

[Ollitrault 1992 ... Miller, Snellings 2003 ... Alver, Roland 2010 ...]



steeper gradient → faster

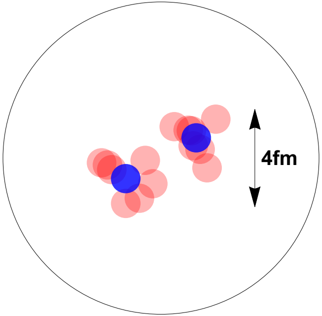
- Any (copious) rescattering will do (hydro, transport)

From nuclear to fireball eccentriities

Methods from heavy-ions applied to nuclear structure
Goal: understand the nuclear structure

From nuclear to fireball eccentricities

The fireball eccentricity is somewhat reduced compared to the nuclear eccentricity:



$$\epsilon_n^F = \epsilon_n^N \left[1 + \mathcal{O}\left(\frac{\langle b^2 \rangle}{\langle r^2 \rangle}\right)\right]$$

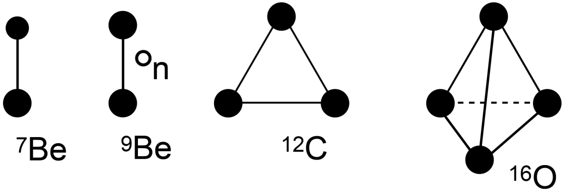
$b \sim 1$ fm – NN wounding distance, r – size of the light nucleus

Analytic expressions in [Bożek, WB, Rybczyński, Stefanek, CPC 245 (2019) 106850, arXiv:1901.04484]

A few percent effect only!

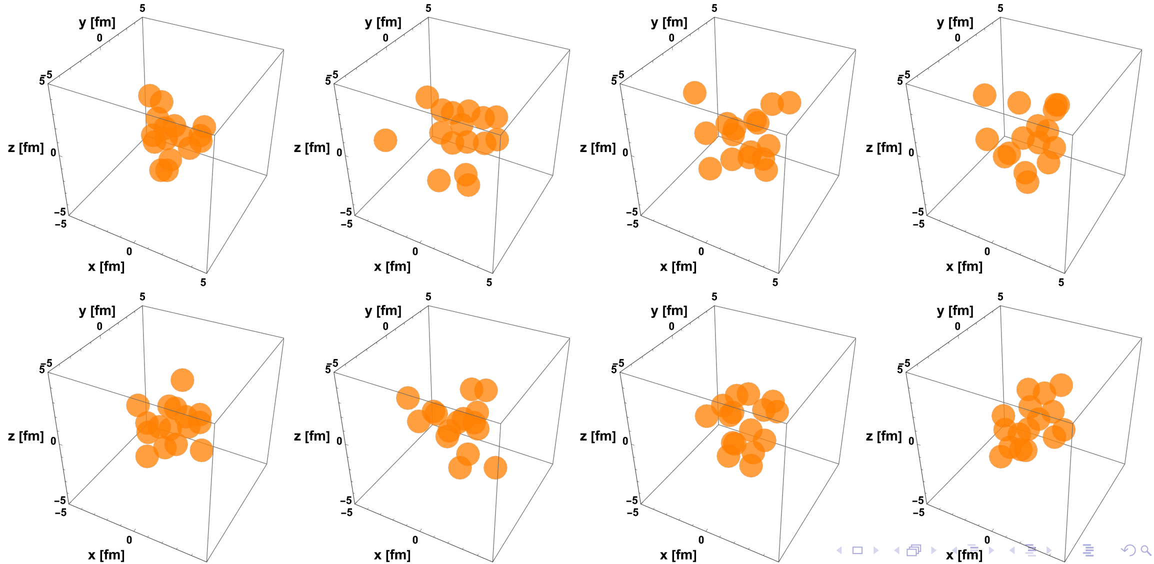
Hence there is a chance to "see" ϵ_n^N in later stages

