# The FAMU experiment at RIKEN RAL for a precise measurement of the Zemach proton radius

M.Bonesini

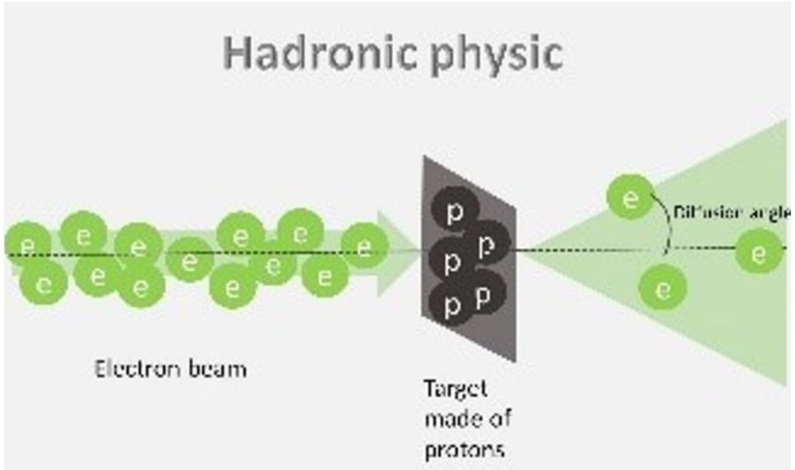
Sezione INFN Milano Bicocca, Dipartimento di Fisica G. Occhialini, Universita' di Milano Bicocca

On behalf of the FAMU Collaboration

# The “starting point”

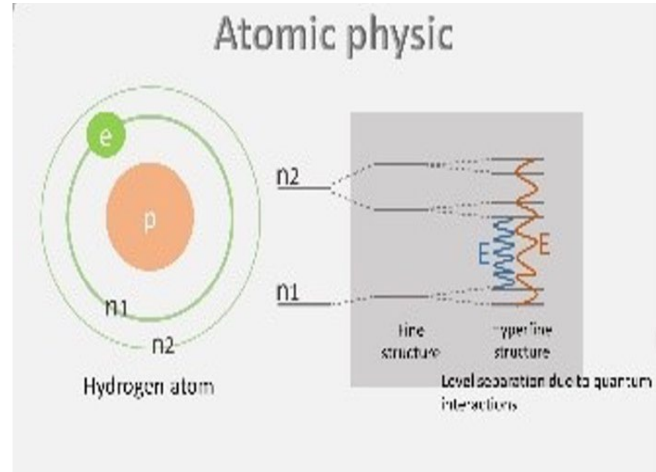
***The early start of the research work linked to the FAMU experiment is related to the Report of the Stopped Muons Working Group for the ECFA-CERN study on Neutrino Factory & Muon Storage Rings at CERN [Physics with Low-Energy Muons at a Neutrino Factory Complex, J Aysto et. al arXiv:hep-ph/0109217v1]. In that document the potentials of high precision spectroscopy in muonic atoms and in particular of muonic hydrogen was underlined.***

# the proton charge radius




***Spatial charge and magnetic moment distributions $\rho_E(r)$, $\rho_M(R)$ in non-relativistic picture .***
***The complete set of moments $R^{(k)}_{E,M}=\int \rho_{E,M}(r) r^k d^3r$ is related to the observable quantities:***

$$r_E=(R^{(2)}_E)^{1/2}$$
$$R_Z=\int \left(\int \rho_E(r')\rho_M(r-r')d^3r' r\right)d^3r$$

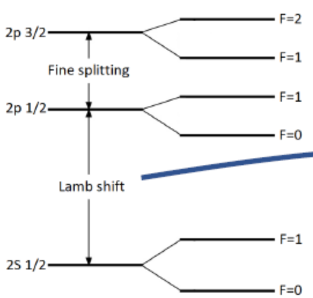



Defined as: $$r_E^2 := -6\left.\frac{dG_E}{dQ^2}\right|_{Q^2\to 0}$$

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.

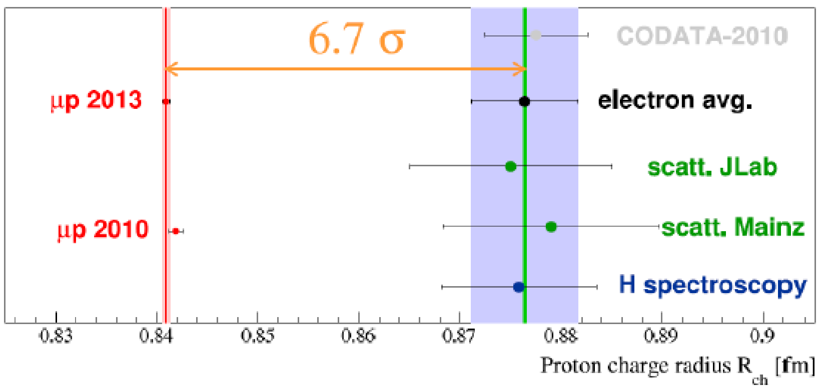



Lamb shift in H has leading order dependency on the charge radius:

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

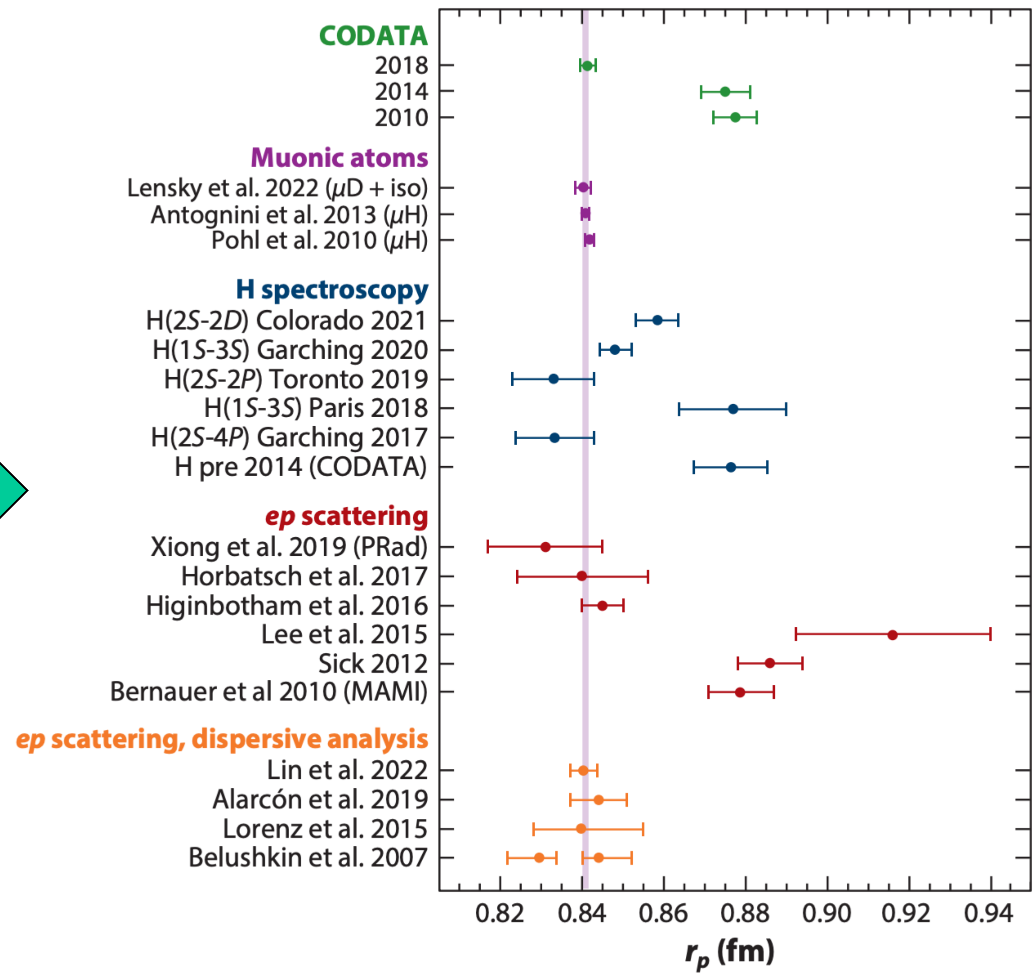
**spectroscopy** technique.

# The anomaly: the proton radius puzzle



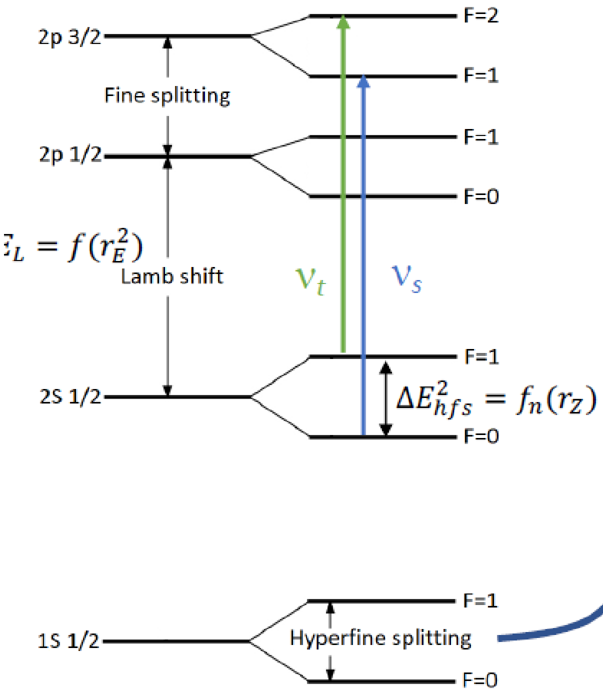

*2010 situation: 6.7 s discrepancy between electron and muon measurements*


*2020 situation: with new measurements PRRAD …*



# The proton Zemach radius

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




By means a linear combination of $\nu_t$ and $\nu_s$ it has been evaluated:

- $\Delta E_L \to r_E$, Pohl et al. Nature 466, 213 (2010)
- $\Delta E^2_{hfs} \to r_Z$, Antognini et al. Science 339 417 (2013)

