Secondary nuclei from ^{16}O fragmentation at the LHC

Aleksandr Svetlichnyi*),
Roman Nepeivoda,
Nikita Kozyrev,
Igor Pshenichnov
INR RAS, MIPT(NRU)

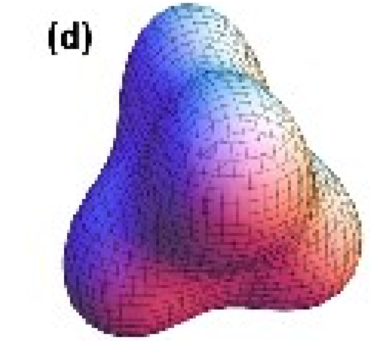
*)aleksandr.svetlichnyy@phystech.edu

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?

Density distributions of ^{16}O



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

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

Outline

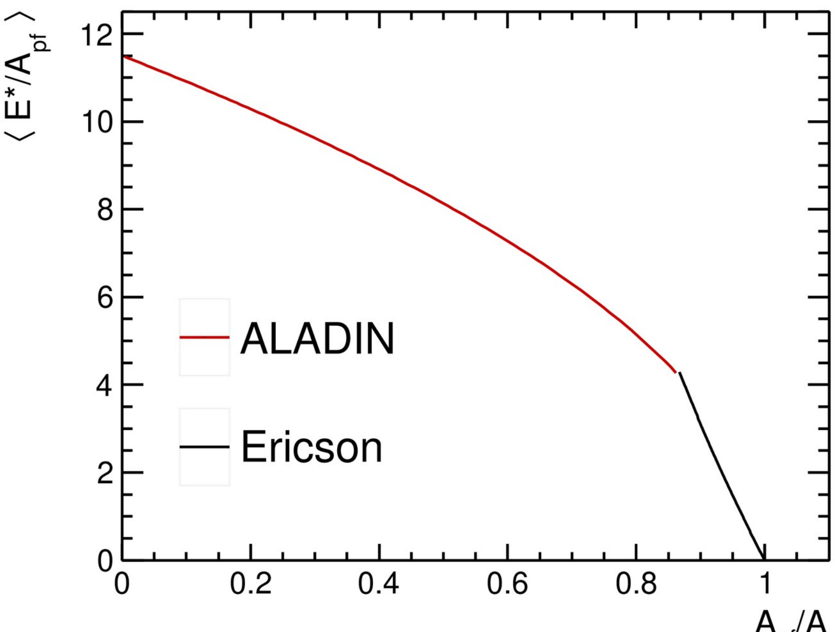
- Our model: Abrasion-Ablation Monte Carlo for Colliders (AAMCC)
- Comparison with data on fragmentation of ^{16}O in nuclear emulsion
- Modelling spectator nucleons and nuclei from hadronic ^{16}O-^{16}O collisions at the LHC
- Secondary nuclei from ultraperipheral ^{16}O-^{16}O collisions at the LHC

Abrasion-Ablation Monte Carlo for Colliders

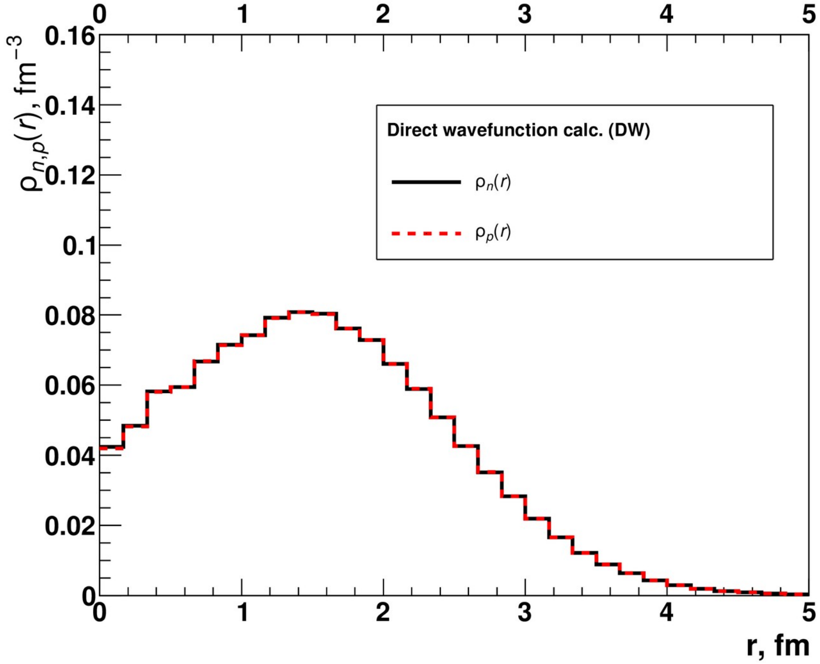
- Nucleus-nucleus collisions are simulated by means of the Glauber Monte Carlo model[1]. Non-participated nucleons form spectator matter (prefragment).
- Excitation energy of prefragment is calculated as follows:
  - in peripheral collisions with less then ~15% of removed nucleons the particle-hole model is used[2] (Ericson formula);
  - otherwise a parabolic ALADIN approximation[3] is applied with parameters tuned to data obtained in nuclear emulsions.
- Decays of prefragments are simulated as follows:
  - pre-equilibrium decays modelled with MST-clustering algorithm;
  - Fermi break-up model from Geant4 v9.2[4];
  - Weisskopf-Ewing evaporation model from Geant4 v10.4[4].

