Peeling away surface neutrons from ^{209}Bi in asymmetric collisions

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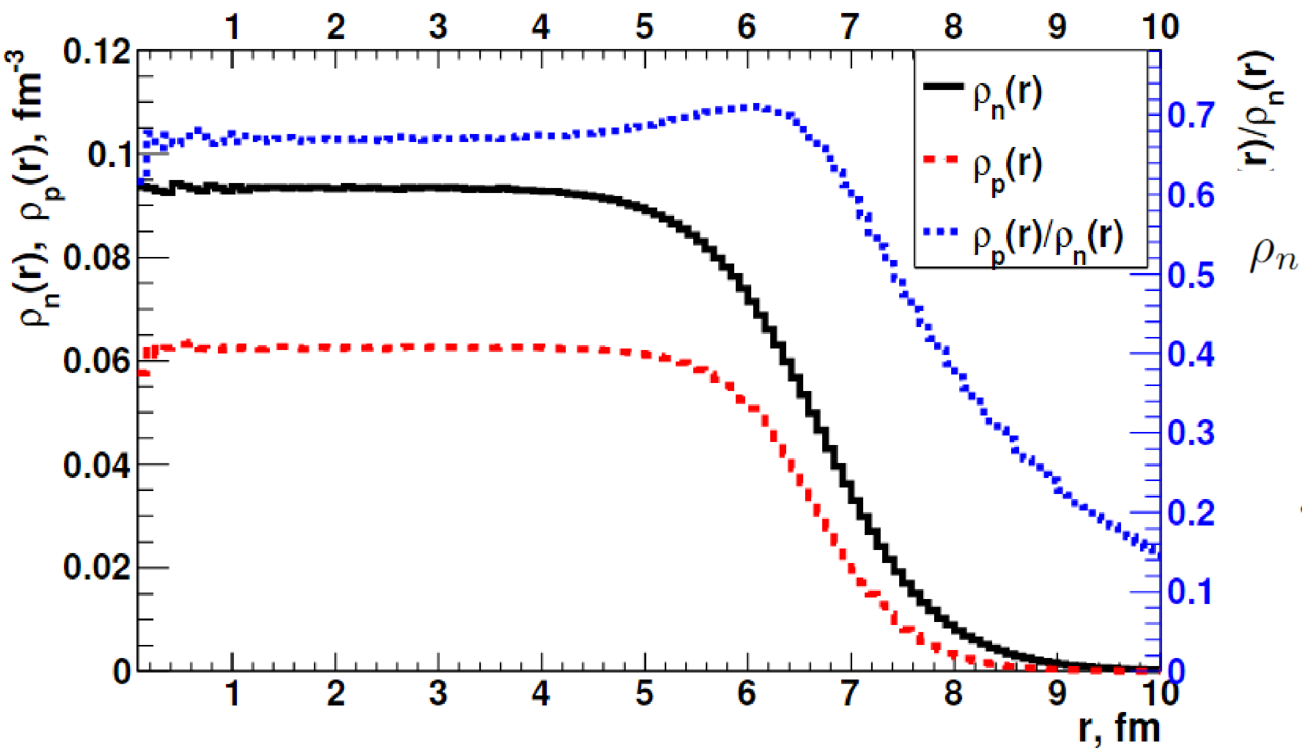
Neutron skin (NS) on the surface of nuclei



$$\rho_{n,p}(r) = \frac{\rho_{0n,p}}{1 + \exp\left\lfloor (r - R_{n,p})/a_{n,p} \right\rfloor} ,$$

$$\int d^3r(\rho_n(r) + \rho_p(r)) = A \; .$$

$$\Delta r_{np} = \left\langle r_n^2 \right\rangle^{1/2} - \left\langle r_p^2 \right\rangle^{1/2}$$

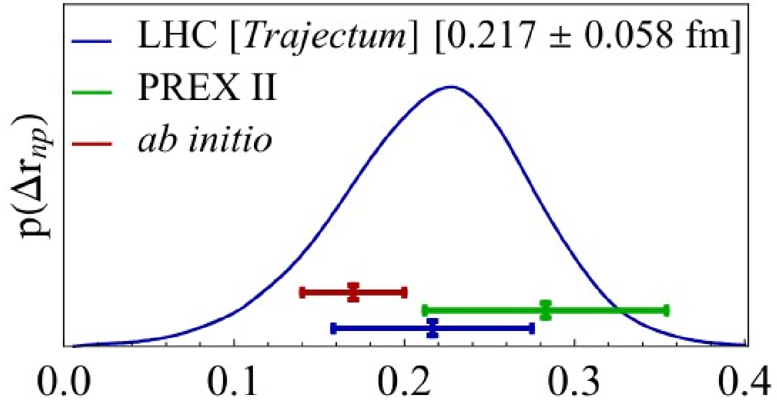
- Two separate Woods-Saxon distributions for protons and neutrons can be used to account for the neutron skin (NS).
- NS thickness is the difference between the RMS radii for neutrons and protons. Typically $R_n > R_p$, $a_n > a_p$.
- In the case of $R_n = R_p$ only the diffuseness $a_n > a_p$ contributes to the NS thickness thus representing halo NS.

NS thickness puzzle

- The neutron-skin thickness is one of the most robust probes in constraining the slope parameter of the symmetry energy around the saturation density.

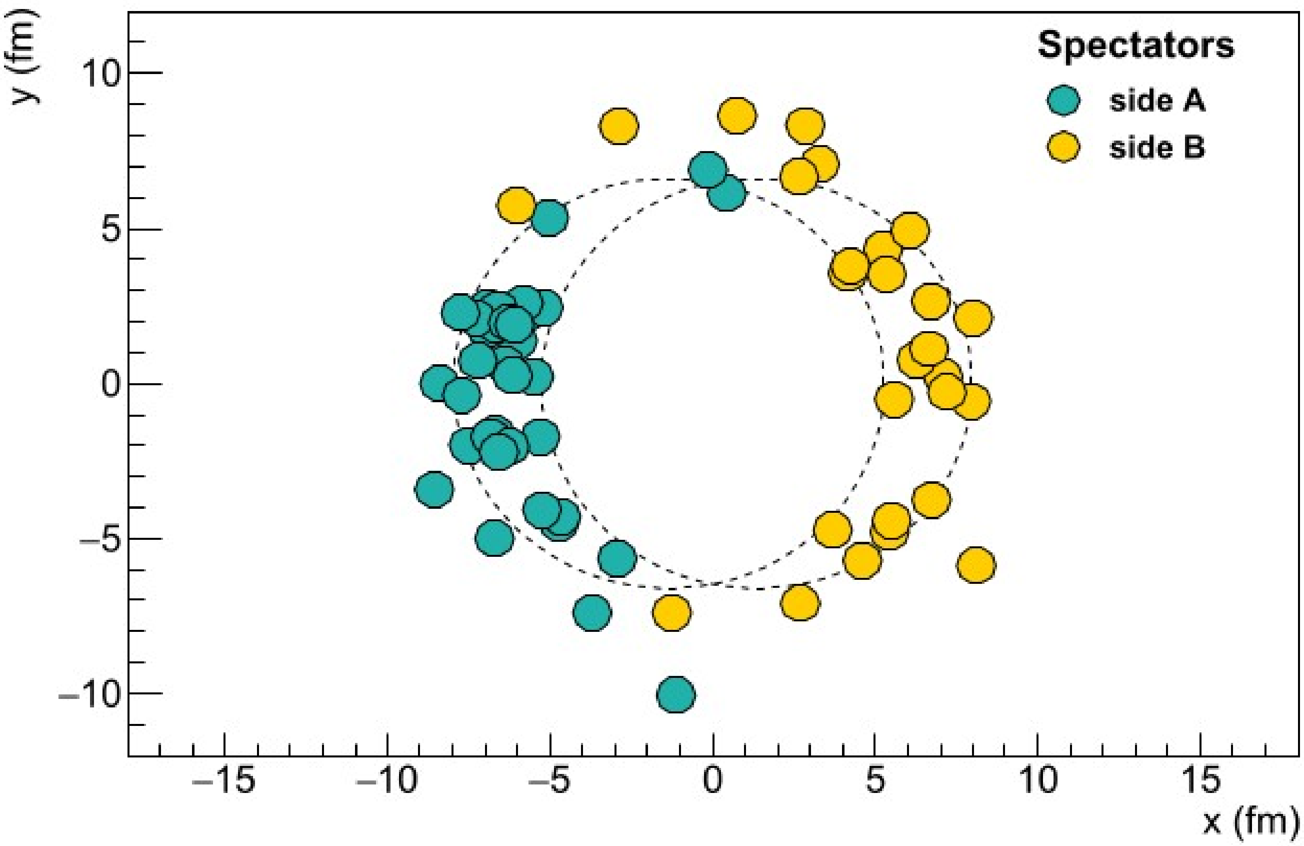
- Recent studies of NS of ^{208}Pb demonstrated a puzzling difference between the NS thickness obtained from ab initio theoretical calculations – 0.171 fm[1)] and that from measurements in elastic scattering of longitudinally polarized electrons (PREXII) – 0.283 fm[2)].

