FAMU: latest results in the measurement of the transfer rate from $\mu^{-}p$ to Oxygen

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for the FAMU Collaboration

International Conference on Precision Physics and Fundamental Physical Constants

FFK-2019

Outline

- Motivation
- The FAMU experiment
- Measurement of the transfer rate from μp to oxygen
- Outlook

FAMU

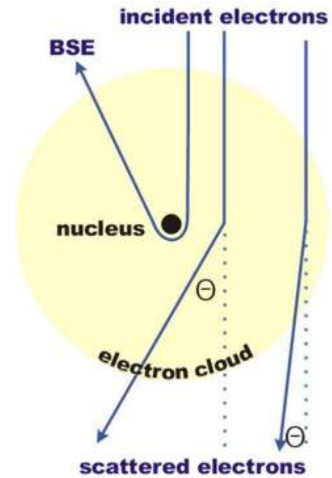
Fisica degli Atomi Muonici

Physics with muonic atoms

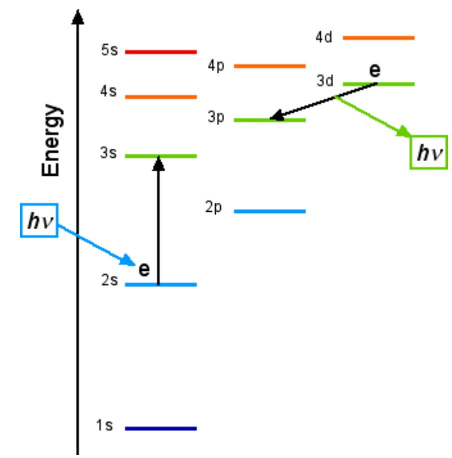
Fundamental physics: the proton

Study of the properties of the proton

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



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

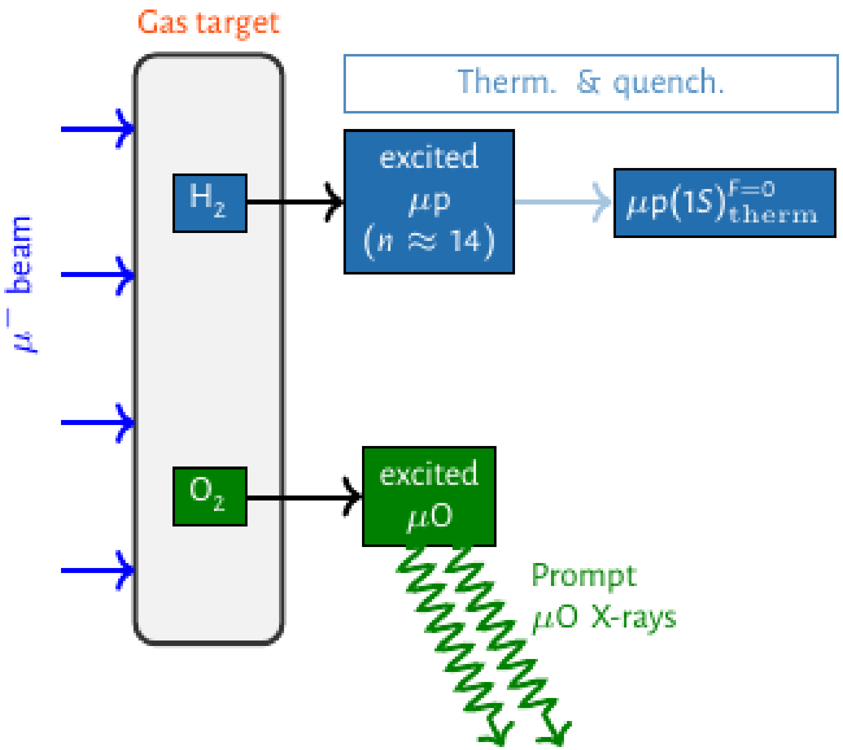


FAMU aim:

HFS of muonic hydrogen ground level

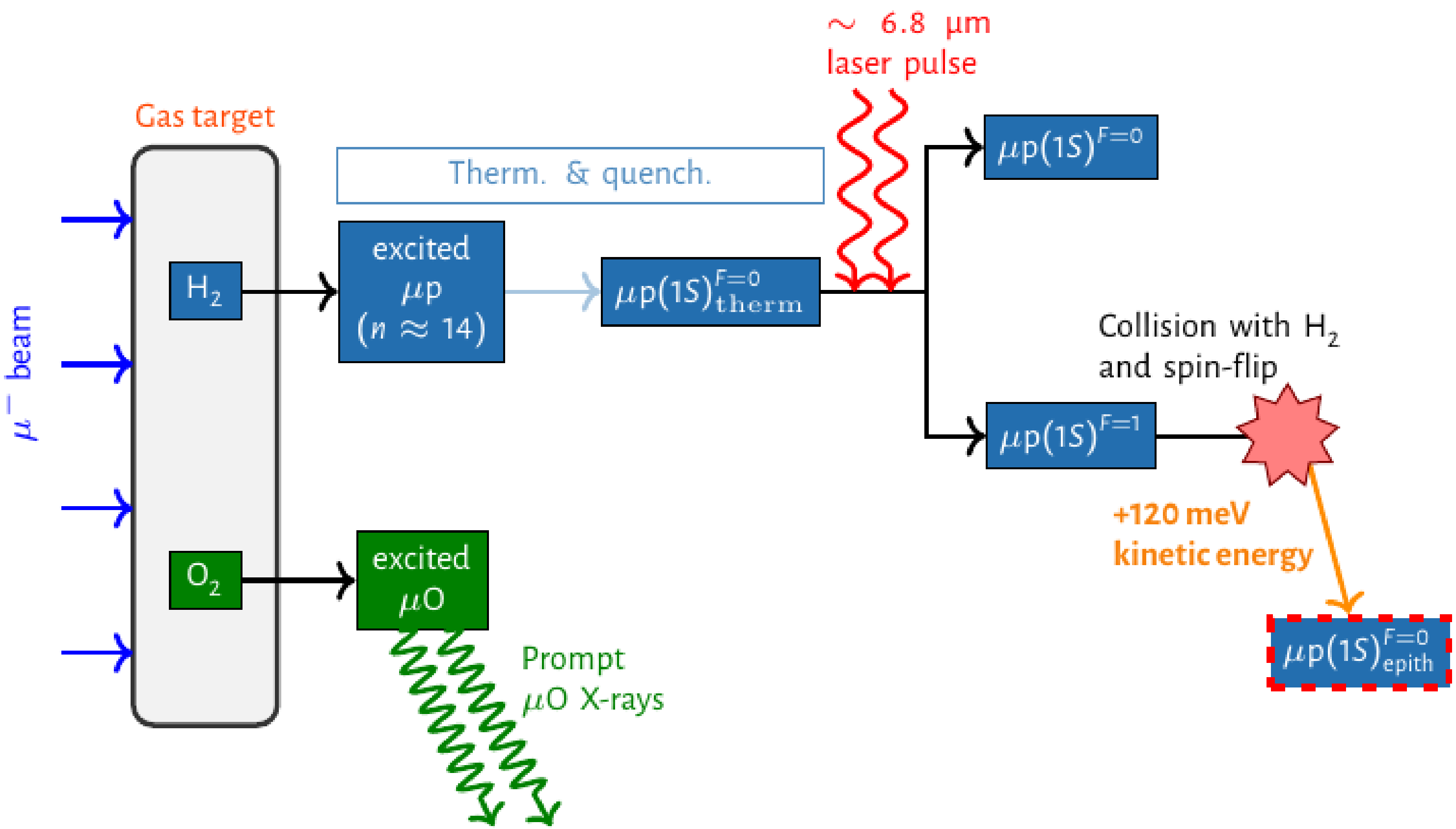
→ the Zemach radius of the proton

FAMU method and workflow (I)



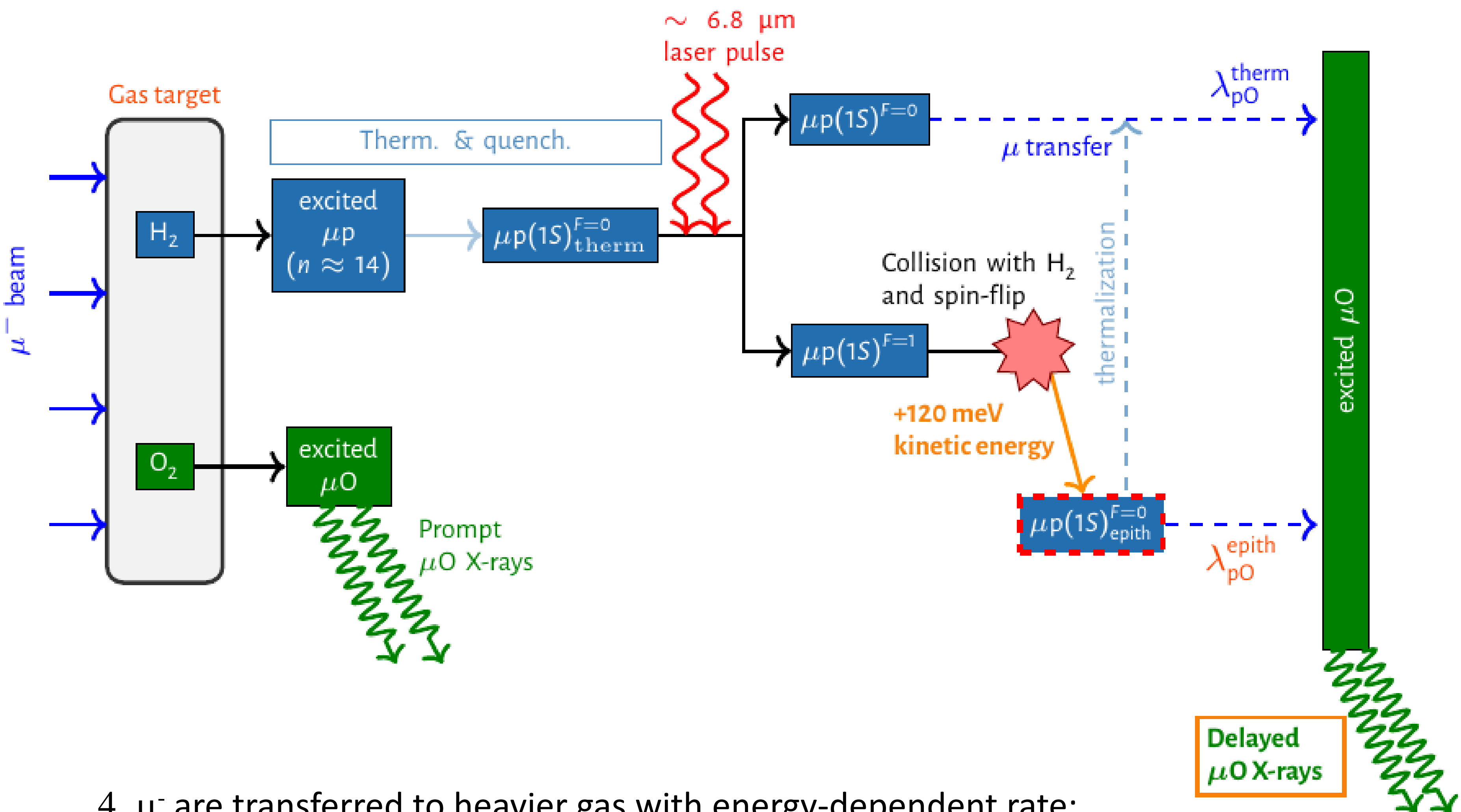
1. Create muonic hydrogen and wait for thermalization;

FAMU method and workflow (I)



1. Create muonic hydrogen and wait for its thermalization;
2. Shoot 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. De-excitation and acceleration: $\mu^-p(\uparrow\uparrow)$ hits a H atom
   It is depolarized back to $\mu^-p(\uparrow\downarrow)$ and is accelerated by ~120 meV ;

FAMU method and workflow (I)



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.