Clusters in light nuclei

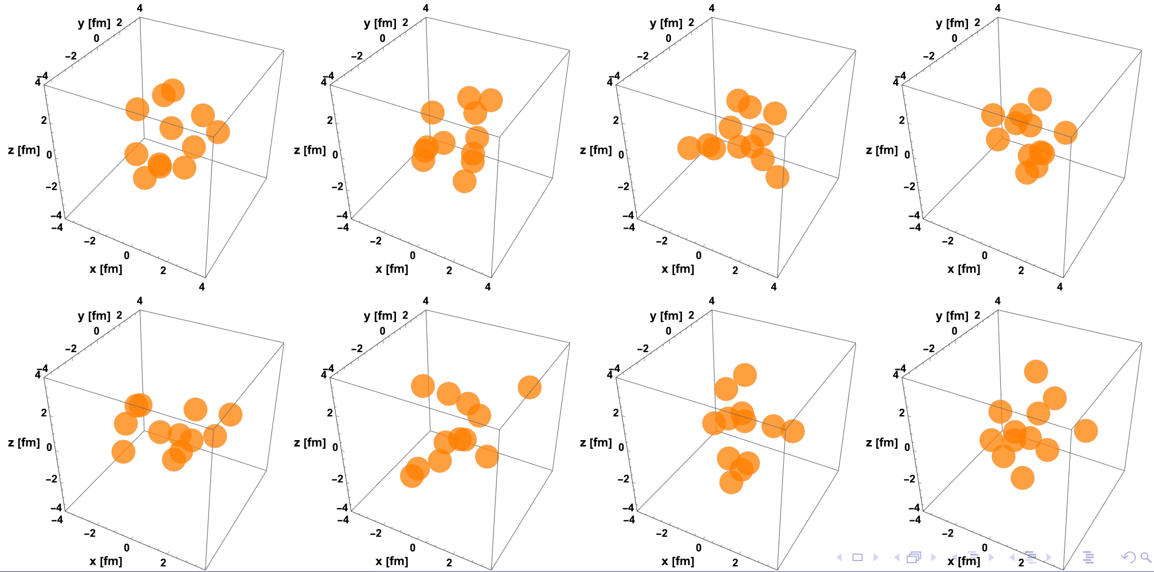


Suggestive, but also somewhat misleading: 1) rms of α is ~ 1.7 fm, quite large on the scale of small nuclei, 2) there is possible configuration mixing

Non-triviality of detecting clusters (^{16}O), even if they are there



Non-triviality of detecting clusters (^{12}C)



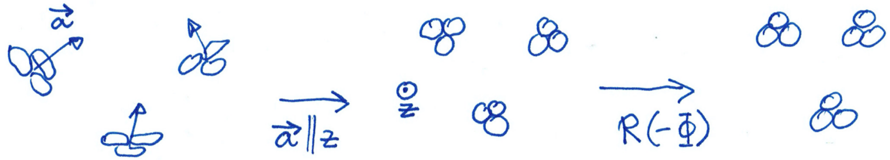
Proposal for nuclei with geometry close to a plane (^{12}C, ^{7,9}Be)

For each nucleus:

1. Find the planarity vector $\vec{a}$, $\vec{a}^2 = 1$, such that $\sum_{i=1}^{A} (\vec{r}_i \cdot \vec{a})^2$ is minimized.
2. Rotate the nucleus such that its a is aligned with the z-axis.
3. Evaluate the eccentricity and angle via ($\rho_i = \sqrt{x_i^2 + y_i^2}$)

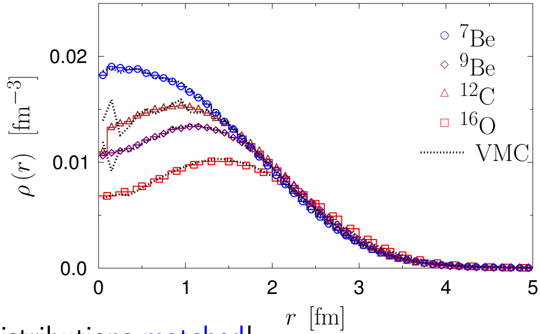
$$\epsilon_n^N e^{in\Phi} = \frac{\sum_{i=1}^{A} \rho_i^n e^{in\phi_i}}{\sum_{i=1}^{A} \rho_i^n}$$