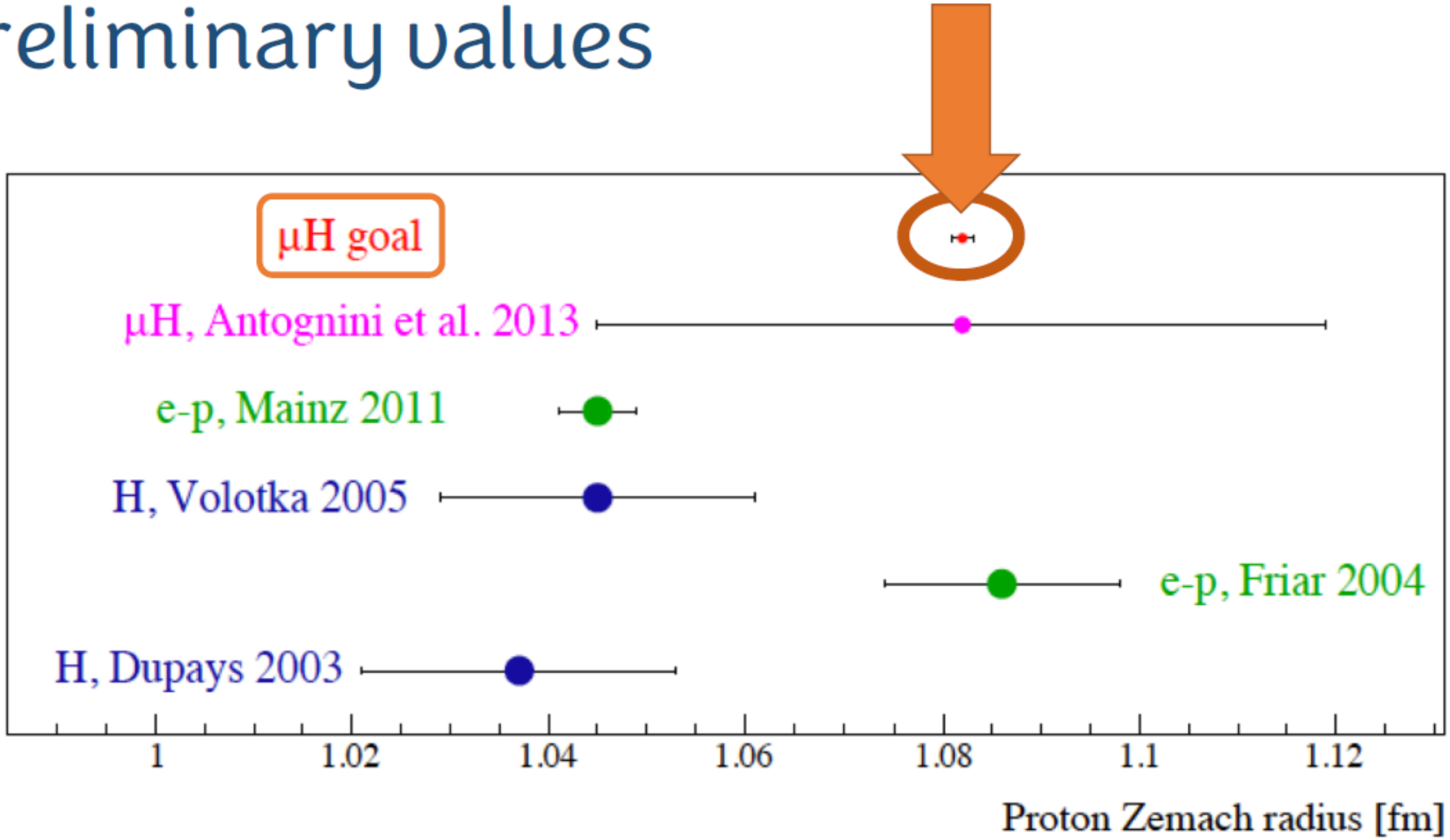
Leading order dependency on the hyperfine splitting:

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

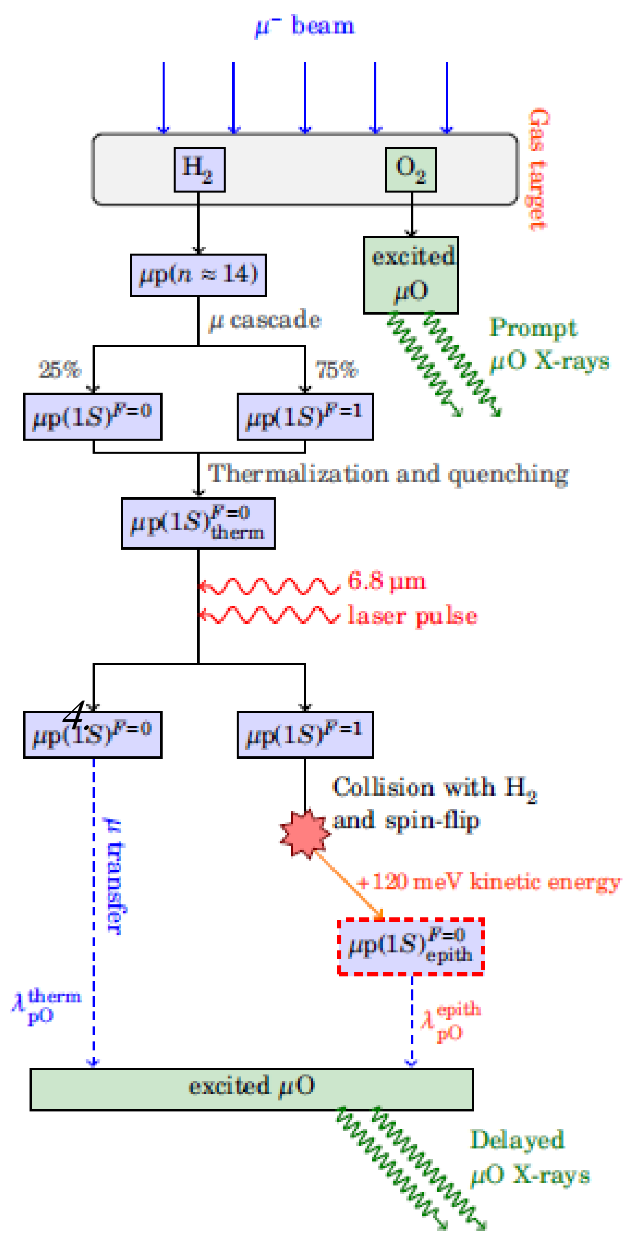
8

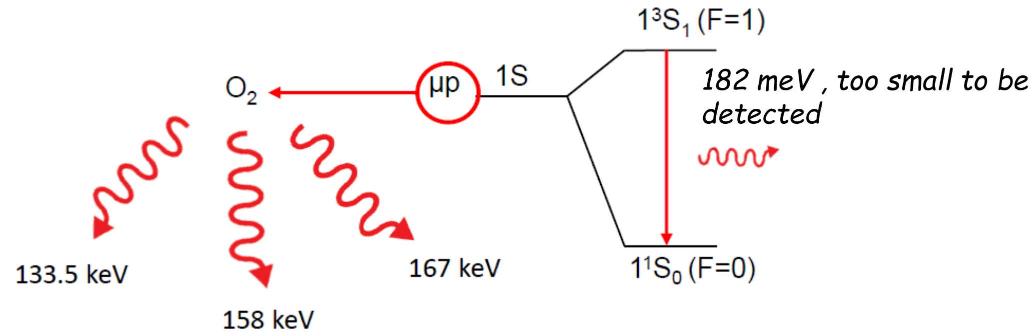
# Our goal

## Preliminary values



# The FAMU (Fisica degli Atomi Muonici) experimental method




*1. Create muonic hydrogen in a hydrogen gas target and wait for its thermalization;*

*2. Shoot laser at resonance ($\lambda_0$ ~6.8$\mu$) spin state of $\mu^-p$ from $1^1S_0$ to $1^3S_1$, spin is flipped: $\mu^-p(\uparrow\downarrow) \rightarrow \mu^-p(\uparrow\uparrow)$ ;*

*3. De-excitation and acceleration: $\mu^-p(\uparrow\uparrow)$ hits a H atom. It is depolarized back to $\mu^-p(\uparrow\downarrow)$ and is accelerated by ~120 meV ;*

*4. $\mu^-$ are transferred to heavier gas contaminant ($O_2$) with energy-dependent rate;*

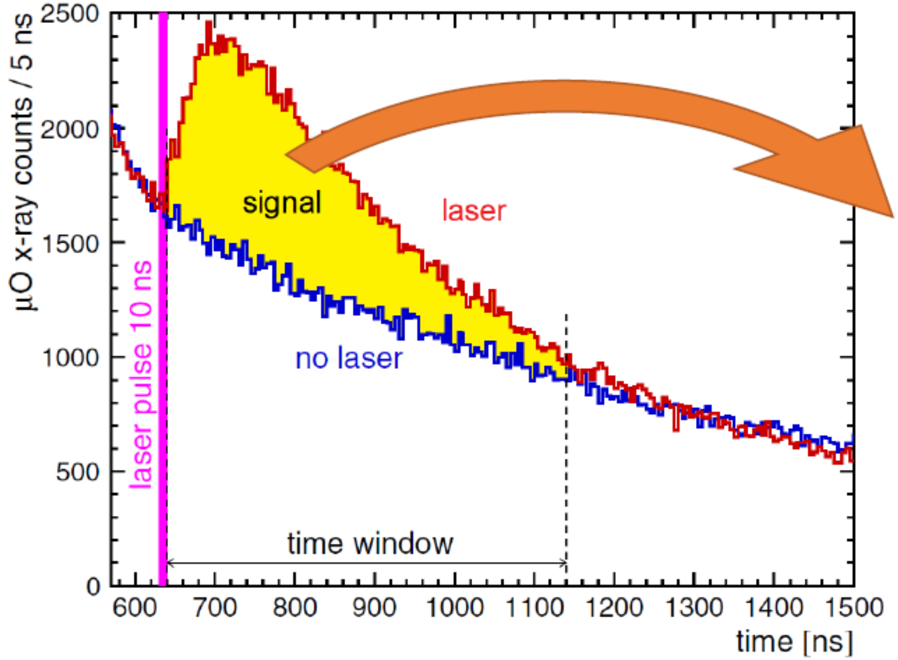
*5. laser resonance $\lambda_0$ is determined by maximizing the time distribution of $\mu^-$ transferred events.*

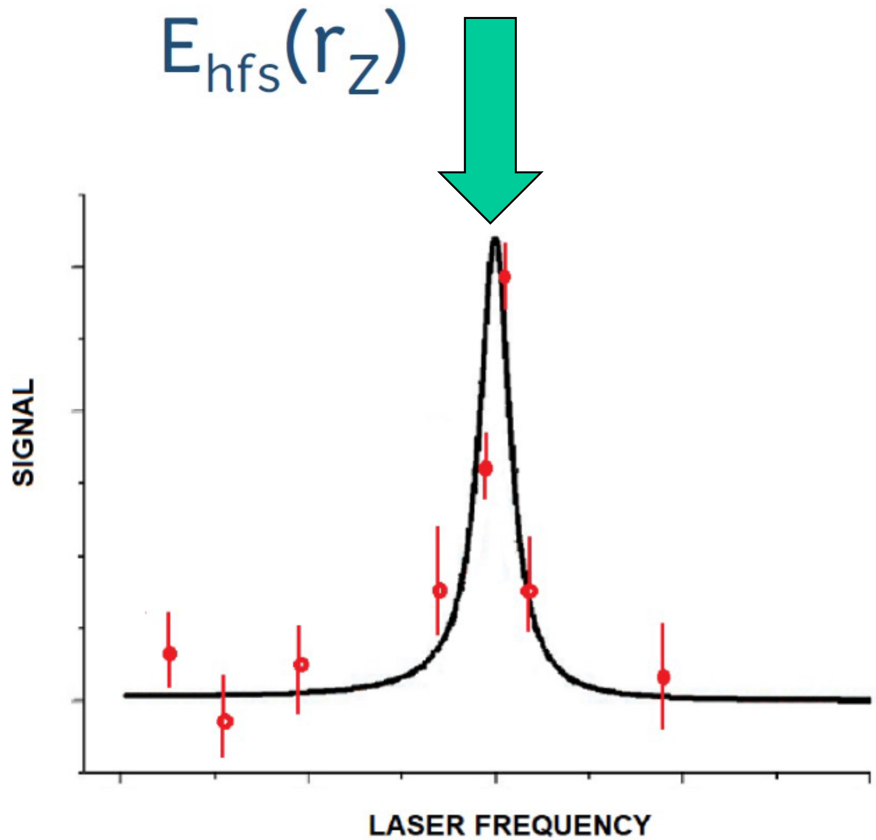
*6.At this point $E_{HFS}$ is determined from:*

