KU LEUVEN

Absolute radii of chlorine and potassium:

A heavyweight solution to a small problem

Michael Heines

On behalf of the muX collaboration

Contents

- Why do we need absolute charge radii?
- Measuring charge radii with muons
- Microgram targets
- Experimental campaign on potassium and chlorine
- Conclusion and outlook

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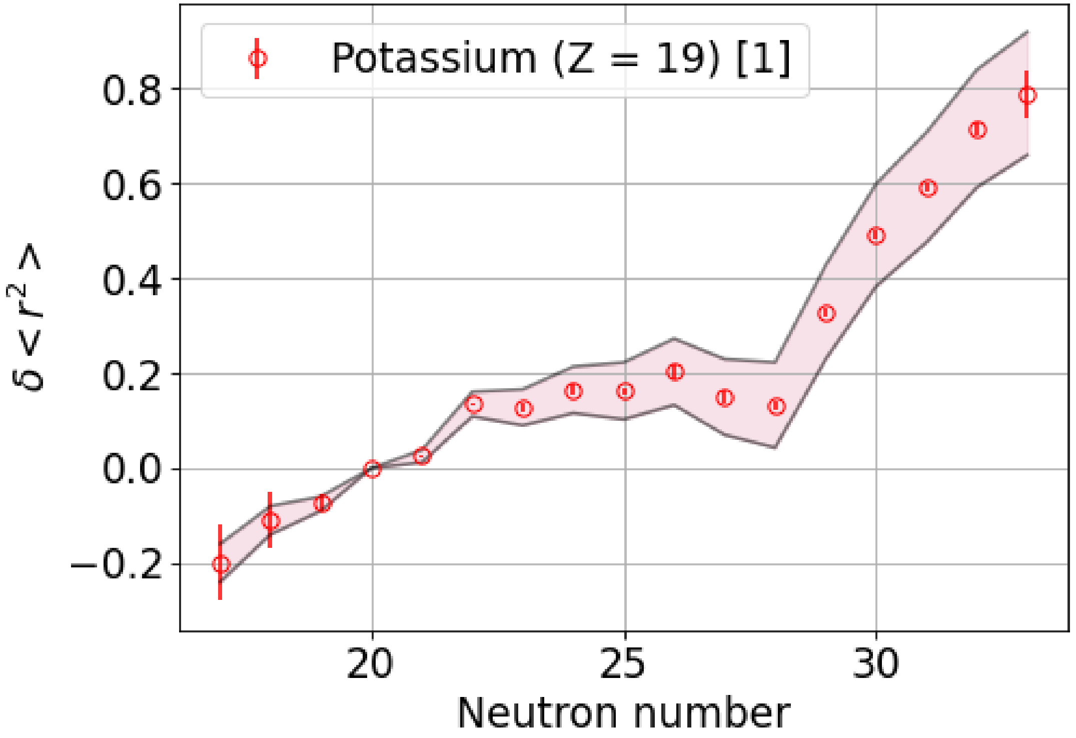
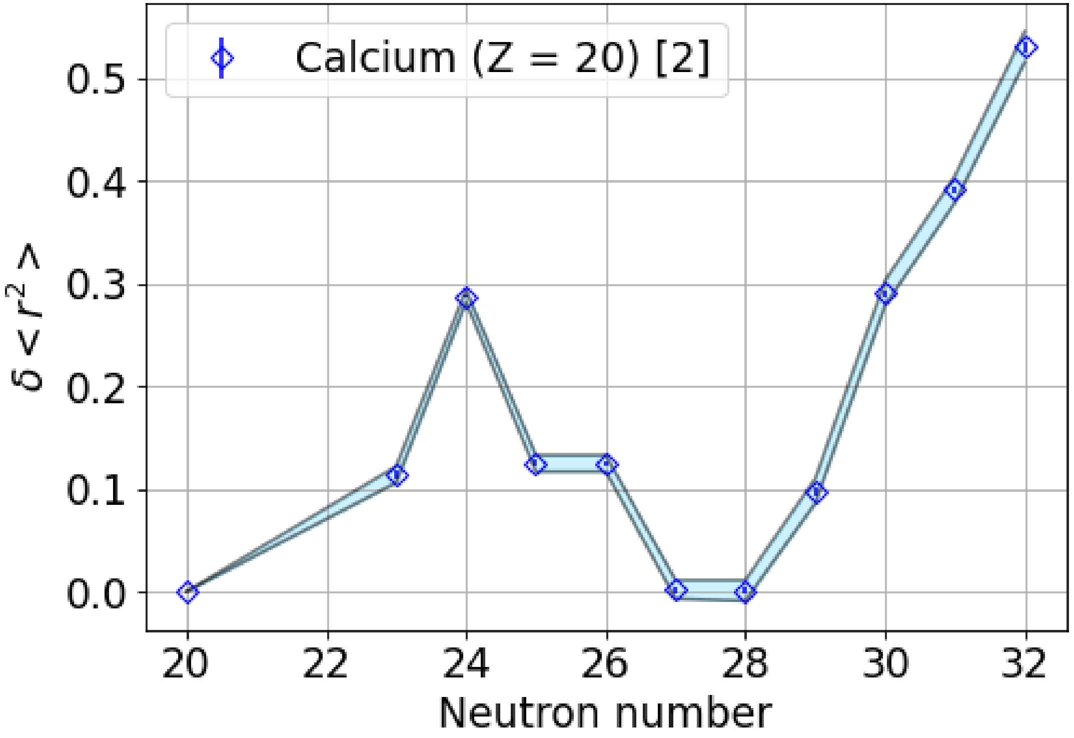
Measurements of $\delta < r^2 >$



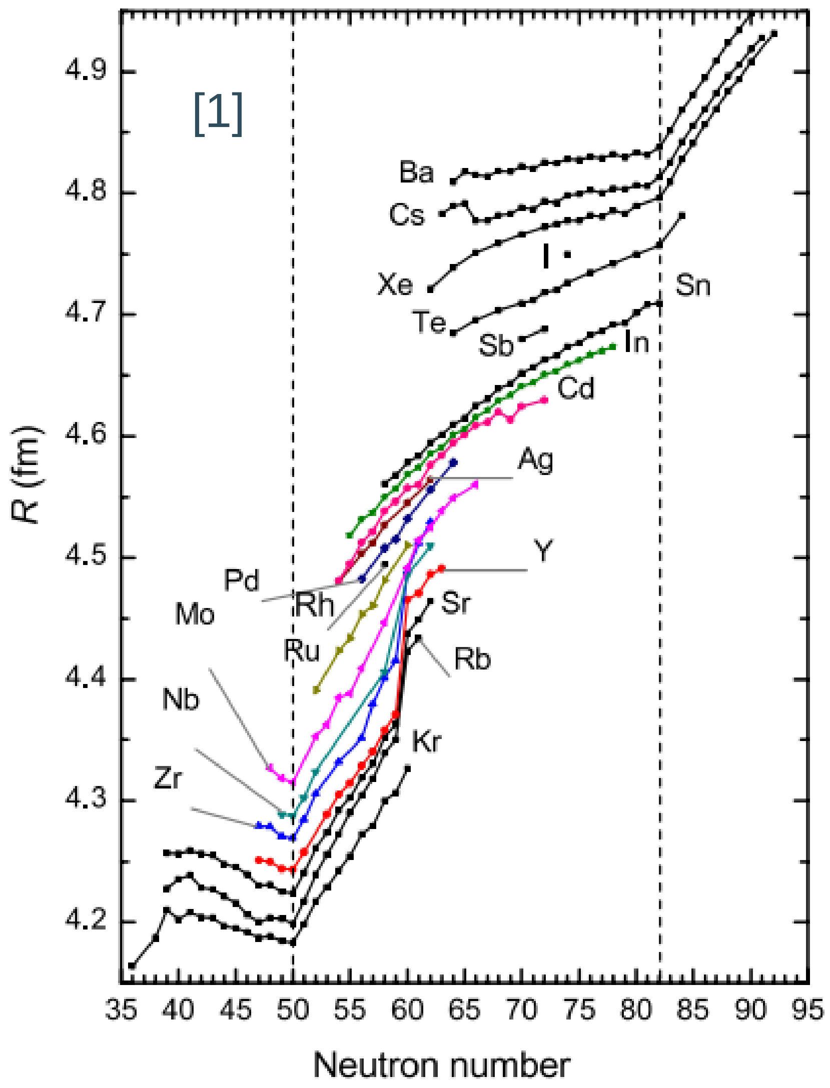


[1] Koszorús, Á., et al. "Charge radii of exotic potassium isotopes challenge nuclear theory and the magic character of N= 32." *Nature Physics* 17.4 (2021): 439-443.

[2] Garcia Ruiz, R. , et al. "Unexpectedly large charge radii of neutron-rich calcium isotopes." *Nature Physics* 12.6 (2016): 594-598.

Benefit of absolute radii

- Visualizing global trends
- Input for other experiments
- Isotone shifts
- Mirror nuclei



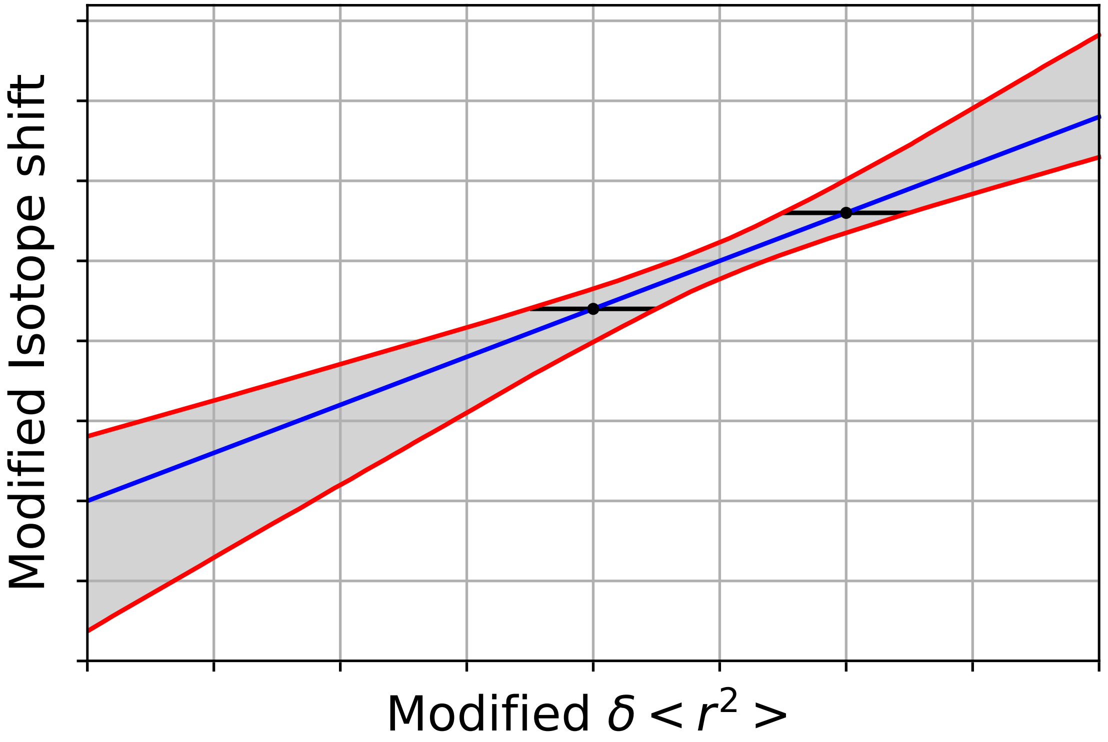
[1] Angeli, István, and Krassimira Petrova Marinova. "Table of experimental nuclear ground state charge radii: An update." *Atomic Data and Nuclear Data Tables* 99.1 (2013): 69-95.