- The NS thickness in ^{208}Pb was estimated from LHC data as 0.217±0.058 fm[3)]. This result is highly sensitive to the total PbPb cross section and may vary from 0.03 fm up to 0.31 fm. So, other methonds are needed to evaluate the NS thickness from the data on nucleus-nucleus collisions.



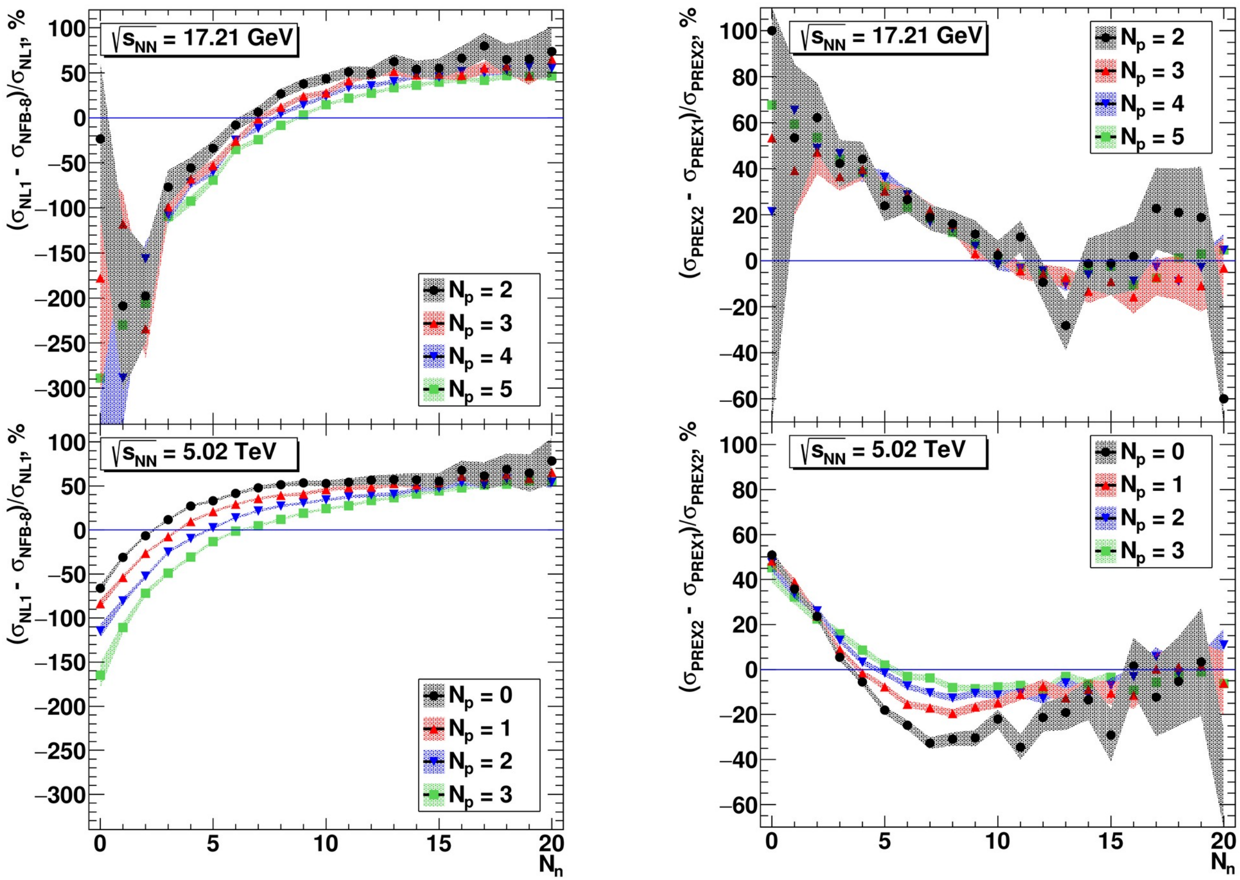
1) Hu, B. et al Nature Phys. 18, 1196 (2022)
2) Adhikari, D. et al Phys. Rev. Lett. 126, 172502 (2021)
3) Giacalone, G. et al Phys. Rev. Lett. 131, 202302 (2023)

Peeling away neutron skin at ultracentral Pb-Pb collisions

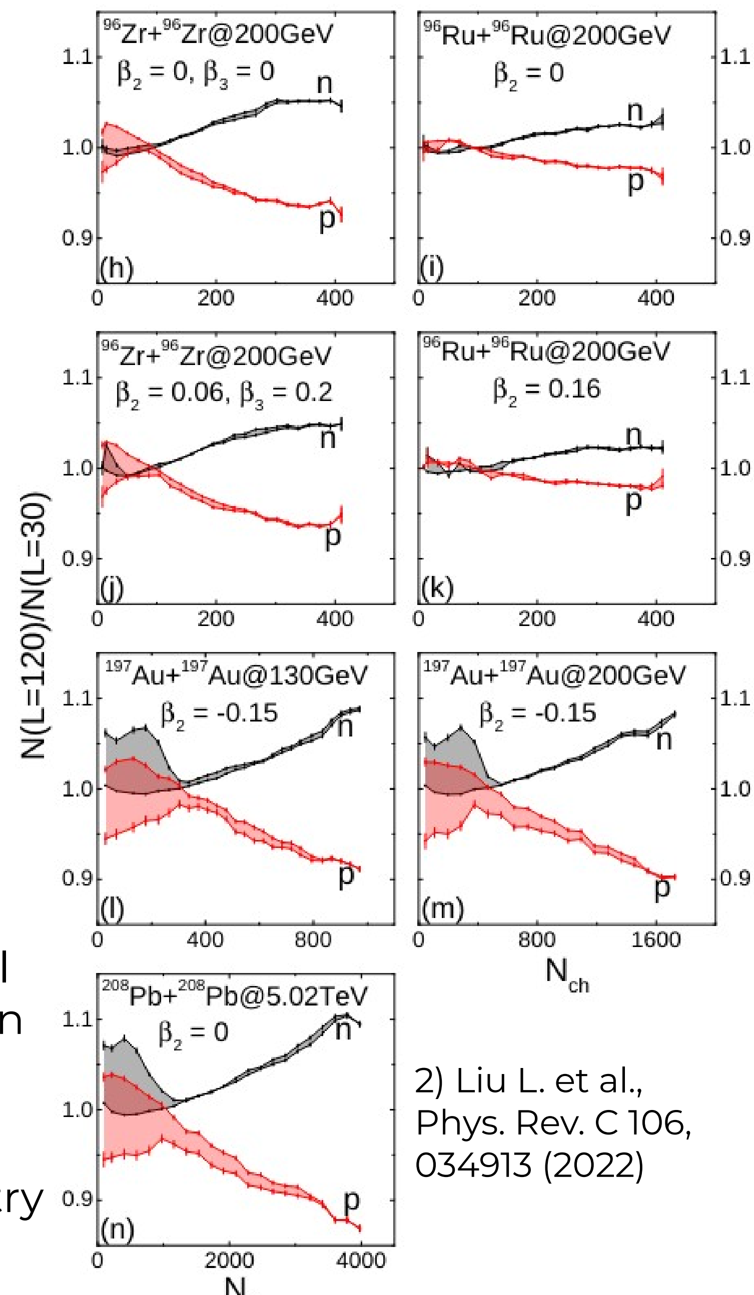


- A narrow cressent-shaped spectator fragment is formed in very central nucleus-nucleus collisions.
- This fragment is represented by the nucleons which are peeled away from nuclear periphery.
- Exploring spectator matter in such collisions allows to study the NS in the colliding nuclei.

