Muonic atoms for particle and nuclear physics

Andreas Knecht
Paul Scherrer Institute

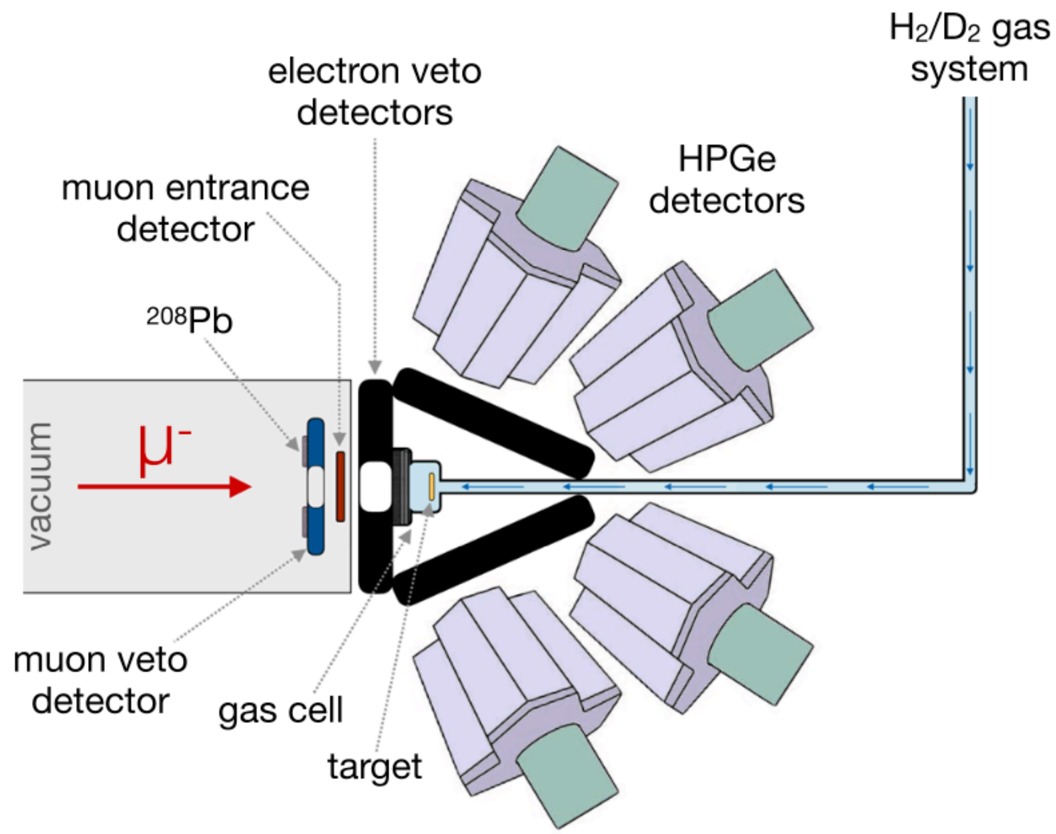
SONAR 1 Workshop
Zoom
15. 4. 2024

Overview

- The muX/ReferenceRadii experiment: Stable & radioactive isotopes
- 2s-1s experiment: APV in a muonic atom
- QUARTET: Going low-Z

muX/ReferenceRadii experiment

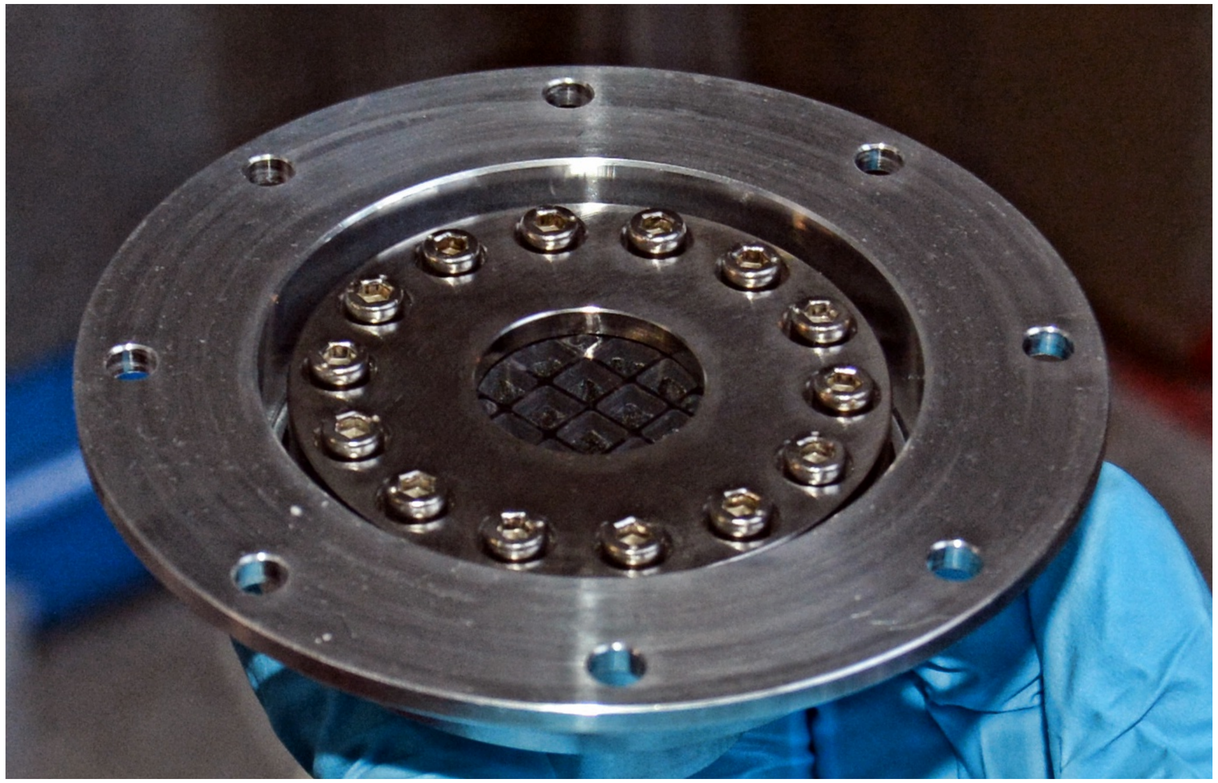
- Measurement of missing absolute charge radii for stable and radioactive targets
- Transfer reactions in high-pressure H2/D2 gas mixture to measure microgram quantities

