Antiprotonic atoms - a tool for the investigation of the nuclear periphery

for PS209 collaboration

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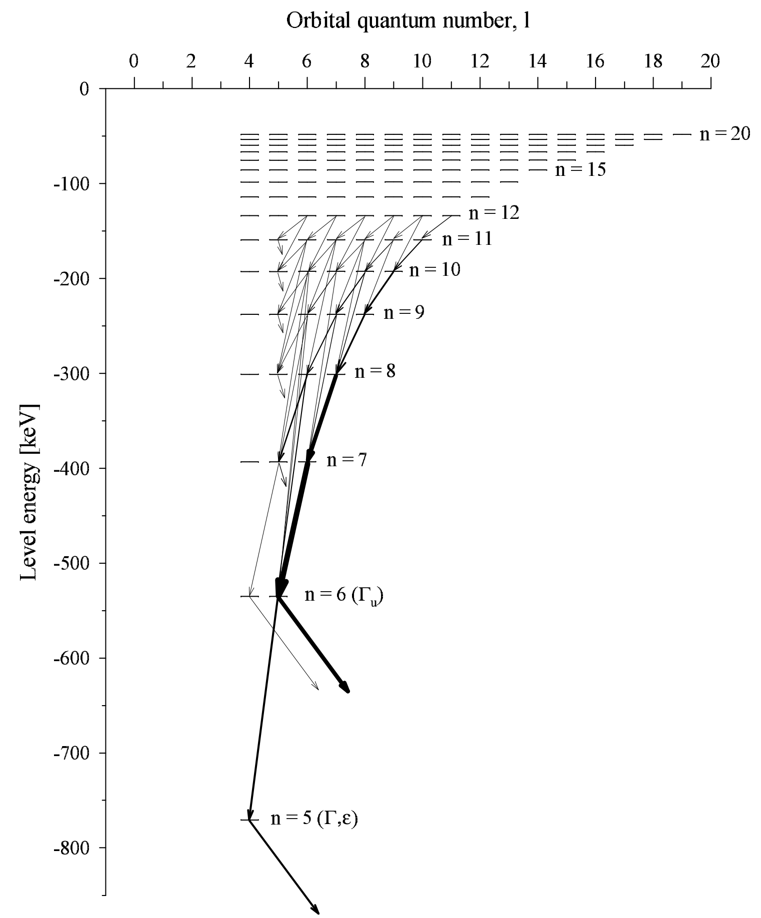
Outline

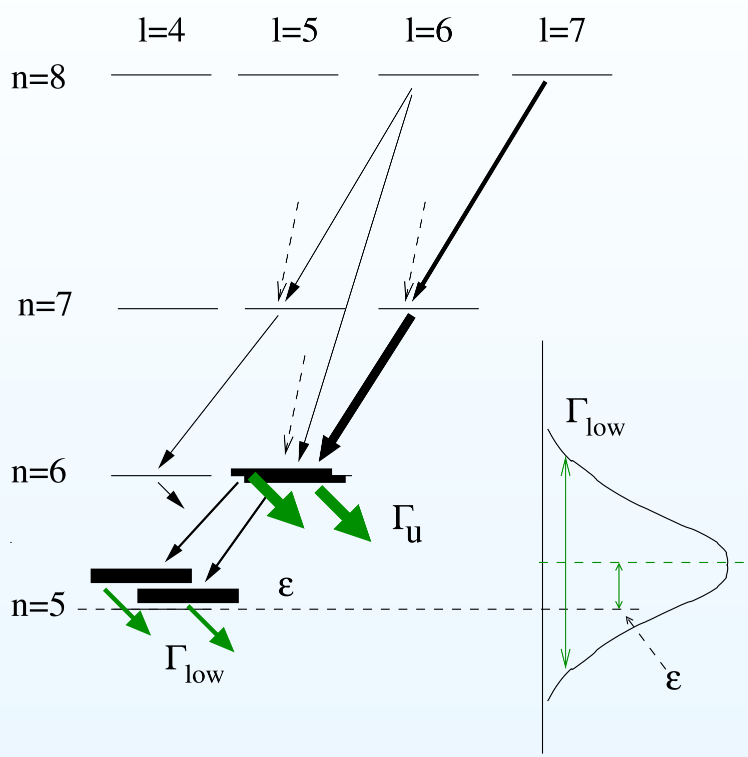
- Antiprotonic atoms – strong interaction effects
- Information on the nuclear surface from annihilation products ($f_{\rm halo}$)
- Neutron density distribution from antiprotonic X rays
- Systematics of Δr_{np}: comparison with theory & other experiments
- Summary & future plans

Antiprotonic atoms

- creation: $\bar{p}$ capture on the “high” orbit ($n_{\bar{p}} \approx 43 \times n_e$)
- cascade: emission of Auger electrons and X rays



Strong interaction effects



strong interaction

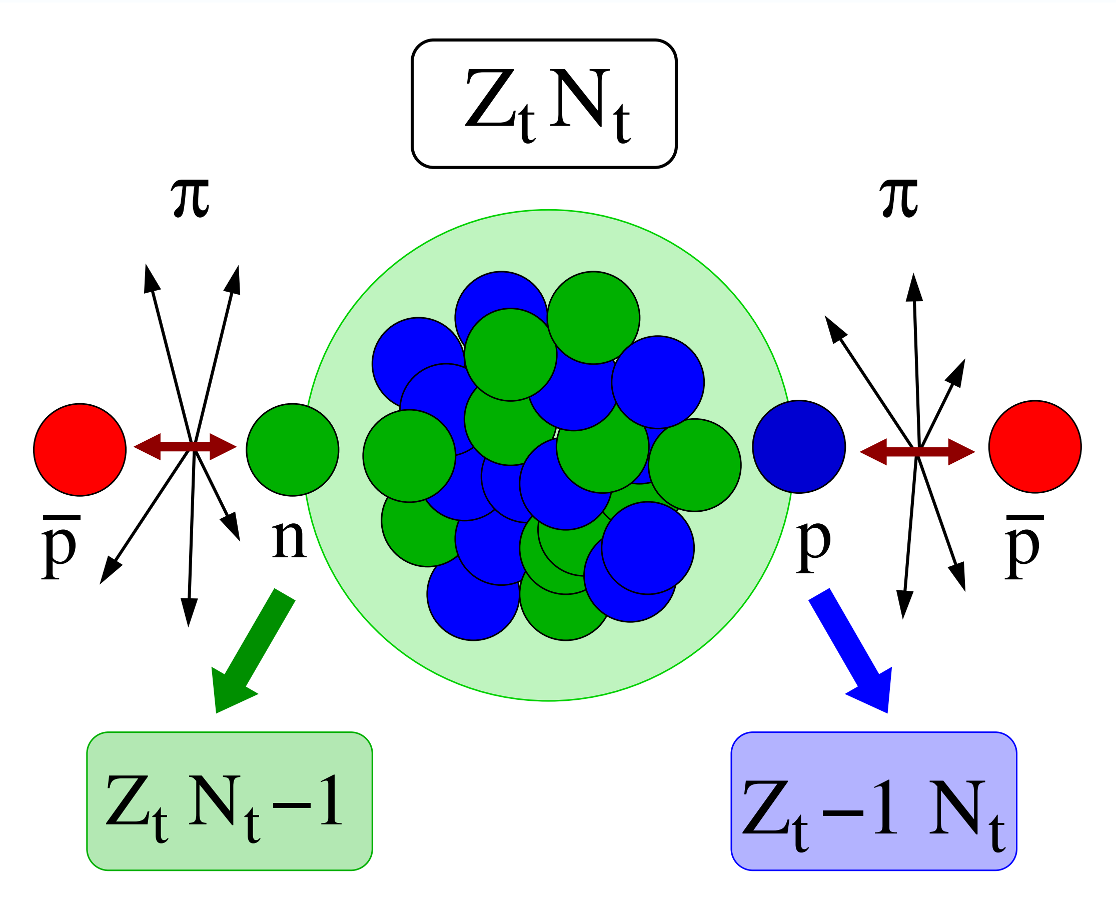
$\Downarrow$

levels **broadening** and **shift**

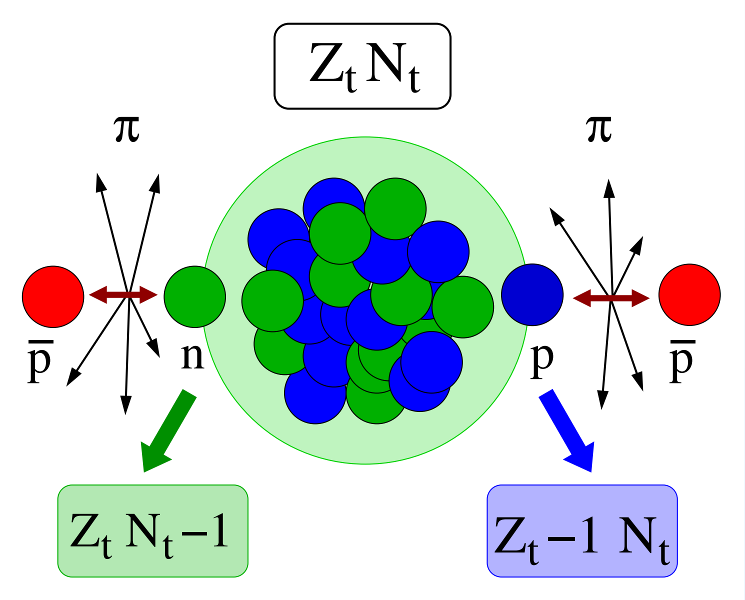
measured in experiment:

$\Gamma_{up}, \Gamma_{low}, \epsilon$

Annihilation products



Annihilation products



measured in experiment:

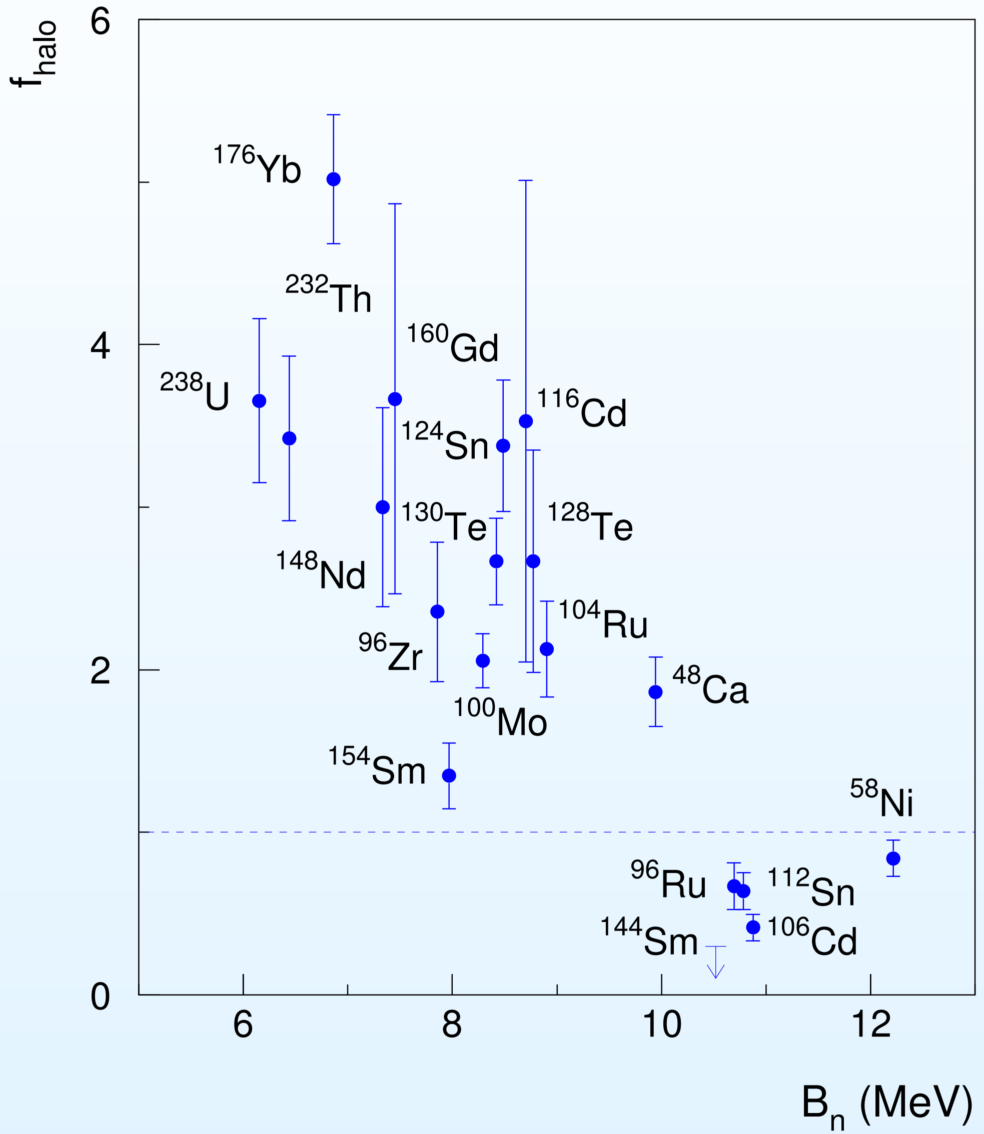
yield of $\begin{cases} Y_{N_t-1} \sim \rho_n(r_{annihil.}) \\ Y_{Z_t-1} \sim \rho_p(r_{annihil.}) \end{cases}$

$$f_{halo} = \frac{Y_{N_t-1}}{Y_{Z_t-1}} \cdot \frac{Z}{N} \cdot \frac{\mathrm{Im}\, a_{p\bar{p}}}{\mathrm{Im}\, a_{n\bar{p}}}$$

$$f_{halo} \sim \frac{\rho_n}{\rho_p}$$

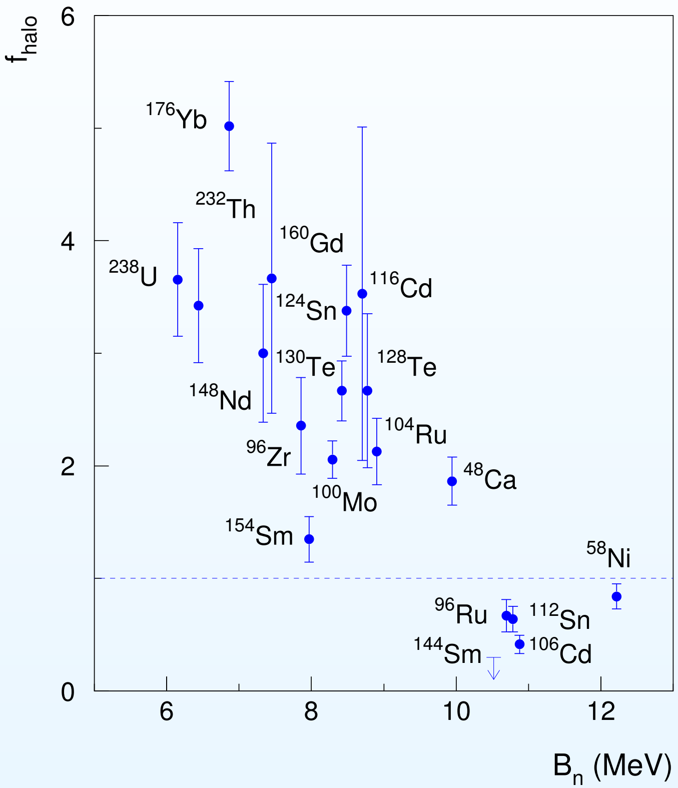
at $r \simeq (r_{1/2} + 2.5)$ *fm*

f_{halo}



f_halo
6
4
2
0
6
8
10
12
B_n (MeV)
176Yb
232Th
160Gd
238U
116Cd
124Sn
130Te
128Te
148Nd
104Ru
96Zr
48Ca
100Mo
154Sm
58Ni
96Ru
112Sn
144Sm
106Cd

f_{halo}



Observations:

- strong correlation between f_{halo} and neutron energy separation
- in nuclei with $B_n < 9$ MeV periphery reach in neutrons

Neutron density from Δr_{np}

$$\rho(r) = \rho_0 \left(1 + \exp(\frac{r - c}{a})\right)^{-1}$$

$$\langle r^2 \rangle = \frac{3}{5} c^2 + \frac{7}{5} \pi^2 a^2 \Rightarrow \langle r^2 \rangle (c, a)$$

let's consider two extreme cases:

- Δr_{np} results from the half-density radii difference ($a_n = a_p$, $c_n \neq c_p$, "neutron skin")
- Δr_{np} results from the surface diffuseness difference ($a_n \neq a_p$, $c_n = c_p$, "neutron halo")

ρ_p known from experiments with e or μ
ρ_n calculated from Δr_{np} (under the above assumptions)

What is difference between these cases?

