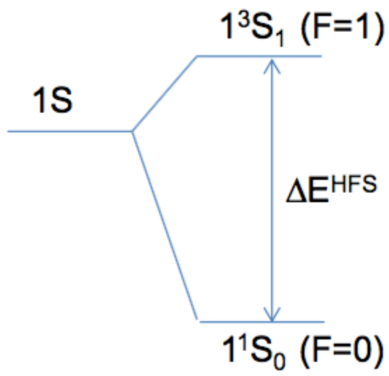
High precision spectroscopy in muonic hydrogen

Towards the measurement of muonic hydrogen ground state hyperfine splitting $\Delta E_{HFS}(\mu p)_{1S}$



F : total angular momentum

Andrea Vacchi on behalf of the FAMU Collaboration

INFN LNF 7 December 2017

FAMU Collaboration

RIKEN Nishina Center
"The RIKEN-RAL Muon Facility"
(International Research Collaboration between RIKEN and SFTC (Science and Technology Facility Council) in the UK)

INFN Trieste: V. Bonvicini, E. Furlanetto, E. Mocchiutti, C. Pizzolotto, A. Rachevsky, L. Stoychev, A. Vacchi (also *Università di Udine*), E. Vallazza, G. Zampa, **Elettra-Sincrotrone**: M. Danailov, A. Demidovich, **ICTP**: J. Niemela, K.S. Gadedjisso-Tossou
INFN Bologna**:** L. Andreani, G. Baldazzi, G. Campana, I. D'Antone, M. Furini, F. Fuschino, A. Gabrielli, C. Labanti, A. Margotti, M. Marisaldi, S. Meneghini, G. Morgante, L. P. Rignanese, P. L. Rossi, M. Zuffa

INFN Milano Bicocca**:** A. Baccolo, R. Benocci, R. Bertoni, M. Bonesini, T. Cervi, F. Chignoli, M. Clemenza, A. Curioni, V. Maggi, R. Mazza, M. Moretti, M. Nastasi, E. Previtali, R. Ramponi (also Politecnico Milano CNR)

INFN Pavia**:** A. De Bari, C. De Vecchi, A. Menegolli, M. Rossella, R. Nardò, A. Tomaselli

INFN Roma3**:** L. Colace, M. De Vincenzi, A. Iaciofano, L. Tortora, F. Somma

INFN Seconda Università di Napoli: L. Gianfrani, L. Moretti

INFN – GSSI: D. Guffanti,

RIKEN-RAL: K. Ishida

INP, Polish Academy of Sciences**:** A. Adamczak

INRNE, Bulgarian Academy of Sciences**:** D. Bakalov, M. Stoilov, P. Danev

OUTLINE

- FAMU background & motivations
- method
- beam
- target
- detectors
- muon transfer rate measurements
- laser
- conclusions

Simple atomic systems

High precision theoretical and experimental studies of the energy spectra of hydrogenic atoms like

muonic hydrogen

provides ***tests of quantum electrodynamics and the theory of electromagnetic bound states with very high accuracy***.

Moreover, ***the values of the fundamental physical constants (the particle masses, fine structure constant, proton charge radius, etc.) can be determined more precisely***.

proton structure

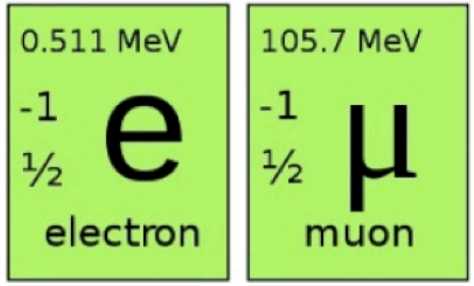
The proton is the lightest and simplest stable hadronic system. Investigating its structure is quite important.

- The **charge radius $r_c = sqr(\langle r^2 \rangle)$** determined by the charge distribution of the proton is one of the universal fundamental physical constants extracted from:
  - scattering experiment & empirical fitting,
  - hydrogen Lamb shift measurements.
  - ***muonic hydrogen*** Lamb shift measurements
- **magnetic radius of the proton r_Z** has been determined only by means of electron-proton scattering, which is not free of controversies.

Muonic hydrogen

Muon (e^-'s heavier twin) orbiting the proton instead of electron.

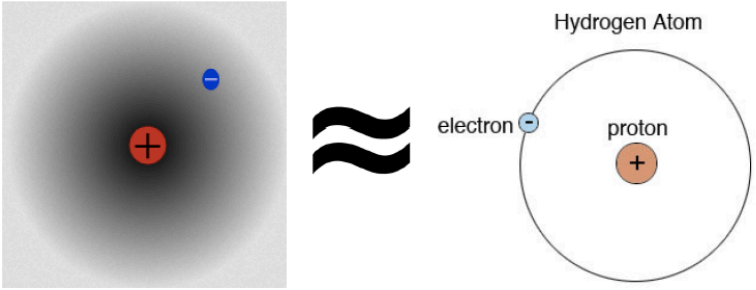
$$m_\mu = 207 m_e$$
$$r_\mu = \frac{1}{186} r_e$$



Due to the large muon mass $m_\mu/m_e \approx 2 \times 10^2$

- the binding energy of the ground state of muonic hydrogen is of the order of 200 Ry,
- the radius of the muon orbit is ~ $a_0/200$ so ***that the energy levels of muonic hydrogen are orders of magnitude more "sensitive" to <u>the details of the proton structure</u> than the levels of normal hydrogen***.
- Muonic hydrogen is the only other hydrogen-like atom in which the ***hyperfine splitting of the ground state can be measured with high precision***.

- Charge radius (r_E, based on the distribution of charge) and a
- Zemach radius (r_Z, reflects the spatial distribution of $\vec{\mu}$ smeared out by $\rho(\vec{r})$).



Muonic hydrogen is a good probe of the proton structure the muon is 200 time closer to the nucleus

E and M charge distribution $\rho_E(r)$, $\rho_M(r)$:

$$\mathbf{r_c}=\left(\int \rho_E(r)\, r^2\, d^3r\right)^{1/2}$$

$$\Delta E_{LS} = 206.0669 - 5.2275\, r_{ch}^{\ 2}$$

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

$$\Delta E^{HFS}{}_{1S} = 184.087 - 1.281\, r_Z$$

The proton radius can be extracted from two independent methods for each lepton probe

- The first is through lepton-proton scattering data, where the radius is given by the slope of the electric form factor at $Q^2 = 0$:

$$\langle r_p^2 \rangle \equiv -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

- The second method measures the Lamb shift in hydrogen which is directly sensitive to the proton radius. **For electronic** measurements, these two methods agree and give a radius of **0.88 fm.**
- However, the **muonic hydrogen** measurements yield a radius of **0.84 fm**.

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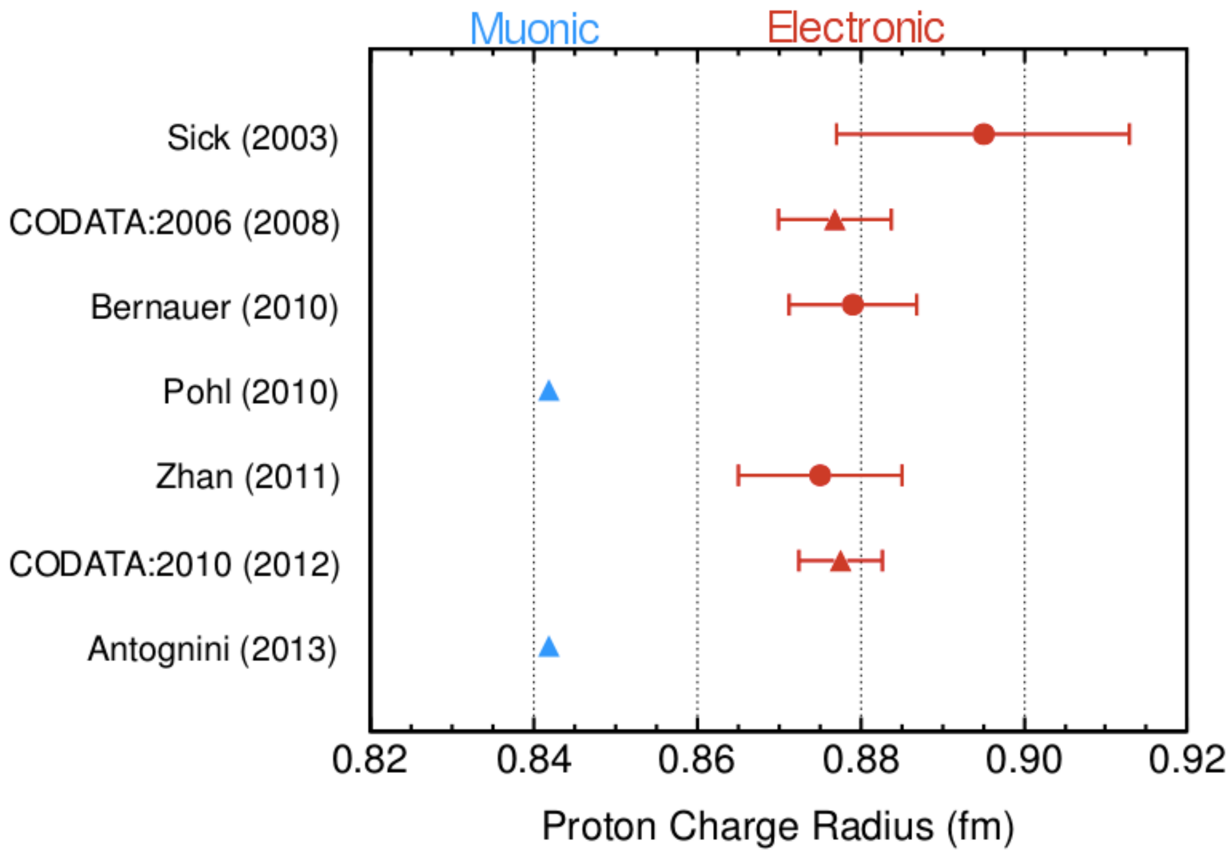
A recent summary of proton radius extractions

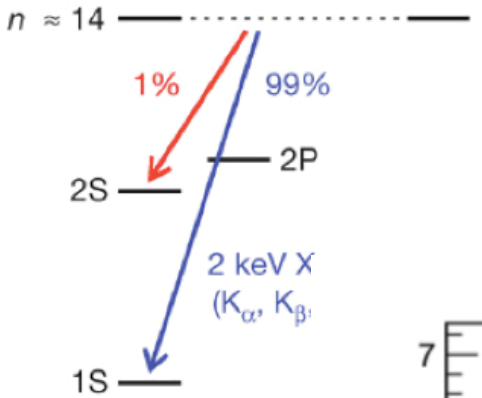


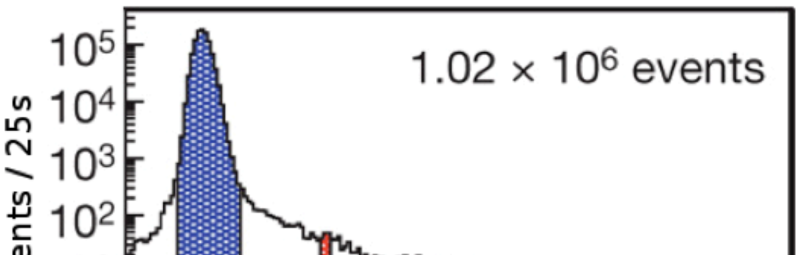
The CODATA value is obtained from a combination of 24 transition frequency measurements in H and deuterium and several results from elastic electron scattering

Proton radius from μp Lamb shift

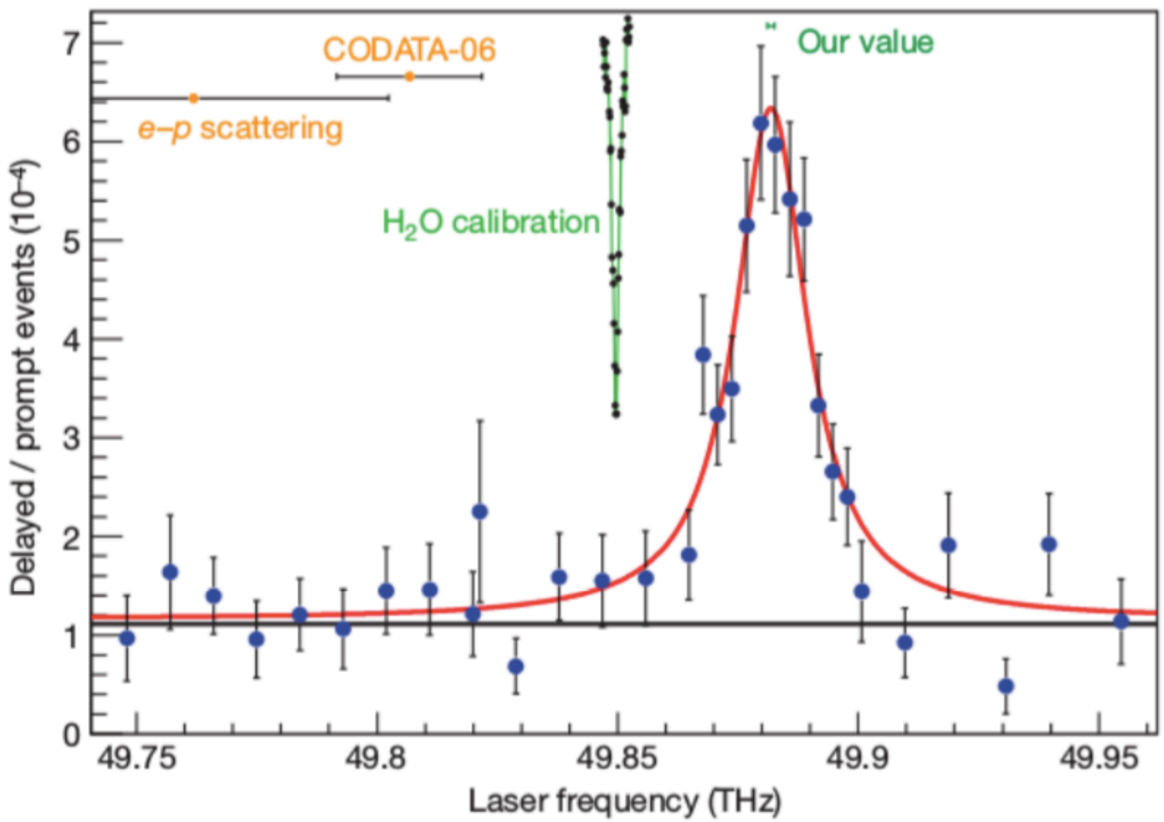
Lamb Shift: 2S-2P splitting in atomic spectrum   Pic: Pohl *et al.* Nature (201(

- **prompt X-ray ($t \sim 0$s):** μ^- stopped in H_2 gases





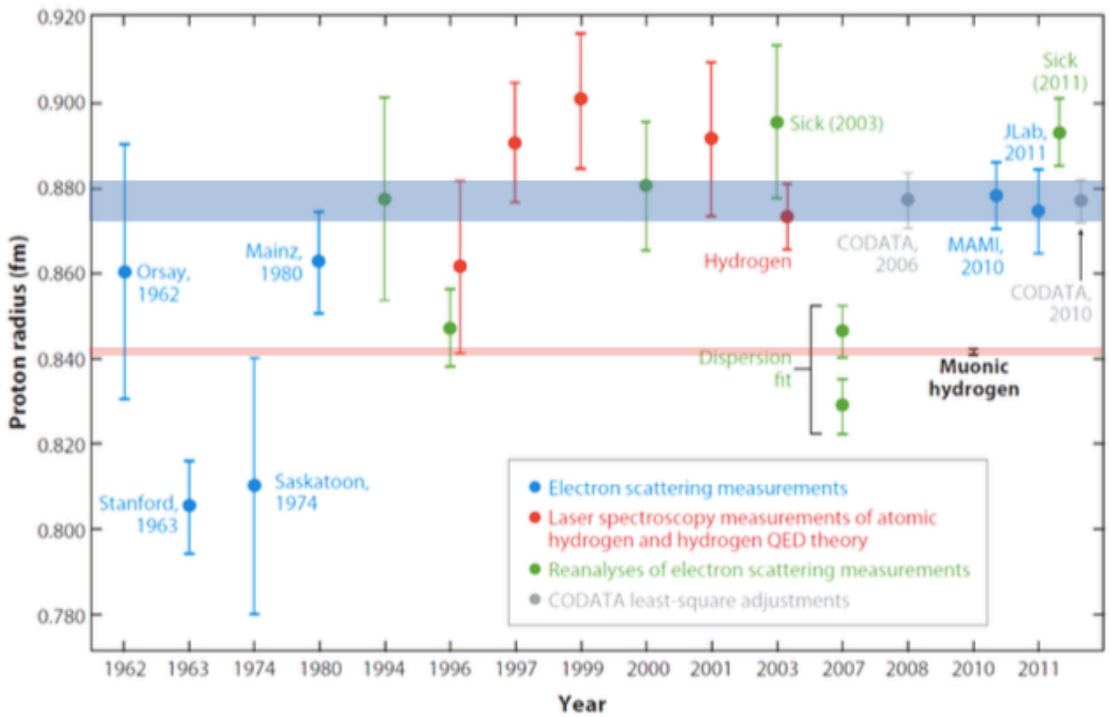
- **delayed X-ray (**



Proton radius from μp Lamb shift

Further measurement and analysis did not ease the discrepancy.

R. Pohl et al., Ann. Rev. Nucl. Part. Sci. 63 (2013)242001



Errors in measurement?
Theoretical corrections wrong?
Broke lepton universality? new physics?

=> So far, no satisfactory explanation is given.

why measuring $\Delta E^{hfs}(\mu^- p)_{1S}$?

New independent high precision measurements on $\mu^- p$ are needed.

The directly observable quantity which is most sensitive to the Zemach radius of the proton R_p is the hyperfine splitting of bound systems involving protons.

The spectroscopic measurement of the hyperfine splitting (hfs) in the 1S state of muonic hydrogen $\Delta E^{hfs}(\mu^- p)_{1S}$, will :

- **provide the proton Zemach radius R_p** with high precision, disentangling discordant theoretical values
- and **quantify any level of discrepancy** between values of R_p as extracted from normal and muonic hydrogen atoms leading to new information **on proton structure and muon-nucleon interaction**.

The experimental value of Rp sets important restrictions on the theoretical models of proton electromagnetic structure and, in particular, on the parametrization of proton form factors, in terms of which the theoretical values are calculated.

a 25 years old idea

Physics Letters A 172 (1993) 277–280
North-Holland

PHYSICS LETTERS A

Experimental method to measure the hyperfine splitting of muonic hydrogen $(\mu^- p)_{1S}$

D. Bakalov [1], E. Milotti, C. Rizzo, A. Vacchi and E. Zavattini

Dipartimento di Fisica dell'Università di Trieste, via Valerio 2, Trieste 34017, Italy and Sezione INFN di Trieste, Area di Ricerca, Padriciano 99, Trieste 34012, Italy

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We propose an experimental method to measure the hyperfine splitting of the energy level of the muonic hydrogen ground state $(\mu^- p)_{1S}$ by inducing a laser-stimulated para-to-ortho transition. The method requires an intense low energy pulsed μ^- beam and a high power tunable pulsed laser.

1. Introduction

The theoretical expression for the hyperfine splitting

Muonic hydrogen Hyperfine splitting

$$\Delta E^{hfs}_{theor} = \Delta E^{F}.(1 + \delta^{QED} + \delta^{str})$$

$$E^{F} = \frac{8}{3}\alpha^{4}\frac{m_{\mu}^{2}m_{p}^{2}}{(m_{\mu}+m_{p})^{3}}\mu_{p}$$

$$\hbar = c = 1$$

μ_p = magnetic moment of the proton

δE^{QED} = correction term related to higher order QED

δ^{str} = correction term related to proton electromagnetic interaction due to strong interaction

δ^{QED} => contribution of higher-order quantum-electrodynamical effects.
This correction is known with an accuracy 10^{-7}.
Note that the expression for δ^{QED} does not involve the mass ratio ml /mp ;
all terms which depend on proton mass or come from strong interactions are included in δ^{str}

Dupays et.al. PHYSICAL REVIEW A 68, 052503 - 2003

Muonic hydrogen Hyperfine splitting

$$\delta^{str} = \delta^{rigid} + \delta^{hvp} + \delta^{pol}$$

$$\Delta E^{hfs}_{theor} = \Delta E^{F}.(1 + \delta^{QED} + \delta^{rigid} + \delta^{hvp} + \delta^{pol})$$

In turn, $\boldsymbol{\delta^{str}}$ splits into:

- a "static" part $\boldsymbol{\delta^{rigid}}$ that accounts for the elastic electromagnetic form factors of the proton and can be calculated using data from elastic scattering experiments,
- a part $\boldsymbol{\delta^{pol}}$ that comes from the internal dynamics of the proton and could only be evaluated using data on inelastic processes with protons,
- and a part $\boldsymbol{\delta^{hvp}}$ describing the strong interaction effects outside the proton, such as hadron vacuum polarization:

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Muonic hydrogen Hyperfine splitting

Two types of "static" proton structure corrections are incorporated in δ^{rigid} , associated with the spatial distribution of the charge and magnetic moment within the proton and with recoil effects, respectively:

$$\delta^{rigid} = \delta^{Zemach} + \delta^{recoil}$$

$$\Delta E^{hfs}_{theor} = \Delta E^{F} .(1+\delta^{QED} + \delta^{Zemach} + \delta^{recoil} + \delta^{hvp} + \delta^{pol})$$

$\delta^{\text{ recoil}}$ denotes the contribution of all terms which depend on the ratio ml /mp

δ^{Zemach} has been calculated in the leading order approximation by Zemach

$$\delta^{Zemach} = \delta^{Zemach}_{(1)} + O(\alpha^2)$$

$$\delta^{Zemach}_{(1)} = 2\alpha \frac{m_{lp}}{\pi} \int \frac{d^3 p}{P^4} \left(\frac{1}{\mu_p} G_E(-P^2) \cdot G_M(-P^2) - 1 \right) = -2\alpha m_{lp} R_p$$

$$m_{lp} = \frac{m_l \cdot m_p}{m_l + m_p}$$

$G_E(k)$ and $G_M(k)$ are the charge and magnetic form factors of the proton, and Rp is the first moment of the convolution of the proton charge and magnetic moment distributions, also known as Zemach radius of the proton.

R_p from Muonic hydrogen Hyperfine splitting

Two types of "static" proton structure corrections are incorporated in $\delta^{\,rigid}$, associated with the spatial distribution of the charge and magnetic moment within the proton and with recoil effects, respectively:

$$\Delta E^{hfs}_{theor} = \Delta E^{F} .(1 + \delta^{QED} + \delta^{Zemach} + \delta^{recoil} + \delta^{hvp} + \delta^{pol})$$

$$\delta^{Zemach} = \delta^{Zemach}_{(1)} + O(\alpha^2)$$

$$\delta^{Zemach}_{(1)} = -2\alpha m_{lp} R_p$$

the explicit expression of the Zemach term becomes $\delta^{Zemach} = -xx \cdot 2\alpha m_{lp} R_p$.

were xx accounts also for the radiative corrections to $\delta^{Zemach}_{(1)}$

for hydrogen $\delta^{Zemach} = -1{,}0152 \cdot \alpha m_{lp} R_p$

Order of magnitude of the various terms

$$\Delta E^{hfs}_{theor} = \Delta E^{F} \cdot (1 + \delta^{QED} + \delta^{Zemach} + \delta^{recoil} + \delta^{hvp} + \delta^{pol})$$

	Hydrogen		Muonic hydrogen	
	Magnitude	Uncertainty	Magnitude	Uncertainty
E^{F}	1418.84 MHz	0.01 ppm	182.443 meV	0.1 ppm
δ^{QED}	1.13×10^{-3}	$<0.001\times10^{-6}$	1.13×10^{-3}	10^{-6}
δ^{rigid}	39×10^{-6}	2×10^{-6}	7.5×10^{-3}	0.1×10^{-3}
δ^{recoil}	6×10^{-6}	10^{-8}	$1{,}7\times10^{-3}$	10^{-6}
δ^{pol}	1.4×10^{-6}	0.6×10^{-6}	0.46×10^{-3}	0.08×10^{-3}
δ^{hvp}	10^{-8}	10^{-9}	0.02×10^{-3}	0.002×10^{-3}

The overall uncertainty of ΔE_{th}^{hfs} is of the order of 2-3 ppm and is entirely due to proton structure effects.

