Cluster formation in spectator matter in collisions of relativistic nuclei

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Abstract Geometry, Phil Perkins

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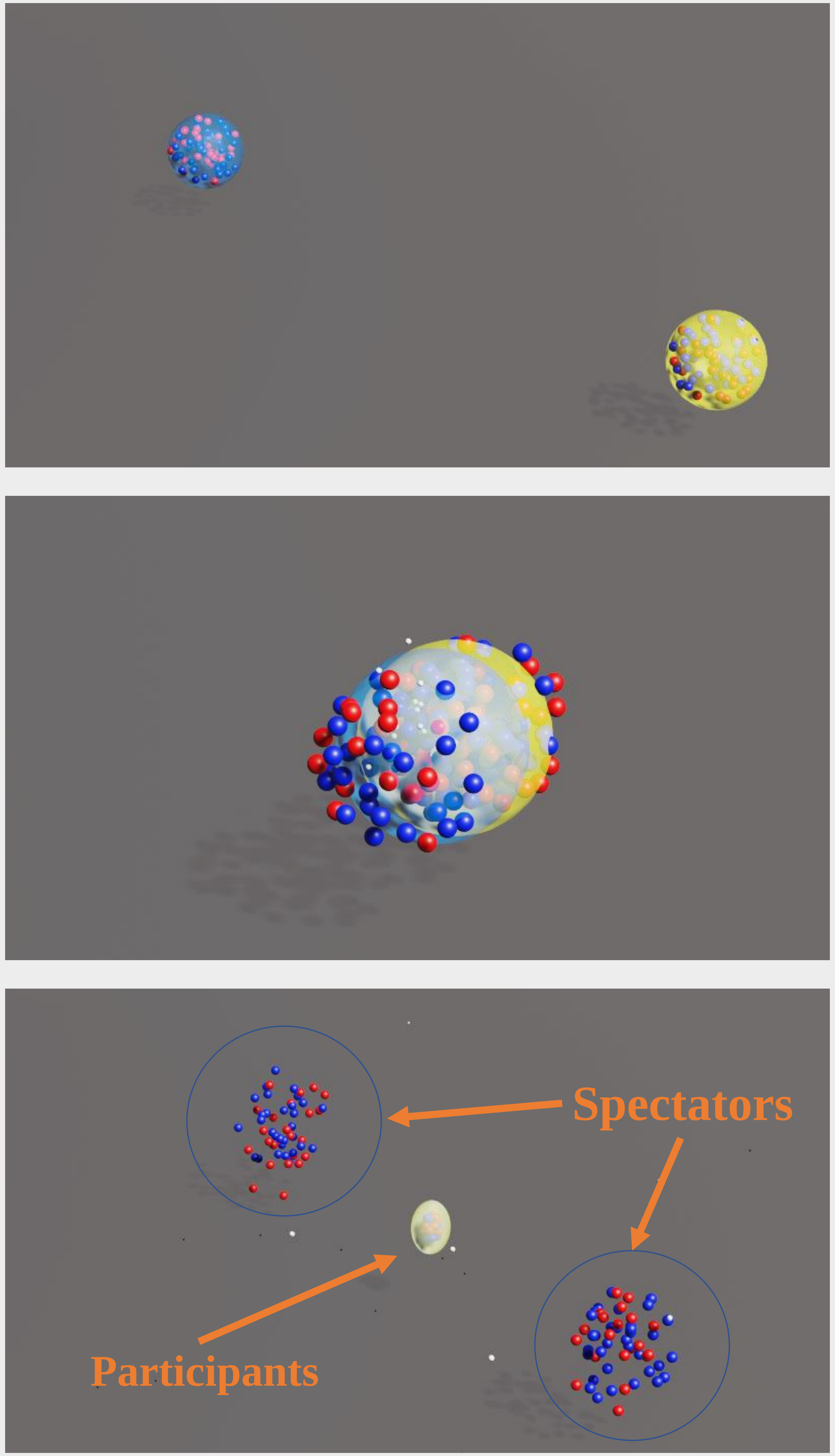
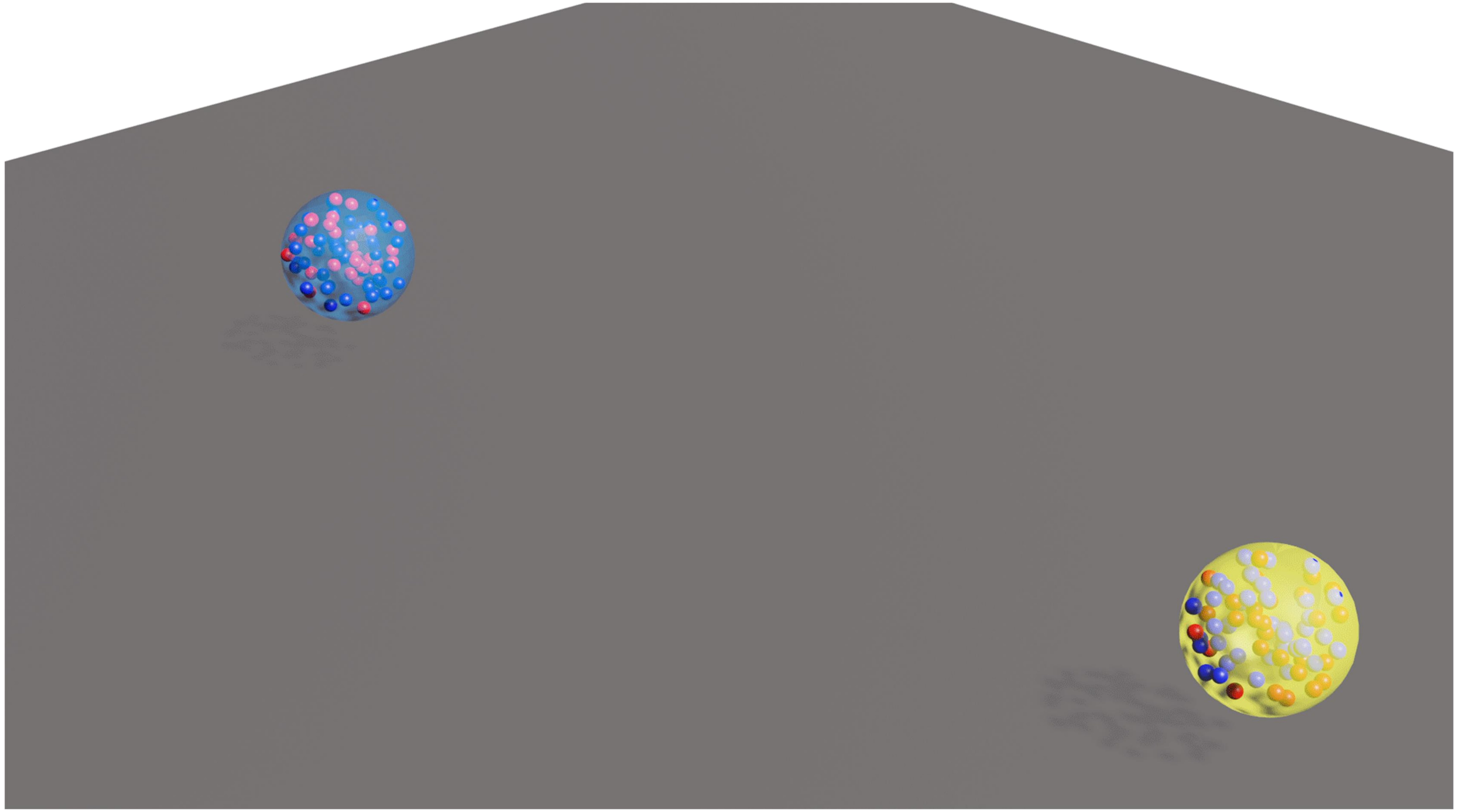
Nuclear physics and elementary particle physics. Nuclear physics technology”

Outline

- Collision geometry: participants and spectators
- Our model: Abrasion – Ablation Monte Carlo for Colliders (AAMCC)
- Specific shape of prefragments in central collisions
- Minimum Spanning Tree (MST) – clusterization algorithm
- Expansion of nuclear matter and clustering parameter
- Clustering in ultracentral ^{208}Pb—^{208}Pb collisions
- ^{16}O—^{16}O collisions at the LHC modelled with AAMCC-MST

Visualization of the collision of relativistic nuclei





Visualization was made in Blender

● - protons

● - neutrons

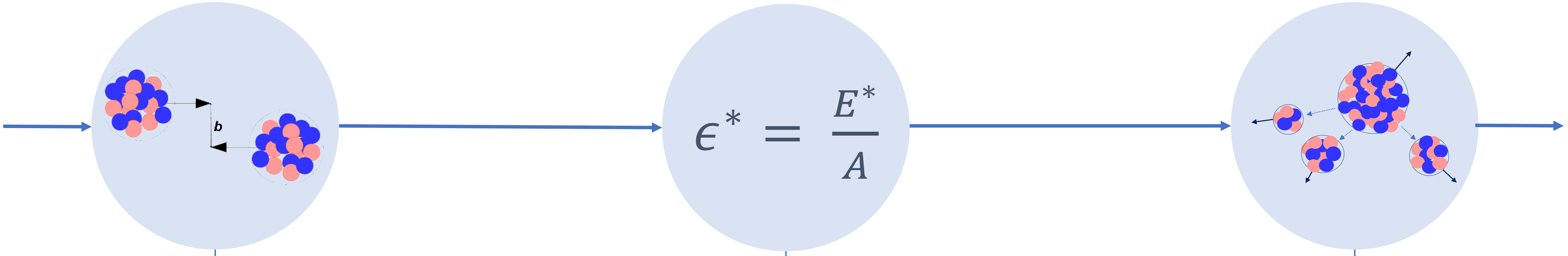
AAMCC model

Abrasion-Ablation Monte Carlo for Colliders*

Abrasion of nucleons

Excitation of prefragments

Fragmentation of prefragments



$$\epsilon^* = \frac{E^*}{A}$$

Glauber Monte Carlo

ALADIN parametrization[1]
Ericson formula[2]
Hybrid parametrization

Geant4 deex. classes[3]