$\lambda_0 = hc/\Delta E^{1S}_{HFS}$ ~ 6.8 µ ~ 0.183 eV

with high precision

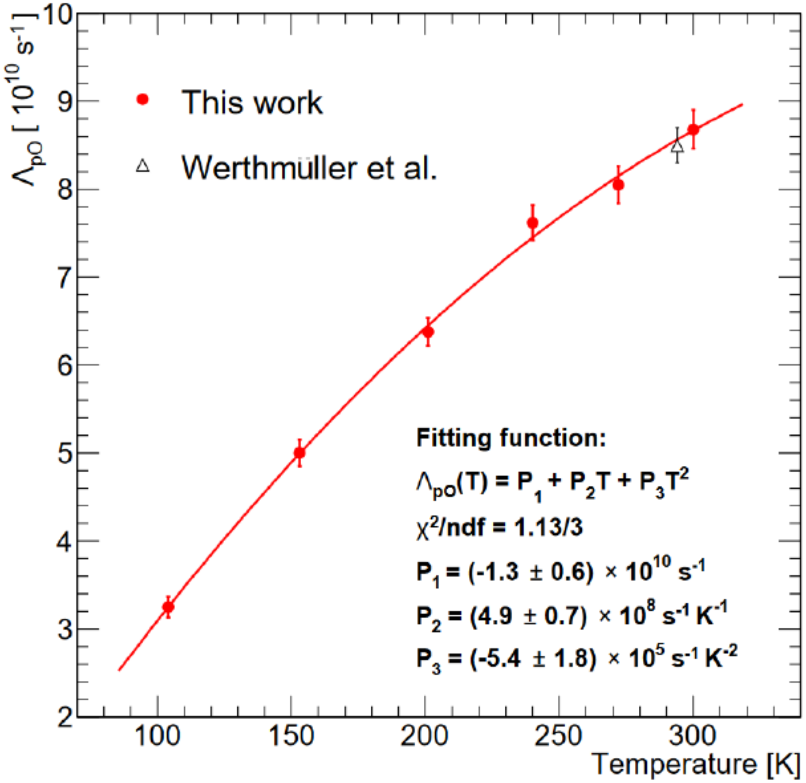
# The FAMU exp method (II)

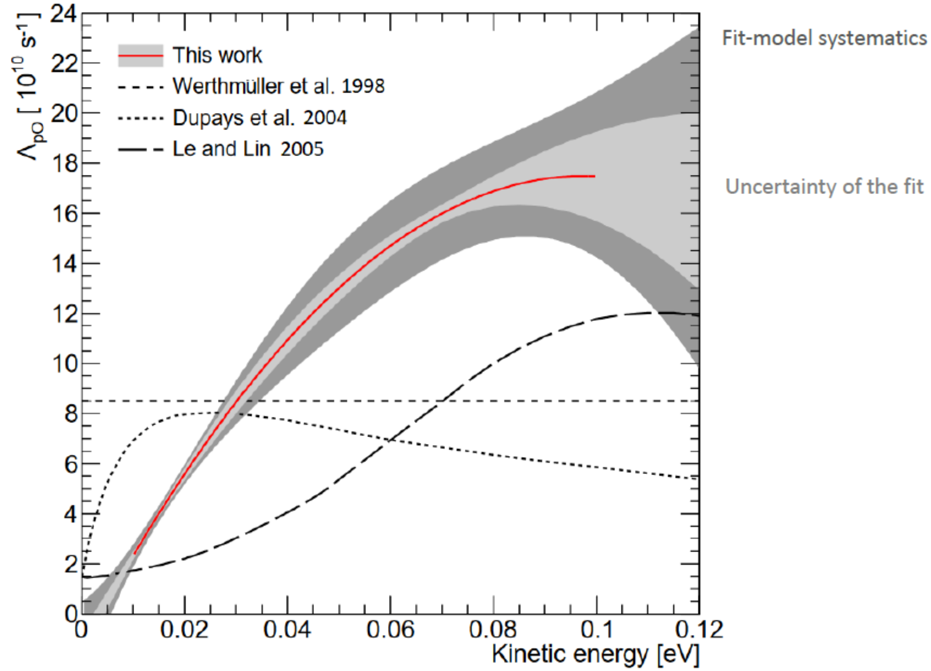


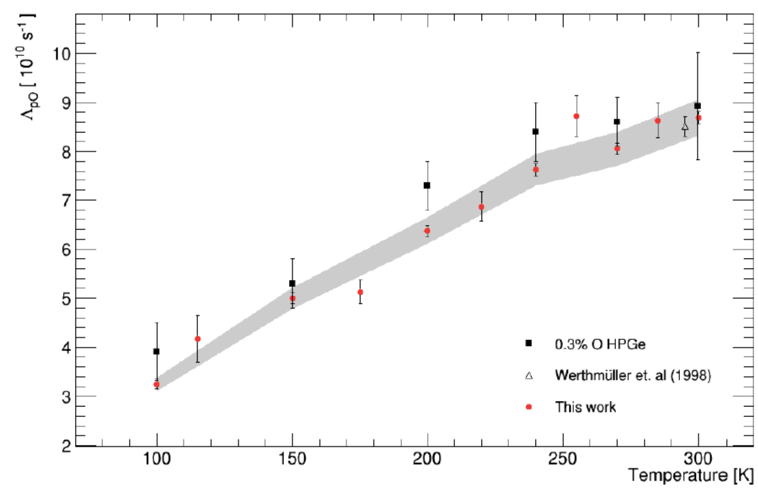




Observable: excess of delayed µO X-rays when the laser is turned on.

# μp transfer rate to Oxygen (measured by FAMU)



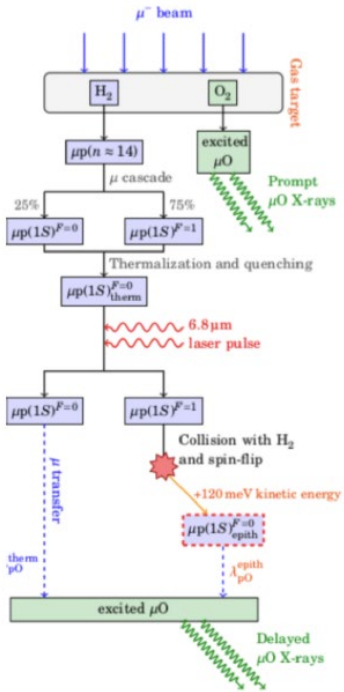




$$dN_{\mu p}(t) = S(t)dt - N_{\mu p}(t)\lambda_{dis}dt$$

$$\lambda_{dis} = \lambda_0 + \phi\,(c_p\Lambda_{pp\mu} + c_d\Lambda_{pd} + c_O\underline{\Lambda_{pO}})$$

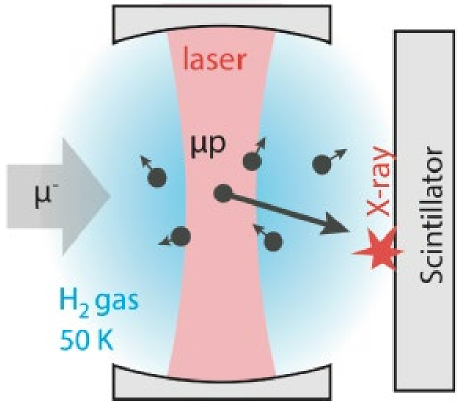
# Three μp-HFS projects

FAMU



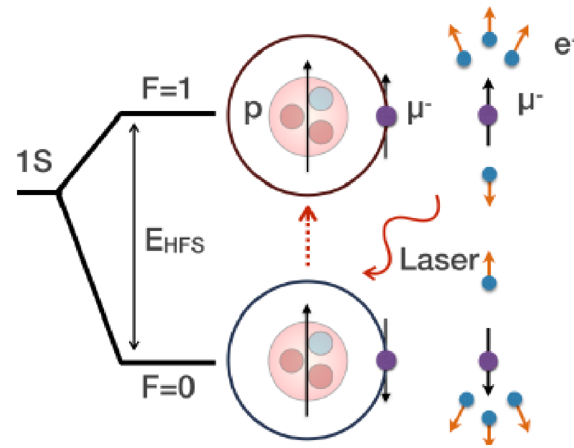

FAMU
energy dependent transfer rate
to admixed oxygen

PSI




PSI
energy dependent
transfer rate to the target wall

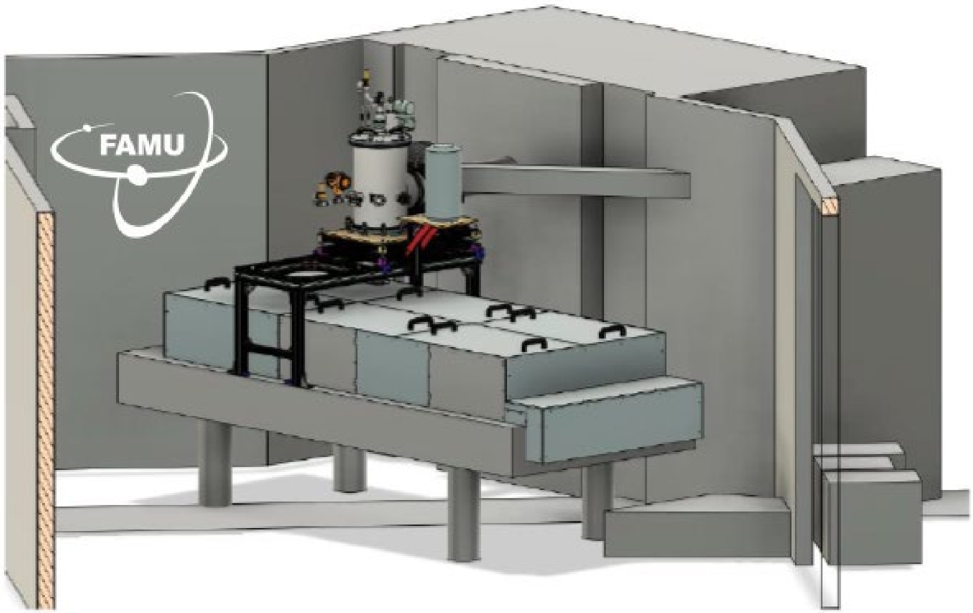
RIKEN




RIKEN
muon spin repolarization
with laser

| | FAMU (UK) | CREMA @PSI | RIKEN (JP) |
|---|---|---|---|
| Method | transfer | diffusion | asymmetry |
| Laser | DFG-MIR 1-5 mJ | | QCL-seeded ZGP-OPO<br>> 20 mJ in development |
| Detection | X-rays | X-rays | electrons |
| Beam | pulsed | continuos | Pulsed |

