Probing intranuclear neutron-neutron correlations by detecting spectator neutrons in collider experiments

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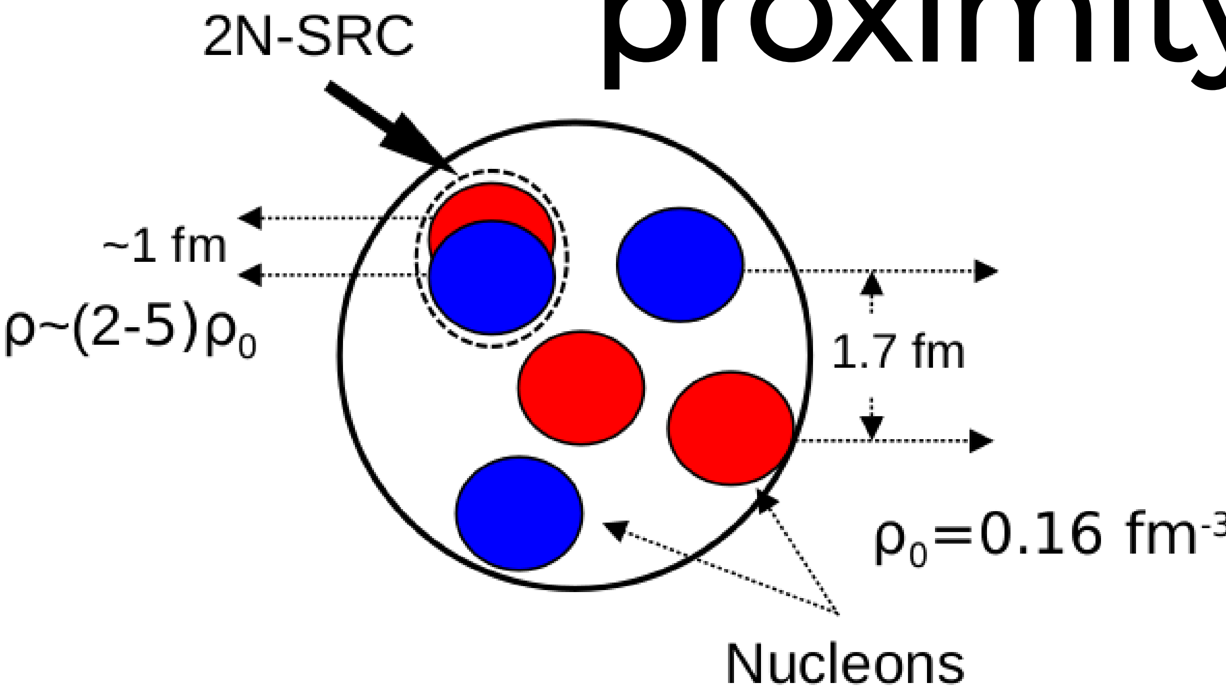
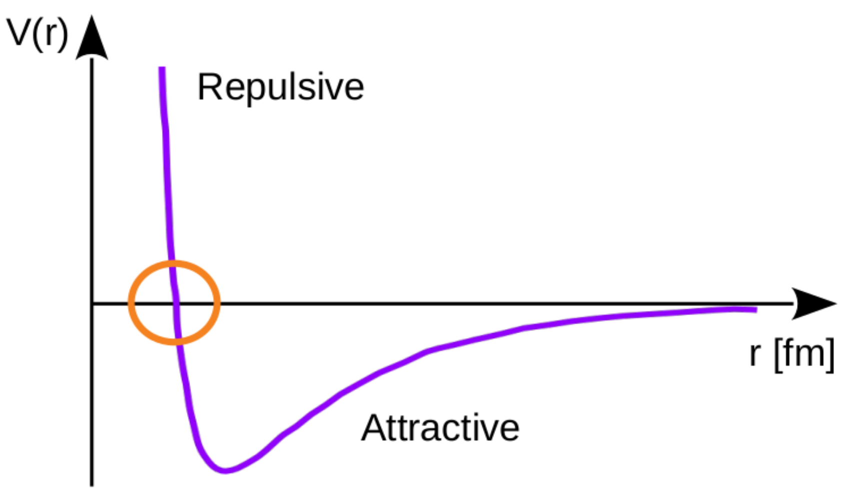
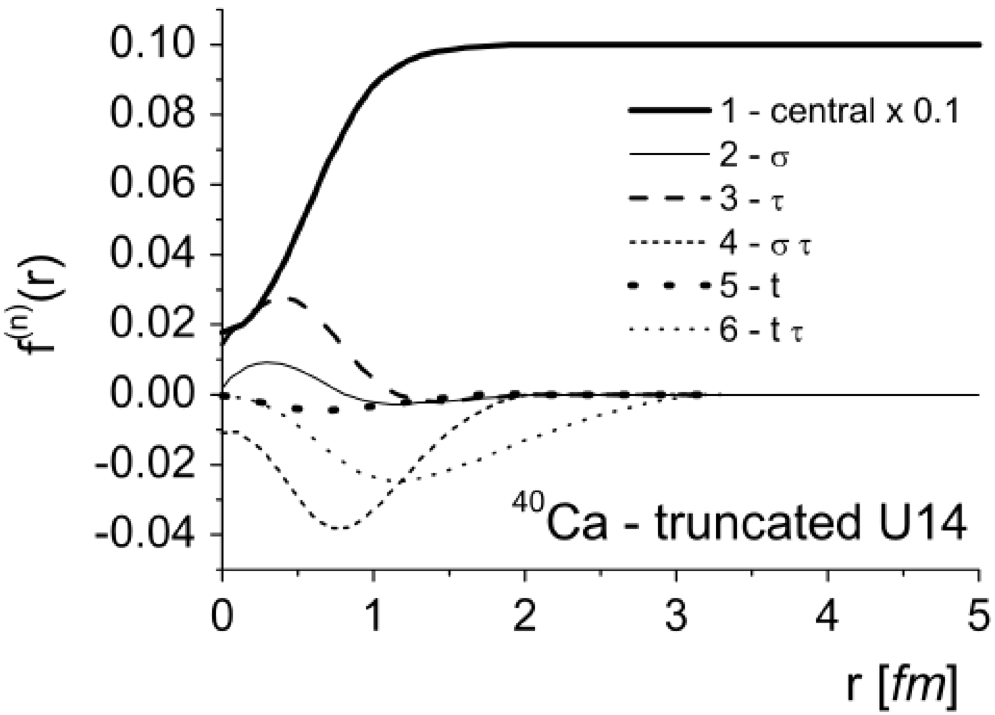
Two nucleons in close proximity…

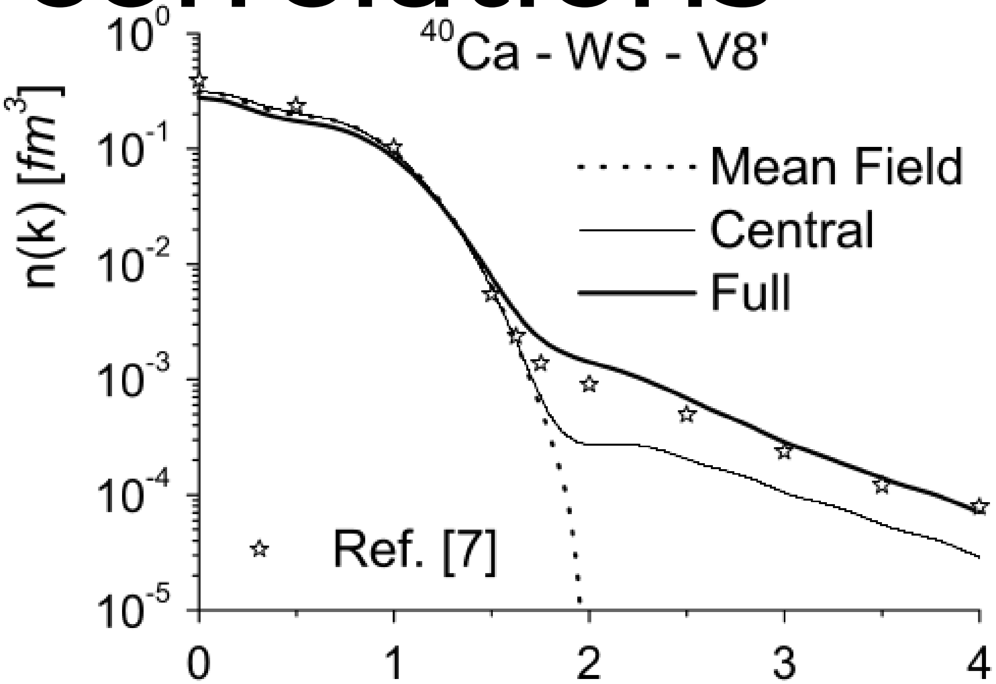




- The attractive part of V(r) in effect at long distance
  - It drives nuclear structure in general
- The repulsive part of V(r) acts at short distance
  - It drives short-range nucleon-nucleon correlations (SRC)

