„Neutron skin- calculations for Pb+Pb, proton+Pb, antiproton+Pb at p~1AGeV (and higher momentum) collisions."

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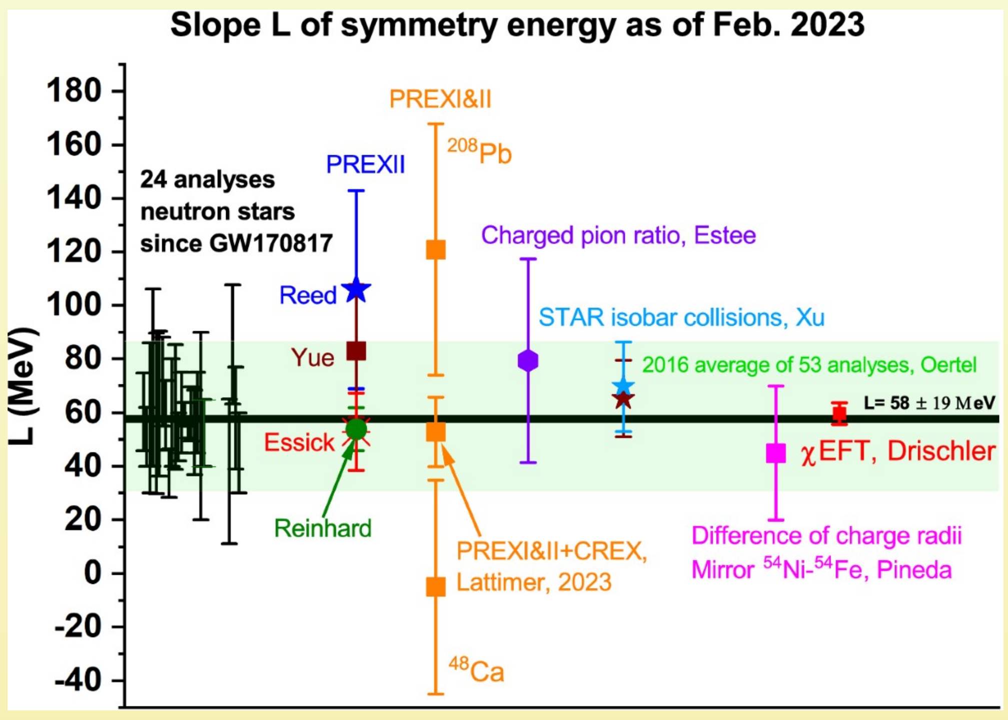
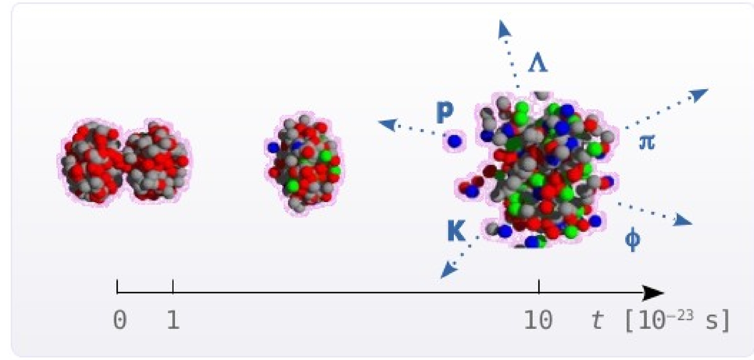


Source: Zhang, NB., Li, BA. Impact of symmetry energy on sound speed and spinodal decomposition in dense neutron-rich matter. Eur. Phys. J. A 59, 86 (2023).



