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Facilities Council

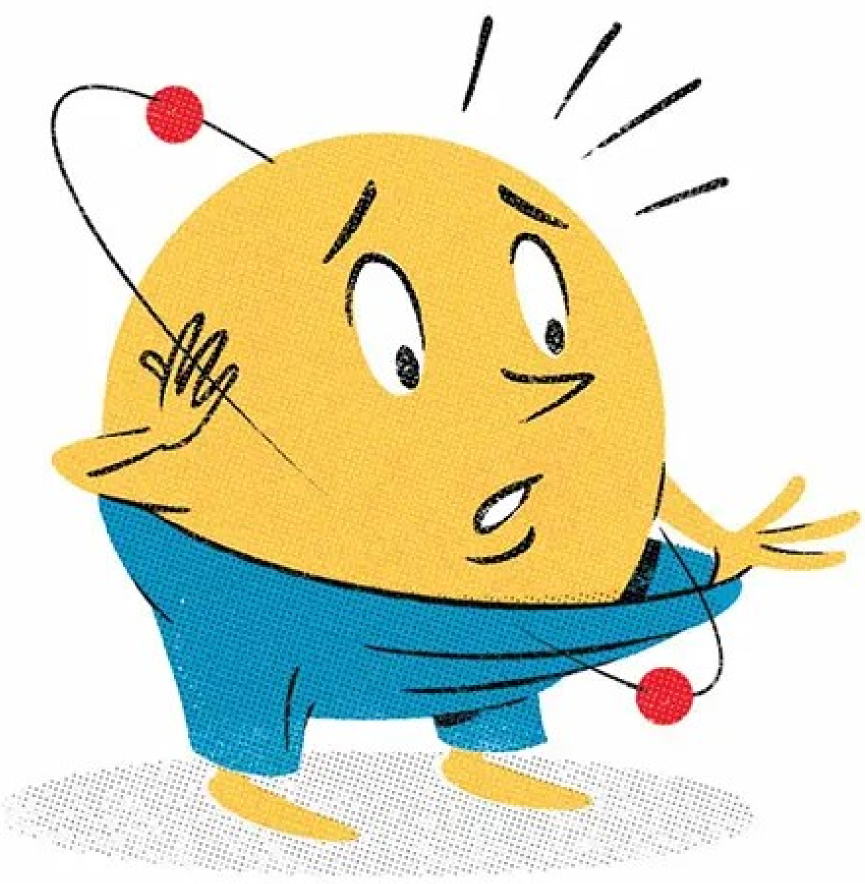
ISIS Neutron and
Muon Source

FAMU

16th Topical Seminar on Innovative Particle and Radiation Detectors (IPRD23)
Siena, 25-20 September 2023

# Status of the FAMU experiment at RIKEN-RAL for a precision measurement of the Zemach radius of the proton in muonic hydrogen

**Riccardo Rossini** on behalf of the International FAMU Collaboration



# The proton radius puzzle

# The proton charge radius

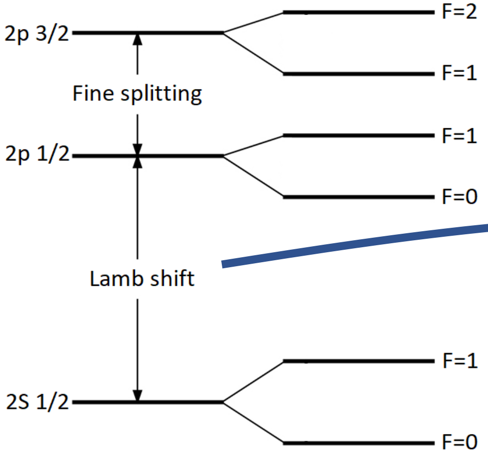
Defined as:

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

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.



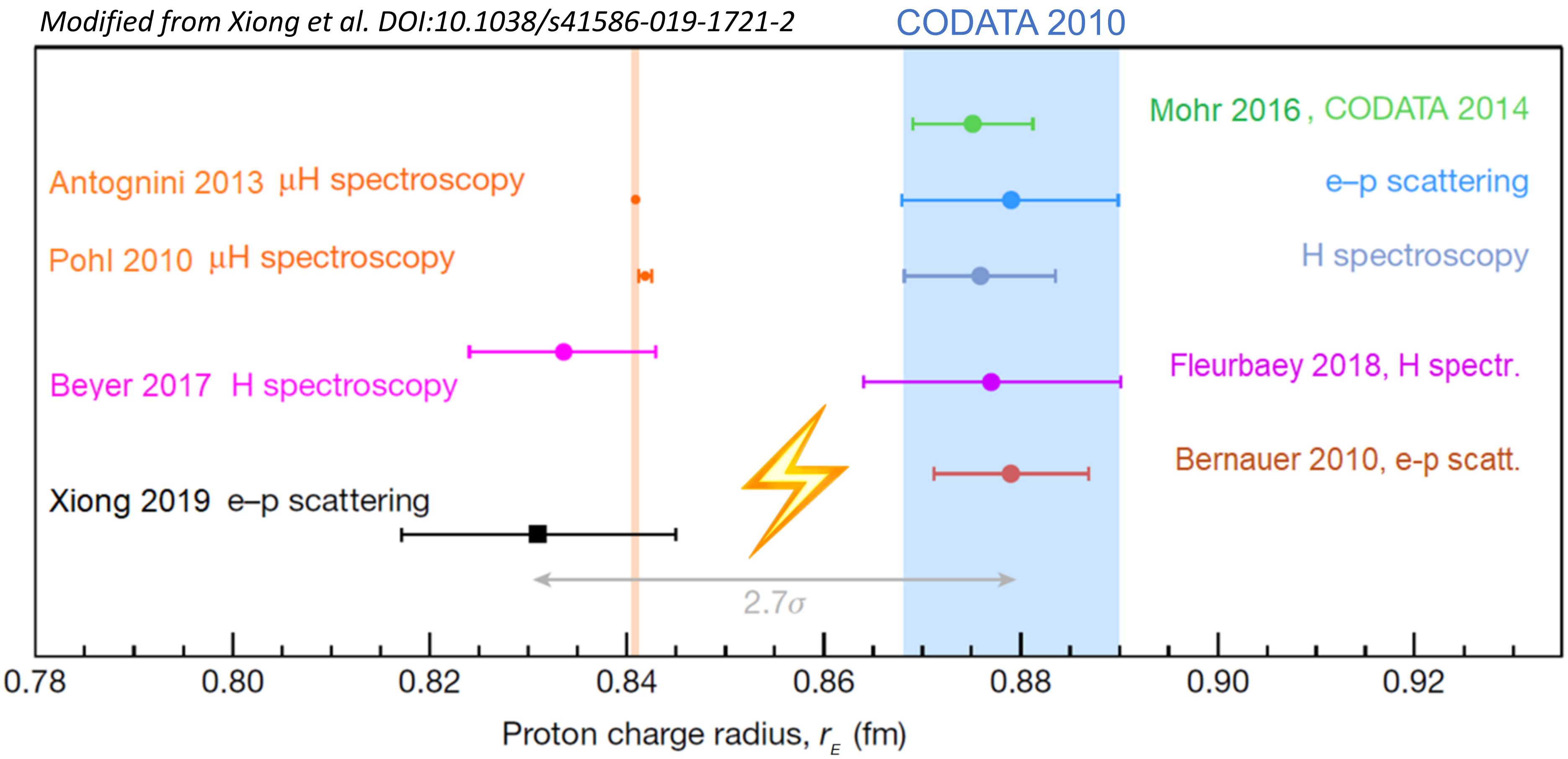
Lamb shift in H has leading order dependency on the charge radius:

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

**spectroscopy** technique.

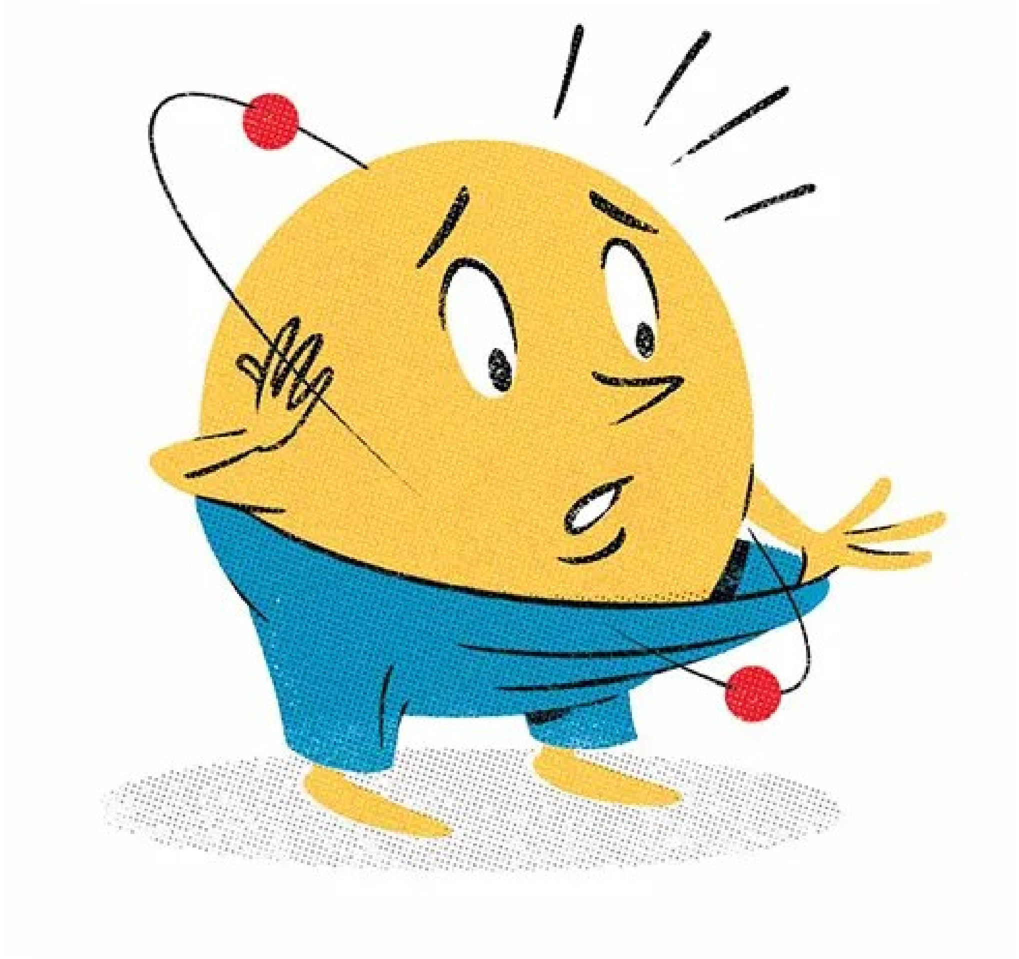
# PRad (2019-2022) @JLab

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



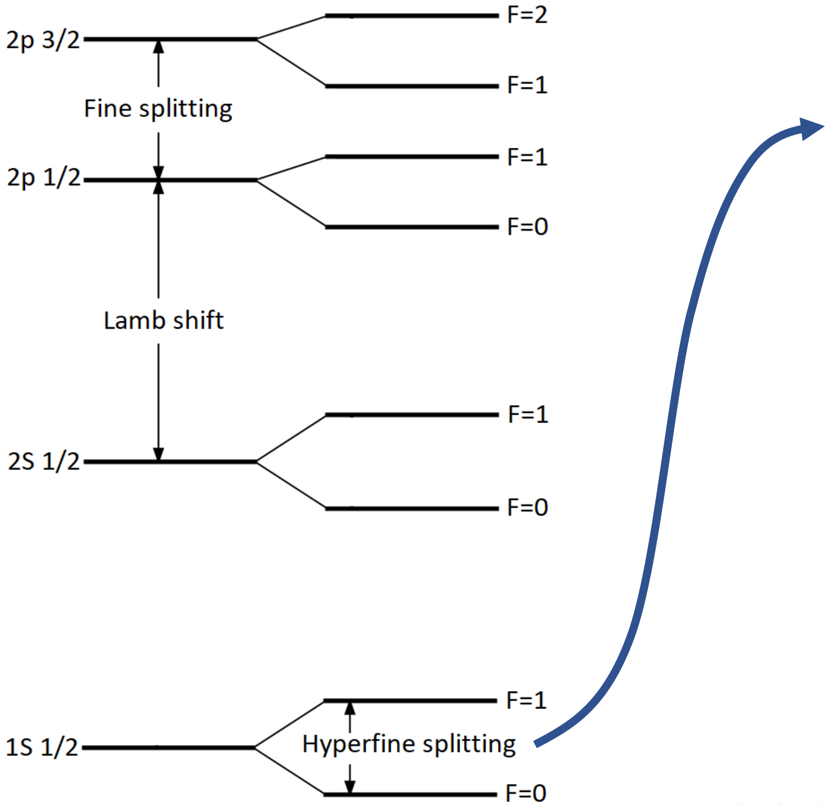
The New York Times

## *For a Proton, a Little Off the Top (or Side) Could Be Big Trouble*



# The proton Zemach radius

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



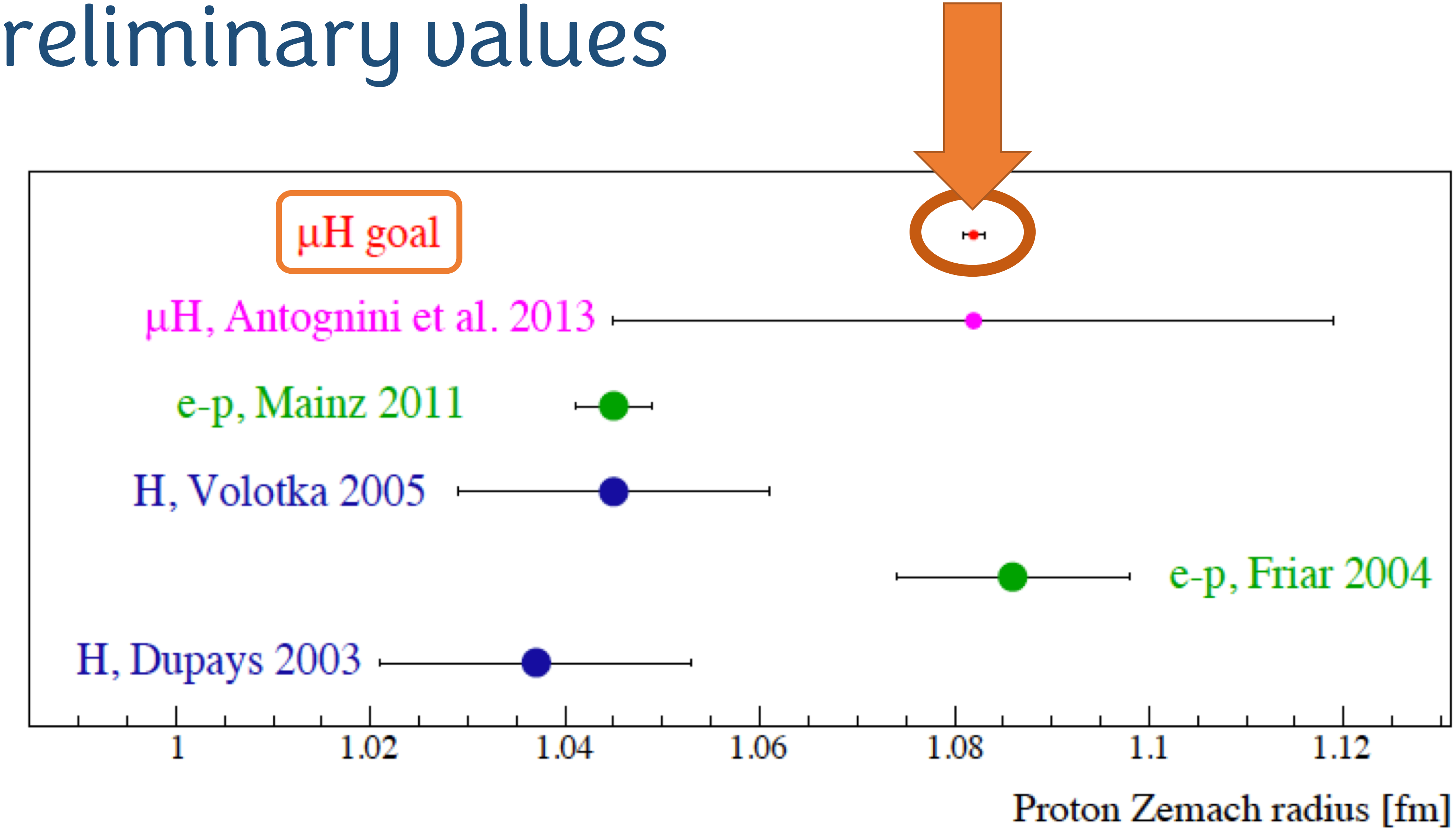
Leading order dependency on the hyperfine splitting:

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

**spectroscopy** technique.

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

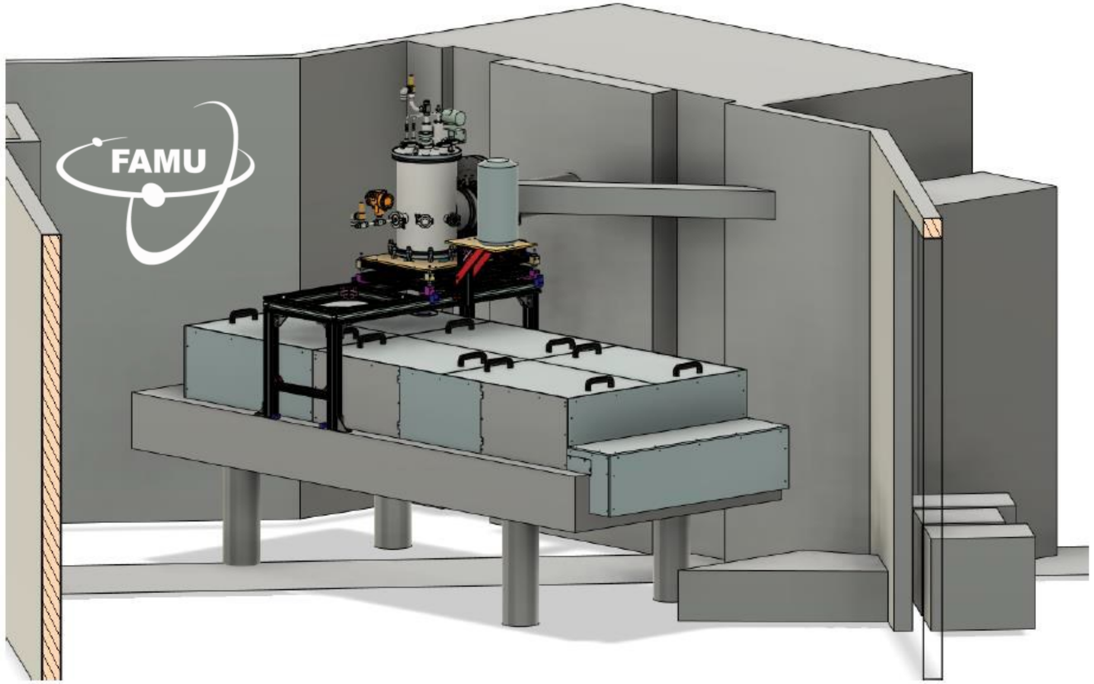
# Preliminary values



# The FAMU experiment

# The FAMU Collaboration

Around 60 researchers (75% Italians) from 20 institutions.



INFN Istituto Nazionale di Fisica Nucleare

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

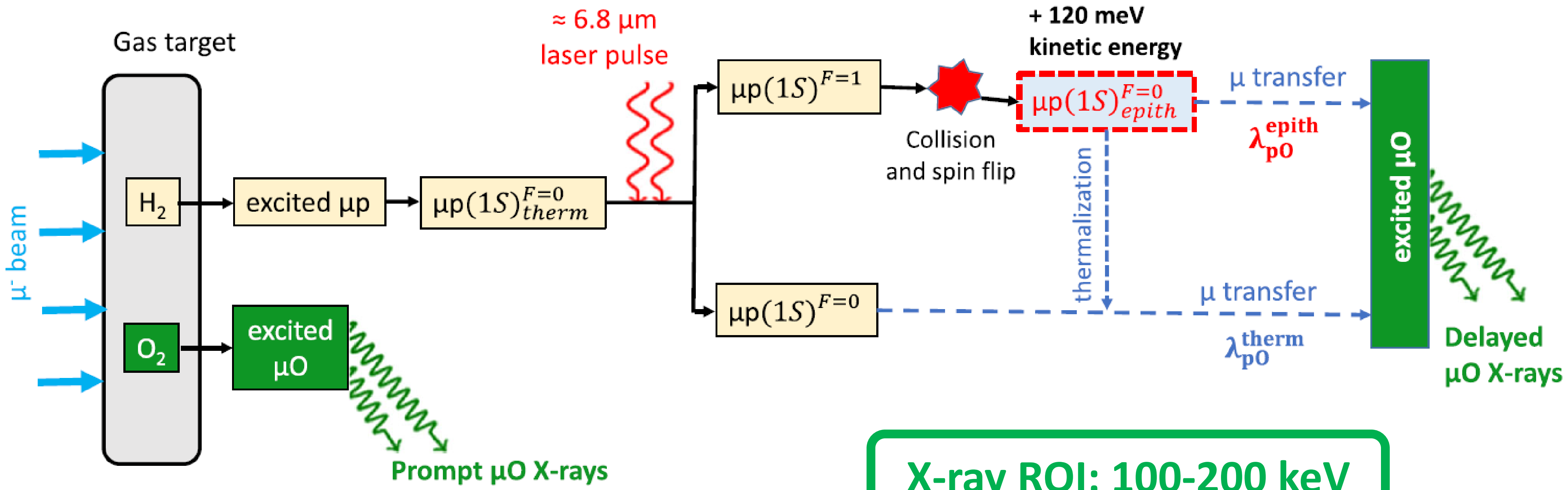
Dalian Institute of Chemical Physics, Chinese Academy of Sciences

Università degli Studi di Milano Bicocca

Università degli Studi di Udine hic sunt futura

# FAMU (2013-now) @RAL

Aim: indirect measurement of $r_Z$ with a relative uncertainty of around 1% in µp.



**X-ray ROI: 100-200 keV**

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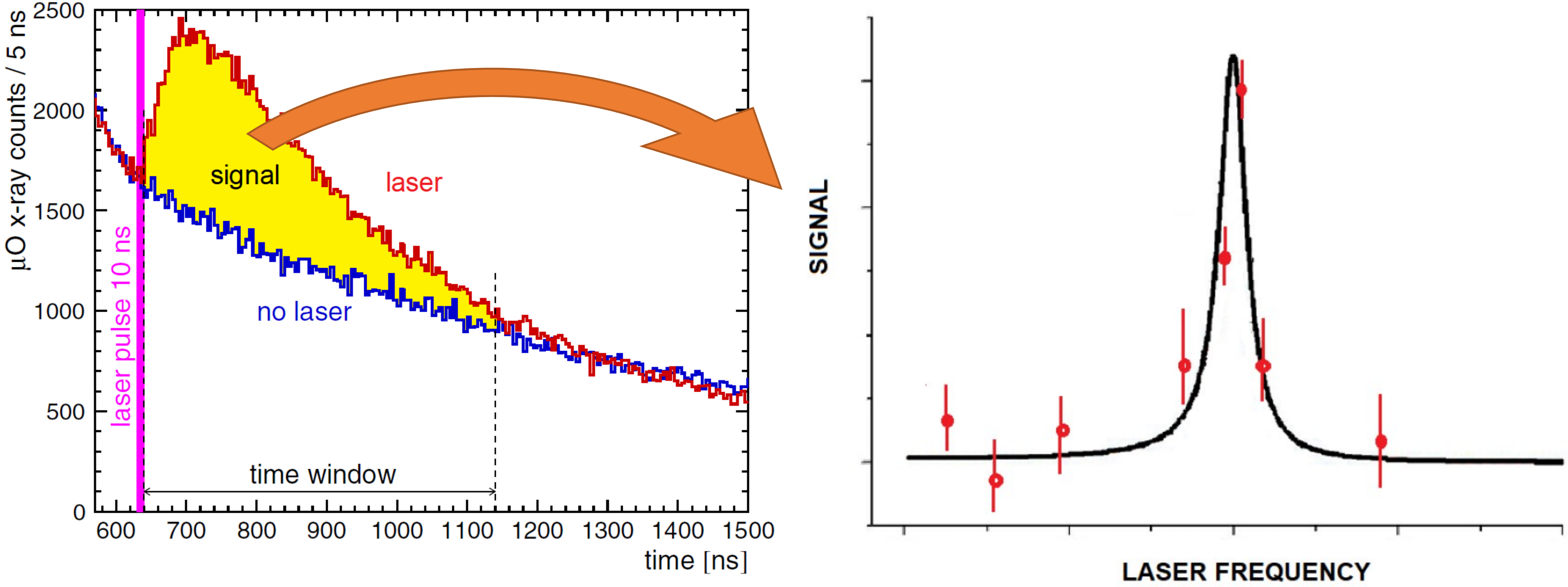
<u>Observable</u>: excess of delayed μO X-rays when the laser is turned on.



