International Conference on High Energy Physics (ICHEP) 2024
Prague (Czech Republic), 17-24 July 2024

Investigating the proton structure with the FAMU experiment at RIKEN-RAL

Riccardo Rossini
(University of Pavia & INFN Pavia)
for the FAMU Collaboration

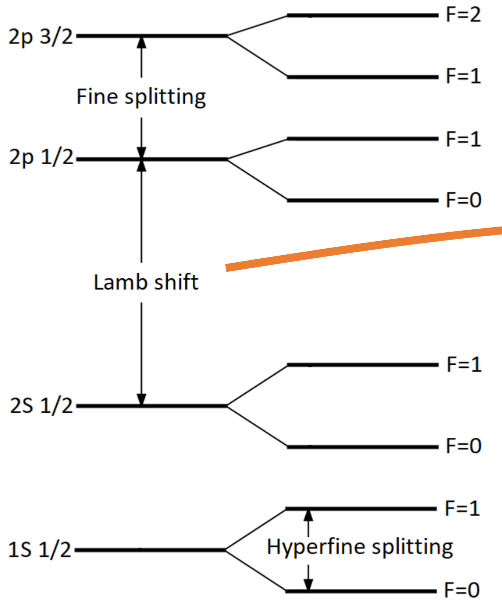
The proton charge radius

Electric form factor of the nucleus, in the ep scattering cross section:

$$\frac{d\sigma}{d\Omega} = \frac{E'}{E}\left\{\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2\left(\frac{\theta}{2}\right)\right\}$$

scattering technique.

Defined as: $$r_E^2 := -6\left.\frac{dG_E}{dQ^2}\right|_{Q^2\to 0}$$



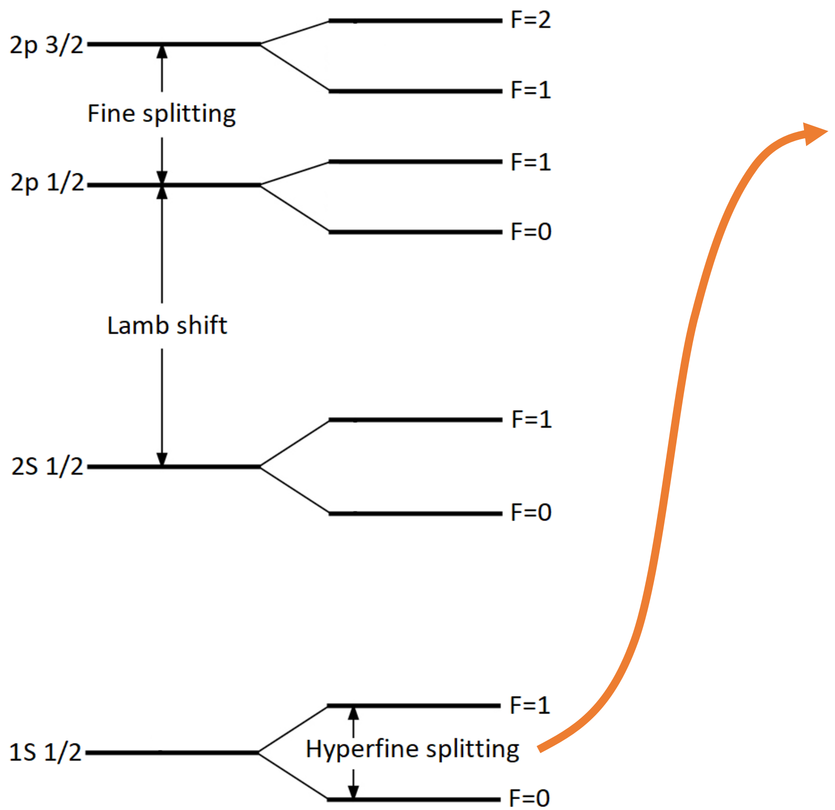
Lamb shift in H has LO dependency on the charge radius:

$$\Delta E_L = \frac{(Z\alpha)^4 m_r^3}{12} r_E^2$$

spectroscopic technique.

The proton Zemach radius

Defined as: $r_Z := -\frac{4}{\pi}\int_0^{+\infty}\frac{dQ}{Q^2}\left[\frac{G_E(Q^2)G_M(Q^2)}{1+\kappa_N}-1\right] = \int r d^3r \int d^3r' \rho_E(\vec{r}-\vec{r'})\rho_M(\vec{r})$



LO dependency on the hyperfine splitting:

$$\Delta E_{hfs} = -\frac{2Z\alpha m_r}{n^3}\frac{8(Z\alpha)^4 m_r^3(1+\kappa_N)}{3mM}r_Z$$

spectroscopy technique.

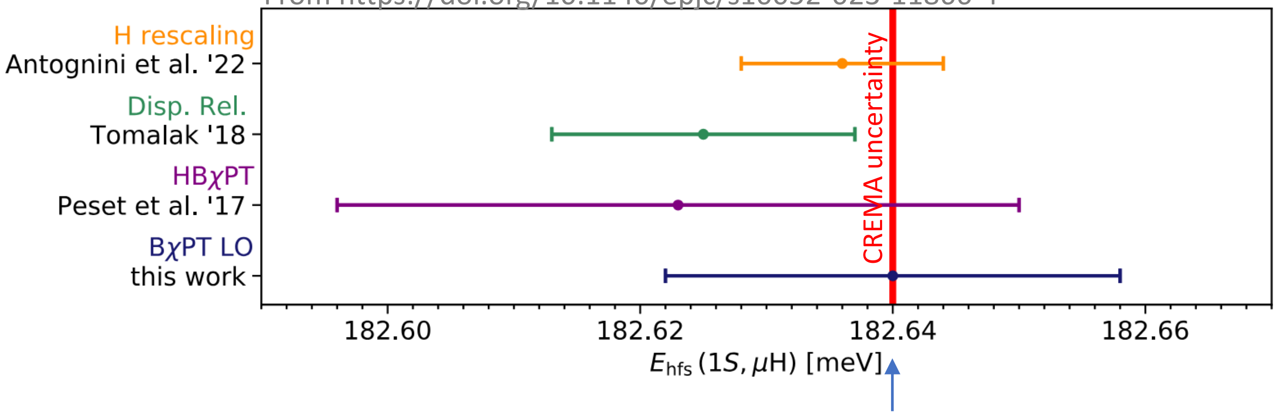
NB: $\frac{\Delta E_L}{\Delta E_{hfs}} \sim 10^{-2}$ → the hfs is far more difficult to meausure!

The FAMU experiment

Aim: measure the hyperfine splitting (hfs) of muonic hydrogen (μp) ground state, to extract the **Zemach radius** of the proton.

Theoretical prediction of the HFS energy for muonic hydrogen

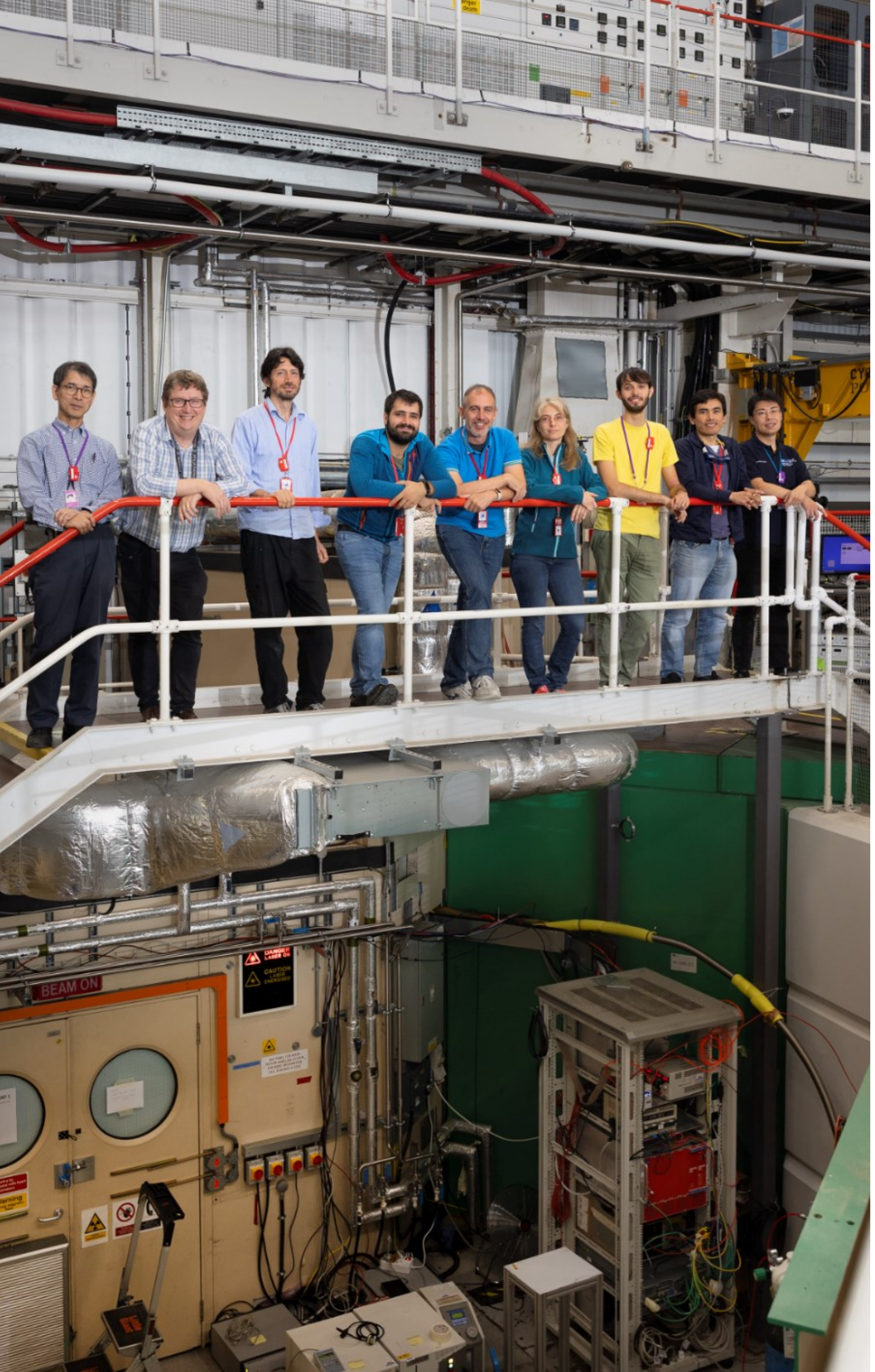
From https://doi.org/10.1140/epjc/s10052-023-11866-4



FAMU expected uncertainty in the same order of magnitude

Scan of energies started in 2023 (21 beam days).

