FAMU experiment: characterization of target and detectors and measurements of muonic transfer rate from hydrogen to heavier gases

Emiliano Mocchiutti

on behalf of the FAMU Collaboration

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FAMU Collaboration

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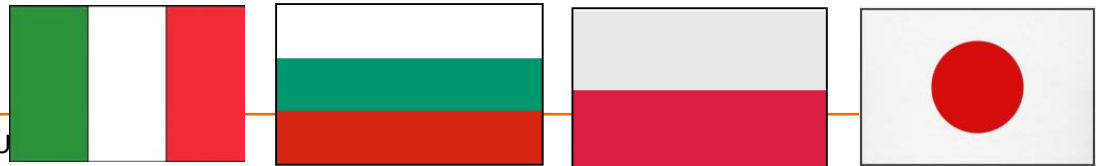
INP Polish Academy of Sciences: A. Adamczak

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

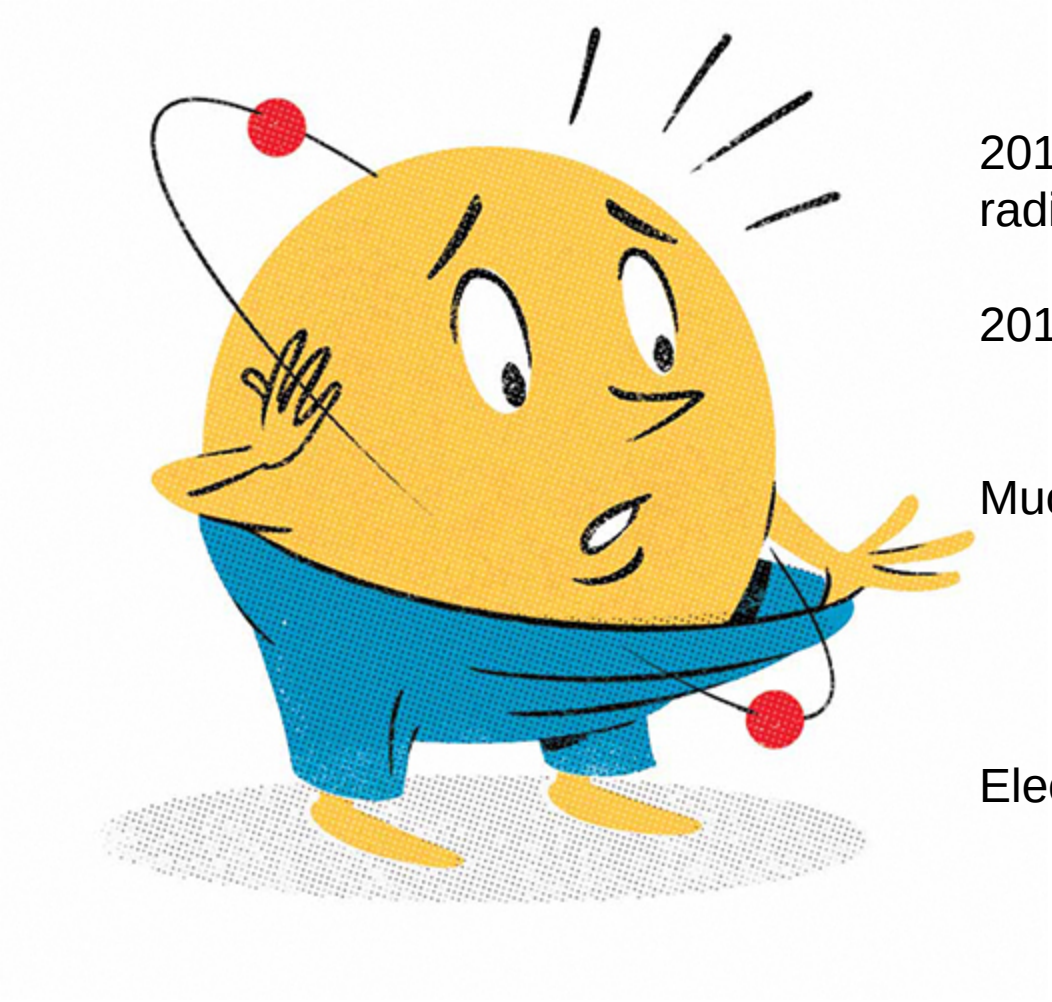


Outline

- **Introduction**
- **The FAMU experiment**
- **Beam test at RAL (2014)**
- **Spectral lines measurements**
- **Muonic transfer rate measurements**
- **Outlook on 2015 beam test**
- **Summary**

Introduction

Proton radius puzzle



2010: first measurement of the proton radius from muonic hydrogen.

2015: the “proton radius puzzle” persists...

Muonic hydrogen transitions

~7 σ

Electron transitions or electron scattering

Proton radius puzzle

	Charge radius r_{ch} (fm)	Zemach radius R_Z (fm)
e^--p scattering & spectroscopy	r_{ch} = 0.8775(51)	R_Z = 1.037(16) [Dupays et al 03] R_Z = 1.086(12) [Friar & Sick 04] R_Z = 1.047(16) [Volotka et al 05] R_Z = 1.045(4) [Distler et al 11]
μ^--p Lamb shift spectroscopy	r_{ch} = 0.84089(39)	R_Z = 1.082(37) [Antognini et al 13] from HFS of $(\mu^-p)_{2S}$

Non-relativistic picture: spatial charge and magnetic moment distributions $\rho_E(r)$, $\rho_M(r)$.

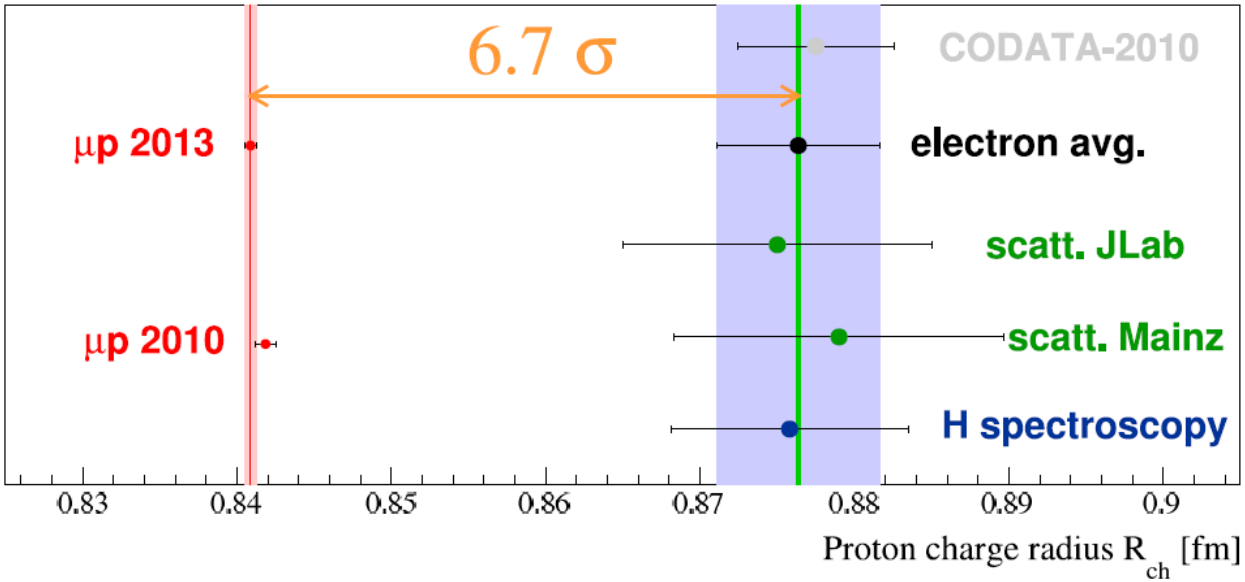
The complete set of moments $R^{(k)}_{E,M} = \int \rho_{E,M}(r)\, r^k\, d^3r$ is directly related to observable quantities:

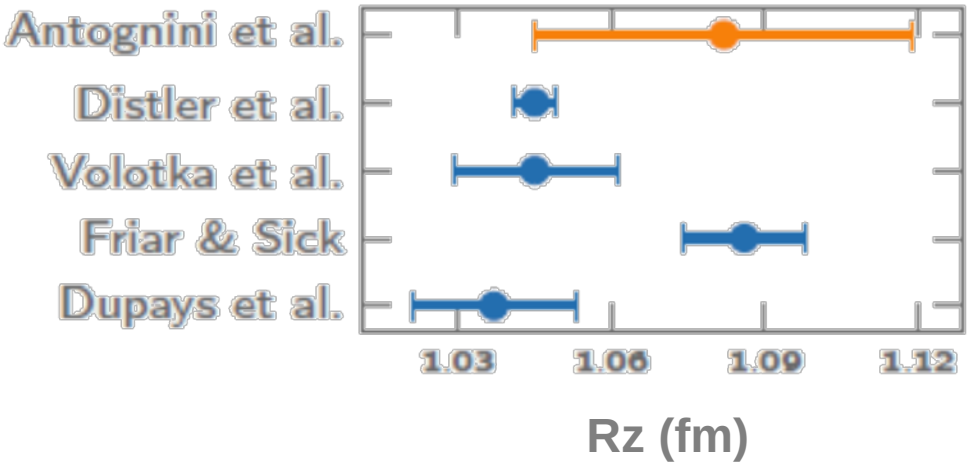
$r_{ch} = (R^{(2)}_E)1/2$

$R_Z = \int(\int \rho E\,(r')\, \rho M\,(r-r')\, d^3r')\, r\, d^3r$

Proton radius puzzle

Charge radius

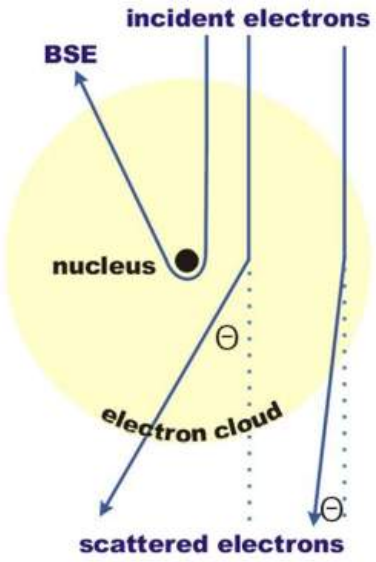




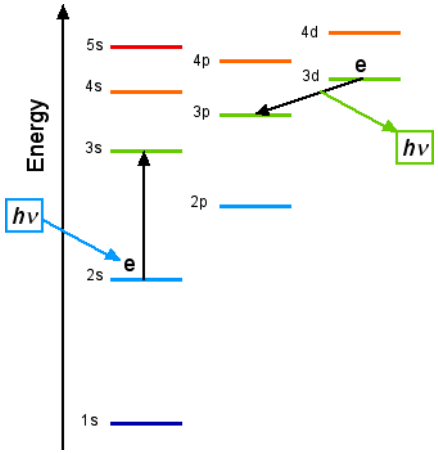
Zemach radius

Proton radius, new measurements

1) scattering: electron experiments
2) scattering: elastic muon-proton

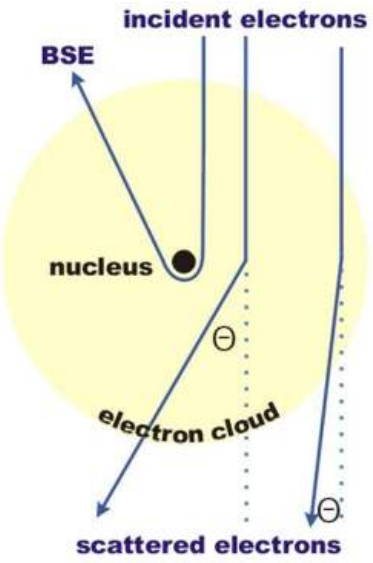


3) spectroscopy: electronic atoms and ions
4) spectroscopy: exotic atoms



FAMU: HFS of μ^-p ground level

1) scattering: electron experiments
2) scattering: elastic muon-proton



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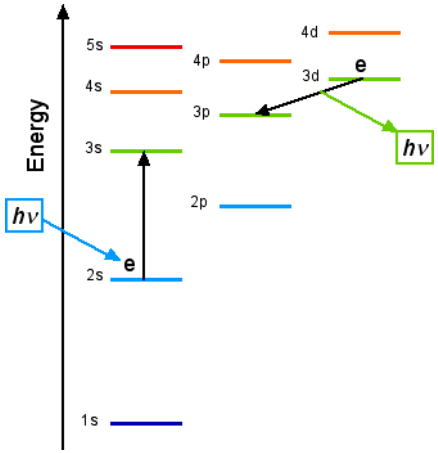
HFS of muonic hydrogen ground level



HFS of $(\mu^- p)_{1S}$: a 20 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 $(\mu^- p)_{1S}$

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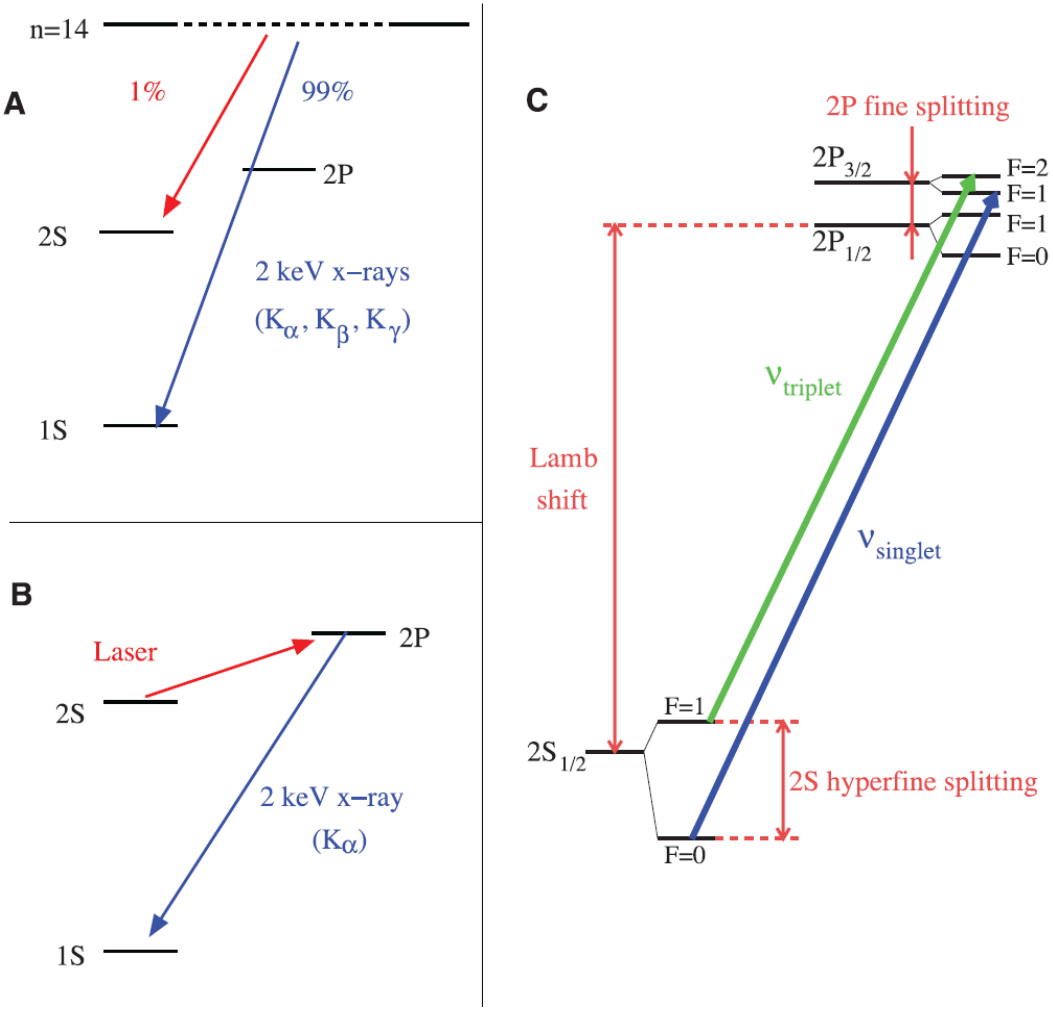
Received 31 July 1992; revised manuscript received 17 October 1992; accepted for publication 8 November 1992
Communicated by B. Fricke

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

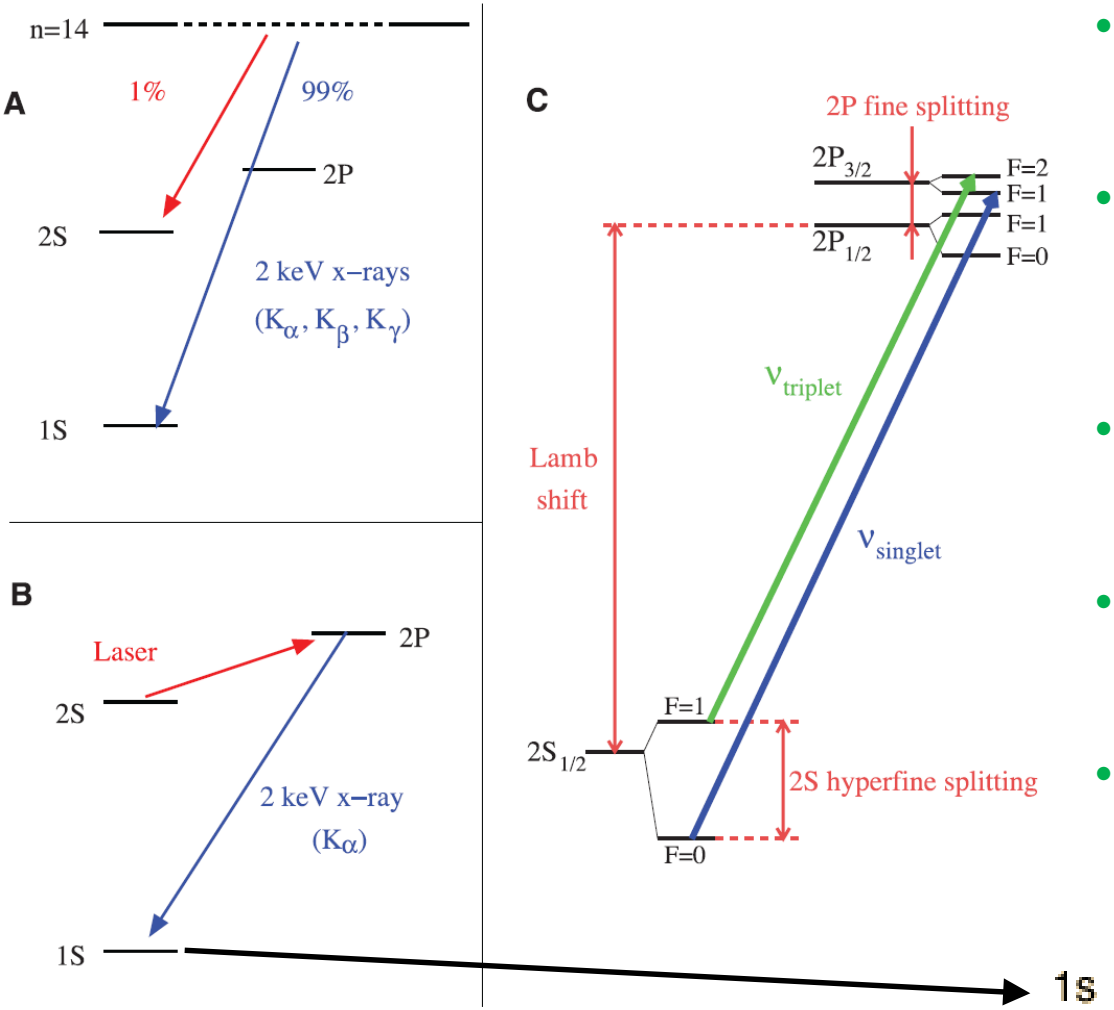
The theoretical expression for the hyperfine splitting

PSI results: Lamb shift (2S states)

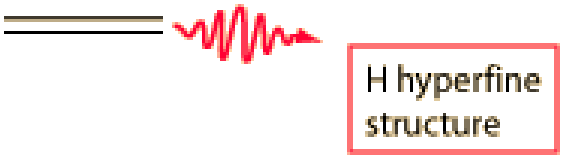


Antognini et al. (2013)

FAMU: a worthwhile challenge



- **First measurement** of the HFS of $(\mu^- p)_{1S}$
- **New and different** measurement respect to PSI results
- **Better estimate** of Zemach radius
- **Different systematics** respect previous experiments
- **Energy dependence of muon transfer** studies



The FAMU experiment

Fisica Atomi MUonici (Physics with muonic atoms)

FAMU: μ^-p spectroscopy

"Usual" spectroscopy flow:
1) create muonic hydrogen
2) laser excitation
3) count triplets
repeat varying laser energy (ΔE) to find resonance value.