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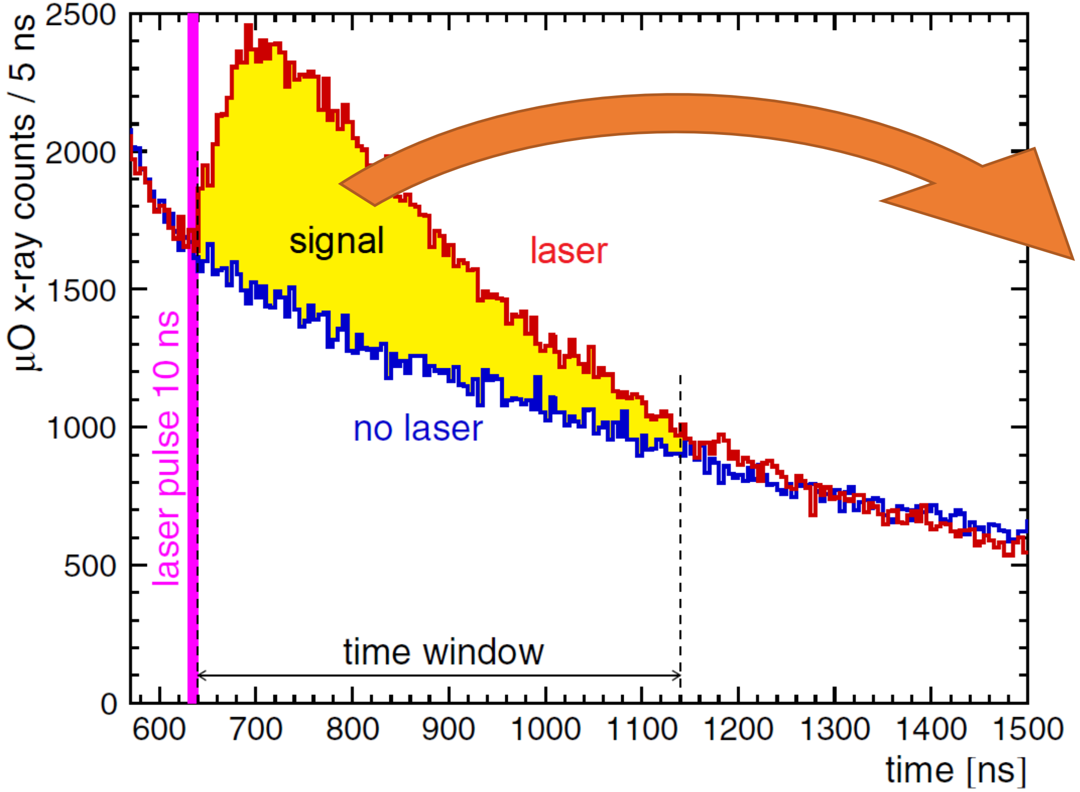
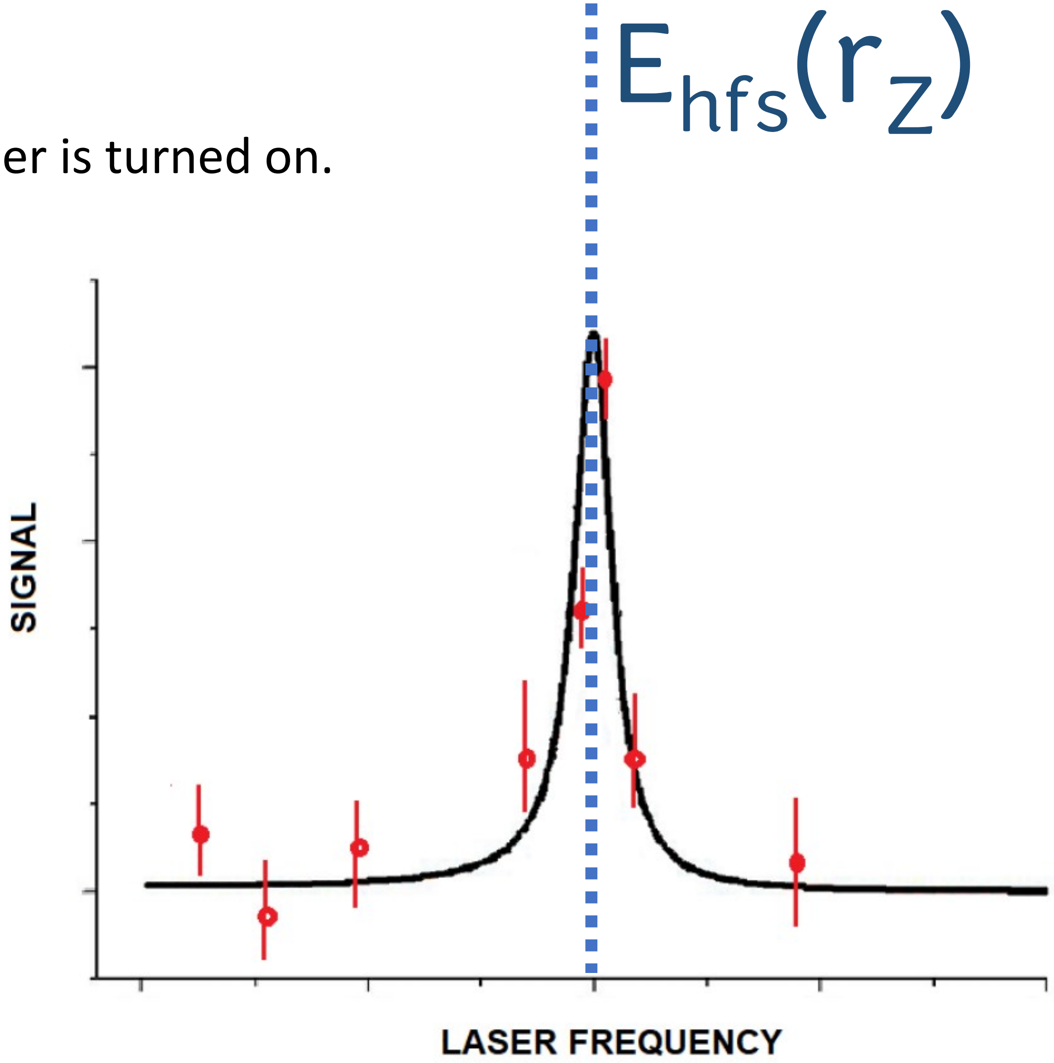




# FAMU target

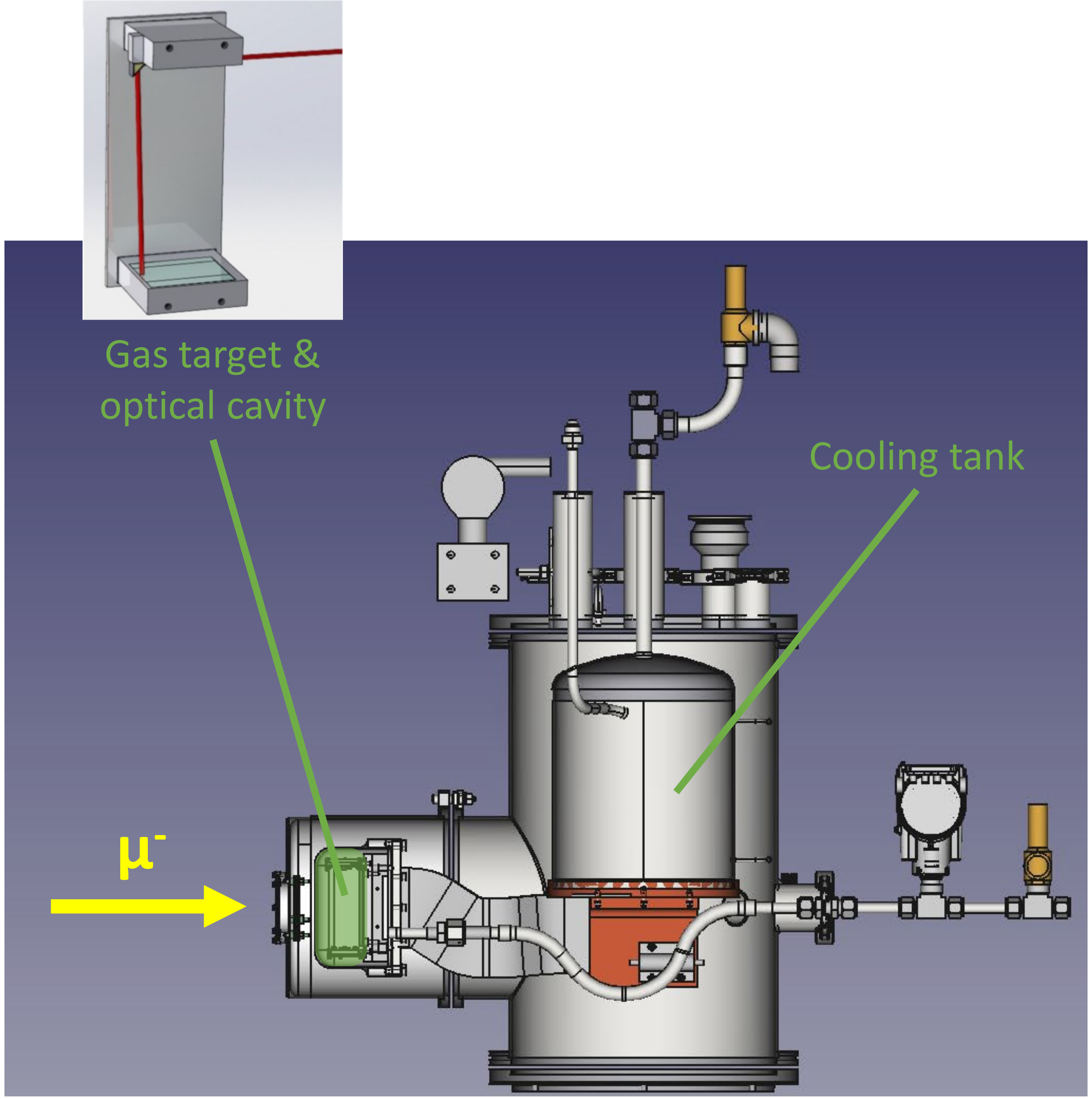
Geometry and working conditions optimised by MC simulation and during the previous experimental runs (2014-2018):

Cavity size: 2 x 2 x 10 $cm^3$,

Temperature: 80 K,

Pressure: 7 bar,

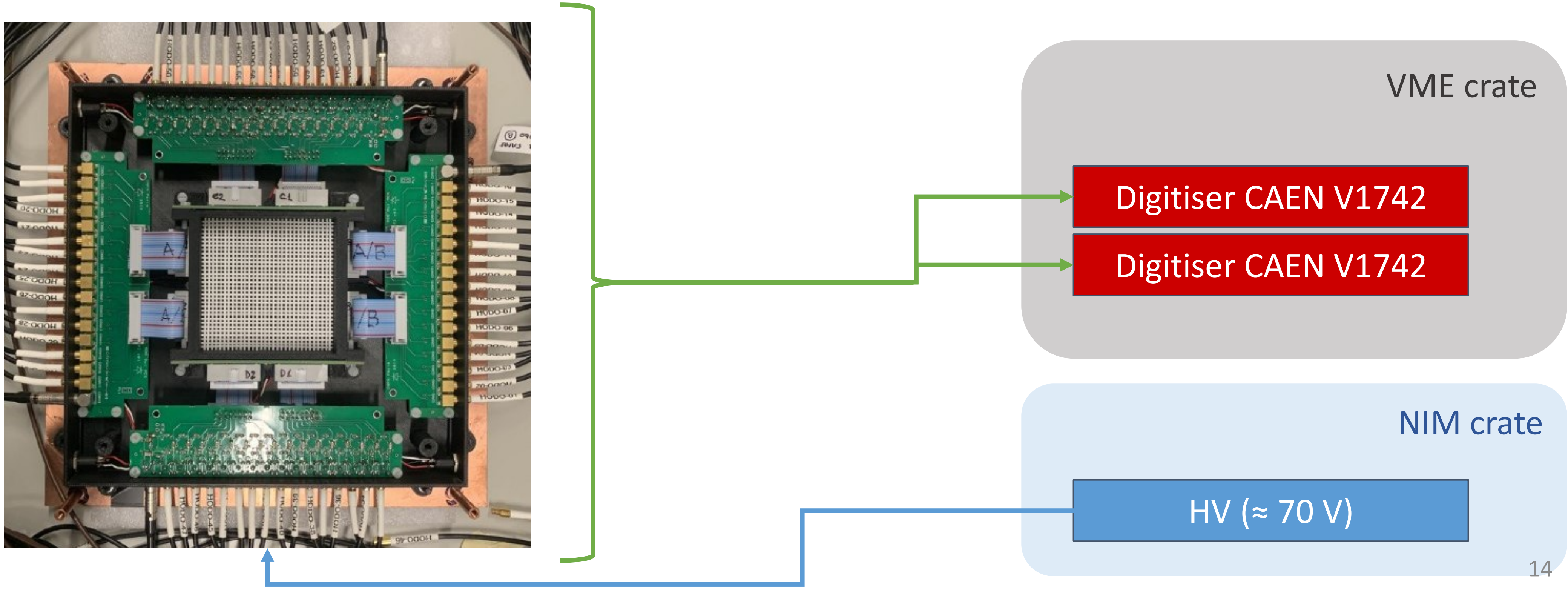
Gas mixture: 99% $H_2$ and 1% $O_2$.