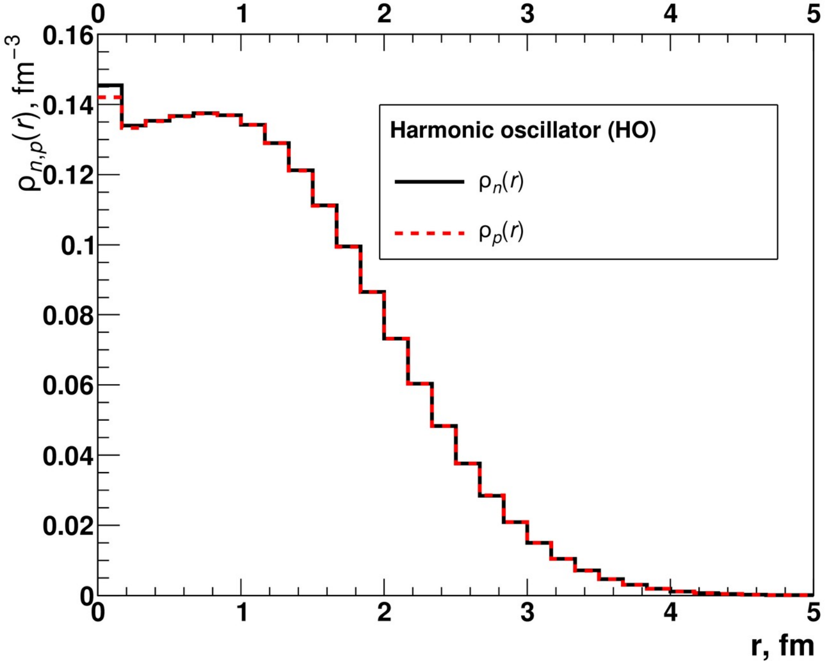
1) C. Loizides, J.Kamin, D.d'Enterria Phys. Rev. C **97** (2018) 054910
2) T. Ericson Adv. In Phys. **9** (1960) 737
3) A. Botvina et al. NPA **584**
4) J. Alison et al. Nucl. Inst. A **835** (2016) 186