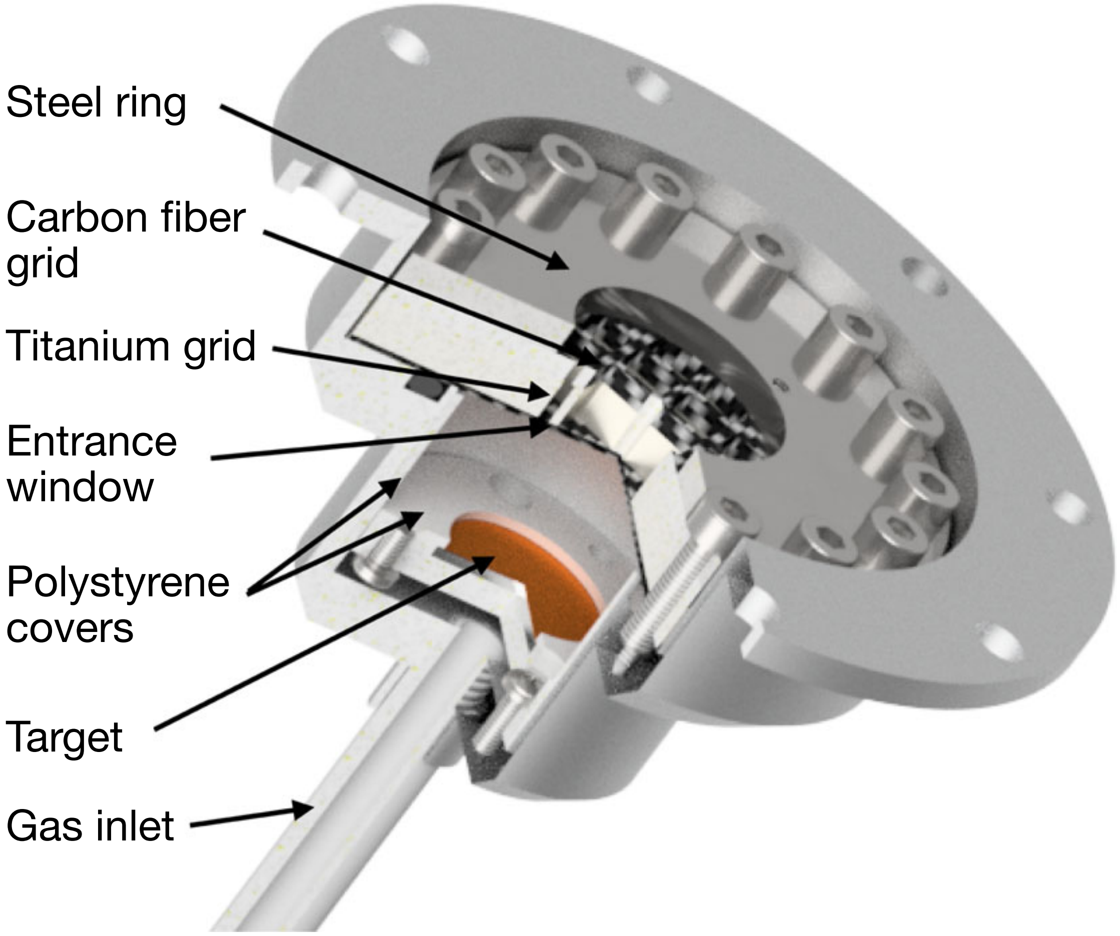


A. Adamczak et al., Eur. Phys. J. A 59, 15 (2023)

100 bar hydrogen target

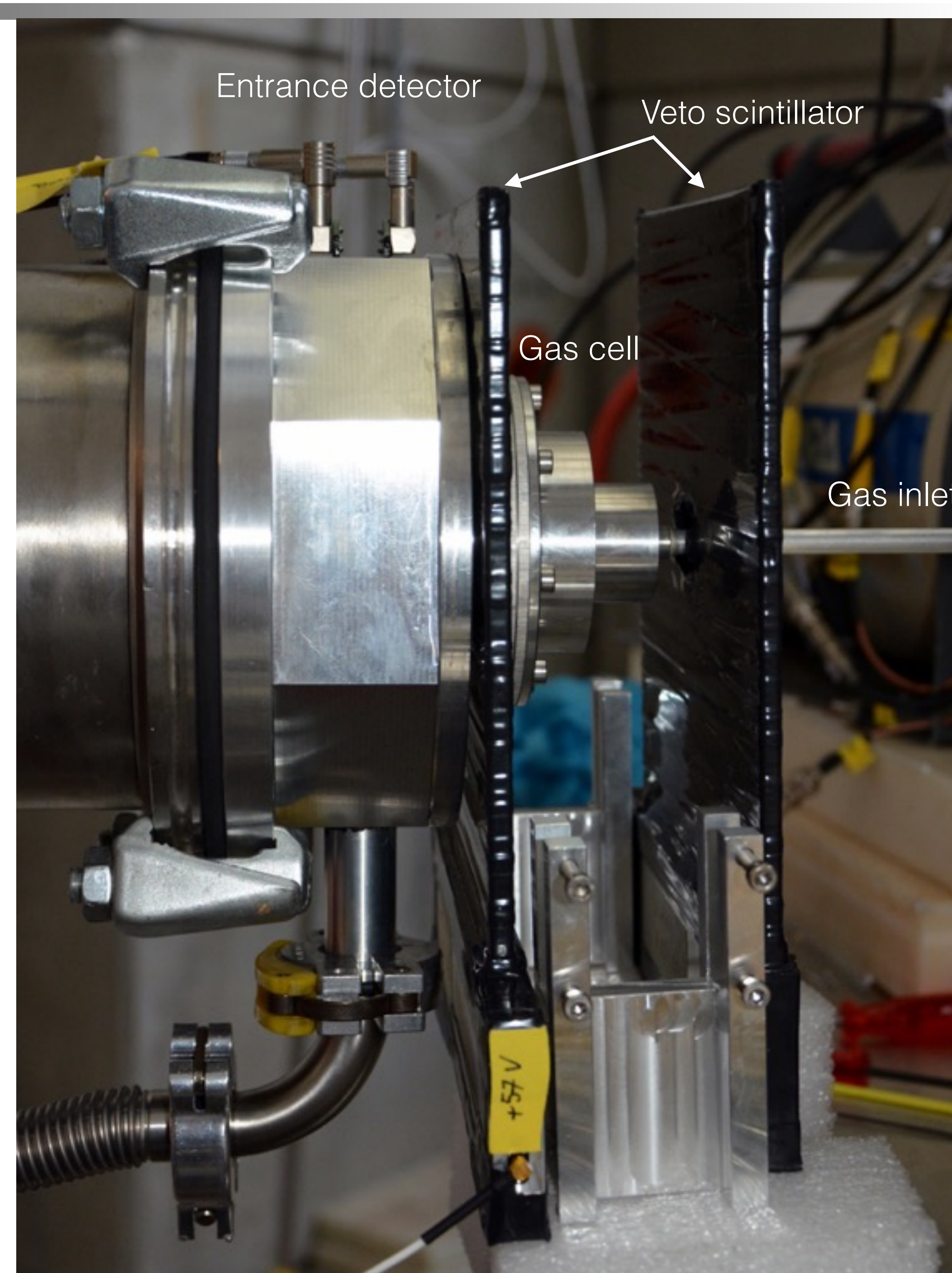
- Target sealed with 0.6 mm carbon fibre window plus carbon fibre/titanium support grid
- Target holds up to 350 bar
- 10 mm stopping distribution (FWHM) inside 15 mm gas volume
- Target disks mounted onto the back of the cell





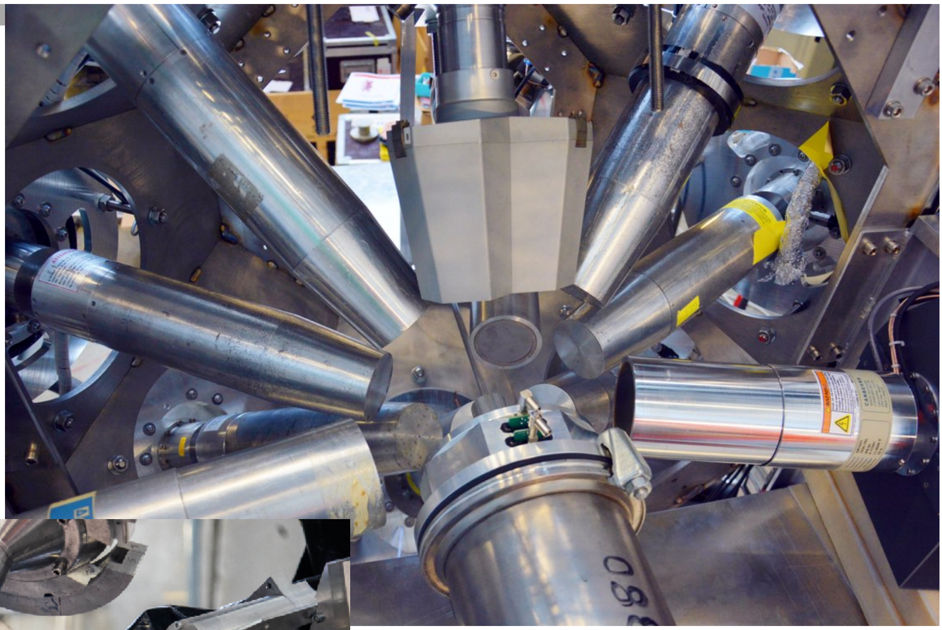
Entrance & veto detectors

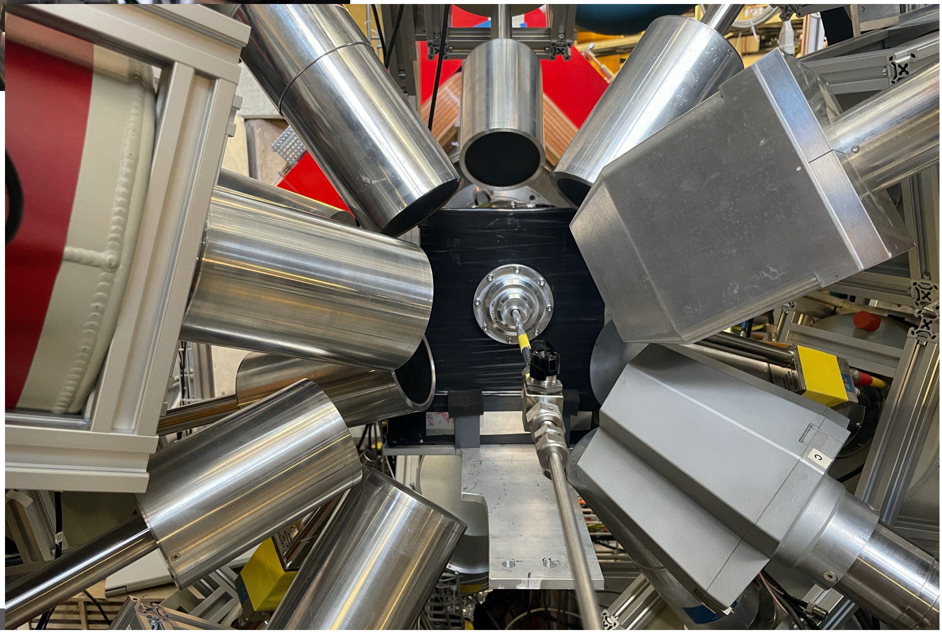
- Entrance detector to see incoming muon
- Veto scintillators to form anti-coincidence with decay electron



Germanium array

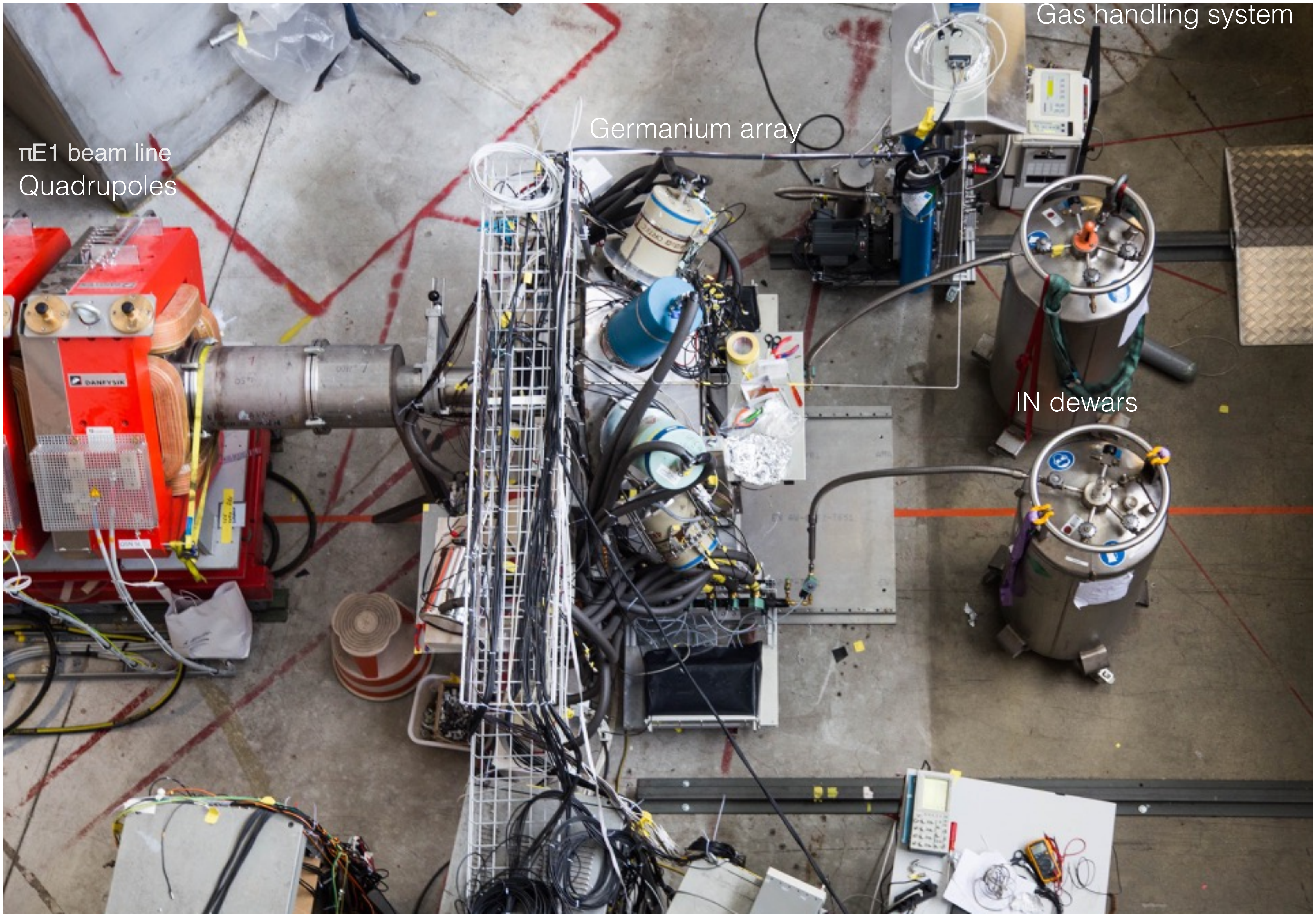
- 2017/2018
  - 11 germanium detectors in an array from French/UK loan pool, Leuven, PSI
  - First time a large array is used for muonic atom spectroscopy
- 2019
  - Miniball germanium detector array from CERN
  - 26 germanium crystals in total
- Since 2020: mixture of various detectors contributed from various collaborating institutions; common array with MIXE