How is it possible to distinguish excited states?
Hyperfine splitting of $(\mu^-p)_{1S}$ ~183 meV...

μ^- transfer rate to high-Z atoms is energy dependent

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Key point:
<u>The muon transfer rate to higher-Z atoms in collisions is (kinetic) energy dependent at epithermal energies (~100/200 meV)</u>

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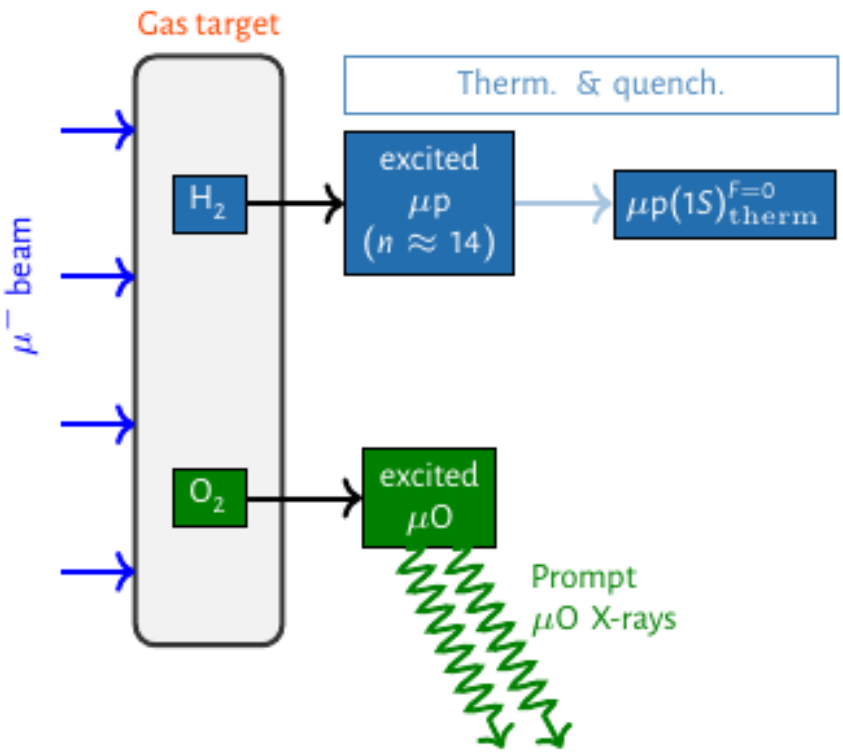
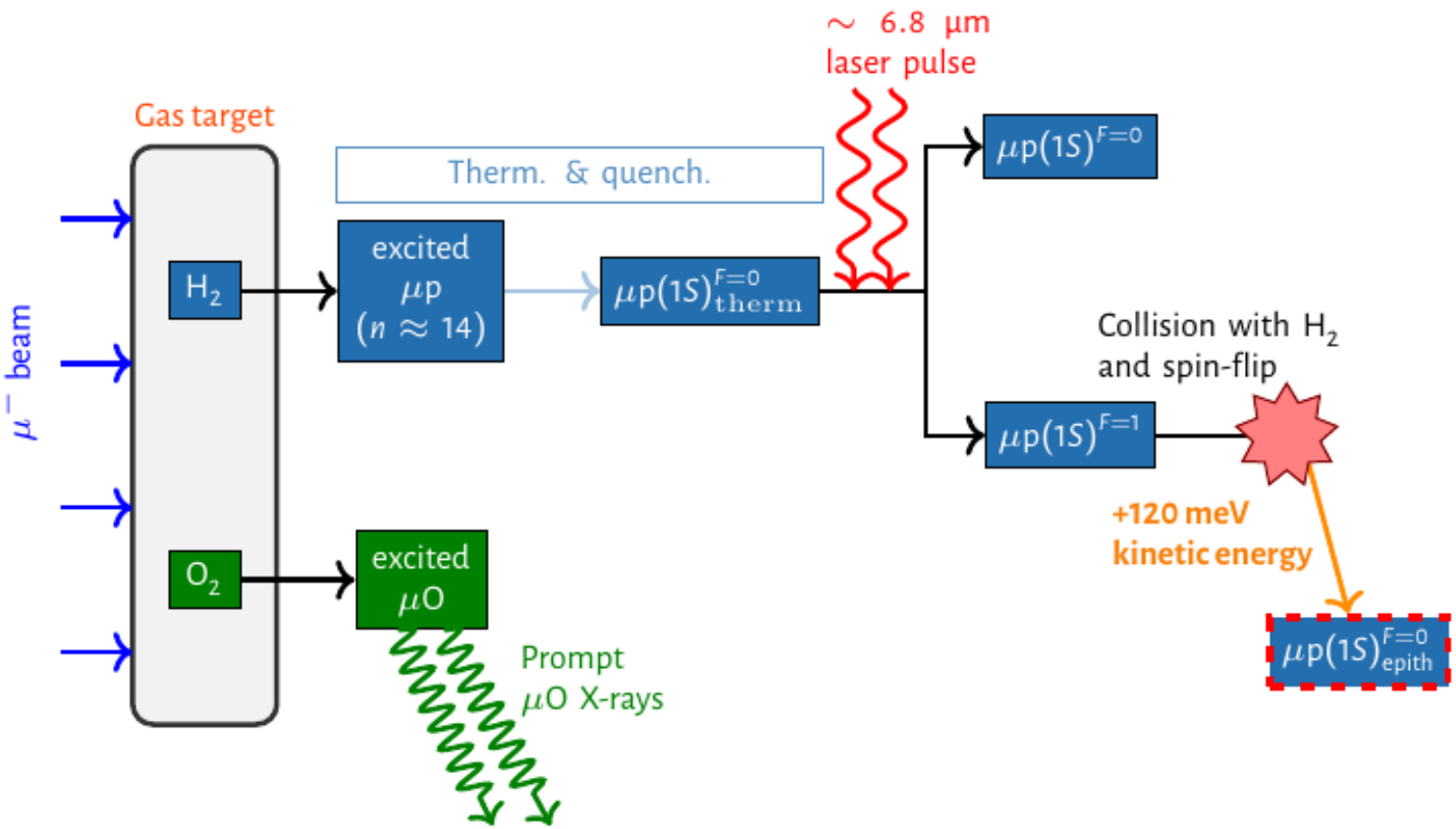
- H. Schneuwly, Z. Phys. C - Particles and Fields 56, 280 (1992).
- R. Jacot-Guillarmod, Muon transfer from thermalized muonic hydrogen isotopes Phys. Rev. A**51**, 2179 ~1995.
- F. Mulhauser and H. Schneuwly, J. Phys. B **26**, 4307 ~1993.
- L. Schellenberg, P. Baeriswyl, R. Jacot-Guillarmod, B. Mis- chler, F. Mulhauser, C. Piller, and L. A. Schaller, in *Muonic Atoms and Molecules*, edited by L. A. Schaller and C. Petitjean ~Birkhaüser-Verlag, Basel, 1993, p. 187.
- R. Jacot-Guillarmod, F. Bienz, M. Boschung, C. Piller, L. A. Schaller, L. Schellenberg, H. Schneuwly, W. Reichart, and G. Torelli, Phys. Rev. A **38**, 6151 ~1988.
- A. Werthmüller, A. Adamczak, R. Jacot-Guillarmod, F. Mulhauser, C. Piller, L. A. Schaller, L. Schellenberg, H. Schneu- wly, Y.-A. Thalmann, and S. Tresch, Hyperfine Interact. **103**, 147~1996.
- A. Werthmüller et. al. Energy dependence of the charge exchange reaction from muonic hydrogen to oxygen ; Hyperfine Interactions 116 (1998) 1–16 1.

FAMU workflow: μ⁻p generation



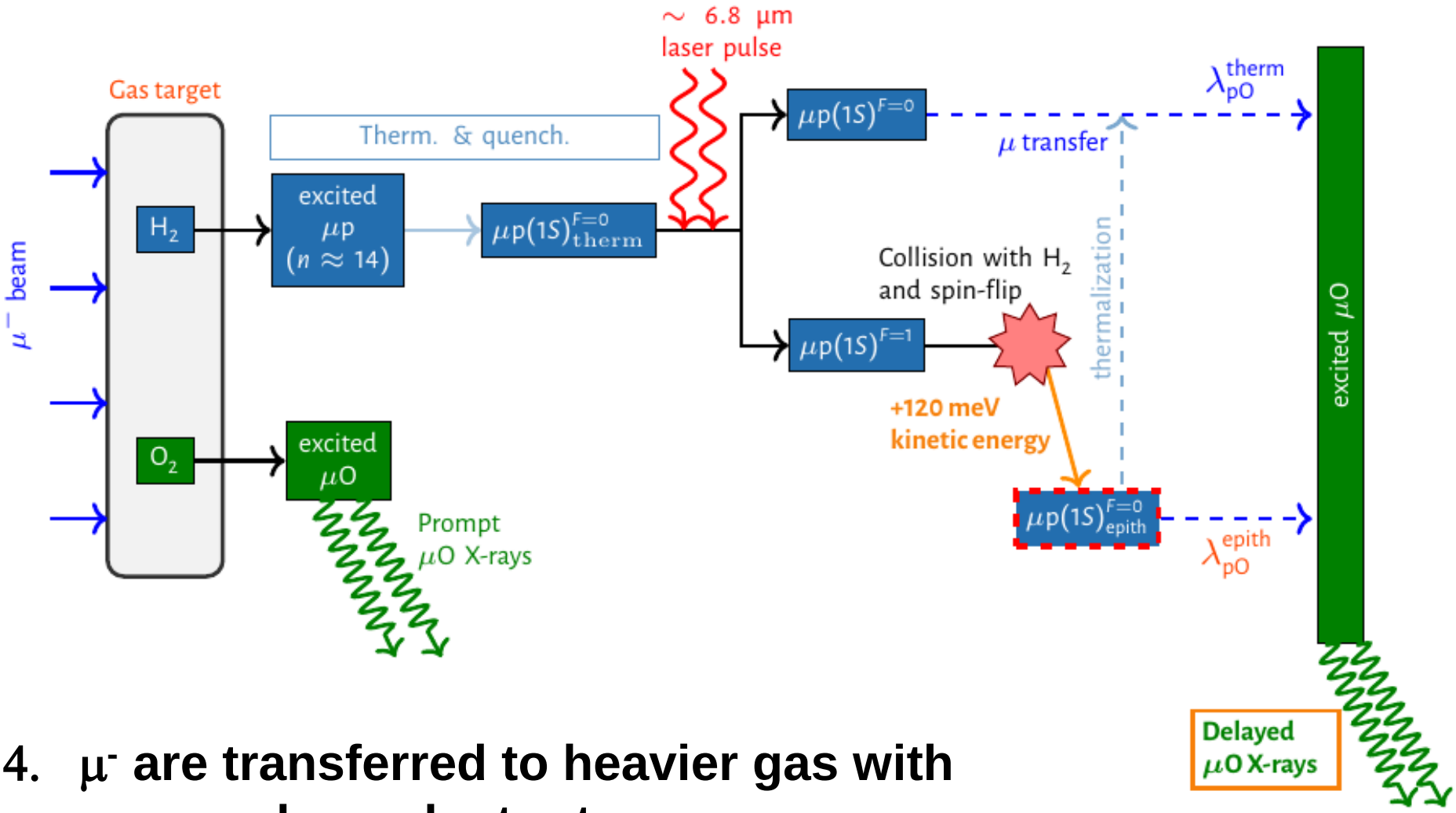
1. Create muonic hydrogen and wait for thermalization

FAMU workflow: laser flash



2. **Laser! at resonance (λ_0 ~6.8μ) spin state of μ^-p from 1^1S_0 to 1^3S_1 , spin is flipped: $\mu^-p(\uparrow\downarrow) \rightarrow \mu^-p(\uparrow\uparrow)$;**
3. **μ^-p (1^3S_1) de-excitation and acceleration, $\mu^-p(\uparrow\uparrow)$ hits a H atom and is depolarized back to $\mu^-p(\uparrow\downarrow)$ and accelerated by ~120 meV ;**

FAMU workflow: μ transfer



4. **μ^- are transferred to heavier gas with energy-dependent rate;**

FAMU: principle of operation

1. Create muonic hydrogen and wait for thermalization
2. Laser! at resonance (λ_0 ~6.8μ) spin state of μ^-p from 1^1S_0 to 1^3S_1 , spin is flipped: $\mu^-p(\uparrow\downarrow) \rightarrow \mu^-p(\uparrow\uparrow)$;
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4. μ^- are transferred to heavier gas with energy-dependent rate;
5. λ_0 **resonance is determined by the maximizing the time distribution of μ^- transferred events.**

<u>Ingredients needed:</u>

- **«proper» gas mixture**
- **high energy and fine-tunable laser**
- **fast and precise X-rays detectors**

Three phases project

1) **Study the muon beam, test target and detectors, measure transfer rate (@ constant conditions of PTV) – 2014 beam test (results in the next slides);**

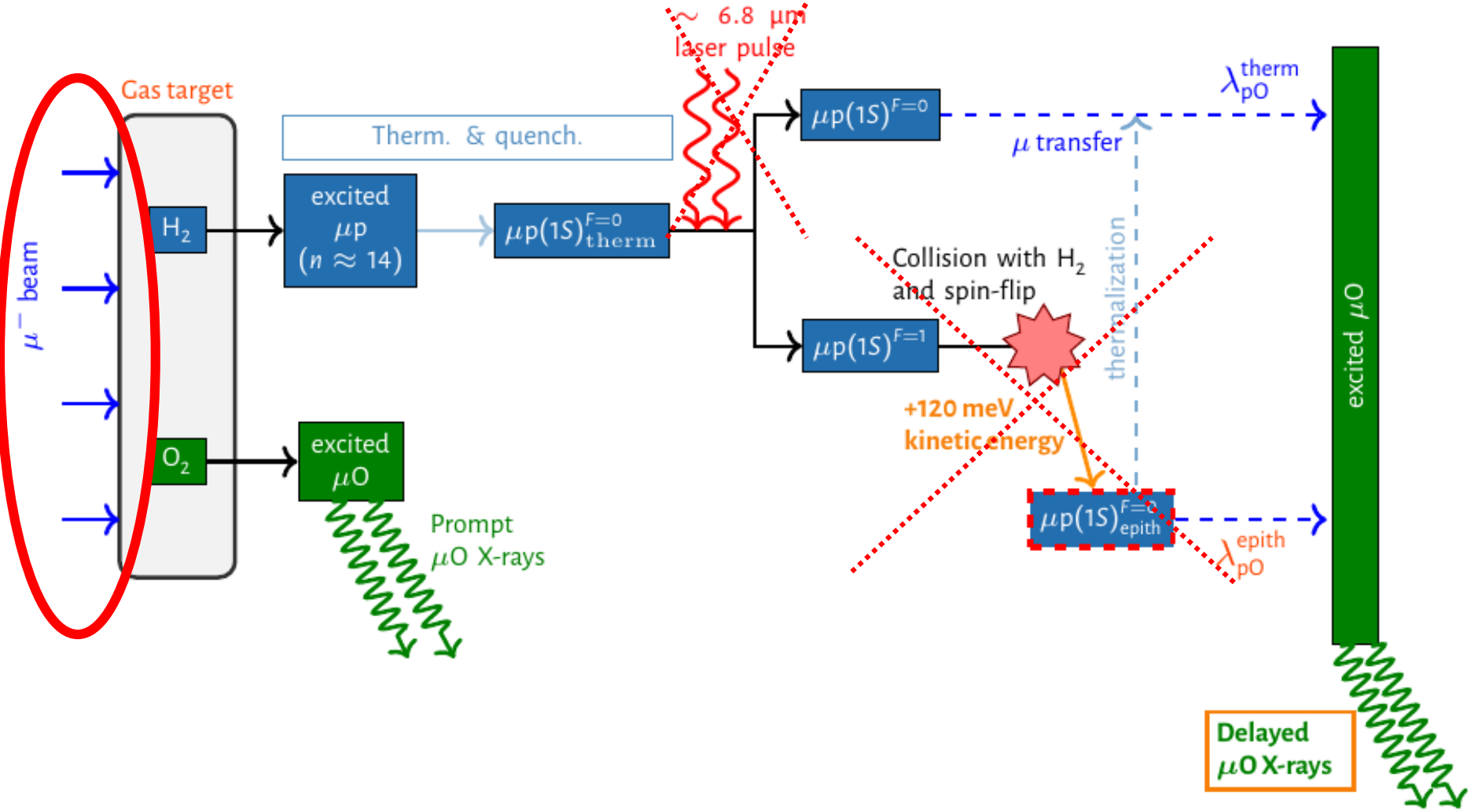
2) **Find the best gas mixture, temperature and pressure in order to observe neatly and measure the transfer rate energy dependence, no laser – 2015 beam test (December 7th - 16th) & February 2016 (one week beam);**

3) **Full working setup with laser, determination of proton Zemach radius – foreseen in 2017.**

