Feasibility studies to measure the neutron skin of nuclei using hyperon-antihyperon pairs

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Exploring the neutron skin by hyperon–antihyperon production in antiproton–nucleus interactions

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Abstract. In this work we propose a new method to measure the evolution of the neutron skin thickness between different isotopes. We consider antiproton–nucleus interactions close to the production threshold of $\Lambda\overline{\Lambda}$ and $\Sigma^{-}\overline{\Lambda}$ pairs. At low energies, $\Lambda\overline{\Lambda}$ pairs are produced in $\overline{p} + p$ collisions, while $\Sigma^{-}\overline{\Lambda}$ pairs can only be produced in $\overline{p} + n$ interactions. Measuring these cross sections provides information on the neutron skin thickness.

https://arxiv.org/pdf/2209.03875.pdf

Introduction

- Neutron-rich nuclei expected to have neutron skin

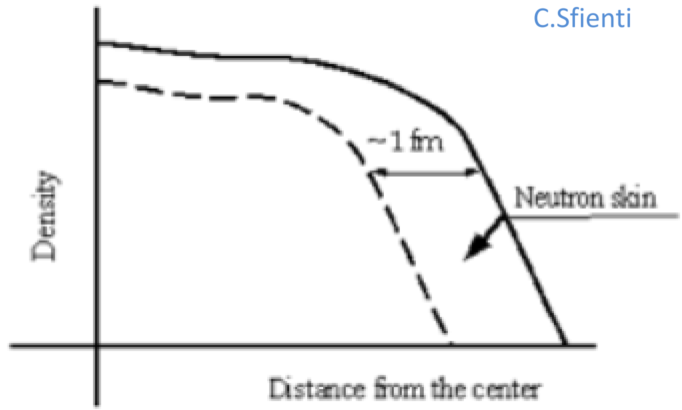
$$\Delta r_{np} = r_{\mathrm{rms,n}} - r_{\mathrm{rms,p}}$$

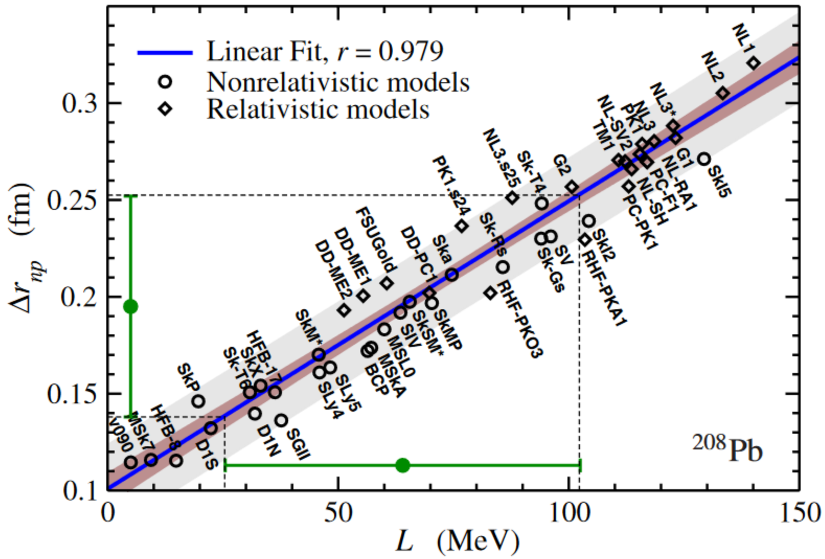
- Correlated with nuclear symmetry energy
  - Energy cost associated with additional neutron-proton assymmetry
- Slope of the symmetry energy **L** quantifies difference between:
  - Saturation density in nuclear core
  - Low density on the surface

