Clustering in oxygen nuclei and spectator fragments in ^{16}O–^{16}O collisions at the LHC

Aleksandr Svetlichnyi[1,2,*)],
Savva Savenkov[1,2)],
Roman Nepeivoda[1,3)],
Igor Pshenichnov[1,2)]
[1)] INR RAS, [2)] MIPT(NRU)
[3)] Lund Univ.

[*)] aleksandr.svetlichnyy@phystech.edu

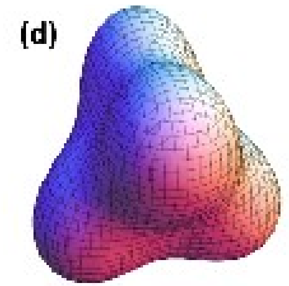
P.Bevza, The temptation of the unconscious, 2020

Motivation

- A short ^{16}O–^{16}O run is planned at the LHC to explore small systems [1)]
- The initial cluster structure of ^{16}O may impact the eccentricity, flow, and R_{AA} for D-mesons [2),3),4),5)]
- The production of alpha-particles is affected by the initial cluster structure of ^{16}O [6)]. The accounting for short range nucleon-nucleon correlations (SRC) affects the production of deuterons [7)]
- Spectator fragments with the Z/A-ratio similar to ^{16}O can be transported in the LHC along with initial nuclei
- Modelling of ^{16}O fragmentation, in particular the yields of alphas, should be improved [8)] to evaluate these effects

1) https://indico.cern.ch/event/975877/
2) Yi-An Li et al., PRC 102 (2020) 054907
3) W. Broniowski et al., NPA 1005 (2021) 121763
4) R.Katz et al., PRC 102 (2020) 041901
5) S. H. Lim et al, PRC 99 (2019) 044904
6) A.S. et al., Phys. of Atomic Nucl. 86 (2022) TBP
7) N.Kozyrev et al., Eur. Phys J. A 58 (2022) 184
8) A.S. et al., PoS EPS-HEP2021 (2022) 310

Density distributions of ^{16}O



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

Outline

- Abrasion-Ablation Monte Carlo for Colliders (AAMCC)
- Comparison with the data on fragmentation of ^{16}O in nuclear emulsion
- Production of spectator matter in ^{16}O-^{16}O collisions at the LHC:
  - free spectator neutrons
  - deuterons
  - secondary nuclei

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 by parabolic ALADIN approximation [2)] tuned to describe the data for light nuclei.

- Decays of prefragments are simulated as follows:

  - pre-equilibrium decays modelled with MST-clustering algorithm [3)]

  - Fermi break-up model from Geant4 v9.2 [4)]

  - Weisskopf-Ewing evaporation model from Geant4 v10.4 [4)]

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

1) C. Loizides, J.Kamin, D.d'Enterria Phys. Rev. C **97** (2018) 054910
2) A. Botvina et al. NPA **584**
3) R. Nepeivoda, et al., Particles **5** (2022) 40
4) J. Alison et al. Nucl. Inst. A **835** (2016) 186

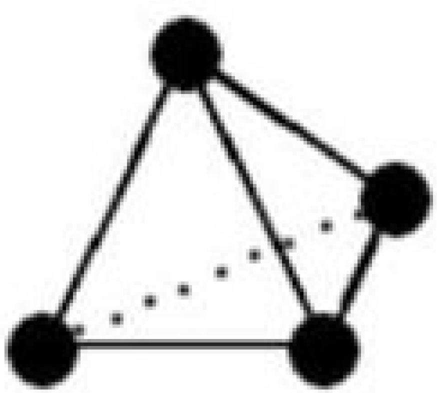
AAMC^2

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

Clusterisation in ^{16}O

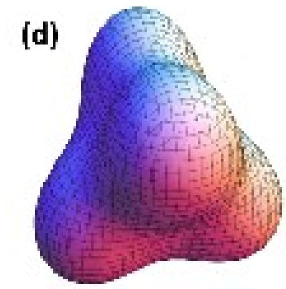
- Some authors assume that 8 neutrons and 8 protons form four alpha-clusters arranged into a tetrahedron [1,2]
- Parameters of the tetrahedron should fit the charge radius of ^{16}O nucleus
- There are other free parameters for clustered ^{16}O:
  - The distribution of nucleons inside alpha-clusters
  - The overall contribution of the clustered state 20-30%

Arrangement of clusters in ^{16}O



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

^{16}O density

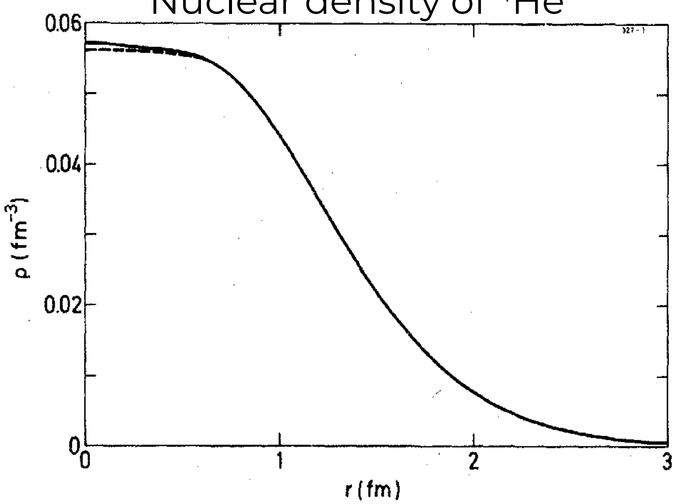


2) X.B. Wang et al. PLB 790 (2019) 498–501

Sampling nucleon configurations in ^{16}O

- Main algorithm exploits Monte Carlo Markov Chain. 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 tetrahedron
- Second, 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.