Spatial correlations vs. momentum correlations



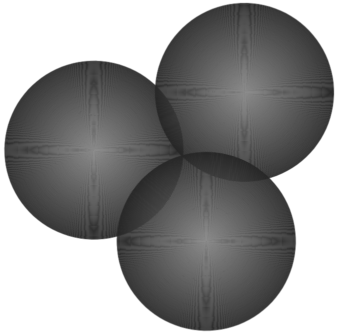


M.Alvioli et al, Phys. Rev. C 72, 054310 (2005)

- Spatial nucleon-nucleon correlations are typically described by the correlation functions f(r) which depend on the relative nucleon distance.
  - Thus it is represented by the distributions of distance between two nucleons.
  - Gaussian and step-like correlation function were adopted.
- The momentum nucleon-nucleon correlations are represented by the high-momentum tail of the nucleons.
- Both are driven by the internucleon potential, so they are connected.

α-clustering

- Correlations between nucleons are driven by the tensor forces in nucleon-nucleon interactions that involve two, three and higher numbers of nucleons[1)]
- Among other studies, Furuta et al[2)] suggested that the ^{12}C nucleus has three α-clusters arranged into a triangle along with SRC[3)]
- Binary nucleon-nucleon correlations and α-clustering can be used as a probe of the NN-potential[1)]
- In contrast, according to Furuta et al[2)] ^{40}Ca does not have α-clusters but does have SRC.

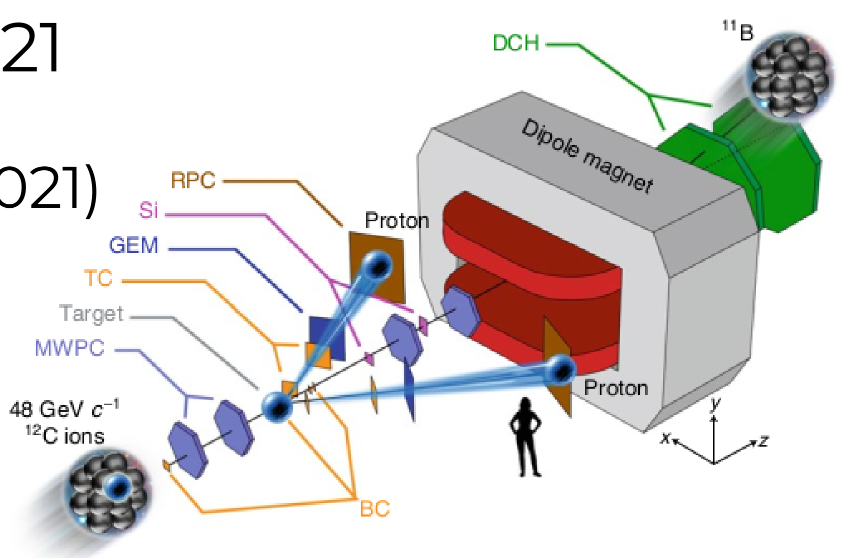


1) L.Frankfurt et al. Int. J. Mod. Phys. A 23, 2991 (2008)
2) T.Furuta et al, Phys. Rev. C 82, 034307 (2010)
3) M.Pasuk et al Nature Phys. 17, 693–699 (2021)

Correlations were studied at BM@N

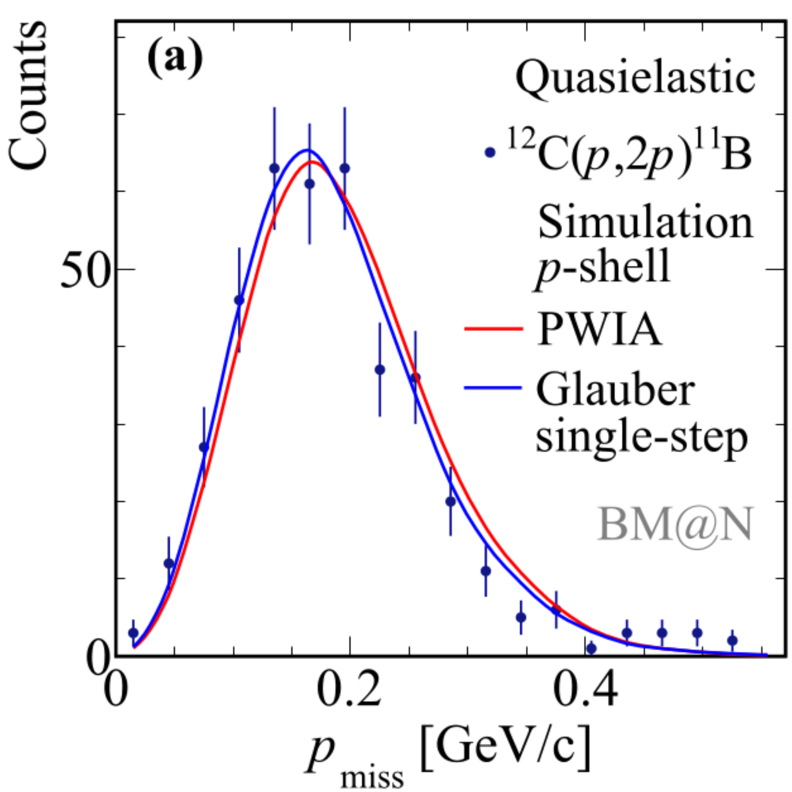
- Nucleon knockout measurements in ^{12}C+p collisions to study momentum SRC were performed.
  - The momentum distribution of protons in ^{12}C was studied by detecting two protons at large angles in the coincidence with intact $^{10,11}B$ nuclei.
  - The 4-momentum of initial proton in ^{12}C was associated with the missing 4-momentum for the two detected protons: $\bar{p}_{miss} \approx \bar{p}_1 + \bar{p}_2 - \bar{p}_{target}$
- The results were published in 2021

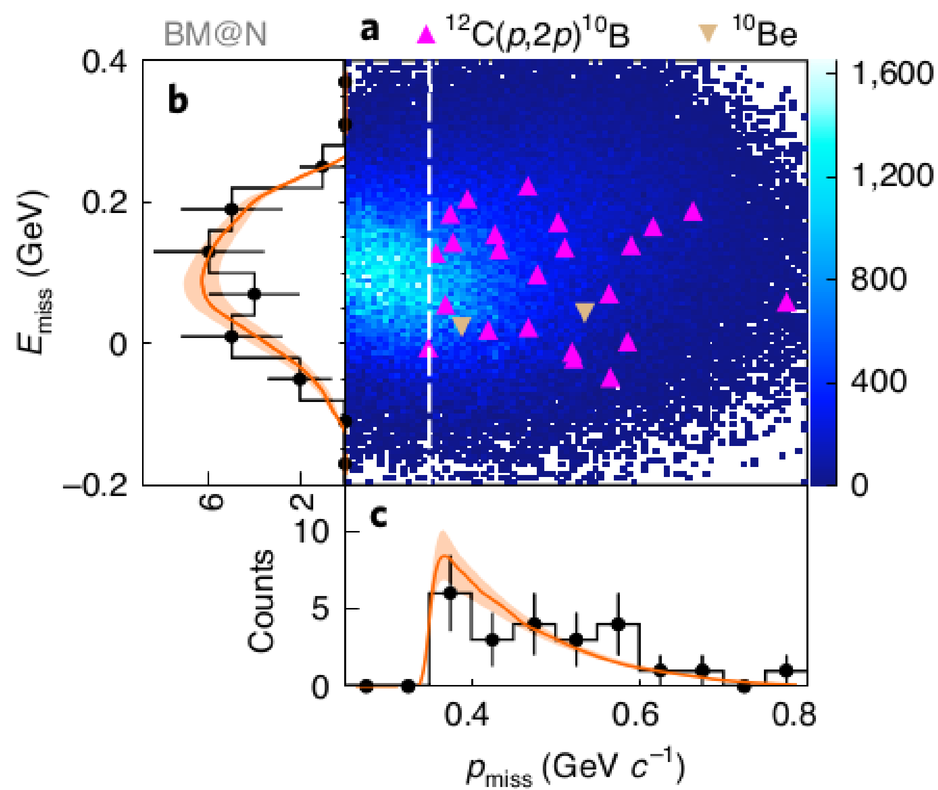
M.Patsuk et al., Nature Phys. 17, 693–699 (2021)