Nucleons' positions sampling

separation of nucleons into spectators and participants

Calculation of the excitation energy using one of the three above-mentioned options

- $\epsilon^* > 3.5\ MeV/nucl$: Multifragmentation (SMM)[4]
- Evaporation[5]
- Fermi BreakUp ($A < 19$)[6]

C. Loizides, J. Kamin, D. d'Enterria
Phys. Rev. C 97 (2018) 054910

[1] A. Botvina et al. Nuclear Physics A 584 (1995) 737-756
[2] T. Ericson Adv. In Physics 9 (1960) 737-756

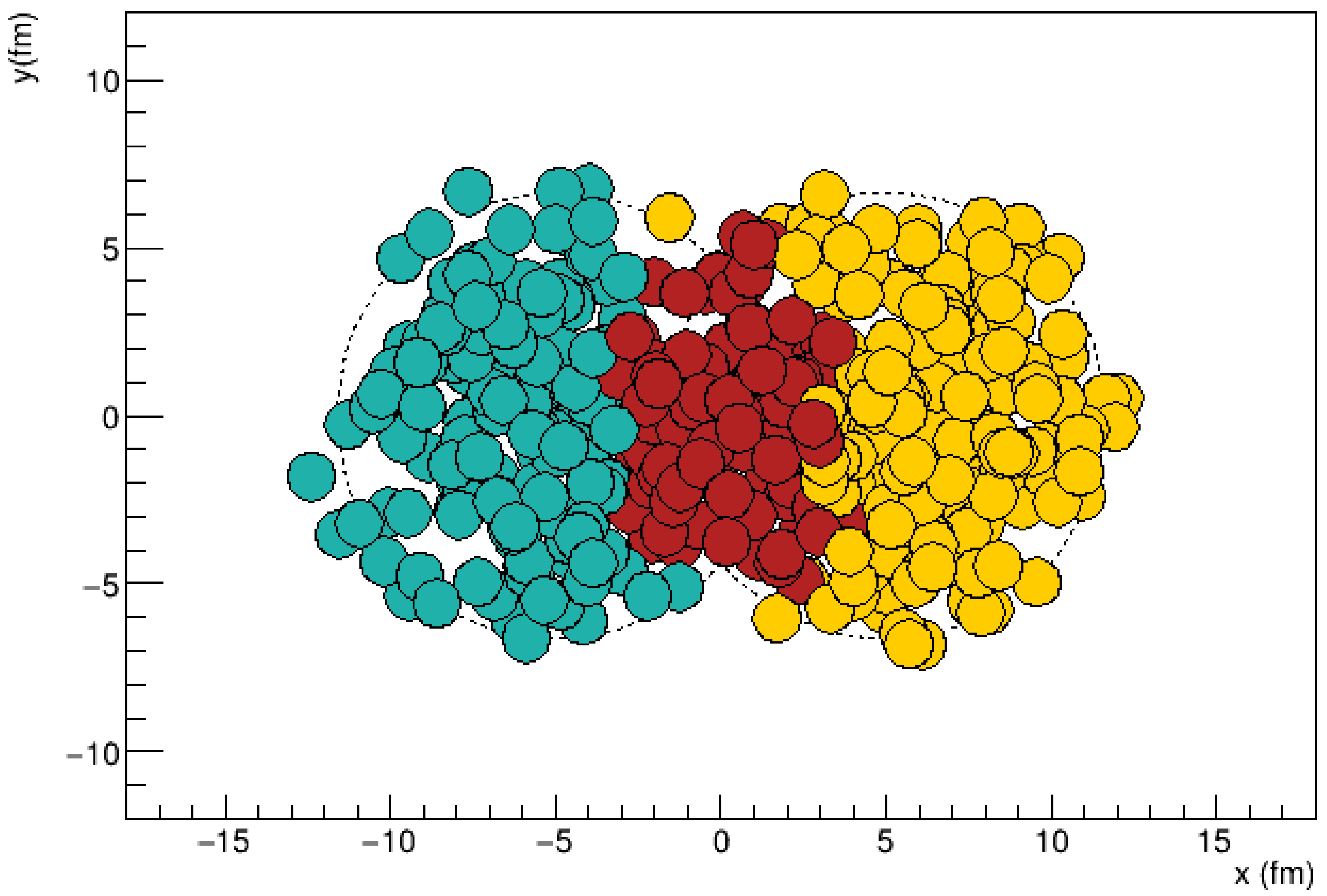
[3] J. Alison et al. Nucl. Inst. A 835 (2016) 186-225
[4] J. Bondorf et al. Phys. Rep. 444 (1985) 460-476
[5] V. Weisskopf Phys. Rev. 52 (1937) 295
[6] E. Fermi Progress of Th. Phys. 5 (1950) 570

***A. Svetlichnyi, I. Pshenichnov Bull. RAS. 84 (2020) 911-916**

Specific shape of prefragments in central collisions

Glauber Monte Carlo v3.2 illustration of ^{208}Pb-^{208}Pb collisions ($\sigma_{NN} = 67.7\ mb$)

Peripheral collision



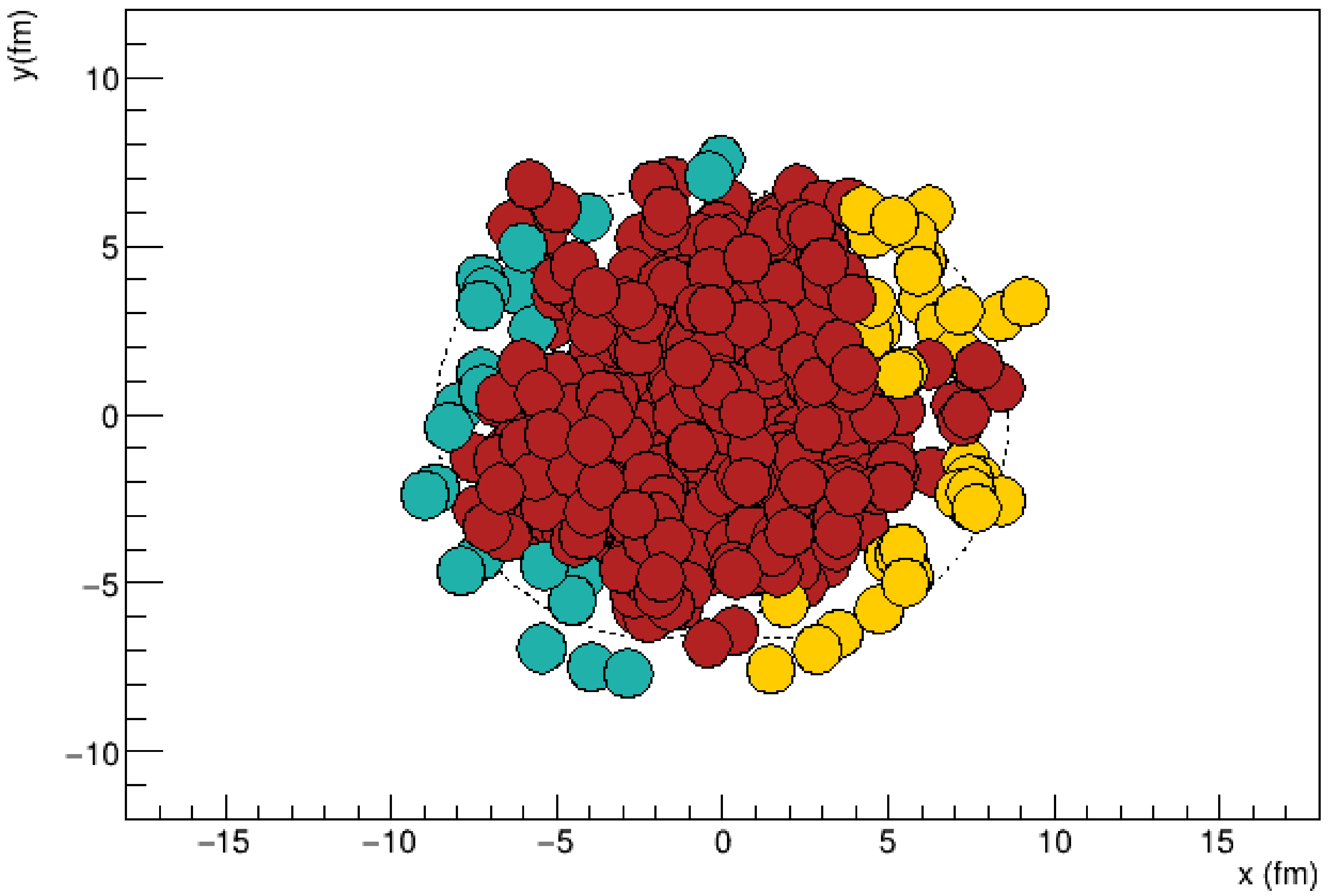
Prefragments represent connected systems

🟢 Spectators from side A

🟡 Spectators from side B

🔴 Participants

Central collision



Highly diluted residual spectator matter has a characteristic shape of a narrow crescent

An additional "geometric" fragmentation of the prefragment is needed, which is absent in traditional abrasion-ablation models