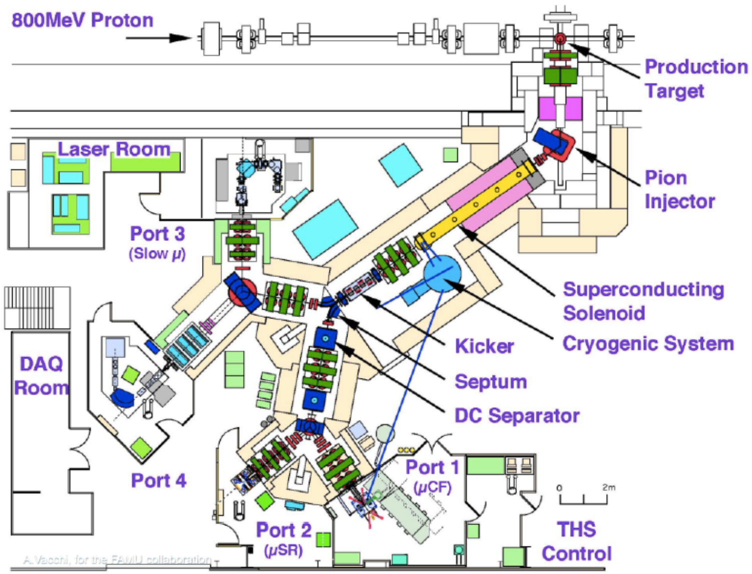
# The FAMU collaboration



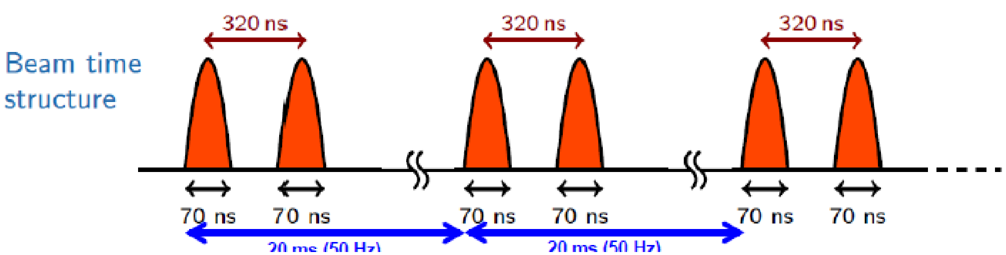

*Around 60 collaborators (75 % Italians) from 20 Institutes*

# The RiKEN-RAL muon facility at RAL

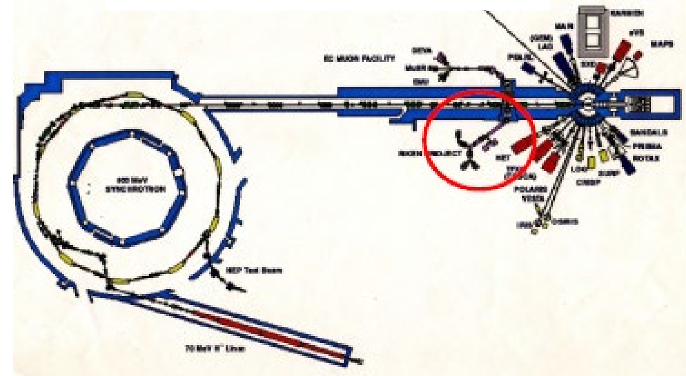
## RIKEN-RAL facility




***Typical beam size ~10 cm$^2$***
***$\Delta p/p$ FWHM 10% (decay), 5% (surface)***
***Double pulse structure (see below)***




## ISIS at RAL



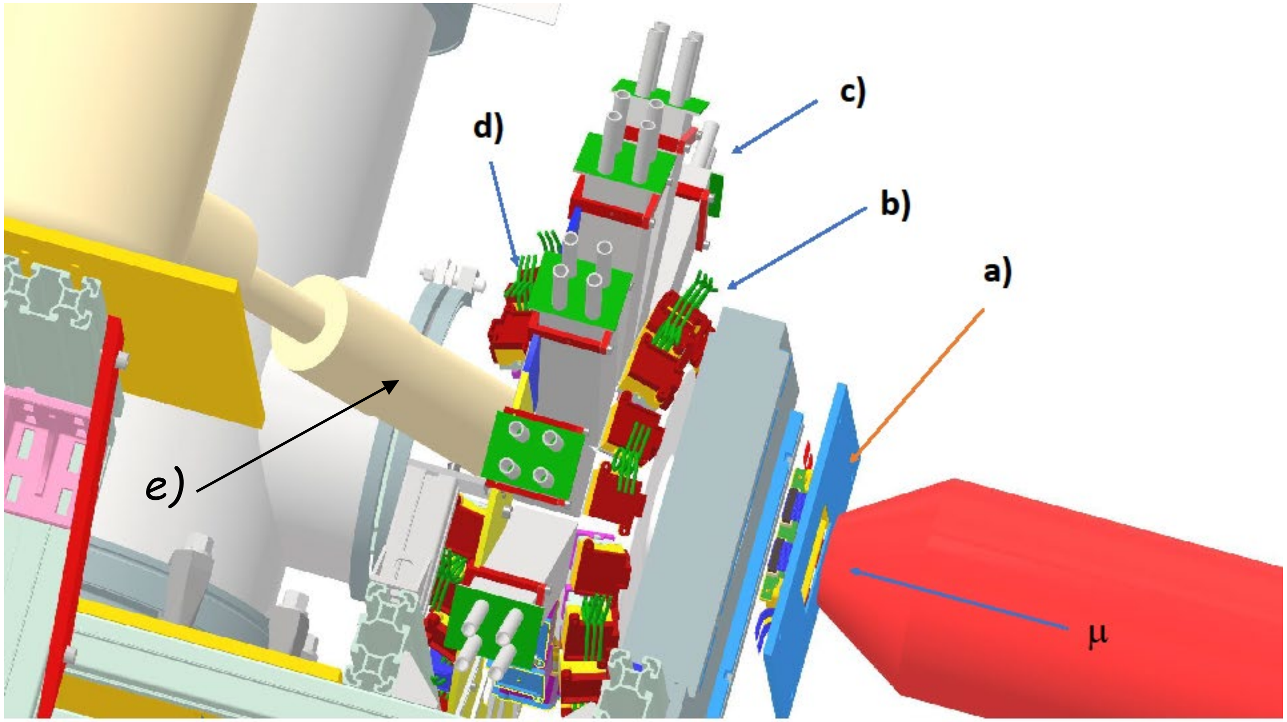
***800 MeV p accelerator , 200 mA, 50 Hz***


***The RIKEN-RAL facility: 4 experimental ports. FAMU presently use port 1 and has used port 4 for previous runs (2014-2016) .***

# The FAMU proposal experiment steps

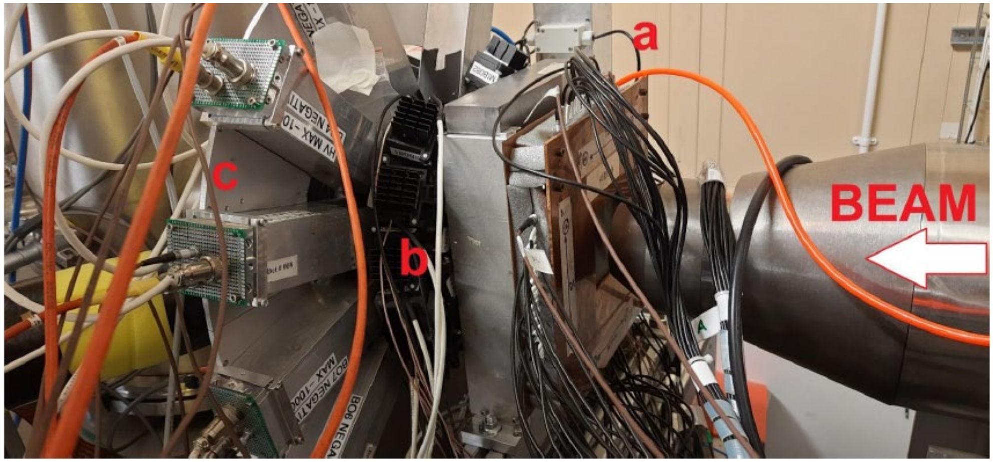
1. Muon beam study, target and detectors tests, preliminary measure of transfer rate (@ constant conditions of PTV) – 2014 beam test
2. Optimize run conditions: best gas mixture at temperature T and pressure p (to be determined) to observe and measure the transfer rate energy dependence – several runs from Dec 2015 up to December 2018
   → At this point the validity of the method to measure HFS is demonstrated
3. Full working setup with laser and cavity to determine proton Zemach radius (2019-2020)
4. Data taking (2023 - …) delayed due to COVID-19 pandemia + ISIS long shutdown for upgrade of target station

# The final FAMU detector setup (2023 run)

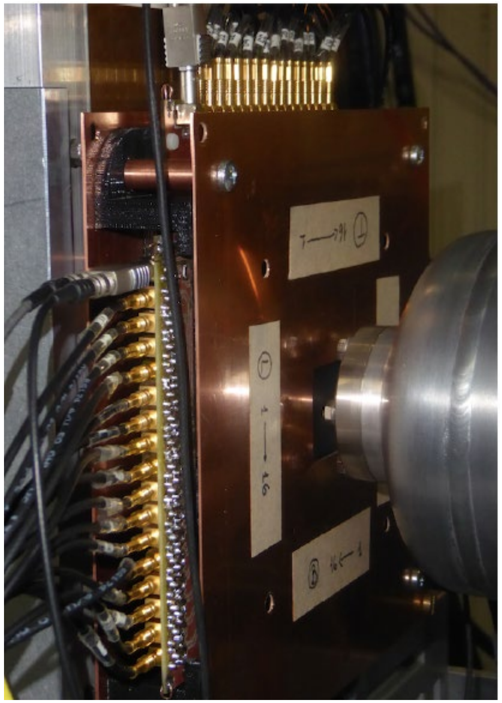


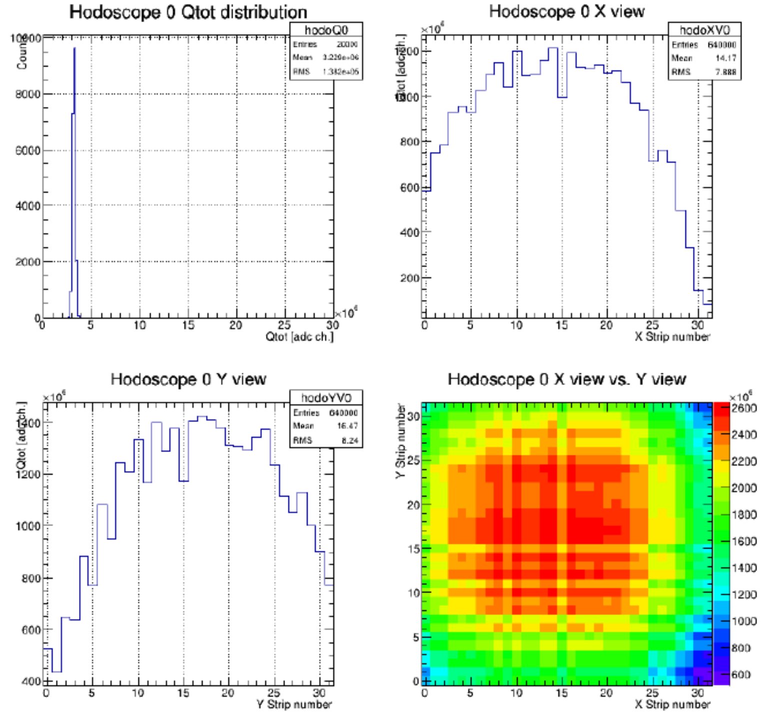

a) Beam hodoscope (1mm pitch)
b) Upstream 1″ LaBr3:Ce detectors (10) with SiPM array readout
c) Central crown with 1″ LaBr3:Ce detectors with PMT readout (6) and with SiPM array readout (6)
d) Downstream $\frac{1}{2}$″ LaBr3:Ce detectors with SiPM array readout (12)
e) one HPGe high resolution detector for inter-calibration

