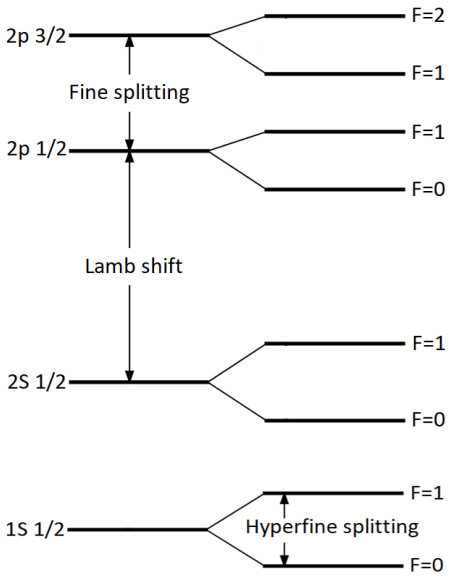
Investigating the proton structure with the FAMU experiment

Cecilia Pizzolotto

for the FAMU Collaboration

FAMU aims to measure the hyperfine splitting in muonic hydrogen

Hydrogen atomic levels:



$$r_Z = \int r\, d^3r \int d^3r' \rho_E(\vec{r} - \vec{r}')\rho_M(\vec{r})$$

➔ *1S-hfs* ➔ Insight on the magnetic properties of the proton strongly dependent on the Zemach radius

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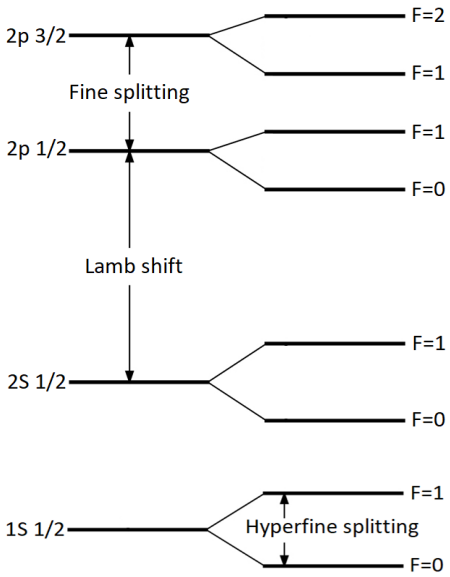
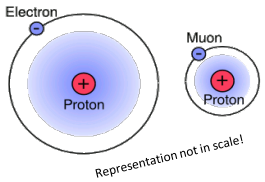


Why muonic atoms?



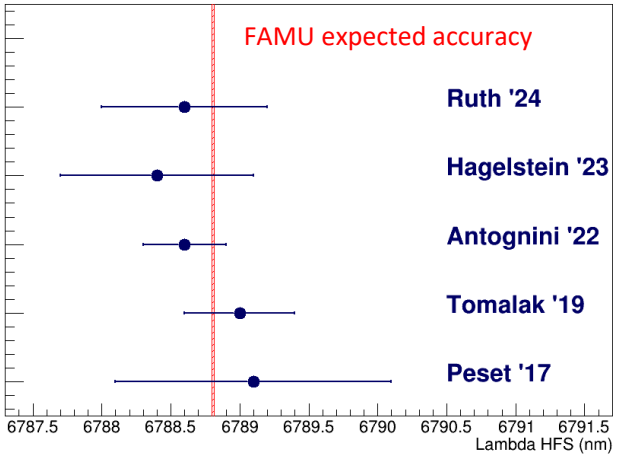
The muon is much closer to the nucleus, because of its heavier mass;
the **overlap of muon and proton** densities is enhanced by $(m_\mu/m_e)^3 \sim 8 \cdot 10^6$

The **energy differences** between levels are therefore much **larger** than in normal hydrogen leading to **higher precision spectroscopy**

➔ *1S-hfs* ➔ Insight on the magnetic properties of the proton strongly dependent on the Zemach radius

HFS Theoretical predictions and expectations

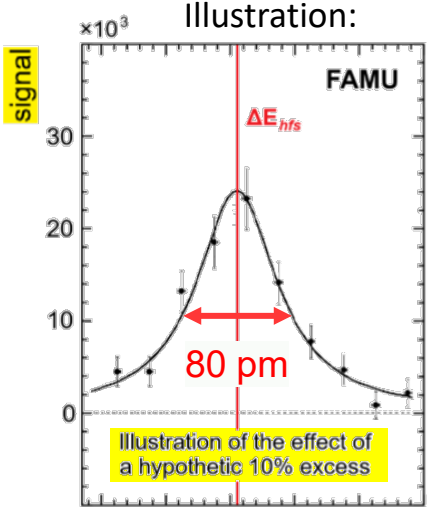
Theoretical predictions for the HFS



10^{-5} on HFS ↔ 0.3% on r_z

Unprecedented accuracy on the Zemach Radius!