King plot

$$\delta\langle r^2\rangle^{A,A'} = \frac{1}{F_i}\left(\delta\nu_i^{A,A'} - \frac{A - A'}{A\,A'} M_i\right)$$

- M_i : Mass shift factor
- F_i : Field shift factor

$$\frac{A\,A'}{A - A'}\,\delta\nu_i^{A,A'} = M_i + F_i\,\frac{A\,A'}{A - A'}\,\delta\langle r^2\rangle^{A,A'}$$



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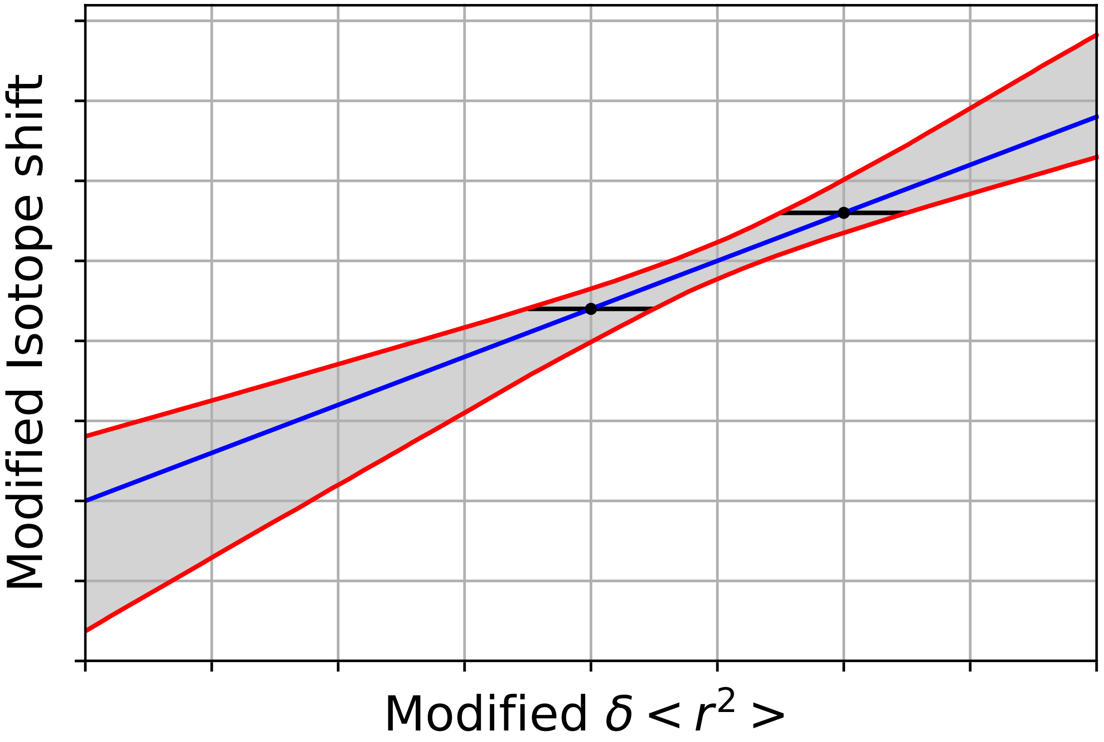

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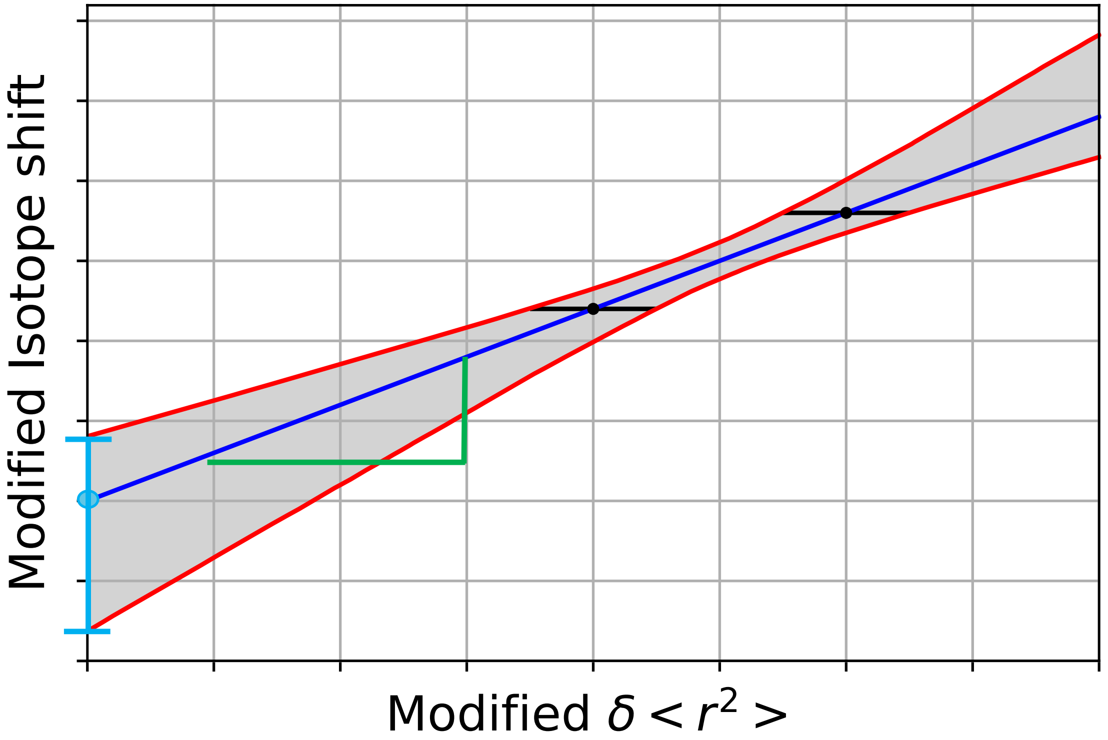
No odd-Z element with 3 stable isotopes!



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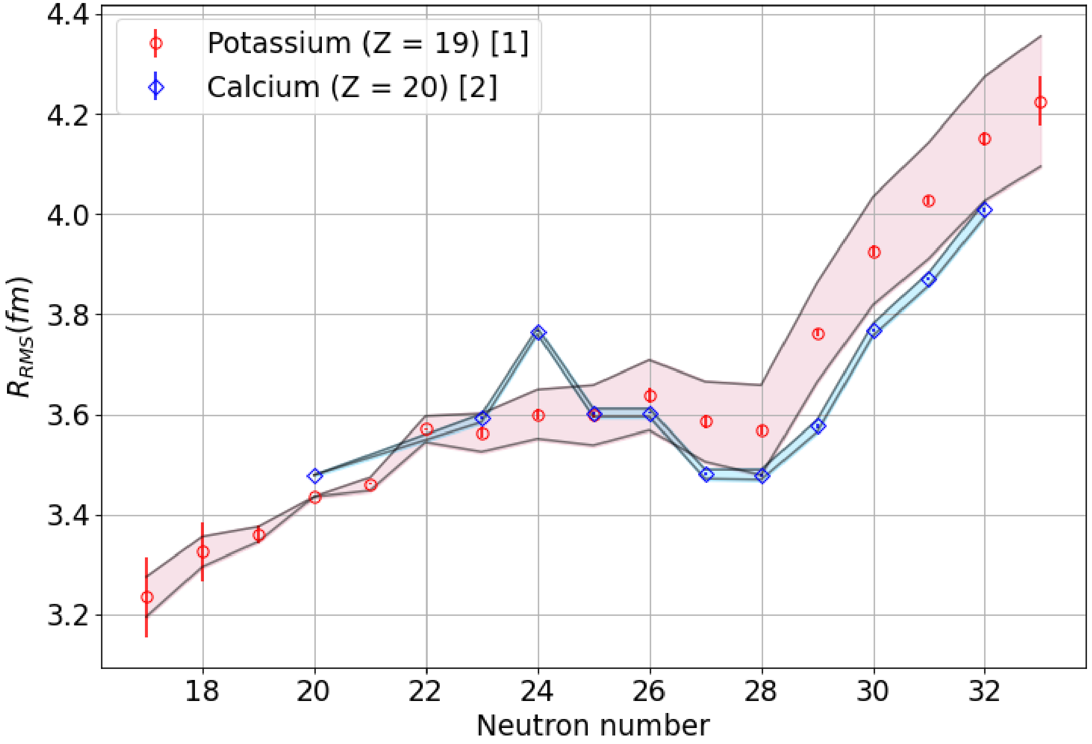

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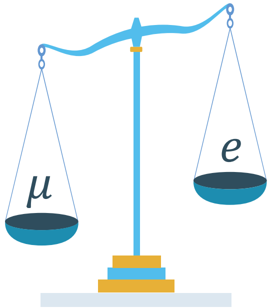
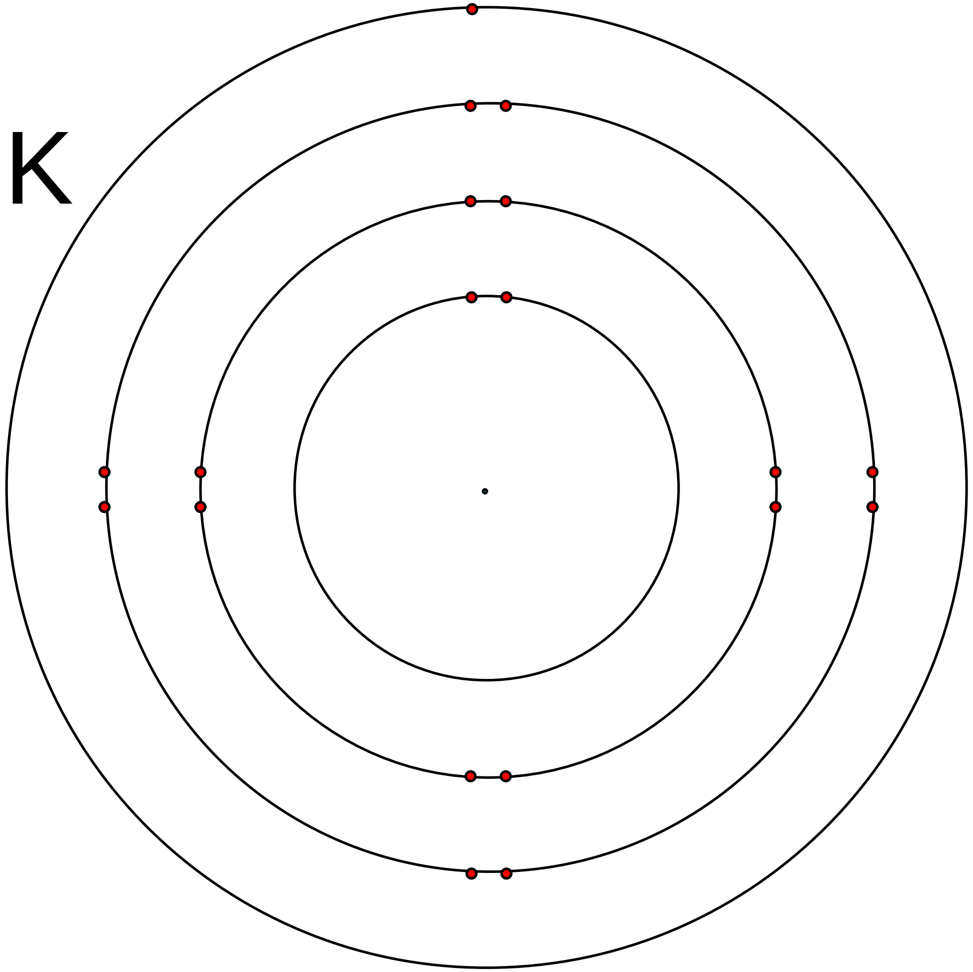
Muonic atoms

- Bohr model
  - $E_n \propto \frac{mZ^2}{n^2}$
  - $r_n \propto \frac{n^2}{mZ}$
- Muons:
  - $m_\mu \approx 207\ m_e$
  - $\tau_\mu \approx 2.2\ \mu s$





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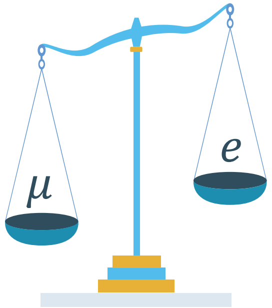

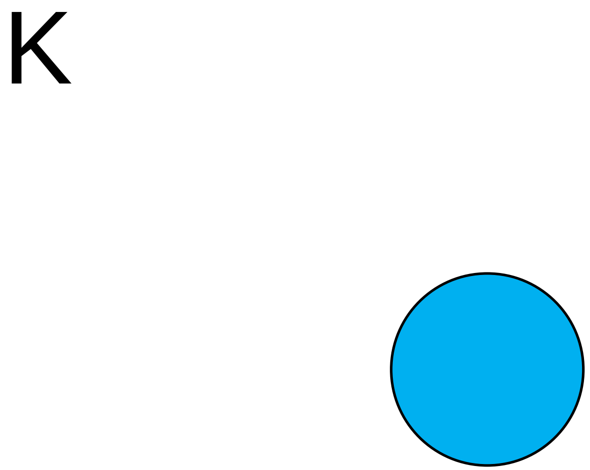

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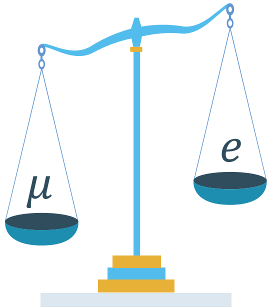
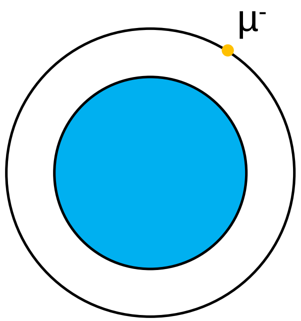


- Effect:
  - Enhanced binding energy
  - Closer to the nucleus → More sensitive to nuclear effects

μK



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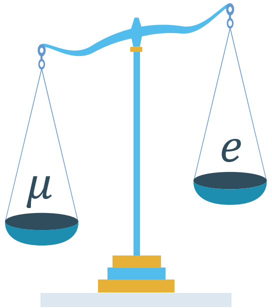

