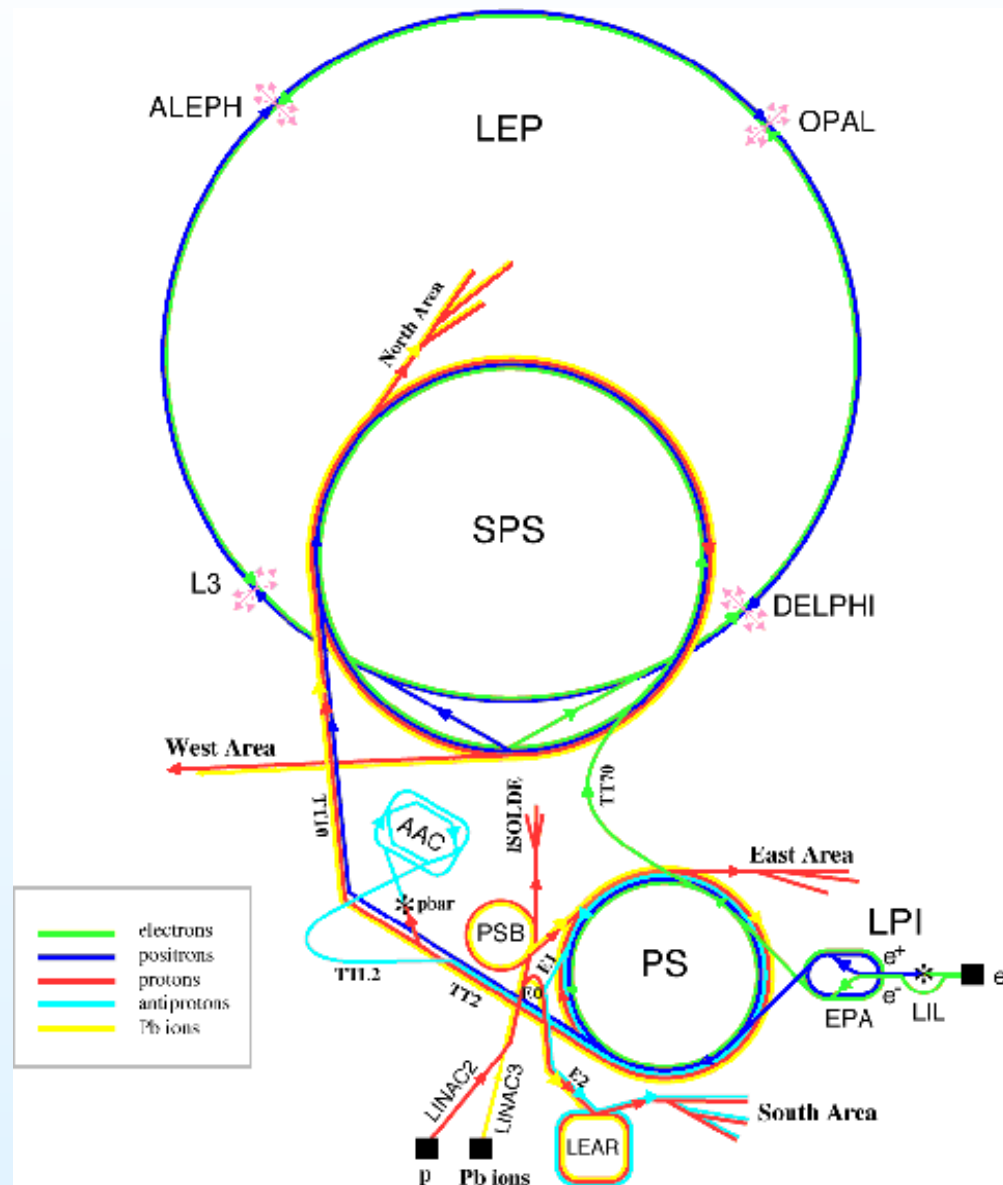


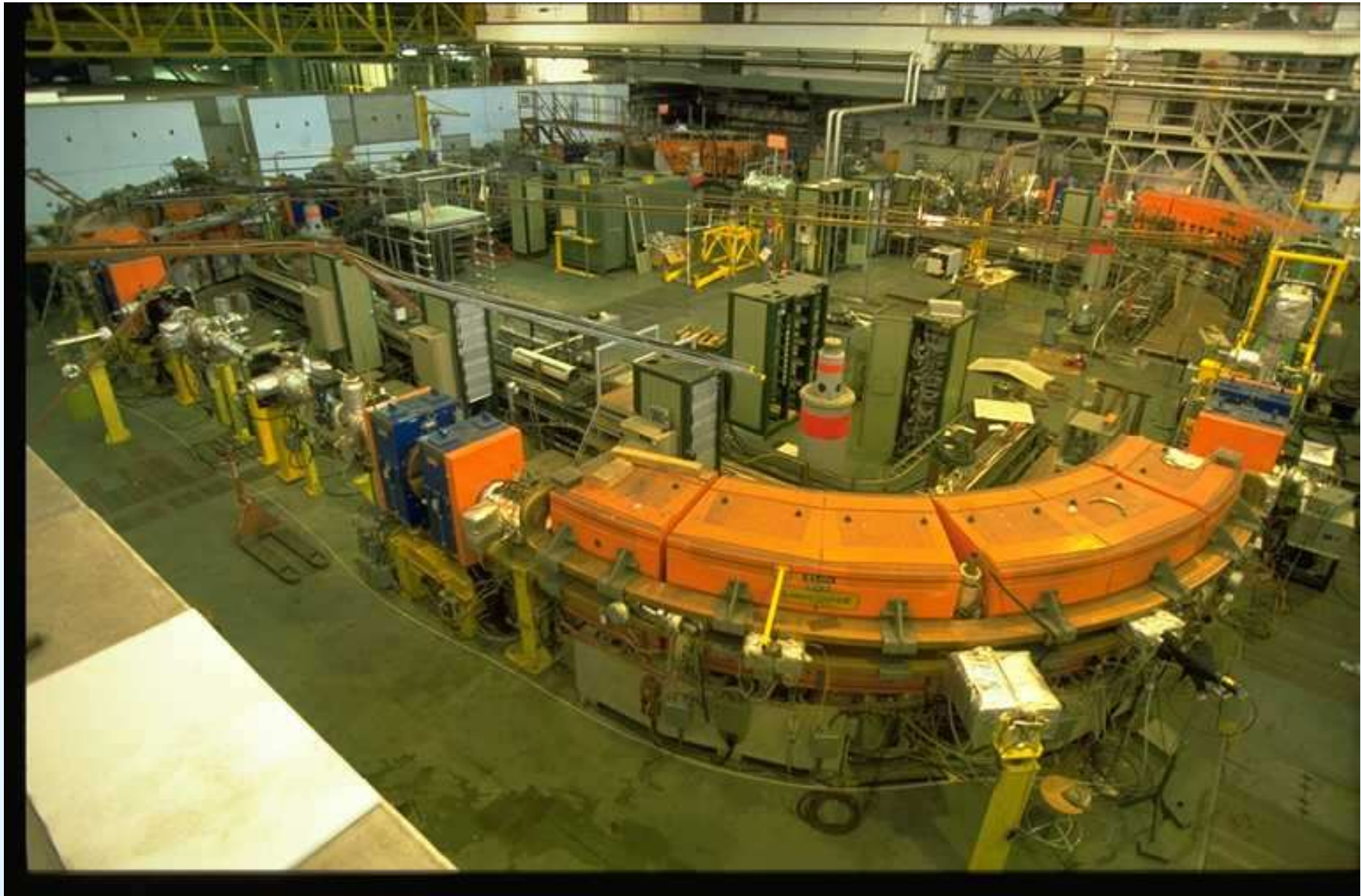
# Antiprotonic atoms

Agnieszka Trzcińska (HIL UW)  
for PS209 Collaboration

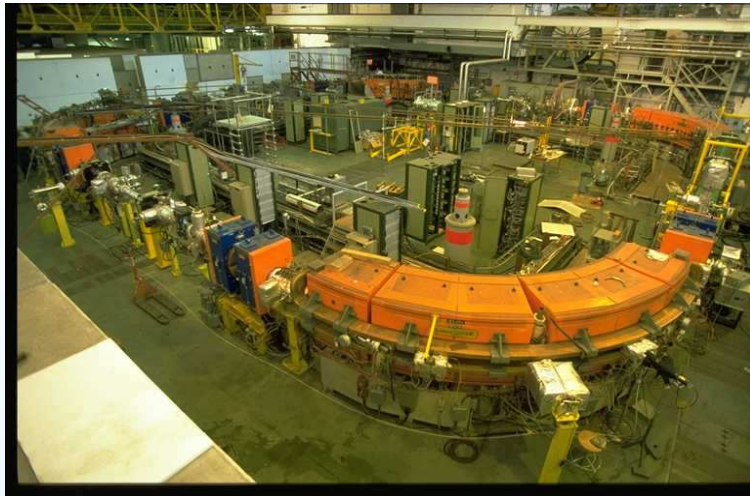
# LEAR (Low Energy Antiproton Ring) @ CERN



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# LEAR (Low Energy Antiproton Ring) @ CERN



LEAR (@CERN 1982 – 1996):

- circumference: 78.54 m
- $\bar{p}$  beams:
  - momenta: 0.1 – 2 GeV/c
  - energy: 5.3 MeV – 1.3 GeV
- emittance:  $\leq 10\pi$  x mm x mrad
- momentum spread:  $\Delta p/p \leq 10^{-3}$
- rate: up to  $\sim 5 \cdot 10^5$  1/s
- typical spill length: 1-2 h

## Experiment @ LEAR/CERN

Experiment – few details:

- 2x 3-week runs: 1995 and 1996 @LEAR
- beam:
  - 300 MeV/ $c$  and 400 MeV/ $c$  (1995)
  - 106 MeV/ $c$  (1996)
- targets:
  - isotopically separated material,
  - thickness:  $\sim 200\text{-}300\text{ mg/cm}^2$  (1995) and  $\sim 50\text{-}100\text{ mg/cm}^2$  (1996)
- measurements for 55 isotopes ( $^{16}\text{O} - ^{238}\text{U}$ )