Correlations were studied at BM@N

- The results were published in 2021.
  - The missing momentum in $^{12}C+p \rightarrow ^{11}B+2p$ reaction was attributed to the quasielastic scattering on an on-shell proton.
  - … in $^{12}C+p \rightarrow ^{10}B+2p+X$ was attributed to scattering on a np-pair.





M.Pasuk et al Nature Phys. 17, 693–699 (2021)

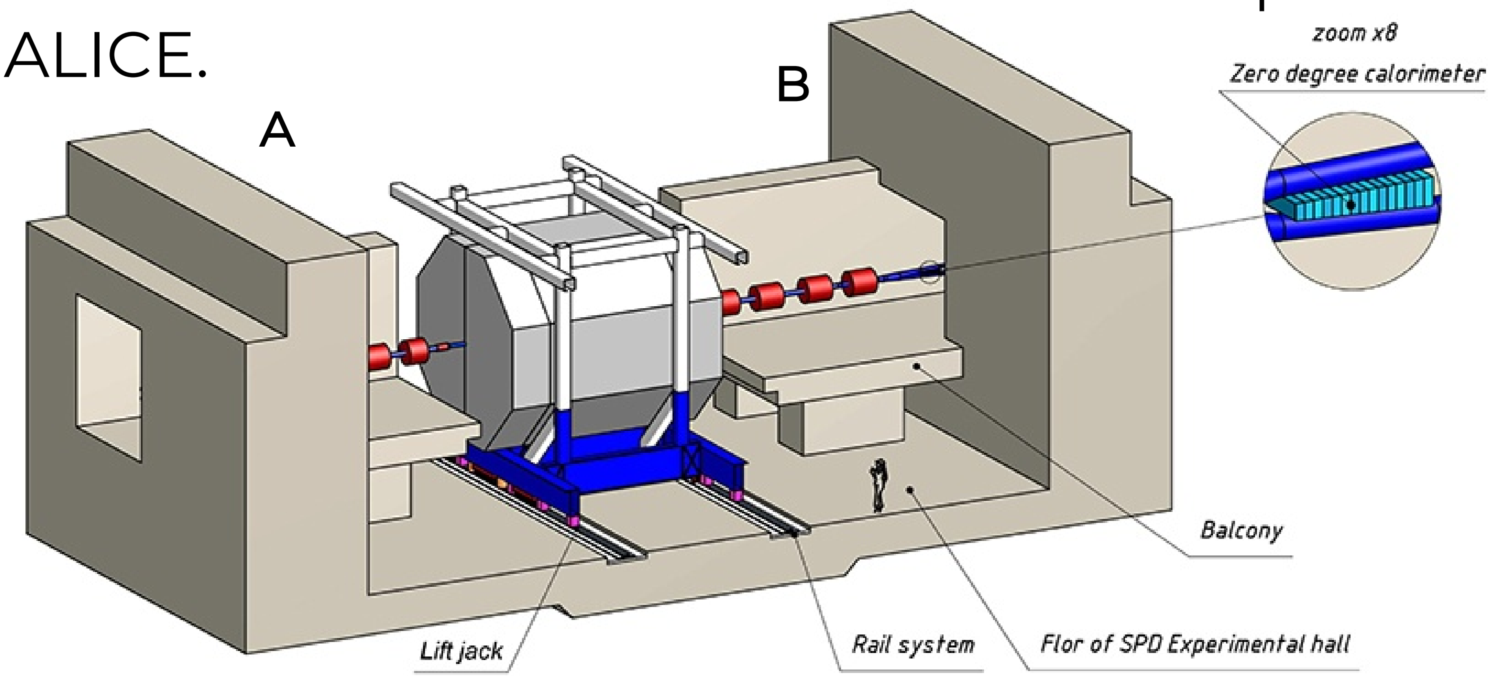
Spatial correlations at NICA

- Momentum correlations were studied at BM@N in ^{12}C+p reactions. Another reaction ^{2}H+p is proposed for studies.
- The spatial correlations of the nucleons inside colliding nuclei impacts the initial conditions of the nucleus-nucleus collision[1)]
  - Can we observe this effect in the final state?
- Can we study the spatial correlations at NICA?

1) M.Alvioli et al, Phys. Rev. C 85, 034902 (2012)

Advantages of SPD

- The first-stage configuration of the SPD includes a pair of neutron Zero Degree Calorimeters (ZDCs)[1].
- Tracker, ToF and other central barrel detectors can be used for the centrality determination.
- There is a well-established technique to measure the multinucleon events with a ZDC of limited acceptance[2,3] used by ALICE.



1) Technical Design Report of the Spin Physics Detector at NICA
2)U.Dmitrieva, I.Pshenicnov, NIM A, 906, 114 (2018)
3) S.Acharaya et al., Phys. Rev. C, 111, 054906 (2025)

SRC at SPD

- Studies of collisions of non-polarised light nuclei, ^{12}C and ^{40}Ca, are considered as a possible extension of the SPD research program[1)].

- The short range correlations between pair of neutrons can be related to the nuclear symmetry energy[2)]

- The production of spectator neutrons is affected by the initial cluster structure of ^{16}O nucleus[3)]. α-clustering is also predicted for ^{12}C nucleus[4)]

- Can we probe the neutron correlations in ^{12}C and ^{40}Ca via forward spectator neutrons detected by ZDCs?

1) V. V. Abramov et al. Phys. Part. Nucl. 52 (2021) 1044
2) S.Gandolfi et al., Phys. Rev. C 85 (2012), 032801
3) A.S. et al. Physics 5 (2023), 381
4) Y.Kanada-En'yo. Progress of Theoretical Physics 121 (2009), 895

Our calculations

- Abrasion-Ablation Monte Carlo for Colliders or AAMCC model

- Production of spectator neutrons in relativistic ^{12}C–^{12}C and ^{40}Ca–^{40}Ca collisions, to be considered:

  - The cross-section of the production of a given number of neutrons

  - The dependence of the average neutron multiplicity on event centrality

  - The multiplicity distributions for the events with the same number of neutrons at both sides

Abrasion-Ablation Monte Carlo for Colliders

- Nucleus-nucleus collisions are simulated by means of the Glauber Monte Carlo model [1]. Non-participating nucleons form spectator matter (prefragment)

- Excitation energy of prefragment is calculated by parabolic ALADIN approximation[2] which is tuned to describe the data for light nuclei.

