The X-rays detecting system of the FAMU Experiment for the measurement of the muon transfer rate to carbon

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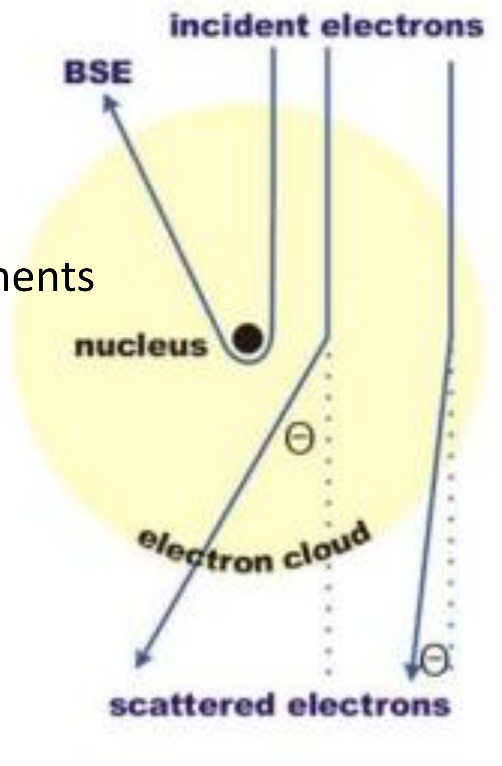
Outline

- Motivation
- The FAMU Experiment
- The X-rays detecting system
- Performances
- Measurement of the transfer rate from μp to carbon
- Conclusions

FAMU: Fisica degli Atomi Muonici (Physics with muonic atoms)

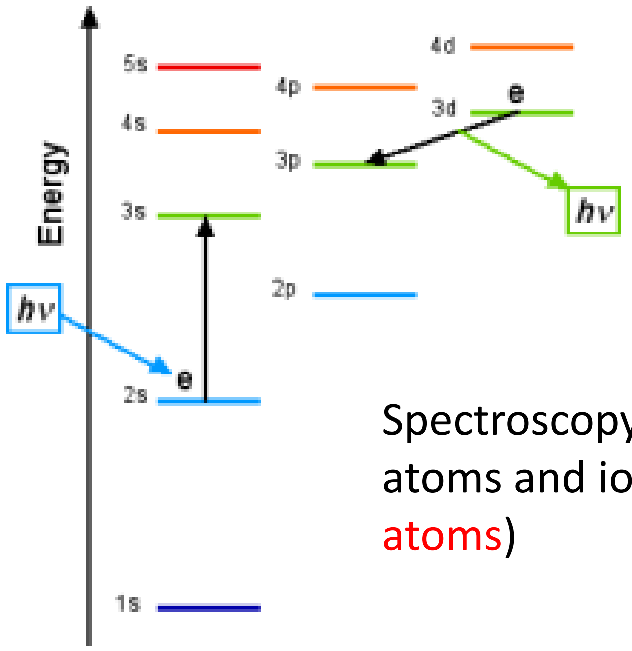
Fundamental physics: the properties of the proton

scattering (electron experiments and elastic muon-proton)



FAMU target: hyperfine splitting (HFS) of muonic hydrogen ground level

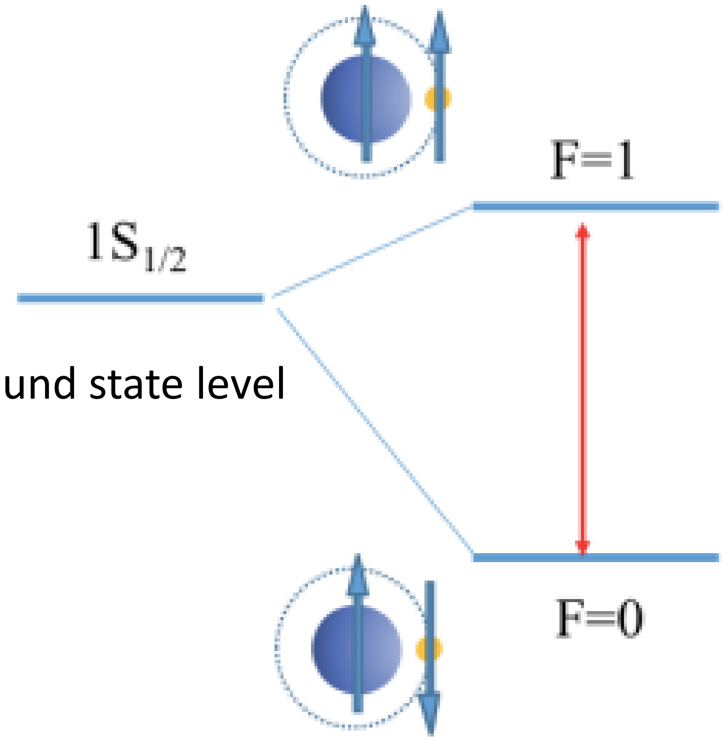
the Zemach radius of the proton



Spectroscopy (electronic atoms and ions, exotic atoms)

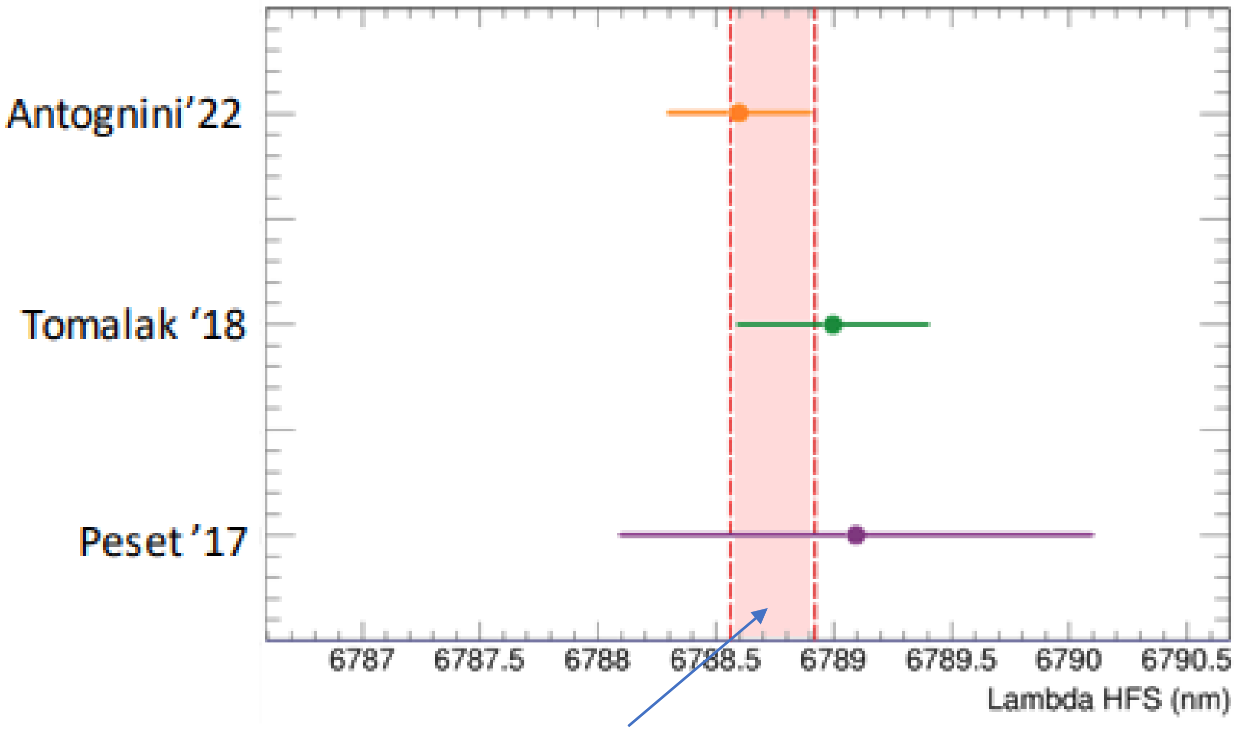
FAMU: Fisica degli Atomi Muonici (Physics with muonic atoms)

- HFS comes from the interaction between the magnetic moment of the muon and the proton
- This enlights the magnetic structre of the proton



Ground state level

Most recent predictions

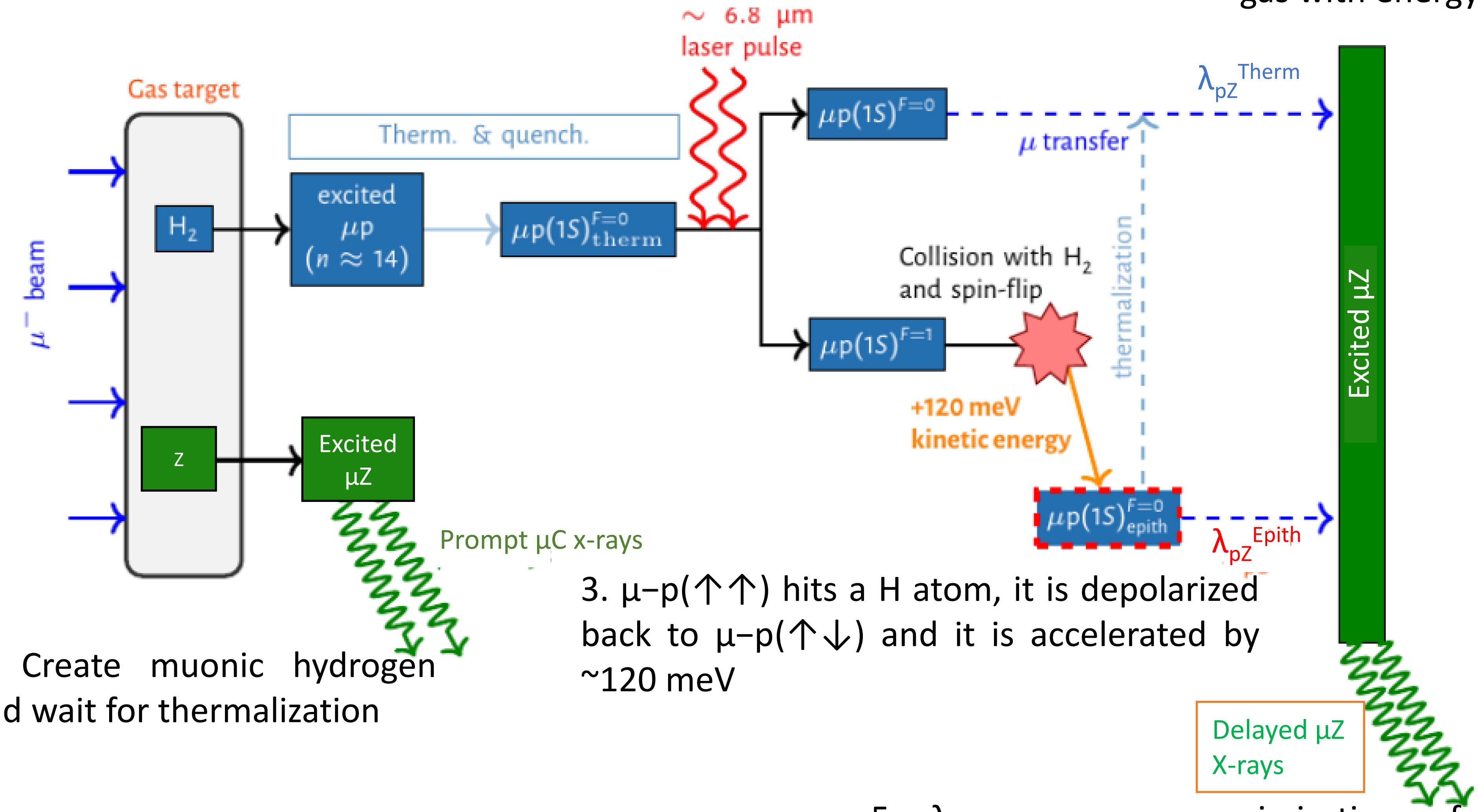


Target range of 20 days of data taking (0.36 nm centered in the weighted mean of the 3 measurements)

FAMU method and workflow

2. Shoot laser at resonance of μp from 1^1S_0 to 1^3S_1: μ−p(↑↓) → μ−p(↑↑)

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

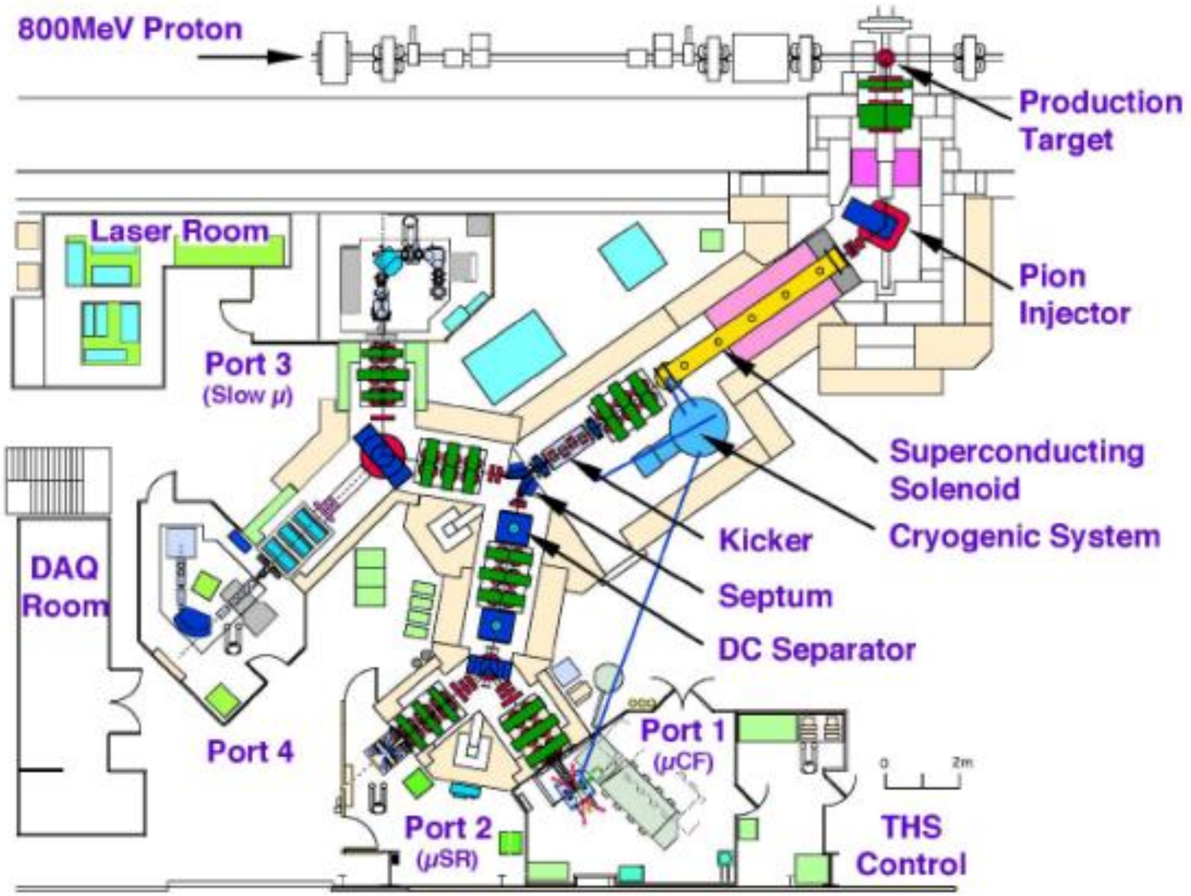


3. μ−p(↑↑) hits a H atom, it is depolarized back to μ−p(↑↓) and it is accelerated by ~120 meV