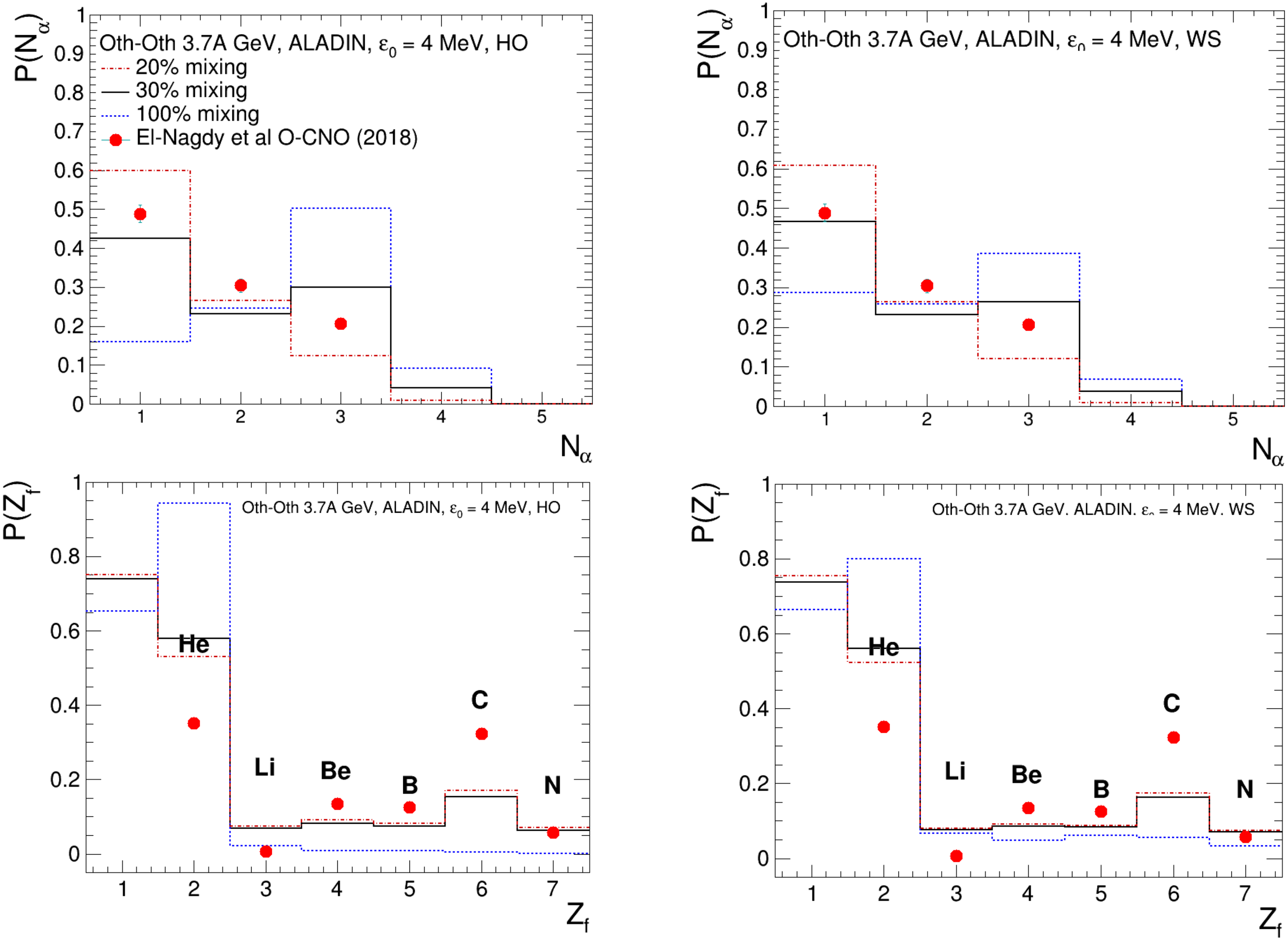
Nuclear density of ^{4}He



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

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

^{16}O fragmentation in nuclear emulsion



M. El-Nagdy et al., J. Phys. Comm. 2 (2018) 035010
A.S. et al., Phys. of Atomic Nucl. 86 (2022) TBP

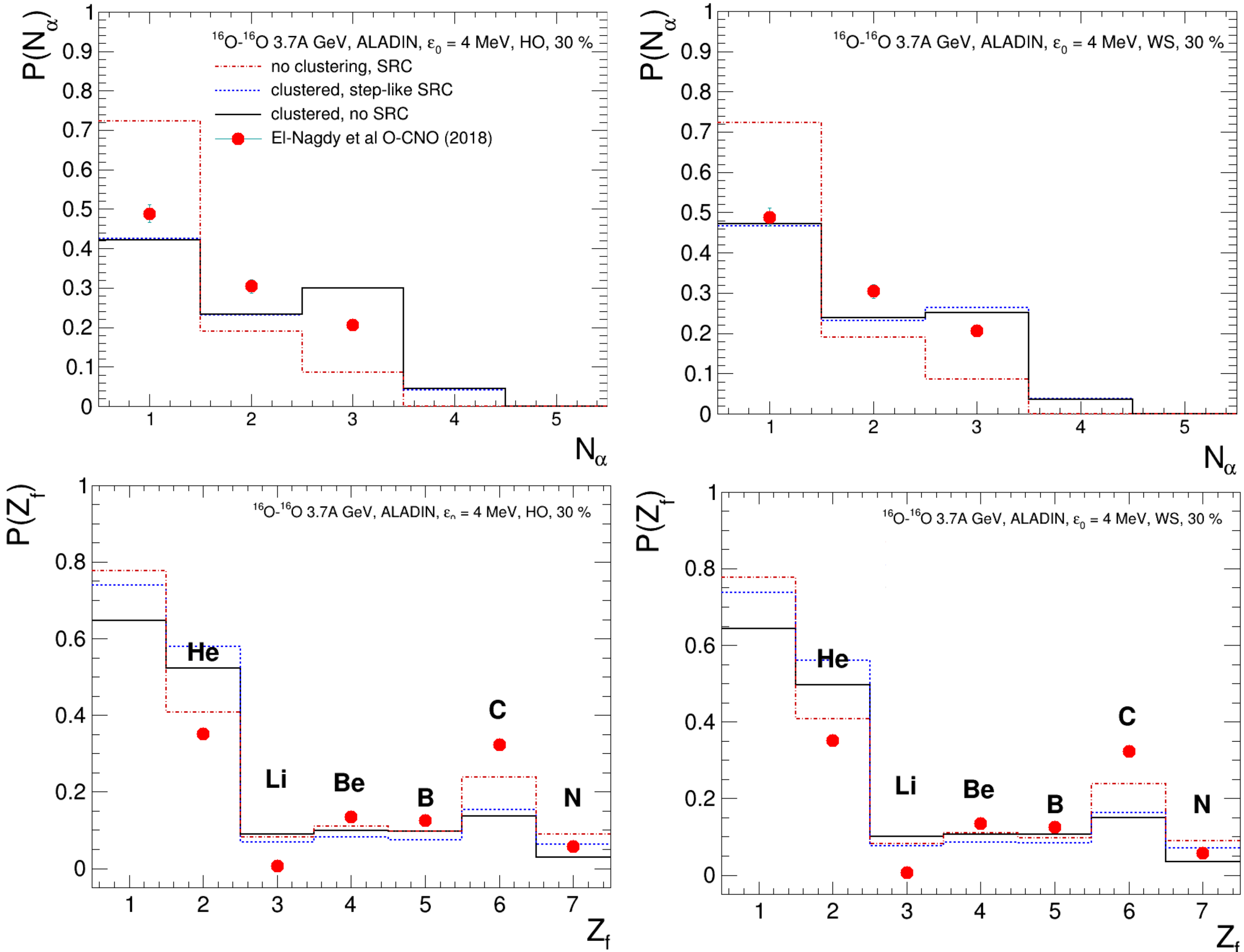
AAMCC describes the data in general with 30% clustering contribution

Short range nucleon-nucleon correlations (SRC)

- Following the papers [1,2], SRC represent the nucleon-nucleon repulsion caused, in particular, by Pauli principle.
- To account for SRC a method based on Monte Carlo Markov Chain[2] was suggested. Two nucleon-nucleon correlation functions can be used: Gaussian or step-like.
- We employ the step-like function to speed up the sampling
- The number of participants is slightly increased with accounting for SRC [1]. The deuterium production is enhanced in Pb-Pb collisions [3]. One can expect a similar effect in O-O collisions.

1) M.Alvioli et al, PRC 85 (2012) 034902
2) M. Alvioli et al, Phys. Lett. B 680 (2009) 225
3) N.Kozyrev et al., Eur. Phys J. A 58 (2022) 184