- Decays of prefragments are simulated as follows:
  - pre-equilibrium decays modelled with MST-clustering algorithm [3]
  - Statistical Multifragmentation Model (SMM) from Geant4 v10.4[4]
  - 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

AAMC²

Introducing SRC in calculations

- Following the papers [1,2], SRC includes the nucleon-nucleon repulsion.
- To account for SRC a method based on random search in nucleons coordinate space was implemented.
- Two nucleon-nucleon correlation functions can be used: Gaussian or step-like.
  - The neutron-neutron, proton-neutron and proton-proton correlations can be treated separately
  - In this study the width of the correlation function σ for the pp and pn was set to 1 fm, while it was varied for nn.
- The number of participants is slightly increased when accounting for SRC[1]. The deuterium production is enhanced in Pb-Pb collisions [3]. One can expect a similar effect in C-C and Ca-Ca collisions.

$$f_{pp}(r) = 1 - Gauss(0, \sigma_{pp})$$
$$f_{pn}(r) = 1 - Gauss(0, \sigma_{pn})$$
$$f_{nn}(r) = 1 - Gauss(0, \sigma_{nn})$$

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

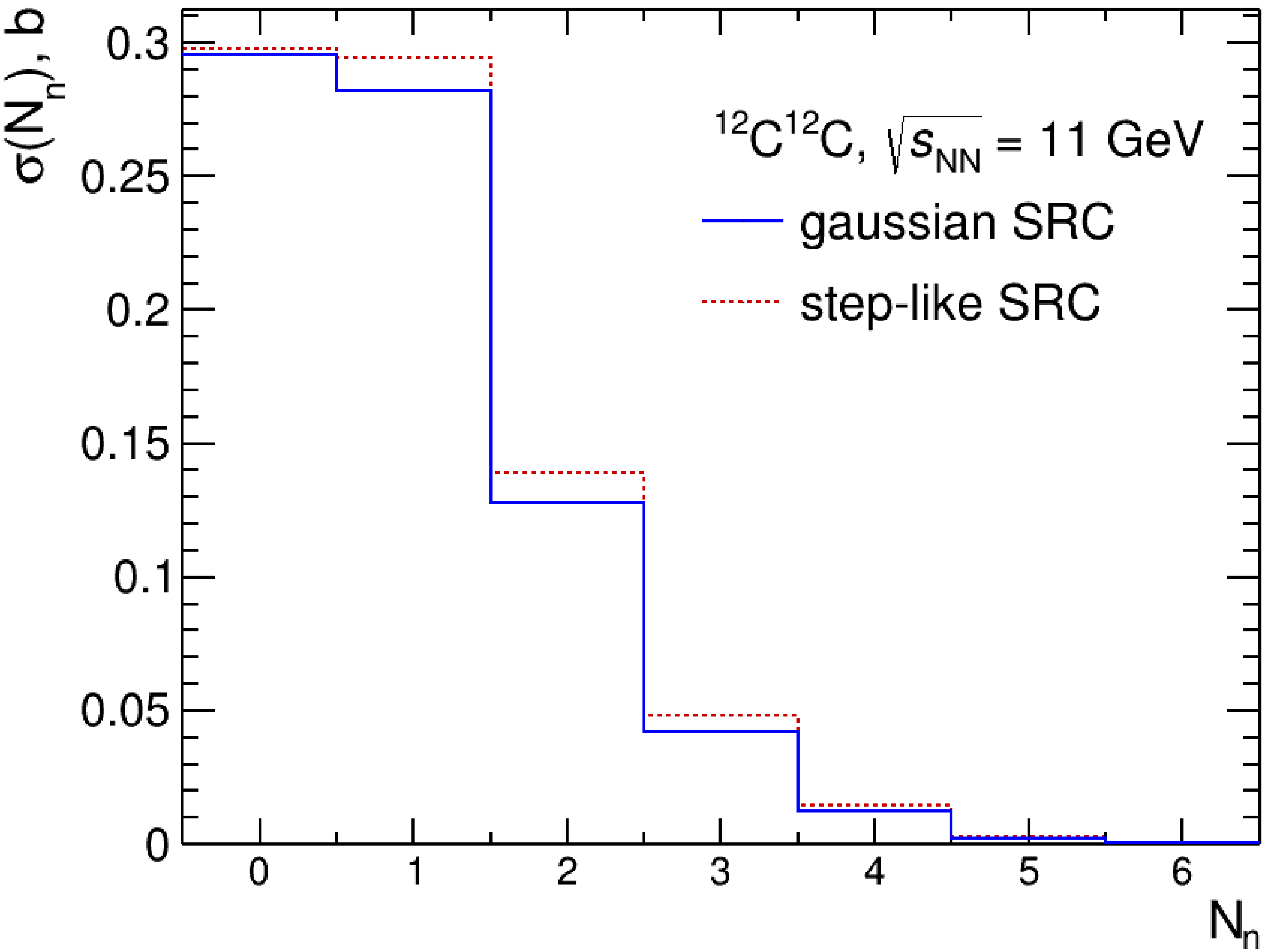
What can we measure with ZDCs at SPD?

I. Cross section for the production of a given number of neutrons

II. Average neutron multiplicity

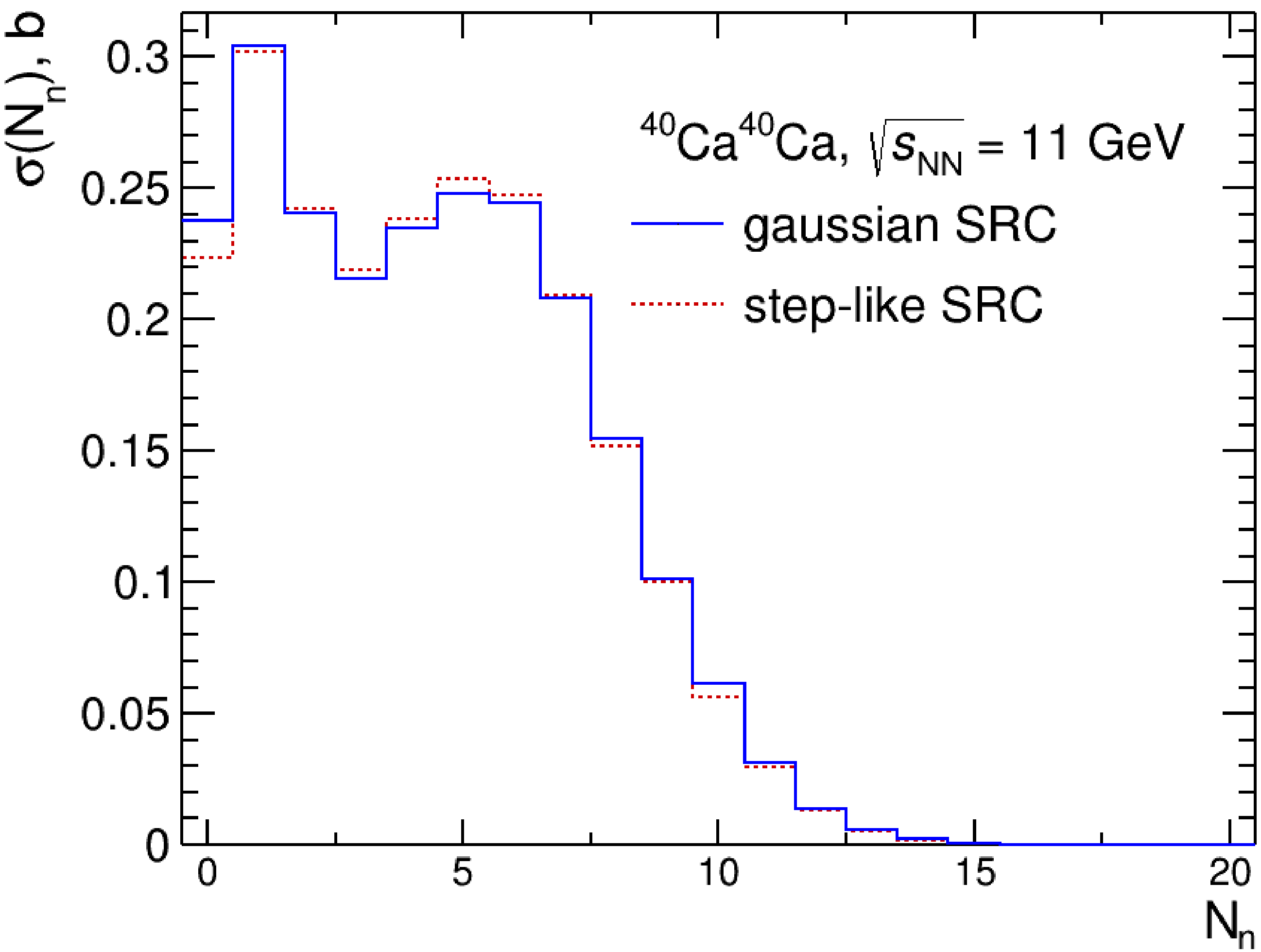
III. Probabilities of having the same number of neutrons on both sides

