Properties of Spectator Matter in Nuclear Collisions at NICA

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Introduction

- We are looking for an extreme state of mater - quark-gluon plasma (QGP) in collisions of relativistic nuclei in the domain of overlap of nuclear densities.
- However, spectator matter represented by remnants of colliding nuclei beyond the fireball attracts less attention.
- It is also a challenge to study forward projectile fragments in collisions of relativistic nuclei with electronics detectors because spectator fragments are emitted in a very narrow forward cone close to the beam (calorimetry, no PID)
- Charged projectile fragments were measured in experiments at JINR, BNL AGS and CERN SPS by various techniques (to name a few):
  - nuclear track detectors. (CR39: H.Dekhissi et al., NPA 662 (2000) 207; PET: L.Y. Geer et al., PRC 52 (1995) 334)
  - stacks of nuclear emulsion (M.I. Adamovich et al., EPJA 5 (1999) 429; A. A. Zaitsev, P.I. Zarubin, Phys. At. Nucl. 81 (2018) 1237)
  - multiple sampling ionization chambers (C.Scheidenberger et al., PRC 70 (2004) 014902)

Outline

- What else can we get from measurements with forward calorimeters in addition to detecting spectator nucleons for centrality or reaction plane determination?

- Is spectator physics interesting?

- Our dedicated model: Abrasion-Ablation Monte Carlo for Colliders (AAMCC) and comparison to experiment.

- New characteristics studied with AAMCC to support centrality determination, e.g.,with ML methods:
  - Asymmetry of spectators
  - Sum of Z^2 per spectator nucleon

- With AAMCC we show that the yields of spectator neutrons in central nucleus-nucleus collisions are quite sensitive to the presence of neutron skin in colliding nuclei.

I. Our model: AAMCC   (or A²MC²)

- 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).

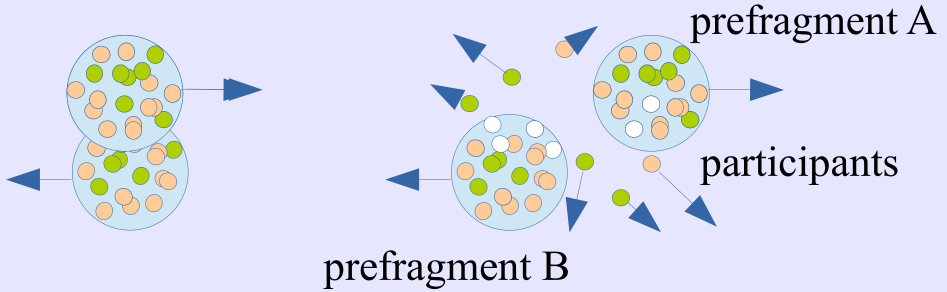
- A difference in proton and neutron density distributions in colliding nuclei is taken into account in GlauberMC v.3

- 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.

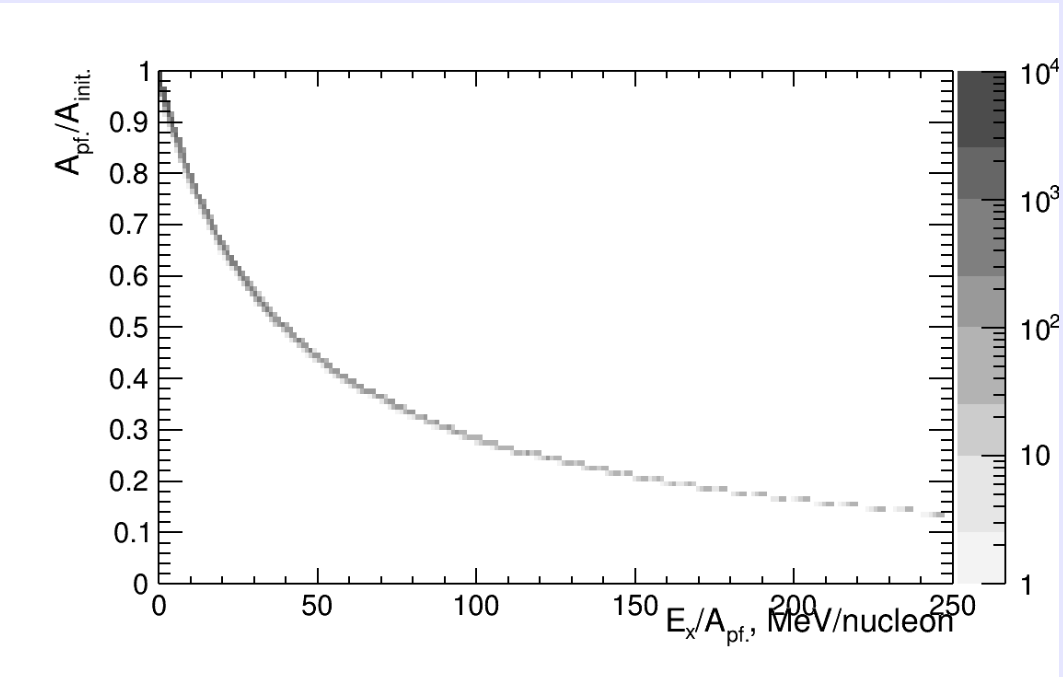
Both prefragments are modelled.

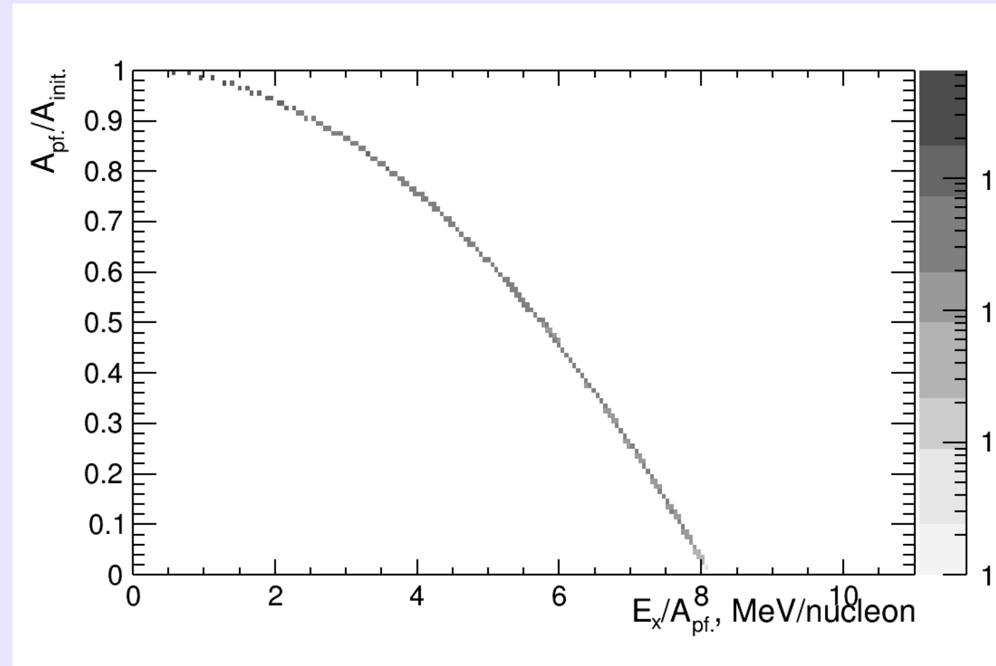
AAMCC is suitable for colliders.