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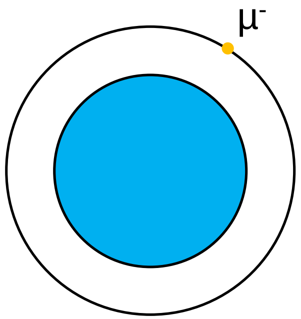
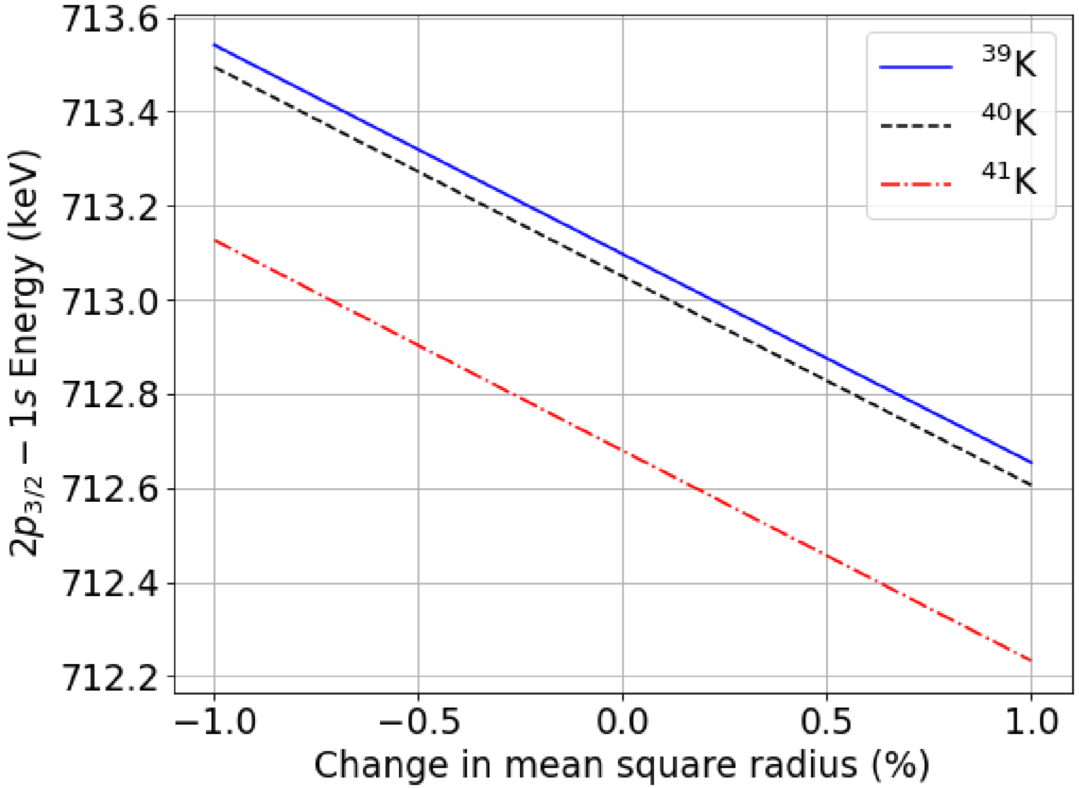


Muon n = 14 orbital is inside electron n = 1 orbital
→ electron correlation is negligible

Extracting radii

- Finite size correction scales with $\frac{1}{r^3} \approx 10^7$
- Calculate transition energy for many radii → Compare with experiment
- Typical limitations:
  - Nuclear polarization (theory)
  - Nuclear shape (electron scattering)
  - Energy calibration



Simple calculations with mudirac code [1]

[1] Sturniolo, Simone, and Adrian Hillier. "Mudirac: A Dirac equation solver for elemental analysis with muonic X-rays." *X-Ray Spectrometry* 50.3 (2021): 180-196.

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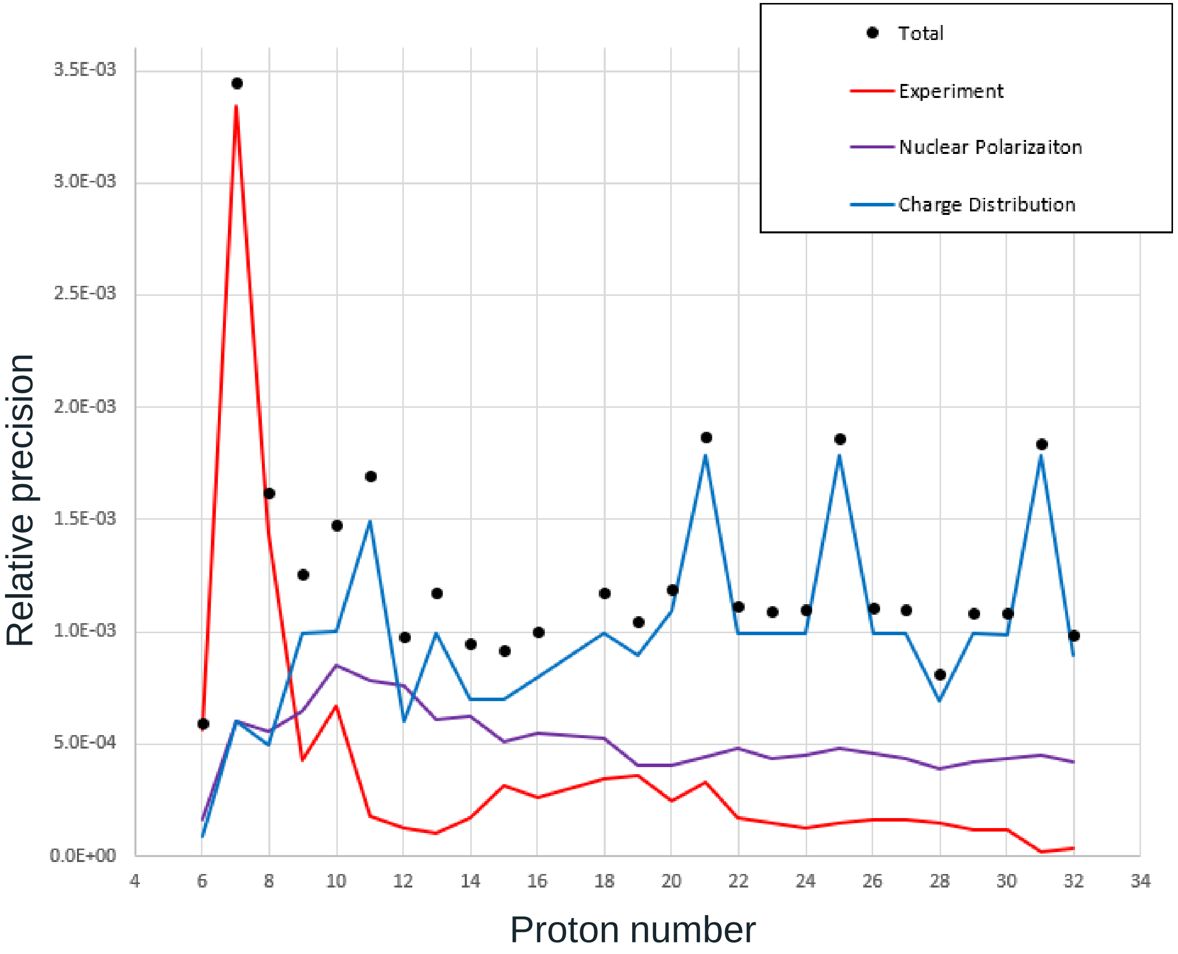
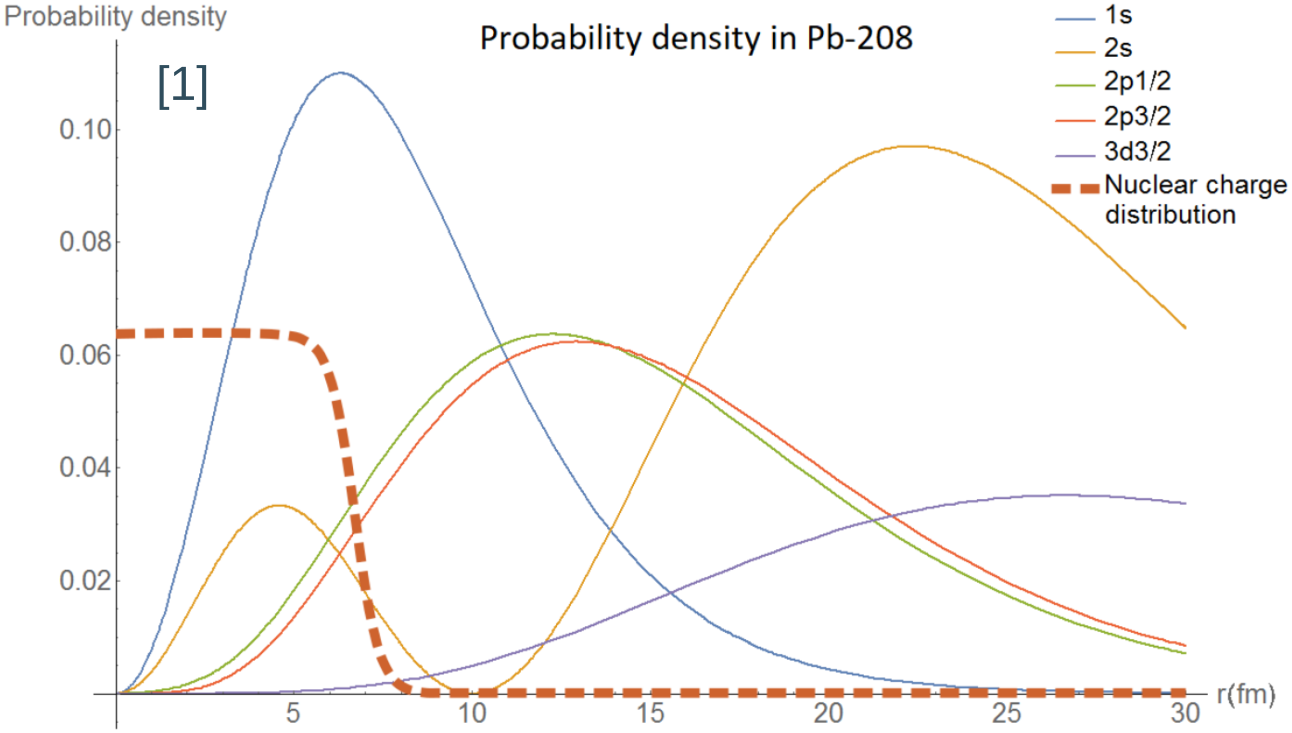


Image courtesy: Ben Ohayon

How sensitive are we?

- Groundstate wavefunction has sizeable overlap with the nucleus

- Sensitivity increase:
  - Nuclear size: $\left(\frac{m_\mu}{m_e}\right)^3 \approx 10^7$
  - Quadrupole: $\left(\frac{m_\mu}{m_e}\right)^2 \approx 5 \times 10^4$
  - Octupole: $\left(\frac{m_\mu}{m_e}\right)^3 \approx 10^7$



[1] S. M. Vogiatzi. The fitting of the hyperfine splitting of the 5 -> 4 transitions in muonic Re-185. Master's thesis, ETH Zurich, 2018.