FAMU: principle of operation

Method:

1. Create muonic hydrogen and wait for thermalization;
2. Shoot laser at resonance (λ_0 ~6.8μ): spin state of μ^-p from 1^1S_0 to 1^3S_1 ,
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Ingredients:

- high intensity muon beam
- proper gas mixture
- high energy and fine-tunable laser
- fast and accurate X-rays detectors

FAMU: Phases of the project

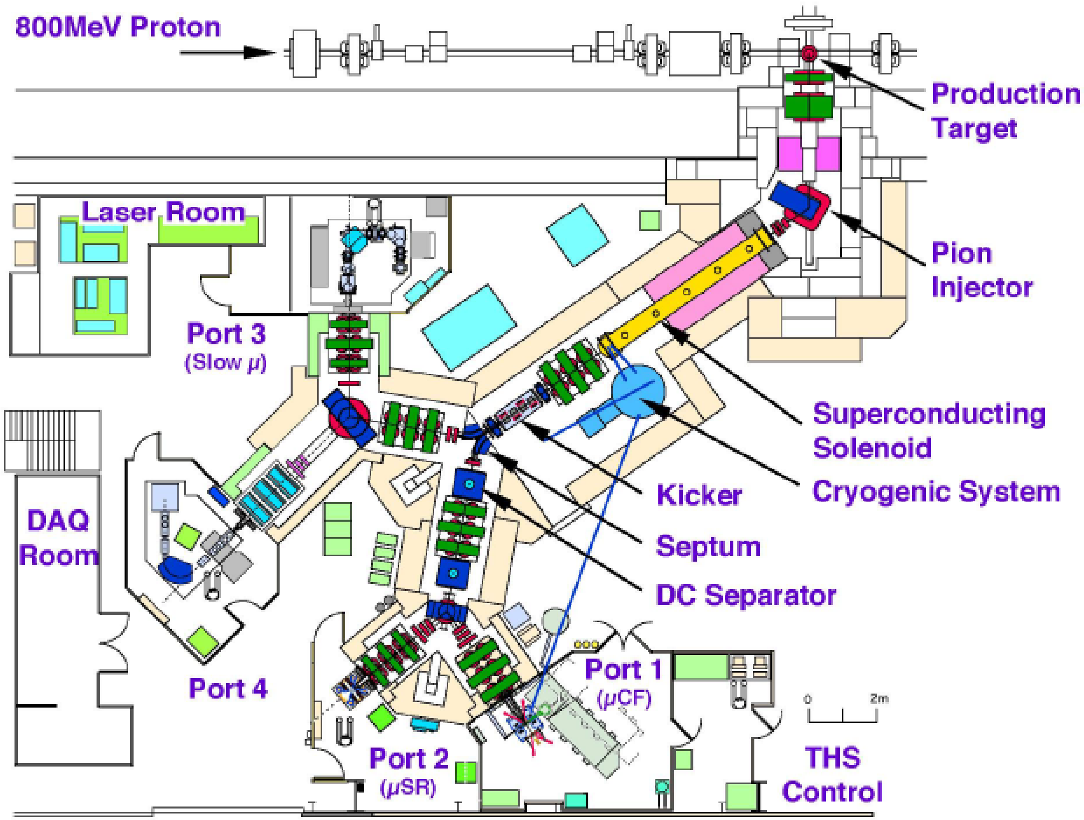
- **1993** — First idea of the experimental method — Physics Letters A 172 (1993) 277–280
- **2014** — First FAMU data taking — Study the muon beam, test target and detectors, measure transfer rate @ constant conditions PTV
- **2016** — Find the best gas mixture, temperature and pressure
  measure the transfer rate energy dependence for oxygen
- **2018** — Data taking: Measurement with the final target PVT conditions
  Optimisation of the laser system
- **2019-2020** — Full set up (with laser) and measurement of the HFS

FAMU - Set Up

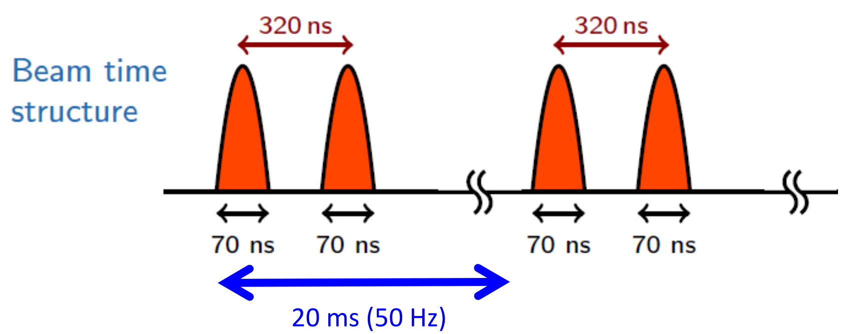
RIKEN RAL muon facility

Rutherford Appleton Laboratory – Oxfordshire UK

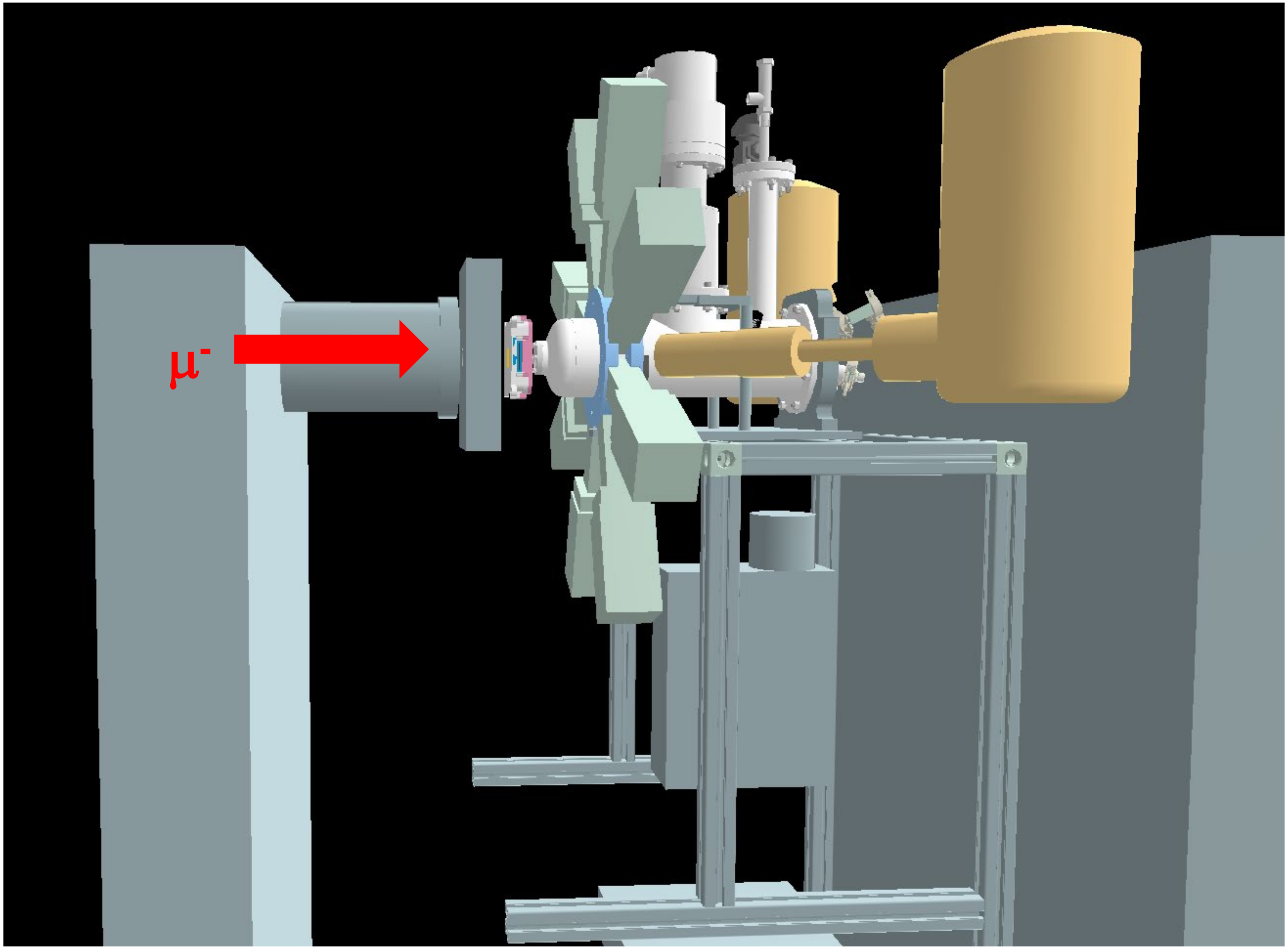
The brightest pulsed muon beam facility in the world!