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)

AAMCC: correlation between excitation energy and prefragment volume





$$\rho_e(E_x, a) = \frac{g_0^a}{a!(a-1)!} E_x^{a-1}$$

Level density in the particle-hole model:
Ericson formula T. Ericson, Adv. Phys. **36** (1960) 425

E_x – excitation energy

a – number of removed nucleons

A – mass number of the initial nucleus

Level density parameter $g_0 \approx 16\ \mathrm{MeV}^{-1}$

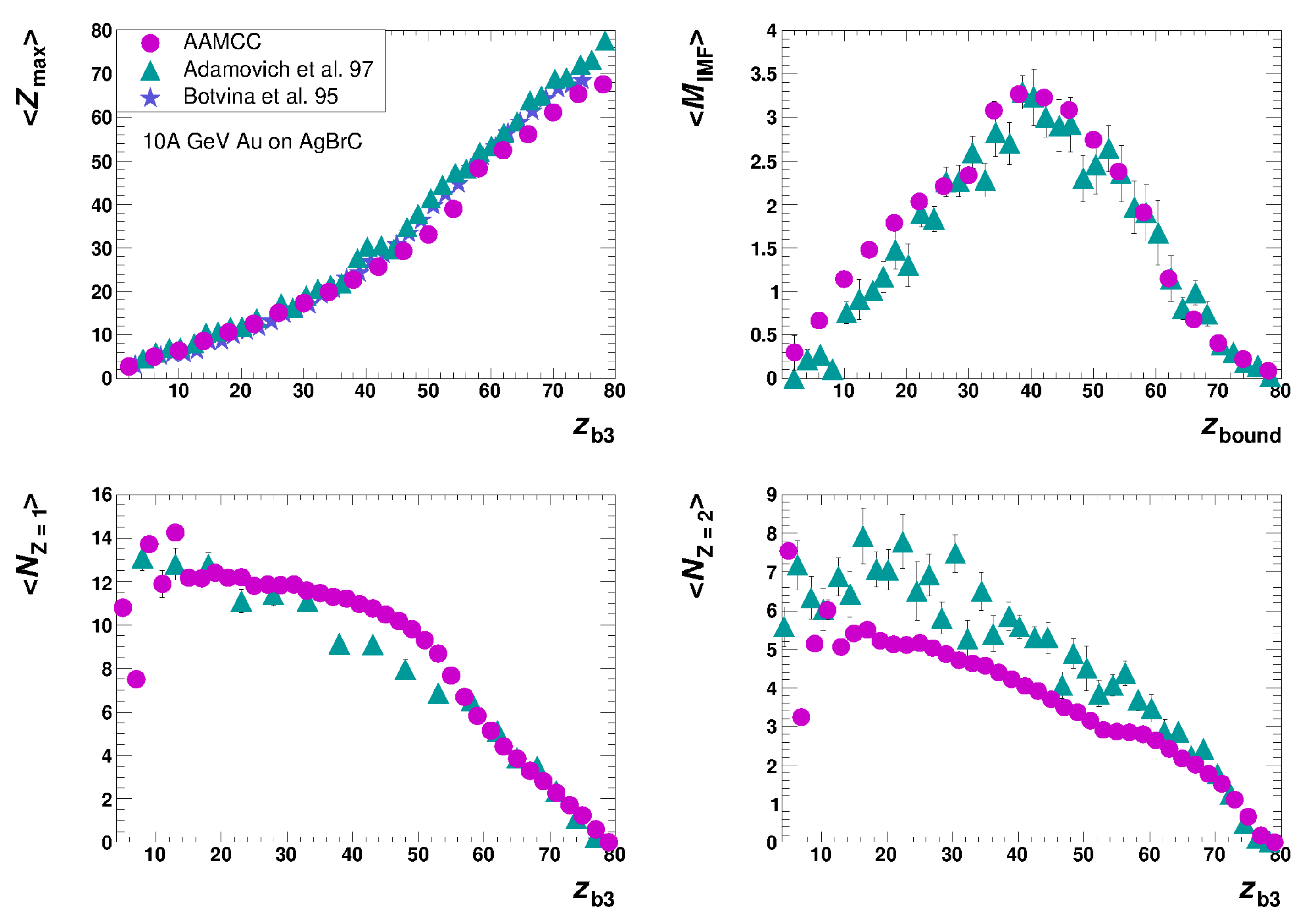
$$1 - a/A = 1 - 0.015[E_x/(A-a)]^2$$

Empirical approximation by ALADIN collaboration

A. S. Botvina et al. – Nucl. Phys. A **584** (1995) 737

See C. Scheidenberger et al., PRC **70**, 014902 (2004) for comparison of these methods

Comparison with data



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

- Collisions of 10.7A GeV ^{197}Au with light and heavy targets
- Rise and fall of multifragmentation is described well
- Dependence on centrality is reproduced
- H fragments are described well, but He fragments are underestimated