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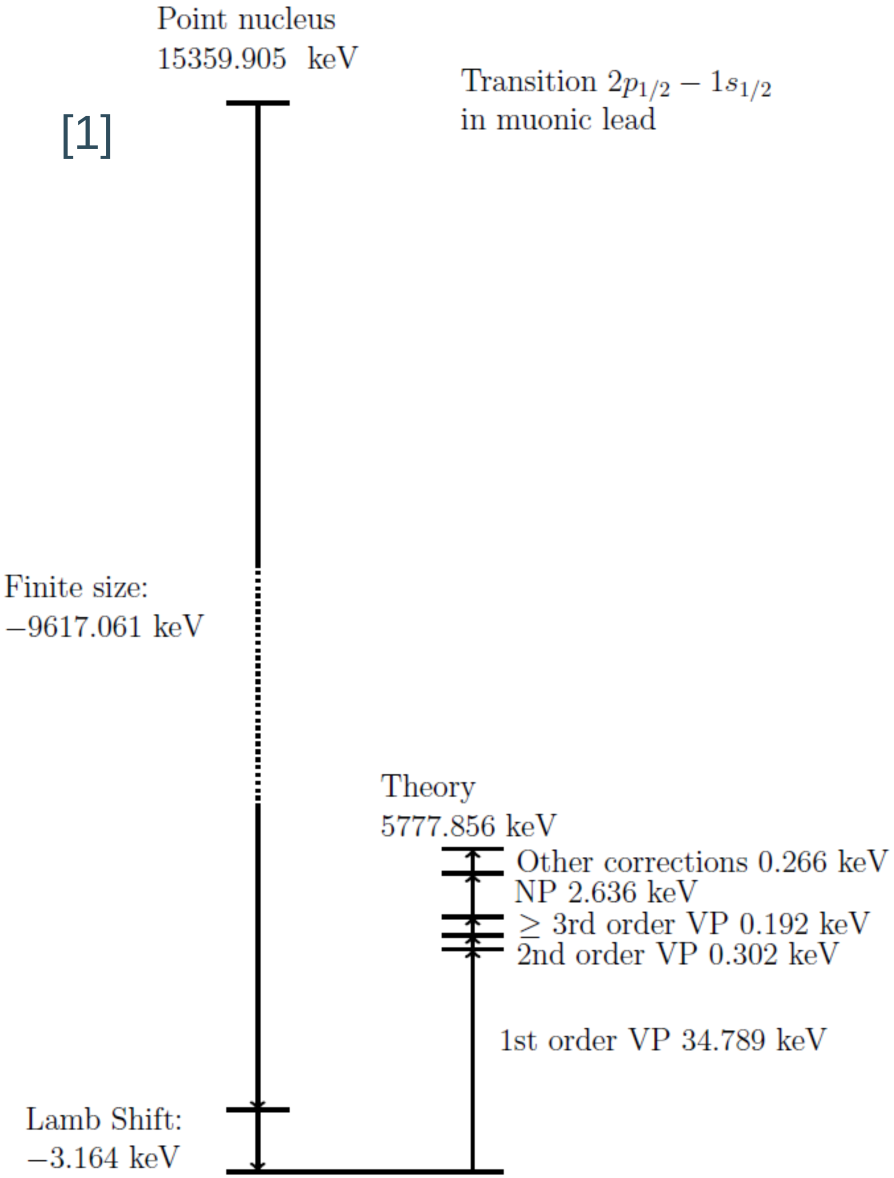

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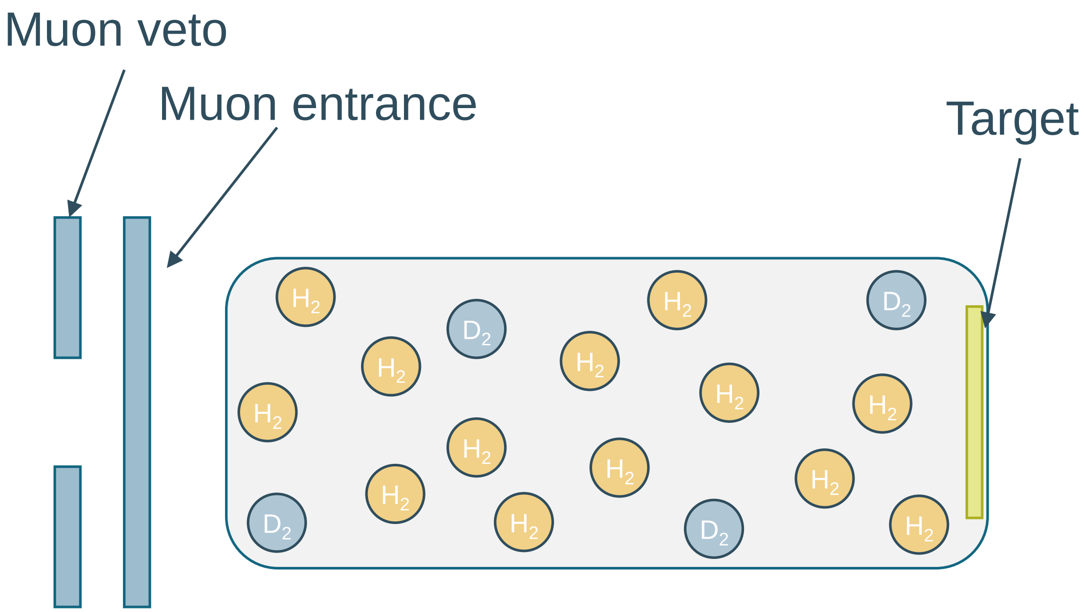
Measuring microgram materials

- Traditionally: Limited to target mass O(10-100 mg)

- Hydrogen gas cell (100 bars; 0.25% deuterium)
  - ➢Limited to O(5 µg)
  - ➢Down to 20 year half-life (radioprotection)



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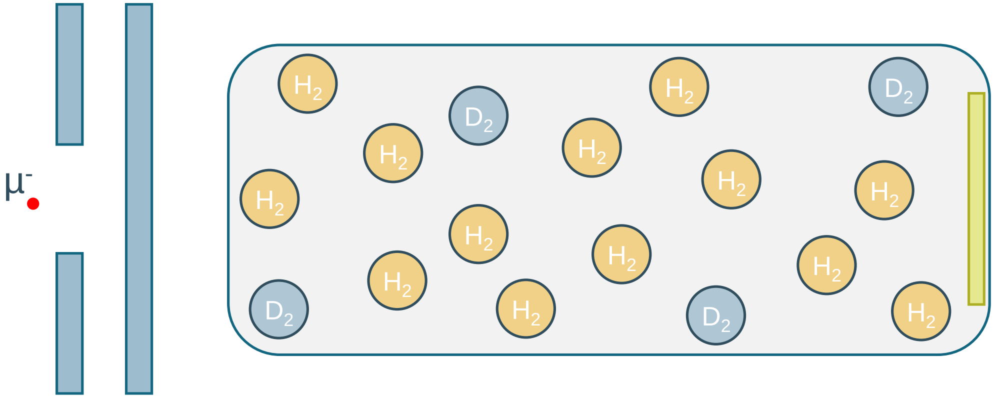

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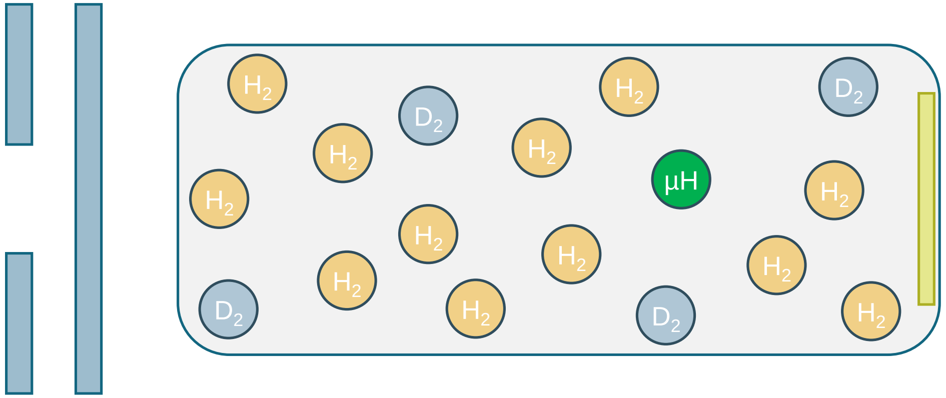

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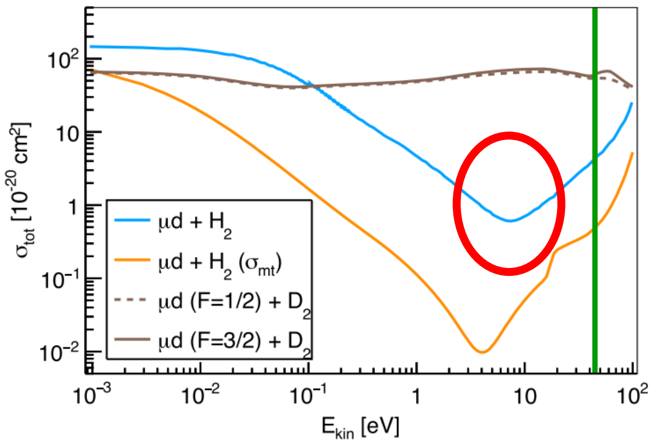

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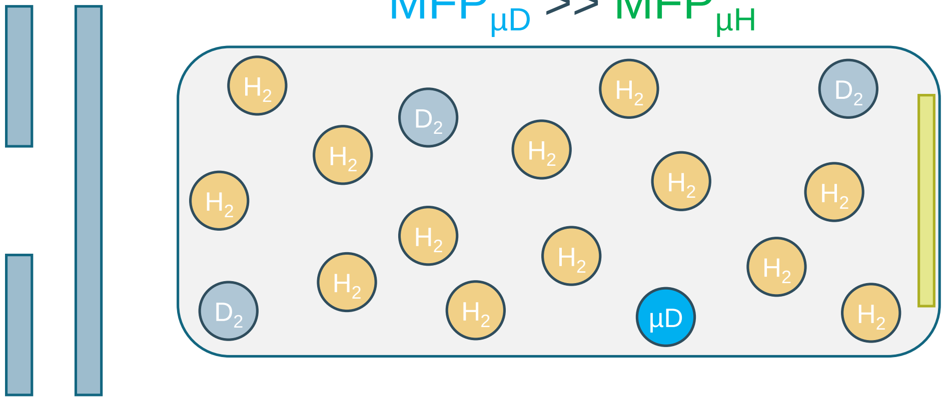
$MFP_{\mu D} >> MFP_{\mu H}$



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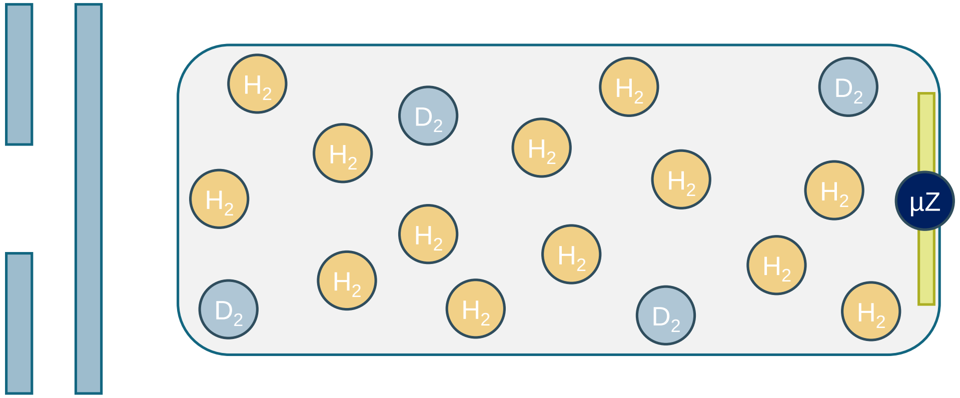

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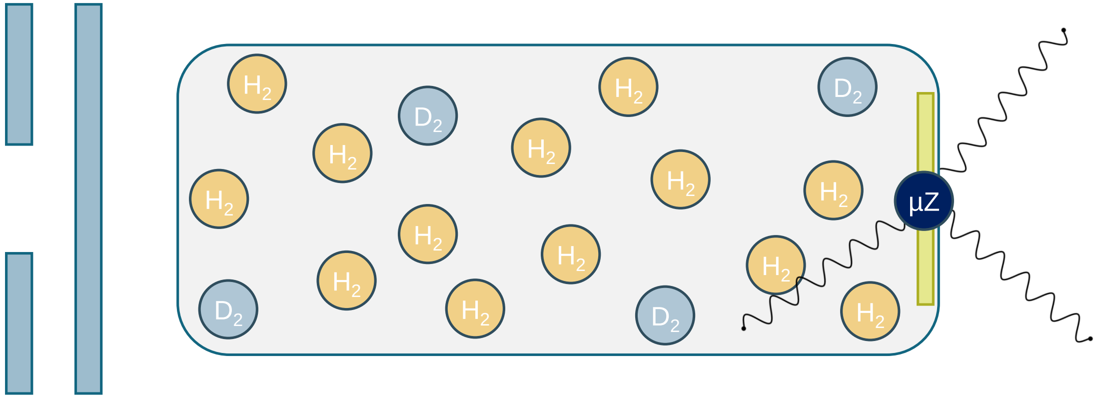

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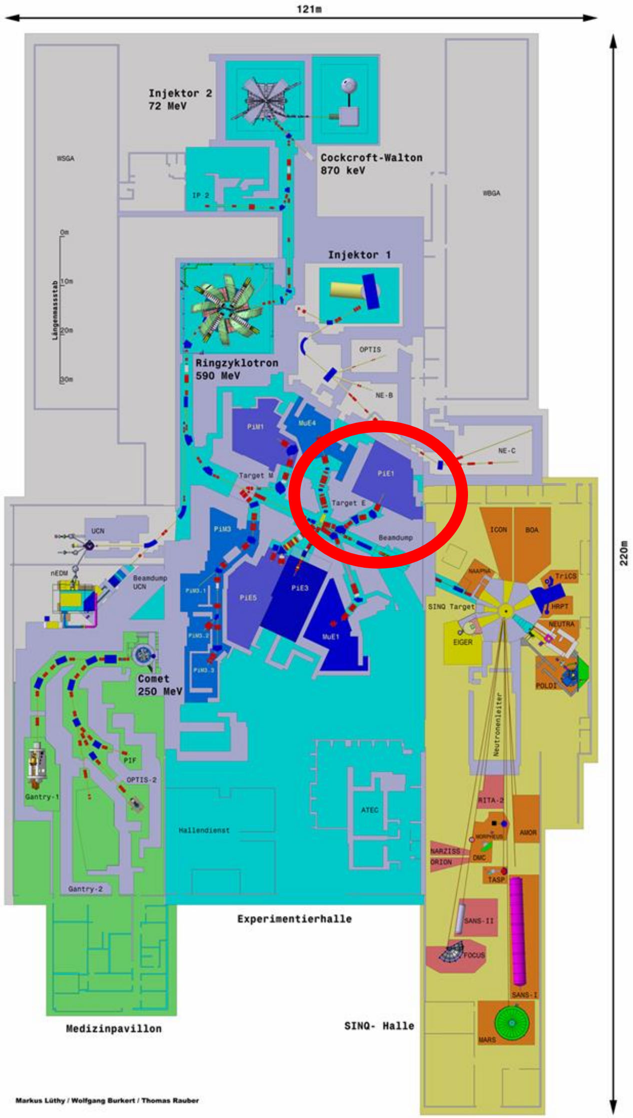
Primary goals

