Smoking gun of nuclear clusterization in collisions of light relativistic nuclei

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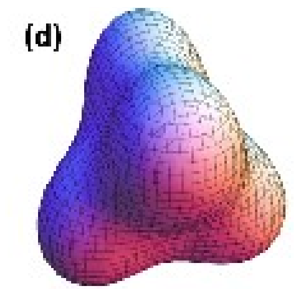
Deepened Impulse, V. Kandinsky 1928

Motivation

- A short ^{16}O–^{16}O run is planned at the LHC to explore small systems
- Discussed at the dedicated workshop "Opportunities of OO and pO collisions at the LHC" https://indico.cern.ch/event/975877/
- The initial cluster structure of ^{16}O may impact eccentricity, flow, and R_{AA} for D-mesons. [1),2),3),4)]
- Does the cluster structure of ^{16}O affects the spectator matter produced in the relativistic ^{16}O–^{16}O collisions?
- How many spectator fragments with the same Z/A-ratio with ^{16}O will be transported in the LHC along with beam nuclei?
- Same questions for the fragmentation of ^{12}C at NICA[5)]
- However, a better description of fragments from ^{16}O fragmentation, in particular ^{4}He, is necessary[6)]

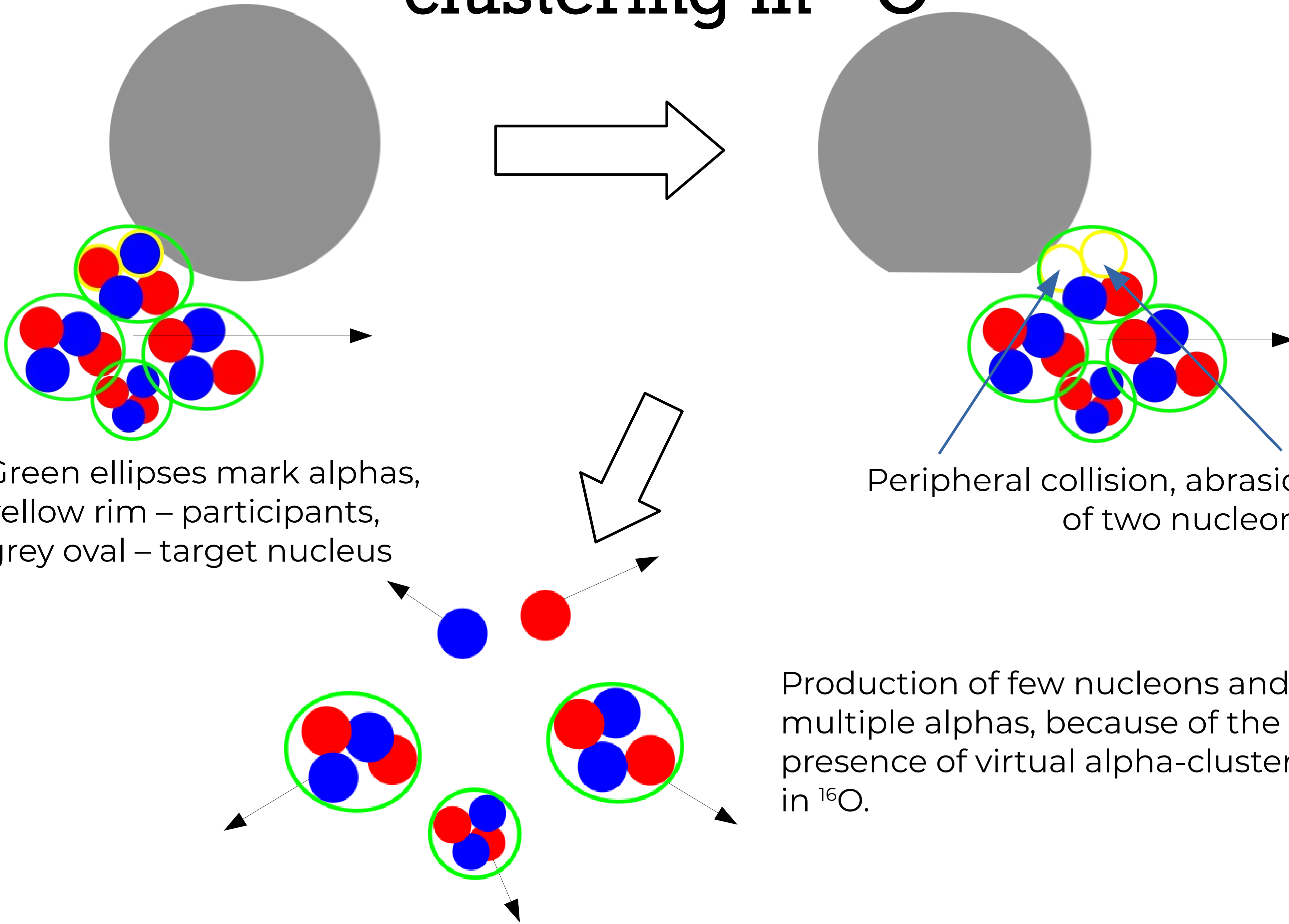
1) Yi-An Li et al., PRC 102 (2020) 054907
2) W. Broniowski et al., NPA 1005 (2021) 121763
3) R.Katz et al., PRC 102 (2020) 041901
4) S. H. Lim et al, PRC 99 (2019) 044904
5) M. Kapishin, JPS Conf. Proc. 32 (2020) 010093
6) A.S. et al., PoS EPS-HEP2021 (2022) 310

Density distributions of ^{16}O



X.B. Wang et al. PLB 790 (2019) 498–501

Enhanced ^{4}He production due to clustering in ^{16}O



Green ellipses mark alphas,
yellow rim – participants,
grey oval – target nucleus

Peripheral collision, abrasion of two nucleons.

Production of few nucleons and multiple alphas, because of the presence of virtual alpha-clusters in ^{16}O.

Outline

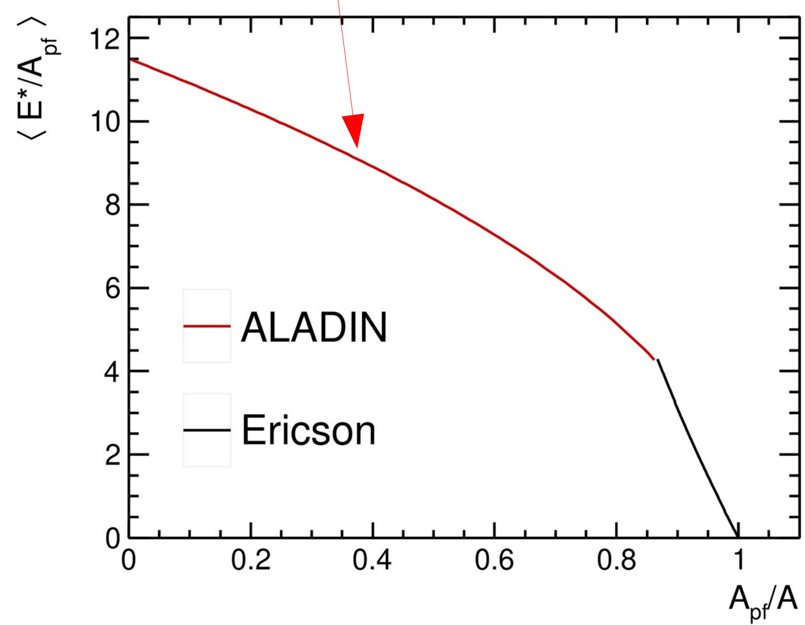
- A brief review: our model – Abrasion-Ablation Monte Carlo for Colliders (AAMCC)
- Comparison with the data on fragmentation of ^{16}O in nuclear emulsion
- Nuclear density of ^{16}O: admixture of clustered states
- Composition of spectator matter in relativistic ^{16}O – ^{16}O collisions depending on
  - the parametrisation of excitation energy
  - the distribution of nuclear density
  - the contribution of clustered states

Abrasion-Ablation Monte Carlo for Colliders

- Nucleus-nucleus collisions are simulated by means of the Glauber Monte Carlo model[1]. Non-participated nucleons form spectator matter (prefragment)
- Excitation energy of prefragment is calculated either by particle-holde model[2], or by parabolic ALADIN approximation[3], or by hybrid parametrisation.
- Hybrid parametrisation is defined as follows:
  - in peripheral collisions with less then ~15% of removed nucleons the particle-hole model is used[2] (Ericson formula);
  - otherwise a parabolic ALADIN approximation[3] is applied with parameters tuned to fragmentation data.

$$\varepsilon^* = \varepsilon_0 \sqrt{1 - c_0 \frac{A_{pf.}}{A}}$$

- Decays of prefragments are simulated as follows:
  - pre-equilibrium decays modelled with MST-clustering algorithm[4];
  - Fermi break-up model from Geant4 v9.2[5];
  - Weisskopf-Ewing evaporation model from Geant4 v10.4[5].



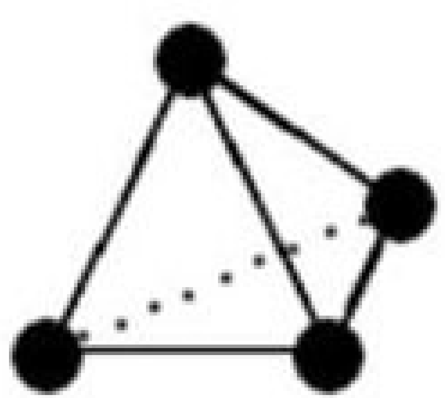
1) C. Loizides, J.Kamin, D.d'Enterria Phys. Rev. C **97** (2018) 054910
2) T. Ericson Adv. In Phys. **9** (1960) 737
3) A. Botvina et al. NPA **584**
4) R. Nepeivoda, et al., Particles **5** (2022) 40
5) J. Alison et al. Nucl. Inst. A **835** (2016) 186

github.com/Spectator-matter-group-INR-RAS/AAMCC

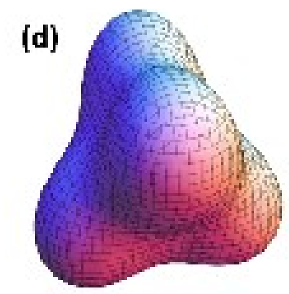
Clusterisation in ^{16}O

- ^{16}O contains 8 protons and 8 neutrons and thus four alpha-clusters can be formed.
- Some authors assume that clusters are arranged into a tetrahedron[1,2].
- Parameters of the tetrahedron should fit the charge radius of ^{16}O nucleus
- There are other free parameters for clustered ^{16}O:
  - The distribution of nucleons inside alpha-clusters
  - The overall contribution of clustered state.