Neutron density from Δr_{np}

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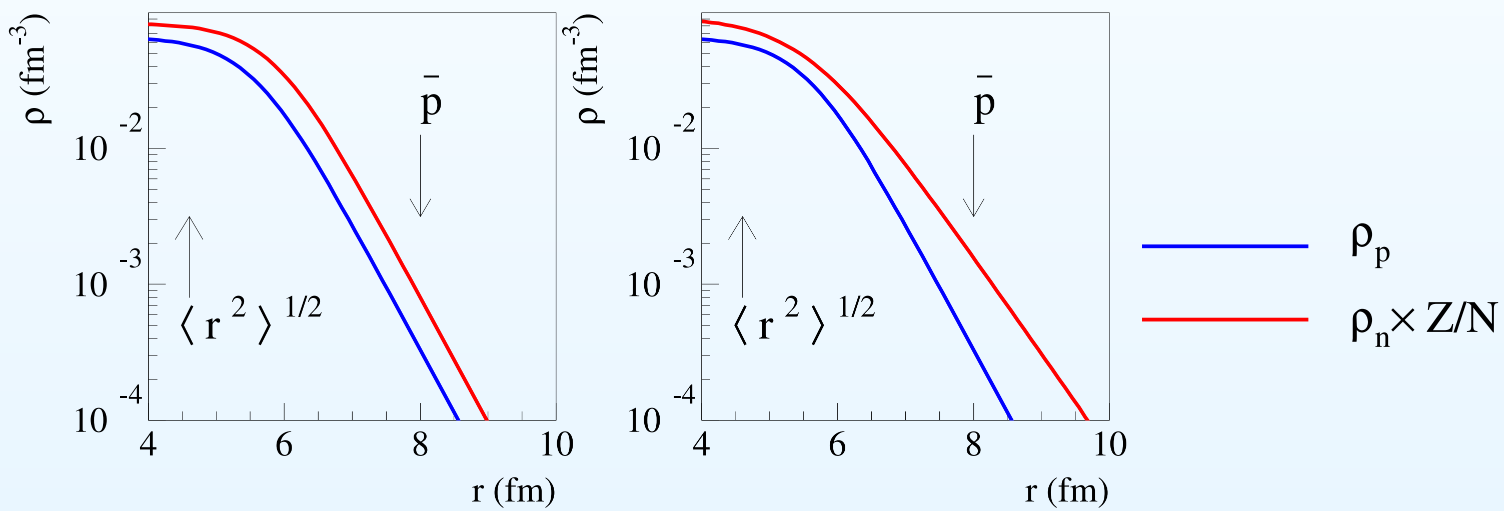
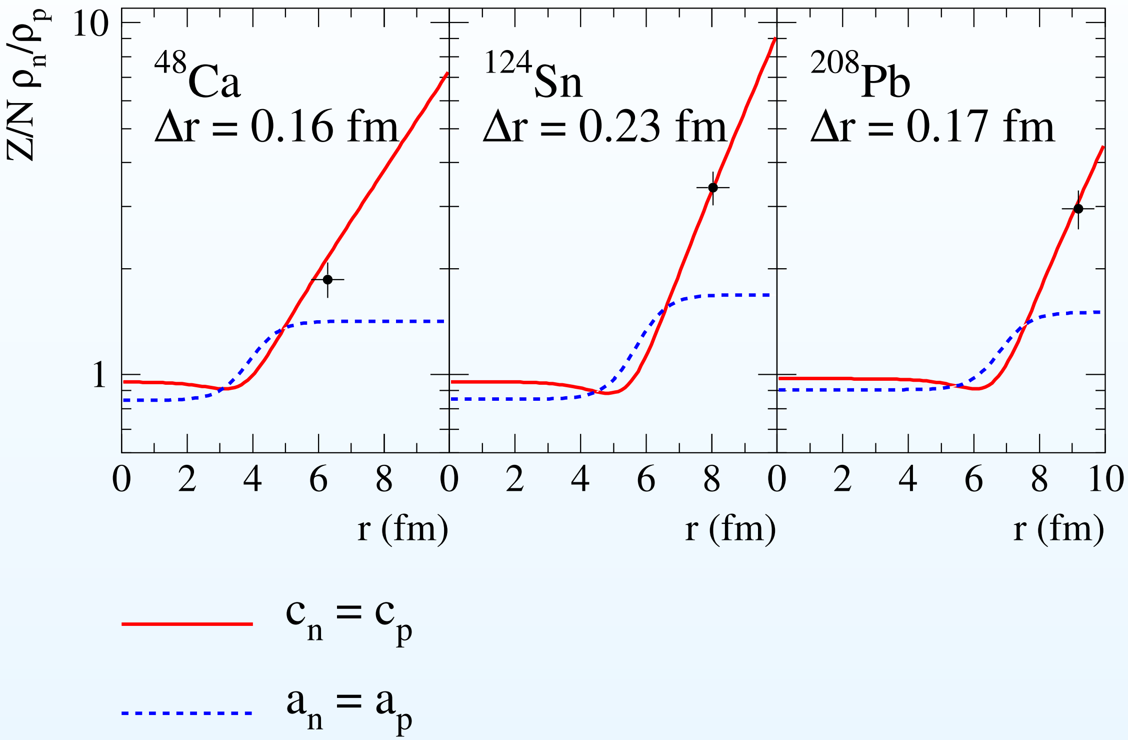


$a_n = a_p$
″neutron skin″

$c_n = c_p$
″neutron halo″

f_{halo} vs Δr_{np}



$\rightsquigarrow$ Δr_{np} caused by $a_n \neq a_p$ rather than by $c_n \neq c_p$

Antiprotonic X-rays ...

... another tool for the investigation of the nuclear periphery: strong interaction level **widths** and **shifts** depend on the antiproton-nucleus potential:

$$\frac{\Gamma}{2} \sim \int \mathrm{Im}\, V(r)\; |\Psi_{nl}(r)|^2\, r^2\, dr$$

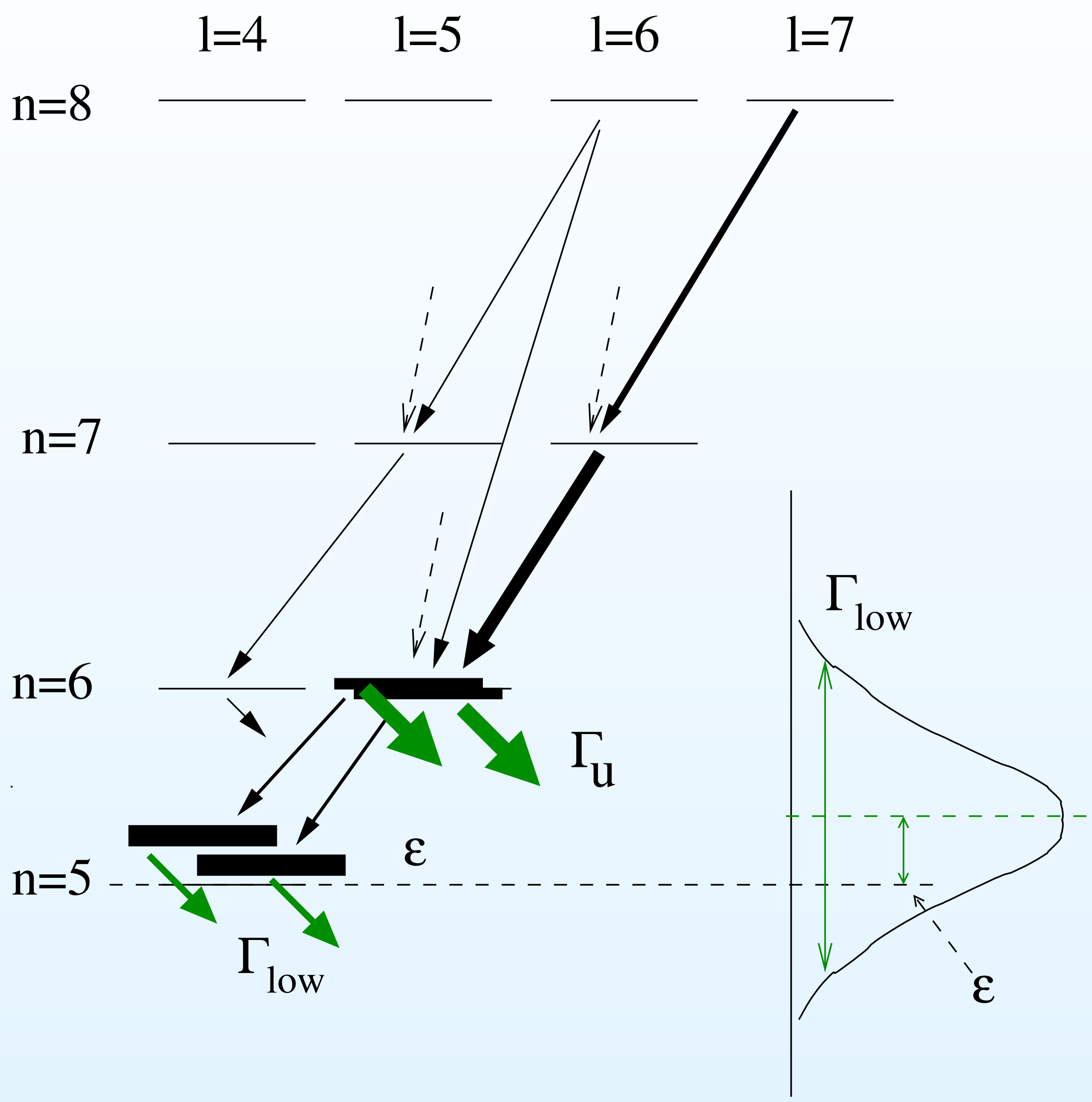
$$\frac{\epsilon}{2} \sim \int \mathrm{Re}\, V(r)\; |\Psi_{nl}(r)|^2\, r^2\, dr$$

$$V_{opt} = -\frac{2\pi}{\mu}\left(\bar{a}_n\, \rho_n(r) + \bar{a}_p\, \rho_p(r)\right)$$

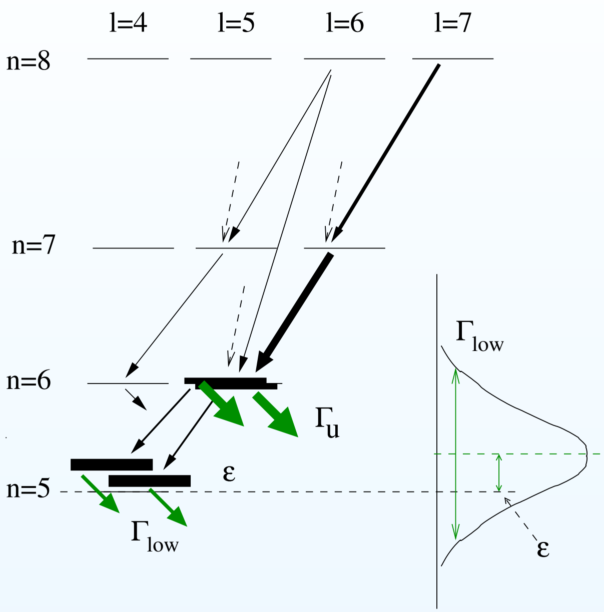
$$\bar{a}_p = \bar{a}_n = 2.5 + i\, 3.4\, \mathrm{fm}$$