# FAMU muon beam monitor

1 mm pitch polystyrene (Saint-Gobain BCF12) scintillating fibres read at one tip with a Hamamatsu S12 SiPM.

32 x 32 fibres on two different planes, 1 mm interspacing → active area 6.4 x 6.4 cm2.



VME crate

Digitiser CAEN V1742

Digitiser CAEN V1742

NIM crate

HV (≈ 70 V)

# FAMU muon beam monitor

Aim: muon beam shape & rate monitoring

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**Problem 1**: RIKEN-RAL beam characteristics:

$p \in [30,80]$ MeV/c $\sigma_{pp}$ = 4% $\mathrm{FWHM}_{x/y} \approx 3.5$ cm

Average μ flux at 60 MeV/c: $7 \cdot 10^4$ muons/second, in two 70 ns pulses with 50 Hz repetition.

In each spill, around $7 \cdot 10^4 / (50 \cdot 2) = 700$ muons are delivered in 70 ns → impossible to resolve.

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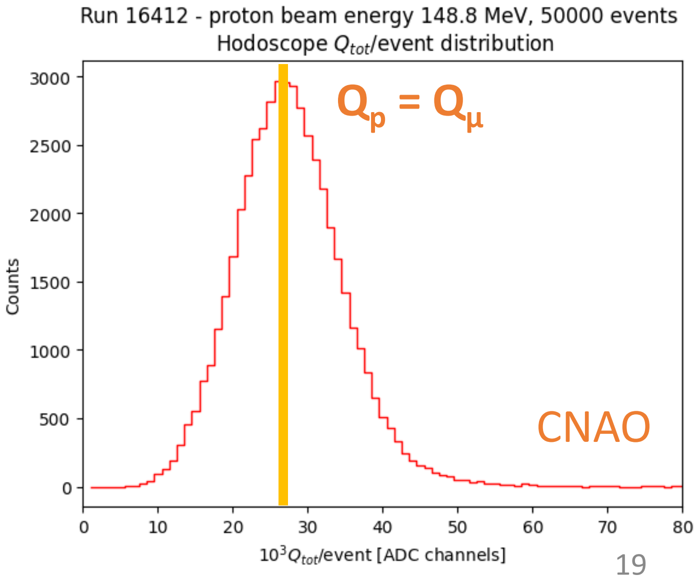
**Problem 2**: a low-rate low-momentum muon beam doesn't exist.

**Solution 2**: Calibrate the detector with a low-rate proton beam with momentum chosen to have the same energy loss (dE/dx) as the used RIKEN-RAL muons.

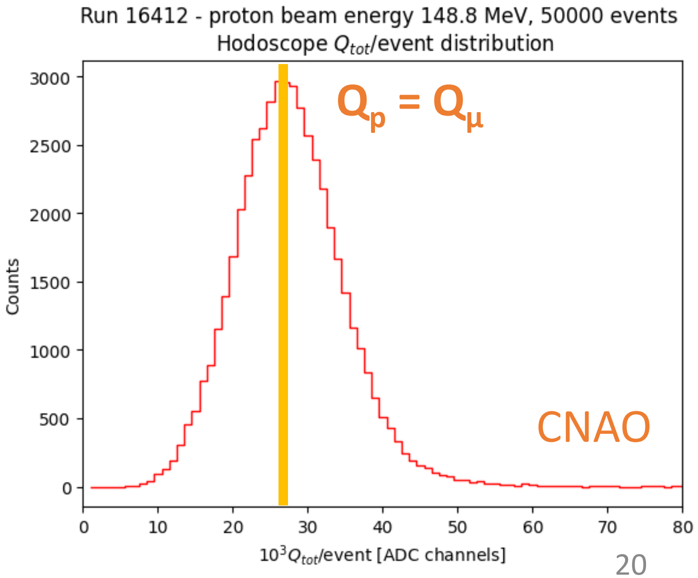


$Q_p = Q_\mu$

CNAO

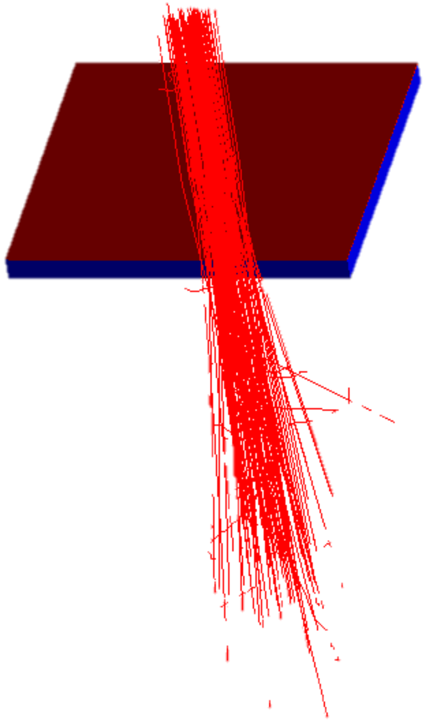
# FAMU muon beam monitor

Procedure carried out at the CNAO synchrotron (Pavia) with $E_p$ = 150 MeV and rate ≈ 50 Hz.



# FAMU muon beam monitor

Simulation of the hodoscope in Geant4 is being carried out to prepare for the CNAO runs, better understand the detector response function and scale the calibration at various muon beam energies.



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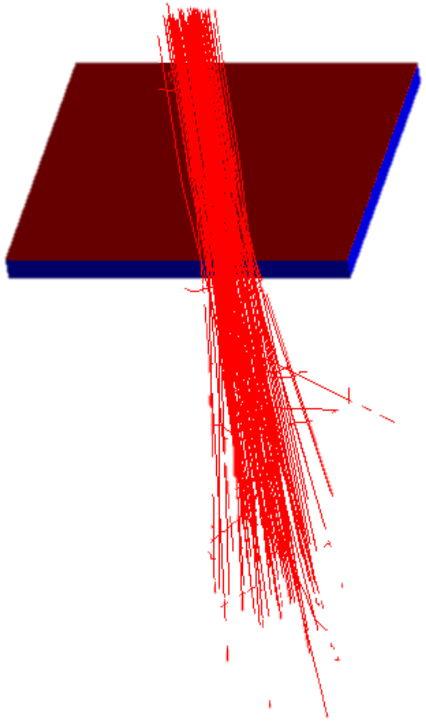

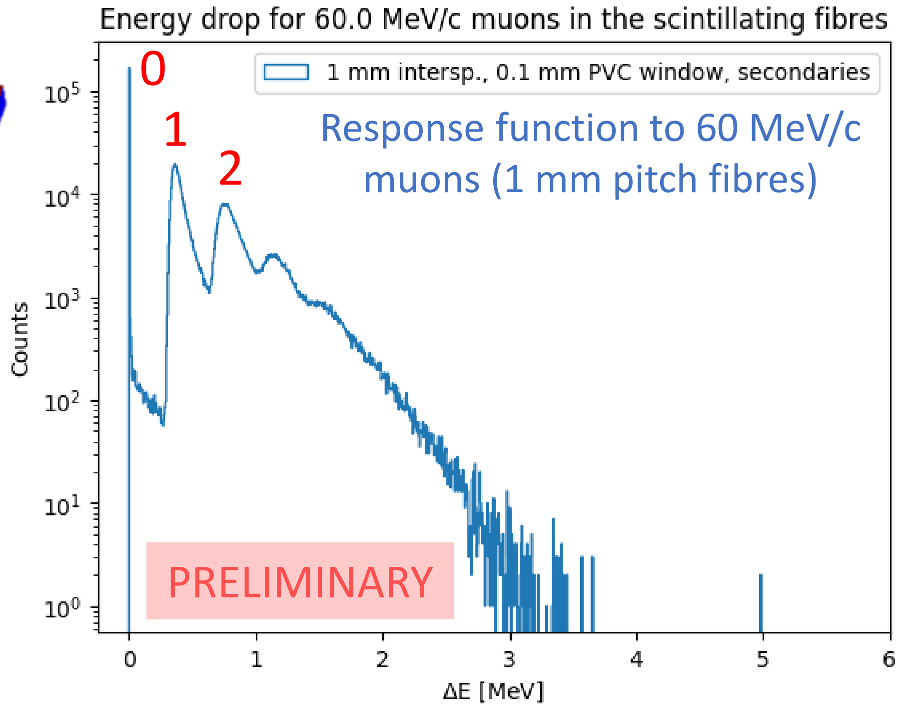

Energy drop for 60.0 MeV/c muons in the scintillating fibres

Response function to 60 MeV/c muons (1 mm pitch fibres)

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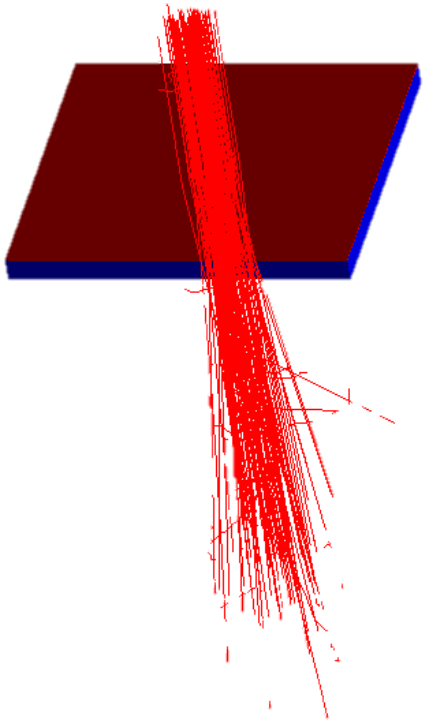

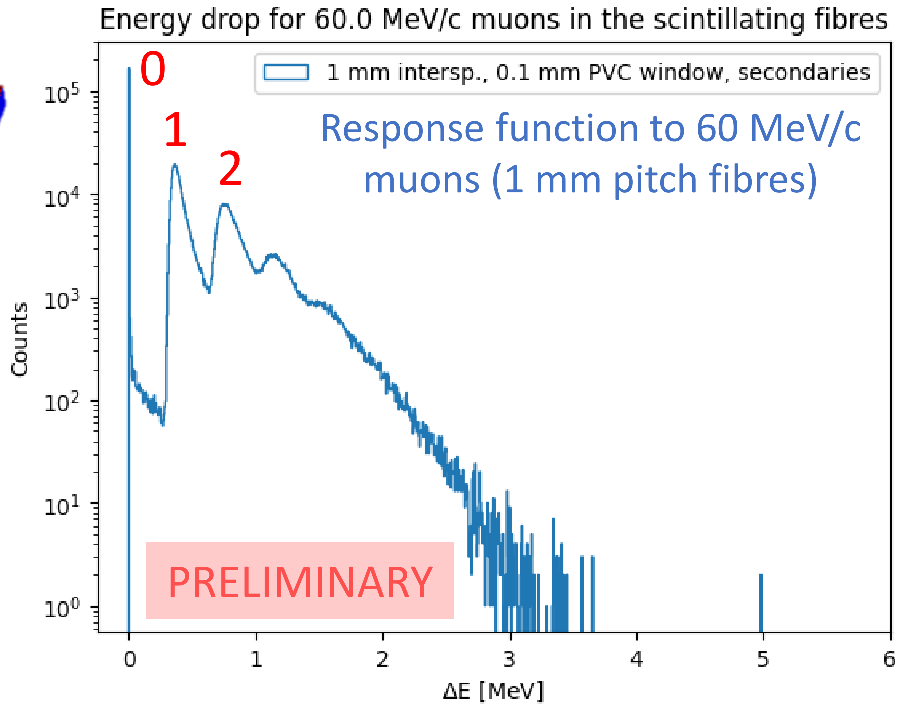
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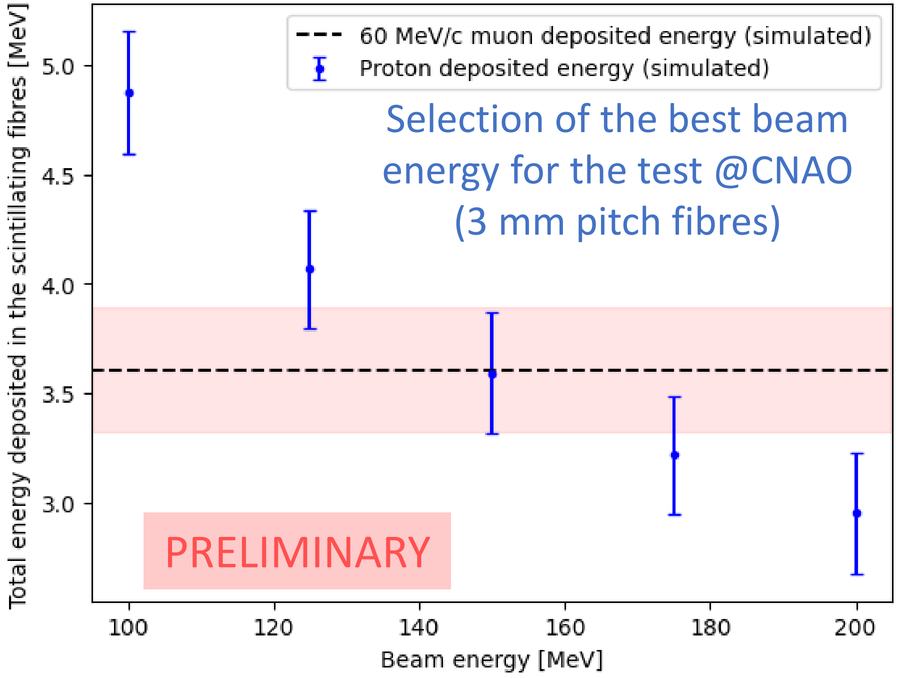