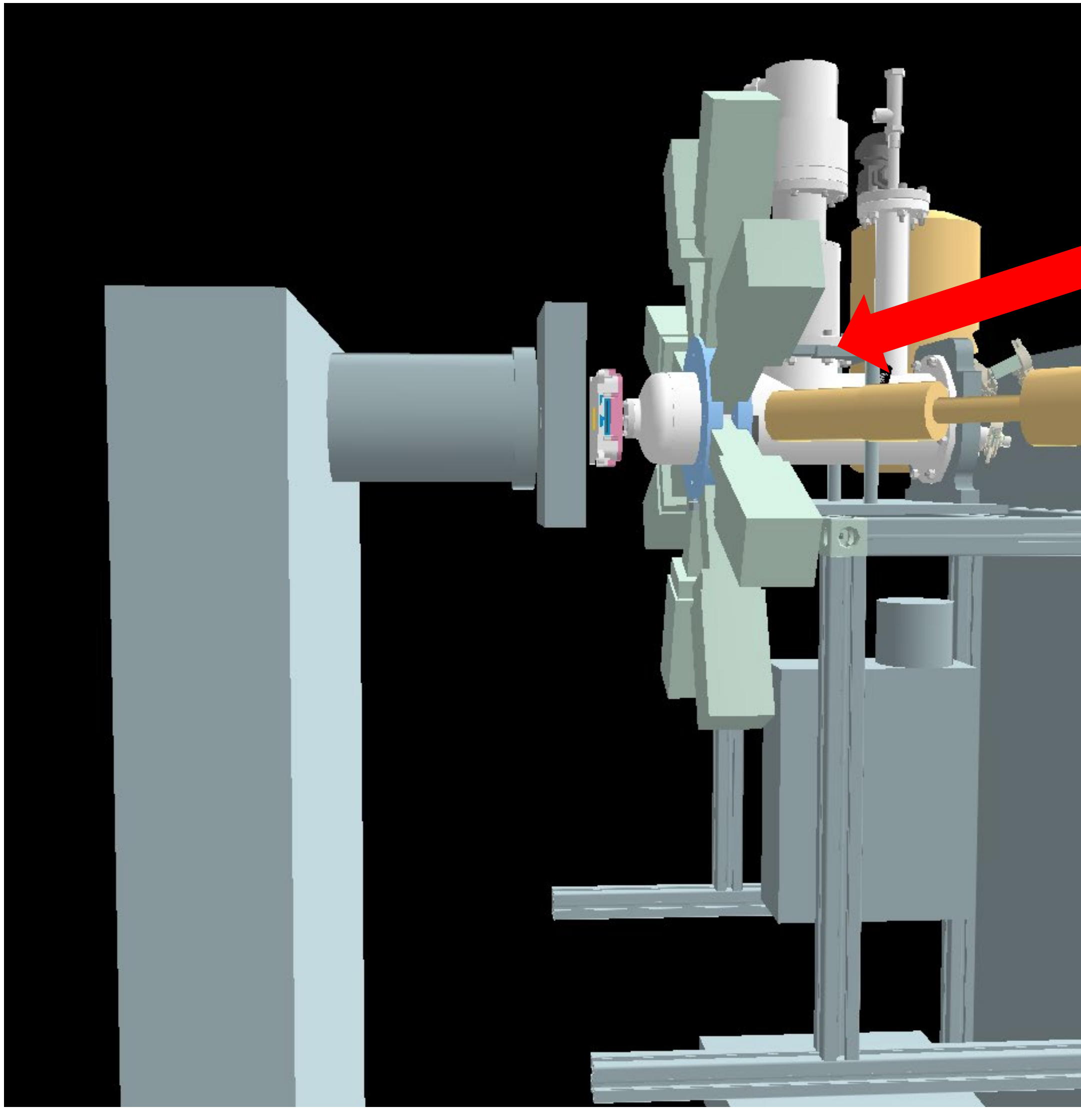
UK - Didcot

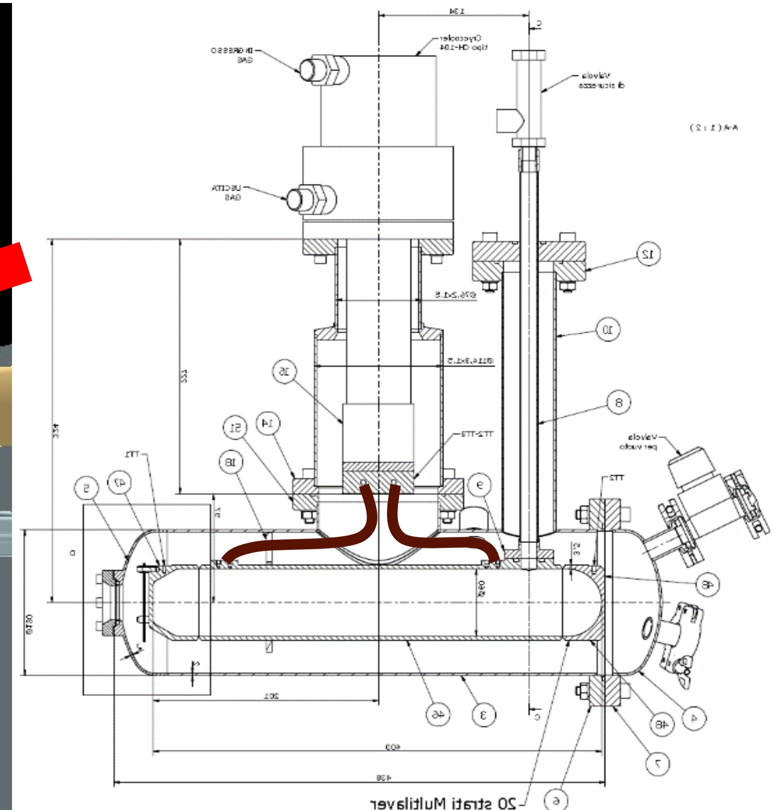


Experimental setup - CAD



Cryogenic thermalized target



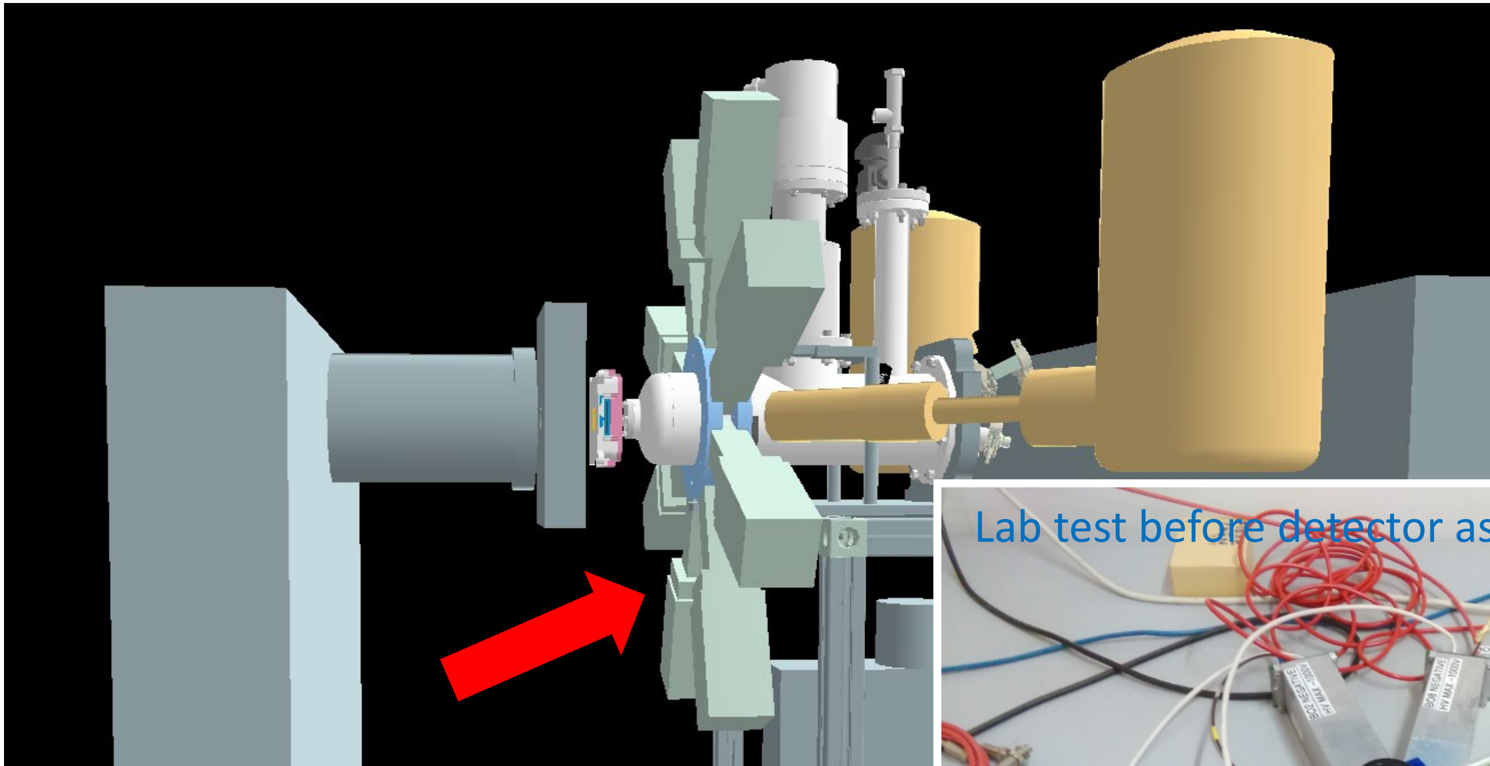


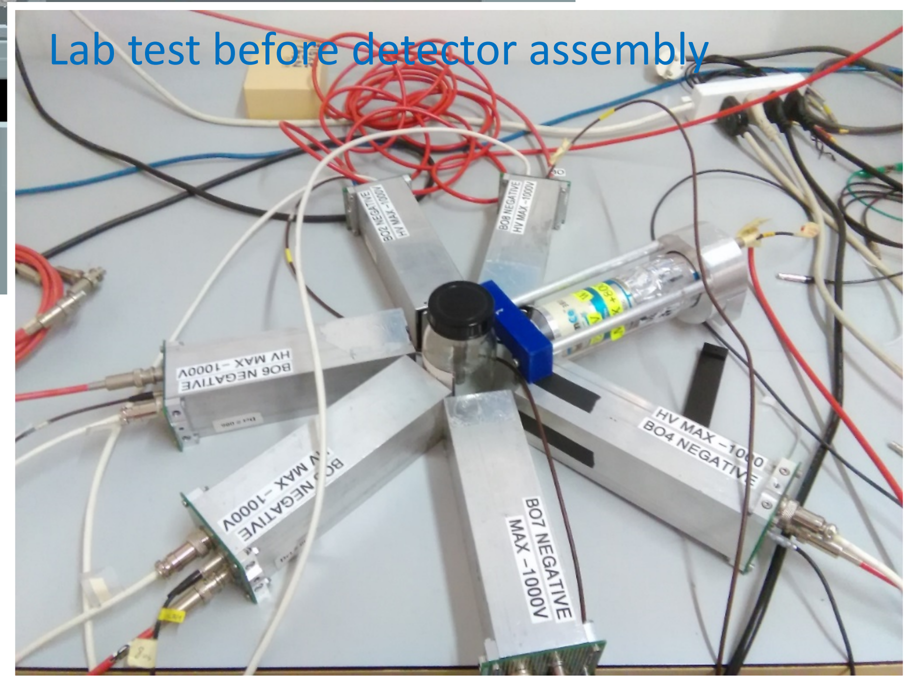
Gas:

H_2+O_2 (120ppm)

41 bar @300 K

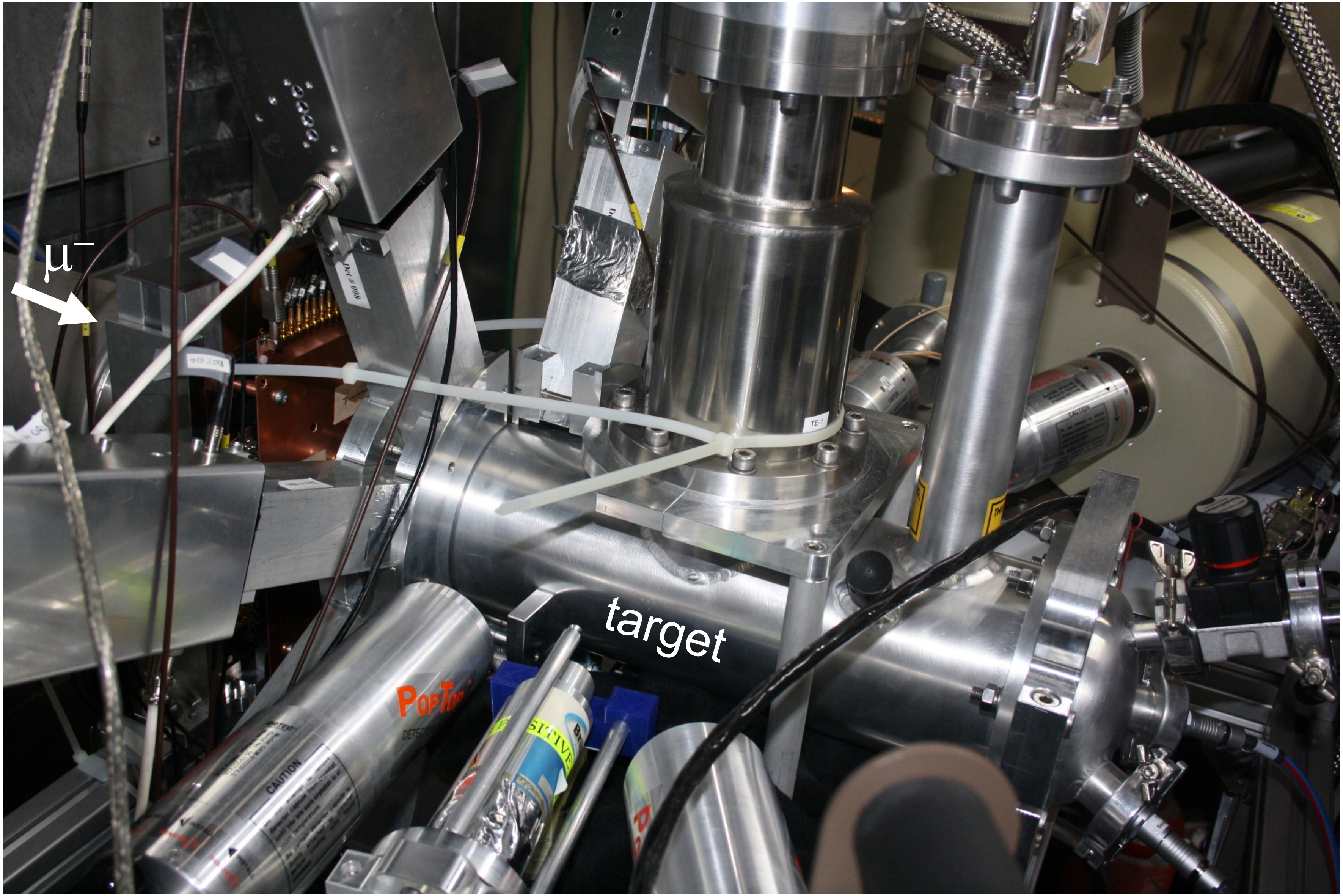
$LaBr_3$(Ce): fast timing X-rays detectors



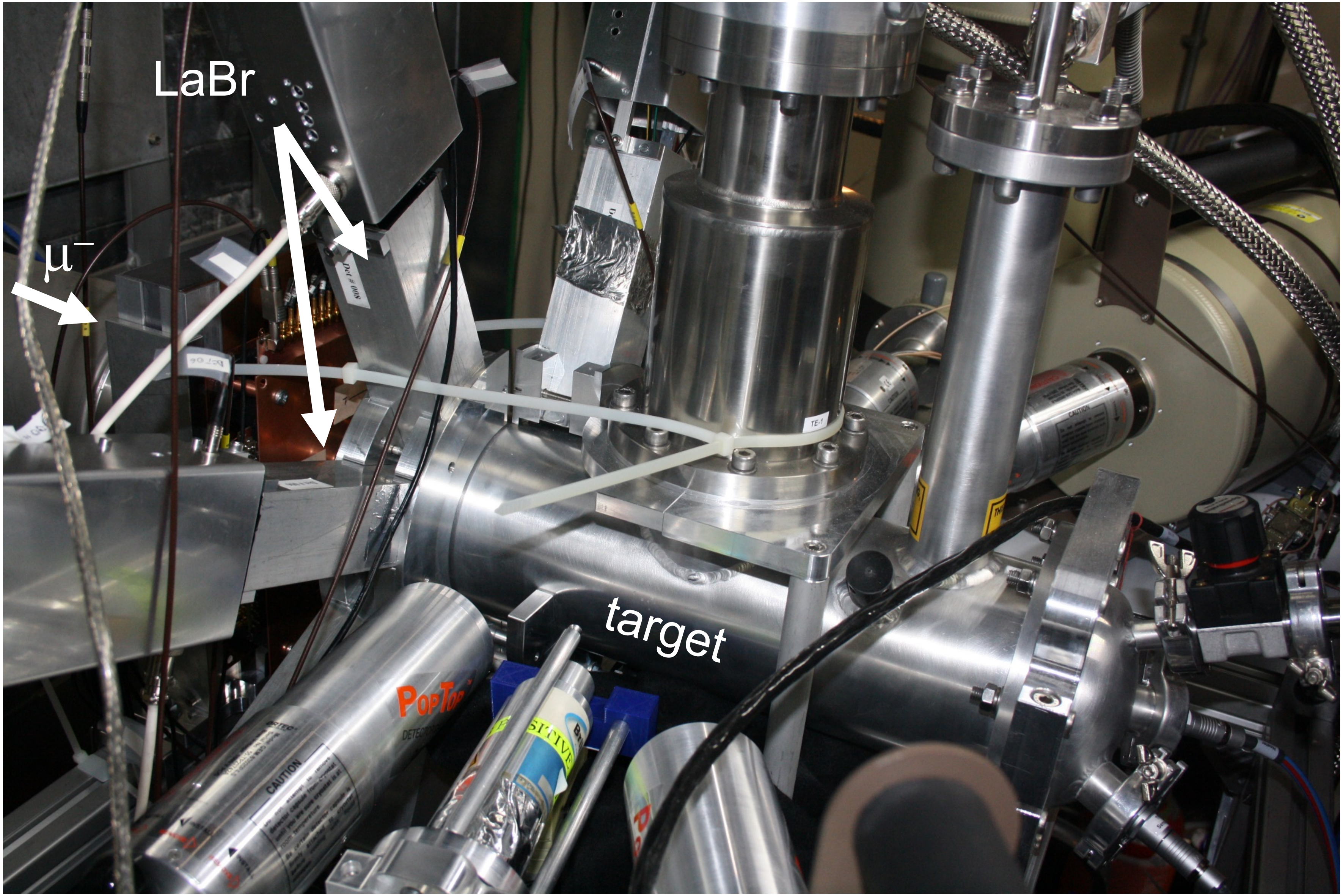


- 8 cylindrical 1 inch diameter 1 inch long lanthanum bromide $LaBr_3$(5%Ce) crystals
- read by PMTs
- fast electronics and fast digital processing signal available