Peeling away neutron skin at ultracentral Pb-Pb collisions



1) Kozyrev N. et al., Eur. Phys. J. A 58, 184 (2022)



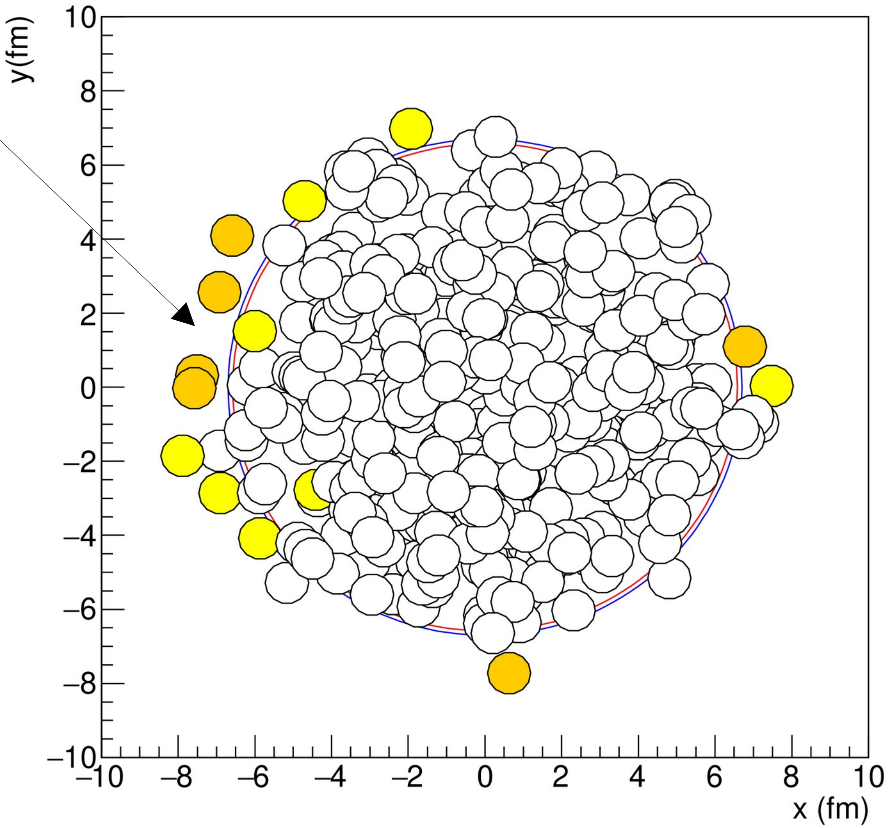
- The yields of spectator neutrons and protons in ultracentral ^{208}Pb-^{208}Pb collisions are sensitive to the parameters of NS in ^{208}Pb[1)]
- One may relate the yields of the spectator nucleons in symmetric collisions to the slope parameter of the symmetry energy[2)]

2) Liu L. et al., Phys. Rev. C 106, 034913 (2022)

Neutron skin in ^{209}Bi

- ^{209}Bi is similar to ^{208}Pb and it is considered as projectile at future BM@N runs. Only one experimental group reports measured neutron skin thickness in ^{209}Bi[1,2] as 0.14 fm, ~15-50% less than in ^{208}Pb.
- In BM@N experiment projectile spectator nucleons and nuclear fragments can be measured. Can ^{209}Bi NS be measured at BM@N?
- A cut of a main part of the neutron skin in very central asymmetric ^{209}Bi + W collisions is expected.
- Events with small numbers of spectator nucleons and also with large numbers of midrapidity particles are good candidates.

Cut of a surface neutrons in Bi+W collision



1) B. Kłos et al, Phys Rev C 76, 014311 (2007)
2)A. Trzcin ´ska et al, Phys Rev Lett 87, 082501 (2001)

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)

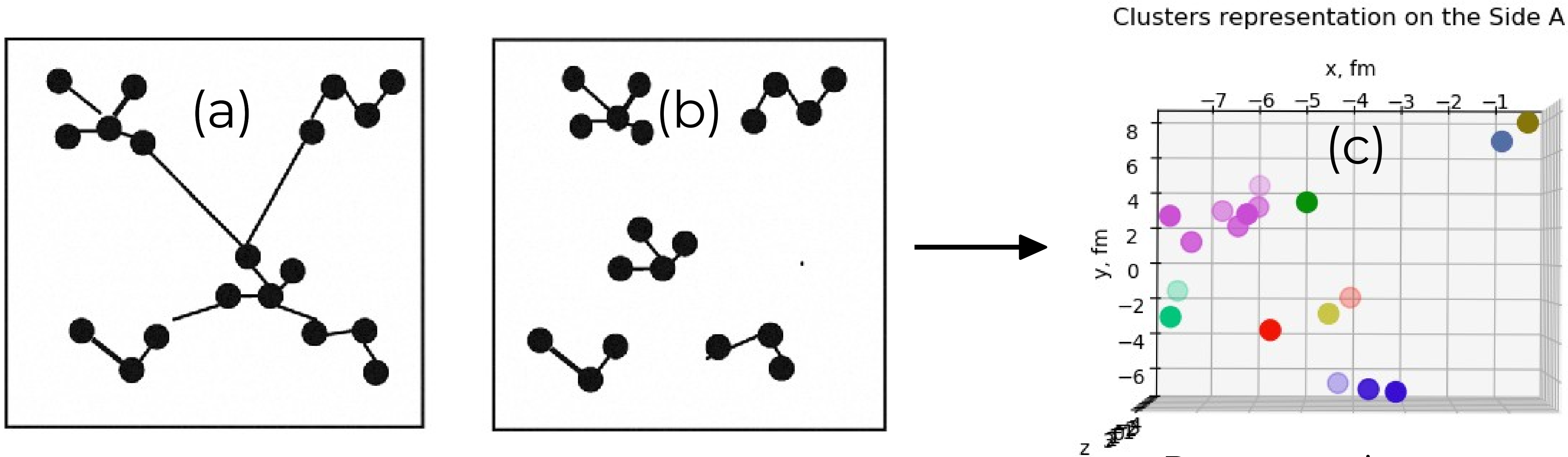
- Excitation energy of prefragment can be calculated via three options:
  - Ericson formula based on the particle-hole model[2]
  - parabolic ALADIN approximation[3] adjusted to describe the data for light and heavy nuclei
  - Hybrid approximation: a combination of Ericson formula for peripheral collisions and ALADIN approximation otherwise

- Deexcitation is simulated via MST-clusterisation[4] accomplished with Fermi Break Up mode from Geant4[5] for ultracentral collisions

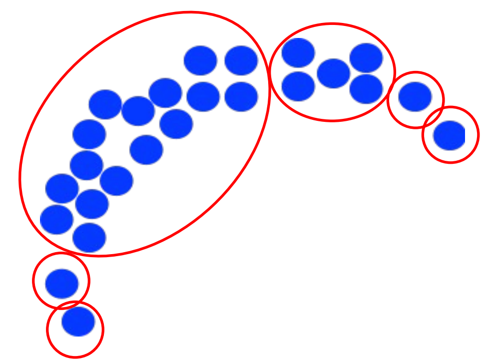
1) C. Loizides, J.Kamin, D.d'Enterria Phys. Rev. C **97** (2018) 054910
2) T. Ericson Adv. In Phys. **9** (1960) 737
3) A. Botvina et al. NPA **584**
4) R. Nepeivoda, et al., Particles **5** (2022) 40
5) J. Alison et al. Nucl. Inst. A **835** (2016) 186