Dupays et.al. PHYSICAL REVIEW A 68, 052503 - 2003

From theory
$\Delta E_{theor}^{hfs}(\mu^- p)_{1S}$ =182.725 meV

- The total splitting of the 1*S* state is 182.725 meV; this value can be used as a reliable estimate in conducting a corresponding experiment with an accuracy of 30 ppm.

- Corrections of orders α^5 and α^6 to the hyperfine ground-state structure of the muonic hydrogen atom have been calculated. The calculations takes into account the effects of the structure of the nucleus on one and two loop Feynman amplitudes with the help of the electromagnetic form factors of the proton and the modification of the hyperfine part of the Breit potential caused by the electronic polarization of the vacuum.

Contribution to the HFS of the μp atom	Contribution, meV	Refs.
Fermi energy E^F	182.443	[18], (12)
Correction for the anomalous magnetic moment of the muon $a_\mu E^F$ of order α^5, α^6	0.213	[18]
Relativistic correction $(3/2)(Z\alpha)^2E^F$ of order α^6	0.015	[43]
Relativistic and radiative corrections for recoil taking into account κ of the nucleus of order α^6	0.014	[30]
Contribution of one-loop electronic polarization of the vacuum to 1γ interaction of order α^5	0.398	(18)
Contribution of one-loop muonic polarization of the vacuum to 1γ interaction of order α^6	0.004	(19)
Second-order perturbation theory corrections determined by the polarization of the vacuum of orders α^5 and α^6	0.797	(30) + (33)
Correction for the structure of the nucleus of order α^5	–1.215	[22], (40)
Correction for the structure of the nucleus of order α^6	–0.014	[8]
Contribution of the electronic polarization of the vacuum + corrections for the structure of the nucleus of order α^6	–0.021	(43)
Contribution of the two-loop electronic polarization of the vacuum to 1γ interaction of order α^6	0.003	(21) + (24)
Correction for the intrinsic muon energy + corrections for the structure of the nucleus of order α^6	0.008	(50)
Vertex corrections + corrections for the structure of the nucleus of order α^6	–0.014	(61)
Jellyfish diagram correction + corrections for the structure of the nucleus of order α^6	0.004	(66)
Correction for the hadronic polarization of the vacuum of order α^6	0.004	(45)
Correction for the polarizability of the proton of order α^5	0.084	[16]
Contribution of weak interaction	0.002	[36]
Total correction	182.725 ± 0.062	

R_p from Muonic hydrogen Hyperfine splitting

assuming that the theoretical values of **δ^{QED}, δ^{recoil}, δ^{hvp} and δ^{pol} are accurate** and use the experimental data to determine the Zemach radius of the proton Rp as:

$$R_p = -\left(\frac{\Delta E^{hfs}_{\exp}}{\Delta E^{F} - 1 - \delta^{QED} - \delta^{recoil} - \delta^{hvp} - \delta^{pol}}\right) \Big/ \left(1{,}0152 x 2 m_{ep} \alpha\right)$$

The above assumption is justifiable since all four correction terms are objects of QED, the only difference of δ^{hvp} and δ^{pol} from the former two being that their evaluation requires the use of additional phenomenological information beyond first principles.

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current status of $(\mu^- p)^{hfs}_{1S}$

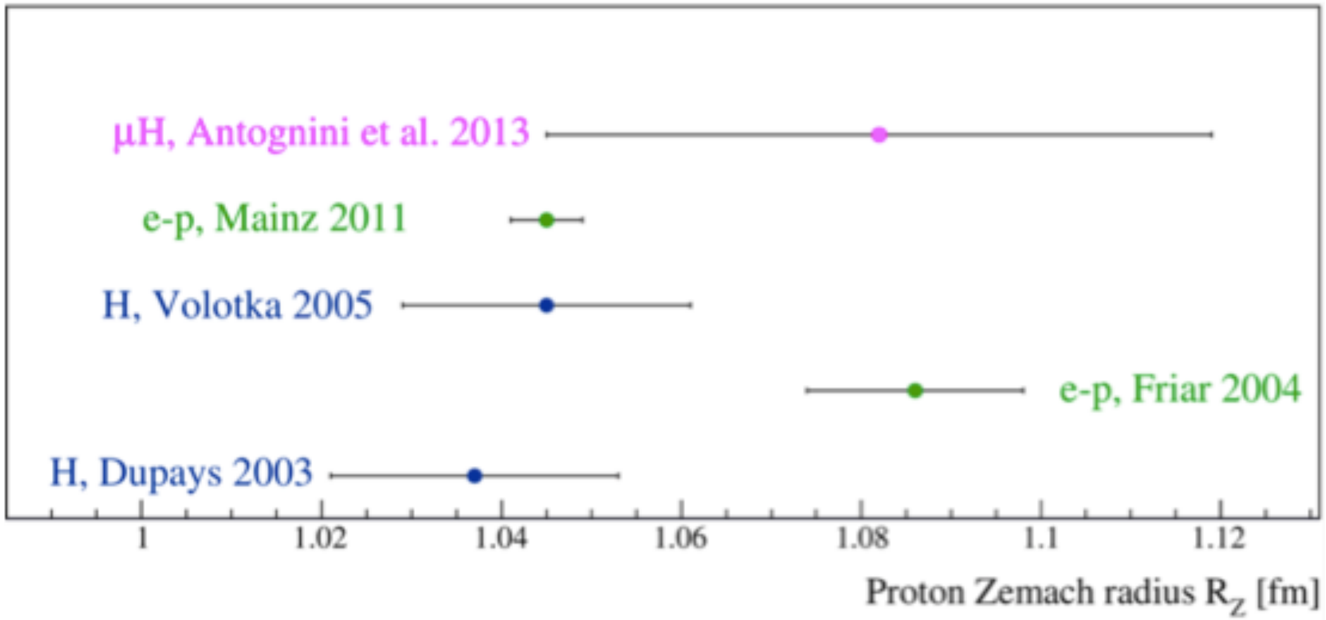
units fm	rms charge radius r_{ch}	Zemach radius R_p
e^--p scattering & spectroscopy	r_{ch} = **0.8751(61)**	R_p=1.037(16) Dupays&*al*' 03 R_p=1.086(12) s Friar&Sick' 04 R_p=1.047(16) Volotka&*al*' 05 R_p=1.045(4) s Distler&*al*' 11
μ^--p Lamb shift spectroscopy	r_{ch}=0.84087(39)	a 20 years old idea: R_p from HFS of $(\mu^- p)_{1S}$ Either confirm a e^-p value or admit: e^-p and μ^-p differ

Recently : R_p = 1.082(37) [PSI'12] from HFS of $(\mu^- p)_{2S}$

=> we need new indipendent measurements

These estimates show that
the current theoretical uncertainty of Rp significantly exceeds the experimental one,
and that the experimental results on the proton Zemach radius may be used as a test for the quality of models of the proton in the limit of low transfer momenta.

current status



The hyperfine splitting is more sensitive to the proton structure than the Lamb shift

- The **main nuclear structure dependent contribution** (so-called 'Zemach correction') is of the form

$$\Delta\nu(Zemach) = \nu_F \frac{2Z\alpha m_e}{\pi^2} \int \frac{d^3\mathbf{q}}{\mathbf{q}^4} \left[\frac{G_E(-\mathbf{q}^2) G_M(-\mathbf{q}^2)}{1+\kappa} - 1 \right]$$

- the comparison of theory and experiment leads *<u>for the hydrogen</u>* hyperfine splitting to

$$\frac{\nu_{hfs}(exp) - \nu_{hfs}(theo)}{\nu_{hfs}(exp)} = \left(0.48 \pm 0.56\right) ppm.$$

- Proton polarizability is not included in ν_{hfs}(theo) and the difference above has to be interpreted as its contribution.

Comparing the theoretical prediction with the experiment, deduce $\mathbf{R_p}$ with a relative accuracy better than 5×10^{-3}

limited by the relative accuracy on the polarizability contribution.

The theoretical prediction for the 1S-hfs in μp can be written approximately:

$$\Delta E^{hfs}_{th}(\mu^- p)_{1S} = 182.819(1)[\mathrm{meV}] - 1.30[\mathrm{meV/fm}]\,\mathbf{R_p} + 0.064(21)\,[\mathrm{meV}]$$

- where the first term includes the Fermi energy, QED corrections, hadronic vacuum polarization, recoil corrections and weak interactions,
- the second term, proportional to $\mathbf{R_p}$, is the finite size contribution containing also some higher order mixed radiative finite size corrections,
- and the third term is given by the proton polarizability contribution.

D_{21} from ($\mu^- p$) hfs

Determination of the proton Zemach r_Z radius is essential for:

1. understanding ***the proton charge and magnetic structure***
2. Testing bound-state QED by measuring

$$D_{21} = \Delta E^{1S}_{HFS} - 8 \times \Delta E^{2S}_{HFS}$$

The difference is weakly affected by the effects of the nuclear structure and thus may be calculated with a high accuracy. The leading nuclear structure contributions are determined by two photon exchanges with a high momentum transfer and have the hard structure and, therefore, cancel when calculating difference.

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Hyperfine Splitting (HFS) of $\mu^- p$ with accuracy 10^{-5}
Zemach radius of the proton with an accuracy of better than 1%

- measure $(\mu^- p)^{hfs}_{1S}$ with <10 ppm accuracy
  - TPE
    - Polarizability
    - Zemach radius
  - Zemach Radius accuracy <1%
    - Magnetic radius

Impact

- In the measurement of **ΔE^{hfs} in $(\mu p)_{1s}$**, the proton structure corrections δ^{str} scale approximately as ($m\mu$ /me), are enhanced (compared to hydrogen) by a factor of 2 10^2, QED effects are overshadowed by the proton structure corrections.

- *In both hydrogen and muonic hydrogen*, the proton structure corrections $\boldsymbol{\delta^{str}}$ is dominated by two independent terms: **the Zemach term $\boldsymbol{\delta^{rigid}}$ and the polarizability term $\boldsymbol{\delta^{pol}}$** .
  - while the Zemach term is directly related to the Zemach radius of the proton Rp, a well defined physical parameter,
  - δ^{pol} is expressed in terms of the form factors and polarized structure functions of the proton in an indirect and case-dependent way and is not associated with a single parameter.
- the measurements of ΔE^{hfs} in hydrogen and muonic hydrogen atoms may be regarded as repeated experimental determination of the Zemach radius of the proton.

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Impact

- The repeated measurements of Rp in hydrogen and muonic hydrogen are the best way to verify the theoretical evaluation:
    - compatible values of Rp extracted from the hyperfine splitting in hydrogen and muonic hydrogen will confirm the reliability of the theoretical values of δ^{pol} and vice versa.
- The accuracy of Rp depends on the uncertainty of δ^{pol} ;
    - a measurement of the hyperfine splitting of the ground state of muonic hydrogen based on the available theoretical predictions would give the value of Rp accurate to 1%.
    - such an accuracy would allow to filter the numerous theoretical estimates of Rp and detect a deviation of GE /GM from 1 by distinguishing the values of Rp obtained with and without account of the JLab experimental results.
- It would be preferable for this purpose to have the value of Rp accurate to 0.5% or better, that requires in turn that the theoretical uncertainty of δ^{pol} be brought below $3\ 10^{-5}$ and that the experimental error of ΔE_{exp}^{hfs} not exceed 30 ppm.

Laser spectroscopy for ΔE^{HFS}_{1S}

HOW ?

Method relying on a two-steps process

μp^* n >14 are formed in a hydrogen gas target, in subsequent collisions with H2 molecules, the μp de-excite to the thermalized μp in the (1S) F =0 state.

$$\mu^- p(\uparrow\downarrow) \rightarrow \mu^- p(\uparrow\uparrow)$$

Laser spectroscopy for ΔE^{HFS}_{1S}
first step
Tunable laser shot

1. $\mu^{-}p(\uparrow\downarrow)$ absorbs a photon @ ***resonance wavelength***

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

Converts the spin state of the ($^{-}\mu p$) atoms from $^1S_0$ to $^3S_1$

$$\mu^{-}p(\uparrow\downarrow) \rightarrow \mu^{-}p(\uparrow\uparrow)$$

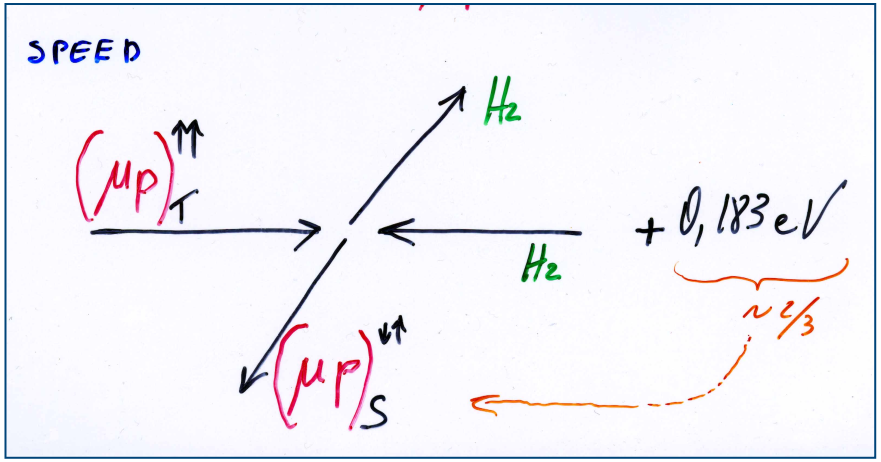
Laser spectroscopy for ΔE^{HFS}_{1S} second-step **energy dependent μ transfer**

2. $\mu^- p(\uparrow\uparrow)$ $^3S_1$ atoms are collisionally de-excited and the transition energy is converted into additional kinetic energy of the μp system

$\mu^- p(\uparrow\downarrow)$ $^1S_0$ and accelerated by ~ 0.12 eV $\sim 2/3\ \Delta E^{HFS}_{1S}$

Energy-dependent muon transfer rates change the time distribution of the cascade X-ray events

λ_0 is recognized by maximal response in the time distribution



D. Bakalov, et al., Phys. Lett. A172 (1993).
A. Dupays, **Phys. Rev. A 68**, p. 052503, 2003.
D. Bakalov, et al., NIM B281 (2012).

Exploit the ***energy dependence of the muon transfer*** from muonic hydrogen to higher-Z gas is to detect the spin flip transition in μp.

- For few gases the muon-transfer rate λ_{pZ} is energy independent ***Oxygen exhibits a peak in the muon transfer rate λ_{pZ}^{epith} at the epithermal energy.***
- Adding small quantities of oxygen to hydrogen one can observe the number of HPF transitions which take place from the muon-transfer events this by measuring the time distribution of the oxygen characteristic X-rays of the added gas.

$$\mu p + Z \Rightarrow \mu Z + p$$

A. Werthmüller et al. / Muon transfer to oxygen 3

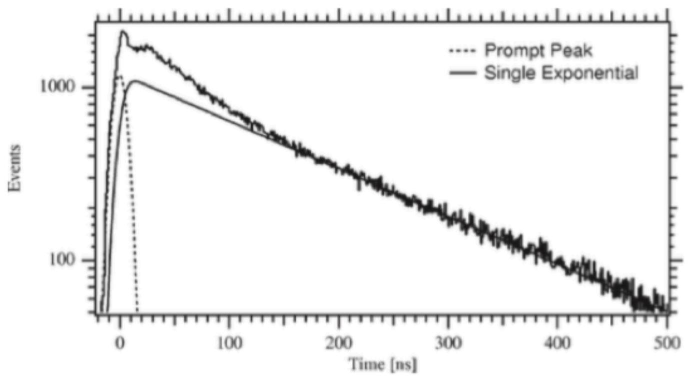


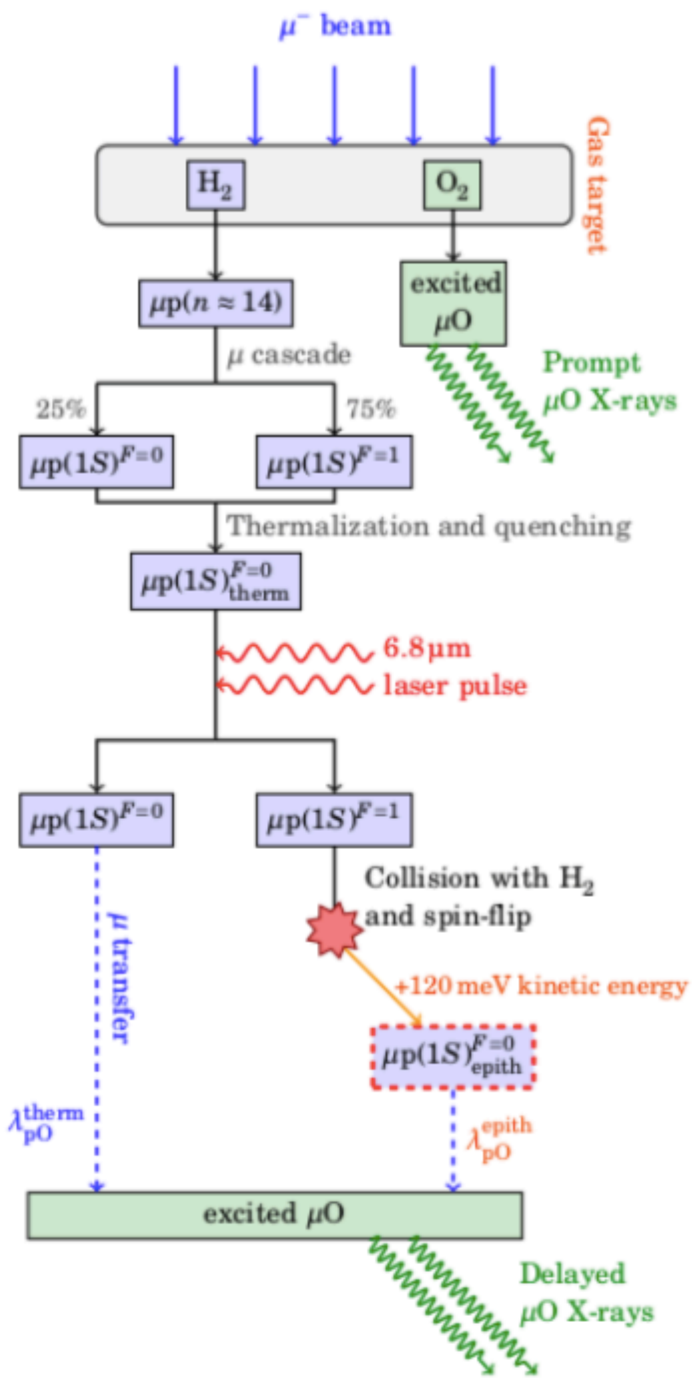
Figure 2. Background subtracted time distribution of muonic oxygen $\mu O(2\text{–}1)$ X-rays measured in a gaseous mixture of $H_2 + 0.4\% O_2$ at 15 bar and room temperature. The prompt peak corresponds essentially to muons directly captured in oxygen whereas the delayed part is due to muon transfer from the ground state of the $(\mu p)_{1s}$ atom. The solid line represents a pure exponential function to stress the additional structure.

D. Bakalov, A. Adamczak et al., Phys. Lett. A379 (2014).
A. Adamczak et al. Hyperfine Interactions 136: 1–7, 2001.
F. Mulhauser, H. Schneuwly, Hyperfine Interact. 82 (1993).
A. Werthmüller, et al., Hyperfine Interact. 116 (1998).

FAMU Principle of operation

μp formation =>>

μp termalization =>>

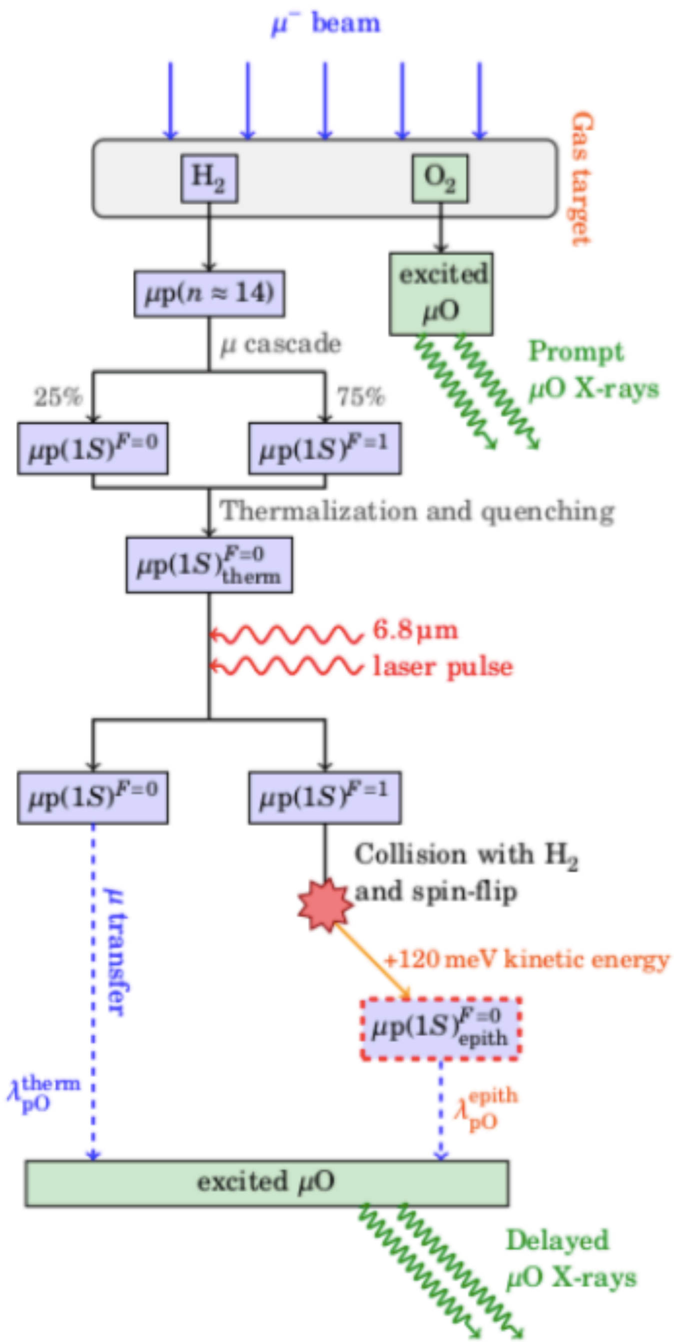


Lay-Out of the experiment

laser exitation F=0 F=1 =>>

μ enhanced transfer to O =>>

μO X-ray time distribution =>



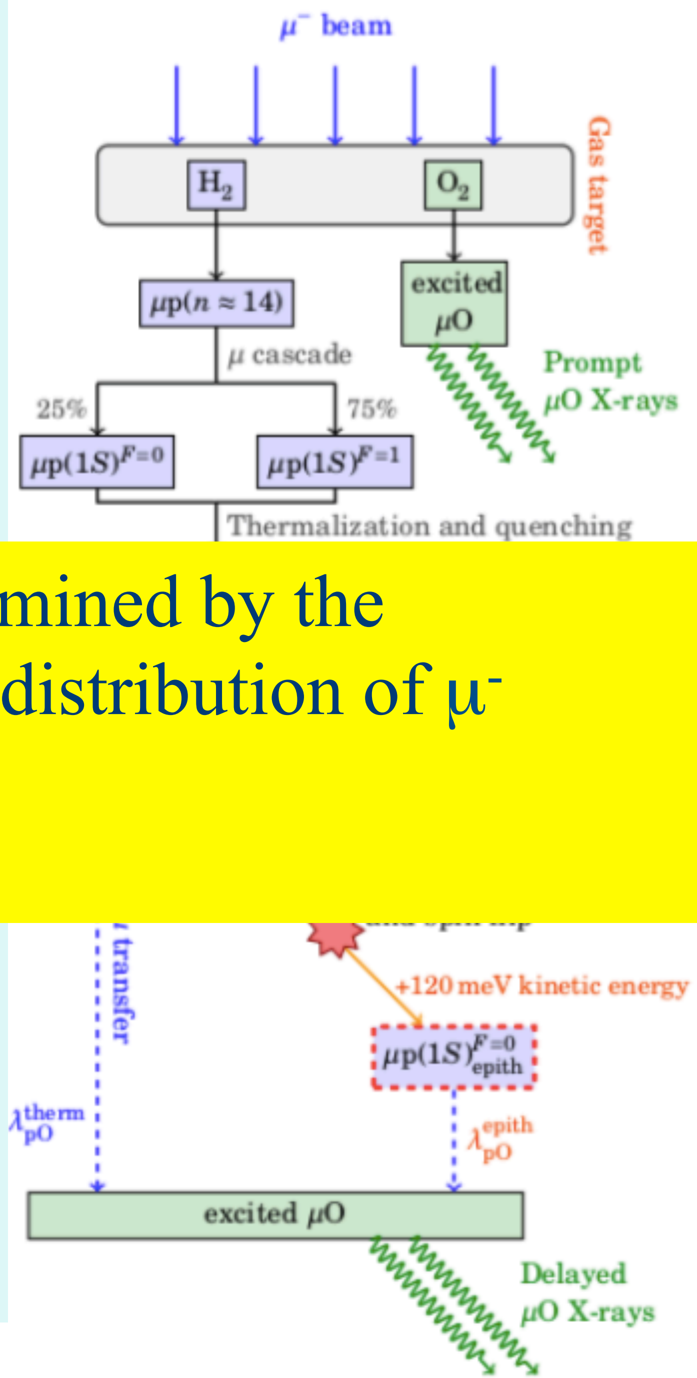
Lay-Out of the experiment

laser exitatio

λ_0 resonance is determined by the maximizing the time distribution of μ^- transferred events.