Currently running (exp. ≈ 40 beam days in 2024-2025).



The FAMU Collaboration

Istituto Nazionale di Fisica Nucleare (INFN)

UKRI Science and Technology Facilities Council
ISIS Neutron and Muon Source

RIKEN

INRNE

Elettra Sincrotrone Trieste

SPIE.

BULGARIAN ACADEMY OF SCIENCE 1869

CNR IFN Istituto di Fotonica e Nanotecnologie

CNR-INO Istituto Nazionale di Ottica, Consiglio Nazionale delle Ricerche

ICTP The Abdus Salam International Centre for Theoretical Physics

Politecnico Milano 1863

IFJ The Henryk Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences

Università di Pavia

Università degli Studi della Campania *Luigi Vanvitelli*

Roma Tre Università degli Studi

Alma Mater Studiorum Università di Bologna

Dalian Institute of Chemical Physics, Chinese Academy of Sciences

Università degli Studi di Milano Bicocca

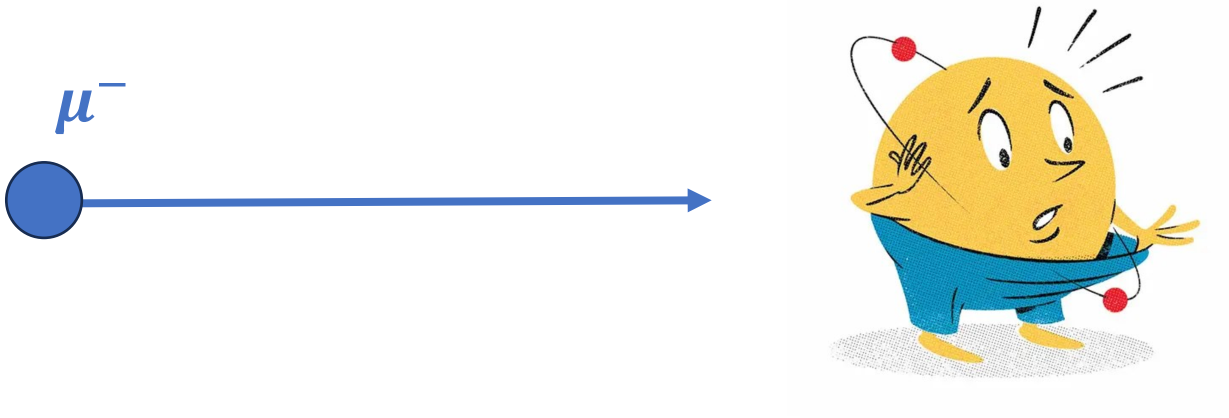
Università degli Studi di Udine hic sunt futura

FAMU experimental method

Fisica degli Atomi Muonici

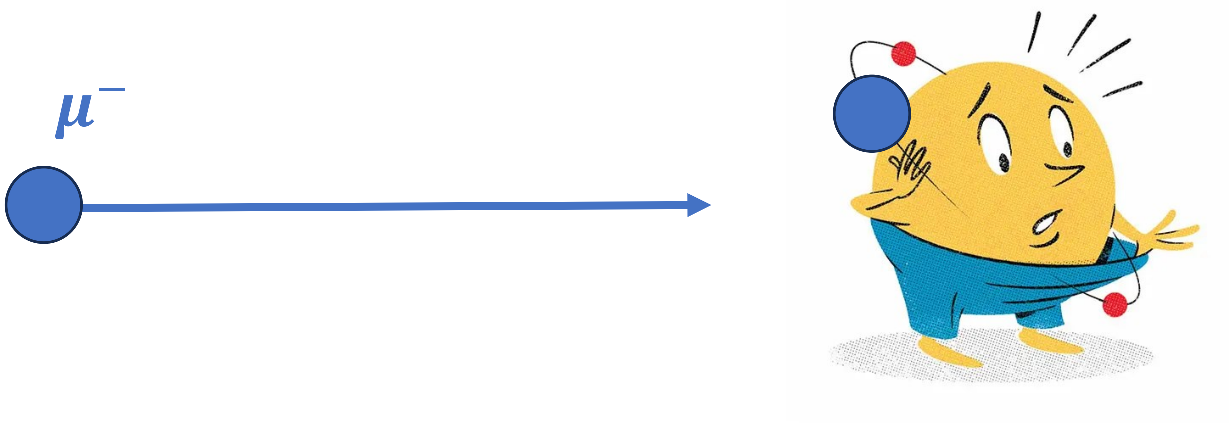
Muonic Atom Physics

Task 1: muonic hydrogen formation



Hydrogen
ep

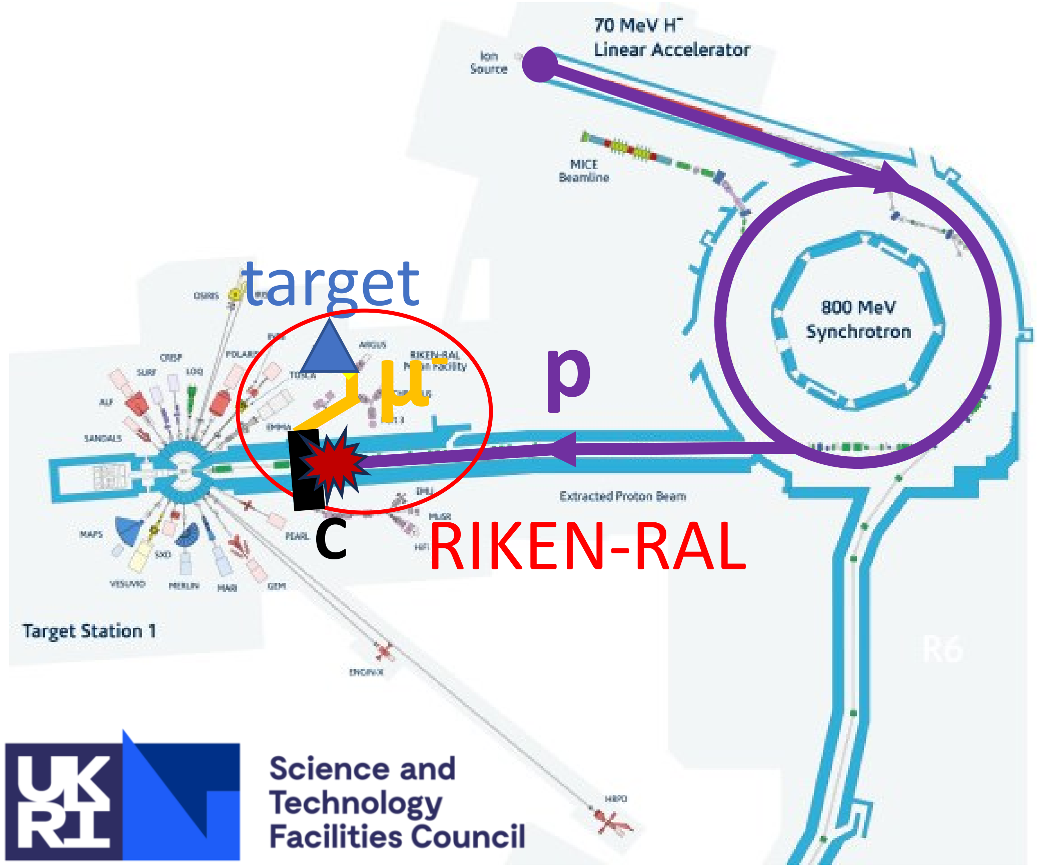
Task 1: muonic hydrogen formation



Muonic
Hydrogen
μp

Task 1: muonic hydrogen formation

The brightest pulsed muon beam facility in the world!



