What can we learn from remnants of spectator matter in central nucleus-nucleus collisions?

I.A. Pshenichnov[1,2,*], N.A. Kozyrev[1,2], A.O. Svetlichnyi[1,2], U.A. Dmitrieva[1,2]

[1]Moscow Institute of Physics and Technology, Dolgoprudny, Russia
[2]Institute for Nuclear Research, Moscow, Russia
*e-mail: pshenich@inr.ru

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Outline

- In central collisions of high-energy nuclei quark-gluon plasma (QGP) is created in the fireball.

- QGP attracts most of attention, but less is known about the spectator matter represented by remnants of colliding nuclei beyond the fireball.

- In this work it is calculated that some spectator nucleons survive even in the most central (0-5%) events and their yields are sensitive to:
  - Excitation energy of spectator matter
  - Presence of neutron skin (NS) in colliding nuclei
  - Initial collision energy

- A new method to study NS at the LHC is proposed.

Our model: AAMCC (or A^2MC^2)

- Our model **Abrasion-Ablation Monte Carlo for Colliders (AAMCC)**[1] is based on the famous Glauber Monte Carlo version 3[2] and models of decays of excited nuclei from Geant4 toolkit[3] (G4Evaporation, G4SMM, G4FermiBreakUp).

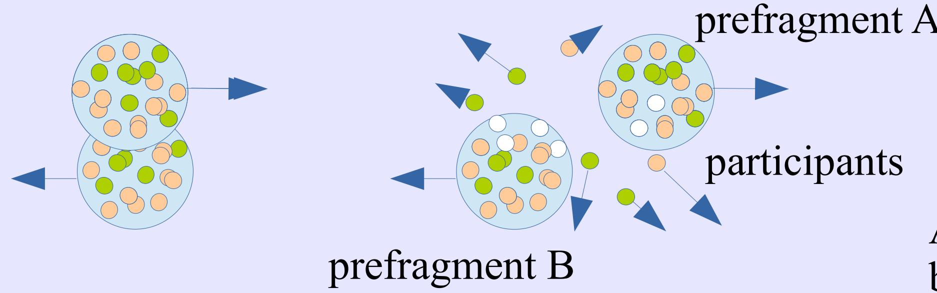
- A difference in proton and neutron density distributions in colliding nuclei is taken into account in GlauberMC v.3

- We tested and improved[4] G4SMM ($E^*/A_{pf} > 3$ MeV) and G4FermiBreakUp (the latter is for explosive decays of $Z < 9$, $A < 19$ nuclei).

- A key ingredient of the model is the calculation of the excitation energy of prefragments. Either Ericson[5] formula (based on level densities in initial nuclei) or a phenomenological approximation based on ALADIN data[6] is used.

Both prefragments are modelled.

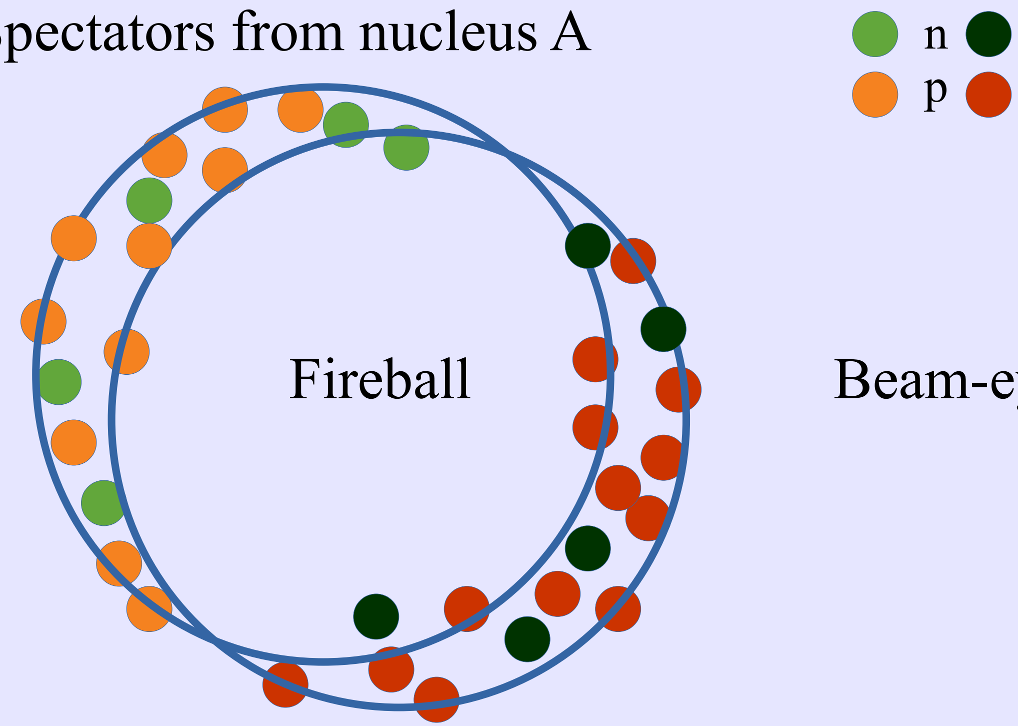
AAMCC is suitable for colliders.



Also in a talk by Alexander Svetlichnyi at this conference

[1] A. Sveltichnyi., I.P. Bull. RAS: Phys. **84** (2020) 1103
[2] C. Loizides, J.Kamin, D. d’Enterria, PRC **97** (2018) 054910
[3] J.M. Quesada,V. Ivanchenko, A. Ivanchenko et al., Prog. Nucl. Sci. Tech. **2** (2011) 936
[4] I.P., A.S. Botvina, I. Mishustin, W. Greiner, NIMB **268** (2010) 604
[5] T. Ericson, Adv. Phys. 9, 425 (1960).
[6] A.S. Botvina et al., NPA **584**, 737 (1995)

Central collisions are suitable to study the surface layers of nuclei in ZDC



- A large part of a thin surface layer is cut-off in central collisions and propagate forward as spectator matter.
- Its n/p ratio can be studied in forward neutron and proton calorimeters.