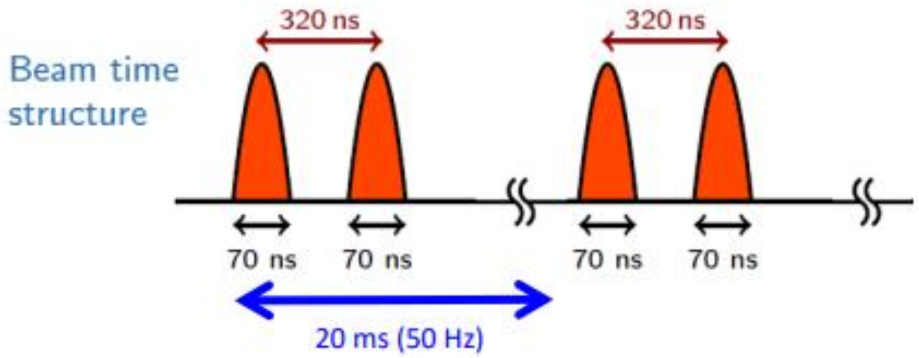
1. Create muonic hydrogen and wait for thermalization

5. λ_0 resonance: maximization of the time distribution of μ- transferred events

RIKEN RAL facility



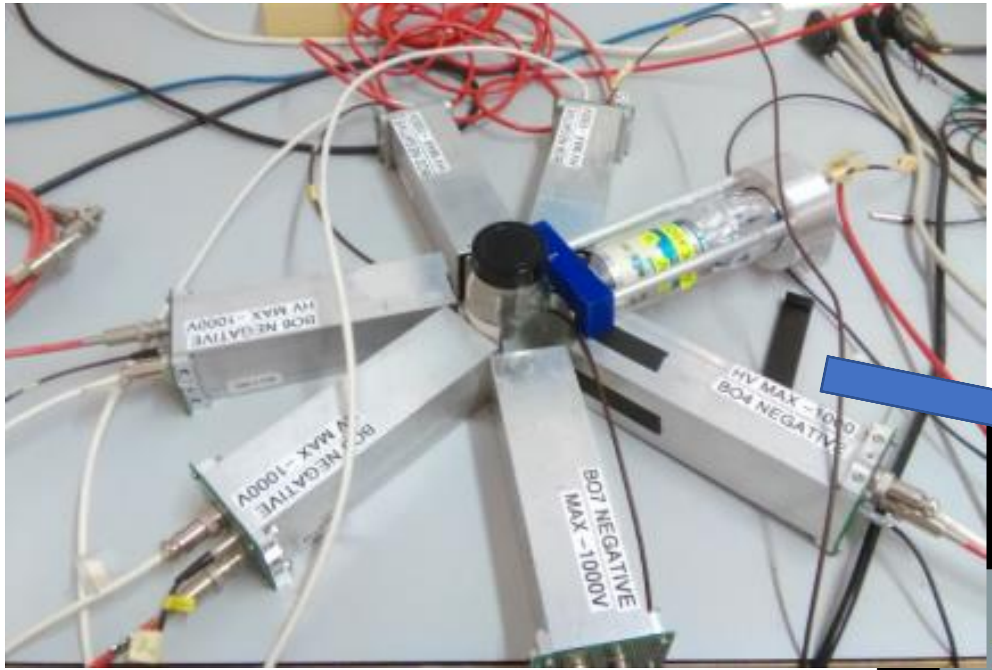
UK - Didcot



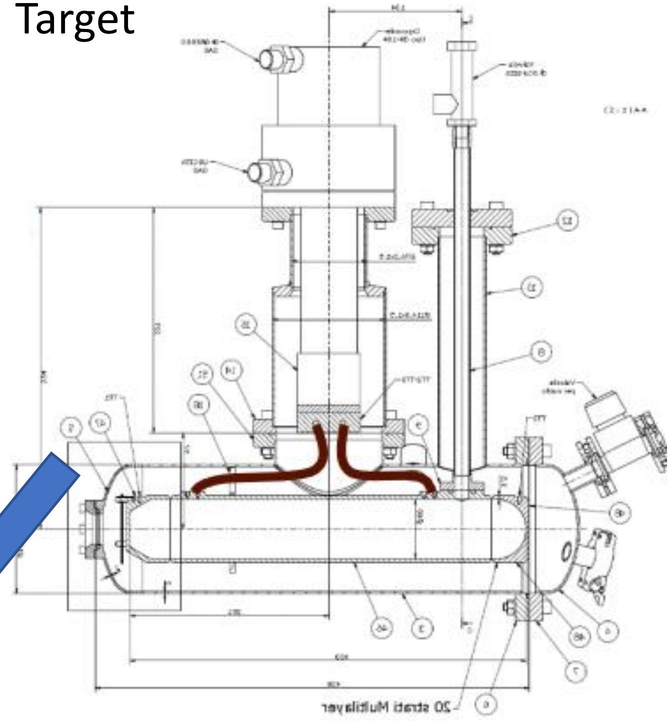
Rutherford Appleton Laboratory – Oxfordshire UK
The brightest pulsed muon beam facility in the world

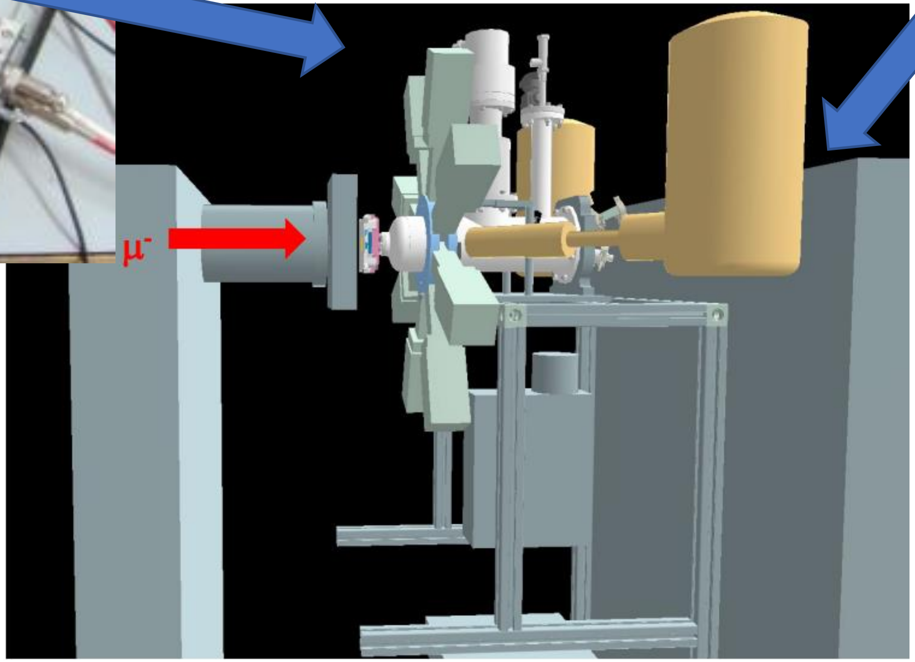
Experimental setup

LaBr3(Ce): fast timing X-rays detectors



Target





Gas: H_2 + CH_4 (0.3%) at different temperatures

7 detectors are available,
placed around the gas target

- read by PMTs
- fast electronics and fast digital processing signal available
- 360° covered

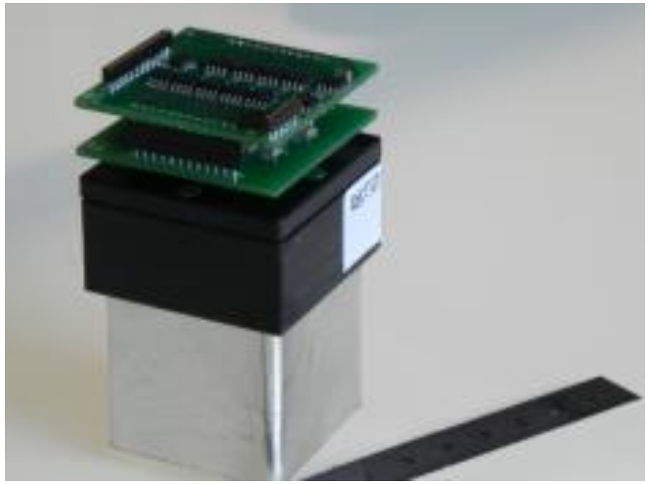
The X-rays detection system

LaBr3(Ce): fast timing X-rays detectors

- up to 3-5% energy resolution (multiple X-rays and electrons are generated due to the muon interaction with matter);
- up to 500 ps timing resolution (the transfer mechanism from μ hydrogen to the carbon occurs in hundreds of nanoseconds);
- small signal duration (to avoid pile-up);
- to be as linear as possible in pulsed high rate conditions;
- high efficiency in the 50-200 keV energy range (signal region);
- cover a large solid angle (X-rays emission by the target is isotropic);
- good over time stability.

Photomultiplier (PMT) guarantees the timing specification preserving the energy resolution and it can be used in high rate applications.

2.5 x 2.5 cm (diameter x thickness)
cylindrical shape

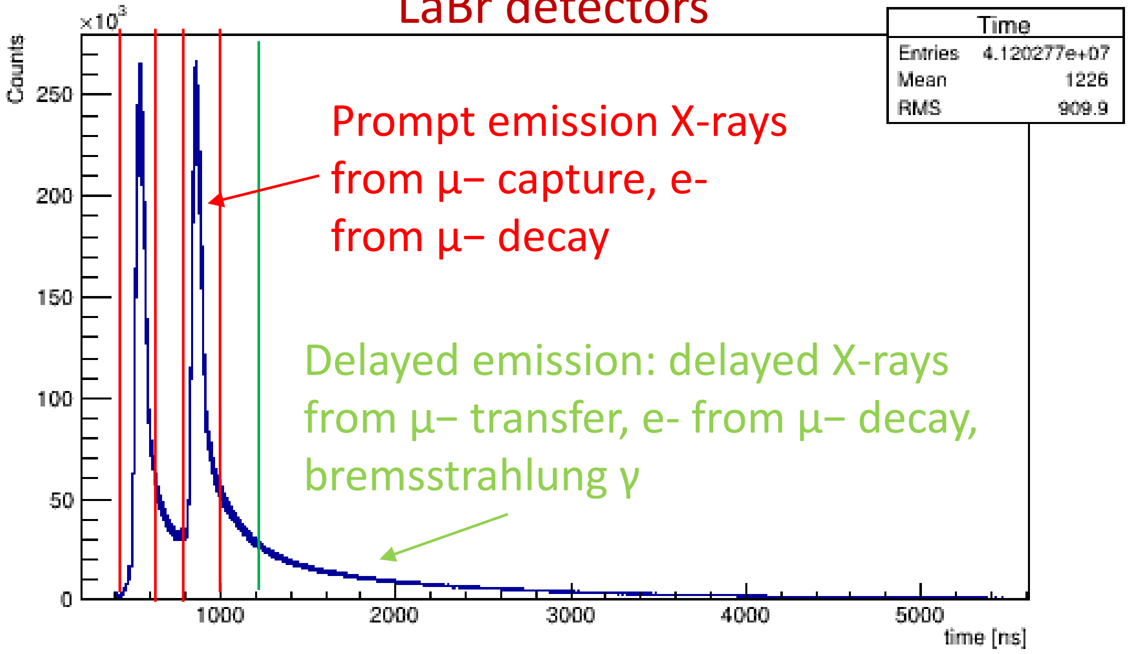


crystals coupled with HAMAMATSU R11265U-200 PMT

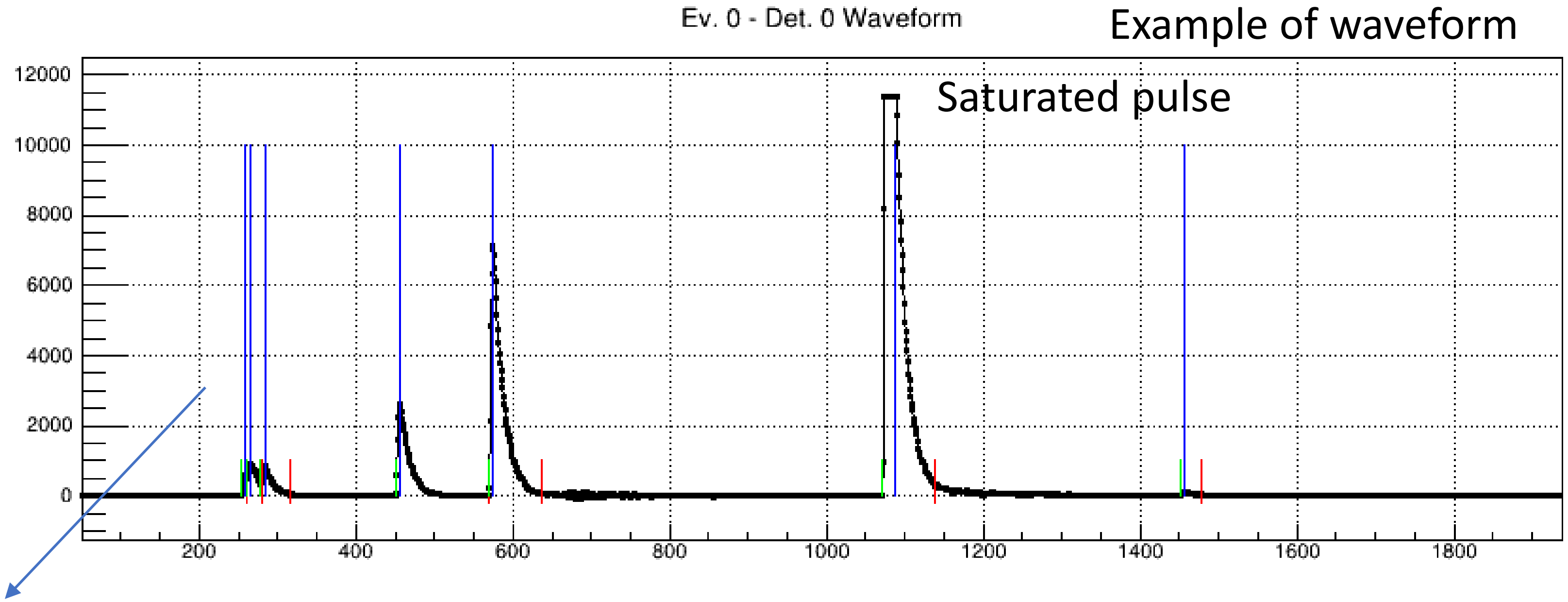
Acquisition method

At each trigger we acquire a window of 10 microsecond
Produce μp's and wait for their thermalization (about 150 ns)
Study the time evolution of Carbon X rays in the delayed region for extracting the transfer rate to carbon

