Spectator nucleons in most central Au-Au collisions at NICA

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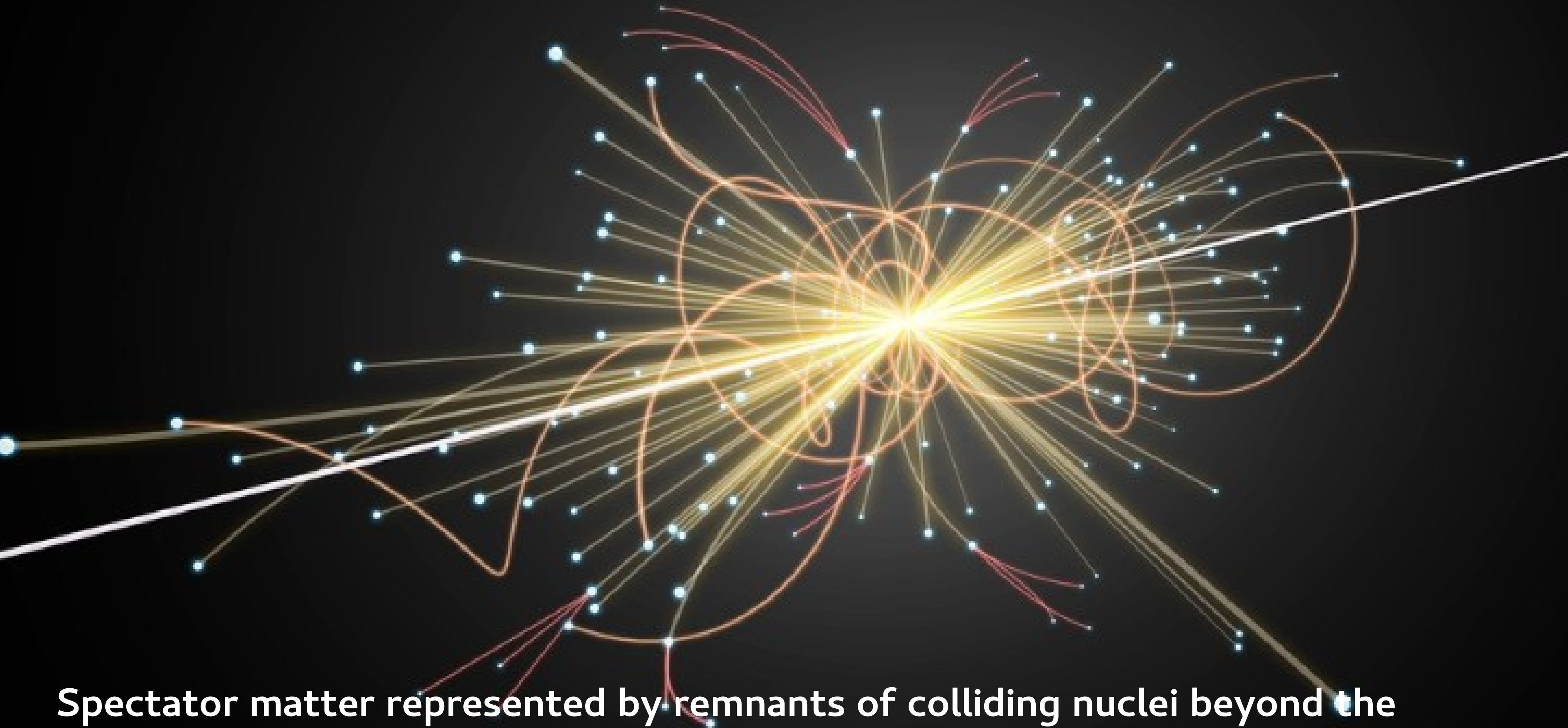
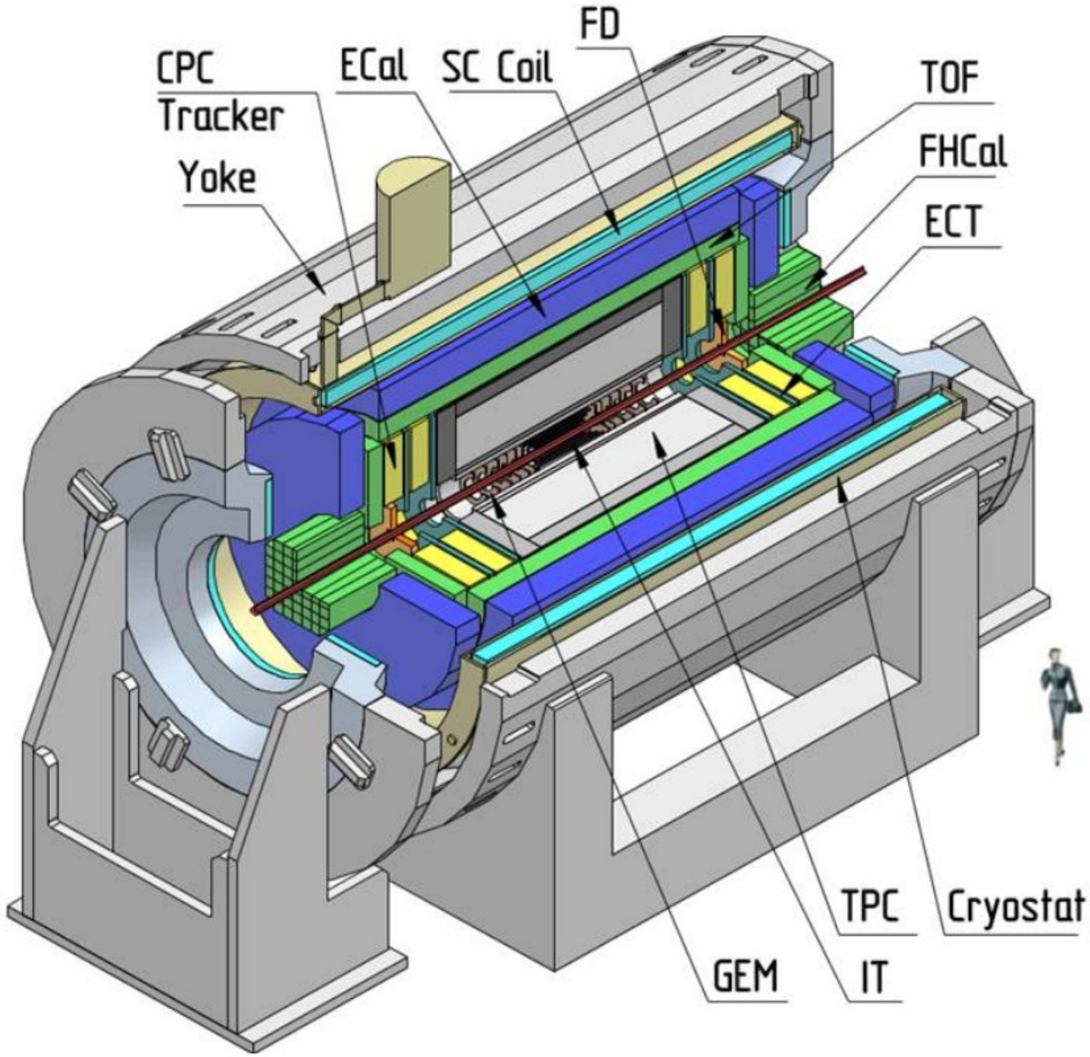
The aim of heavy-ion program at NICA is to study strongly interacting matter under extreme conditions, where a transition to the quark-gluon plasma (QGP) is observed in nucleus-nucleus collisions.

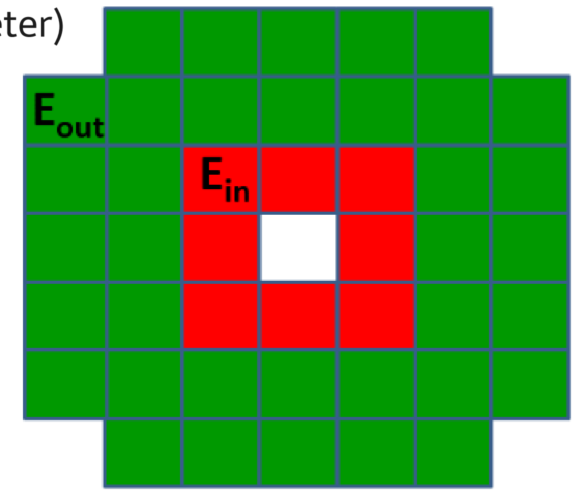


Spectator matter represented by remnants of colliding nuclei beyond the fireball attracts less attention.
But physics of spectators study is also very interesting.

Multi-Purpose Detector (MPD) @ NICA



FHCal (Forward Hadron Calorimeter)



^{197}Au–^{197}Au and ^{209}Bi–^{209}Bi collisions are planned at NICA.

Instead of ^{209}Bi we consider ^{208}Pb as a well-studied nucleus with its characteristics similar[1] to ^{209}Bi.