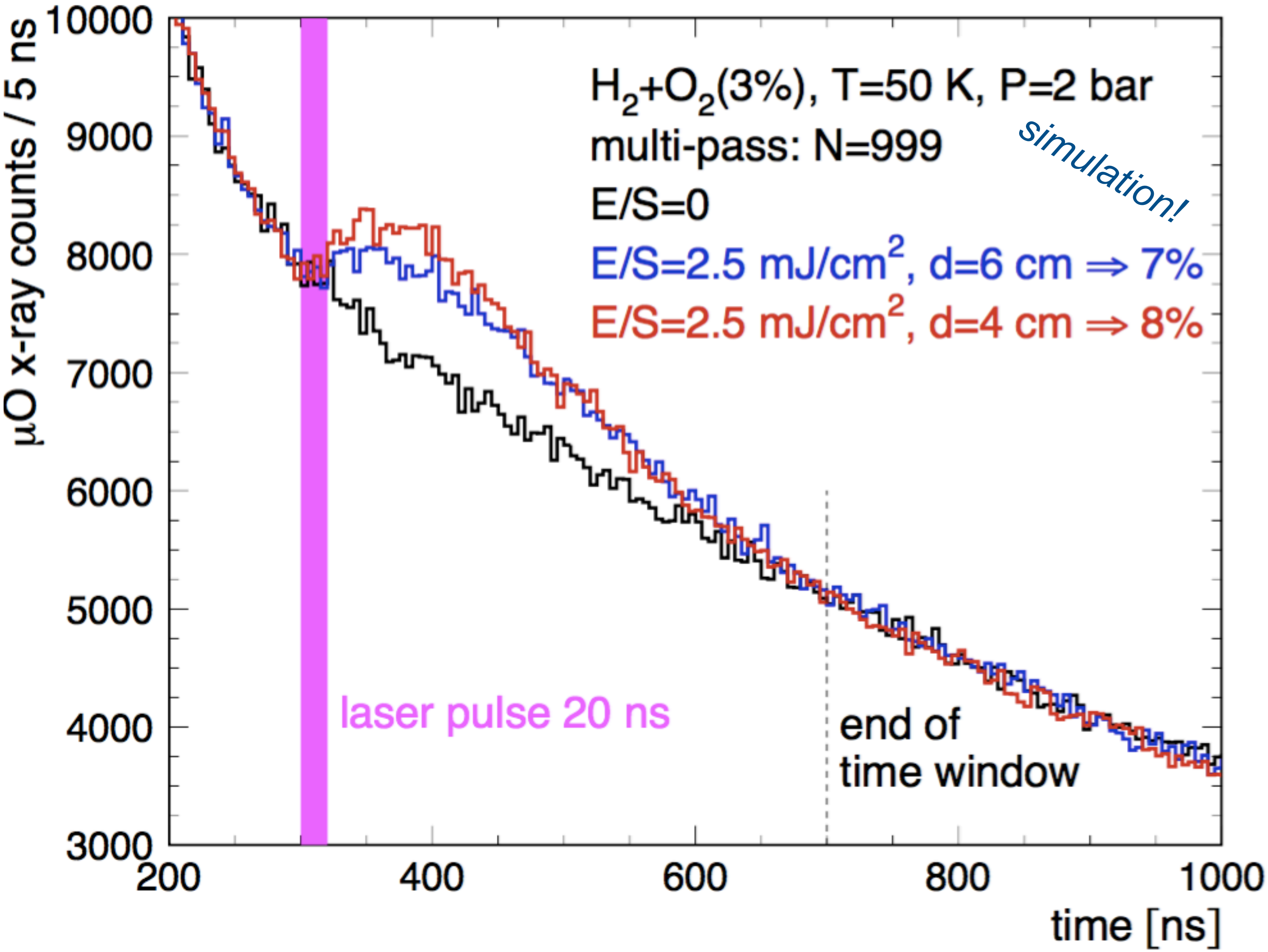
μ enhanced transfer to O =>>

μO X-ray time distribution =>



FAMU

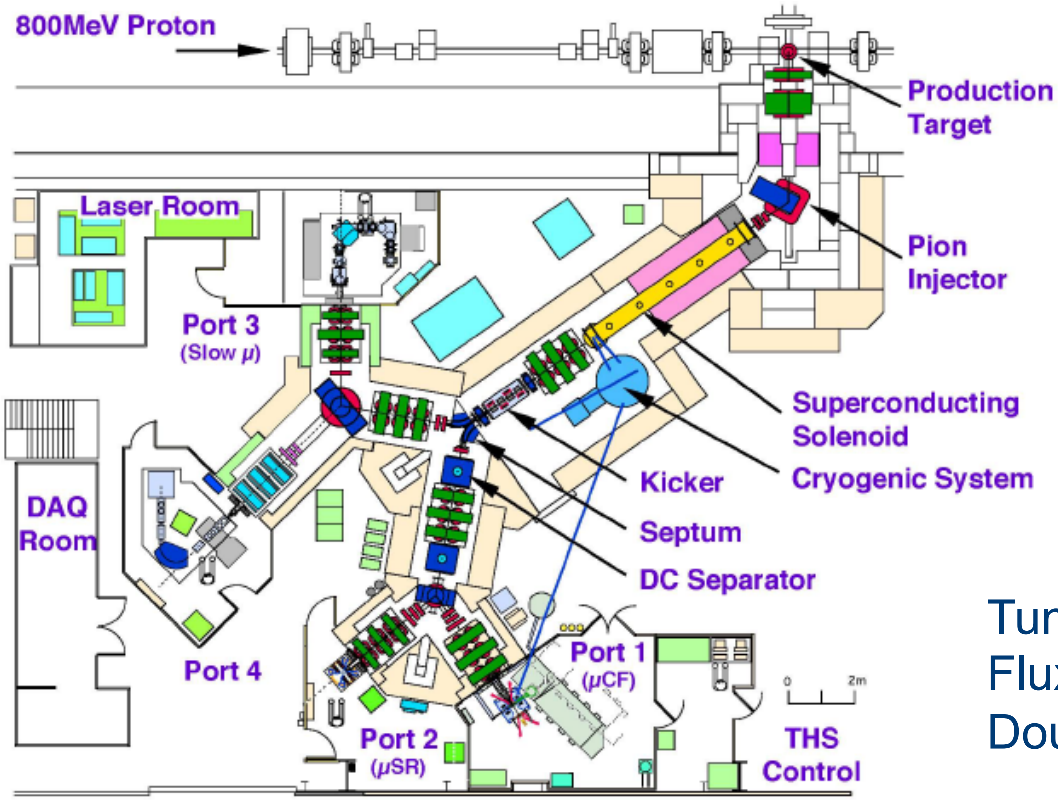
Study of best setup to maximize signal



FAMU: key ingredients

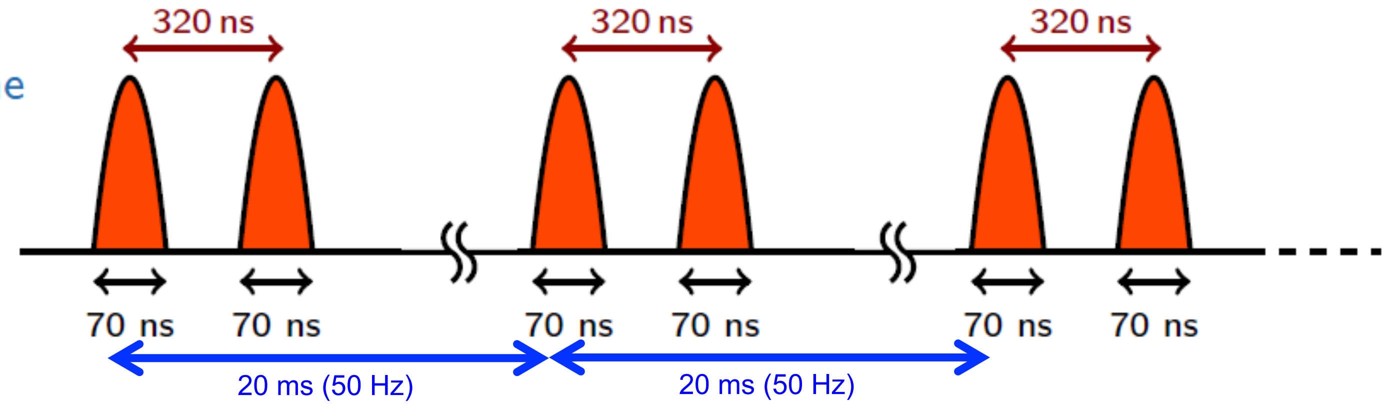
- high intensity muon beam
- proper gas mixture and target
- innovative high energy and fine-tunable laser
- best X-rays detectors (fast and accurate)

High intensity muon beam



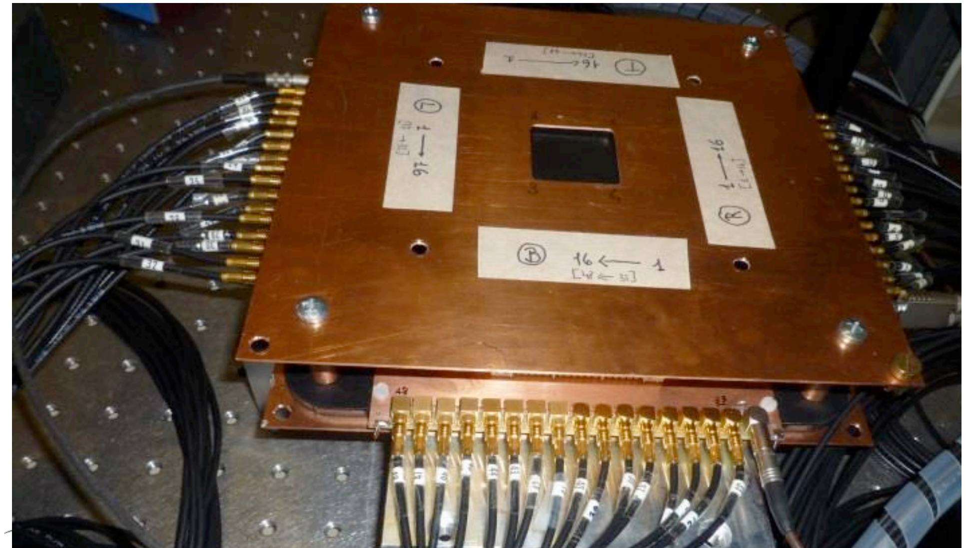
Tunable momentum: 20 – 120 MeV/c
Flux μ^- : 7 x 10^4 muons/s
Double pulsed beam

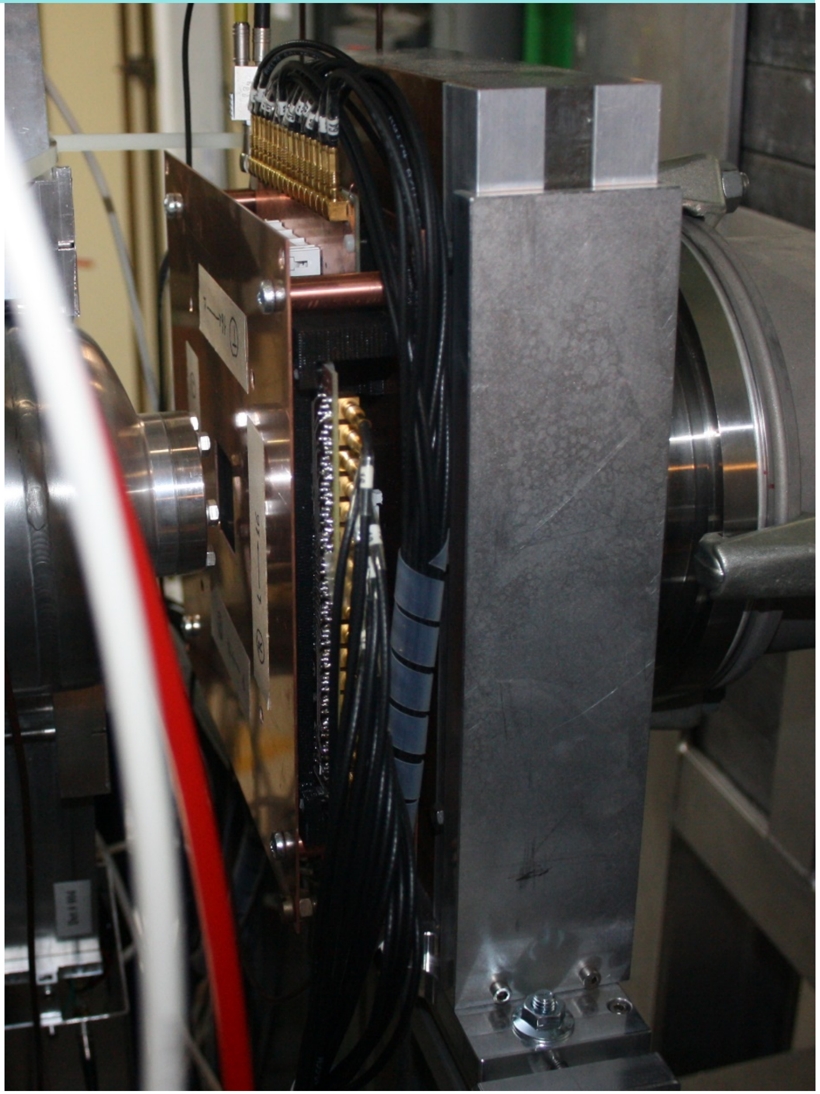
Beam time structure



Hodoscope for beam shape monitoring

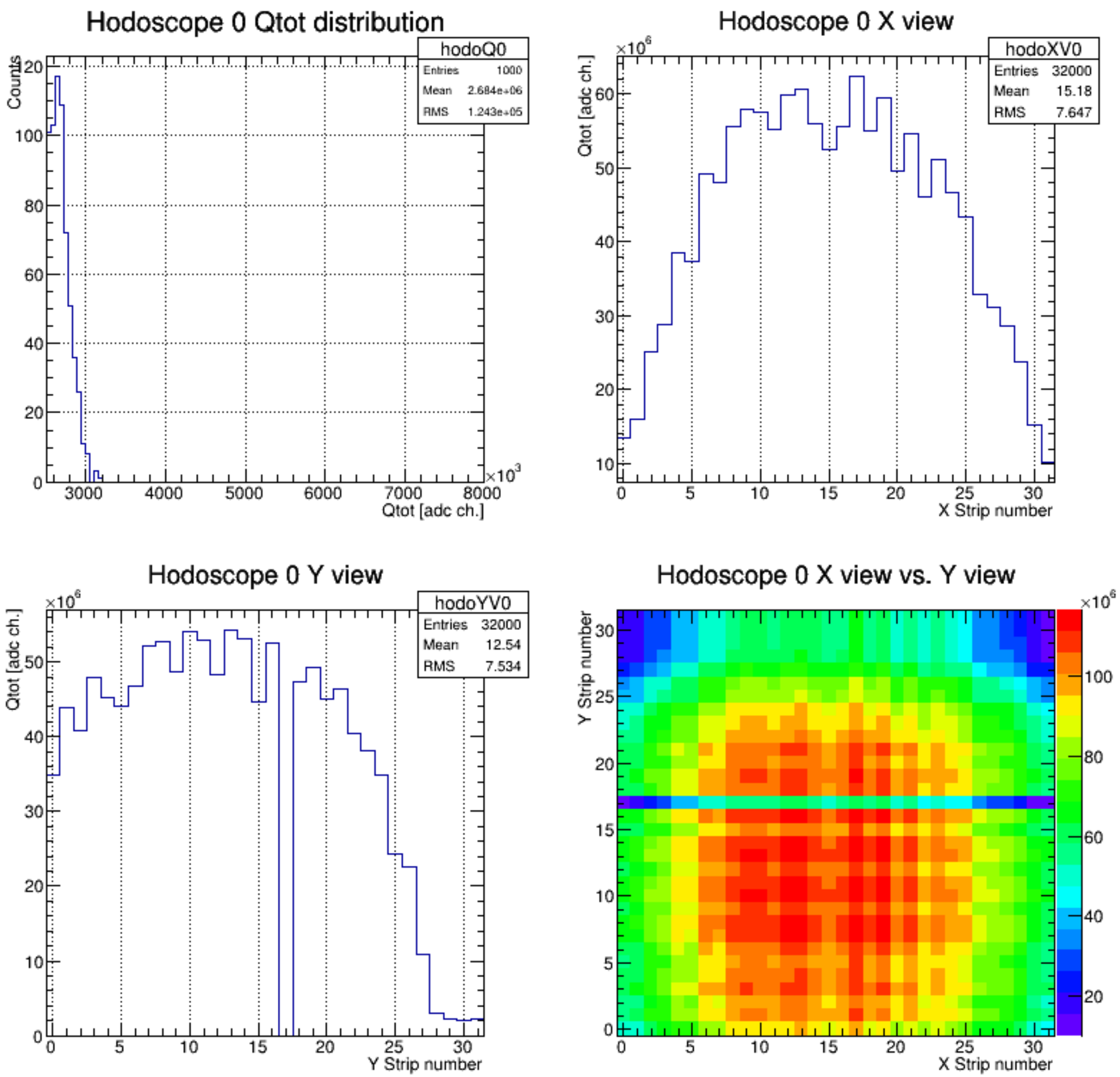
Final version:
two planes (X and Y) of 32 scintillating fibers 1 x 1 mm^2 square section
SiPM reading with fast electronics
3D printed supports





hodoscope in the 2016 setup

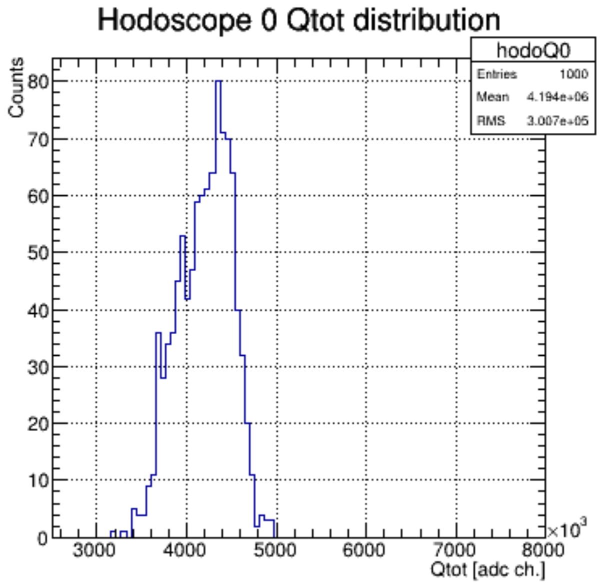
Hodoscope: PORT1 commissioning

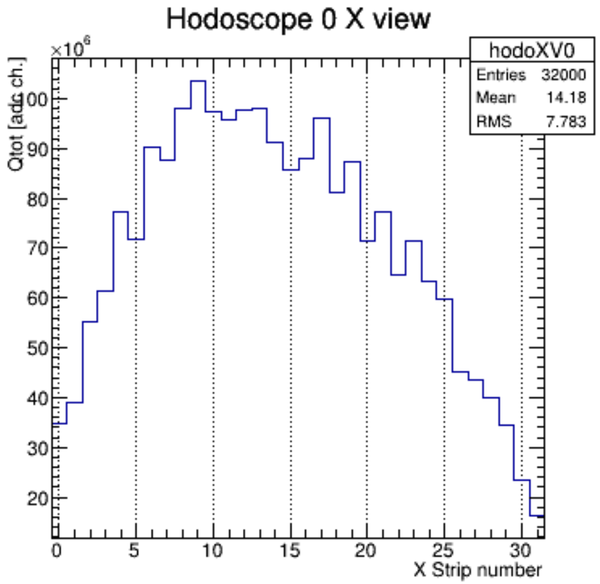


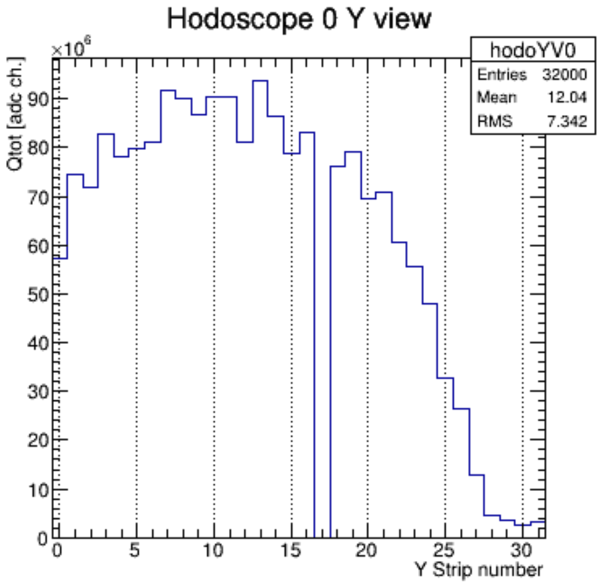
2017 data at PORT1:

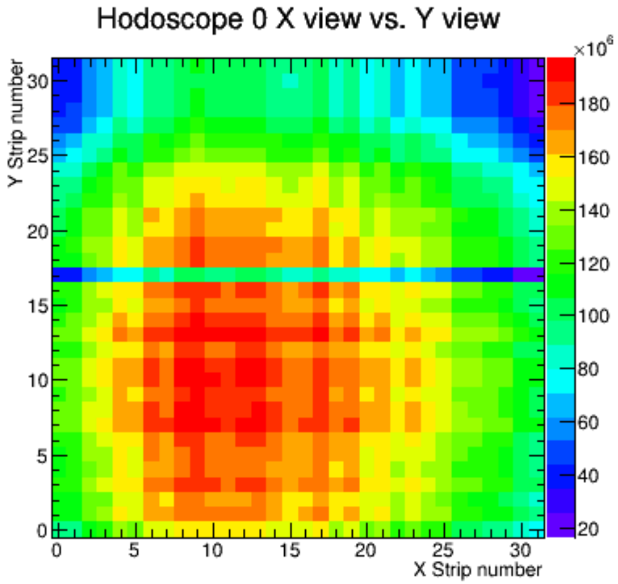
tuning magnets currents to change beam shape with millimetric resolution