Arrangement of clusters in ^{16}O



^{16}O density



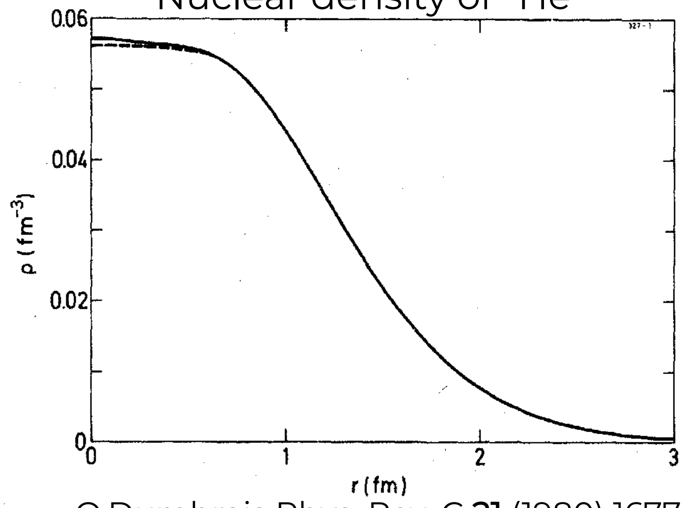
2) X.B. Wang et al. PLB 790 (2019) 498–501

1) R. Bijker and F. Iachello, Phys. Rev. Lett. (2014) 112, 152501

Sampling nucleon configurations in ^{16}O

- Our sampler is written in Julia
  - Main algorithm exploits Gibbs sampling.
  - The Pauli blocking is represented by the exclusion of the finite volume of nucleons.
- The centres of alpha-clusters are arranged first in the vertices of the thetrahedron.
- Then the positions of nucleons inside each cluster are sampled according to one of three options: Gaussian, Woods-Saxon distribution and Harmonic oscillator parametrisation.
- Non-clustered state is parametrised by Harmonic oscillator.

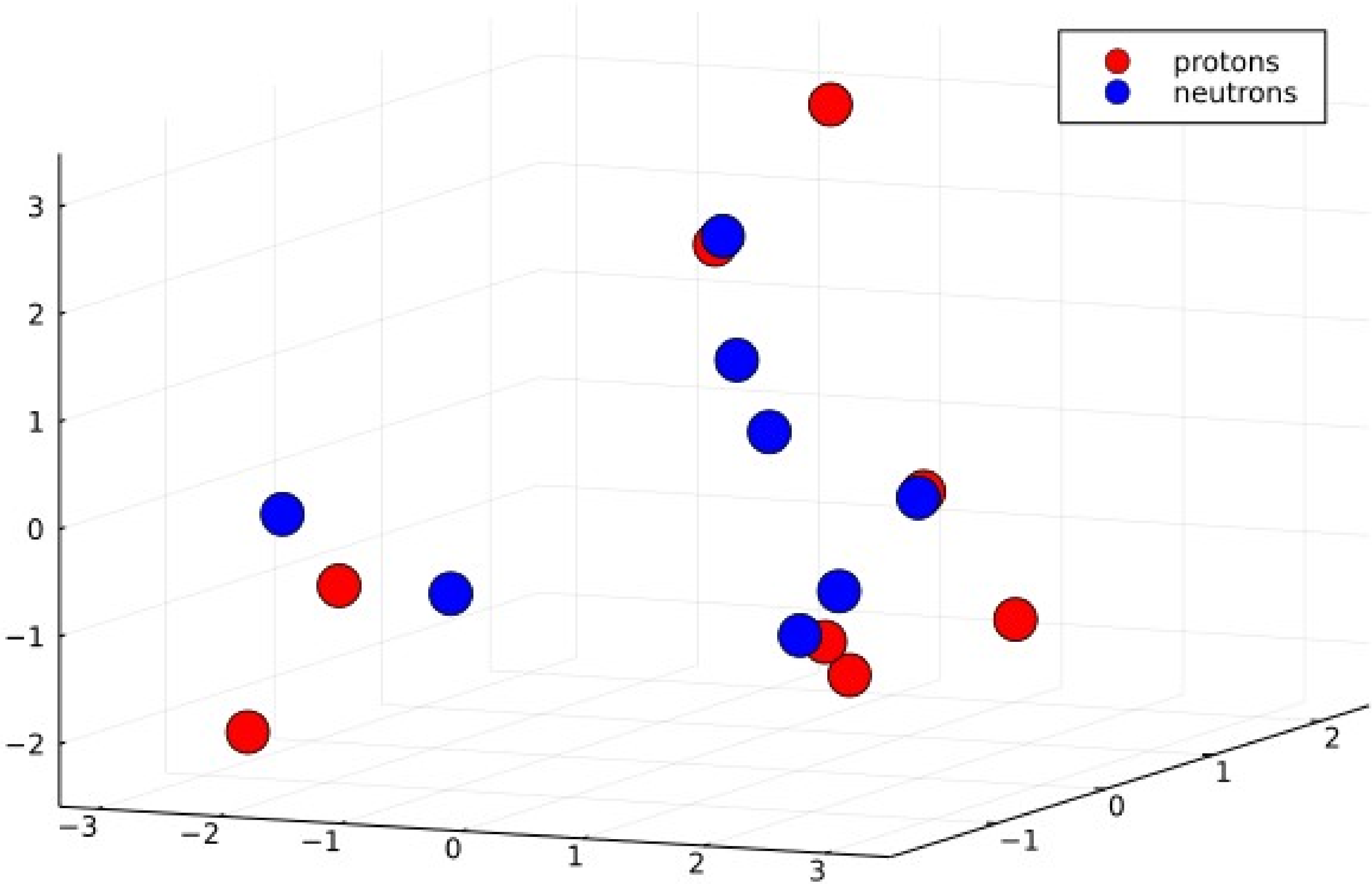
Nuclear density of ^{4}He



O.Dumbrajs Phys. Rev. C **21** (1980) 1677

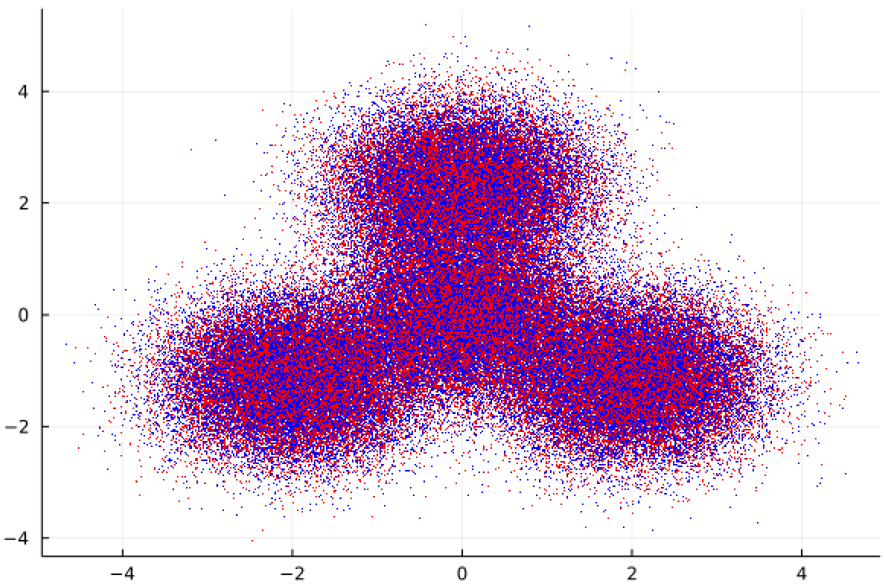
Alpha-cluster density is assumed to be similar to the ^{4}He