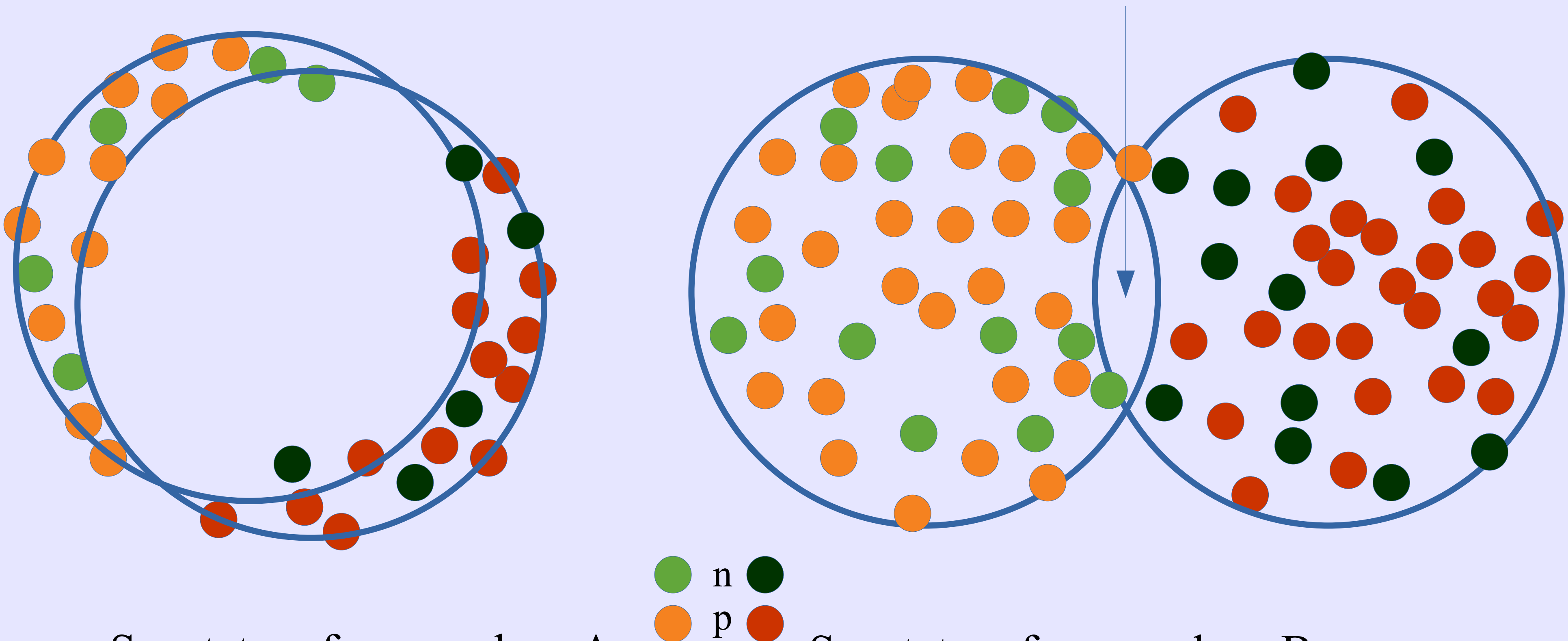
Studying NS in nucleus-nucleus collisions by neutron removal: proposed at low energy

	low or intermediate energies 0.1 - 1 GeV/nucleon	relativistic energies (RHIC or LHC)
central collisions	• Bending by nuclear forces - nuclear fusion. • Difficult to distinguish participant and spectator nucleons. • Inner and outer nucleons have enough time to be exchanged during the collision.	• Participant and spectator nucleons are well separated. • Outer nucleons are cut-off adiabatically and can be detected in forward calorimeters • A large part of neutron skin can be peeled off in one event
peripheral collisions	• Residual nuclei can be detected, e.g., in a mass separator following neutron removal to measure σ_{-N} for evaluating NS parameters[1,2)] 1) D.Q. Fang et al., PRC **81** (2010) 047603 2) C.A.Bertulani et al., PRC **100** (2019) 015802	• It is impossible to detect residual nuclei in colliders • Peripheral events are less sensitive to neutron skin as only a small part of it is removed

Peripheral vs central collisions: peeling the nuclear skin

A large part of neutron skin is peeled off

Only few nucleons from neutron skin are removed



Spectators from nucleus A

Spectators from nucleus B

<u>Central collisions are more favorable to study nuclear surface when spectator nucleons can be registered.</u>

Surface layers in heavy nuclei are enriched by neutrons

- Protons are pushed out by Coulomb repulsion and this have to be balanced by nuclear forces to keep a heavy nucleus stable.

- Extra neutrons atop the protons create extra surface tension.

- For spherical nuclei like ^{208}Pb both radial distributions are usually parameterized by two-parametric Wood-Saxon/Fermi functions:

$$\rho_{n,p}(r) = \frac{\rho_{0n,p}}{1+\exp\lfloor (r-R_{n,p})/a_{n,p} \rfloor}, \int d^3r(\rho_n(r) + \rho_p(r)) = A$$

- A case of $R_n > R_p$, $a_n = a_p$ is defined as <u>neutron skin</u>.

- In contrast, $R_n = R_p$, $a_n > a_p$ is defined as <u>neutron halo</u>.

- In reality it is mixed: $R_n > R_p$, $a_n > a_p$ or the parameters are too uncertain. Termed as NS in the following for simplicity.

Neutron skin in ^{208}Pb

- Proton distribution[1)]

$$R_p = 6.68 \pm 0.02 \text{ fm},\ a_p = 0.447 \pm 0.01 \text{ fm}$$

- Neutron distribution[1,2)]

$$R_n = 6.69 \pm 0.03 \text{ fm},\ a_n = 0.560 \pm 0.03 \text{ fm}$$

- Rather halo case, same half-radii, but with a wider diffuseness for neutrons:

$$R_p \approx R_n,\ a_n - a_p \approx 0.1 \text{ fm}$$

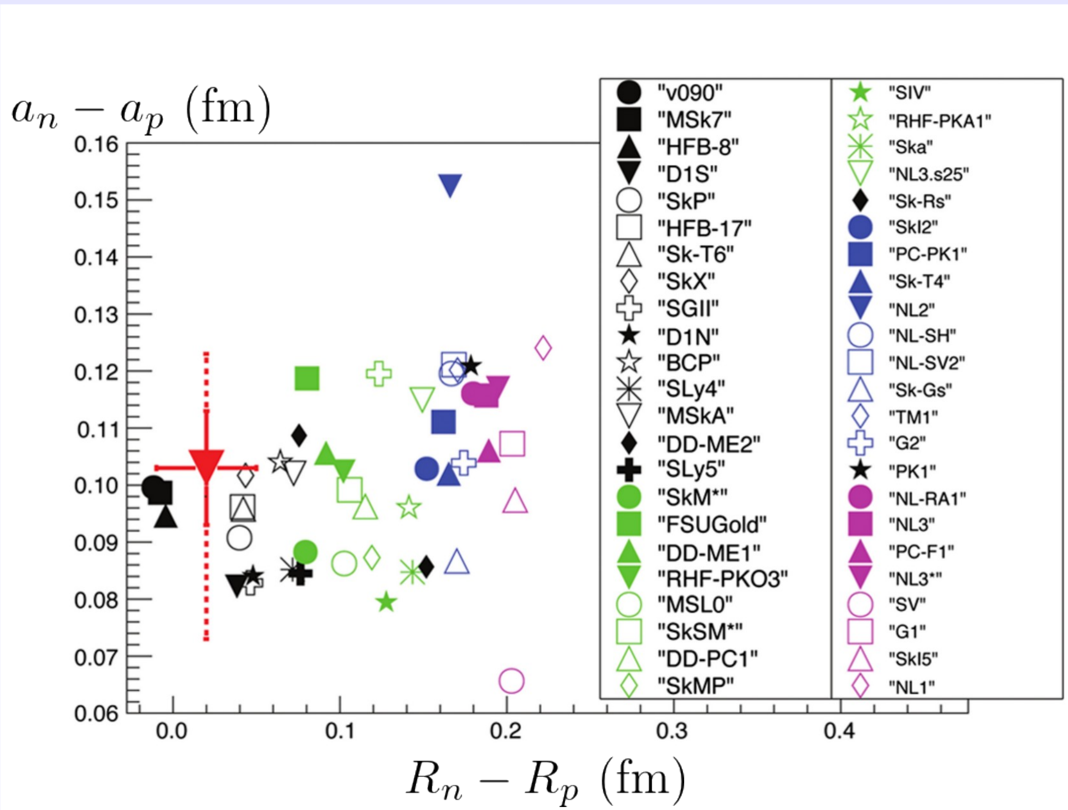
- NS/NH can be also characterized by the difference of r.m.s. radii[3)]:

$$\Delta r_{np} = \left\langle r_n^2 \right\rangle^{1/2} - \left\langle r_p^2 \right\rangle^{1/2} \quad \left\langle r_{n,p}^2 \right\rangle^{1/2} = \sqrt{\tfrac{1}{5}(3R_{n,p}^2 + 7\pi^2 a_{n,p}^2)}$$

- For ^{208}Pb with these parameters: $\Delta r_{np} \approx 0.15$ fm

1) B.Klos et al., PRC **76** (2007) 014311
2) C.M. Tarbert et al., PRL **112** (2014) 242502
3) G.A. Miller, PRC **100** (2019) 044608

Various measurements and calculations diverge ...



State-of-the-art nuclear theories predict for ^{208}Pb[1]:

$$\Delta r_{np} = 0.05 - 0.35 \text{ fm}$$

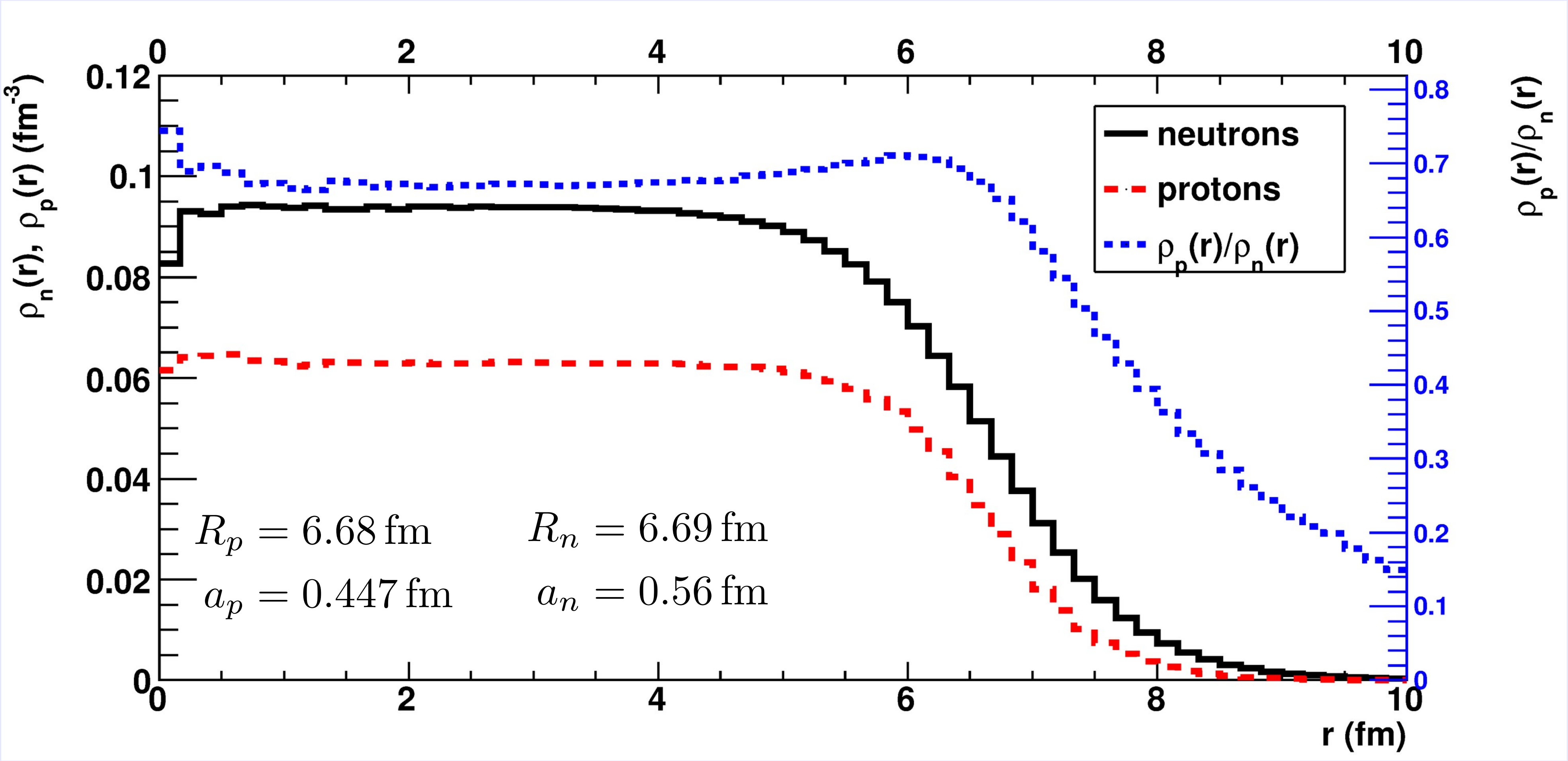
Red cross – measurements[2].

As shown[3], the total systematic uncertainty in extracting NS from (γ, π^0) is actually much larger.