Hodoscope: PORT1 commissioning





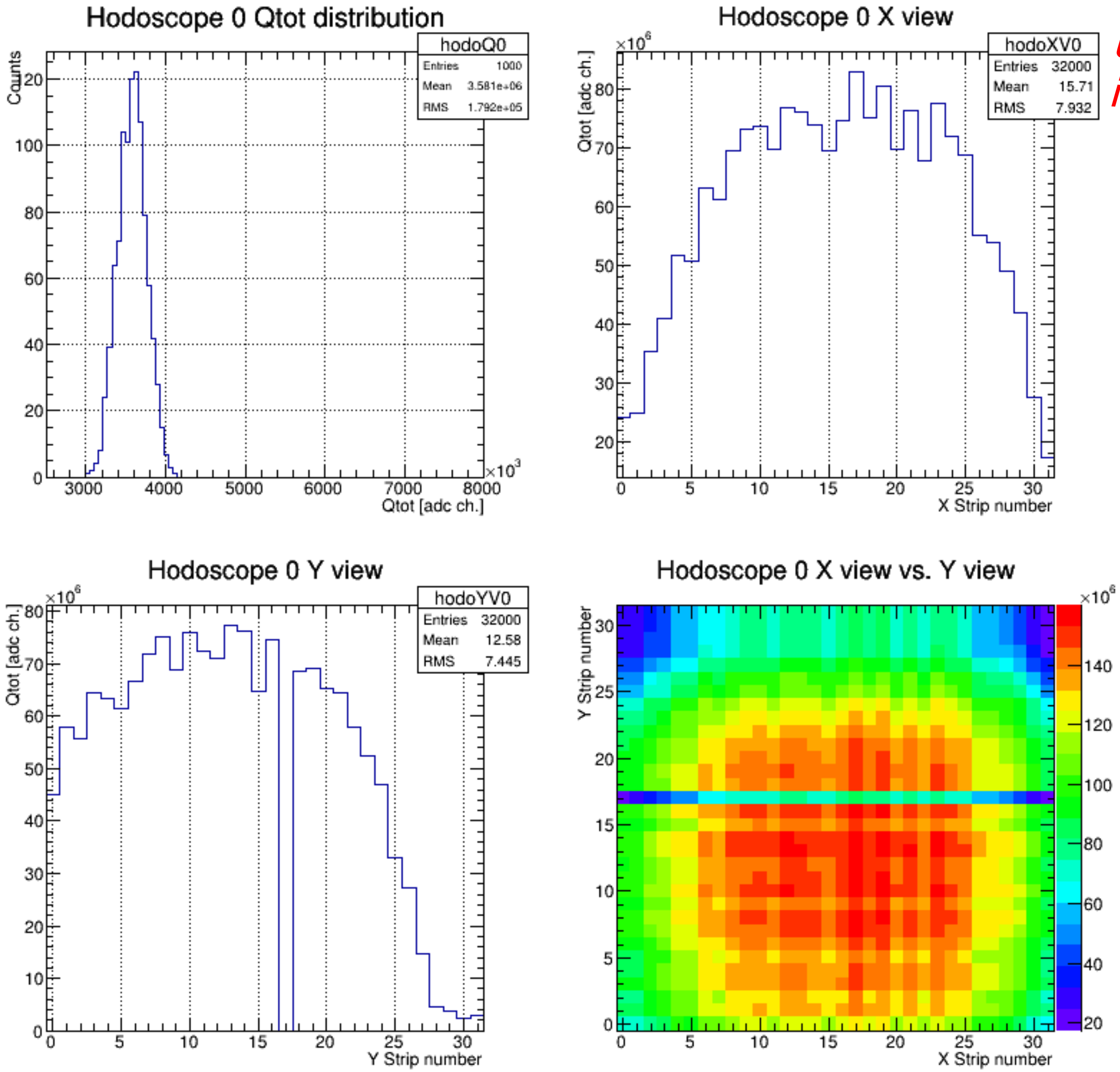




2017 data at PORT1:

tuning magnets currents to change beam shape with millimetric resolution

Hodoscope: PORT1 commissioning



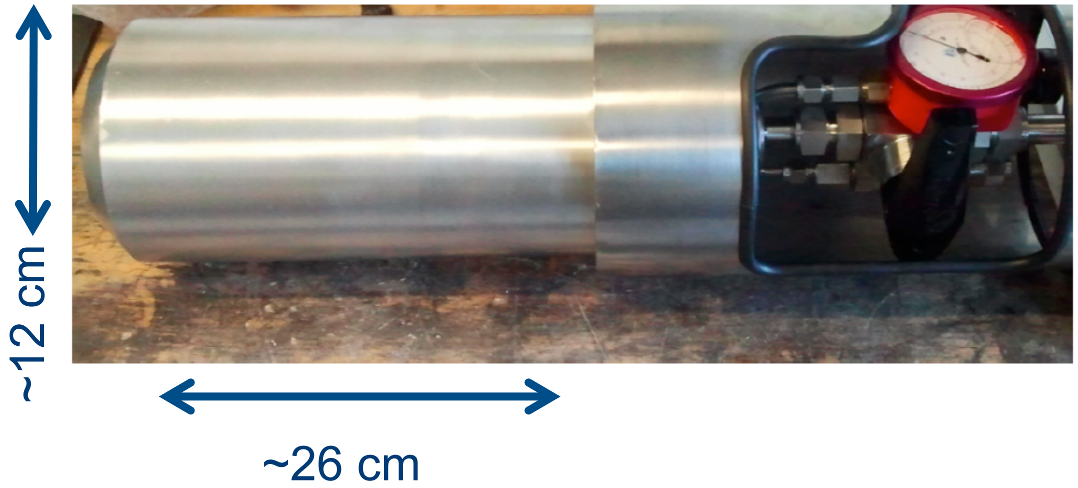
unprecedented precision in beam monitoring at RAL

2017 data at PORT1:

tuning magnets currents to change beam shape with millimetric resolution

Target: a challenge itself

- 2015 target: detectors and beam test and validation



- 2016 target: cryogenic target, transfer rate measurement

- 2018 target: cryogenic target + optical path and cavity, Zemach radius measurement

Target: a necessary trade-off

Main requirements:

-Operating temperature range: 40 K ≤ T ≤ 325 K

-Temperature control for measurement runs at fixed T steps from 300 K to 50K

-Gas @ constant density, H_2 charge pressure at room T is ~40 atm

-International safety certification (Directive 97/23/CE PED)

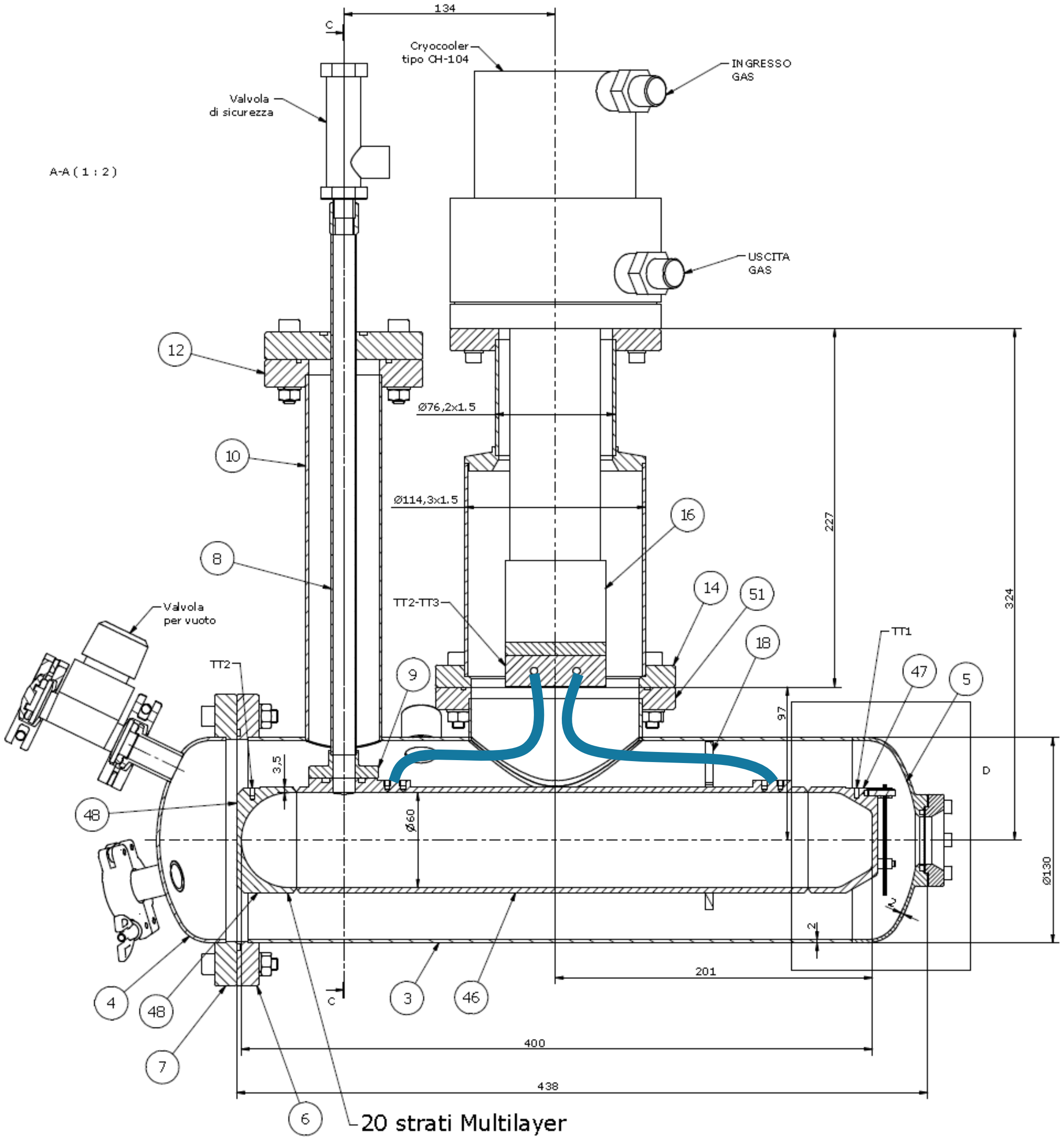
-Minimize walls and windows thickness

-Target shape and dimensions to

- maximize muon stop in gas
- to minimize distance gas – detectors
- to be compliant to allowable volume at Riken Port

-H_2 compatible

Best solution



Target= Inner vessel with high P gas (44 bar)

-Al alloy 6082 T6 cylinder D = 60 mm and L = 400 mm, inner volume of 1.08 l

-Internally Ni/Au plated (L = 280 mm)

-Cylinder side wall thickness = 3.5 mm

-Wrapped in 20 layers of MLI

-Front window D= 30 mm 2.85 mm thick

-Three discs of 0.075 mm Al foil for window radiative shield

-304L SS gas charging tube

-304L SS cooler cold-end support

-G10 mechanical strut

-Two Cu straps for cooling

Vacuum vessel = outer cylinder (P atm)

-Al6060 D=130 mm, 2 mm thick walls

-≈30mm between inner/outer walls

-Flanged Al window 0.8 mm thick

-Pumping valve & harness feed-tru’s

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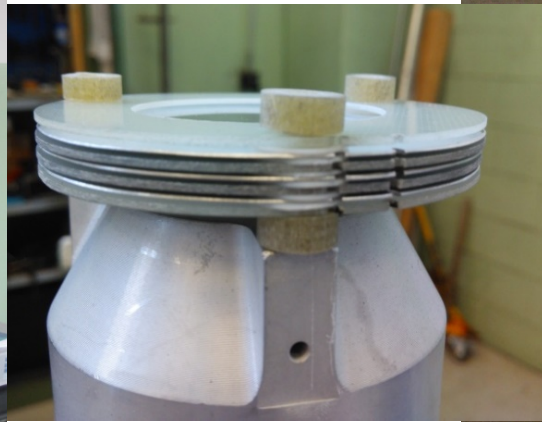
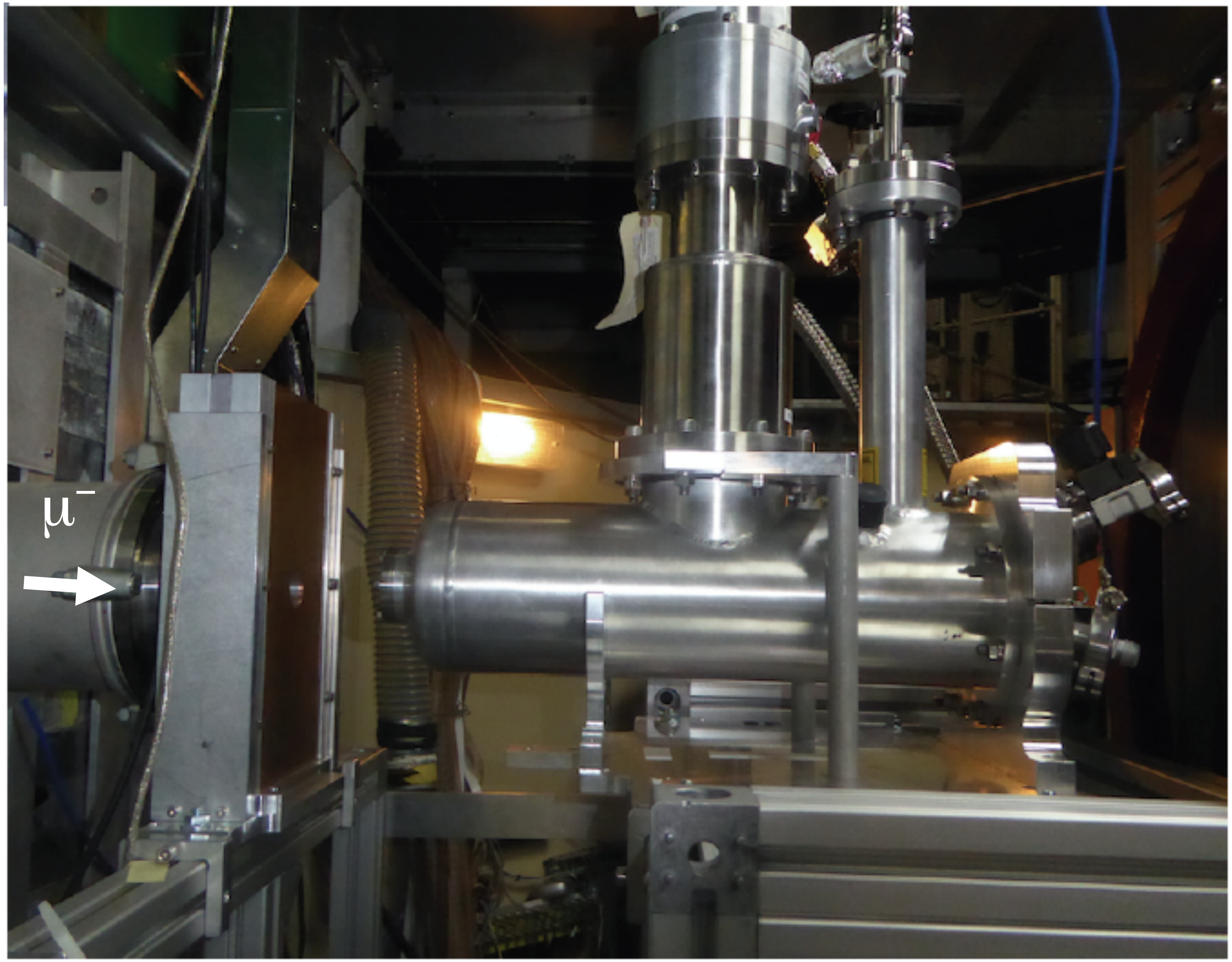
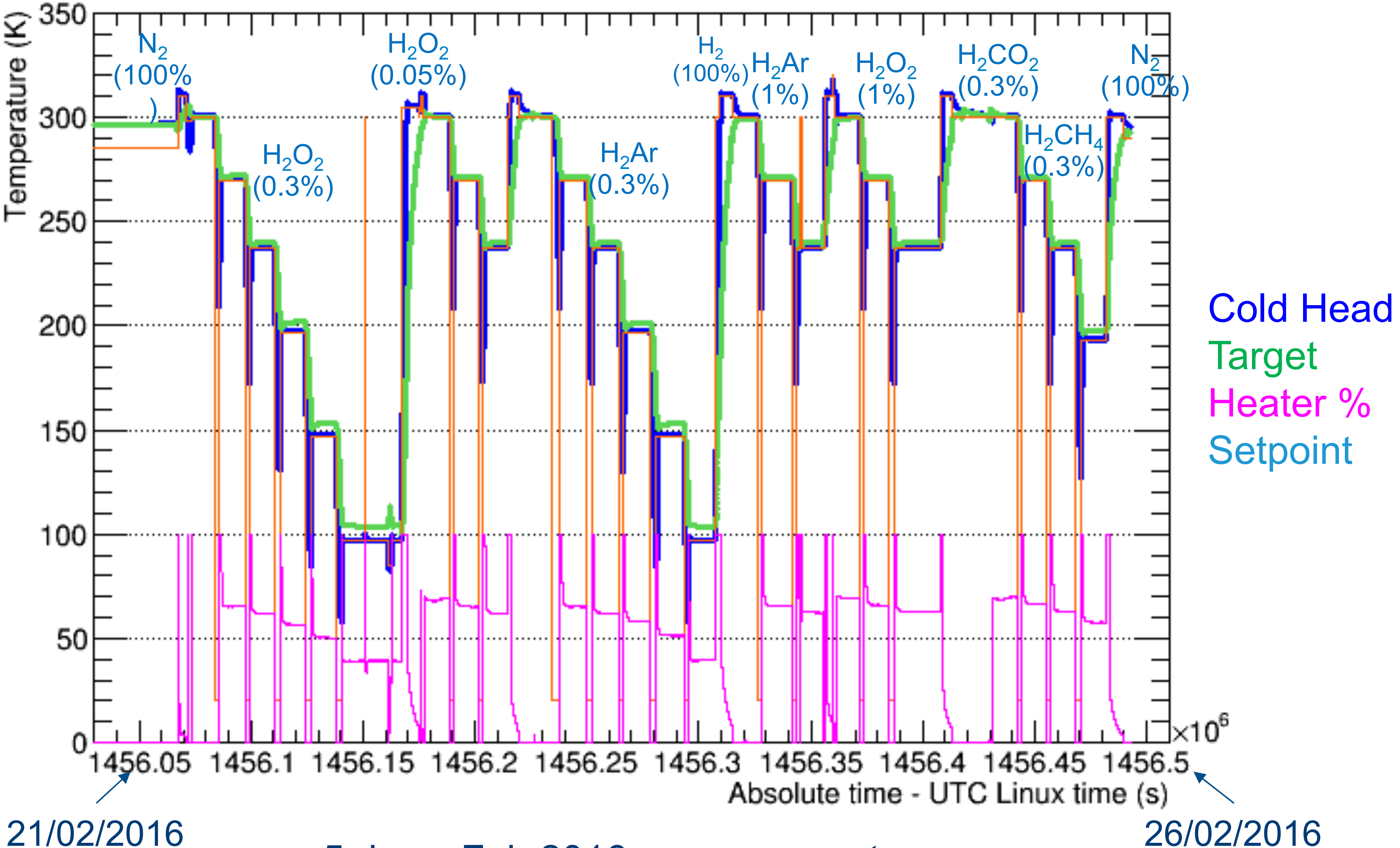
Target in lab



Target on beam line



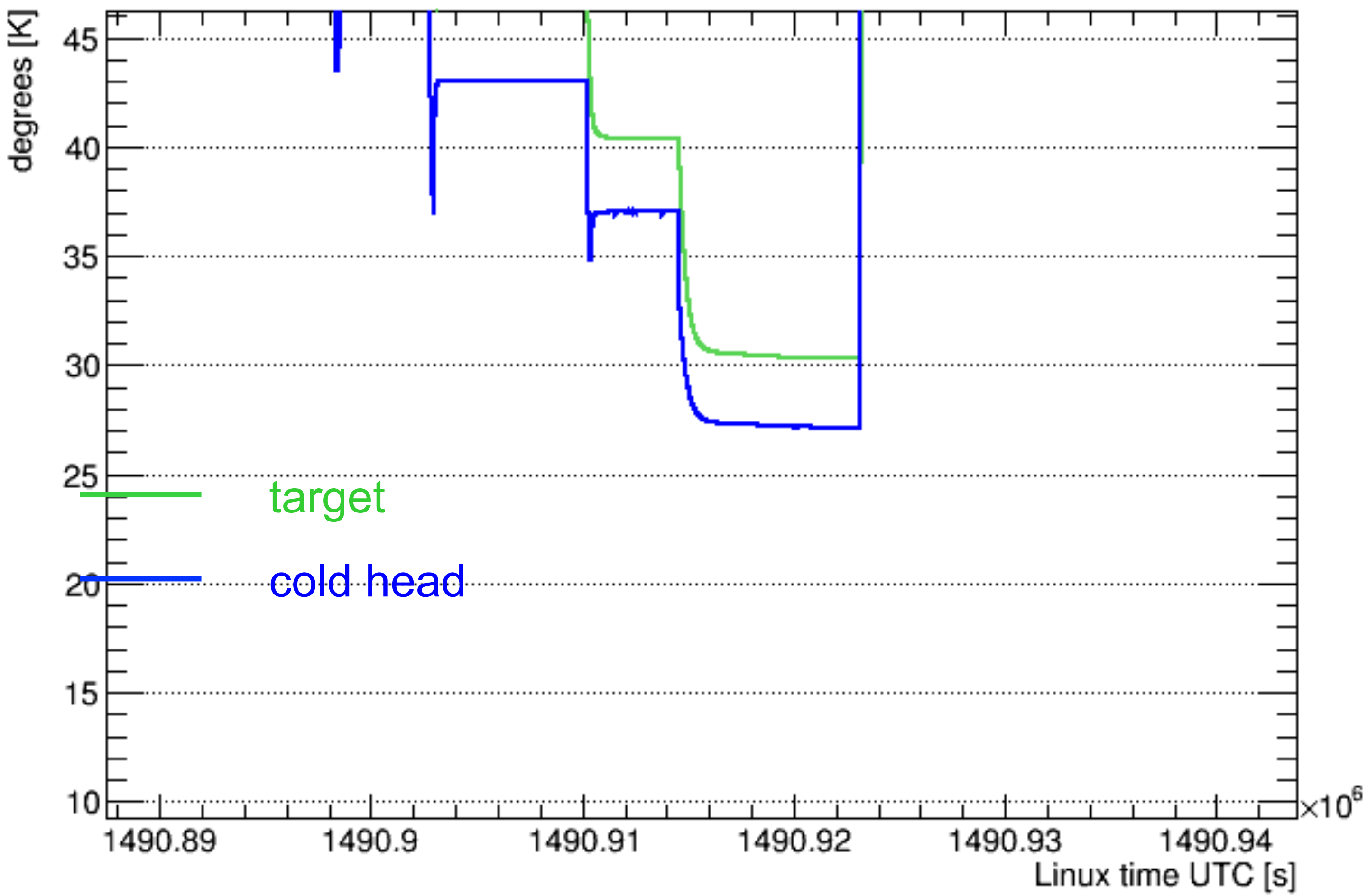
Thermal cycles 2016



5 days: Feb 2016 measurements run

Target cryo performances: T control steps

2017 on beam: lowest temperature



Detectors: suited for time-resolved X-ray spectroscopy

Germanium HPGe: low energy X-rays spectroscopy

ORTEC GLP:
Energy Range: 0 – 300 keV
Crystal Diameter: 11 mm
Crystal Length: 7 mm
Beryllium Window: 0.127 mm
Resolution Warrented (FWHM):
- at 5.9 keV is 195 eV (T_{sh} 6 μs)
- at 122 keV is 495 eV (T_{sh} 6 μs)

ORTEC GMX:
Energy Range: 10 – 1000 keV
Crystal Diameter: 55 mm
Crystal Length: 50 mm
Beryllium Window: 0.5 mm
Resolution Warrented (FWHM):
- at 5.9 keV is 600 eV (T_{sh} 6 μs)
- at 122 keV is 800 eV (T_{sh} 6 μs)

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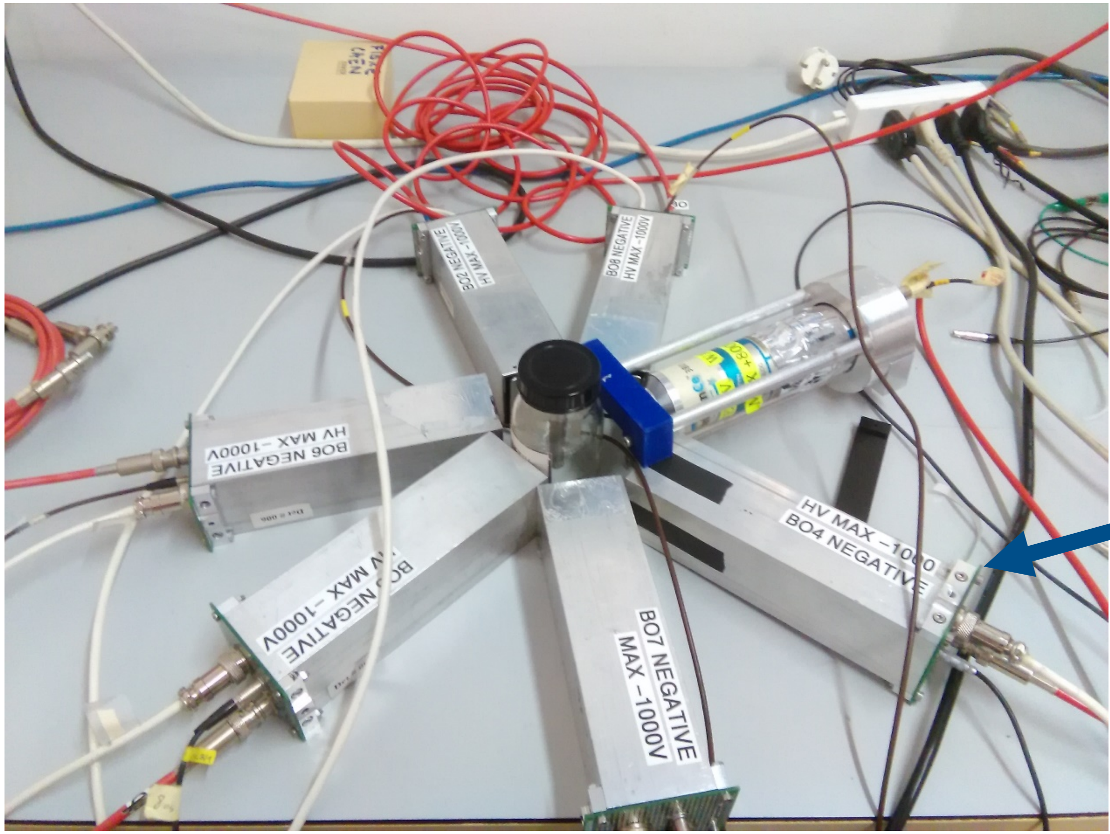
Detectors: suited for time-resolved X-ray spectroscopy