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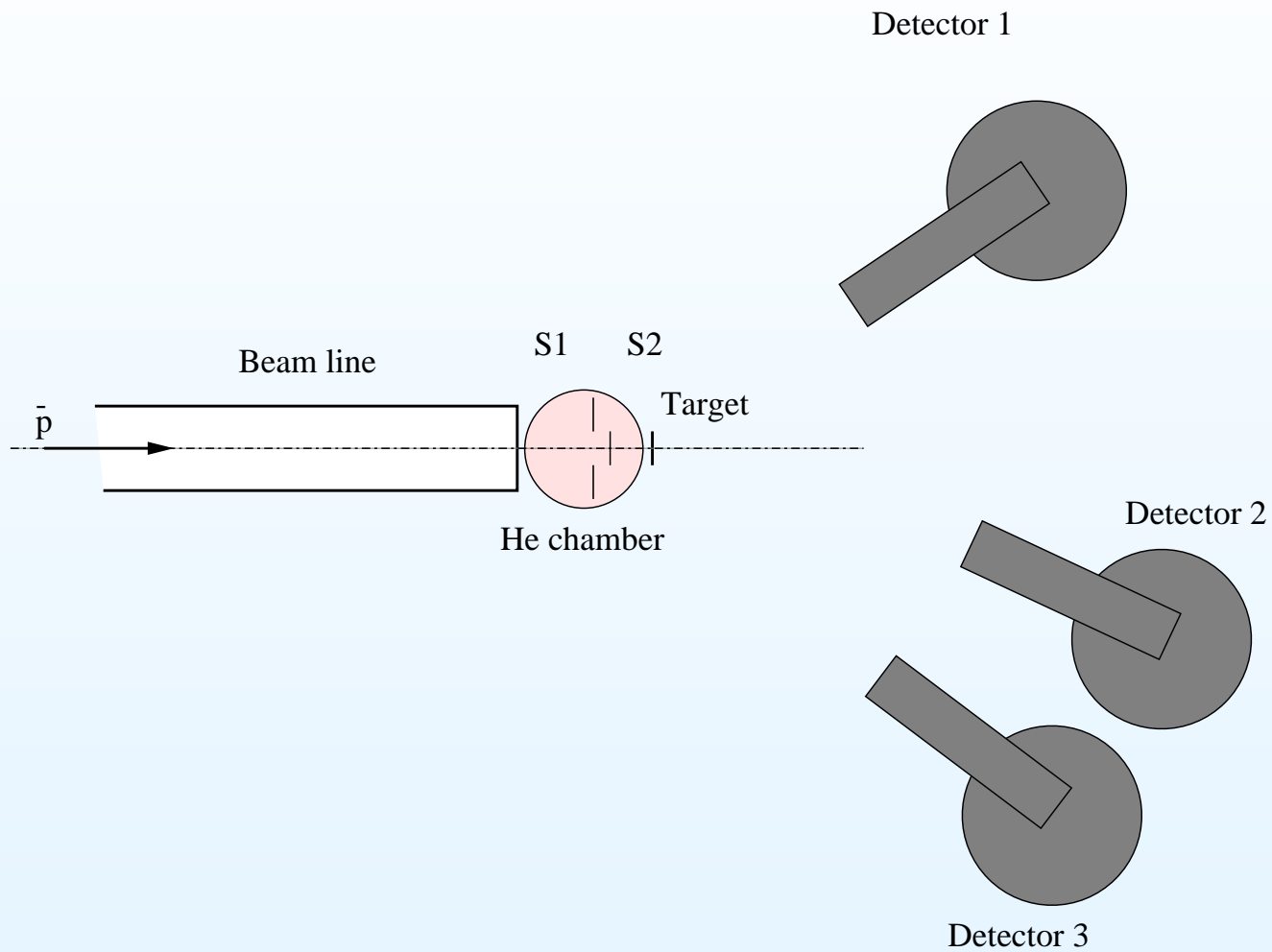
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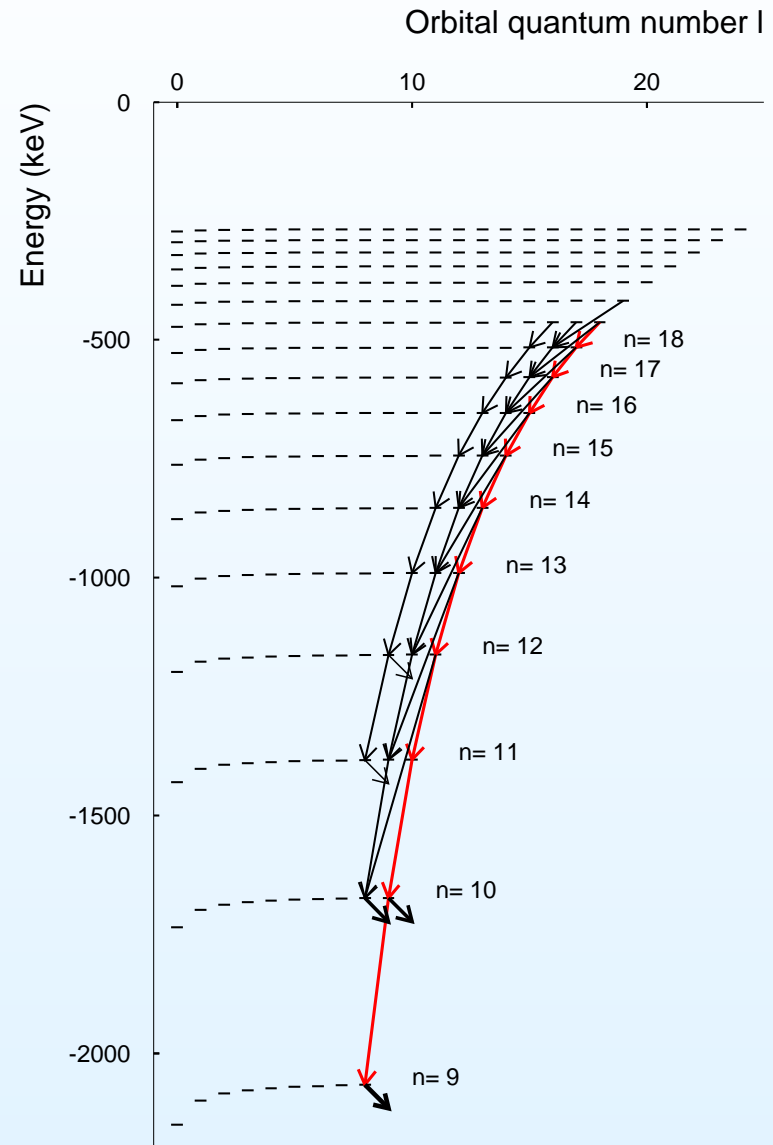
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# Experimental set-up

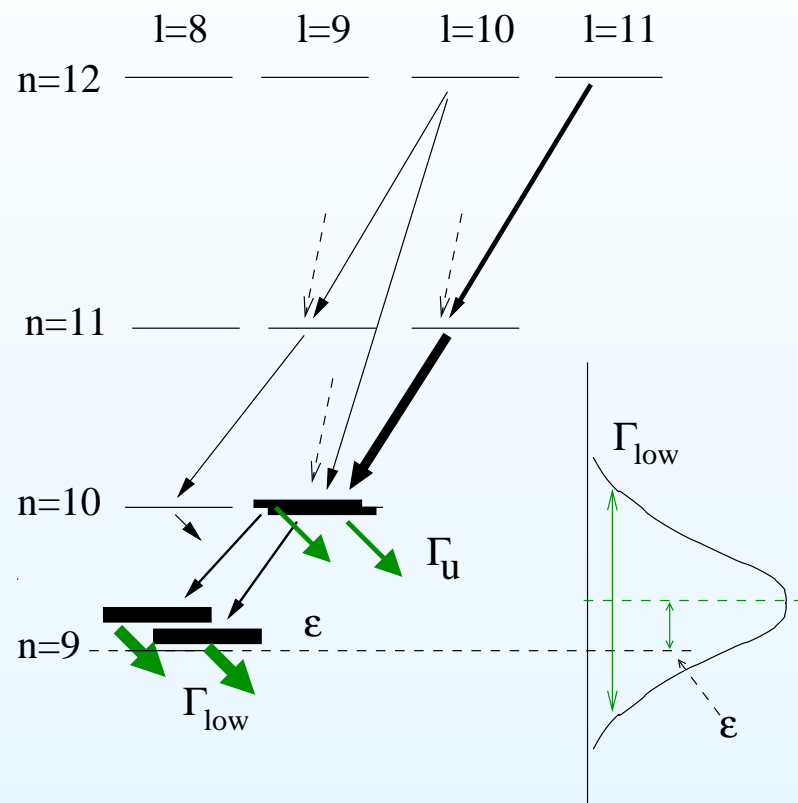


# Antiprotonic atoms

- creation:
  - $\bar{p}$  capture onto a “high” orbit
  - $n_{\bar{p}} = \sqrt{m_{\bar{p}}/m_e} \times n_e \approx 43 \times n_e$
- deexcitation:
  - emission of Auger electrons,
  - X-rays emission,
  - annihilation



# Strong interaction effects

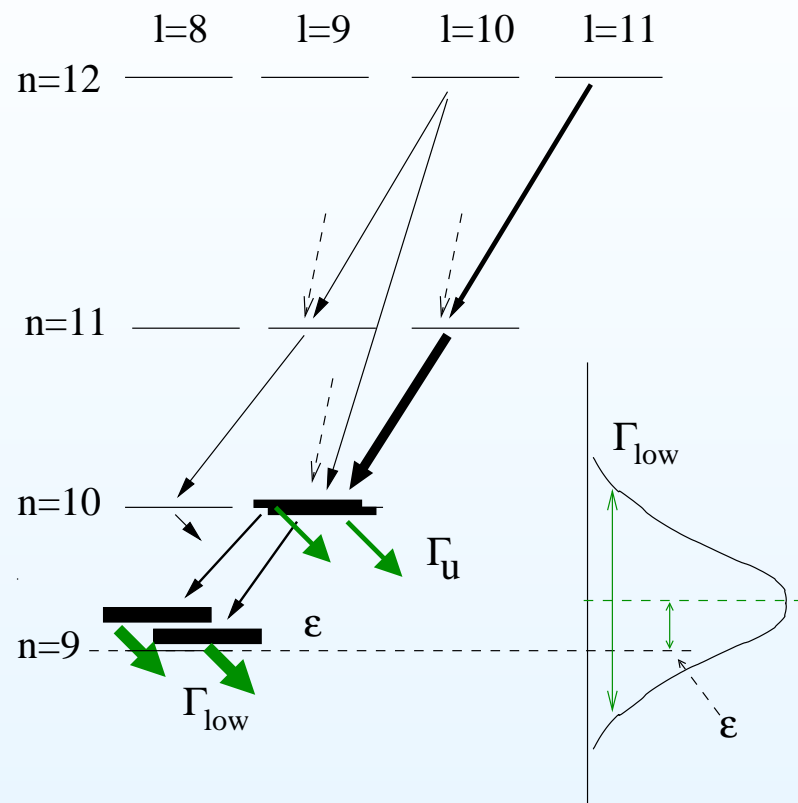


**strong interaction**



**broadens and shifts  $\bar{p}$  levels**

# Strong interaction effects



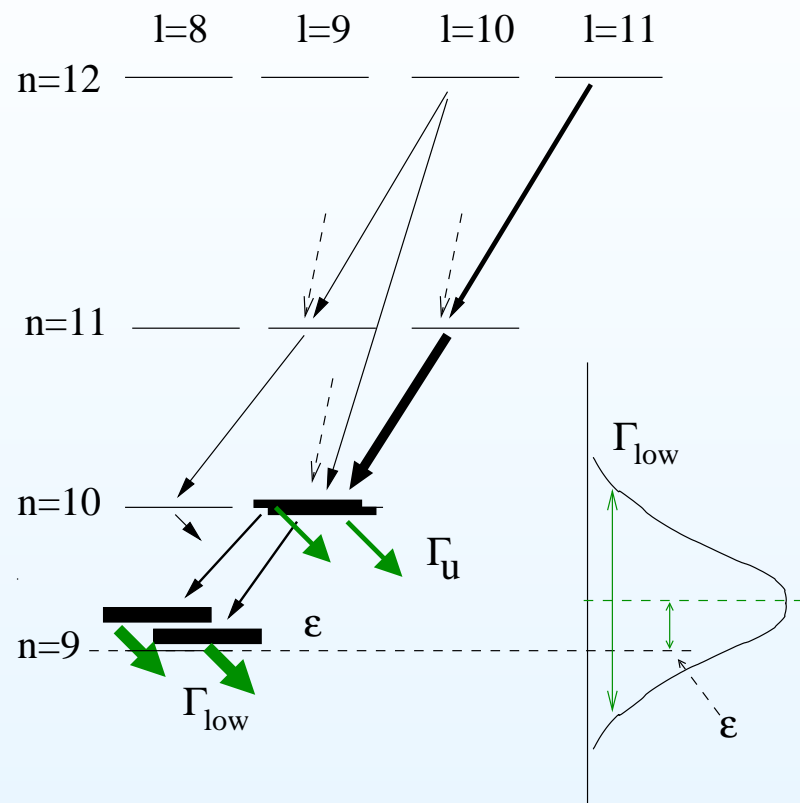
**strong interaction**



**broads and shifts  $\bar{p}$  levels**

in the experiment we measure:

## Strong interaction effects



**strong interaction**

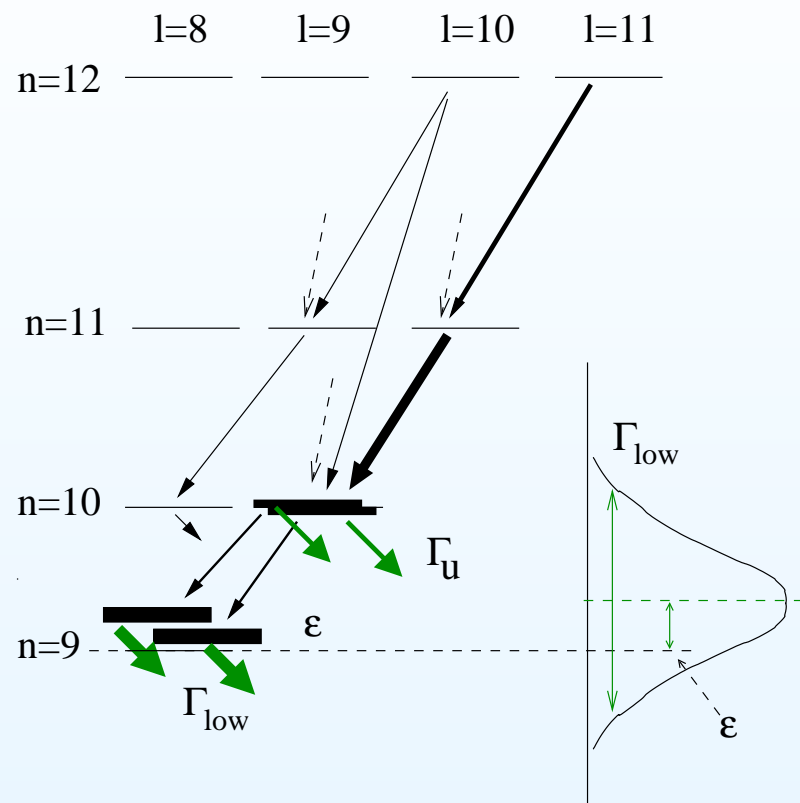


**broadens** and **shifts**  $\bar{p}$  levels

in the experiment we measure:

$\Gamma_{low}$  – directly from the line shape

## Strong interaction effects



**strong interaction**



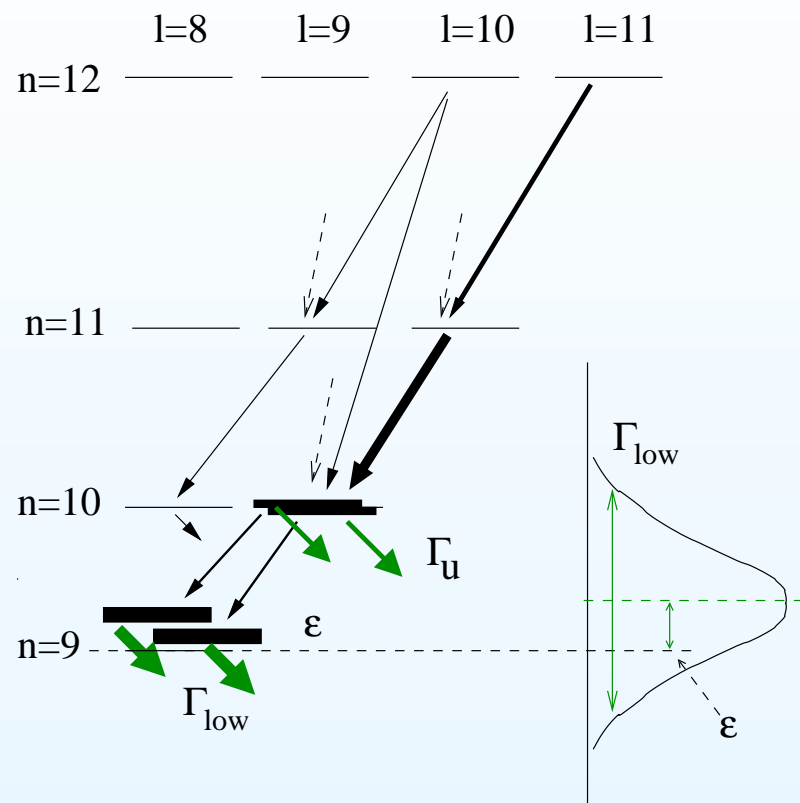
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$\epsilon$  – determining the line energy

## Strong interaction effects



**strong interaction**



**broadens** and **shifts**  $\bar{p}$  levels

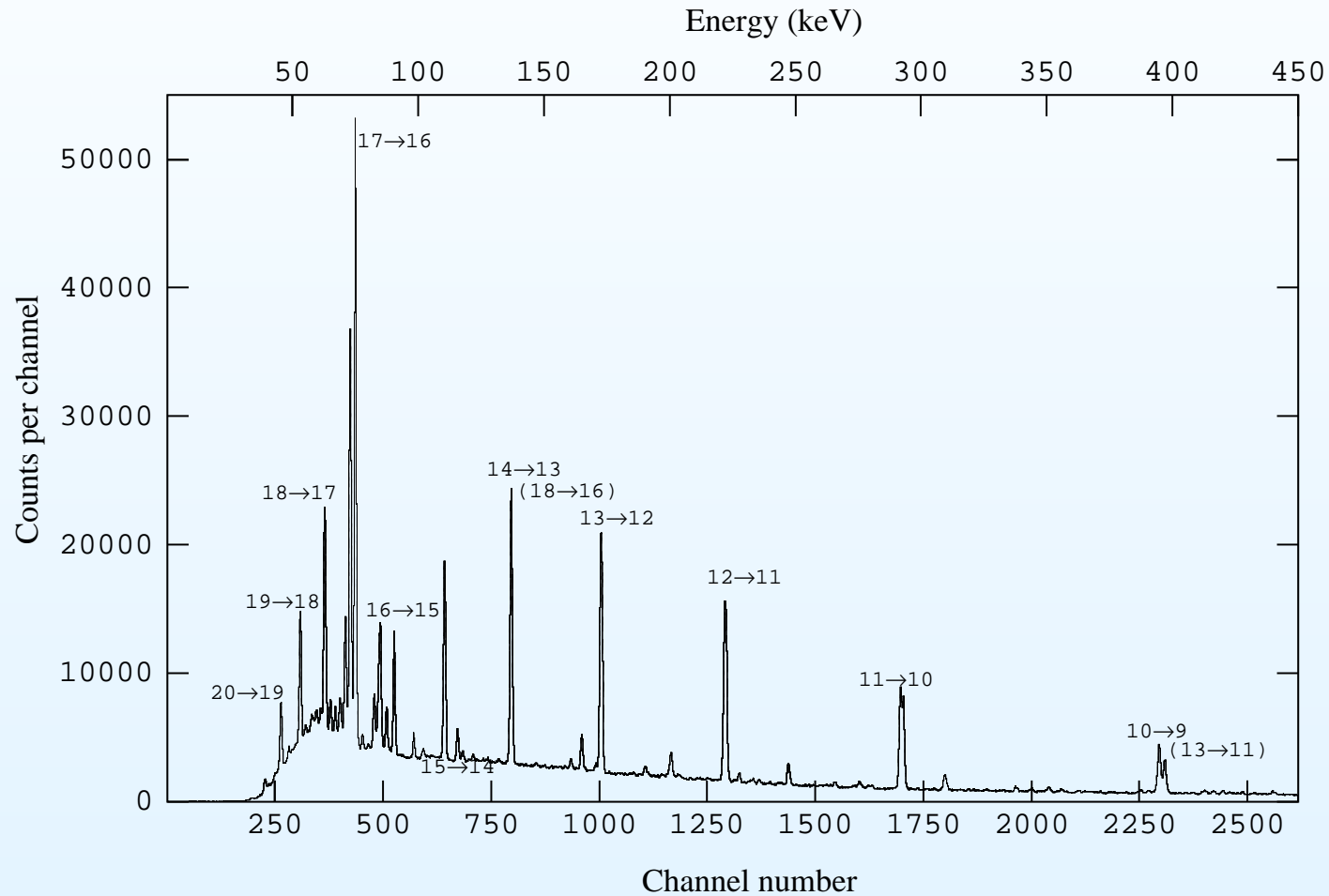
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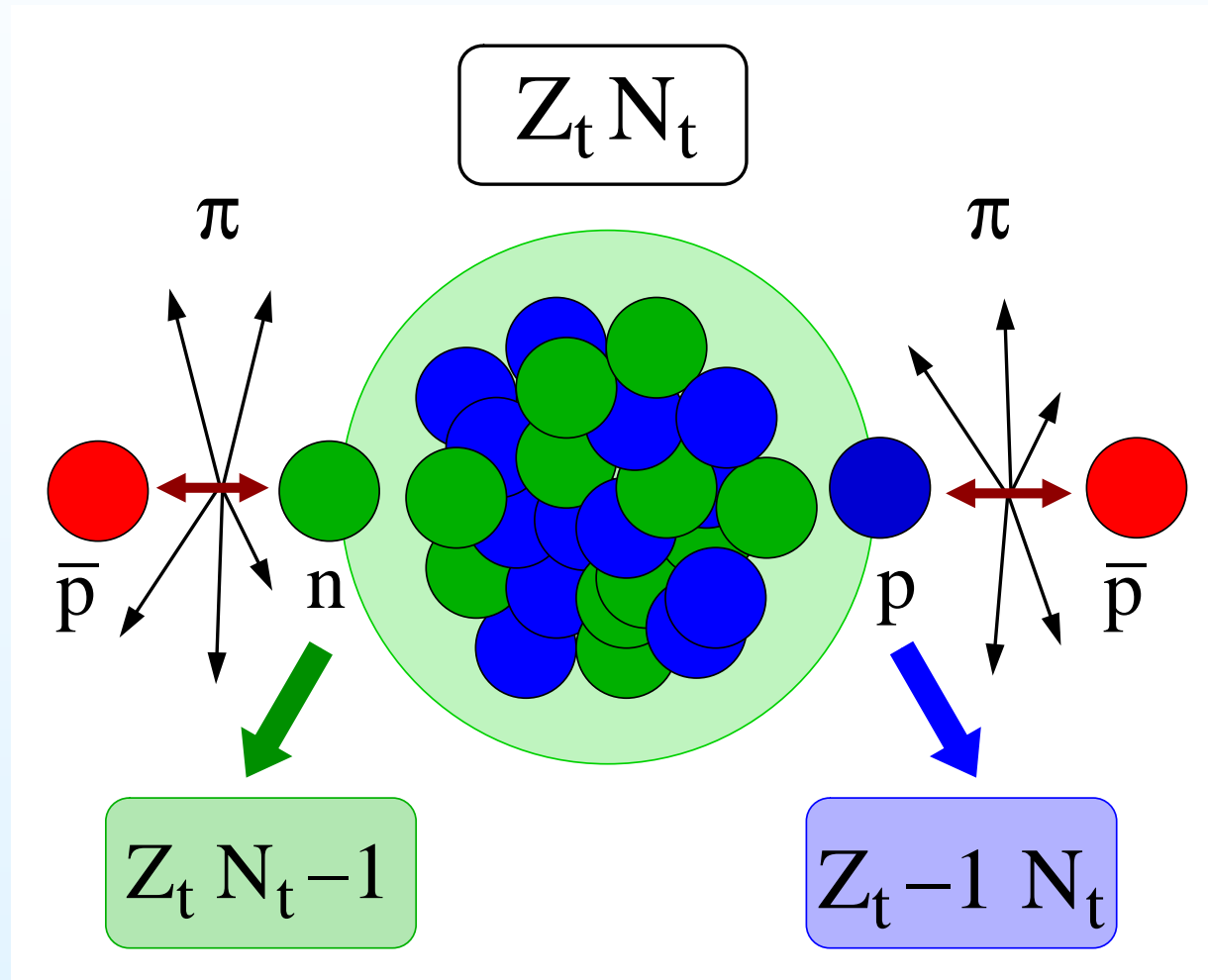
$\Gamma_{up}$  – indirectly from the intensity balance