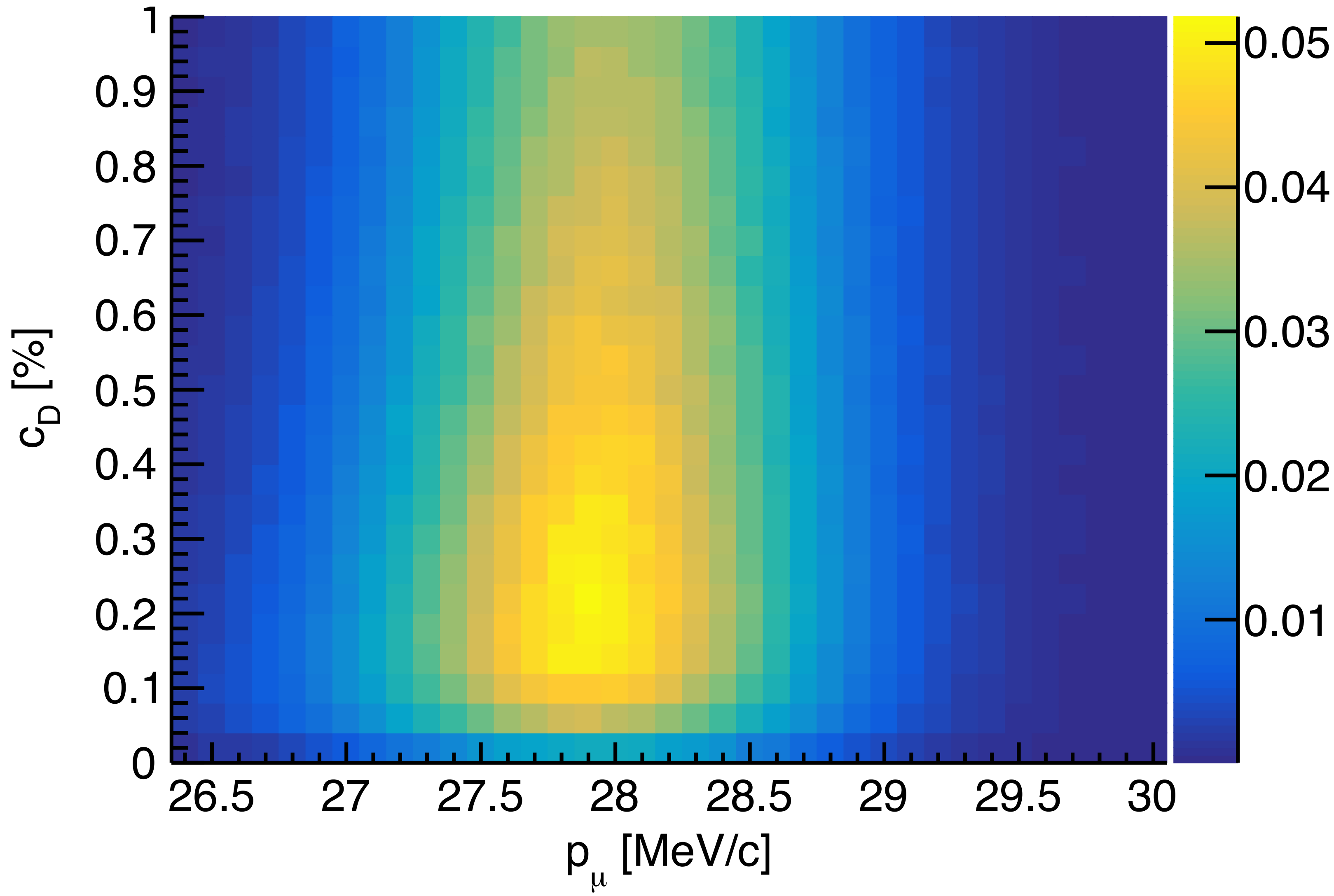


N. Warr et al., Eur. Phys. J. A 49, 40 (2013)
L. Gerchow et al., Rev. Sci. Instrum. 94, 045106 (2023)

Experimental setup



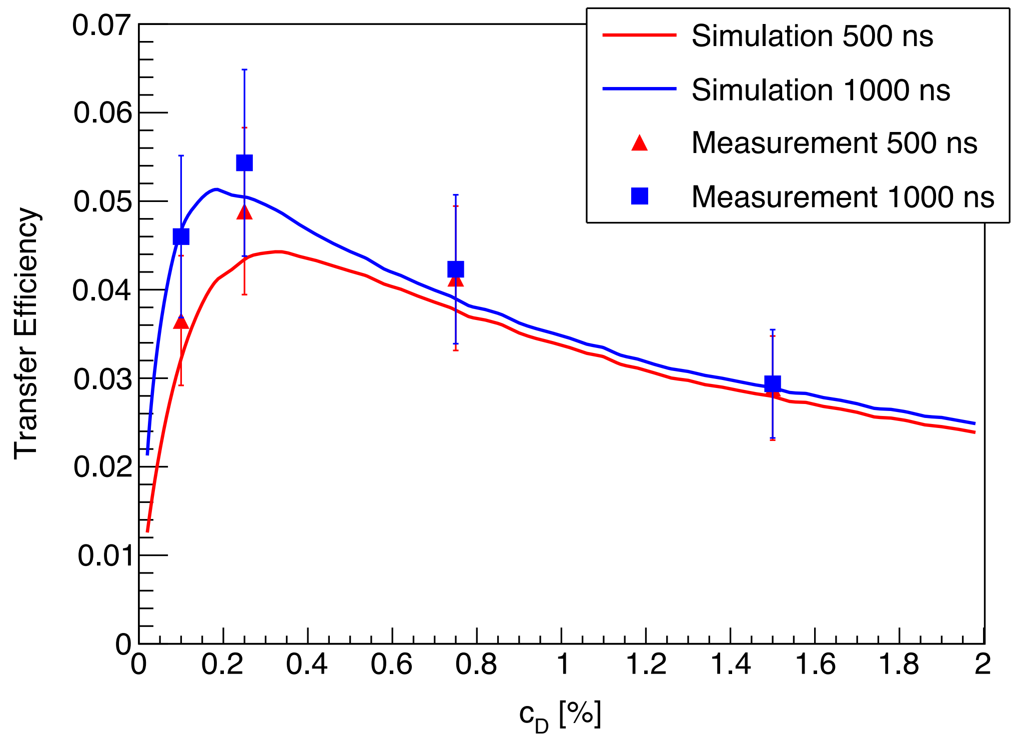
Simulation of transfer

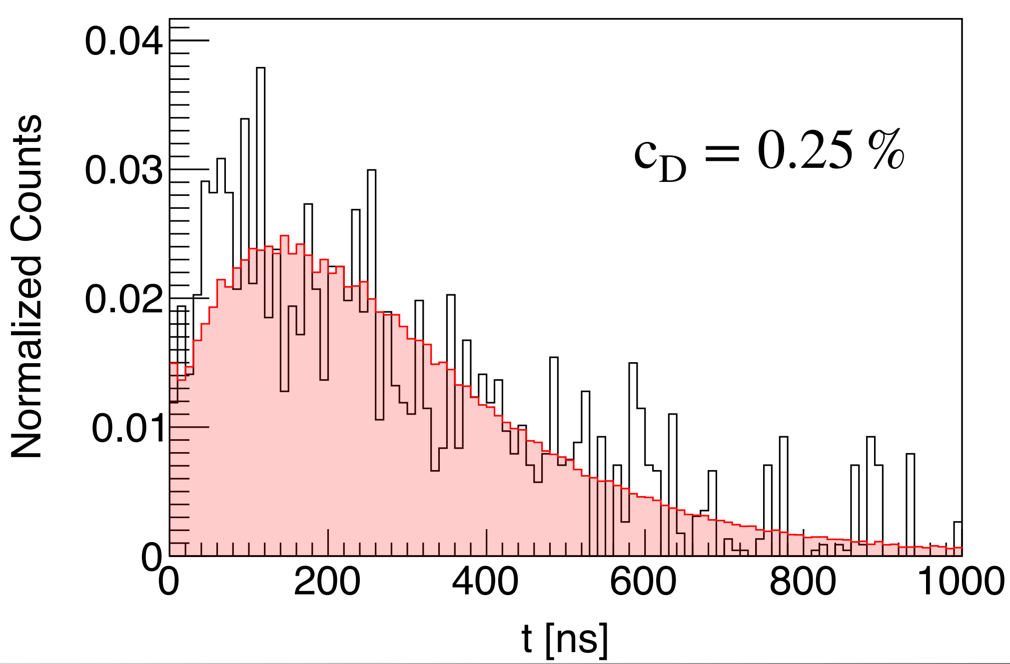


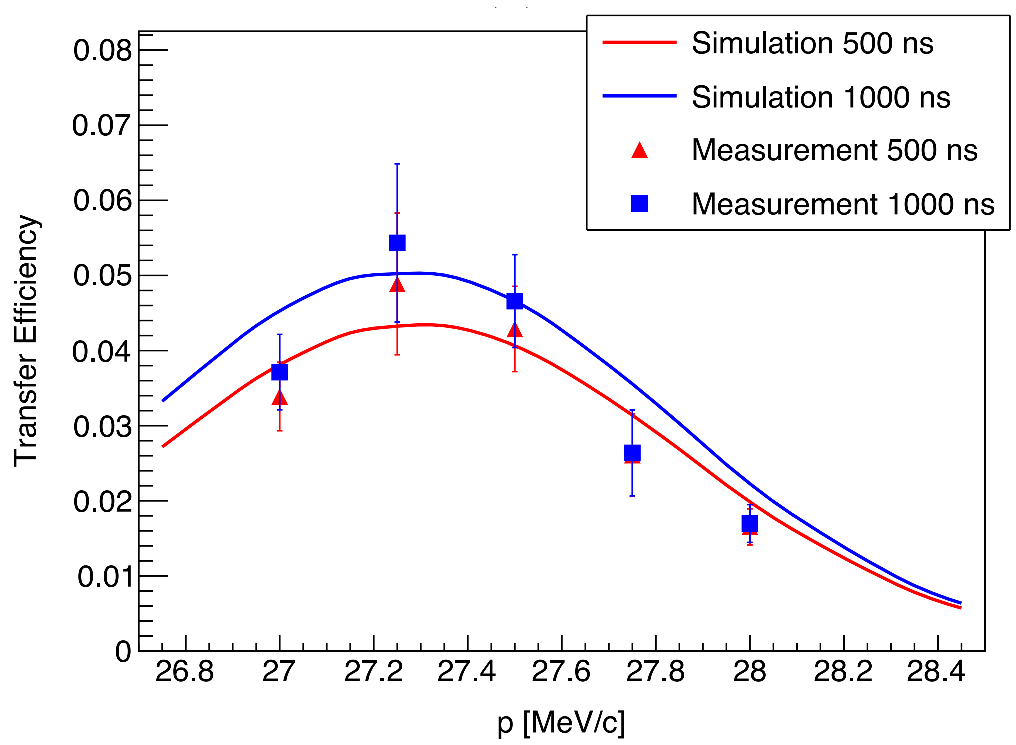
- Developed simulation to predict efficiency of transfer
- Momentum of beam determines stopping distribution with respect to the target
- Deuterium concentration determines speed of transfer but limits range due to $\mu d + D_2$ scattering

Optimisation of the transfer yield

- A 0.2 mg Au target was mounted inside the gas cell
- The amount of the 2p-1s µAu X-rays was measured by scanning the:
  - c_D: D2 admixture in H2 gas (cD)
  - p: stopping position of the muon beam
- Good agreement of all observables with simulation