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

MST-clustering



Beam-eye view



Prefragments in a central collision

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

AAMC²

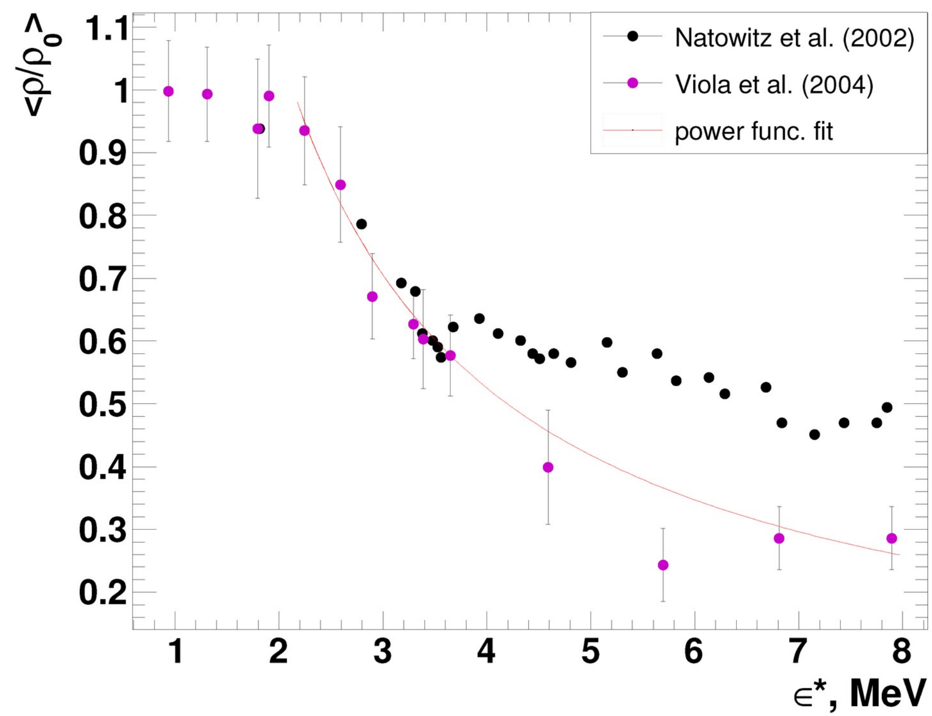
The prefragment is dynamically divided into several prefragments until thermodynamic equilibrium is reached.

R. Nepeivoda, et al., Particles **5** (2022) 40

Prefragment expansion

- While the size of the prefragment increases, the average distance between nucleons increases as well
- Therefore, if this increase is neglected, d should be decreased to emulate this effect. 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, with the parameters taken from experimental data

$$\varepsilon^* > 2 \text{ MeV/nucl}$$
$$\rho/\rho_0 = (\varepsilon^*/\varepsilon_s)^{-\alpha}$$
$$\alpha = -1.02 \pm 0.07$$
$$\varepsilon_s = 0.46 \pm 0.05 \text{ MeV}$$

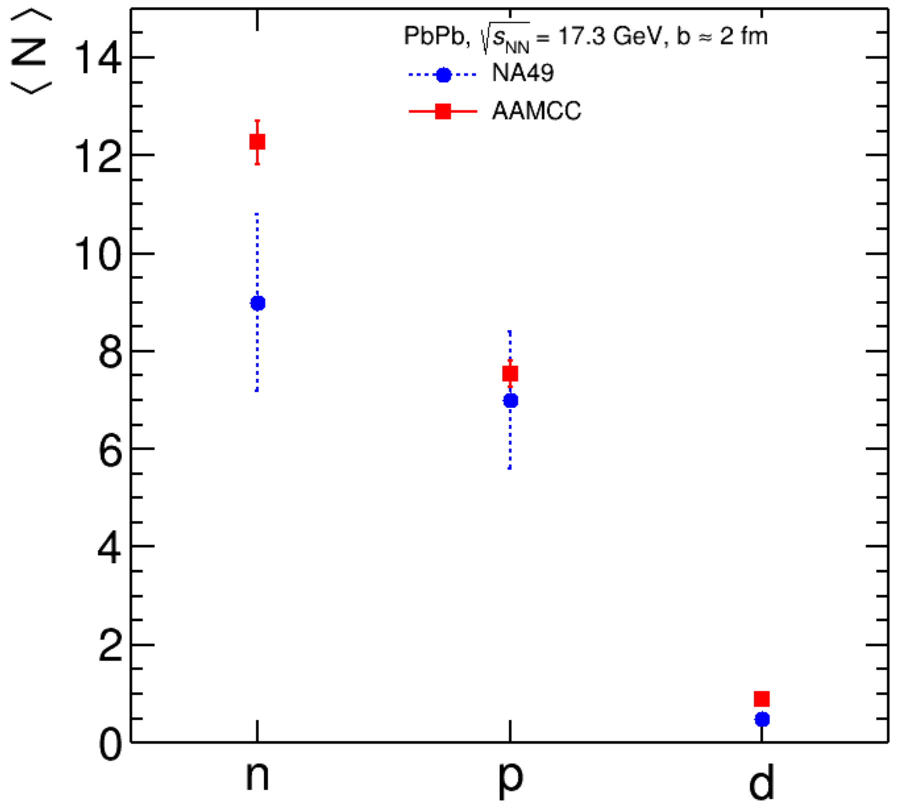


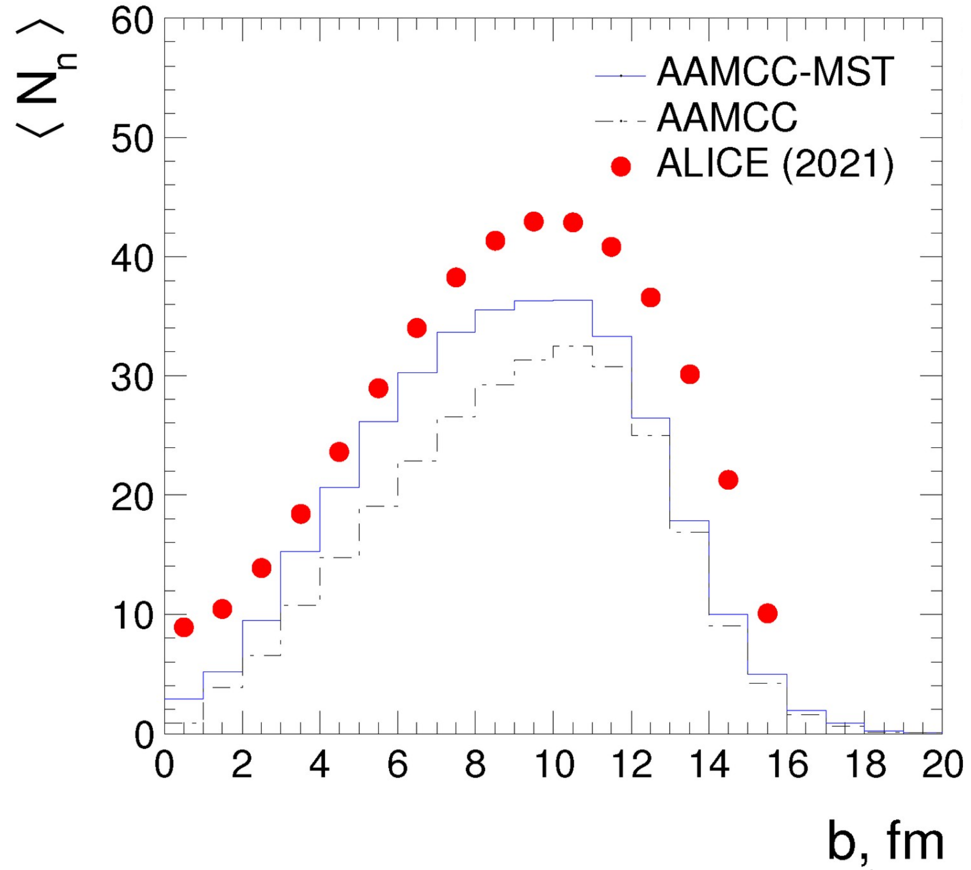
AAMC²

R. Nepeivoda, et al., Particles **5** (2022) 40

V.Viola et al., Phys. Rev. Lett. **93** (2004) 1
J.Natowitz et al., Phys. Rev. C **66** (2002) 031601