[1] M. Centelles et al., PRC **82** (2010) 054314
[2] C.M. Tarbert et al., PRL **112** (2014) 242502
[3] G.A. Miller et al., PRC **100** (2019) 044608

<u>It is important to find new methods to study NS!</u>

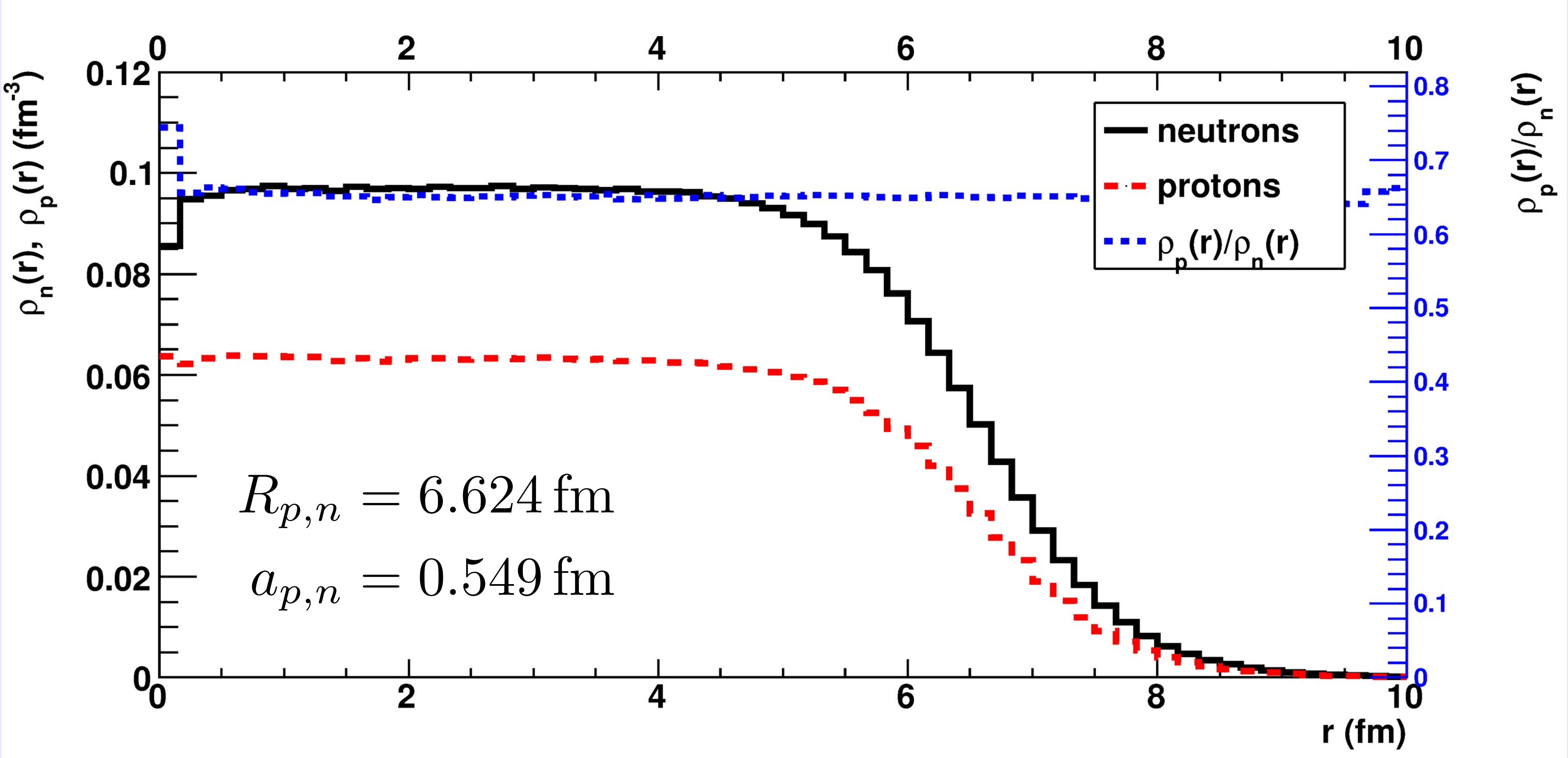
NS implemented in Glauber MC v3[1)]



Neutrons dominate at far nuclear periphery of ^{208}Pb,
note the left scale for $\rho_p(r)/\rho_n(r)$, it can be as small as 0.2!

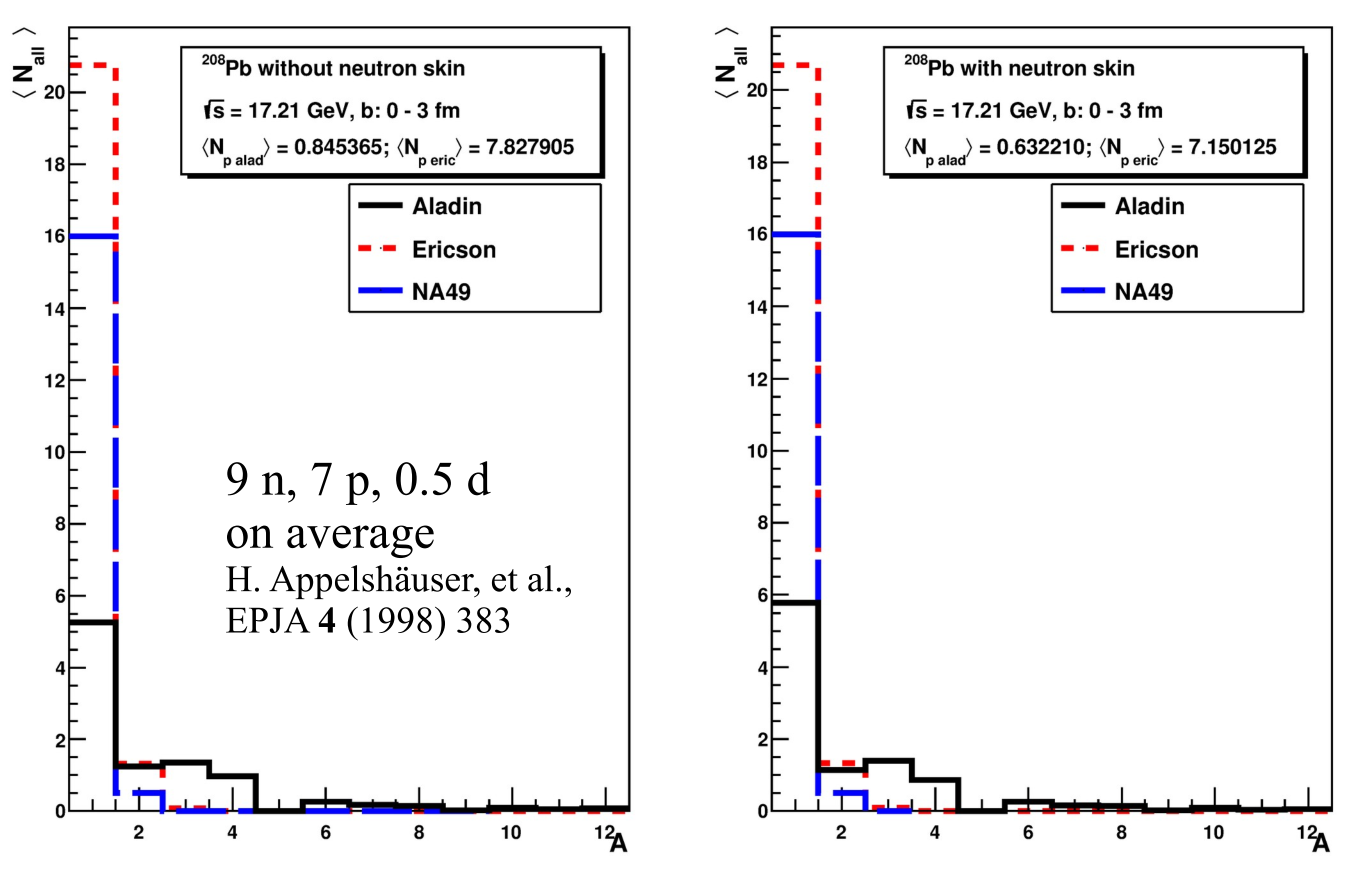
[1)] C.Loizides, J.Kamin, D. d'Enterria, PRC **97** (2018) 054910