I. Cross section of the production of a given number of spectator neutrons



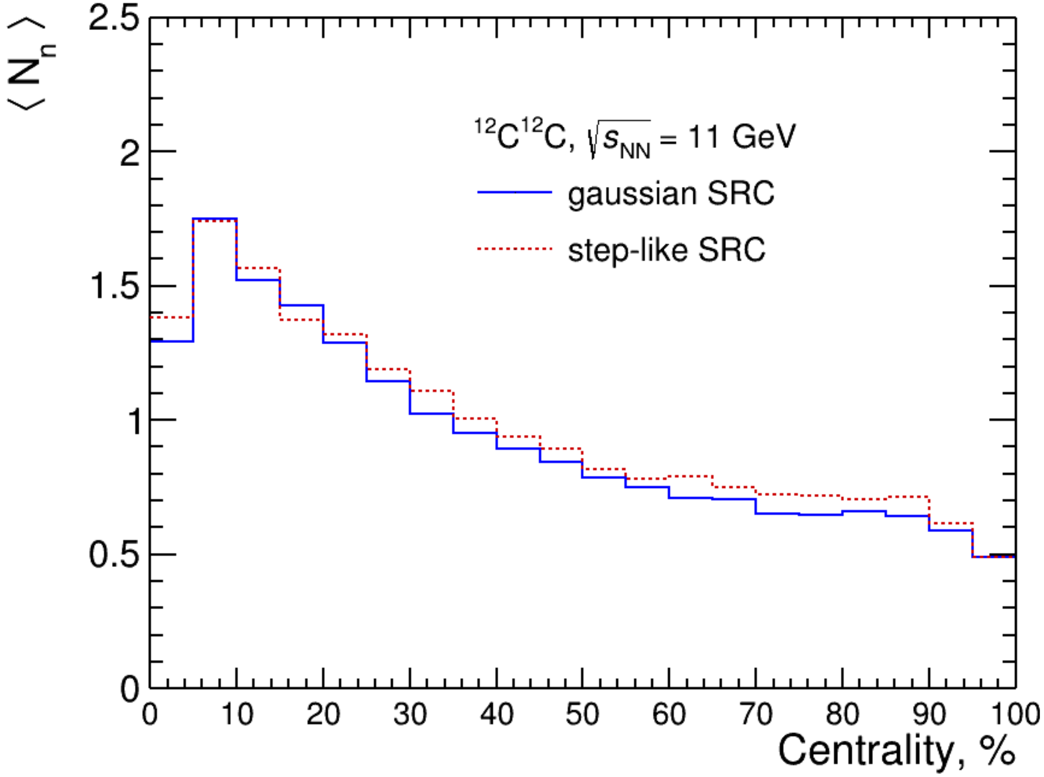
No significant difference is observed between the cross sections obtained with the two parametrisations of SRC.

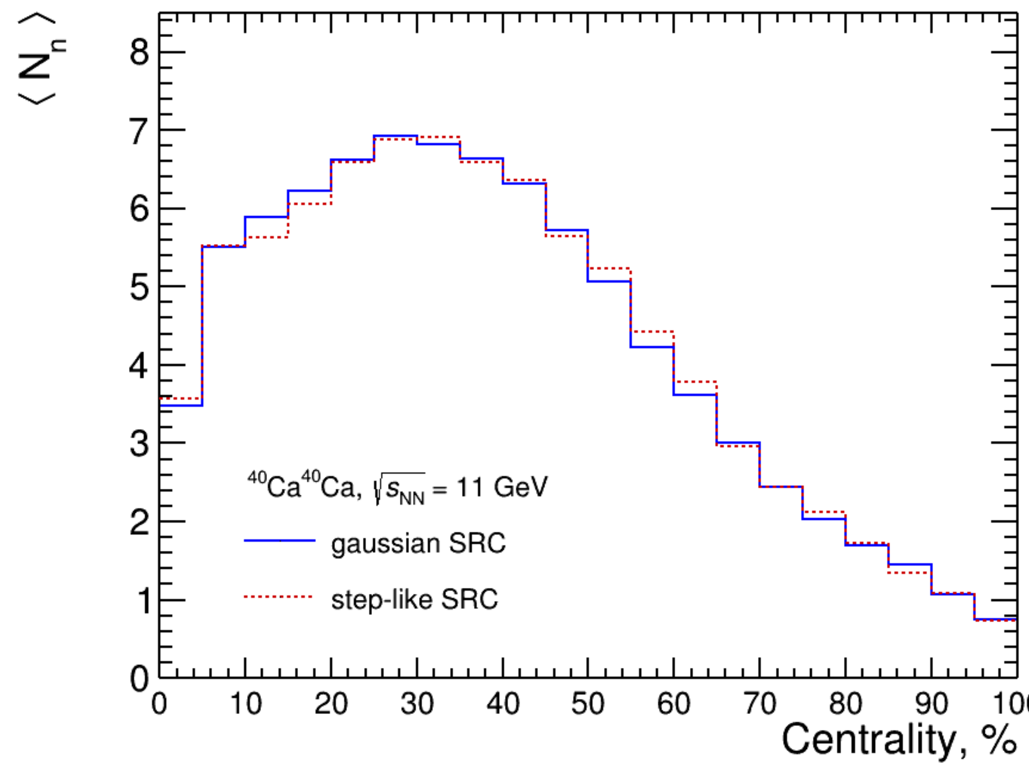
I. Cross section of the production of a given number of spectator neutrons



No significant difference is observed between the cross sections obtained with the two parametrisations of SRC.

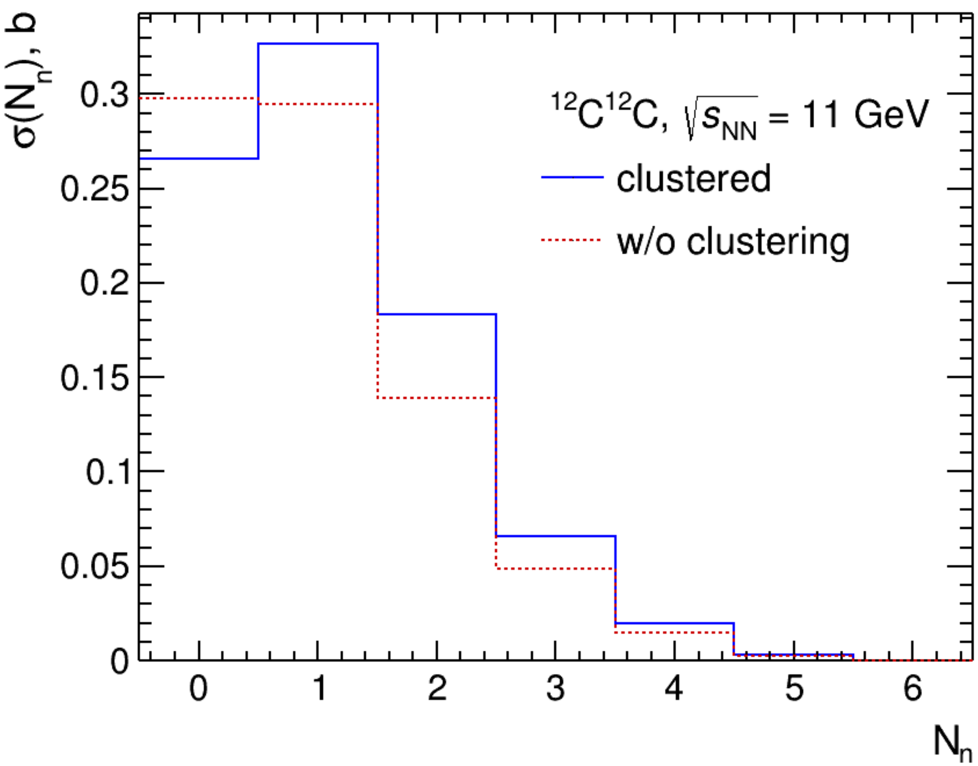
II. Average spectator neutron multiplicity