AAMC²



Parametrization of nuclear density in ^{16}O in GlauberMC





Total hadronic cross section

$$\sigma_{DW} = 1.281\text{b}$$

$$\sigma_{HO} = 1.050\text{b}$$

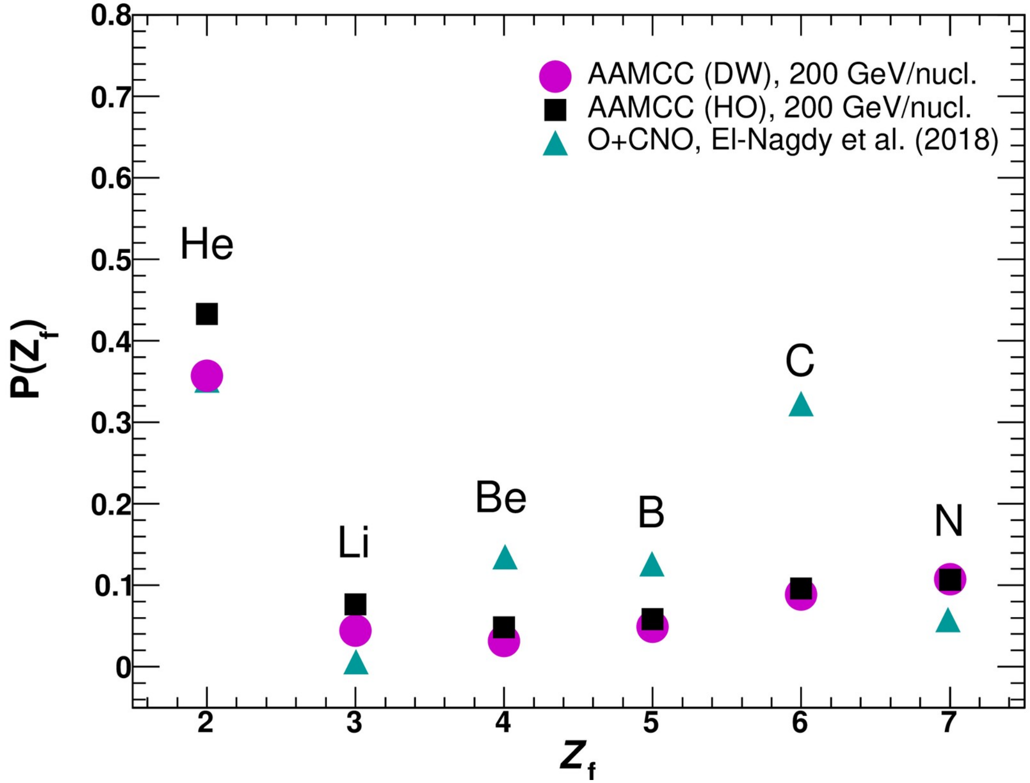
Total EM cross section

$$\sigma_{EM} \simeq 0.13\text{b}$$

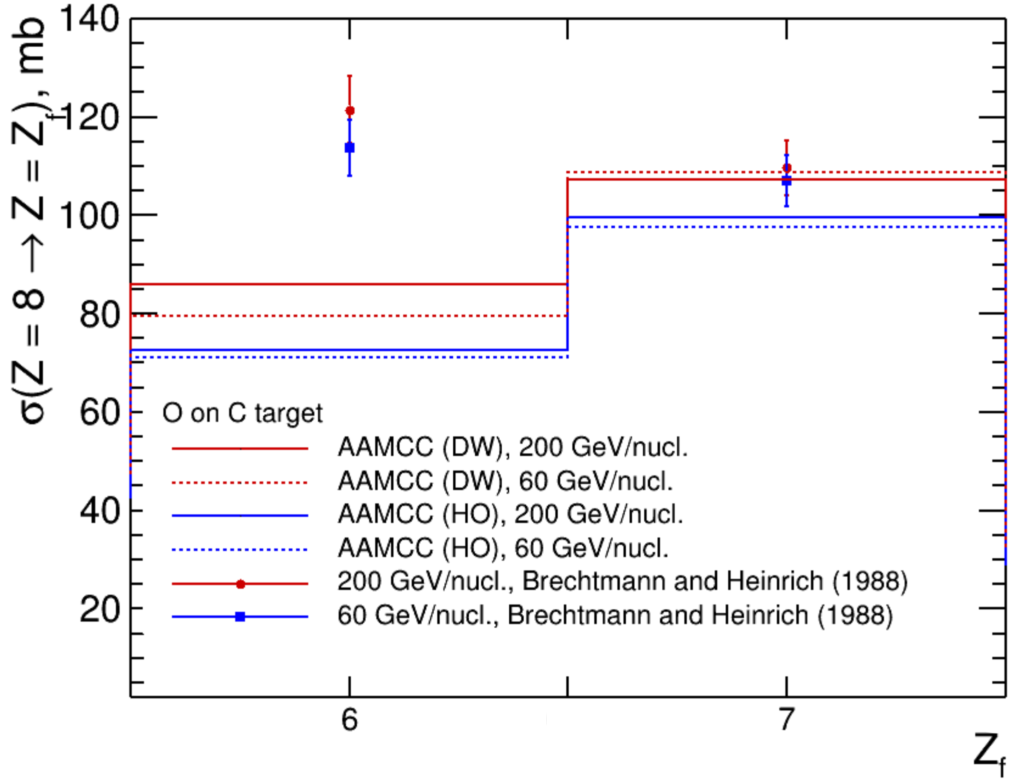
- Harmonic oscillator (HO) is based on $\rho(r) = \rho_0 \cdot r^2(1 + R(r^2/a^2))\exp(-r^2/a^2)$ with R=1.833 fm and a=1.544 fm[1].
- For the details of direct wavefunction (DW) calculation see [2]. Alpha-clustering is not taken into account, only two- and three-body interactions.
- DW radial density distribution possess a longer "tail" compared to HO.
  - This results in larger total hadronic cross section for DW and different abrasion geometry.

1) C.Loizides et al, arXiv:1408.2549v9
2) S. H. Lim et al, PRC 99 (2019) 044904

Production of specific elements



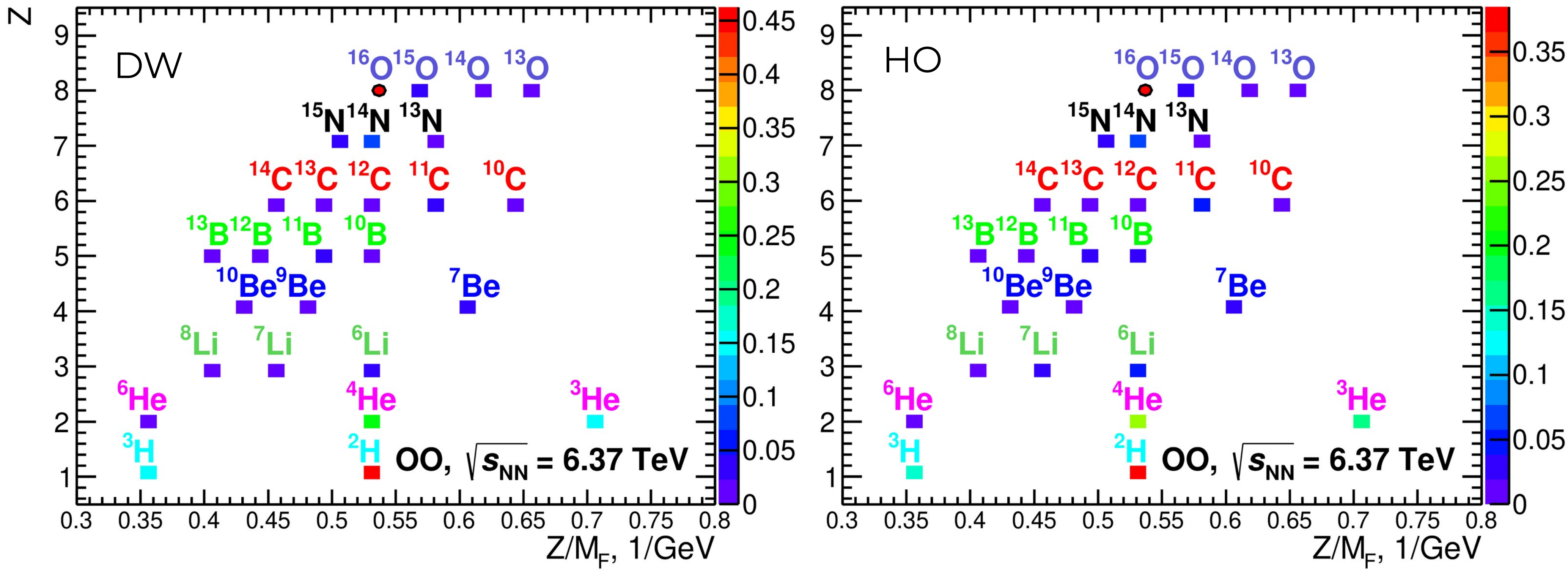
M. El-Nagdy et al., J. Phys. Comm. 2 (2018) 035010



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.