C.J. Batty et al., Nucl. Phys. ***A592****, 487 (1995)*

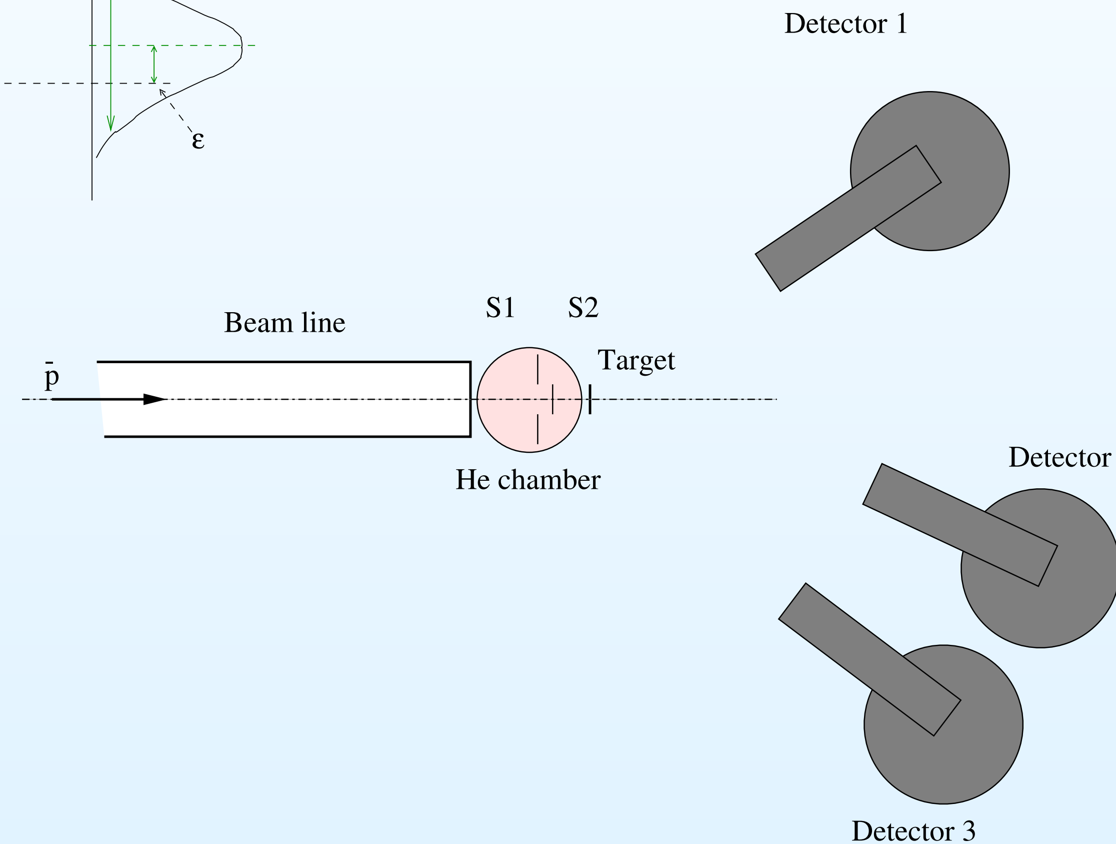
Experiment



Experiment

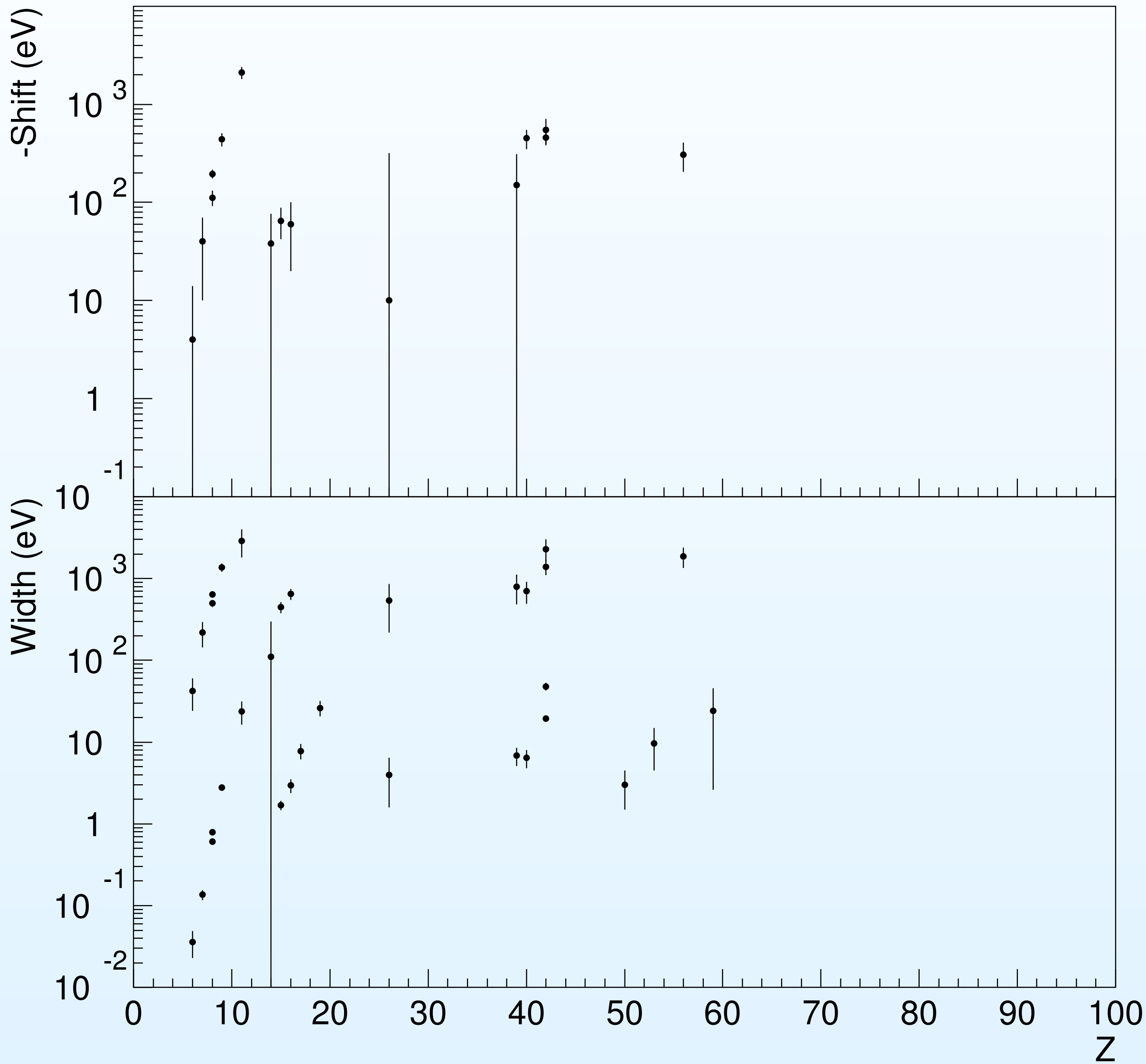


measured in experiment:
$\Gamma_{\rm up}, \Gamma_{\rm low}, \epsilon$

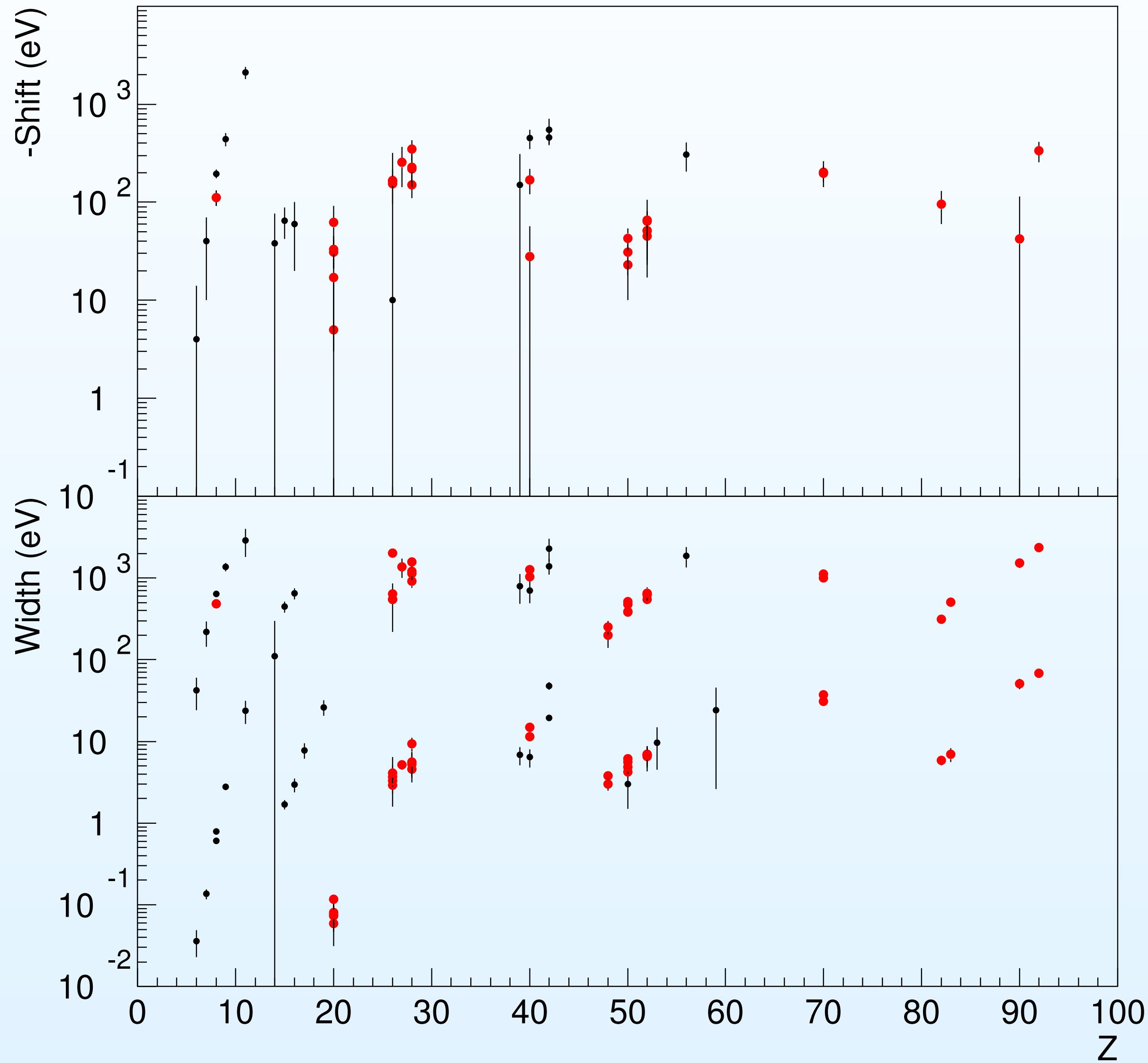


Harvest of the PS209 measurements

before PS209 measurements