4. The planar intrinsic nuclear distribution is defined as a sample-average of azimuthally rotated (aligned) distributions: $$|\Psi_{\rm intr}(x,y)|^2 = \left\langle R(-\Phi)\, |\Psi(x,y)|^2 \right\rangle_{\rm sample}$$



We consider:

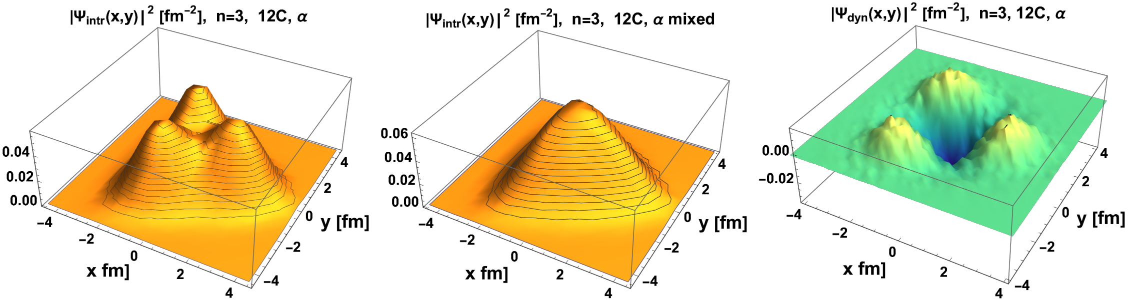
- α-clustered distributions used in GLISSANDO
- Correlated distributions from cluster Variational Monte Carlo (CVMC) [Lonardoni et al. 2017]
- "Mixed" distributions, with correlations broken



GLISSANDO and CVMC radial distributions matched!

^{12}C, α-clustered, $n = 3$

Outcome of the above procedure: "a pictorial measure"