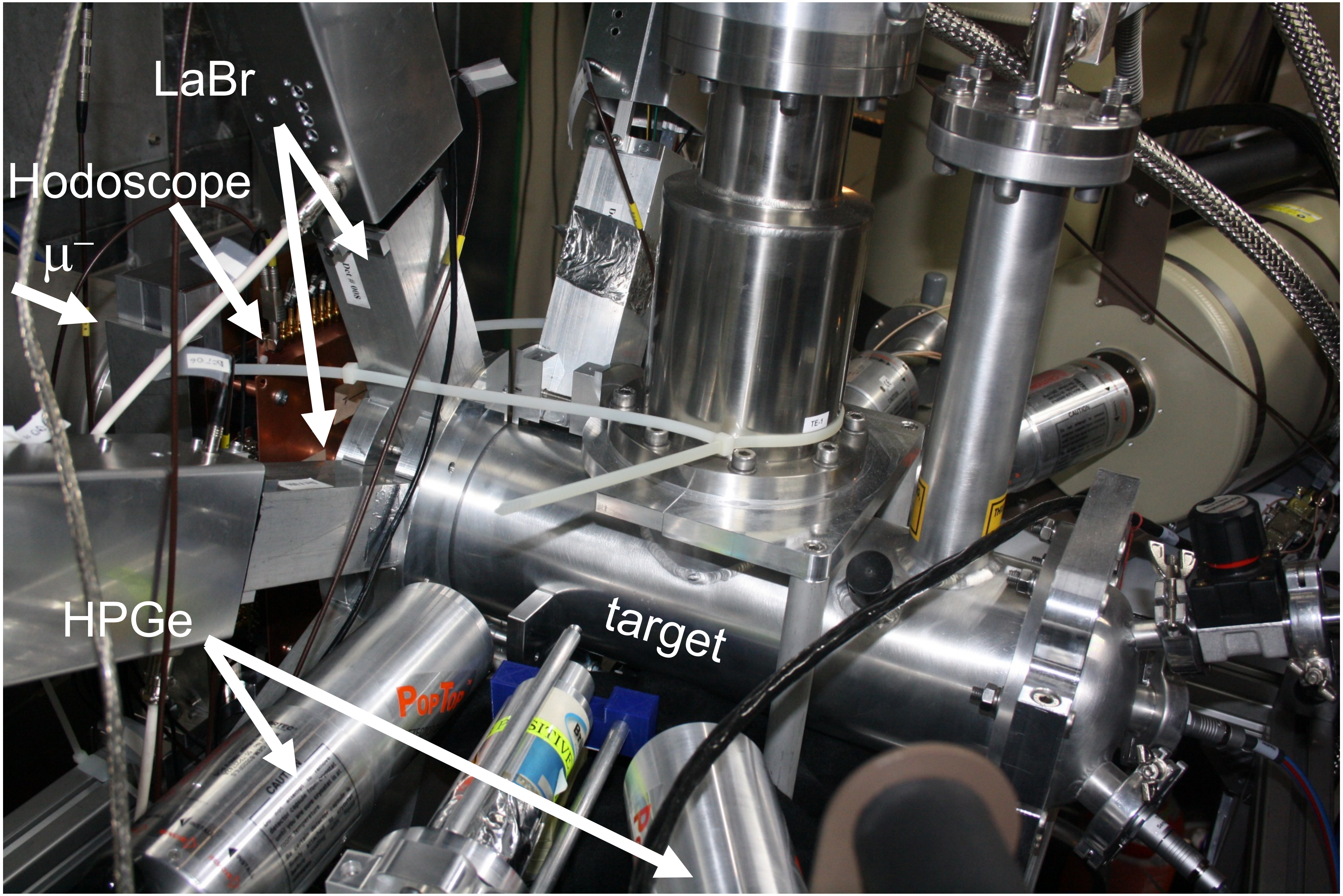
Experimental setup



Experimental setup



Experimental setup

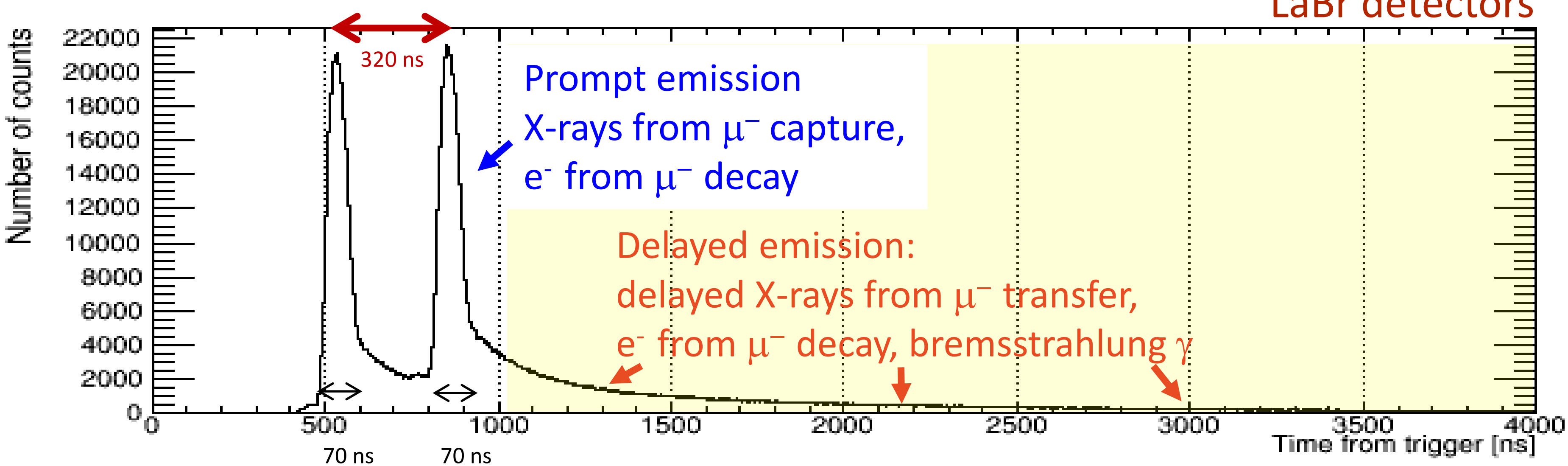


Measurement of the transfer rate $\Lambda_{\mu p \rightarrow \mu O}$

Transfer rate measurement

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

LaBr detectors



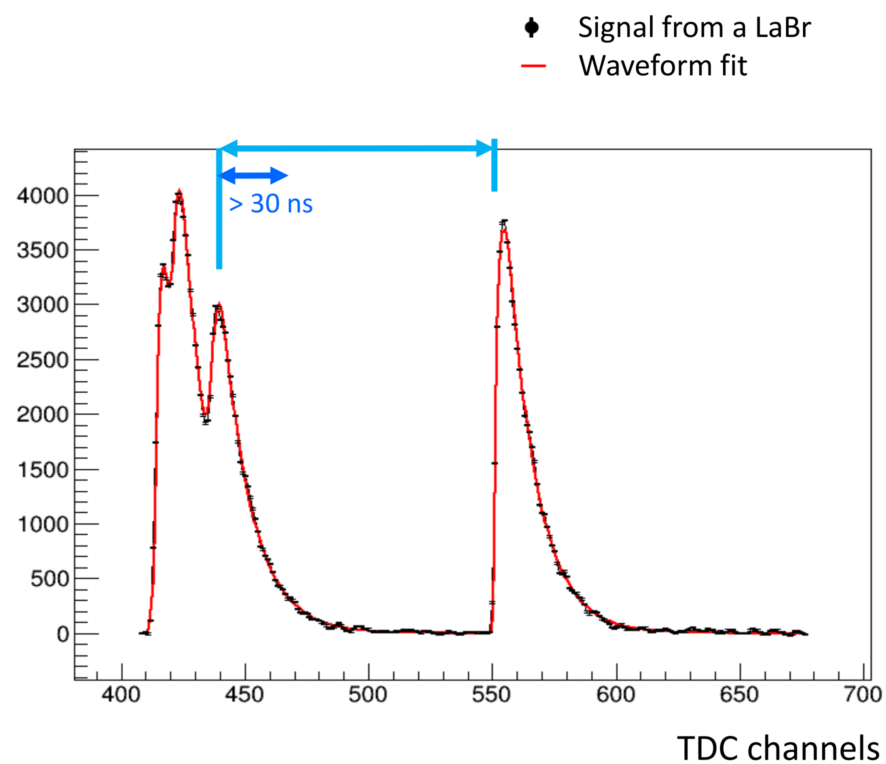
Data Analysis

Signal amplitude:

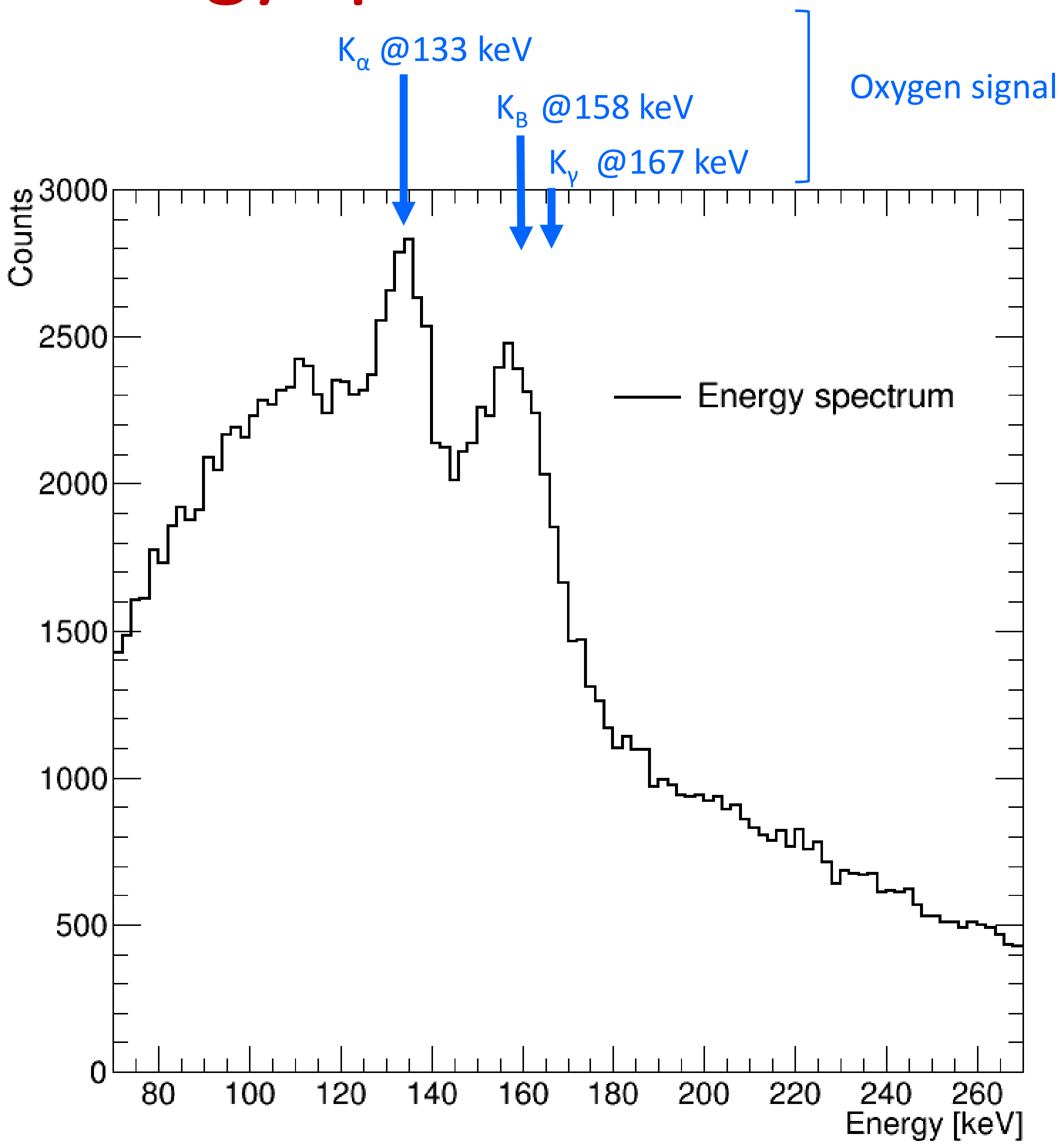
- Detector signals are fitted

Loose data selection:

- Good Chi2 from the wavefit
- Distance between pulses > 30 ns
- No saturated events