Harvest of the PS209 measurements



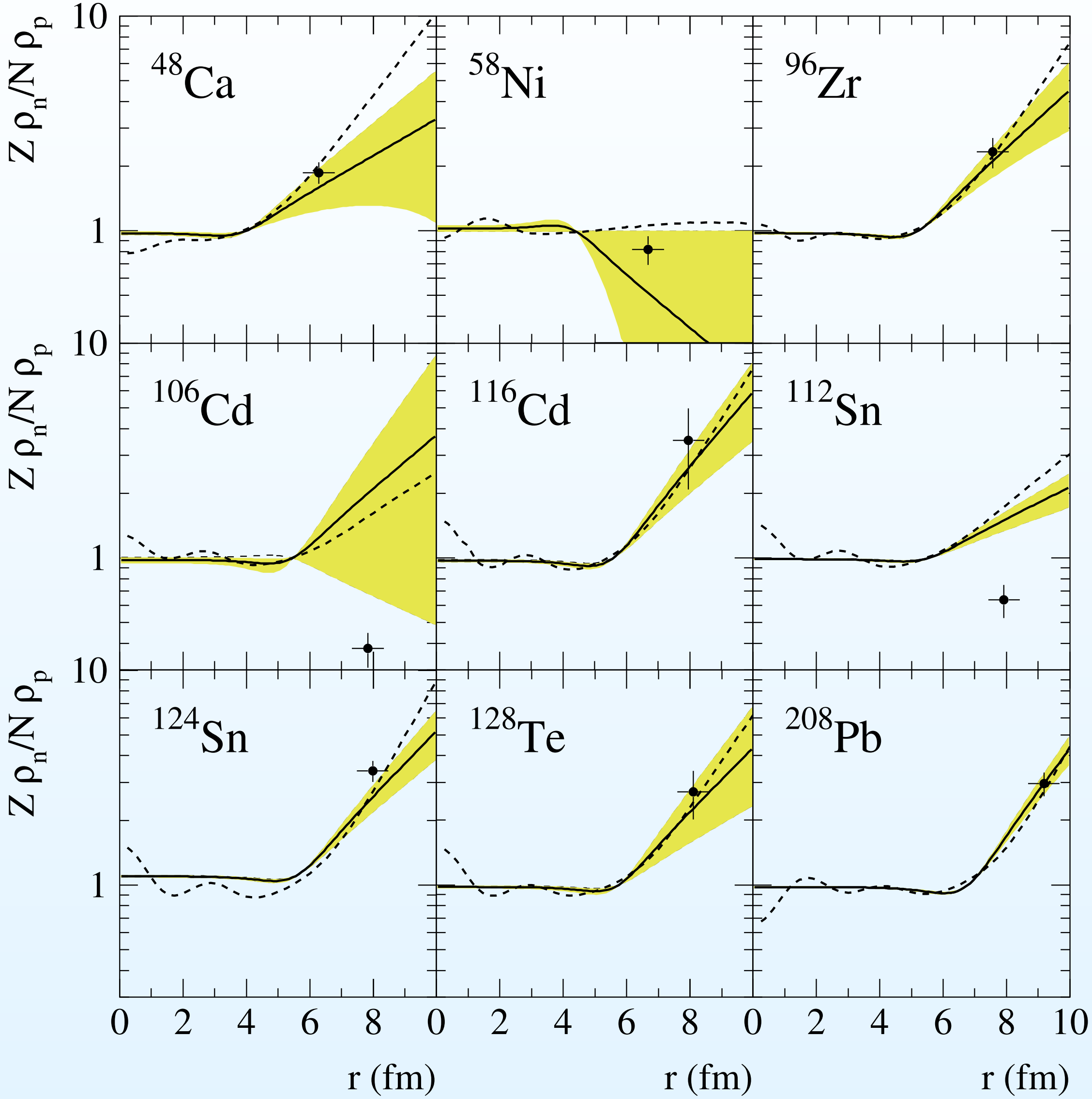
Determination of ρ_n from antiprotonic X rays

- known:
  - ρ_p (from electromagnet. interacting probes: e, μ)
  - $V_{opt}(\rho_p,\rho_n)$
- assumed:
  - 2-parameter-Fermi density distribution
  - $c_n = c_p$ *(to be discussed)*
- fitted: $a_n(V_{opt},\, \Gamma_{low},\, \Gamma_{up},\, (\epsilon))$