Science and Technology Facilities Council

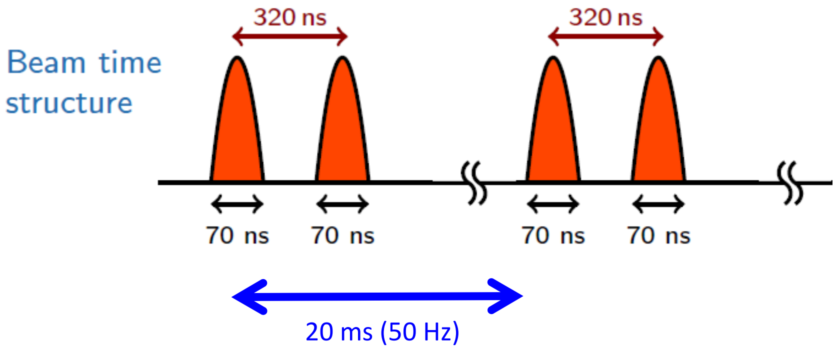
ISIS Neutron and Muon Source

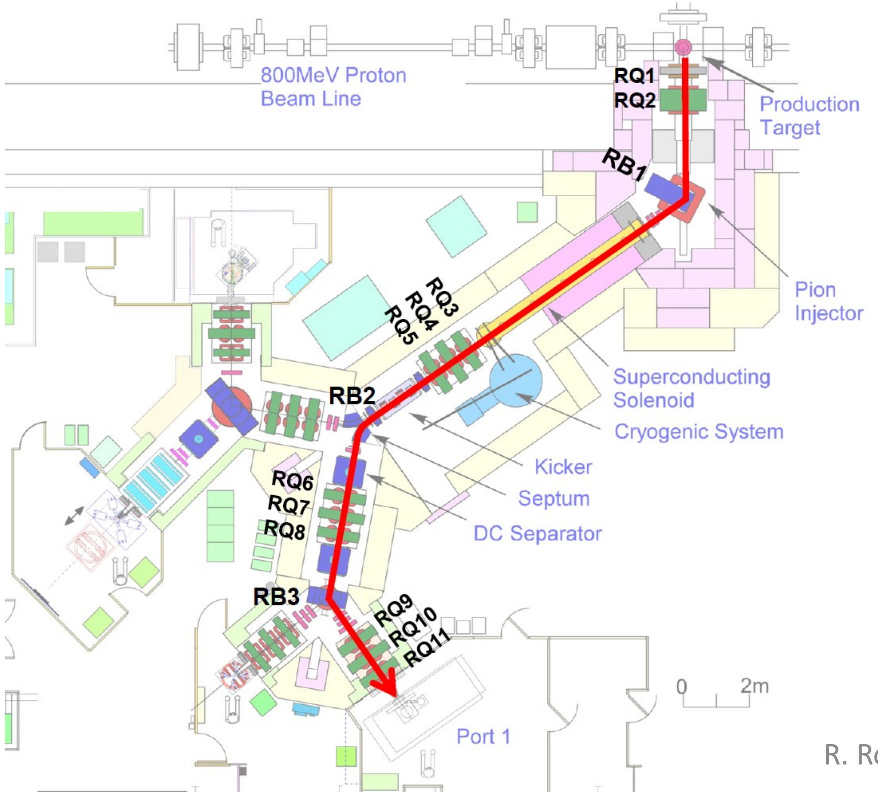
RIKEN-RAL pulsed muon facility at the Rutherford Appleton Laboratory (RAL, Didcot, United Kingdom), part of the ISIS Neutron & Muon Source.

Task 1: muonic hydrogen formation

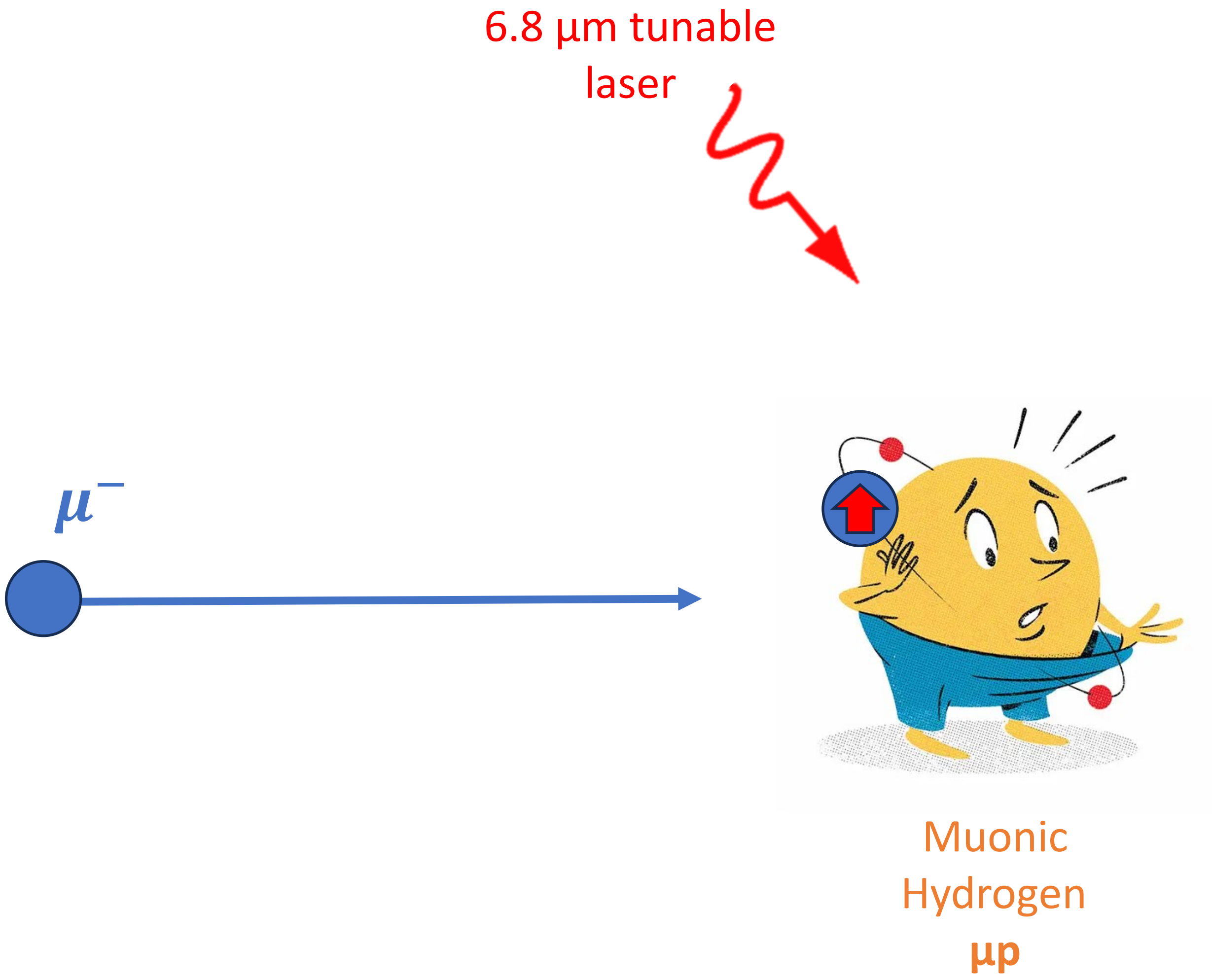
RIKEN-RAL Port 1 μ^- beam at the ISIS Neutron and Muon Source (Didcot, UK).

Momentum 60 MeV/c, average flux ≈ 10^4 μ^-/s.