LaBr detectors



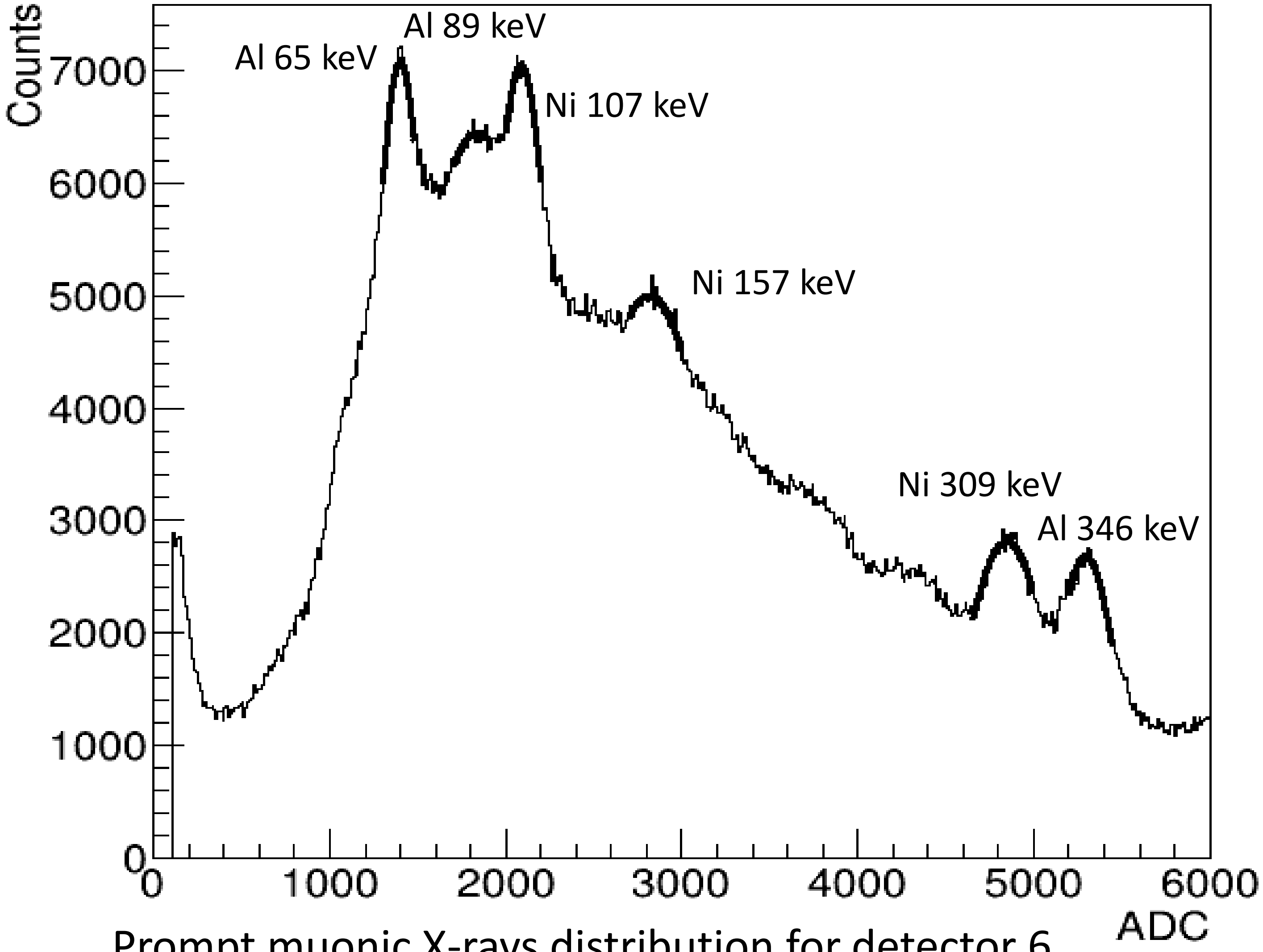
Detectors waveform



For the signal amplitude detector signals are fitted and the preliminary cut is done through the study of the derivative of the waveform

- Rise time is very fast equal to 10 ns
- Decay time is around 30 ns
- Baseline is constant in time and no relevant background is present
- No undershoot is present
- Pile-up is solved modeling the single pulses with Landau functions

Prompt muonic X-rays distribution



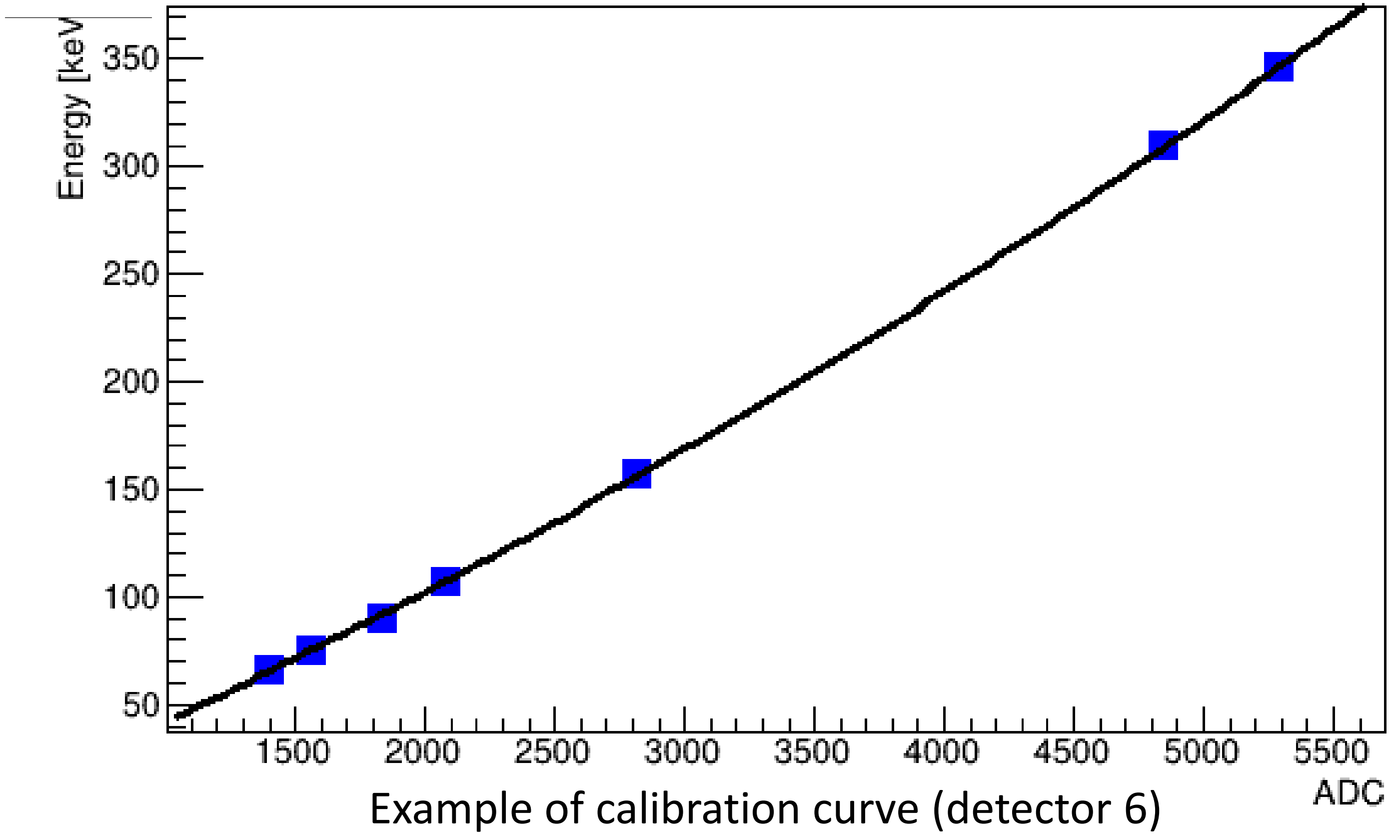
Prompt muonic X-rays distribution for detector 6

- Selection cuts were applied to clean the sample
- 6 emission lines are clearly visible
- Aluminium and Nichel are well evident and used for the detector calibration
- The single fit is converging in all the detectors
- Resolution ranges between 10 and 30%
- Increasing slope at low energy is due to the muon spill
- Background is mainly due to Bremsstrahlung

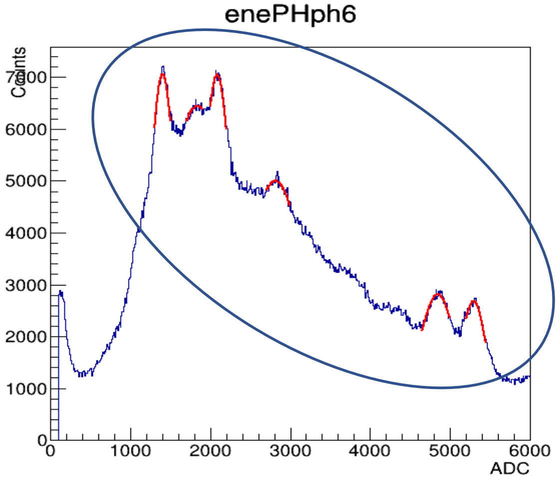
Energy calibration curve

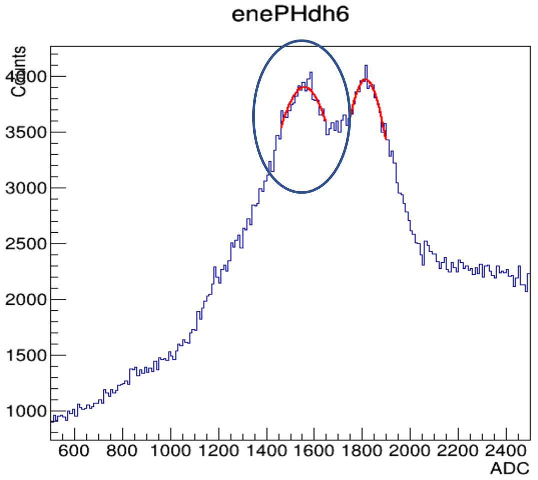
- Single fit applied on prompt and delayed signal, error has been estimated as the variation of the mean value of the fit in different ADC ranges
- Higher density of points in our region of interest

LaBr6



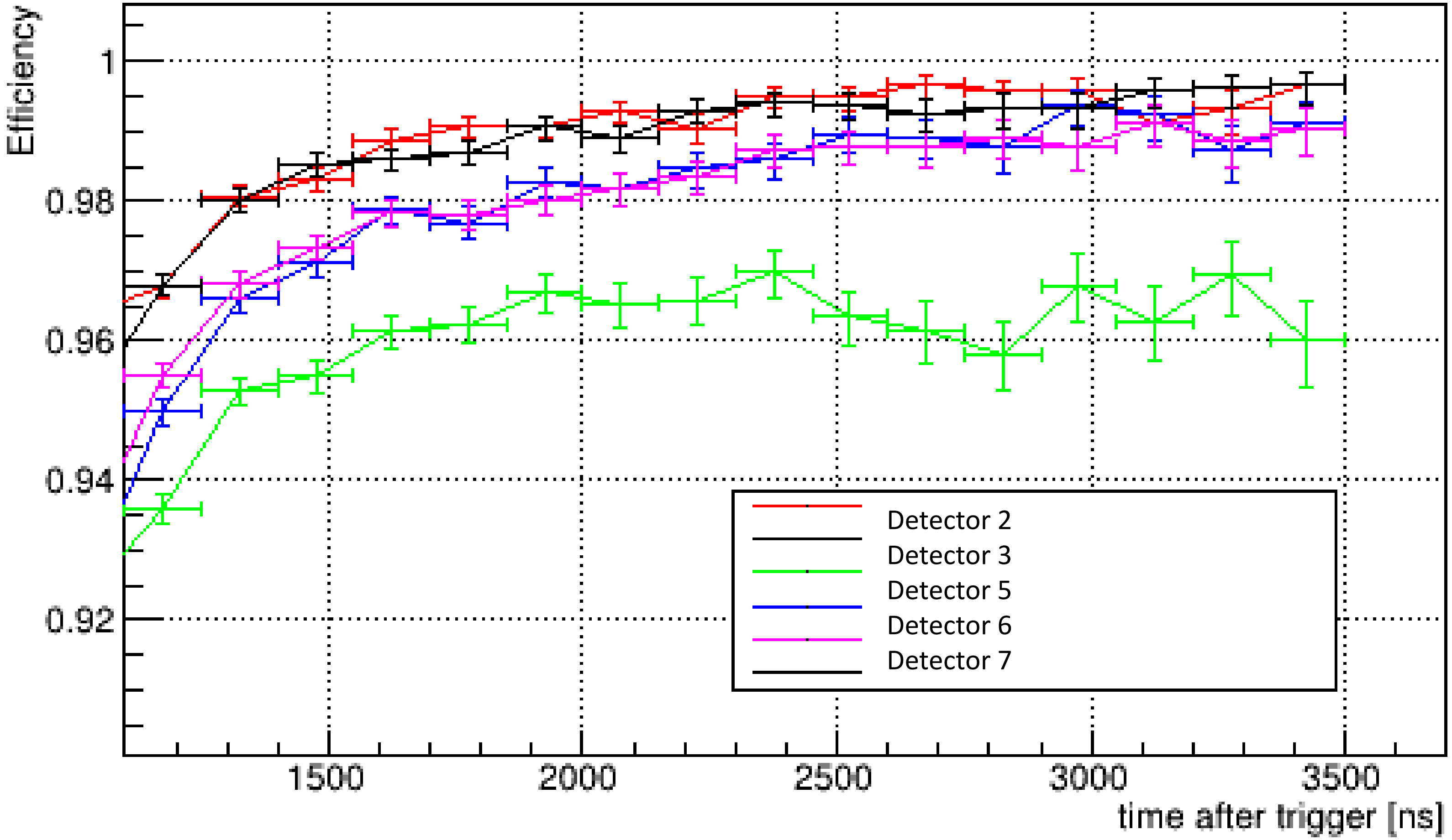
Example of calibration curve (detector 6)