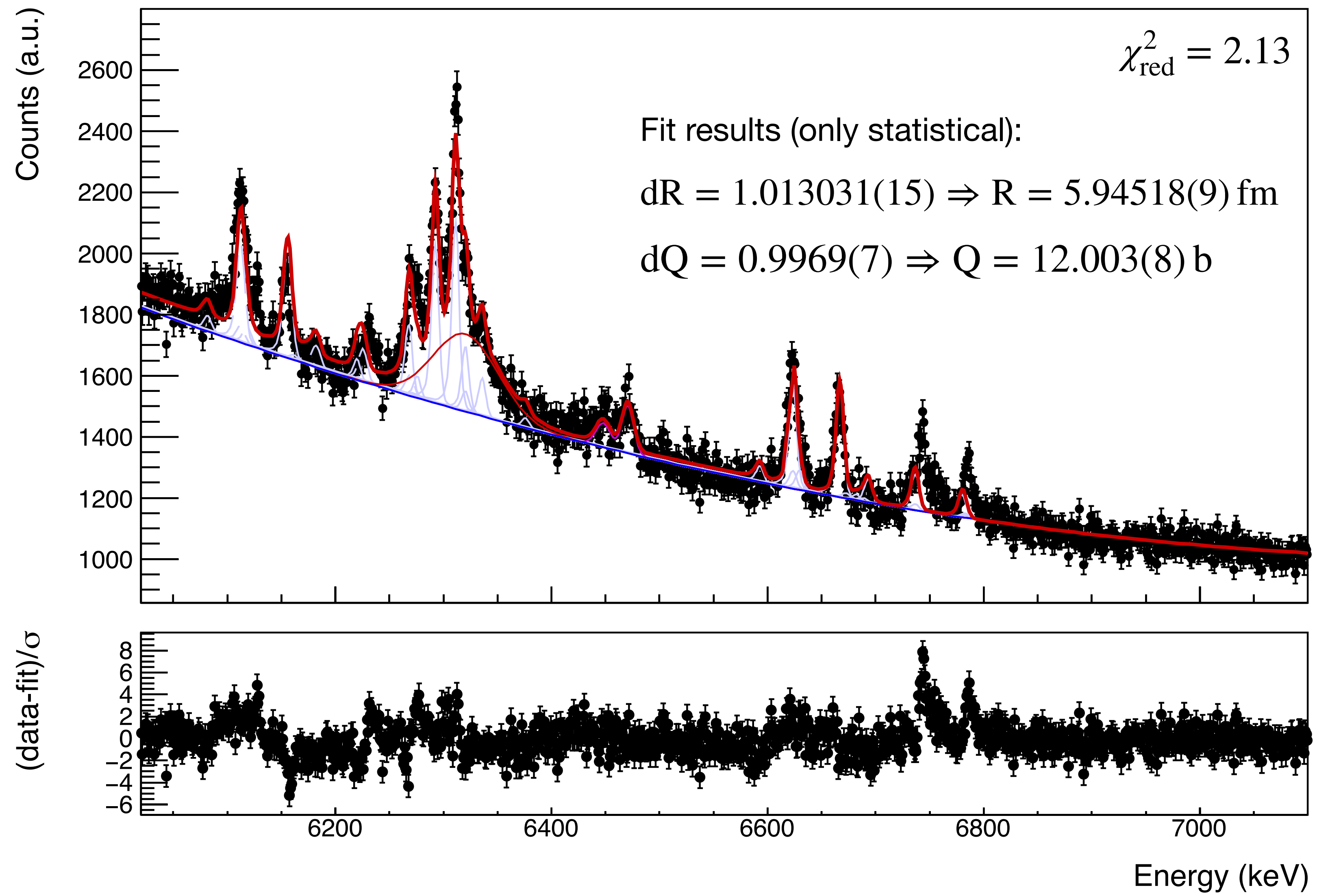






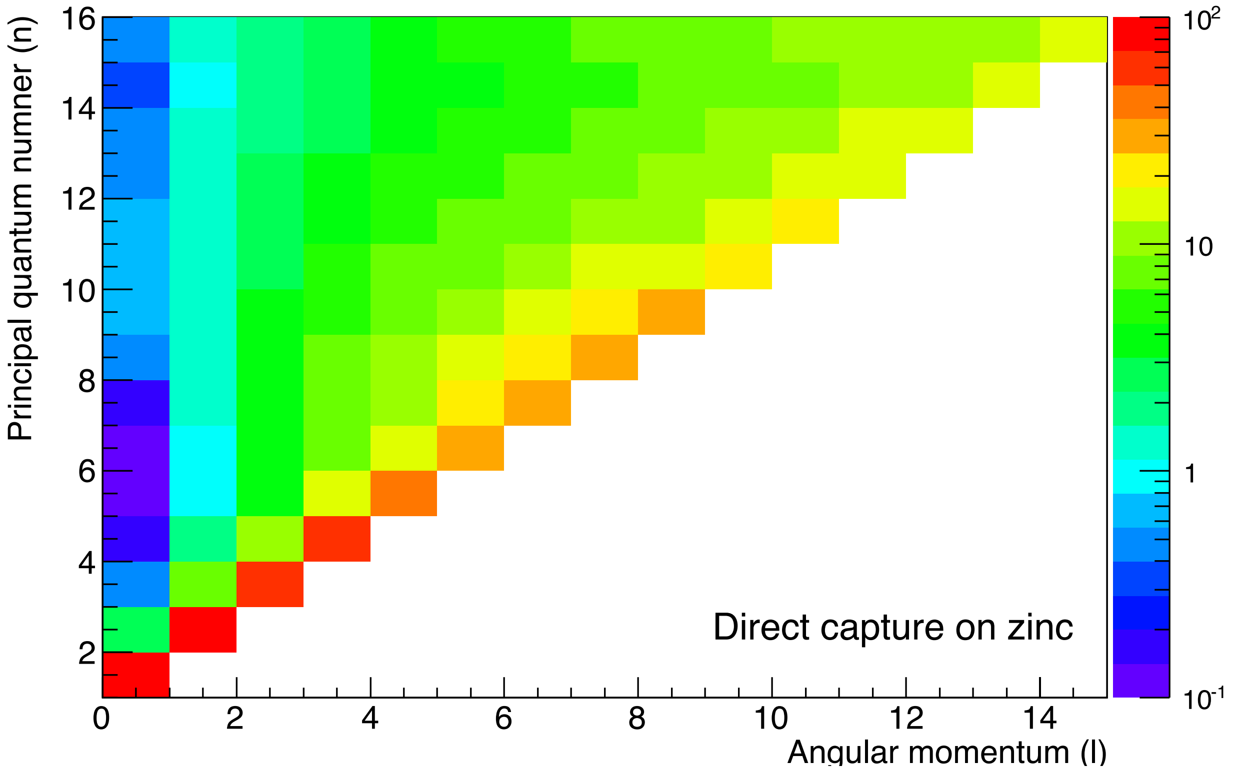
Muonic curium spectrum

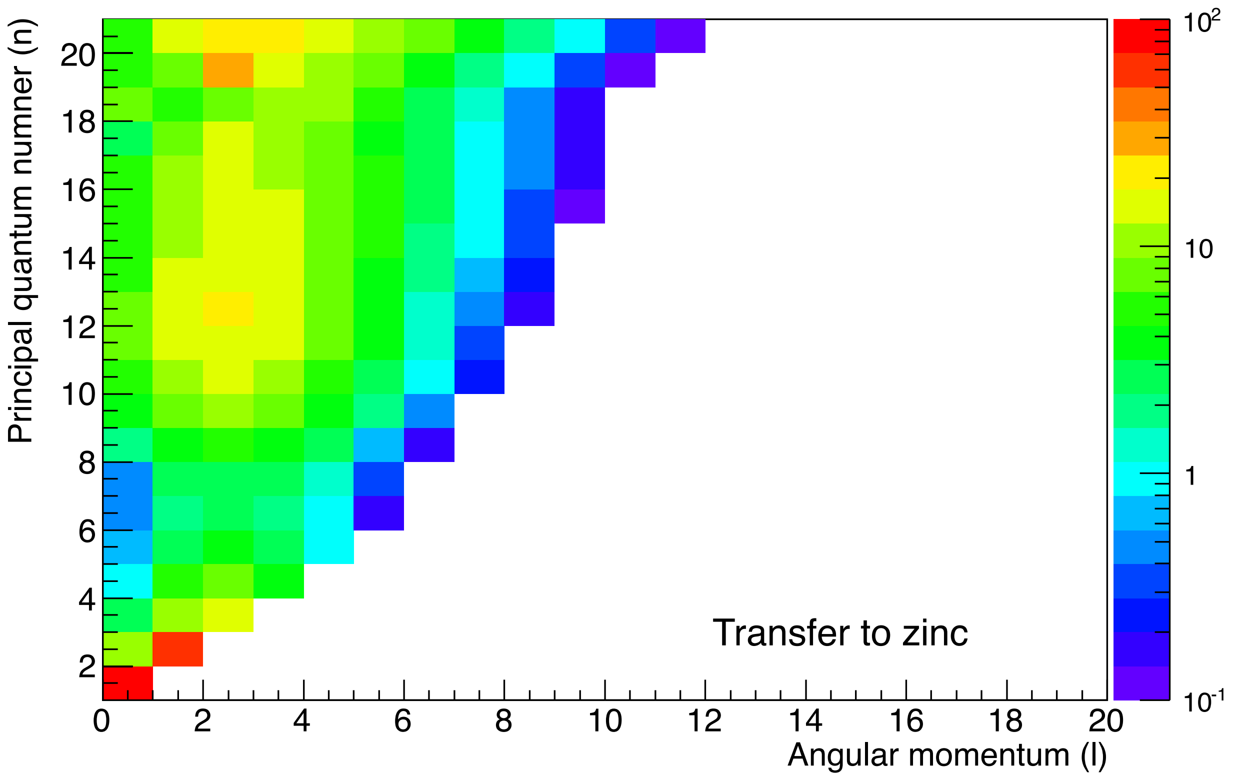
- Succeeded to measure muonic curium for the first time
- Effectively a 5 µg target