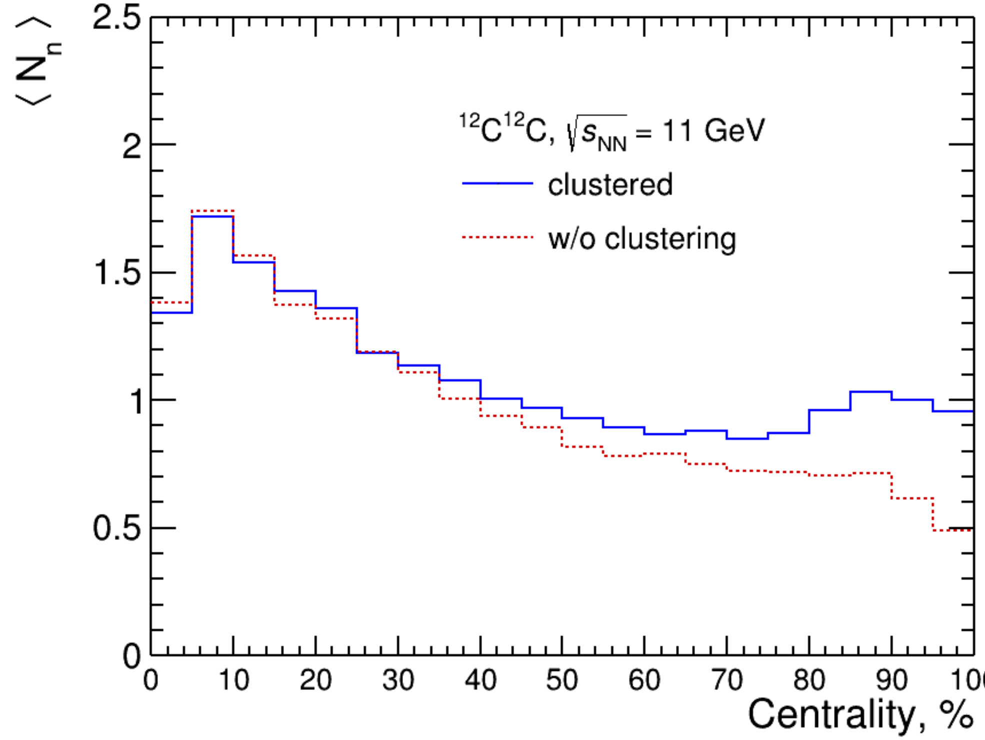




A slight increase in multiplicity for more peripheral events is observed for both ^{12}C and ^{40}Ca

Neutrons from clustered ^{12}C



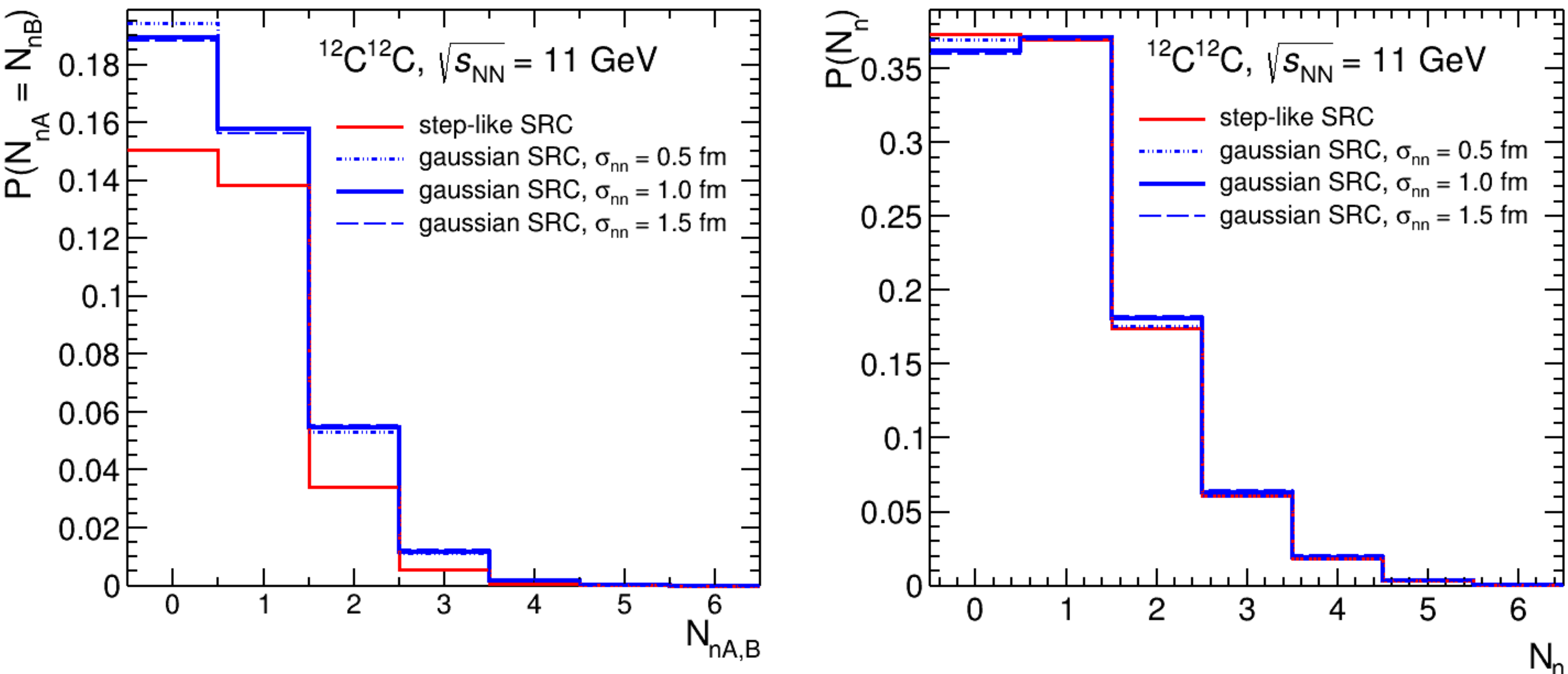


Following the Ref. 1, the step-like parametrization of SRC was considered.

Similarly, accounting for the α-clusterisation in ^{16}O increases the average neutron multiplicity, also in the most peripheral events.

1) A.S. et al. Physics 5 (2023), 381

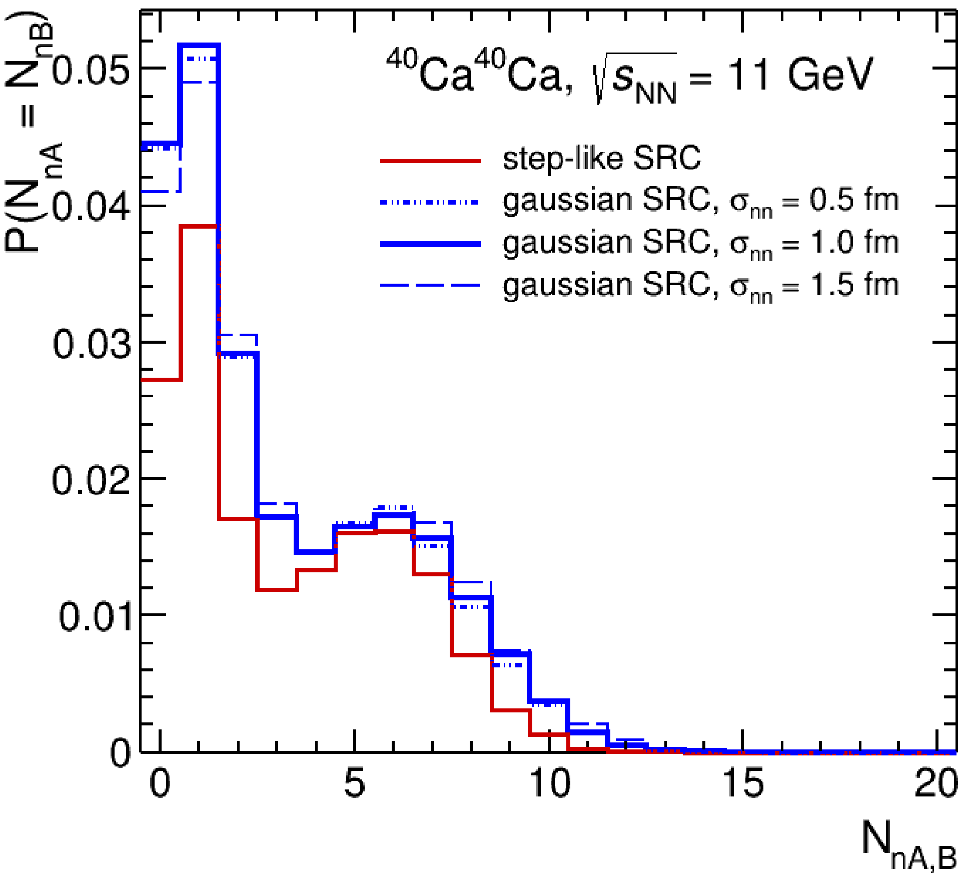
III. Probabilities to have the same number of neutrons on both sides