Efficiency

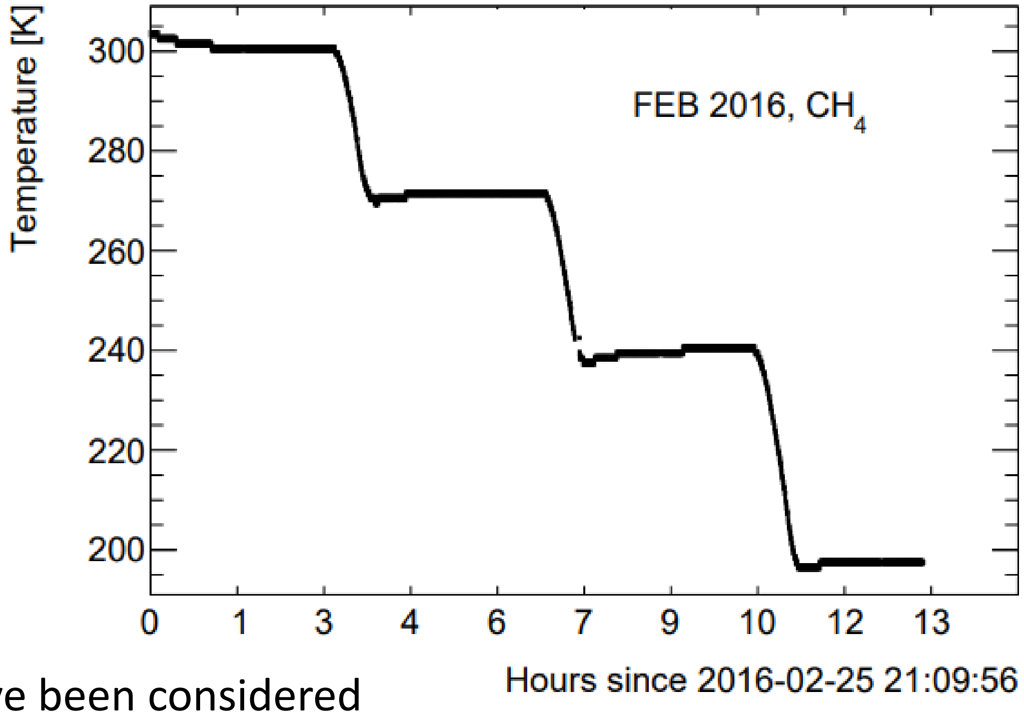
Efficiency always higher than 95% for all detectors in the time region selected for extracting the transfer rate to carbon



Muon transfer rate to carbon

Transfer rate measured with different temperatures

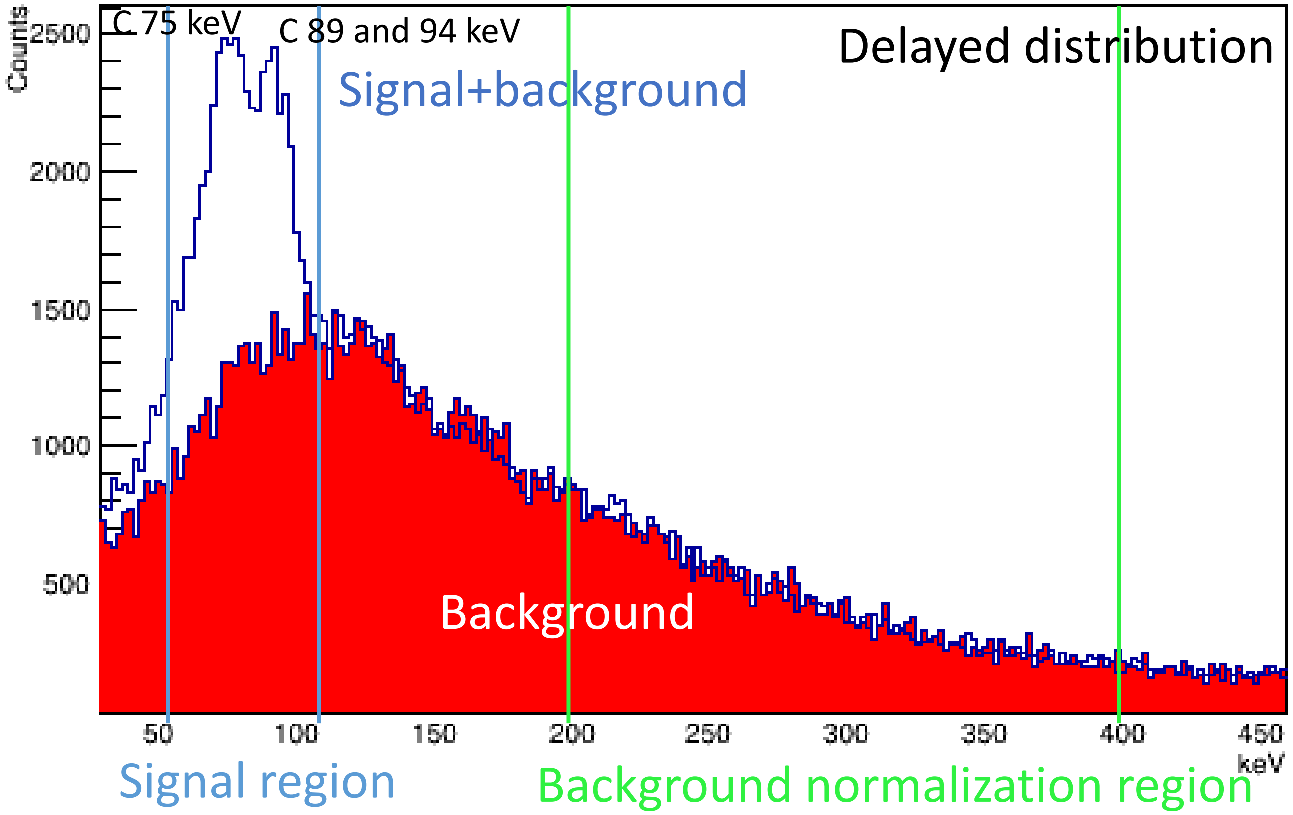
- Hydrogen and CH_4 gas mixture, with a nominal concentration of CH_4 equal to 0.3%
- Gradual cooling down from room temperature (300 K) to 197 K
- 197 K is the lowest limit in order to avoid condensation



4 temperatures have been considered

Example of signal and background at 197 K

Example from all detectors in a time between 1552 and 1691 ns after trigger



- Signal is well visible confirming the high performances of the X-rays detecting system
- Distributions are corrected by efficiency and livetime
- Resolution of the k_α ranges between 25% and 40% (acceptable considering the low energy region and similar to the low energy prompt ones)
- Background is estimated from the hydrogen only sample

Carbon X-rays per time interval

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

μ decay rate (p-bound)

$$\lambda_{dis} = \lambda_0 + \varphi(c_p\lambda_{pp\mu} + c_D\lambda_{pD} + c_C\lambda_{pC})$$

transfer rate to carbon

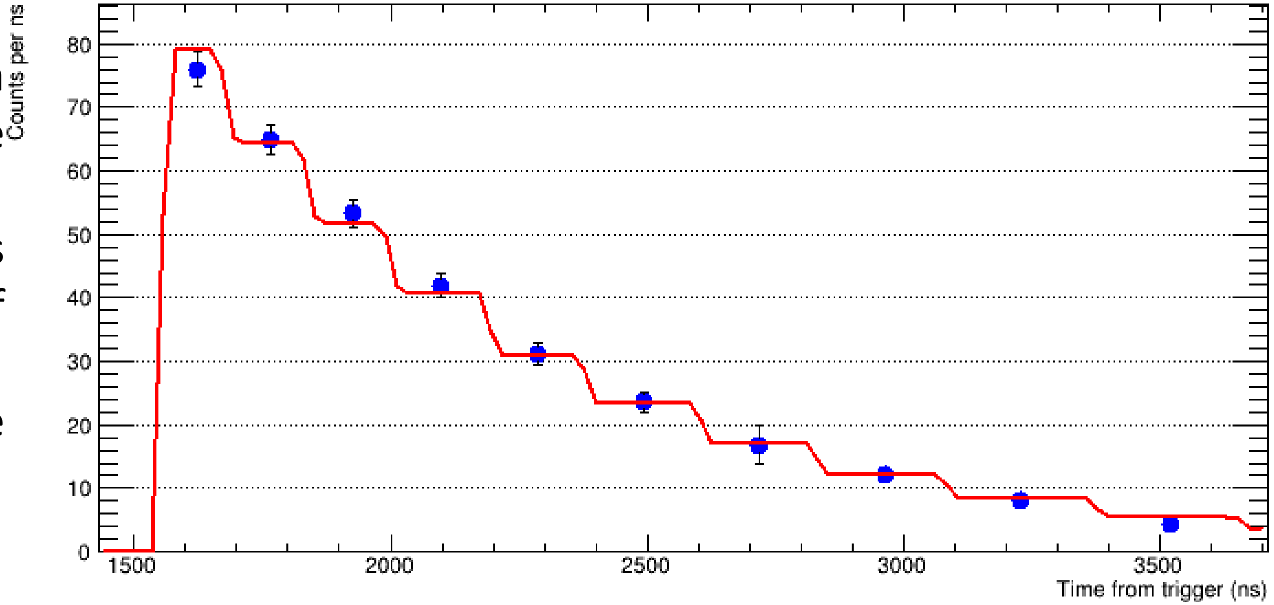
Gas density in LHD units
(4.25*10^{22} atoms cm^3)

Rate of formation of ppμ

μ transfer rate to deuterium

Measurement at 300 K

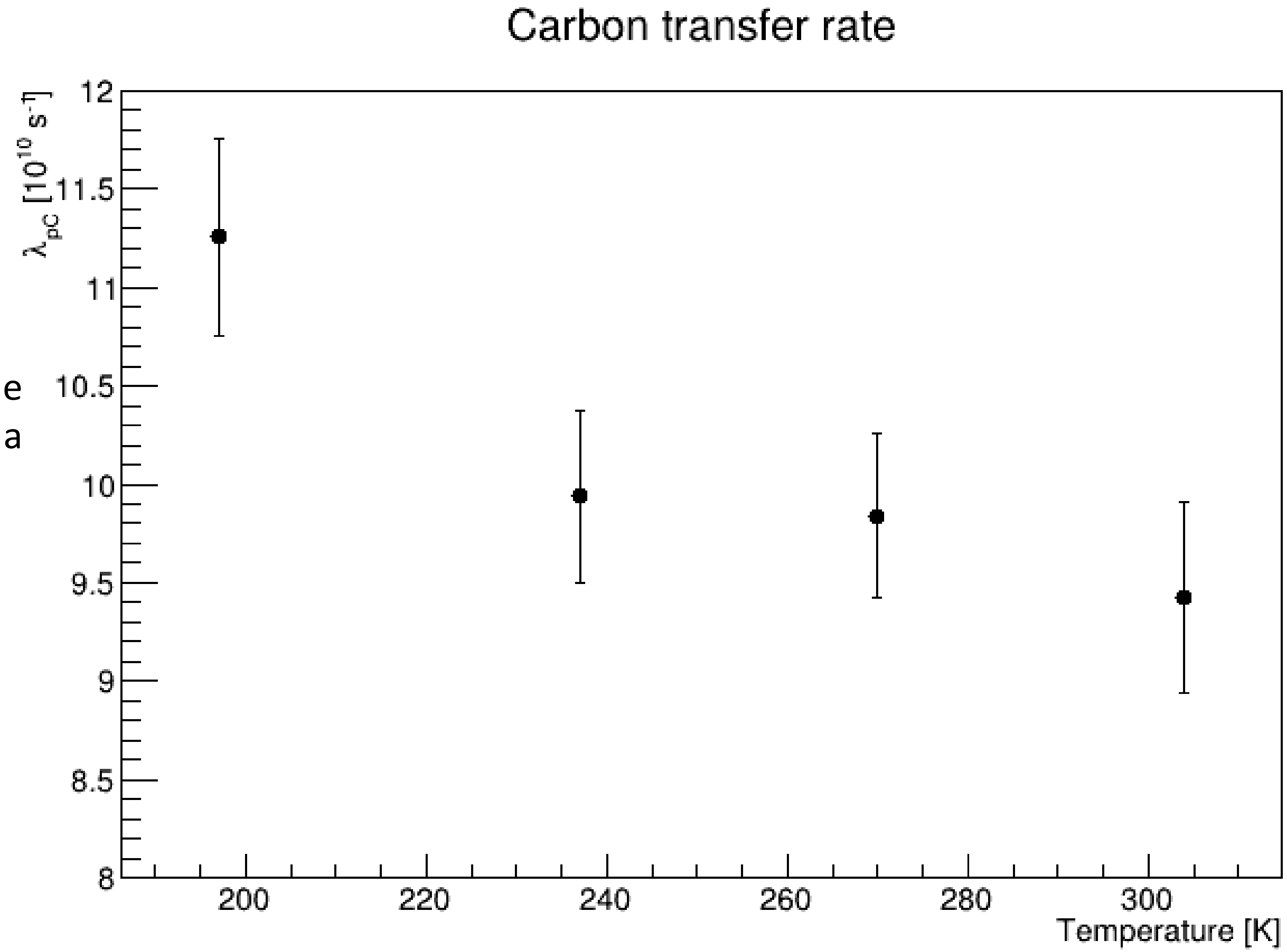
- Also a linear binning with a different number of bins have been tested
- Consistency check of results show that the optimal choice of time threshold is 1500
- The best starting time value have been defined as around 1500 ns



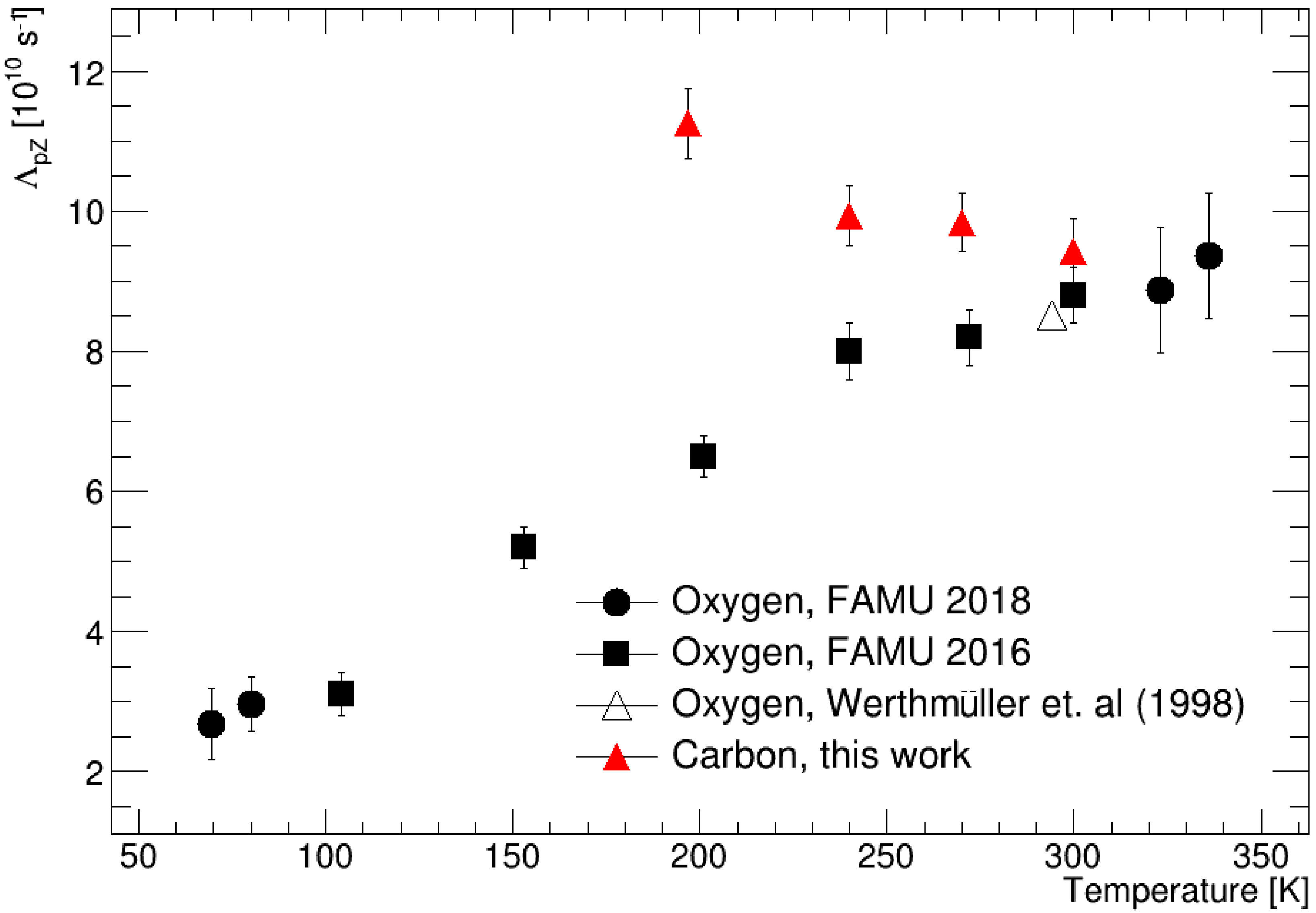
chi/ndf=0.495639

Carbon transfer rate as a function of temperature

Results are compatible with a constant and a linear fit.