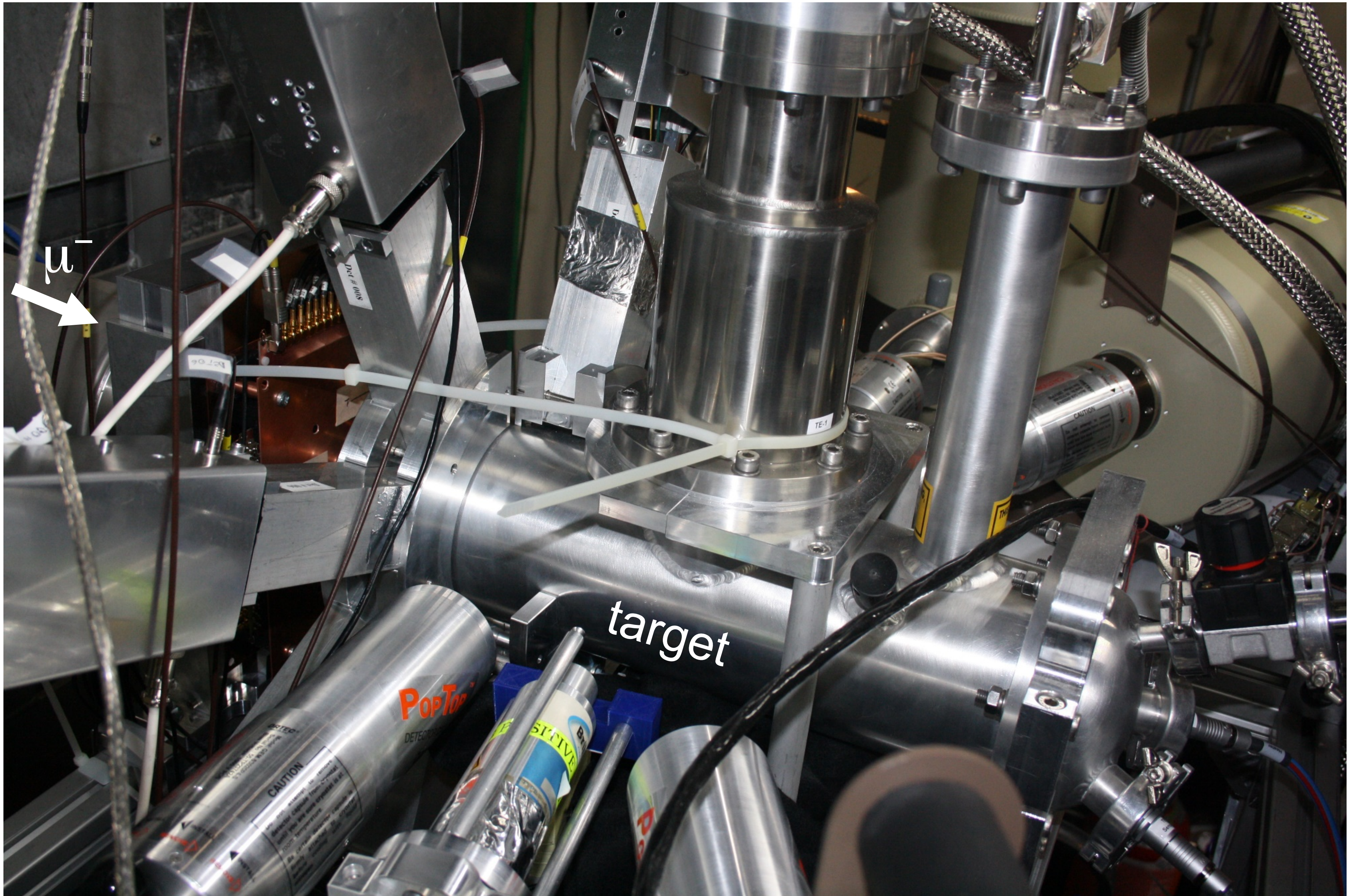
Lanthanum bromide scintillating crystals [$LaBr_3(Ce)$]: fast timing X-rays detectors



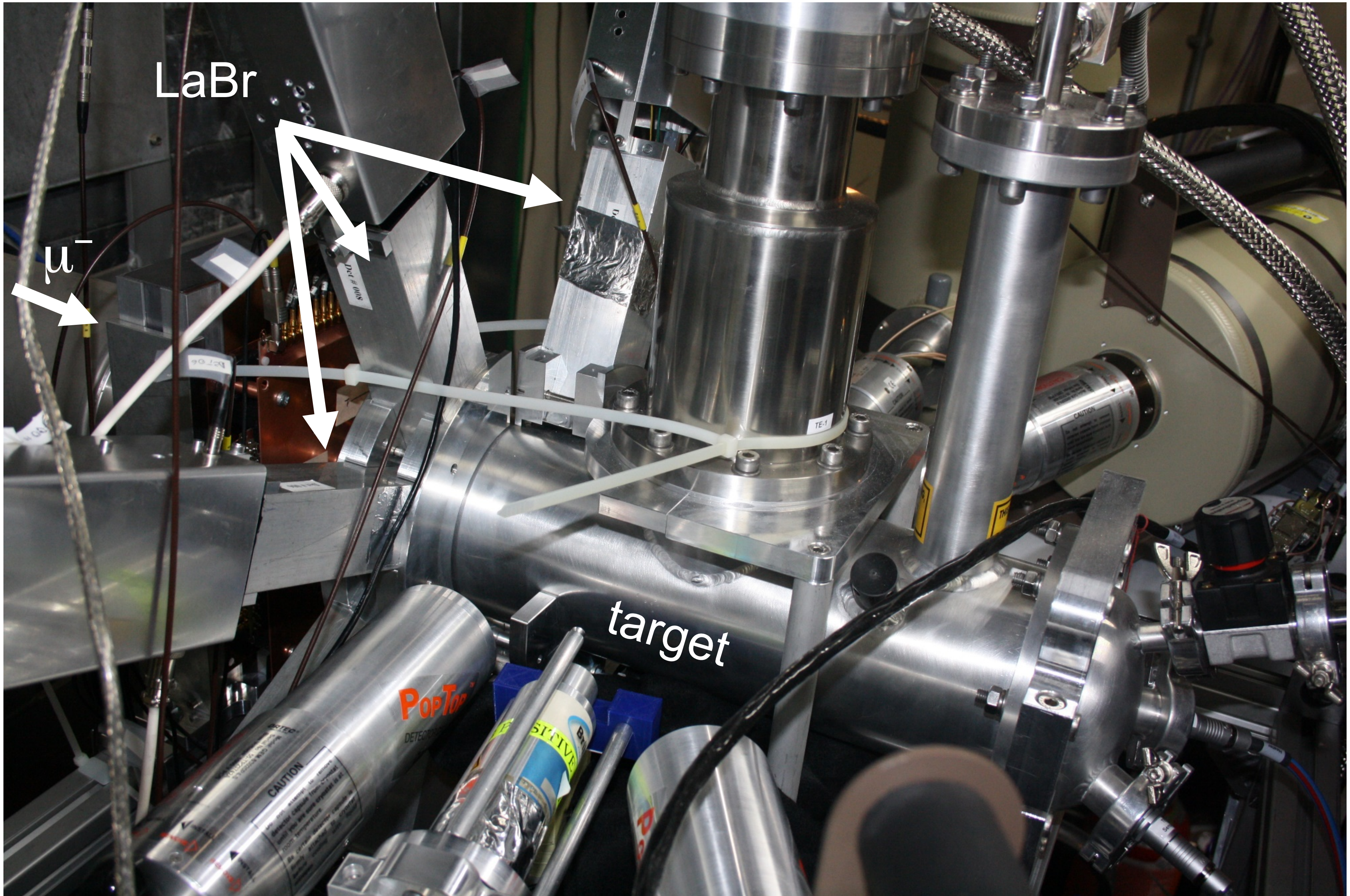
Lab test

Eight cylindrical 1 inch diameter 1 inch long $LaBr_3$(5%Ce) crystals read by PMTs. Fast electronics and fast digital processing signal available