EMU-01/12 Collaboration Z. Phys. A **359** (1997) 277

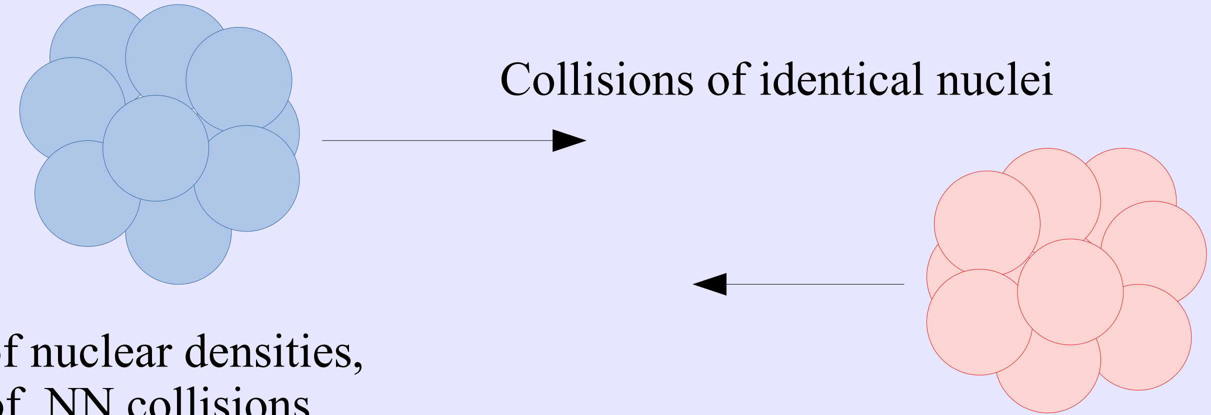
ALADIN data: NPA **584** (1995) 737

II. Forward-backward asymmetry in a collider

Side A

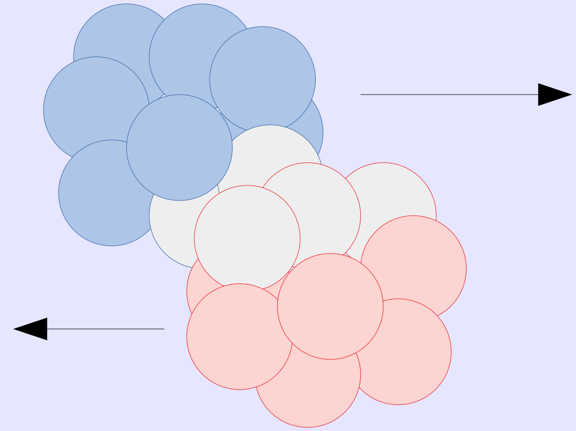
Collisions of identical nuclei

Side B



Fluctuations of nuclear densities,
stochasticity of NN collisions

Unequal numbers of spectator
nucleons



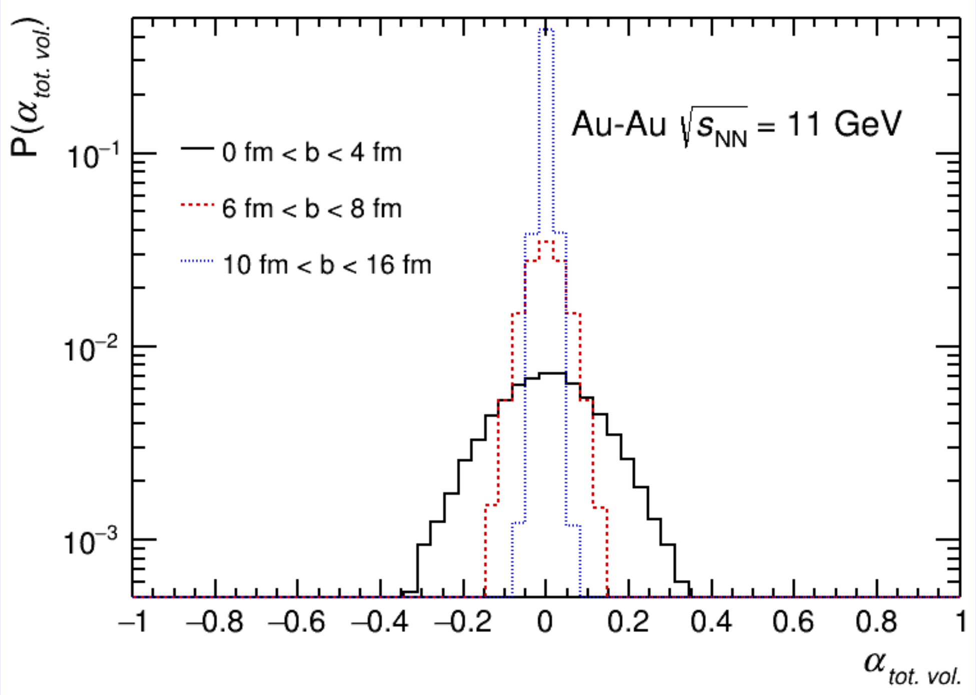
The forward-backward asymmetry of a quantity N is defined as:

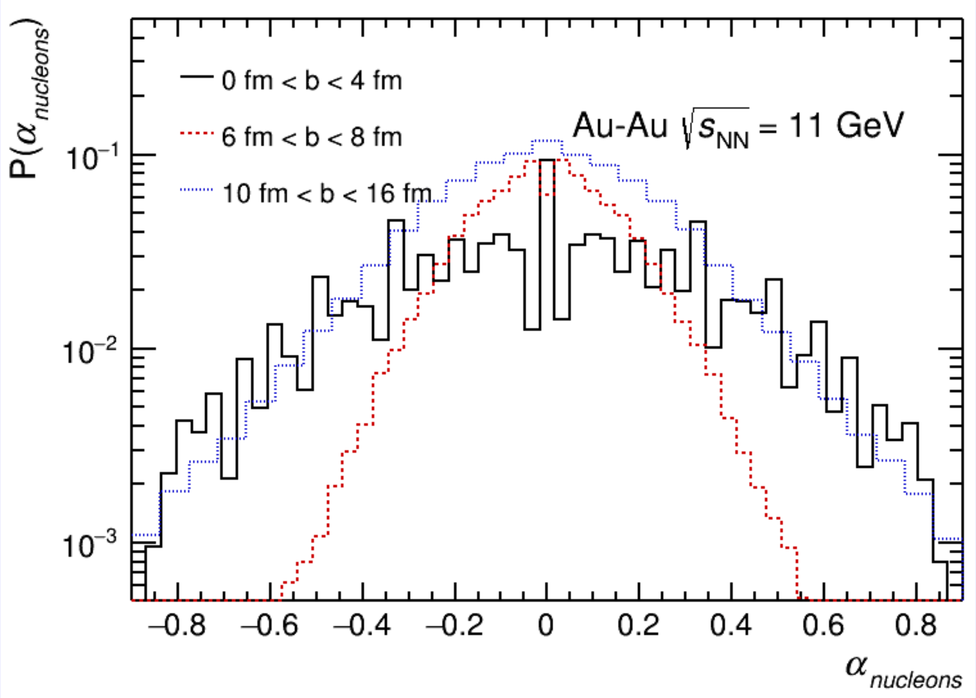
$$\alpha_N = \frac{N_A - N_B}{N_A + N_B}$$

N_A, N_B stand for the numbers of spectator nucleons, neutrons etc. at the sides A and B, respectively.

L.P. Csernai, G. Eyyubova, V.K. Magas, PRC **86** (2012) 024912
R. Raniwala, R. Raniwala, C. Loizides, PRC **97** (2018) 024912

Asymmetry of the total spectator volume and of free spectator nucleons

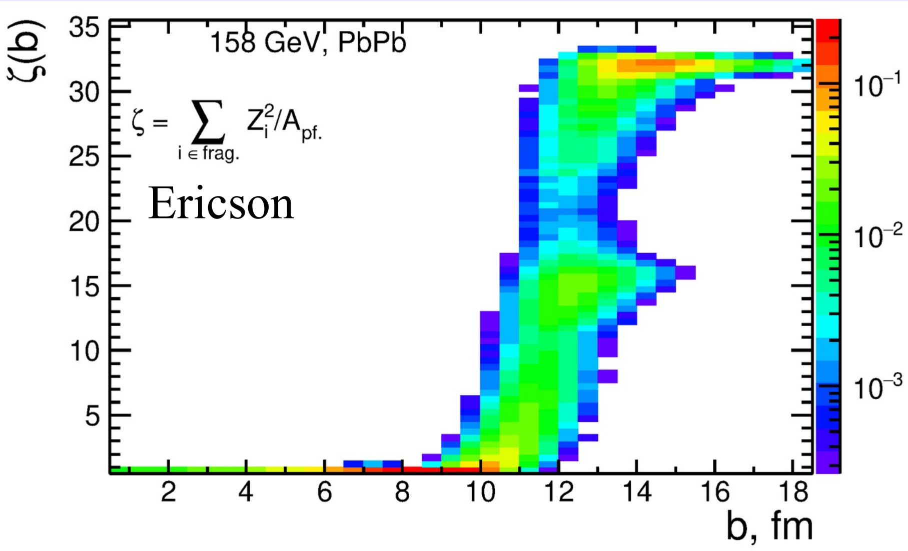


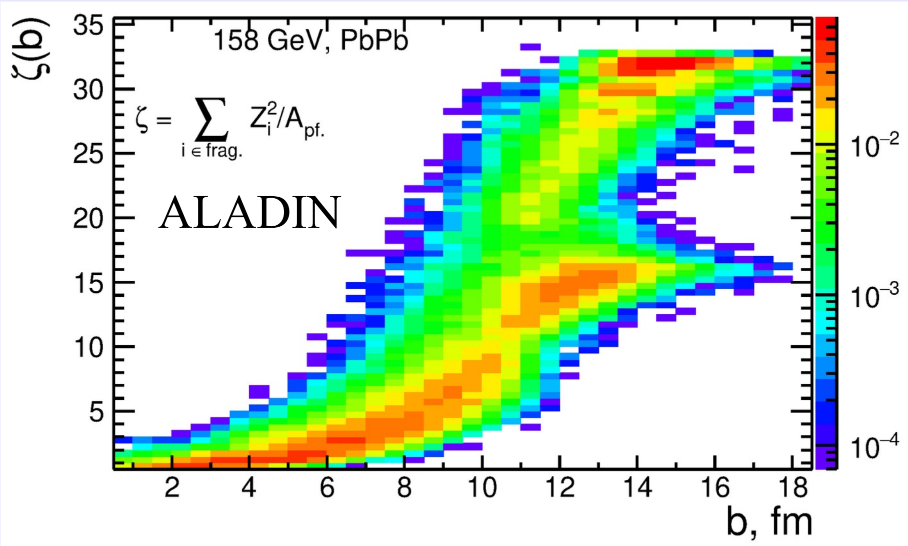


- The total spectator volumes (=A_{pf}) includes all nuclear fragments and nucleons
- Asymmetry decreases from central to peripheral collisions.
- Only small parts of large spectator volumes are affected by fluctuations in numbers of participants.
- This effect is of trivial statistical nature.