Yields of n, p and d in collisions at NA49 and ALICE energies

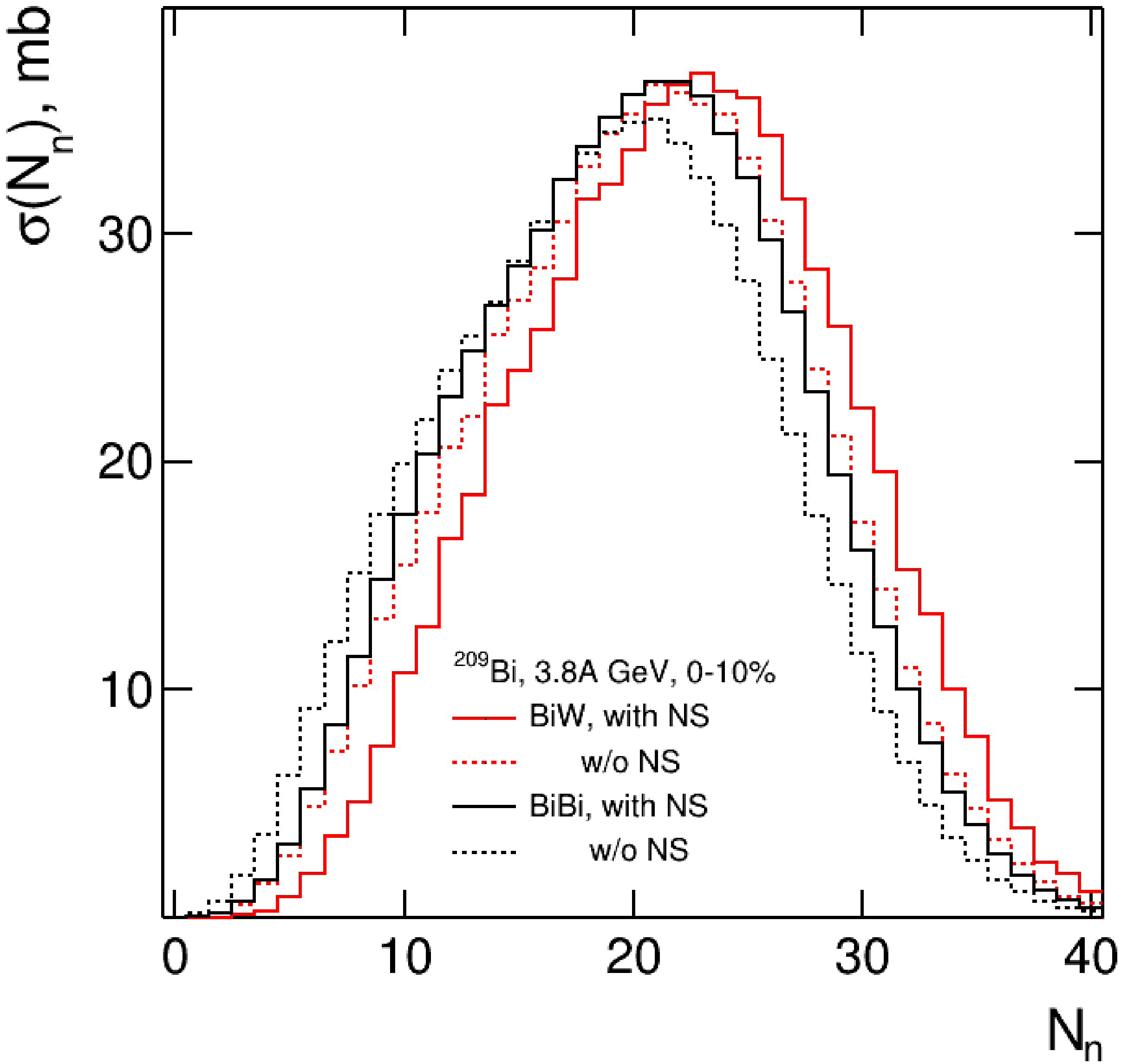




- Data were obtained from NA49*). AAMCC overestimates the production of neutrons, but describes protons and deuterons.
- AAMCC qualitatively agrees with preliminary ALICE data on spectator nucleon yields in general, but underestimates the data by ~10%.

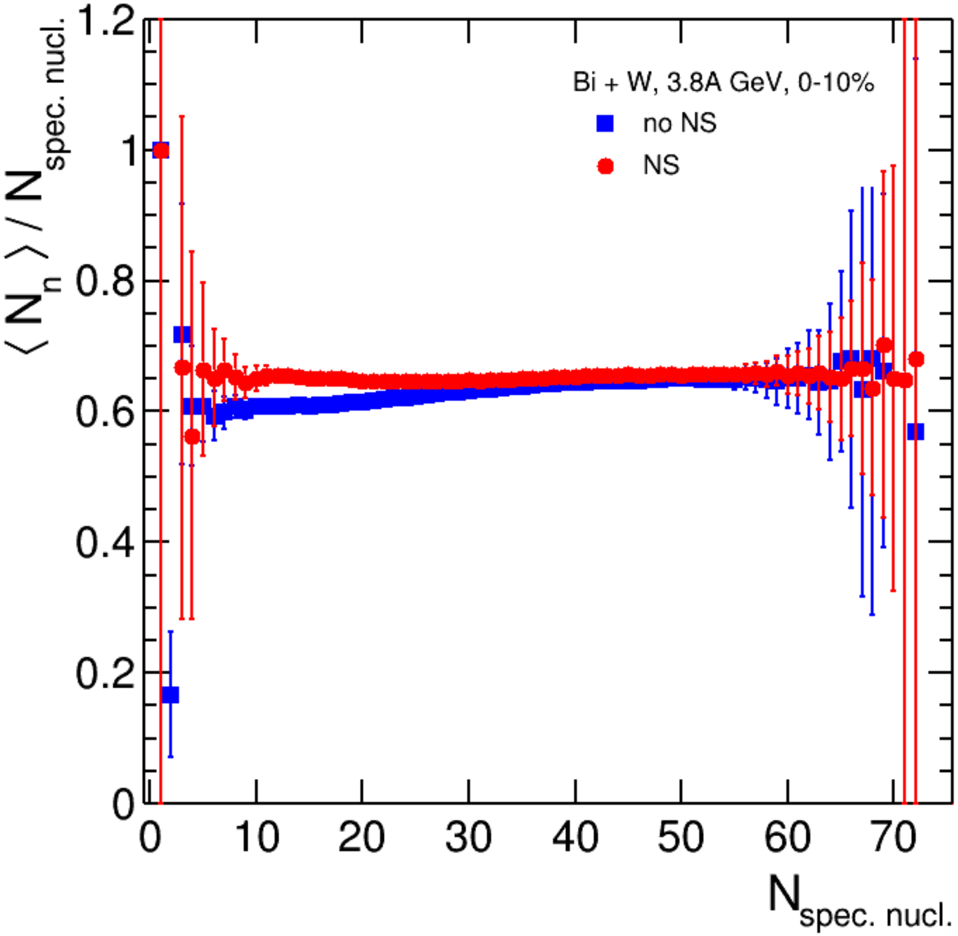
*) H. Appelshauser et al. Eur. Phys. J. A **2** (1998) 383