# X-ray spectrum - $^{208}\text{Pb}$ example

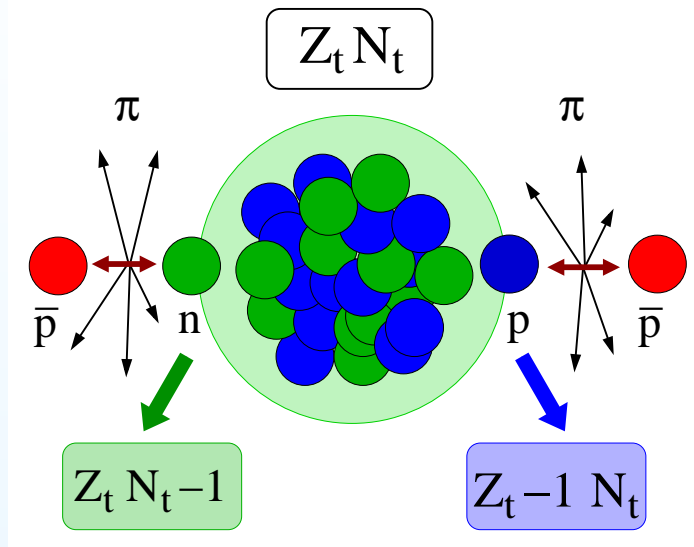


# Annihilation

$\bar{p}$  ends its life in the atom annihilating with a peripheral nucleon (**p** or **n**)



# Annihilation



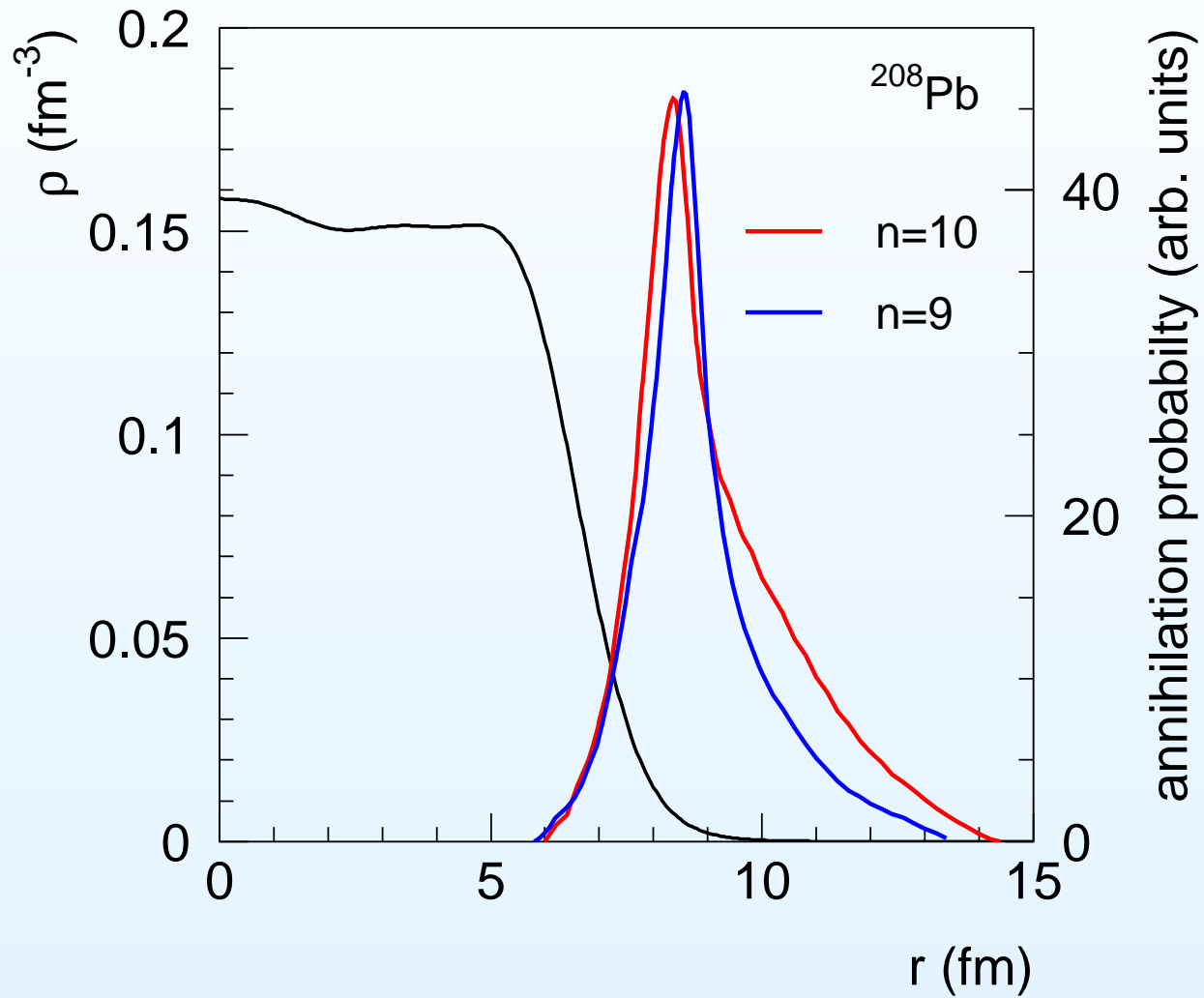
in the experiment we measure:

$$\text{yields} \begin{cases} Y_{N_t-1} \sim \rho_n(r_{\text{anh.}}) \\ Y_{Z_t-1} \sim \rho_p(r_{\text{anh.}}) \end{cases}$$

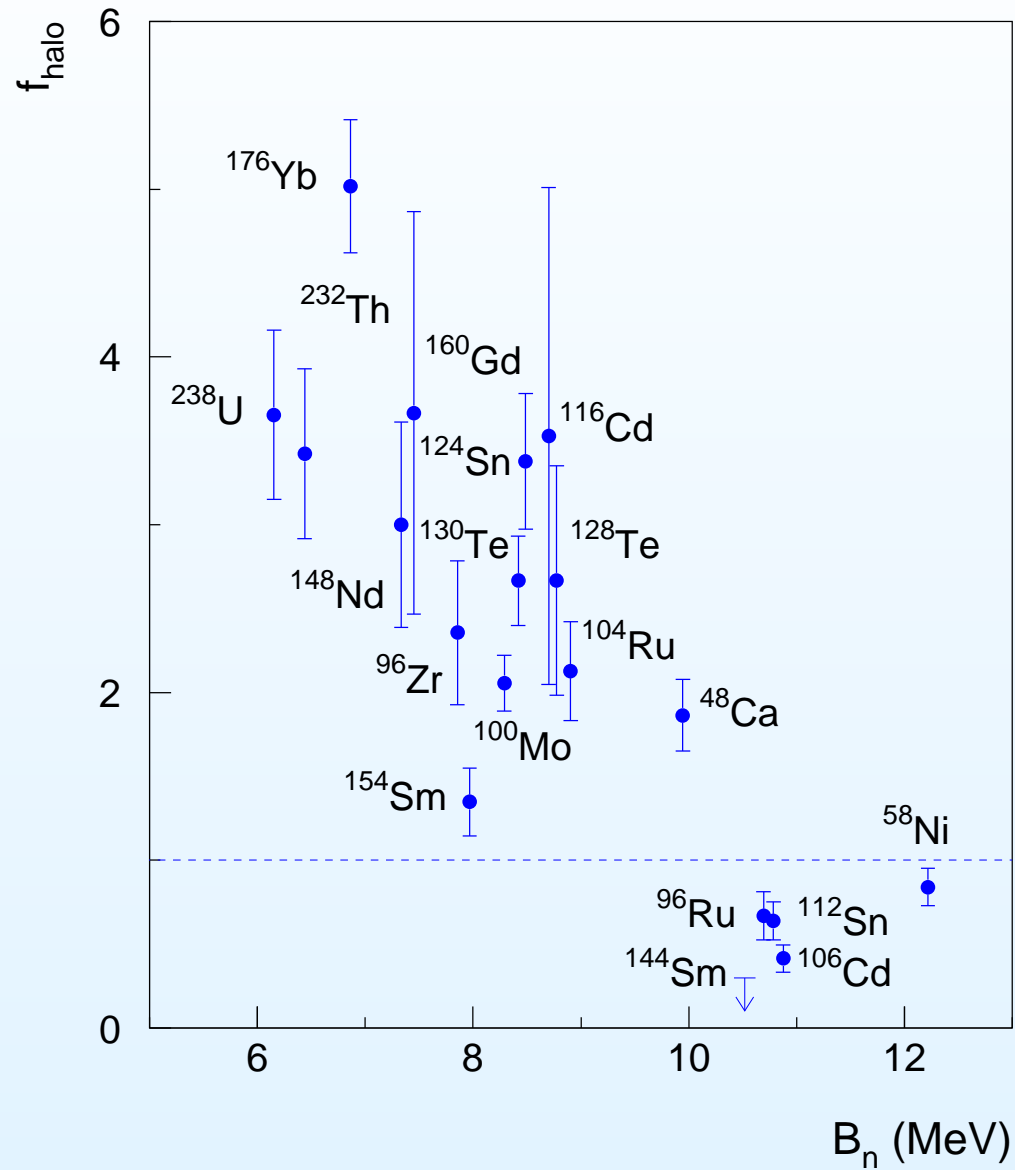
$$f_{\text{halo}} = \frac{Y_{N_t-1}}{Y_{Z_t-1}} \cdot \frac{Z}{N} \cdot \frac{\text{Im } a_{p\bar{p}}}{\text{Im } a_{n\bar{p}}}$$