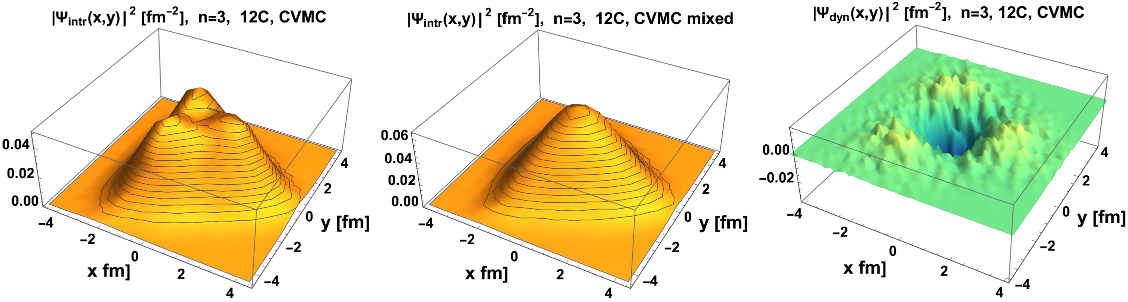


physical

mixed

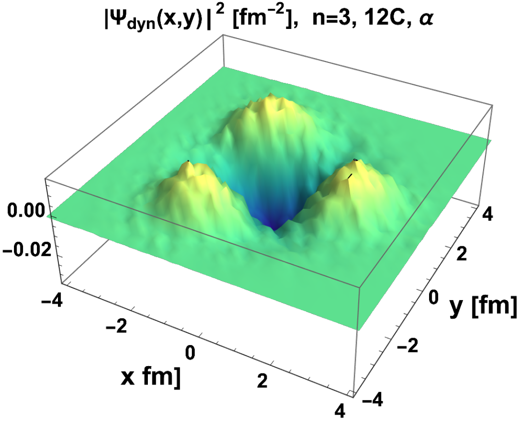
dynamical = physical − mixed

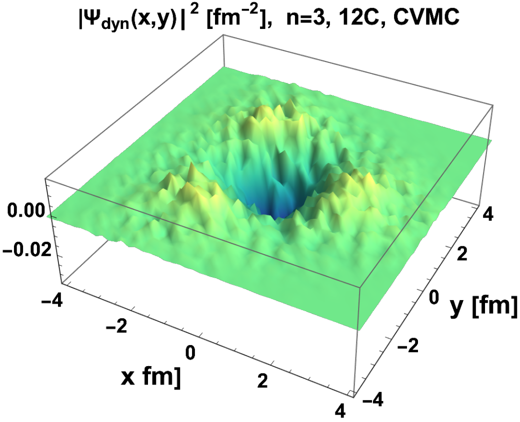
^{12}C, CVMC, $n = 3$



|Ψintr(x,y)|2 [fm-2], n=3, 12C, CVMC
0.04
0.02
0.00
-4
-2
0
2
4
x fm]
y [fm]
|Ψintr(x,y)|2 [fm-2], n=3, 12C, CVMC mixed
0.06
0.04
0.02
0.00
|Ψdyn(x,y)|2 [fm-2], n=3, 12C, CVMC
0.00
-0.02