Beam test at RAL – 2014

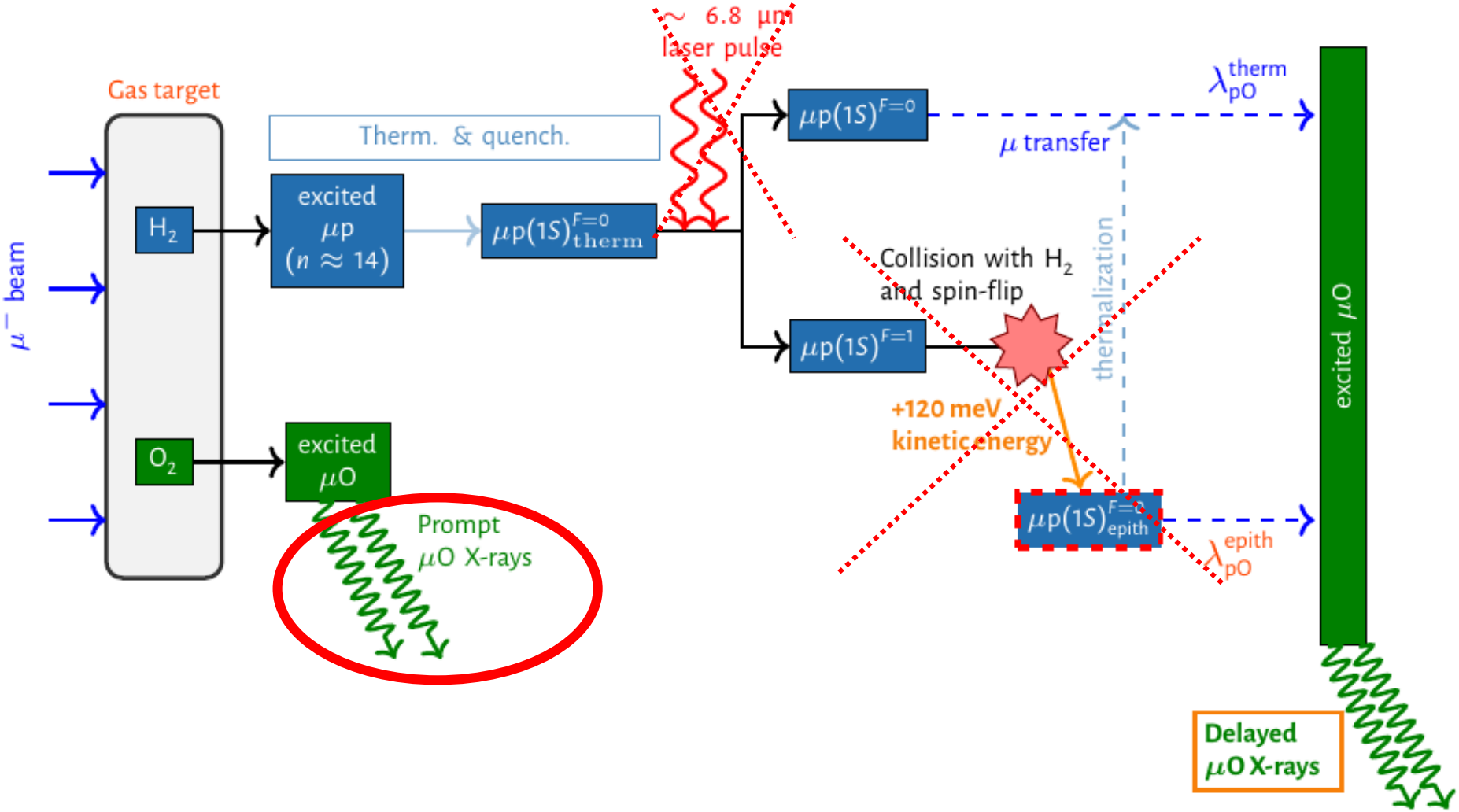
Phase 1

Beam characteristics



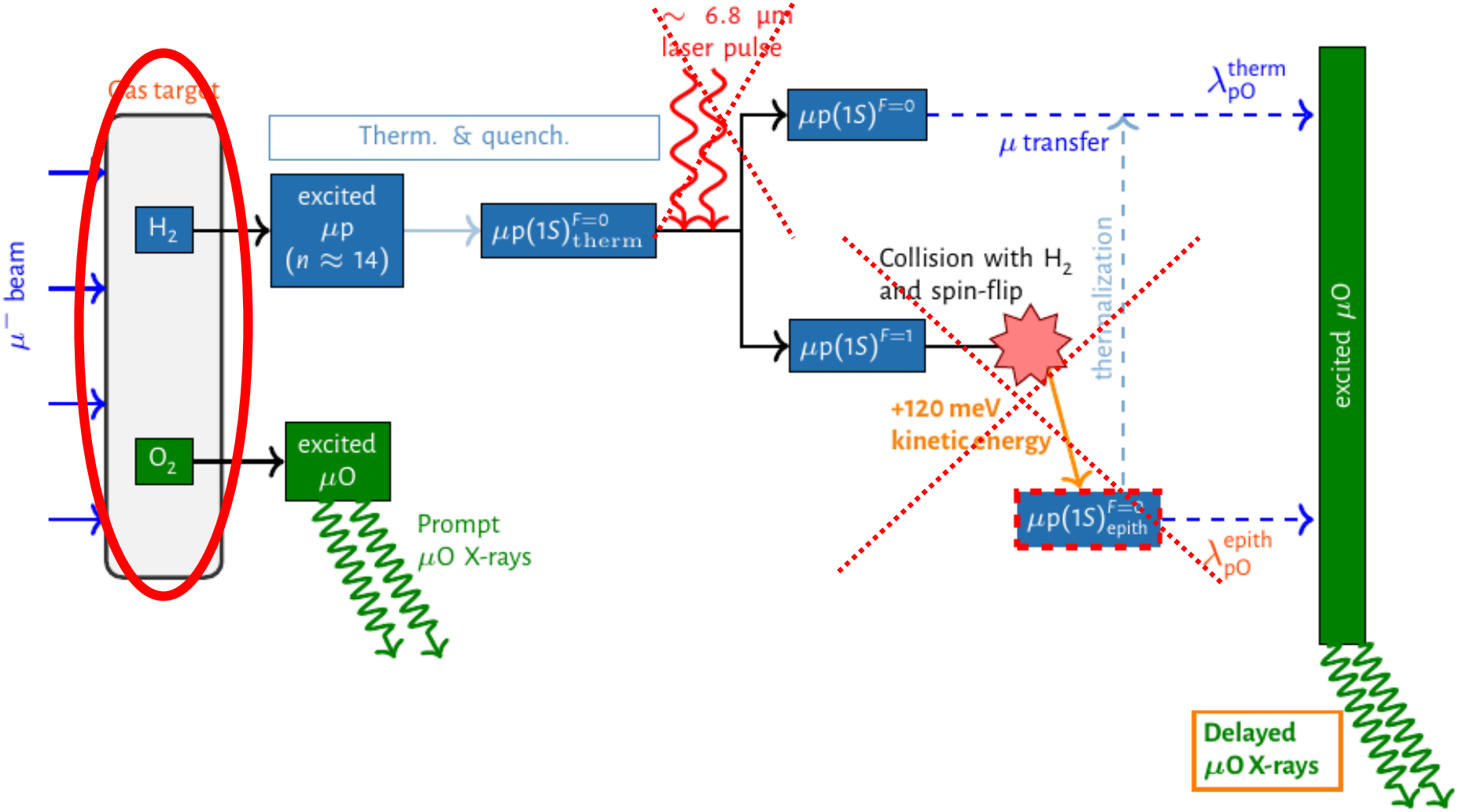
Phase 1

X-rays signals



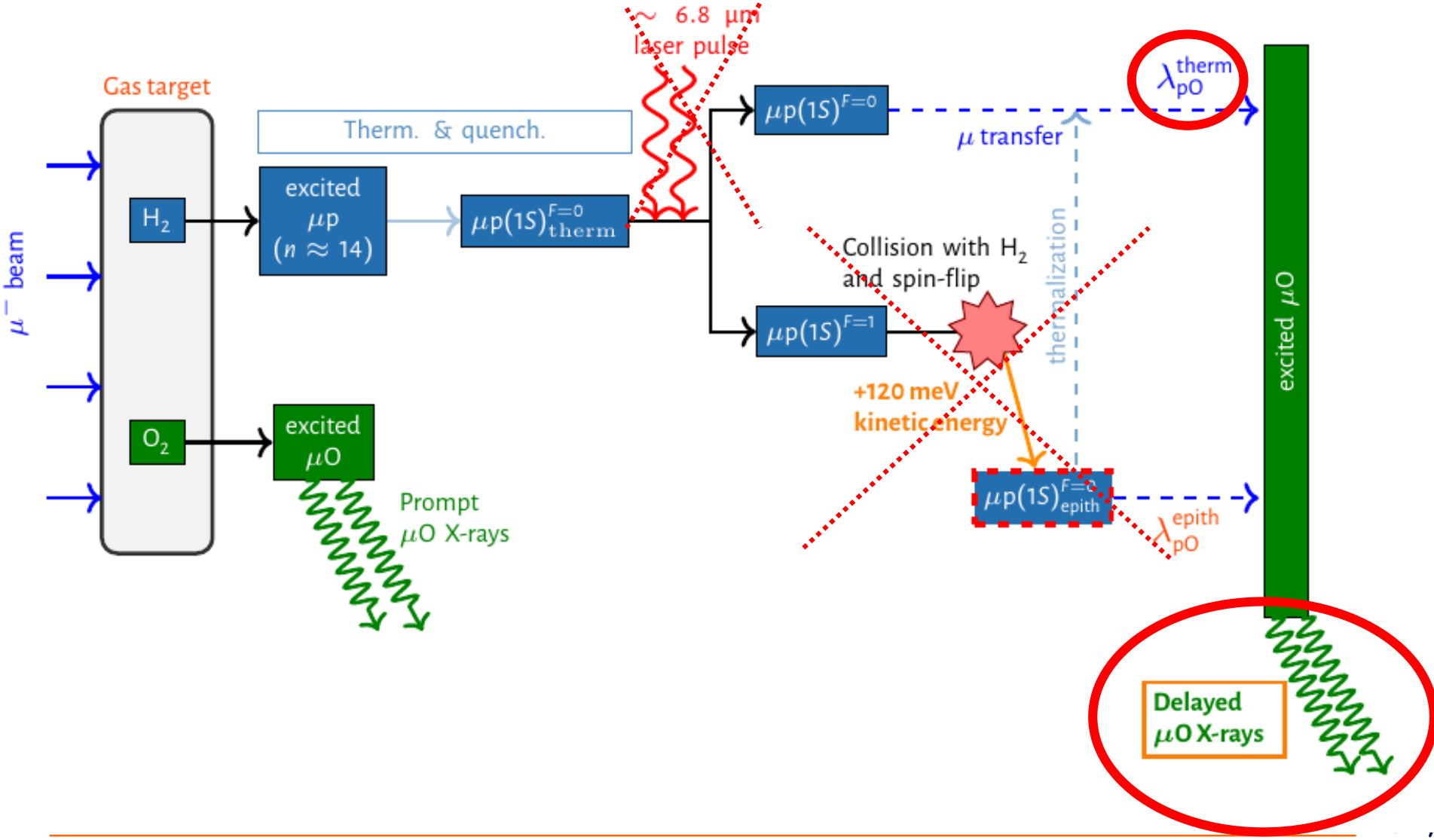
Phase 1

Target, gas purity and gas operations

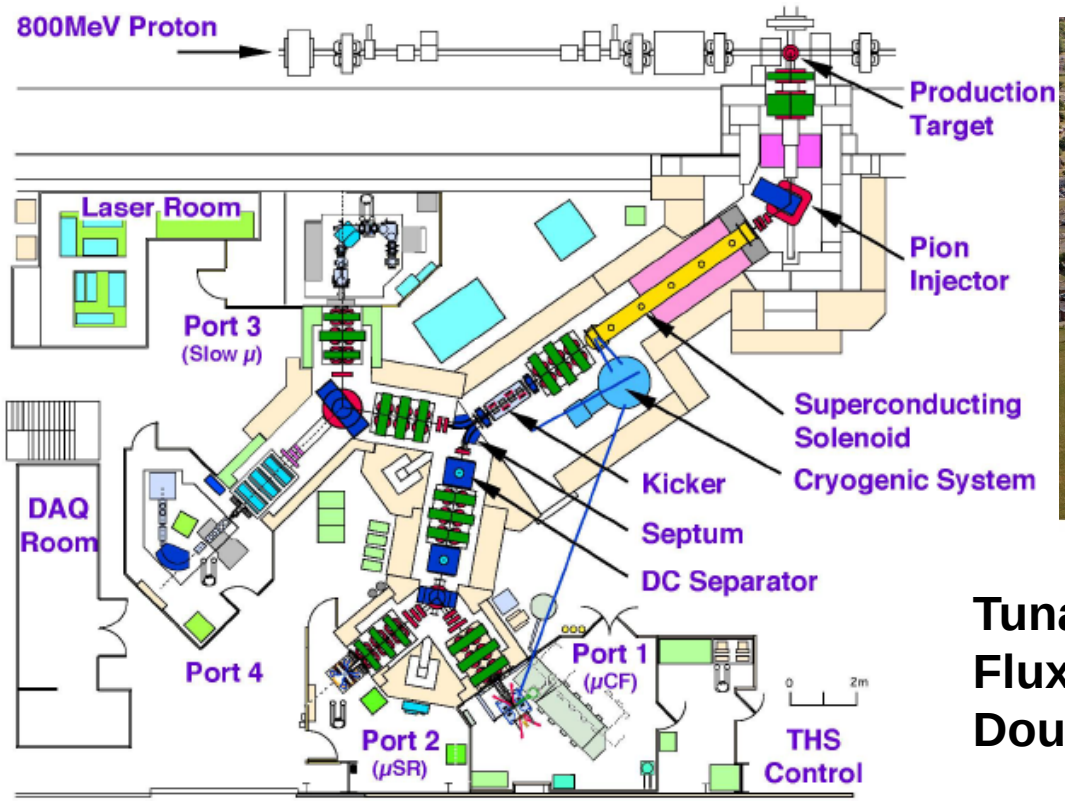


Phase 1

Observation of delayed X-rays, measurement of transfer rate

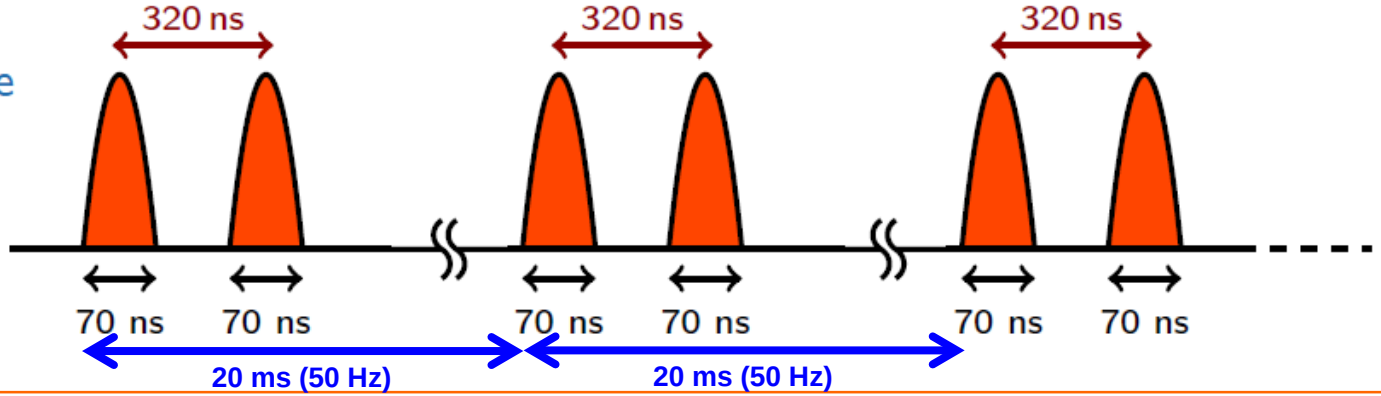


RIKEN – RAL muon facility



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

Beam time structure



Detectors: suited for time-resolved X-ray spectroscopy

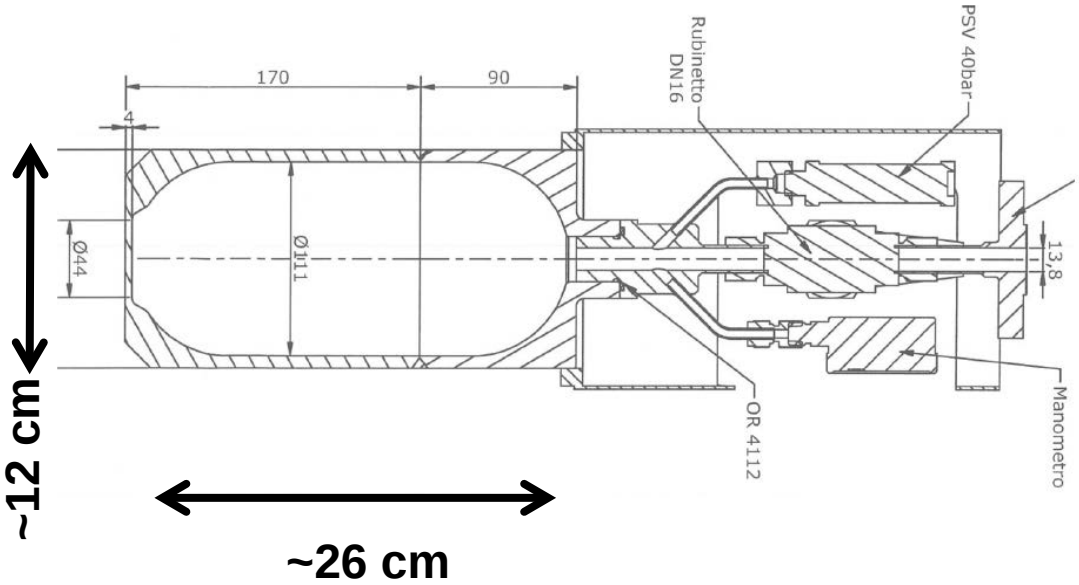
Three gas targets in an Aluminium vessel @ 40 atm:

1. pure H_2 gas

2. H_2 + (2% w/v)Ar gas mixture

3. H_2 + (4% w/v)CO_2 gas mixture

+ test on solid graphite target.



Detectors: suited for time-resolved X-ray spectroscopy

Hodoscope: beam shape monitoring

Two planes (X and Y) of 32 scintillating fibers 3 x 3 mm^2 square section

3D printed supports

SiPM reading with fast electronics (SuperB/TPS front-end)

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)

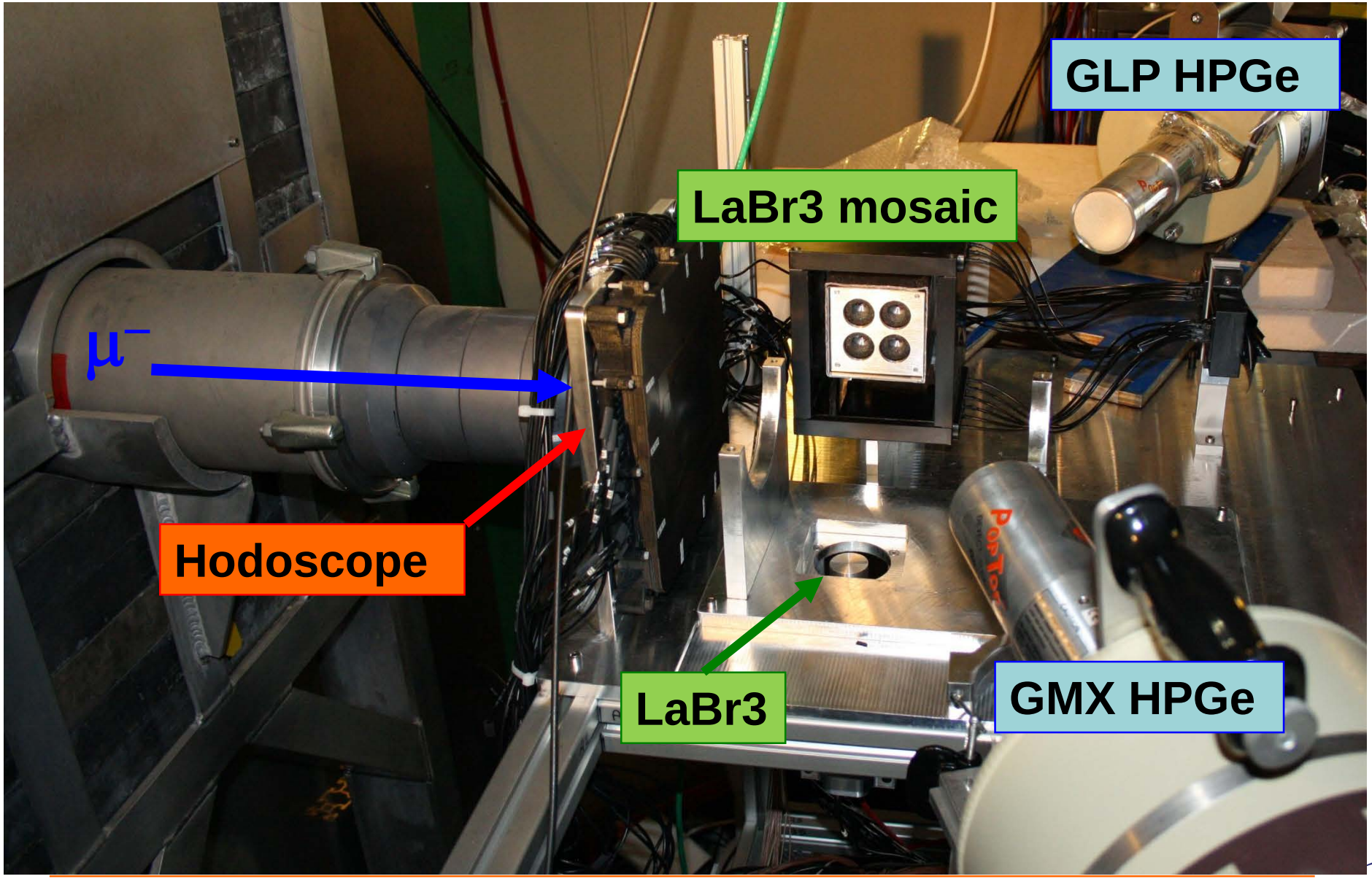
Detectors: suited for time-resolved X-ray spectroscopy