$$f_{\text{halo}} \sim \frac{\rho_n}{\rho_p} \text{ (at annihilation place)}$$

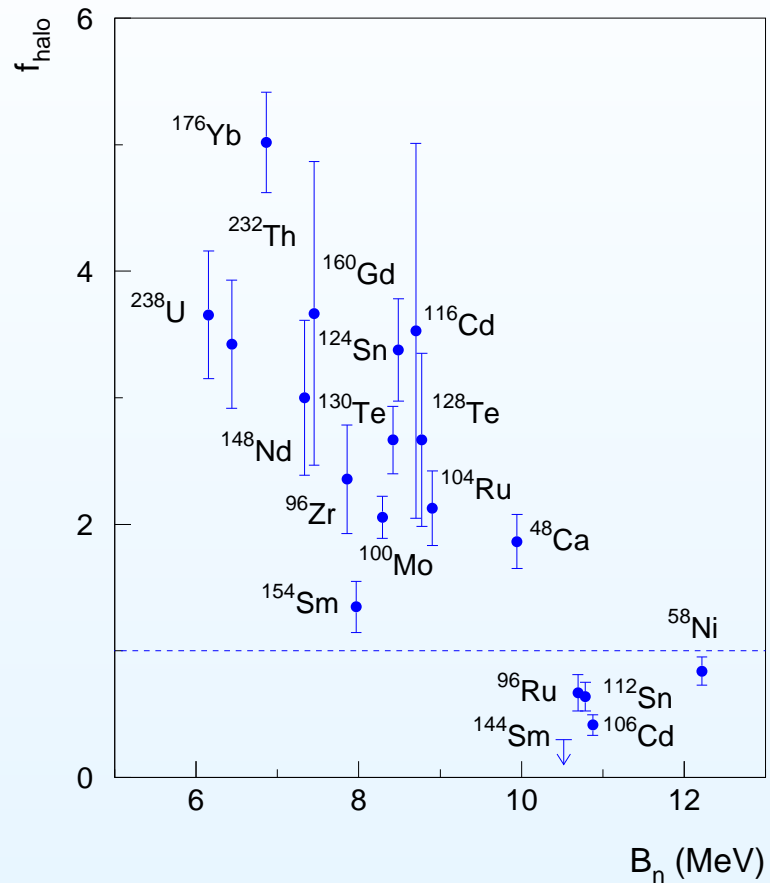
# Annihilation probability



# $f_{\text{halo}}$ (neutron halo)



## $f_{\text{halo}}$ (*neutron halo*)



### Observations:

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

## $f_{\text{halo}}$ vs $\Delta r_{\text{np}}$ (comparison with results of other experiments)

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

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

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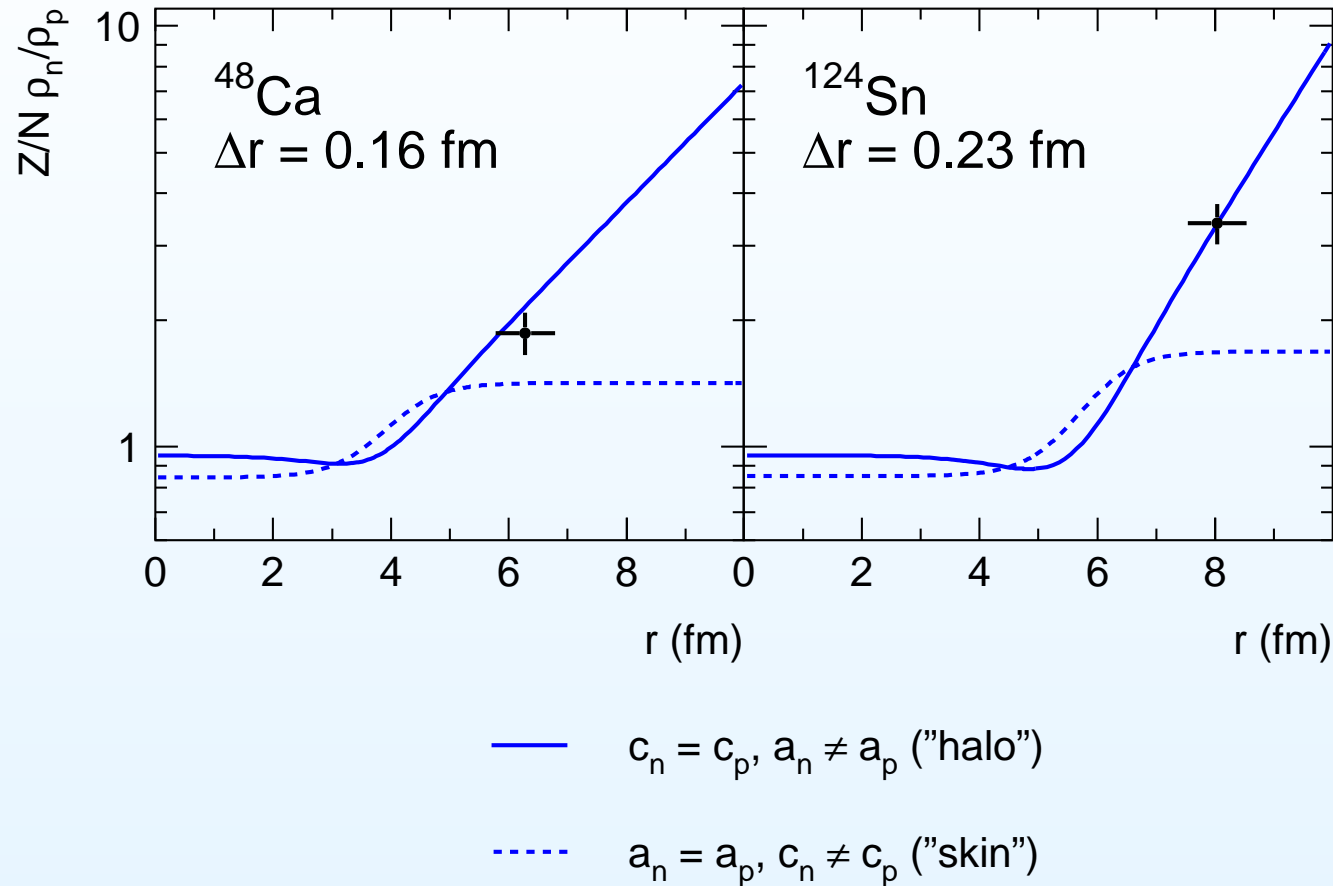
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let's consider 2 extreme situations:

- $a_n = a_p, c_n \neq c_p \Rightarrow \Delta r_{\text{np}}$  (“neutron skin”)
- $a_n \neq a_p, c_n = c_p \Rightarrow \Delta r_{\text{np}}$  (“neutron halo”)

# $f_{\text{halo}}$ vs $\Delta r_{\text{np}}$ (comparison with results of other experiments)



$\implies \Delta r_{\text{np}}$  is caused rather by  $a_n \neq a_p$  than by  $c_n \neq c_p$

## Antiprotonic atom X rays ...

... are also a good tool for the investigation of the nuclear periphery: strong interaction level **widths** and **shifts** depend on the  $\rho_p$  and  $\rho_n$  via antiproton-nucleus potential:

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

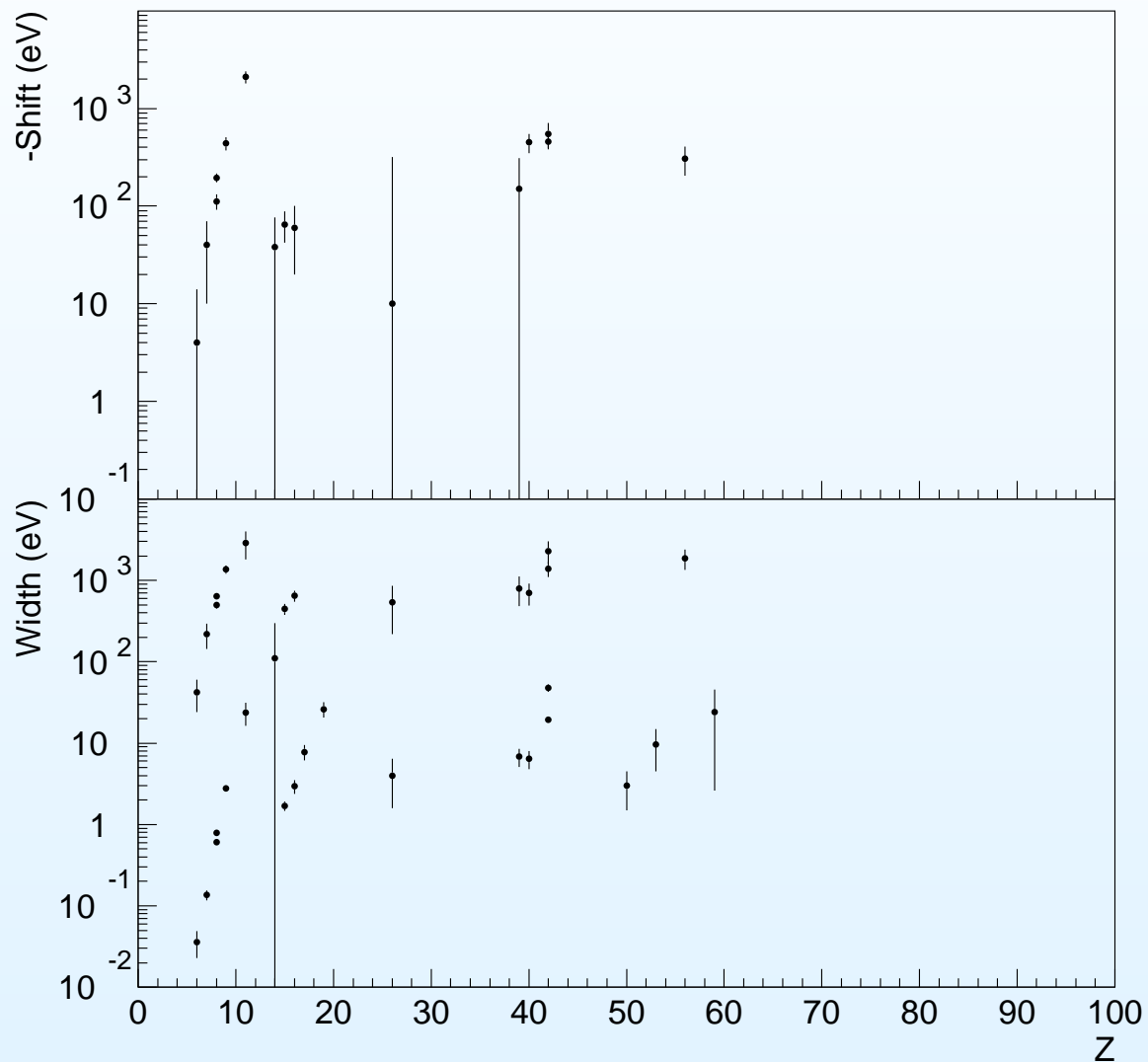
$$\frac{\epsilon}{2} \sim \int \text{Re } V(r) |\Psi_{nl}(r)|^2 r^2 dr$$

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

- $\bar{a}_p = \bar{a}_n = 2.5 + i 3.4$  fm  
zero-range  $\bar{p}$ -nucleus interaction *C.J. Batty et al., Nucl. Phys. A592, (1995) 478*
- $\bar{a}_p = \bar{a}_n = 1.3 + i 1.9$  fm  
finite range  $\bar{p}$ -nucleus interaction *E. Friedman et al., Nucl. Phys. A761, (2005) 283*
- more sophisticated potentials (e.g. *S. Wycech, 2006, <http://arxiv.org/abs/nucl-th/0702029>*)