$$\Downarrow$$

$$\rho_n(c_n, a_n)$$

Neutron density – results

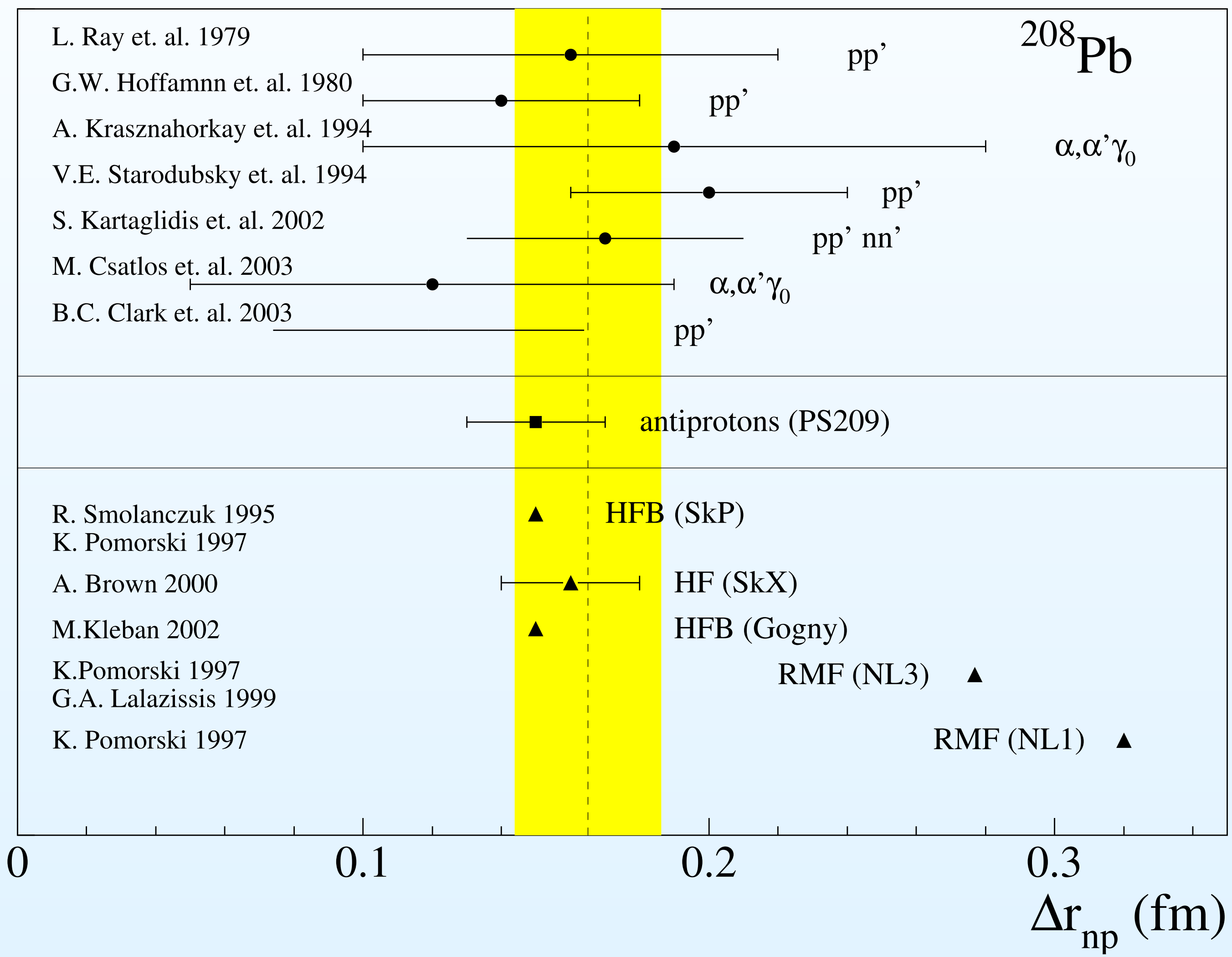


Δr_{np} from X-ray data – ^{208}Pb example

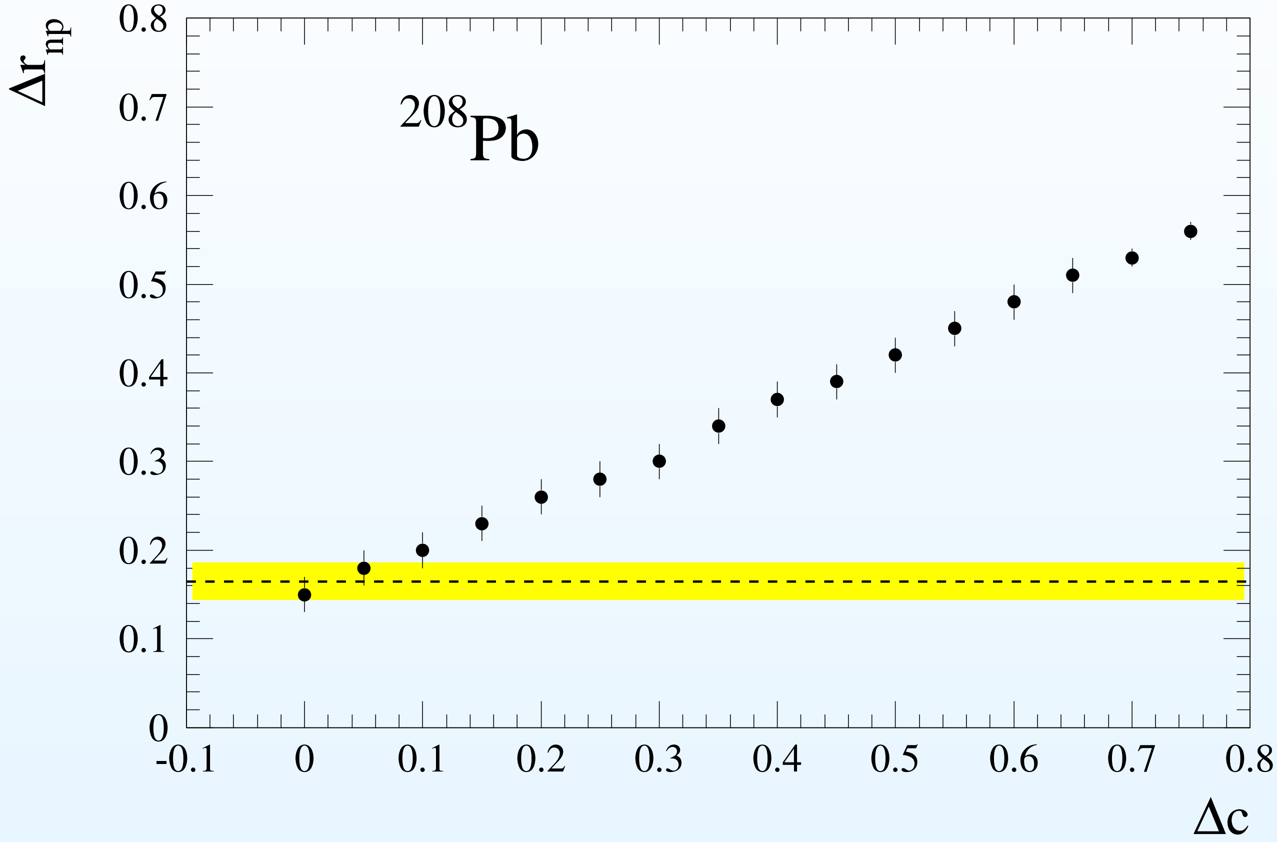
$$\rho_p(c_p, a_p),\ \rho_n(c_n, a_n) \Longrightarrow \Delta r_{np}$$

Δr_{np} from X-ray data – ^{208}Pb example

$$\rho_p(c_p, a_p),\ \rho_n(c_n, a_n) \Longrightarrow \Delta r_{np}$$



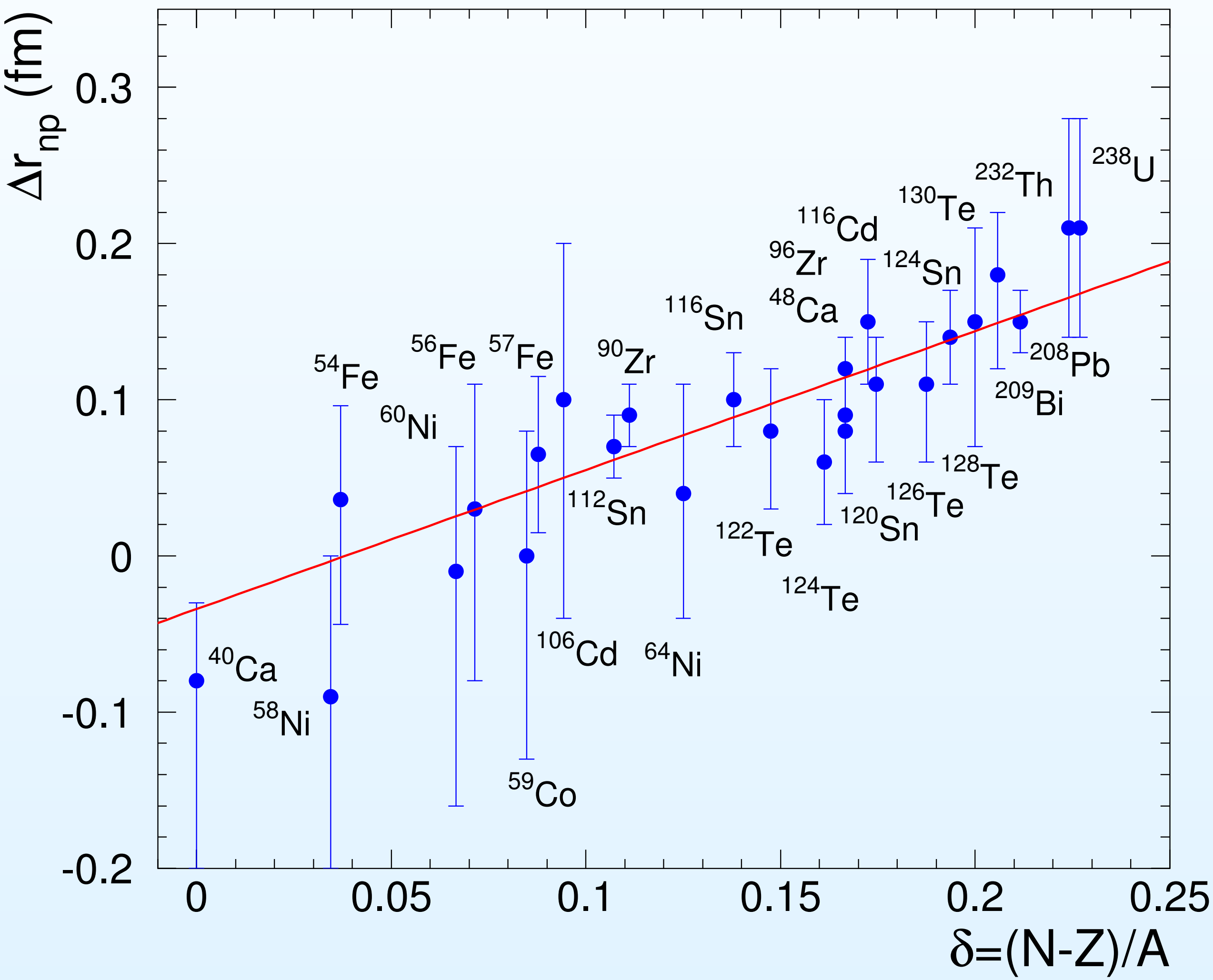
$c_p = c_n$?