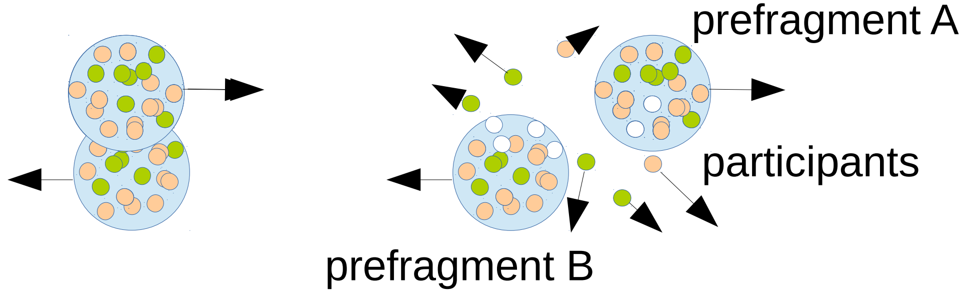
[1] B. A. Brown, A. Derevianko, V. V. Flambaum, PRC **79** (2009) 035501

Our model: AAMCC

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

Both prefragments are modelled.

AAMCC is suitable for colliders.



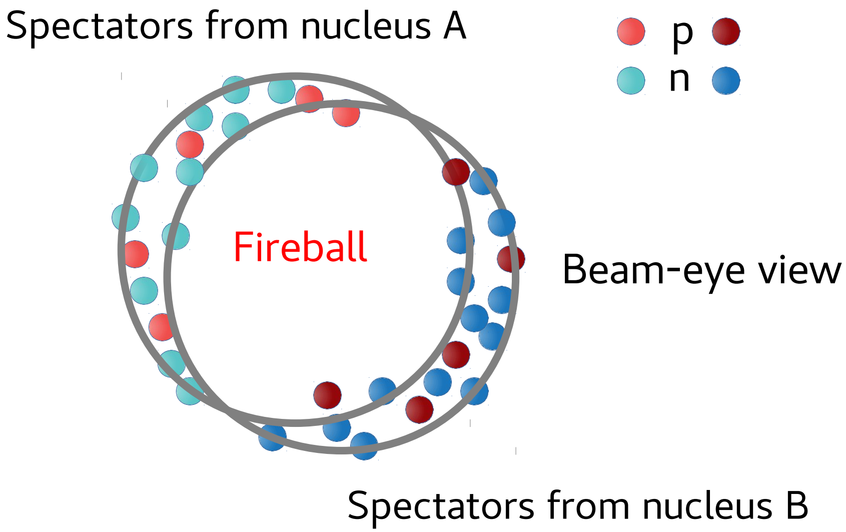
A key point of the model is the calculation of the excitation energy of prefragments. Presently two different options could be used:

- Ericson formula (calculated via energies of hole states created in initial nuclei);
- phenomenological relation between prefragment excitation energy and its mass; based on ALADIN experiment data.

Modeling results are sensitive to the choice of excitation energy approximation.

1) A. Sveltichnyi., I.Pshenichnov, 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

Central collisions: impact of geometry



Since a large part of a thin surface layer is cut-off in central collisions and propagates forward as spectator matter, **the nuclear periphery** can be studied by investigating spectator matter in such collisions.

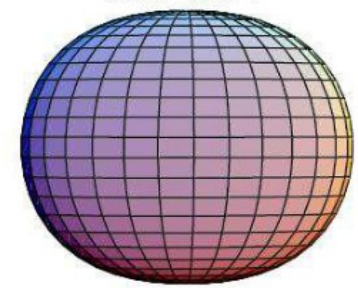
Volume and composition of spectator matter is determined by the initial nucleon distributions in colliding nuclei and their shapes.

The influence of

- **nuclear deformation** and
- **presence of a neutron skin/halo**

is investigated in this work.

Nuclear density distribution in deformed nuclei



*)

Deformed nuclei ^{197}Au is described:

$$\rho(x,y,z) = \frac{\rho_0}{1+\exp\lfloor(r-R(1+\beta_2 Y_{20}+\beta_4 Y_{40}))/a\rfloor},$$

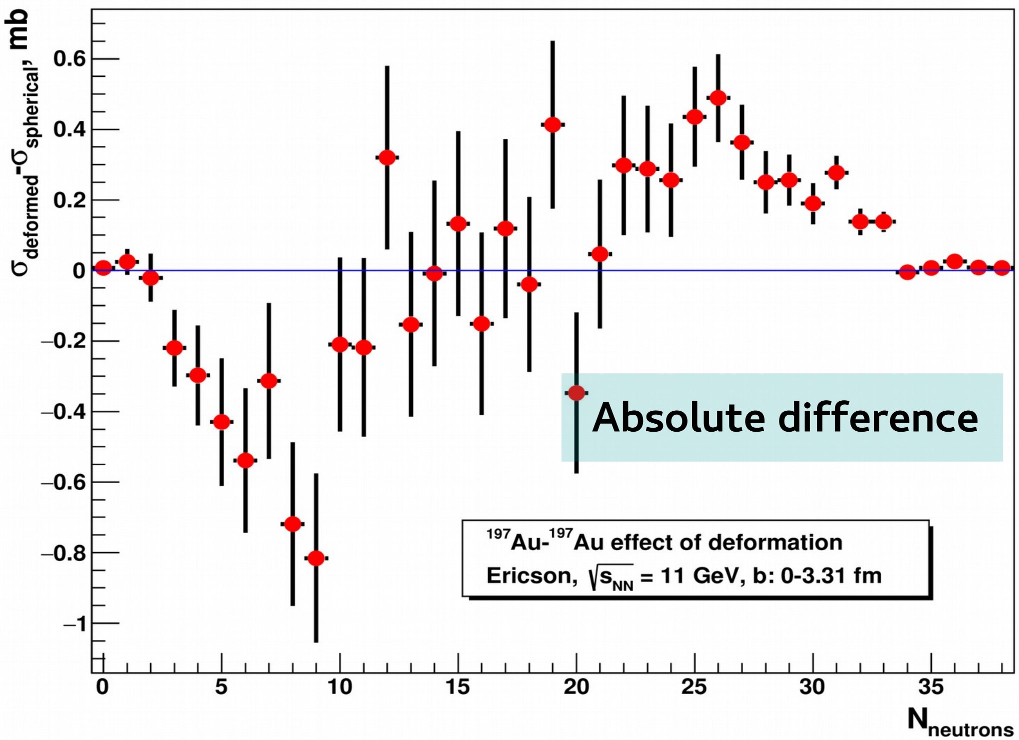
$$Y_{20} = \sqrt{\frac{5}{16\pi}}(3\cos^2(\theta)-1),$$

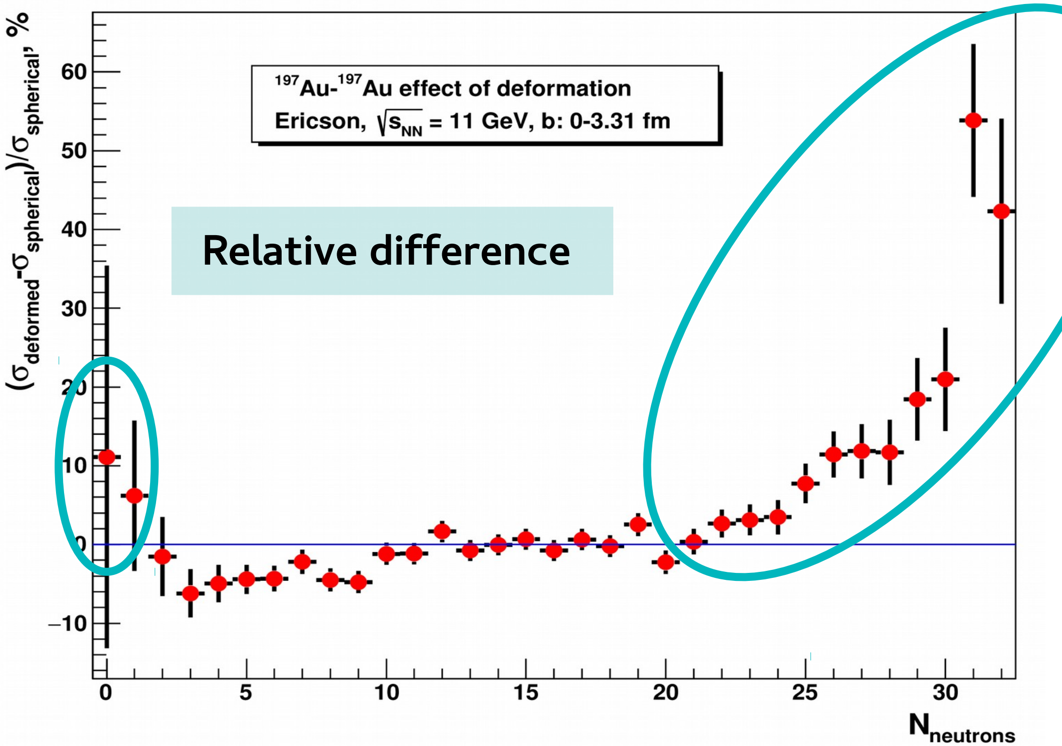
$$Y_{40} = \frac{3}{16\sqrt{\pi}}(35\cos^4(\theta)) - 30\cos^2(\theta)+3)$$

with deformation parameters β_2 = -0.131 and β_4 = -0.031.