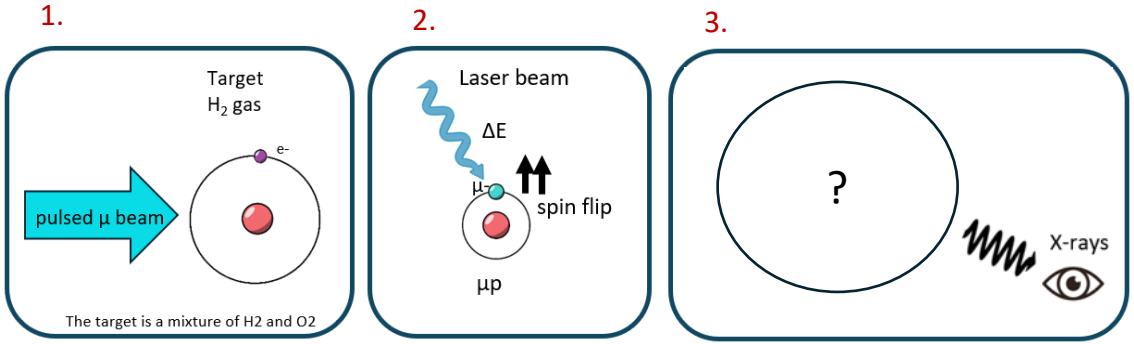
Illustration:



1S hyperfine splitting

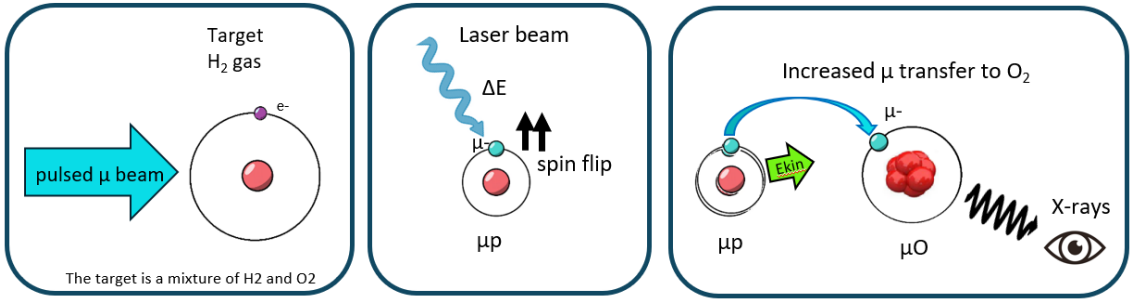
FAMU has been acquiring data during several beamtimes since 2023

FAMU experimental method



1. Produce ground state muonic hydrogen
2. Excite the 1S-hfs transition with a laser of tunable wavelength (λ_0 ~6.8μm)
3. Measure an observable that is sensitive to the transition

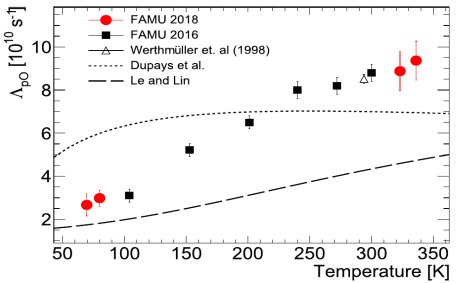
FAMU experimental method



Observable that is sensitive to the transition:
Number of Muonic Oxygen Xrays

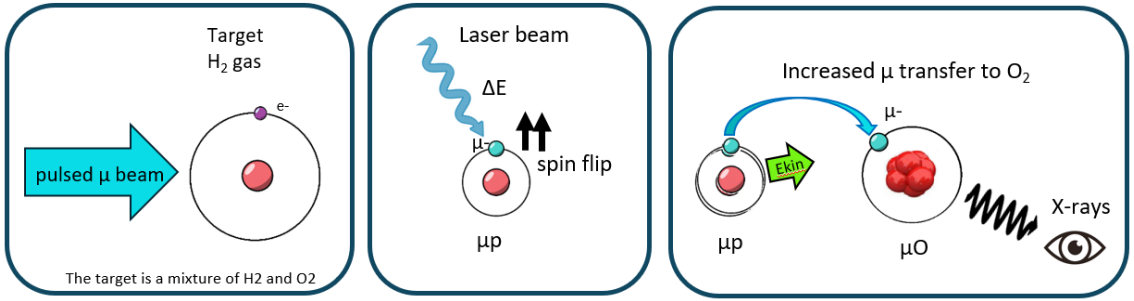
Target: gas mixture of H_2 and O_2 (1.5%)
μH de-excitation ➔ recoil ~120 meV ➔
enhanced probability of μ transfer to Oxygen