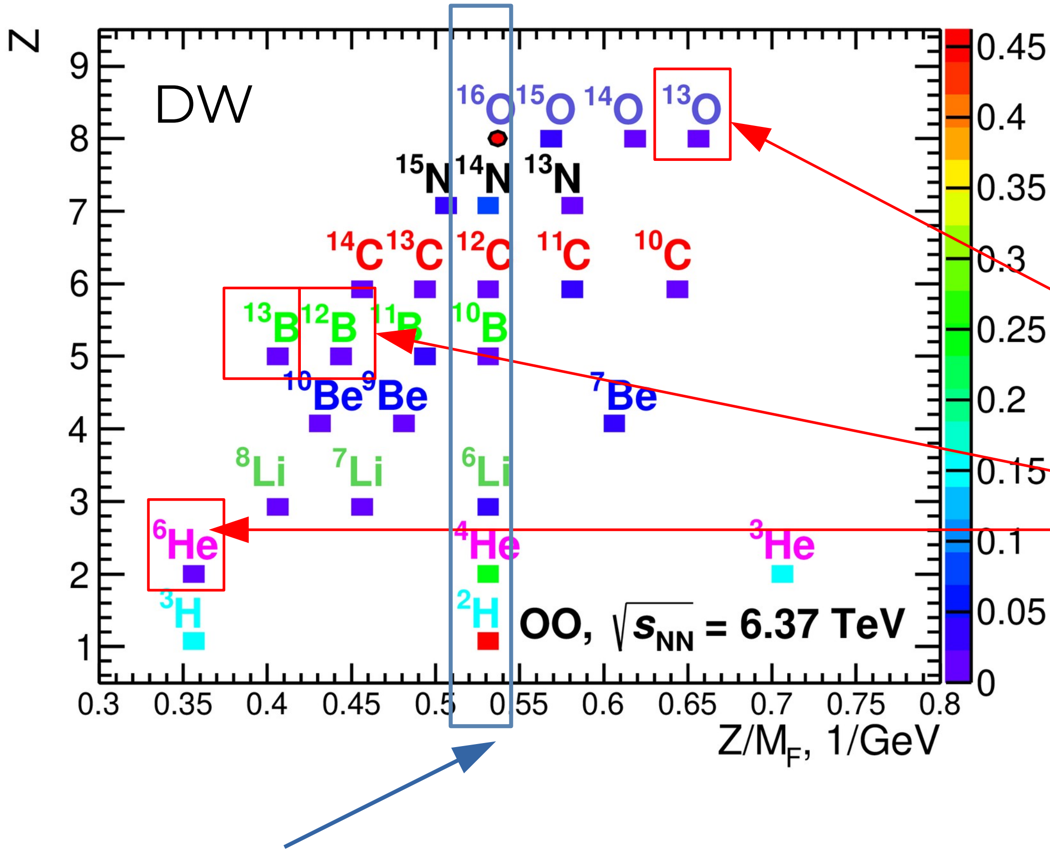
Secondary nuclei from hadronic interactions at the LHC



- Calculated with masses from nuclear data tables*).
- Many isotopes of each element: $^{16\text{-}13}$**O**, $^{15\text{-}13}$**N**, $^{14\text{-}10}$**C**, $^{13\text{-}10}$**B**, ^{10,9,7}**Be**, $^{8\text{-}6}$**Li**, ^{6,4,3}**He**, ^{3,2}**H**.
- ^{2}**H**, ^{3}**He** and ^{4}**He** are most frequent.
- Same sets of secondary nuclei are predicted with DW and HO, but with slightly different cross sections.

*)JAEA Tables of Nuclear Data

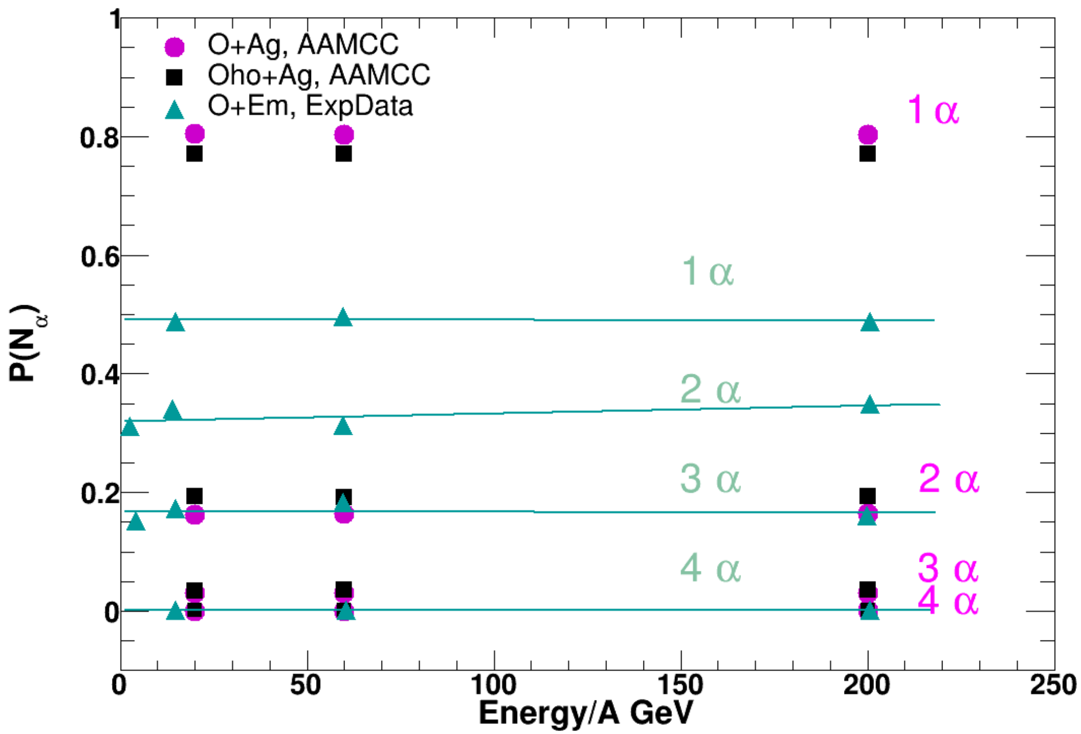
Secondary nuclei from hadronic interactions at the LHC