*) P. Filip, Phys.Atom.Nucl. **71** (2008) 1609–1618

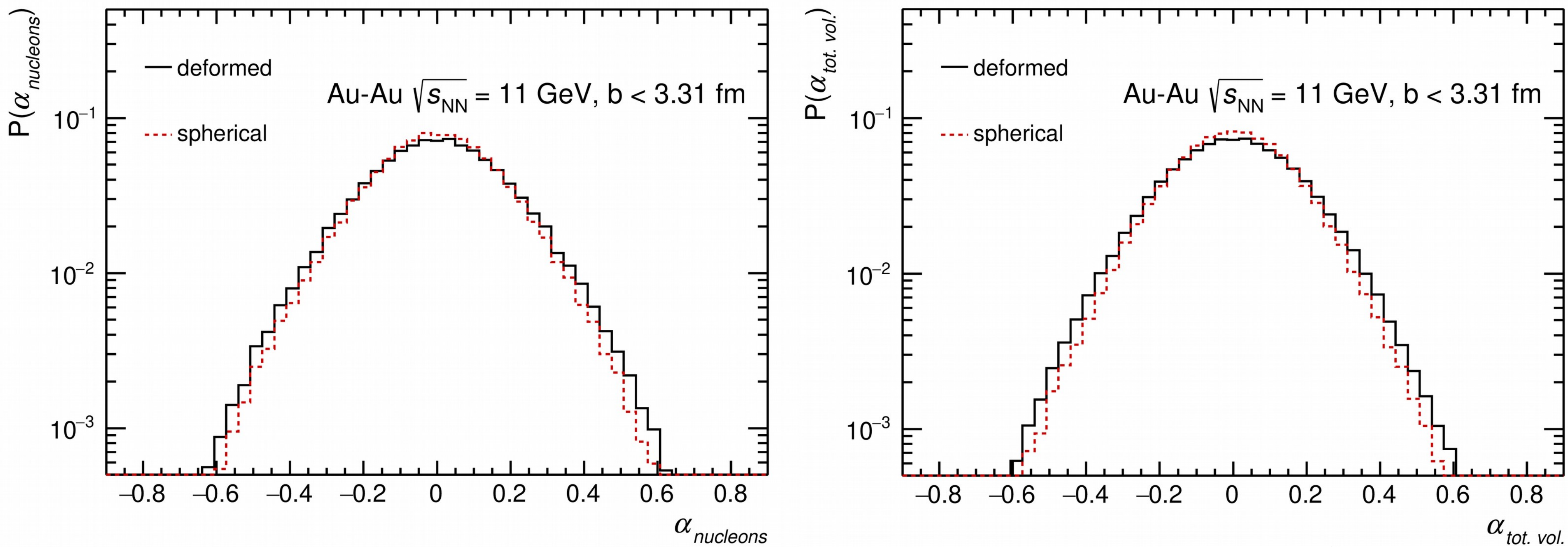
Impact of nuclear deformation on neutron multiplicities in central Au–Au collisions





Due to nuclear deformation, the emission less than 2 and especially more than 20 neutrons is enhanced.

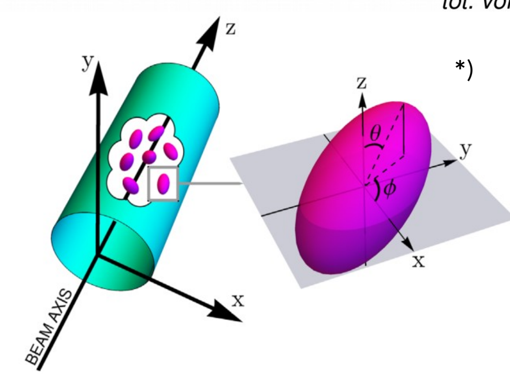
Forward-backward asymmetry of spectators



Forward-backward asymmetry $\alpha = \frac{N_A - N_B}{N_A + N_B}$ is observed because of

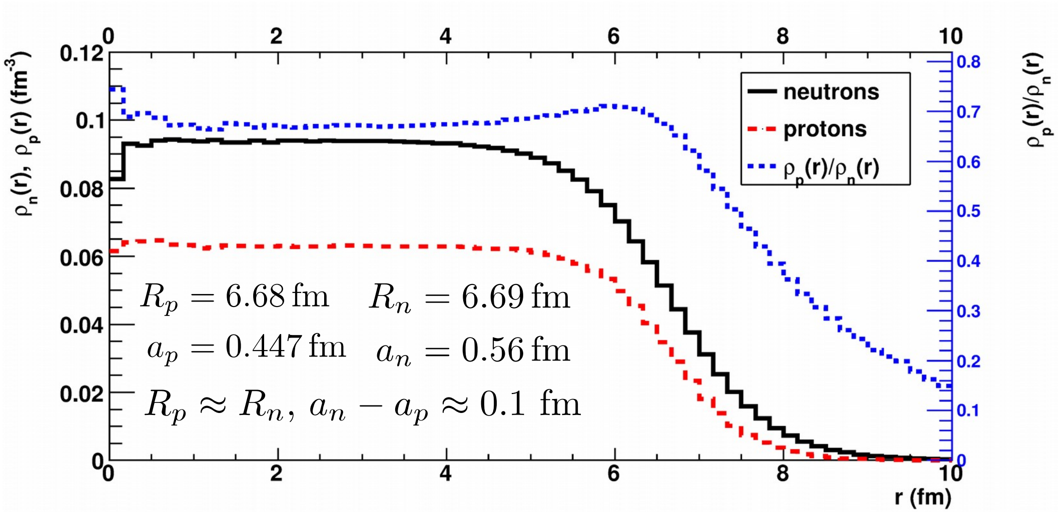
- unequal number of nucleons participating in the overlap region of each nucleus (due to nuclear density fluctuations and stochasticity of NN-collisions);
- stochasticity of excitation and decay processes of spectator matter.

Asymmetry magnitude is larger for deformed nuclei due to the randomness of their orientation*) in collisions.



*) G. Giacalone, PRL **124** (2020) 202301

Neutron skin in ^{208}Pb



For spherical nuclei radial distributions are usually parameterized by two-parametric Wood-Saxon functions:

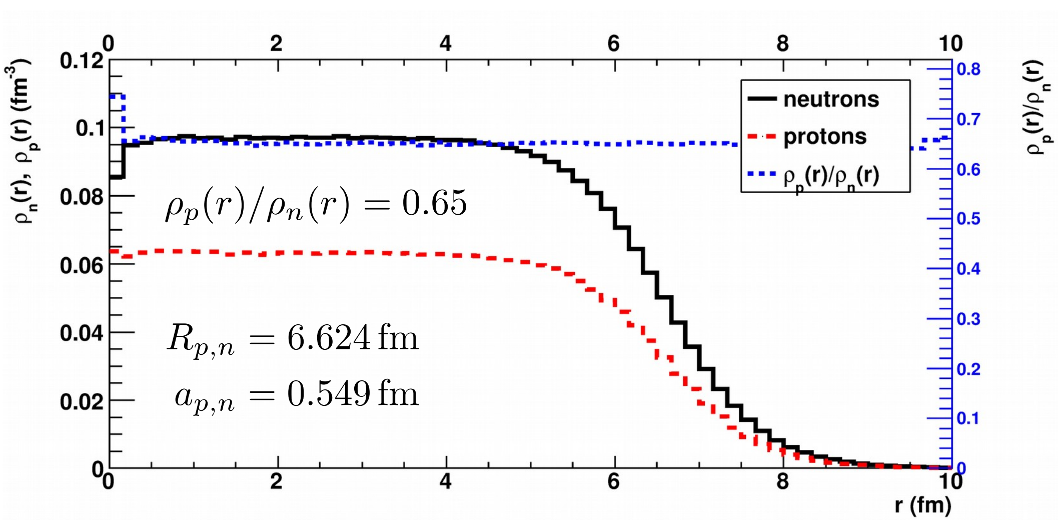
$$\rho_{n,p}(r) = \frac{\rho_{0n,p}}{1+\exp[(r-R_{n,p})/a_{n,p}]},$$

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

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.