Muon transfer rate from H to O



https://doi.org/10.1016/j.physleta.2021.127401
https://doi.org/10.1016/j.physleta.2020.126667

FAMU experimental method



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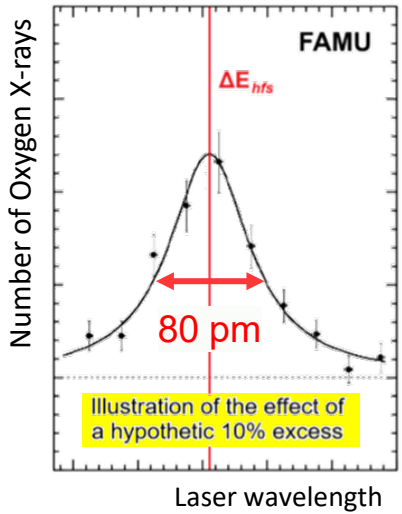
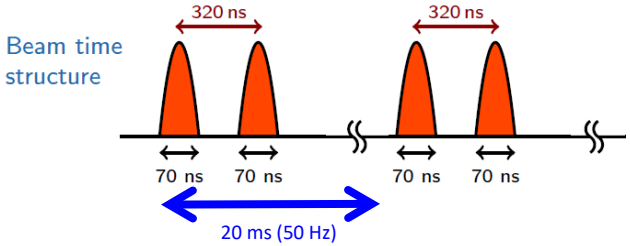
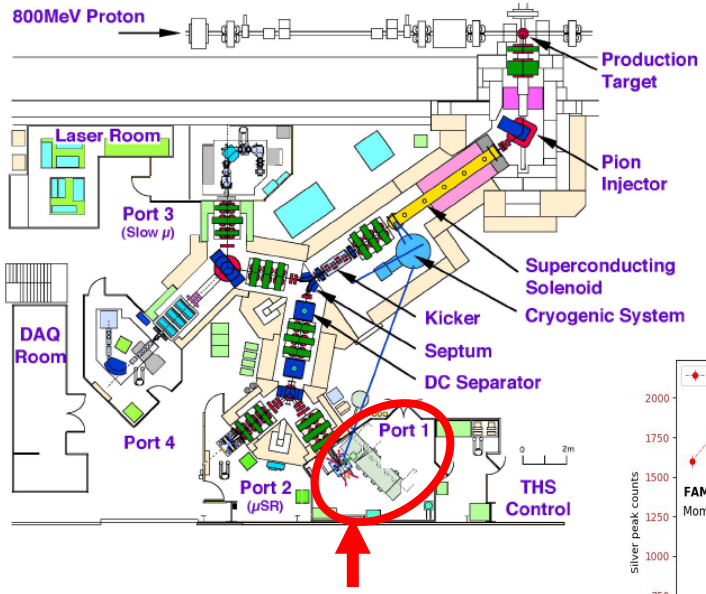


Where: Rutherford Appleton Laboratory - UK

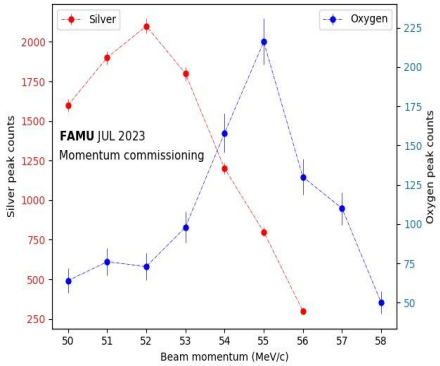
The brightest pulsed muon beam facility in the world!



Riken RAL Muon Facility:

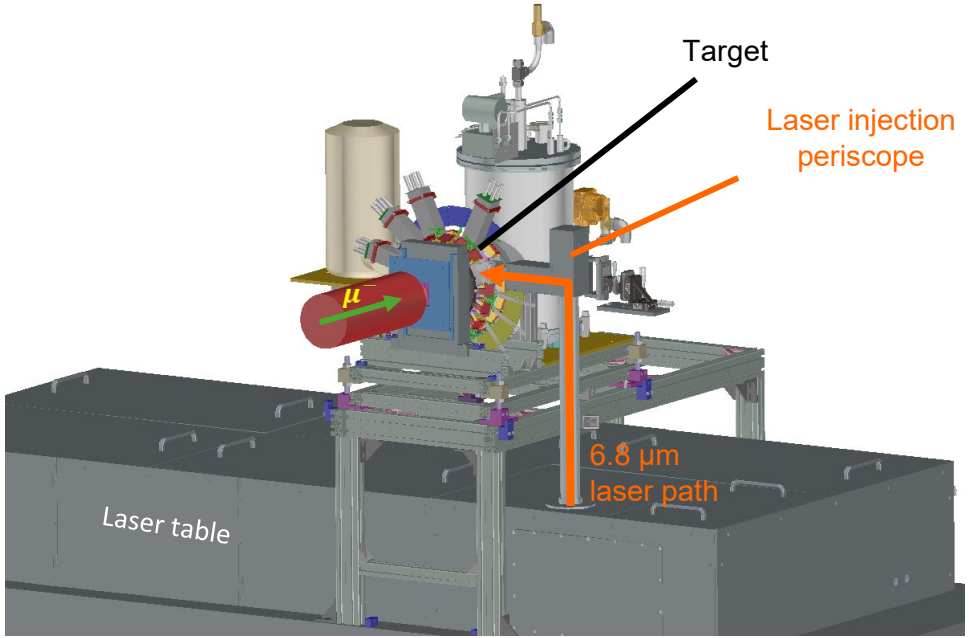


Momentum 55 Mev/C



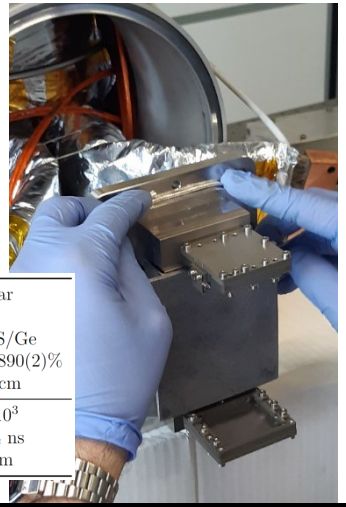
The experimental setup

FAMU Setup in PORT1 at RIKEN-RAL



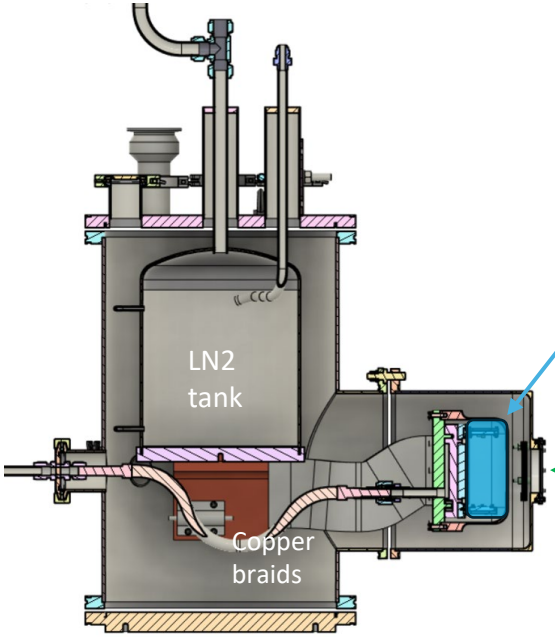
Cyogenic target and optical cavity

Cavity during assembly



Target cavity / gas chamber

Structure material	invar
Mirror material	Si
Mirror coating	ZnS/Ge
Mirror 6.78 µm reflectivity	99.890(2)%
Distance between mirrors	10 cm
Simulated number of reflection	$\sim 10^3$
Simulated laser lifetime in the cavity	304 ns
Simulated mean laser path	91 m

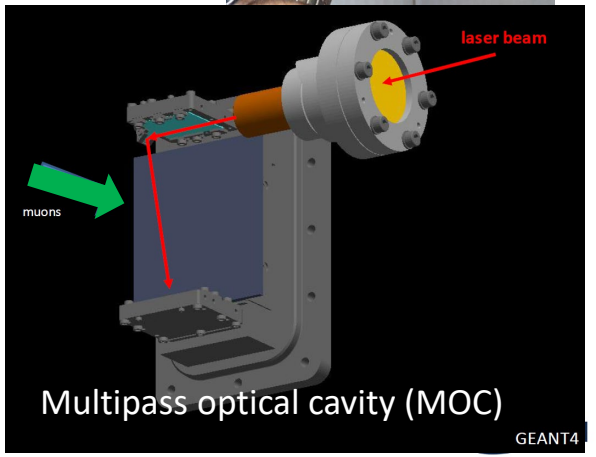


H2
gas
inlet

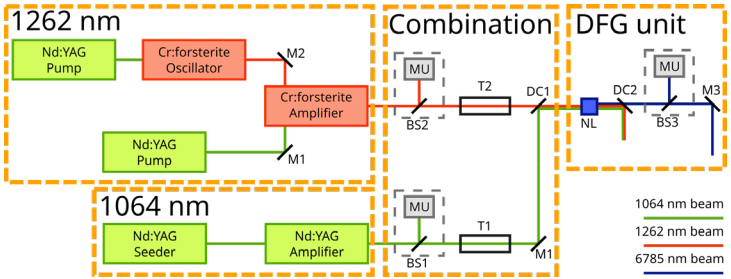
µ beam

Gas mixture of Hydrogen
and 1.5% Oxygen at ~80 K

To **increase the interaction** between µH atoms and laser photons the target contains a **Multipass Optical Cavity (MOC)**