^{16}O fragmentation in nuclear emulsion: SRC

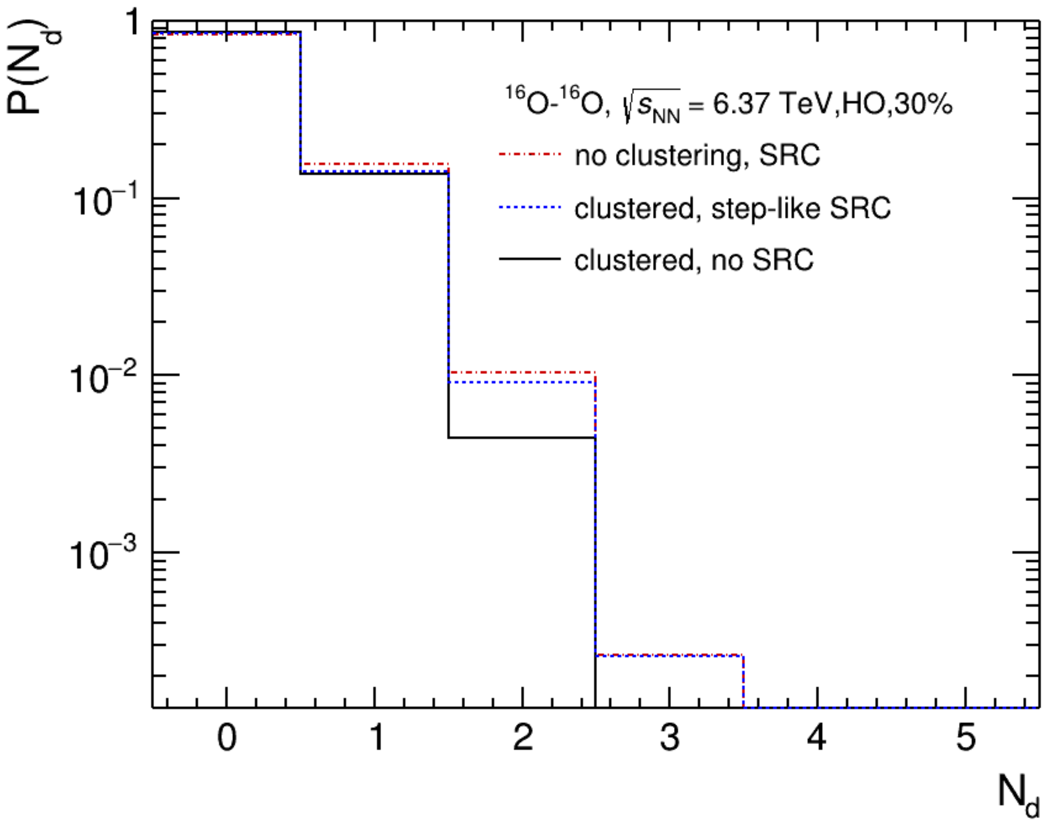


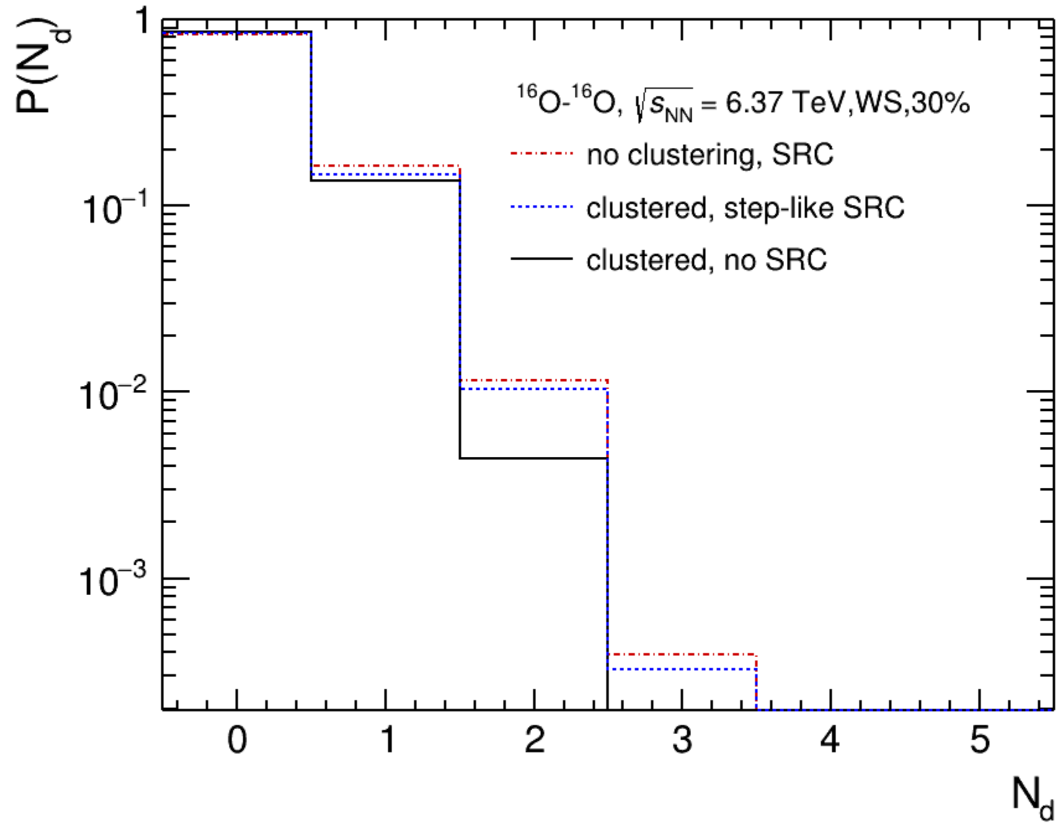
The distributions of alphas are not described without clustering