Foreseen upgrade for 2024 run: replacement of 12 $\frac{1}{2}$″ LaBr3:Ce detectors with 10 1″ ones

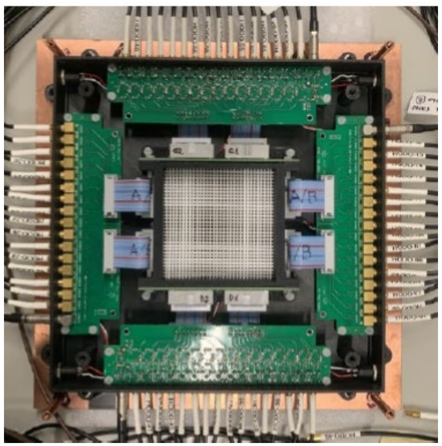


# Beam hodoscope






*→it is impossible to resolve single-muon response*
*→single-particle response function has to be measured and used to estimate the number of muons per each spill at RAL.*

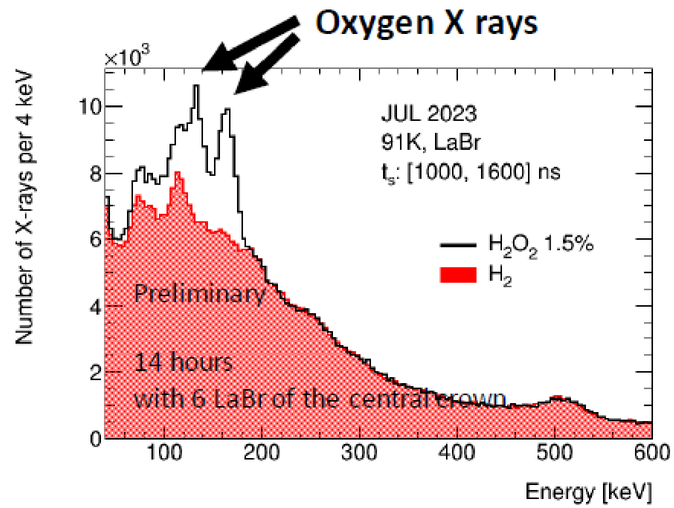


*Inside the beam hodoscope*

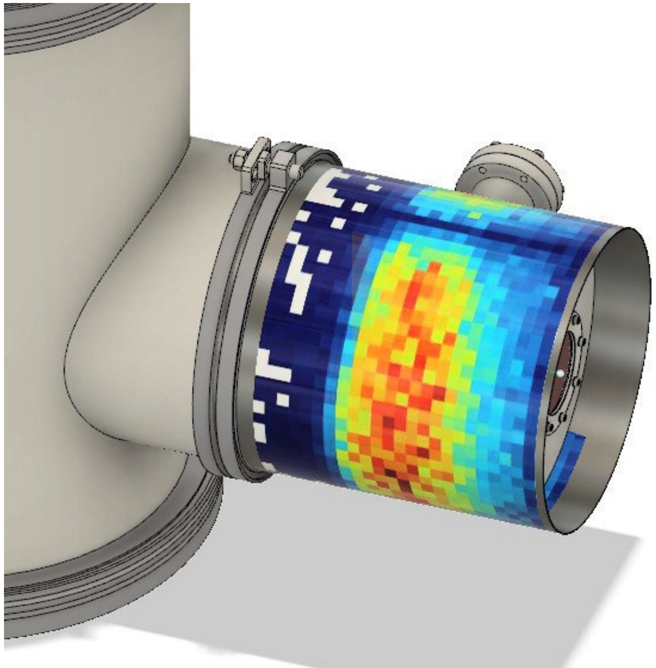
- *2 planes (X/Y) with 64x 64 mm² active area*
- *1 mm square BCF12 from Bicron with EMA coating (to avoid cross-talk) read by Hamamatsu SiPM + 1 mm Air*
- *Alternate up/down-left/right readout for 32+32 X/Y chs*
- *Mechanics printed out on 3D printer*
- *Readout with CAEN V1742 FADC ( waveform info)*
- *One side (16 channels) is powered by a single HV channel*
- ❑ *x/y beam RMS resolution (after collimator) ~7/8 mm*

# X-rays detectors

- *High statistics: maximize solid angle coverage & detection efficiency (fast risetime, pile-up rejection)*
- *Excellent control of detector behavior: minimize noise and unexpected behavior (tails/cross-talk,undershoots ..)*
- *Energy range: best @ 100-200 KeV, with some efficiency at higher ones*

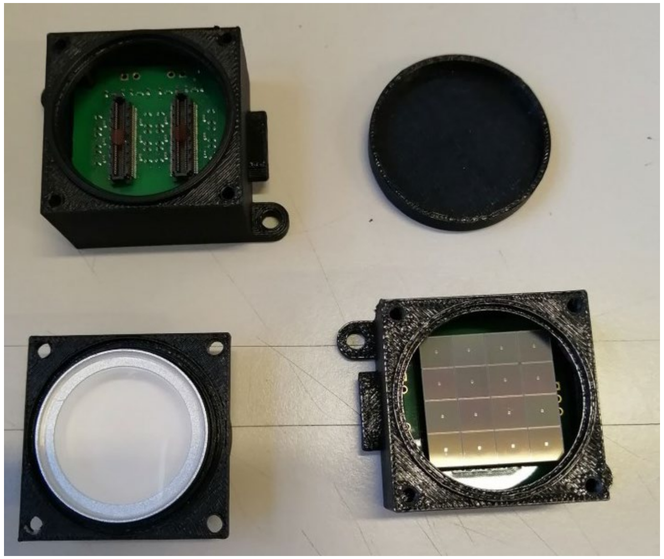



Energy spectrum 500 ns after muons arrival, 14 hours data taking [only 6 detectors]



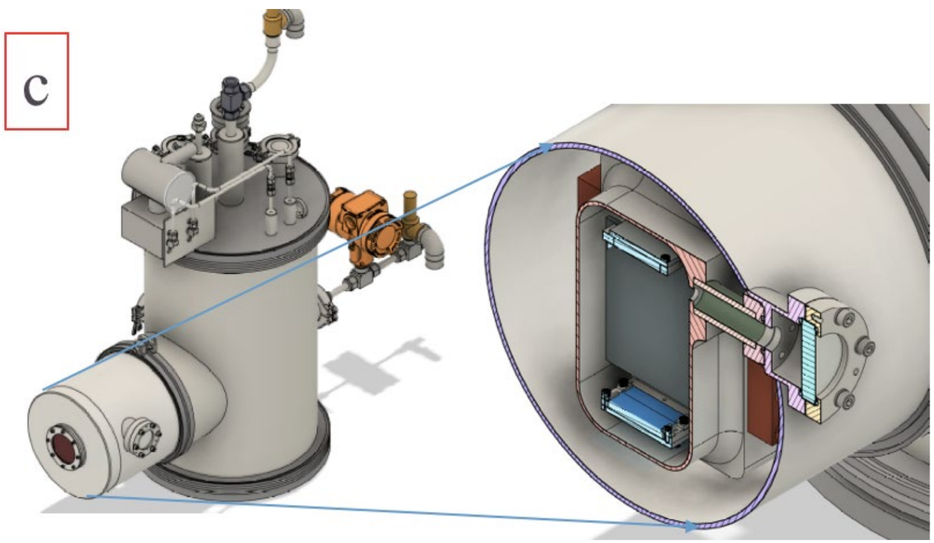
*X-rays distribution from simulation*

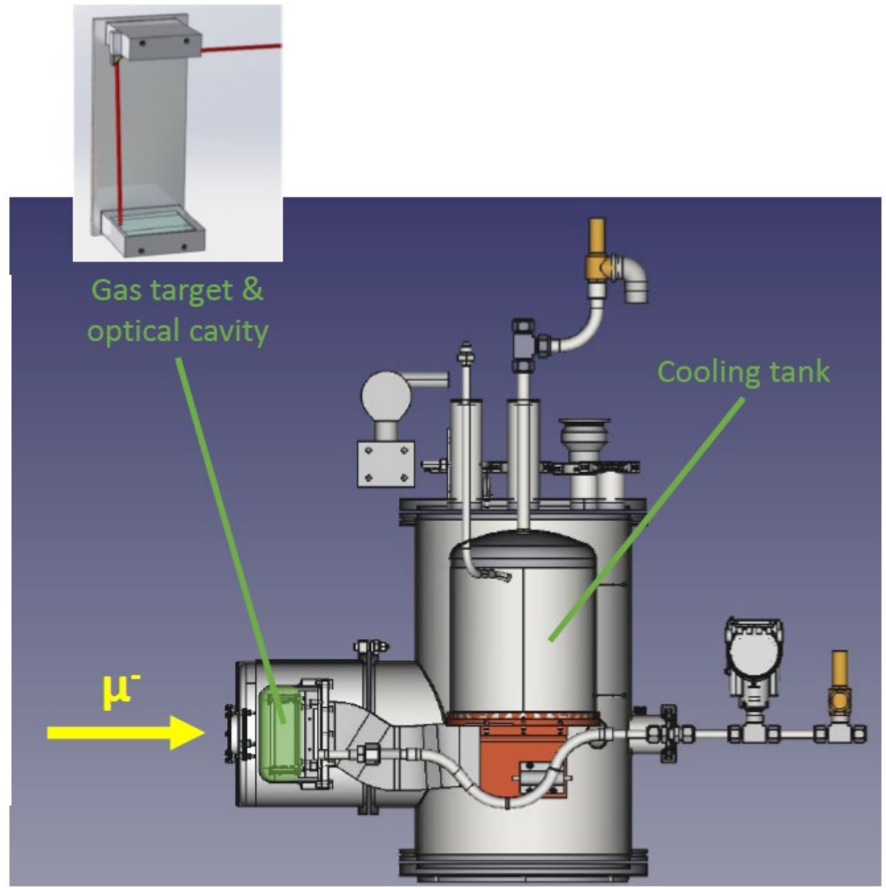
*1" LaBr3:Ce detectors with SiPM array readout*