We calculated with Glauber MC also without NS



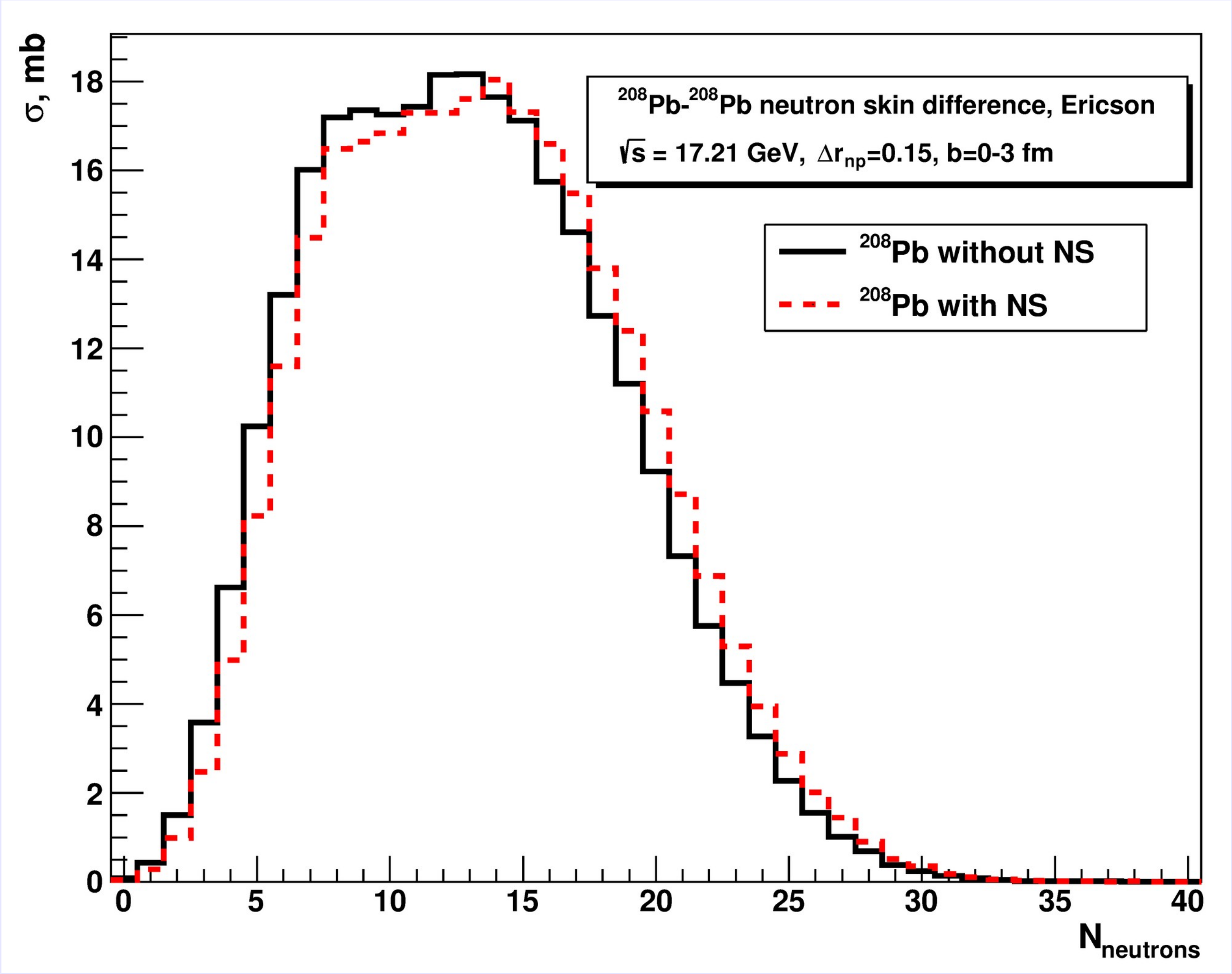
Used as a reference to estimate the sensitivity to NS:
$\rho_p(r)/\rho_n(r) = 0.65$ at all radii.

Average numbers of spectator nucleons and fragments in central ^{208}Pb–^{208}Pb collisions