- First measurement of isotopically pure $^{35,\,37}$Cl (macroscopic target)

- Remeasurement of $^{39,\,41}$K (macroscopic target)

- First measurement of ^{40}K (microscopic implanted target)

PSI – High-intensity proton



Markus Lüthy / Wolfgang Burkert / Thomas Rauber

Setup

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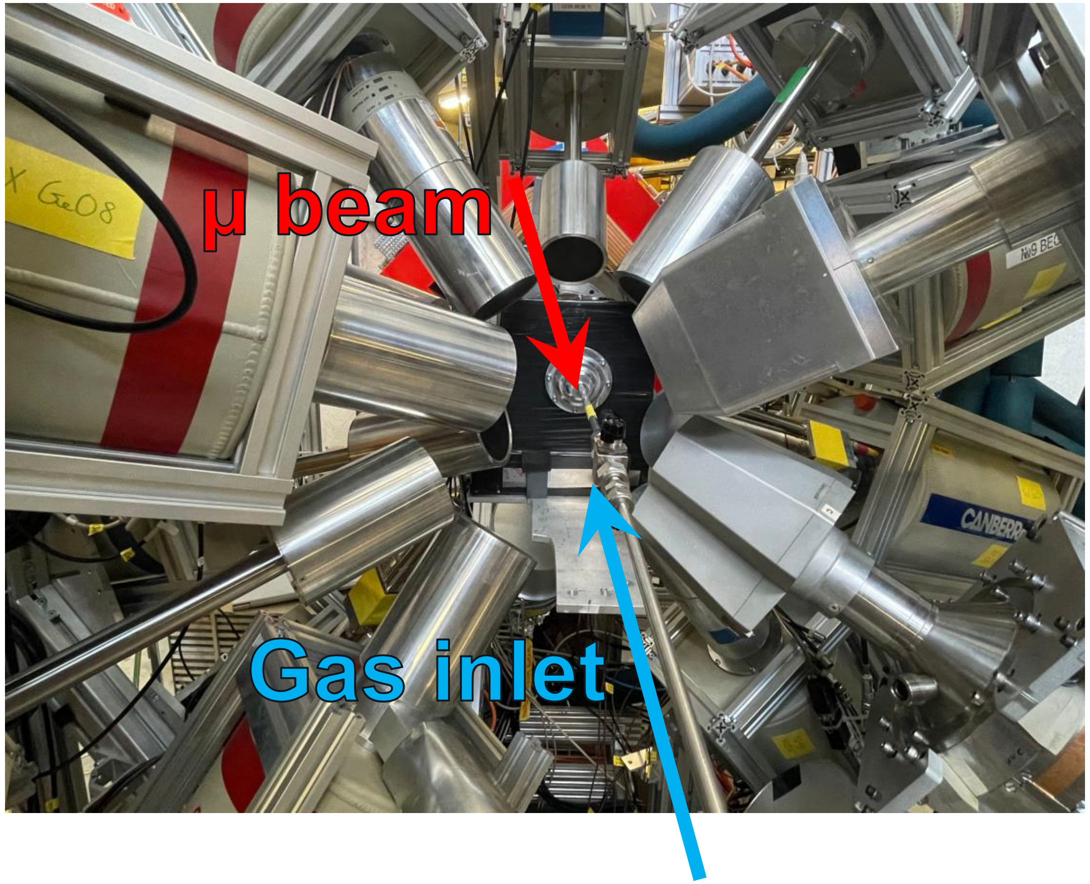
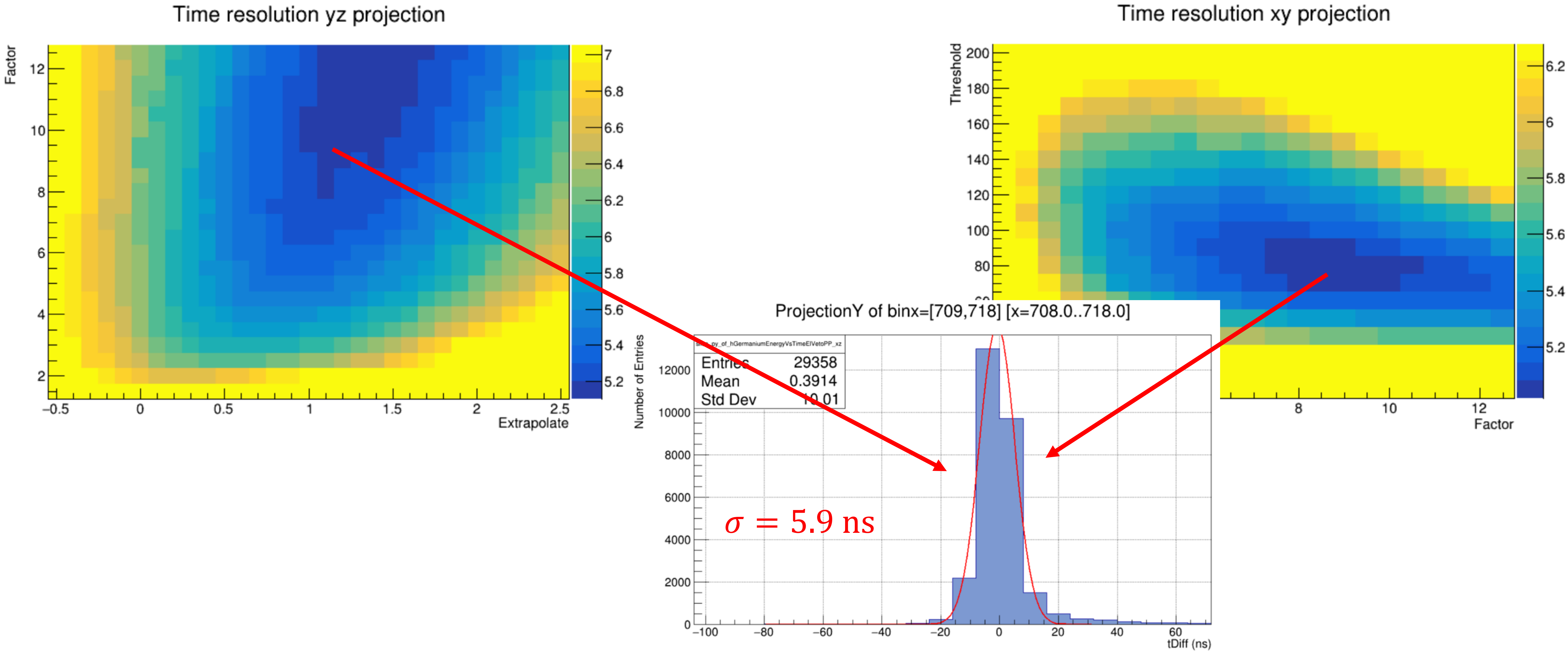


Data filtering: Timing optimization


Time resolution yz projection

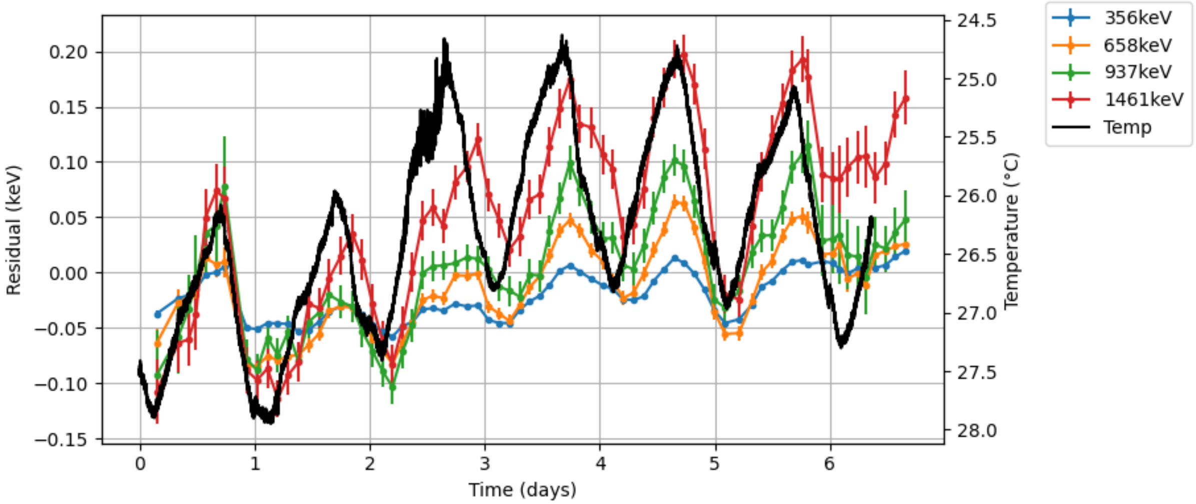
Time resolution xy projection

ProjectionY of binx=[709,718] [x=708.0..718.0]

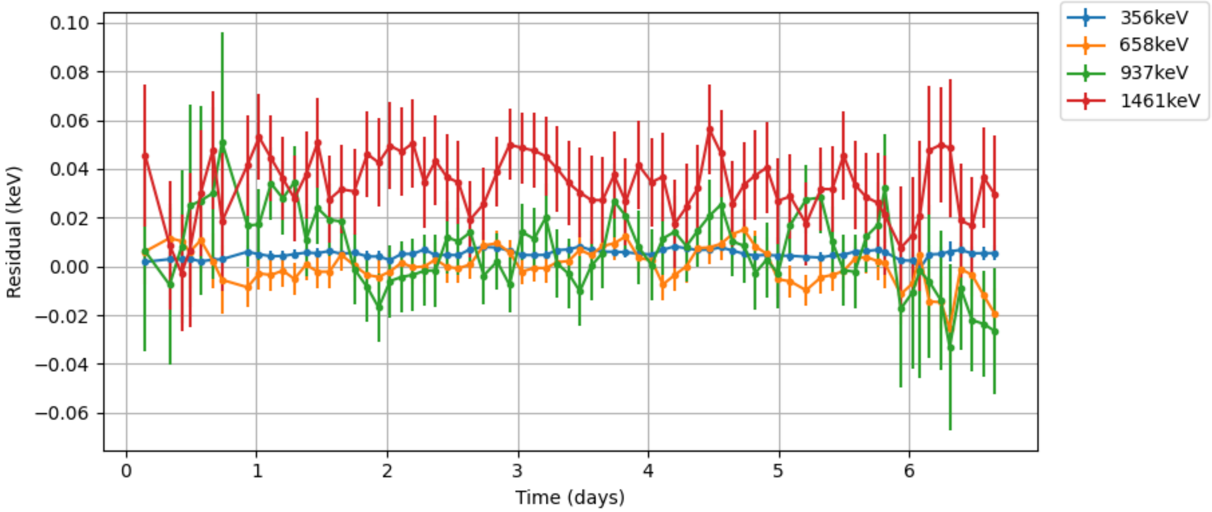
$\sigma = 5.9$ ns

Data filtering: Gain drift correction

- Before correcting



- After correcting



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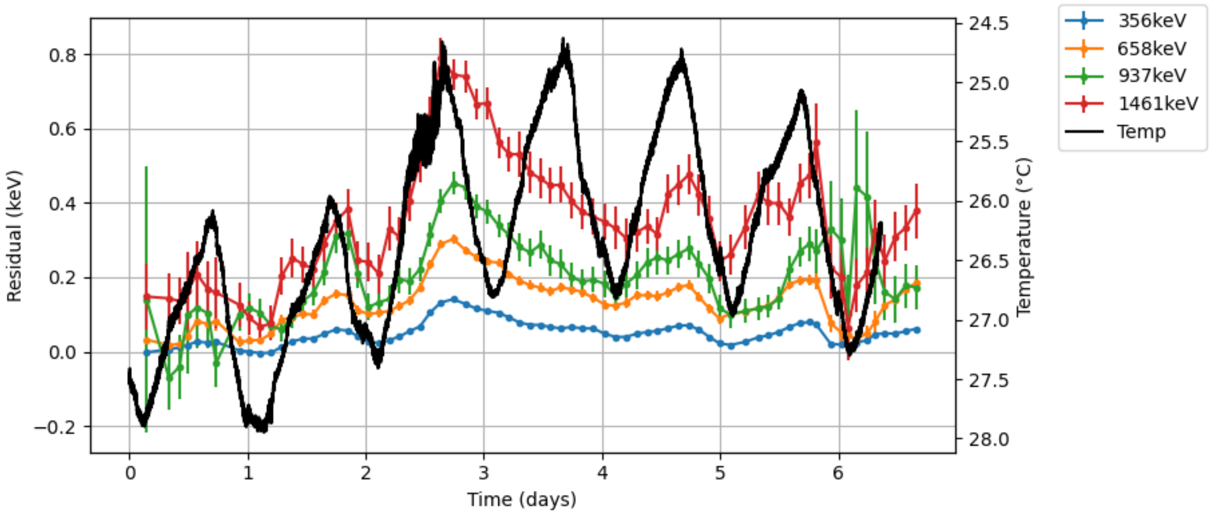