# Cryogenic target

- *Geometry and working conditions optimized via MC simulations and previous experimental data taking (2014-2018)*
- *Optical cavity size: 3x3x10 cm$^3$ (multipass to increase laser – muons interactions)*
- *Temperature 80 K*
- *Pressure 7 ba*
- *Gas mixture: 99% H2, 1% $O_2$*



# MIR laser working principle

Innolas Nd:YAG laser commercially available → **1064 nm beam**

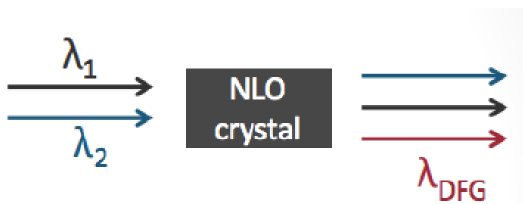
**1262 nm beam** ← Cr:forsterite laser developed within the collaboration

↓

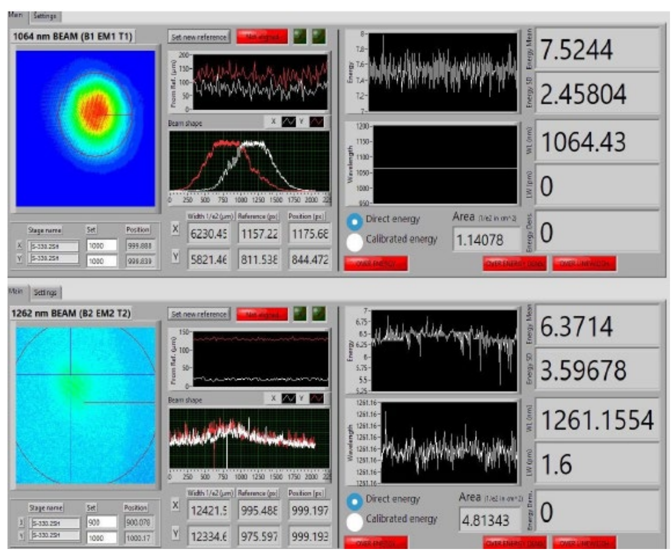
**Coupling of the beams** ← Beams synchronized in time; Beams aligned in space; Characterization of the beams

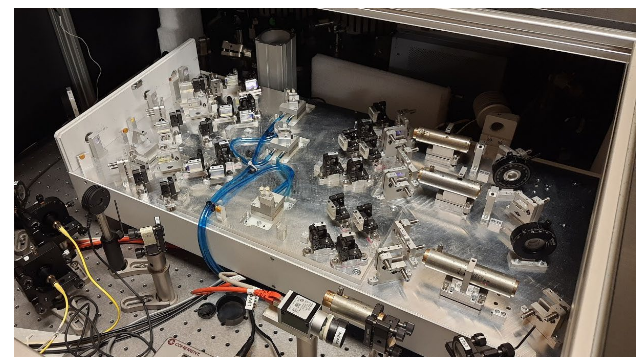
↓

**DFG process 6,78 um beam** ← Using nonlinear crystal; Energy and wavelength measurements; Beam to the target



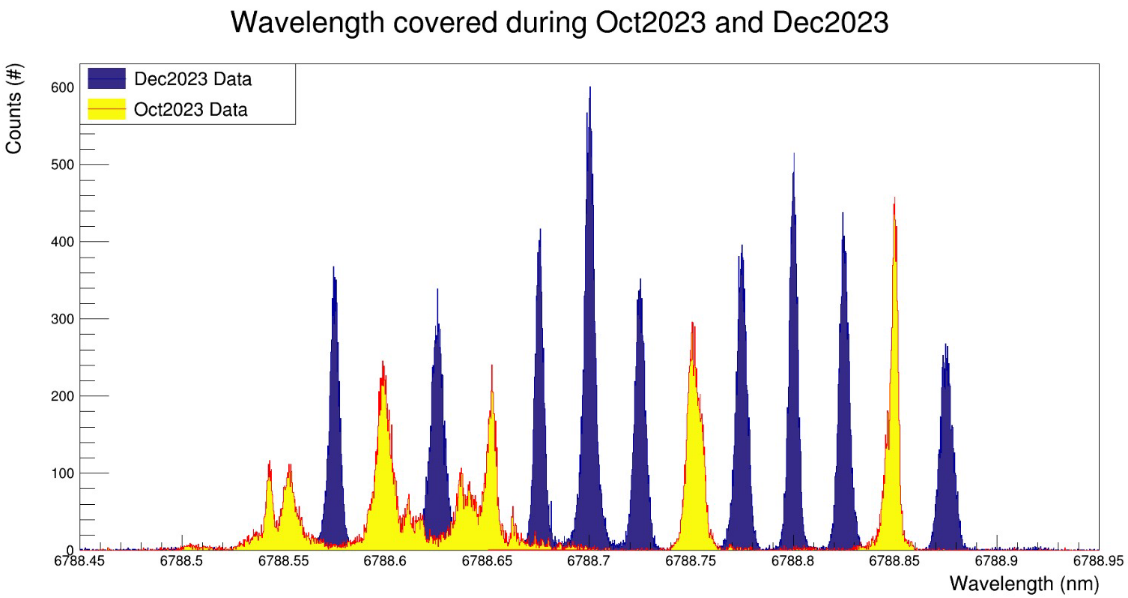

$$\lambda_{DFG}^{-1} = \lambda_1^{-1} - \lambda_2^{-1}$$



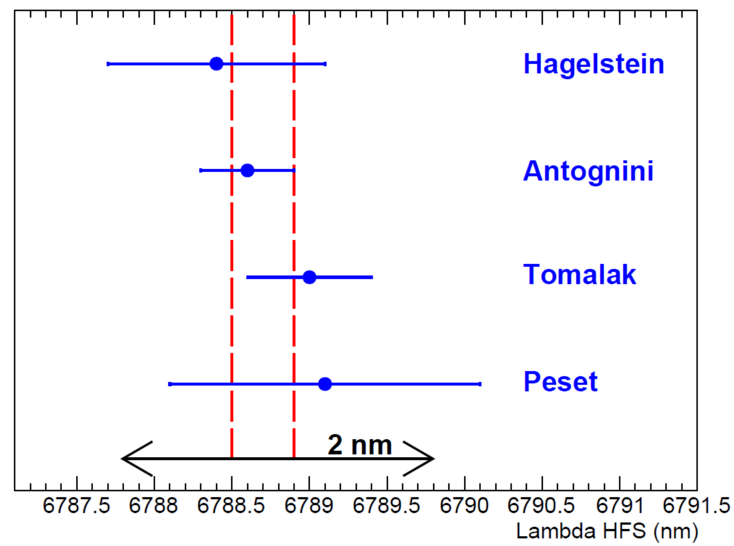



| | | |
|---|---|---|
| Wavelength range | 6800 ± 50 nm | ≈ 44 THz |
| Energy output | > 1 mJ | Progressiv. up to >4 mJ |
| Linewidth | < 0.07 nm | 450 MHz |
| Tunability steps | 0.03 nm | 200 MHz |
| Pulses duration | 10 ns | |
| Repetition rate | 25 Hz | |

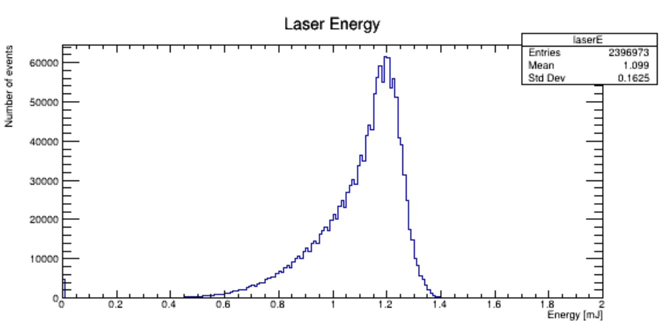
# 2023 data taking: covered wavelengths




- ❑ Measurement range: [6786.5 ; 6791] nm (width 4.5 nm)
- ❑ 100 runs to cover the foreseen range with 45 pm steps



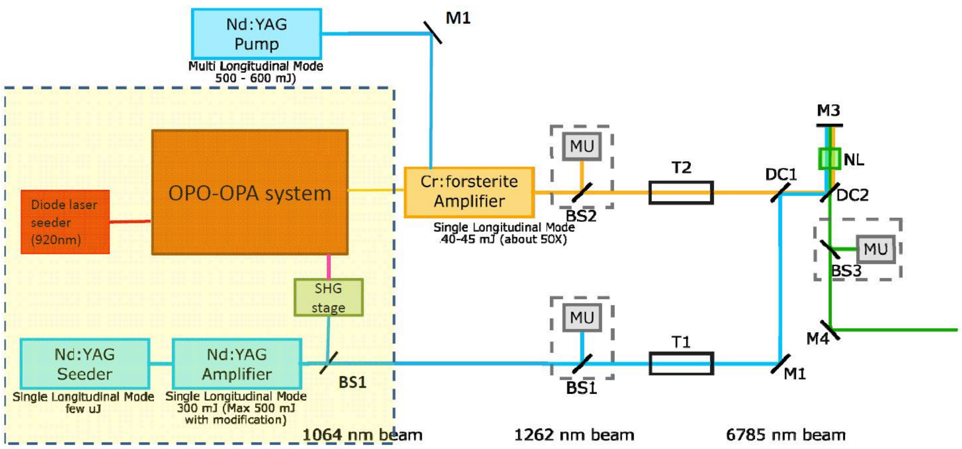

*Theoretical predictions for the hfs energy of muonic hydrogen*




*Laser energy*

# Foreseen upgrades/possible interaction at CERN

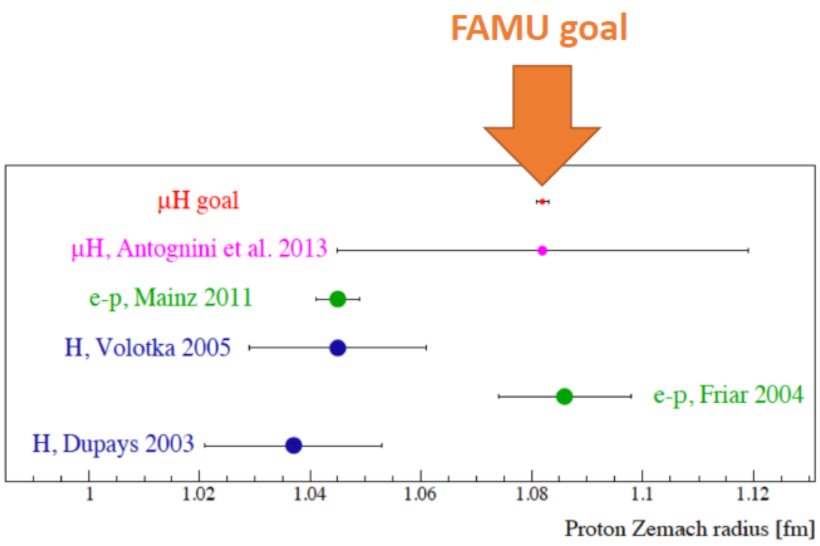
- PRIN 2022: MENPHYS (MEtrology and Nonlinear optics for Precision muonic HYdrogen physicS) to develop, implement and apply the most advanced nonlinear optical methods and laser technologies to strengthen the potentials of the FAMU experiment. Replace the current Cr:Forsterite laser system with tunable emission at 1262 nm with an Optical Parametric Oscillator/Amplifier with improved performances in terms of output energy (x2), stability and spectral purity