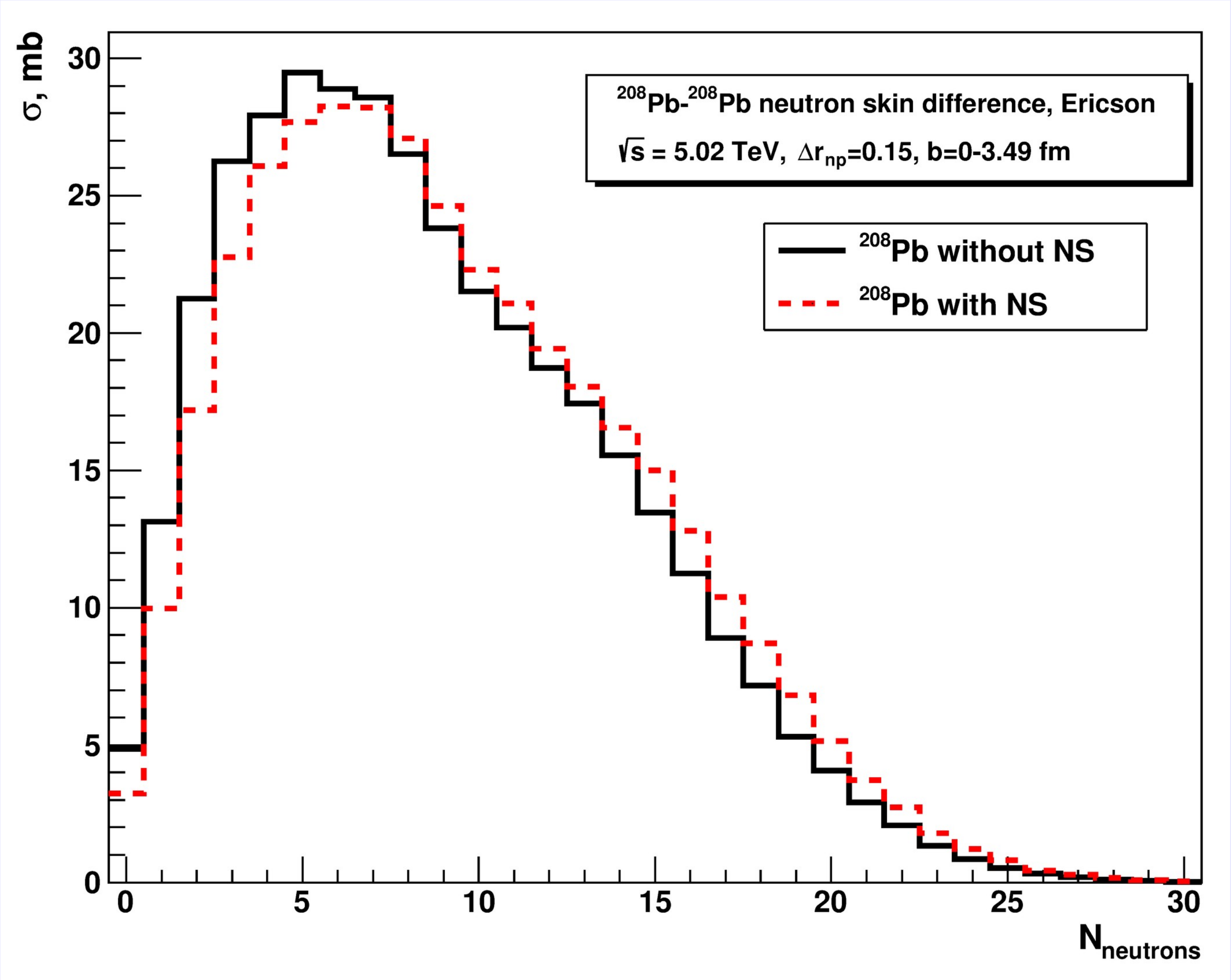
- AAMCC results are very sensitive to the method of calculating excitation energy of prefragments.
- With Ericson formula nucleons are overestimated, while with ALADIN – underestimated.
- Very small changes when calculated with NS: the total number of nucleons is not sensitive to NS.
- Take Ericson formula and calculate other characteristics in central collisions ?

Neutron multiplicity distributions - SPS



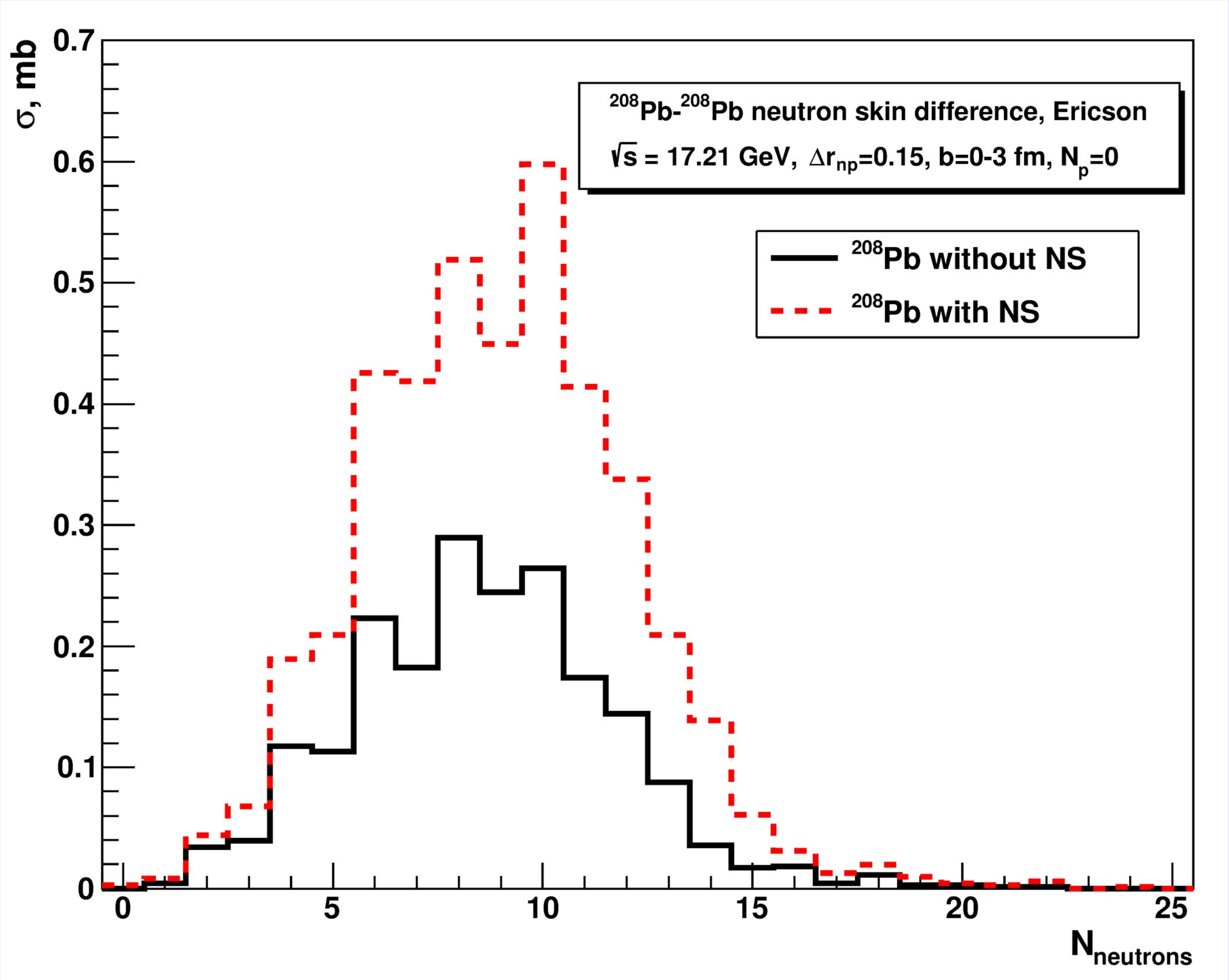
- This distribution is more sensitive to NS, some $\sigma(N_{neutrons})$ are larger by ~20% with NS.
- w/o NS: $\langle N_{neutrons} \rangle = 12.9$, with NS $\langle N_{neutrons} \rangle = 13.5$