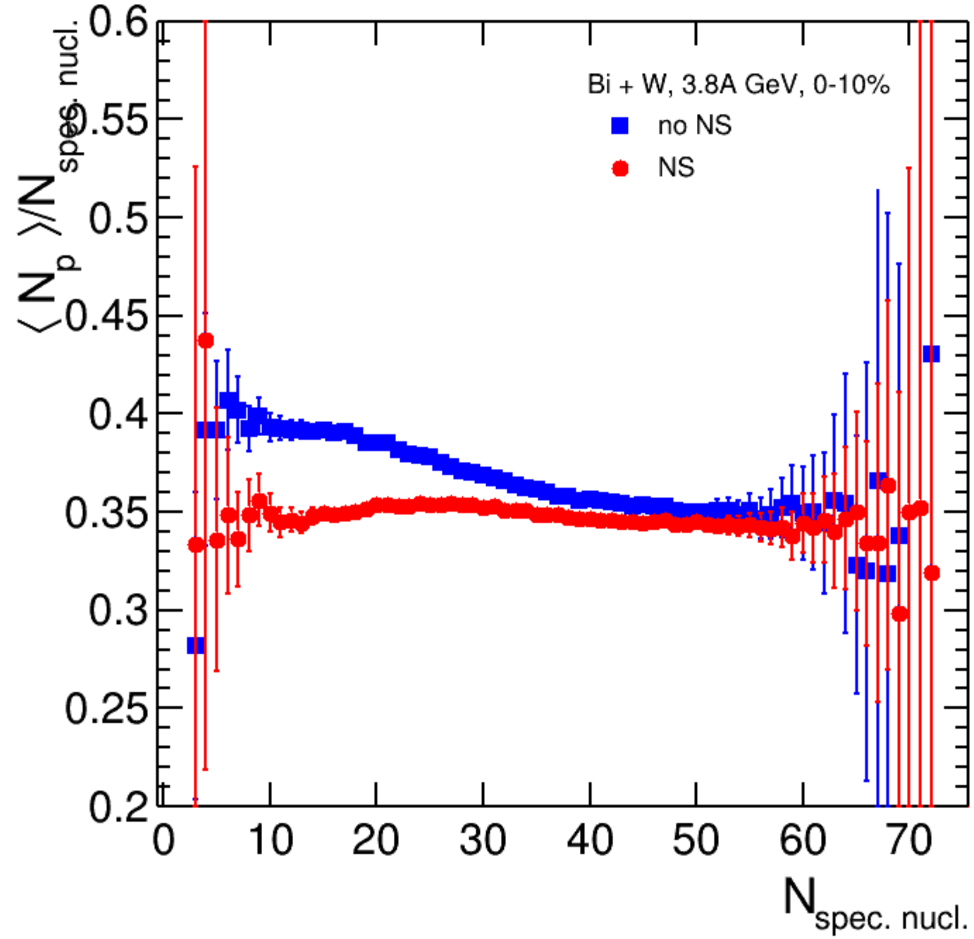
Cross section of the multiple neutron production as a probe of NS in ^{209}Bi



- As expected, the neutron multiplicity distribution in most central collisions is sensitive to the presence of neutron skin.
- To measure these cross sections an efficient detection of multineutron events is needed
- Any other parameters sensitive to neutron skin?

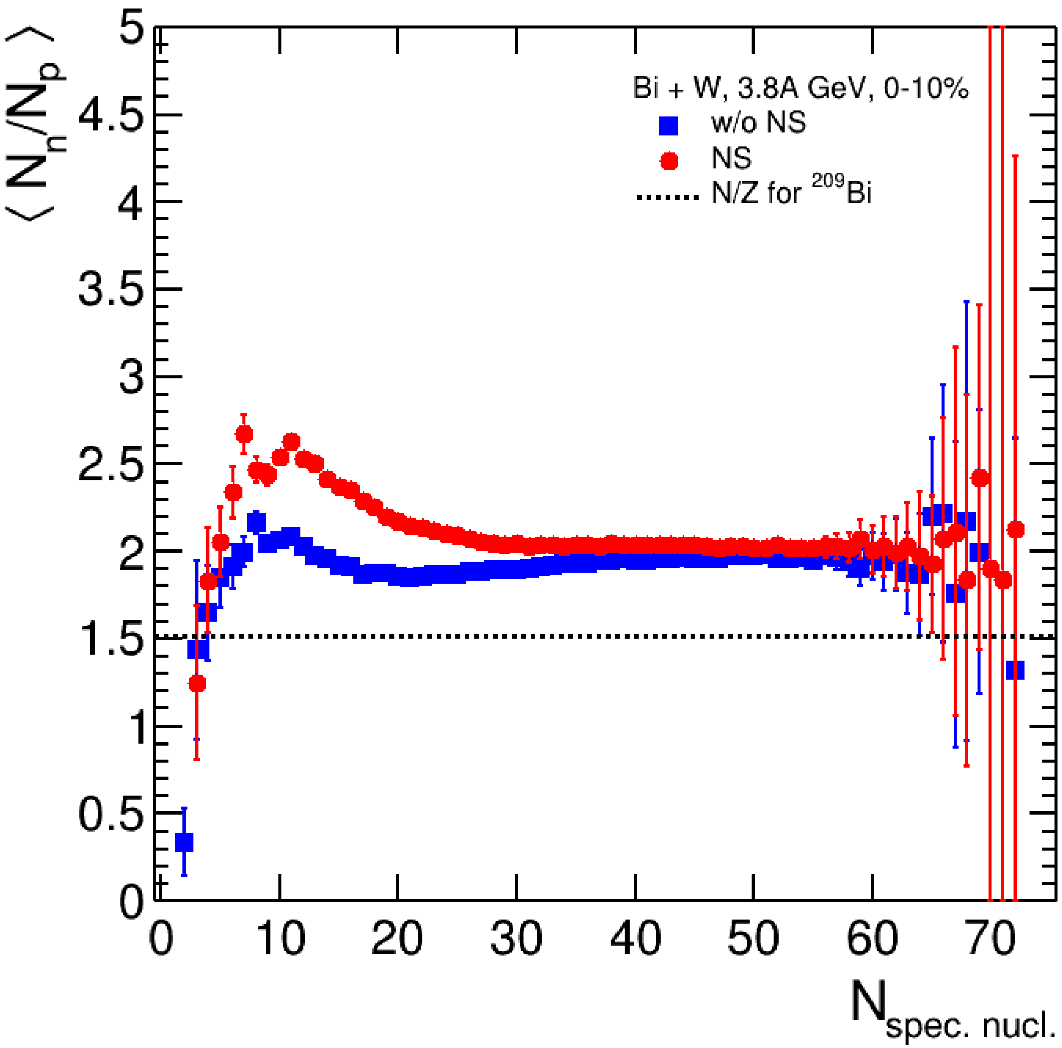
Yields of nucleons as a probe of NS in ^{209}Bi





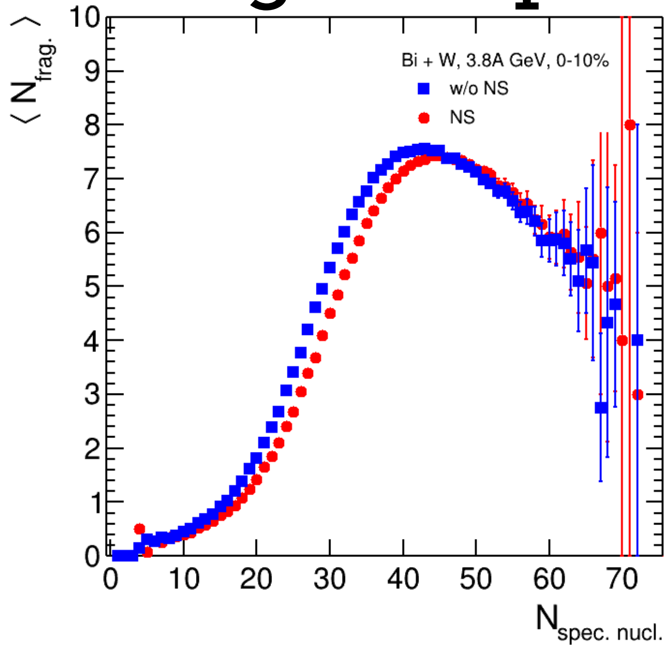
- With NS, $\langle N_n \rangle / N_{spec.nucl.}$ increases by ~8% for events with less than 20 nucleons.
- With NS, $\langle N_p \rangle / N_{spec.nucl.}$ decreases by ~15% for events with less than 20 nucleons.
- This suggests a higher sensitivity of n/p-ratio to the presence of NS.