- Interactions inside PBC forum to enlarge scope of our project (AMBER,exotic atoms studies, …)
- Interactions with CERN to improve our apparatus (targetry, X-rays detectors, laser setup, optical multipass cavity, …)

# Conclusions

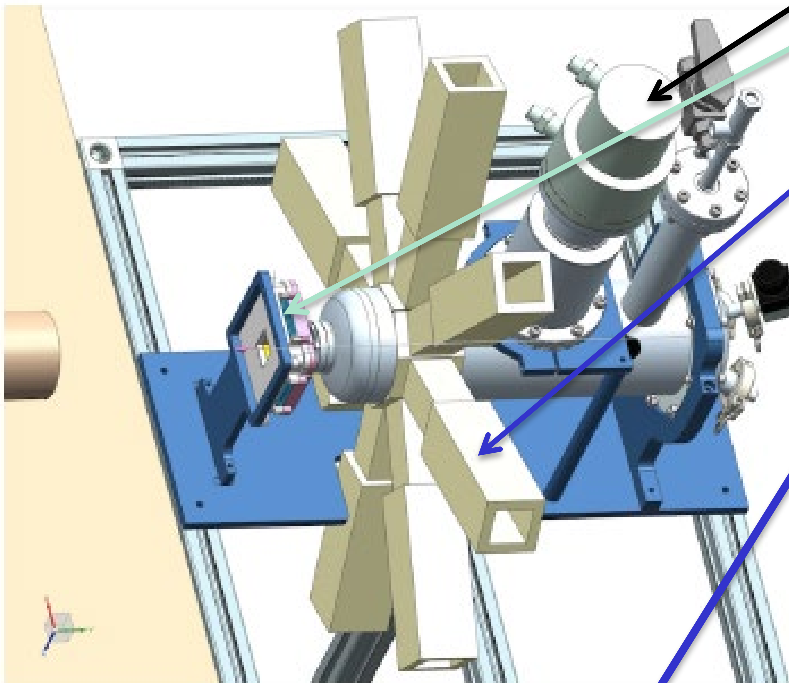
- FAMU is finally taking data from 2023 after delays due to COVID-19 pandemics & ISIS upgrades
- Aim: measurement of *hfs* in μH with $10^{-5}$ relative uncertainty, in order to obtain $r_Z$ with uncertainty of around 1%.
- Main references:
  - C. Pizzolotto et al., Eur. Phys. J. A, 56 7 (2020) 185.
  - A. Vacchi et al., "Investigating the Proton Structure: the FAMU Experiment", Nuclear Physics News, https://doi.org/10.1080/10619127.2023.2198913



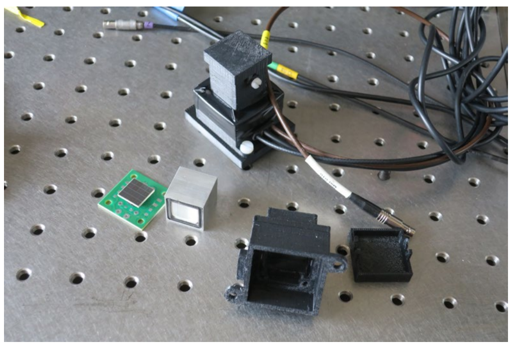

# Backup material

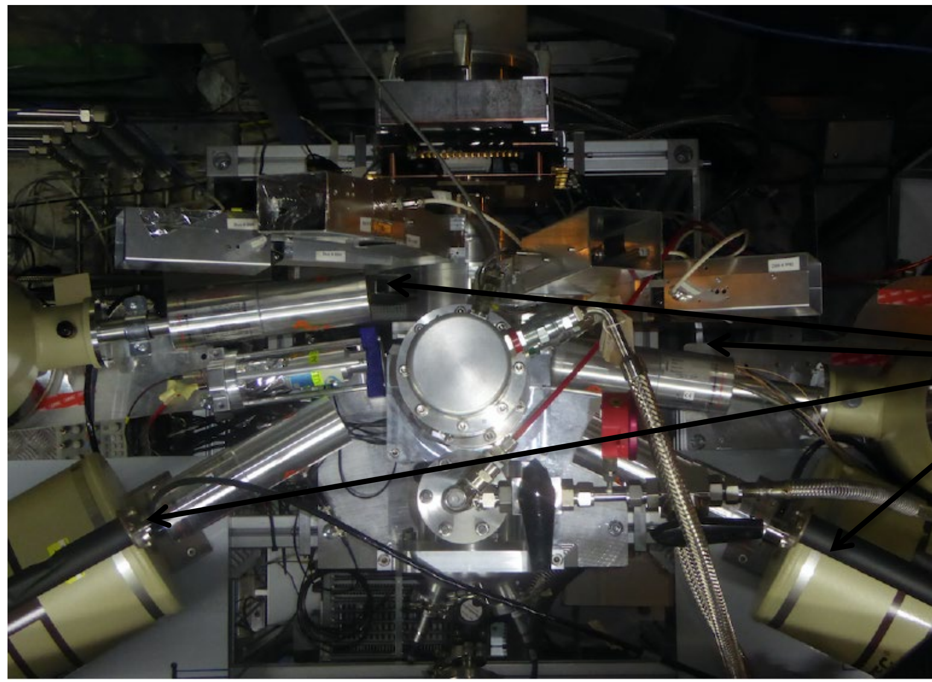
# The setup for the 2015-2018 run

- ❑ *Cryogenic target*
- ❑ *Beam hodoscope with 1 mm pitch (scintillating fiber with SiPMT readout)*
- ❑ *LaBr3 crystals with PMT readout (8 detectors arranged as a star) for X-ray fast detection*
- ❑ *Complemented by 8 ½" Labr3 crystals read by SiPM arrays to equip difficult regions*
- ❑ *HpGe detectors for precise X-rays detection (4)*