$$L = 3\rho_0 \frac{\partial E_{sym}(\rho)}{\partial \rho}\bigg|_{\rho_0}$$

- Important parameter in equation of state in neutron rich systems

C.Sfienti

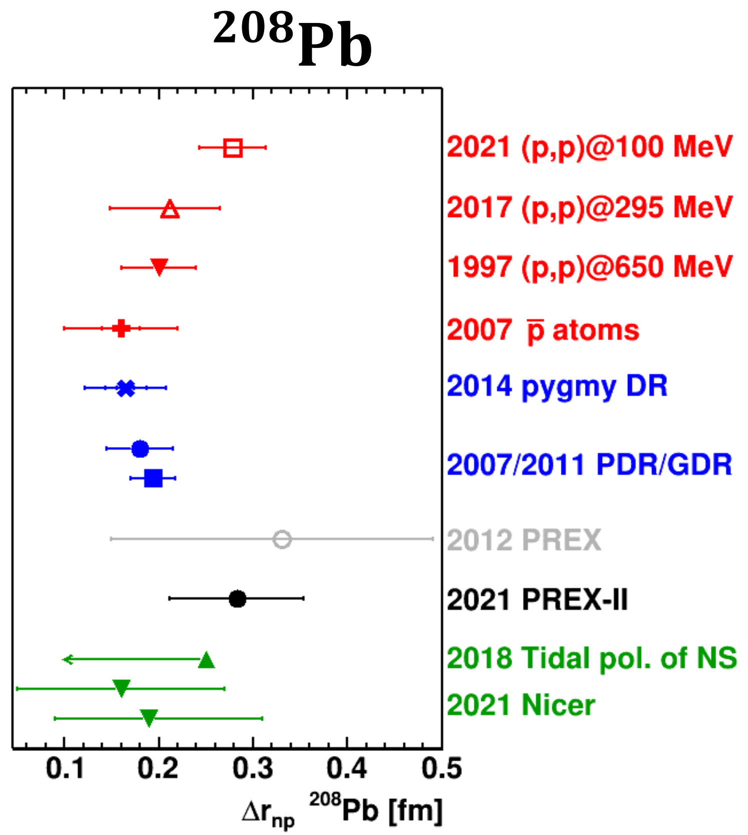




X. Roca-Maza, at al. Phys. Rev. Lett. 106, 252501 (2011)

Approaches to the neutron skin

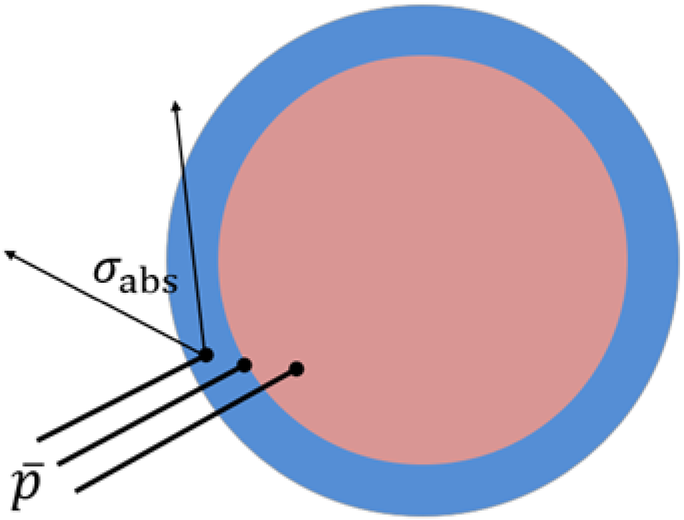
- Many different approaches to determine neutron skin
- Using hadronic probes:
  - Proton-Nucleus elastic scattering
  - Pion, Alpha, d scattering
  - Heavy ion collisions
  - Antiprotonic atoms
- Using electromagnetic probes:
  - Pion photoproduction
  - Electric dipole polarizabilites (GDR, PDR)
- Using weak interaction:
  - Parity violating asymmetry (PREX/CREX)
- Using astrophysical observations of neutron stars



Exclusive antiproton annihilation in nuclei

- New approach
  - Exclusive antiproton annihilation in nuclei
  - Using hyperons as tool for measurement

- Advantages
  - Strong absorption due to annihilation
    ⇒ High sensitivity to the nuclear periphery
    ⇒ Neutron skin



- Antiprotons absorption in the neutron skin

  - Absorption length:

$$r_{abs} = \frac{1}{\sigma_{\bar{p}n} \cdot \rho} \approx 1\ \text{fm} \cdot \frac{\rho}{\rho_0} \sim \text{neutron skin thickness } \Delta r_{np}$$

  - Survival propability:

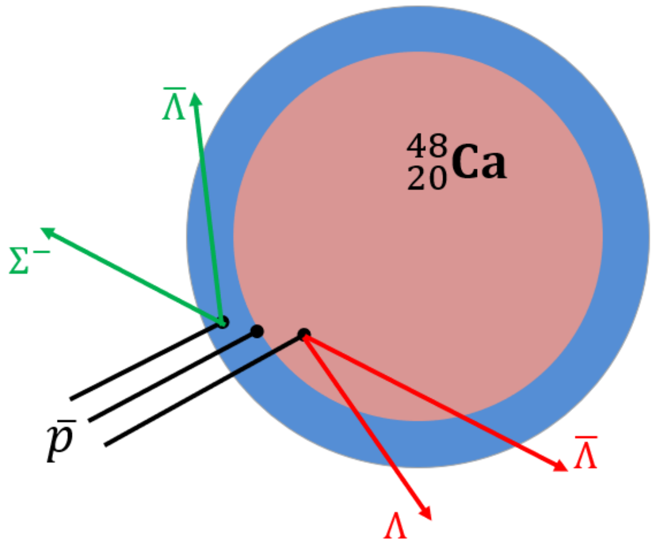
$$p_{abs} = \exp\left(-\frac{r_n}{r_{abs}}\right)$$

Antiproton annihilation in nuclei

- Simultaneously measure exclusive pair production close to threshold :

$$\bar{p}n \rightarrow \bar{\Lambda}\,\Sigma^-$$
$$\bar{p}p \rightarrow \bar{\Lambda}\,\Lambda$$

  - $\Sigma\bar{\Lambda}$ production only with neutrons
  - $\Lambda\bar{\Lambda}$ production only with protons



- Thicker neutron skin:
  - $\Sigma\bar{\Lambda}$ production increased
  - $\Lambda\bar{\Lambda}$ production decreased

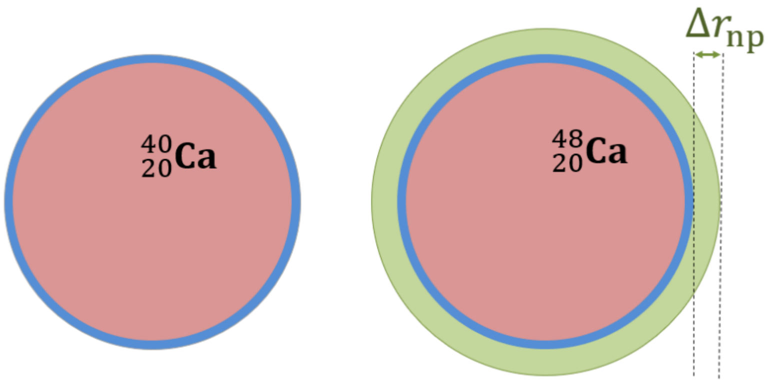
- Using ratio of exlusive pair production probabilities as observable for one isotope

$$R = \frac{P(\bar{p}n \rightarrow \bar{\Lambda}\,\Sigma^-)}{P(\bar{p}p \rightarrow \bar{\Lambda}\,\Lambda)}$$

- But for single isotope model dependencies may exist:
  - Rescattering
  - Absorption antihyperon
  - Both cross section required

Isotope pairs : simple analytic consideration

- Compare two different isotopes under assumptions
  - Same proton distribution, e.g. $^{40}\mathrm{Ca}/^{48}\mathrm{Ca}$
  - Neutron density inside nucleus unchanged
  - Additional neutron skin Δr_{np}



- Define double ratio of these two isotopes:

$$DR = \frac{R_{^{48}\mathrm{Ca}}}{R_{^{40}\mathrm{Ca}}} = \frac{P(\bar{\Lambda}\,\Sigma^-)_{48}}{P(\bar{\Lambda}\,\Sigma^-)_{40}} \cdot \frac{P(\bar{\Lambda}\Lambda)_{40}}{P(\bar{\Lambda}\Lambda)_{48}} \approx \frac{(1+\Delta p_{\mathrm{abs}})\cdot P(\bar{\Lambda}\,\Sigma^-)_{40}}{P(\bar{\Lambda}\,\Sigma^-)_{40}} \cdot \frac{P(\bar{\Lambda}\Lambda)_{40}}{(1-\Delta p_{\mathrm{abs}})\cdot P(\bar{\Lambda}\Lambda)_{40}}$$

$$DR \approx \frac{1+\Delta p_{\mathrm{abs}}}{1-\Delta p_{\mathrm{abs}}} \approx 1 + \frac{2}{r_{\mathrm{abs}}}\cdot \Delta r_{\mathrm{np}} + O\left(\Delta r_{\mathrm{np}}^2\right) \sim \sigma_{\bar{p}n}\cdot \rho_n \cdot \Delta r_{\mathrm{np}}$$

- Many systematic effects are suppressed, e.g.
  - Acceptance
  - Efficiency
  - Rescattering
- Influence of $\sigma_{\bar{p}p\to\bar{\Lambda}\Lambda}$ (nearly) eliminated

Why a transport calculation is needed?