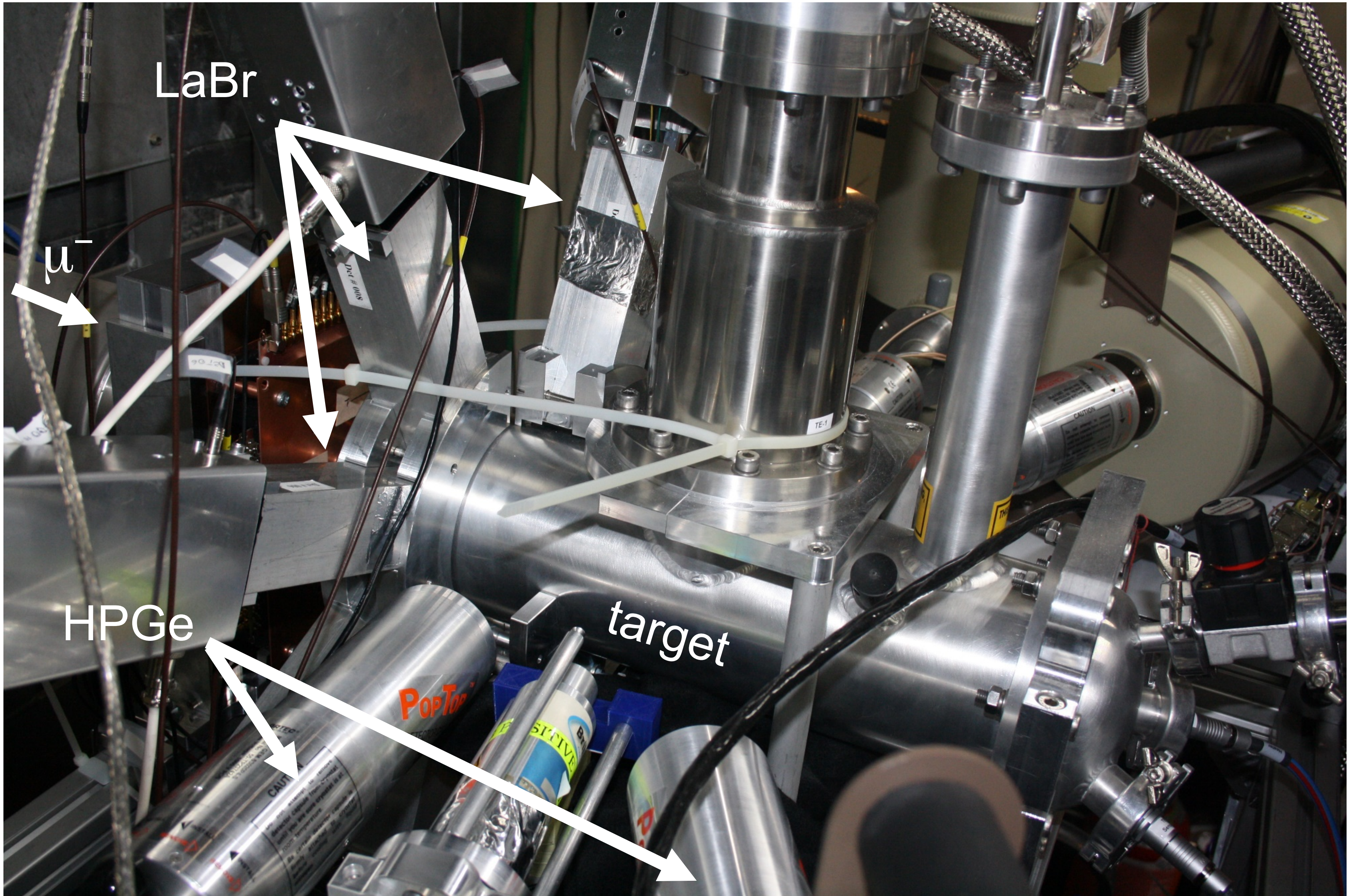
2016: experimental setup



2016: experimental setup



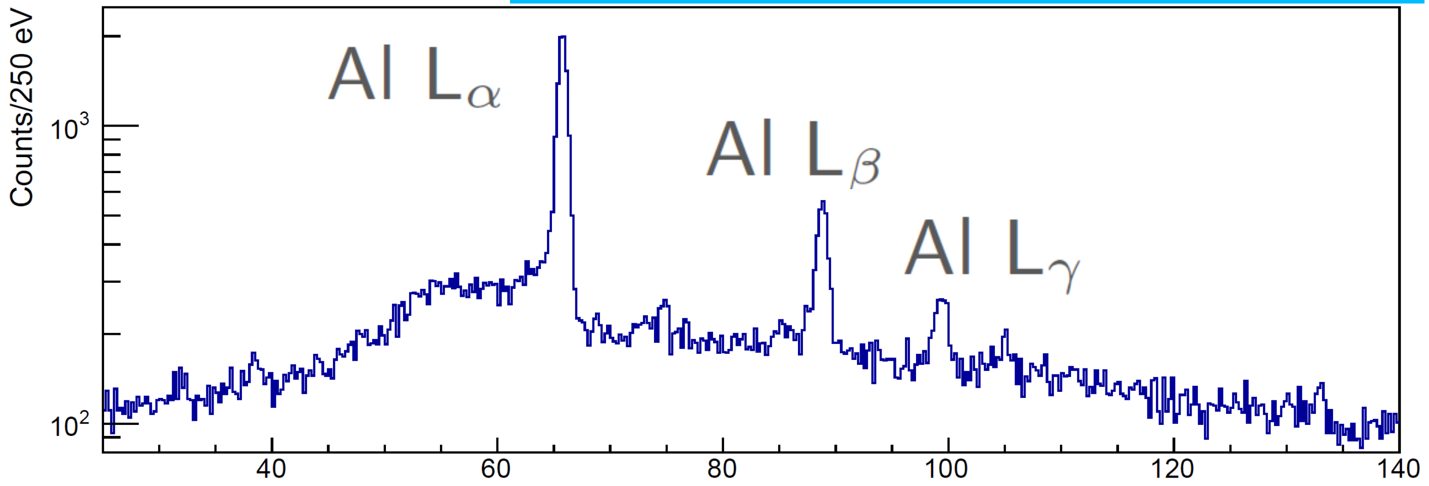
2016: experimental setup



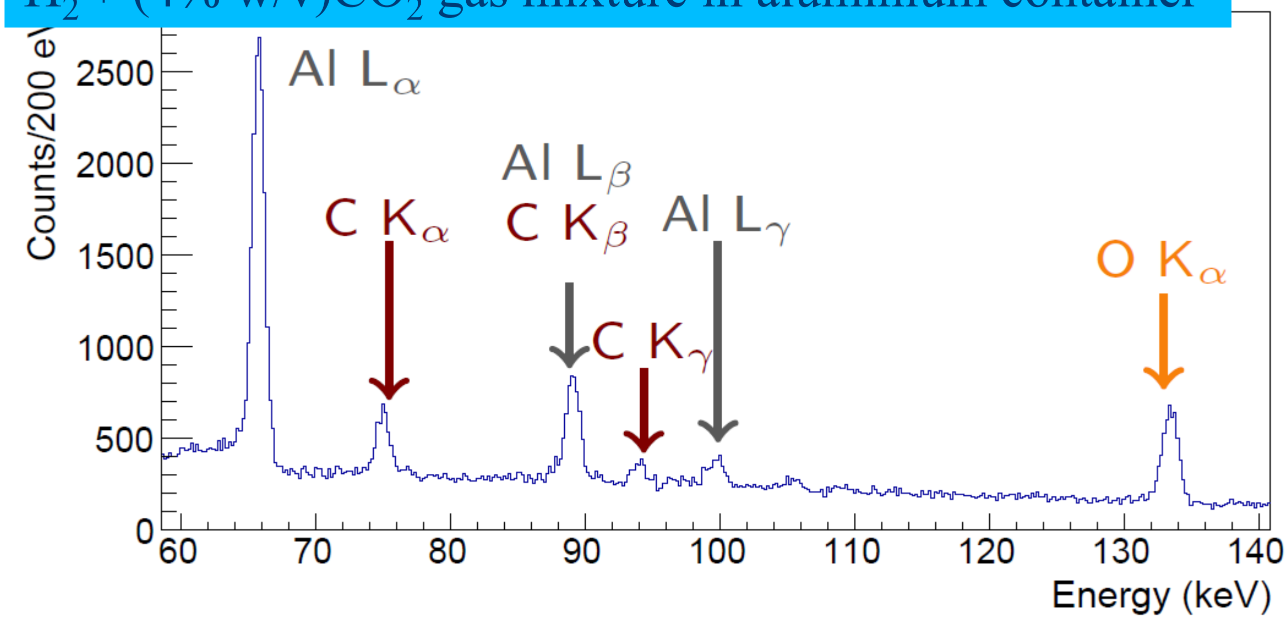
Spectral lines measurements

Germanium detectors: excellent energy resolution

Pure H_2 target in aluminium container

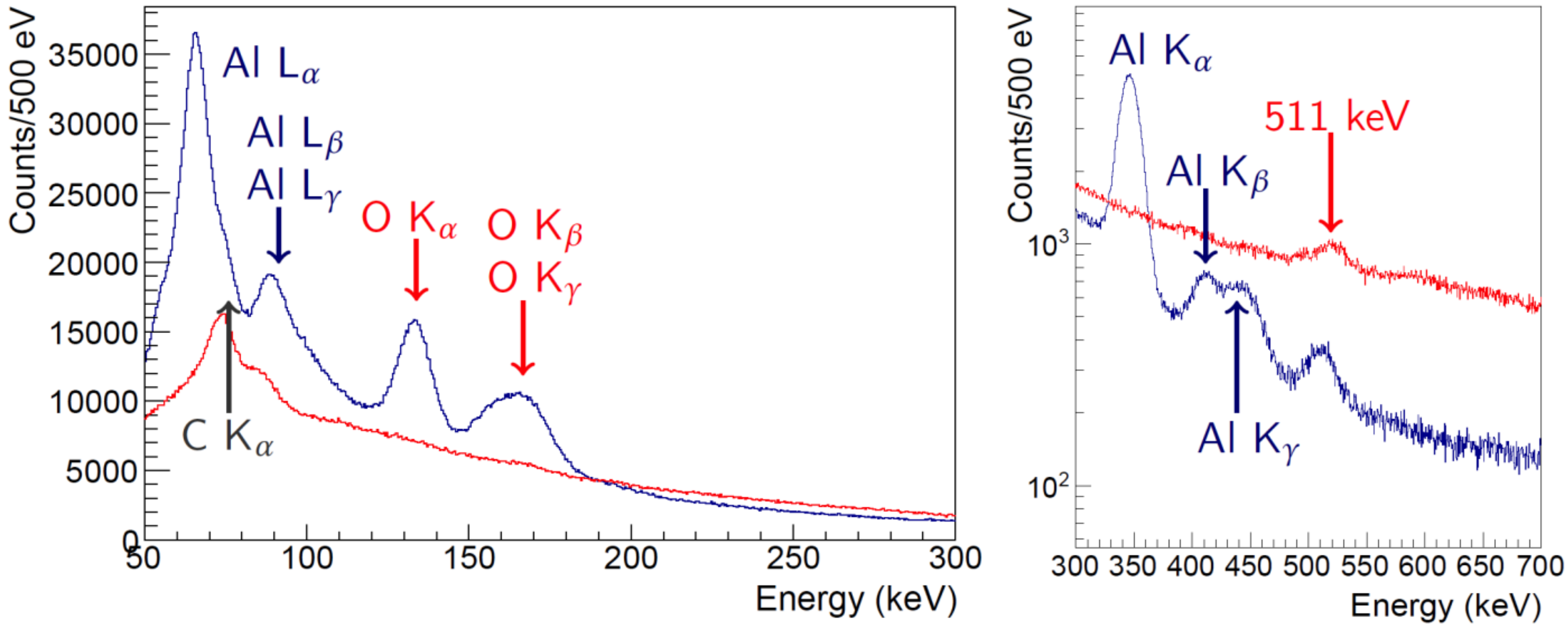


H_2 + (4% w/v)CO_2 gas mixture in aluminium container

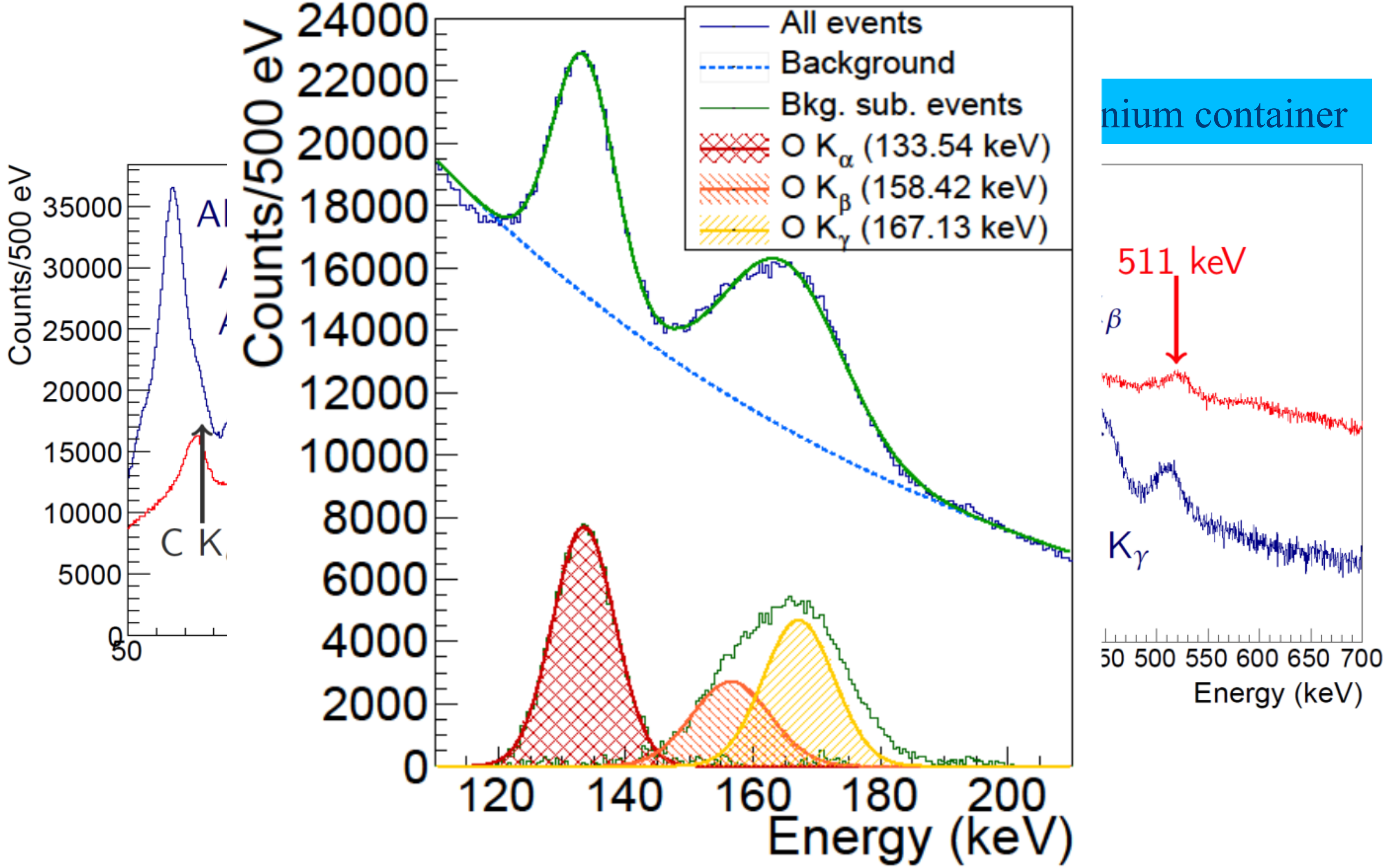


$LaBr_3(5\%Ce)$ scintillating crystals

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

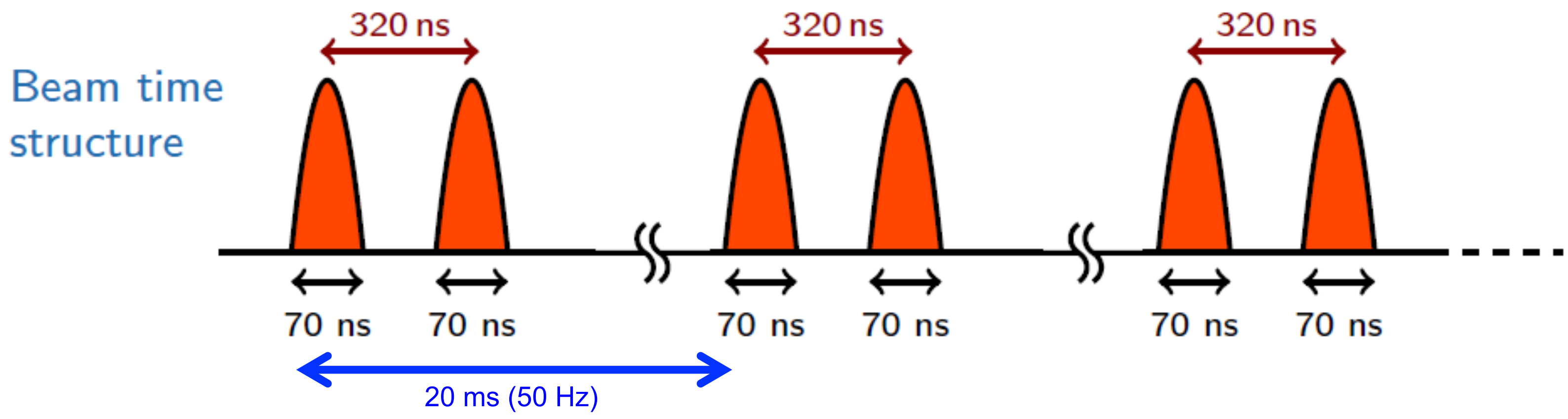


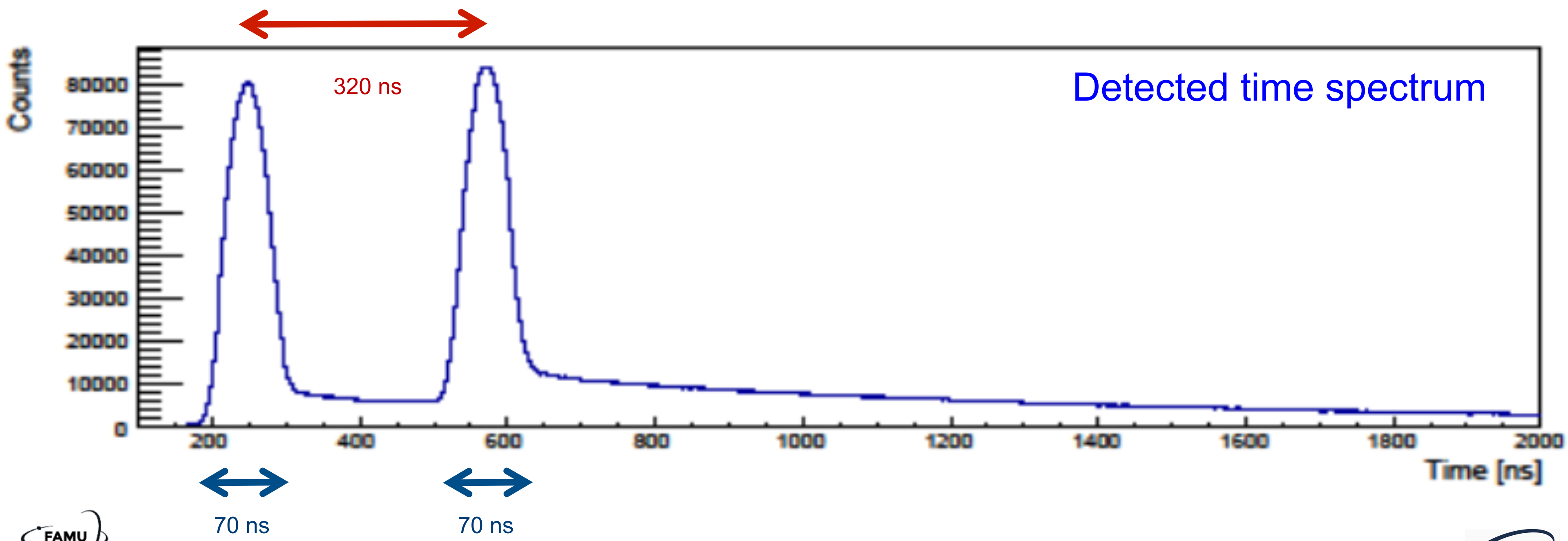
LaBr$_3$(5%Ce) scintillating crystals



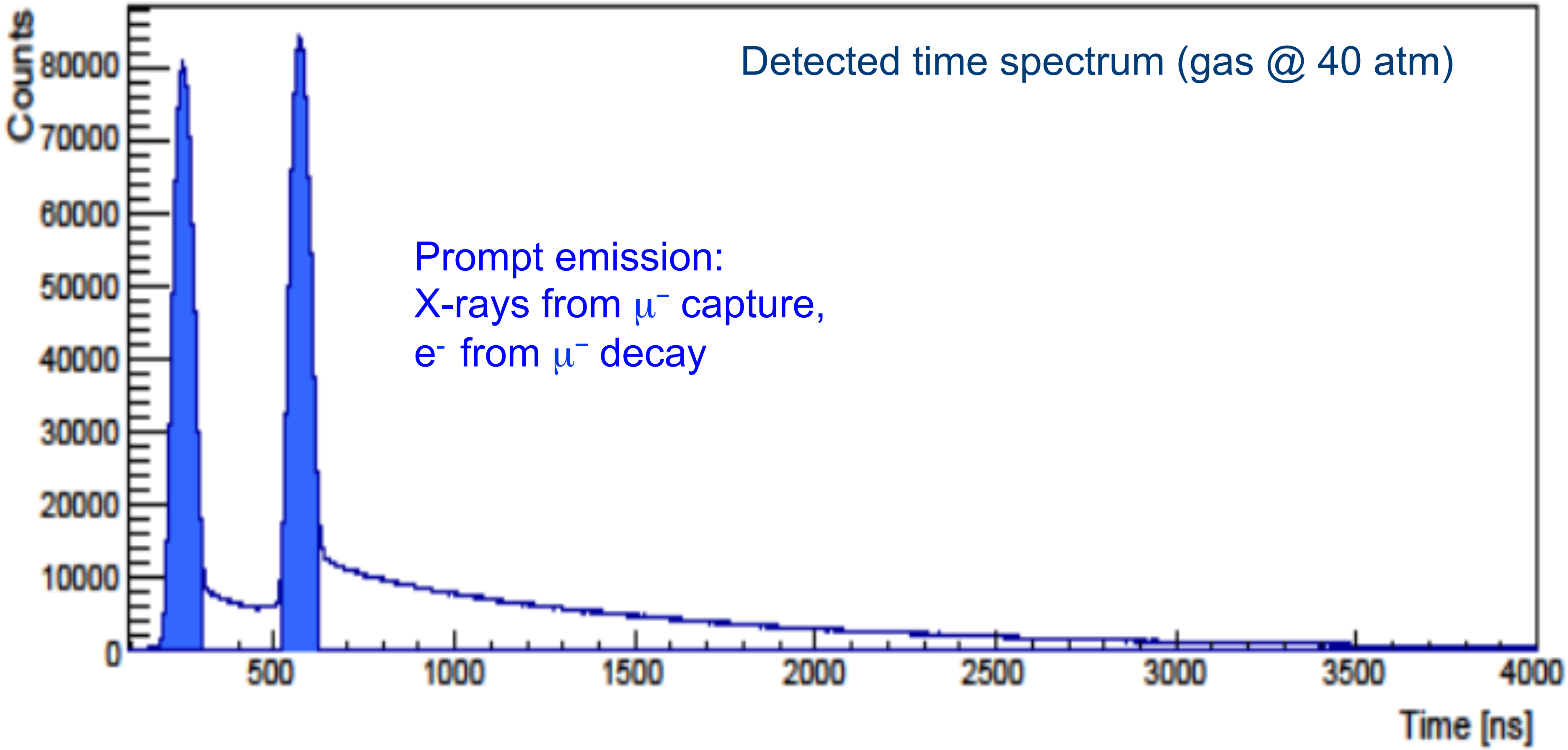
Muonic transfer rate measurement

Time spectrum: peaks and tails

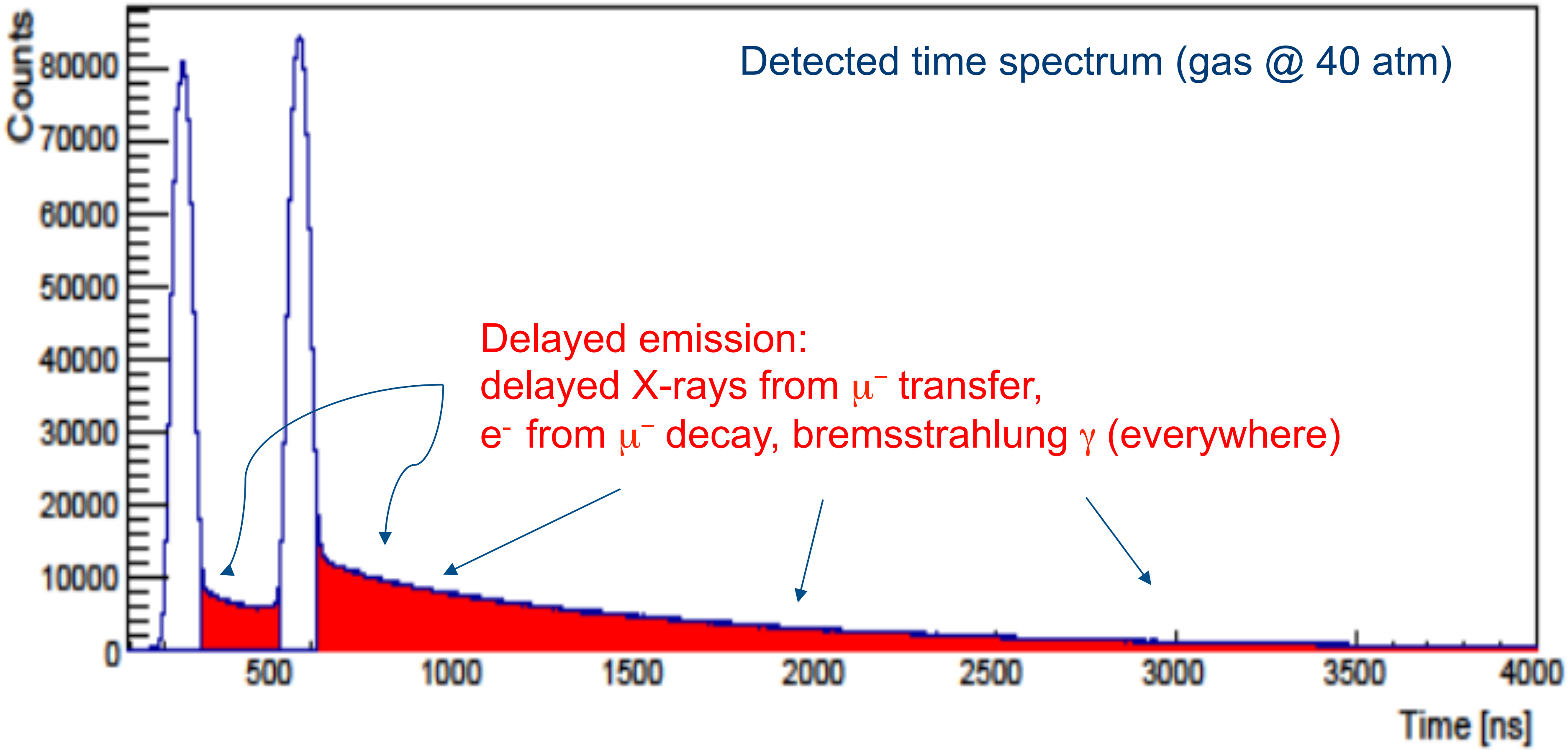




Peaks: prompt emission of X-rays



Tails: (bounded) muon live time



2016: transfer rate measurement

Steps:

1) fix a target temperature (i.e. mean kinetic energy of gas constant)
2) produce μp and wait for thermalization
3) study time evolution of Oxygen X-rays
4) repeat with different temperature

2016: transfer rate measurement

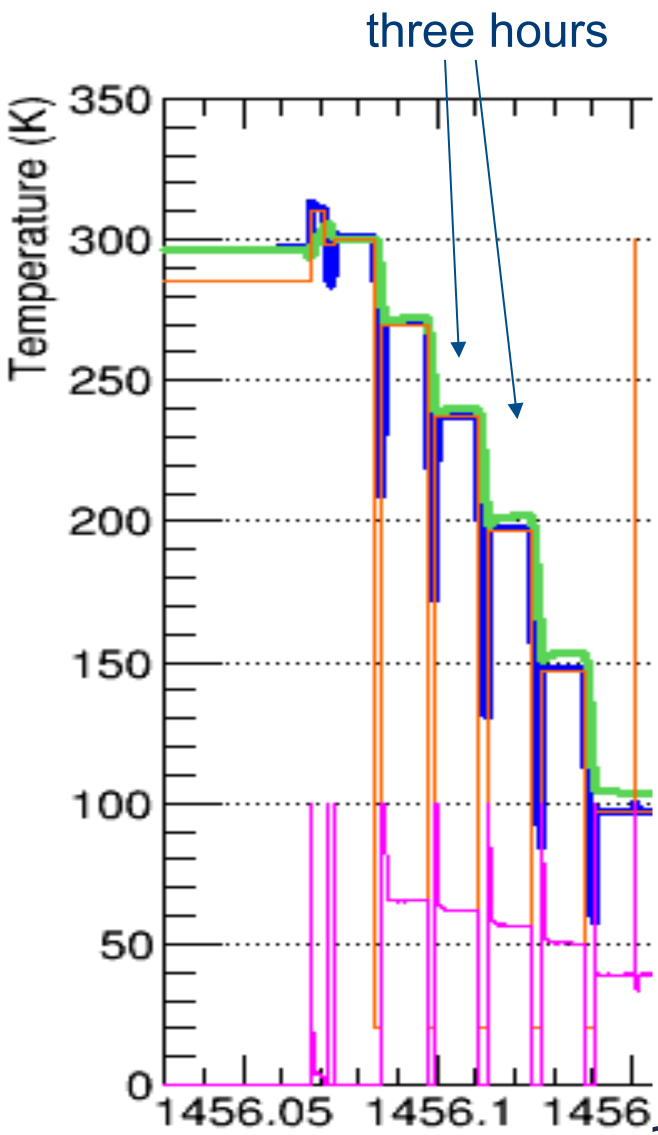
Steps:

1) fix a target temperature (i.e. mean kinetic energy

2) produce μp and wait for thermalization

3) study time evolution of Oxygen X-rays

4) repeat with different temperature



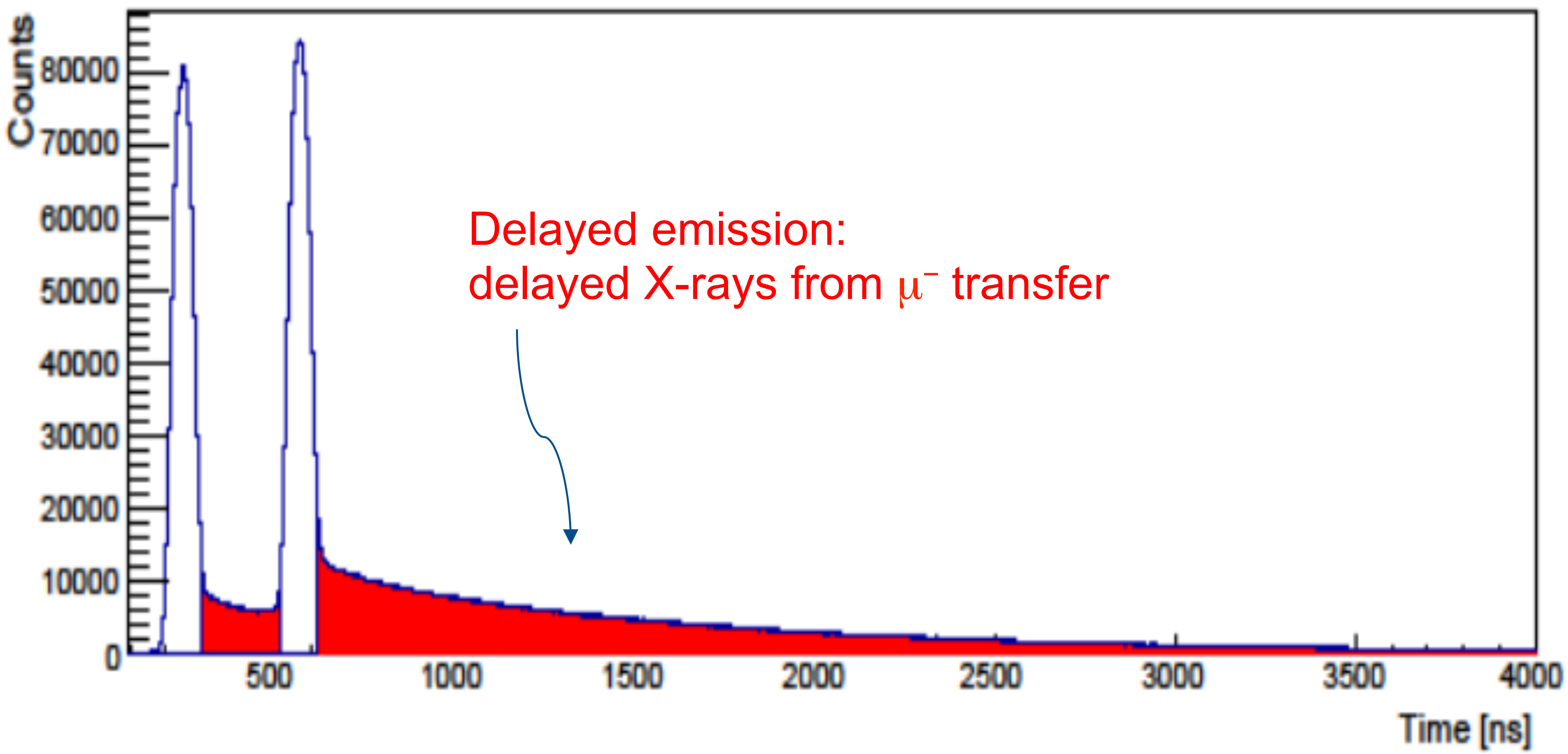
2016: transfer rate measurement

Steps:

1) fix a target temperature (i.e. mean kinetic energy of gas constant)

2) produce μp and wait for thermalization

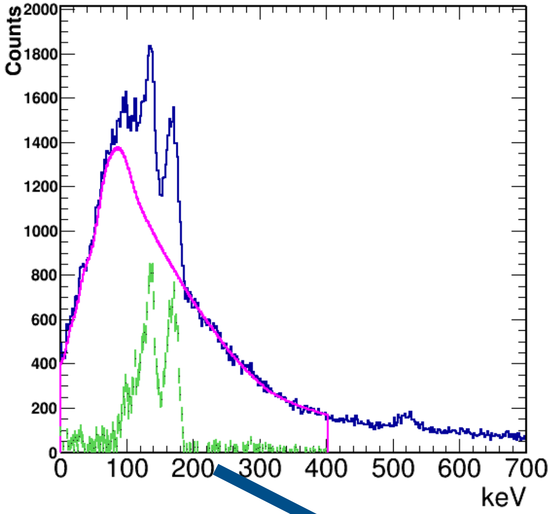
3) study time evolution of Oxygen X-rays