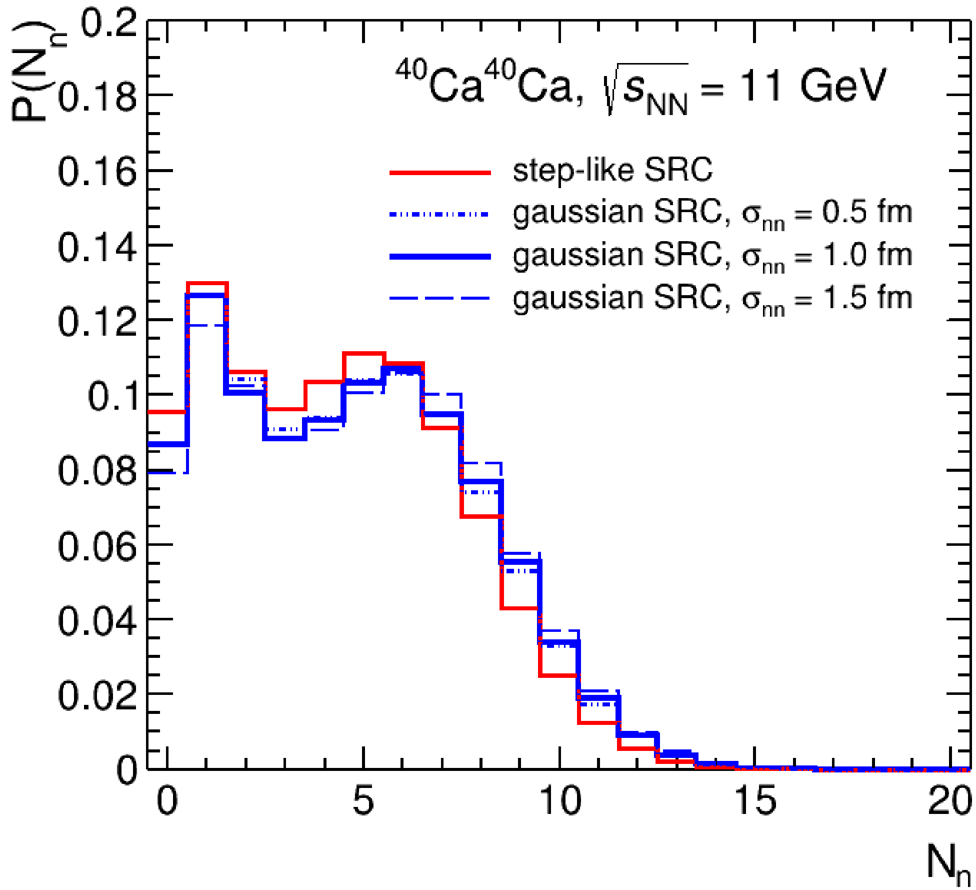


A difference in the probabilities for the symmetric events is evident for the different parametrisations of SRC

However, the sensitivity to σ_{nn} is low.

III. Probabilities to have the same number of neutrons on both sides



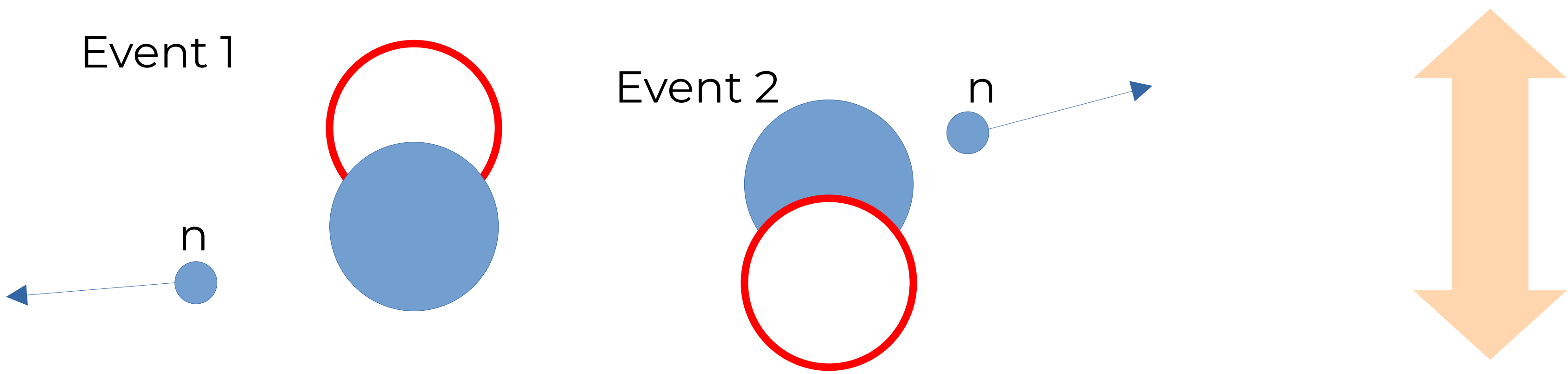


A difference in the probabilities for the symmetric events is evident for the different parametrisations of SRC.

In contrast to ^{12}C, a small difference in the probabilities for the different σ_{nn} is observed.