- Simplified geometrical picture still has deficiencies :
    - Not all antiprotons traverse the neutron skin radially
      ⇒ Absorption probability depends on impact parameter
    - Absorption of produced antihyperons $\overline{\Lambda}$ inside nucleus
      ⇒ Favors peripherly produced pairs
      ⇒ Will depend on neutron skin thickness
    - Often slight modification of proton distribution for different isotopes

⇒ Use more realistic simulations to verify the sensitivity of the double ratio to the variation of neutron skin thickness

Simulation with GiBUU

- Using GiBUU software framework
  - Relativistic meanfield transport model

- On the Mogon2 supercomputer at the university of Mainz

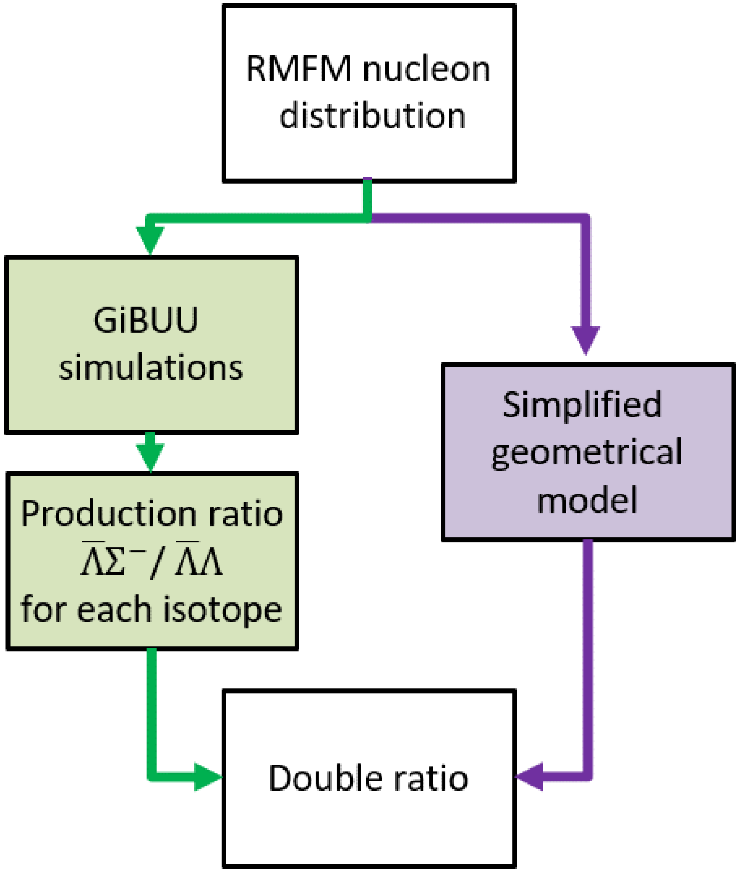
GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