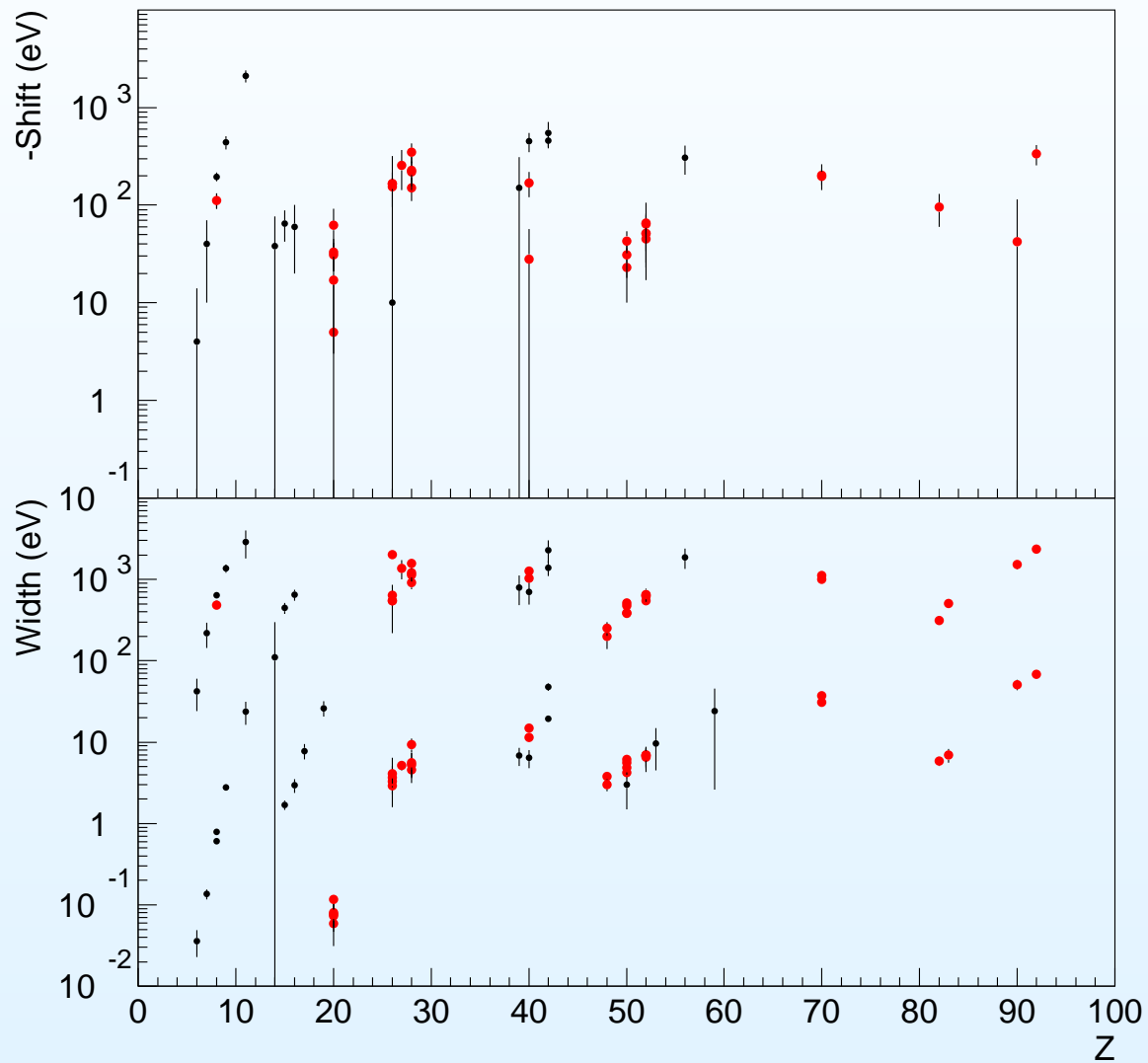
# Harvest of the PS209 measurements

before PS209 measurements



# Harvest of the PS209 measurements

after PS209 measurements



## Determination of $\rho_n$ from antiprotonic X rays

- known:
  - $\rho_p$  (from electromagnet. interacting probes: e,  $\mu$ )
  - $V_{\text{opt}}(\rho_p, \rho_n)$
- assumed:
  - 2-parameter-Fermi density distribution
  - $c_n = c_p$  (information from comparisons  $f_{\text{halo}}$  and  $\Delta r_{np}$ )
- fitted:  $a_n(V_{\text{opt}}, \Gamma_{\text{low}}, \Gamma_{\text{up}}, (\epsilon))$

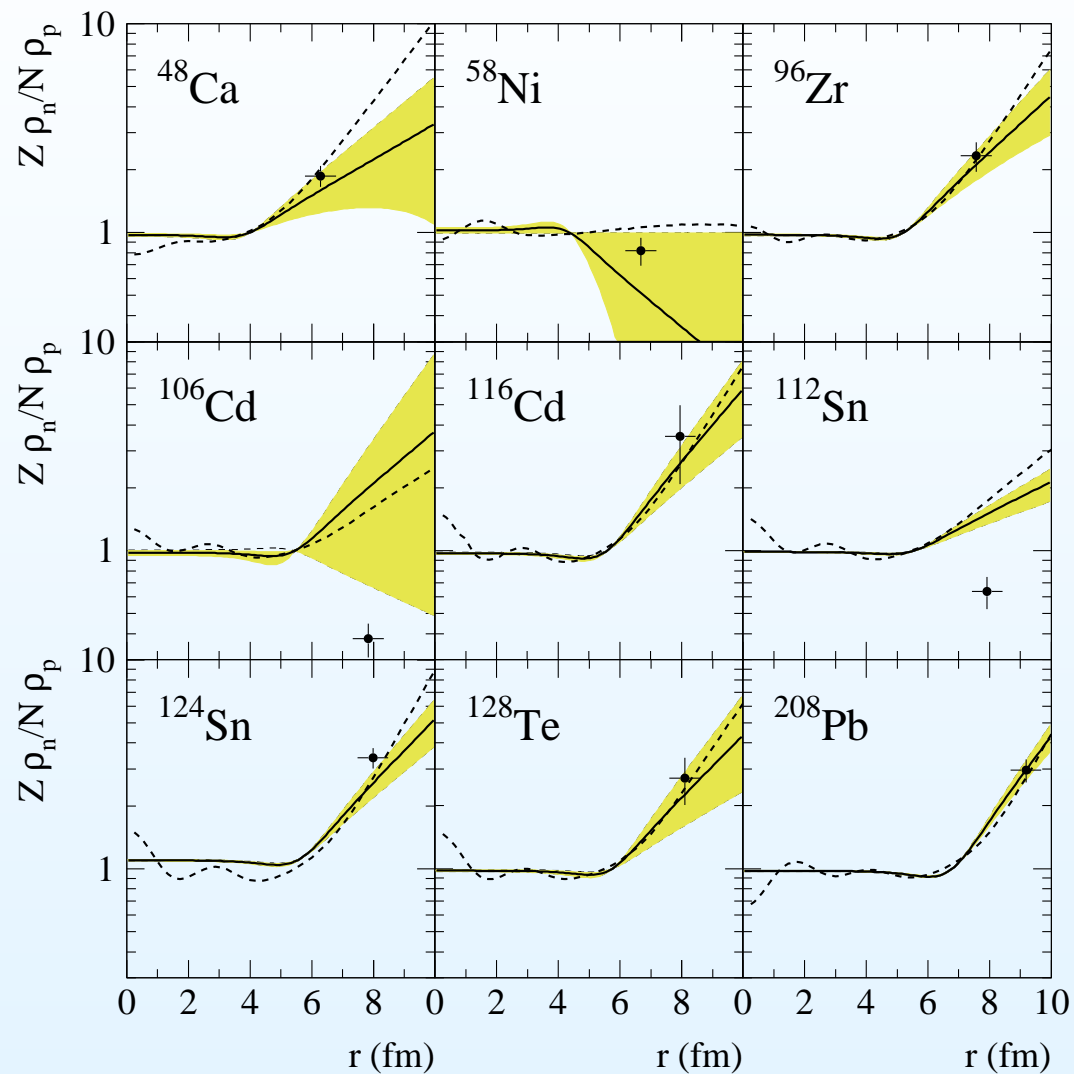
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$$\rho_n(c_n, a_n)$$