Source: Krzysztof Piasecki, Faculty of Physics, University of Warsaw

Introduction. Nuclear matter equation of state

Equation of state (EOS) is given by the equation:

$$\varepsilon(\rho,\alpha) = \varepsilon_{SNM}(\rho) + \alpha^2 S(\rho)$$

$$\varepsilon(\rho_0,\alpha) \equiv \frac{-B(Z,N)}{A} = \varepsilon_0 + \alpha^2 J$$

where:

$\varepsilon_{SNM}(\rho) = \varepsilon(\rho, \alpha = 0)$ - energy per nucleon in symmetric nuclear matter (SNM)

$S(\rho)$ - symmetry energy $\quad S(\rho) = S(\rho_0) + \frac{L}{3}(\frac{\rho-\rho_0}{\rho_0}) + \frac{K_{sym}}{18}(\frac{\rho-\rho_0}{\rho_0})^2 + ...$

$J = a_a$

$\varepsilon_0 = a_V$ $\quad \alpha \equiv \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$ - neutron-proton density asymmetry

$\varepsilon_{SNM} = \varepsilon_0 + \frac{1}{2}K_0 x^2 + ...$ - expansion of SNM energy around saturation density

$x = (\frac{\rho - \rho_0}{3\rho_0})$

$L = 3\rho_0(\frac{\partial S}{\partial \rho})_{\rho=\rho_0}$ - slope parameter

$S(\rho_0) = (31,6 \pm 2,7) MeV$

$K_0 = (230 \pm 20) MeV$

$K_{sym} = 9\rho_0^2(\frac{\partial^2 S}{\partial \rho^2})_{\rho=\rho_0}$ - curvature of symmetry energy

$K_0 = 9\rho_0^2(\frac{\partial^2 \varepsilon_{SNM}}{\partial \rho^2})_{\rho=\rho_0}$ - curvature of (SNM) symmetric nuclear matter energy

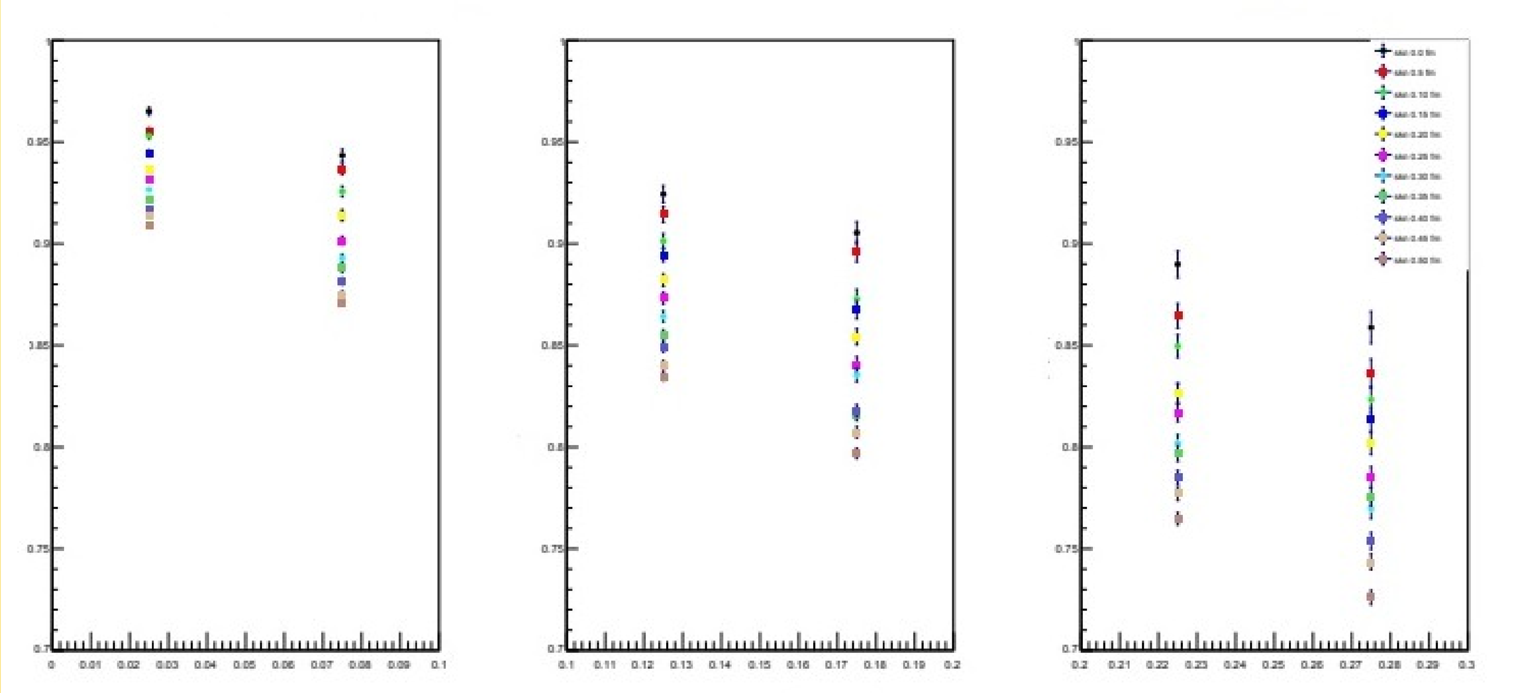
Calculations were done using UrQMD program (Ultrarelativistic Quantum Molecular Dynamics). UrQMD is Monte Carlo type code of relativistic collision; equation of state can be in 2 modes: (CASCADE+Woods-Saxon) or (hard Skyrme) and every particle is represented in a below form. Total cross section is:

$$\varphi_j(\boldsymbol{x}_j, t) = \left(\frac{2\alpha}{\pi}\right)^{\frac{3}{4}} \exp\left\{-\alpha(\boldsymbol{x}_j - \boldsymbol{r}_j(t))^2 + \frac{i}{\hbar}\boldsymbol{p}_j(t)\boldsymbol{x}_j\right\}$$

$$d_{\text{trans}} \leq d_0 = \sqrt{\frac{\sigma_{\text{tot}}}{\pi}}, \qquad \sigma_{\text{tot}} = \sigma(\sqrt{s}, \text{type})$$

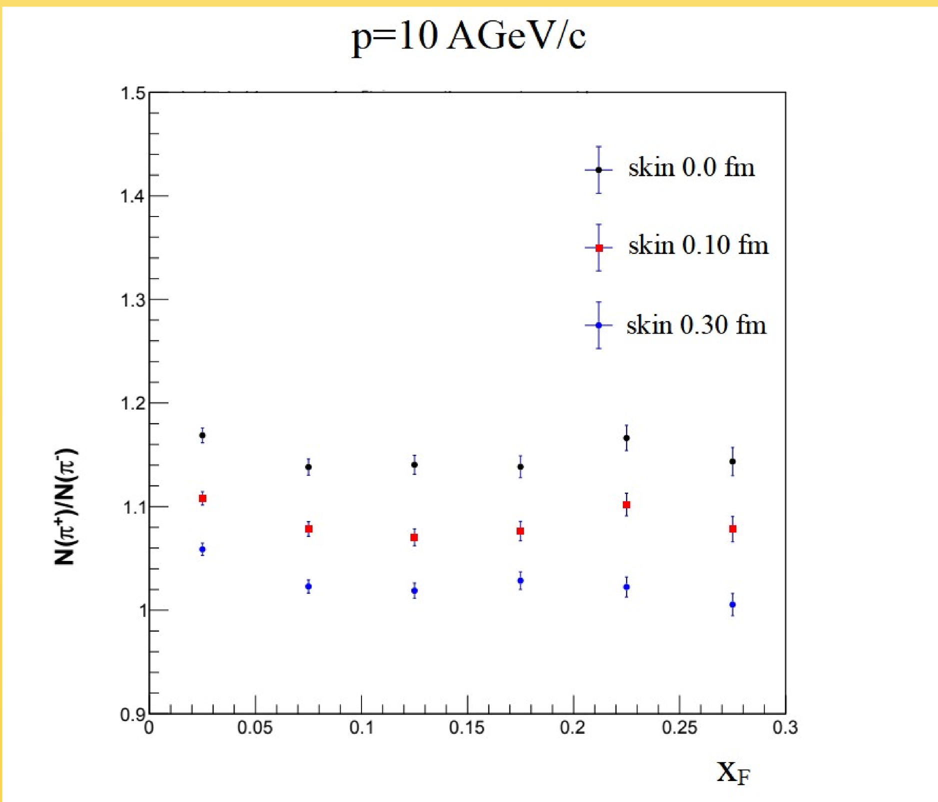
^{208}Pb+^{208}Pb collision, p=150AGeV/c, b=16 fm. Ratio of pions vs x_F:

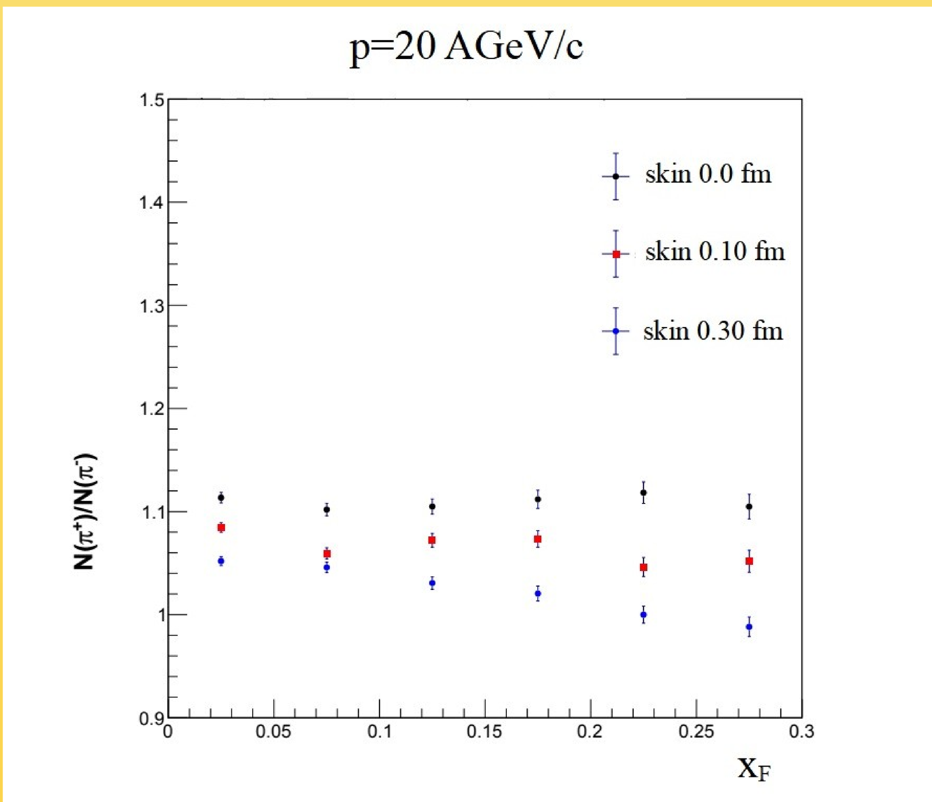
Ratio $N(\pi^+)/N(\pi^-)$ (from 0,70 till 1,00) as a function of x_F, b=16 fm. 11 skin thicknesses: from 0,0 fm, to 0,50 fm