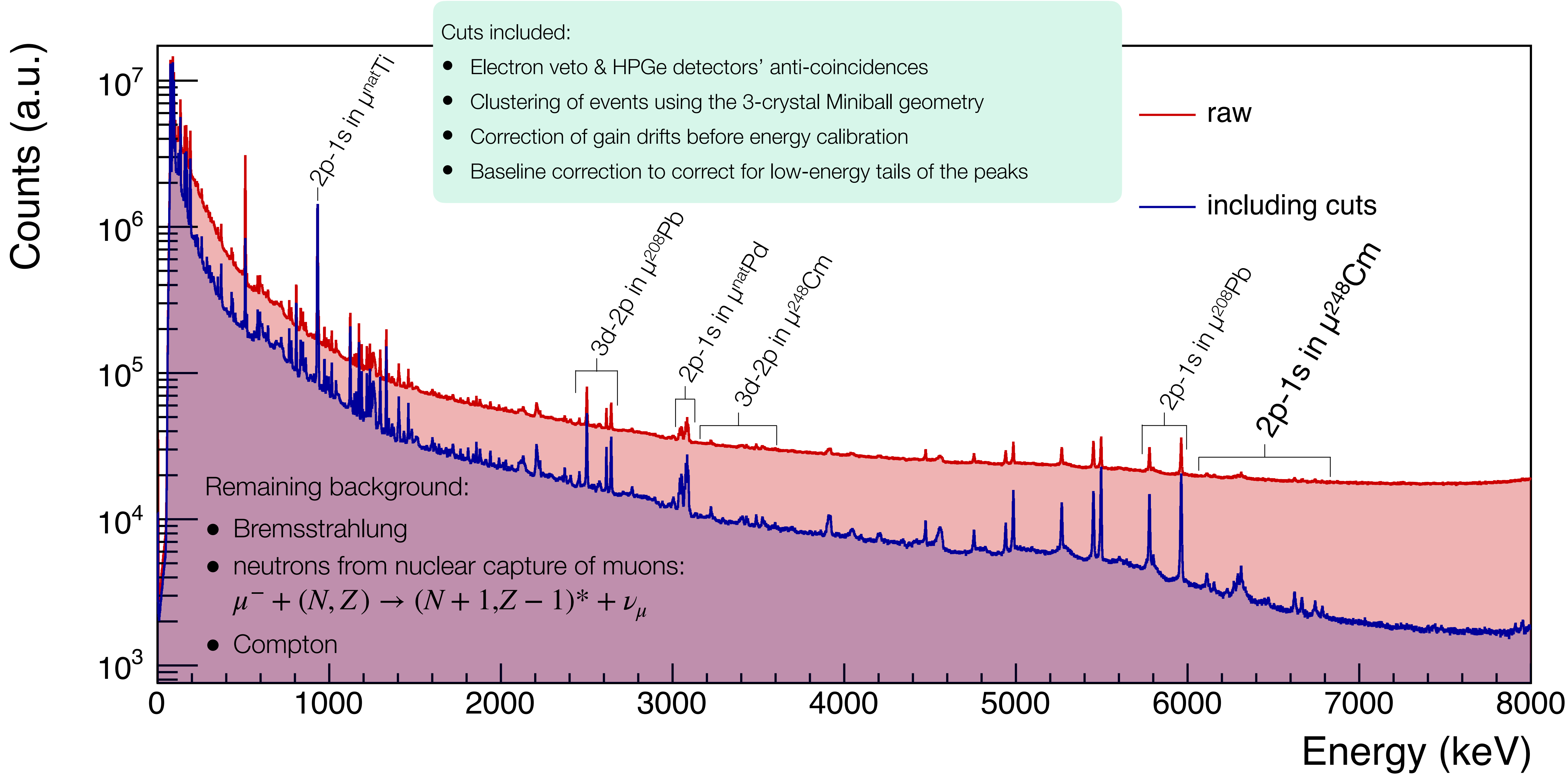
By the way: cascade after transfer

- Muonic cascade after transfer favors higher np-1s transitions
  - $n_{initial}(Z)$
  - $P_{l,initial}(Z)$
- Experimentally confirmed for many low- and medium-Z atoms
- Have data and cascade simulations on argon, krypton, xenon that we'll publish soon





How to get to good S/B ratio at high energies?



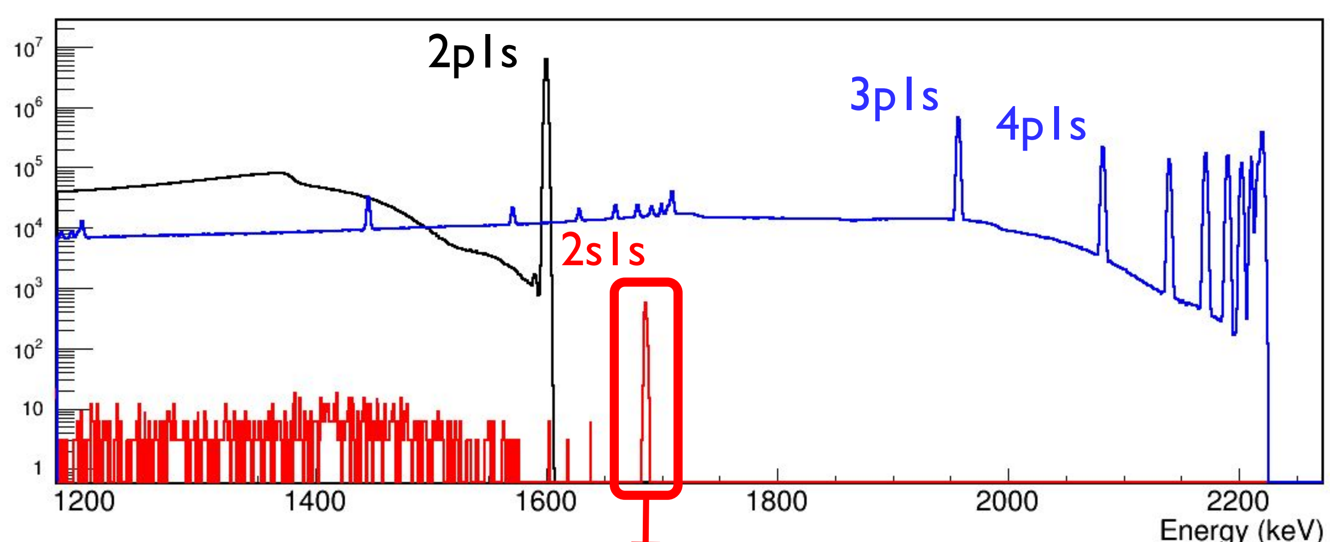
- What we would like to simulate:
  - Exact nature of remaining background to guide future developments
  - What is the dominant component? How do the proportions change as we, e.g., change cell designs?

2s-1s experiment

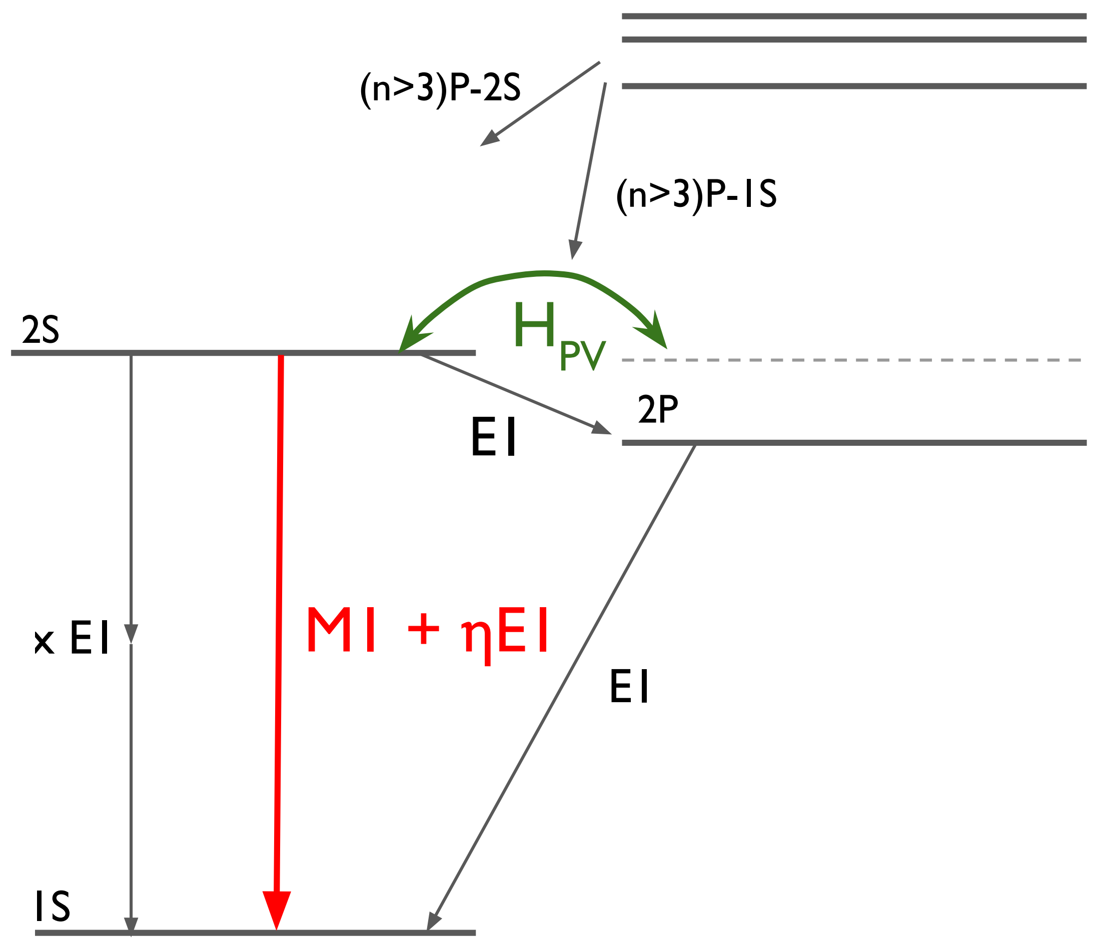
Motivation

Measure 2S1S for Z≈30 nuclei → Can we measure APV with muons directly?

- Motivation:
  - Can we get $\sin^2(\theta_w)$?
  - Is the muon special
  - Neutral currents at low Q^2 have not yet been measured
- **Goal of muX:**
  - **Observe 2S1S single photon transition**
  - **Achieve good S/B for a 10^{-4} B.R. transition**



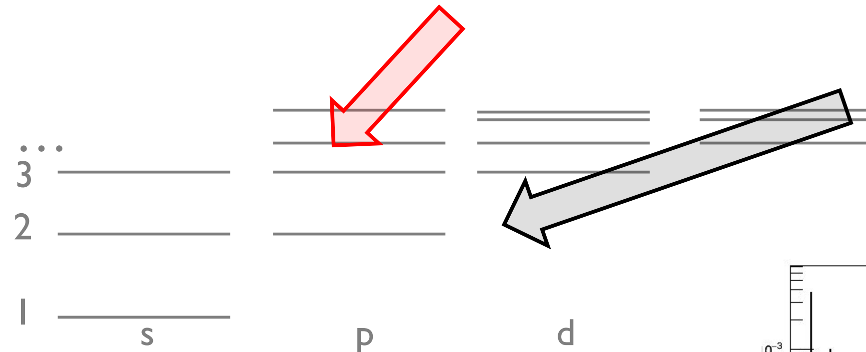
(crude) MC estimate of signal to background in μZn: 0.05