# Neutron density – results

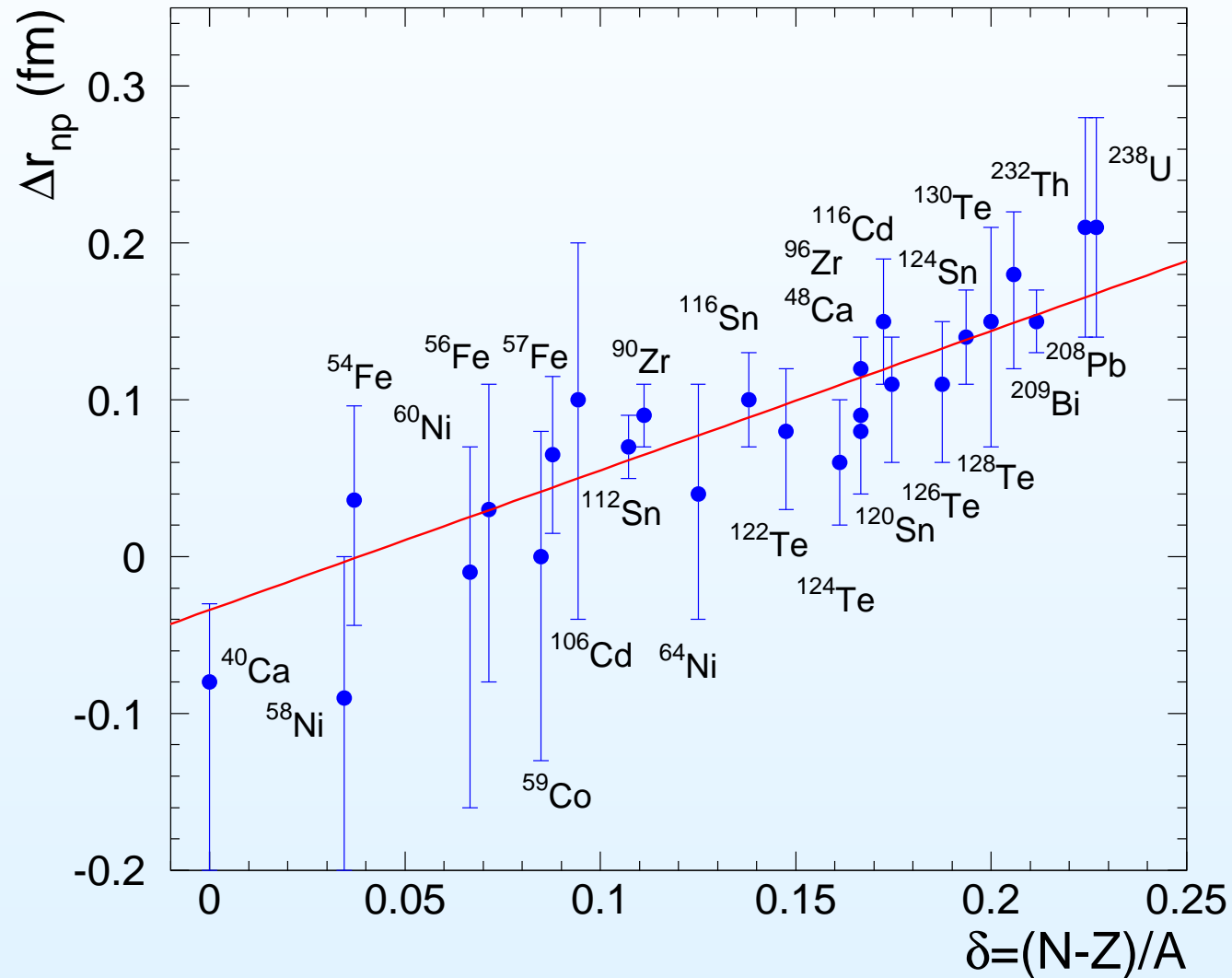


## $\Delta r_{np}$ systematics from X-ray data

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

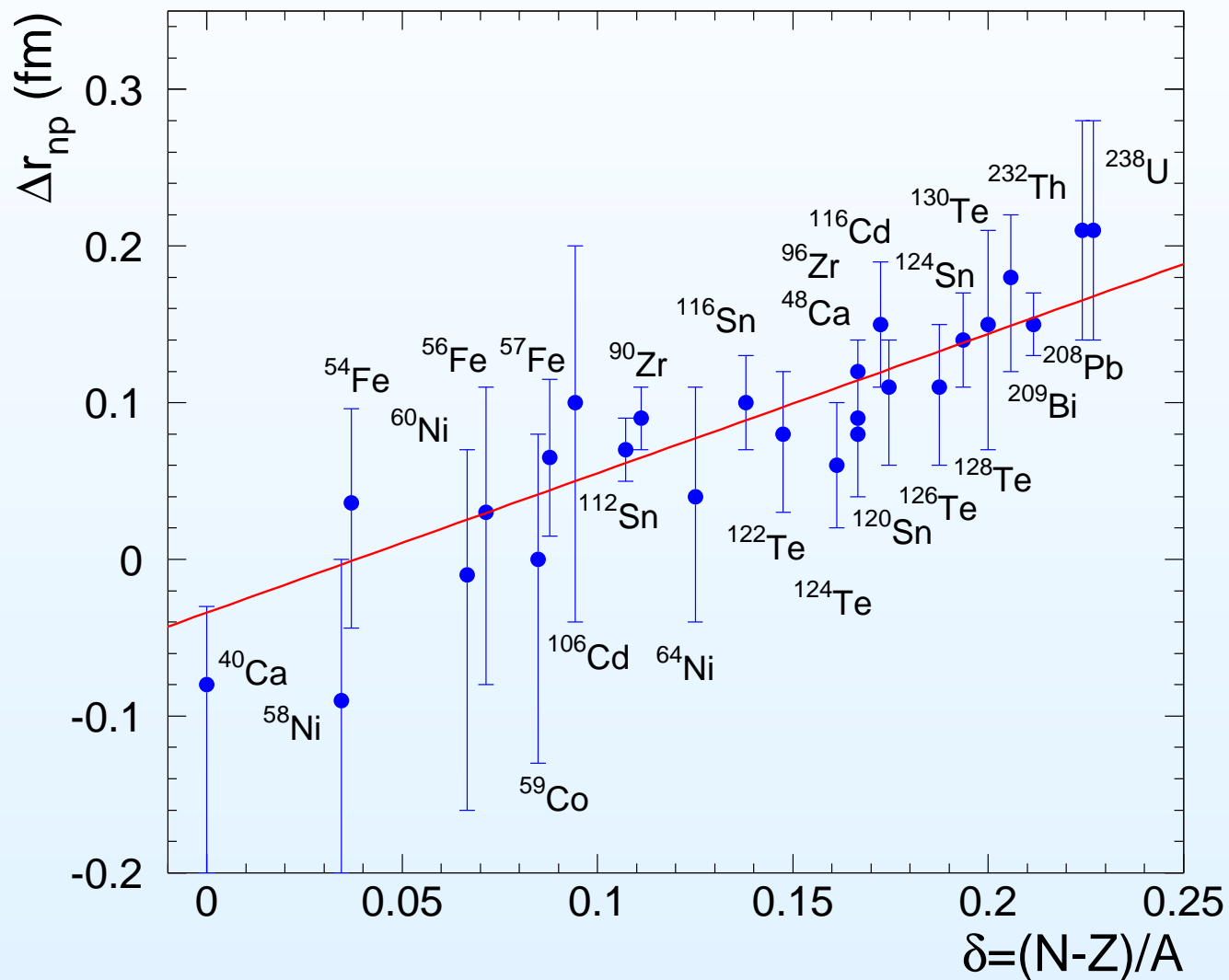
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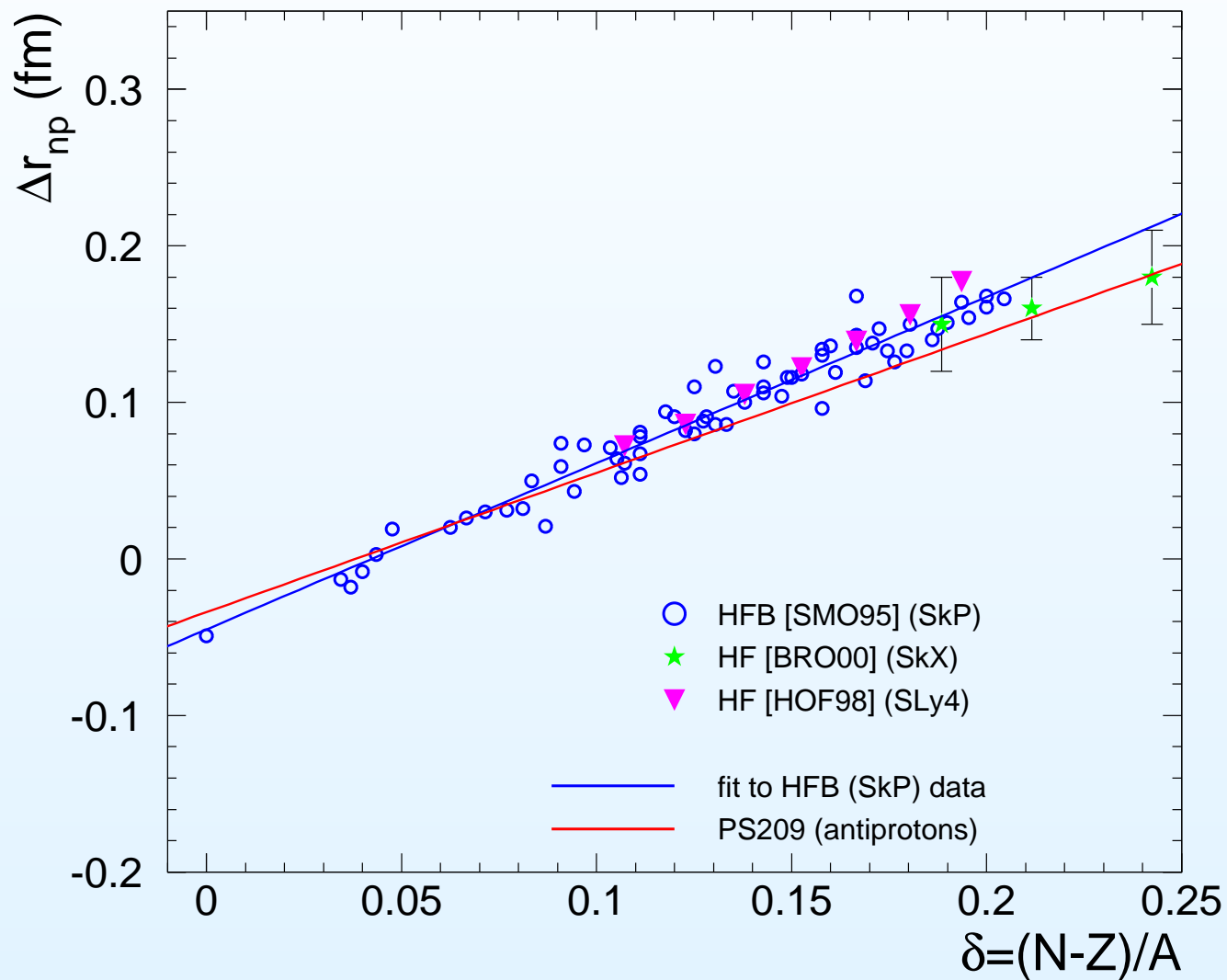
# Comparison with theory