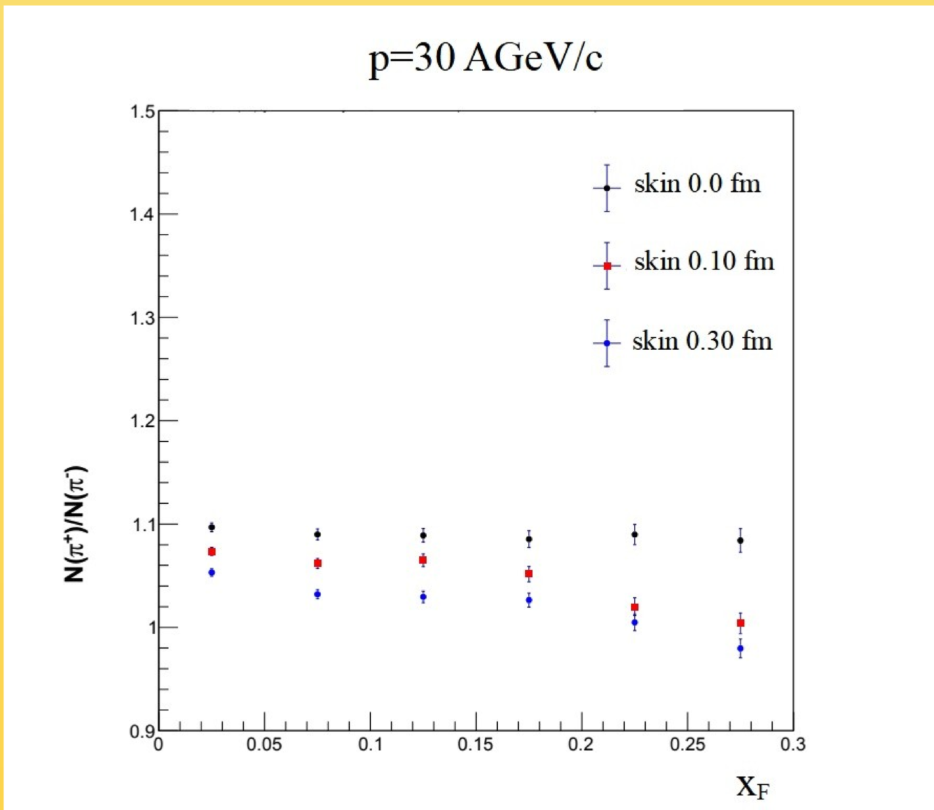


Results of ratio of number of pions as a function of Feynman variable for collision: p+^{208}Pb at different momenta (p=10, 20, 30 AGeV/c), EOS0 in UrQMD. (from 0,90 till 1,50). Radius of ^{208}Pb is about 7,1 fm. Impact parameter is in the range of 6-8fm.