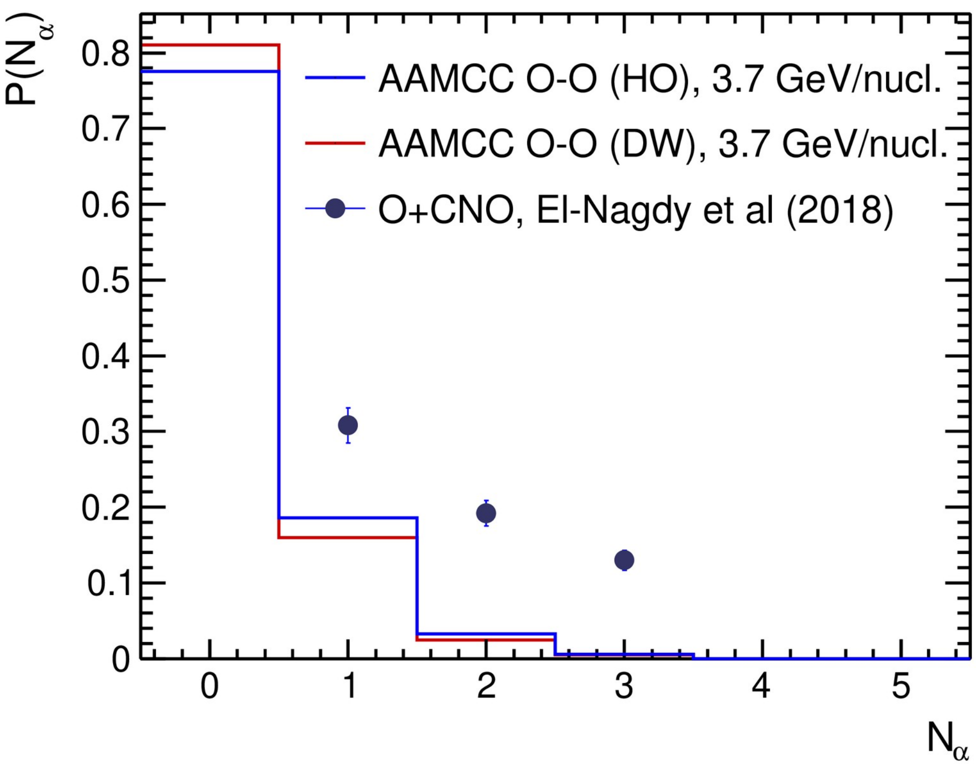


- Production of several secondary nuclei far from stability line is possible.
- Produced by excessive removal of neutrons…
- …or protons

- Nuclei with Z/M close to this ratio in ^{16}O.
- May be transported by the accelerator magnetic system along with ^{16}O.
- Largest production cross sections for ^{2}H and ^{4}He.