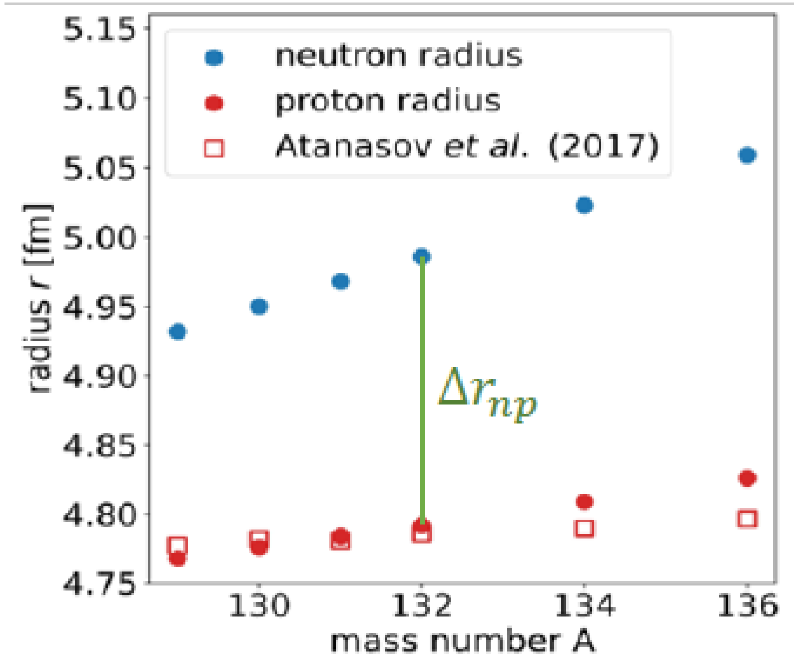
- Simulated ~28M events ($\bar{p}A$) at 2.40 GeV/c for each isotope
  - Computationally expensive: ~2d
  - ~5s of PANDA run time

  - For same statistics, taking detector effiencies into account: $\mathcal{O}$(hours)

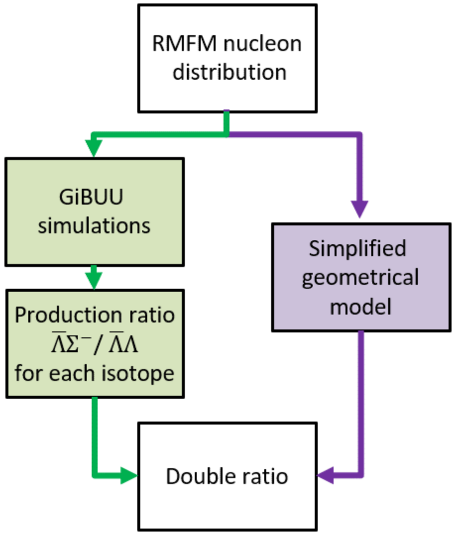
Xenon isotope chain – proof of principle

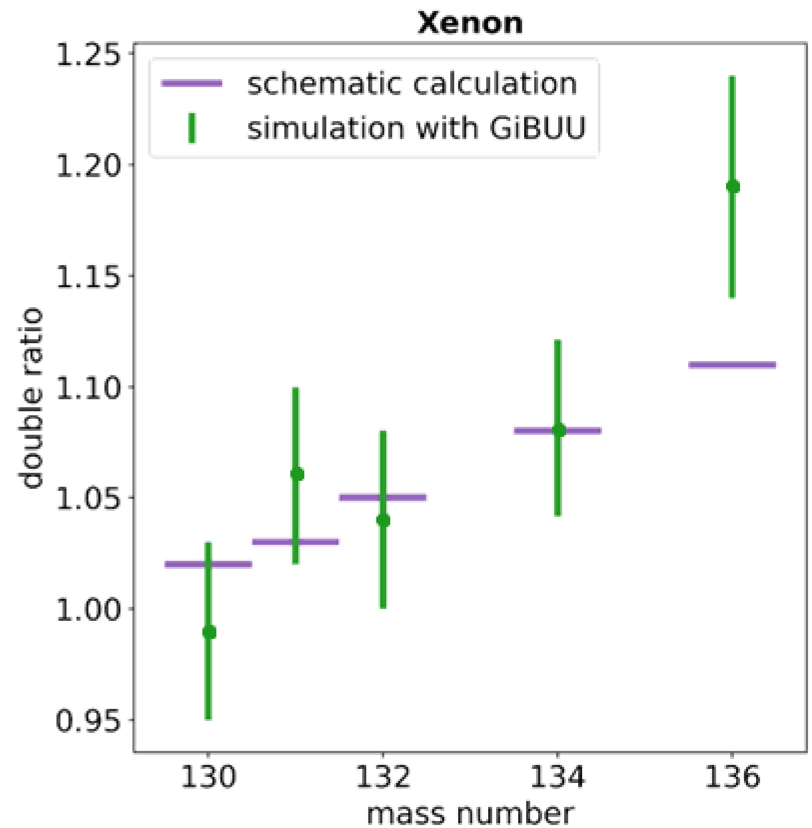
- Xenon was calculated first
  - Many stable isotopes with sufficient abundance
  - Gas jet target