Carbon and oxygen transfer rate temperature



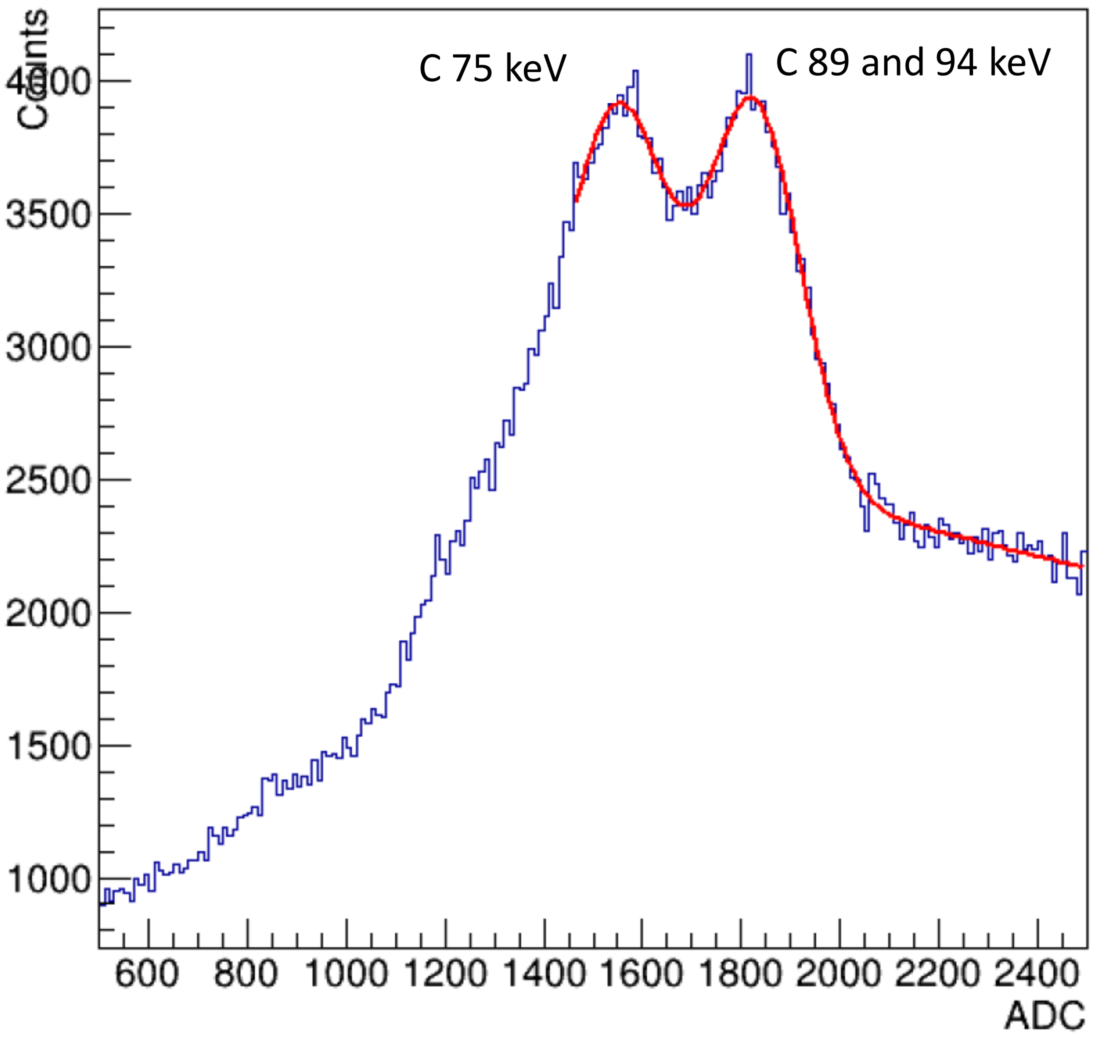
Conclusions

- This recent result confirms the fitness of the detection system in the pulsed intense muon beam;
- Prompt and delayed signals are clear with enough accuracy and precision to be suitable for a fine calibration
- The LaBr technology show an efficiency higher than 95% and a livetime higher than 99% in the whole signal region
- The detector high performances let the measurement of the carbon signal well evident above the background
- This allows us to measure the carbon transfer rate and to compare it with the previous results for oxygen;
- New Data taking on progress with laser and an improvement of this technology for the determination of the HF splitting.

Back-up

Energy distribution

Delayed distribution for detector 6



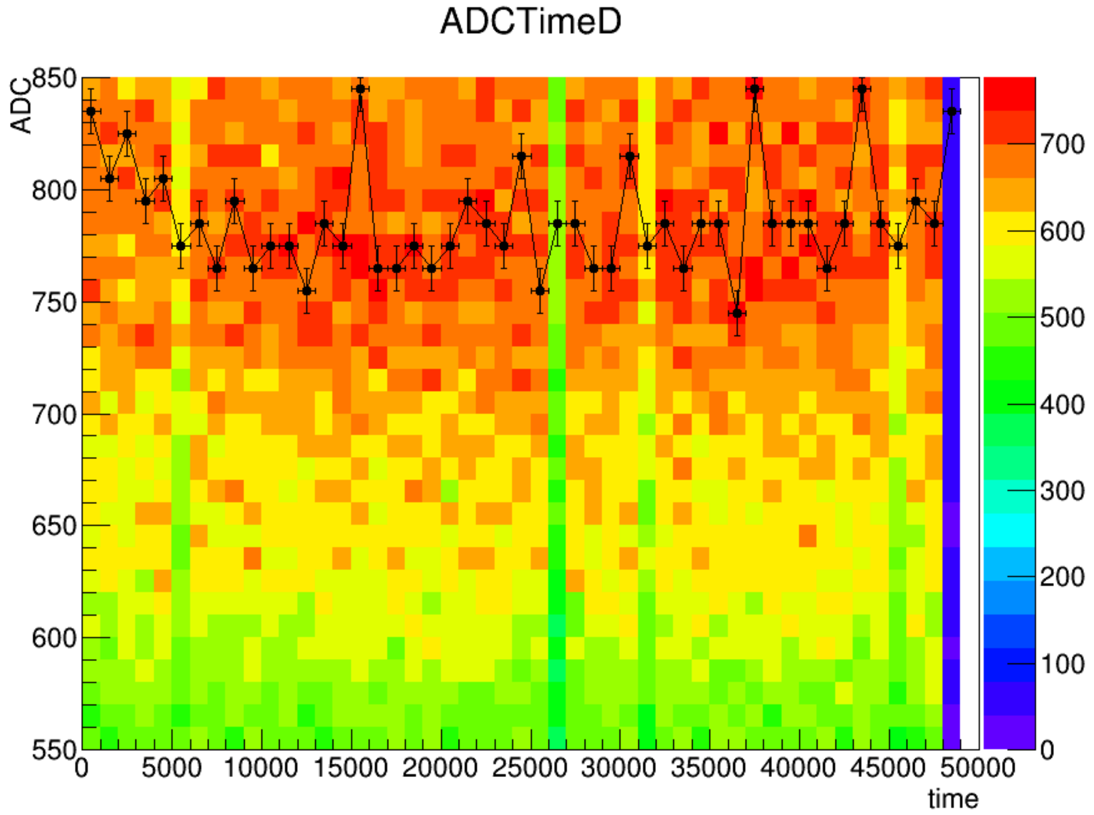
10 logarithmic time after trigger intervals

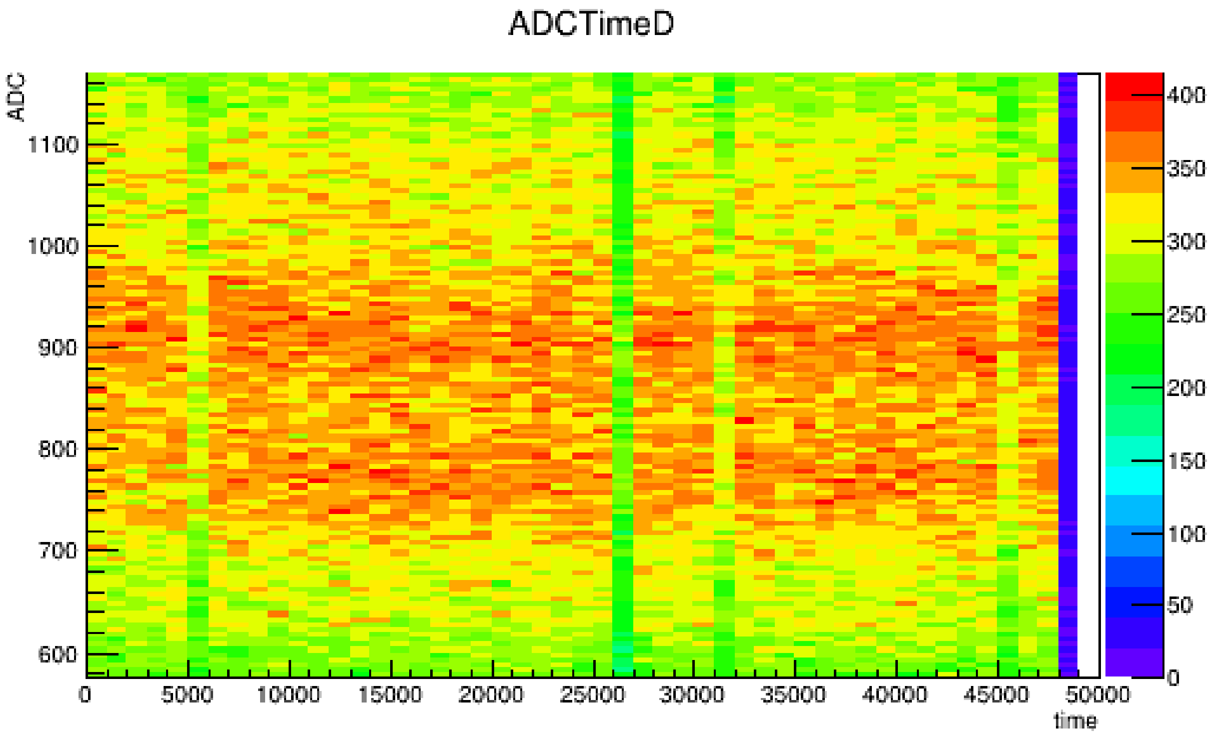
- 1552<t<1691
- 1691<t<1844
- 1844<t<2009
- 2009<t<2190
- 2190<t<2387
- 2387<t<2601
- 2601<t<2835
- 2835<t<3089
- 3089<t<3367
- 3367<t<3670

- Gaussian+exponential fit around the transition energies
- The exponential fit is not fundamental

Time dependency

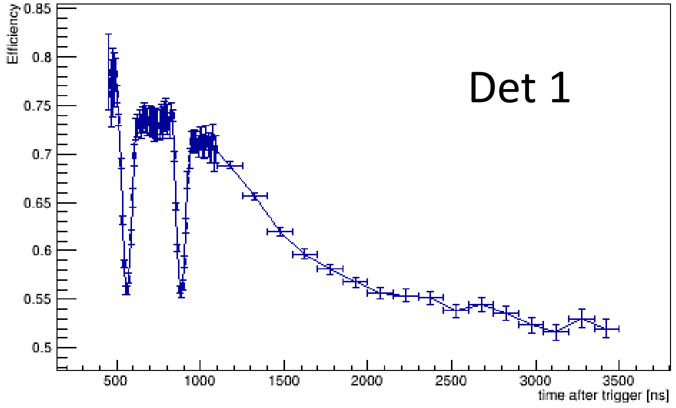
C 75 keV, to check the time dependency with all detectors