Example of sampling of nucleons in ^{16}O

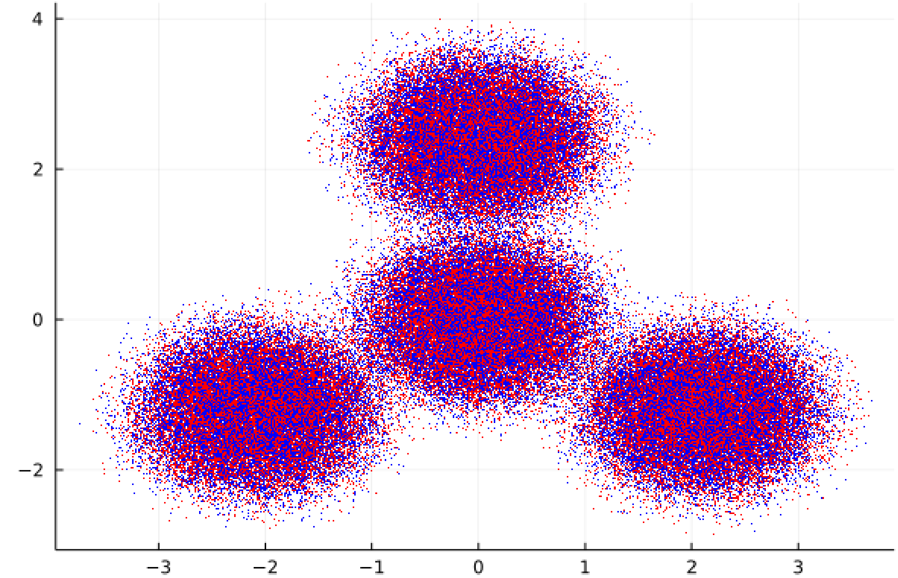


$4 \cdot 10^5$ samples of ^{16}O

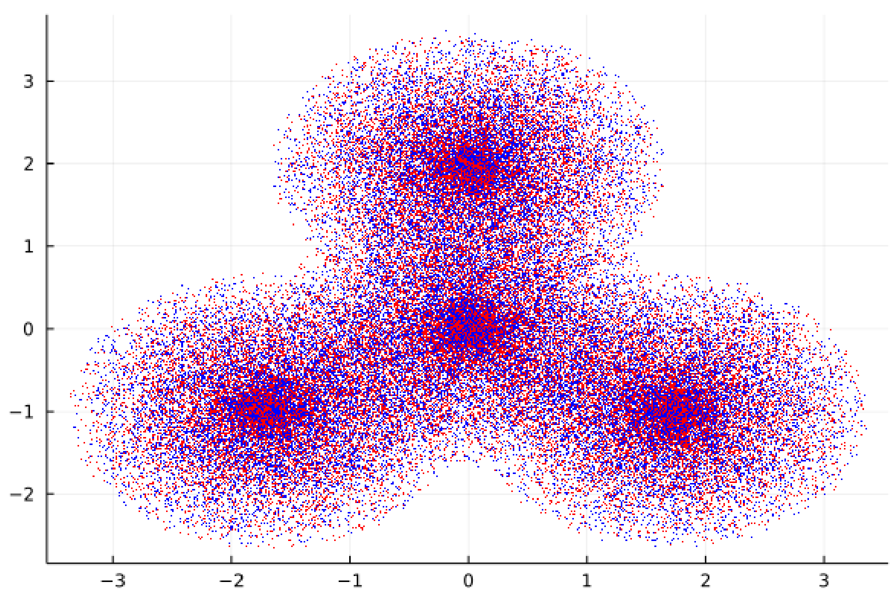
Clustered state, gaussian density



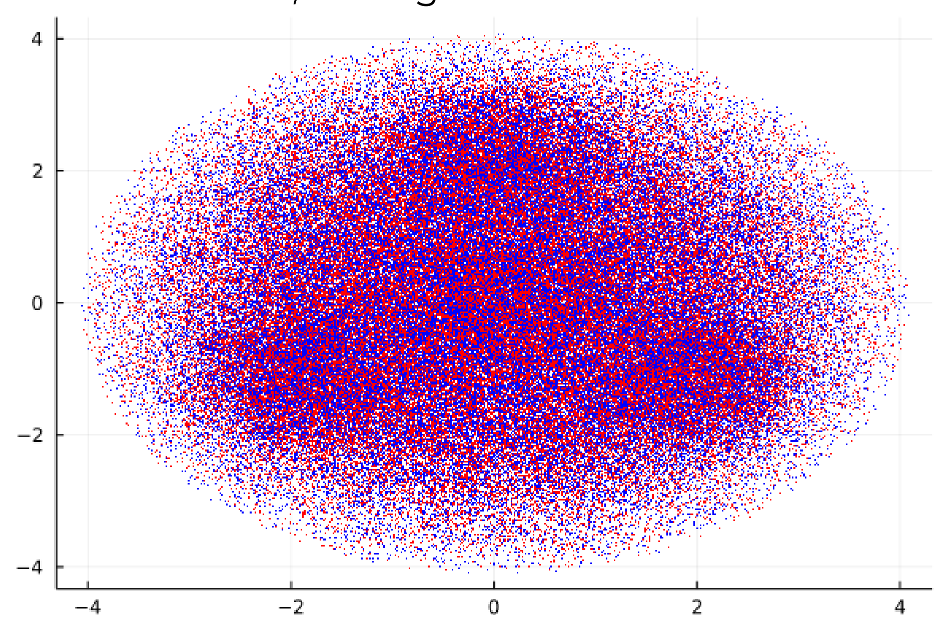
Clustered state, HO density



Clustered state, WS density

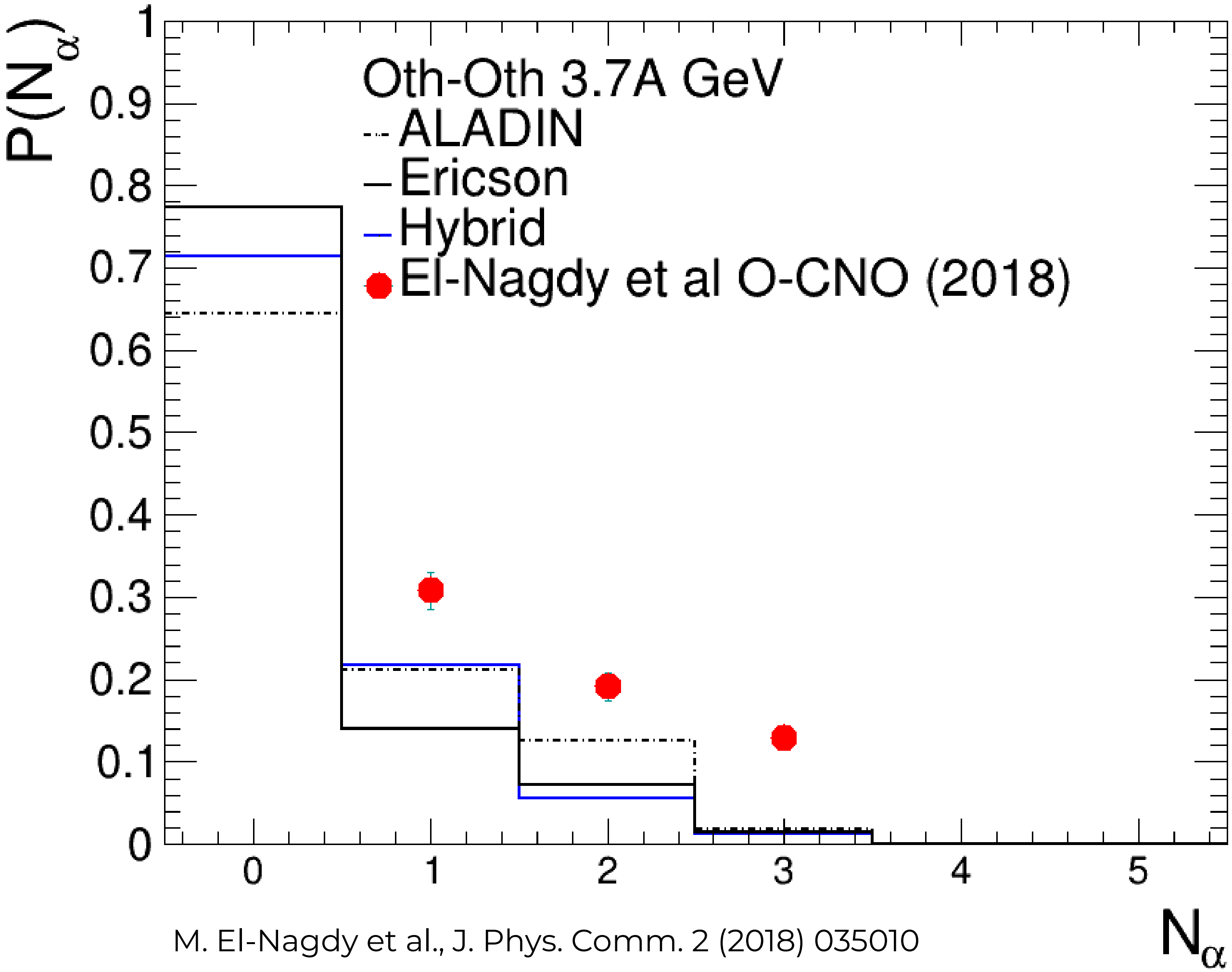


Mixed state, mixing 20%



Same orientation assumed for all 4 options.

The production of ^{4}He

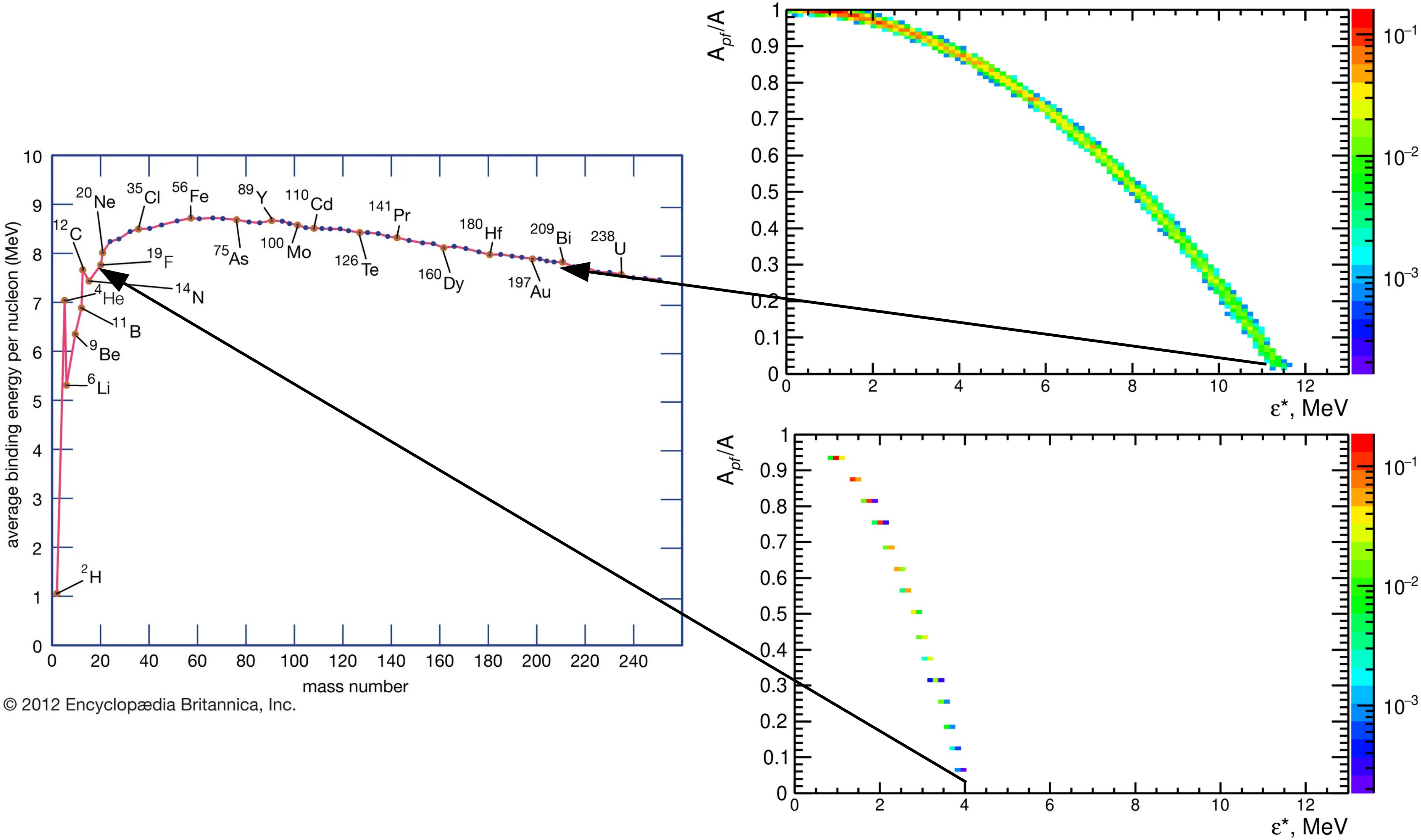


M. El-Nagdy et al., J. Phys. Comm. 2 (2018) 035010

- Here and futher Oth represent nuclear density with accounting for clusterisation
- Pure tetrahedral state with gaussian density of the clusters was used
- None of the approximations of the excitation energy describes data well
- The ALADIN parametrisation demonstrates better agrement with the data
- The calculations of ALADIN and Hybrid differ mostly for an $N_\alpha = 2$ produced in peripheral collisions, since the approximations differ for such collisions.