- The dependence on *b* is not monotonic
- The stochasticity of nucleon evaporation in peripheral events adds extra fluctuations.
- According to AAMCC, events with low nucleon asymmetry can be classified with confidence as semi-peripheral events.

III. Sum of squares of fragment charges per spectator nucleon



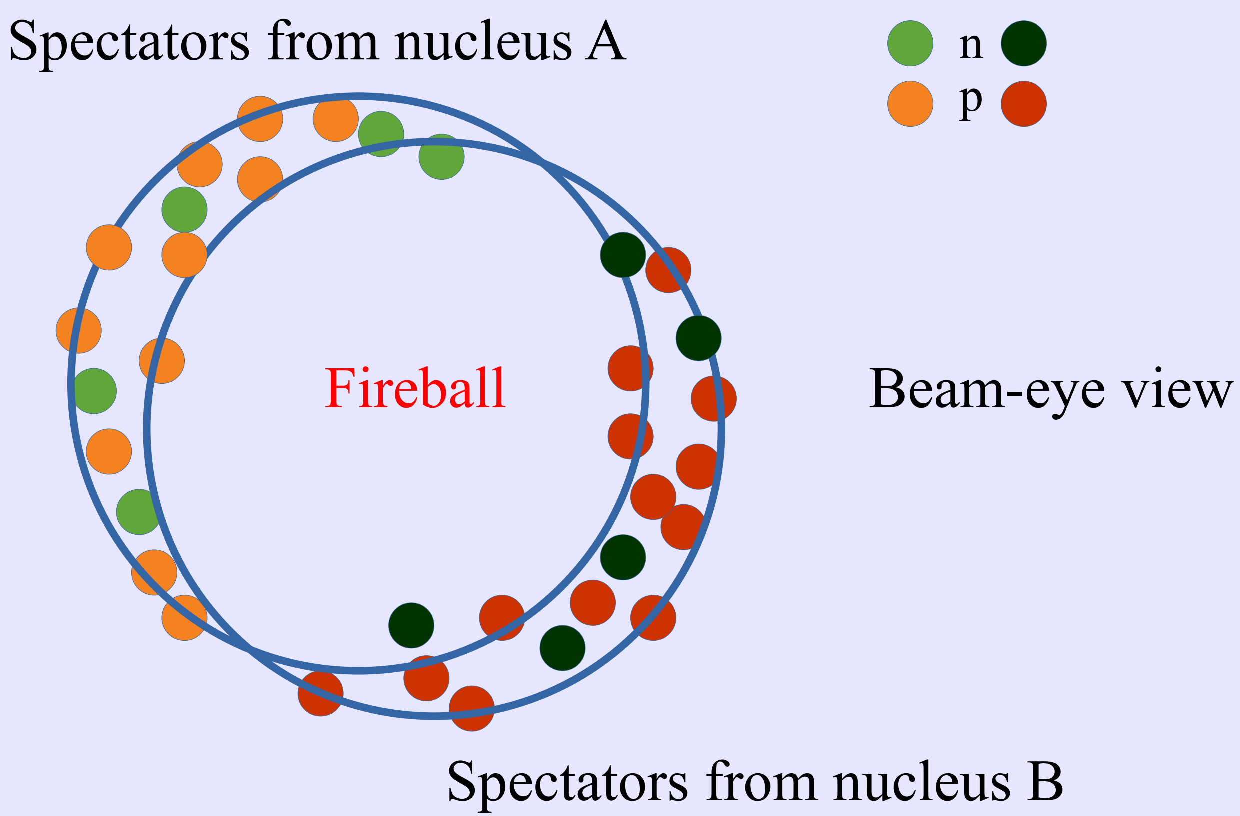


Providing that a scintillator detector is installed in front of a calorimeter, $\sum_i Z_i^2$ can be measured along with the total spectator energy (or $A_{\rm pf}$)

$\sum_i Z_i^2/A_{\rm pf}$ can be proposed as an additional measure of centrality because of its monotonic dependence on impact parameter b.

Large values can be attributed to peripheral events, but the exact procedure depends on AAMCC tuning – subject of future work.

IV. Central collisions are suitable to study the surface layers of nuclei



- A large part of a thin surface layer is cut-off in central collisions and propagate forward as spectator matter.

- The relation between n and p can be studied in forward neutron and proton calorimeters, e.g. by ALICE@LHC

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:

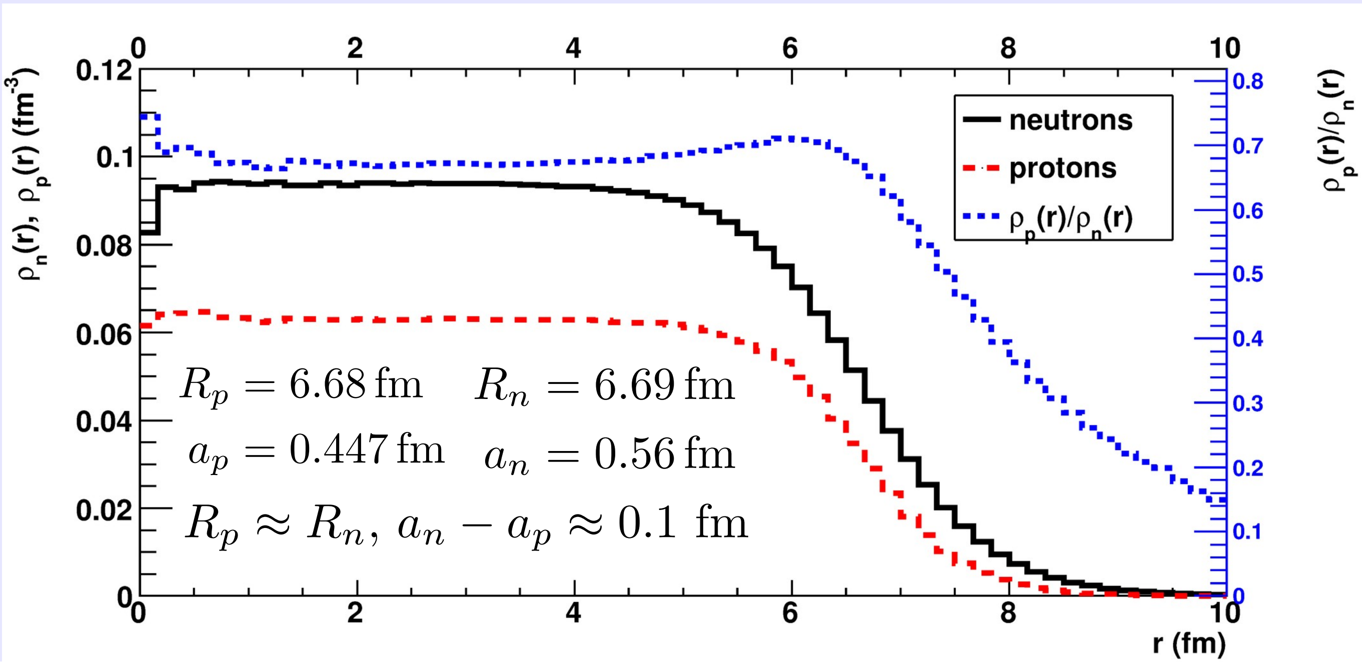
$$\rho_{n,p}(r) = \frac{\rho_{0n,p}}{1+\exp\lfloor(r-R_{n,p})/a_{n,p}\rfloor}, \int d^3r(\rho_n(r)+\rho_p(r)) = A$$