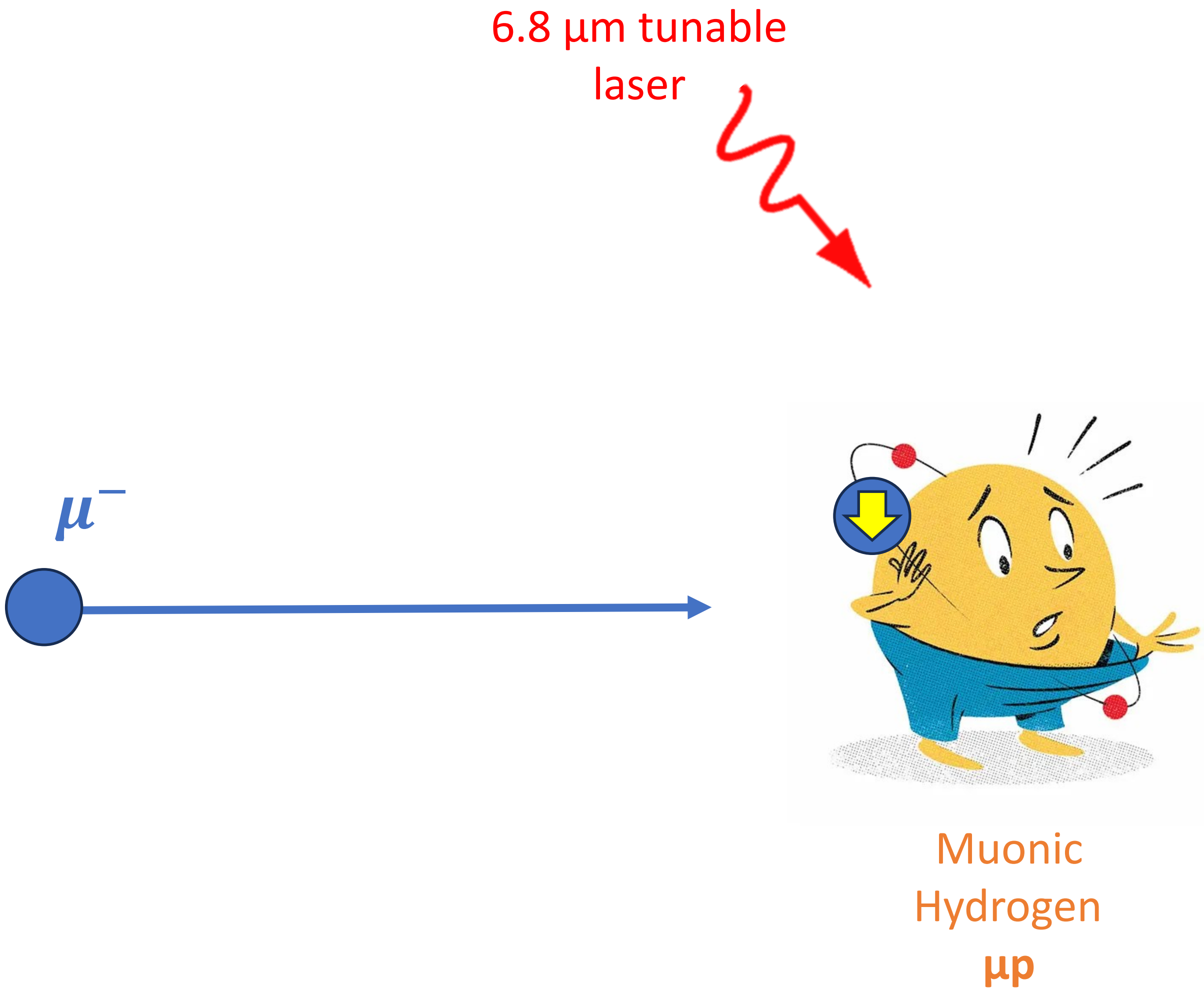




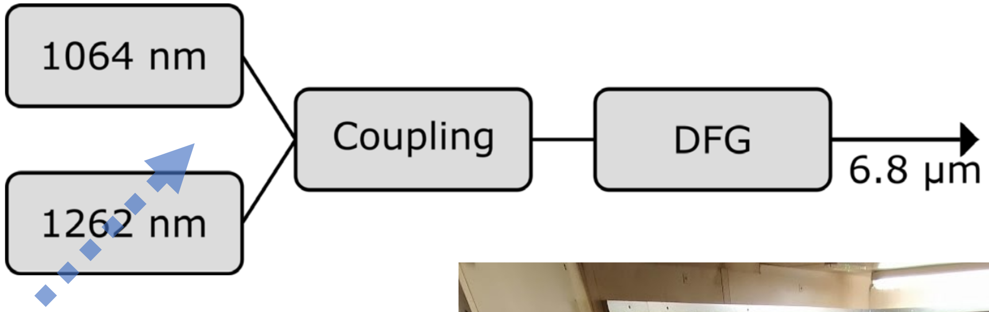
Task 2: spin flip



Task 2: spin flip



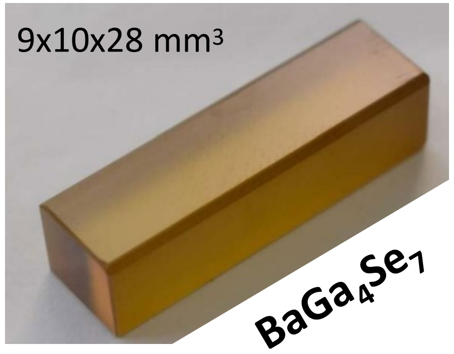
Task 2: spin-flip



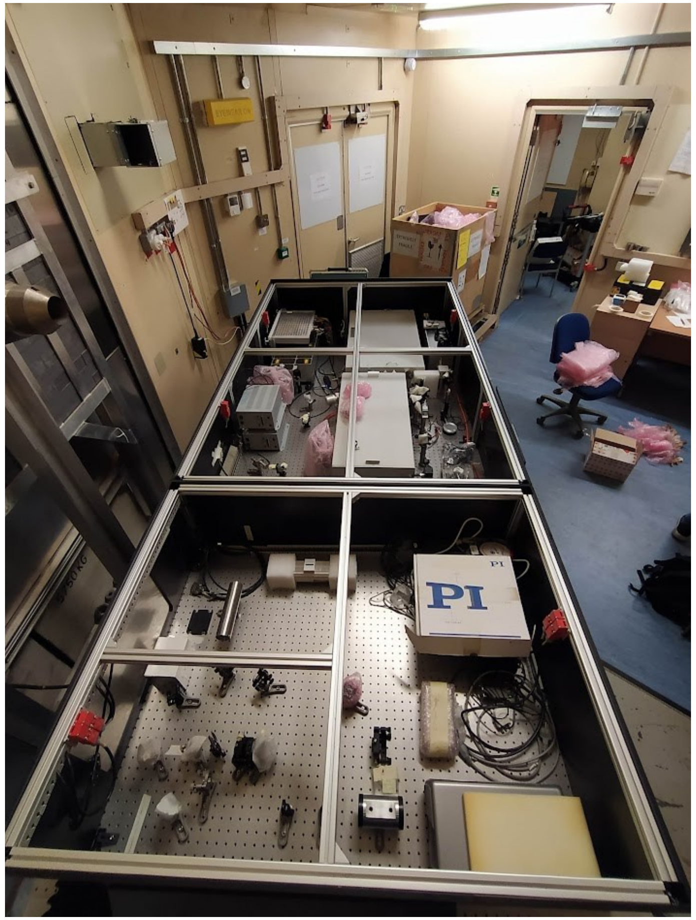
The most powerful pulsed 6.8 μm tunable narrow-linewidth laser in the world!

Expected resonance width: 73 pm.
→ the laser needs stable wavelength, narrow linewidth and high energy per pulse.

DFG:
non linear crystal



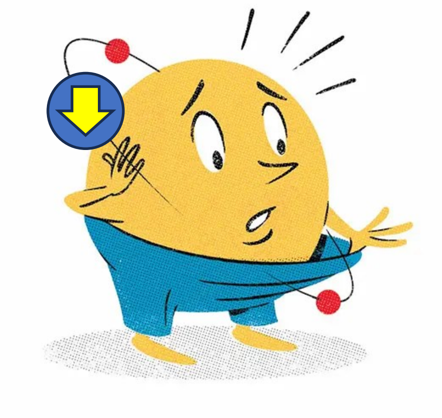
$$\lambda_{DFG}^{-1} = \lambda_1^{-1} - \lambda_2^{-1}$$



Wavelength range	6800 ± 50 nm
Energy output	> 1 mJ
Linewidth	< 30 pm
Tunability steps	~9 pm
Pulses duration	10 ns
Repetition rate	25 Hz

we reached better values than our goal (Linewidth, Tunability steps)

Task 3: find an observable

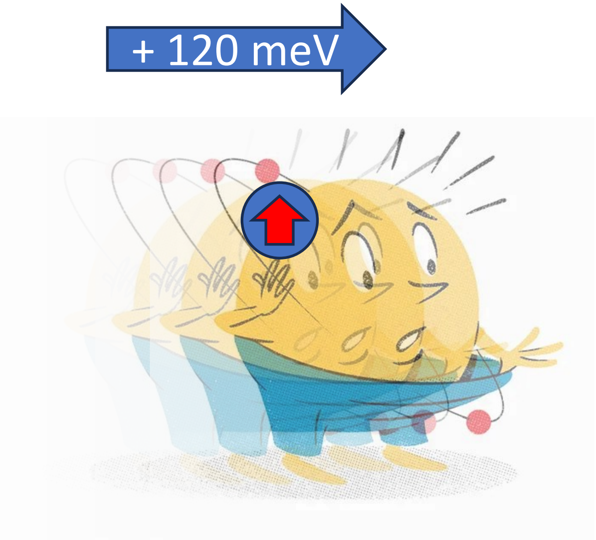


Muonic
Hydrogen
μp

Task 3: find an observable

After the spin flip, the atom returns to the ground state gaining 120 meV recoil kinetic energy.

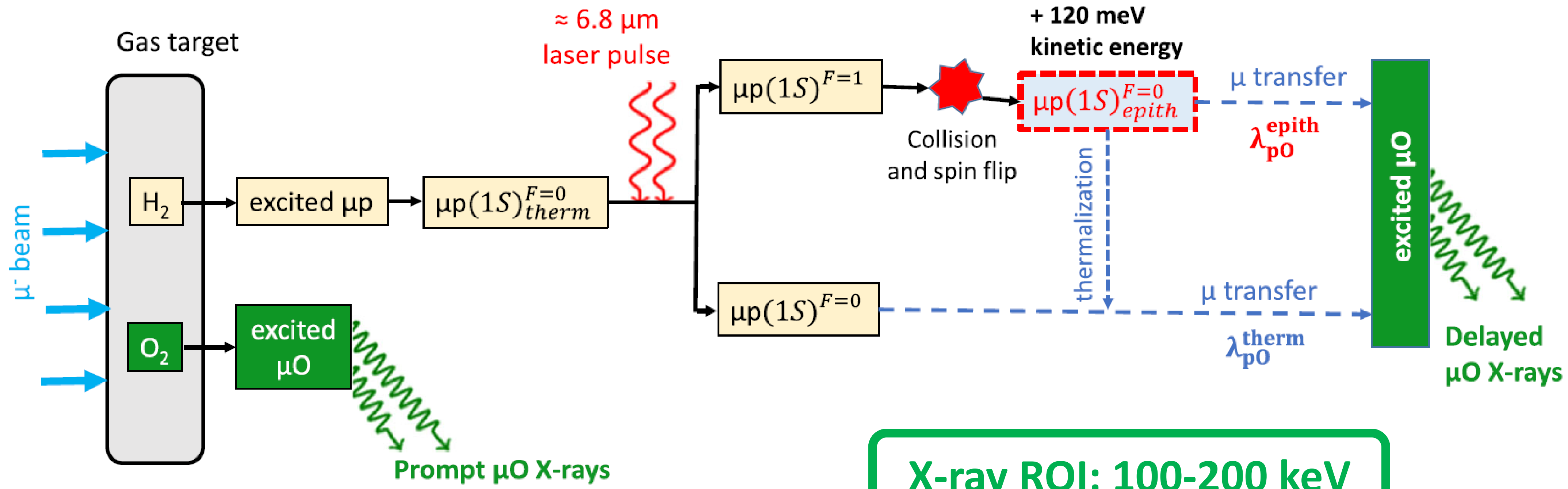
This kinetic energy enhances the probability of transferring the muon to another atom with a collision.