Production of ^{4}He

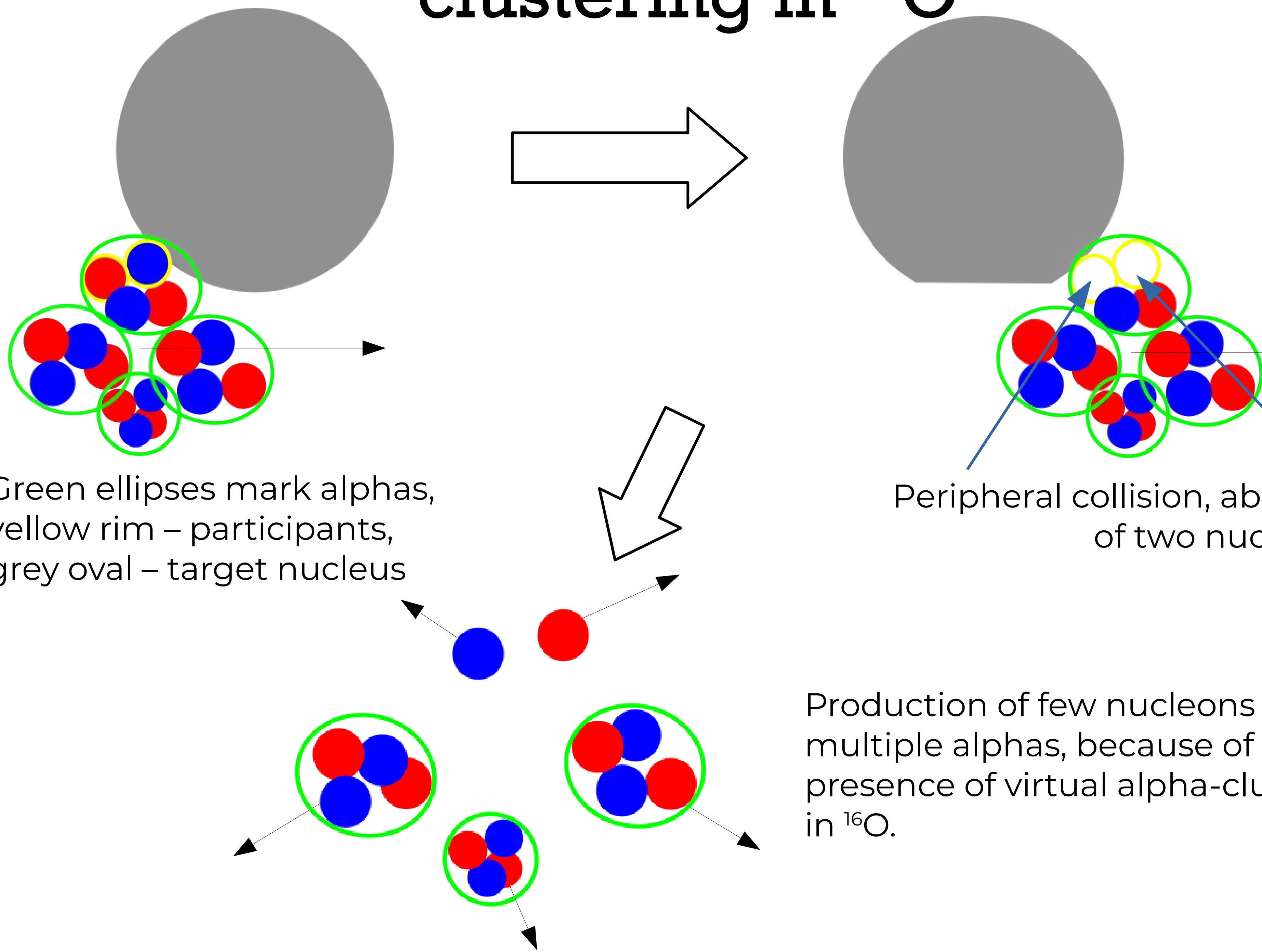




M. El-Nagdy et al., J. Phys. Comm. 2 (2018) 035010

- 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.
- Indicates the presence of alpha-clustering in the initial nuclei