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

one cylindrical 1 inch diameter 1 inch long $LaBr_3$(5%Ce) crystal
Integrated design provided by Saint-Gobain

2x2 matrix of four cylindrical 0.5 inch diameter 0.5 inch long $LaBr_3$(5%Ce) crystals read by PMTs
Housing: iron box coated on sides by a 2mm thick lead sheet

2014: experimental setup



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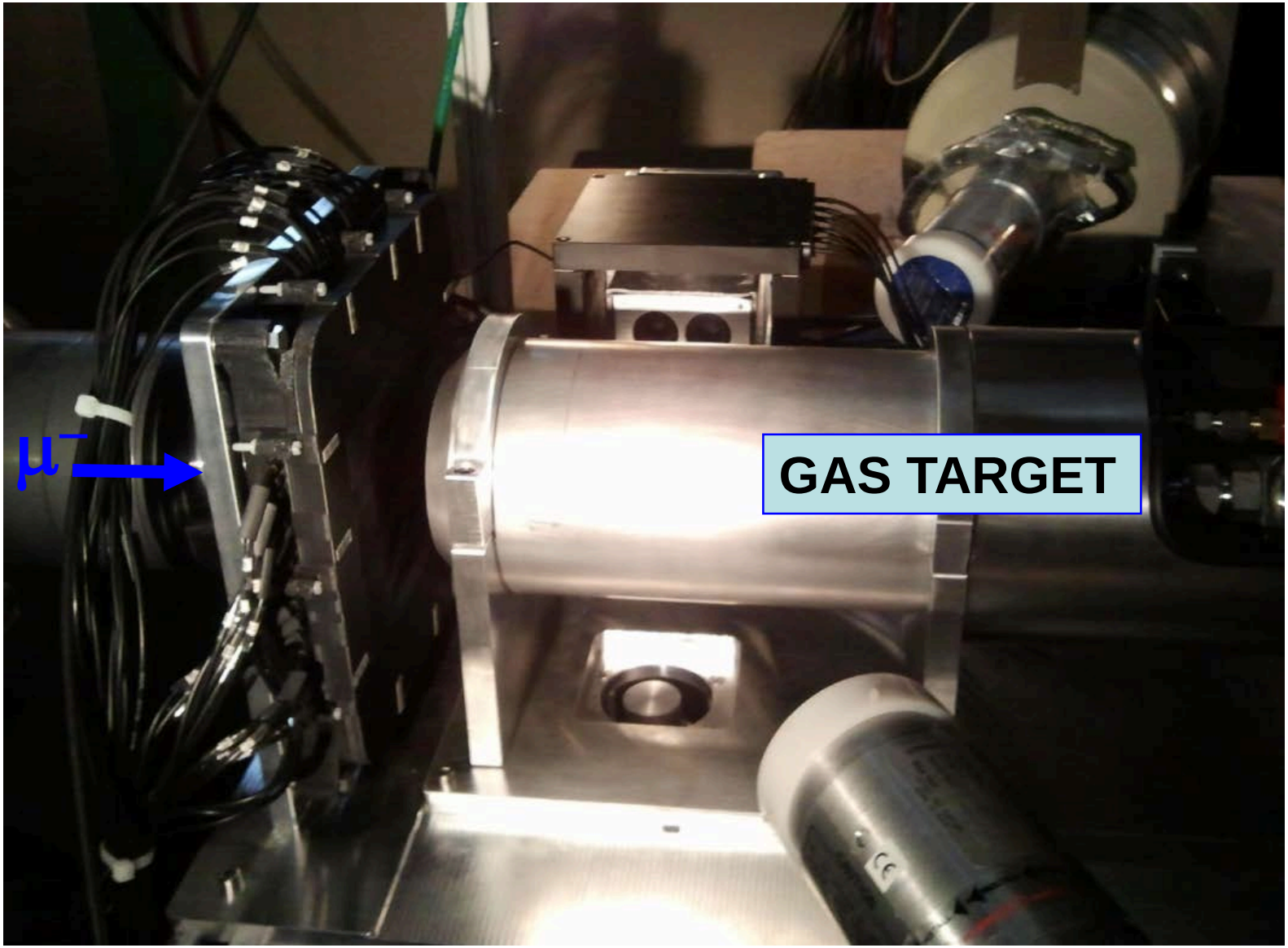
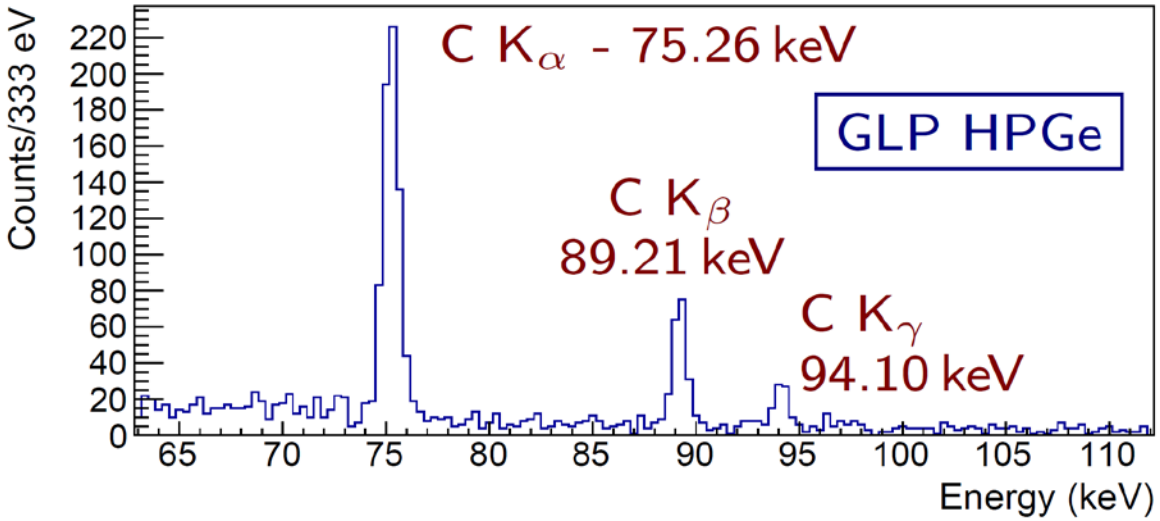


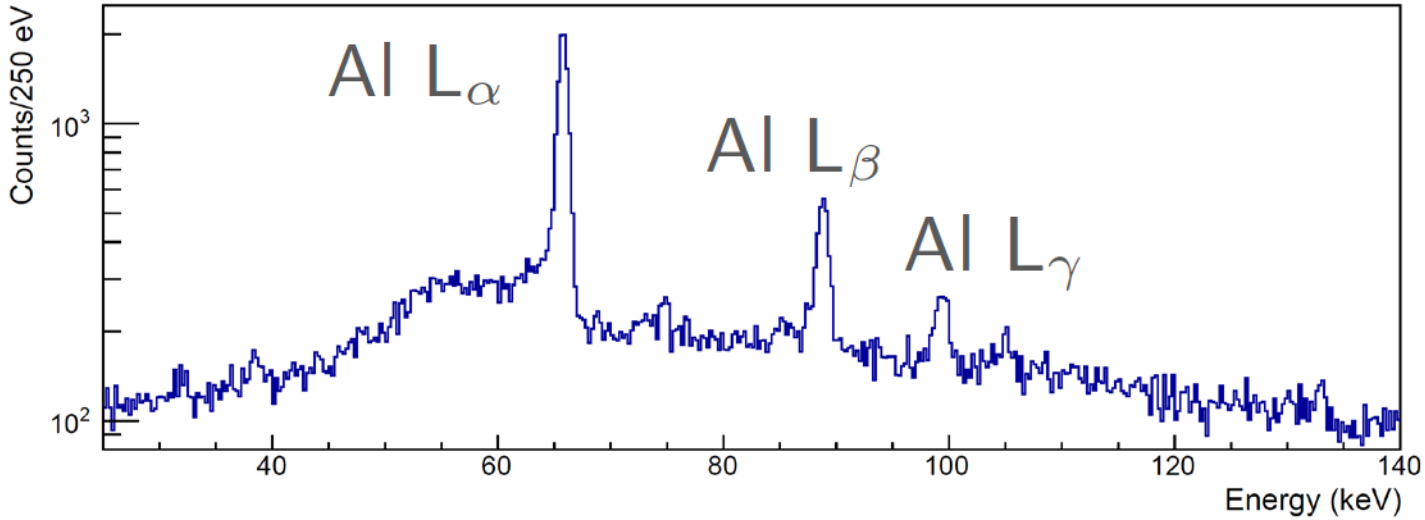
Spectral lines measurements

Germanium detectors: excellent energy resolution

Graphite target

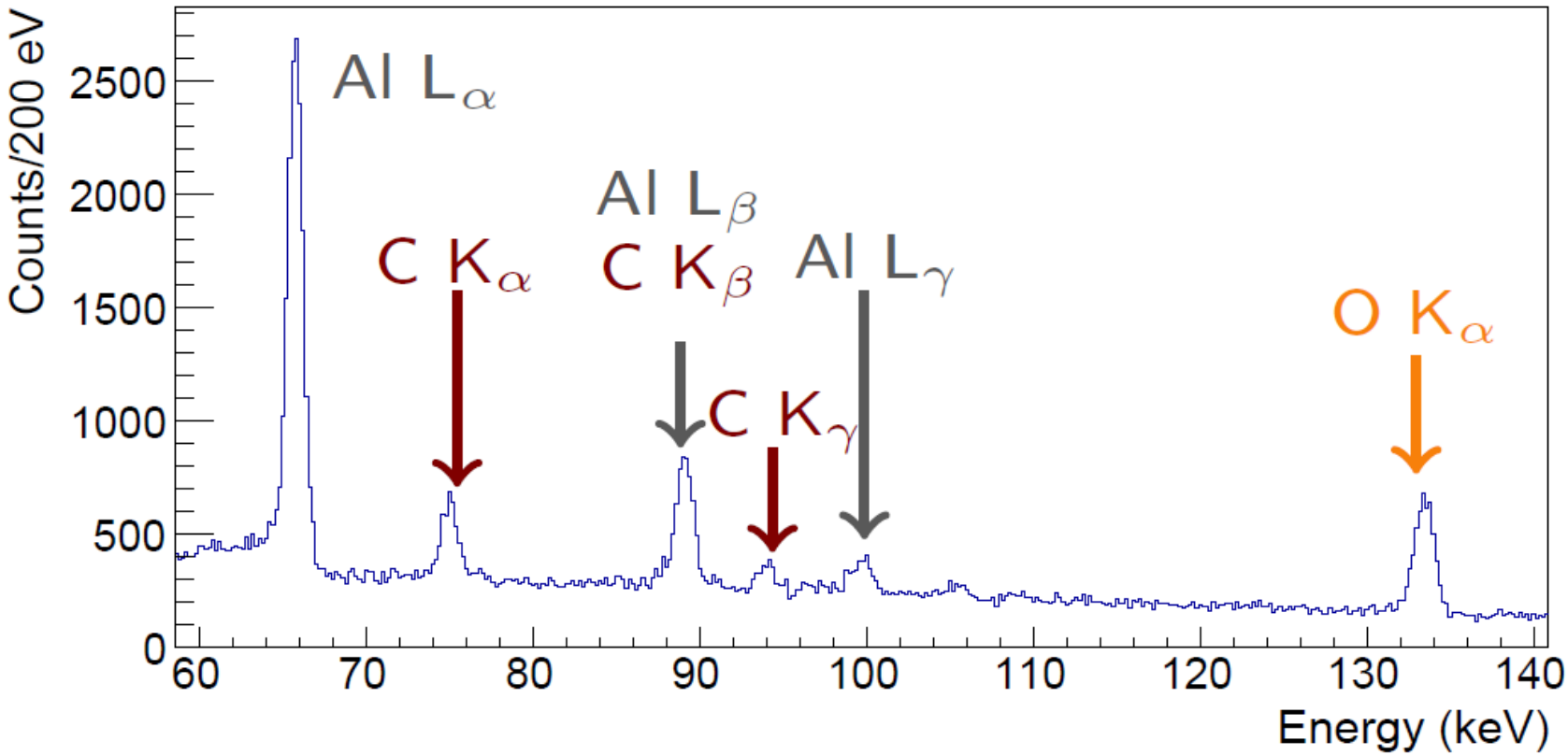


Pure H_2 target in aluminium container



Germanium detectors: excellent energy resolution

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



Lines observed with Ge detectors

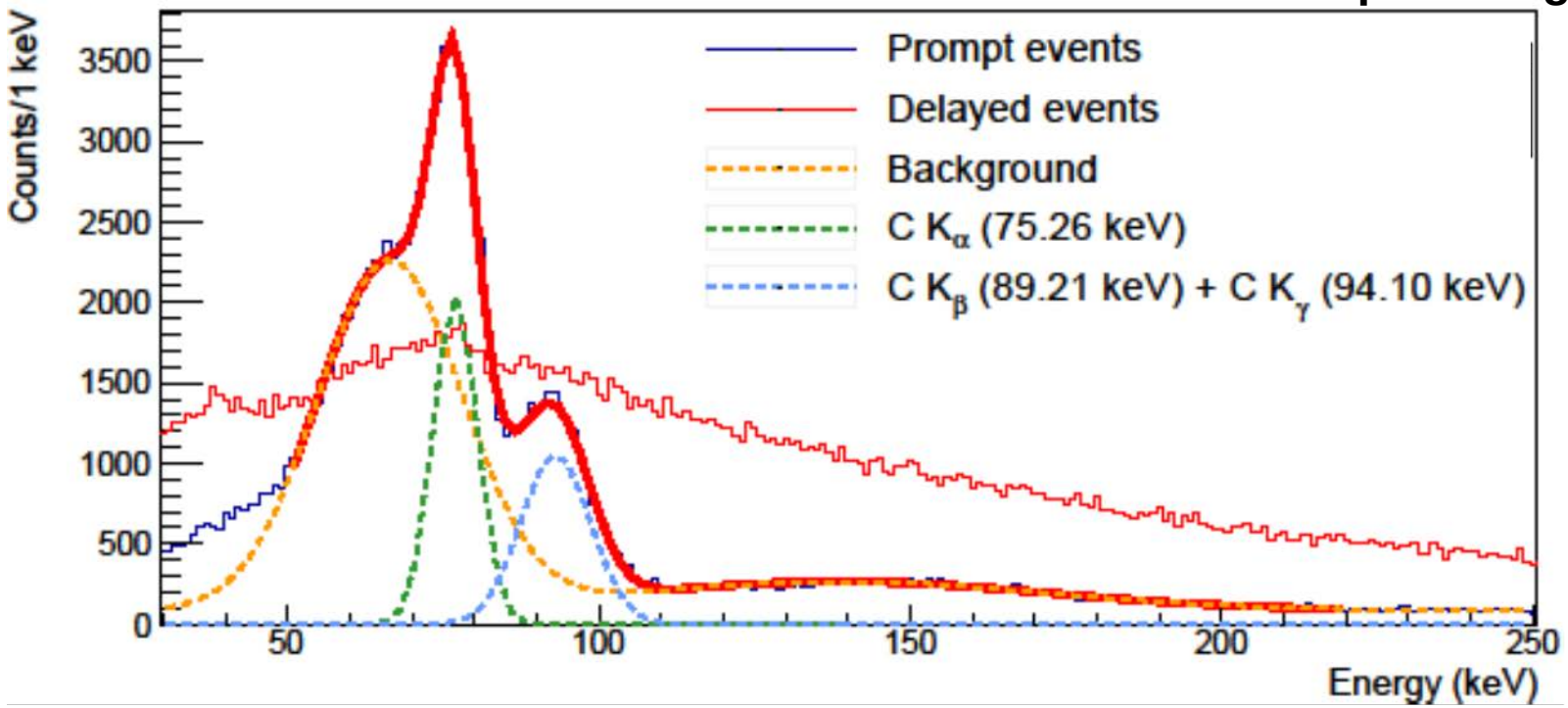
Transition	Transition energy (keV)				
	C	N	O	Al	Ar
K_α	75.258	102.556	133.535	346.828	644.004
K_β	89.212	121.547	158.422	412.877	770.6
K_γ	94.095	128.194	167.125	435.981	815.0
L_α			24.830	65.756	126.237
L_β			33.521	88.771	170.420
L_γ				99.360	190.870

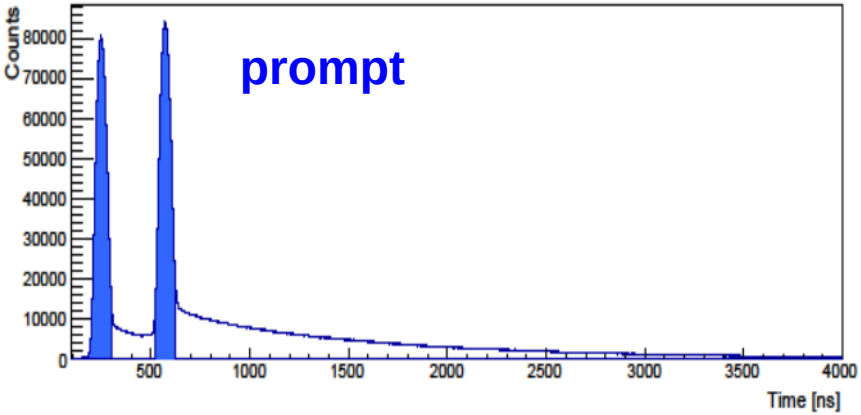
Legenda: resolved, not resolved, not seen, low statistics

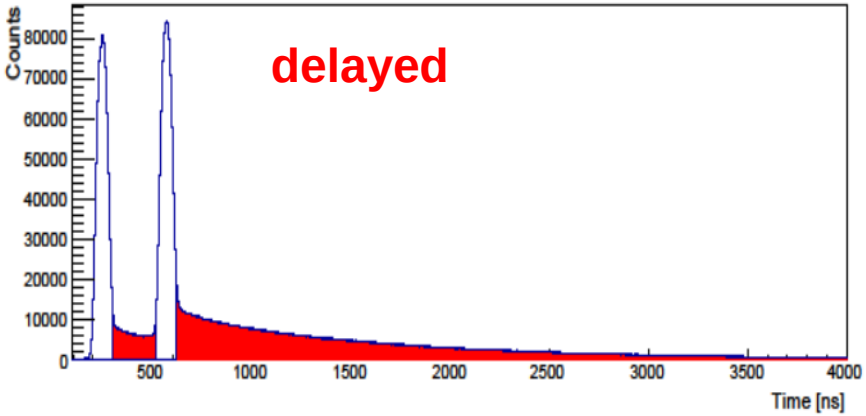
Measured energy resolution: FWHM 1 keV @ 133 keV