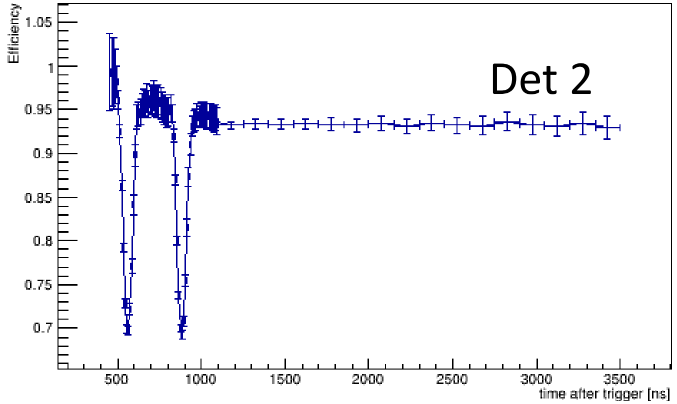


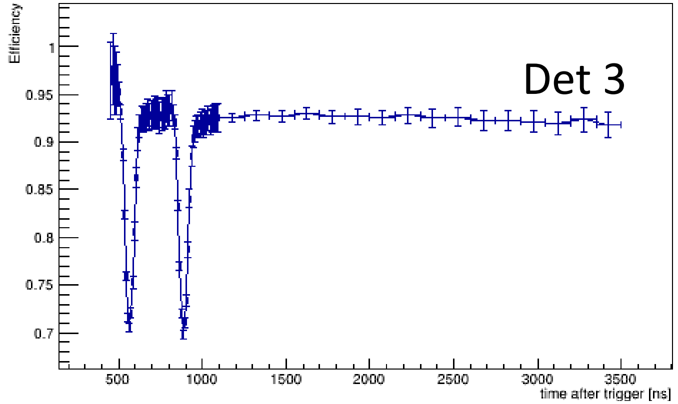


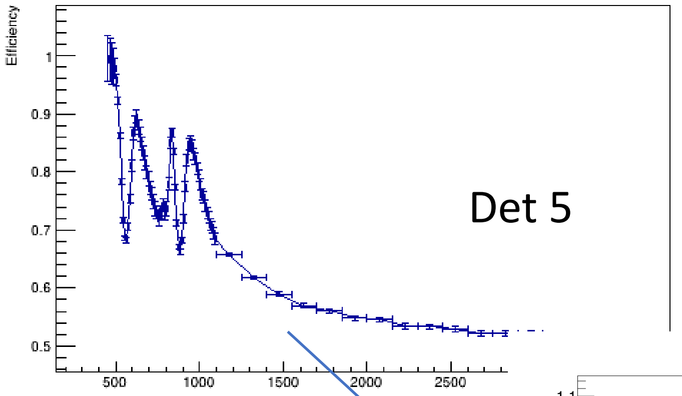
Efficiency

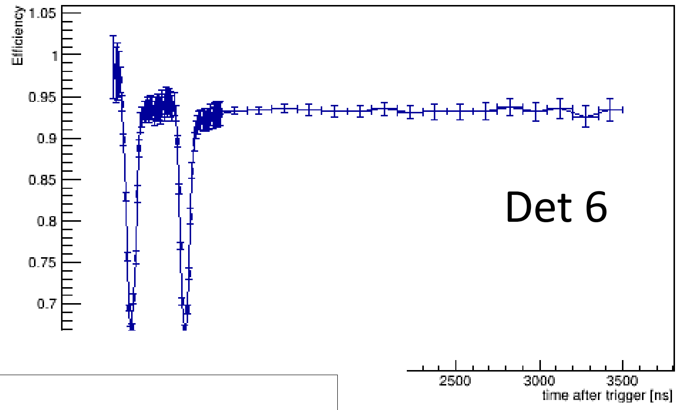
304 K case

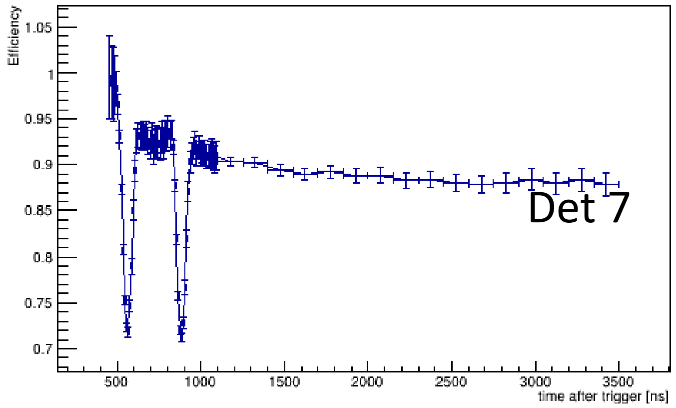


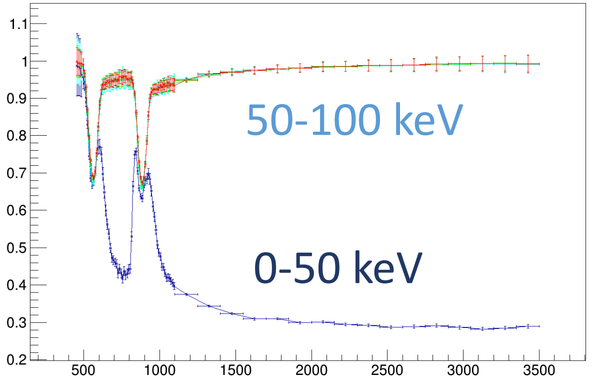








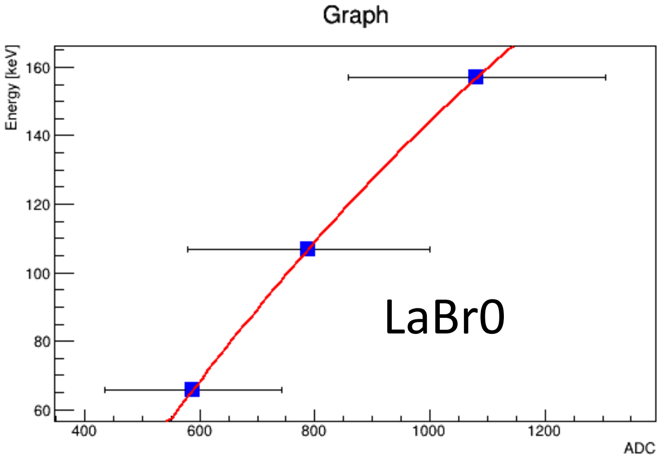


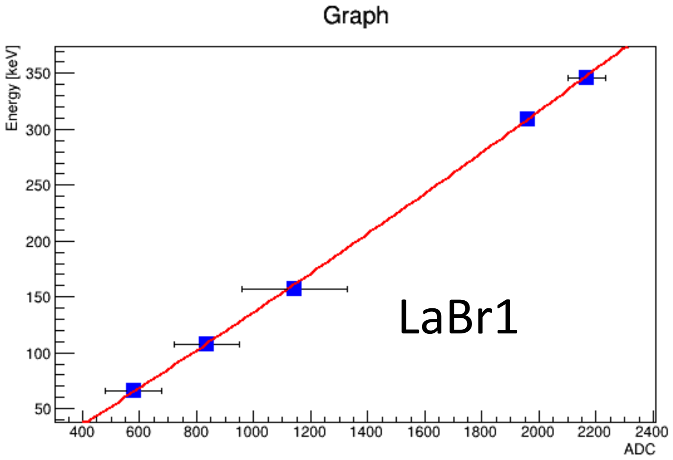


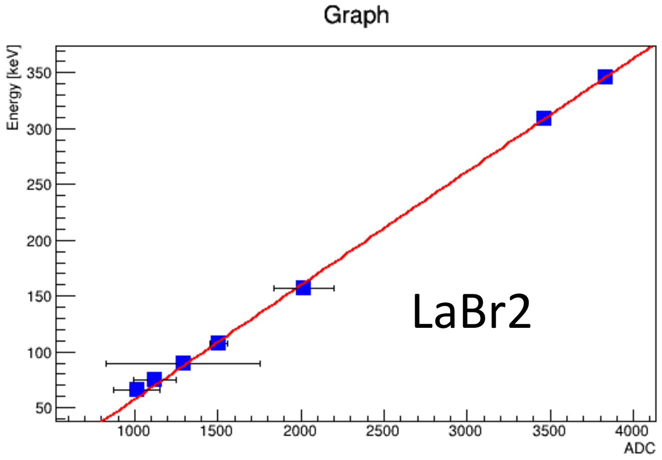
- Detectors 1 and 5 show a loss of efficiency at one of the cuts
- Detector 5 has ineffeciency only at low energy
- Detector 1 has inefficiency also at higher energy so it had been excluded