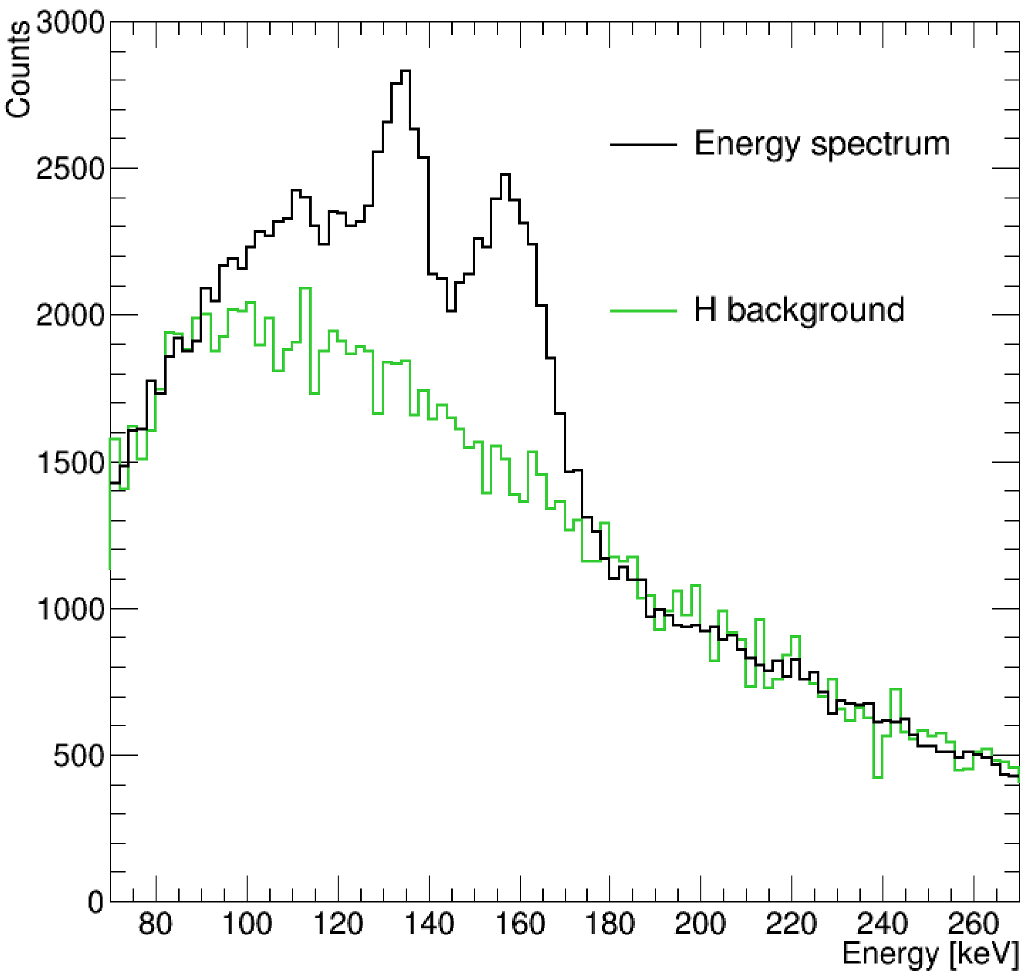
Energy spectrum



T = 300 K

Time bin = [1450,1650] ns

Background evaluation: pure hydrogen



T = 300 K
Time bin = [1450,1650] ns

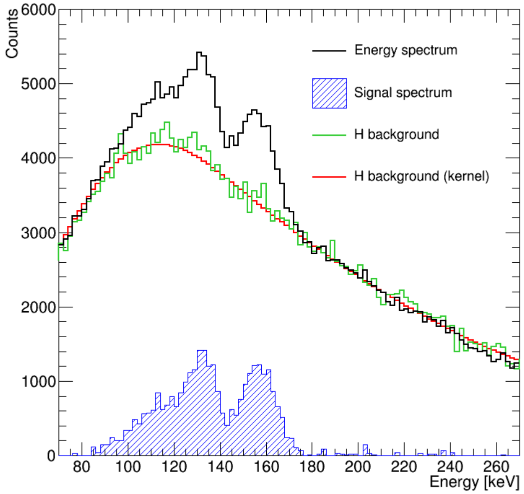
Pure hydrogen data taking within the same beam time and with the same pressure and temperatures.

However: poor statistics…

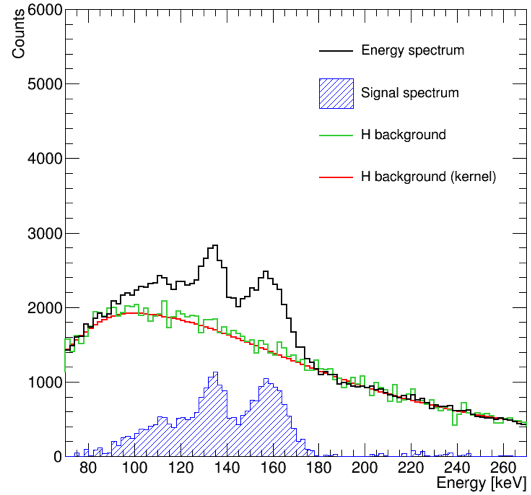
Smoothed with a Gaussian kernel algorithm