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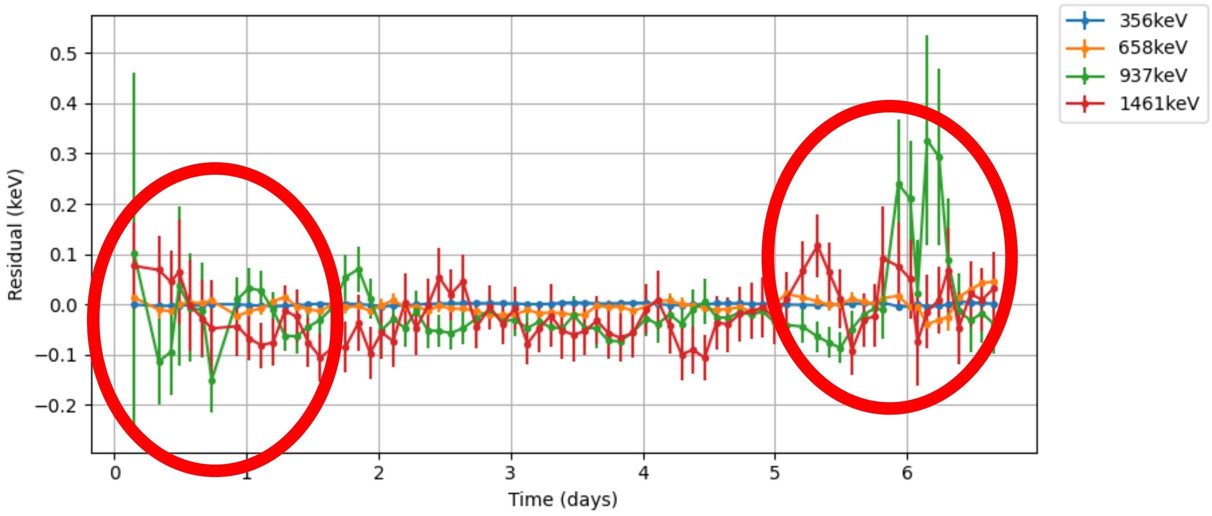
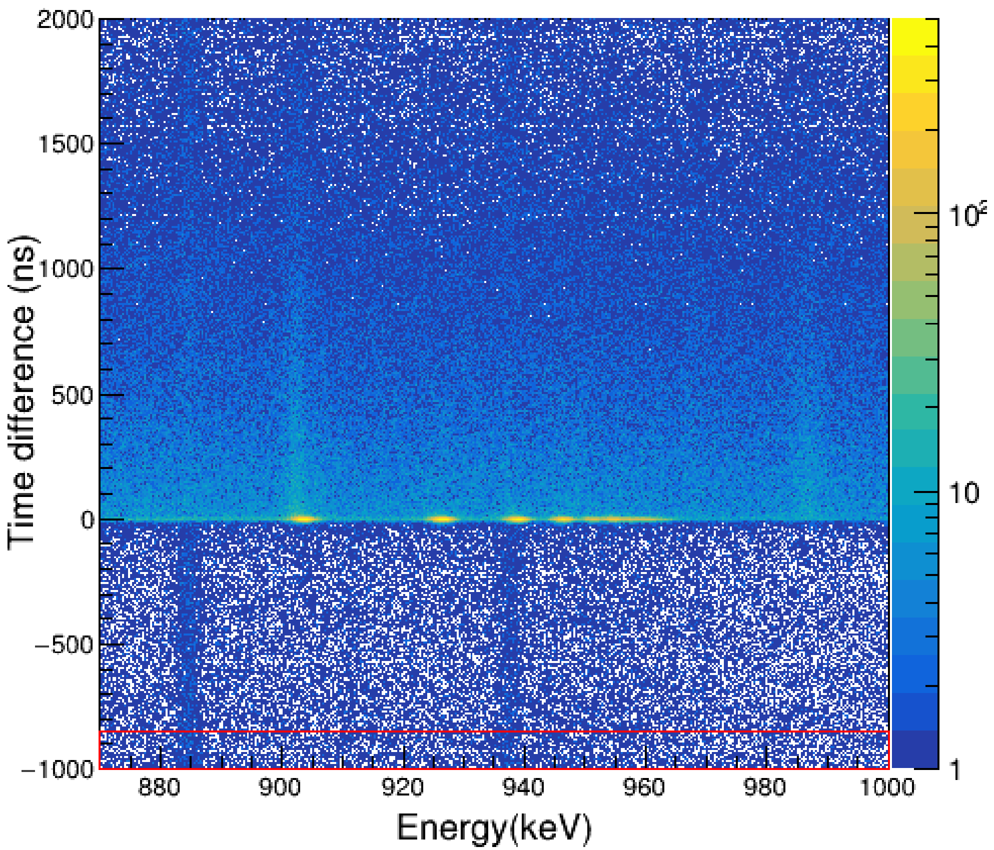
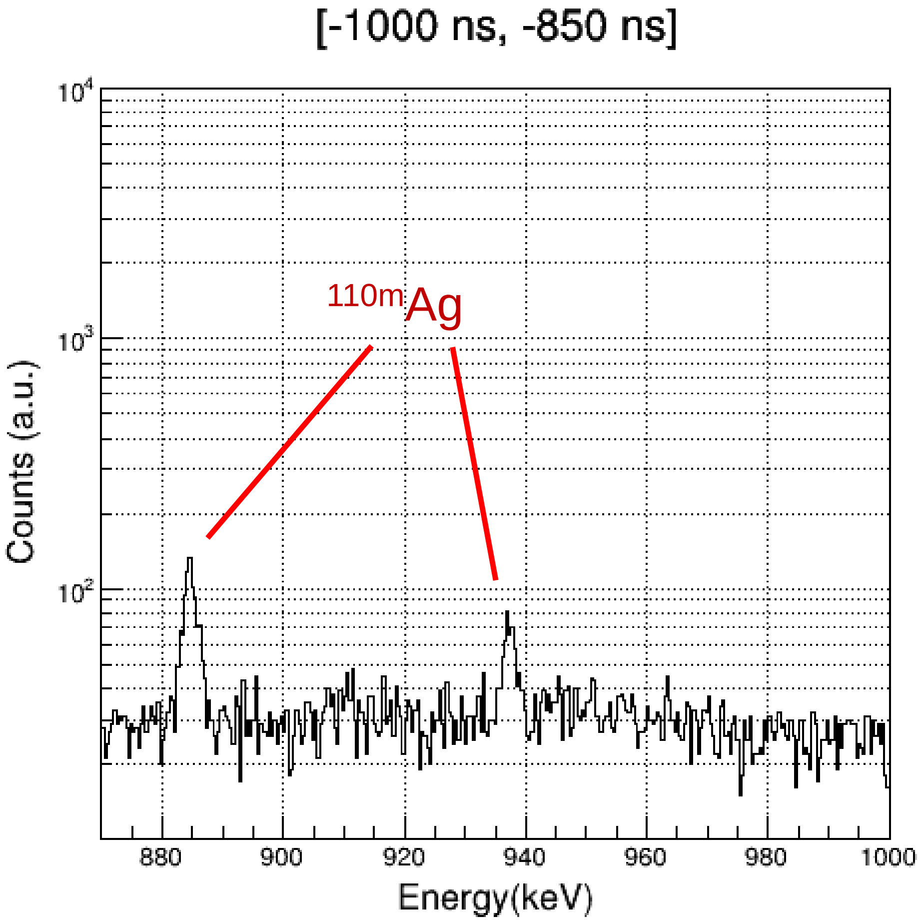


Interpreting energy Vs time plots





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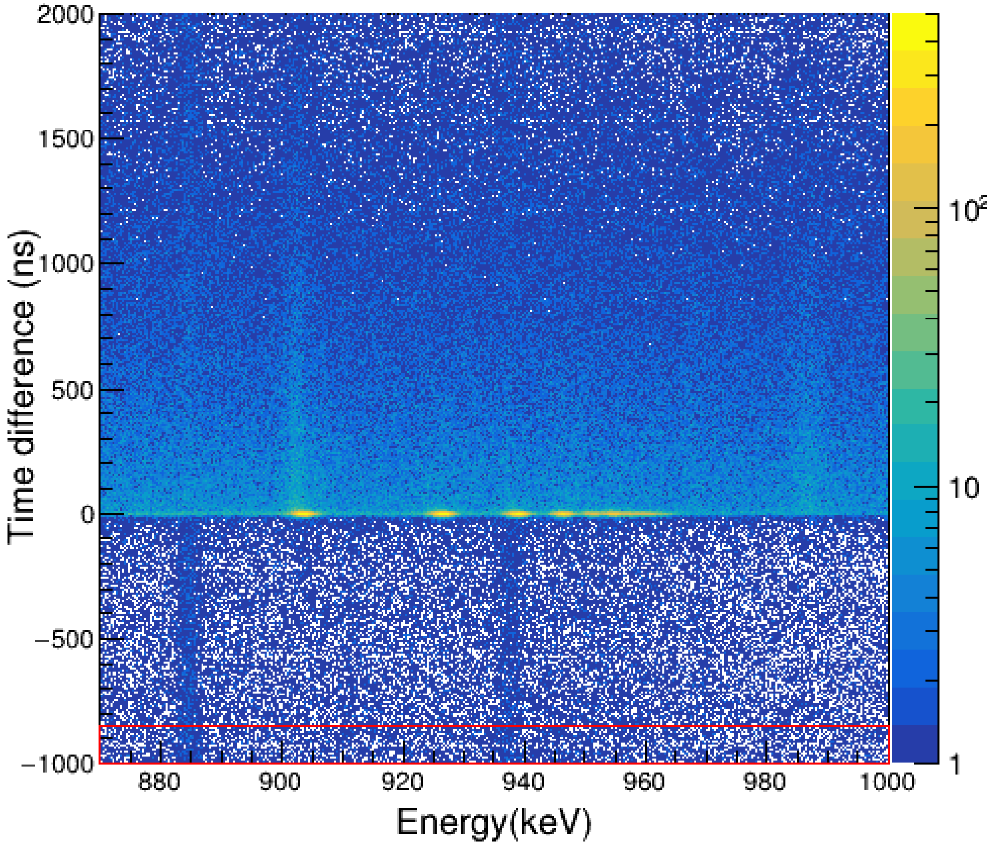

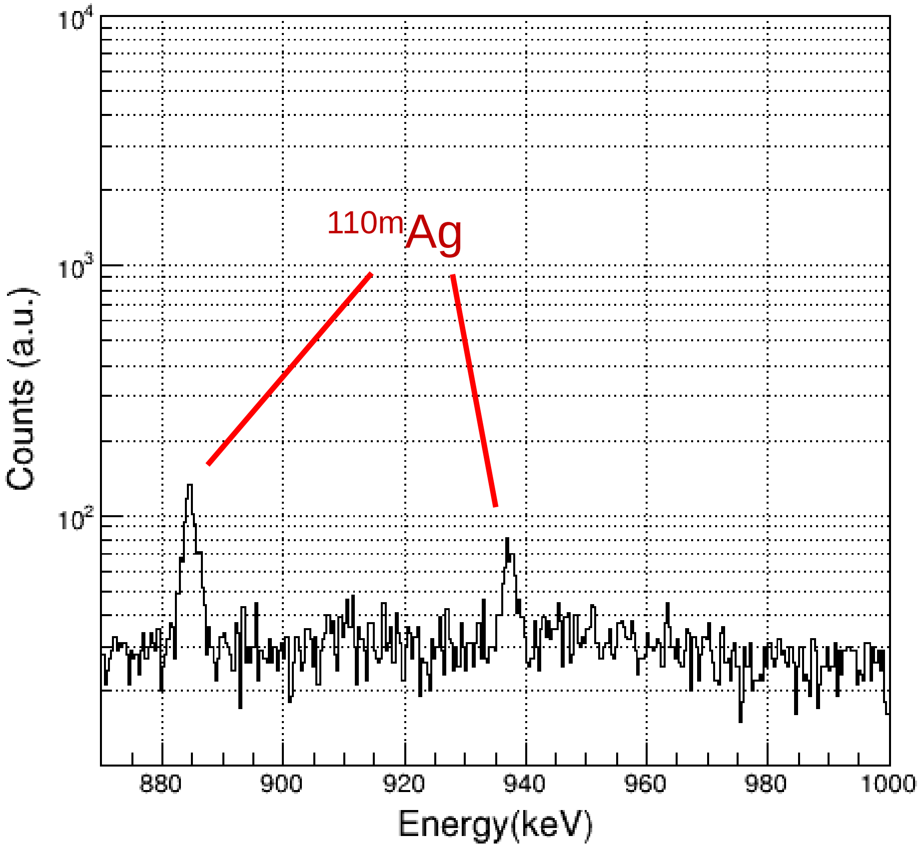
[-1000 ns, -850 ns]