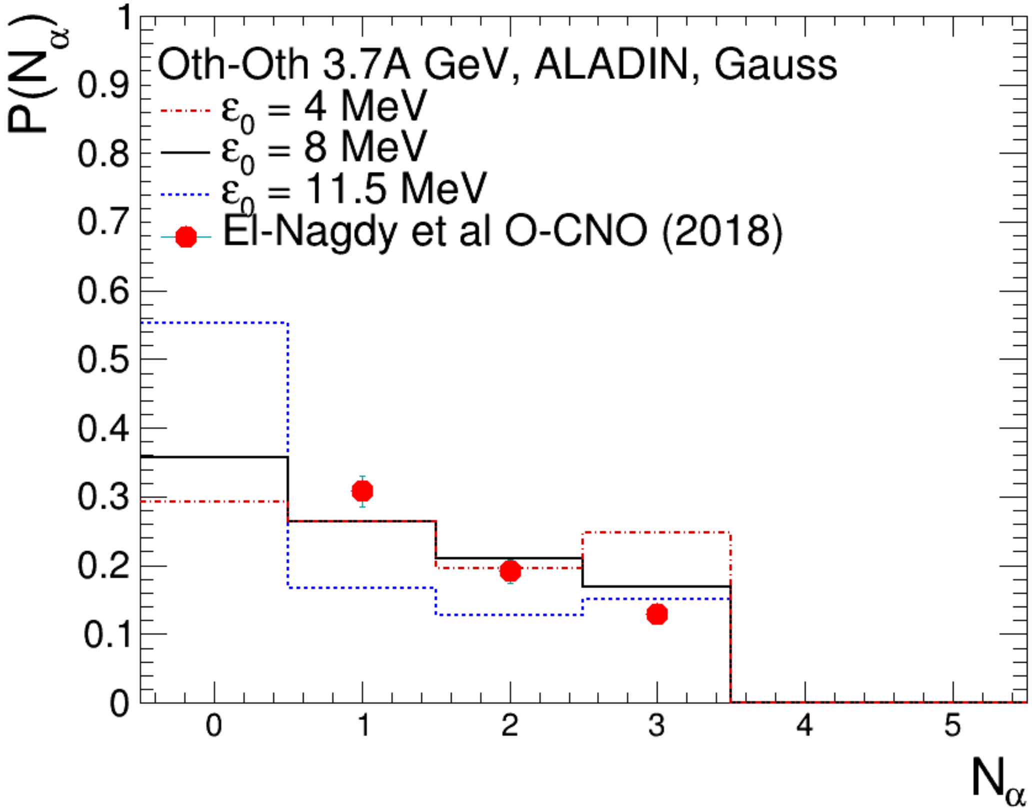
Using the tetrahedral density is not enough for describing the data!

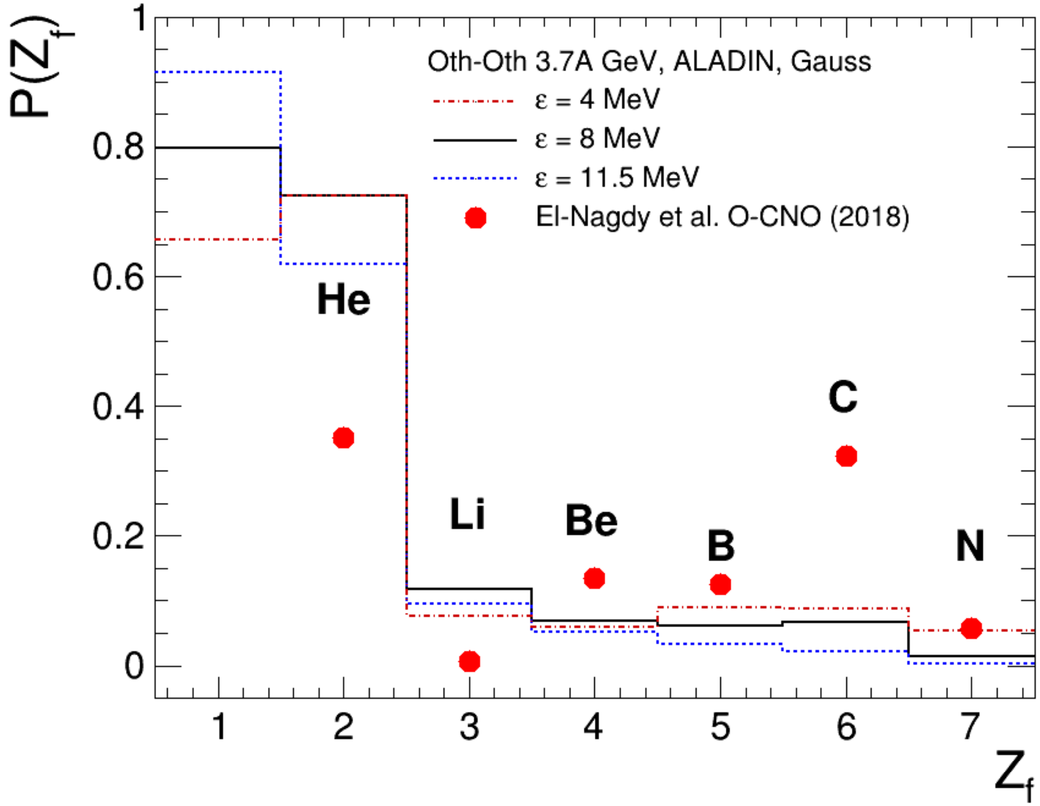
Parametrisation of excitation energy: heavy vs. light nuclei



An additional tuning of ALADIN parametrisation is required for light nuclei

Pure clustered state with different ε_0: Gauss

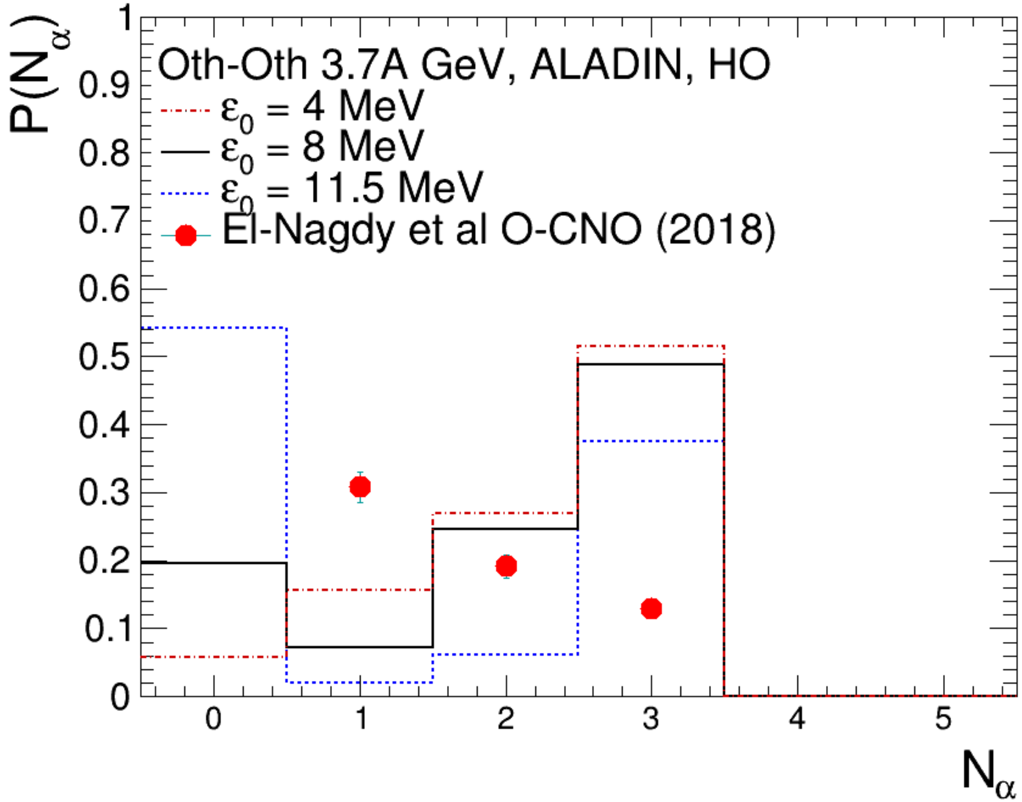


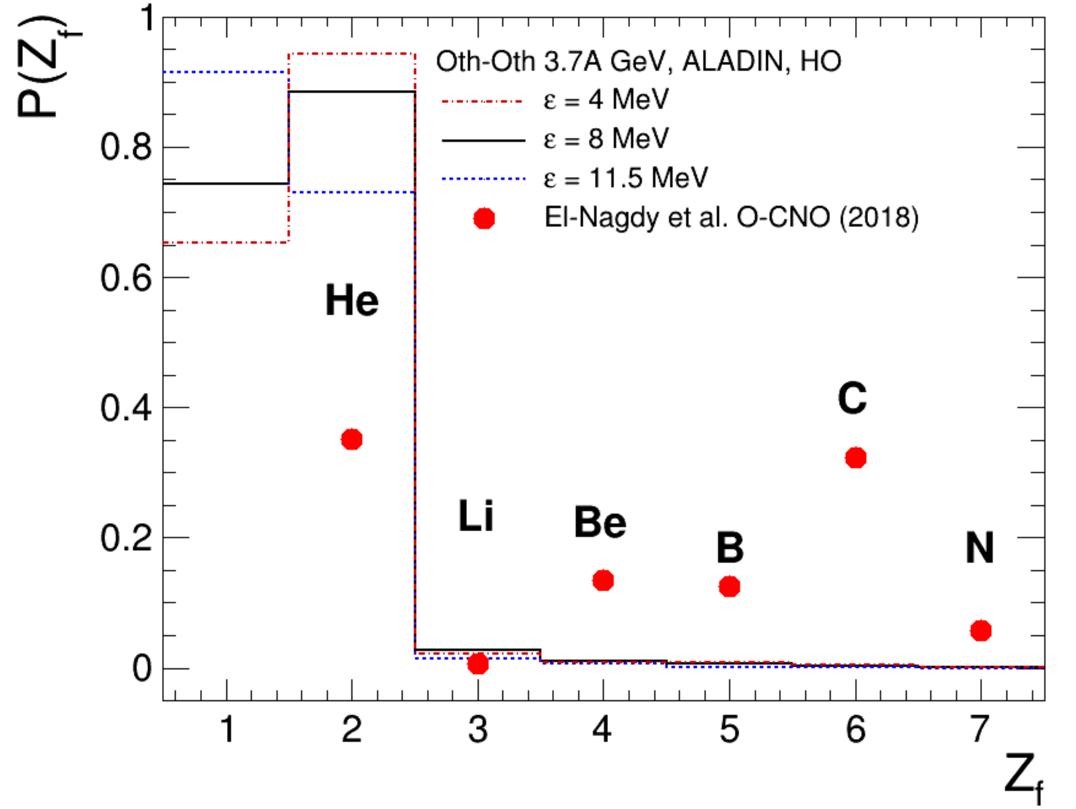


- ^{16}O–^{16}O collisions were modeled with pure tetrahedral state and **gaussian** density of the clusters.
- Smaller ε_0 provides better agreement with the data.
- The contribution of clustered states at the level of 20% is predicted*), this may affect the results.