Time evolution at a fixed temperature

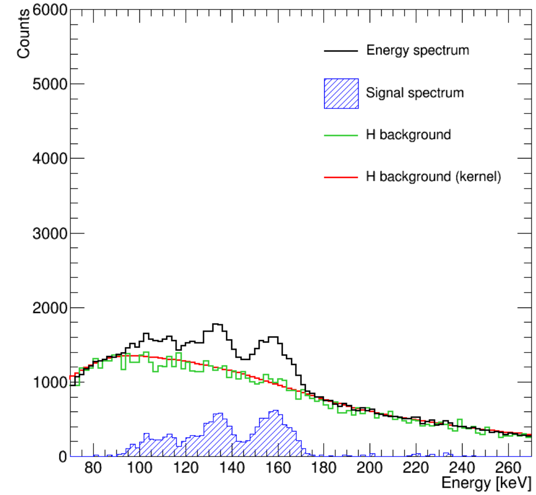
Time bin 6

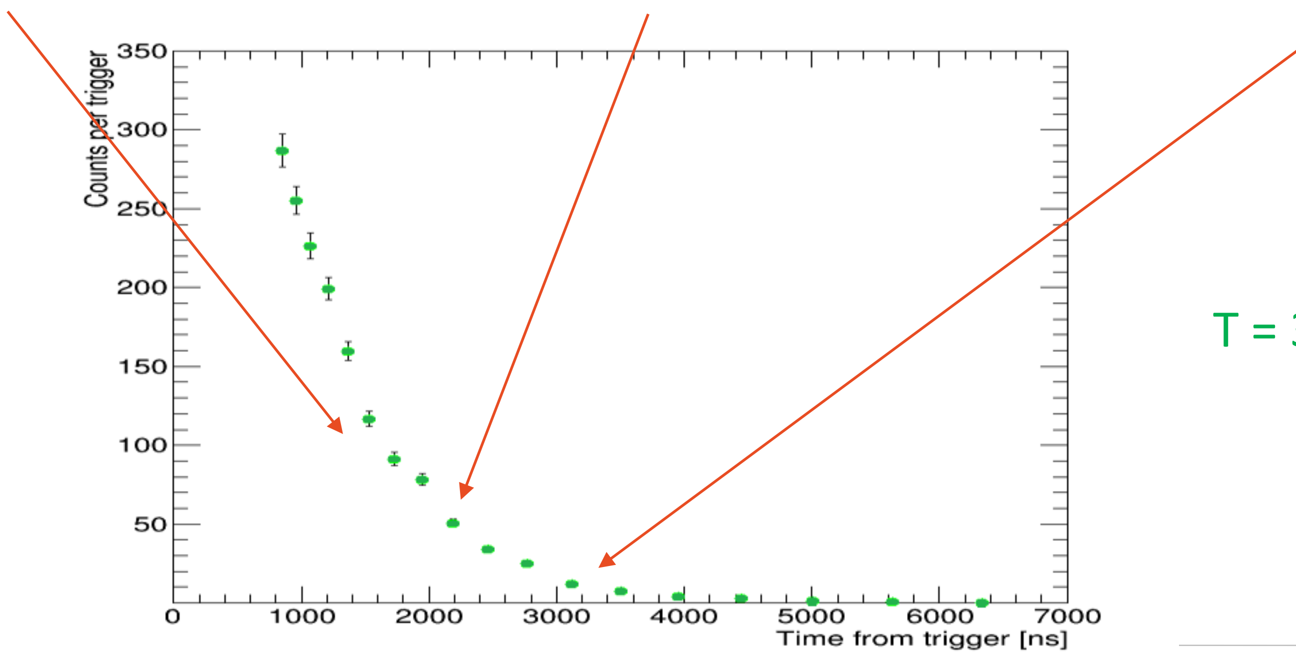


Time bin 9



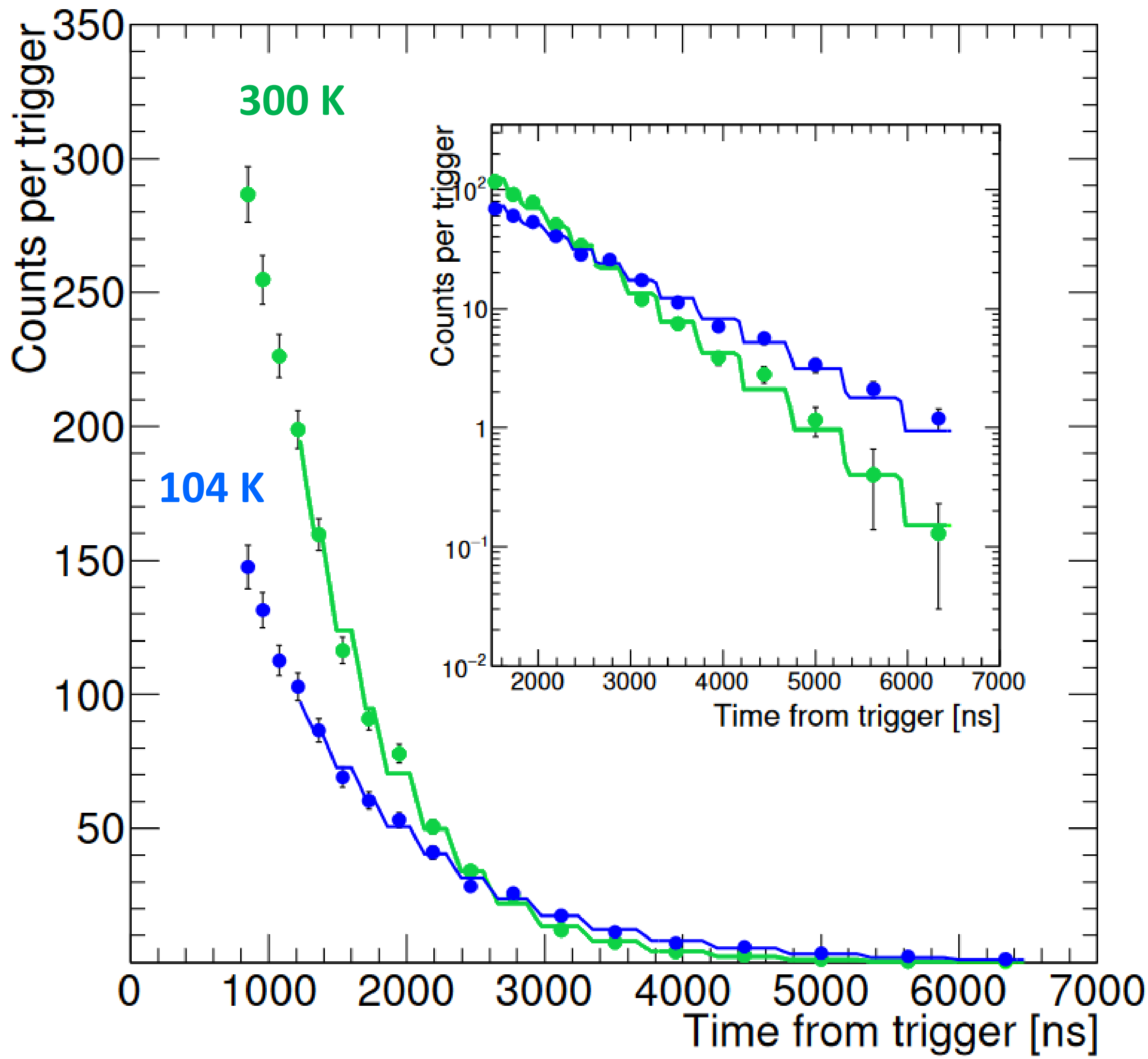
Time bin 12



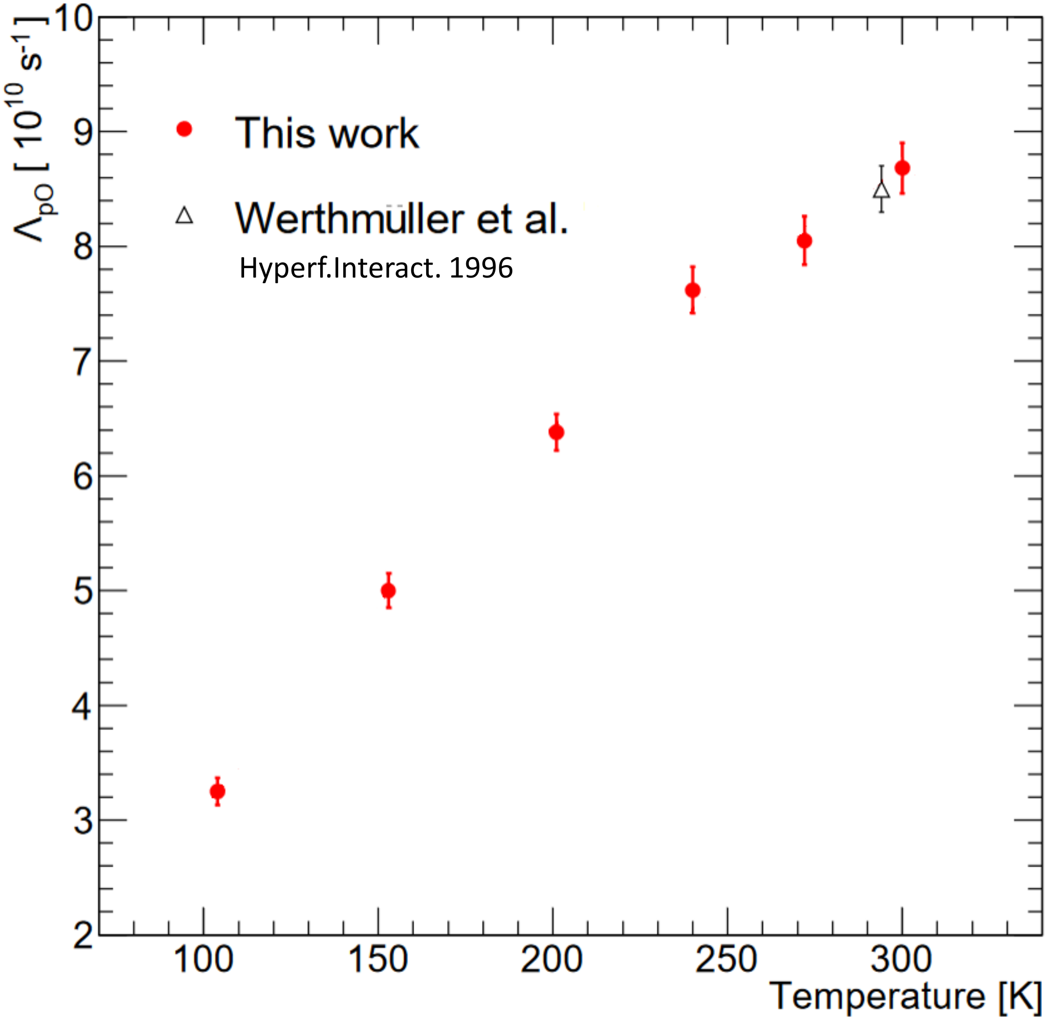


T = 300 K

Data fit

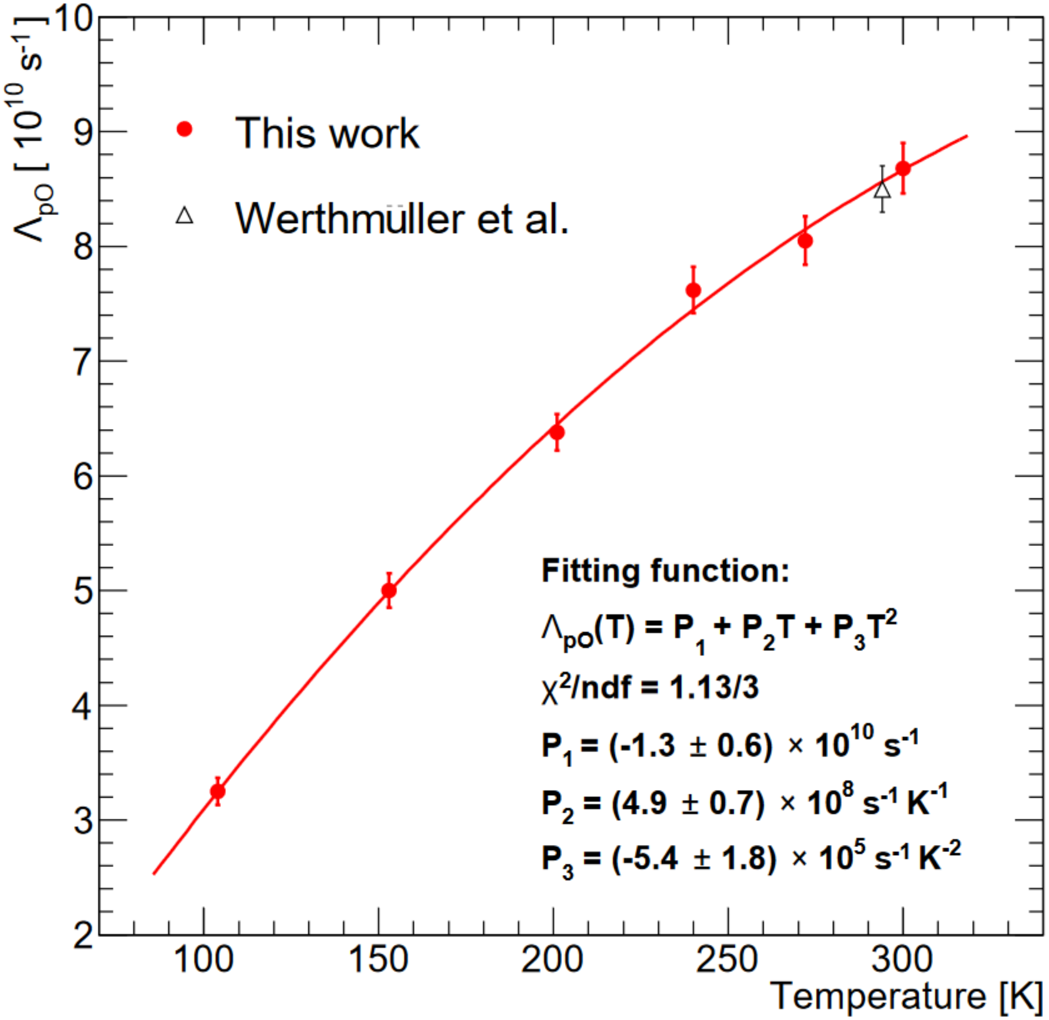

300 K
104 K
Counts per trigger
Time from trigger [ns]
0
1000
2000
3000
4000
5000
6000
7000
50
100
150
200
250
300
350
Counts per trigger
Time from trigger [ns]
10^{-2}
10^{-1}
1
10
10^{2}
2000
3000
4000
5000
6000
7000

Transfer rate vs Temperature



Submitted to PRA and http://arxiv.org/abs/1905.02049

Transfer rate vs Temperature



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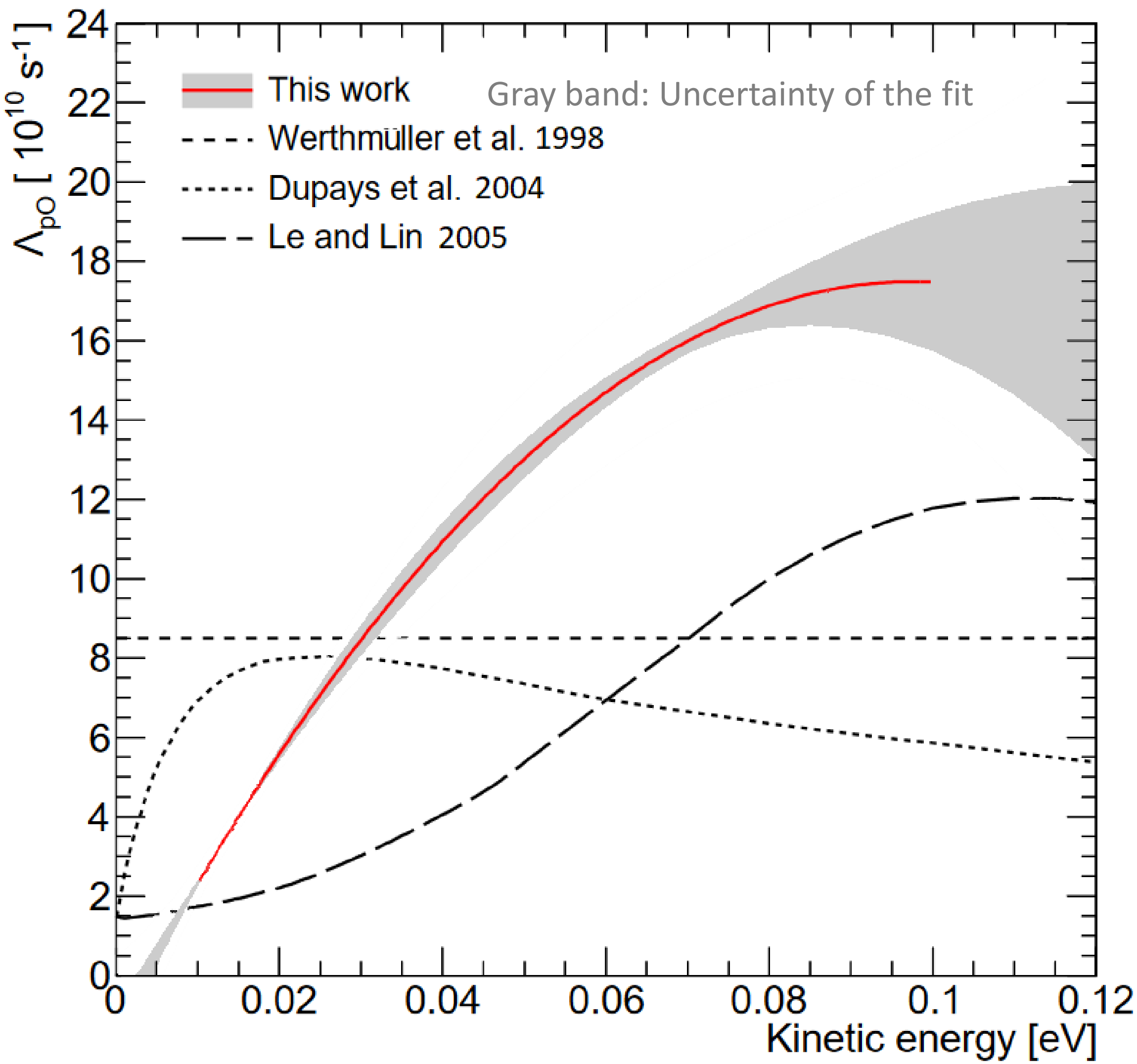
Transfer rate vs Energy