Neutron multiplicity distributions - LHC



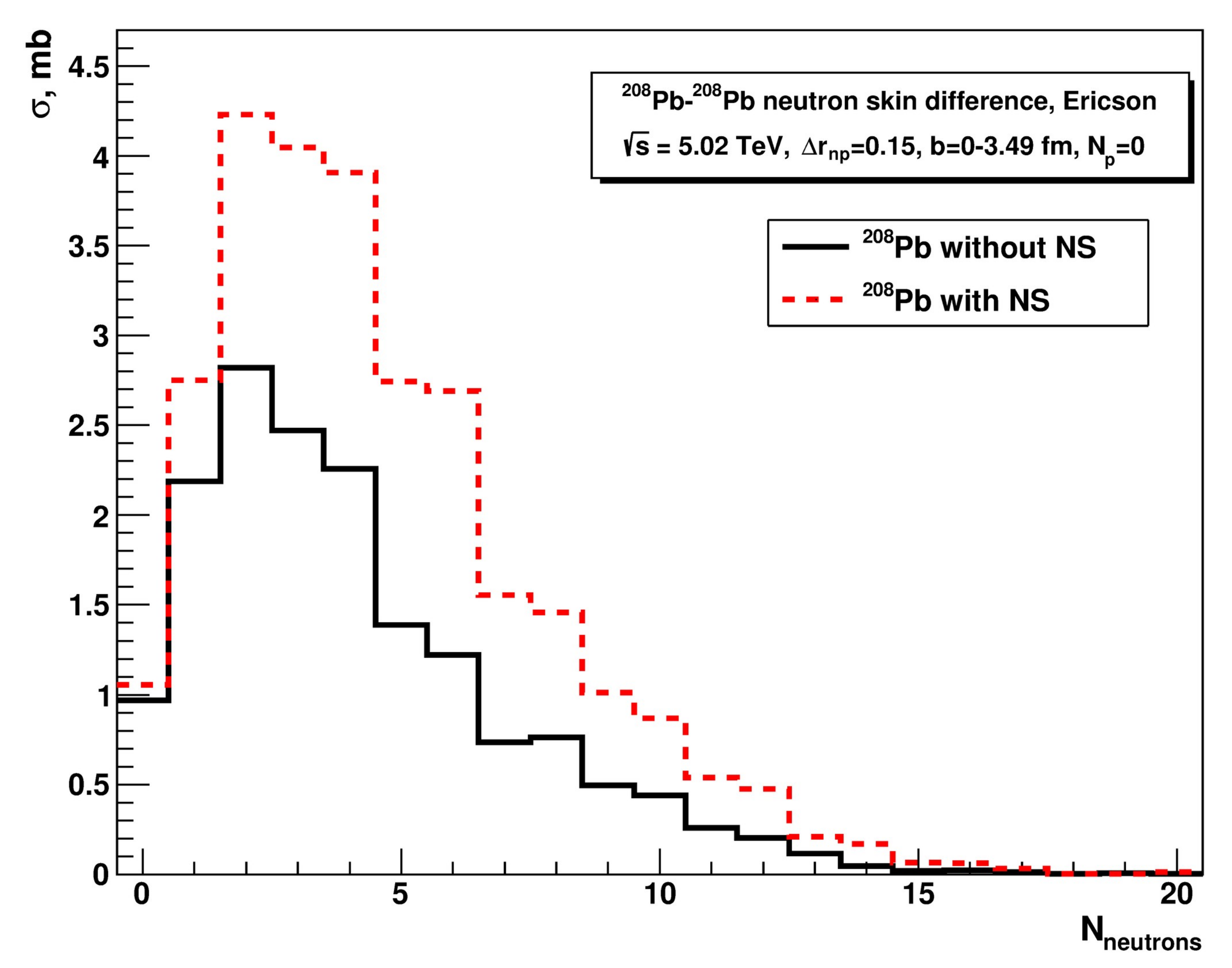
- Modest changes (~20%) also at the LHC. Average neutron multiplicity is slightly higher with NS.
- w/o NS: $\langle N_{neutrons} \rangle = 8.7$, with NS $\langle N_{neutrons} \rangle = 9.3$

Neutron multiplicity, 0p - SPS



- With NS taken into account the cross sections to remove given numbers of neutrons, but without proton removal, become twice as large.
- The effect of NS is obvious.