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

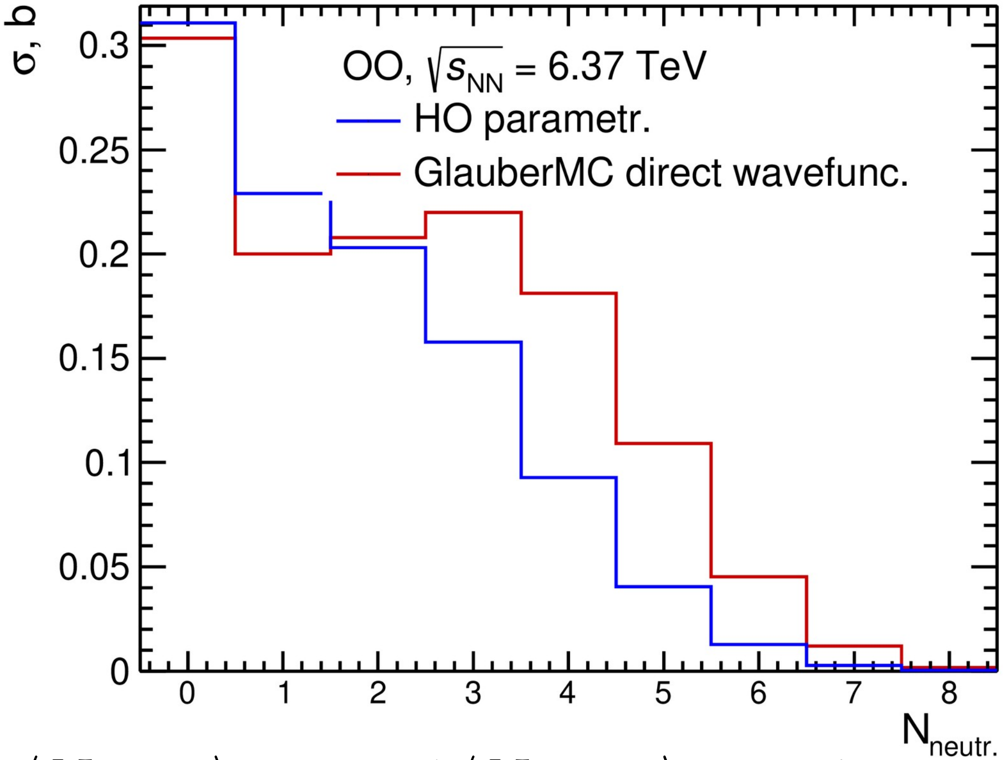


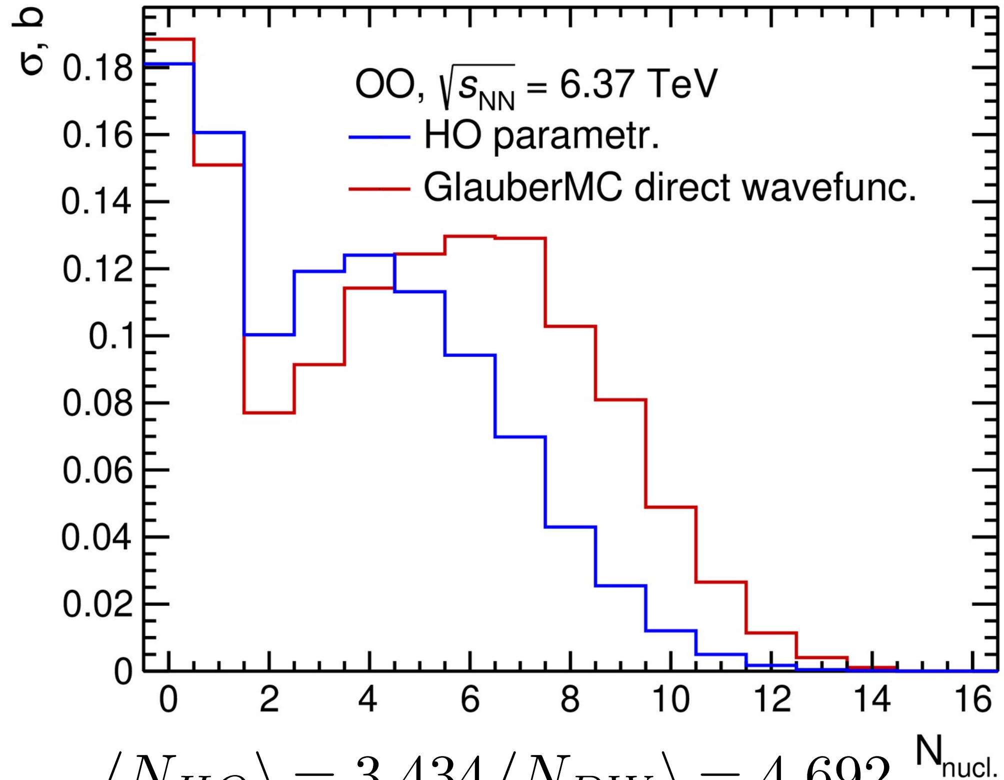
Green ellipses mark alphas, yellow rim – participants, grey oval – target nucleus

Peripheral collision, abrasion of two nucleons.

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

Multiplicity distributions of spectator neutrons and nucleons

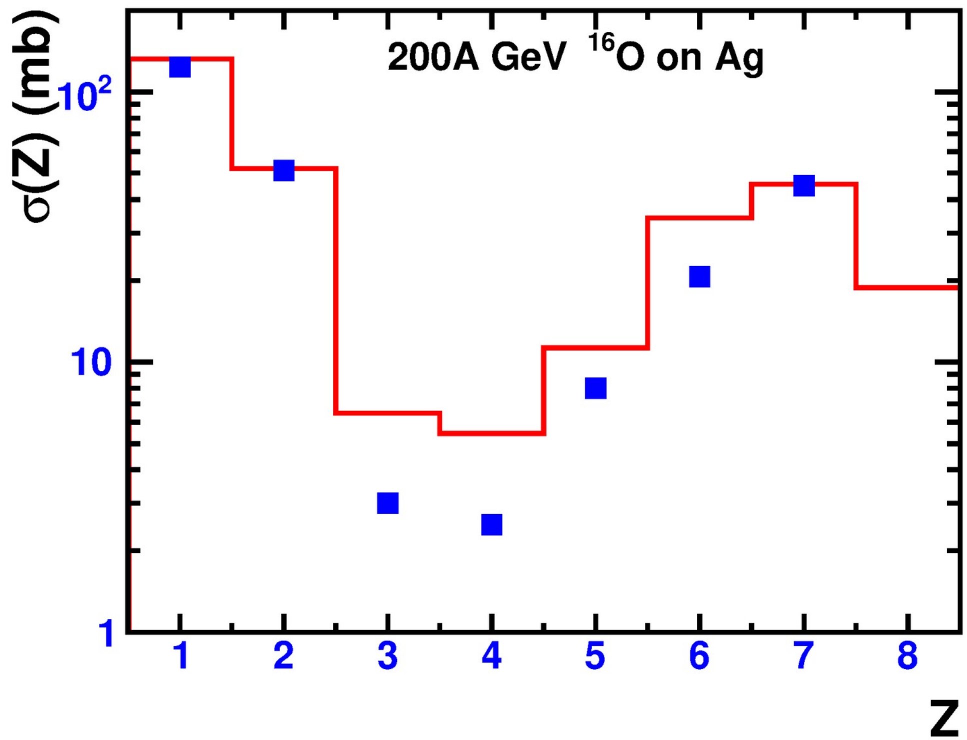




$\langle N_{n,HO} \rangle = 1.694 \, \langle N_{n,DW} \rangle = 2.275$ $\langle N_{HO} \rangle = 3.434 \, \langle N_{DW} \rangle = 4.692$

- More free nucleons are predicted with DW, because the density distribution extends to larger radii.
- Note a large fraction of neutronless events, up to 0.3 b (~20% of had. c.s.).
- Neutron Zero Degree Calorimeters are useless in triggering such neutronless events.