Selection of the best beam energy for the test @CNAO (3 mm pitch fibres)

# FAMU muon beam monitor

Further details in the following poster:

R.Rossini for the FAMU Collaboration

*Characterisation of a low-momentum high-rate muon beam monitor for the FAMU experiment at RIKEN-RAL.*

# FAMU X-ray detection system

# X-ray detector requirements

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FAMU X-ray detectors should satisfy the following requirements:

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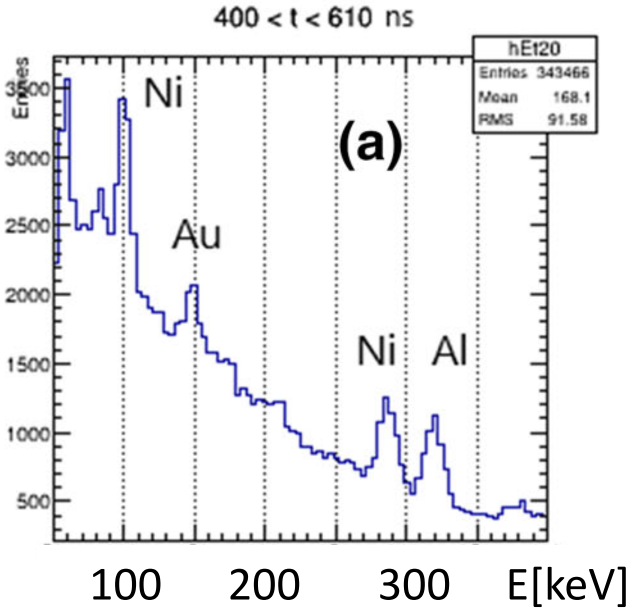
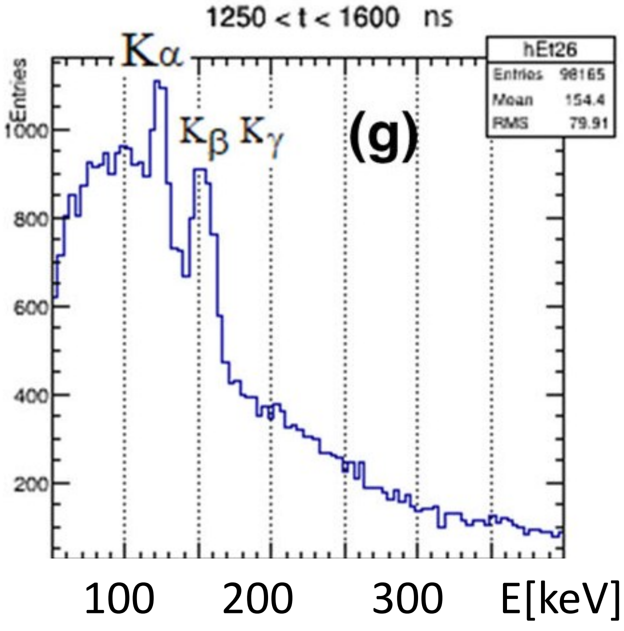
- **Good energy resolution**

**Prompt**



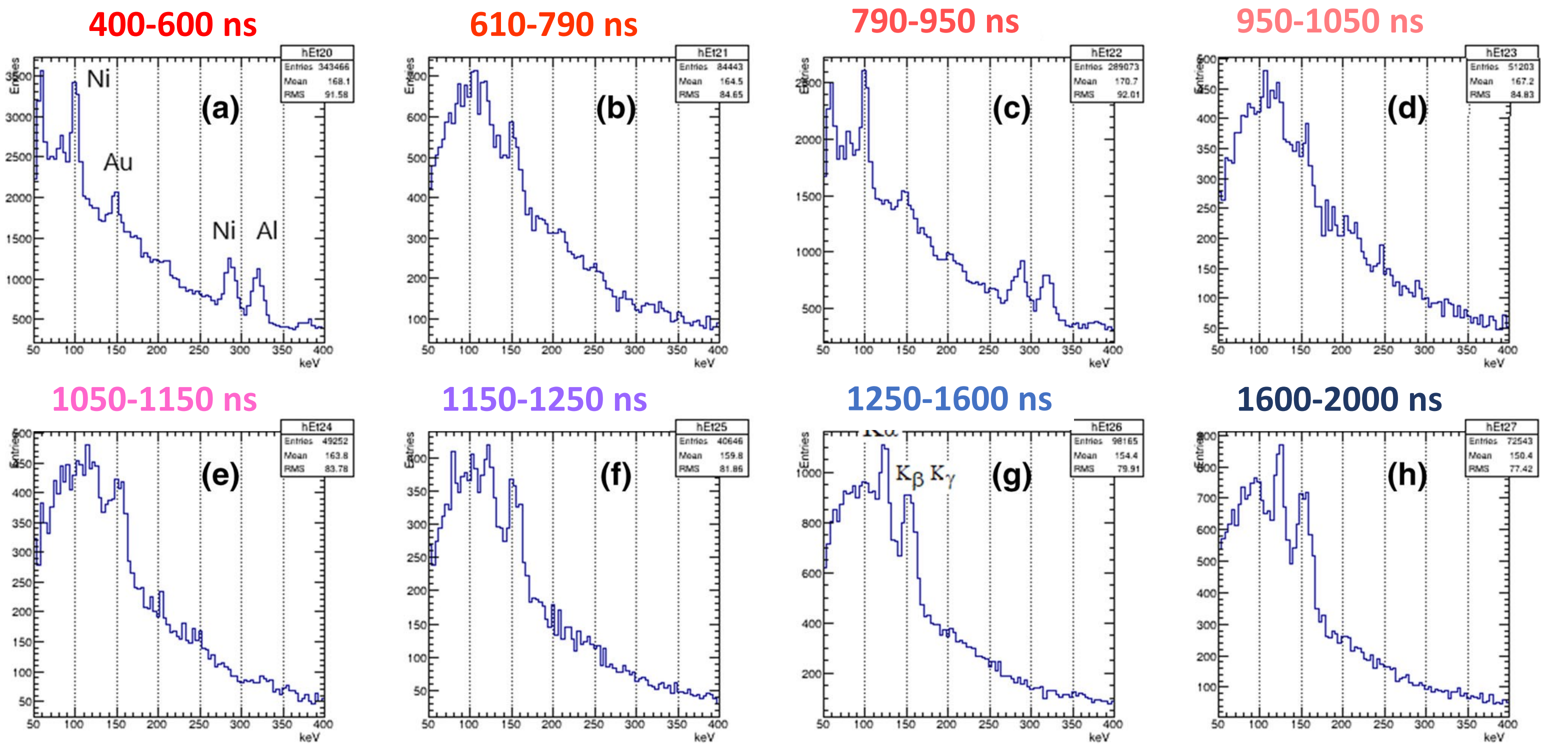
**Delayed**



# X-ray detector requirements

FAMU X-ray detectors should satisfy the following requirements:

- High efficiency (solid angle coverage + intrinsic efficiency)
- Good energy resolution
- **Good timing performance**



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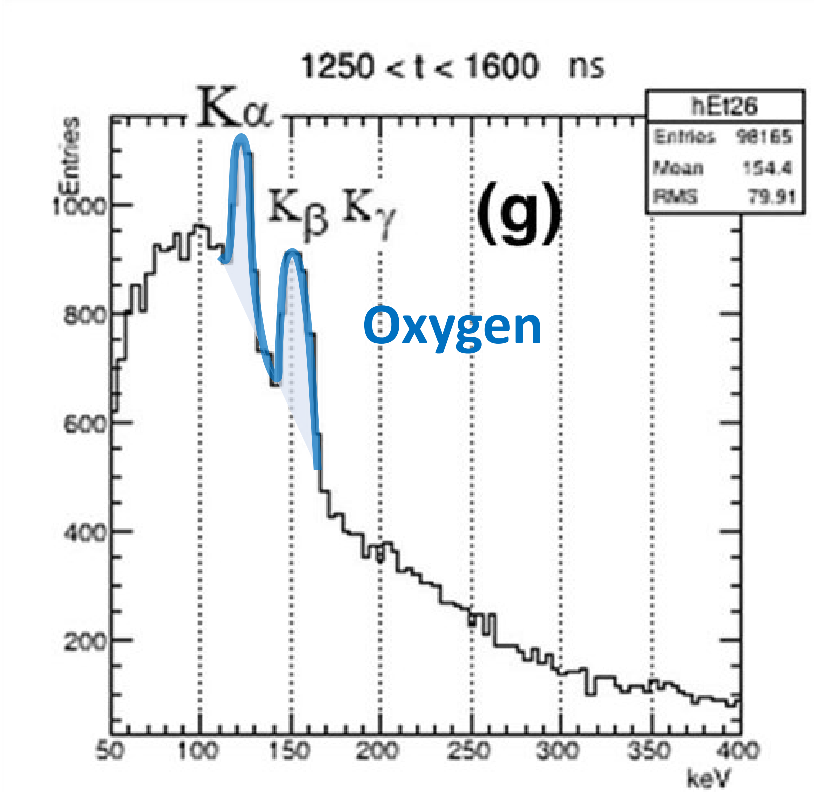
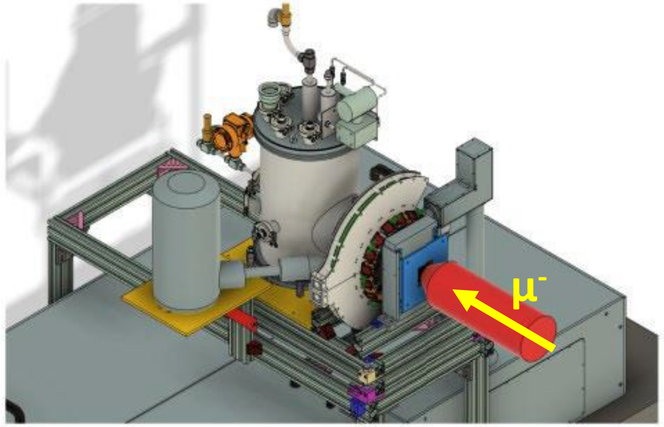