Accounting for SRC improves agreement with the data on Li – N

Spectator fragments at the LHC

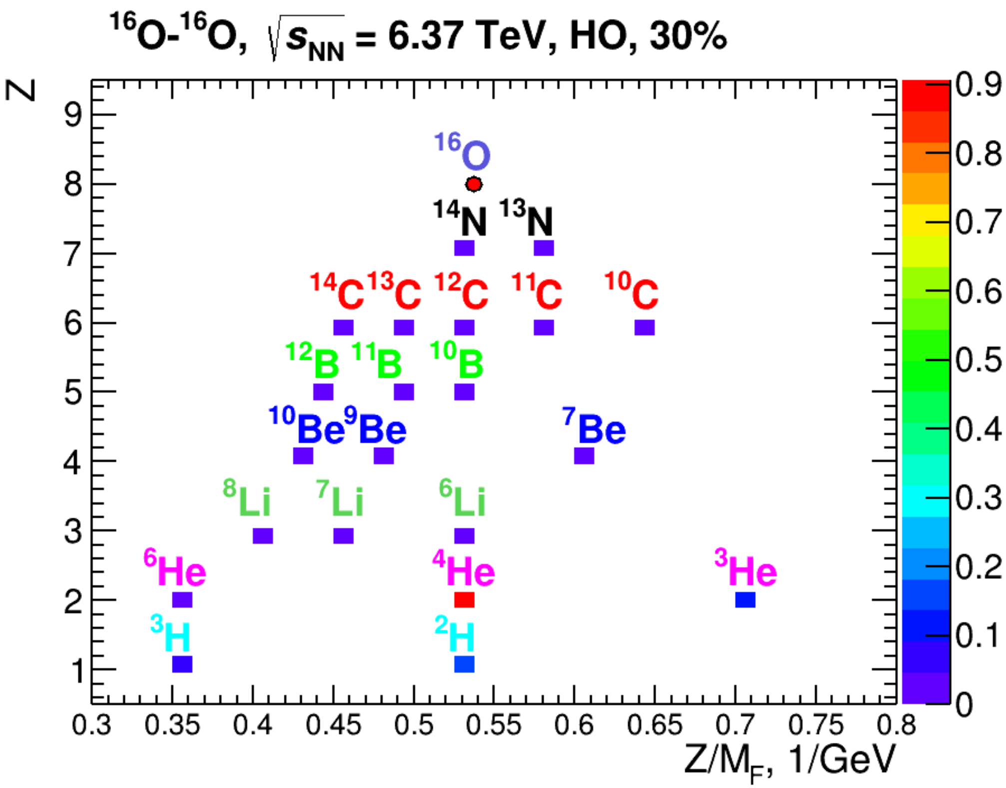
Production of deuterons at the LHC

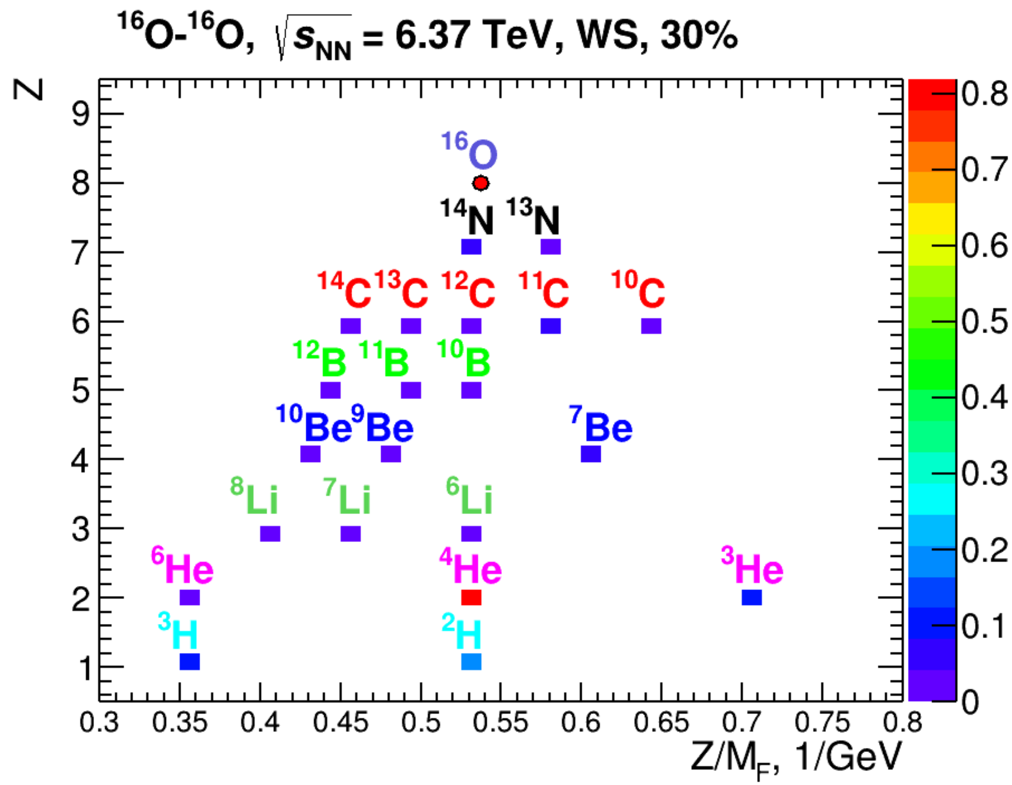




- Up to 85% of O–O events are without deuterons, while ~15% of the events have only one deuteron
- The calculated multiplicity distributions of deuterons are almost the same for all nuclear density parametrisations. Accounting for SRC enhances the multiple production of deuterons.
- Deuterons are mostly produced in peripheral events