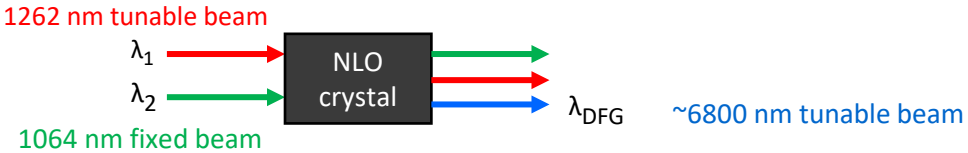
FAMU Laser system



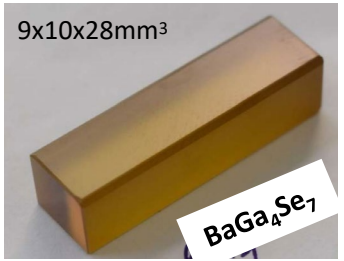
Parameter	FAMU requirement	Current FAMU result
Wavelength	6786–6792 nm	6730–7135 nm
Energy output	> 1 mJ	1.5 mJ
Line-width	< 0.07 nm	0.009 nm
Tunability step	< 10 nm	7 nm
Pulse duration	< 10 ns	7 ns
Repetition rate	25 Hz	25 Hz

Light at ~6800 nm is produced by a difference frequency generation (DFG) process in a BaGa4Se4 crystal.
Tunable laser at 1262 nm allows final λ tuning

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



Non Linear crystal



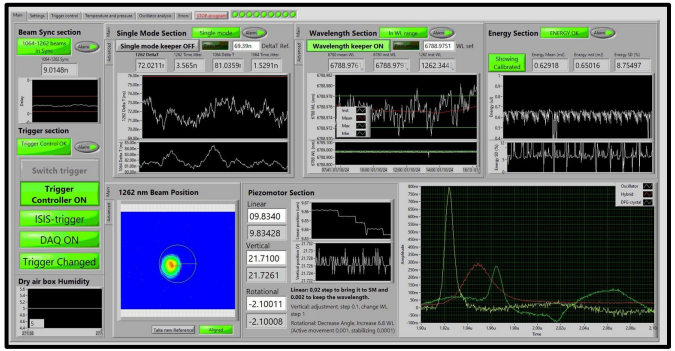
Laser performances

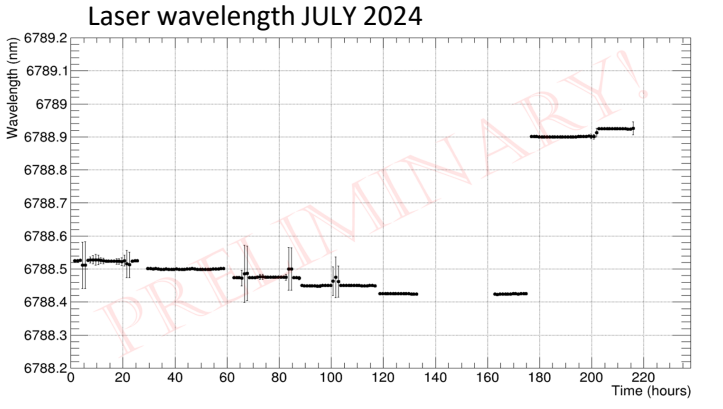
Automatic system to control and optimize the stability

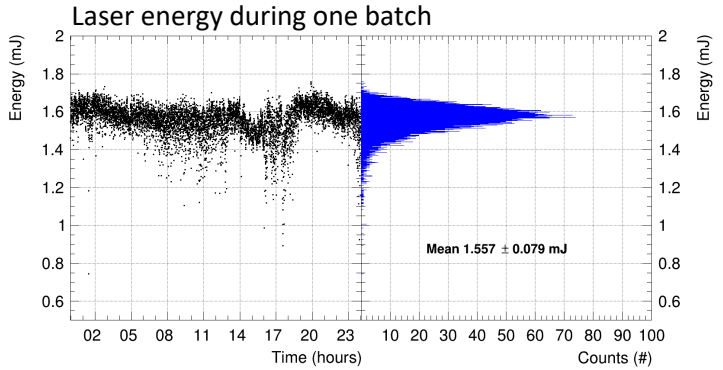
Excellent laser performances:

- long time stability (>10 days)
- Narrow wavelength distribution in 24 hours
- Average energy during acquisition ~1.5mJ