Muonic Hydrogen
μp

Task 3: find an observable

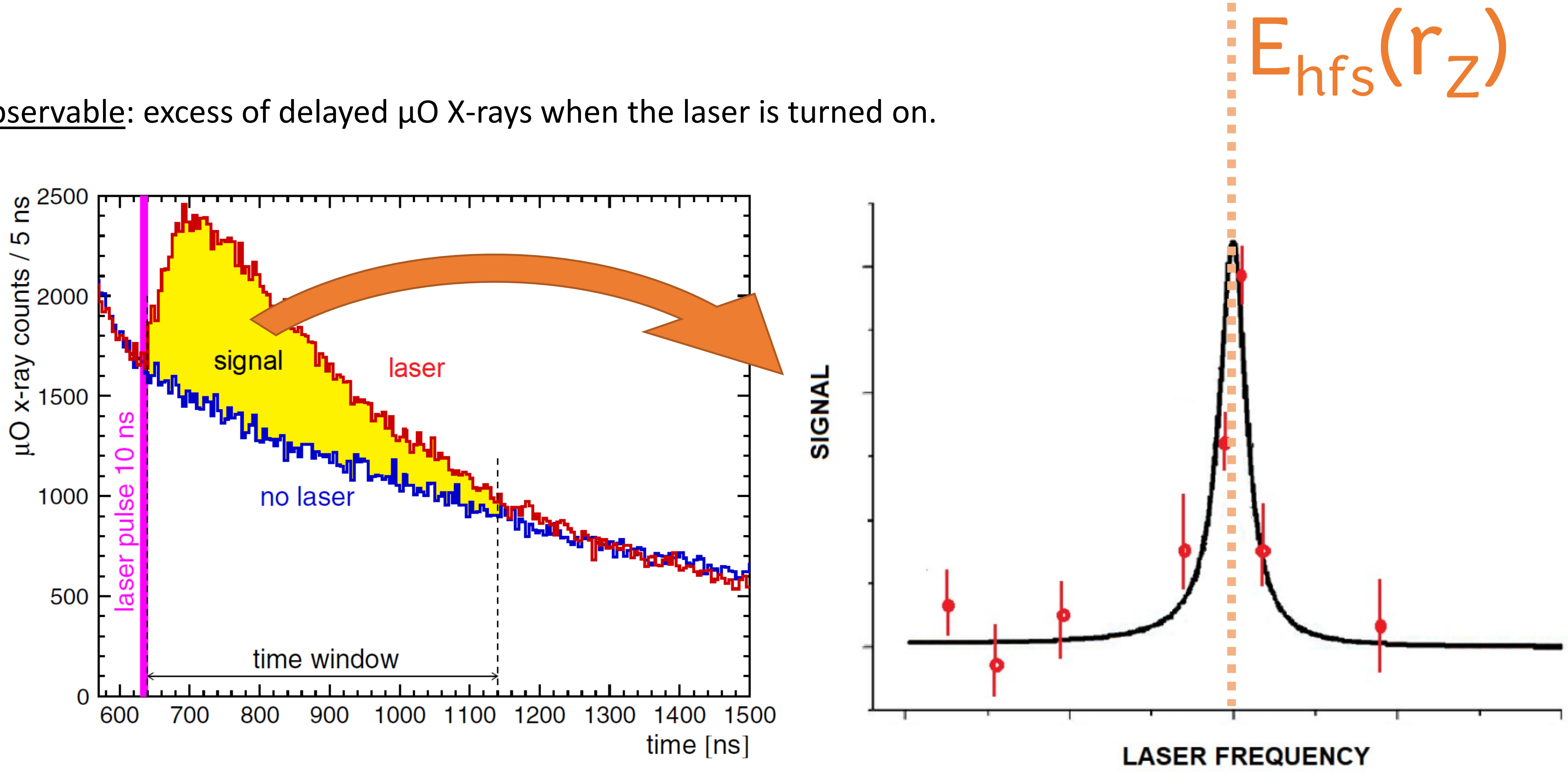
Observable: excess of delayed μO X-rays when the laser is turned on.



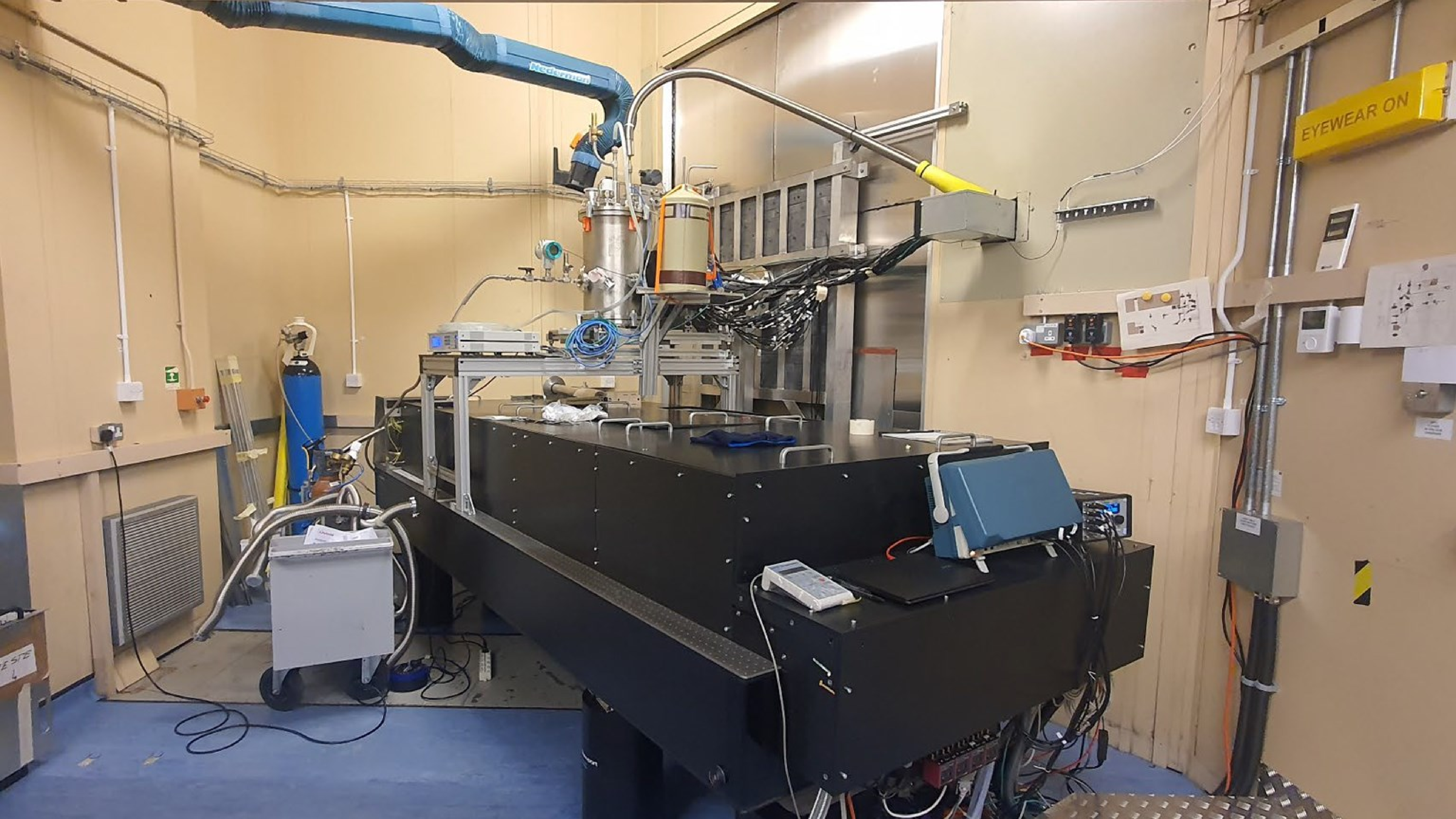
X-ray ROI: 100-200 keV

Task 3: find an observable

Observable: excess of delayed μO X-rays when the laser is turned on.



FAMU experiment setup and status

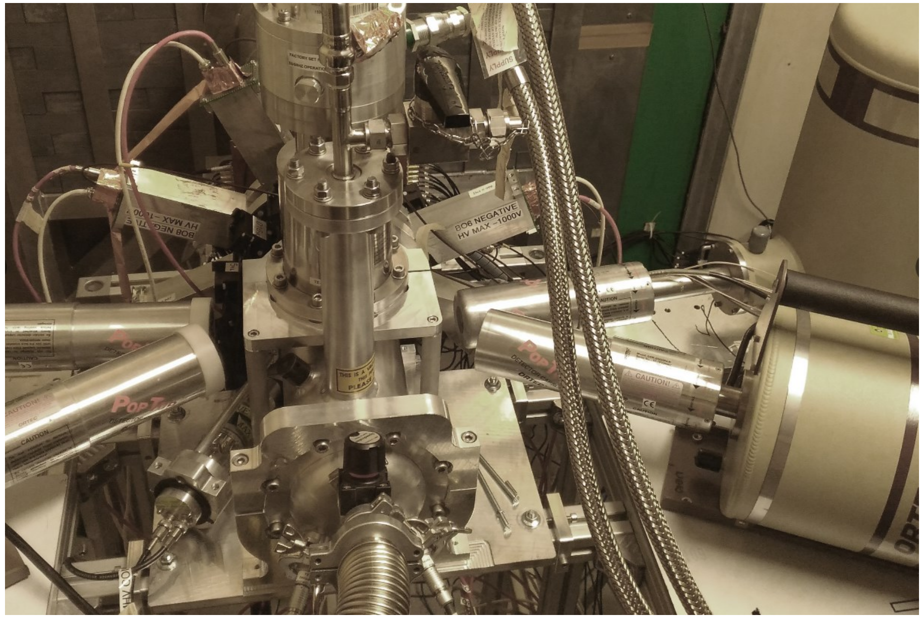

Nederman
EYEWEAR ON

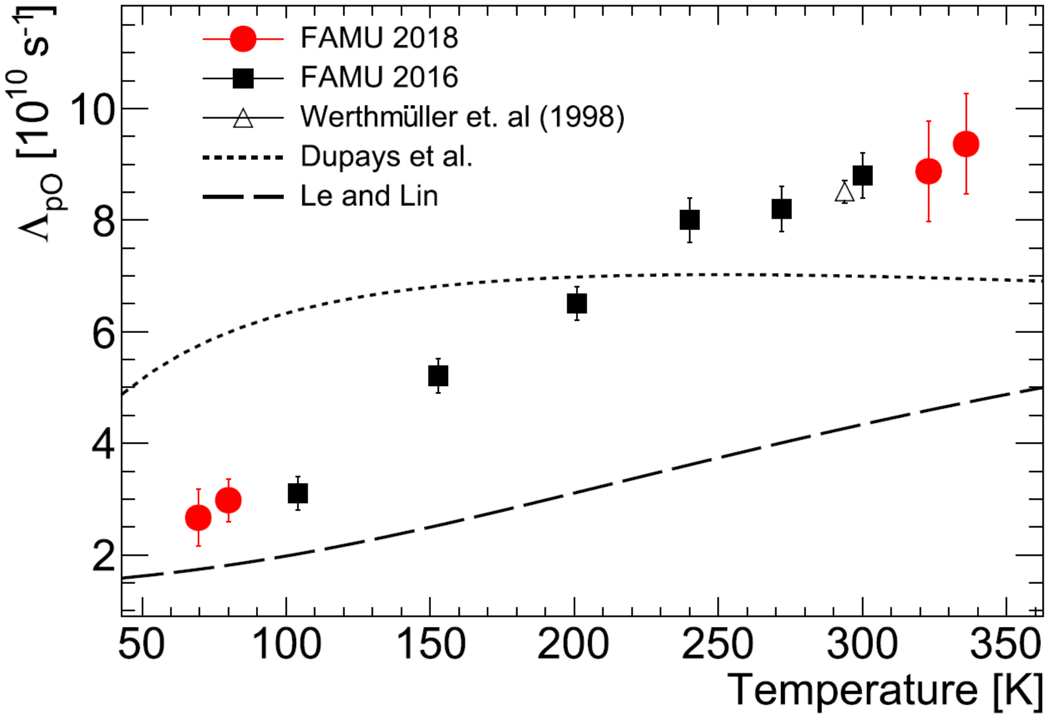
Optimisation of gaseous target

<u>FAMU 2014-2019</u> at RIKEN-RAL Port4:

Muon transfer function Λ_{pX} in various H+gas mixtures X = (O_2, Ar, CO_2, CH_4).