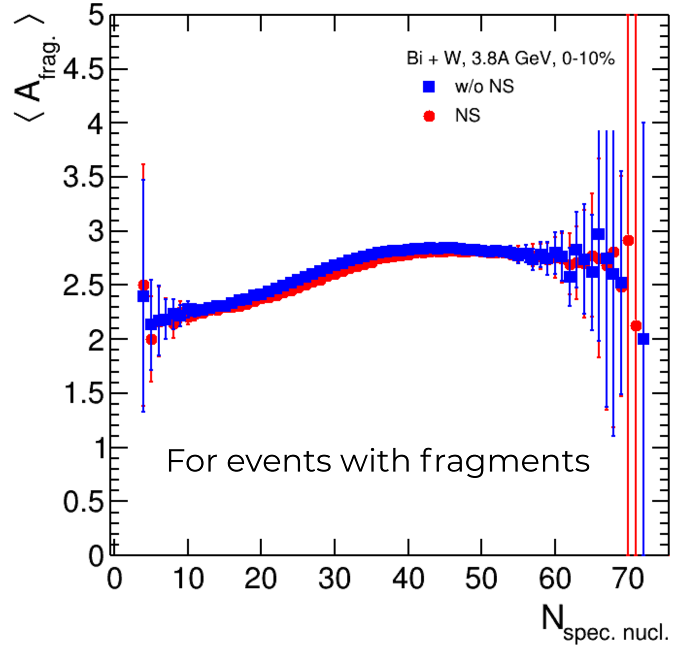
Increase of n/p-ratio for free nucleons

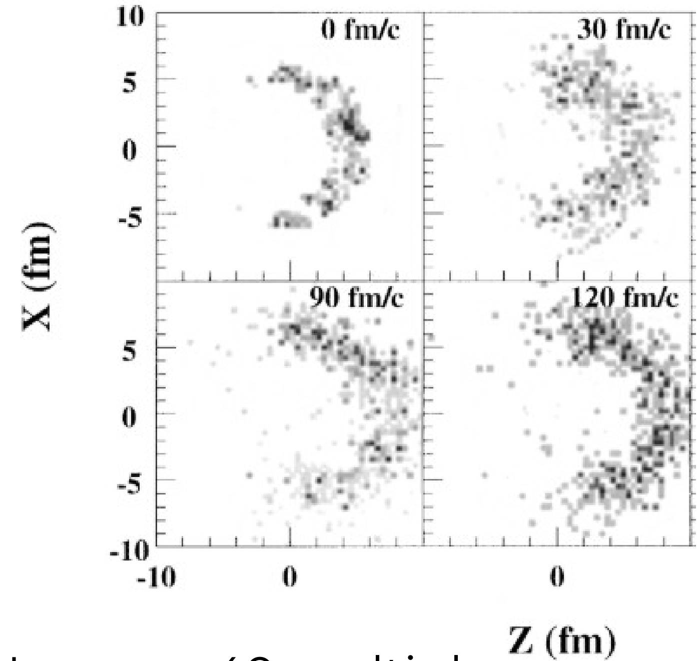


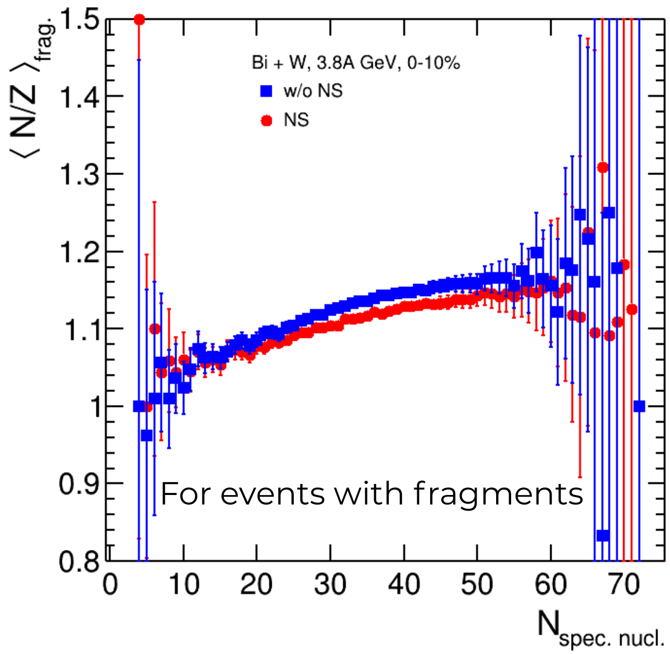
- With NS, <N_n/N_p> increases 25% for the events with ~10 released nucleons.
- Note a significant reduction of uncertainties in comparison to proton or neutron yields alone.
- For events $N_{spec.nucl.}$ ~ 40 the n/p ~ 2 is connected with the production of ~7.5 fragments with <$A_{frag.}$> ~ 3 and <N/Z>$_{frag.}$ ~ 1.1