*) A.Zuker, B.Buck and J.McGrory, Phys. Rev. Letters, **21** (1968), 39

Pure clustered state with different ε_0: HO

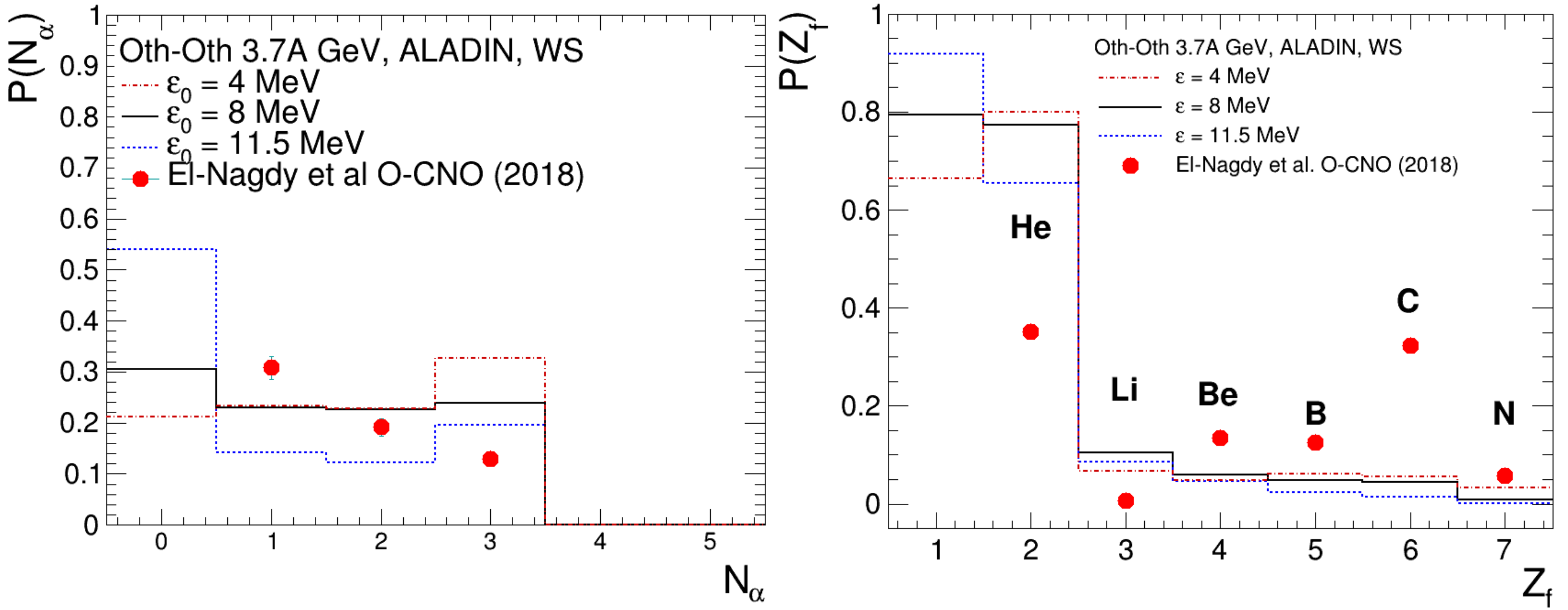




- ^{16}O–^{16}O collisions were modeled with pure tetrahedral state and **harmonic oscillator** density of the clusters.

- The results significantly differ from previous one as a sequence of more dense clusters.

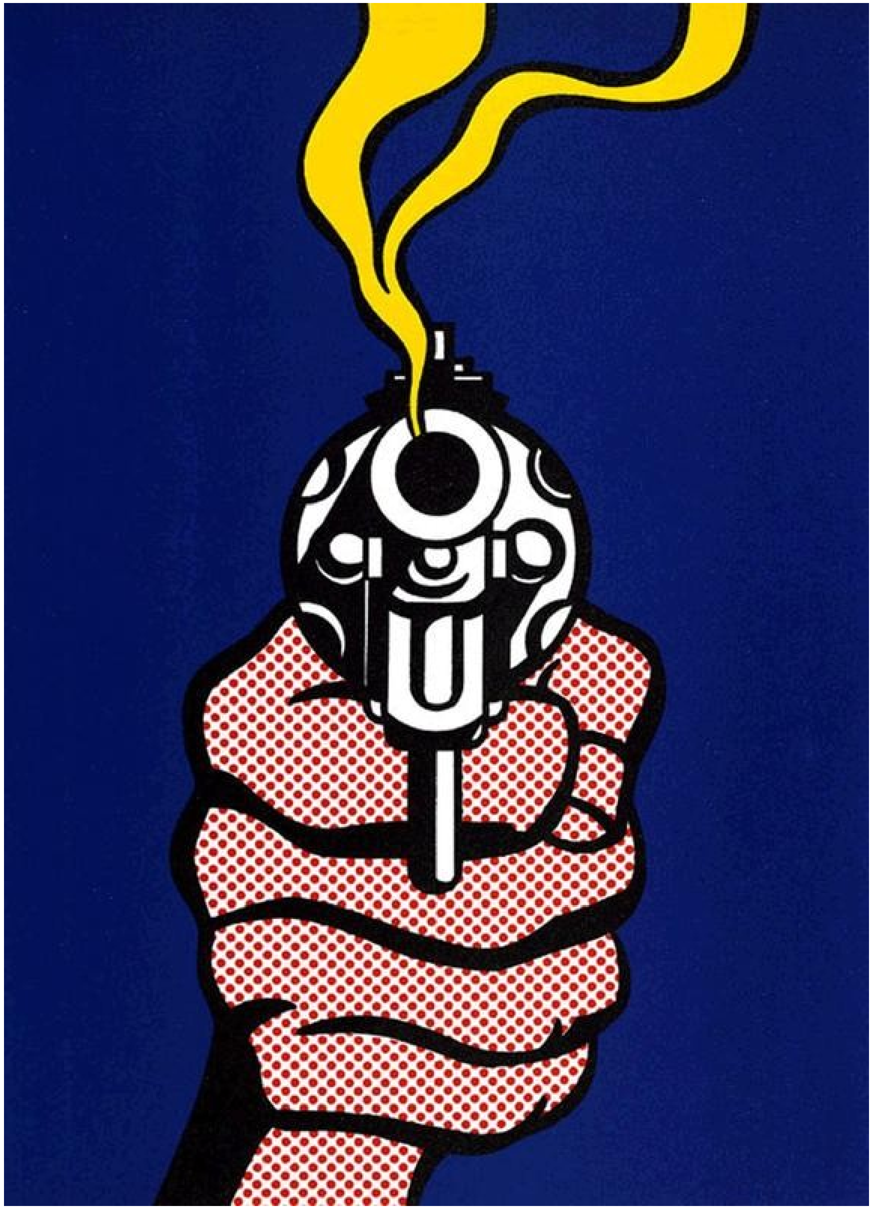
Pure clustered state with different ε_0: WS



- ^{16}O–^{16}O collisions were modeled with pure tetrahedral state and **Woods-Saxon** density of the clusters.

- The distributions obtained with Woods-Saxon are intermediate between the calculations with HO and gaussian density of clusters.

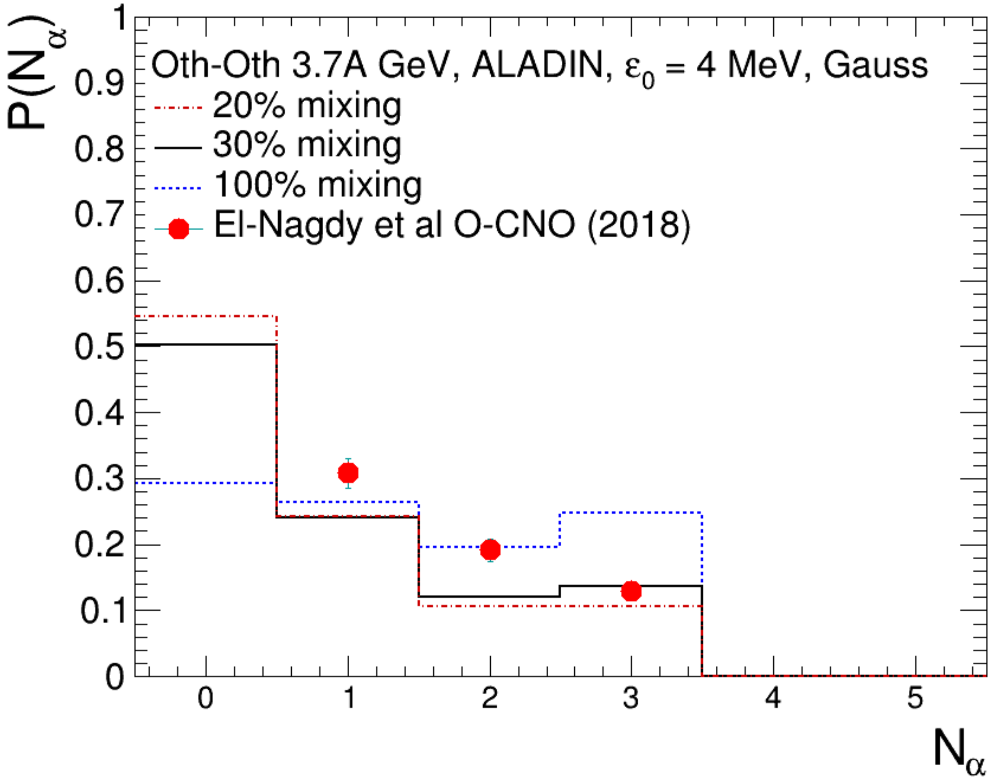
A smoking gun of clusterisation?