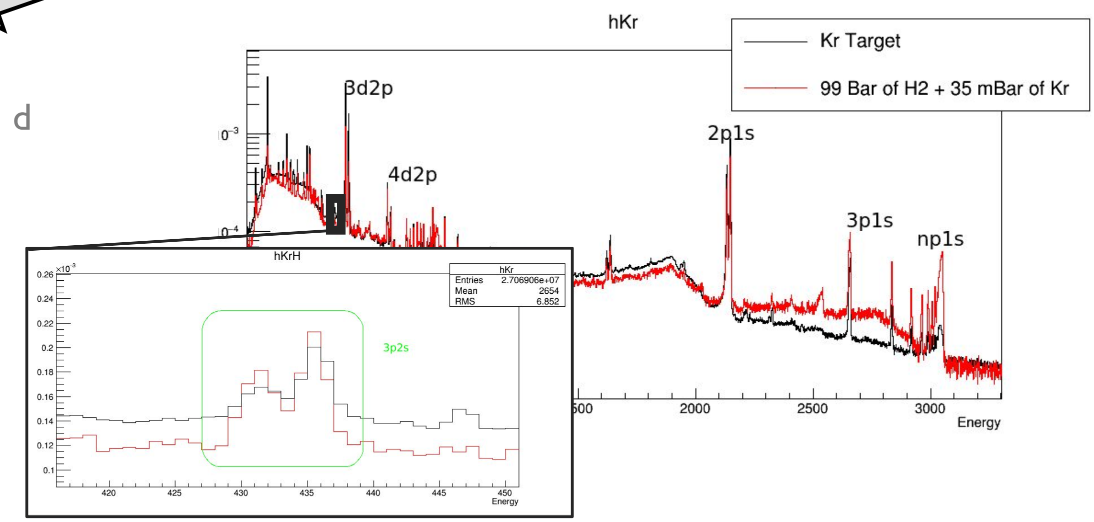


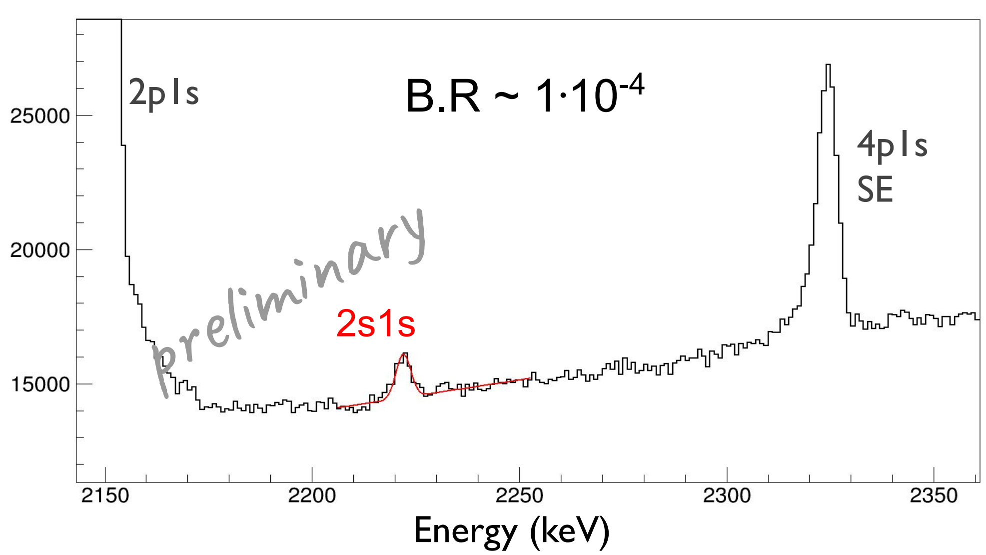
2s-1s experiment

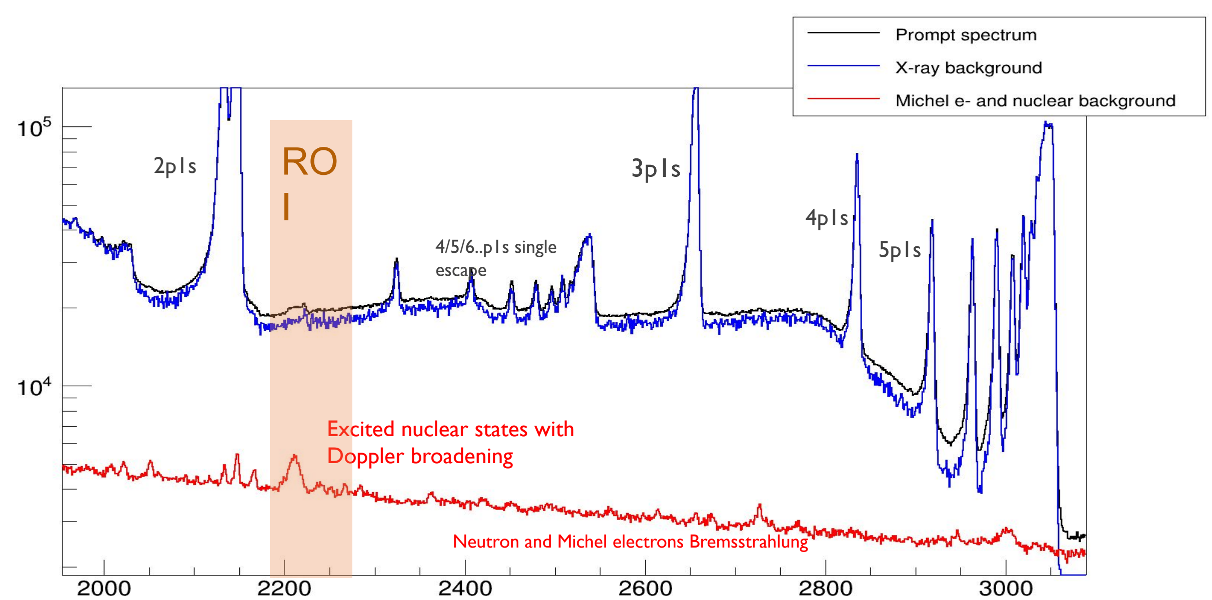
Kr measurements

- Increase 2S population
  - $\mu^- \rightarrow \mu H \rightarrow \mu Kr$
  - Suppress circular transition in cascade
- 2017 & 2018 measurements with 100Bar H2 + 35 mBar Kr target
- First observation of 2s1s
  - B.R> 10^{-4}, S/B ~0.06
  - Background description 100% data driven





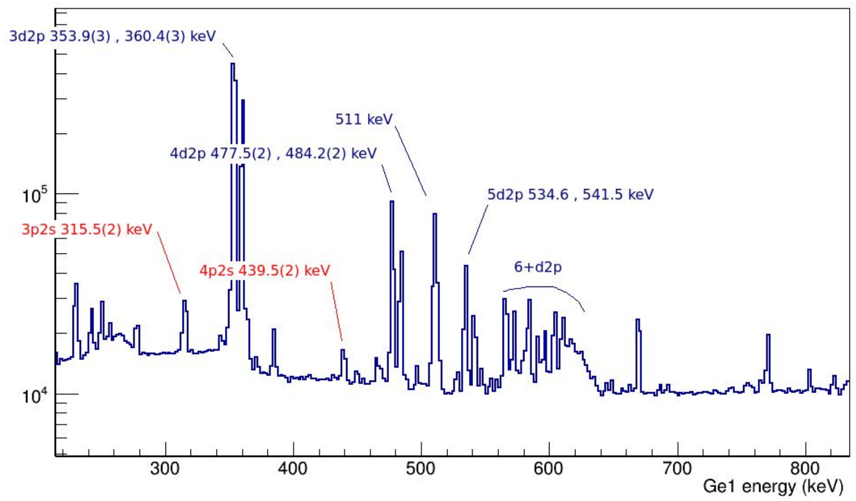


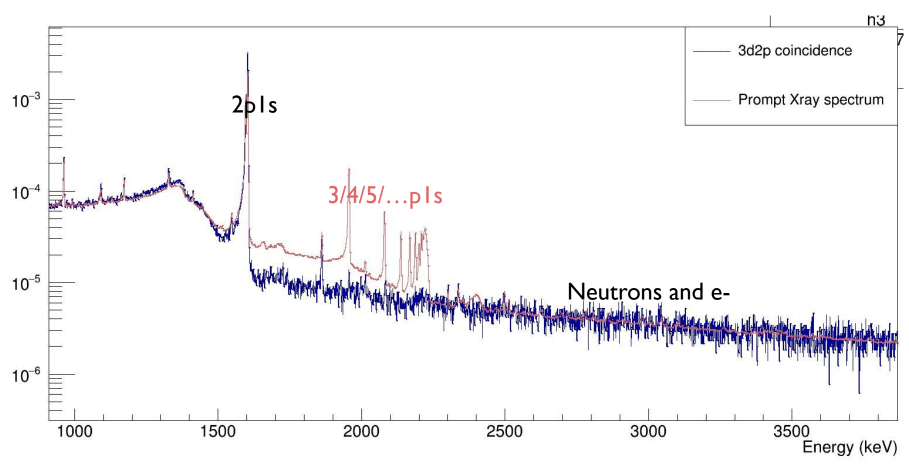


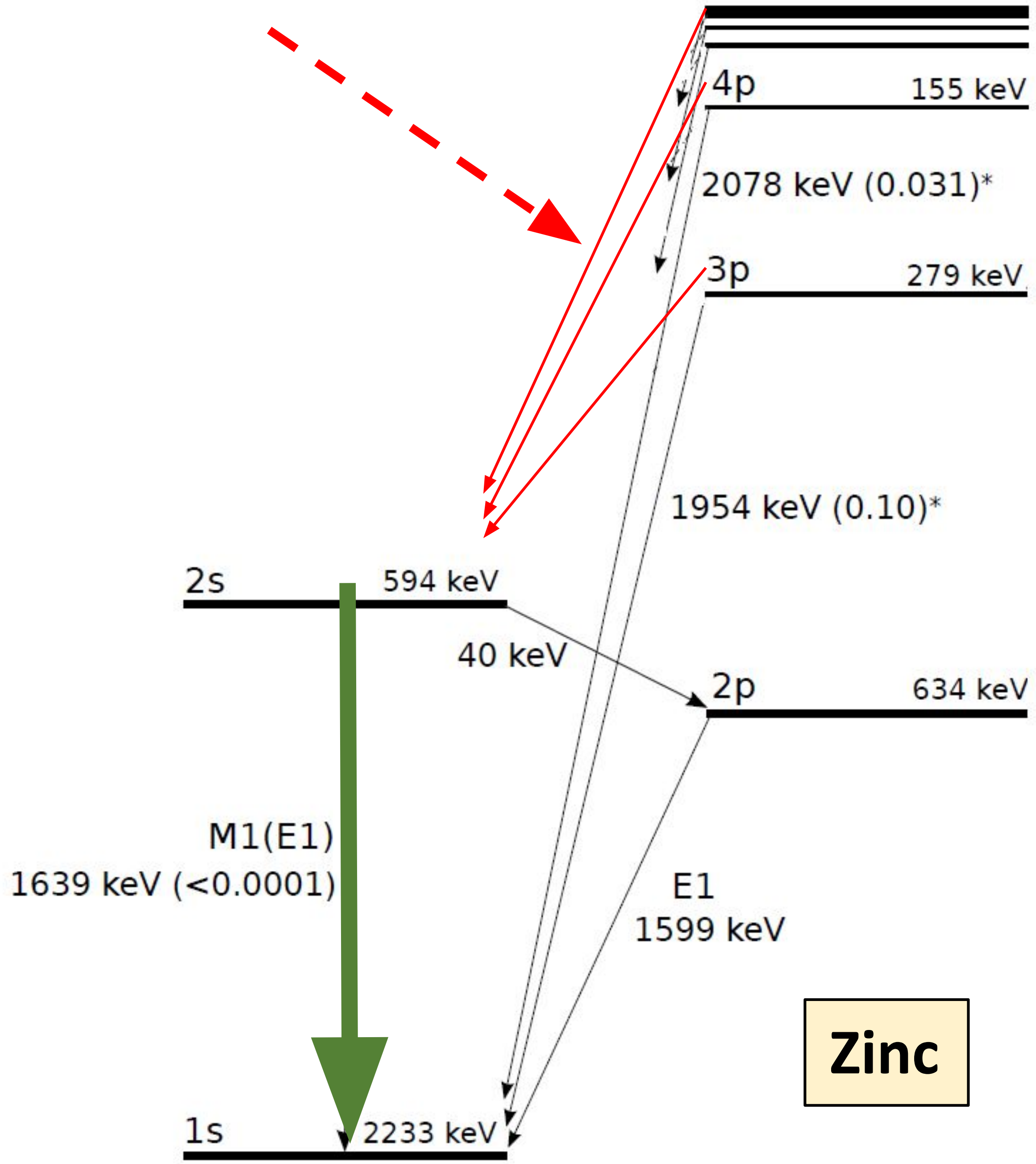
2s-1s experiment

Zn measurements

- Suppress 3/4/5/…p→1s Compton background with a 3p→2s tag
- 5 days campaign in 2017 & 2019
- Loss of efficiency, but effective continuous background suppression