/. Bairathi et al. Phys. Rev. C 91 (2015) 054903

MST clustering algorithm

Minimum Spanning Tree

Kruskal algorithm

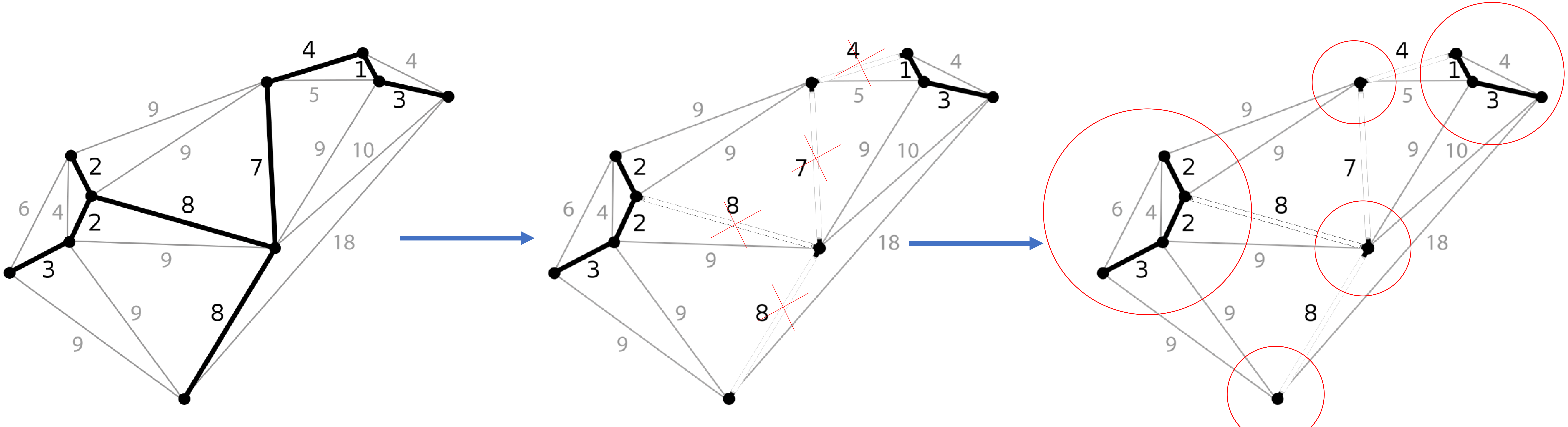
to find the minimum spanning tree

Critical distance

search for **inconsistent** edges so the MST can be subdivided

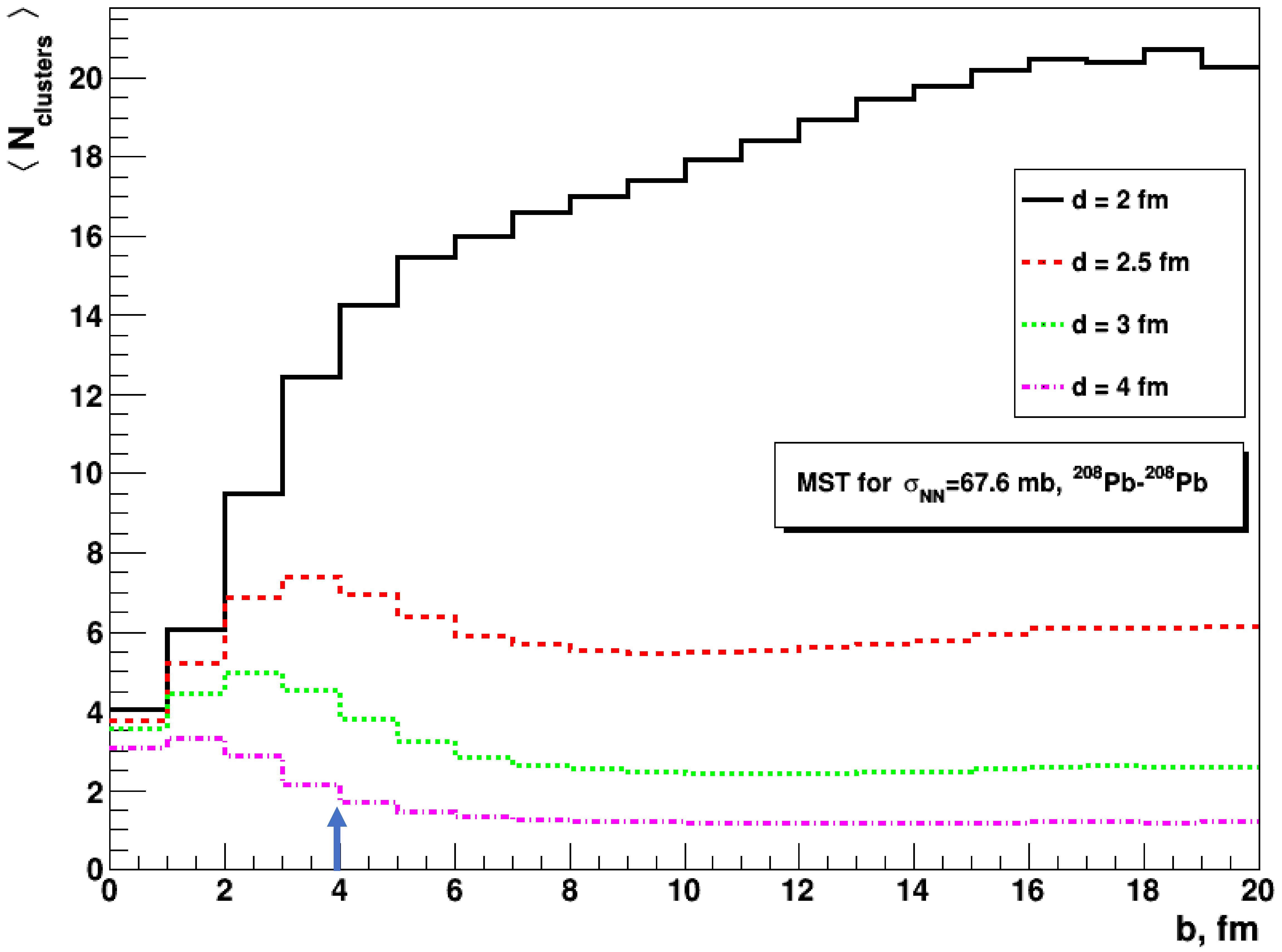
Components of connectivity

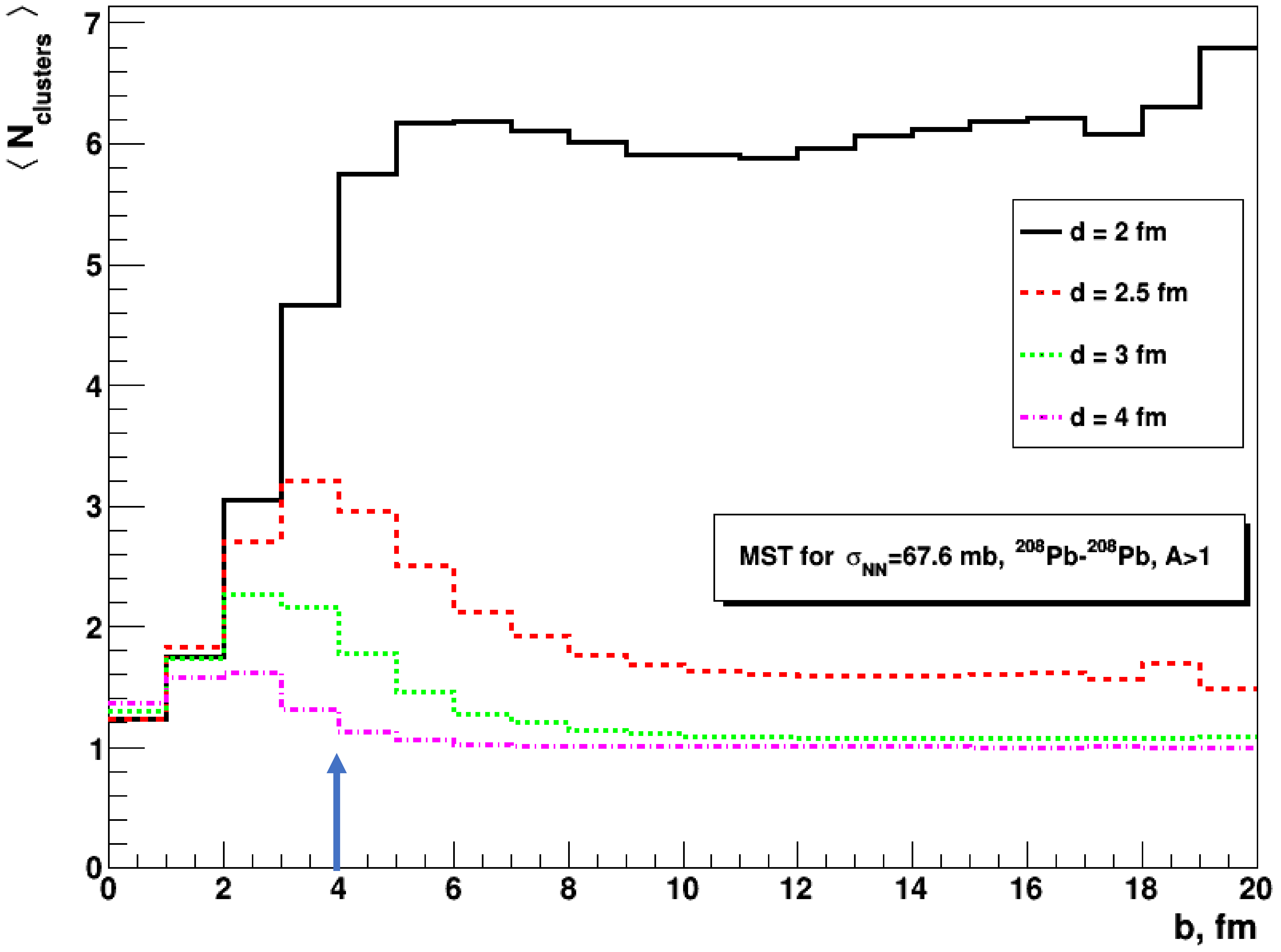
depth-first search



Vertices – nucleons; weight – modulus of the distance in 3D space*

The average number of clusters as a function of b for different values of the critical parameter d





The value of $d = 4\ fm$ was taken for normal nuclear density.