Transfer function of H-O mixture (Λ_{pO}) as a function of the temperature.

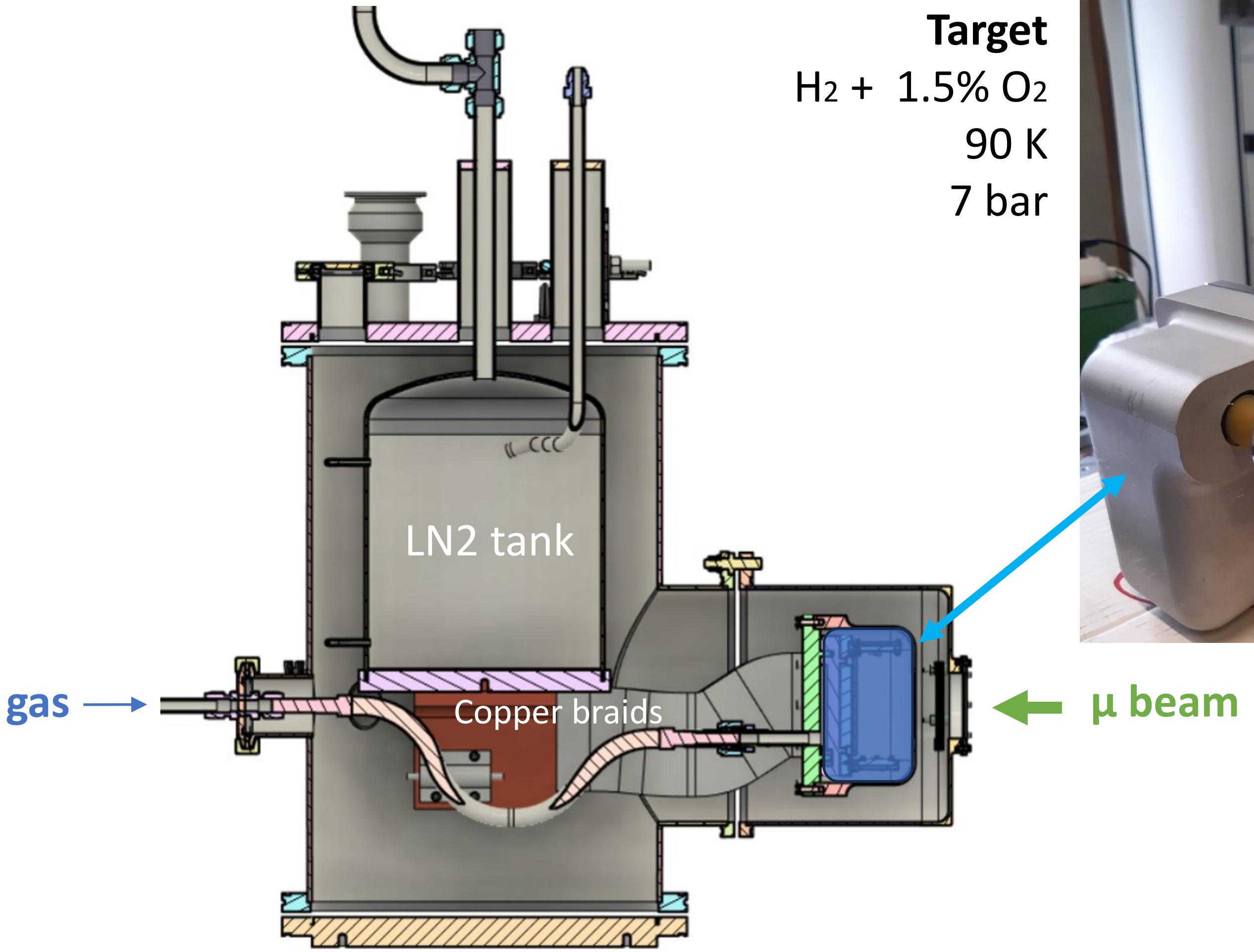




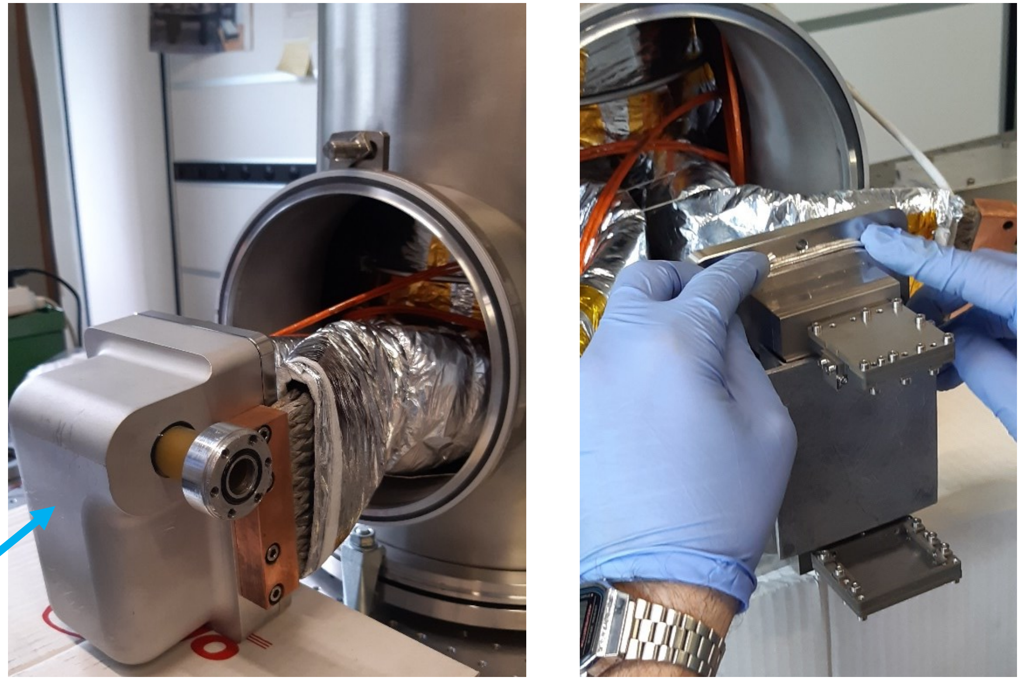
C. Pizzolotto *et al*, 2021 *Phys Lett A* **403** 127401