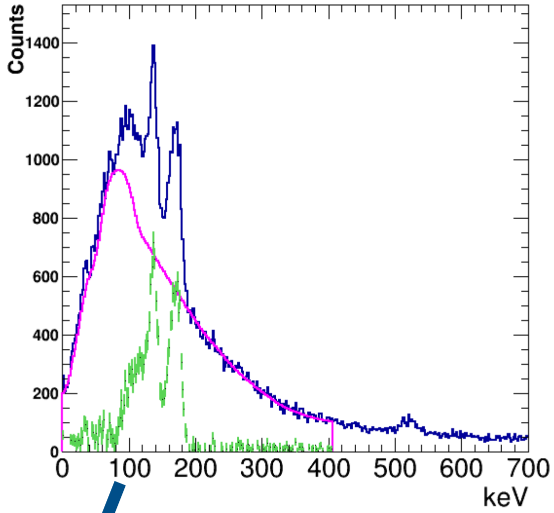
2016: transfer rate measurement

3) study time evolution of Oxygen X-rays

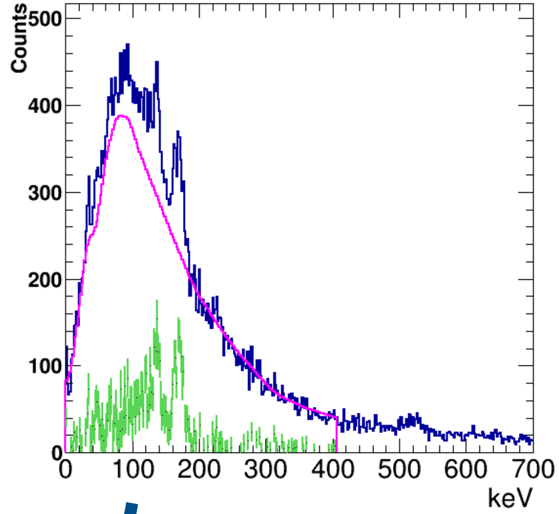
time bin 1

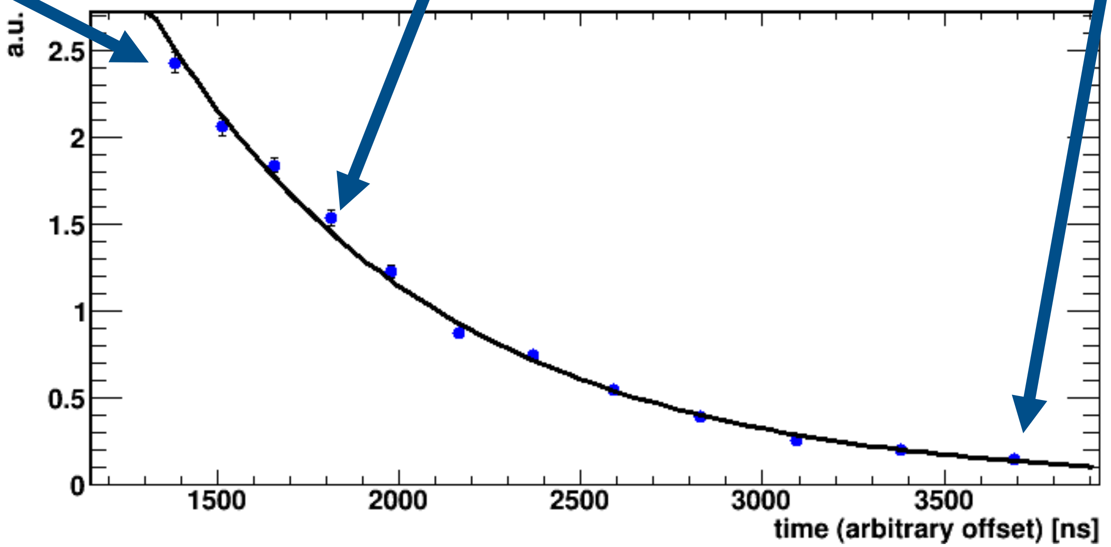


time bin 4



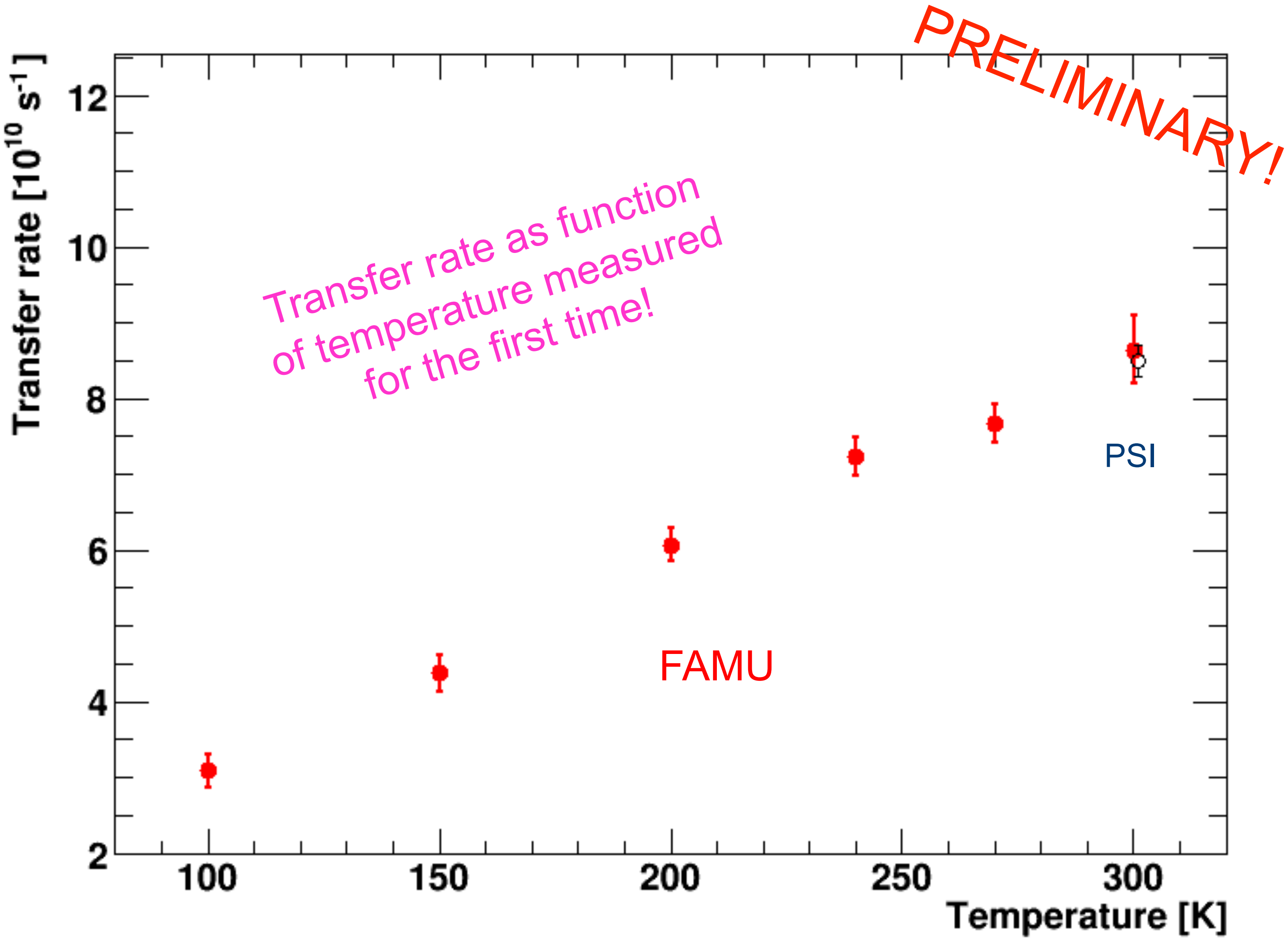
time bin 12



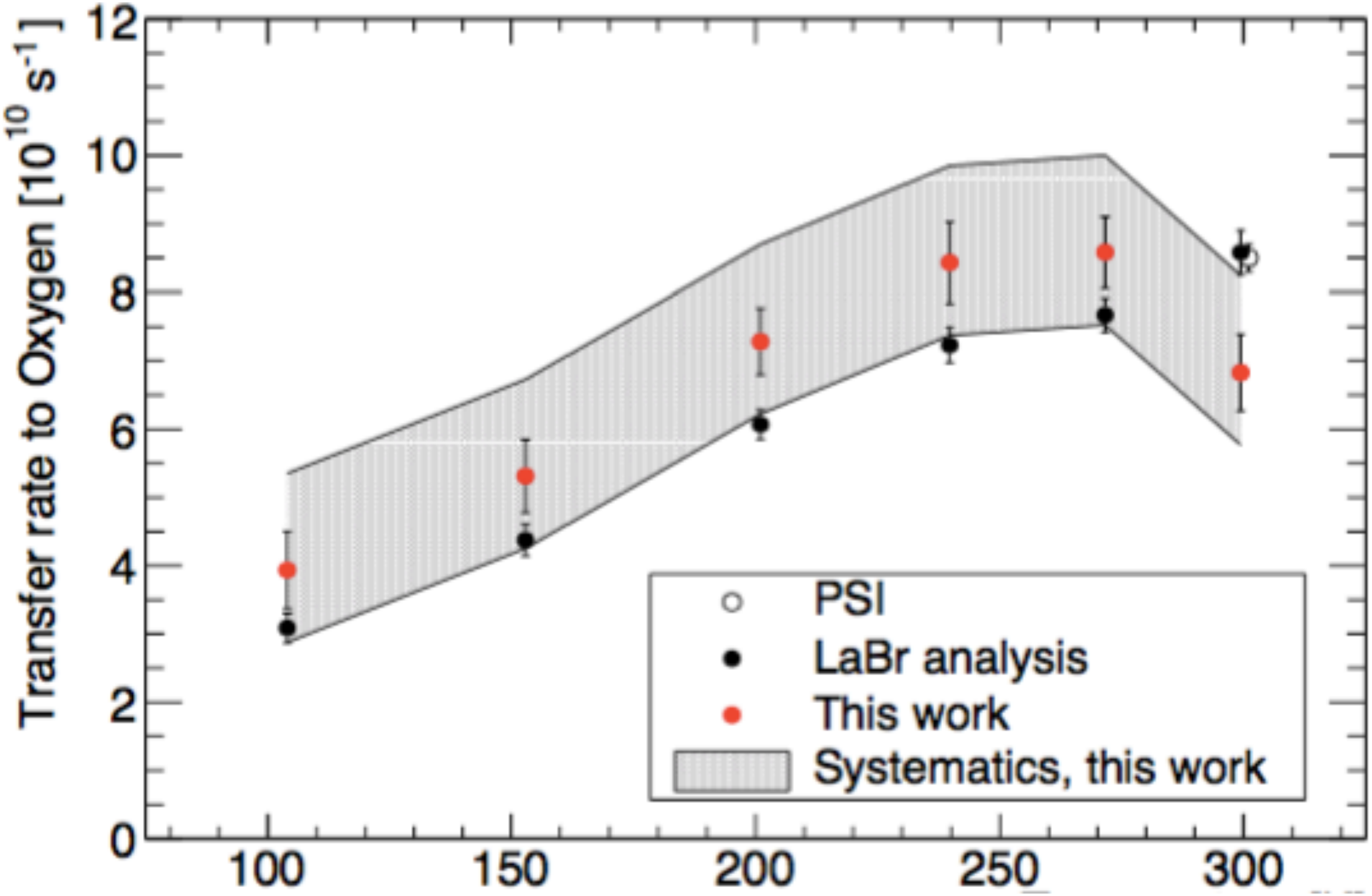


T = 300 K

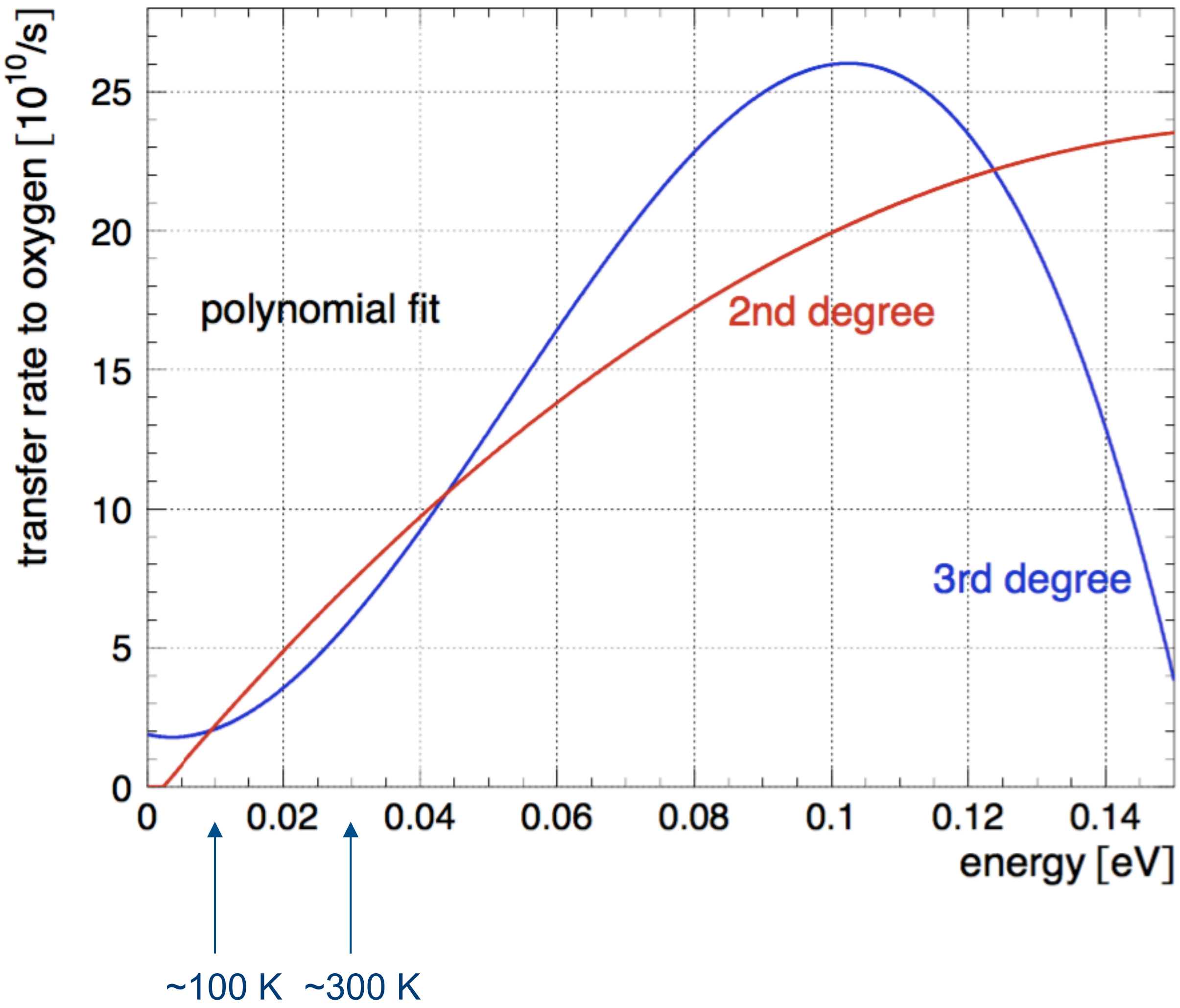
2016: transfer rate measurement

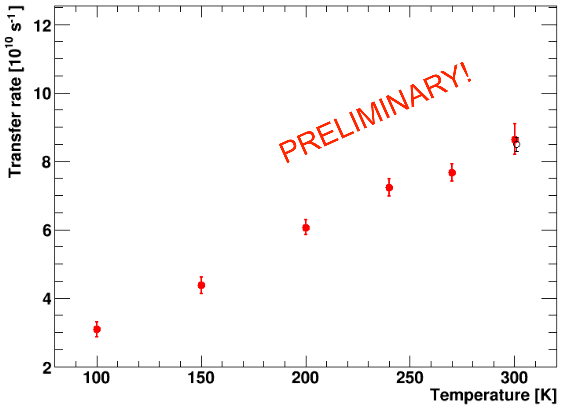


LaBr & HpGe

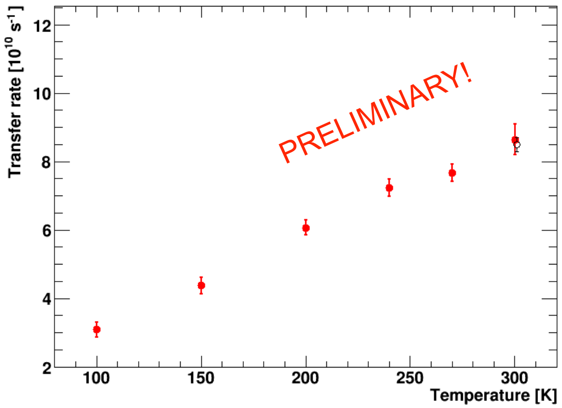

Transfer rate to Oxygen [10^{10} s^{-1}]
0
2
4
6
8
10
12
100
150
200
250
300
PSI
LaBr analysis
This work
Systematics, this work

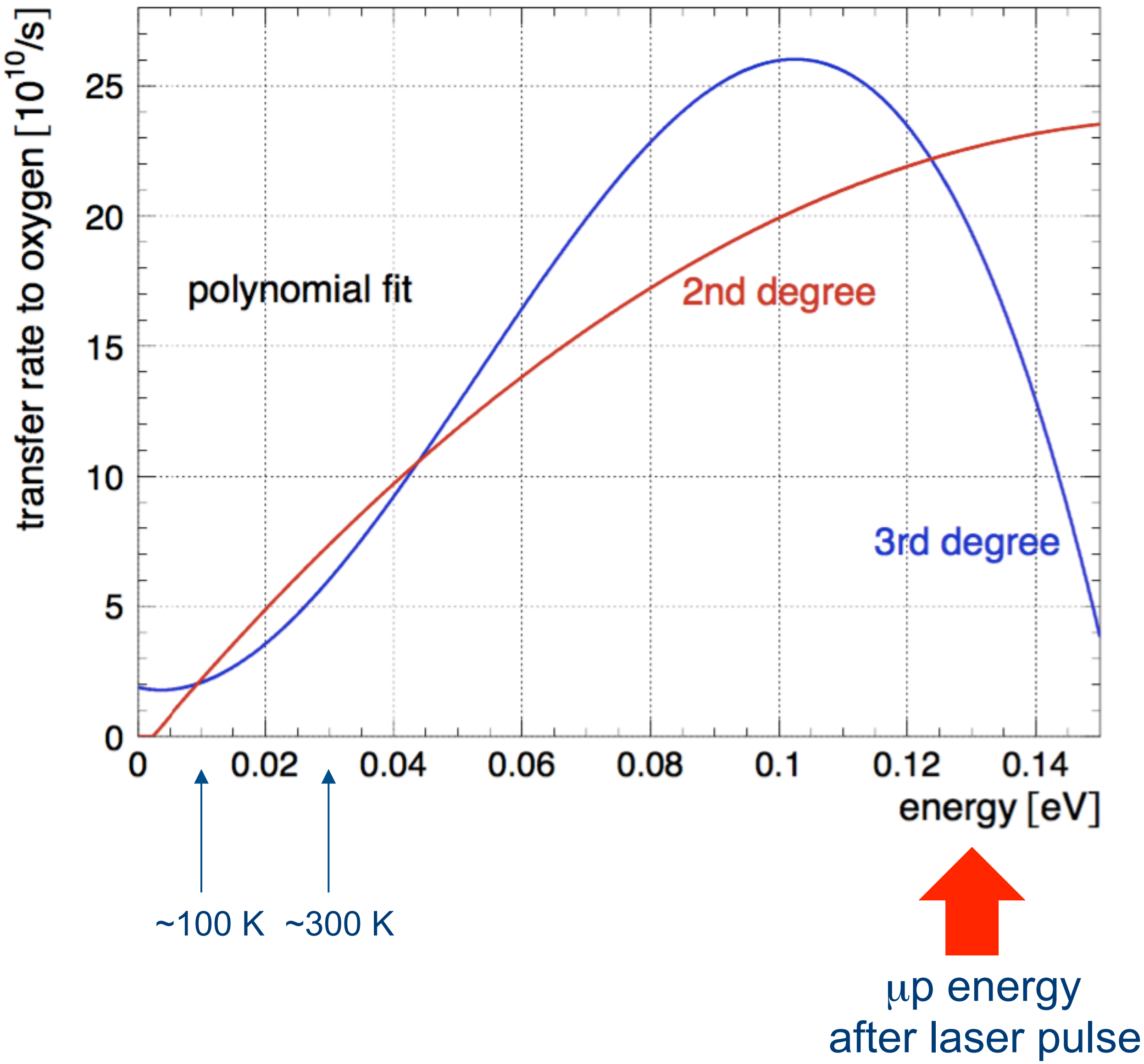
Transfer rate up to 120 meV



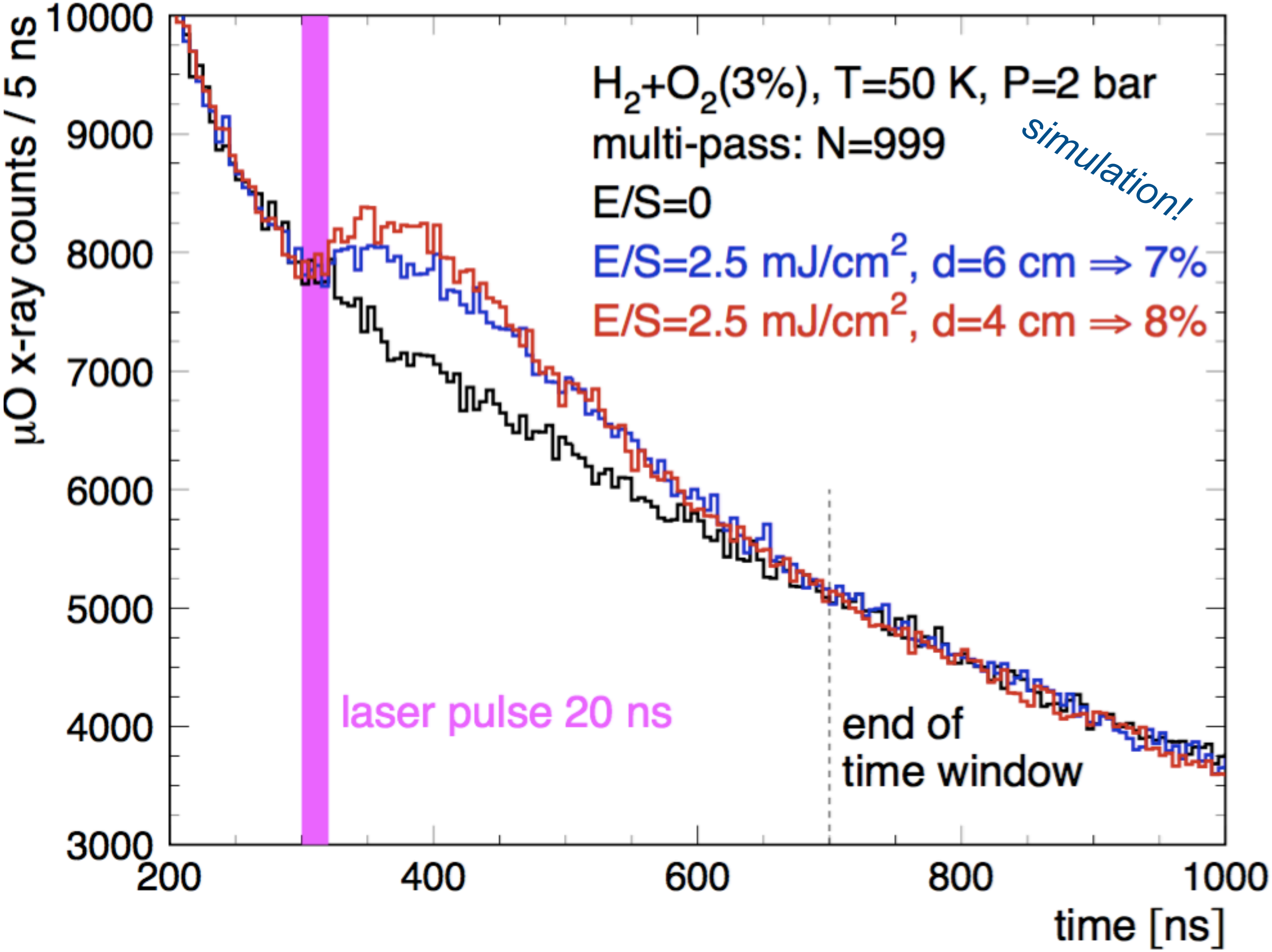


Transfer rate up to 120 meV





Study of best setup to maximize signal



FAMU key elements high energy MIR laser

Tunable pulsed IR laser at λ=6.8μ

**Direct difference frequency generation
in non-oxide non linear crystals using
single-mode Nd:YAG laser and tunable Cr:forsterite laser**

Targeted characteristics (L.Stoychev, EOSAM '14)

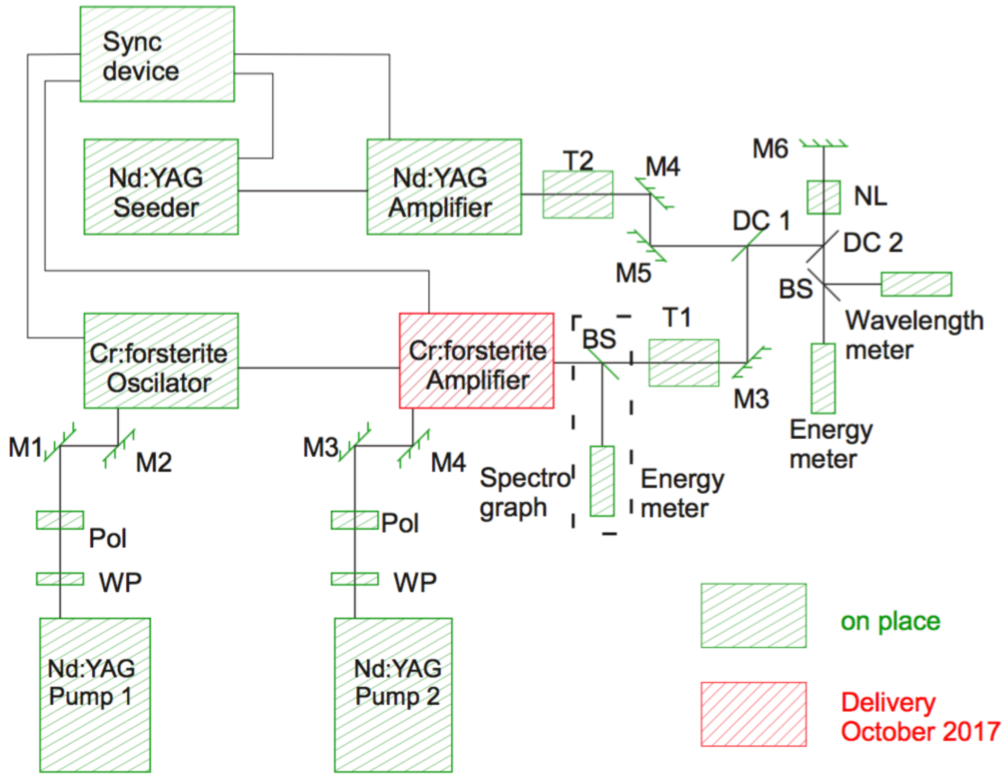
Proc. of SPIE Vol. 9135, 91350J · © 2014 SPIE · CCC code: 0277-786X/14

Wavelength:	λ =6785 nm	44.22 THz
Line width:	$\Delta\lambda$ = 0.07 nm	450 MHz
Tunability range:	6785 +- 10 nm	130 GHz
Tunability step	= 0.007nm	45 MHz
Repetition rate:	25 Hz	

The Nd:YAG will be at "fixed" wavelength 1064.14nm with linewidth max - 0.34pm (90MHz) and min - 0.11pm (30MHz).
The Cr:forsterite will have linewidth max - 1pm (188MHz) and min - 0.5pm (90MHz).