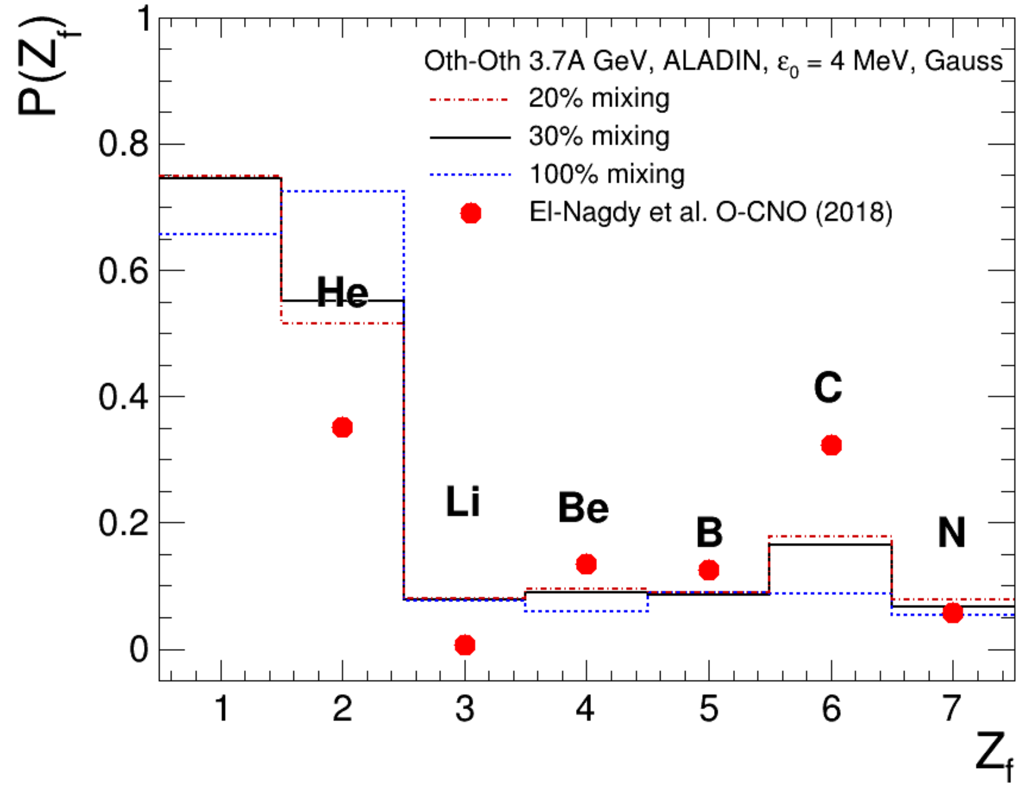


Roy Lichtenstein, Gun in America, 1968

The multiplicity distributions of produced alpha-particles are affected by the choice of density distributions of nucleons in alpha-clusters.

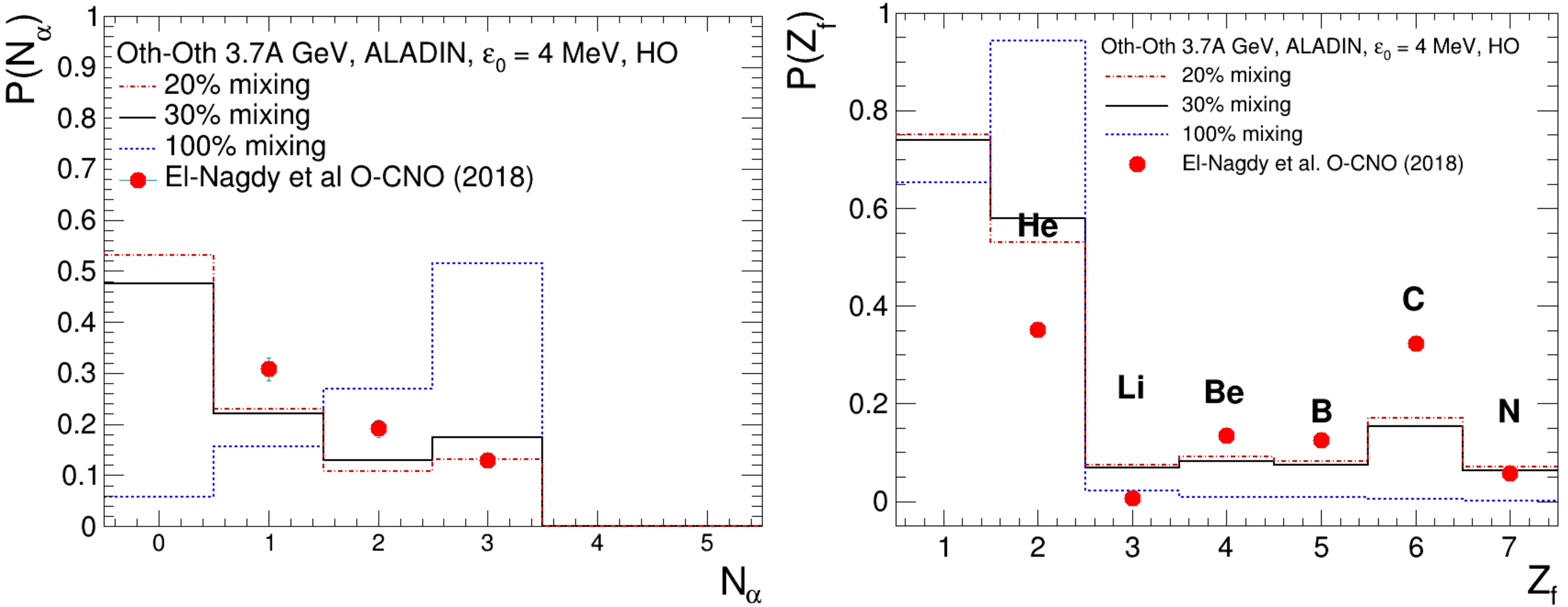
Contribution of clustered states: Gauss





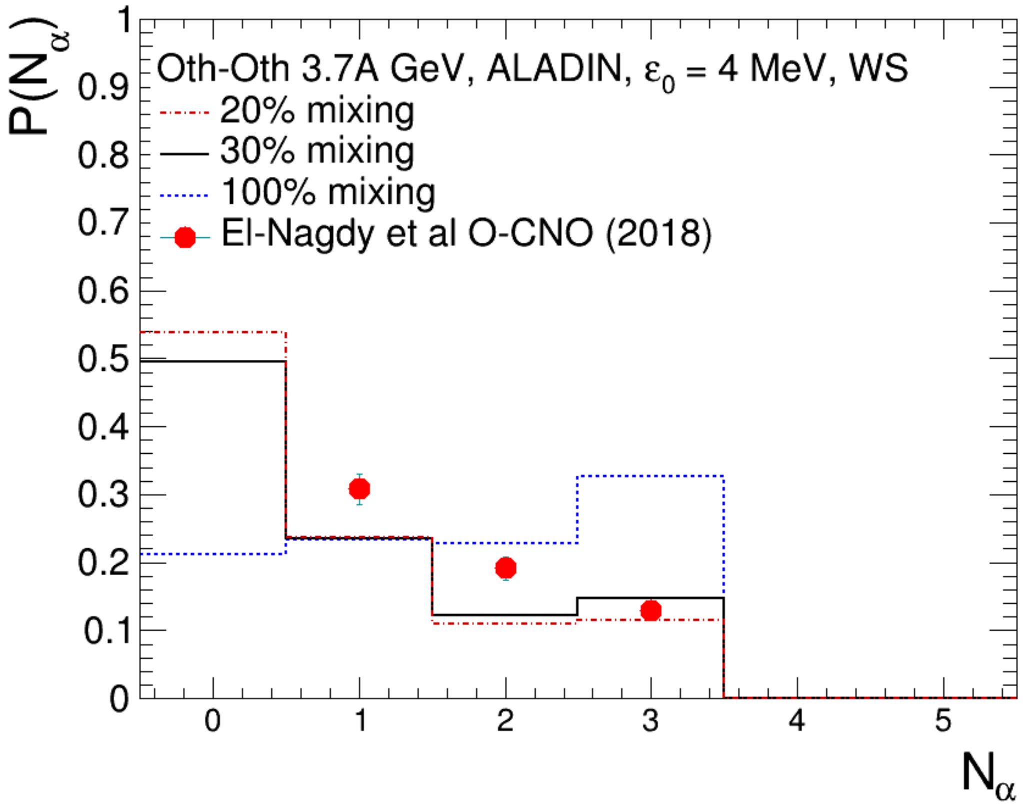
- The best agreement with data is obtained for both 20% and 30%.
- The production of the specific elements except **He** and **C** remains in the reasonable agreement for all the mixing values.
- The rates of the production of single alpha-particles are underestimated for all the mixing values, while the rate of the production of two alpha-particle is desribed for 100% mixing and three alpha-particle for 30% mixing

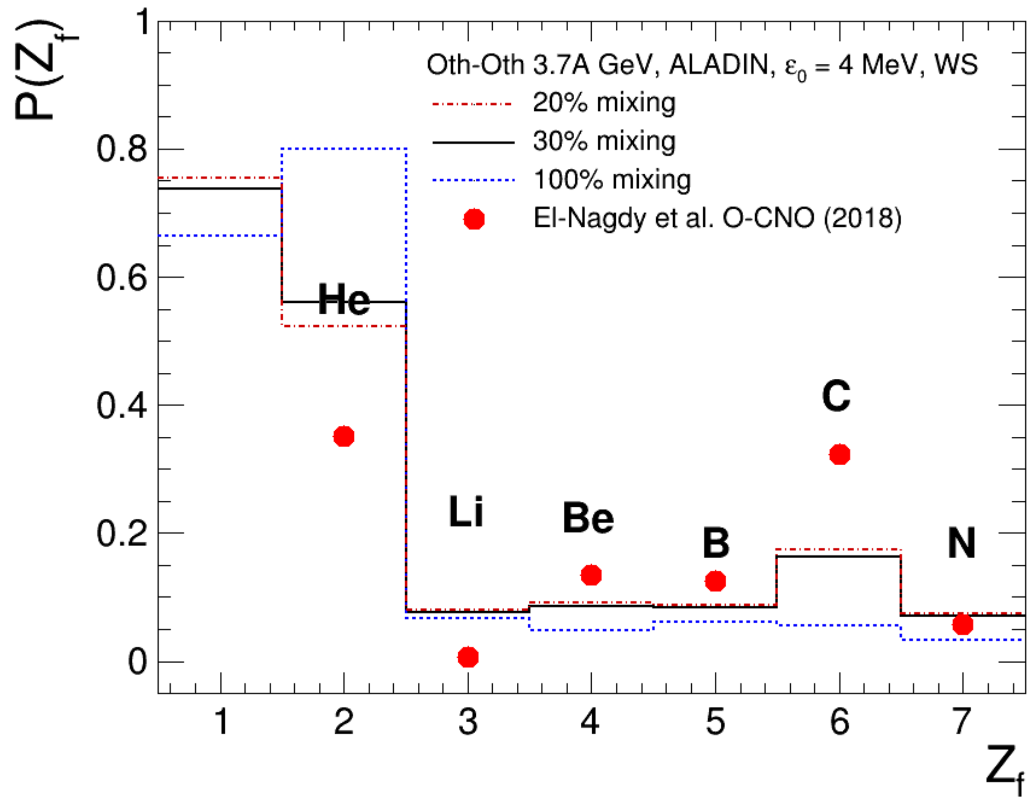
Contribution of clustered states: Harmonic oscillator



- The best agreement with the data is obtained for 20% mixing.
- The production of the specific elements beside **He** and **C** remain in the reasonable agreement for 20% as well as for 30% mixing.
- The rates of the production of one and two alpha-particles are underestimated.
- The rates of the production of three alpha-particles are described with 20% mixing.