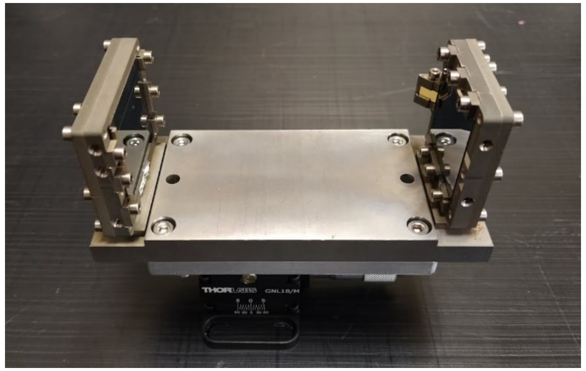
Target and optical cavity

Target
H_2 + 1.5% O_2
90 K
7 bar



Insertion of the cavity in the target

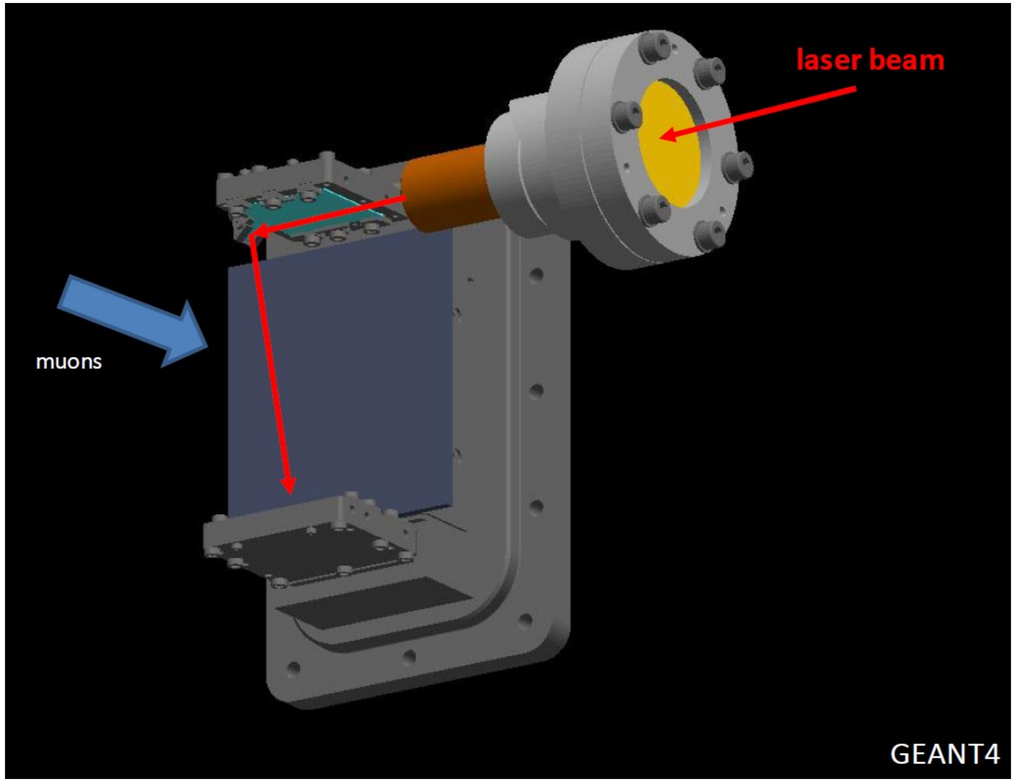




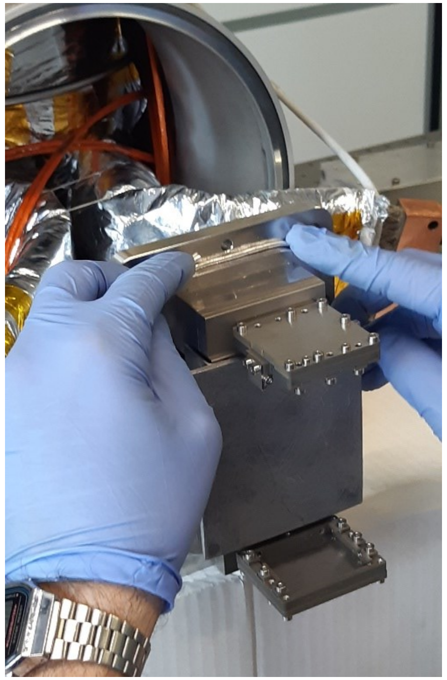
Cavity

Target and optical cavity

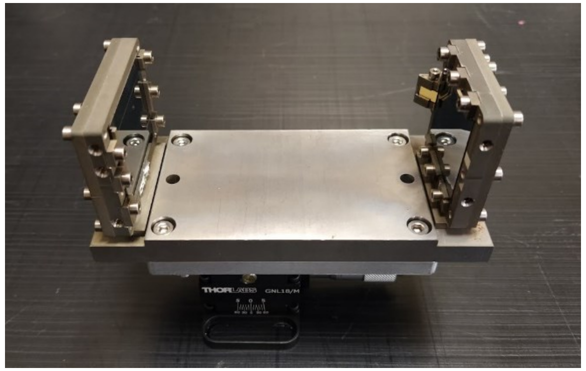
Target
H_2 + 1.5% O_2
90 K
7 bar



Insertion of the cavity in the target



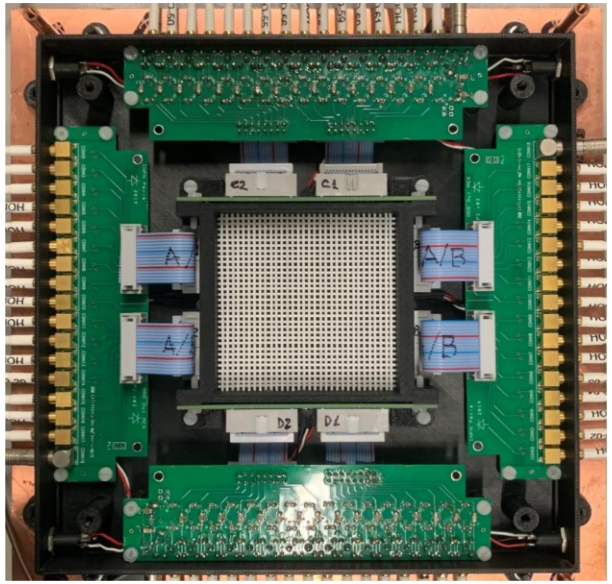
Cavity



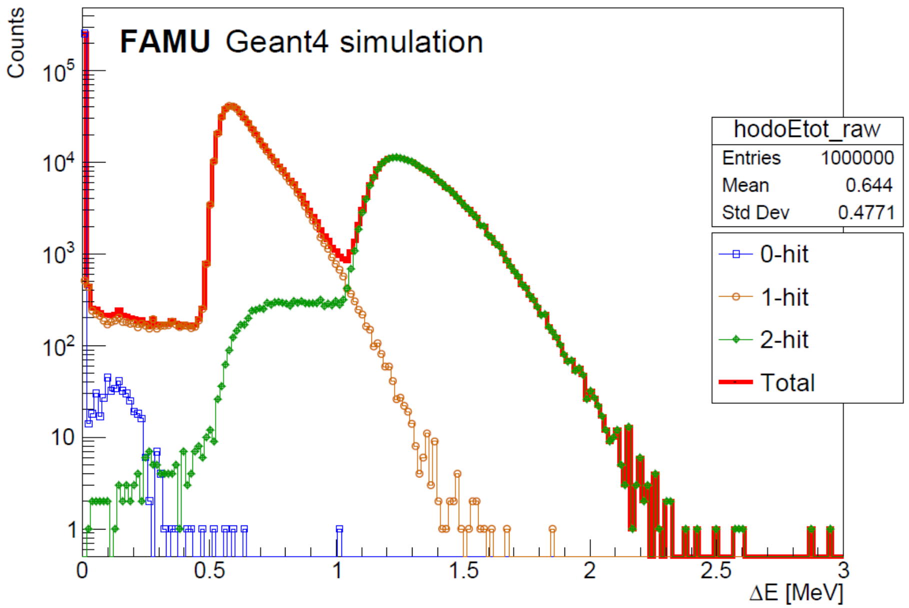
Beam monitor

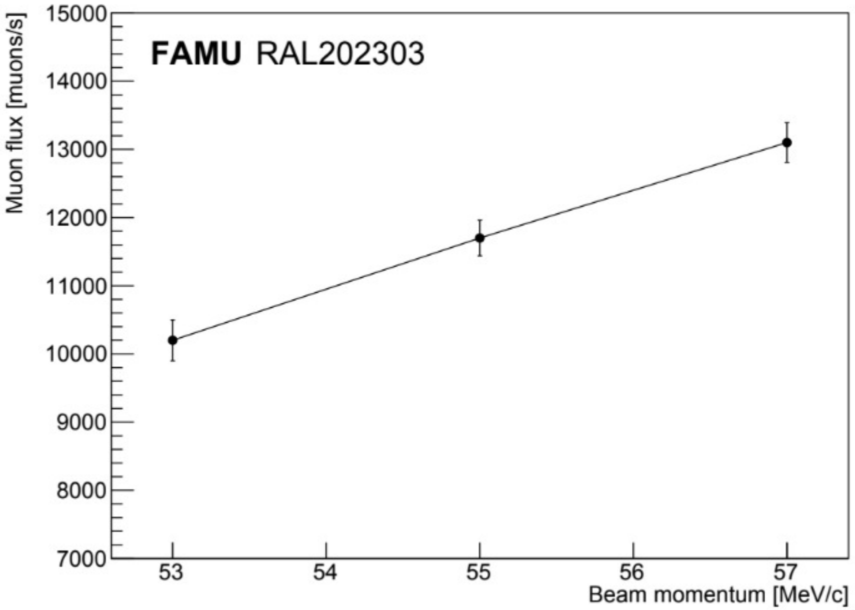
Two crossed planes with 32x 1 mm cubed scintillating fibres each.

Initially designed for beam focusing and centering (beam hodoscope), now used as muon flux-meter.



Total deposited energy

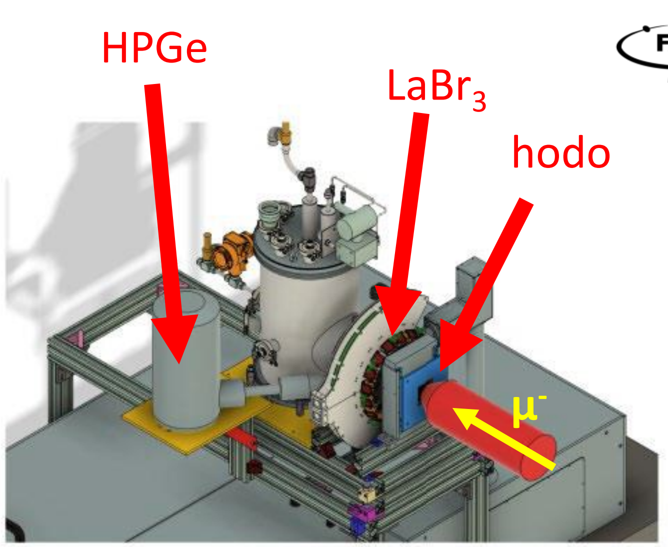




X-ray detectors

34x $LaBr_3$:Ce crystals for time-resolved measurements:

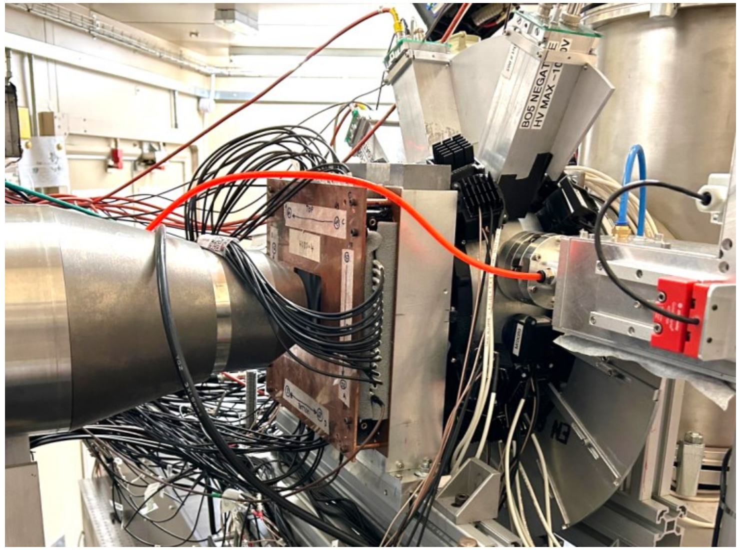
- **6x** 1'' cylinders read by PMTs;
- **16x** 1'' cylinders read by SiPMs;
- **12x** ½'' cubes read by SiPMs.



2024 upgrade: substitution of ½''-SiPM detectors with 1''-SiPM.

Table 1: Average detector performance in the 2023 setup[3].