$LaBr_3$(5%Ce) scintillating crystals

Graphite target

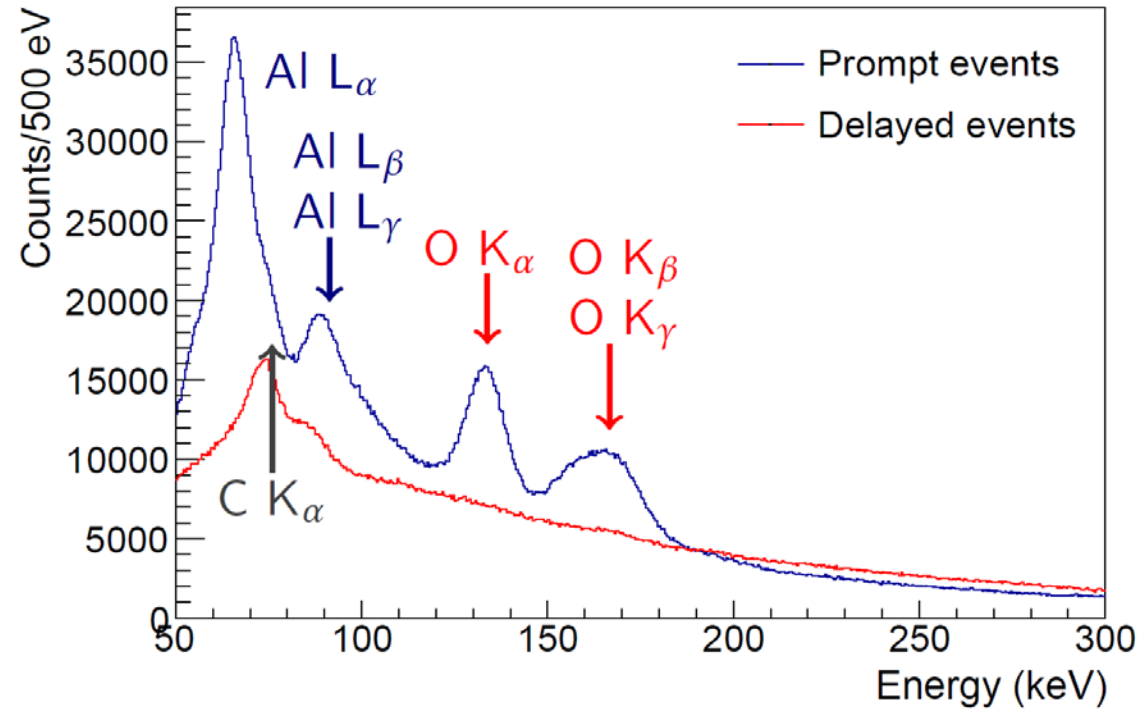


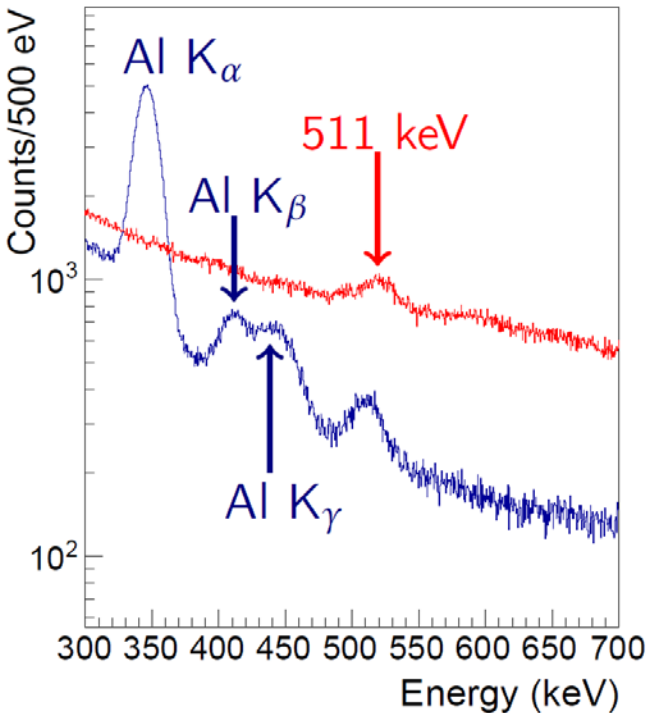


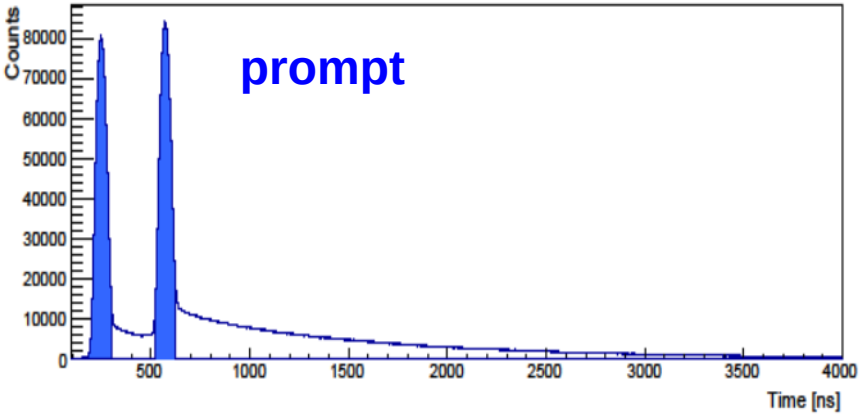


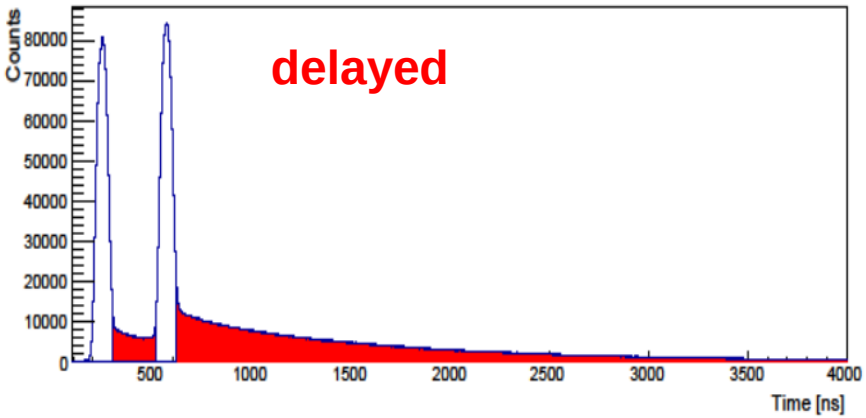
$LaBr_3$(5%Ce) scintillating crystals

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









$LaBr_3$(5%Ce) scintillating crystals

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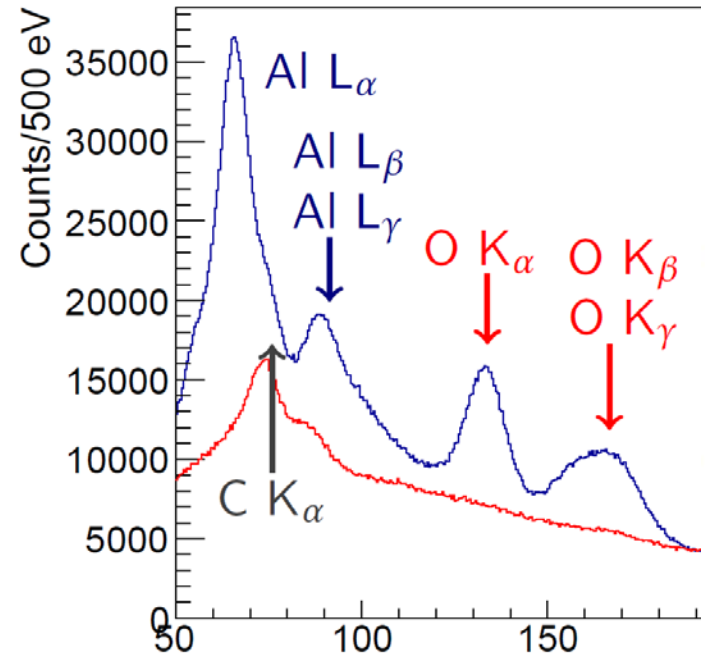

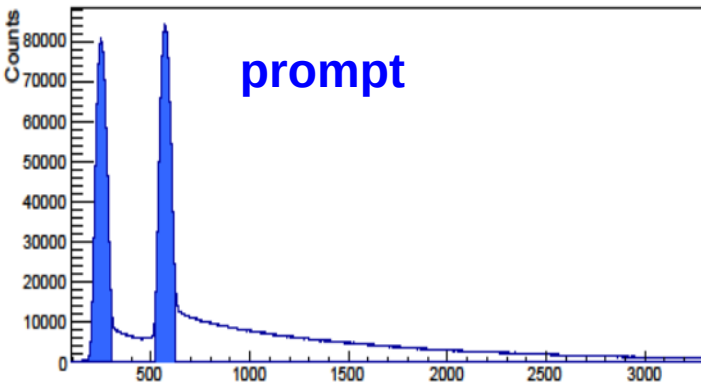

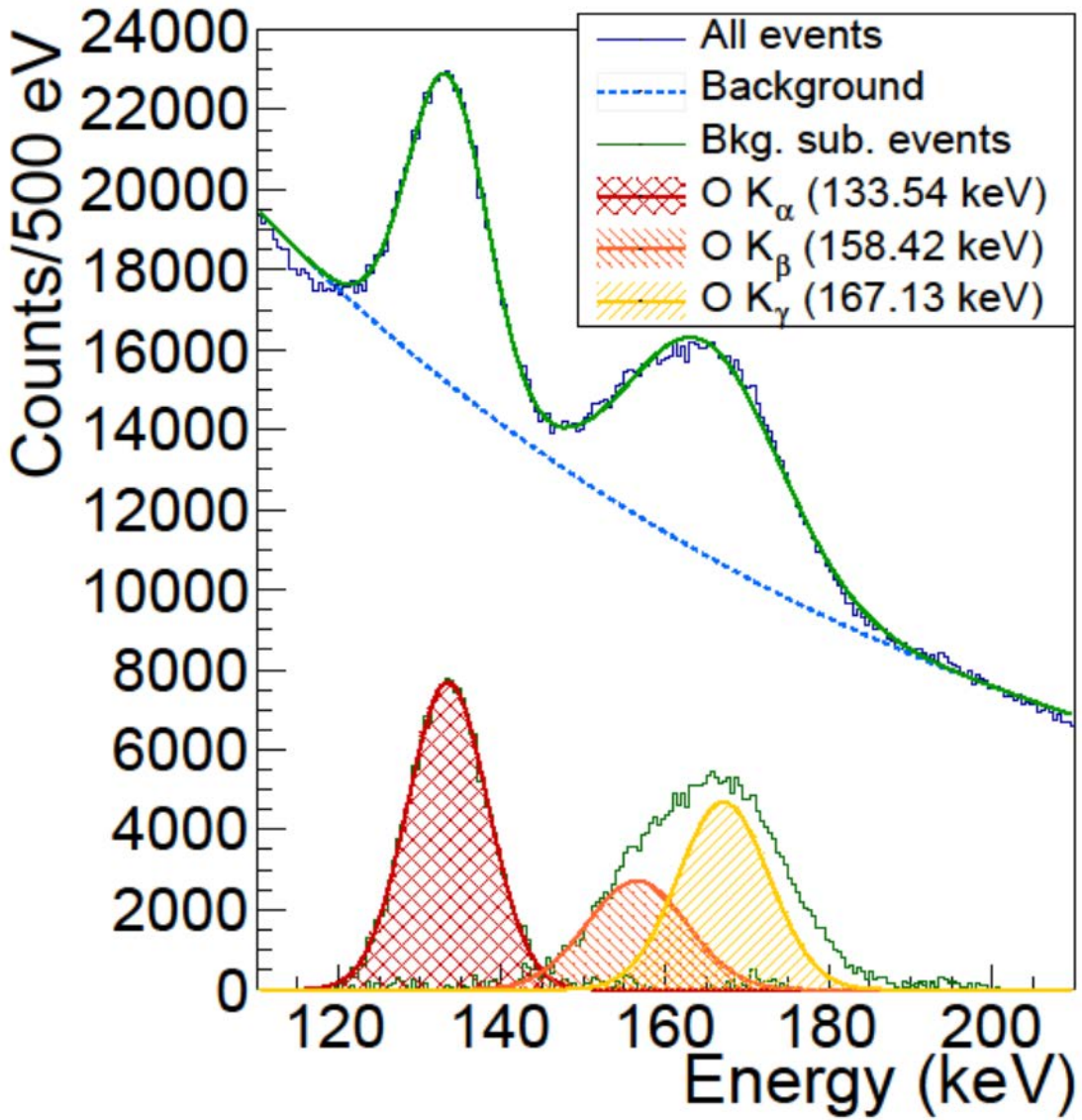

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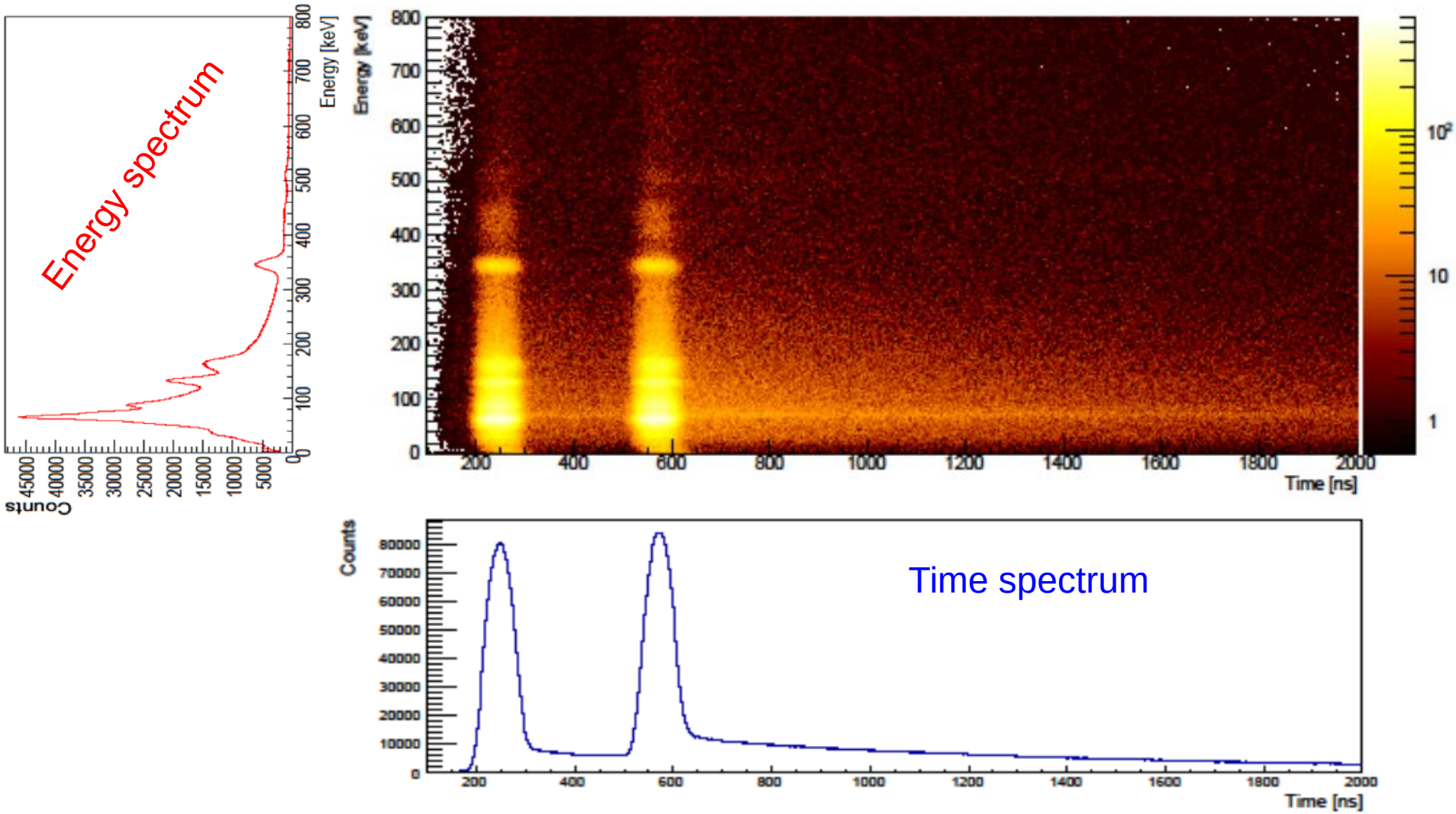
K_α	75.258	102.556	133.535	346.828	644.004
K_β	89.212	121.547	158.422	412.877	770.6
K_γ	94.095	128.194	167.125	435.981	815.0
L_α			24.830	65.756	126.237
L_β			33.521	88.771	170.420
L_γ				99.360	190.870

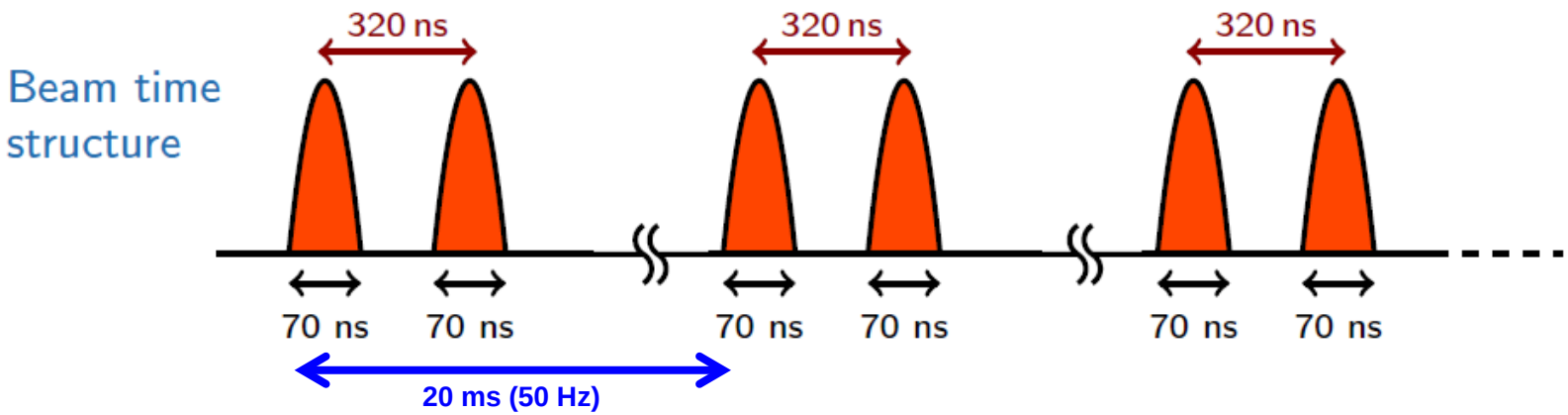
Legenda: resolved, not resolved, not seen, low statistics