experimental data



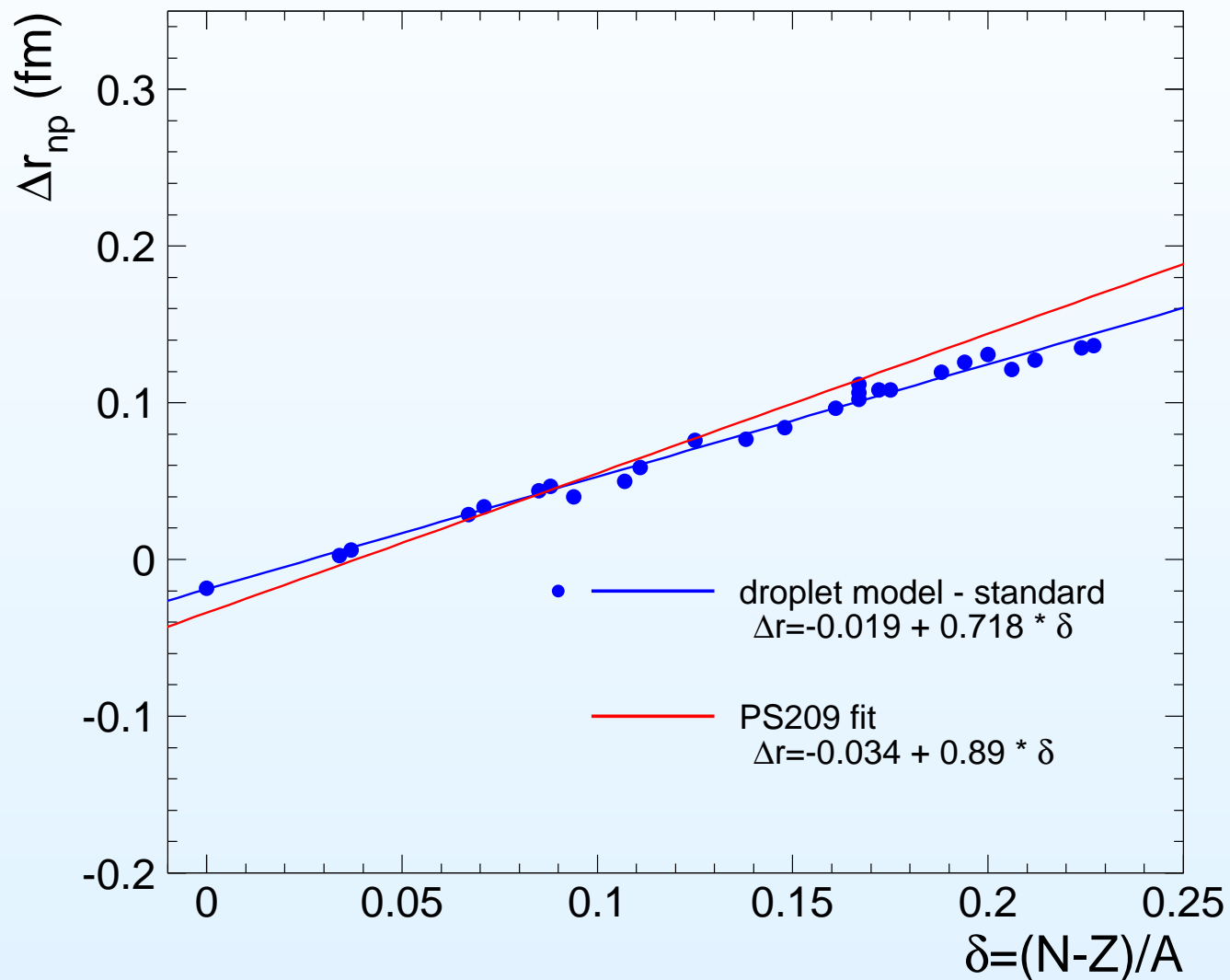
## Comparison with theory

### HF and HFB calculations

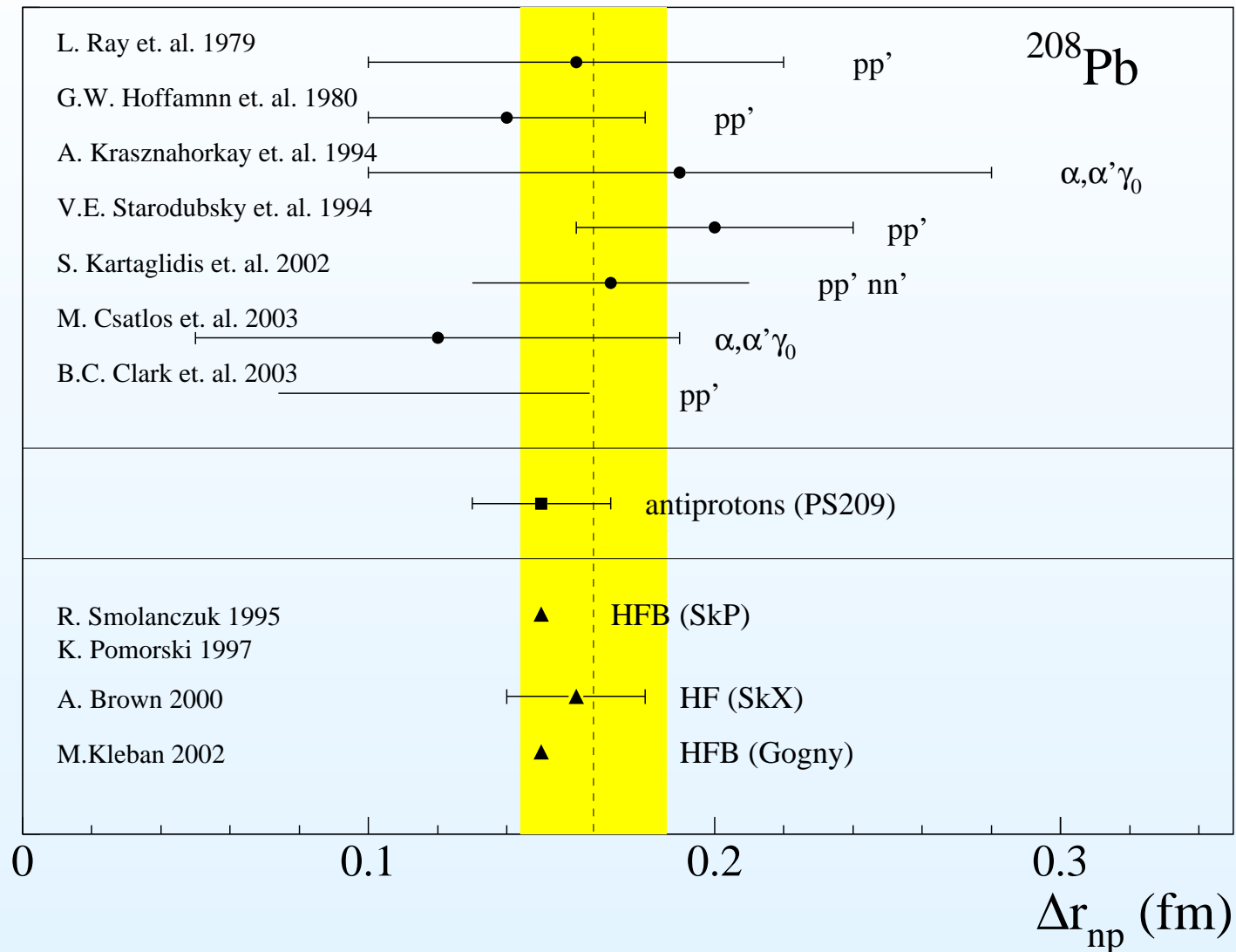


## Comparison with theory

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

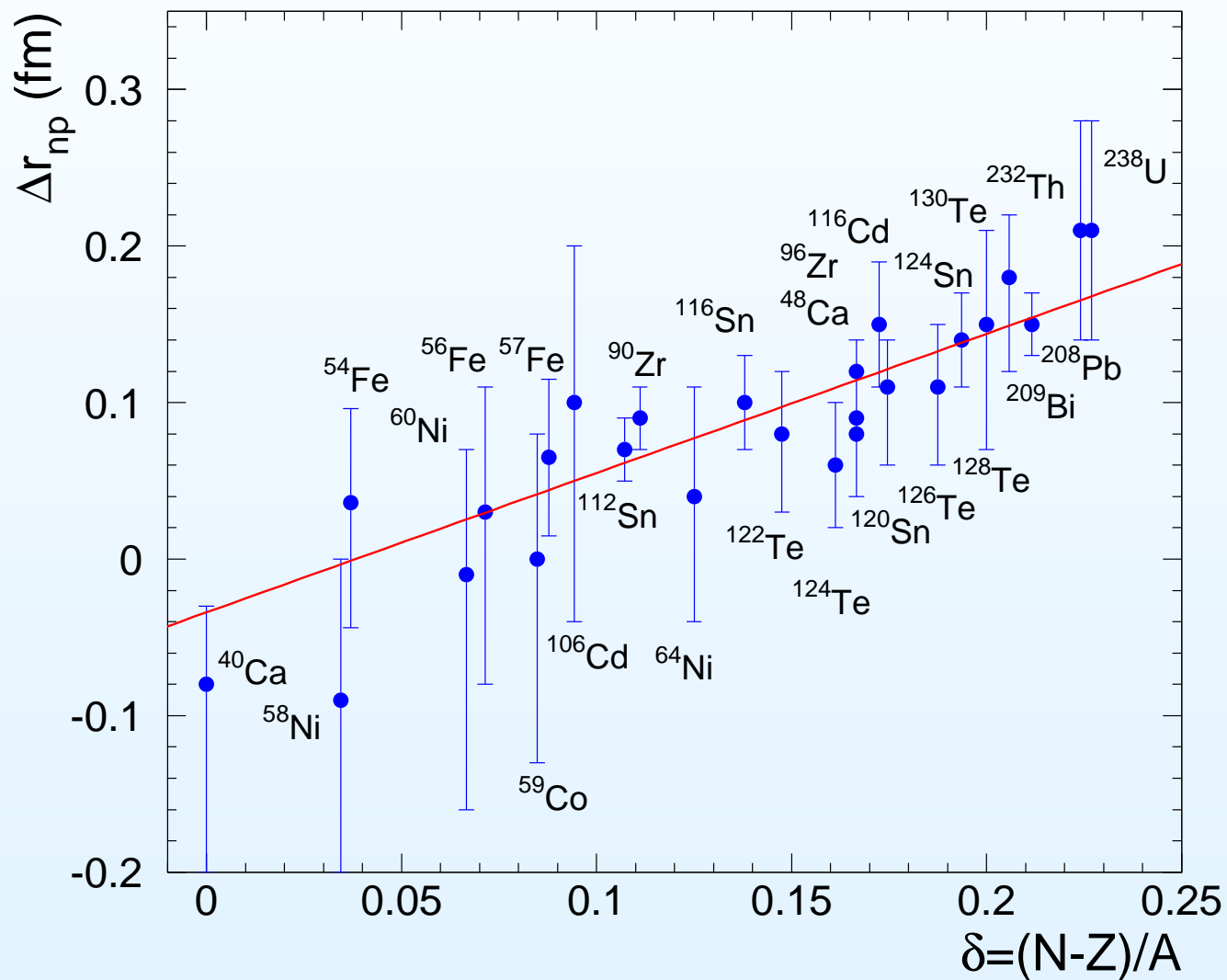


# $\Delta r_{np}$ in $^{208}\text{Pb}$



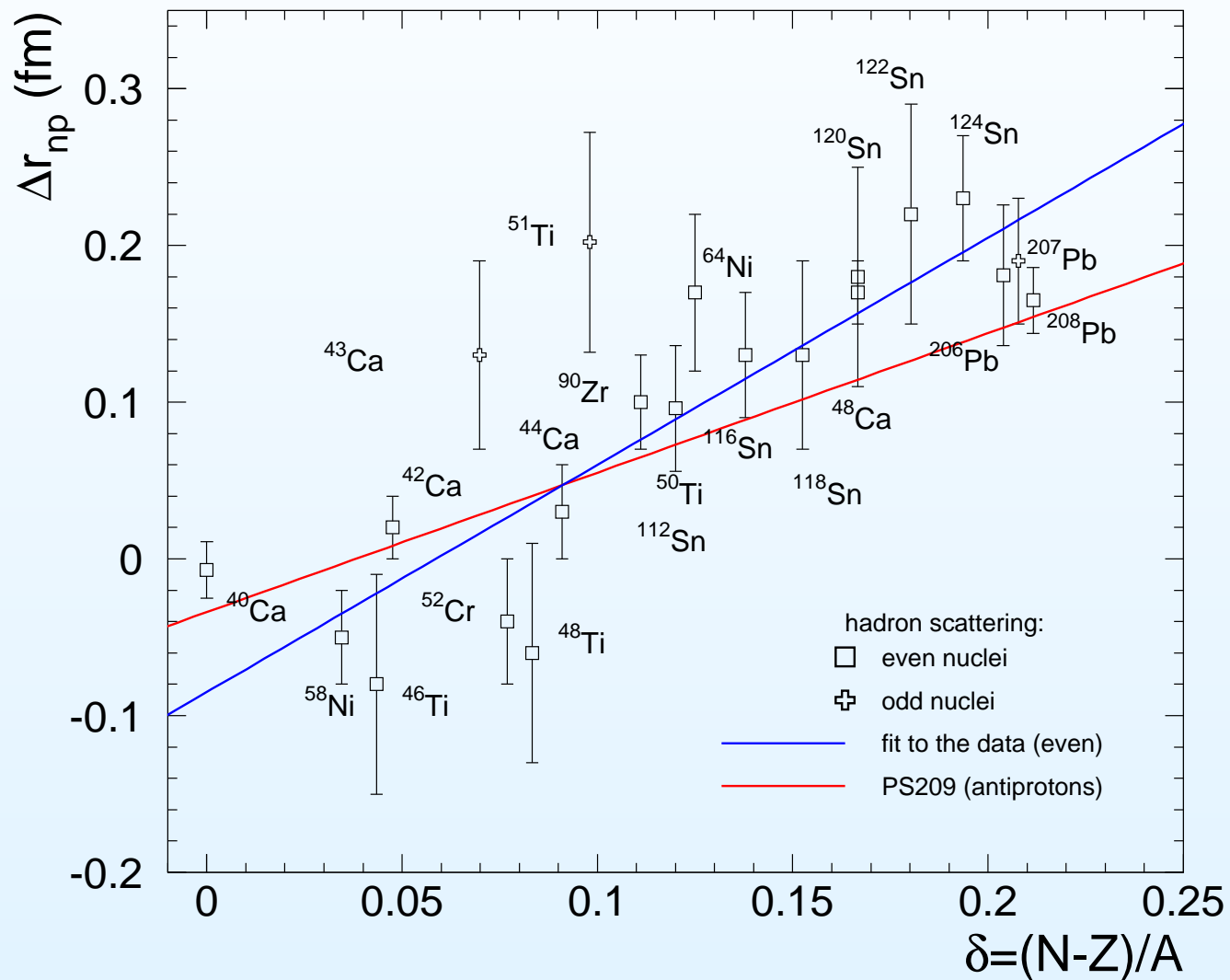
# Comparison with experiments

PS209 experimental data



# Comparison with experiments

hadron scattering experiments



## Summary & conclusions

- Two experimental methods using antiprotonic atoms were applied to investigate nuclear periphery:
  - **radiochemical method:**  $\rho_n/\rho_p$  @  $r \simeq c_p + 2.5$  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)
- Neutron density distribution deduced for 26 isotopes
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  - excellent agreement of  $\Delta r_{np}$  from antiprotonic X rays and hadron scattering for  $^{208}\text{Pb}$
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# PS209 Collaboration

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B. Kłos

## **Sołtan Institute for Nuclear Studies**

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