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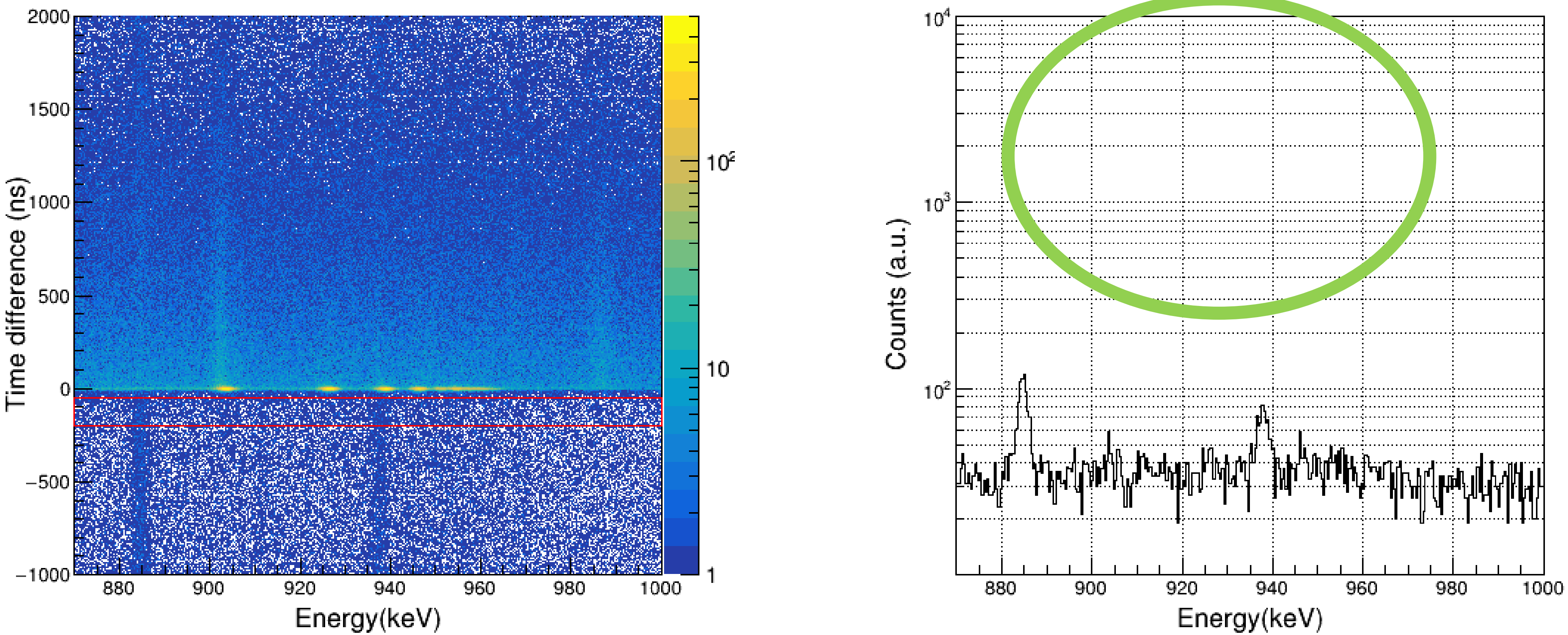

[-200 ns, -50 ns] ^{39}K np-1s

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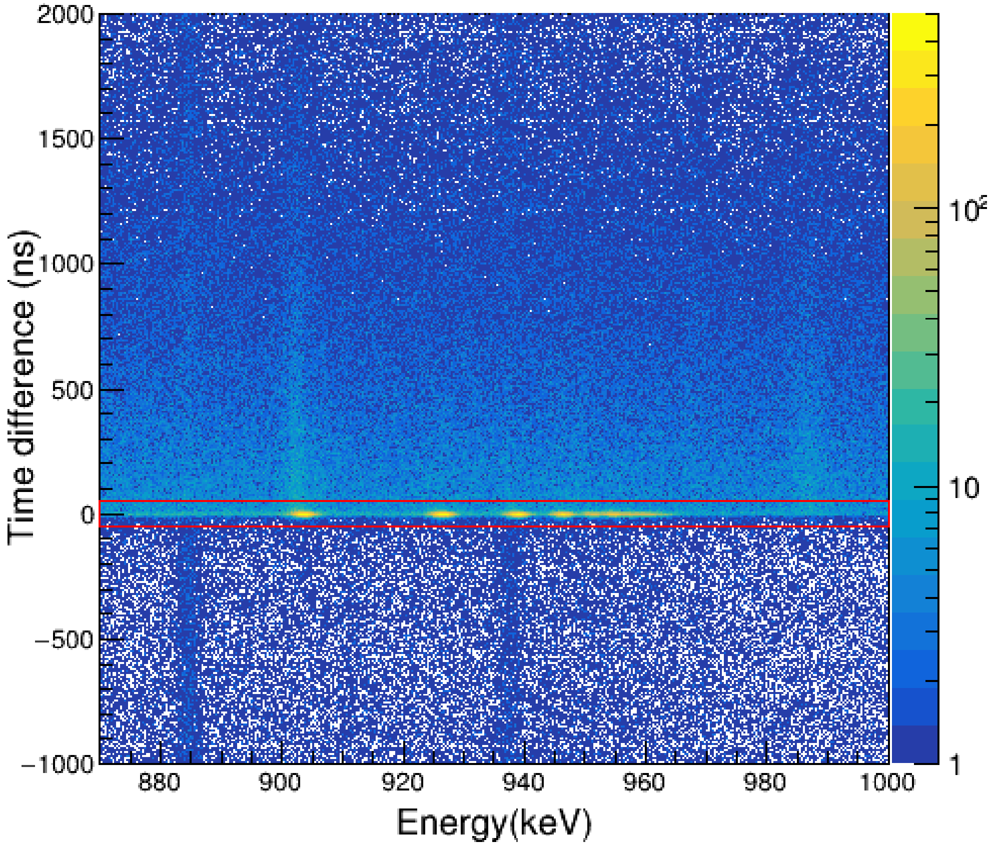
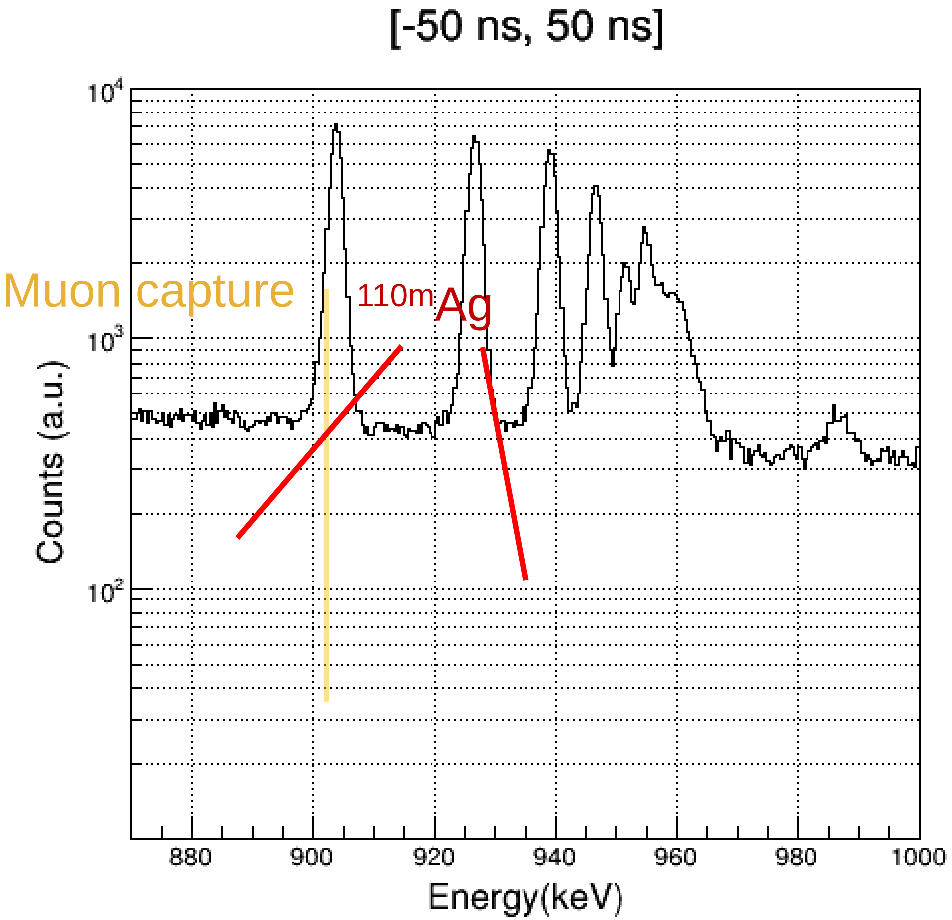
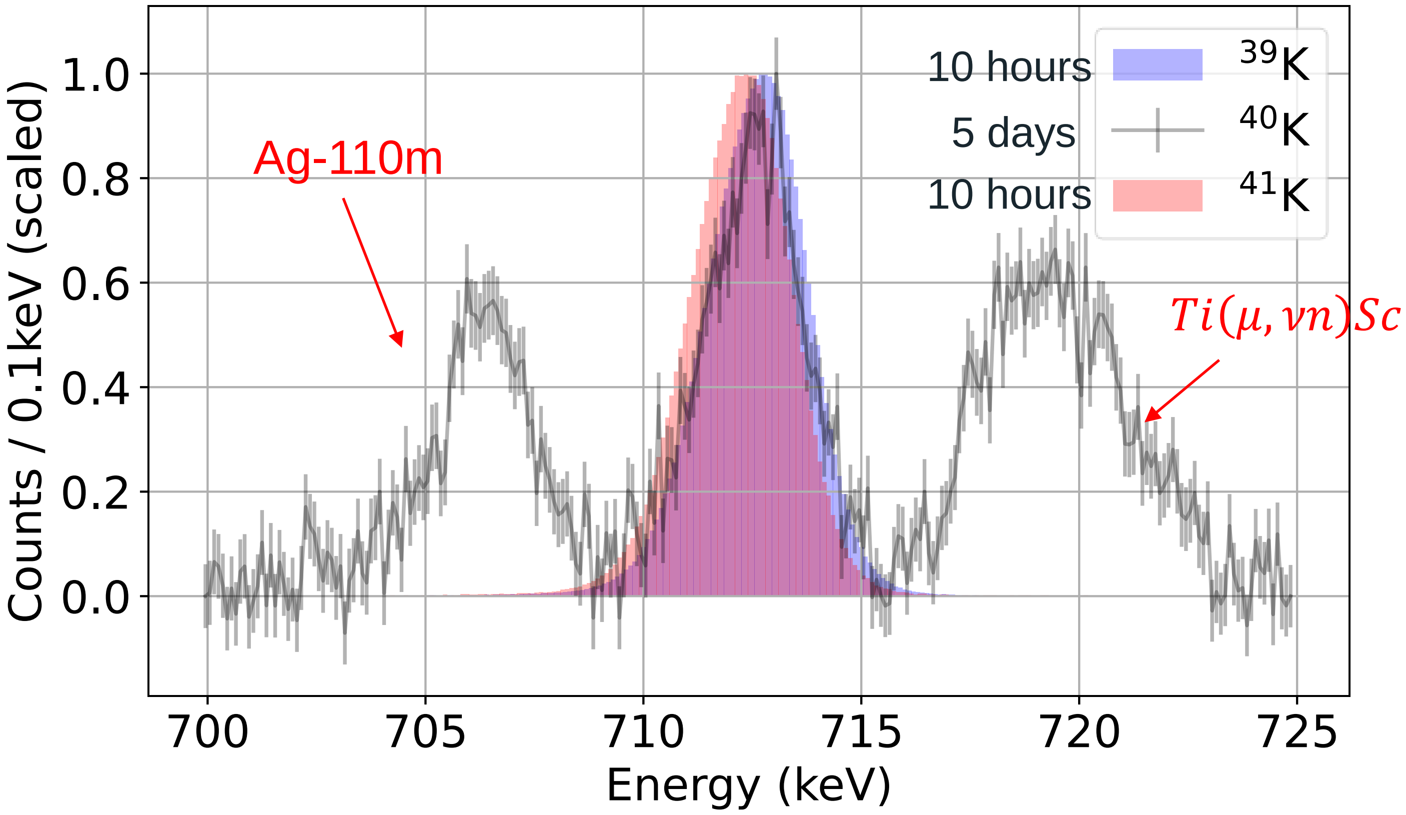