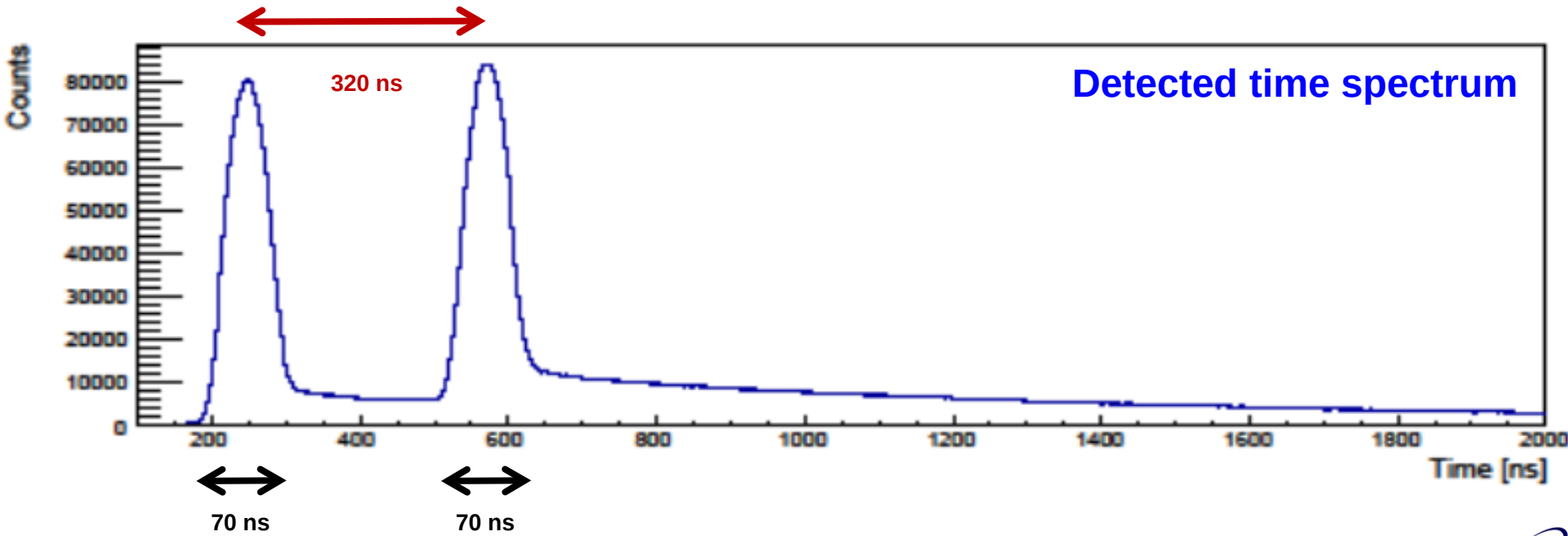
$LaBr_3$: spectral evolution over time



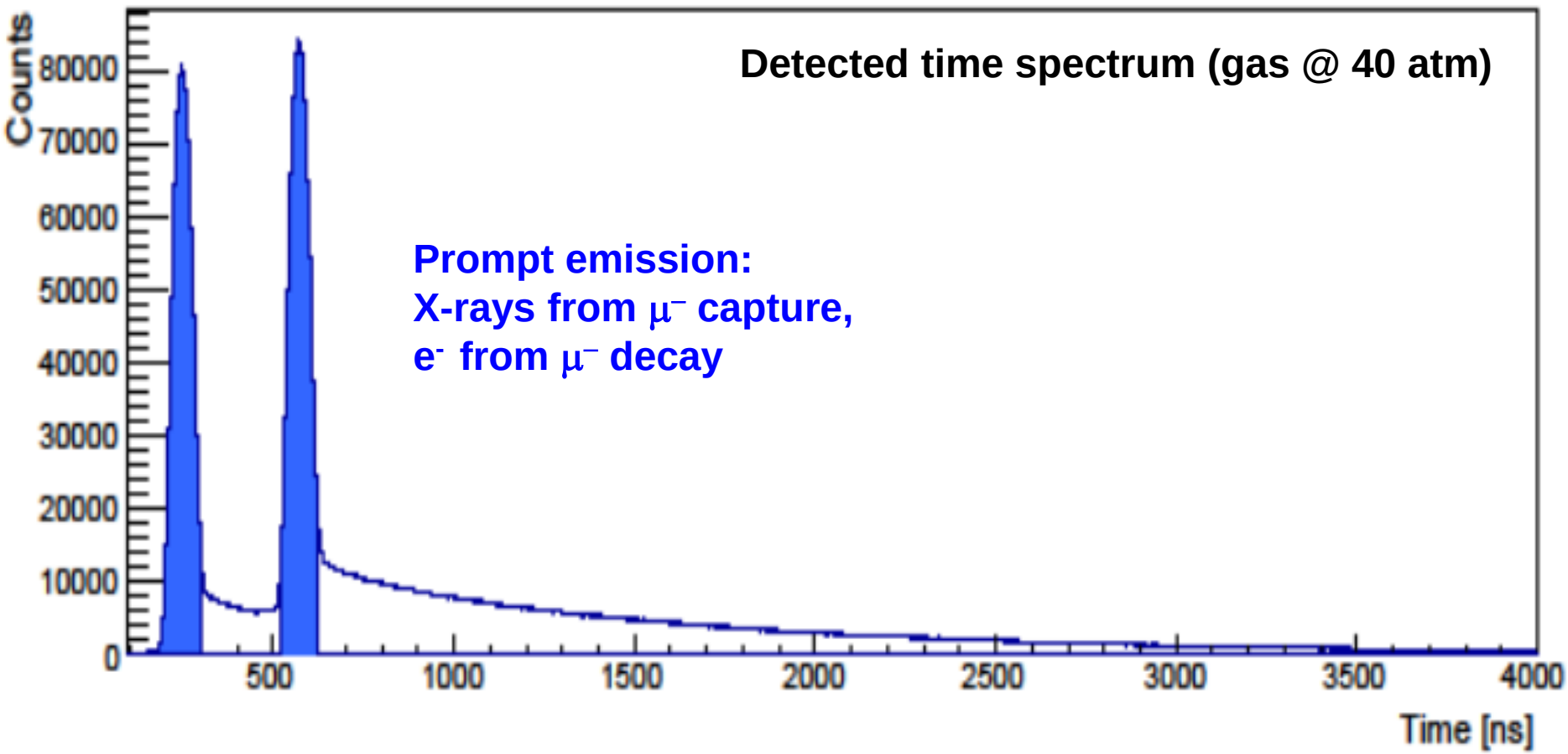
Muonic transfer rate measurement

Time spectrum: peaks and tails

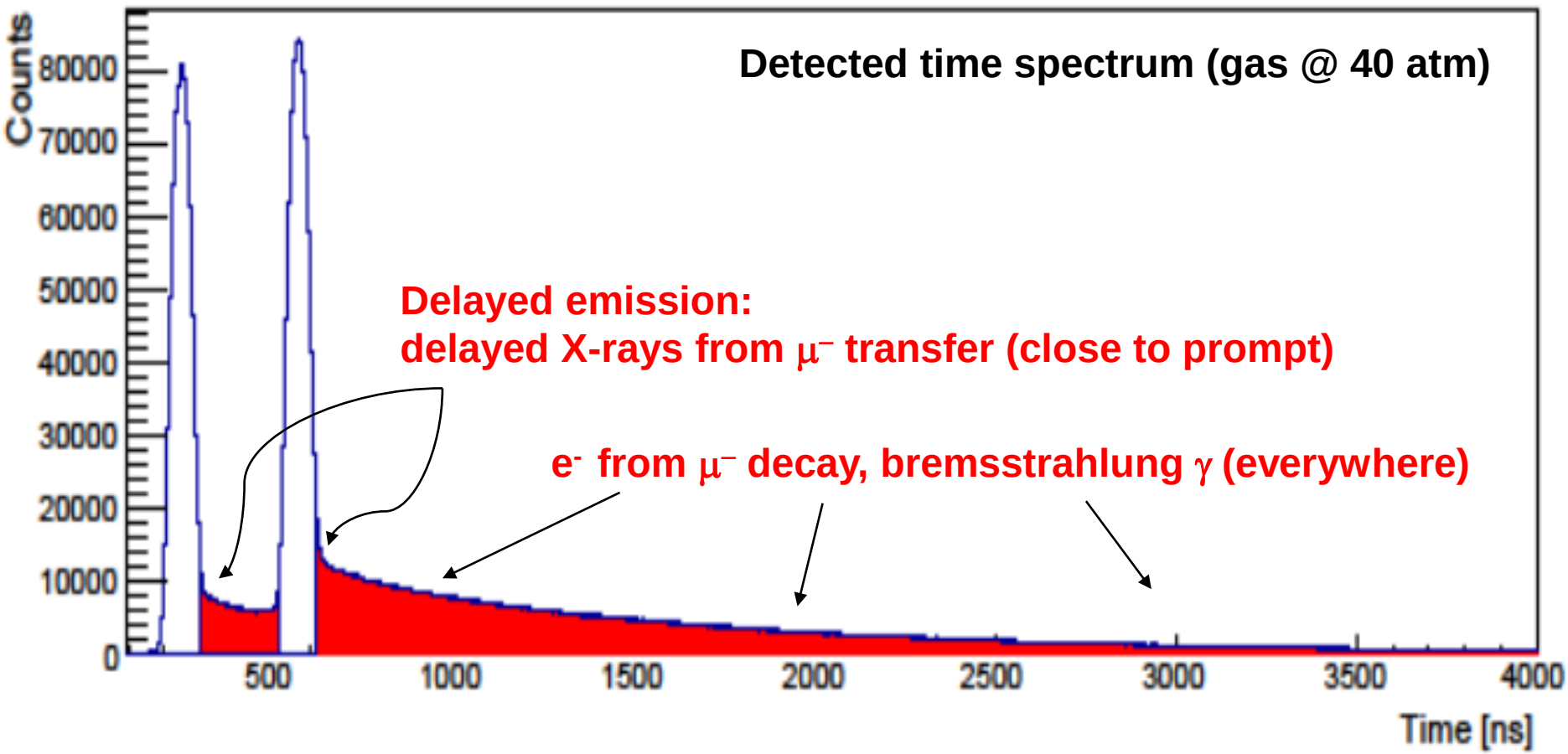




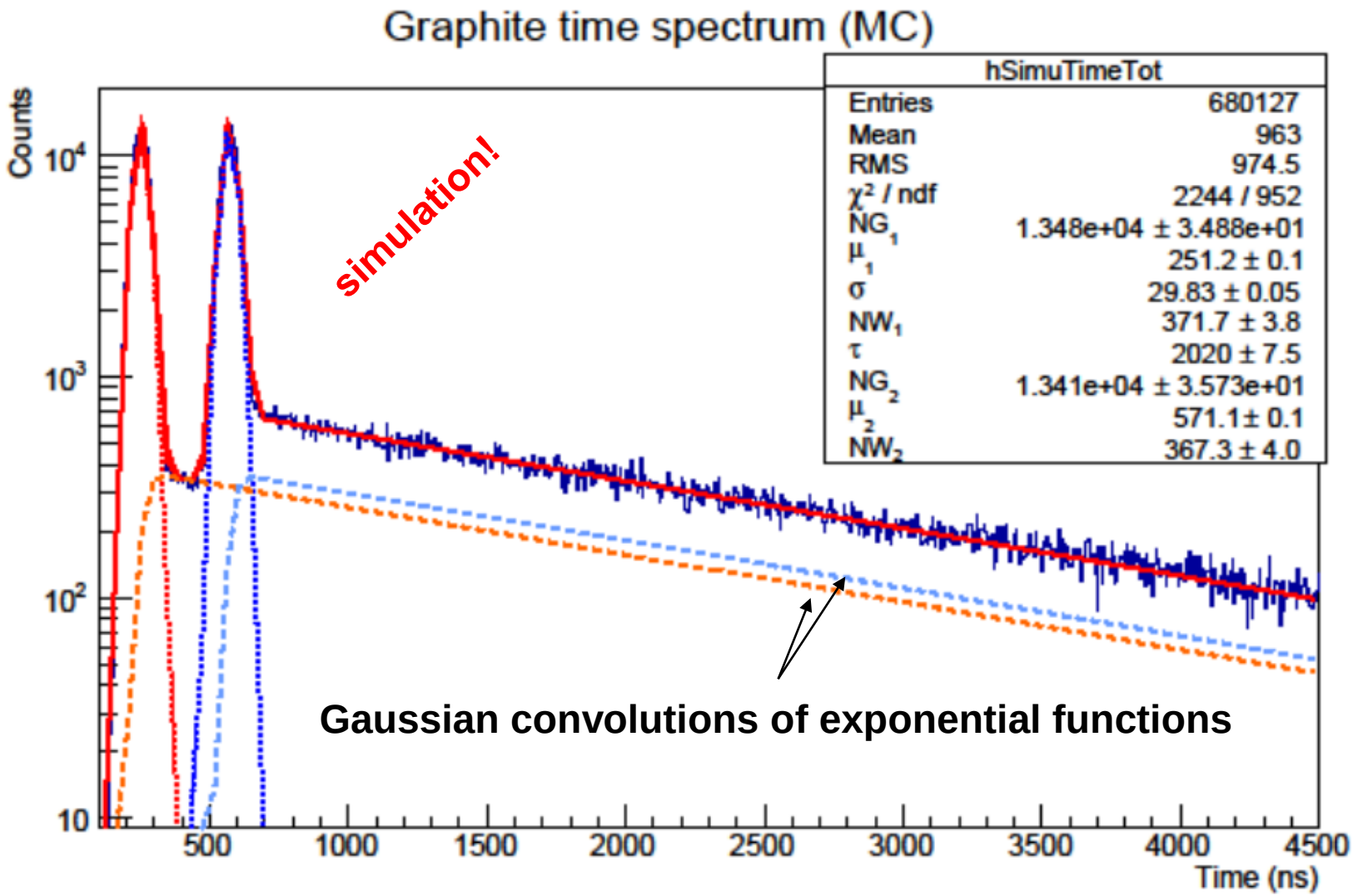
Peaks: prompt emission of X-rays



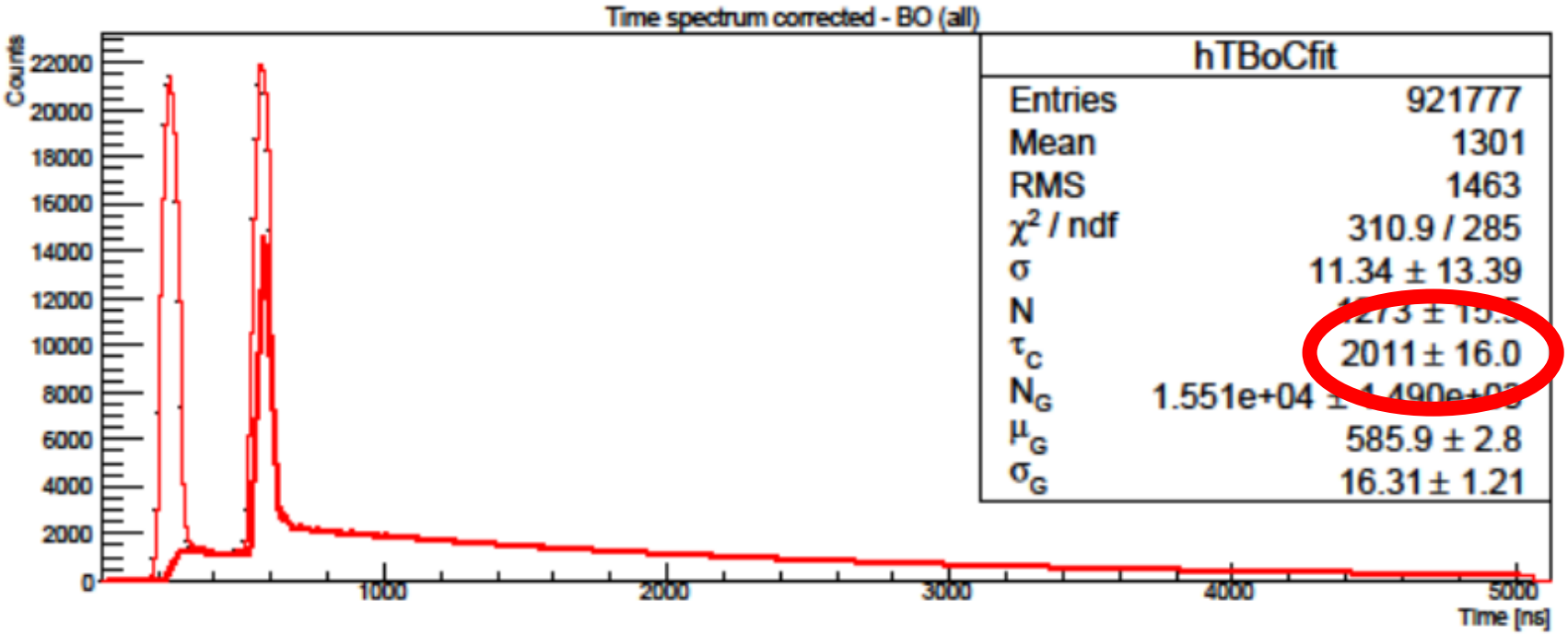
Tails: (bounded) muon live time



Graphite: exp & gaus twice...



2014 data: graphite

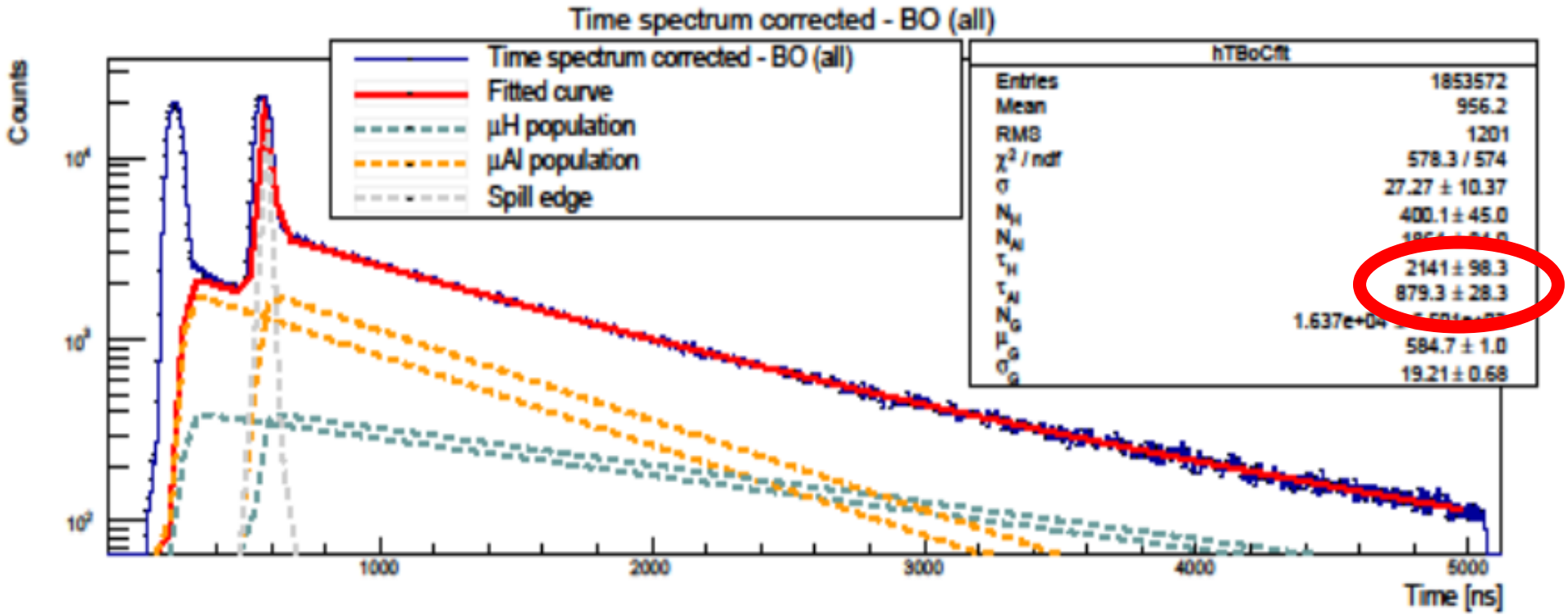


Reference: τ_C = 2026.3 ± 1.5 ns

T. Suzuki, D. F. Measday, and J. P. Roalsvig, "Total nuclear capture rates for negative muons", Phys. Rev. C35/6, 2212-2224, 1987.