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

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

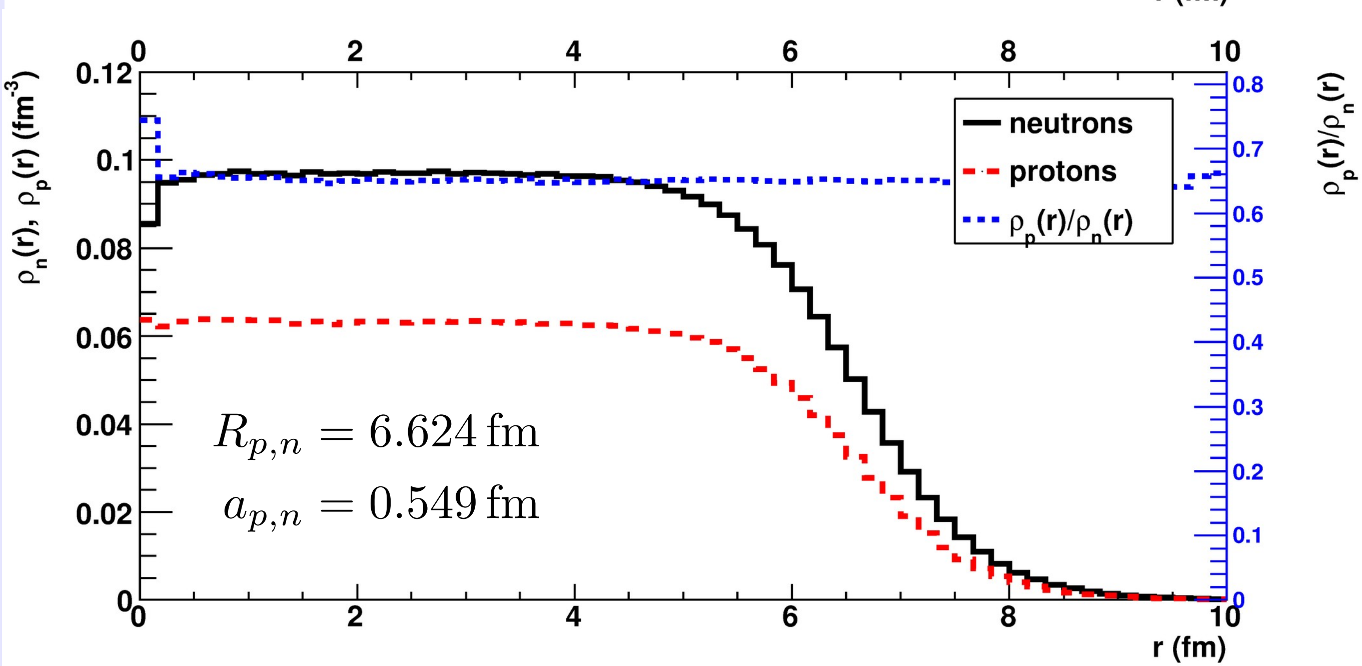
- In reality it is mixed: $R_n > R_p$, $a_n > a_p$ or the parameters are too uncertain. Termed as NS in the following for simplicity.

Neutron skin in ^{208}Pb, GMC 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!

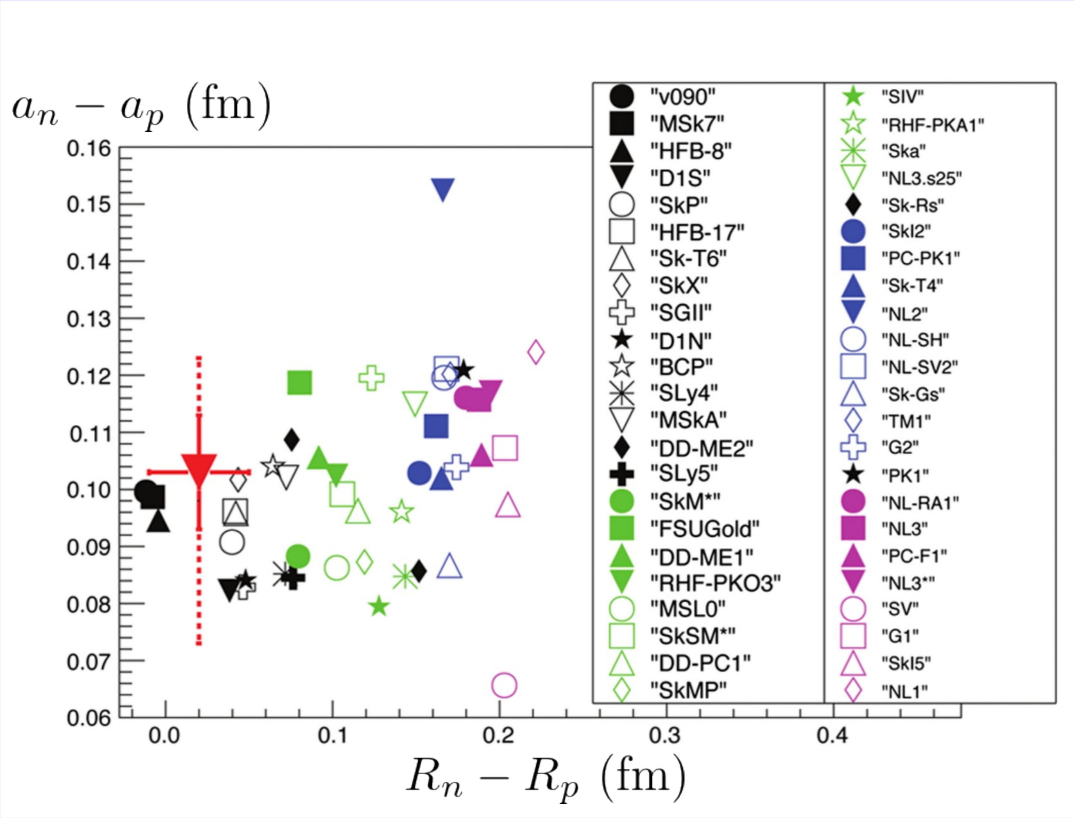
$$\Delta r_{np} = \langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2} = 0.15 fm$$



Used as a reference to estimate the sensitivity to NS: $\rho_p(r)/\rho_n(r) = 0.65$ at all radii – no NS

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

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.