Detector	t_{rise} [ns]	En.Res @140 keV [%]
1"-PMT	14 ± 1	11.5 ± 0.2
1"-SiPM	29 ± 2	8.2 ± 0.7
½"-SiPM	43 ± 5	7.5 ± 0.3



Beam time

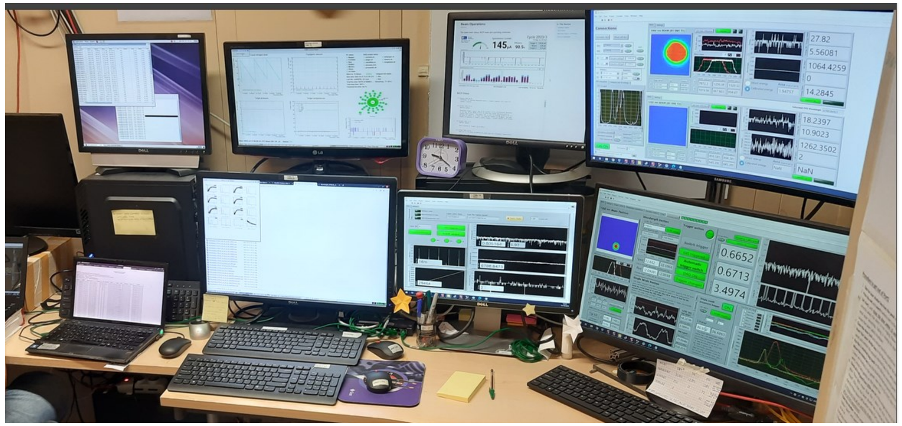
Commissioning:

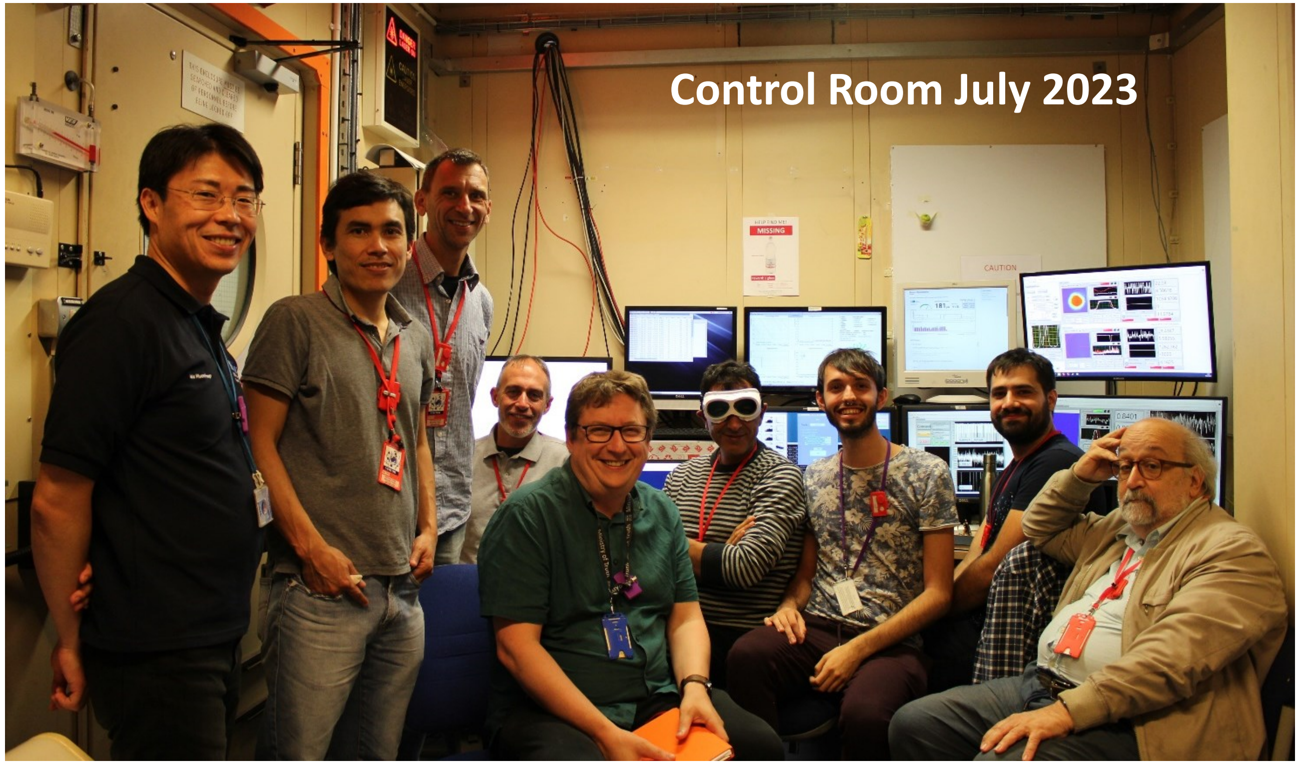
July 2023

Physics data taking:

October 2023
December 2023
(total 21 days)

July 2024
October 2024
tbd in 2025

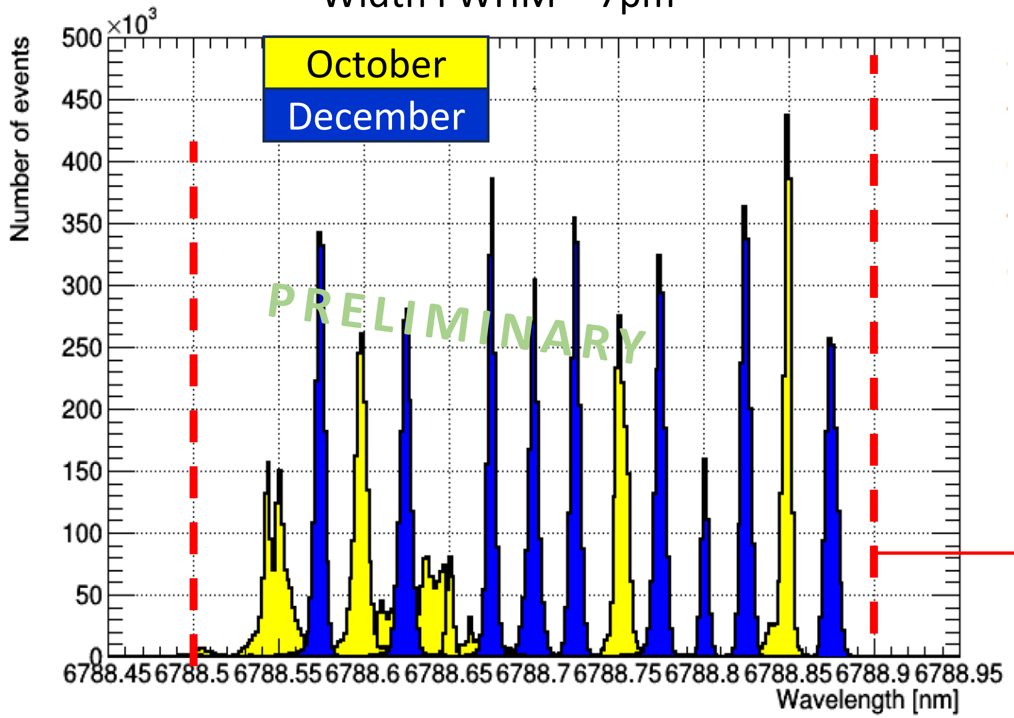




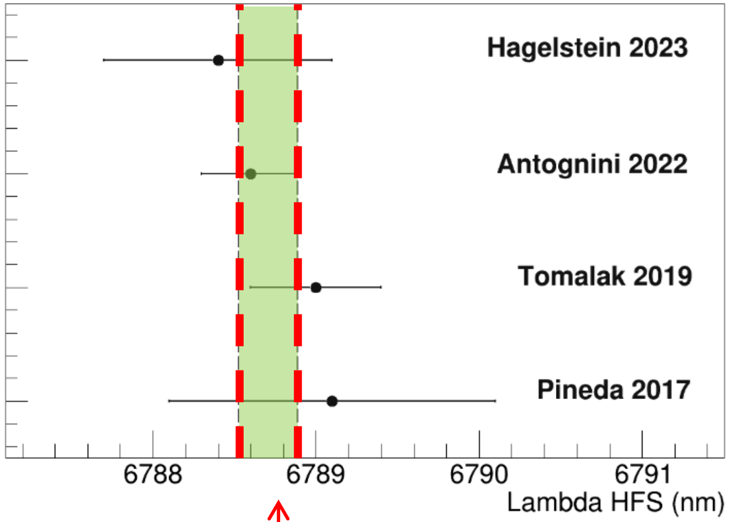
Beam time

Laser wavelengths investigated in 2023:

14 frequencies investigated
in steps of 25 pm
~ 24 h for each frequency
Width FWHM ~7pm



Theoretical prediction of the HFS

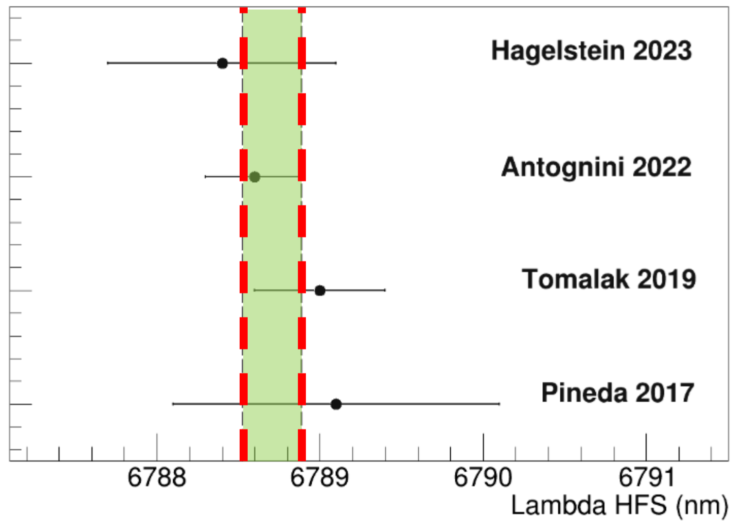


Summary

FAMU → looking for *hfs* in μp ground state, to extract the Proton Zemach radius with accuracy better than 1%.

Successful Physics data taking in 2023 (21d): the setup performed as expected, analysis is ongoing.

Improvements for 2024-2025 runs: larger X-ray detector solid angle coverage, expand the WL region by a factor 2-3.



Backup slides

Proton charge radius measurements

Modified from Xiong et al. DOI:10.1038/s41586-019-1721-2