Feynmann variable: $(x_f = 2p_{lab}/\sqrt{s})$



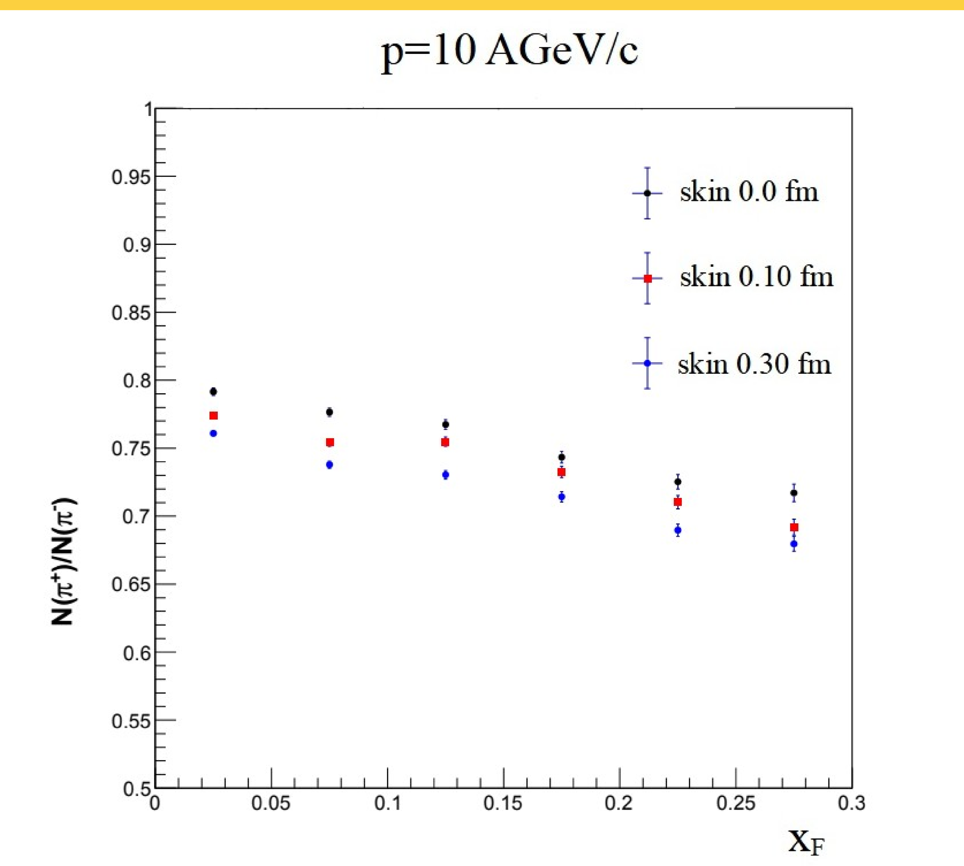


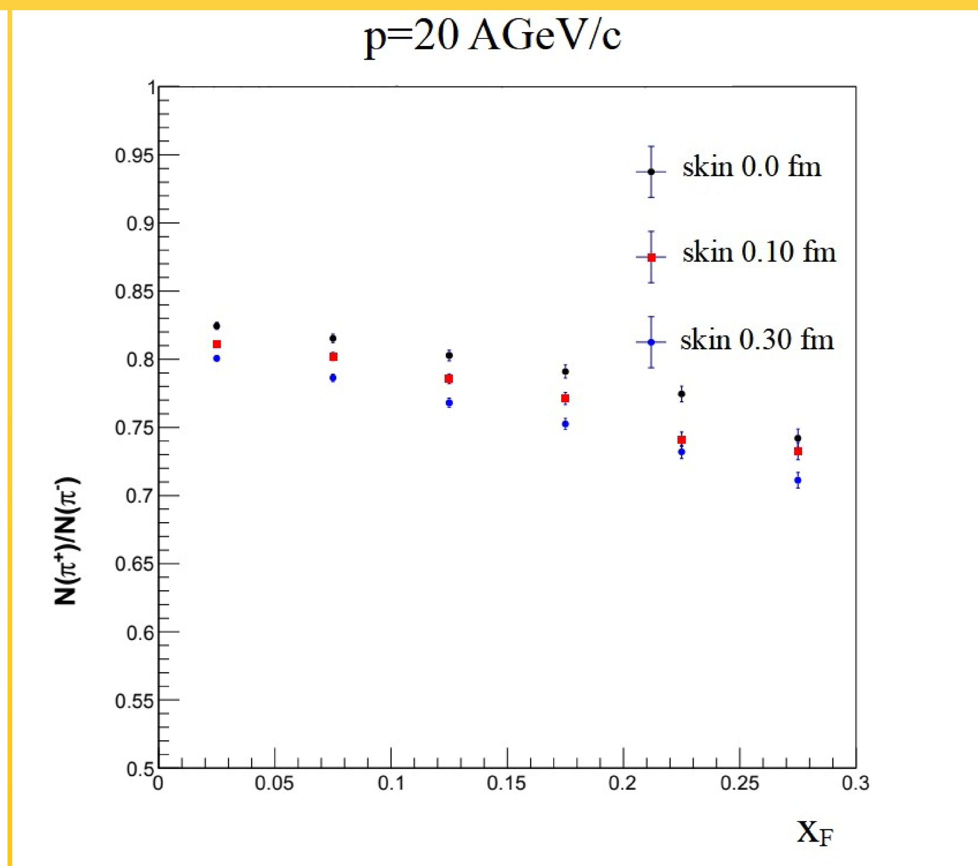


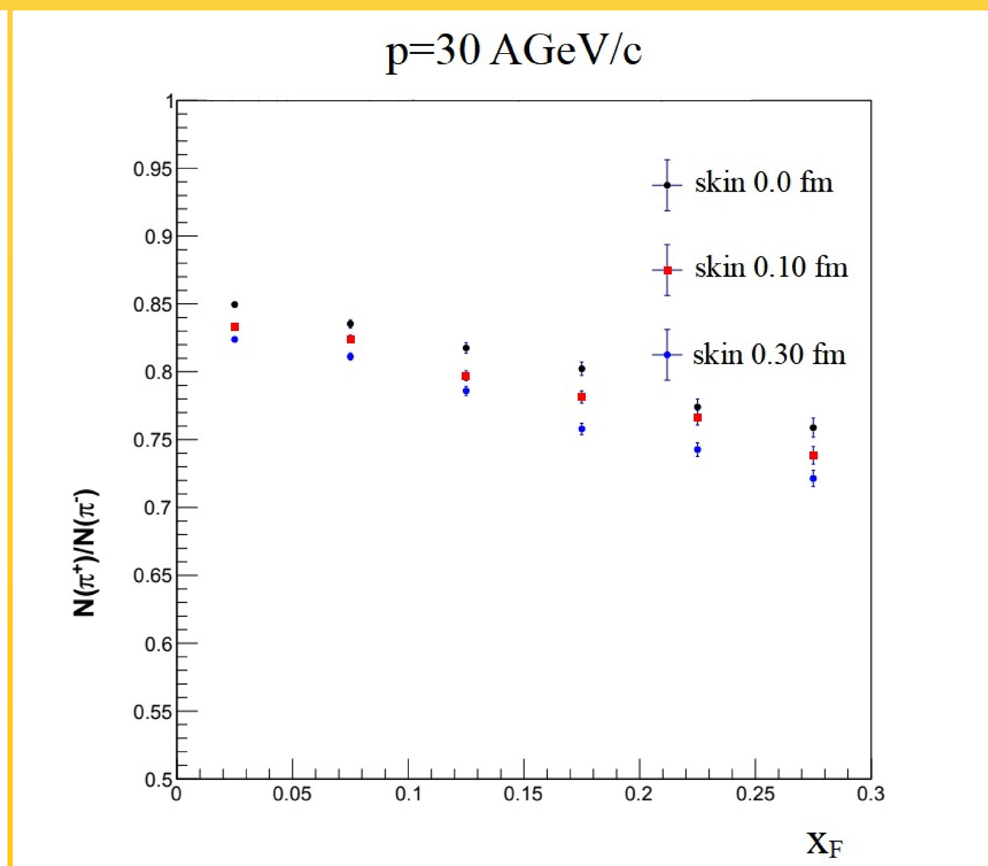
Some conclusions:

- for p=10AGeV/c ratio is always greater than one
- in all cases the ratio decreases with increasing thickness of skin
- ratio decreases with increasing momenta

The same results of collision but in case of antiproton: p$^-$+^{208}Pb at three mentioned momenta.







Some conclusions:

- in all cases ratio is smaller than one
- decreasing (linear ?) function for all skin thickness and all momenta
- ratio slightly increases with increasing momenta

References:

1. "On the Importance of Isospin Effects for the Interpretation of Nuclear Collisions", Ondrej Chvala for the NA49 Collaboration (2004)
2. NUSYM2023 Conference: https://indico.gsi.de/event/17017/timetable/#20230918
3. "$\pi^+ - \pi^-$ asymmetry and the neutron skin in heavy nuclei", Antoni Szczurek(2004)
4. "Ab initio predictions link the neutron skin of 208Pb to nuclear forces", Baishan Hu et al. (2022)
5. "Neutron skin systematics from microscopic equations of state", Francesca Sammarruca (2022)
6. "Probing neutron-skin thickness in peripheral relativistic nuclear collisions" A. Morawiec, 2023

Summary:

1. Topic of neutron skin is area of nuclear physics related to: properties of atomic nucleus (like symmetry energy, slope parameter), neutron stars and others
2. Interesting area of research: equation of state and slope parameter
3. UrQMD is not the only one, but useful tool in research.
4. In case of ^{208}Pb+^{208}Pb collision, ratio of pions decreases for increasing skin thickness (and decrease is stronger). This was observed before in master thesis of A. Morawiec in 2023, here extended to more skin thicknesses.
5. In proton+^{208}Pb or antiproton+^{208}Pb behaviour is as described in frames.