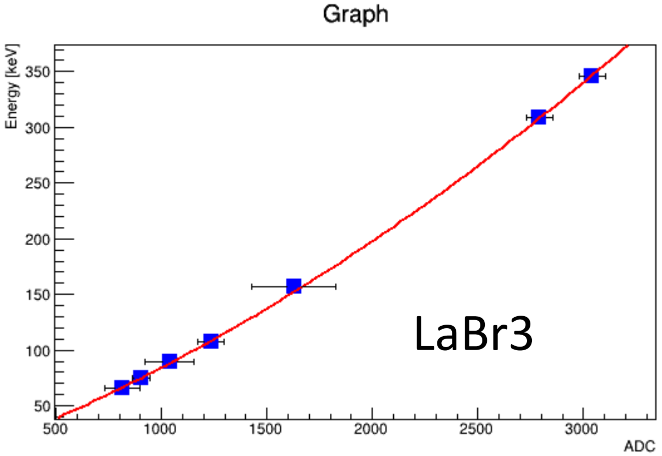
Calibration curves

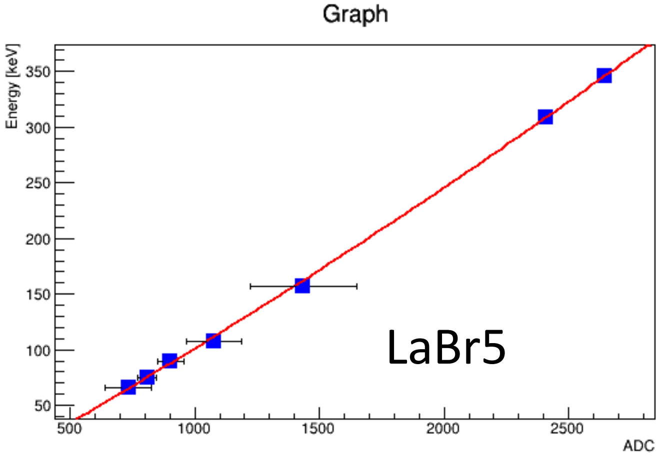
Detector 0 is excluded

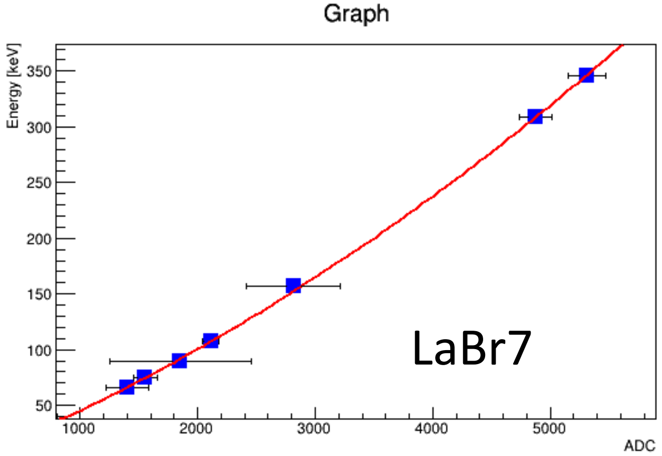




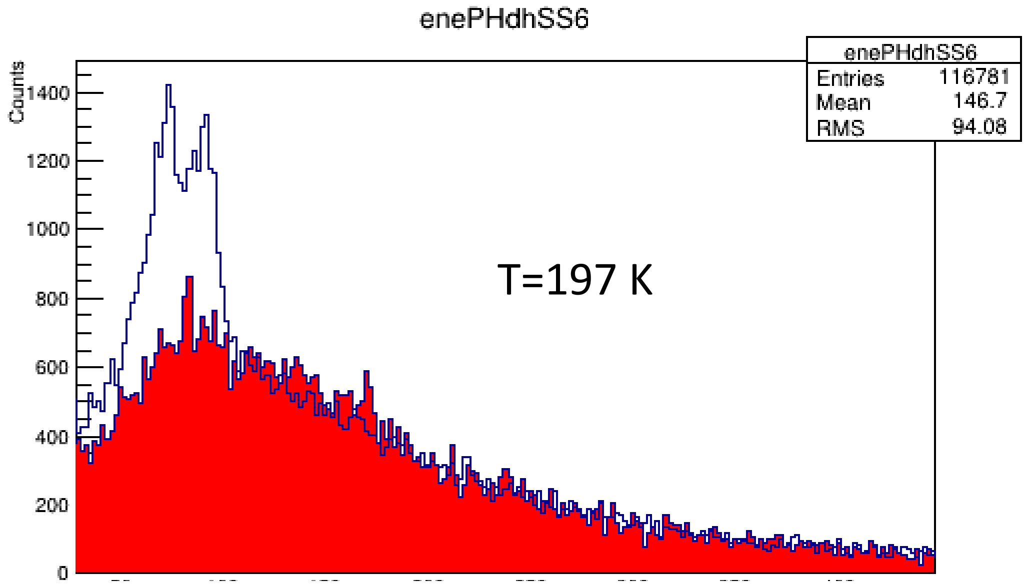


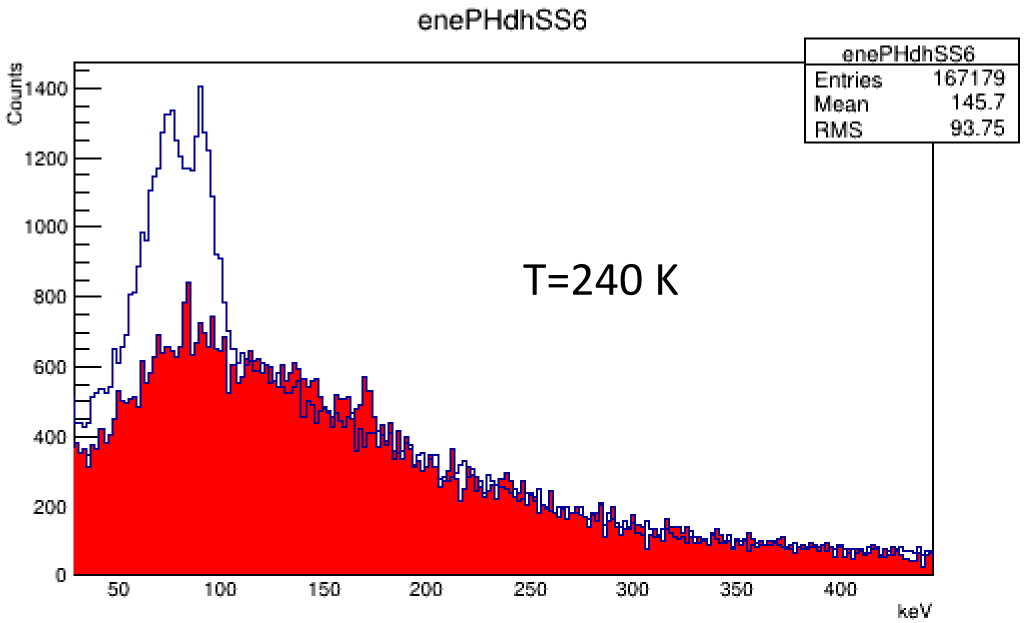


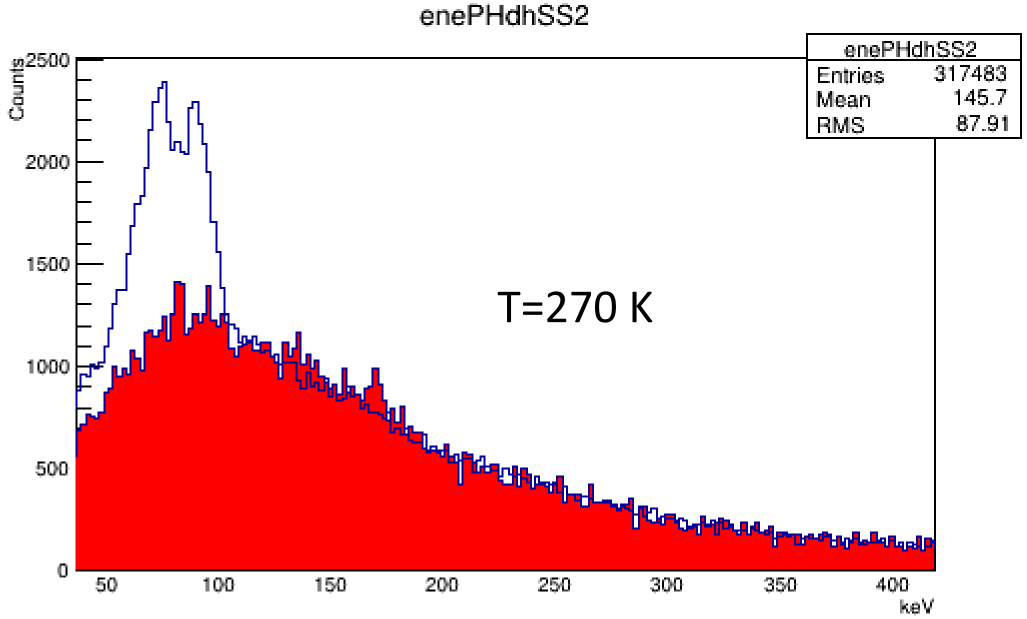


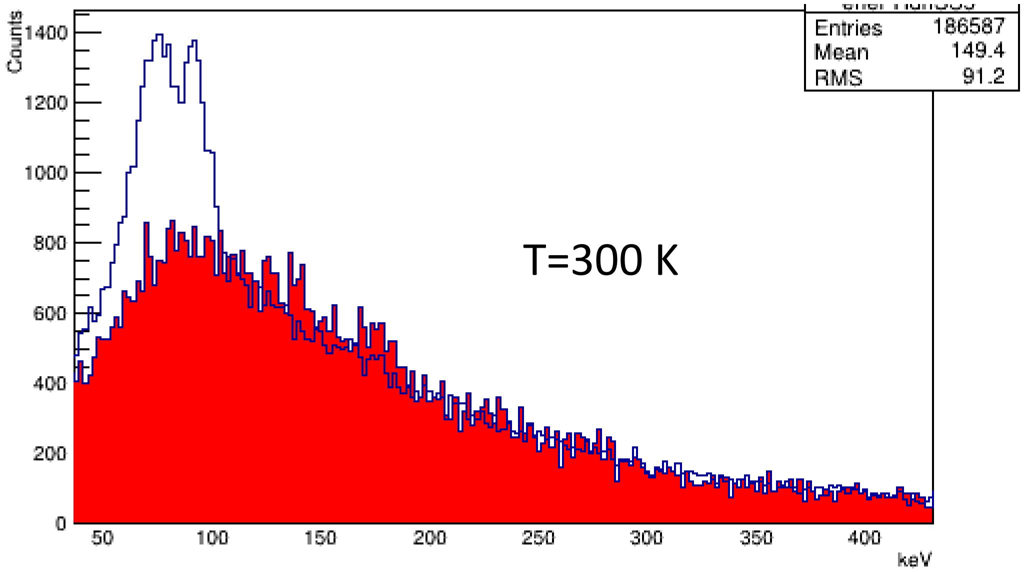


Time interval 2





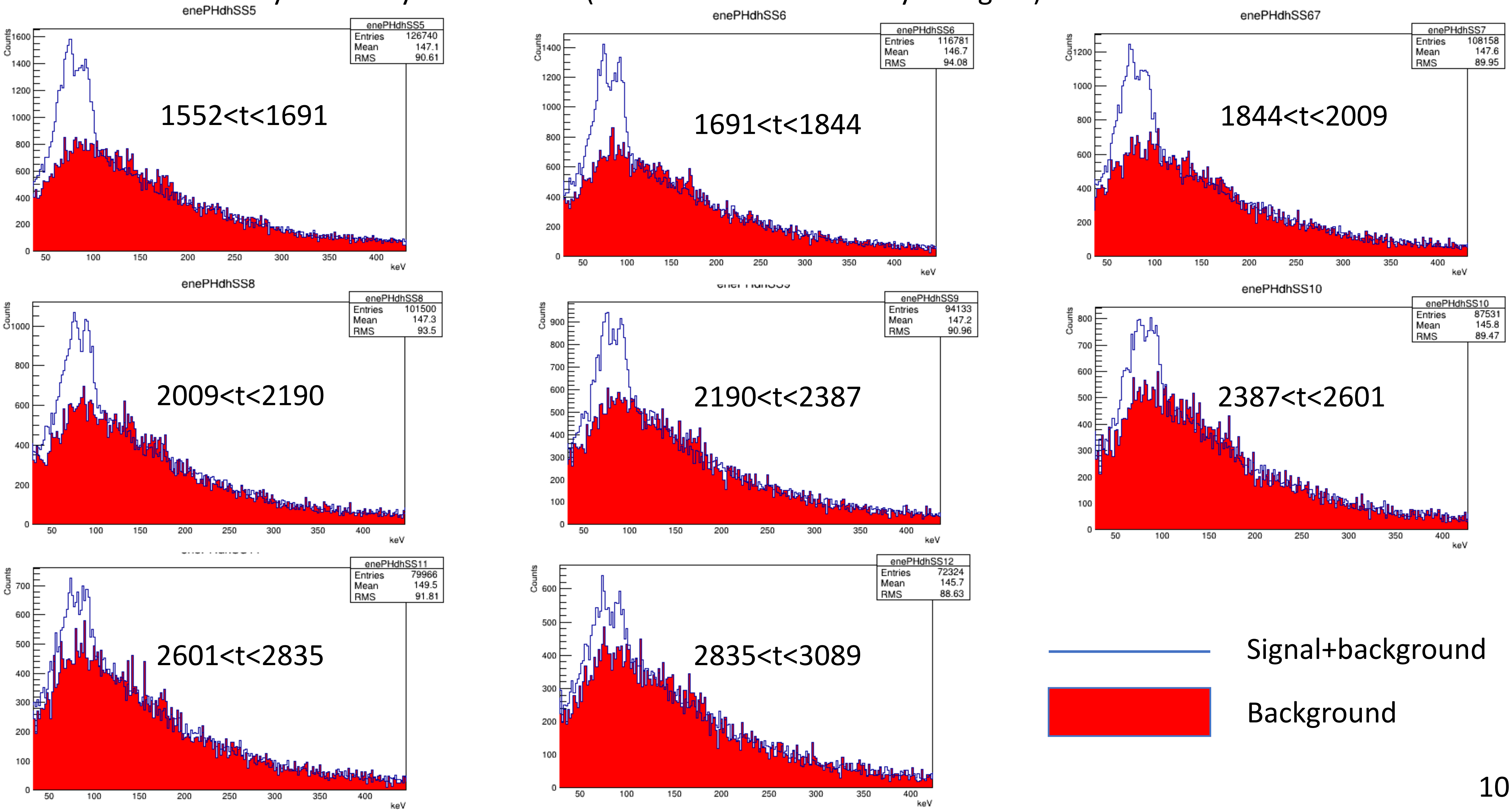




Normalization: 200-400 keV

Time intervals at 197 K

Distributions are corrected by efficiency and livetime (almost 100% in the delayed region)



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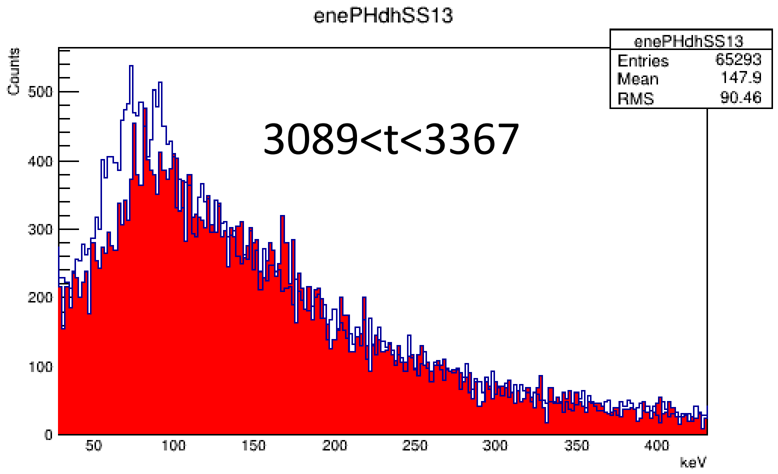
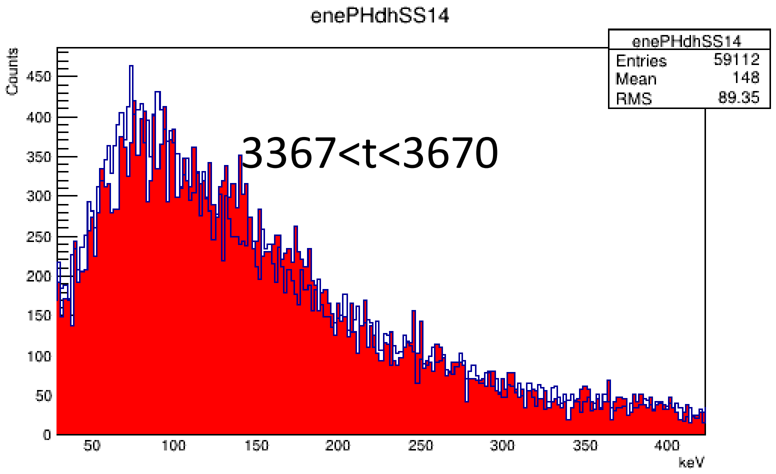


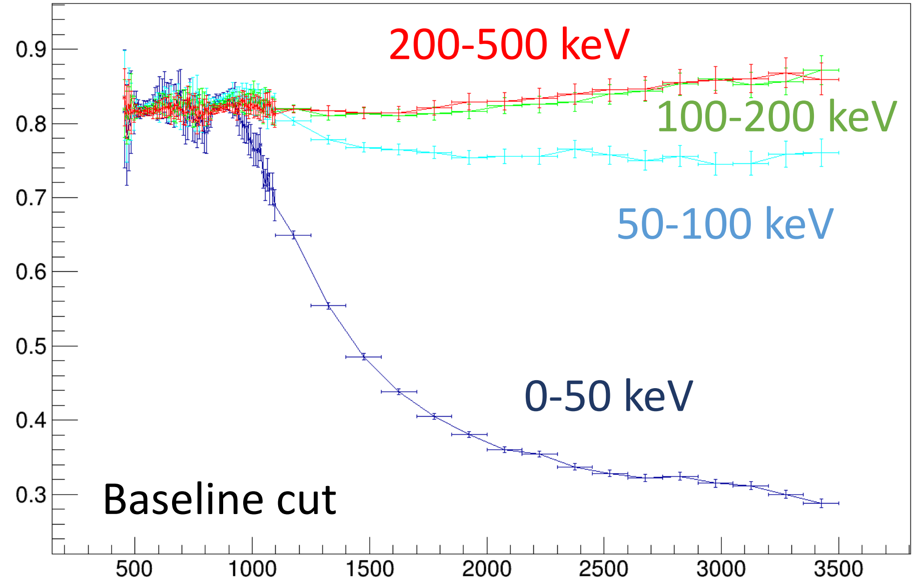


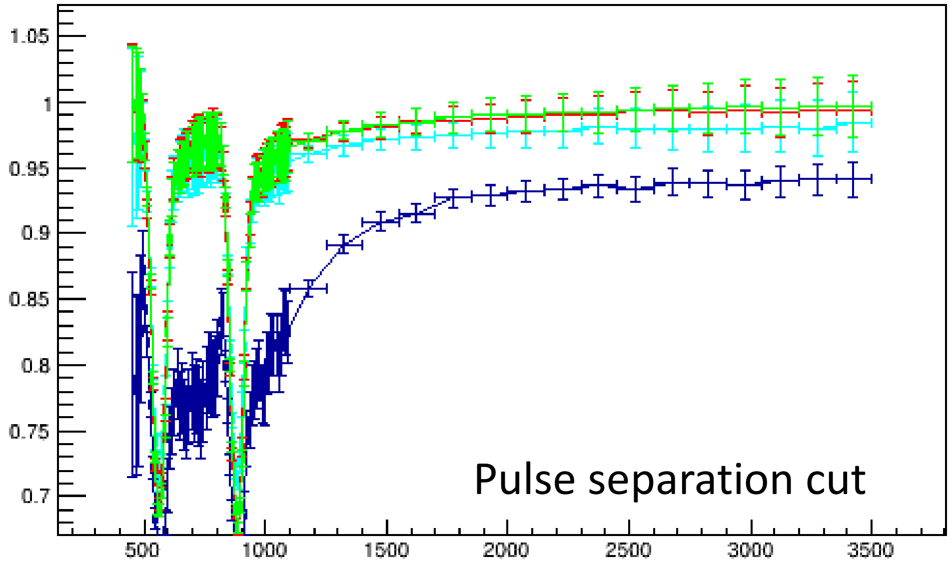
Signal+background

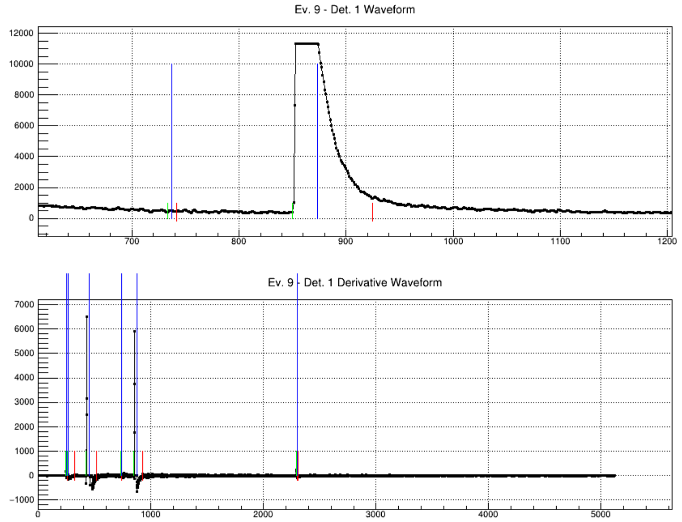
Background

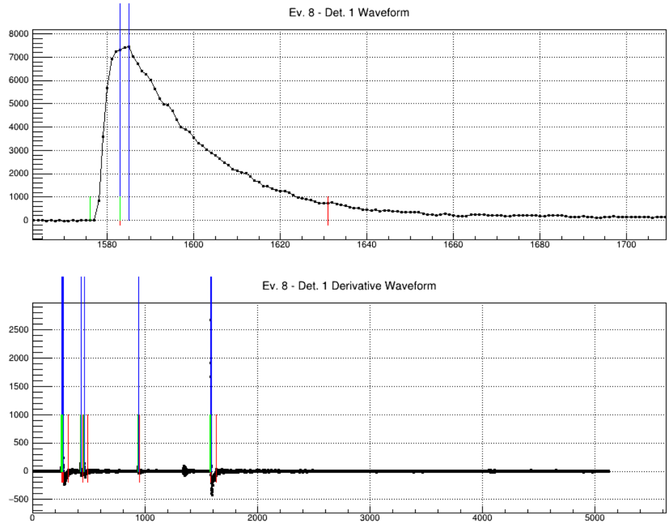
Efficiency

Detector 1







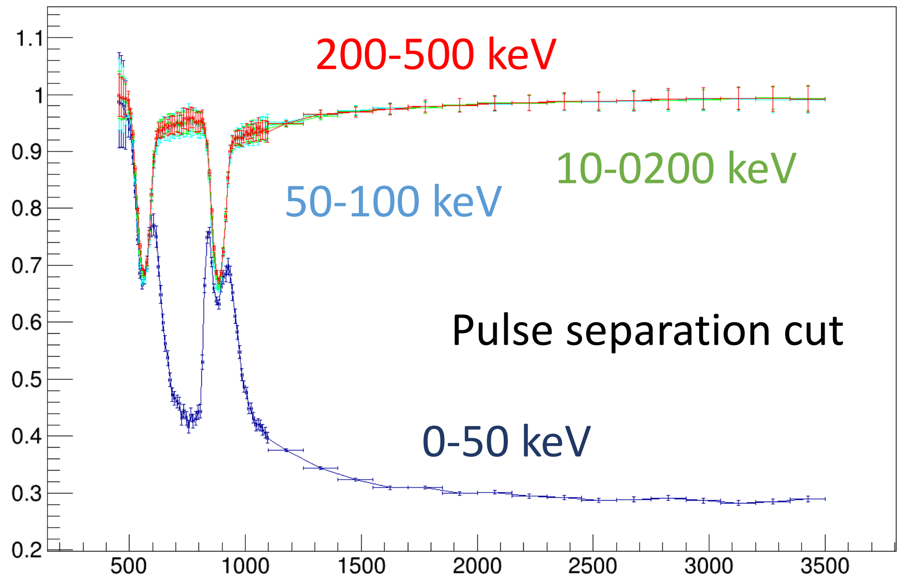


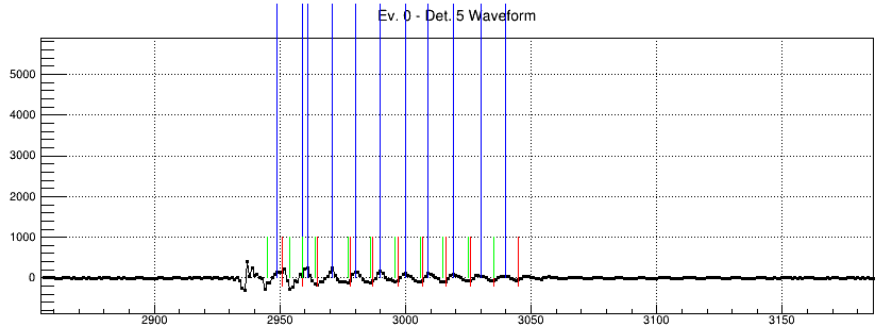
Double identification or background identified as signal