Max Energy >3 mJ : **Energy record** for a pulsed MIR laser



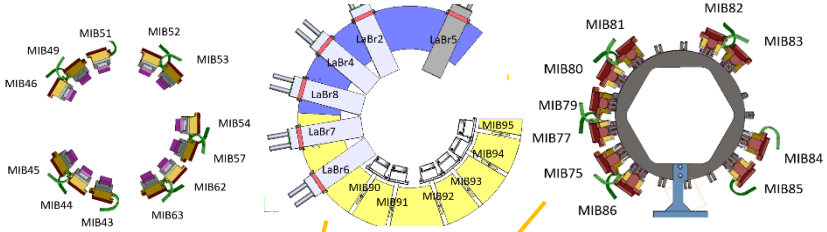


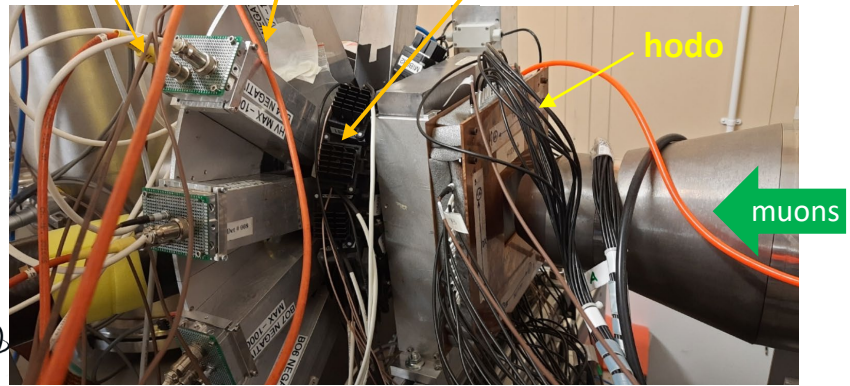


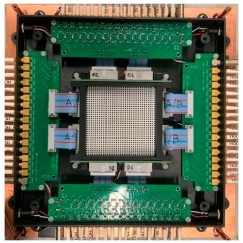
https://dx.doi.org/10.2139/ssrn.5464154 subm. to Optics Laser & Technology

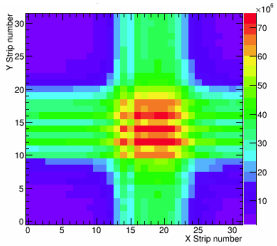
X-rays detectors

- the **beam hodoscope**, 1mm fibers + SiPM
- **LaBr3:Ce scintillating crystals** with PMTs (6) and SiPM (28) arranged **in three rings** around the target
  - Fast scintillation time
  - High density -> high efficiency
  - Good energy resolution at ~100 keV
- One HPGe detector for cross calibration





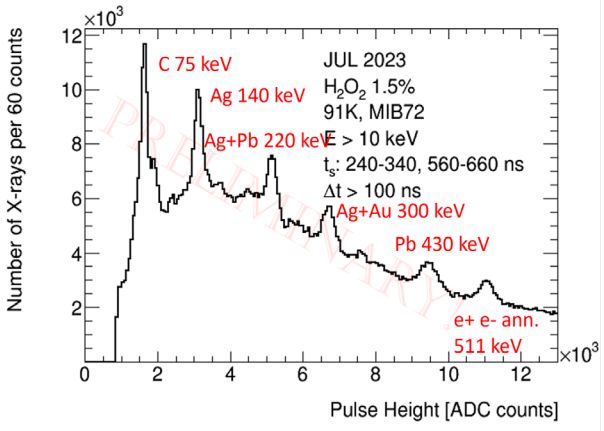




Hodo for beam positioning and measurement of the muon flux

https://doi.org/10.3389/fdest.2024.1438902

Automatic detector calibration based on known muonic X-rays from target materials.



FAMU physics runs

July 2023: commissioning

4 physic runs in 2023 and 2024

Period	Setup	No. triggers
Oct 2023	A	$1.60\ 10^7$
Dec 2023	A	$2.65\ 10^7$
Jul 2024	B	$2.12\ 10^7$
Sept 2024	B	$2.15\ 10^7$