**X-ray ROI:**
**100-200 keV**

# FAMU X-ray detectors



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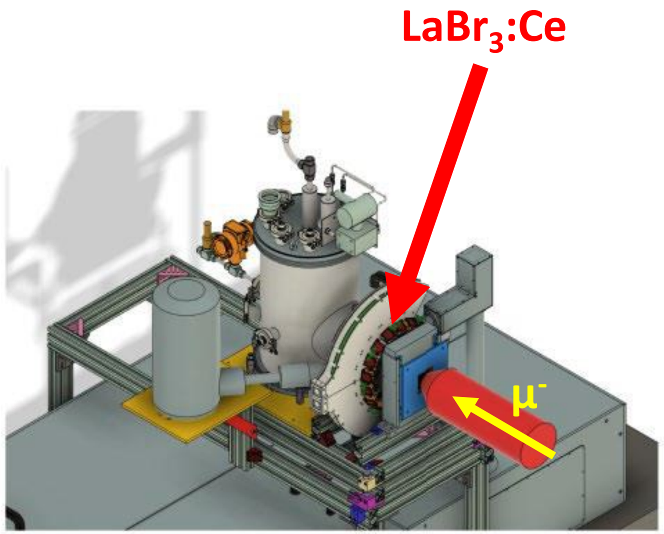
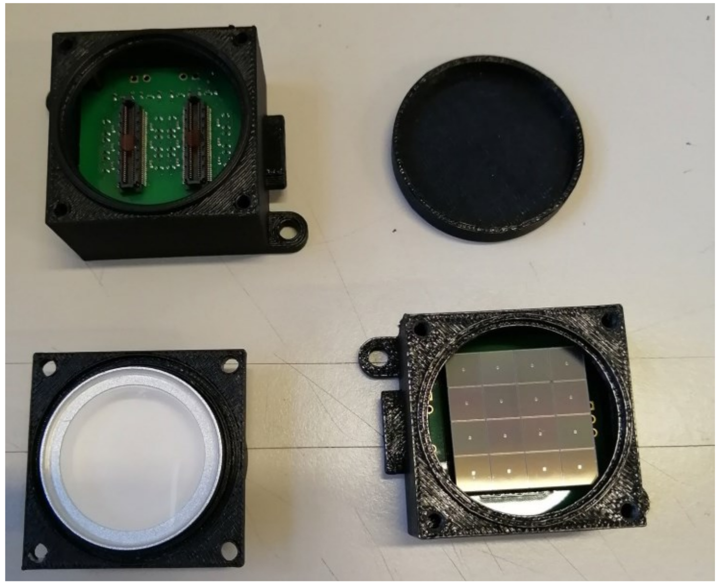
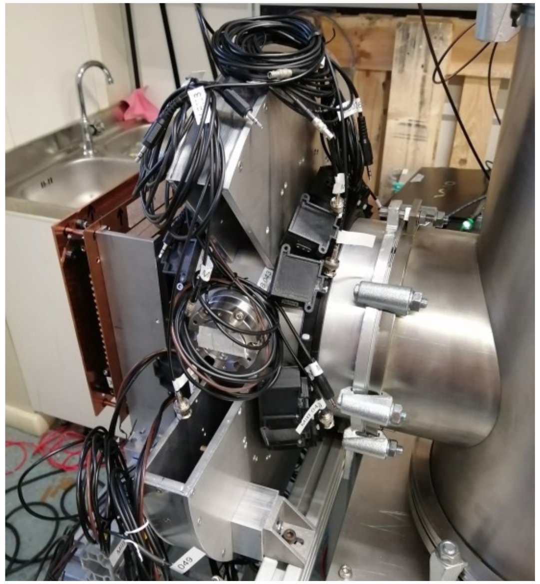


$LaBr_3$:Ce crystals (1’’ and ½’’) read by SiPMs and PMTs for time-resolved measurements.





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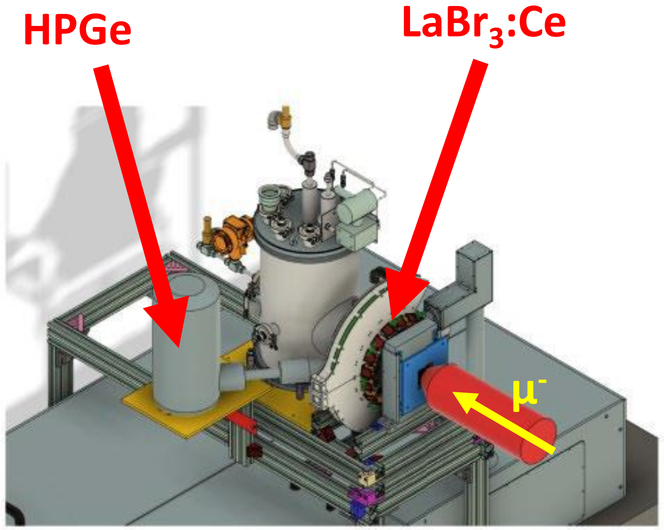


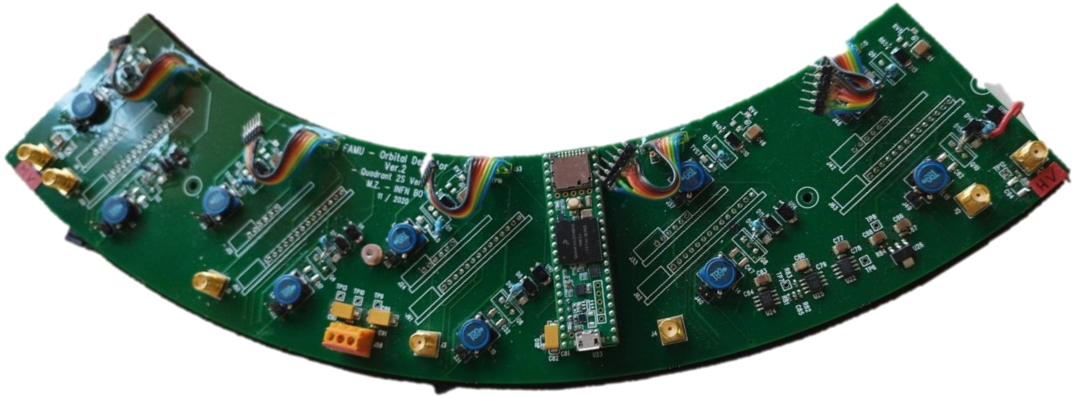
$LaBr_3$:Ce crystals (1'' and ½'') read by SiPMs and PMTs for time-resolved measurements.

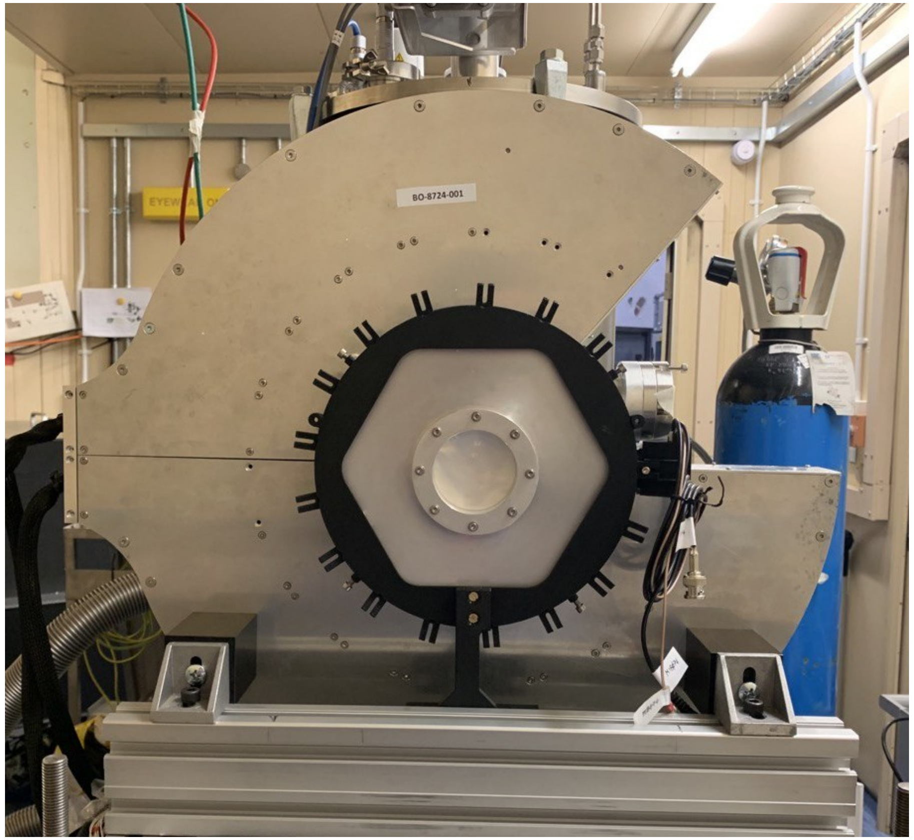
Coaxial HPGe for energy-resolved measurements.

# $LaBr_3$:Ce detectors read by PMTs

Set of lanthanum bromide crystals read by PMTs.

| Rise(fall)-time [ns] | FWHM/E (@137Cs) |
|---|---|
| 12 (100) | 4% |



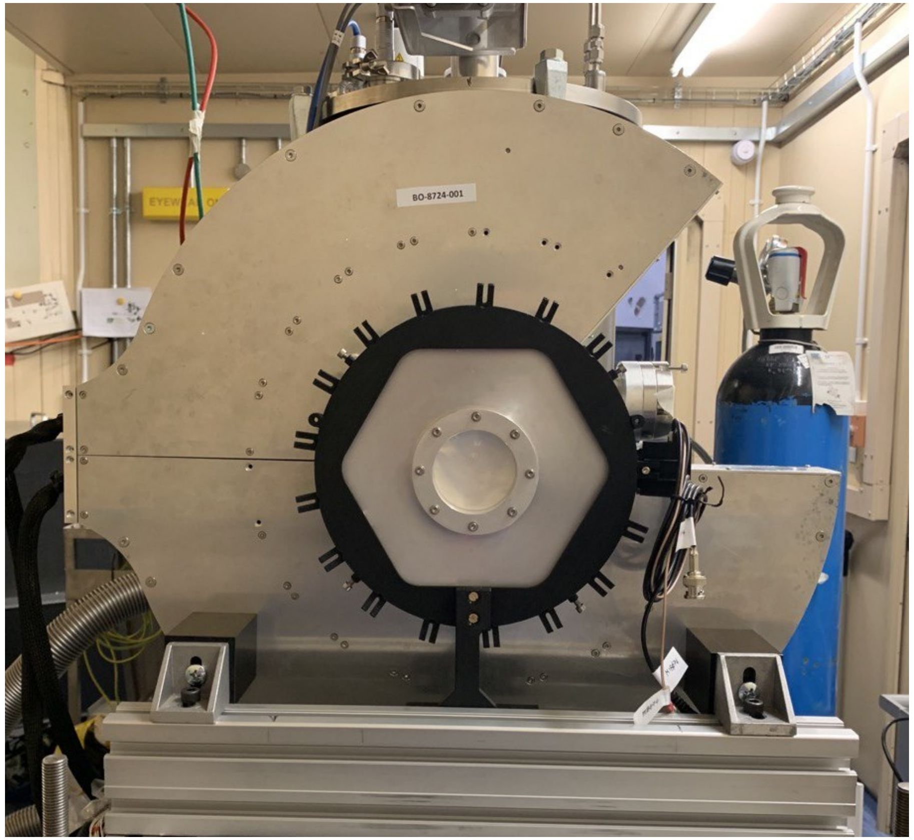


# $LaBr_3$:Ce detectors read by SiPMs

**PROs of the SiPM**

low-voltage supply

smaller



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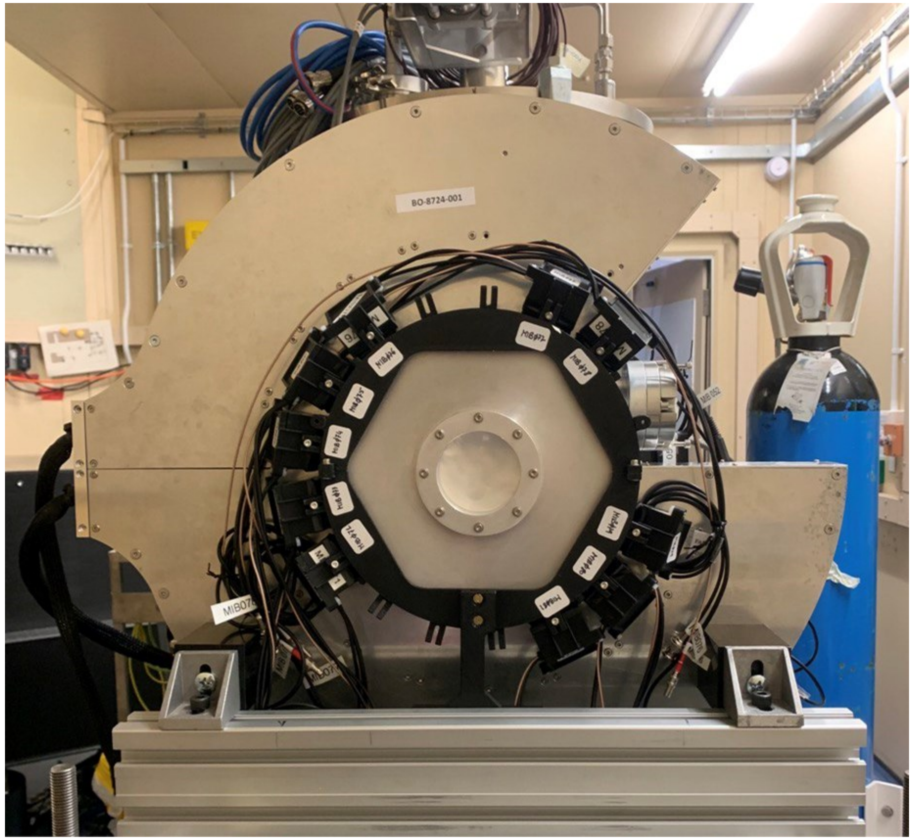