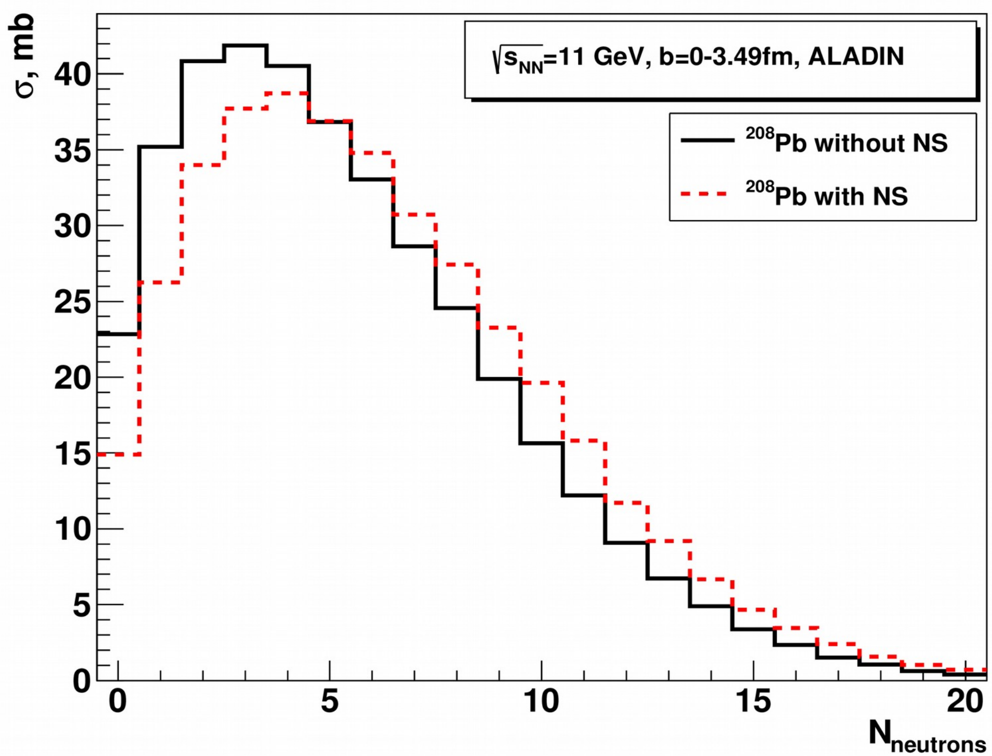
Surface layers in heavy nuclei are enriched by neutrons – neutron skin (NS) or neutron halo:

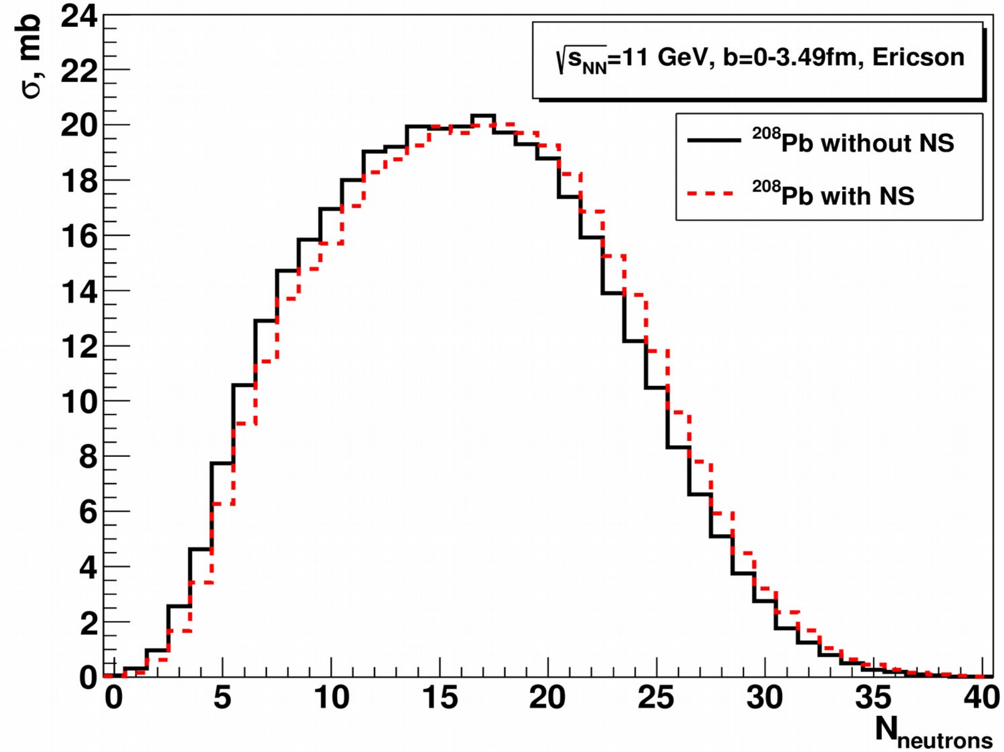
$$\Delta r_{np} = \langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2} = 0.15 fm$$



Configuration without neutron skin $\Delta r_{np} = 0$ is used as reference to estimate the sensitivity of the results to NS.

Neutron multiplicity distributions

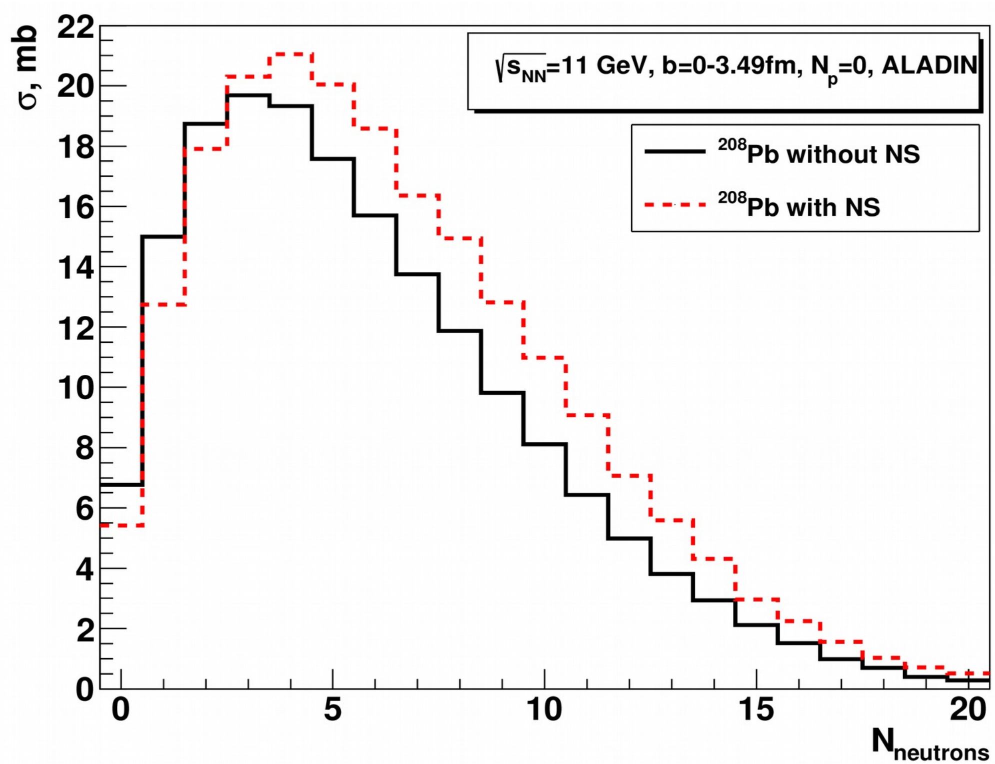


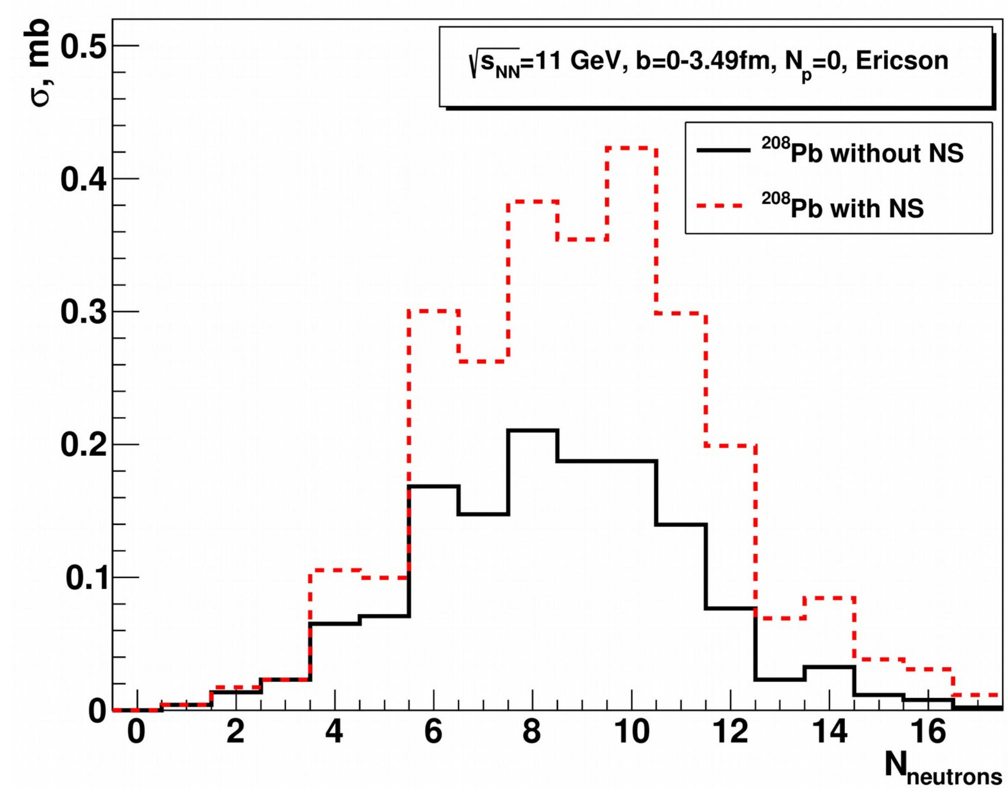


$\langle N_{\mathrm{neutrons}} \rangle$	without NS		with NS		Experiments
	ALADIN	Ericson	ALADIN	Ericson	
SPS	4.4	12.9	5.2	13.5	9
NICA	5.4	16.1	6.2	16.7	

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

Neutron emission without protons





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

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

Conclusions

- As shown by calculations with AAMCC, due to nuclear deformation of ^{197}Au, the emission more than 20 neutrons is enhanced in central ^{197}Au–^{197}Au collisions.