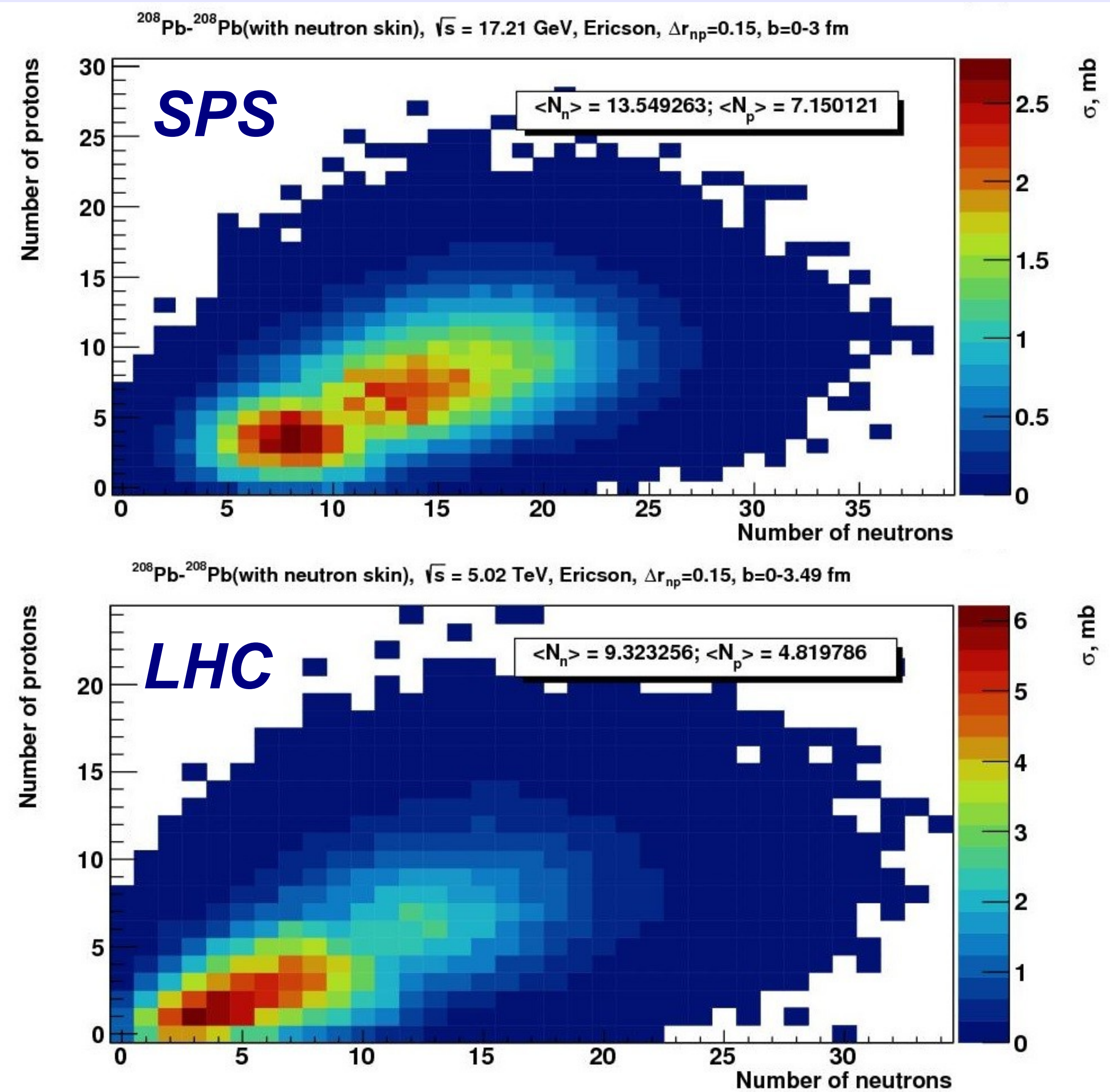
[1] M. Centelles et al., PRC **82** (2010) 054314
[2] C.M. Tarbert et al., PRL **112** (2014) 242502
[3] G.A. Miller et al., PRC **100** (2019) 044608

"Relationships between the neutron-rich skin of heavy nuclei and the properties of neutron-star crusts"
C.J. Horowitz, J. Piekarewicz, PRL **86** (2001) 5647

"Neutron skins as laboratory constrains on properties of neutron stars"
C.A. Bertulani, J. Valecia, PRC **100** (2019) 015802

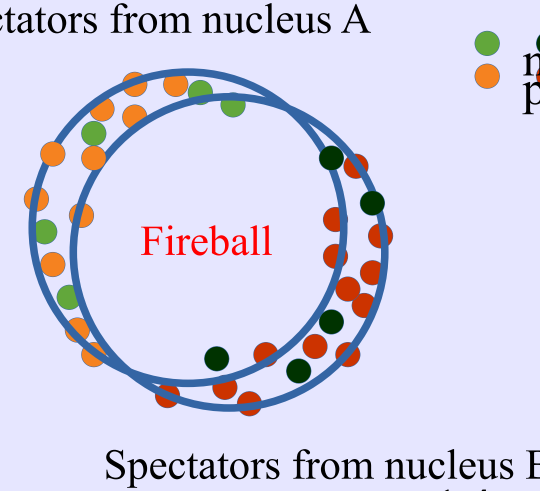
<u>It is important to find new methods to study NS!</u>

Cross sections of central events with given numbers of spectator protons and neutrons