Production of secondary nuclei at the LHC

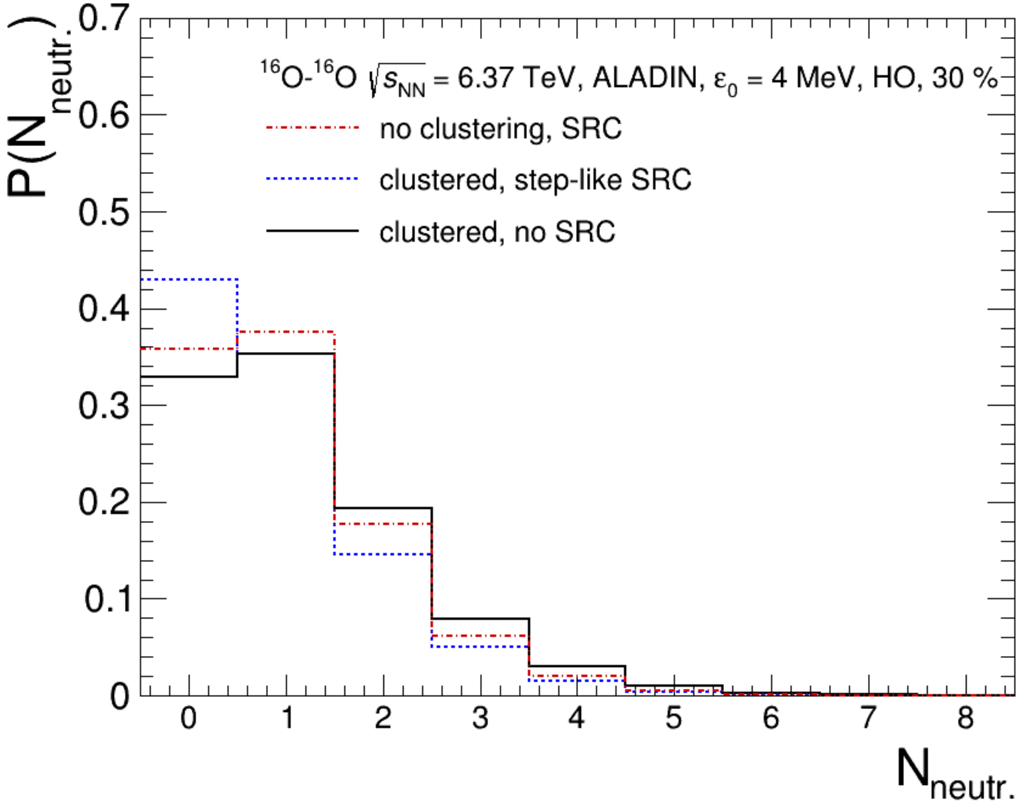


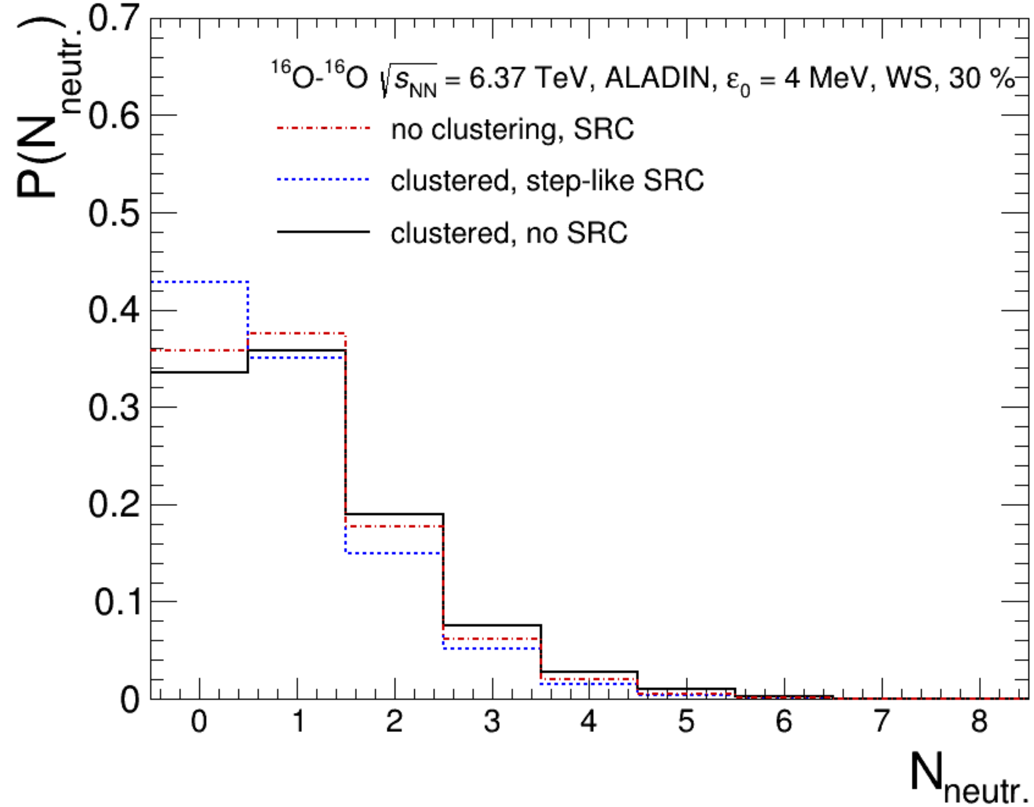


- M_f is taken from the nuclear data tables [1)]
- Various isotopes of **He, Be, B, C, N** are produced. (Almost all the O nuclei transmutate to other elements.)
- In contrast to previous calculations [2)], the most frequent nucleus is **^{4}He** rather than **^{2}H**
- Exotic nuclei ^{6}He, ^{12}B and ^{10}C are produced by asymmetric abrasion of protons or neutrons
- Note the various isotopes with Z/M_f close to ^{16}O: **^{14}N, ^{12}C, ^{10}B, ^{6}Li, ^{4}He**