- The distributions calculated for spectator asymmetry reveal a modest sensitivity to nuclear deformation of ^{197}Au in ^{197}Au–^{197}Au collisions.

- 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.

Thank you for your attention!

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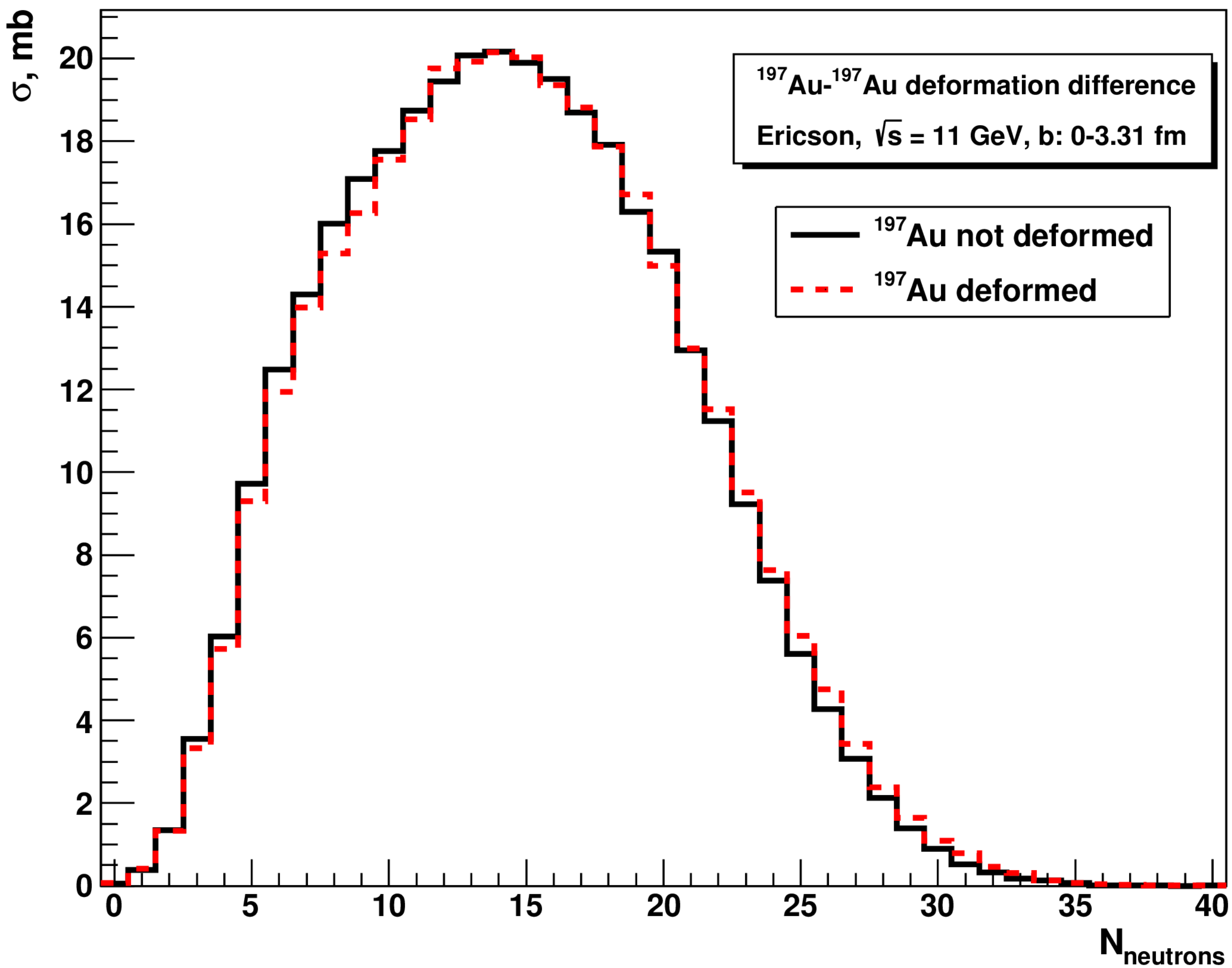
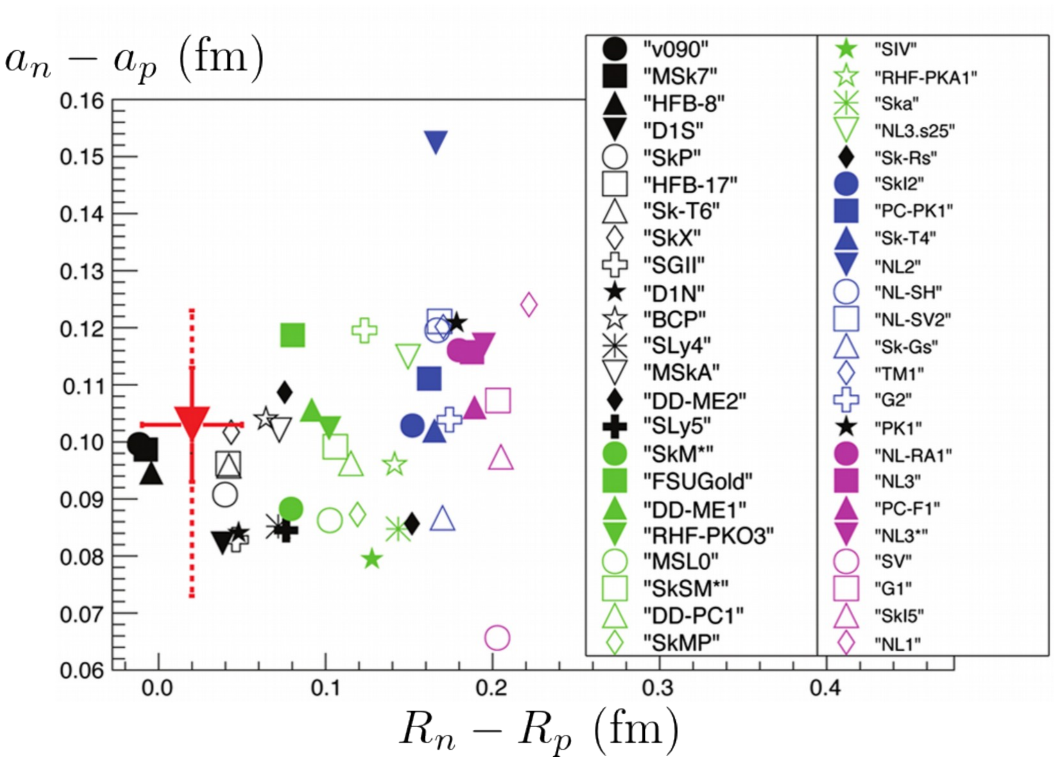
Backup