Contribution of clustered states: Woods-Saxon





- The best agreement with data is obtained for 20% mixing as well.
- The production of the specific elements except **He** and **C** remain in the reasonable agreement for 20% as well as for 30% mixing.
- The rates of the production of one and two alpha-particles are underestimated.
- The rates of the production of three alpha-particles are in agreement with data for 20% as well as for 30% mixing.

Summary

- The description of experimental data on ^{16}O fragmentation is obtained not only by introducing the tetrahedral configuration in ^{16}O, but also by tuning an excitation energy of prefragment.

- The multiplicity distributions of produced alpha-particles are affected by the choice of density distributions of nucleons in alpha-clusters while the production of specific elements is not.

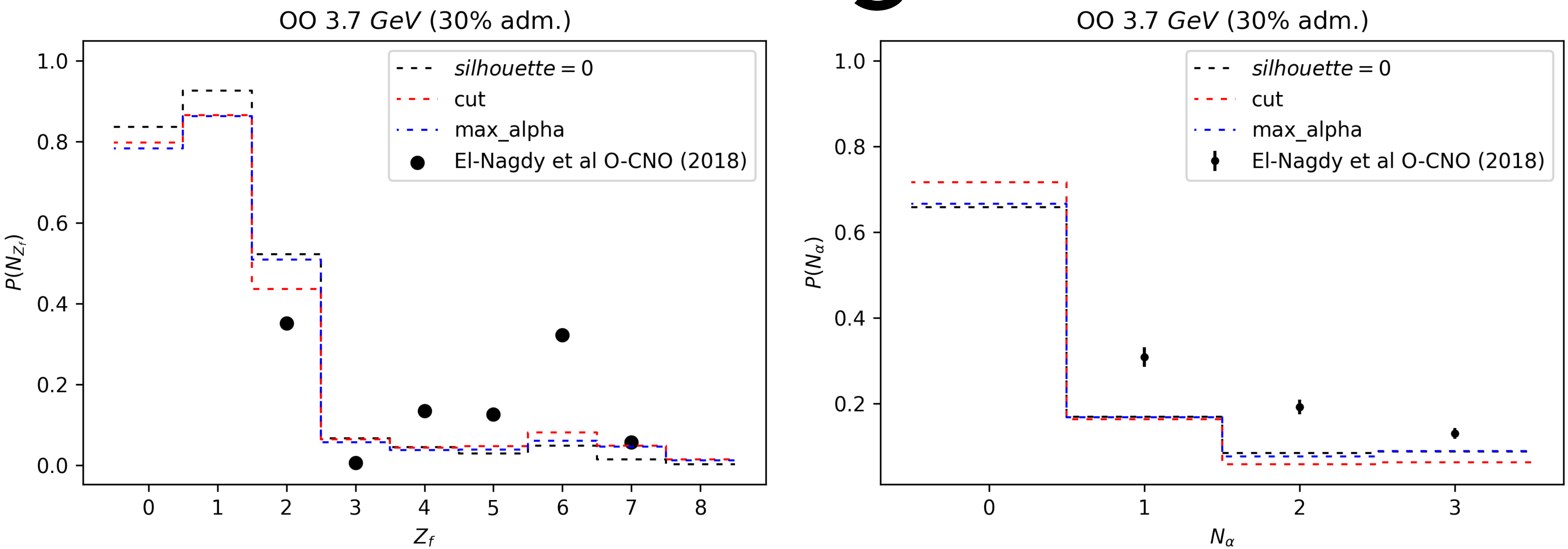
- From the comparison with the data the contribution of clustered states in ^{16}O is estimated at level of 20%.

Thank you for attention!

Five Tetrahedra, Dave Peacock 2013

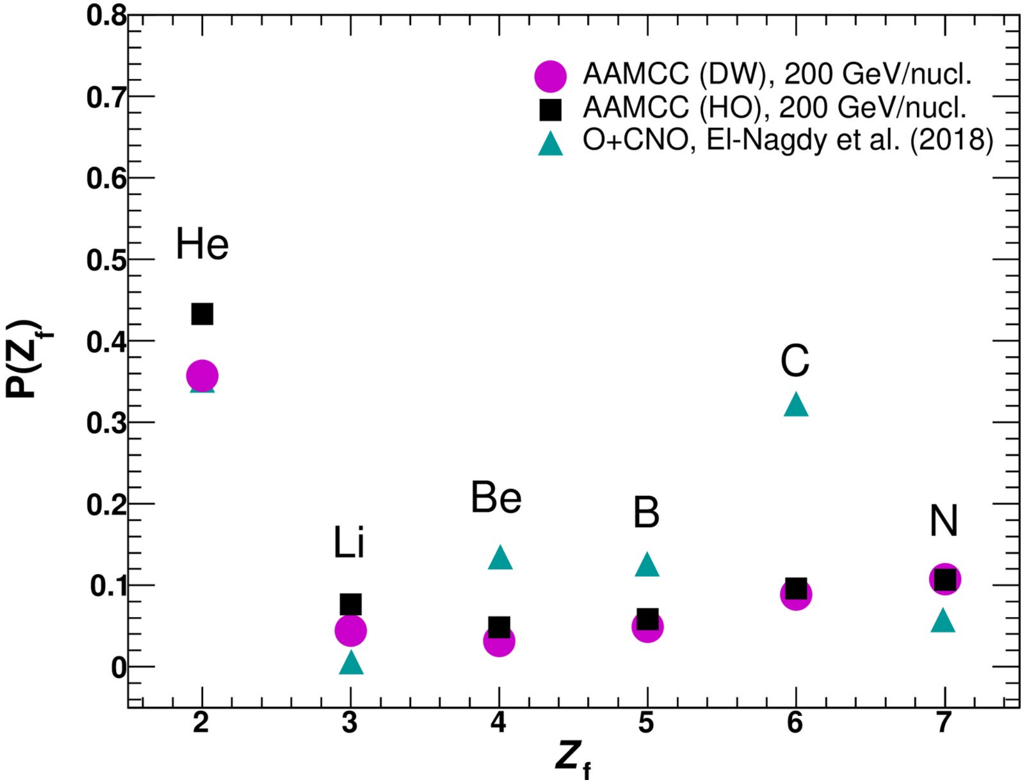
Backup slides

MST-clustering extention

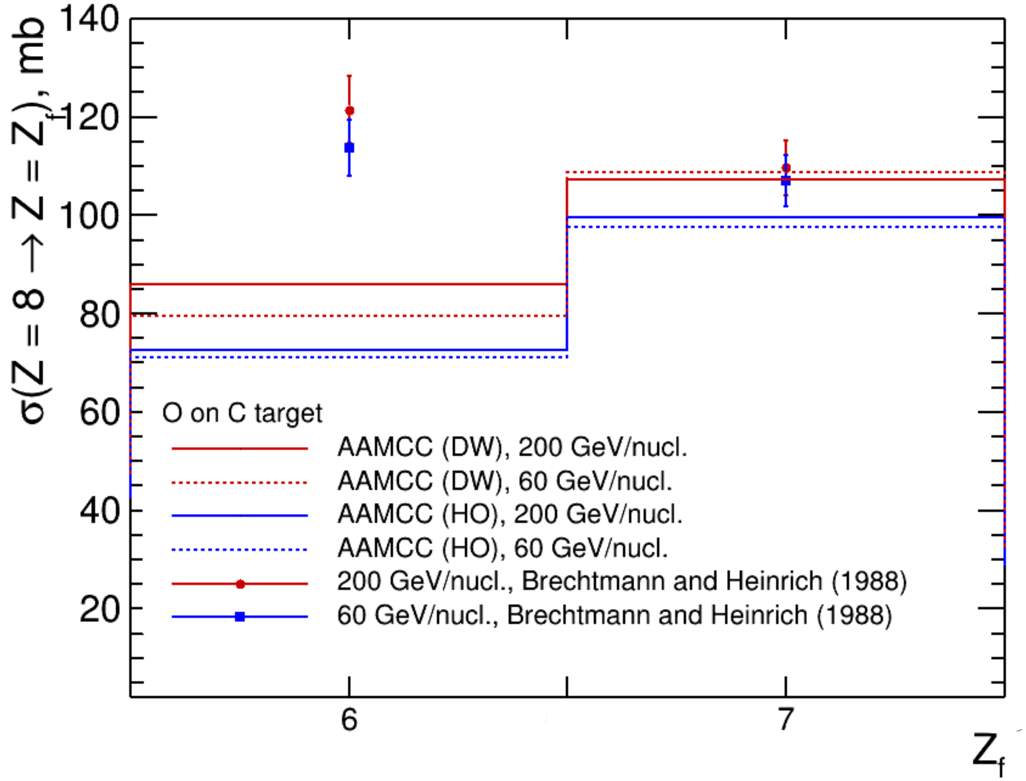


- To account for the clustering parameter d fluctuations we exploit hierrarchial clusterring algorithms and allow the clustering parameters to deviate from the average at the level of 30%
- We employ two different mechanism of clustering parameter choose
  - Maximisation of the alpha-particles for d clossest to the average one (**max_alpha**)
  - Maximisation silhouette clusterisation parameter that leads to a choose of the partition with the most separate clusters (**silhoettes**)
- **Cut** represents the traditional MST-clustering
- Nevertheless, the results are close only with the slight changes in H and He production.

Production of specific elements



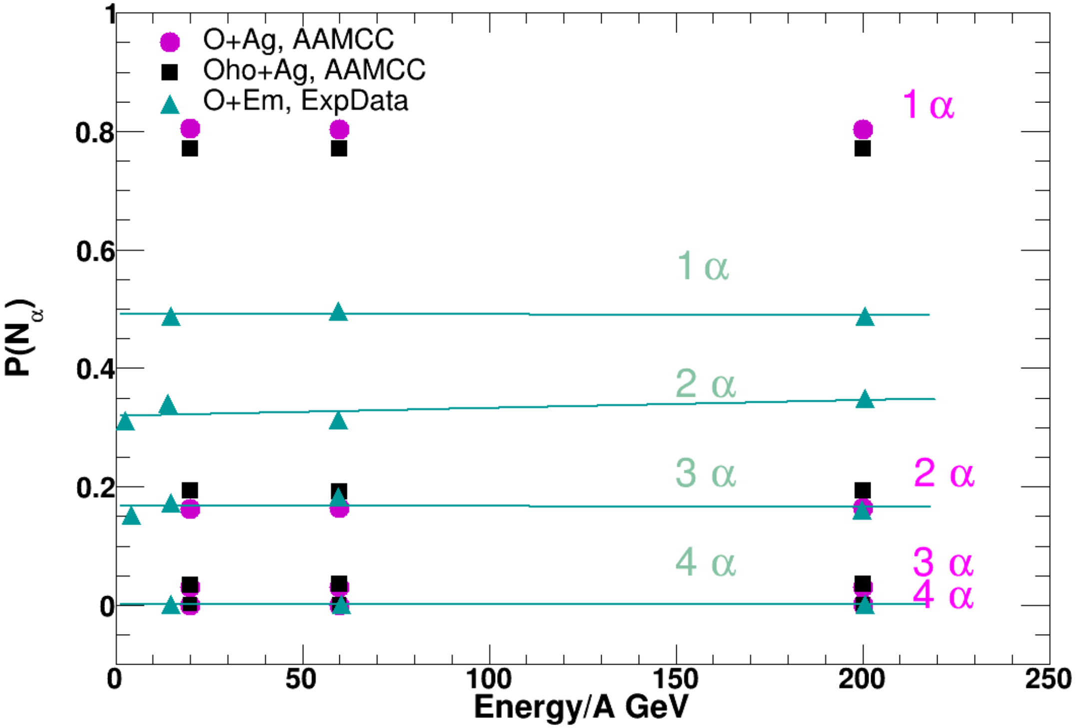
M. El-Nagdy et al., J. Phys. Comm. 2 (2018) 035010