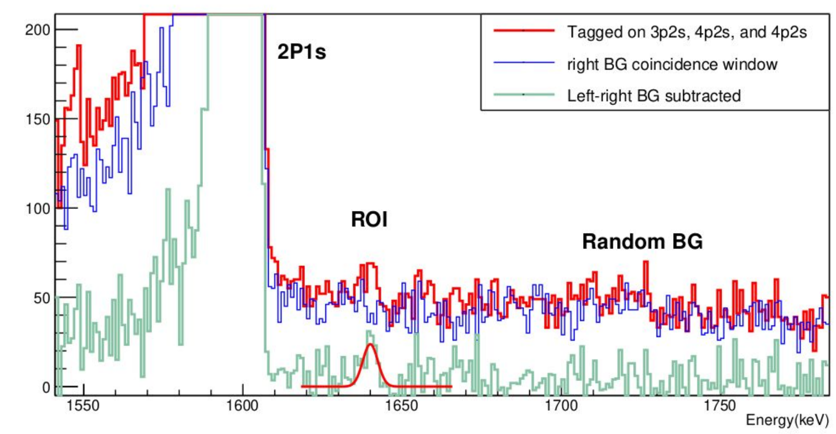




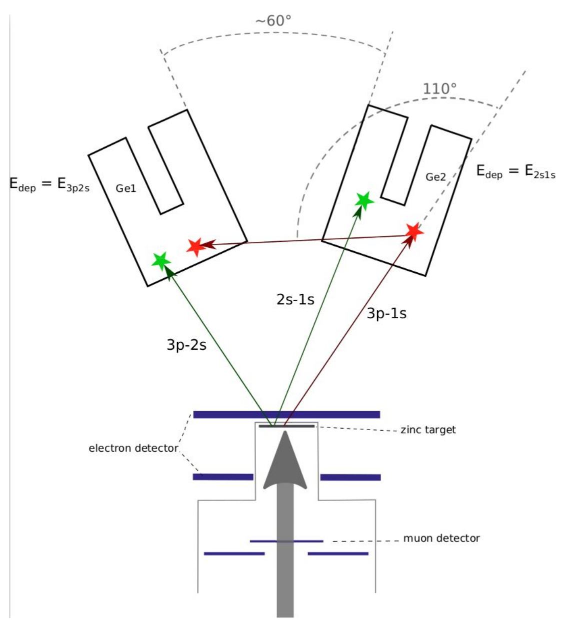
2s-1s experiment

Zn measurements

- Suppress 3/4/5/…p→1s Compton background with a 3p→2s tag
- 5 days campaign in 2017 & 2019
- Loss of efficiency, but effective continuous background suppression
- Coincidence measurements in the muonic cascade create satellite peaks
- Optimize geometry and cuts with the help of MC
- Works, but hard to interpret quantitatively

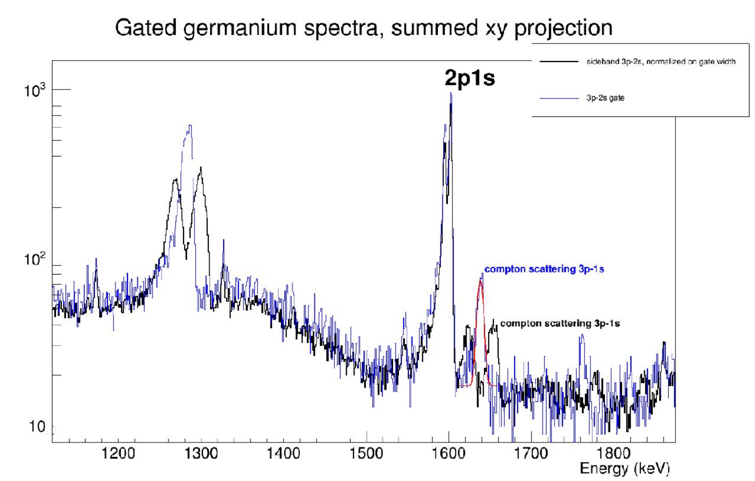


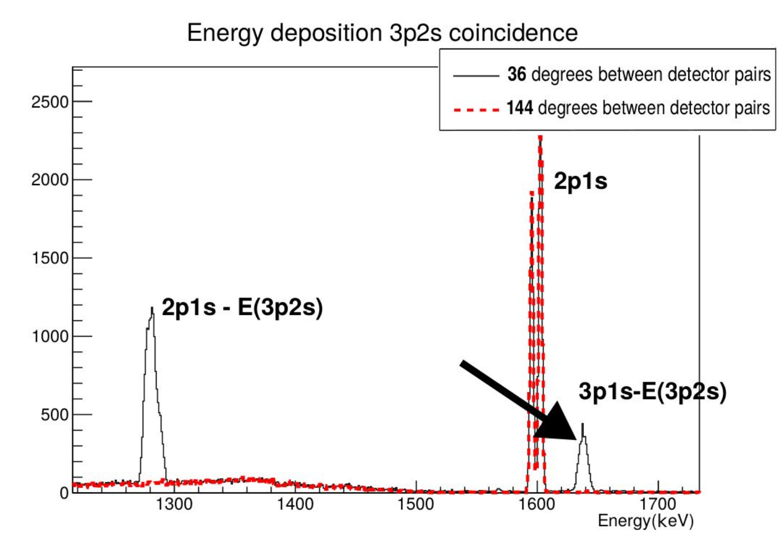
Optimized miniBall detector array



Satellite peaks in coincidence spectrum are reproduced with a (less crude) G4 MC:

- ❏ MUON and RURP code from G.A. Rinker to calculate energies *Fortran*
- ❏ V.R. Akylas and P. Vogel cascade code to get intensities *Fortran*
- ❏ Homebrew MC cascade generator based on these inputs *C++/Geant4*





2s-1s experiment: simulation wishlist

Lessons learned / requirements

Input for Cascade Monte Carlo:

- ❑ Muonic level energies including NFS effects
- ❑ Transition intensities including:
  - ❑ Finestructure
  - ❑ Low branching ratio transitions
  - ❑ Auger transition intensities
    (or the generated cascade is completely wrong)

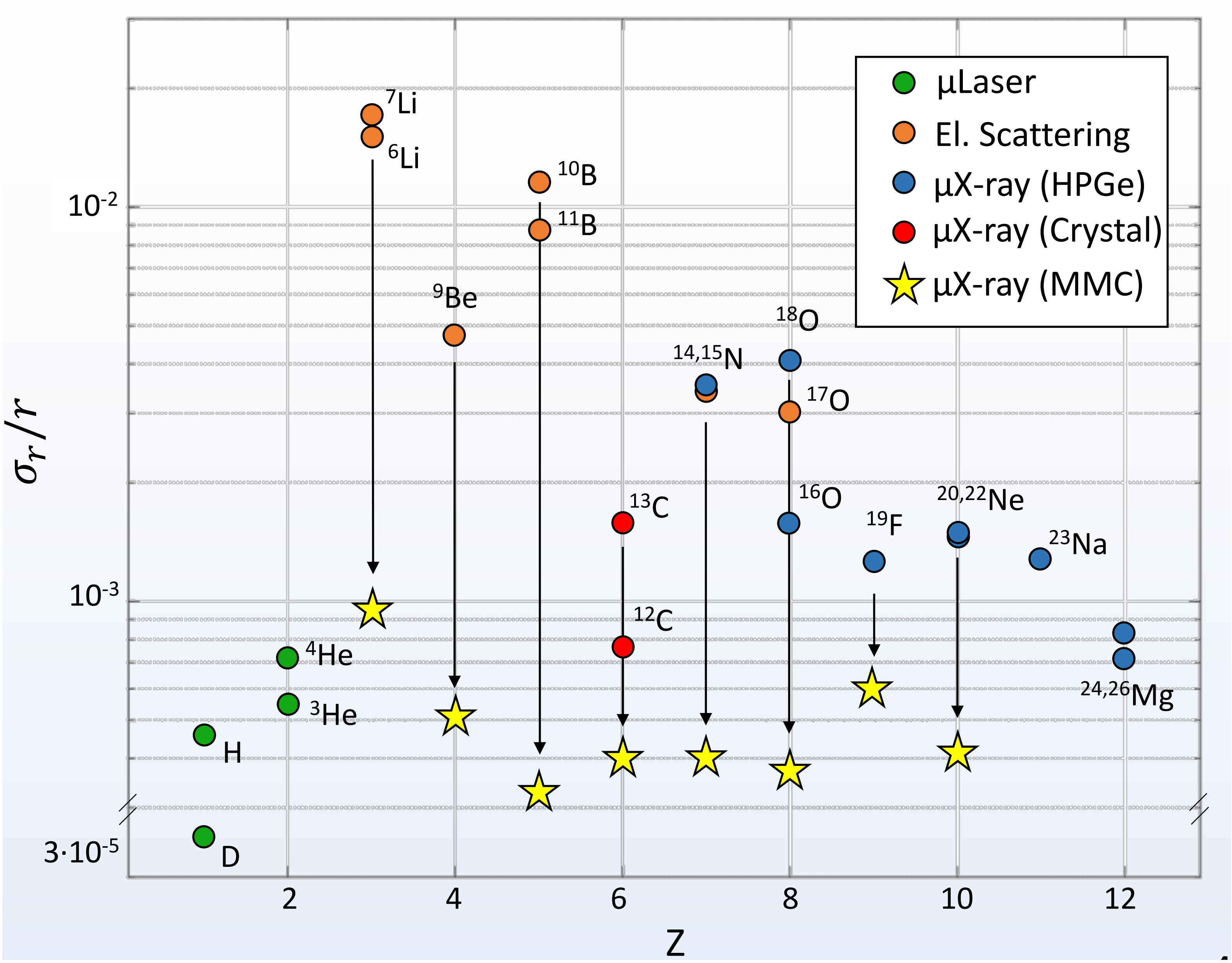
What about angular correlations in cascade?

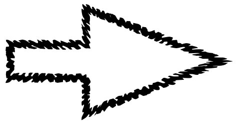
It would be nice:

- ❑ Have a decent cascade generator interface with Geant4
- ❑ Even better: Start from negative muons on target
- ❑ Common code infrastructure so we don't reinvent the wheel for every study

QUARTET experiment

- Significantly improve nuclear charge radii of light stable isotopes by measuring $nP - 1S$ x-rays in muonic atoms
- Commission a dedicated x-ray detector array based on Metallic Magnetic Microcalorimeter (MMC) at the PiE1 beamline.