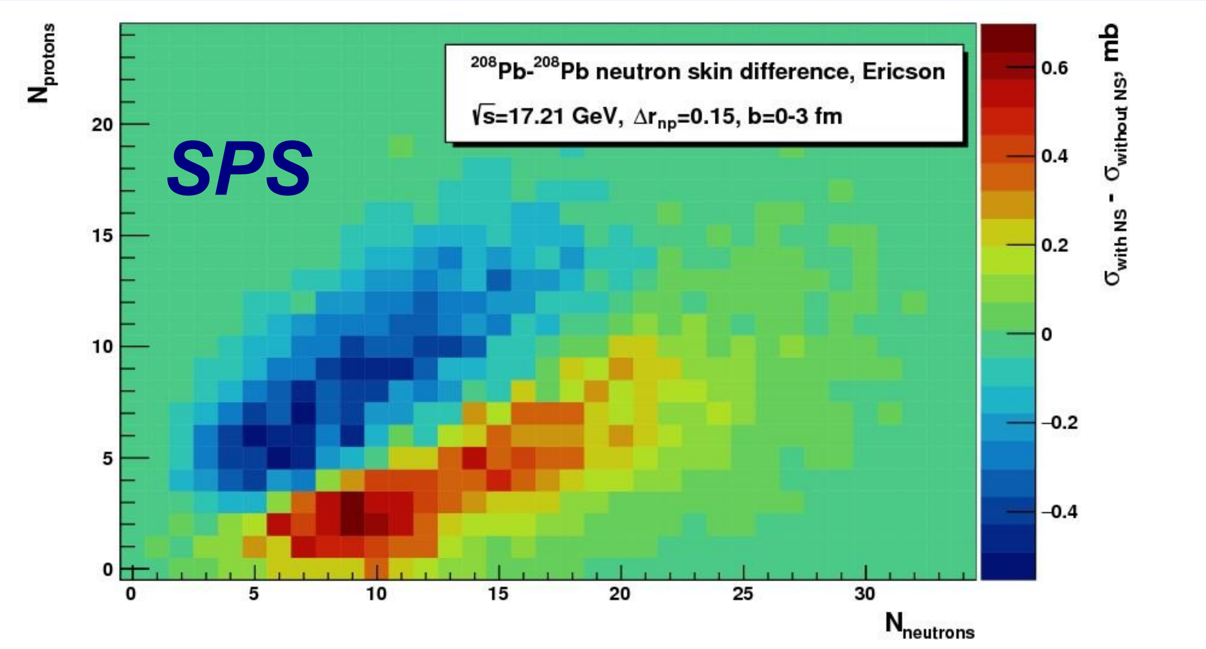


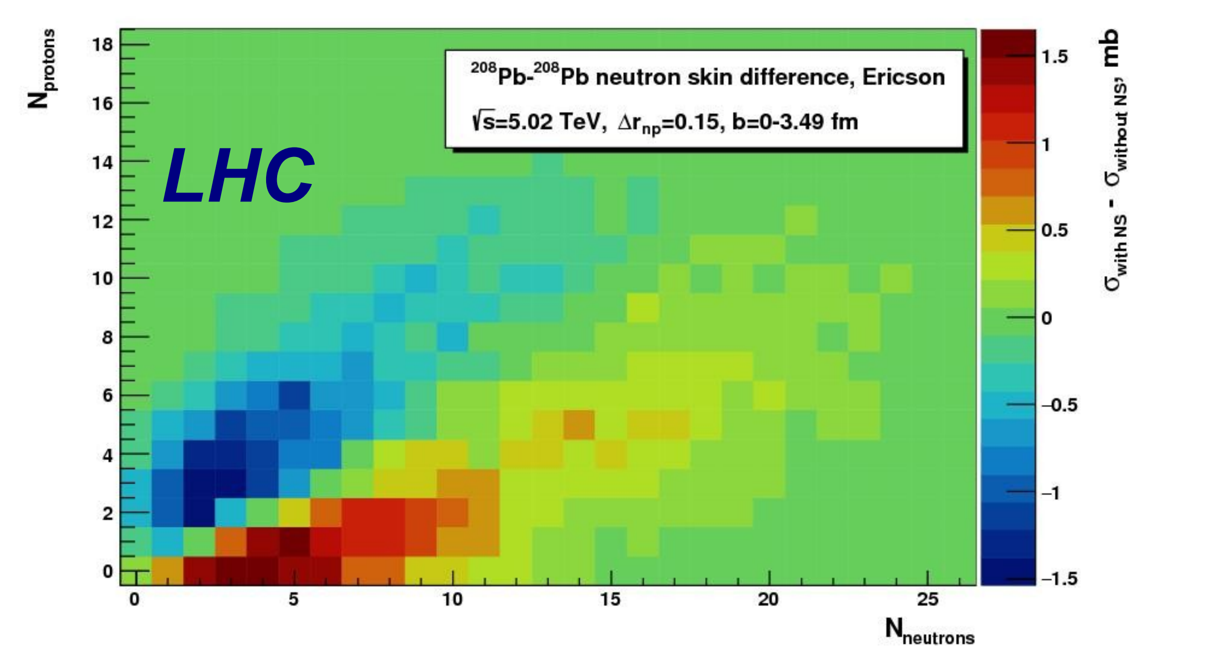
Decrease of the average numbers of spectator protons and neutrons is due to the rise of nucleon-nucleon interaction cross-section with energy.

A kind of depletion of spectator matter.



Difference between calculations with and without neutron skin for central collisions





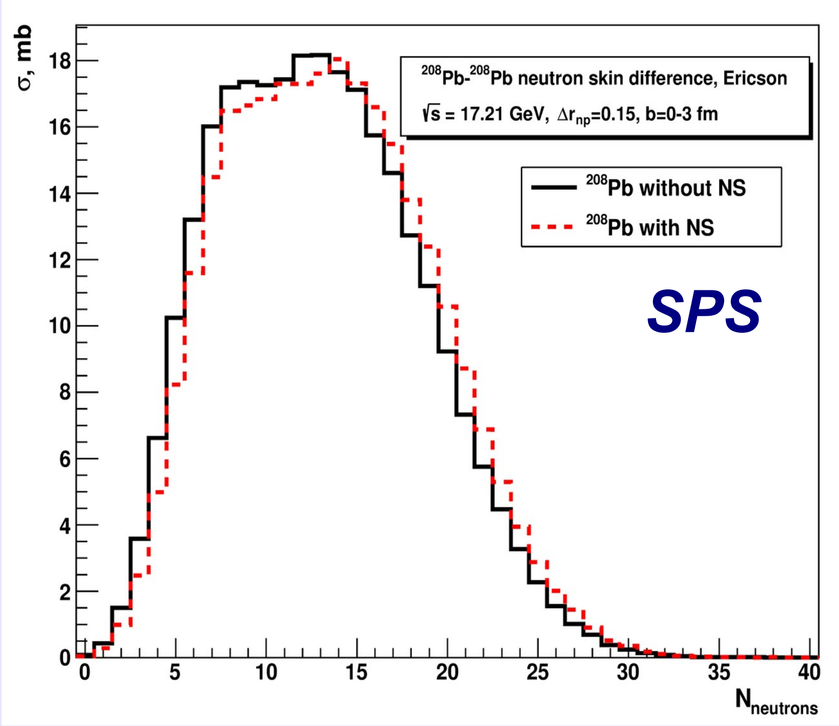
The number of spectator neutrons increases, while the number of spectator protons drops when NS is taken into account.

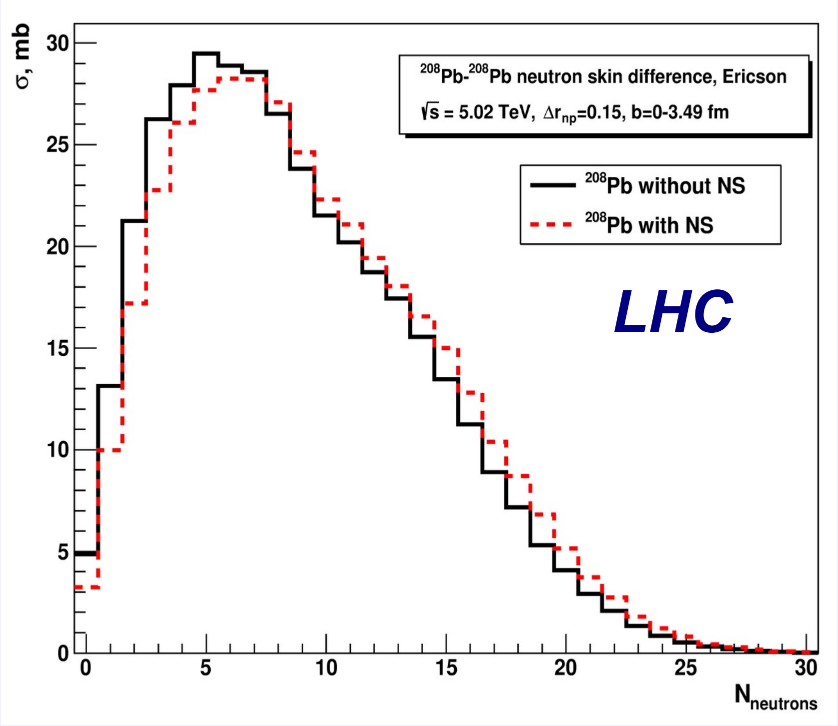
Multiplicity of spectator neutrons in central collisions

$\langle N_{neutrons} \rangle$	without NS		with NS		Experiments[1,2]
	ALADIN	Ericson	ALADIN	Ericson	
SPS	4.4	12.9	5.2	13.5	9
LHC	3	8.7	3.8	9.3	9

[1] H.Appelshäuser et al., Eur. Phys. J. A **2** (1998) 383
[2] ALICE public note 2020-001, http://cds.cern.ch/record/2712412