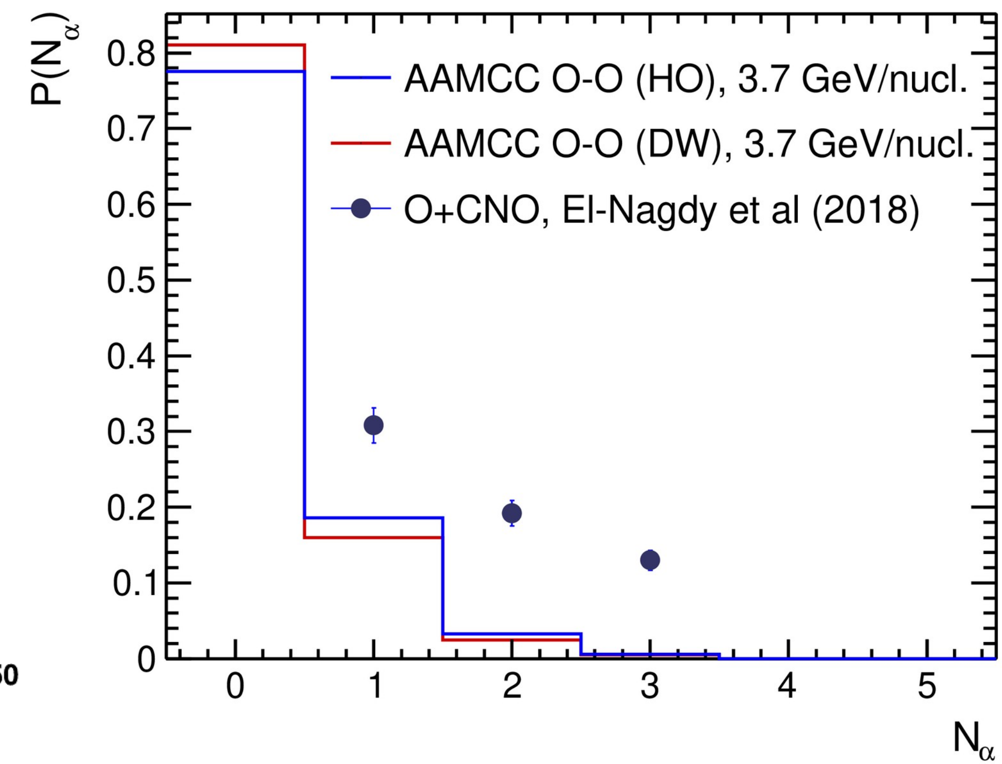


C. Brechtmann, W. Heinrich, Z. Phys. A 330 (1988), 407416

- Collisions of ^{16}O with nuclear emulsion (Em), CNO (light) + AgBr (heavy).
- The production of **He**, **Li**, **B**, **N** is **described** by AAMCC in general.
- The production of **carbon** is underestimated for both experiments.
- Slightly **better** agreement obtained with the **DW** parametrisation.

Production of ^{4}He

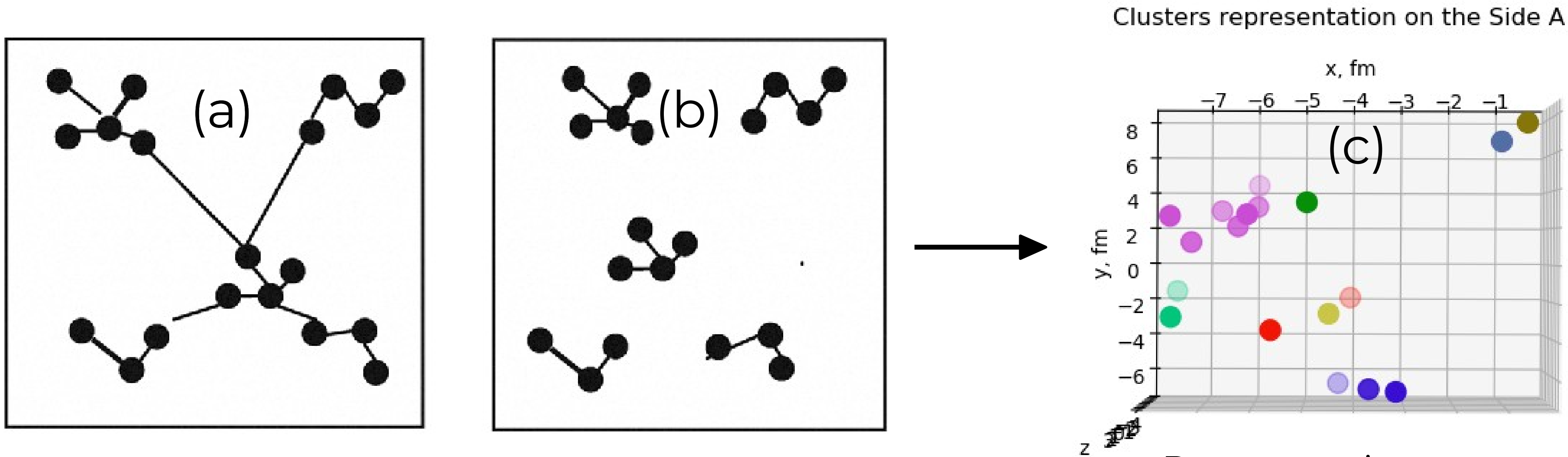




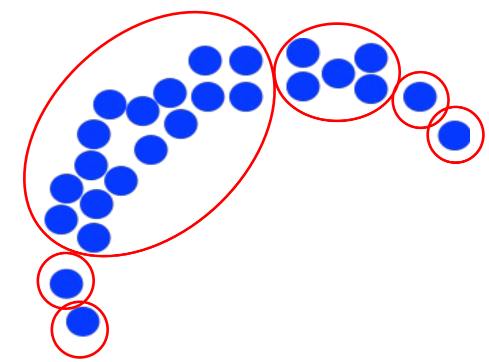
M. El-Nagdy et al., J. Phys. Comm. 2 (2018) 035010

- The production of single alpha-particles is overestimated in O+Em interactions.
- In contrast, the production of single alpha-particles in O+CNO interactions is underestimated.
- The rates of two and three alphas are underestimated in both cases.

MST-clustering



Beam-eye view



Prefragments in central collision

- Graph vertexes – nucleons, edges weights – Cartesian between them.
- The minimum spanning tree is selected from the complete graph (a)
- All edges with a weight greater than *d* are removed. *d* is the clustering parameter depending on the excitation energy (b)
- Connectivity components are separate (pre-)fragments (c)

AAMC²

The prefragment is dynamically divided into several prefragments until thermodynamic equilibrium is reached.

Prefragment expansion

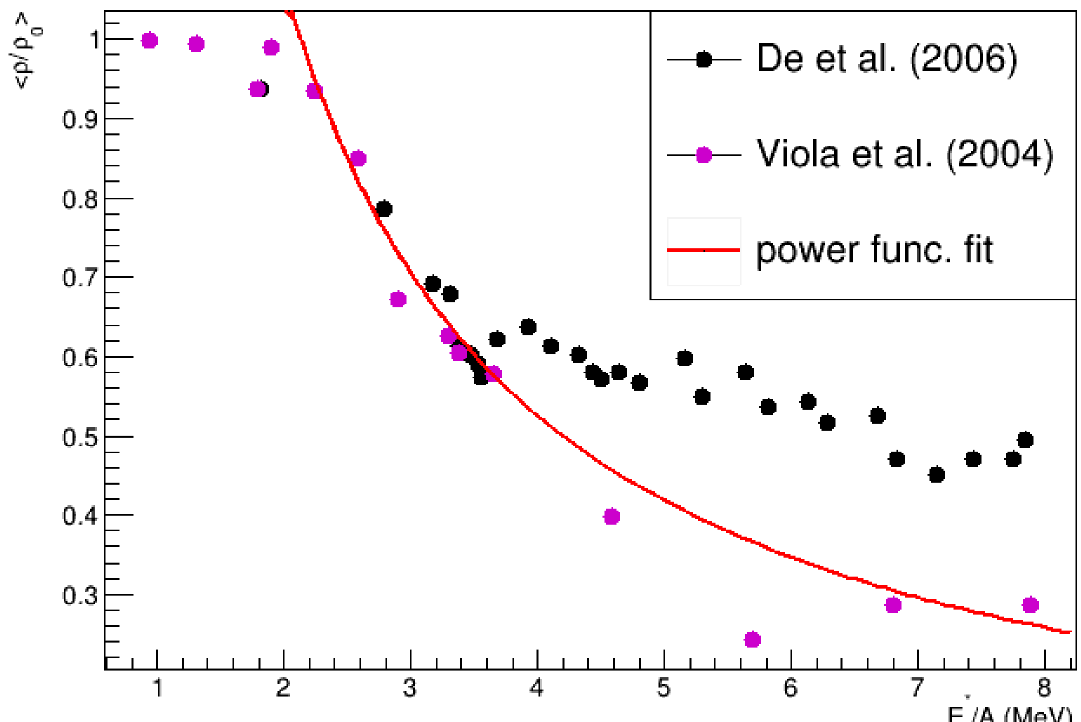
- With an increase in the size of the prefragment, the average distance between nucleons increases; therefore, *d* decreases. The characteristic dependence on the density of the prefragment is $d \propto \rho^{1/3}$.

- The density parametrization is taken in the form of a piecewise power function, which determines the parameters of the experimental data (see figure).

$$\rho/\rho_0 = \left(\frac{1}{\epsilon_0}\frac{E_x}{A}\right)^{\alpha}, E_x/A > 2\,MeV$$

$$\alpha = -1.02 \pm 0.07$$

$$\epsilon_0 = 0.46 \pm 0.05\,MeV$$



V.Viola et al. Phys. Rev. Lett. **93** (2004) 1
J.De et al., Phys Lett B **638** (2006) 160

AAMC²