Prefragment Expansion

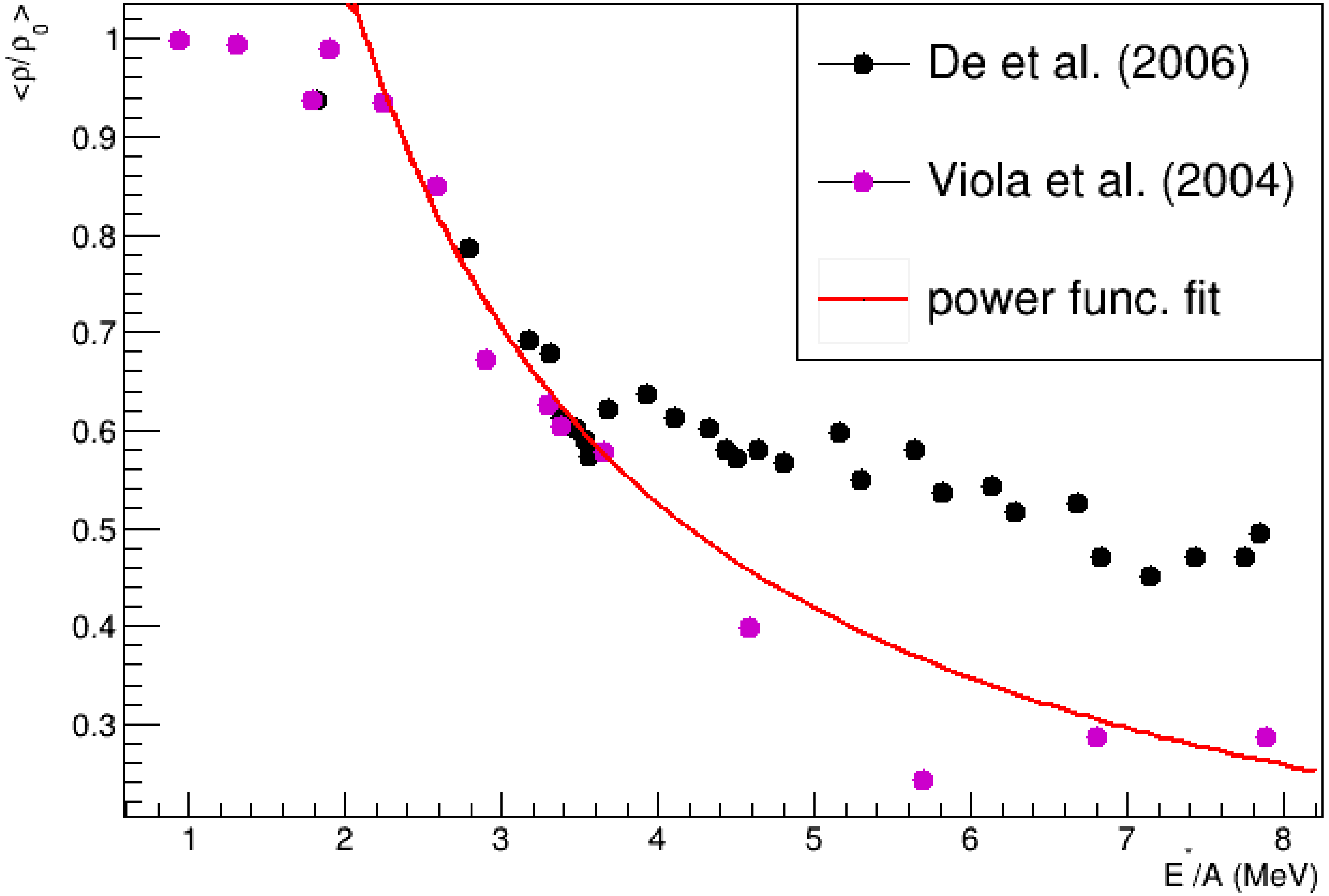
- When $\epsilon^* > 2\ MeV/nucl$, nuclear matter undergoes liquid-gas phase transition
- The larger the size of the prefragment, the longer the average distance between nucleons
- Therefore, d increases with the density of the prefragment:

$$d \propto V^{-1/3} \longrightarrow d \propto \rho^{1/3}(\epsilon^*)$$

Following J. De (2006) and V. Viola (2004) we assume:

$$d = \begin{cases} d_0,\ \epsilon^* < 2\ MeV/nucl \\ d_0 \cdot (\epsilon^*/\epsilon_0)^{\frac{\alpha}{3}},\ \epsilon^* > 2\ MeV/nucl \end{cases}$$

Where $d_0 = 4\ fm, while\ \alpha = 1.02 \pm 0.07, \epsilon_0 = 0.46 \pm 0.05\ MeV$ are the fitting parameters