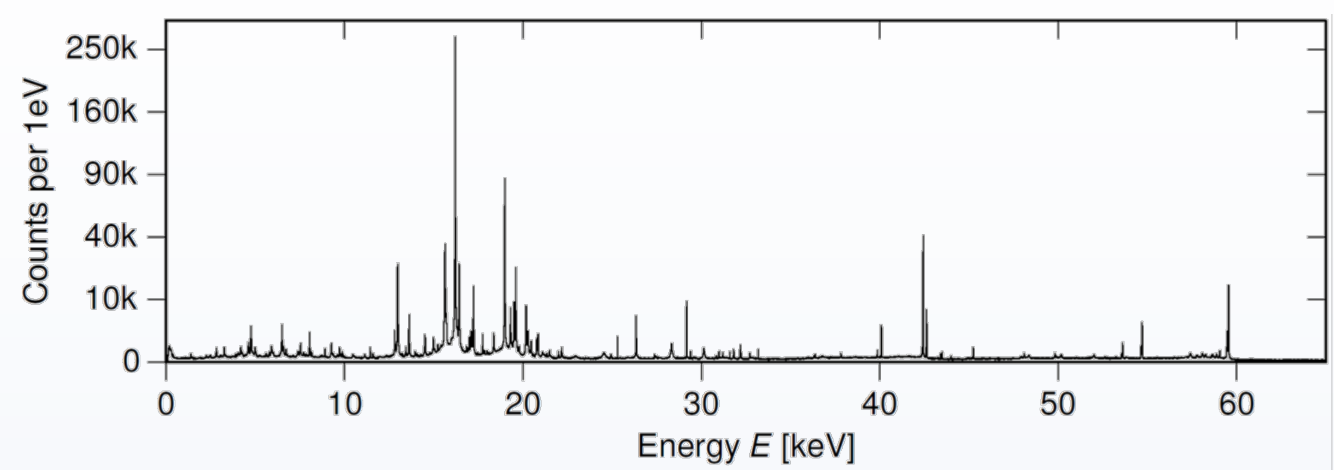


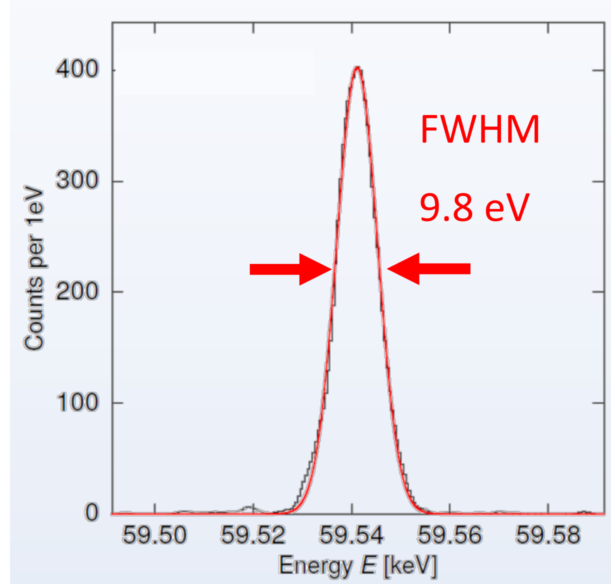


Benchmarks for ab-initio nuclear theory
Input for QED precision tests

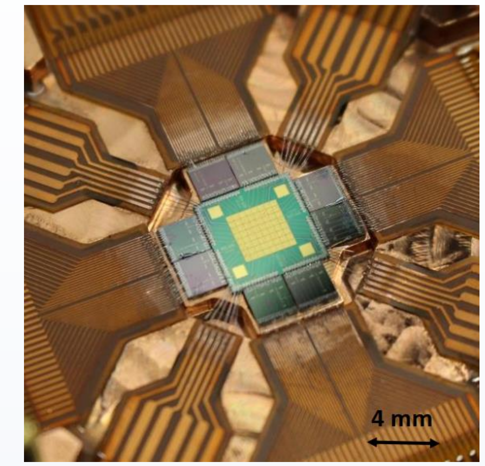
MMC: maXs-30

High efficiency (>90%) for photons 10-60 keV





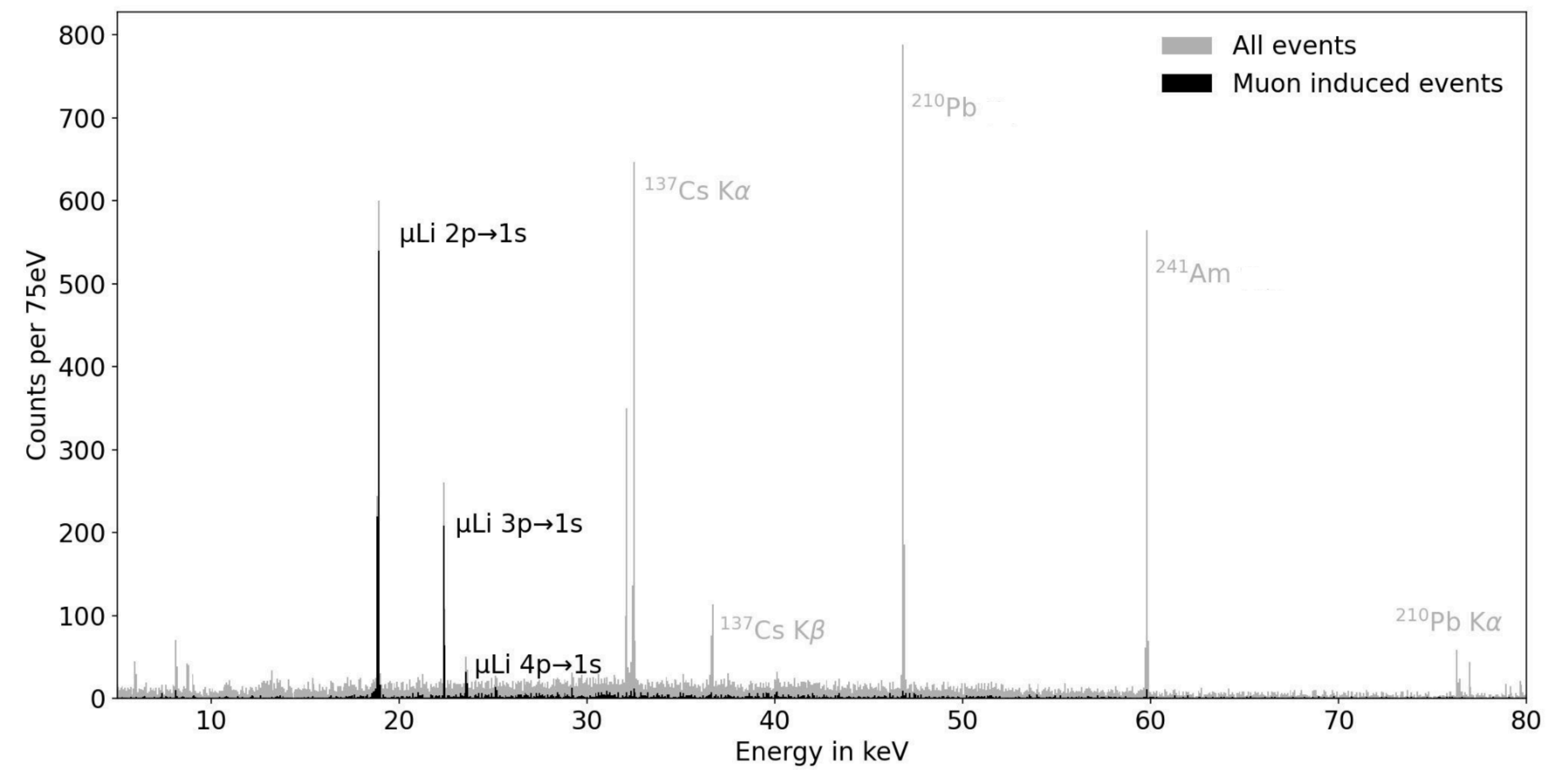
8×8 pixel array, area $16mm^2$

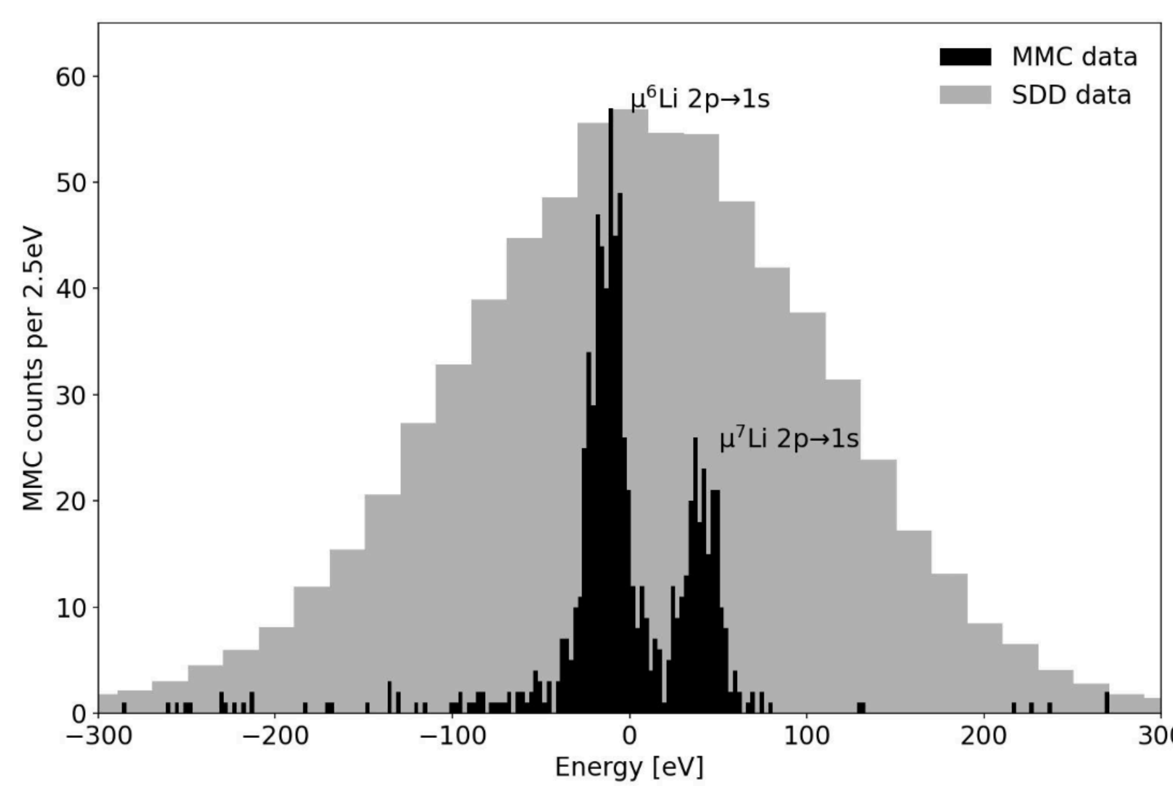


- First tests of an MMC operating at piE1 beamline of PSI last fall

First results

- Very successful test run and promising first results
- Sensitivity to low-Z isotopes
- Calibration crucial to achieve final precision of around 0.1 eV





QUARTET experiment: simulation wishlist

- Simulate backgrounds coming from
  - Decay electrons
  - High-lying muonic x-ray transitions of background elements lying in the ROI (needs good cascade model!)

Conclusions

- Apart from **accurate energy calculations** of muonic x-ray transitions (see Ben's talk), experiments in nuclear and particle physics need good simulations to understand backgrounds and guide detector design and setup
- **Good cascade model** including all effects (Auger, angular correlations, …)
- **Reasonable muon capture model** to understand delayed signals and backgrounds