1) JAEA Tables of Nuclear Data
2) A.S. et al., PoS EPS-HEP2021 (2022) 310

Production of neutrons at the LHC



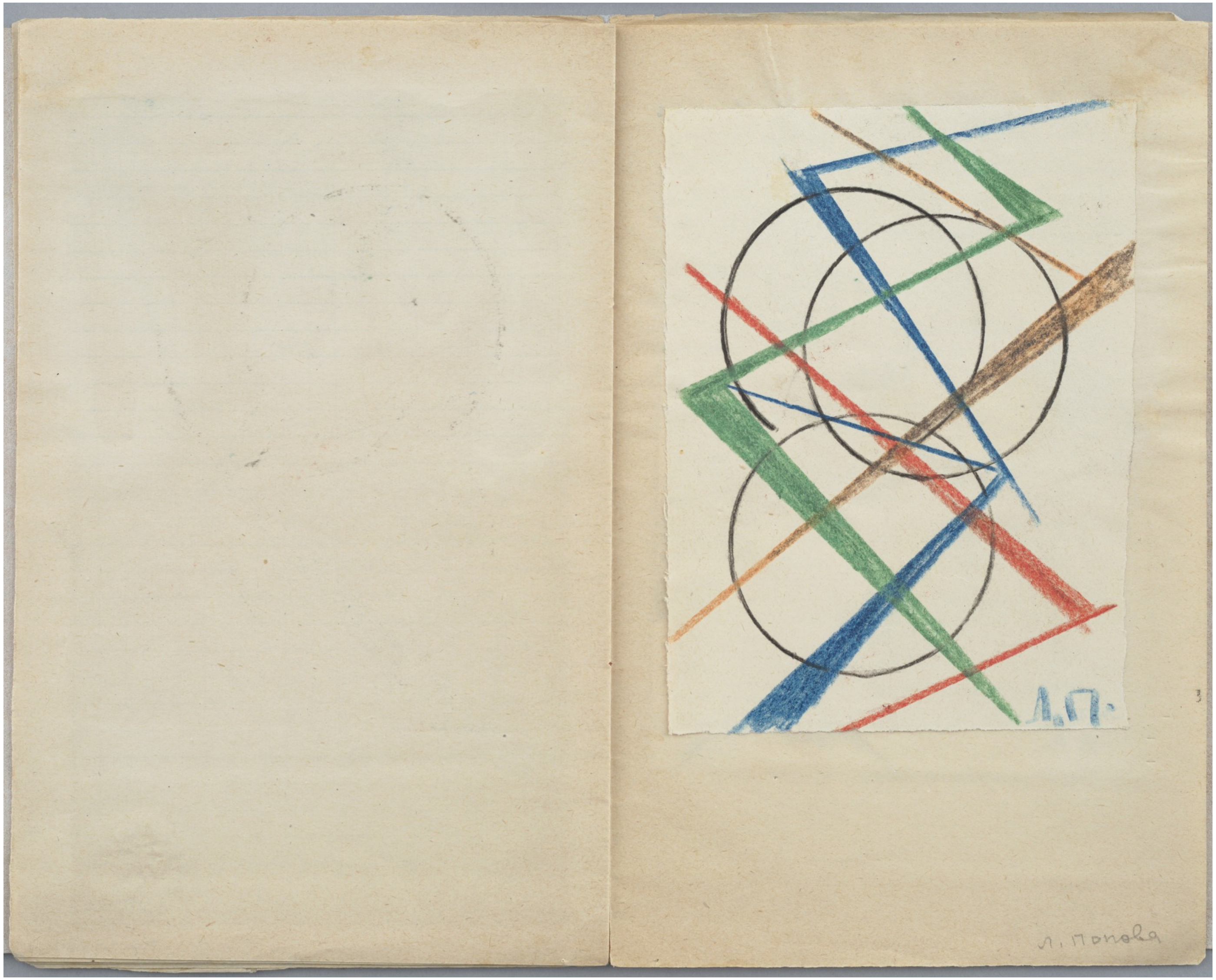


- The highest neutron multiplicity is calculated with clustered density without SRC
- Note a large (>30%) fraction of events without spectator neutrons
- A slightly larger fraction of events without neutrons is calculated for the clustered density with the step-like SRC

Summary

- The production of the spectator neutrons slightly depends on the ^{16}O density parametrisation. A large fraction of events without neutrons (>30%) was predicted.
- The multiple production of deuterons is sensitive to the SRC.
- Various isotopes can be formed in the collisions of ^{16}O–^{16}O. The intranuclear clustering results in the highest yield of ^{4}He.