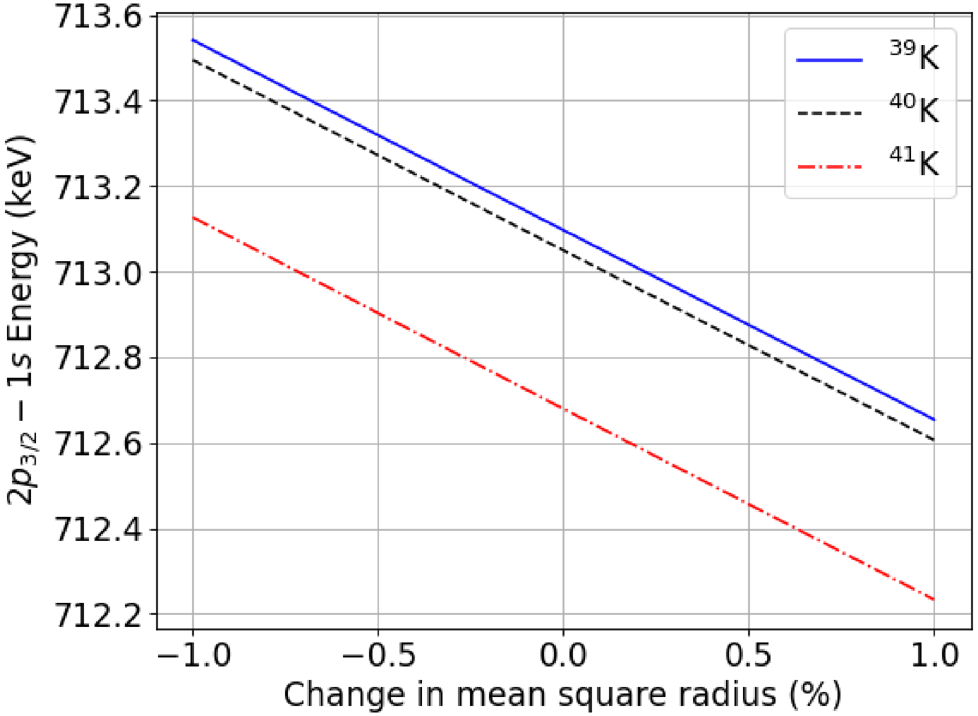

[-50 ns, 50 ns]

Muon capture

^{110m}Ag

Potassium muonic isotope shift





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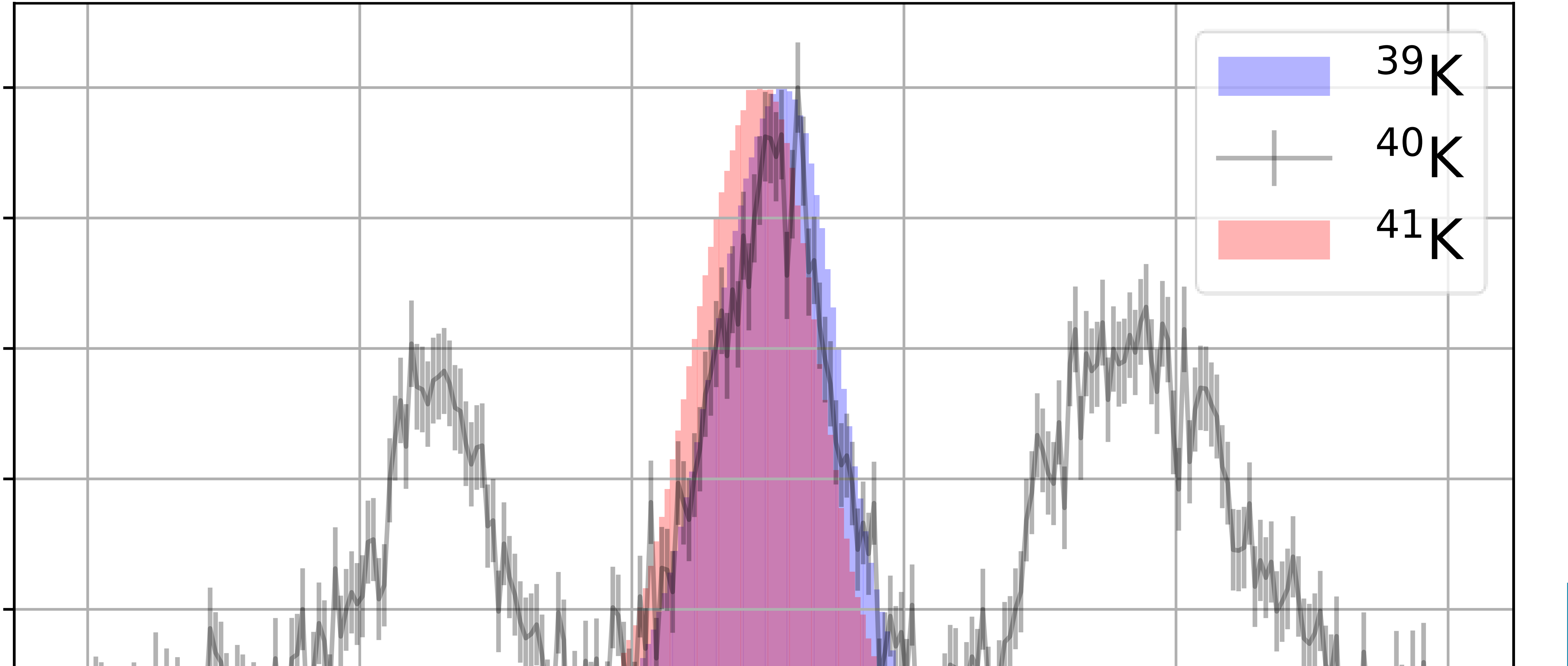


Chlorine measurement

- Muonic 2p-1s energy:

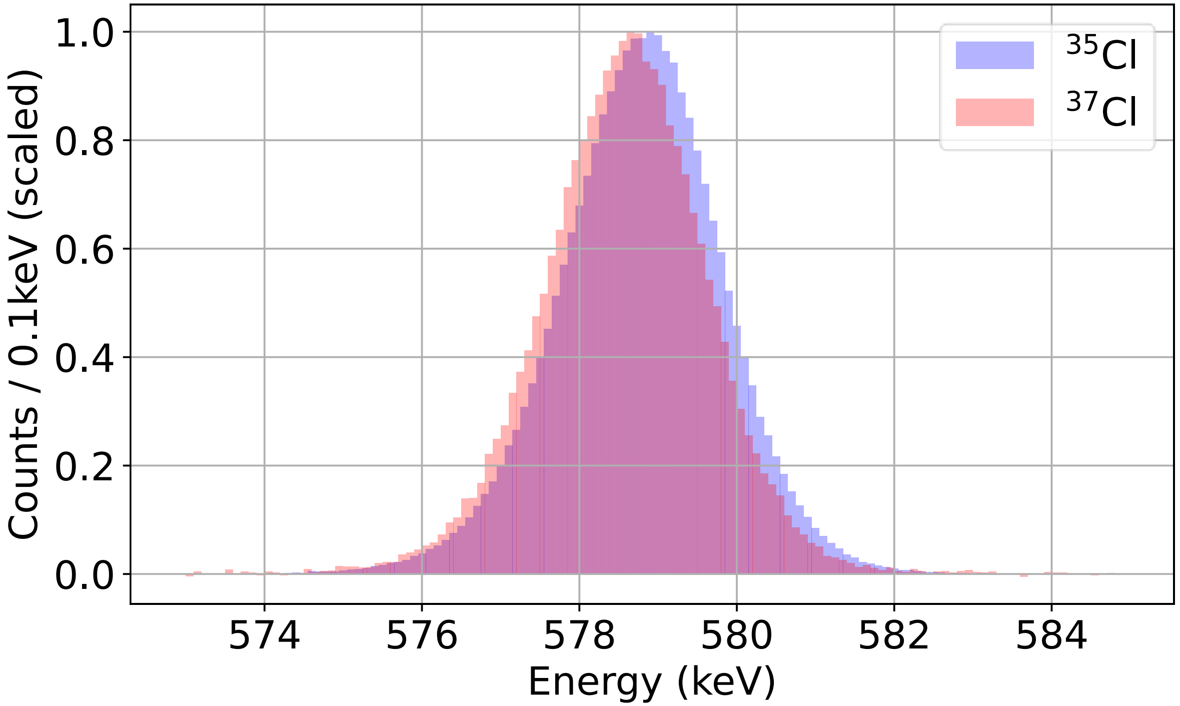
  ^{nat}Cl: 578.56(30) keV

- Expected improvement on 2p-1s transition energy:

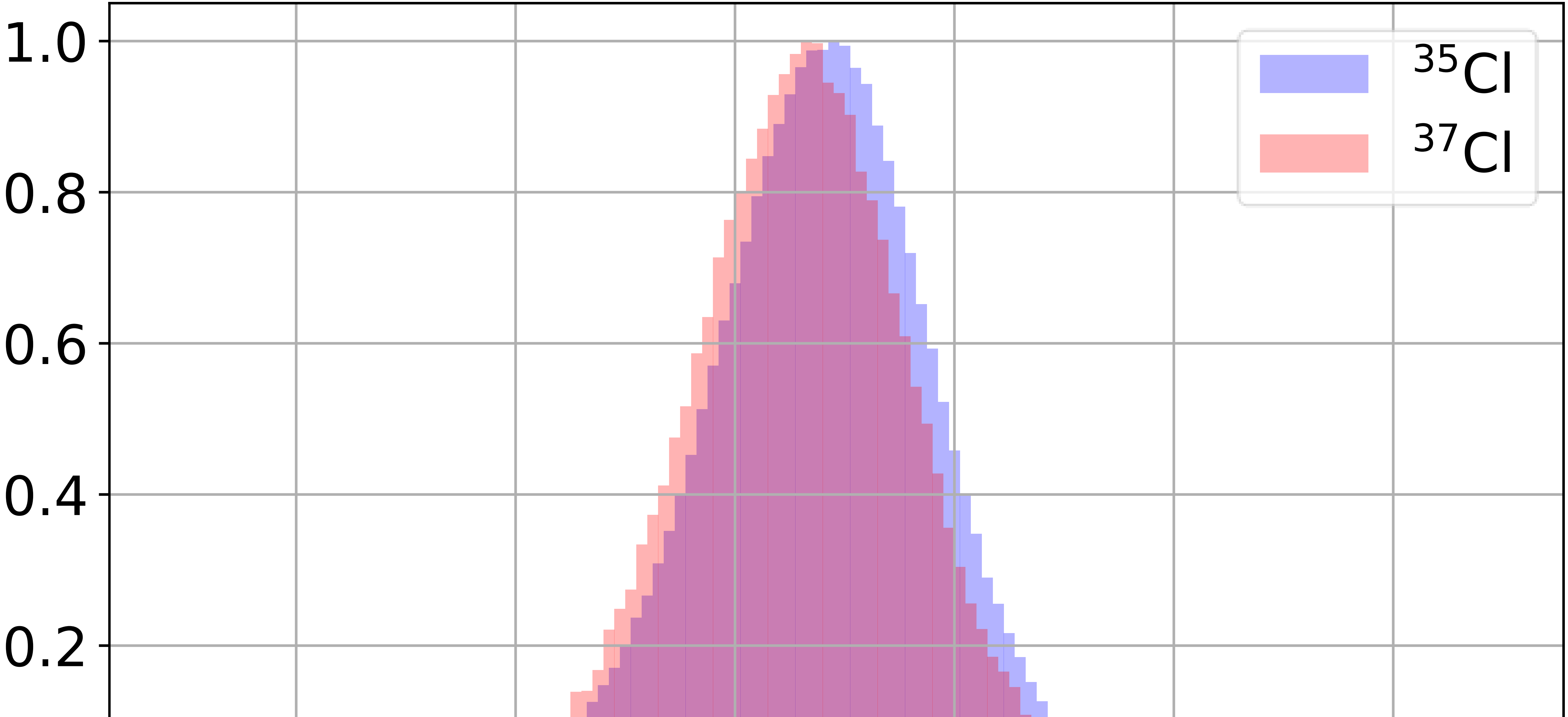
  300 eV → Most likely < 30 eV

- Expected improvement on radii:

  0.45% → ~0.10-0.15 % (including systematics)



Chlorine measurement



Conclusion and outlook

- Muonic atoms can be used as precise probes for the nucleus
  - ➢ Giving input for laser spectroscopy
  - ➢ Radii comparison across elements
  - ➢ Inputs for other experiments

- Measured transition energies of Cl and K
  - ➢ Theory calculations have been initiated
  - ➢ In-depth analysis ongoing (ideal precision < 20 eV)

- Some of our other work:
  - Low-Z: Li, Be, B, C
  - Medium-Z: Cl, K, Ag
  - High(er)-Z: Re, Cm

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Thank you for your attention!

Thanks to the muX collaboration and the QUARTET collaboration:

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Backup slides

Muonic x rays

- Captured in high-n state → Cascade down
- X rays emitted in atomic transition
  - Electronic atoms: < 100 keV
  - Muonic atoms: Up to 10 MeV
- Information about energy levels → Extract nuclear properties