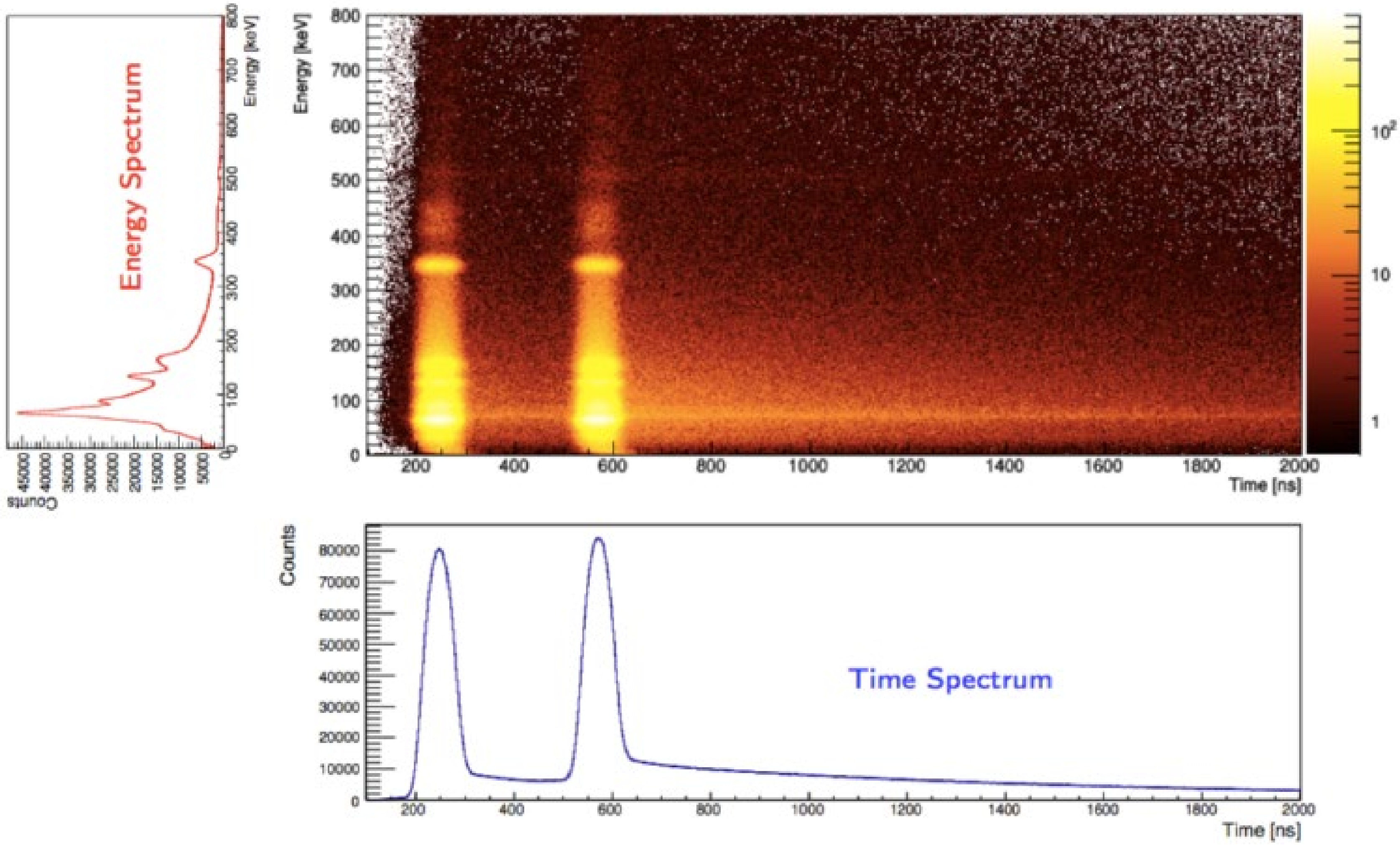


*a croppy layout*



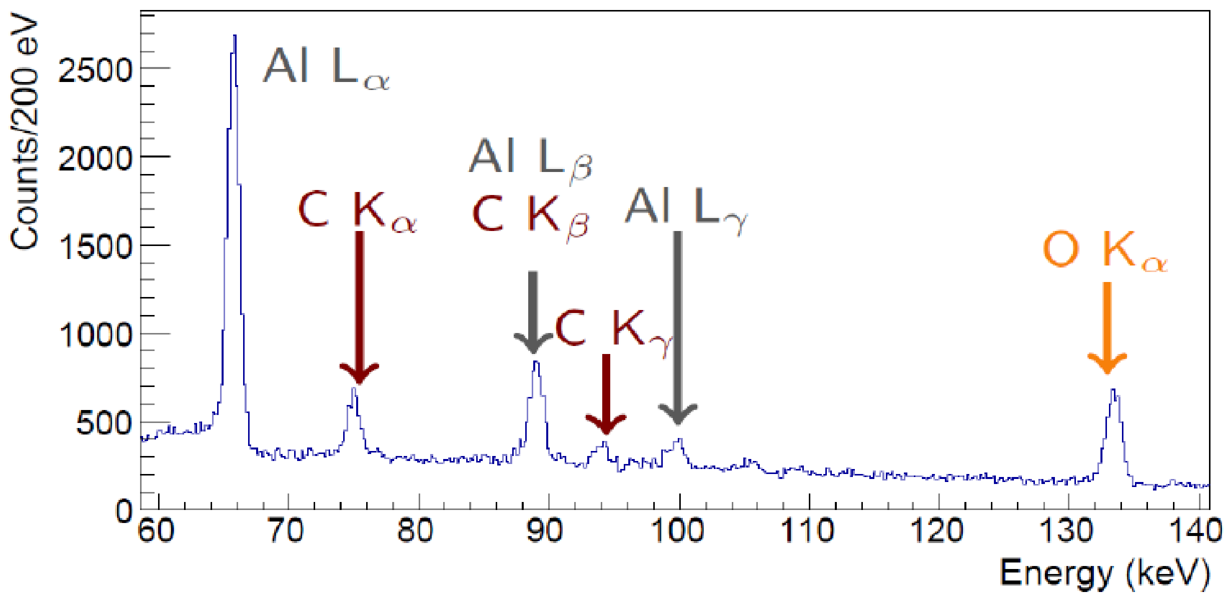


# A snapshot of X-rays spectrum

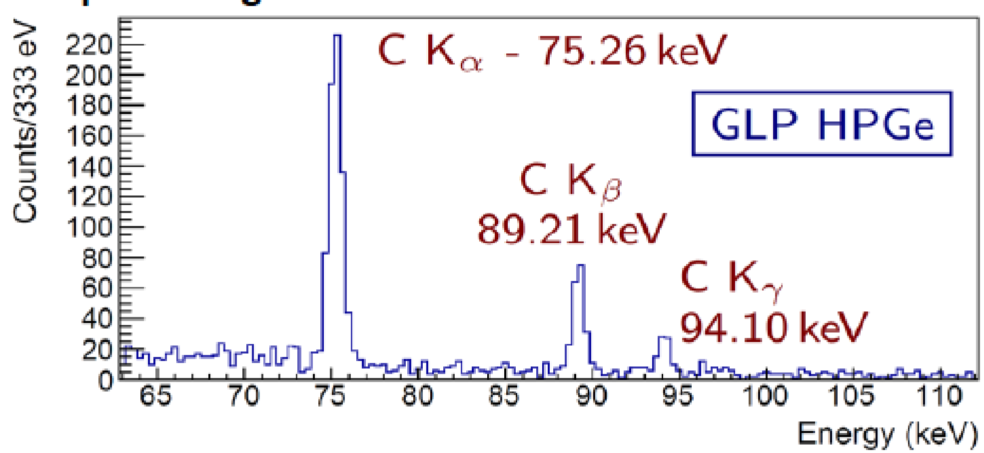


# Detector performances: HpGe detectors

$H_2$ + (4% w/v)$CO_2$ gas mixture in aluminium container

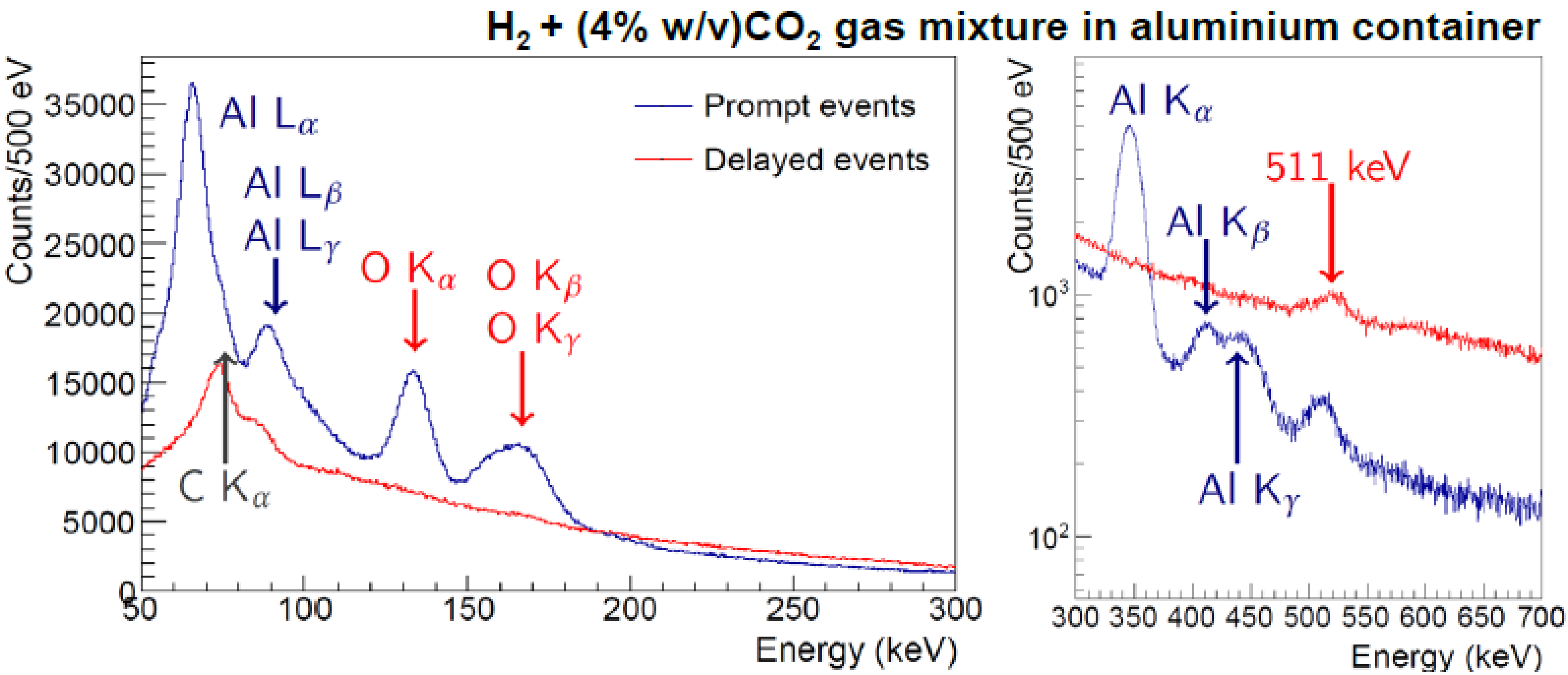


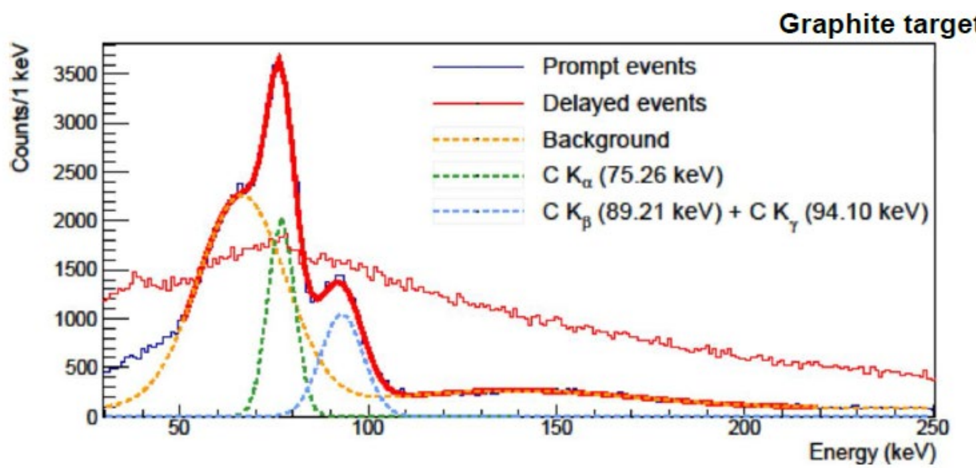

Graphite target




***Used for inter-calibration : high energy resolution, limited timing resolution***

# Detector performances: LaBr3(Ce) detectors

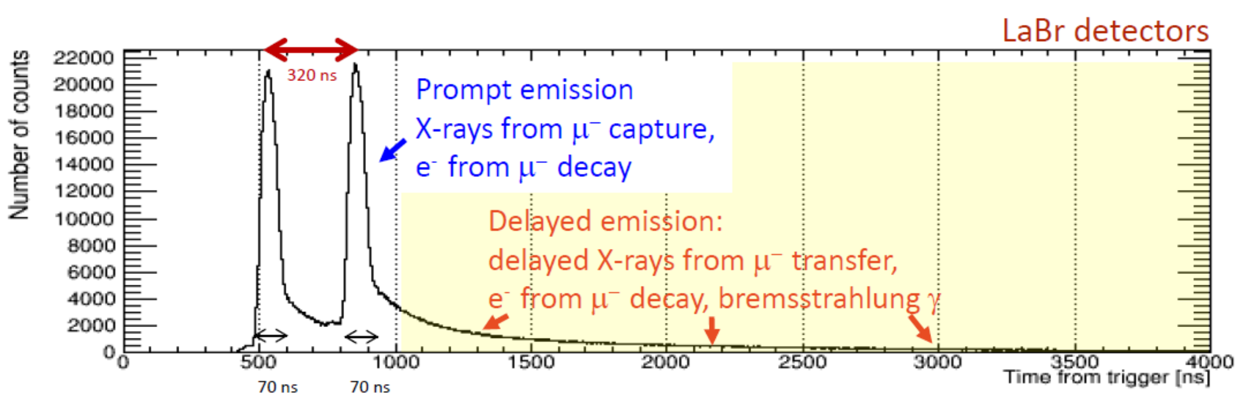



- ***In these plots we see both***
- ***prompt X-rays (in time with beam spill) → reflect beam spill structure***
- ***Tails of the distribution (products of $\mu$ decay) → convey infos on muonic atom lifetimes***

# Physics measurements: transfer rate μp→ μO

- Transfer rate measured as a function of temperature
  - Target filled $H_2$+(120 ppm)$O_2$ at 41 bar at 300 K
  - Six temperatures (300, 272, 240, 201, 153, 104 K)
  - Each temperature kept stable for three hours each
- At each trigger we acquire a window of 10 microsecond
  - Produce μp's and wait for their thermalization (about 150 ns)
  - Study the time evolution of Oxygen X rays



# Muonic transfer rate measurement