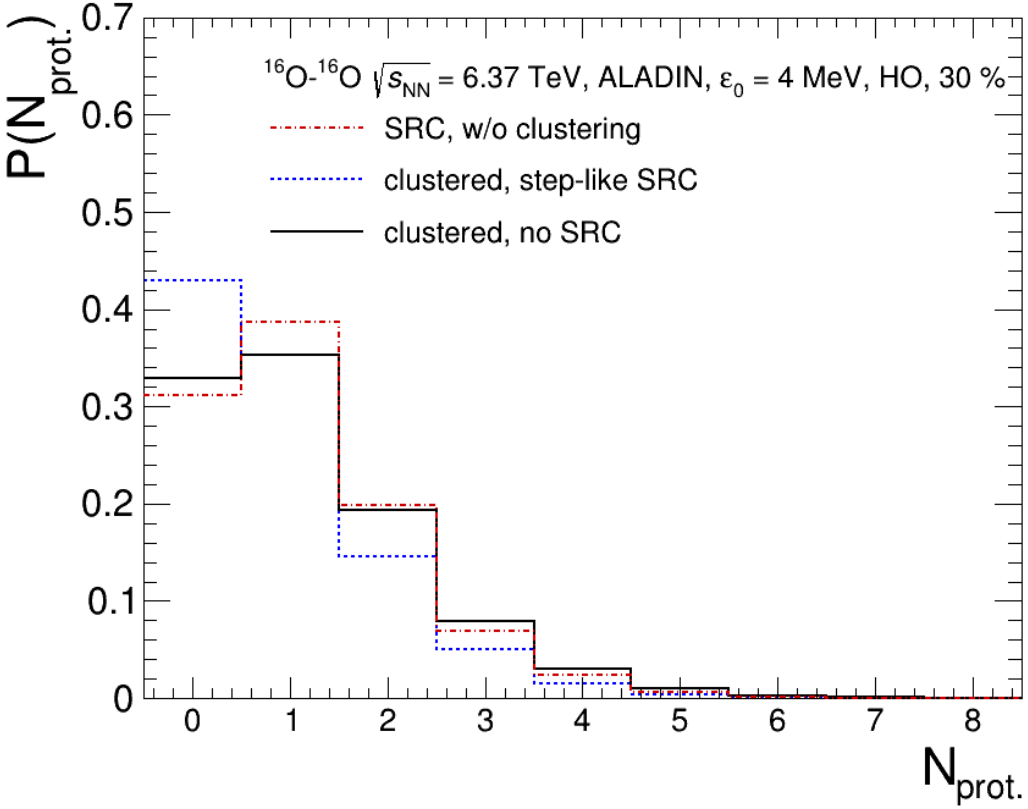
To conclude, an artists view of the oxygen nuclei fragmentation

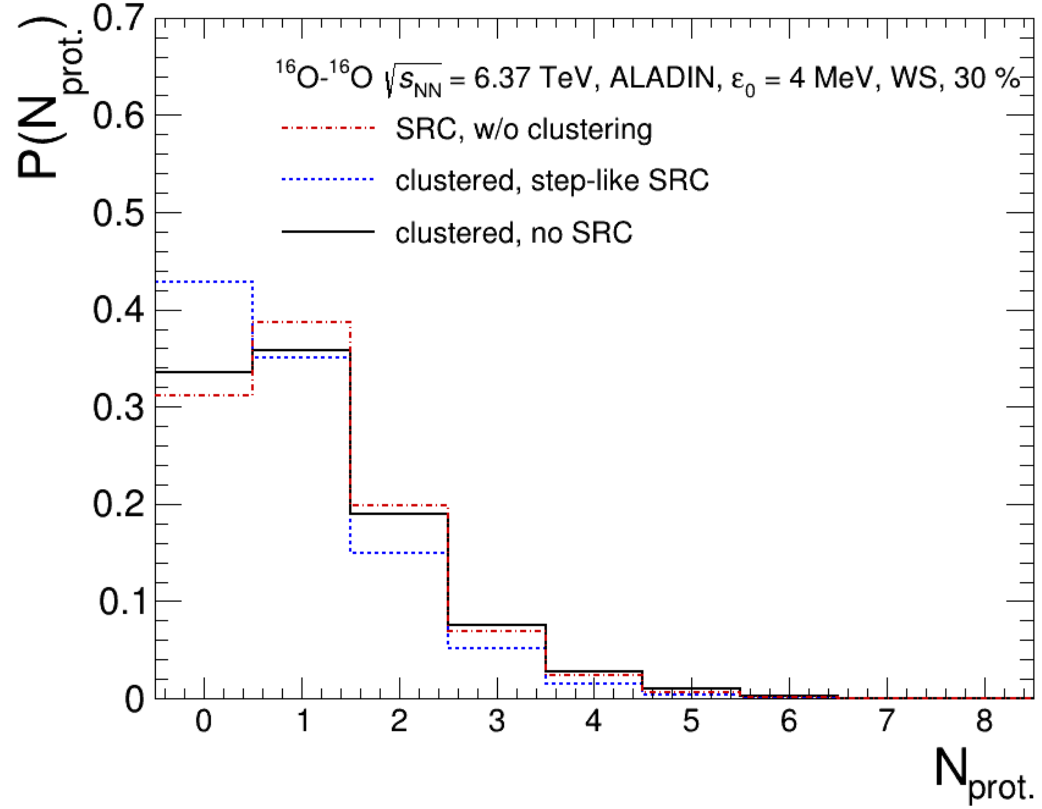


Liubov Popova, Folio from 5 x 5 = 25: Vystavka zhivopisi, 1921

Backup slides

Production of protons at the LHC





- The highest proton multiplicity is predicted for clustered without SRC nuclear density, same for non-clustered one.
- Note a large (~30%) fraction of events without protons
- A slightly larger fraction of events without protons is calculated for the clustered density with step-like SRC