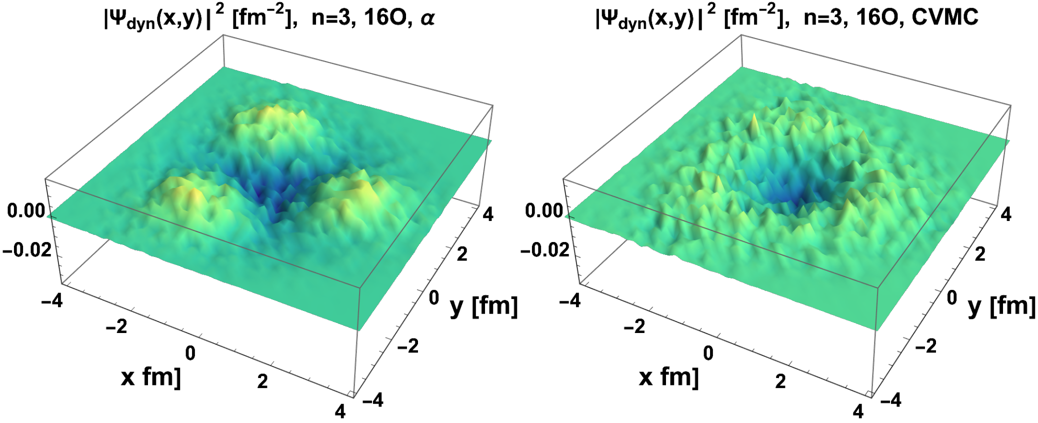
^{12}C, $n = 3$



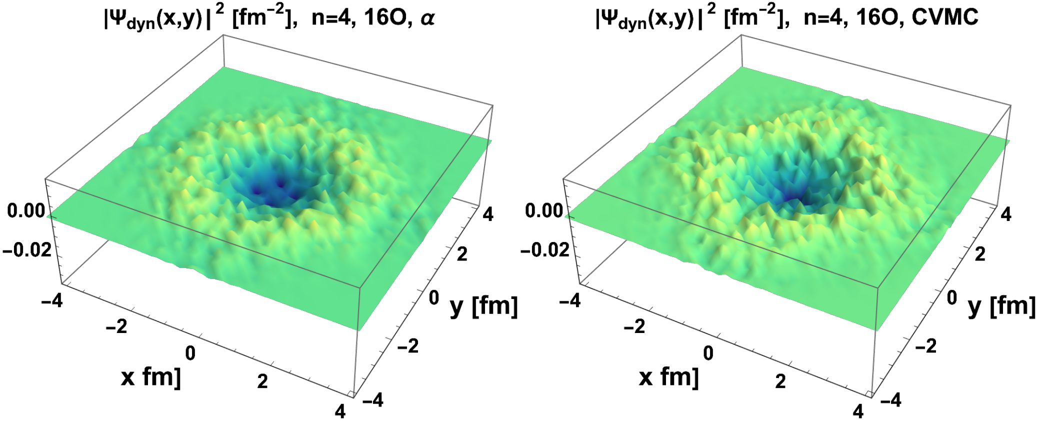


- We see correlations mod 120^o, coming from the arrangement of the clusters
- Less effect in CVMC

^{16}O (somewhat abusive), $n = 3$



^{16}O, $n = 4$

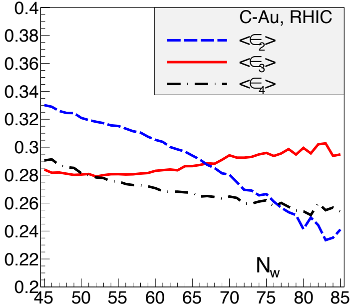


|Ψdyn(x,y)|² [fm⁻²], n=4, 16O, α
0.00
–0.02
–4
–2
0
2
4
x fm]
y [fm]
|Ψdyn(x,y)|² [fm⁻²], n=4, 16O, CVMC

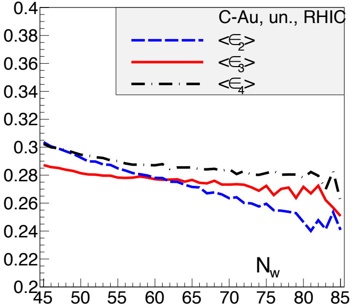
Heavy-light collisions

C-Au

clustered



mixed



Hallmark behavior of clustering: increasing triangularity with number of participants

^{12}C-A – role of α clusters

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

Nuclear structure from ultra-relativistic collisions

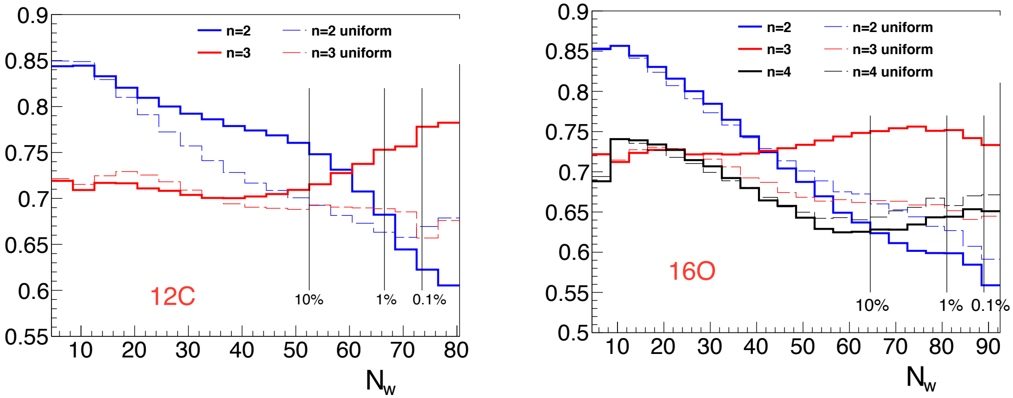
Probe to what degree ^{12}C is made of three α's via collisions with a "wall" of Pb or Au:

The cluster plane parallel or perpendicular to the transverse plane:

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

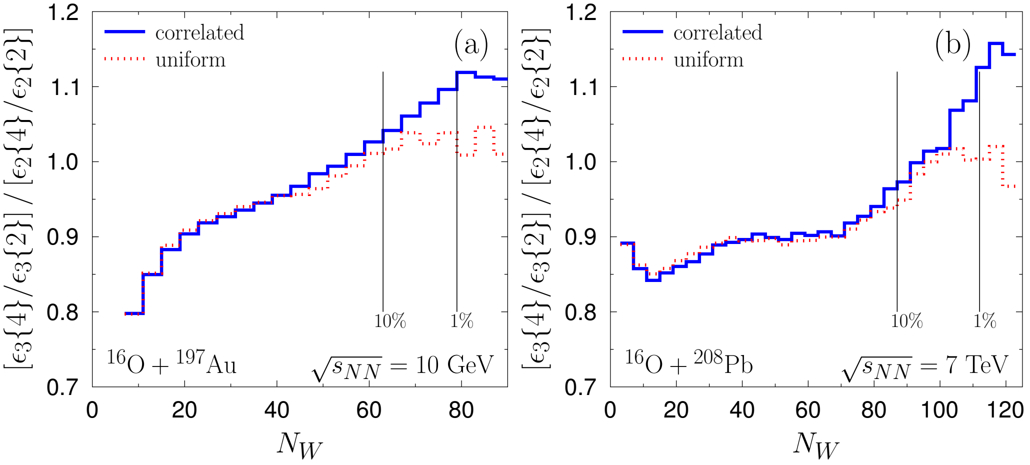
O-A, ratio $\epsilon_n\{4\}/\epsilon_n\{2\}$ (less sensitive to hydro response)

(correlated = CVMC, uniform = mixed)