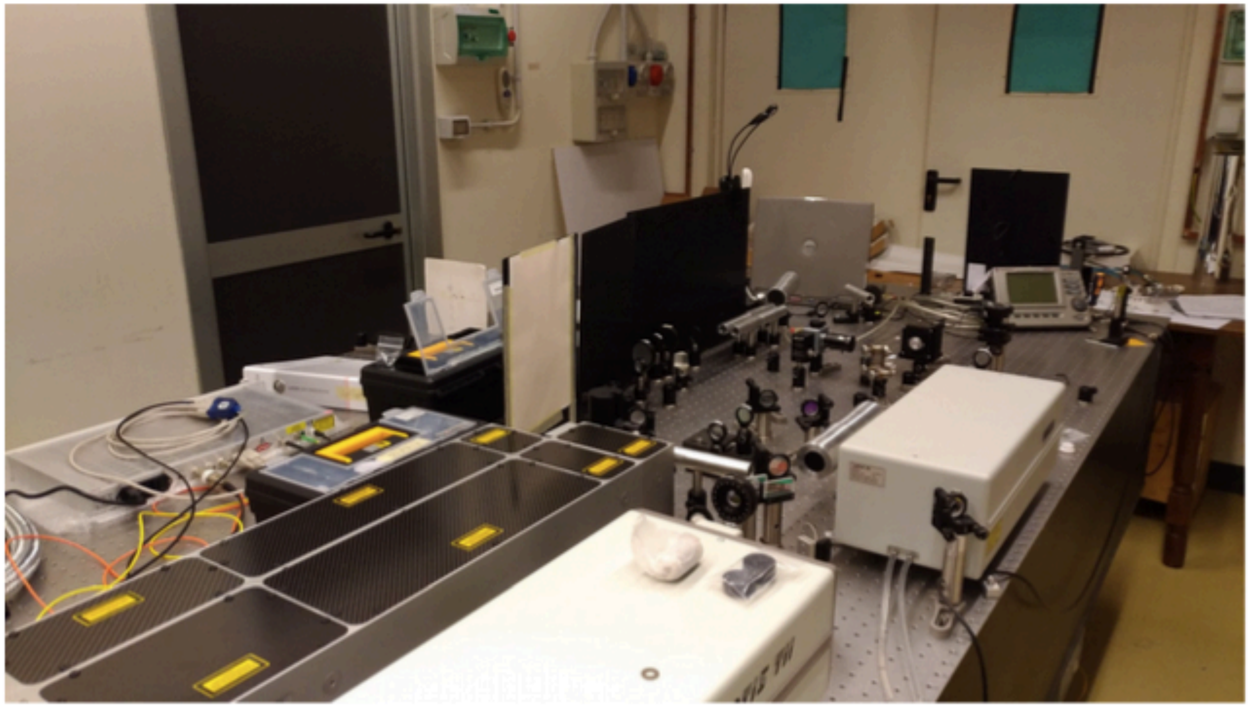
The Cr:forsterite will be tunable from 1252nm to 1272 nm which corresponds to tunability from 6500nm to 7090nm, which is 3765GHz.
The required tunability 6760nm ±3nm corresponds to tunability range ~ 39GHz.

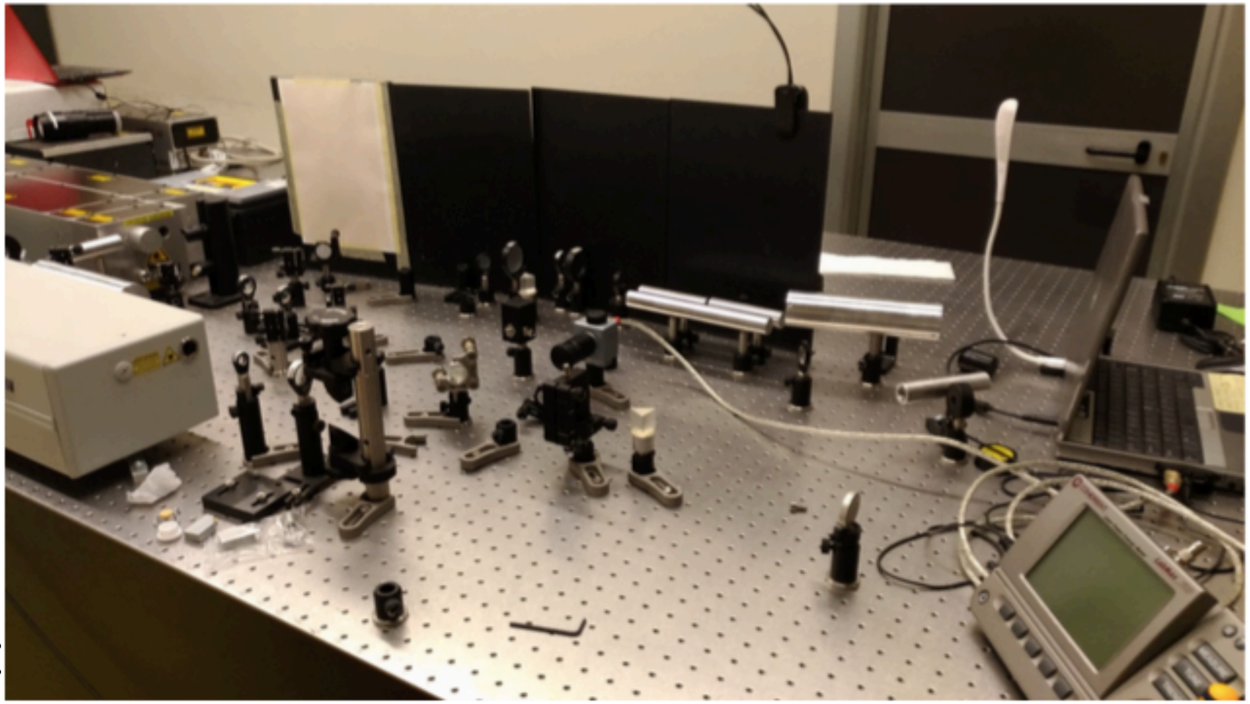
Final scheme of the DFG based laser system for the FAMU experiment



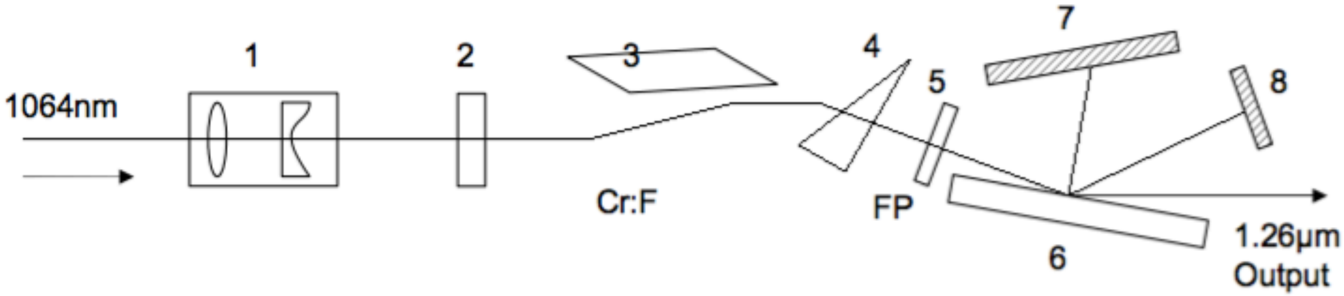
WP - waveplate, Po - polarizer, M1-M5 - mirrors, T1 and T2 - telescopes, BS - beamsplitters, DC1 - dichroic mirror (reflecting 1.26μm, transmitting1.06μm), DC2 - dichroic mirror (reflecting 1.06 and 1.26 μm, transmitting 6.76μm)

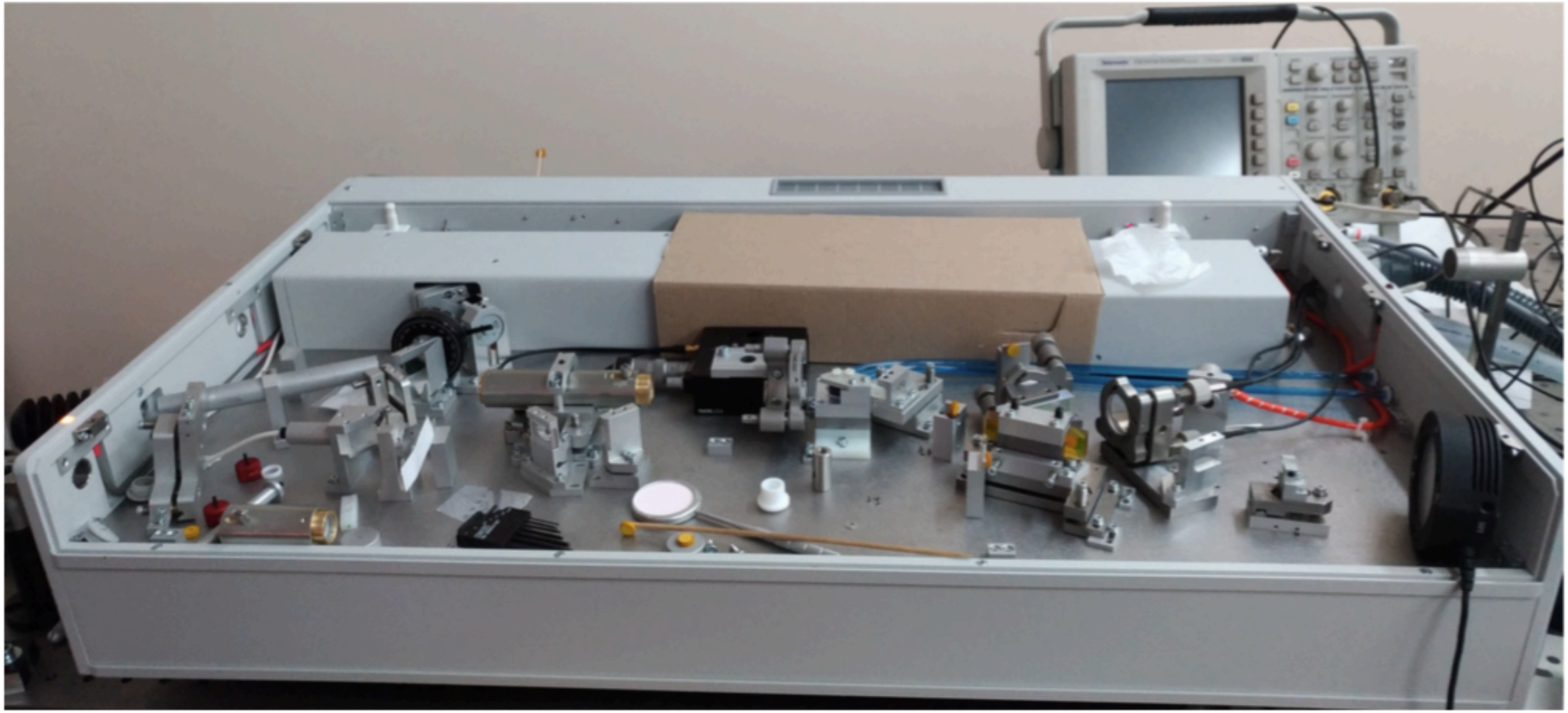
How it's at the moment





Our Cr:forsterite oscillator





Cavity reflectivity

(R = 99.97% or better)
can be achieved with a ThF4 /ZnSe coating,

(LohnStar Optics, 1863 Commercial St., Escondido, CA 92029, USA.)
OPTICS EXPRESS 13051 2 June 2014 | Vol. 22, No. 11 | DOI:10.1364/OE.22.013050 |

- the small amount of alpha particles emitted from the coating tolerable.

$P=2\times10^{-5}\times W/((1-R)\times S\times\sqrt{T})$ OK!

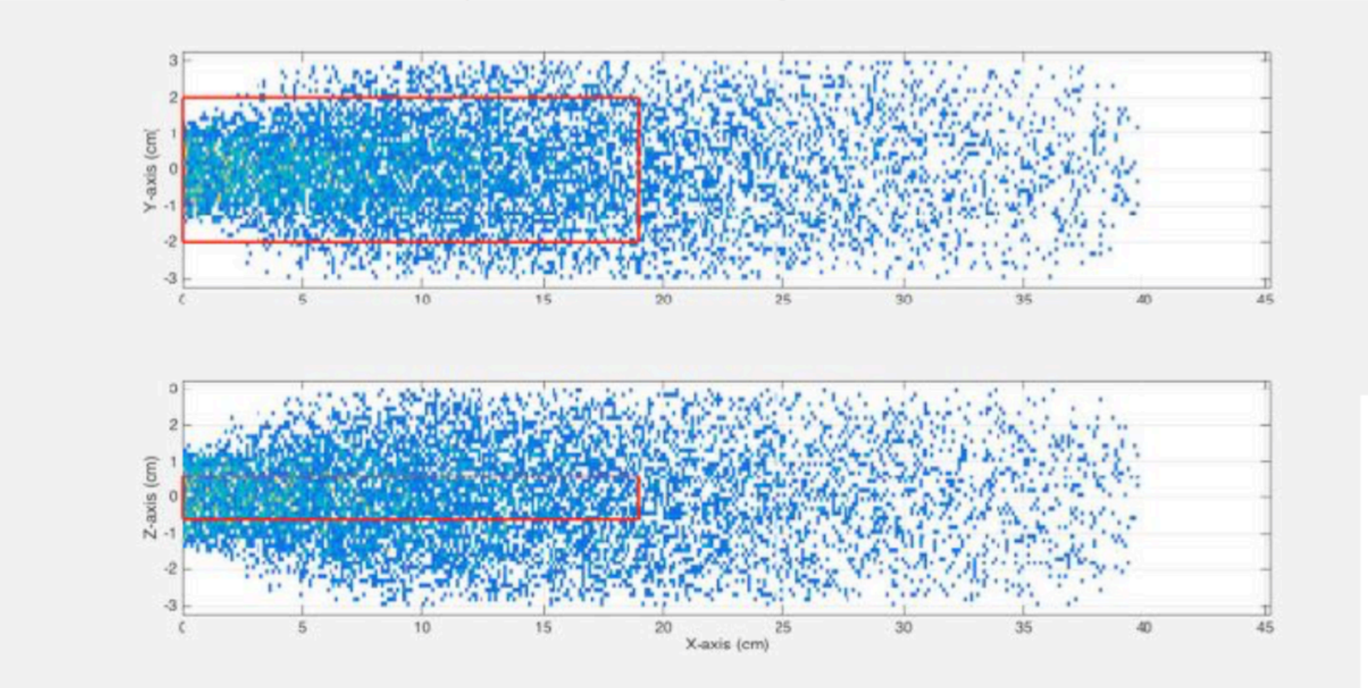
W= 5 mJ;
T= 70 K;
S=some cm^{-2};
R=0.9995

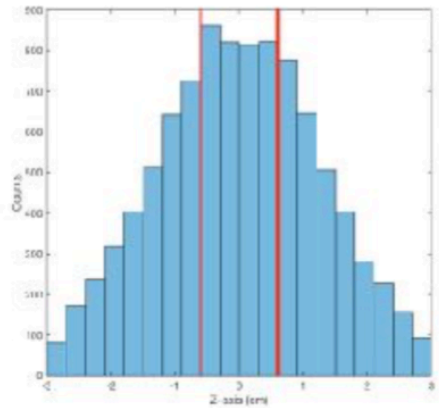
P will reach ~20%.

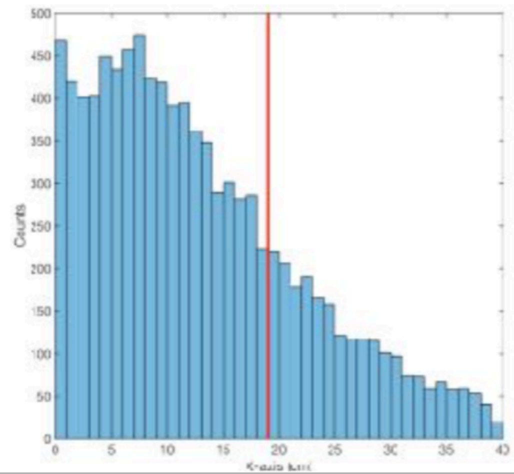
Muons beam density

GEOV07R0180K2BH2O2
like 2016 target (GEOV06R05300K40AH2O2) but with:

- gas : H2 O2(3%) (density: 0.877 kg/m3) temperature : 80 K
  pressure : 2 BAR
  berillium flange (vacuum vessel) : 0.3 mm aluminium entrance window : 0.5 mm
- no hodoscope
- no coating on entrance window (NB: in this version coating volumes just changed the material not the name nor the shape, hence there is a sub- mm shape distortion at the edges)



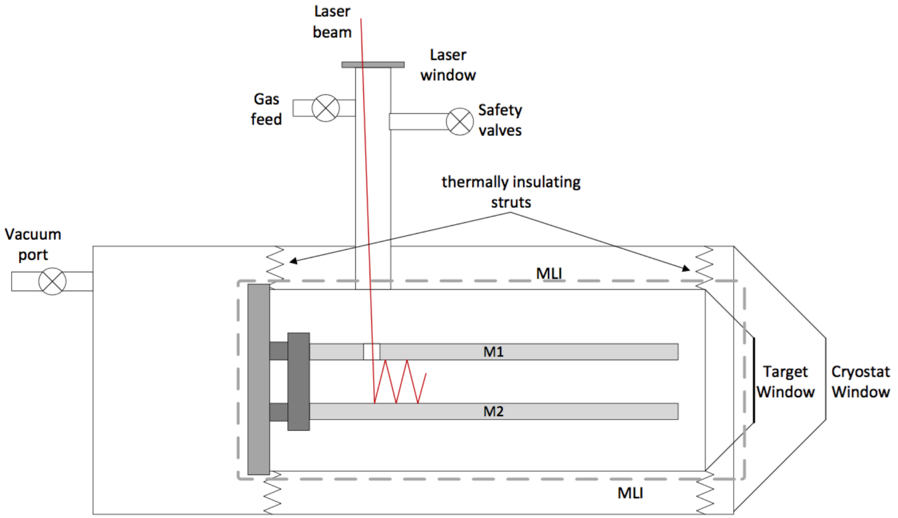


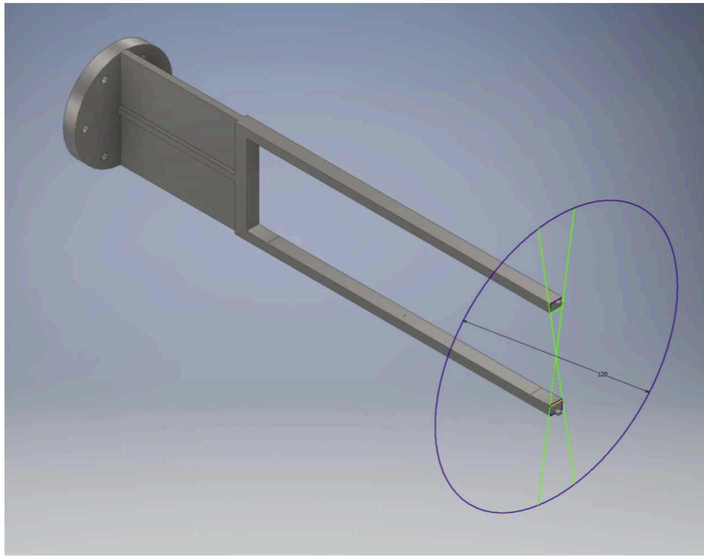


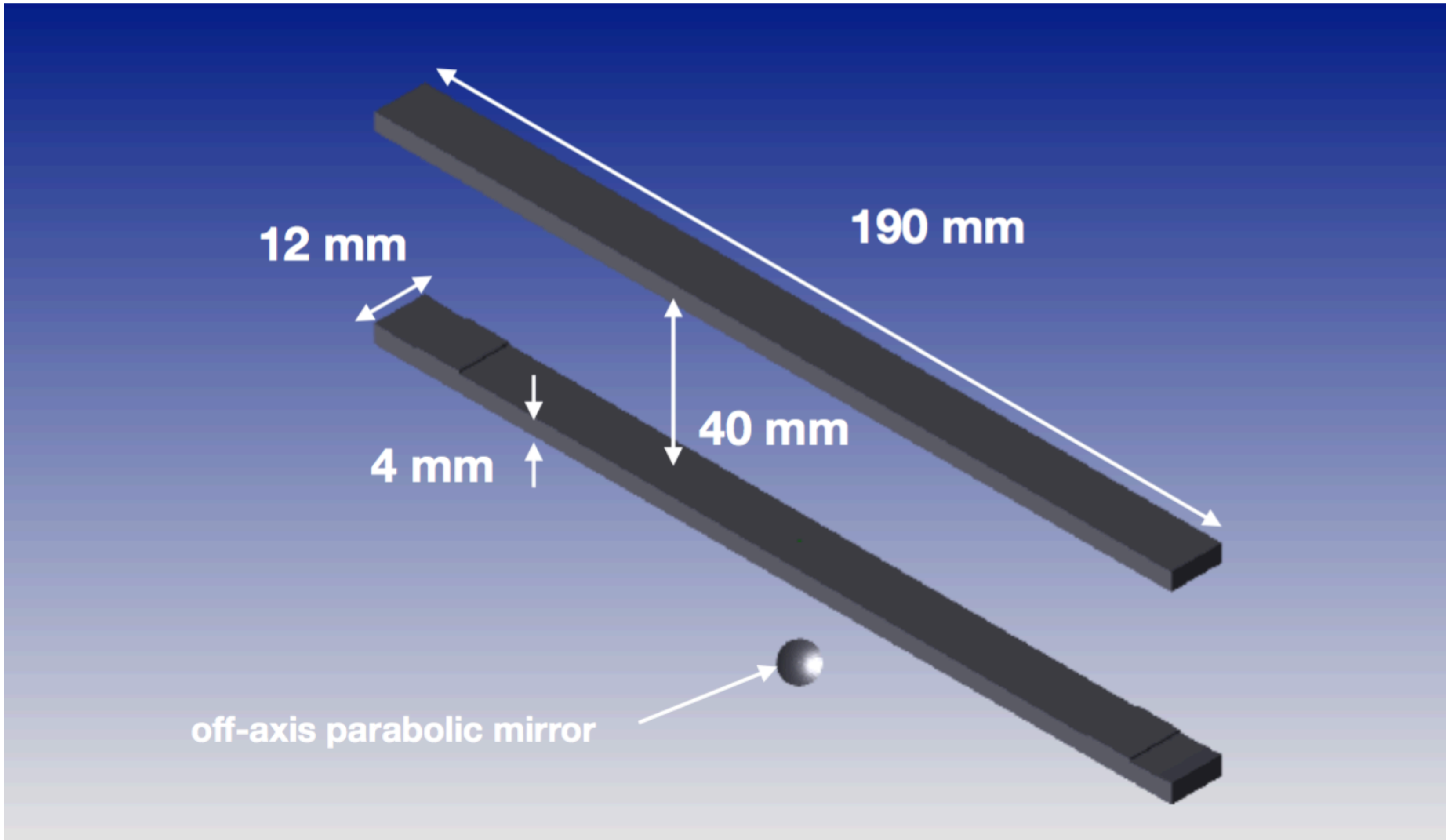
From Emiliano, july 2017.

Laser & gas feeding solution

- ❑ Cryostat shell: Al alloy
- ❑ Cryostat windows:
  - Kapton disc, thickness < 1 mm
  - Al alloy disc, thickness < 1 mm
  - Laser window?
- ❑ Target shell: Al alloy. Coating needed?
- ❑ Target window:
  - Machined (fixed) or
  - flanged (can be replaced)?







- Reflectivity 0.9989 (ZnS/Ge), R_{cyl}=130 mm, R_{end}=120 mm
- Injection light hole radius 0.315 mm
- OAP mirror are able to focus the light in the injection hole
  - Effectively path L_{eff}=15 m
  - Time cavity decay t_d=50 ns
  - Number of reflections about 670

Measurement plan

- From data analysis:
  - about 10 muon transferred events were observed per second per detector: with 16 detectors ~2 10^6 events/(3 hours) are expected.
- From simulations:
  - laser shot: ~6% event excess, i.e. about 10^5 events/(3 hours), enough statistics at a given fixed laser frequency.

➡ 6 hours = one step (0.1 nm) – half signal (laser), half background (no laser)

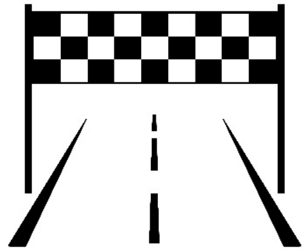
Rough scan: 420 hours to acquire 70 different laser frequencies.

Fine scan around resonance peak: 180 hours, 30 different laser frequencies.

Total time (with setup and preparation): ~40 days

Summary

- FAMU: investigation of the proton radius puzzle with HFS of $(\mu^{-}p)_{1S}$



- An exciting journey:
  - started *25 years ago*
  - *most intense pulsed beam* in the world
  - *best detectors* for energy and time observation
  - *first time measurement* of the muon transfer rate to Oxygen
  - *innovative* and powerful laser system

Looking forward to perform the final measurement!

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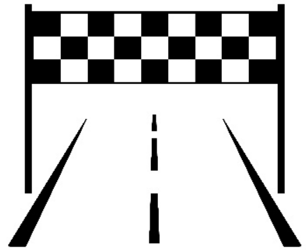
- FAMU: investigation of the proton radius puzzle with HFS of $(\mu^- p)_{1S}$



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Thanks!

FAMU

INFN Istituto Nazionale di Fisica Nucleare