Xenon isotope chain





- **Double ratio from GiBUU simulation is related to neutron skin thickness which is assumed as input**

- However: Isotopically pure gas targets extremely expensive $\mathcal{O}$(100g)
- Solid state target afordable $\mathcal{O}$(mg)

Calcium isotope

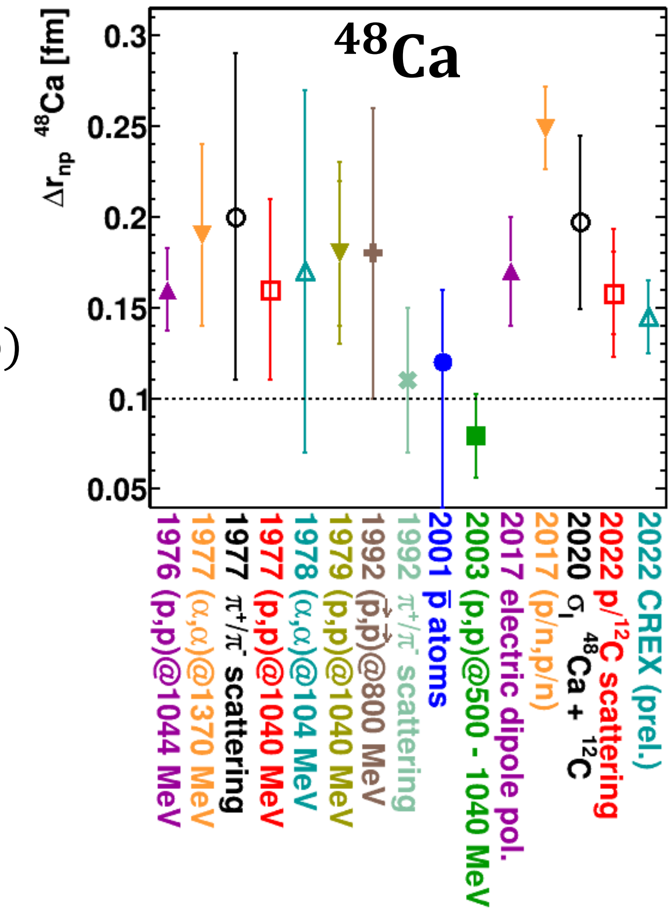
- Target $^{40}\mathrm{Ca}$ and $^{48}\mathrm{Ca}$
  - Double magic nuclei
  - Nearly identical proton distribution
  - Ab initio calculation possible

- Expected: $\Delta r_{\mathrm{np}}(^{48}\mathrm{Ca})$ strongly related to $\Delta r_{\mathrm{np}}(^{208}\mathrm{Pb})$
- Tension between PREX2 and CREX(prel.)
- Any new measurement of calcium welcome

- 80M Events at 2.40 GeV/c for each isotopes

Simplified model	GiBUU
1.37	1.41 ± 0.03

- $\Delta \mathrm{DR} = 0.03 \;\Rightarrow\; \frac{\Delta(\Delta r_{\mathrm{np}})}{\Delta r_{\mathrm{np}}} \approx 10\%$
  - **@PANDA** → $\mathcal{O}$(5 hours) measurement time



$\Delta r_{\mathrm{np}}(^{208}\mathrm{Pb}) = 0.283 \pm 0.071$ fm

D. Adhikari et al. (PREX),
Phys. Rev. Lett. 126, 172502 (2021).

Current work and outlook

- Improving statistical error:
  - Simulating additional events for Xenon isotopes
  - Goal: factor 4 more events
  - Simulations almost completed

- Systematic effects and their uncertainty still need to be studied
  - Reaction cross sections
    - $\sigma_{\bar{p}n\rightarrow\Sigma^-\bar{\Lambda}}$, $\sigma_{\bar{p}p\rightarrow\Lambda\bar{\Lambda}}$
    - Sensitivity of double ratio on the neutron skin thickness by varying the cross sections in GiBUU
    - Experimentally: Measurement on proton and deuterium with PANDA

  - Neutron and proton distribution
    - Implement different nucleon distributions in GiBUU and explore sensitivity

- Feasibility to use this method with PANDA needs to be studied in the future

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To summarize:

- New method to measure the neutron skin variation for isotope pairs using antiprotons
  - Short measuring time sufficient for high statistics
    ⇒ small statistical error
  - Large sensitivity on neutron skin thickness

Thank you for your attention

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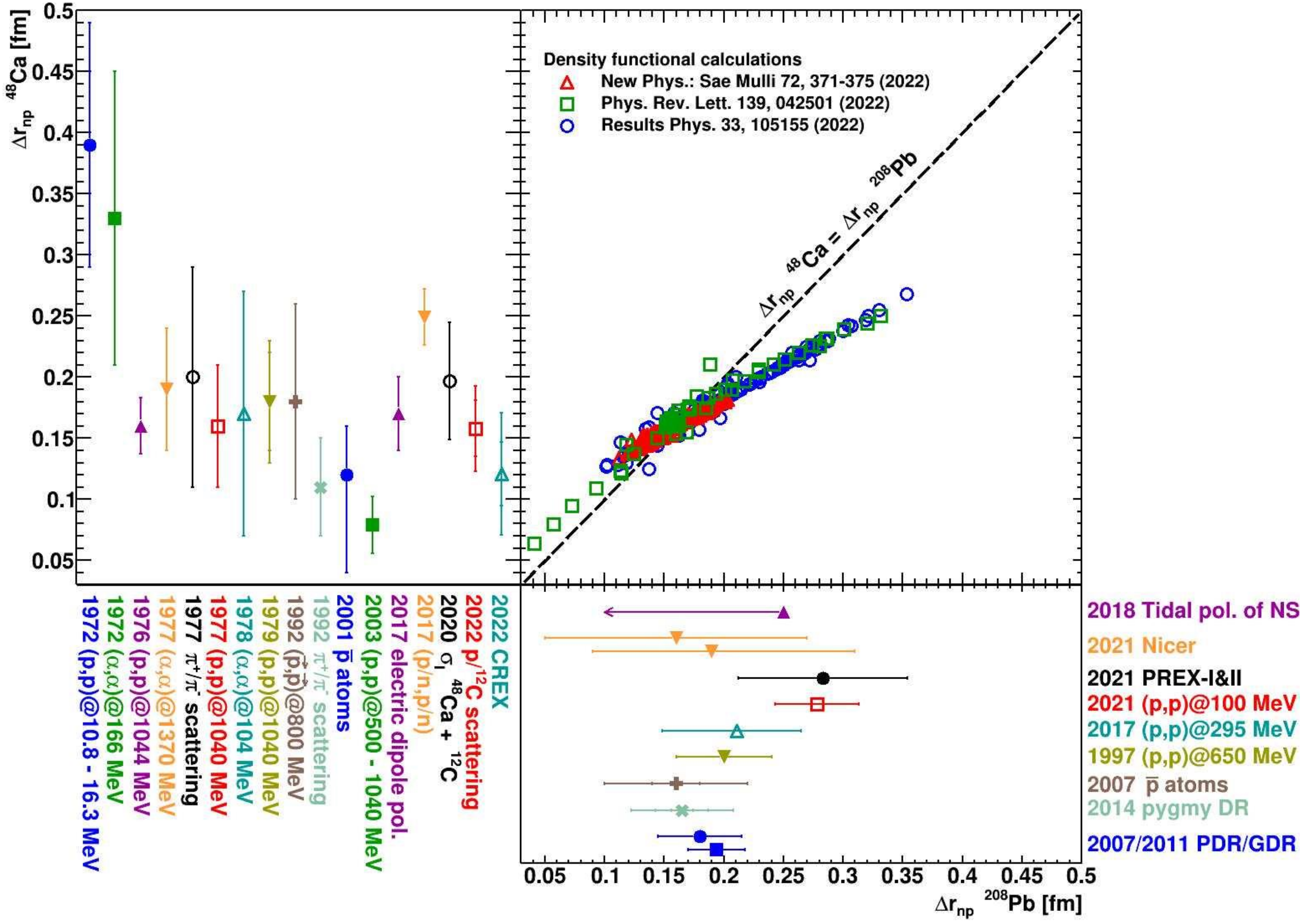
Backup slides

Calcium isotope



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D. Atanasov et al. In: J Phys G Nucl Part Phys 44.4 (2017), p. 044004