Fragment production in central Bi+W collisions





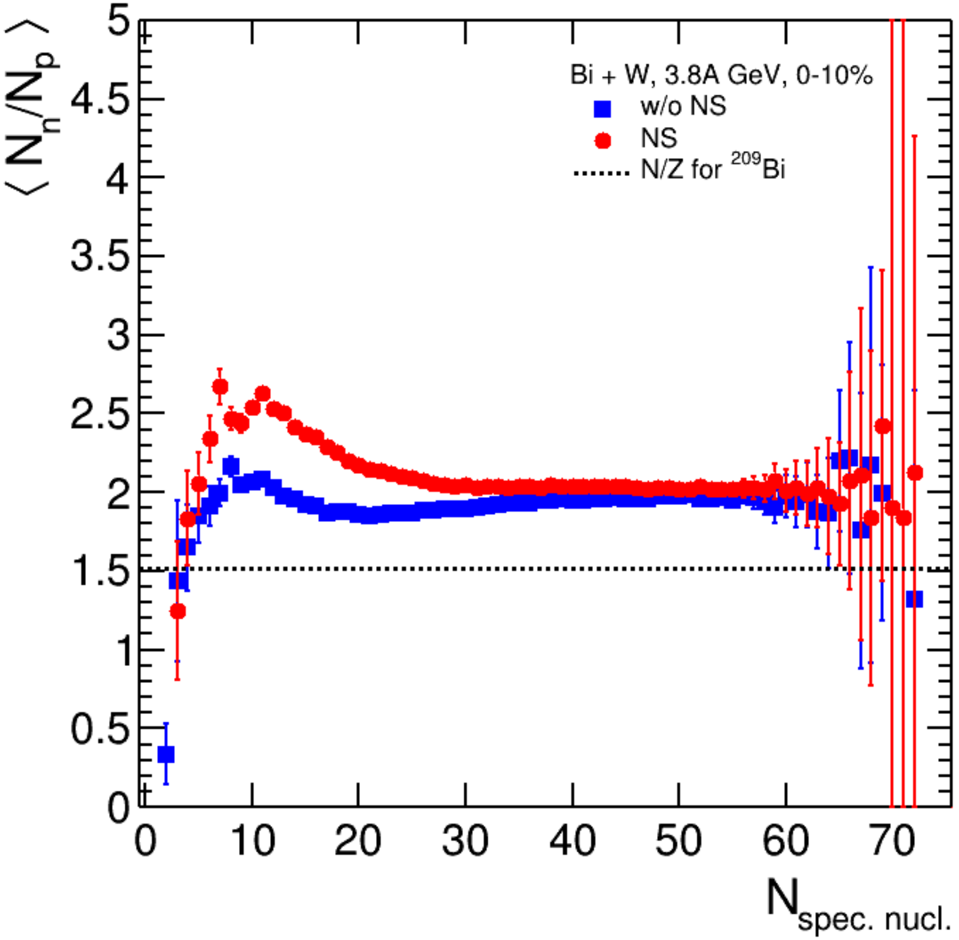


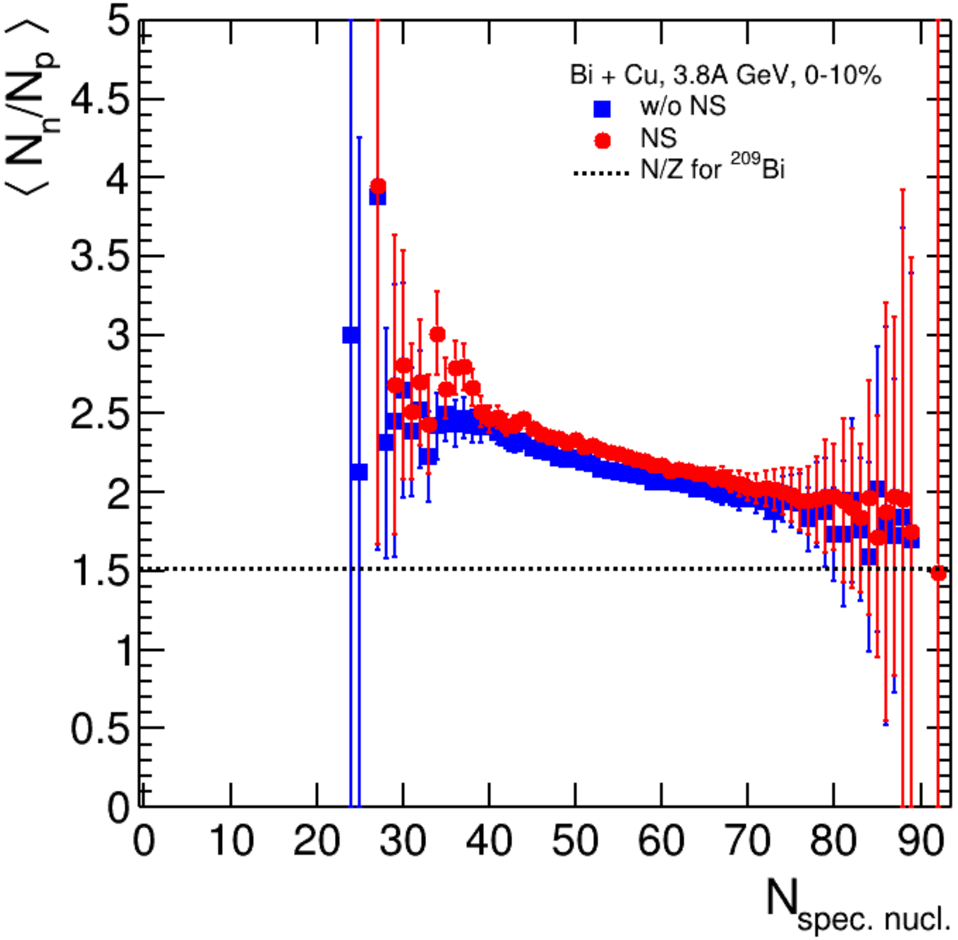


- In the collisions with $20 < N_{spec.nucl.} < 40$ multiple fragments is produced with $\langle A_{frag.} \rangle \sim 2.5$ and $\langle N/Z \rangle_{frag.} \sim 1.1$ so mostly deuterons are produced
- Average fragments multiplicity is up to 7.5 with $\langle A_{frag.} \rangle \sim 3$ so multiple various fragments can survive the collision
- These effects are closely related to the resilience of nuclear matter[1)], as the production of fragments in such central events is strongly dependent on pre-equilibrium clustering[2)].

1) M.Colonna et al, Phys. Rev. C 55 1404 (1995)
2) R. Nepeivoda, et al., Particles **5** (2022) 40

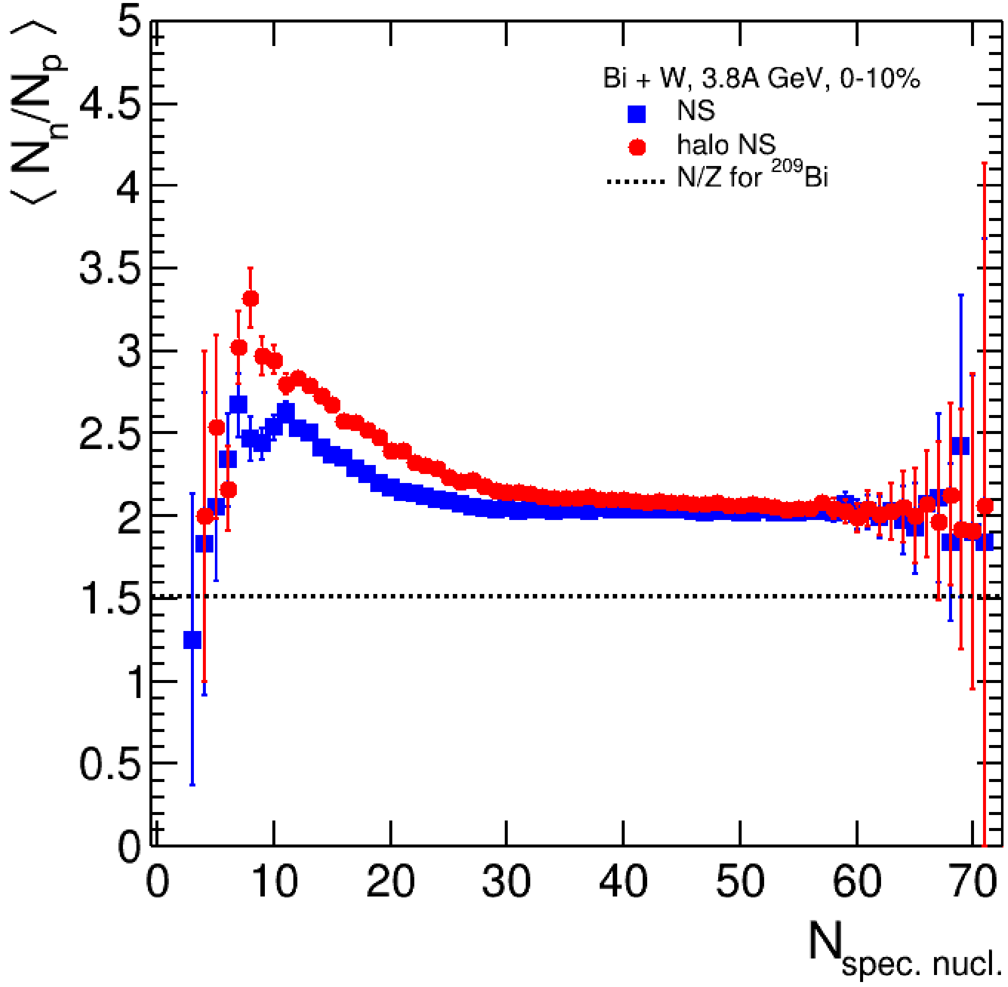
Dependence on the target nucleus





- For the Cu target the difference almost vanishes.
- With a smaller target a wider nuclear periphery is peeled away with its N/Z-ratio approaching the average N/Z for ^{209}Bi.

Pure halo vs. neutron skin



- Halo NS has $R_n = R_p$ and $a_n > a_p$.
- With halo NS, a higher average n/p-ratio is obtained.
- Higher diffuseness increases the probability of the neutron being at the periphery of the nucleus (~8 fm).
- The maximum average n/p-ratio is 3.25 for halo NS and 2.5 otherwise, but its dependendence on $N_{spec.nucl.}$ remains the same in general.

Conclusions

- The $<N_n>$, $<N_p>$ and $<N_n/N_p>$ in the collisions of ^{209}Bi with W are sensitive to the presence of neutron skin in ^{209}Bi in contrast with BiCu collisions.

- The ratio $<N_n/N_p>$ defined for free nucleons is more sensitive to the presence of neutron skin in ^{209}Bi.

- Increasing the diffuseness has the same effect as increasing the neutron skin thickness, so one needs additional data to distinguish the contribution of R_n and a_n of the neutron profile.

- Previously asymmetric nucleus-nucleus collisions were proposed to study the resilience of nuclear matter to explore the effect of the breaking into pieces instead of going back to a spherical shape*)

- We propose such collisions to study the effect of neutron skin

*) M.Colonna et al, Phys. Rev. C 55 1404 (1995)

Thank you for your attention!

Deepened Impulse, V. Kandinsky 1928

We are open to collaboration, please contact:

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