Influence of nuclear deformation on neutron multiplicities



Divergence between different models predictions and measurements



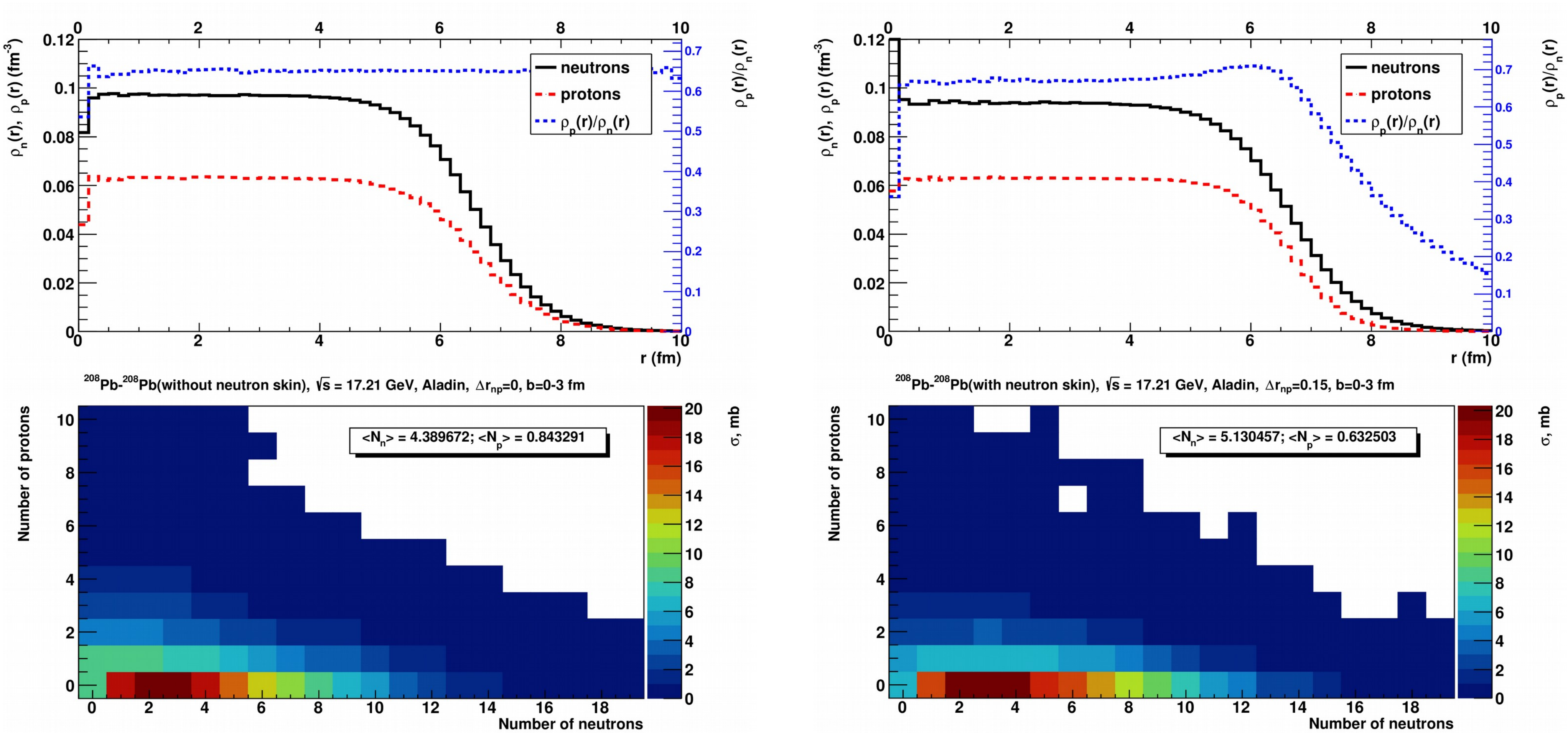
State-of-the-art nuclear theories predict for ^{208}Pb:

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

Red inverted triangle – info about neutron skin on ^{208} Pb extracted from coherent pion photoproduction cross sections

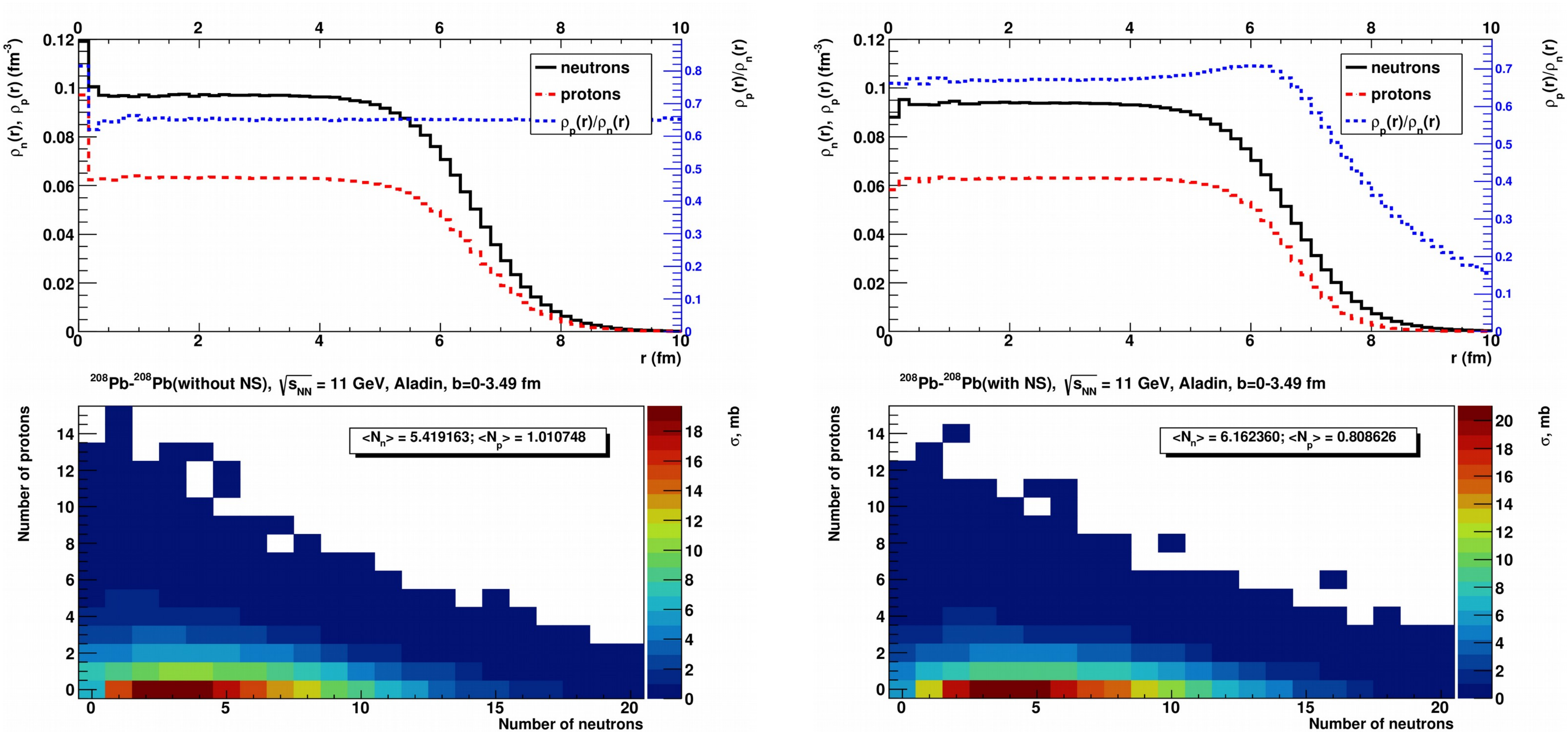
Could we study neutron skin in high-energy experiments? Which characteristics we should investigate?

SPS

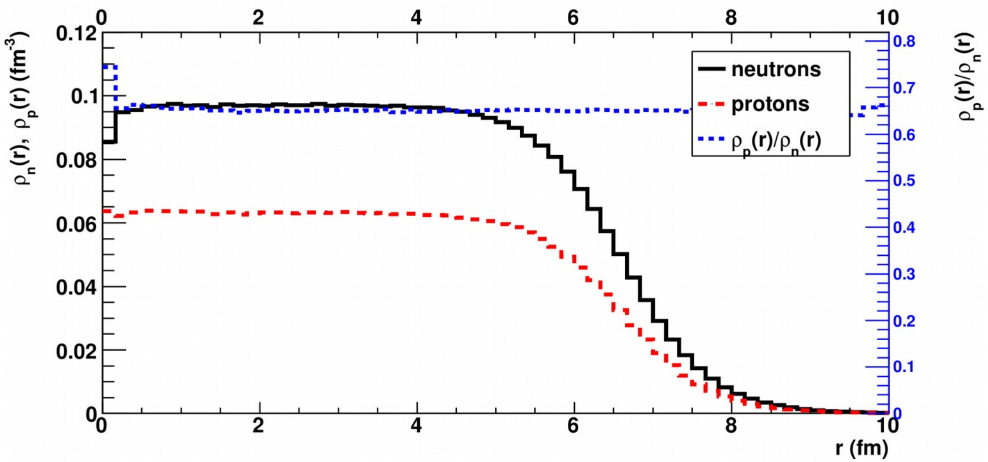


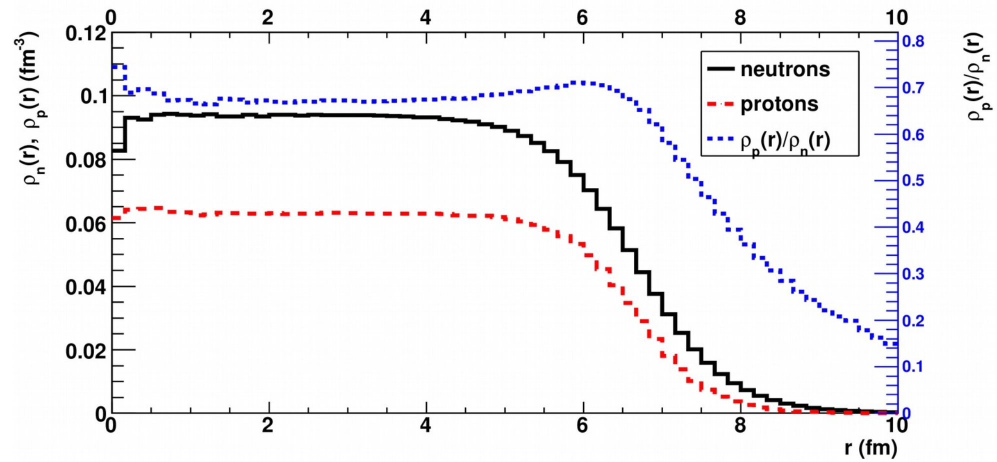
neutrons
protons
$\rho_p(r)/\rho_n(r)$
$\rho_n(r),\ \rho_p(r)\ (fm^{-3})$
r (fm)
^{208}Pb-^{208}Pb(without neutron skin), $\sqrt{s}$ = 17.21 GeV, Aladin, Δr_{np}=0, b=0-3 fm
^{208}Pb-^{208}Pb(with neutron skin), $\sqrt{s}$ = 17.21 GeV, Aladin, Δr_{np}=0.15, b=0-3 fm
$\langle N_n \rangle$ = 4.389672; $\langle N_p \rangle$ = 0.843291
$\langle N_n \rangle$ = 5.130457; $\langle N_p \rangle$ = 0.632503
Number of protons
Number of neutrons
σ, mb