Δr_{np}
^{208}Pb
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Δc

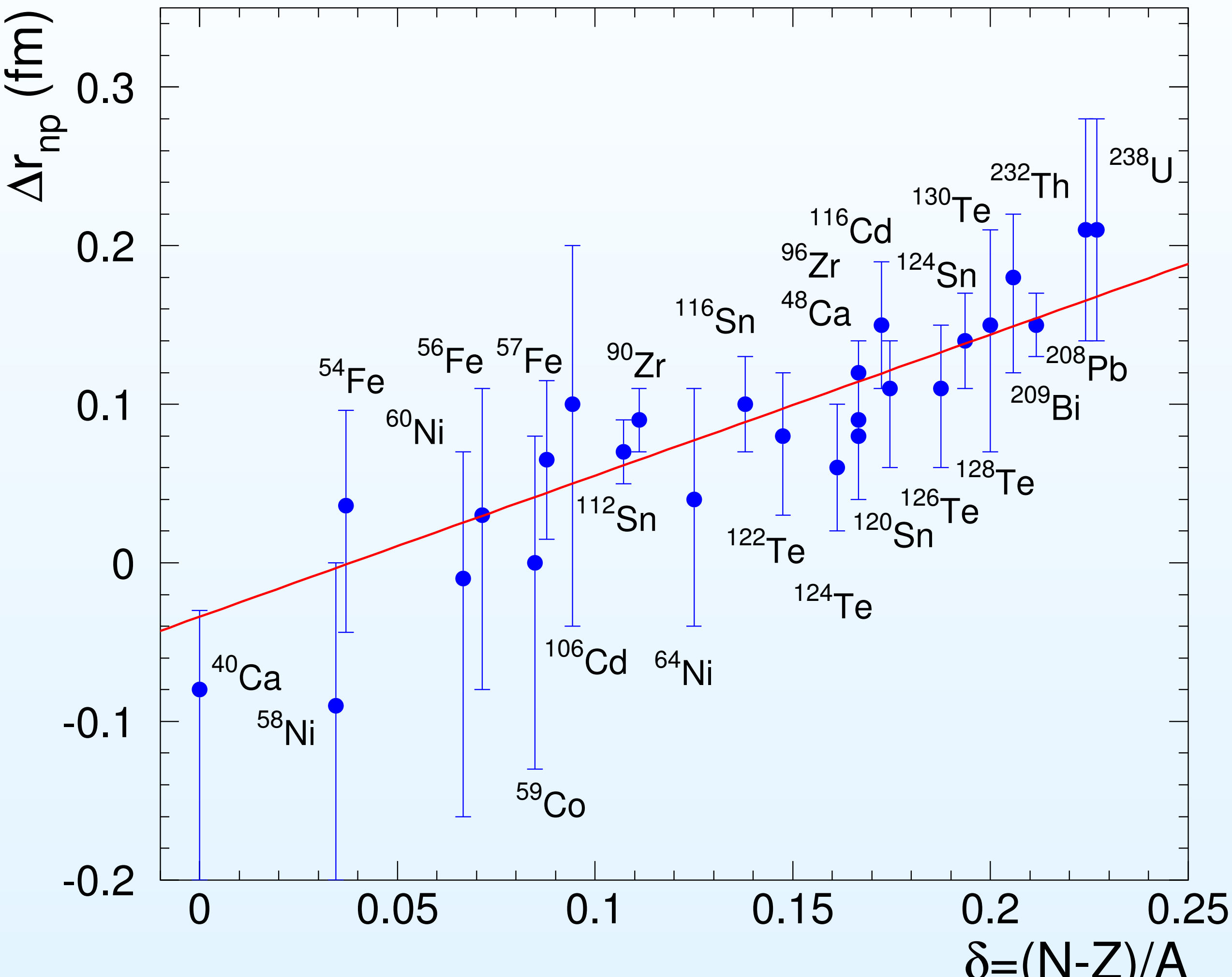
Δr_{np} systematics from X-ray data

$\rho_p(c_p, a_p)$, $\rho_n(c_n, a_n) \Longrightarrow \Delta r_{np}$



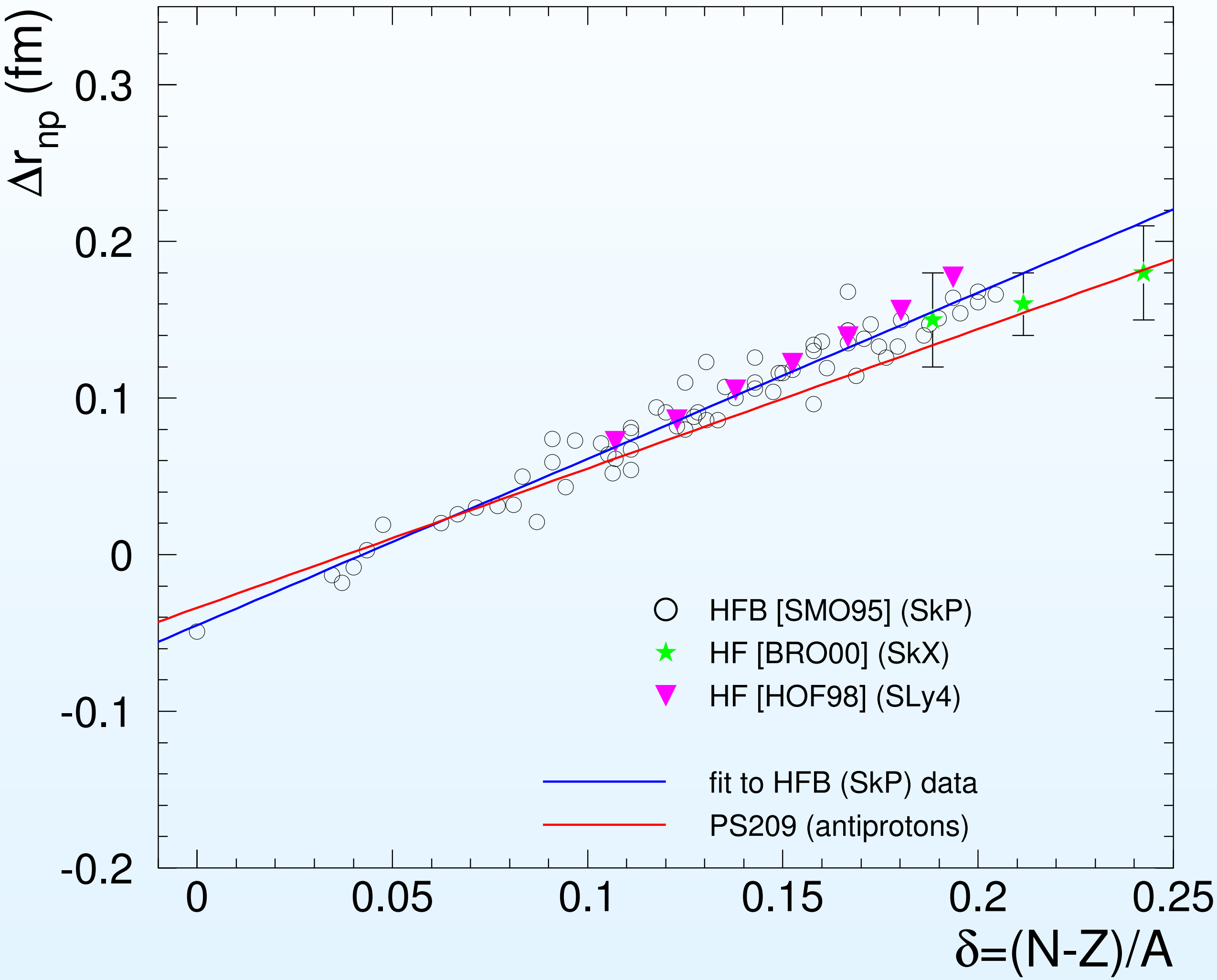
Comparison with theory

experimental data



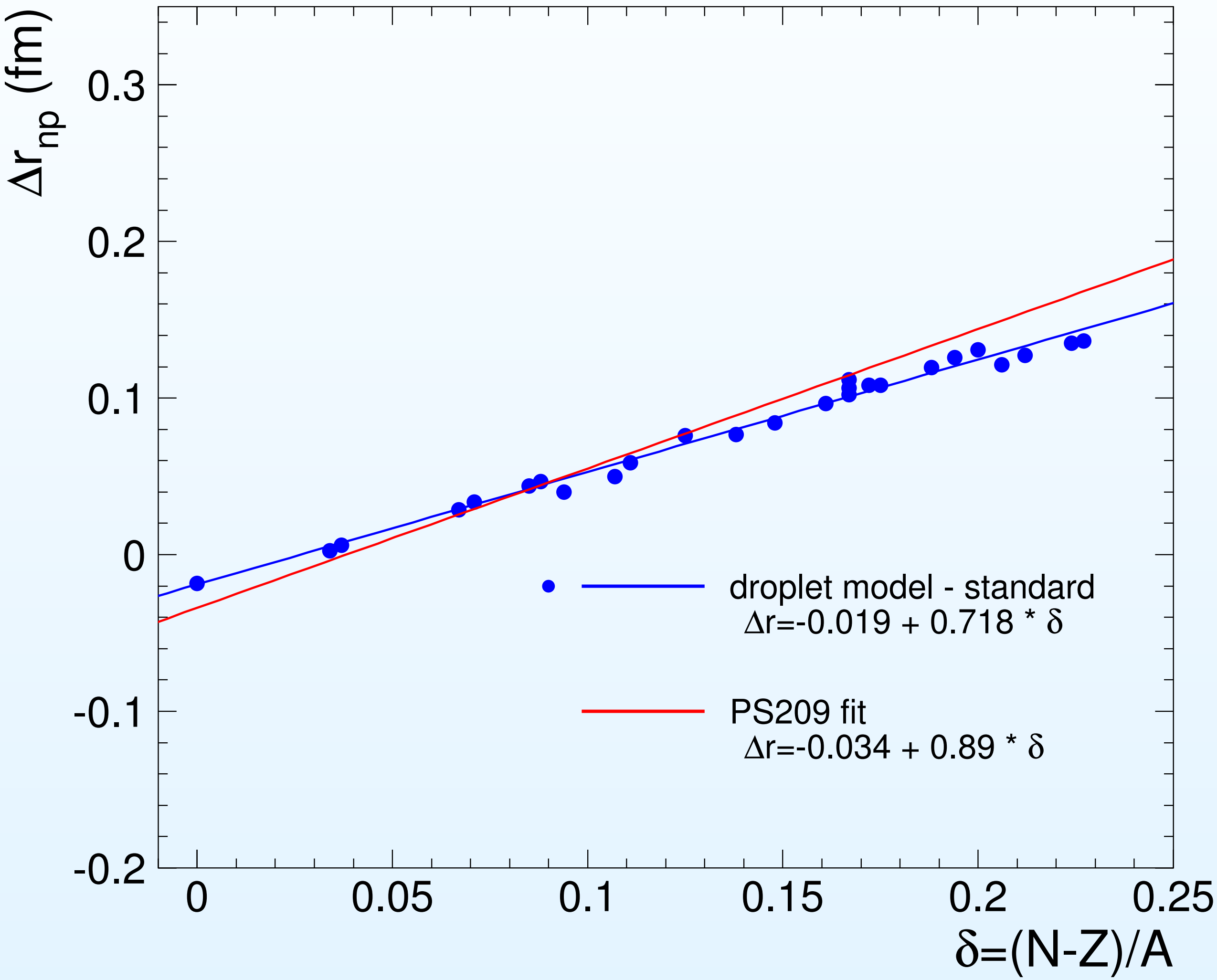
Comparison with theory

HF and HFB calculations



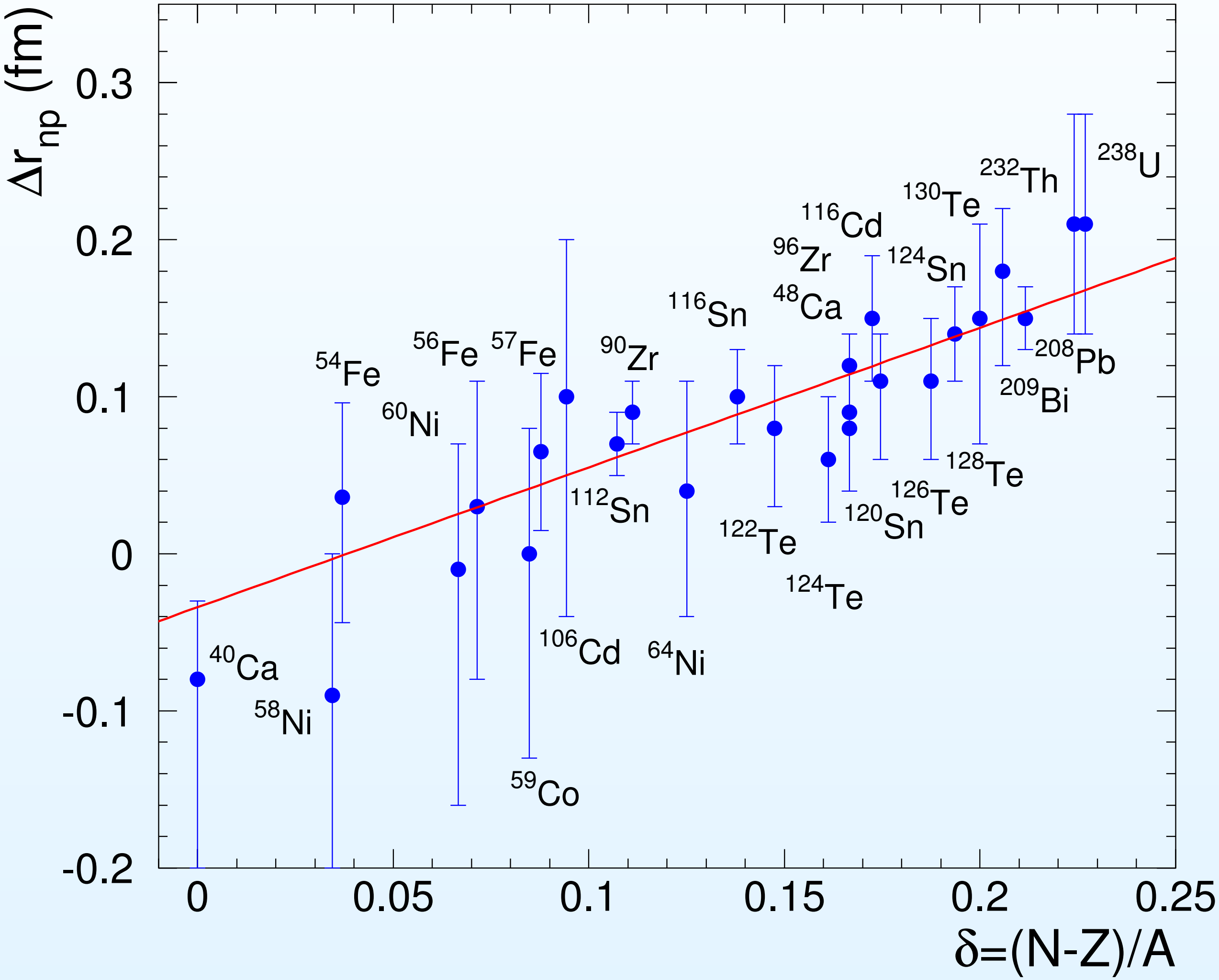
Comparison with theory

Droplet Model *D. Meyers, W. Swiatecki, Nucl. Phys.* **A336** *(1980) 267*



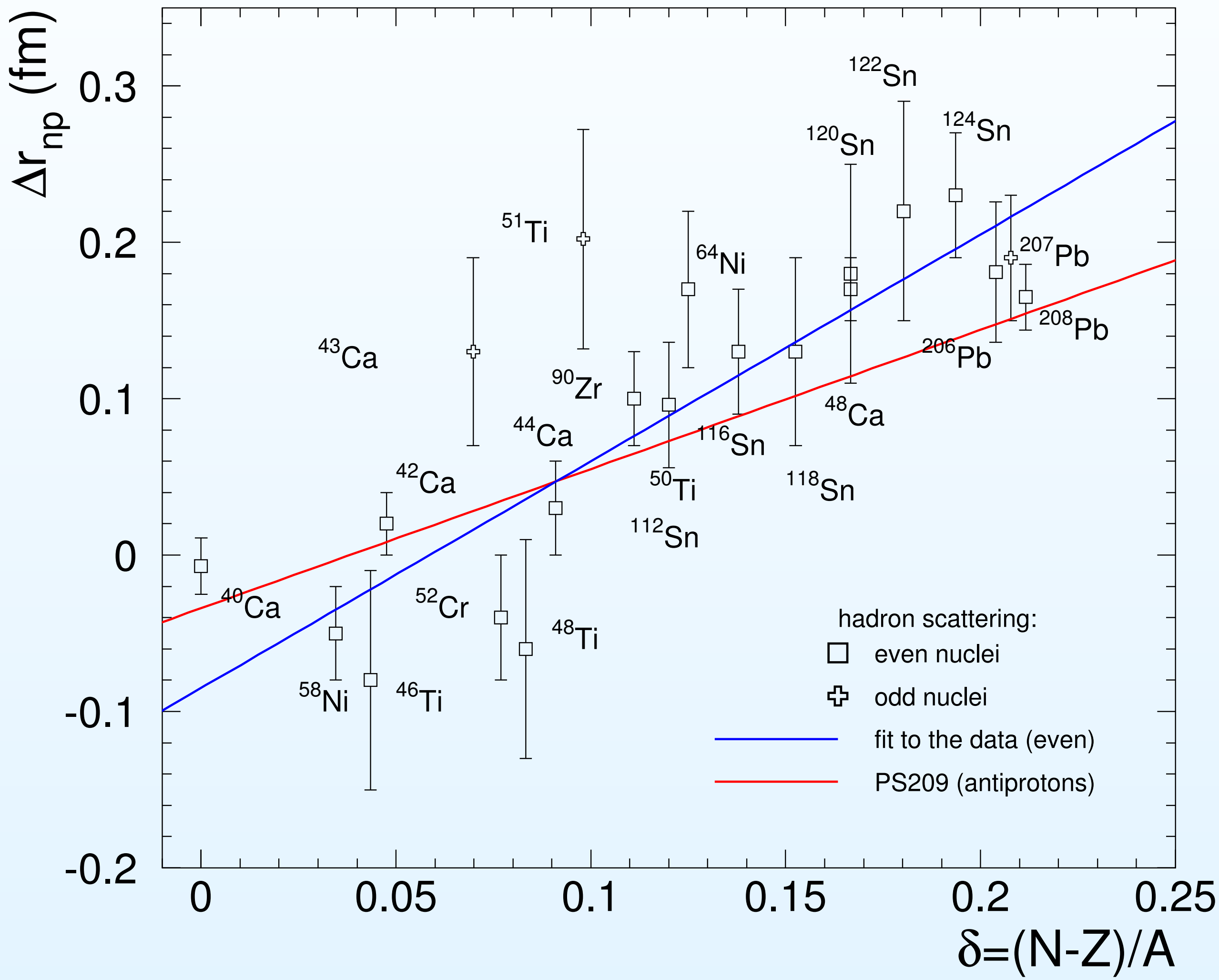
Comparison with other experiments

PS209 data



Comparison with other experiments

other experiments (hadron scattering data)



Summary & conclusions

- Two experimental methods using antiprotonic atoms were applied to investigate nuclear periphery:
  - radiochemical method: ρ_n/ρ_p @ r$\simeq c_p$+2.5 fm
  - antiprotonic X rays: $(\rho_p + \rho_n)$ @ r $\simeq c_p$+1.5 fm
- Reach set of precise data collected: material for theory (e.g. optical potential)
- Experimental data were interpreted using 2pF density distribution
- Neutron density distribution deduced for 26 isotopes
- Δr_{np} systematics deduced from the data
  - excellent agreement of Δr_{np} from antiprotonic X rays and hadron scattering for ^{208}Pb
  - good agreement of $\Delta r_{np}(\delta)$ established from antiprotonic data and theoretical models
  - fair agreement with the data from other experiments (hadron scattering)

What next? $\leadsto$ Future...

Future

What else is worth doing?

- measurements for deformed even-A nuclei (LS effect?)
- measurements for odd-A nuclei (e.g. Sn isotopes) – ??
- detailed study of Ca (double-magic isotopes ^{40}Ca and ^{48}Ca and possible measurement 3 levels for each isotope)
- investigation the properties of deeply bound states via E2 resonance
- search for a quasi-bound $\bar{p}p$ state - ??

Possibilities of measurements: AD @ CERN,
FLAIR @ Darmstadt

PS209 Collaboration

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