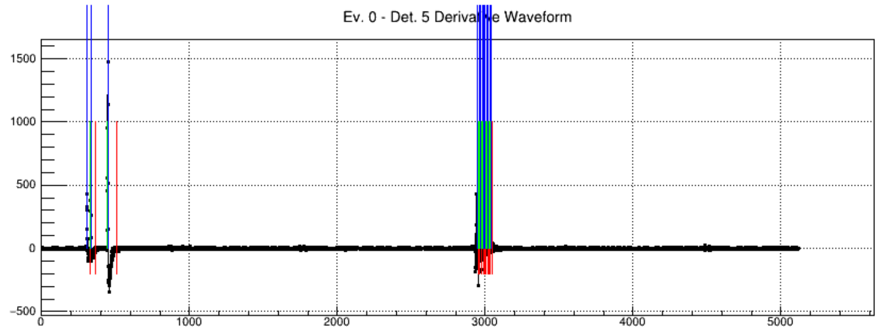
We decided to remove detector 1 from the analysis (loss of efficiency also in the 50-100 keV region

Efficiency

Detector 5



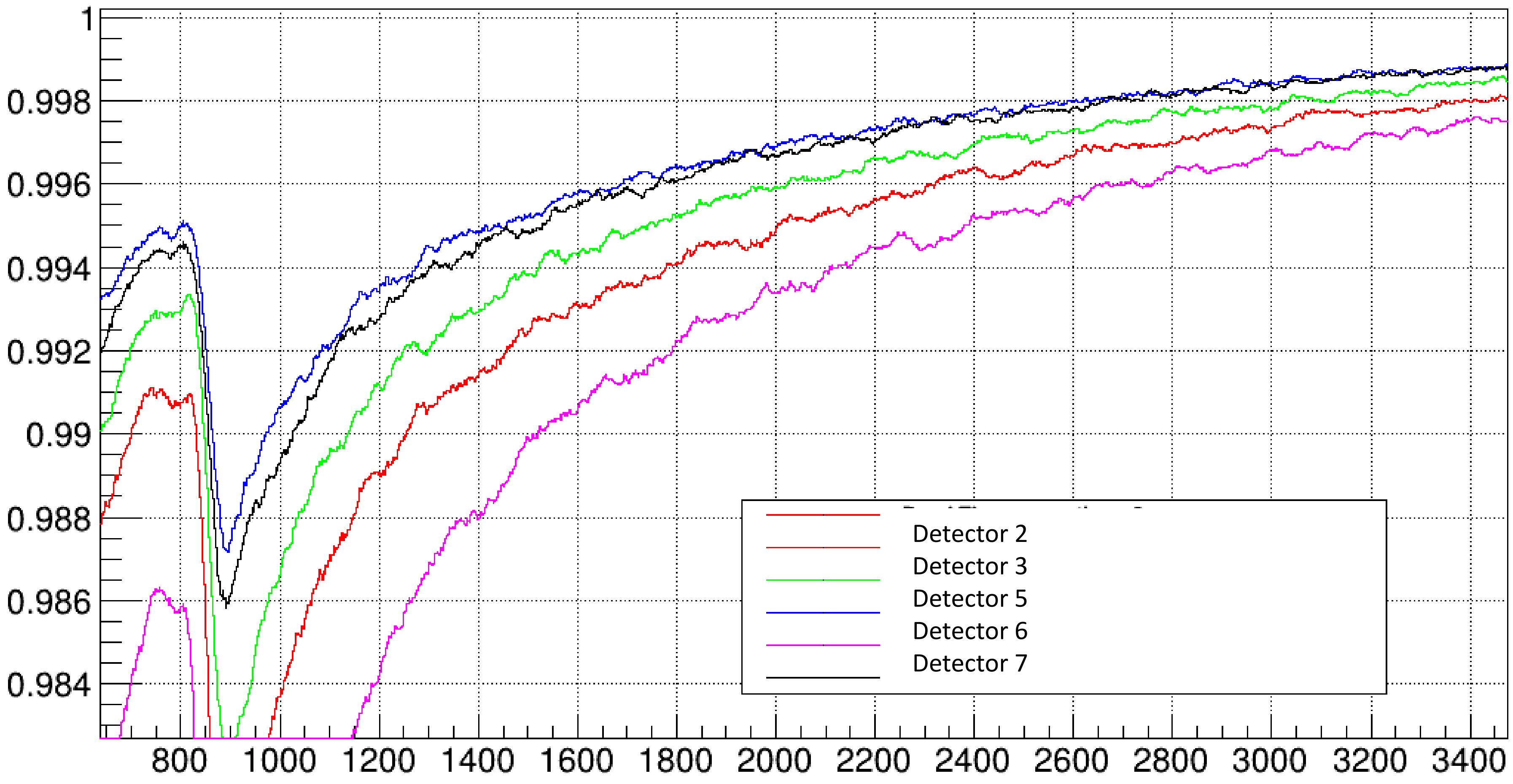




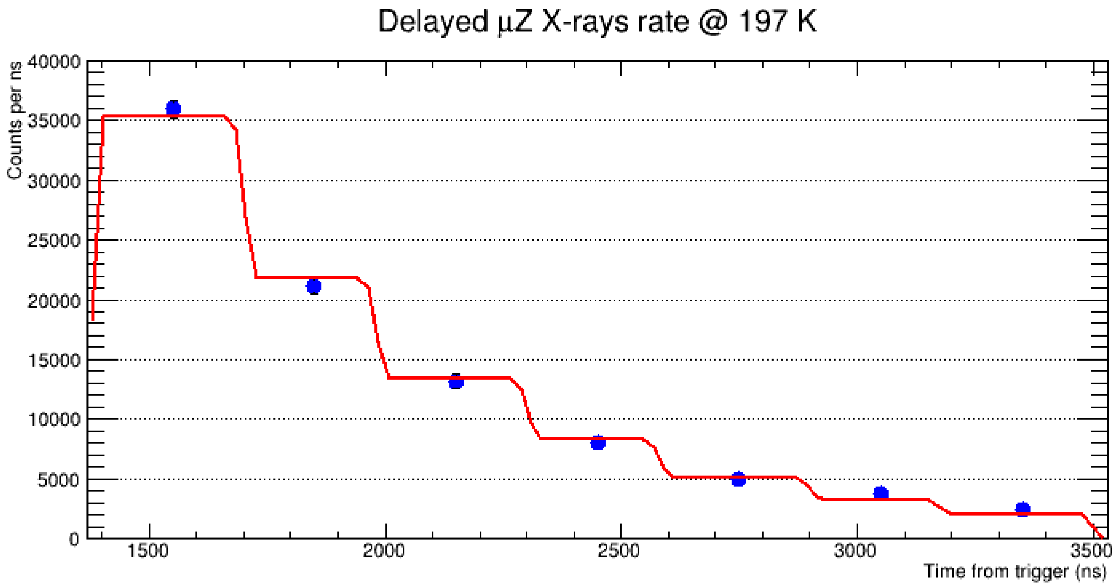
- Very frequent and several reconstructed pulses
- This does not affect signal (50-100 keV is fully efficient)

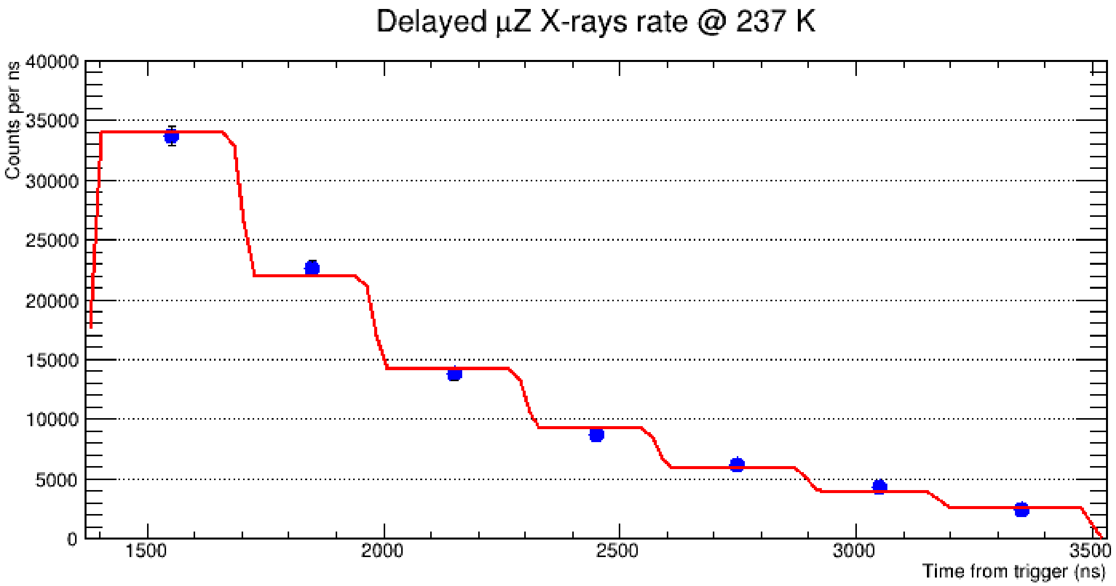
Livetime

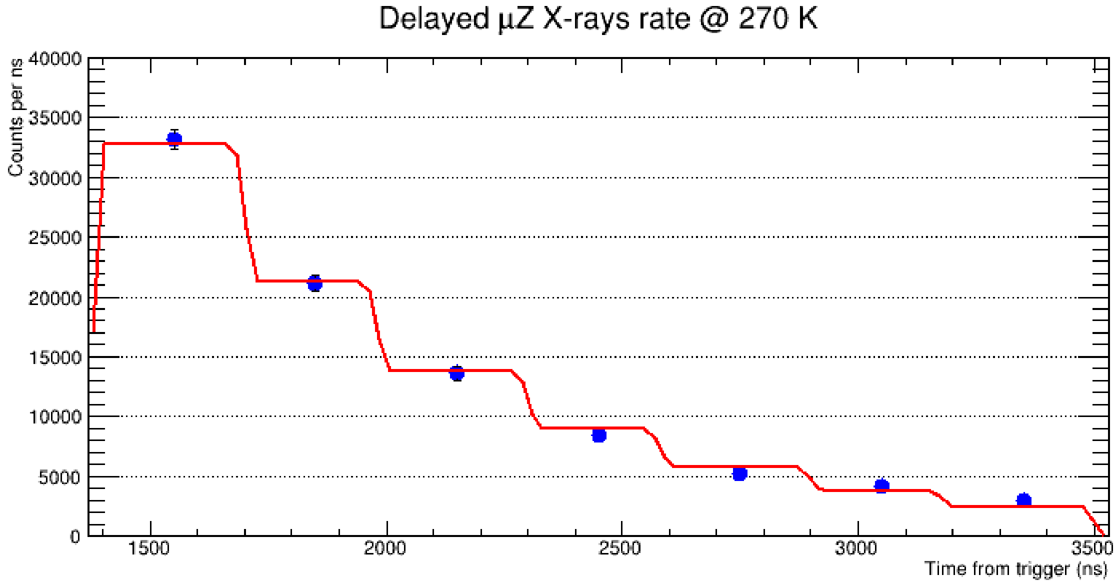
Livetime always higher than 99% for all detectors in the time region selected for extracting the transfer rate to carbon

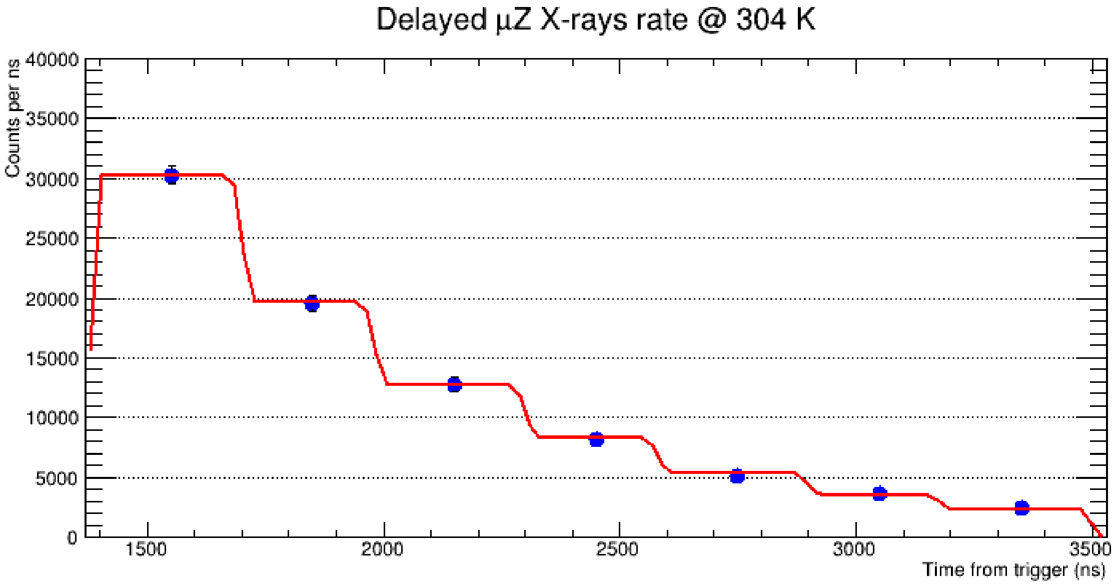


Counts per time interval









Overview of next data taking

- The same procedure used for oxygen is repeated for the laser and no laser data samples
- The signal is the difference of the two integrals of laser and no laser data

Expected systematics

- Detector gain drift (expected 30 days acquisition time), change of the position of the peaks and consequently of the range of the integral;
- Detector efficiency
- Pressure of the target, a lower pressure means that less muons are captured and it affects also the transfer rate (phi parameter);
- Number of muons
- Laser energy stability, different probability of transition
- Length of the measurement;