NICA

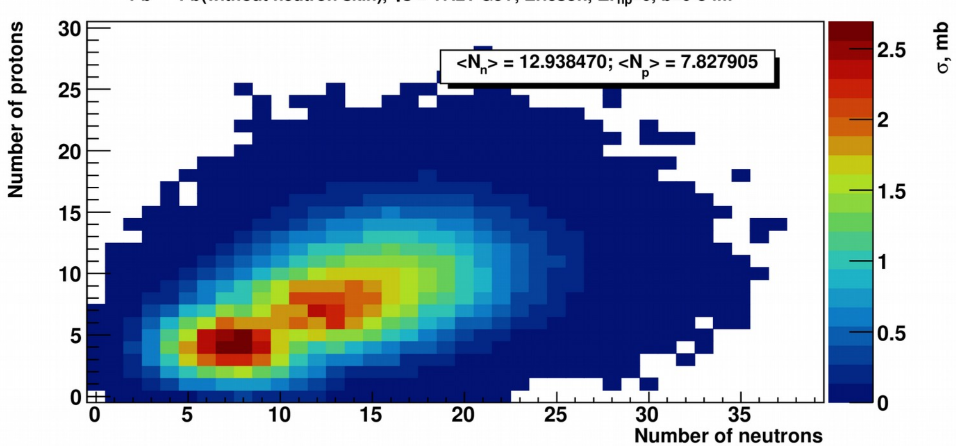

neutrons
protons
ρp(r)/ρn(r)
r (fm)
ρn(r), ρp(r) (fm-3)
208Pb-208Pb(without NS), √sNN = 11 GeV, Aladin, b=0-3.49 fm
208Pb-208Pb(with NS), √sNN = 11 GeV, Aladin, b=0-3.49 fm
<Nn> = 5.419163; <Np> = 1.010748
<Nn> = 6.162360; <Np> = 0.808626
Number of protons
Number of neutrons
σ, mb

SPS

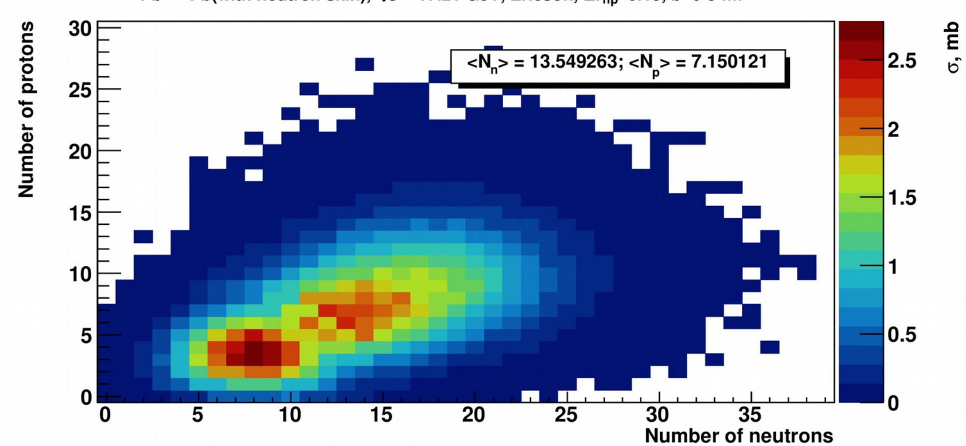




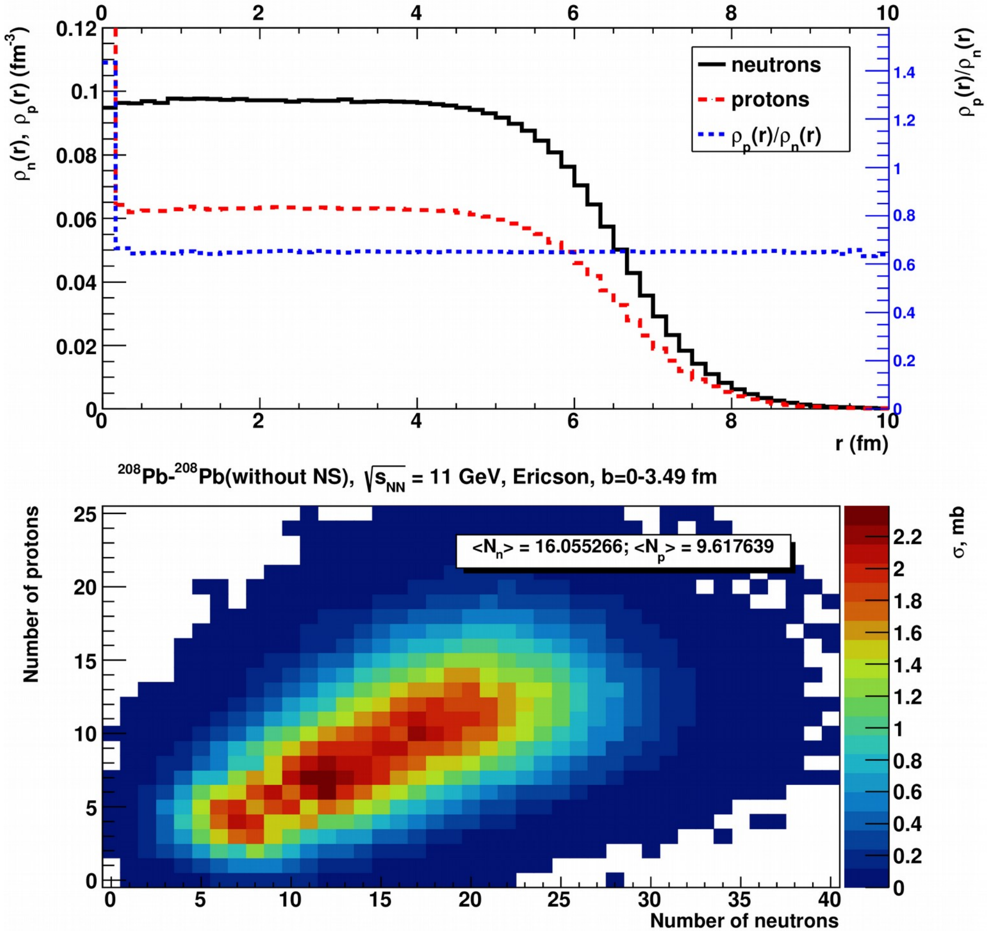
^{208}Pb-^{208}Pb(without neutron skin), $\sqrt{s}$ = 17.21 GeV, Ericson, Δr_{np}=0, b=0-3 fm



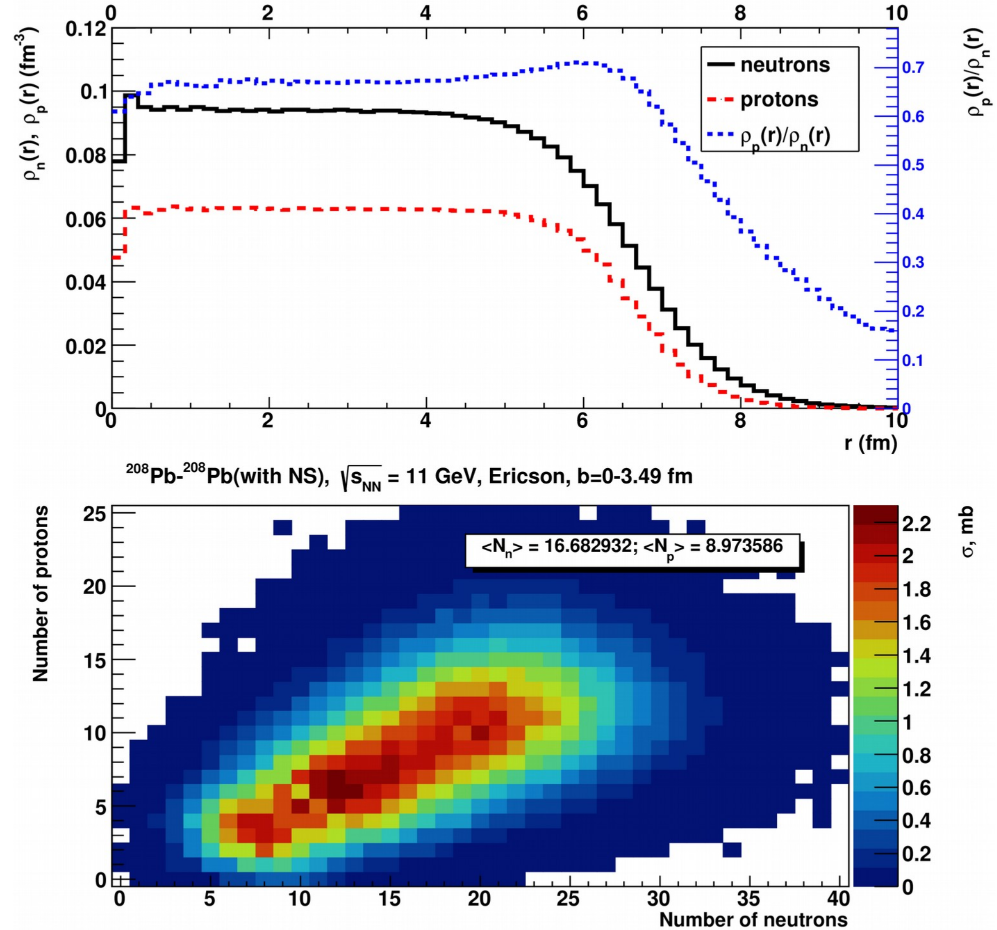
^{208}Pb-^{208}Pb(with neutron skin), $\sqrt{s}$ = 17.21 GeV, Ericson, Δr_{np}=0.15, b=0-3 fm