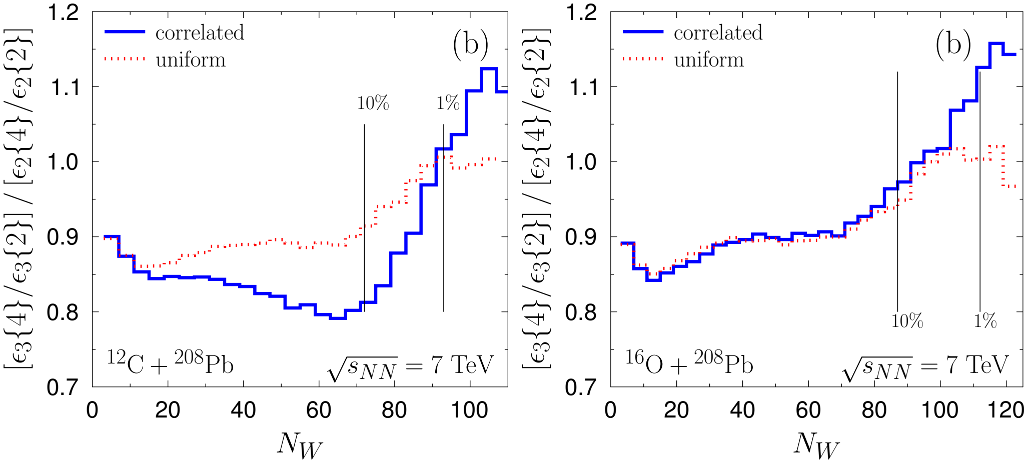


Effects of correlations seen in most central collisions

O-A, double ratio

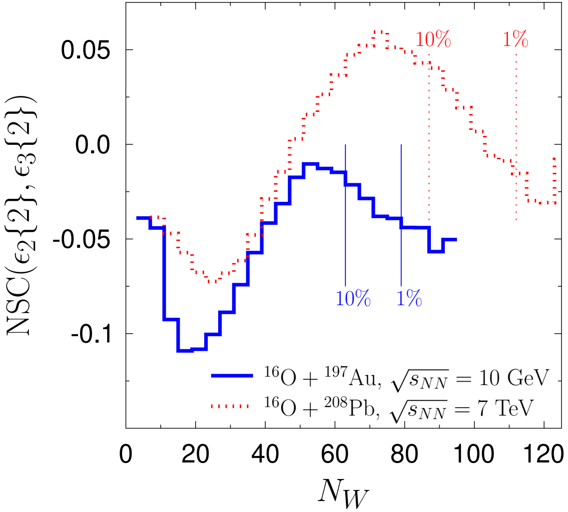


C-A vs O-A



correlated
uniform
(b)
10%
1%
$[\epsilon_3\{4\}/\epsilon_3\{2\}] \,/\, [\epsilon_2\{4\}/\epsilon_2\{2\}]$
$^{12}\mathrm{C} + {}^{208}\mathrm{Pb}$
$\sqrt{s_{NN}} = 7$ TeV
N_W
1.2
1.1
1.0
0.9
0.8
0.7
0
20
40
60
80
100
correlated
uniform
(b)
10%
1%
$[\epsilon_3\{4\}/\epsilon_3\{2\}] \,/\, [\epsilon_2\{4\}/\epsilon_2\{2\}]$
$^{16}\mathrm{O} + {}^{208}\mathrm{Pb}$
$\sqrt{s_{NN}} = 7$ TeV
N_W
1.2
1.1
1.0
0.9
0.8
0.7
0
20
40
60
80
100
120

O-A, normalized symmetric cumulants

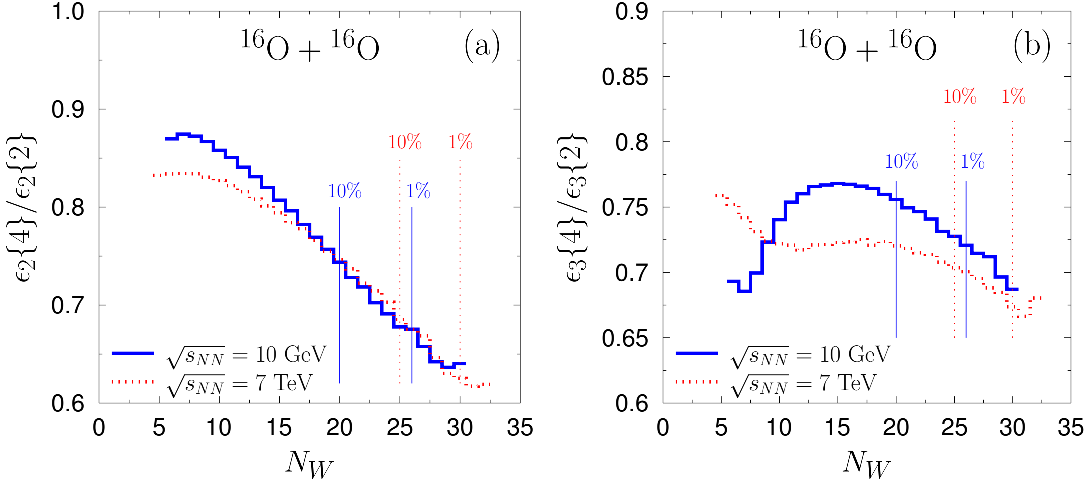


O-O

Simple geometry (as in light-heavy) no more!

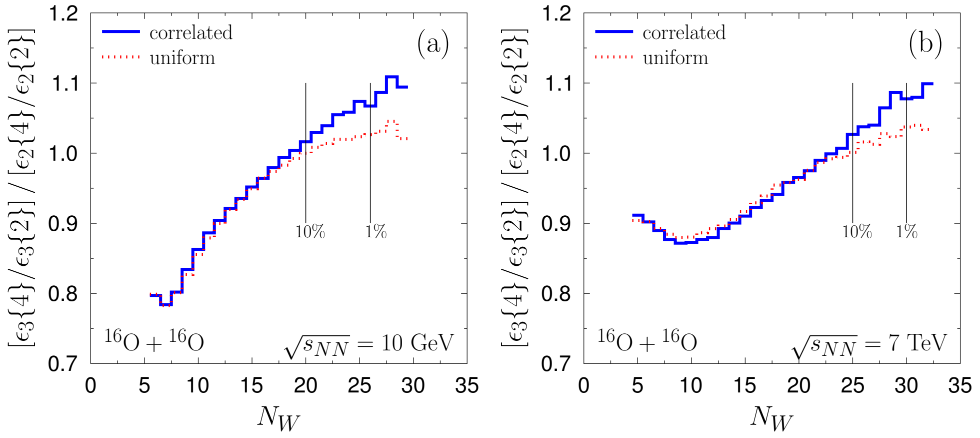
[see also Sievert, Noronha-Hostler, Phys. Rev. C100 (2019) 024904]