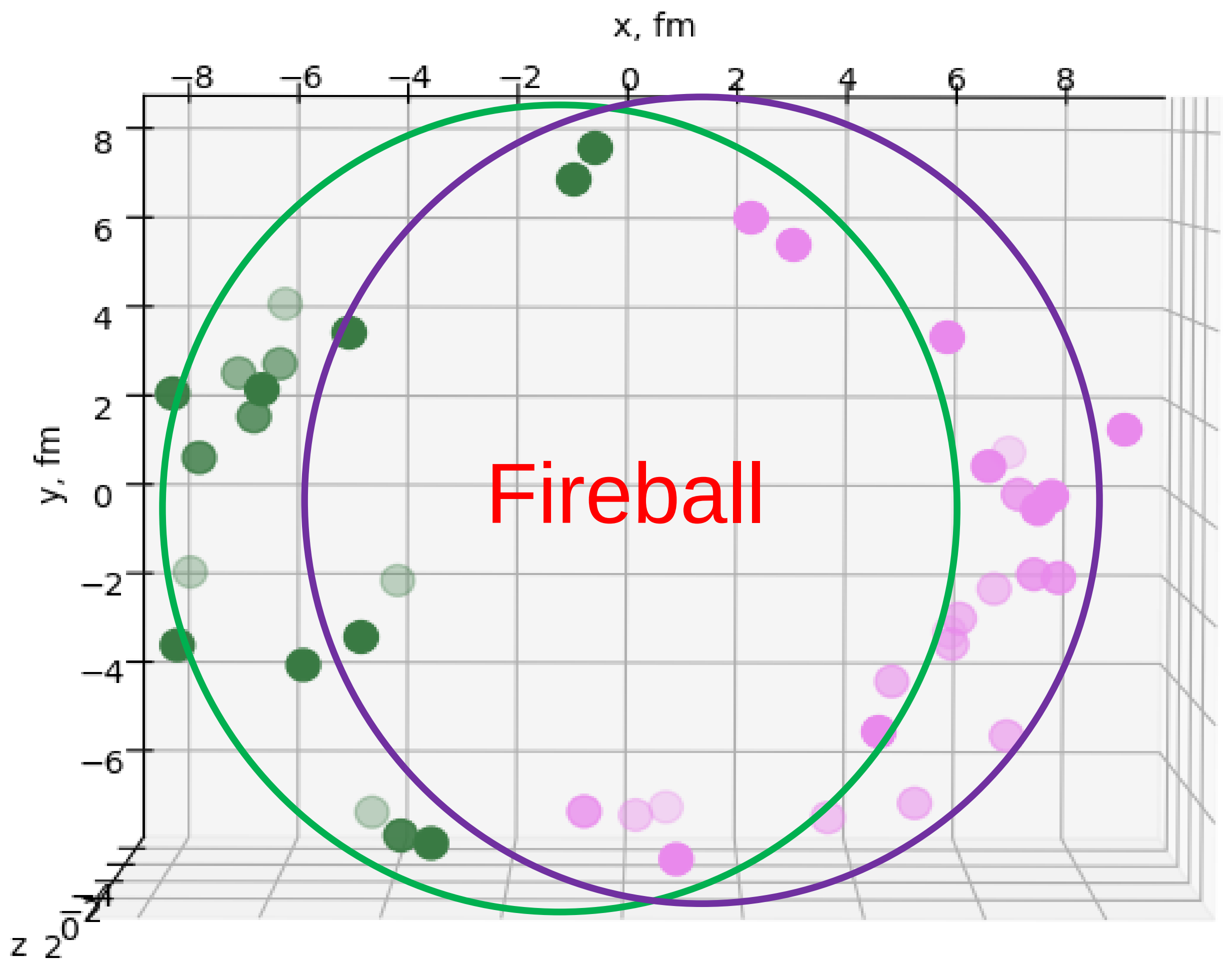


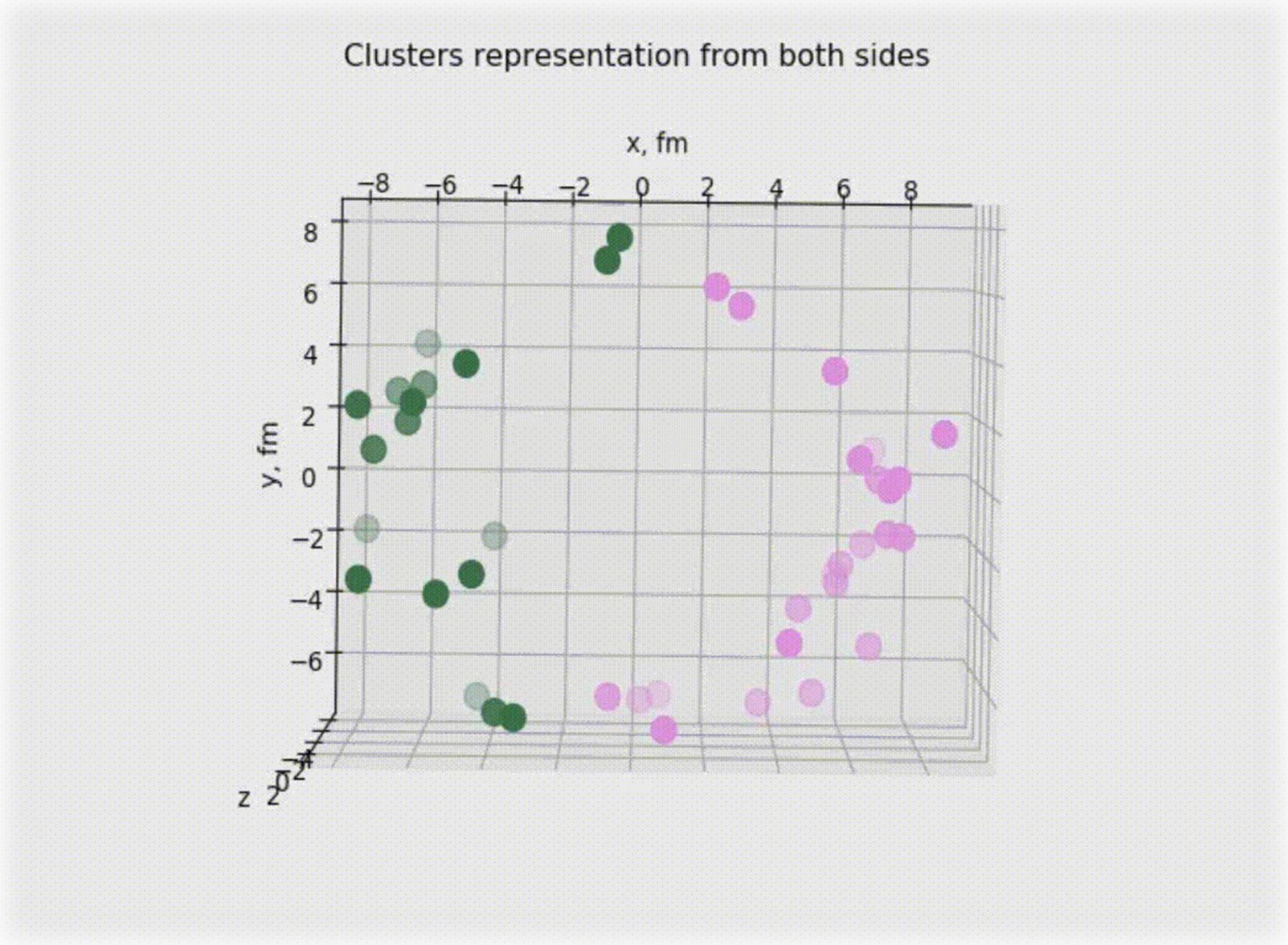
J. De et al. Phys. lett. B 638 (2006) 160-165

V. Viola et al. Phys. Rev. lett. B 93 (2004) 1-4

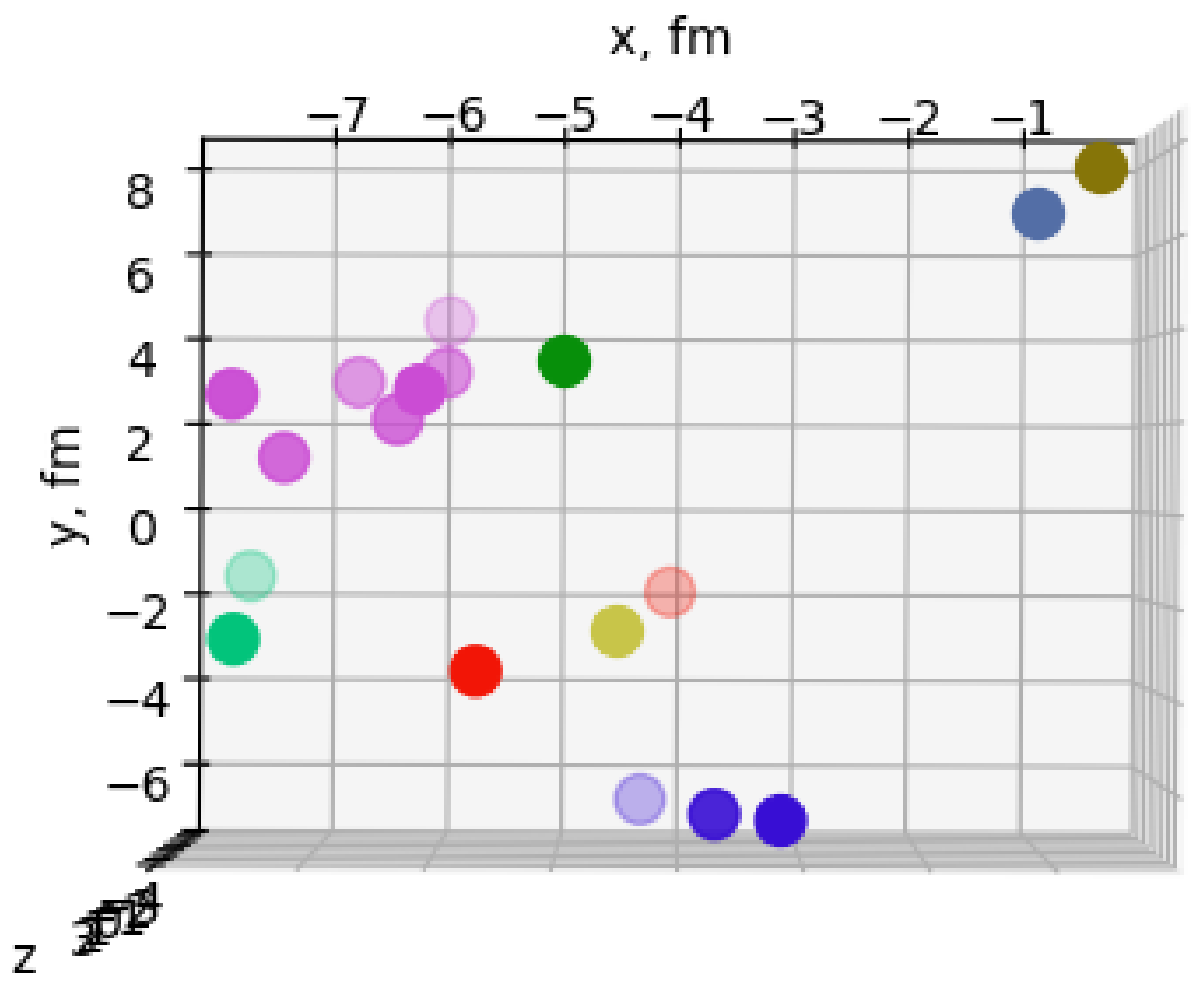
Visualization of the results of the MST algorithm in central collisions