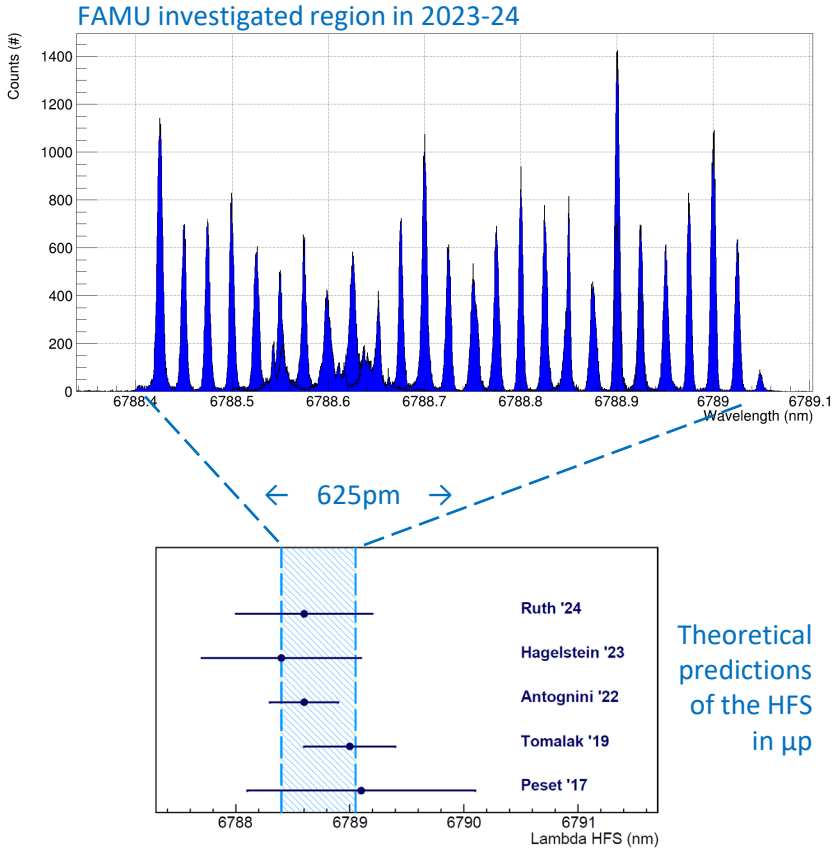
Solid angle coverage increased by ~30%

Total of $85 \cdot 10^6$ triggers corresponding to

25 investigated wavelengths in steps of 25pm

1 wavelength = ~ 24 hours

Other 22 days of beamtime foreseen in Autumn 2025



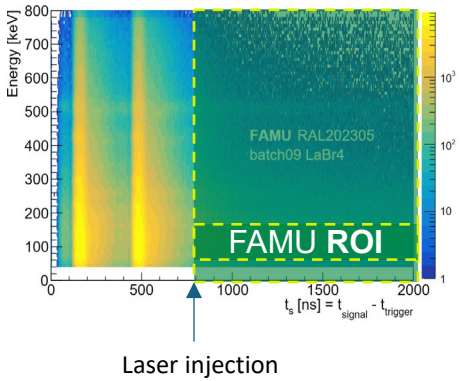
Theoretical predictions of the HFS in μp

Preprint: https://doi.org/10.48550/arXiv.2509.10350
Subm. To EPJA

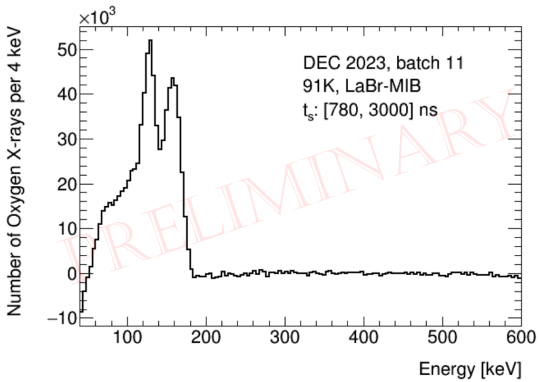
Data analysis (I)

Data analysis is based on the observation of the **excess of the number of muonic Oxygen X-rays** when laser is injected in the target, as respect to no-laser events

Systematics is reduced taking alternatively one spill with laser and one spill without laser
24h of data taking at the same laser wavelength for enough X-rays statistic



Partial sample Laser+NoLaser events

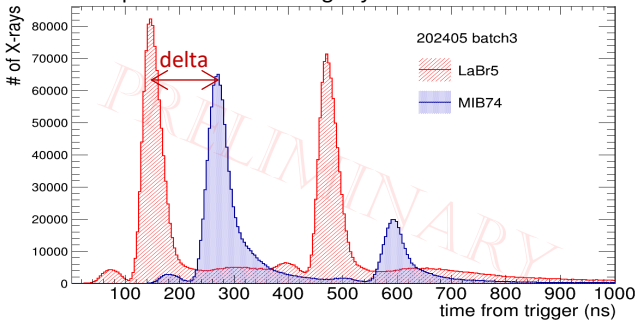


Data analysis (II)