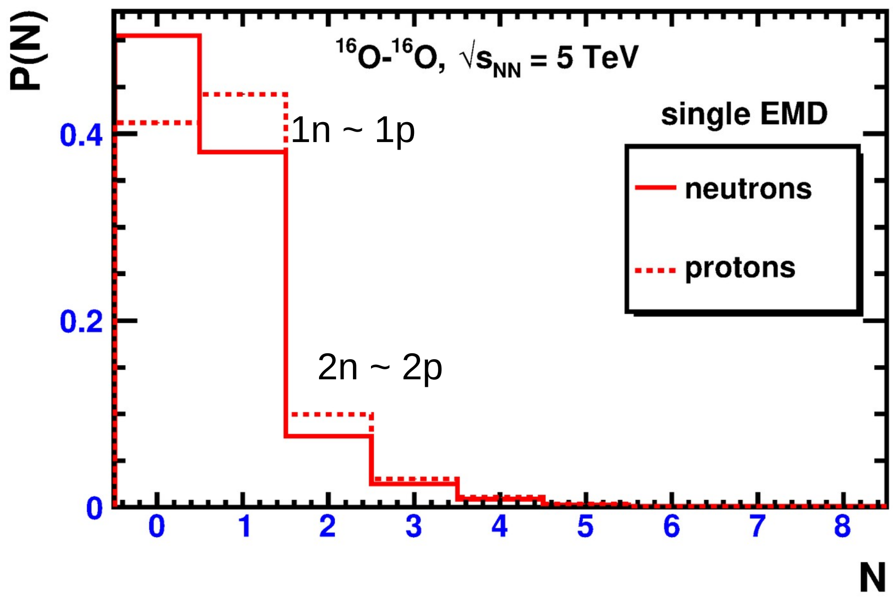
EMD of 200A GeV ^{16}O in nuclear emulsion

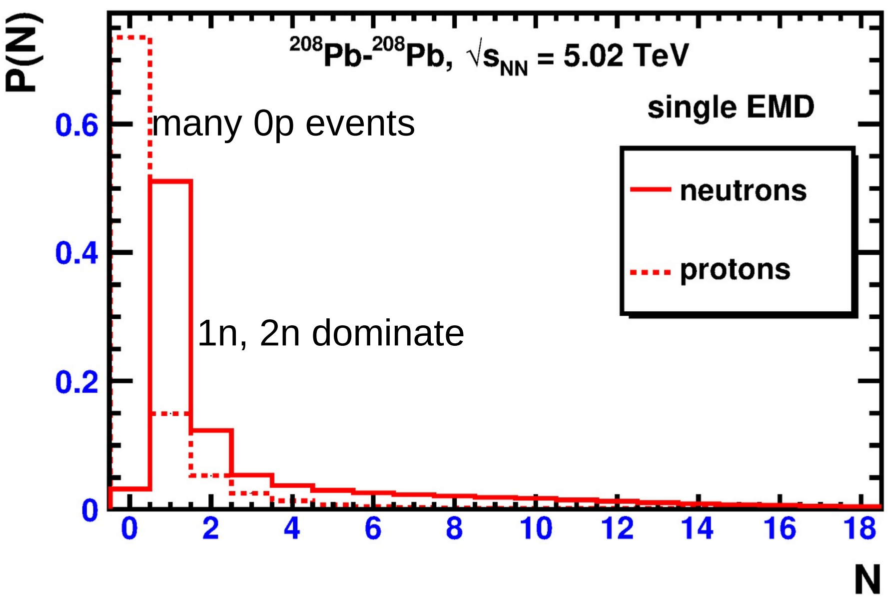


- Data on fragmentation of ^{16}O in nuclear emulsion[1),2)] (points) are described well by RELDIS[3)] (histogram).
- Here the data on relative yields of specific elements[1),2)] were normalized to RELDIS result for the absolute inclusive cross section σ(Z=7).
- RELDIS was also validated with data[4)] on multifragmentation of ^{12}C by 700-1500 MeV photons.

1) G. Baroni et al., NPA 516 (1990) 673
2) G. Singh, P.L. Jain, ZPA 344 (1992) 73
3) I.A. Pshenichnov et al., PRC 57 (1998) 1920
4) V. Nedorezov et al., NPA 940 (2015) 264

Tagging UPC events with ZDC





- Signatures of EMD of ^{16}O will differ from those of ^{208}Pb:
  - Forward protons are expected to be emitted by ^{16}O nearly with the same probability as neutrons – ALICE proton ZDC have to be employed in addition to neutron ZDC
- In contrast to EMD of ^{208}Pb, where a single nuclear residue typically left after the emission of neutrons, multifragmentation of ^{16}O is expected in UPC.

Conclusion

- The production of He, Li, B, N in O+CNO is described by AAMCC in general, while the production of C is underestimated.
- The production of various nuclei is predicted by AAMCC for the ^{16}O-^{16}O collisions at the LHC. The sets of secondary nuclei are same for DW and HO parametrisation of nuclear density in ^{16}O.
- The total rate of ^{4}He is described well by AAMCC, but not the channels with specific multiplicity.
- Multiplicity distributions of secondary nucleons are sensitive to the parametrisation of nuclear density of ^{16}O.
- Ultraperipheral ^{16}O-^{16}O collisions at the LHC were modelled by means of RELDIS. Protons are produced as frequently as neutrons, multifragmentation of ^{16}O is expected.
- The disagreement with data on production of ^{4}He and C suggests that alpha-clustering in ^{16}O should be taken into account in calculations.

Thank you for attention!

Deepened Impulse, V. Kandinsky 1928

Five Tetrahedra, Dave Peacock 2013