III. Probabilities to have same number of neutrons for the mixed events

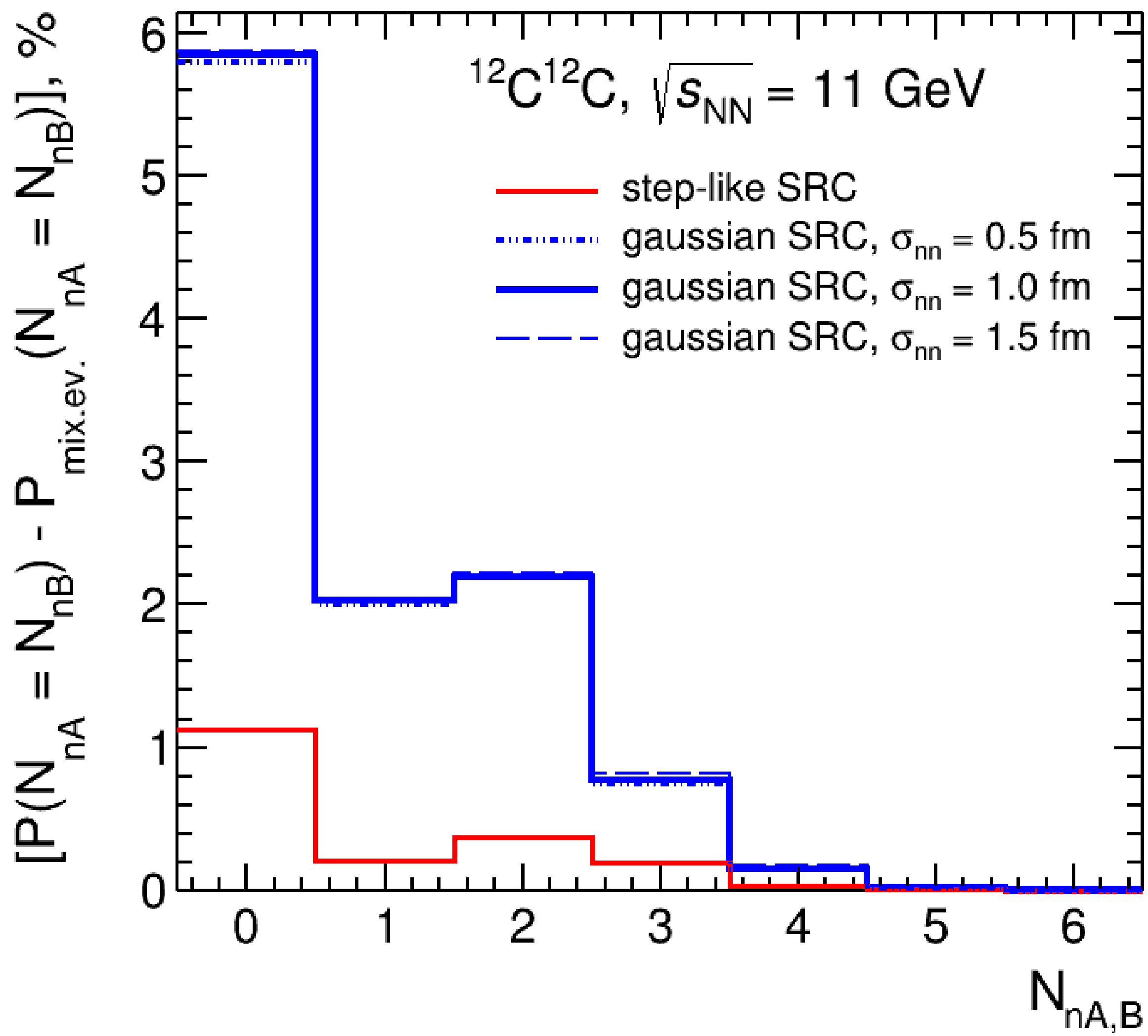
$$P(N_{nA} = N_{nB} = N_n) = P_A(N_n) \cdot P_B(N_n) + \boxed{CORR(N_n)}$$



$$P_{\text{mix}}(N_{nA} = N_{nB} = N_n) = P_A(N_n) \cdot P_B(N_n)$$

- In the same event the production of neutrons is correlated and is not equal to the product of the two probabilities $P(N_n)$.
- For the different events the production of neutrons is independent. Thus, it is equal to the product of the probabilities
- The correlation part can be obtained by subtracting the mixed events contribution.

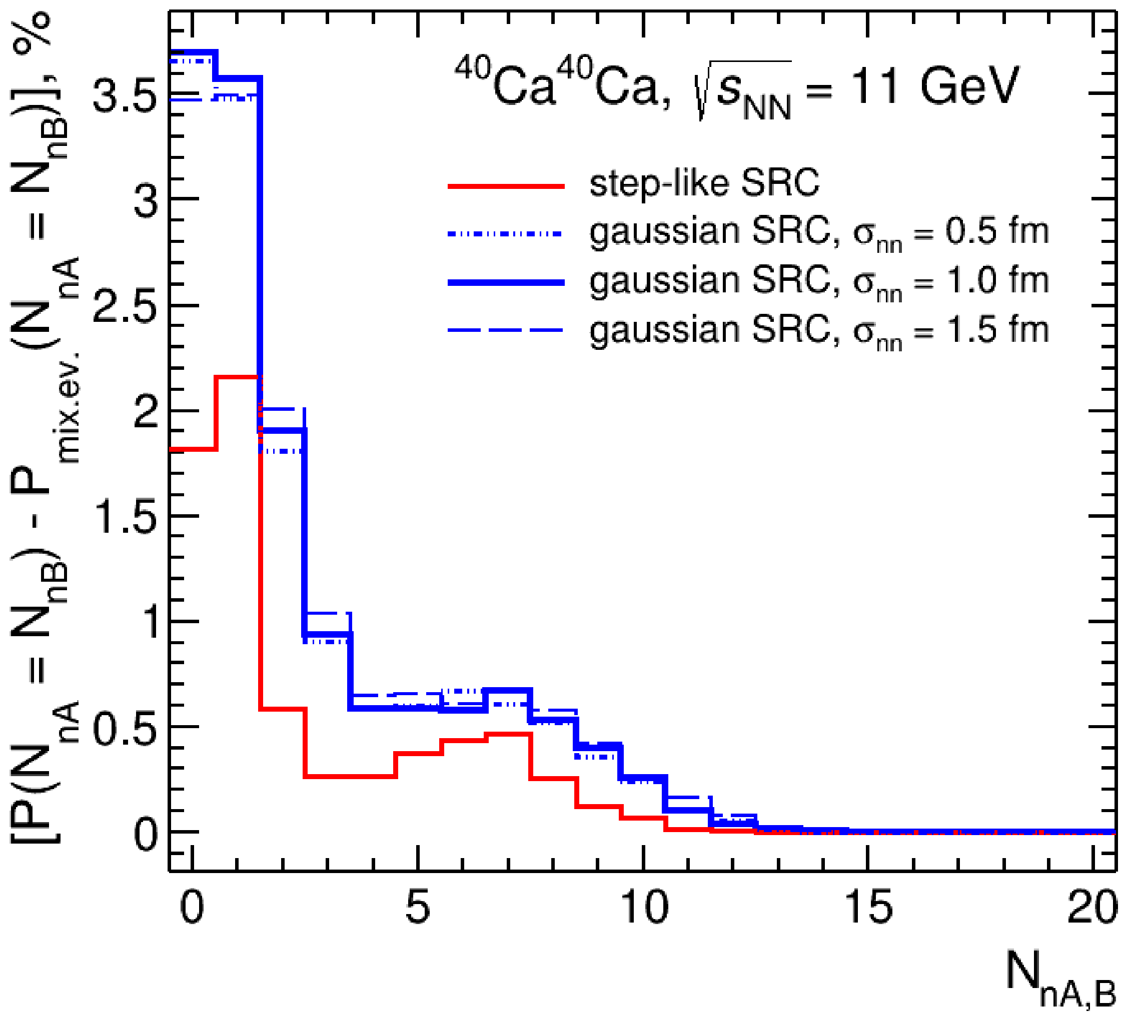
III. Extracting the correlations



A clear difference can be seen for the different SRC parametrisations, but not for the different σ_{nn}.

Employing the Gaussian SRC parametrisation provides more pronounced correlations between the neutrons on the sides A and B.

III. Extracting the correlations



A clear difference can be seen for the different SRC parametrisation, but not for different σ_{nn}.

Difference is less pronounced than that for ^{12}C.

Employing the Gaussian SRC parametrisation provides more pronounced correlations between the neutrons on the sides A and B.

What can we measure with ZDCs at SPD?

I. ~~Cross section for the production of a given number of neutrons~~

II. ~~Average neutron multiplicity~~

III. Probabilities of having the same number of neutrons on both sides

To-do list for theorists

- More pronounced effect can be expected for more central events.
  - We need to consider the centrality dependence for symmetric collisions.
- Comparison of the case of ^{12}C to the one for ^{40}Ca can provide more information about multinucleon correlations.

Summary

- Momentum correlations of nucleons were studied at BM@N in proton knockout reactions via missing momentum reconstruction.
- The spatial correlation can impact the final-state nucleons. Thus we can consider to study the spatial SRC at NICA.
- As calculated, the yields of spectator neutrons are sensitive to the presence of α-clusters in ^{12}C, but not to the SRC in ^{12}C and ^{40}Ca.
- In contrast, the correlation between the spectator nucleons from both colliding nuclei provides information on neutron-neutron correlations in the colliding nuclei.
- The yields of spectator neutrons in the events with the same number of neutrons on both sides are sensitive to the specific parametrisation of the SRC for both ^{12}C and ^{40}Ca but not to the parameters of the correlations.

To conclude, an artists view of the carbon nucleus fragmentation

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