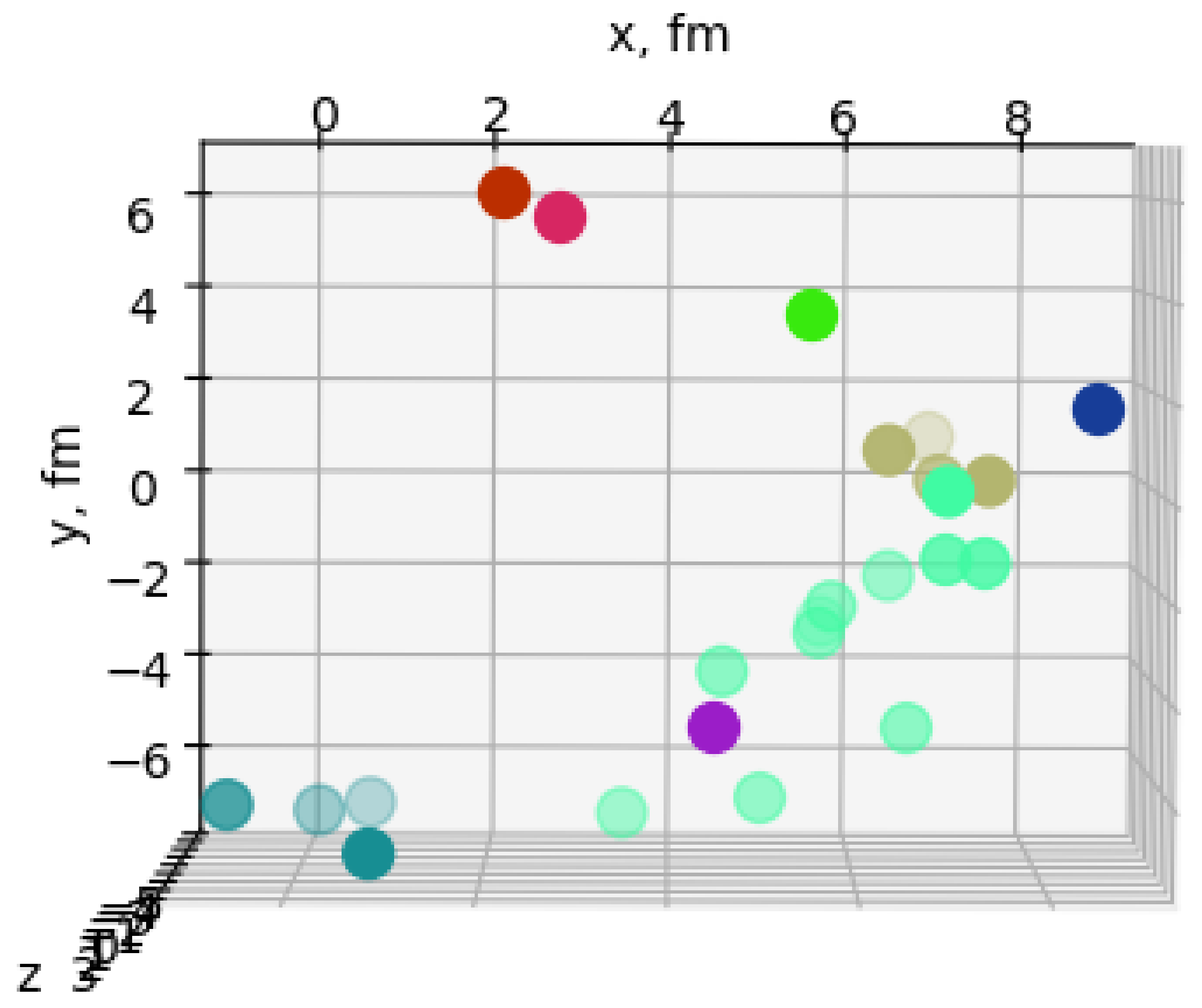
Clusters representation from both sides




Clusters representation from both sides

PbPb 158AGeV, $b = 2\ fm$


Clusters representation on the Side A

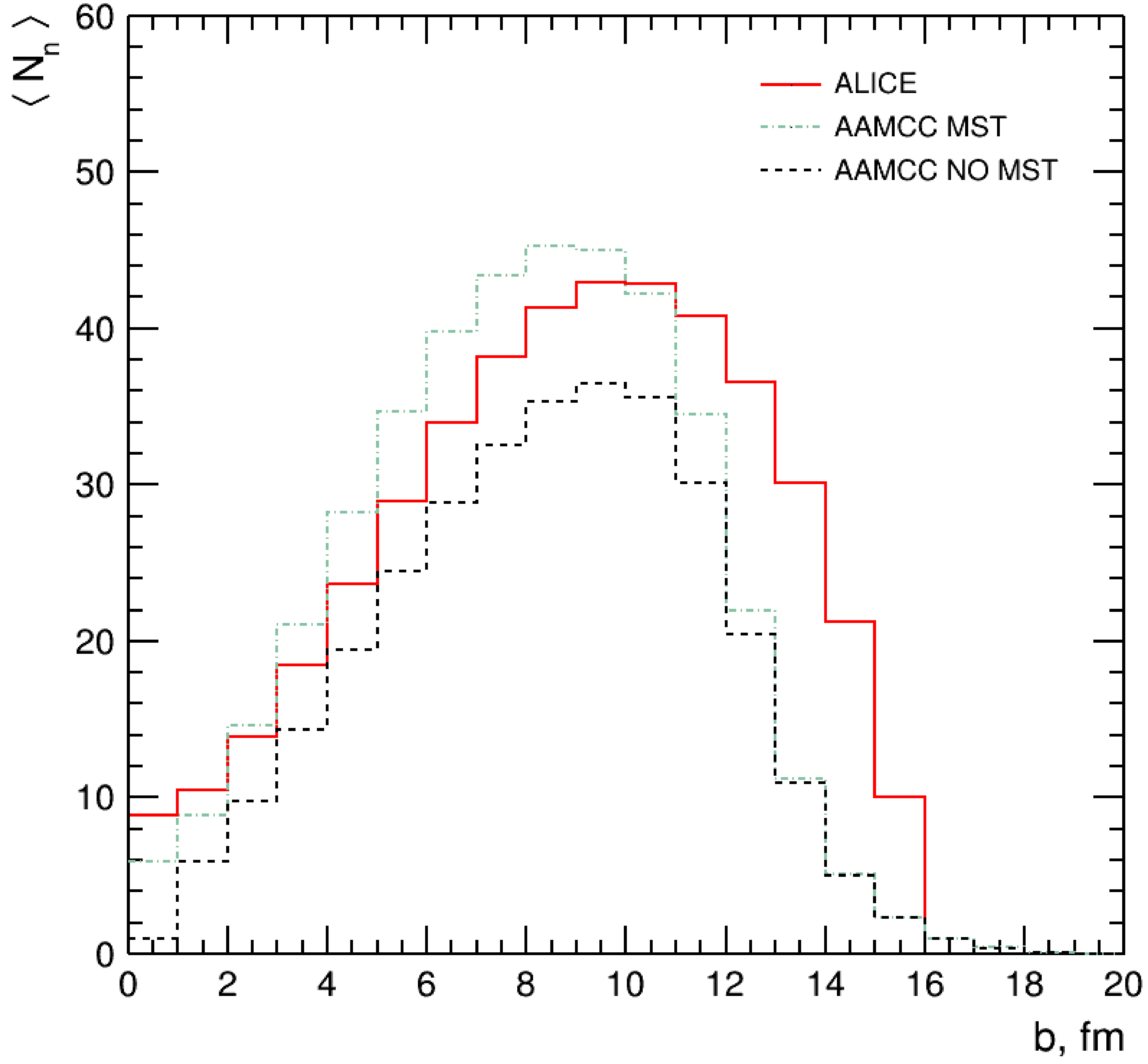

Clusters representation on the Side B

Axis Z – beam axis, XY – transverse plane*

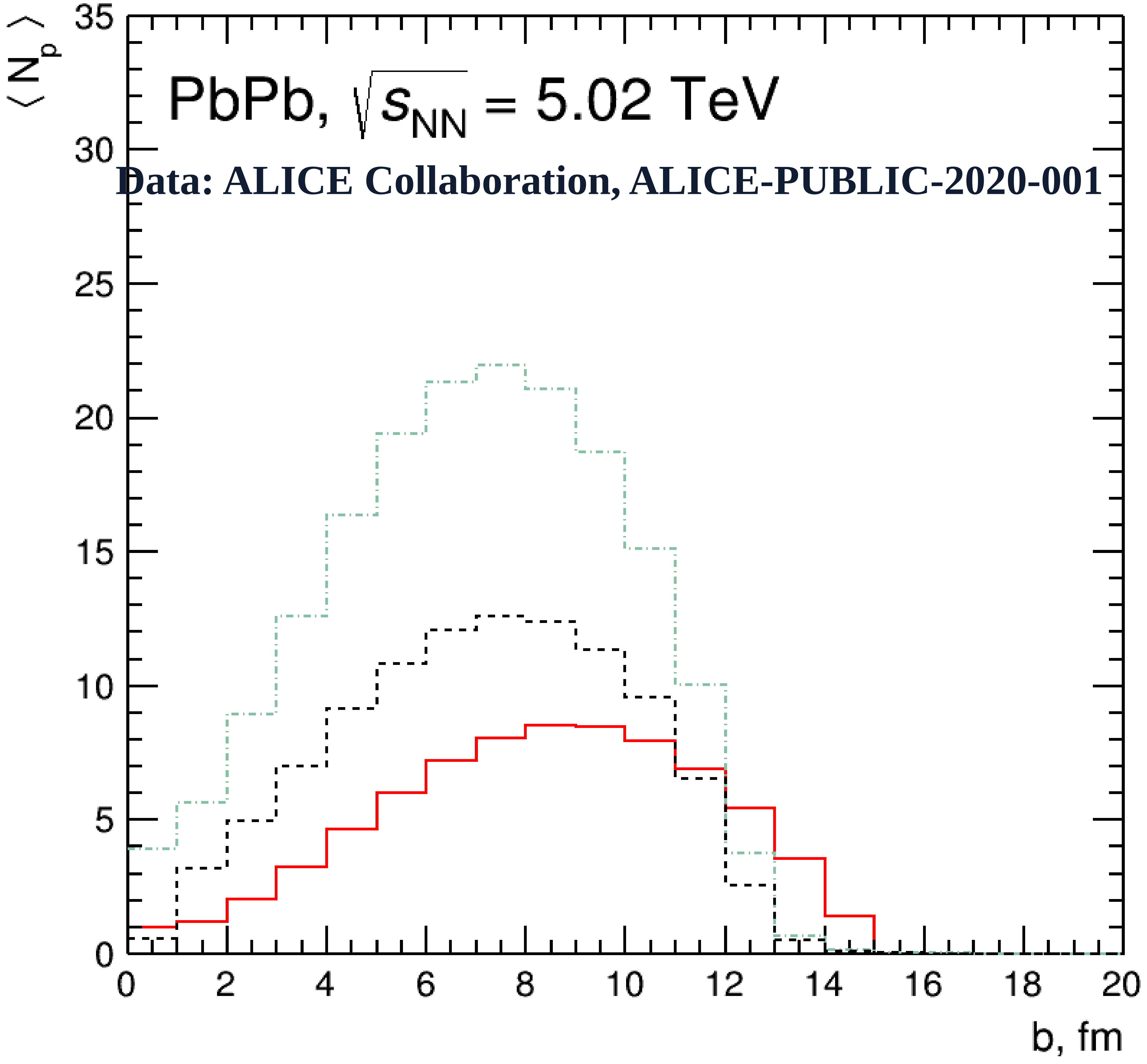
- The colors of the nucleons indicate different clusters
- In the central collisions, the prefragment has the shape of a narrow crescent
- MST-clustering increases the yield of free nucleons