# LaBr$_3$:Ce detectors read by SiPMs

**PROs of the SiPM**

- low-voltage supply
- smaller

**CONs of the SiPM**

- worse timing performance
- gain drift with temperature

# LaBr$_3$:Ce detectors read by SiPMs

Many solutions were considered to improve time performances in 1-inch-diameter cilindric crystals:

| **PCB solution** | **Rise(fall)-time [ns]** | **FWHM/E (@137Cs)** |
|---|---|---|
| Parallel ganging | 50 (300) | 3% |
| Hybrid ganging | 20 (170) | 6% |
| Parallel ganging + pole-zero circuit | - undershoot - | 3% |
| decoupling ¼ the SiPM array * | 28 (140) | 3% |

worse timing performance

gain drift with temperature

*developed together with Nuclear Instruments

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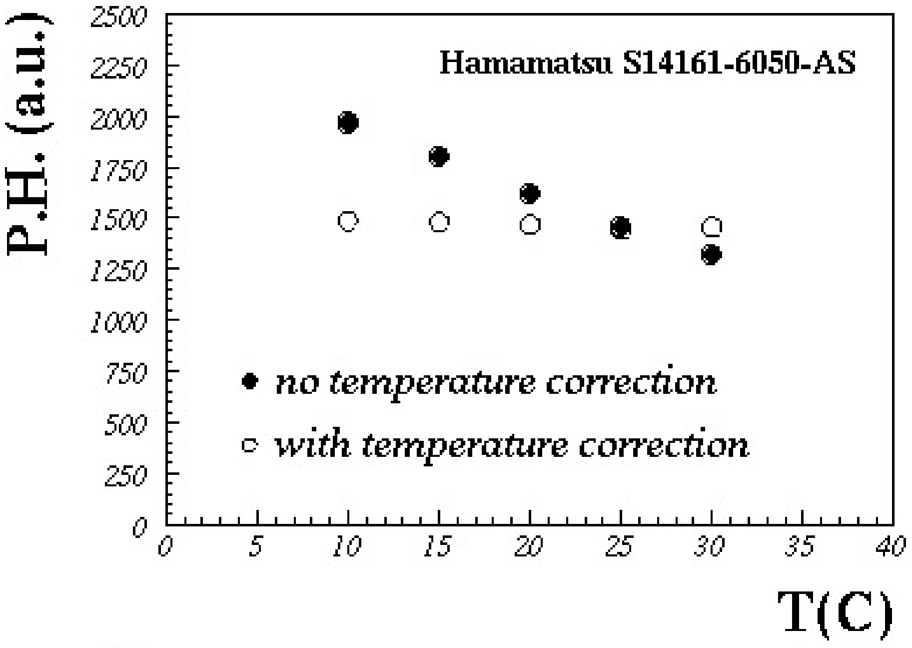
Gain drift correction based on real-time temperature reading and HV fine-tuning



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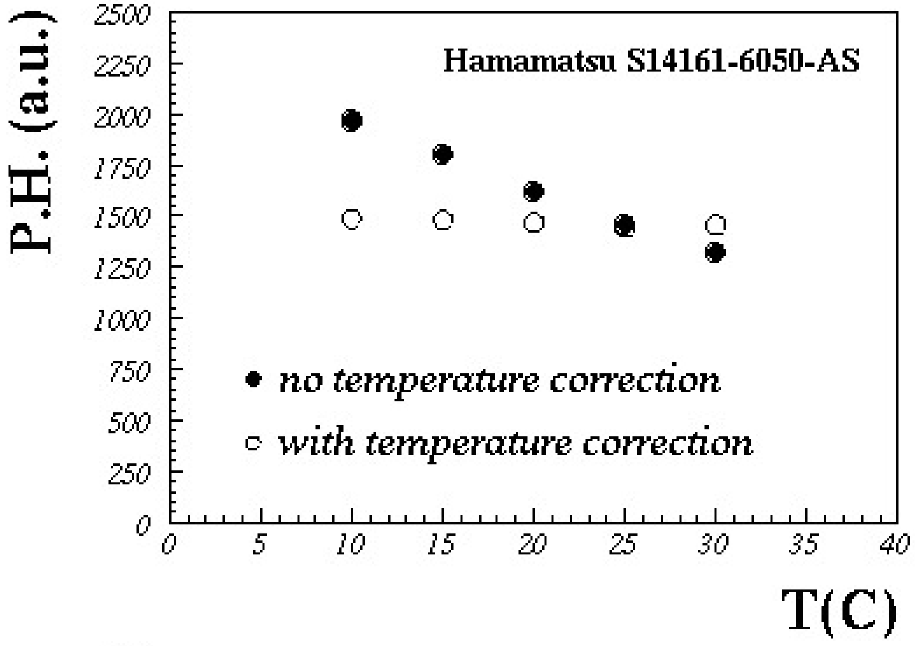
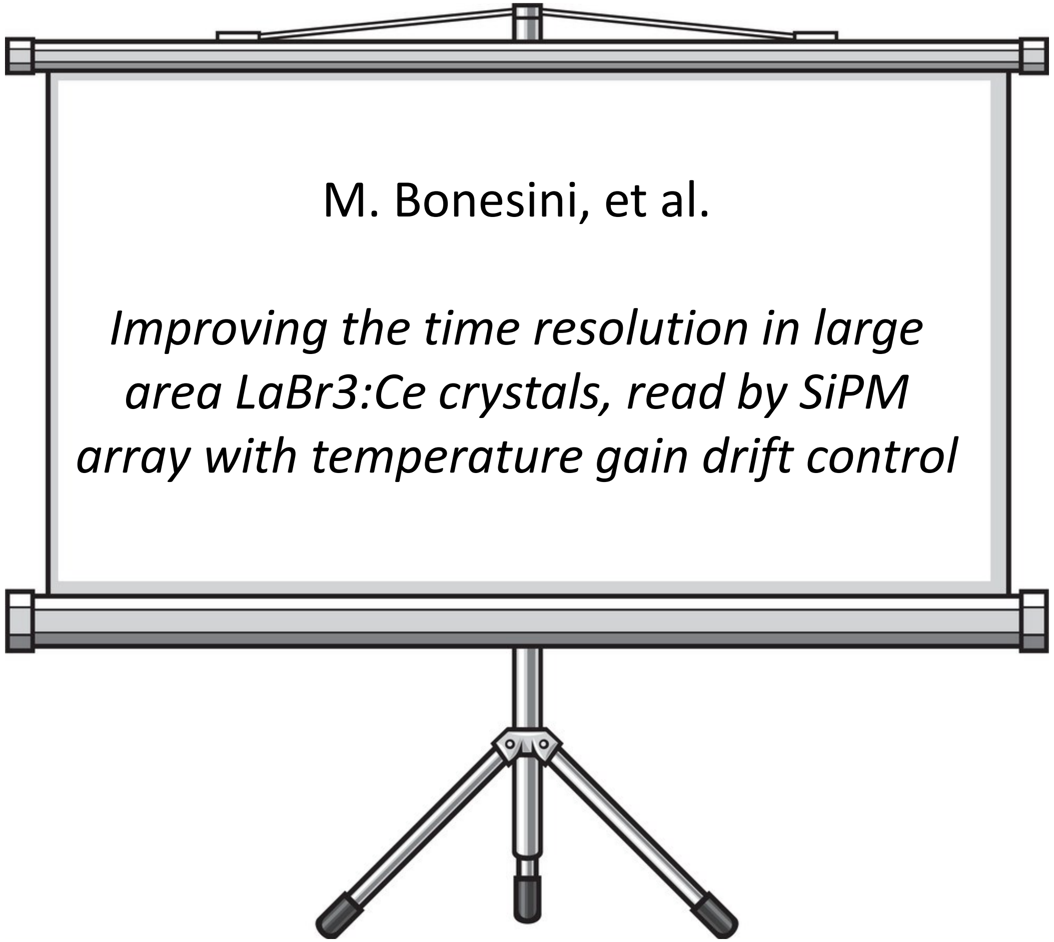


worse timing performance ✓

gain drift with temperature ✓

# LaBr$_3$:Ce detectors read by SiPMs

Further details in the following talk **tomorrow at 14:40**:



M. Bonesini, et al.

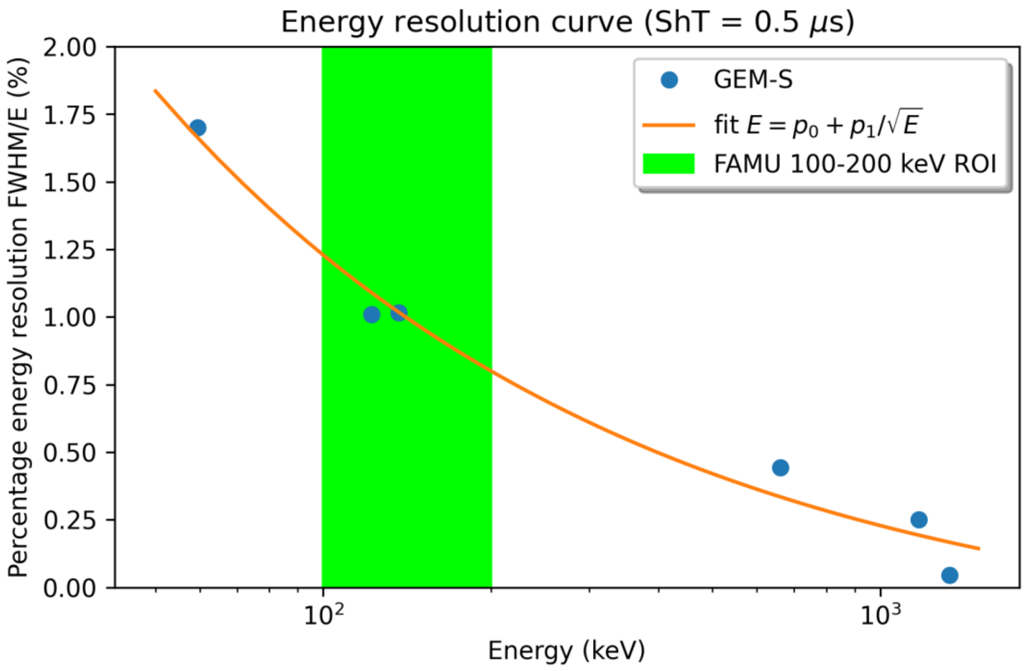
*Improving the time resolution in large area LaBr3:Ce crystals, read by SiPM array with temperature gain drift control*

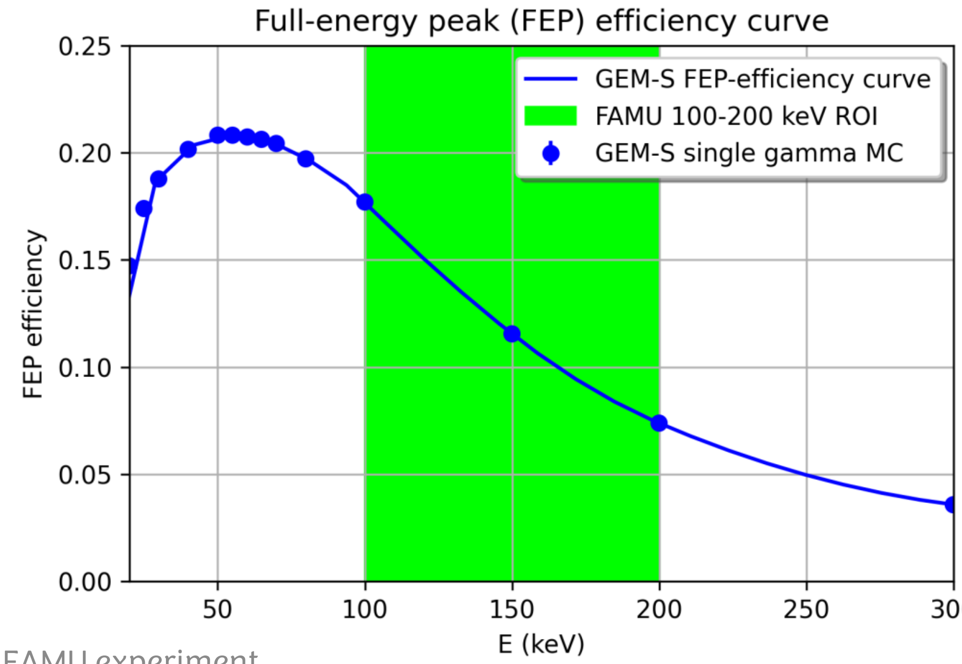
# HPGe detector

| Rise(fall)-time [ns] | FWHM/E (@137Cs) |
|---|---|
| 100 ($10^5$) | 0.5% |

Slow-signal detector with high energy resolution, mainly used for target commissioning, detector calibration and peak identification.