Measured: τ_C = 2011 ± 16 ns

2014 data: pure H_2 target

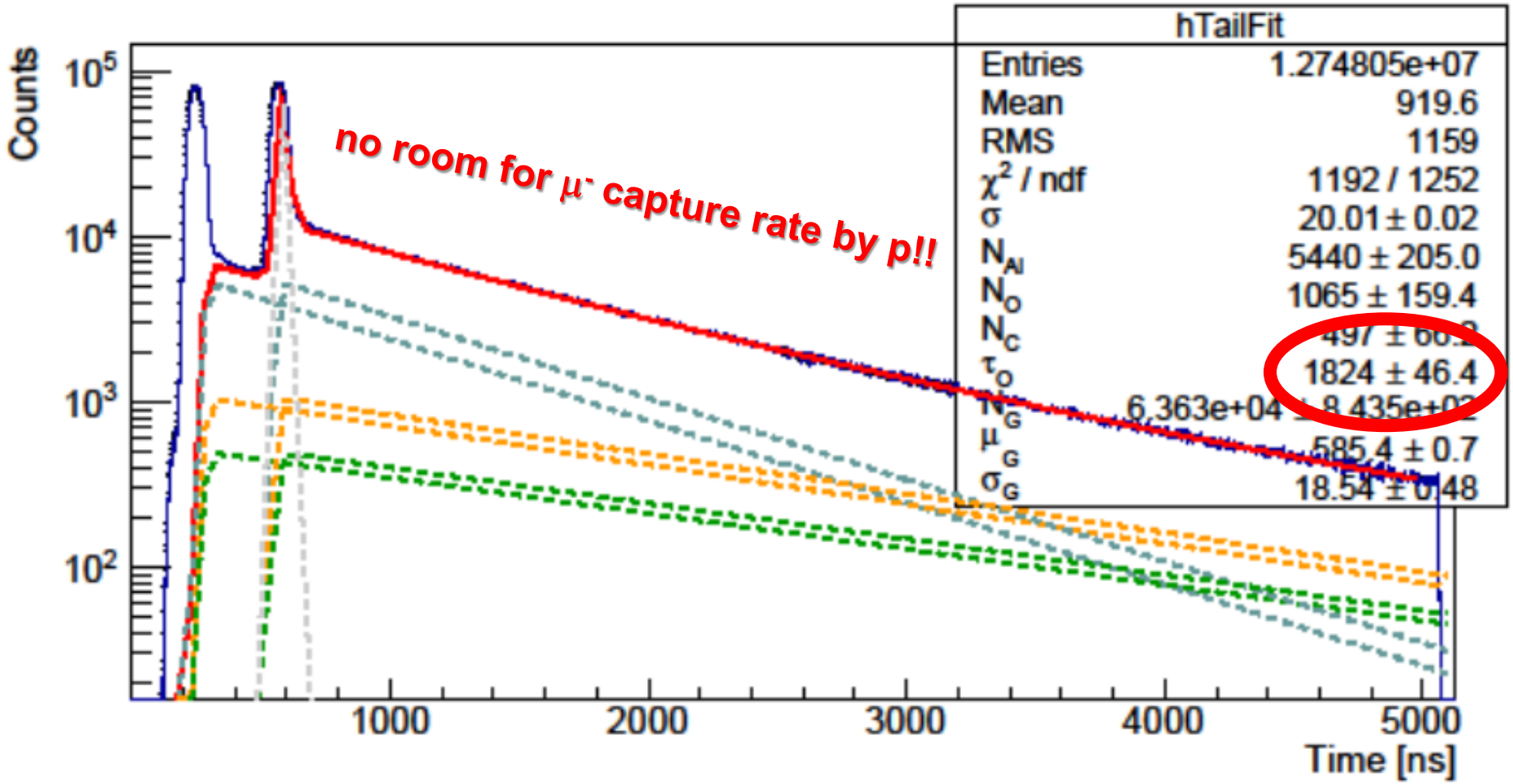


Reference: τ_H = 2194.903 ± 0.066 ns τ_{Al} = 864.0 ± 1.0 ns

T. Suzuki, D. F. Measday, and J. P. Roalsvig, "Total nuclear capture rates for negative muons", Phys. Rev. C35/6, 2212-2224, 1987.

Measured: τ_H = 2141 ± 98 ns τ_{Al} = 879 ± 28 ns

2014 data: H_2CO_2 target... no H!



Reference: τ_O = 1795.4 ± 2.0 ns

T. Suzuki, D. F. Measday, and J. P. Roalsvig, "Total nuclear capture rates for negative muons", Phys. Rev. C35/6, 2212-2224, 1987.

Measured: τ_O = 1824 ± 46 ns

μ transfer, first approximation

No transfer dependence on energy!

Oxygen concentration

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

muon source — muon decay — muon transfer to Oxygen

hence the μO generation rate is given by:

$$dN_{\mu O} = N_{\mu p}c_O\lambda_{pO}dt$$

μ transfer rate to Oxygen only unknown

No transfer dependence on energy!

Oxygen concentration

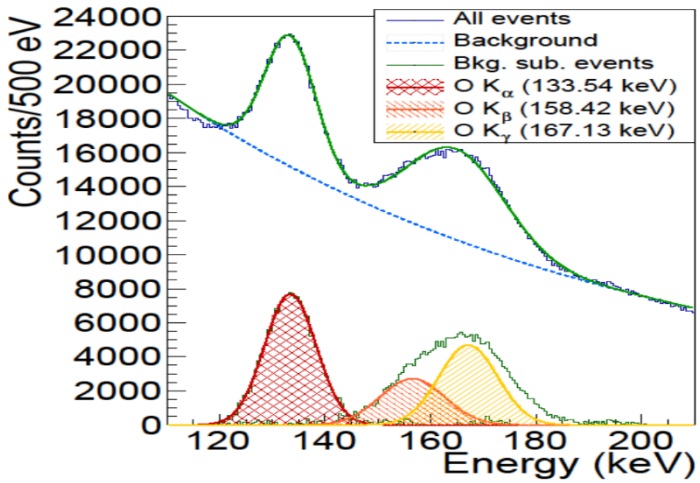
$$dN_{\mu p} = S(t)dt - N_{\mu p}\lambda_{dec}dt - N_{\mu p}c_O\lambda_{pO}dt$$

muon source — muon decay — muon transfer to Oxygen

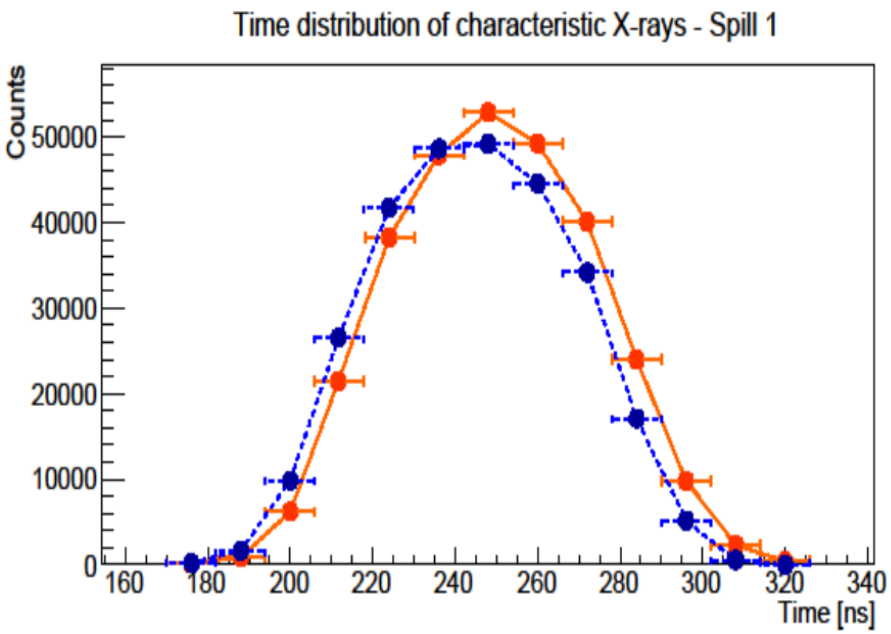
$\lambda_{dec} = 2141$ ns $c_O = 0.0025$ (atomic concentration)

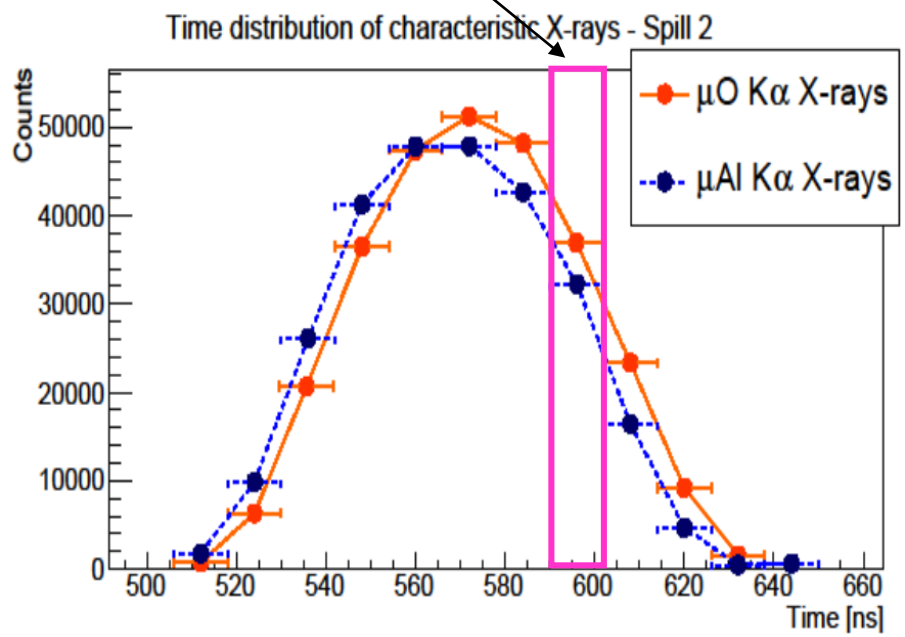
$S(t) = K\, I^{Al}_{K\alpha}(t)$ spill profile given by Aluminium X-rays prompt emission

Al and O X-ray time evolution

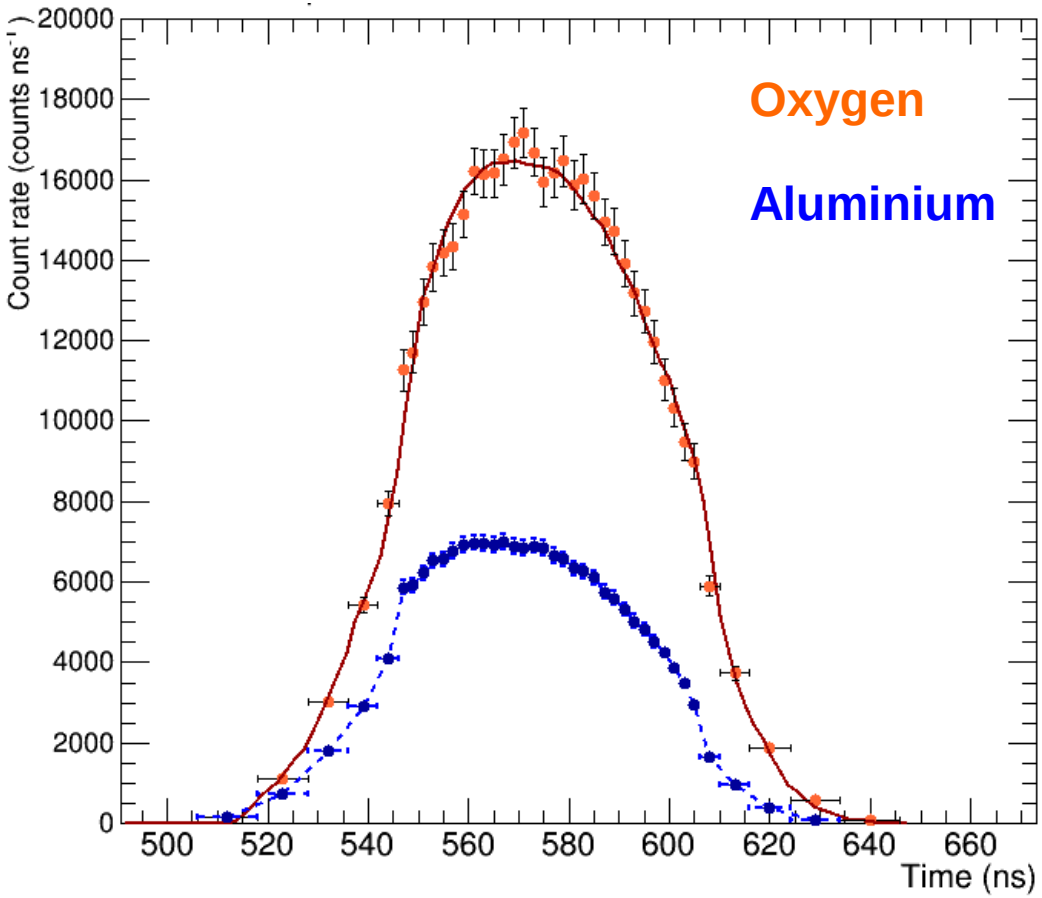


count characteristic X-rays for each time slice





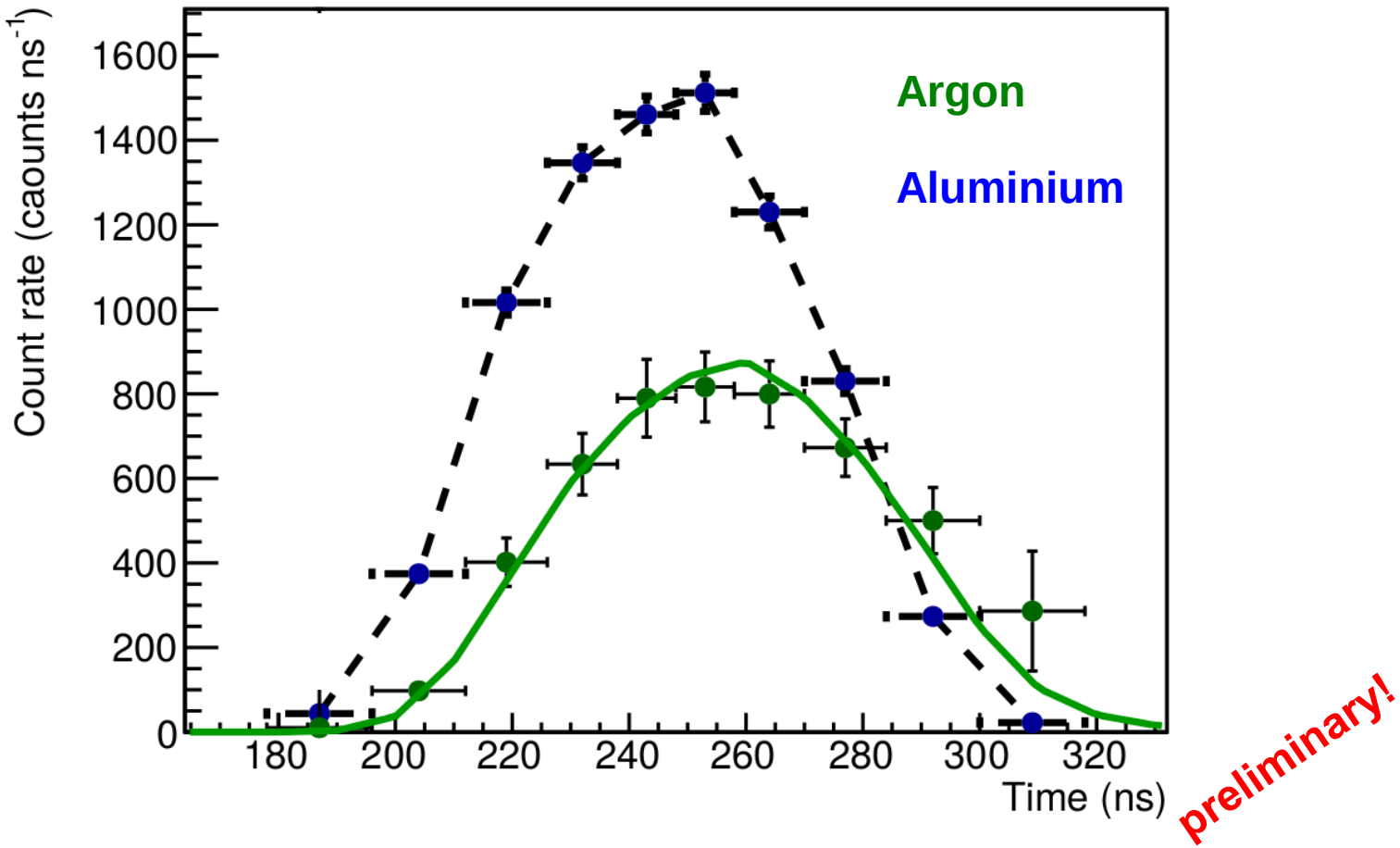
μ transfer to Oxygen



preliminary!

Average muon transfer rate from p to O: $\lambda_{pO} = 172 \pm 6\ ns^{-1}$

μ transfer to Argon



Average muon transfer rate from p to Ar: λ_{pAr} = 162 ± 21 ns^{-1}

Expected μ transfer rate

Oxygen:

$\lambda_{pO} = 85 \pm 2\ ns^{-1}$ **thermic**

$\lambda^*_{pO} = 390\ ^{+5}_{-13}\ ns^{-1}$ **epithermic (0.12 – 0.22 eV)**

A. Werthmüller et al., "Energy dependence of the charge exchange reaction from muonic hydrogen to oxygen", Hyperfine Interactions 116, 1998.

Argon:

$\lambda_{pAr} = 163 \pm 9\ ns^{-1}$ **thermic**

R. Jacot-Guillarmod et al., "Muon transfer from thermalized muonic hydrogen isotopes to argon", Pyhs. Rev. A55/5, 1997.

μ transfer rate, comparison

Oxygen:

$\lambda_{pO} = 85 \pm 2\ ns^{-1}$ **thermic**

$\lambda^*_{pO} = 390\ ^{+5}_{-13}\ ns^{-1}$ **epithermic (0.12 – 0.22 eV)**

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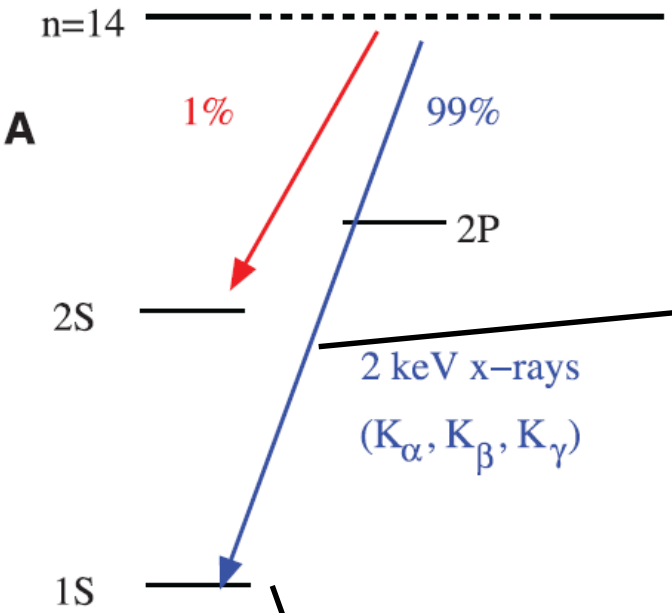
μ fate in our setup (300K, 40 atm)



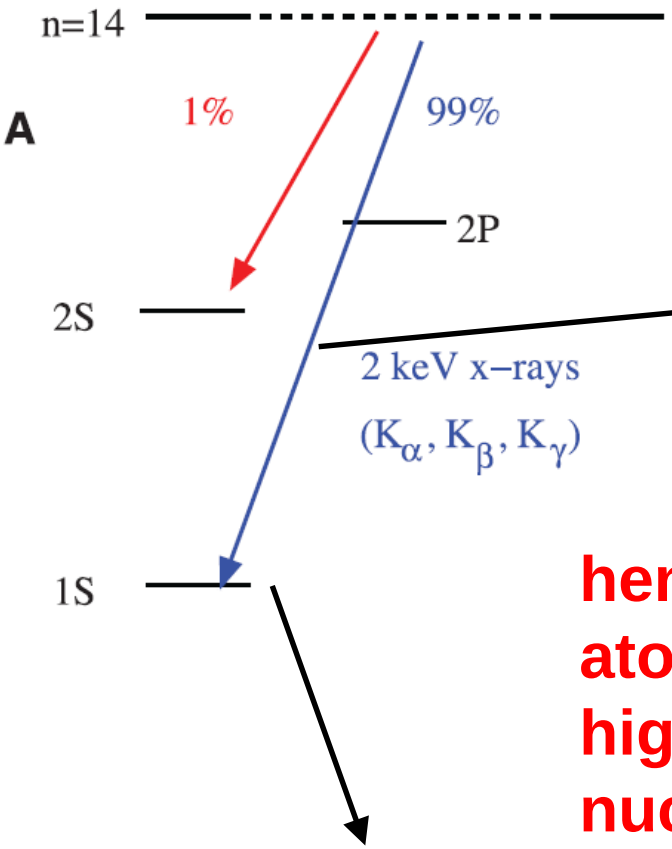
de-exciting from n=14 to ground level:

$E_k \approx O(eV)$

thermalization time O(tens of ns)

3/4 triplets, 1/4 singlets
de-excitation in O(10 ns)

μ fate in our setup (300K, 40 atm)



de-exciting from n=14 to ground level:

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thermalization time O(tens of ns)

hence: transfer of only thermal muonic atoms at ground state – *unless* very high atomic concentrations of high-Z nuclei

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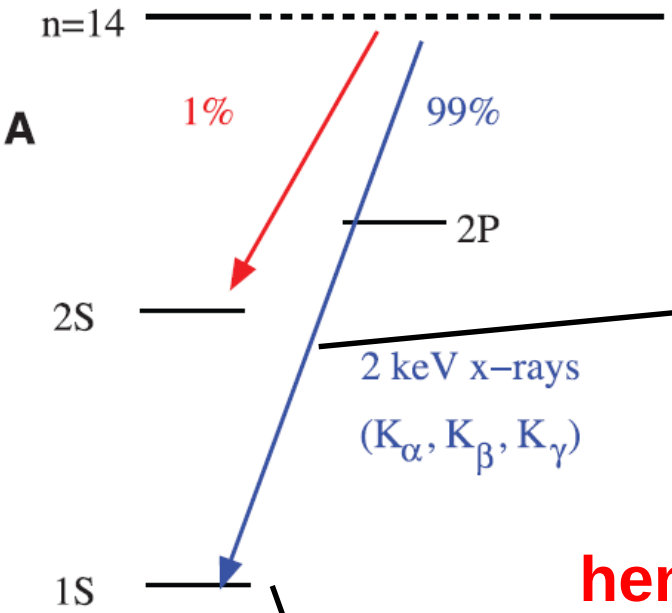
μ fate in our setup (300K, 40 atm)



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$E_k \approx O(eV)$

thermalization time O(tens of ns)

hence: transfer of only thermal muonic atoms at ground state – *unless* very high atomic concentrations of high-Z nuclei

Oxygen 4% w/v, 2.5 per mil

Argon 2% w/v, 0.5 per mil

3/4 triplets, 1/4 singlets
de-excitation in O(10 ns)

Phase 1, results

1) **Double pulsed muon beam ok for the project**
2) **Confirmed high purity of the gas target**
3) **Excellent detection of X-rays and transition lines**
4) **Excellent time resolution**
5) **Observation of muon transfer to higher Z charged nuclei**

Future measurements

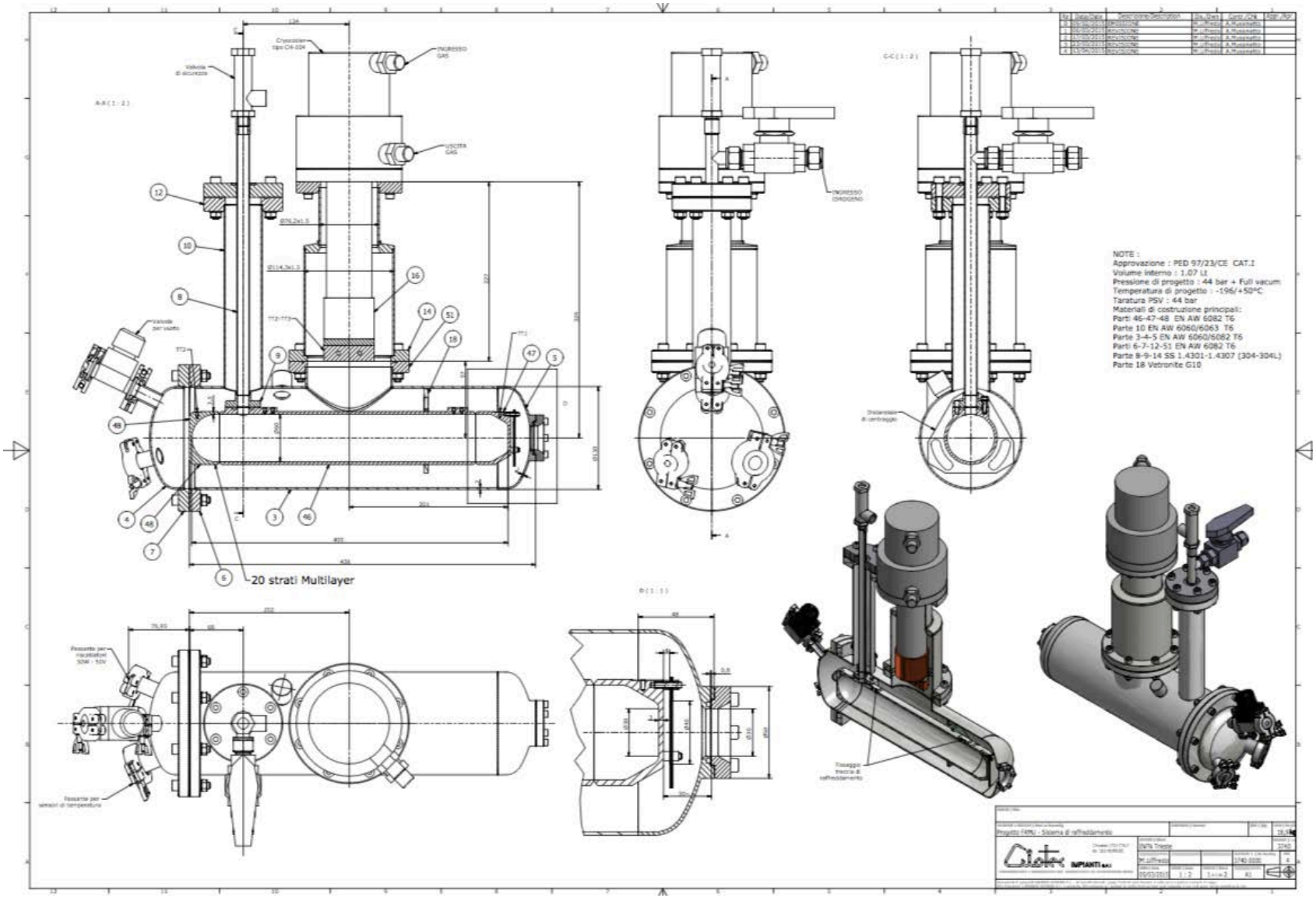
Three phases project

1) **Study the muon beam, test target and detectors, measure transfer rate (@ constant conditions of PTV) – 2014 beam test (results in the next slides);**

2) **Find the best gas mixture, temperature and pressure in order to observe neatly and measure the transfer rate energy dependence, no laser – 2015 beam test (December 7th - 16th) & 2016 February (one week beam);**

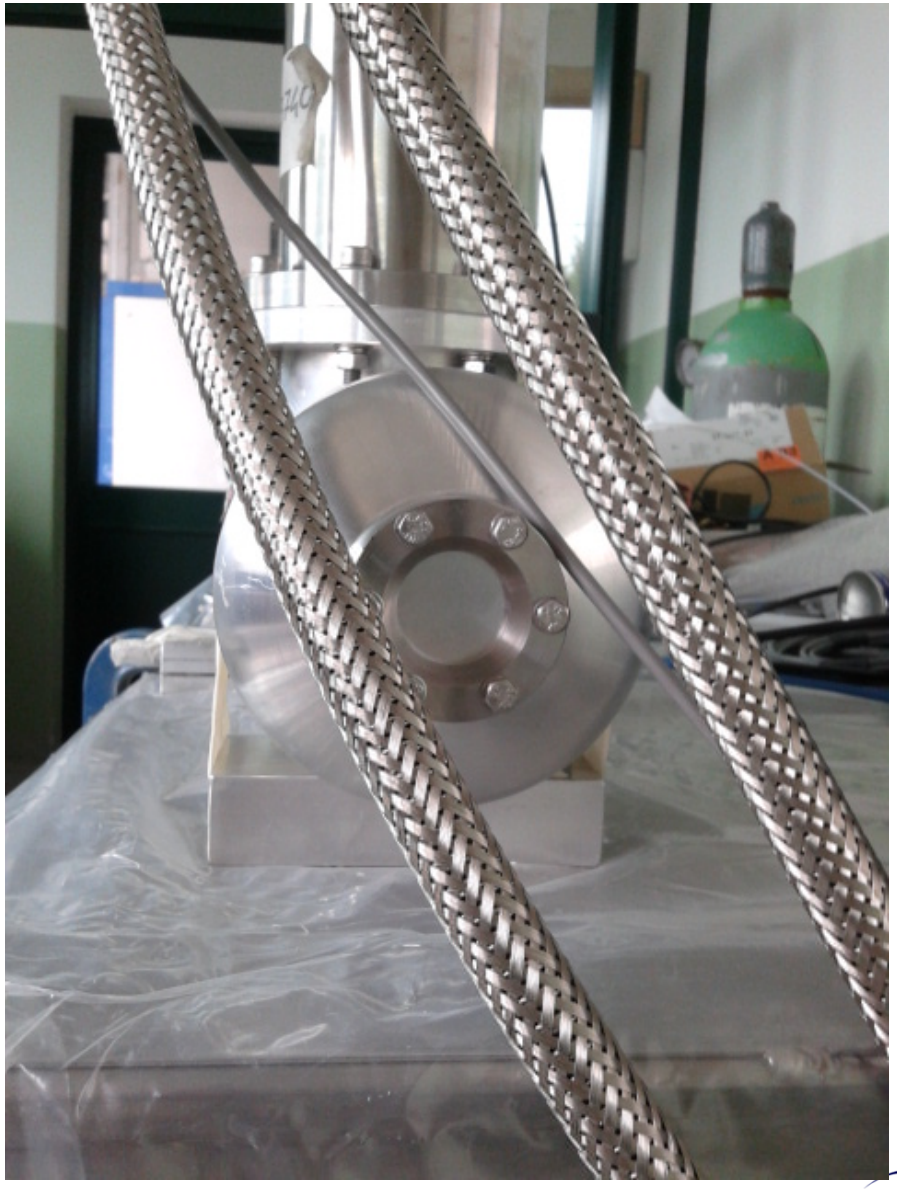
3) **Full working setup with laser, determination of proton Zemach radius – foreseen in 2017.**

New cryogenic target

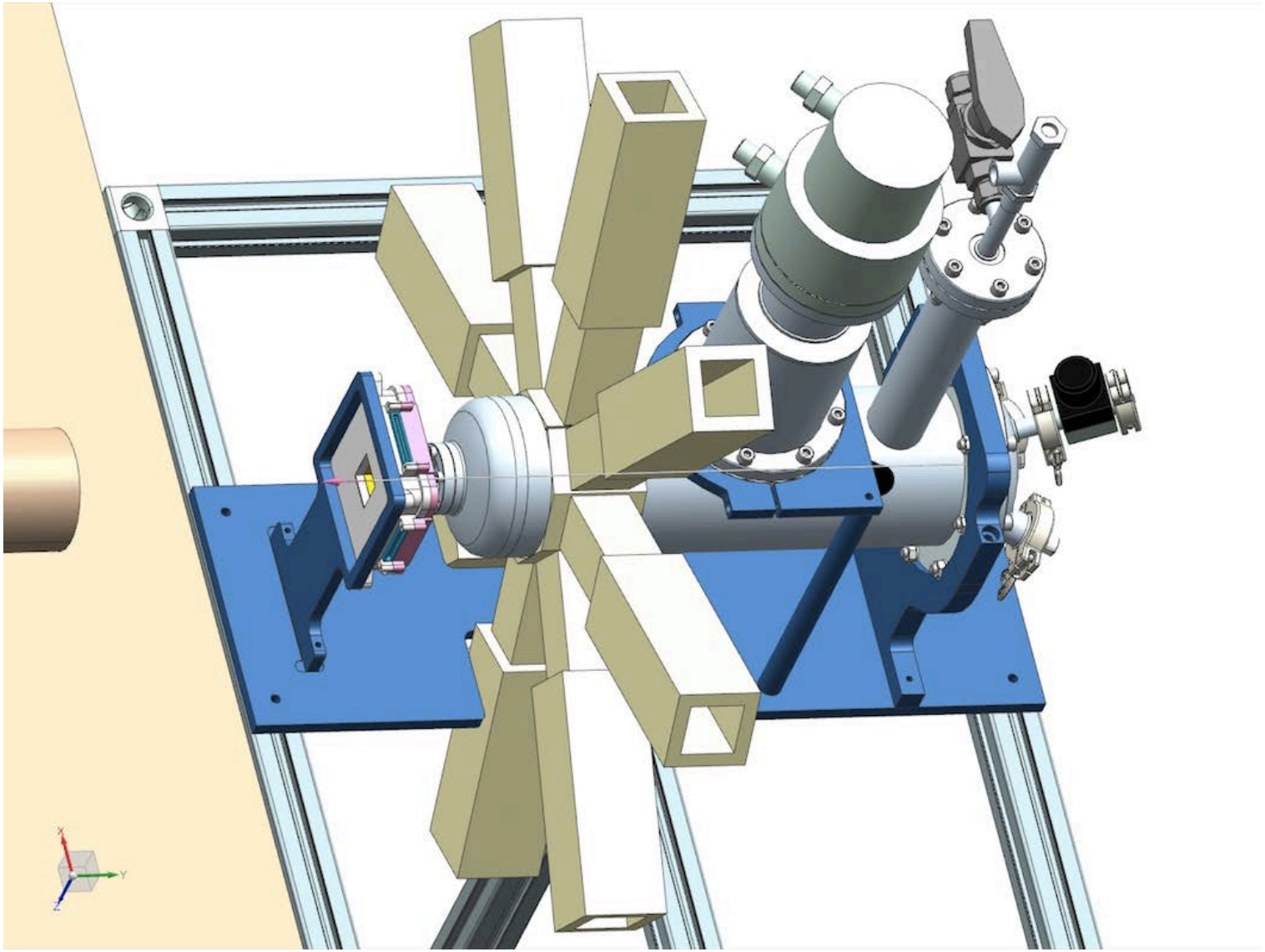


High pressure vessel

New setup in the lab



Star-shaped support for detectors



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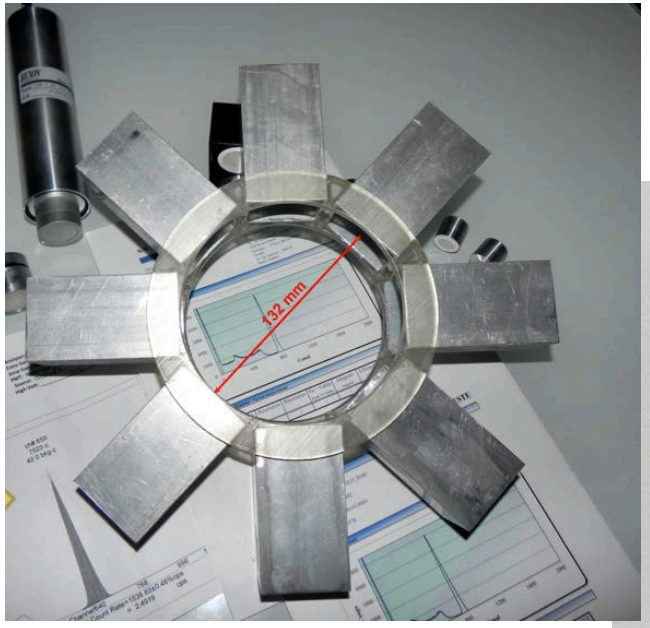

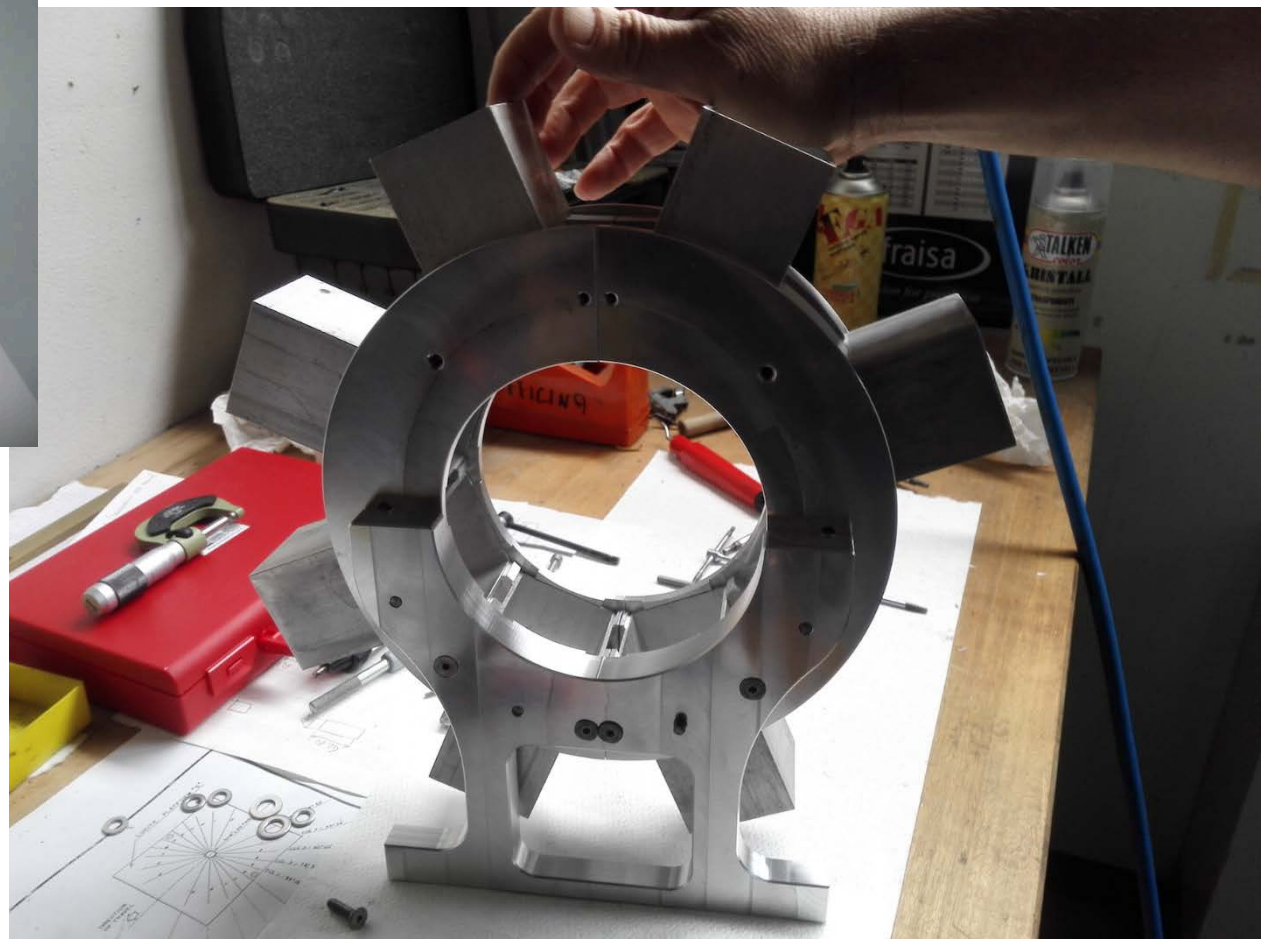

Time plan

- **H_2 + 6** high-Z gas mixtures: O_2, Ar, Ne, CH_2, C_2H_4, CO_2
- 6 temperatures x 3 concentrations for **each** gas mixture at **40 bars**
- run at **15 bars** for H_2O_2 (to check previous results on muon transfer)
- 7 different targets => **7 x 18 = 126** different measurements

Summary

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

- **Three phases project, first phase results:**
  - **beam and detectors characterization**
  - **excellent energy and time resolution capabilities**
  - **measurement of the average transfer rate for O and Ar**

- **New phase started and test coming very soon**

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Thanks!