Clustering in ^{208}Pb—^{208}Pb collisions

MST-clustering increases the yield of free neutrons and protons



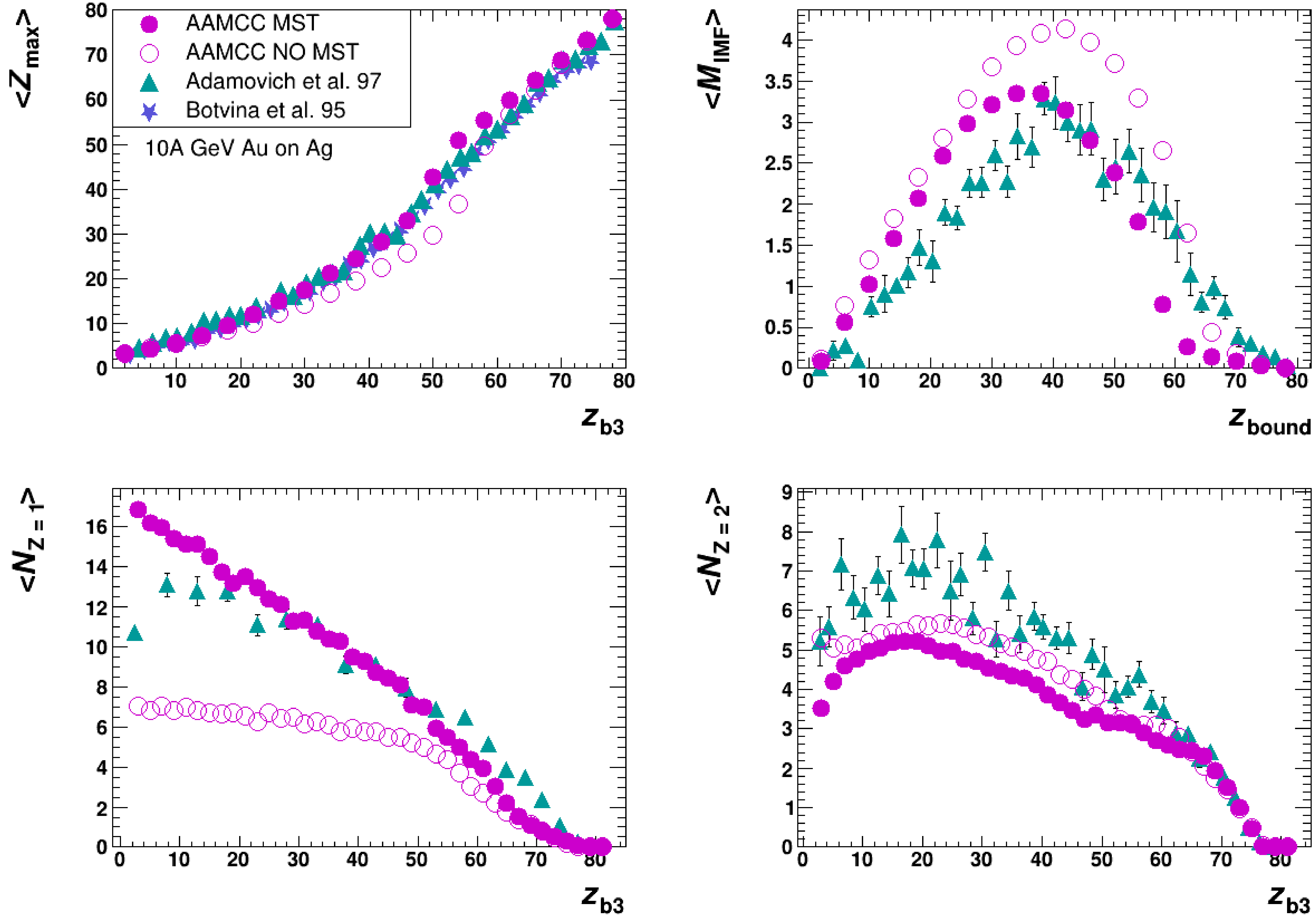
Neutron yields are described better with MST



Data: ALICE Collaboration, ALICE-PUBLIC-2020-001

Note: proton data are not corrected for the efficiency of proton ZDC

Comparison between the AAMCC-MST results and EMU-01/12 data



1. Z_{bound} – total charge confined in fragments with $Z \geq 2$
2. Z_{bn} – same as Z_{bound}, but for $Z \geq n$.
3. M_{IMF} – number of intermediate mass fragments $(3 \leq Z \leq 30)$
4. $N_{Z=n}$ – number of fragments with $Z = n$, $N_{Z=1}$ of H, $N_{Z=2}$ of He ...
5. Z_{max} – charge of fragment with largest Z

MST-clustering makes it possible to improve the description of

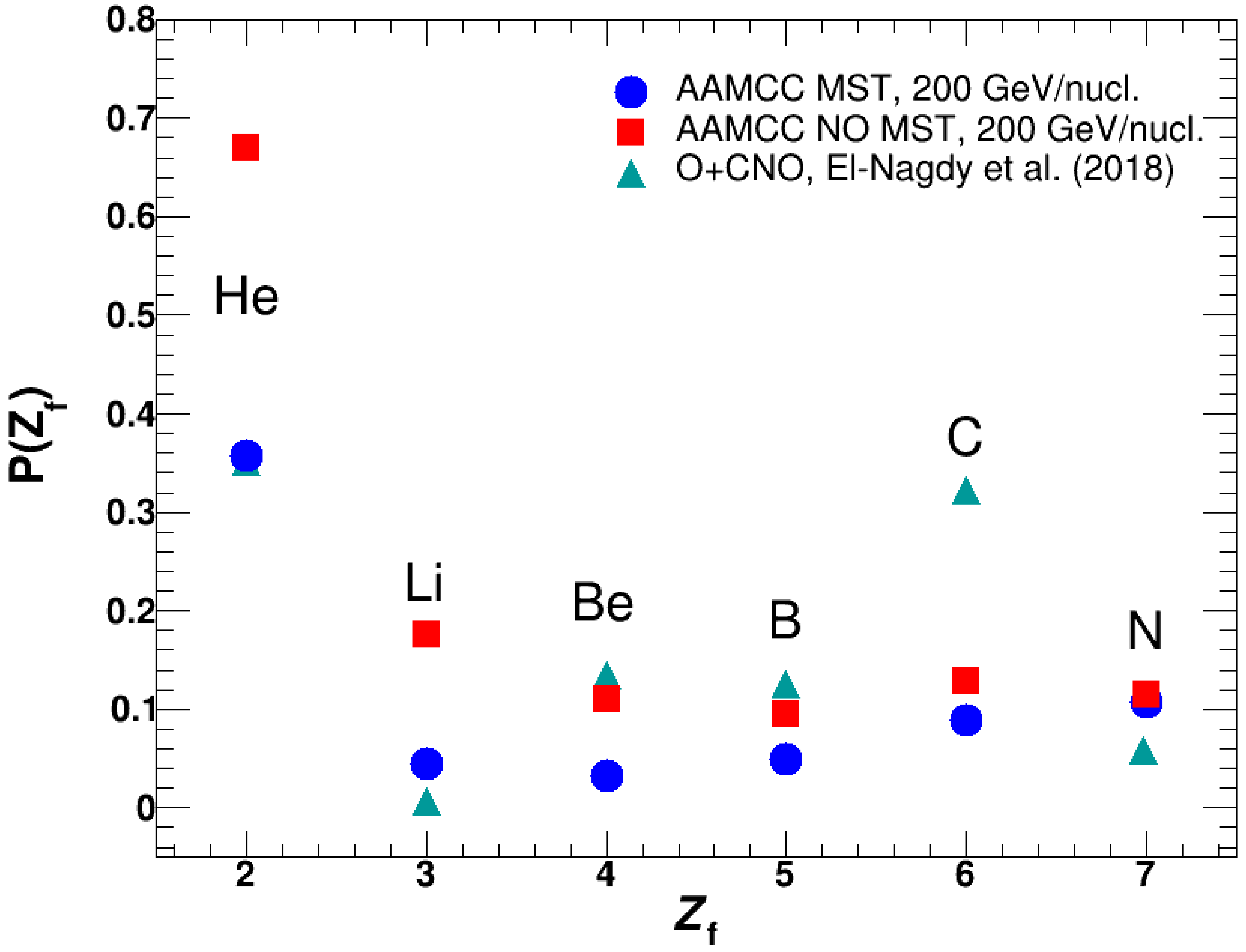
- the maximum charge of the fragments
- intermediate mass fragments
- the yields of hydrogen nuclei

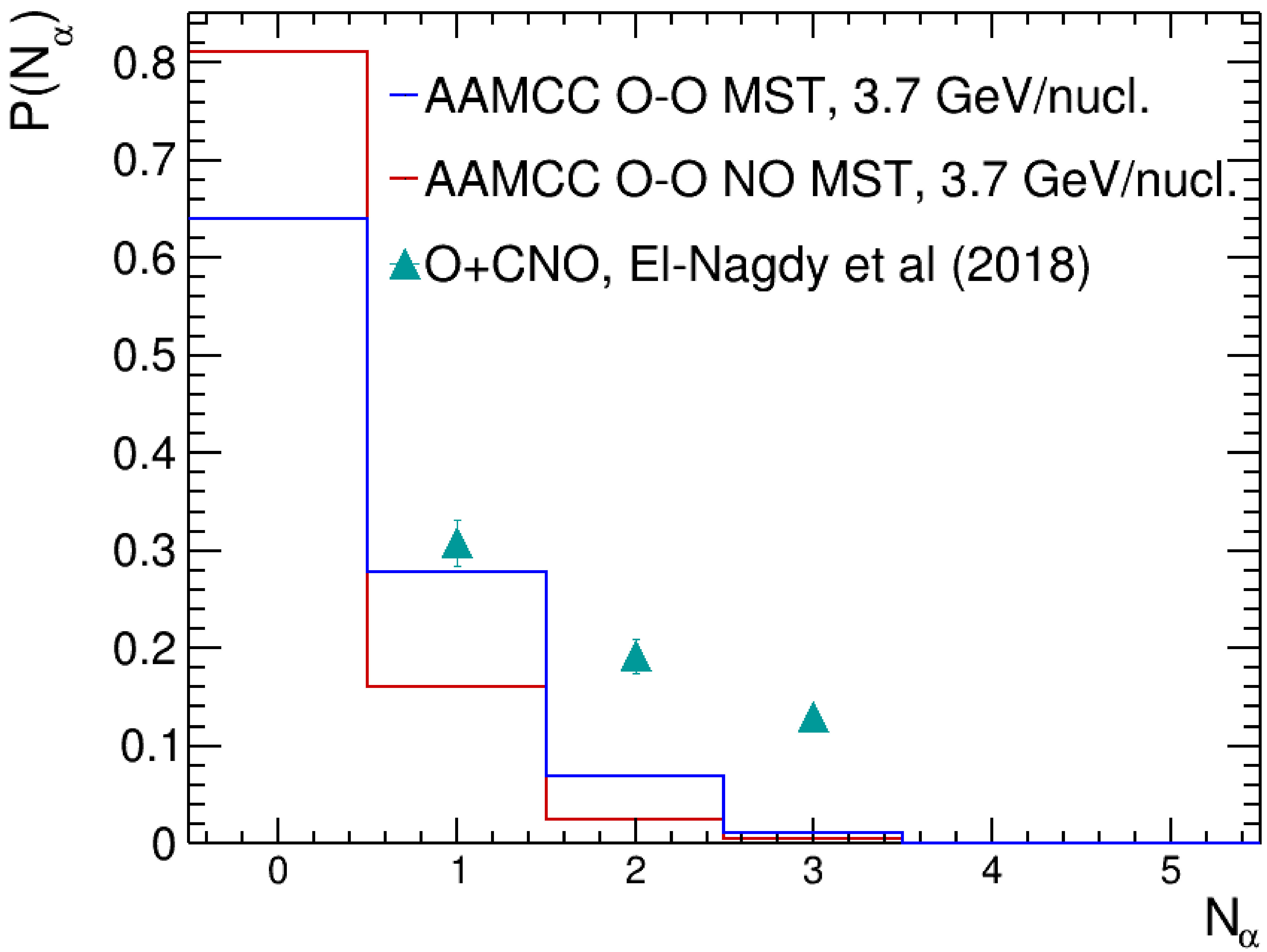
In contrast, the yields of helium nuclei are described better without MST