NICA

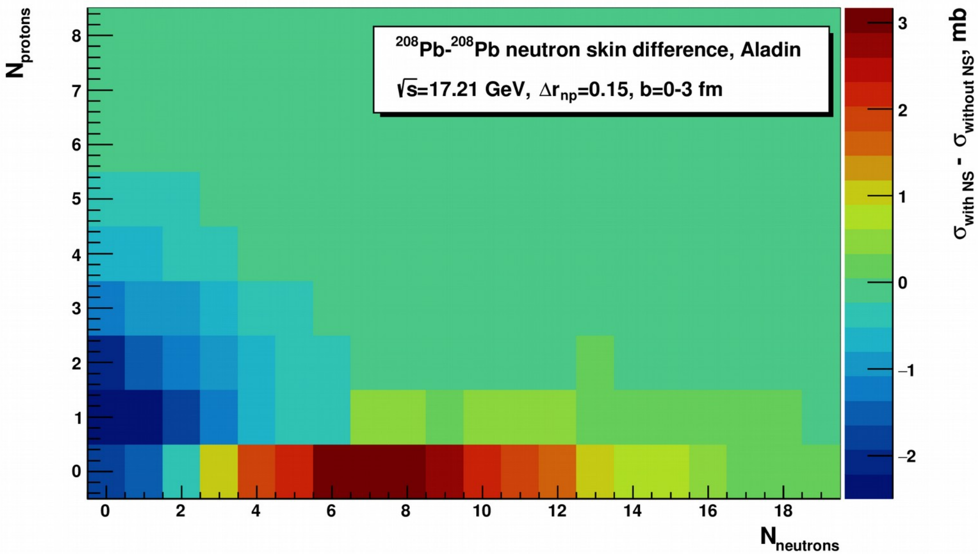


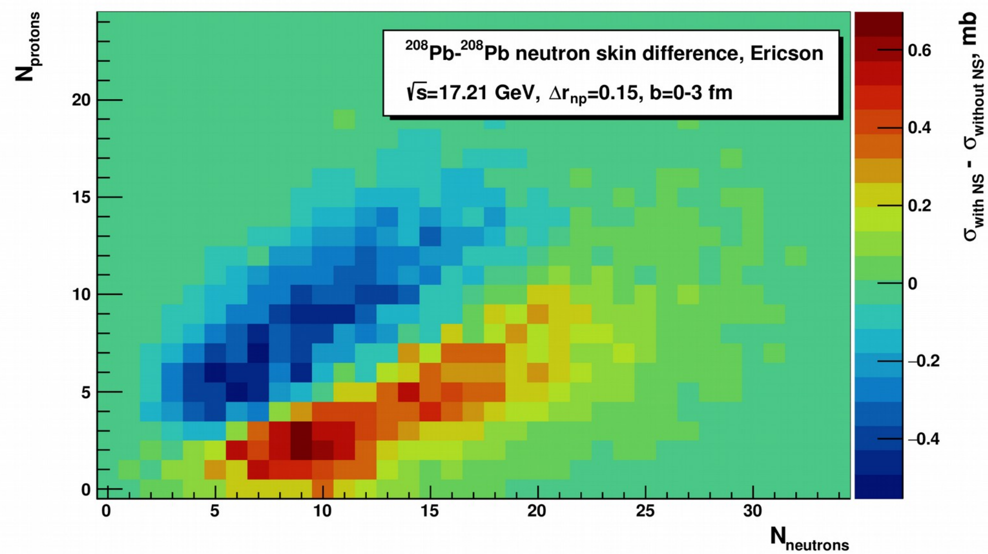
neutrons
protons
ρp(r)/ρn(r)
ρn(r), ρp(r) (fm^-3)
r (fm)
208Pb-208Pb(without NS), √sNN = 11 GeV, Ericson, b=0-3.49 fm
<Nn> = 16.055266; <Np> = 9.617639
Number of protons
Number of neutrons
σ, mb



neutrons
protons
ρp(r)/ρn(r)
ρn(r), ρp(r) (fm^-3)
r (fm)
208Pb-208Pb(with NS), √sNN = 11 GeV, Ericson, b=0-3.49 fm
<Nn> = 16.682932; <Np> = 8.973586
Number of protons
Number of neutrons
σ, mb

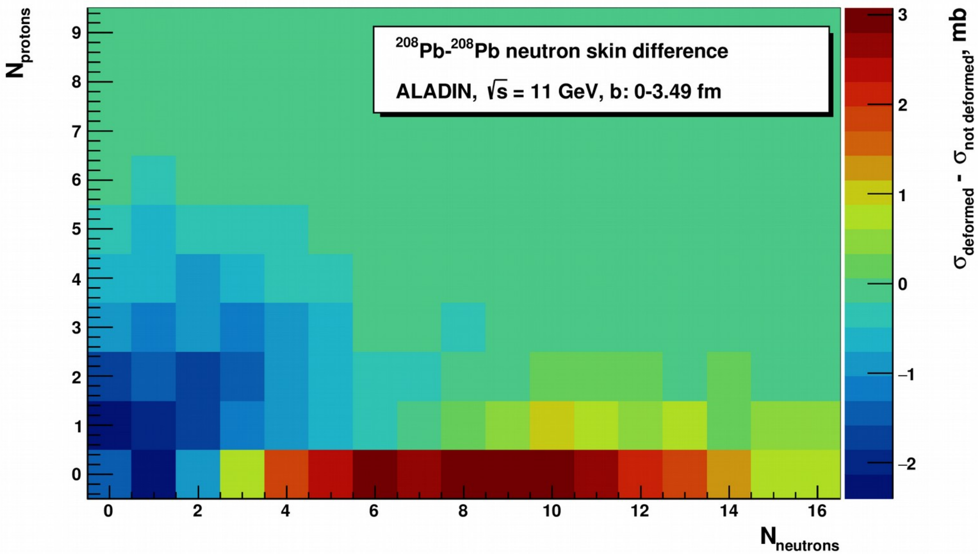
SPS

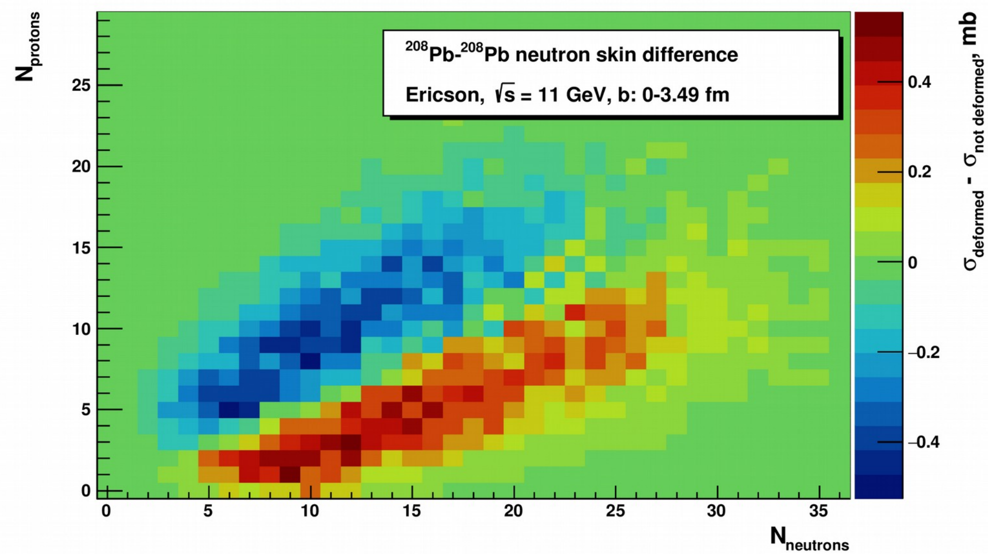




Distinctly less spectator protons and more spectator neutrons

NICA





Distinctly less spectator protons and more spectator neutrons