Shaped with ORTEC 672 – gaussian, shaping time 0.5 µs.



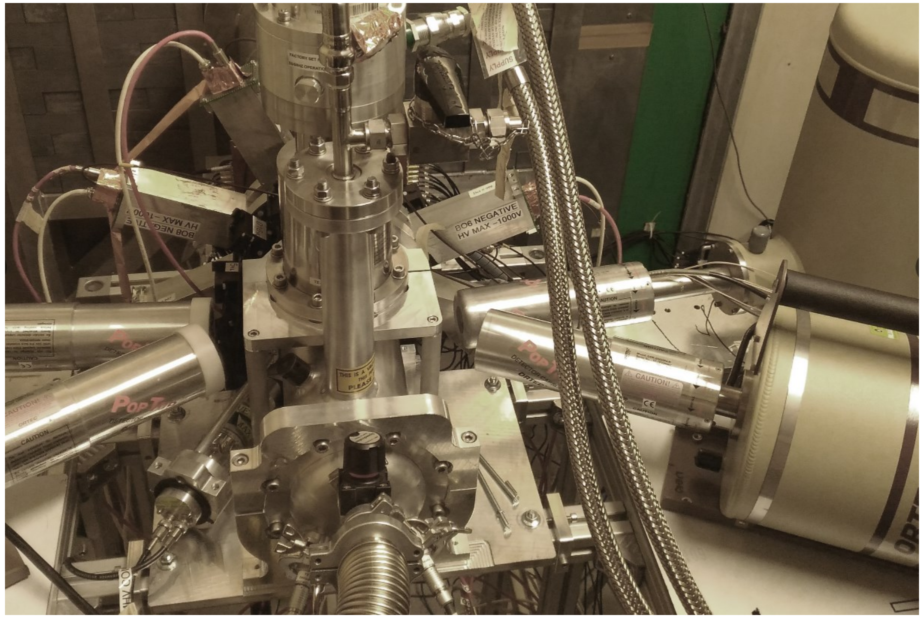


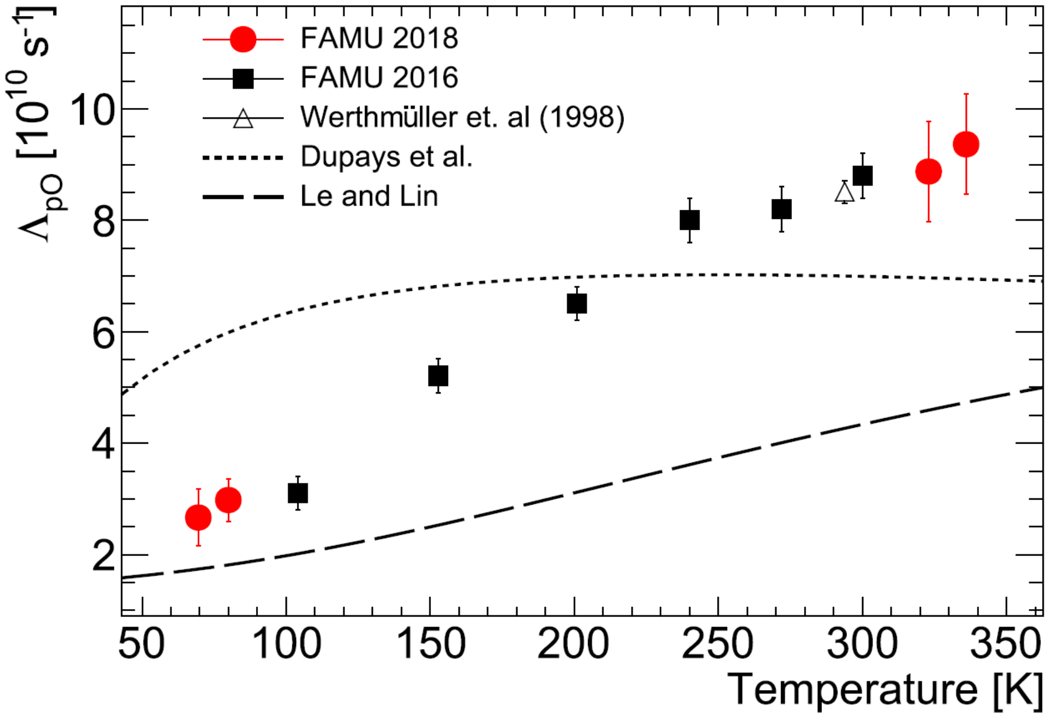
# Conclusion

# FAMU 2013–2022 results

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

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





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

# Current status and perspectives

The full detector setup has eventually been assembled, tested and commissioned at RAL.

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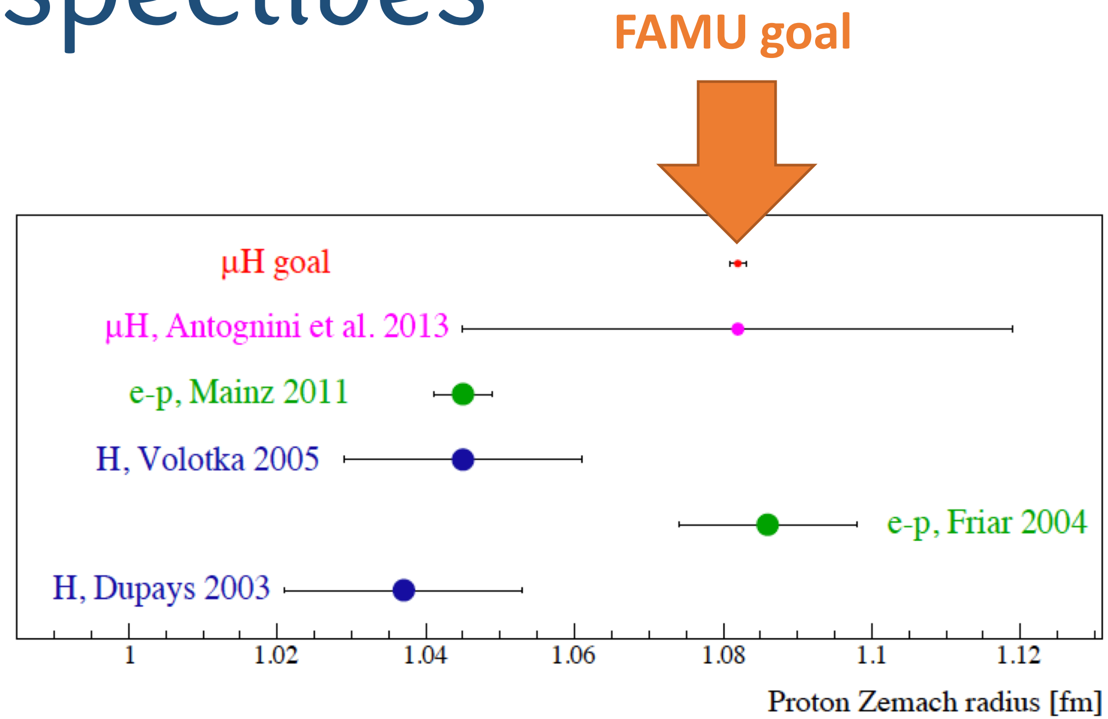
FAMU is finally starting data taking at RAL (UK) in late 2023 with the detector setup described here.

<u>Aim</u>: hfs in μH with $10^{-5}$ relative uncertainty, in order to obtain $r_Z$ with uncertainty of around 1%.

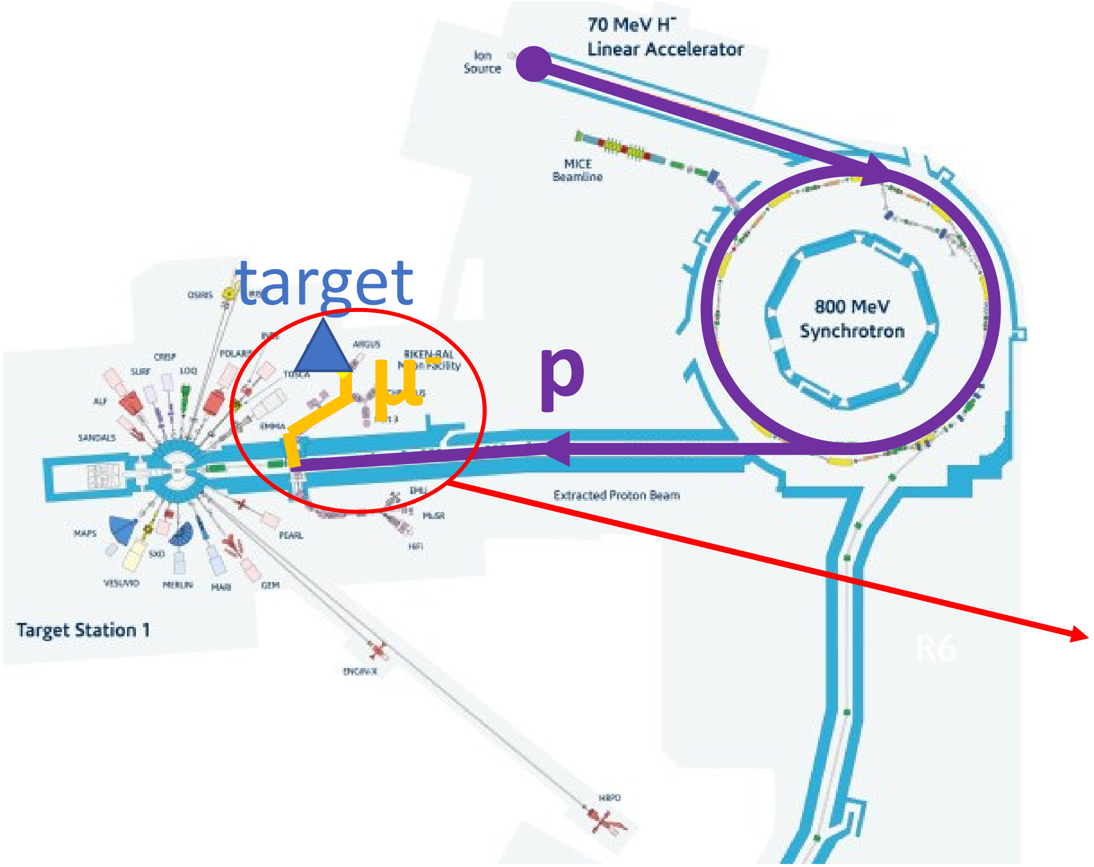


<u>Main references:</u>

C. Pizzolotto et al., Eur. Phys. J. A, 56 7 (2020) 185.

A. Vacchi et al., Nucl. Phys. News (2023).

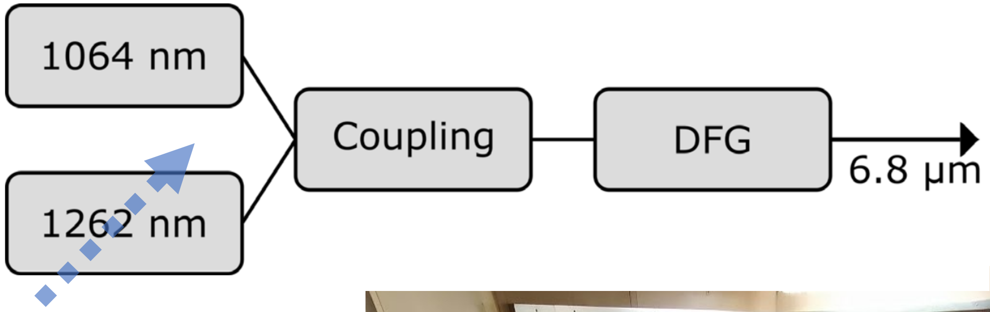
# FAMU muon beam



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

Momentum 60 MeV/c, average flux $3 \cdot 10^4$ Hz.

# FAMU laser


1064 nm

1262 nm

Coupling

DFG

6.8 μm

Difference Frequency Generation (DFG) exploits two lasers to produce the required frequency.

Fixed 1064 nm laser and tunable 1262 nm laser.

The two lasers are coupled with a non-linear crystal.

| | | |
|---|---|---|
| Wavelength range | $6800 \pm 50$ nm | $\approx 44$ 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 | |