EMU-01/12-collaboration. 359 (1997) 277-290

A.S. Botvina et al. Nuclear Physics A. 584(1995) 737-756

Spectator fragments from ^{16}O—^{16}O collisions at the LHC



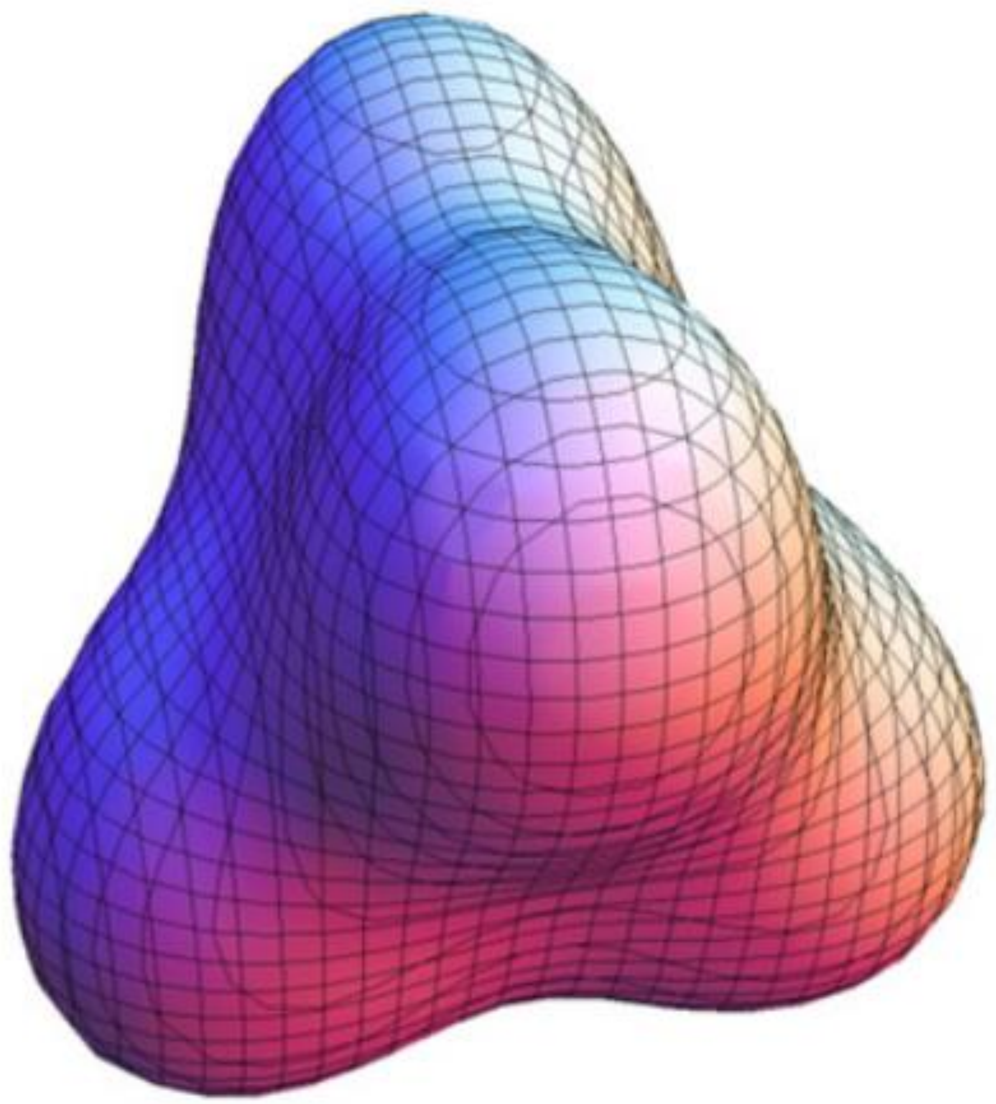


- Production of He, Li, Be, B and N is described well by the AAMCC-MST
- However AAMCC-MST underestimates the production of C

Note: the α −clustering in initial ^{16}O is neglected in AAMCC-MST.

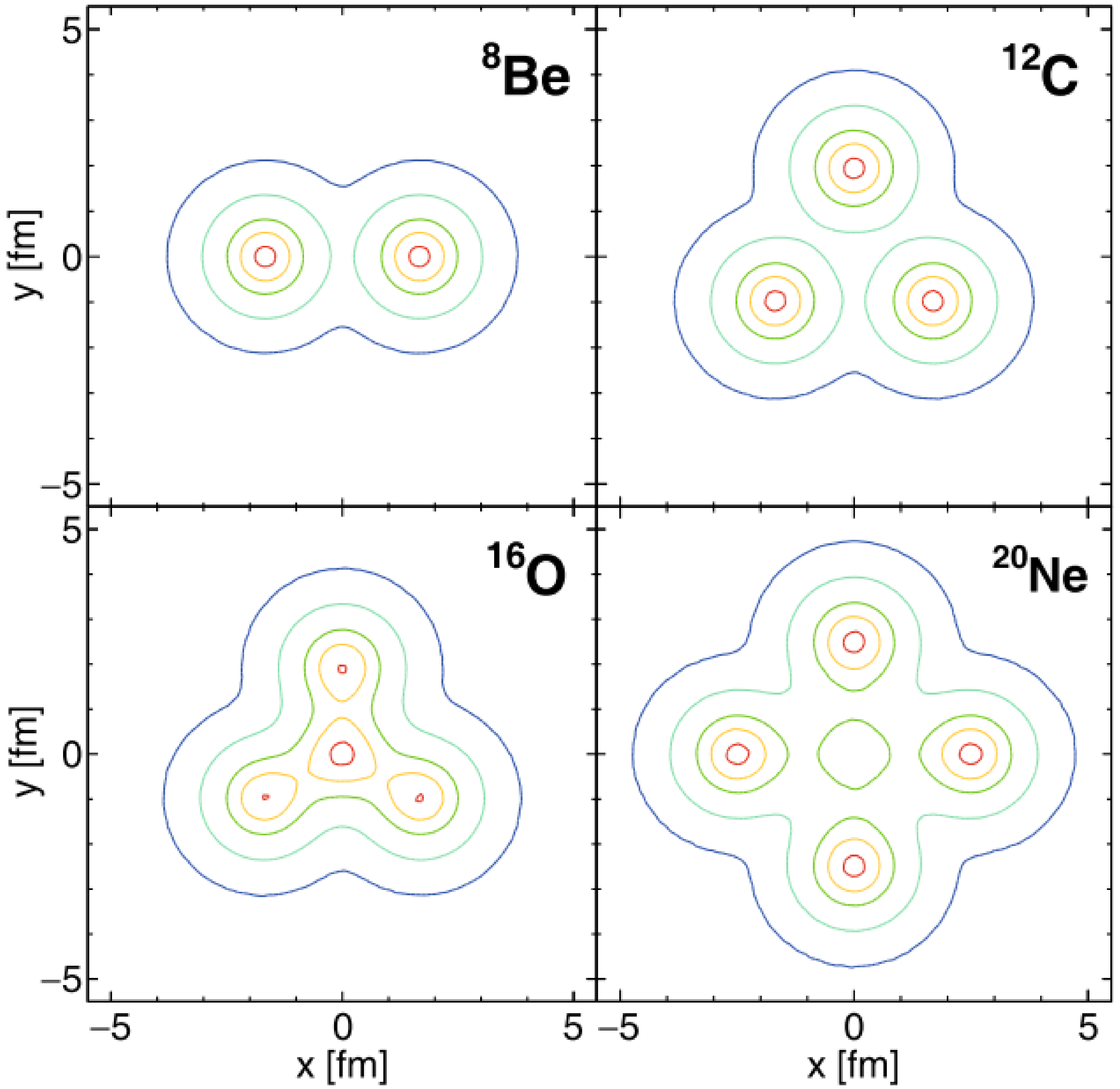
- The rates of one, two and three alphas are underestimated in contrast to the helium production in the left panel.
- The overestimation of ^{3}He could be a reason

Alpha-cluster model of ^{16}O



Density distributions of ^{16}O calculated by HF based on SkV functional

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



Shapes of nuclei with α −clustering. The isodensity lines correspond to 1, 15, 50, 75 and 95% of the maximum density

Z. Sosin et al. Eur. Phys. J. A 52, 120 (2016)

- Accounting for the α −clustering structure of ^{16}O can change the composition of spectator matter produced in the relativistic ^{16}O–^{16}O collisions.
- MST-clustering algorithm can also improve the description of the yield of secondary ^{12}C due to their α −clustering structure.

See the talk by A. Svetlichnyi at EPS HEP Conference 2021 explaining the need in accounting for α −clustering in ^{16}O—^{16}O collisions.

https://indico.desy.de/event/28202/contributions/105829/

Conclusion

- The Minimum Spanning Tree (MST) clustering algorithm has been developed to account for preequilibrium decays of prefragments in AAMCC.
- The expansion of hot prefragments is considered.
- MST-clustering improves the description of production of hydrogen, IMF fragments and free neutrons.
- The production of He, Li, B, N in O+CNO collisions is described by AAMCC-MST in general, while the production of C is underestimated.
- The total rate of ^{4}He is described well by AAMCC, but not the channels with specific multiplicity.
- The disagreement with data on production of ^{4}He and C suggests that alpha-clustering in ^{16}O should be taken into account in future calculations.

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Thank you for attention!