Eccentricity ratios in O-O, Glauber MC



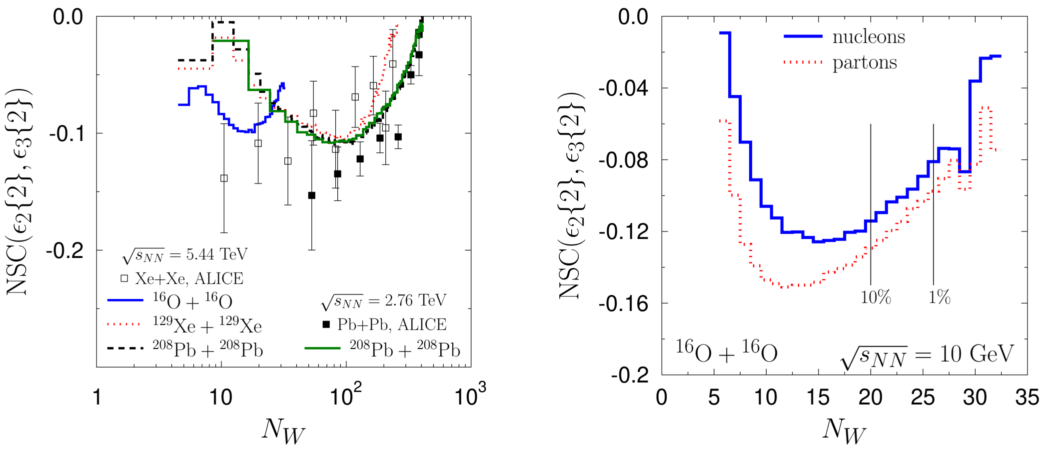
Role of clusters in O-O

(correlated = CVMC, uniform = mixed)



Some quantitative but not qualitative effect for most central collisions

Flow correlation, normalized symm. cumulants, wounded quarks

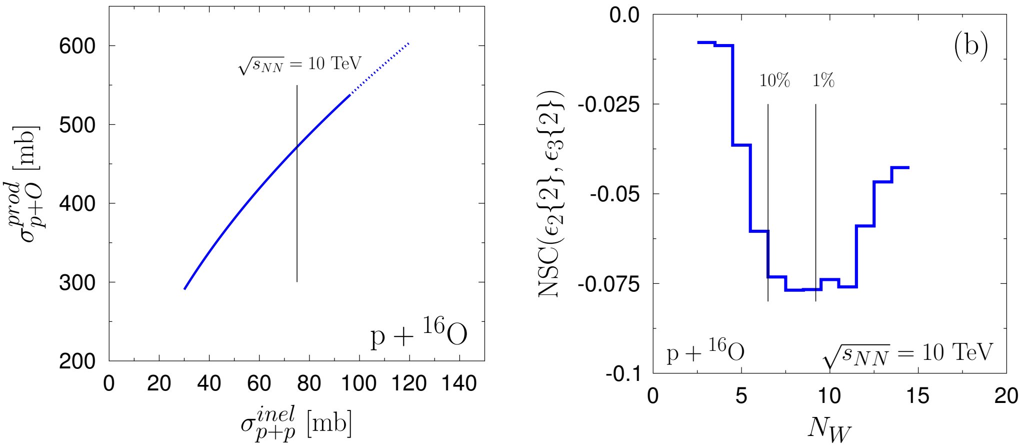


O-O compared to p-Pb at the same N_W → more dilute initial condition

p-O

Cosmic rays

p-O from GLISSANDO



Summary

My ranking (from the point of view of nuclear structure effects):

1. C-A
2. O-A
3. O-O, p-O

THANKS FOR YOUR ATTENTION!