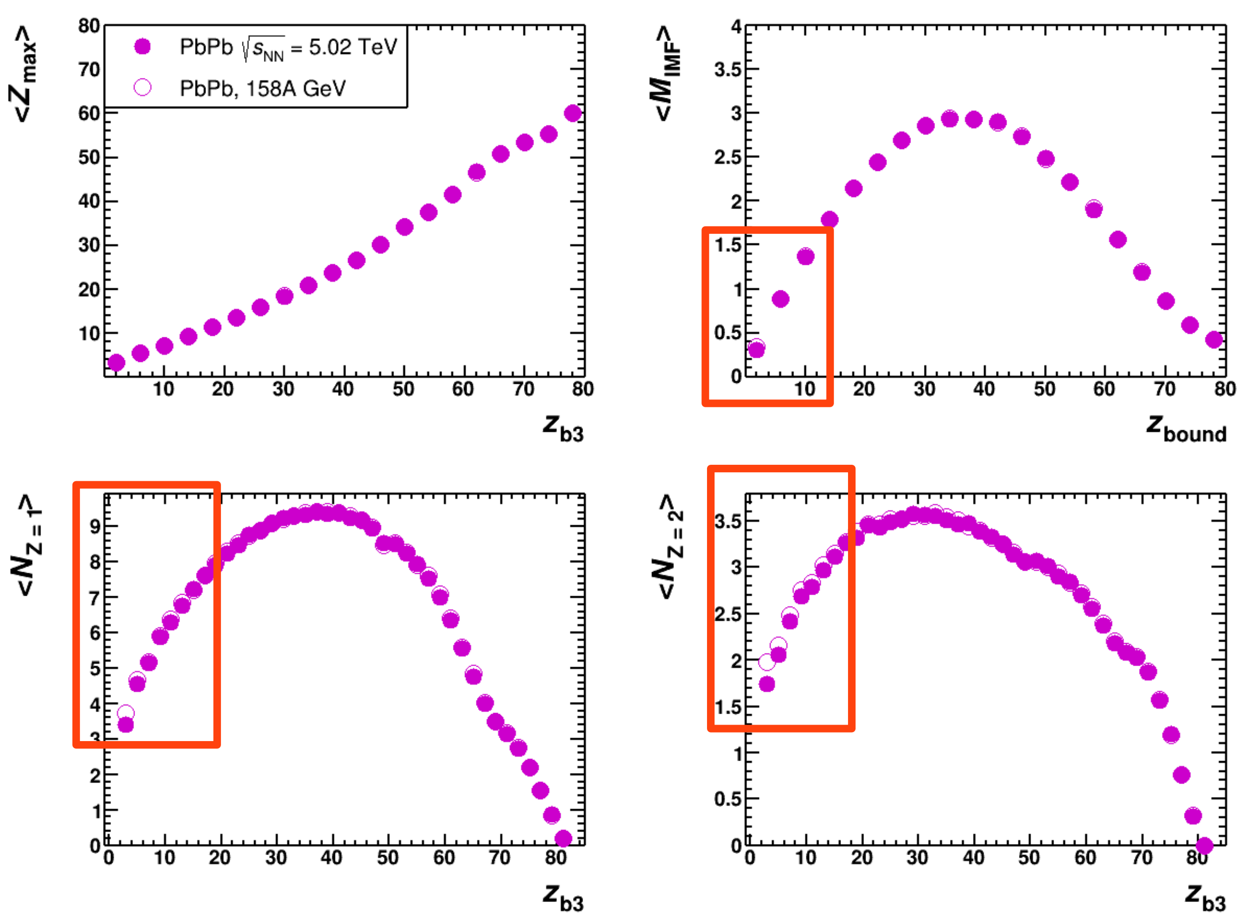
Neutron multiplicity, 0p - LHC



- Also at the LHC the cross sections to remove 2 – 10 neutrons and 0 protons rise dramatically with NS.

Why does the multiplicity of spectator nucleons decrease at the LHC w.r.t. SPS?

At the first glance this contradicts to the well-known universality of spectator fragmentation observed at low and intermediate energies, but it is predicted by AAMCC only for central collisions.



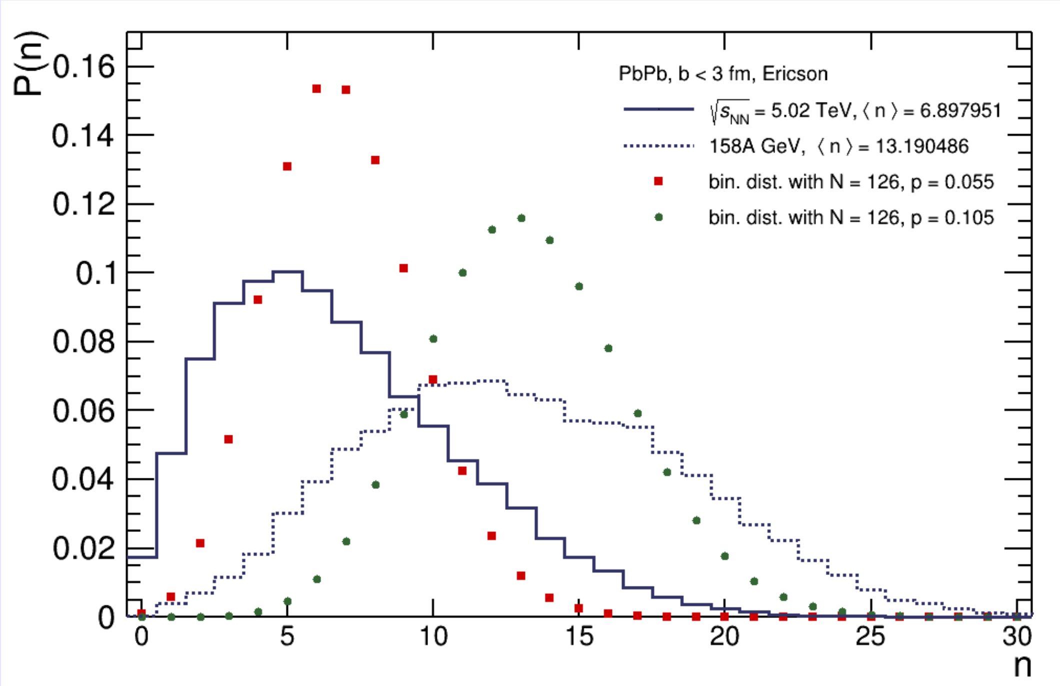
1. Z_{bound} – total charge confined in fragments with $Z \geq 2$, $Z_{bound} \sim b$
2. Z_{bn} – same as Z_{bound}, but for $Z \geq n$, $Z_{bn} \sim b$
3. M_{IMF} – number of intermediate mass fragments ($3 \leq Z \leq 30$)
4. $N_{Z=n}$ – number of fragments with $Z = n$, $N_{Z=1}$ of H, $N_{Z=2}$ of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

In central collisions nucleons pass through the largest thickness of the collision partner

- A kind of depletion of spectator matter at the LHC is estimated because the probability for nucleon to avoid interaction and become a spectator drops as σ_{NN} increases from 32.4 mb at the SPS to 67.6 mb at the LHC.

- The collision energy trend of AAMCC results can be understood by the comparison with binomial distributions.

- Imagine *n* = 126 neutrons propagating through a slab of nuclear matter of the average thickness *L* of normal nuclear density $\rho_o = 0.16$ fm^{-3}.



Average probability *p* for a neutron to survive in a Pb-Pb collision and become a spectator:

$$p = \exp(-L\rho_o\sigma_{NN}) = \langle n \rangle /126$$

$$\ln p = -L\rho_o\sigma_{NN}$$

SPS: $p = 13.19/126 = 0.105$

LHC: $p = 6.9/126 = 0.055$

$$\frac{\ln 0.105}{\ln 0.055} = 0.78$$

$$\frac{\sigma_{NN}^{SPS}}{\sigma_{NN}^{LHC}} = \frac{32.4\text{mb}}{67.6\text{mb}} = 0.48$$

Not exactly, but of similar scale ...

Conclusions

- As shown by calculations with AAMCC, the cross sections of emission of given numbers of spectator neutrons in central ^{208}Pb-^{208}Pb collisions are sensitive to the presence of neutron skin (NS).

- When only spectator neutrons are emitted without spectator protons, the cross sections with NS are calculated twice as large as without NS.

- Further AAMCC developments are necessary to improve the description of central collisions.

- ALICE experiment at the LHC is equipped with forward neutron and proton calorimeters. The effect of NS in central collisions of ultrarelativistic nuclei can be studied there.

Thank you for attention!

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