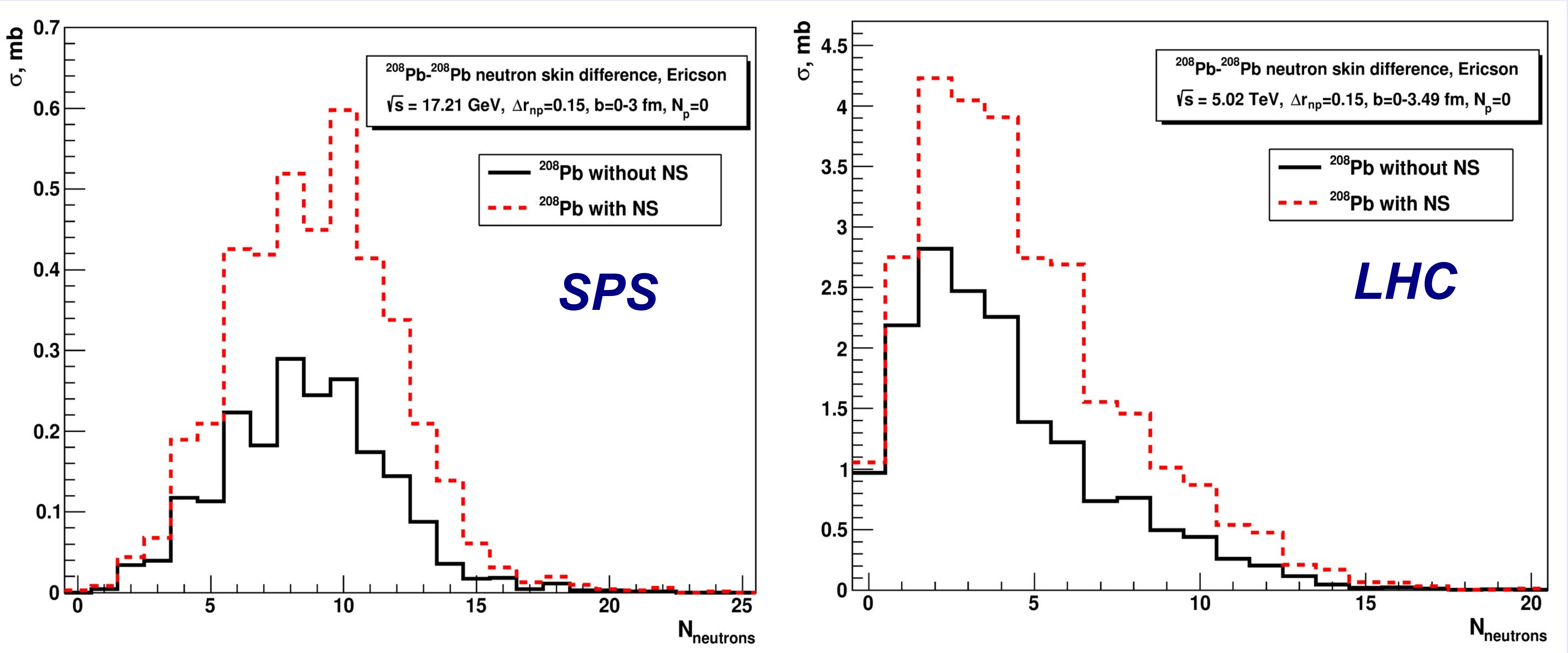
Modest increase of $<N_{neutrons}>$ when NS is taken into account in AAMCC





CS distributions are more sensitive to NS, $\sigma(N_{neutrons})$ are larger by ~20% with NS.

Neutron multiplicity distributions, but with zero protons



When NS is taken into account the cross sections to get given numbers of spectator neutrons, but without spectator protons, become twice as large.

It is these cross sections most sensitive to NS that can be proposed for measurements in central events.

Conclusions

- Various characteristics of spectator matter can be calculated with our AAMCC model.
- The first comparisons with fragmentation data are encouraging.
- Forward-backward asymmetry of spectator nucleons and $\sum_i Z_i^2/A_{\mathrm{pf}}$ can be considered as additional centrality criteria.
- As shown by calculations with AAMCC, the cross sections of emission of given numbers of spectator neutrons without protons in central ^{208}Pb–^{208}Pb collisions are sensitive to the presence of neutron skin (NS). May be extrapolated to ^{209}Bi–^{209}Bi at NICA.

Thank you for attention.

We are grateful to RFBR for the support!

- This work has been carried out with financial support of the Russian Fund for Basic Research within the project 18-02-40035

- It made possible to organize a small theory research group consisting of two students, two PhD students and two senior scientists.

- A new model has been created from scratch, three new directions of research have been proposed at the second year in addition to the original plan drafted in the grant application.

Back-up slides

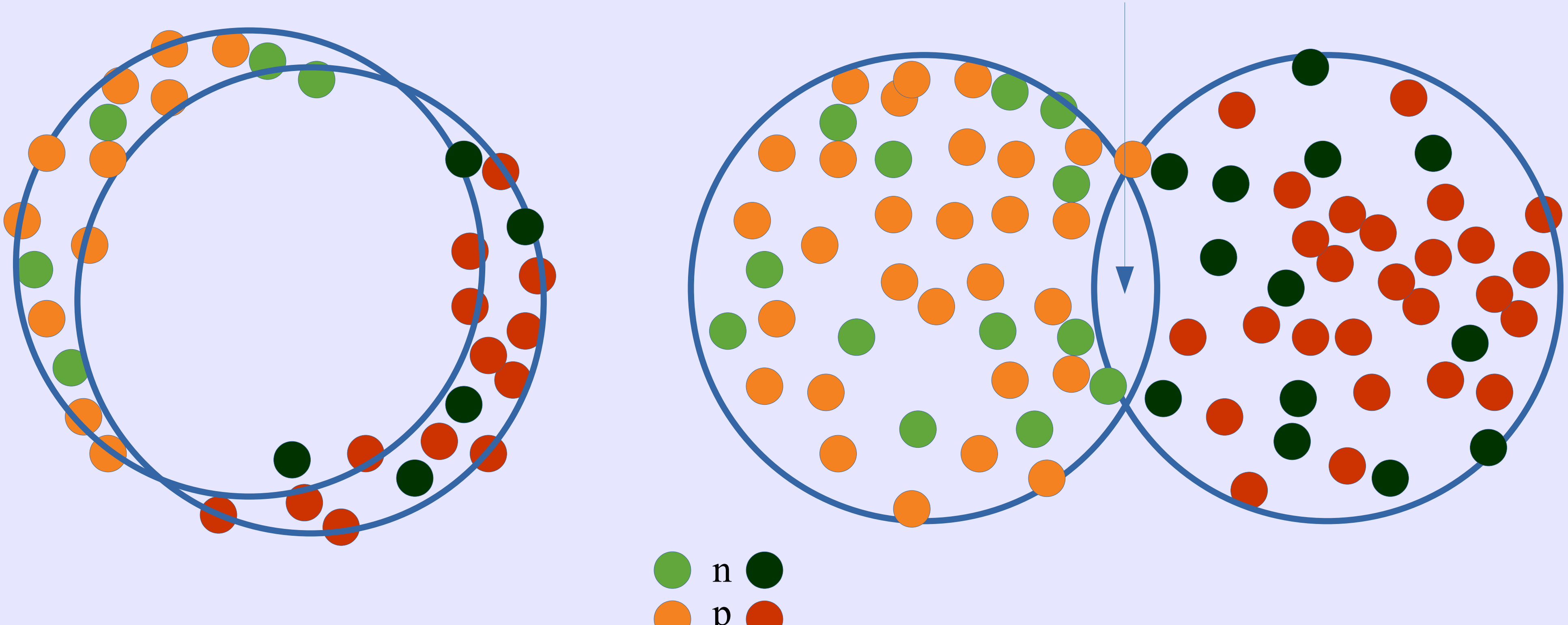
Studying NS in nucleus-nucleus collisions by neutron removal: proposed at low energy

	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>