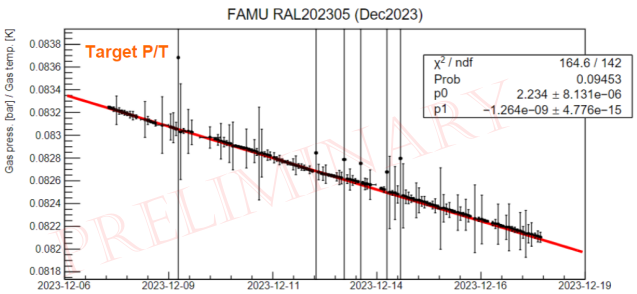
Effects to be taken into account

- Calibrations: energy calibrations and gain drifts; time synchronization (as respect to laser shot) of detector response
- Fluctuations of the muon beam
- Target conditions(T,p)…
- Laser quality (wavelength stability)

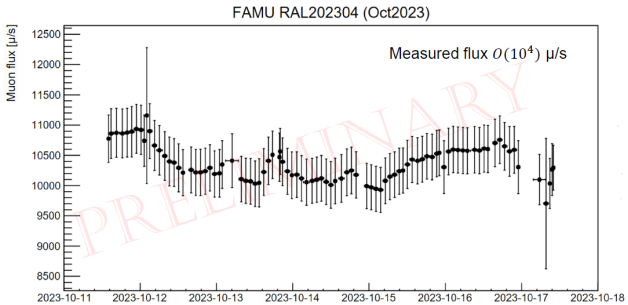
Example of detector timing *before* calibration



Different timing due to: different electronic channels, different type and size of detectors (rise-time of the signal)
Linear shift (time scale does not expand or contract)



Muon flux measured by the hodo

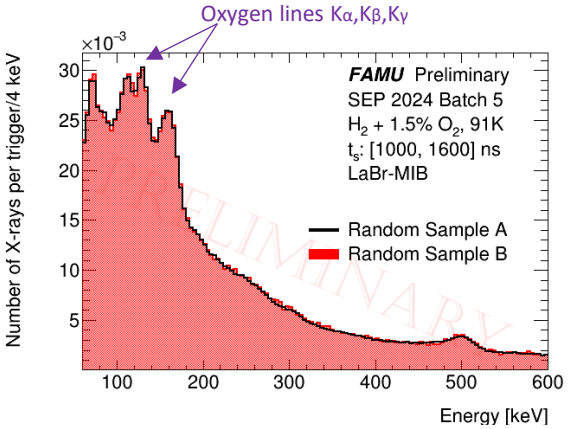


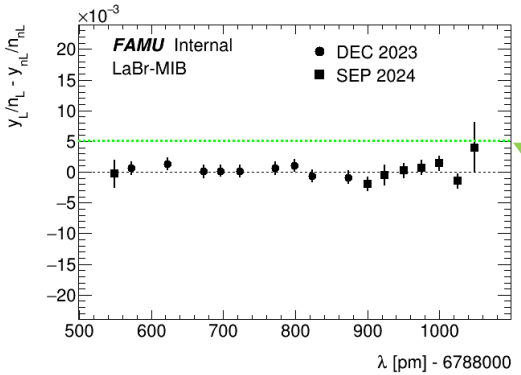
Data analysis: random laser tagging

Consistency check: random laser data tagging (=random mixing of laser and no-laser events in sample A and B)

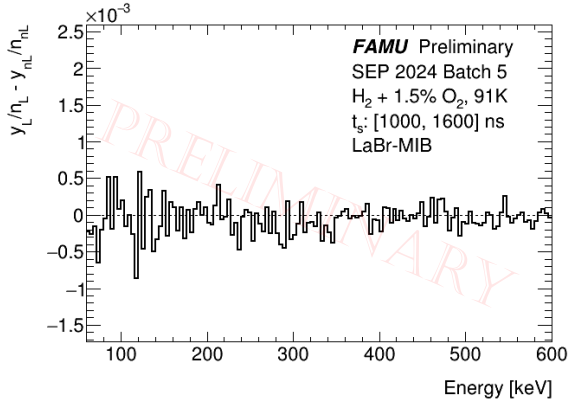
If $\lambda \neq \lambda_{hfs} \rightarrow$

$$y = \frac{y_{Laser}}{n_{Laser}} - \frac{y_{NoLaser}}{n_{NoLaser}} = \frac{y}{n} - \frac{y}{n} = 0$$





signal in case of an Oxygen X-rays excess of 3%



Summary

- **FAMU Experiment:**
  Designed for high-precision measurement of the hyperfine splitting in muonic hydrogen
- **July 2023:** Experiment achieved fully operational status for the first time after years of methodological development.
- **2023-2024:** Flawless operation of the experimental setup, enabling precise wavelength scanning within 625pm.
- **Fall 2025:** more physics runs and data collection.
- **Data Analysis in Progress**
  Stay tuned for next results!

Thank you for your attention