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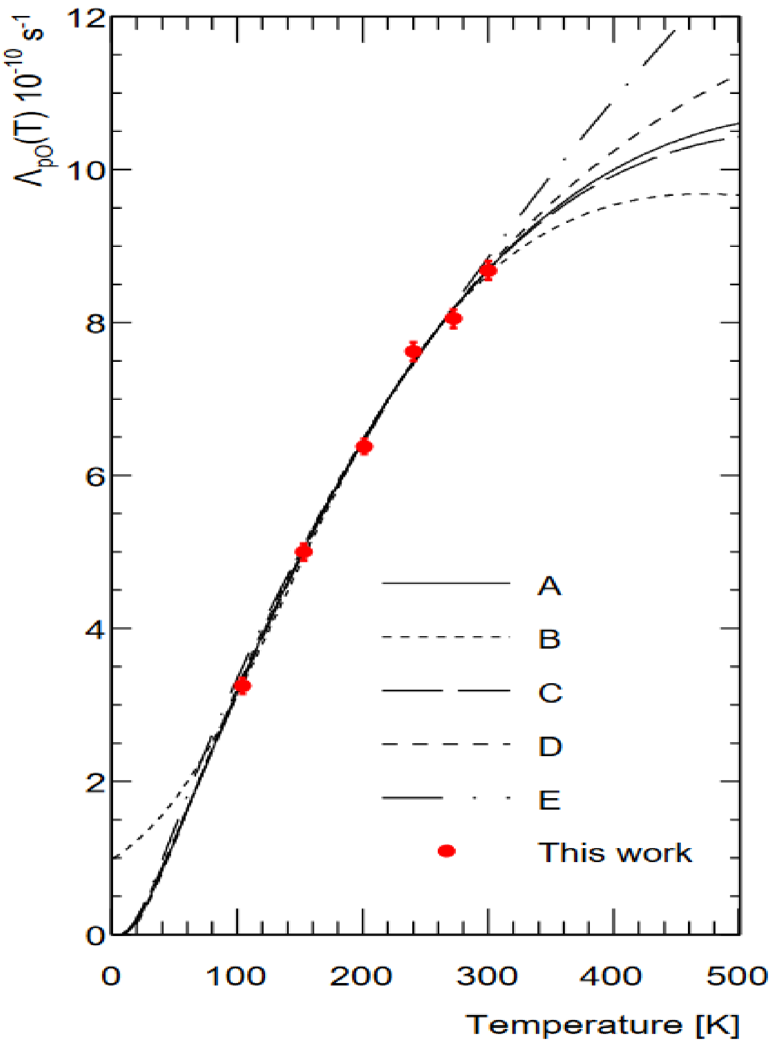
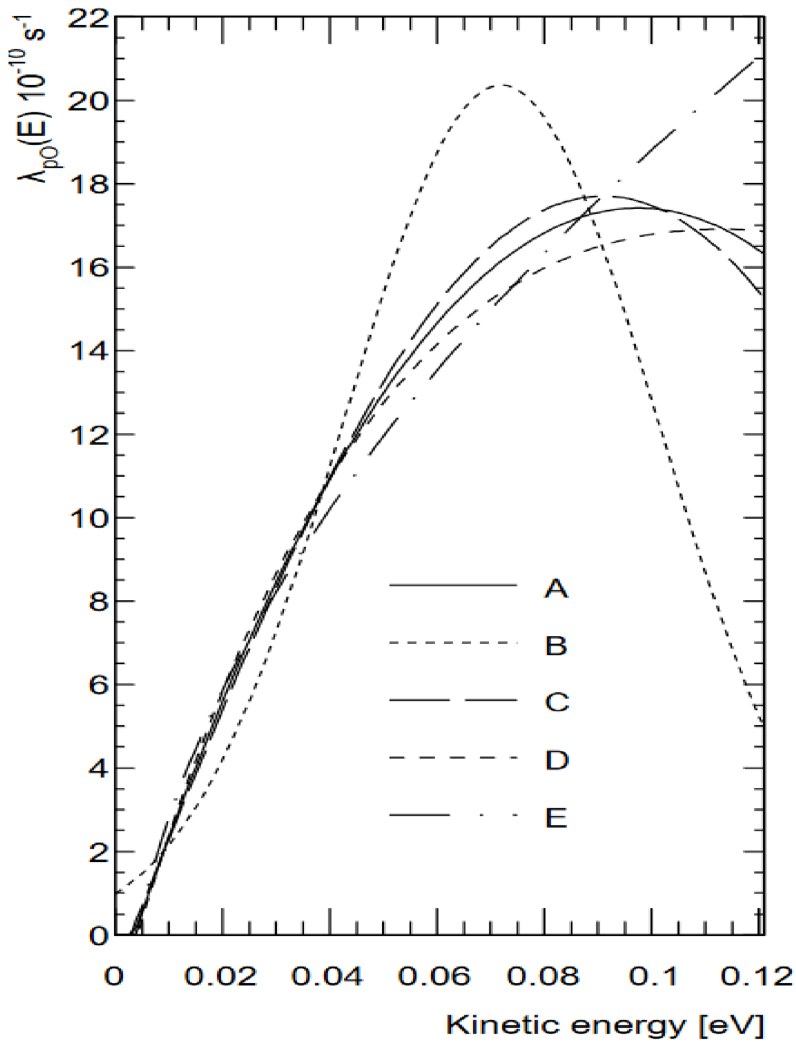
Transfer rate model systematics





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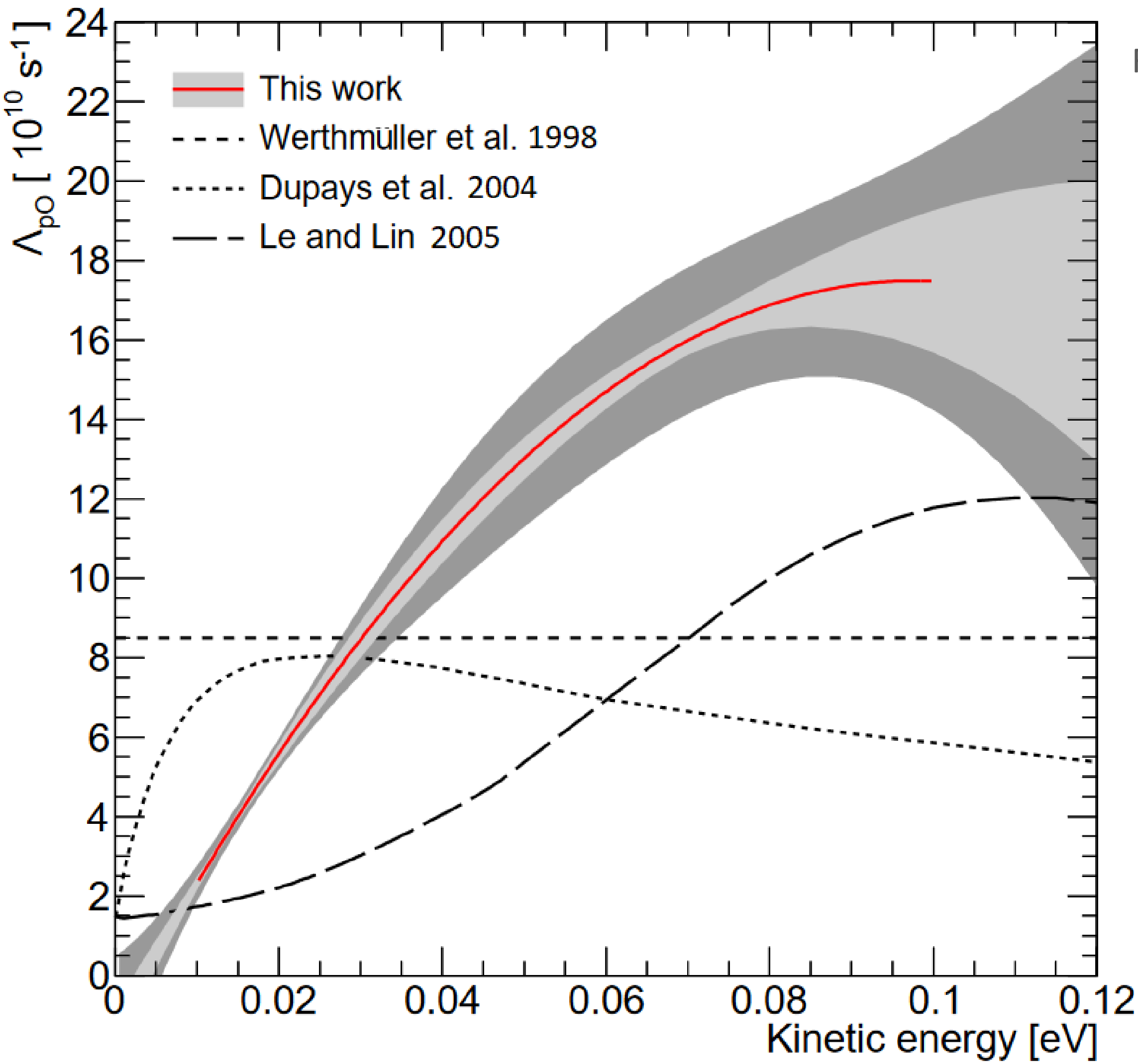
Transfer rate vs Energy



Fit-model systematics

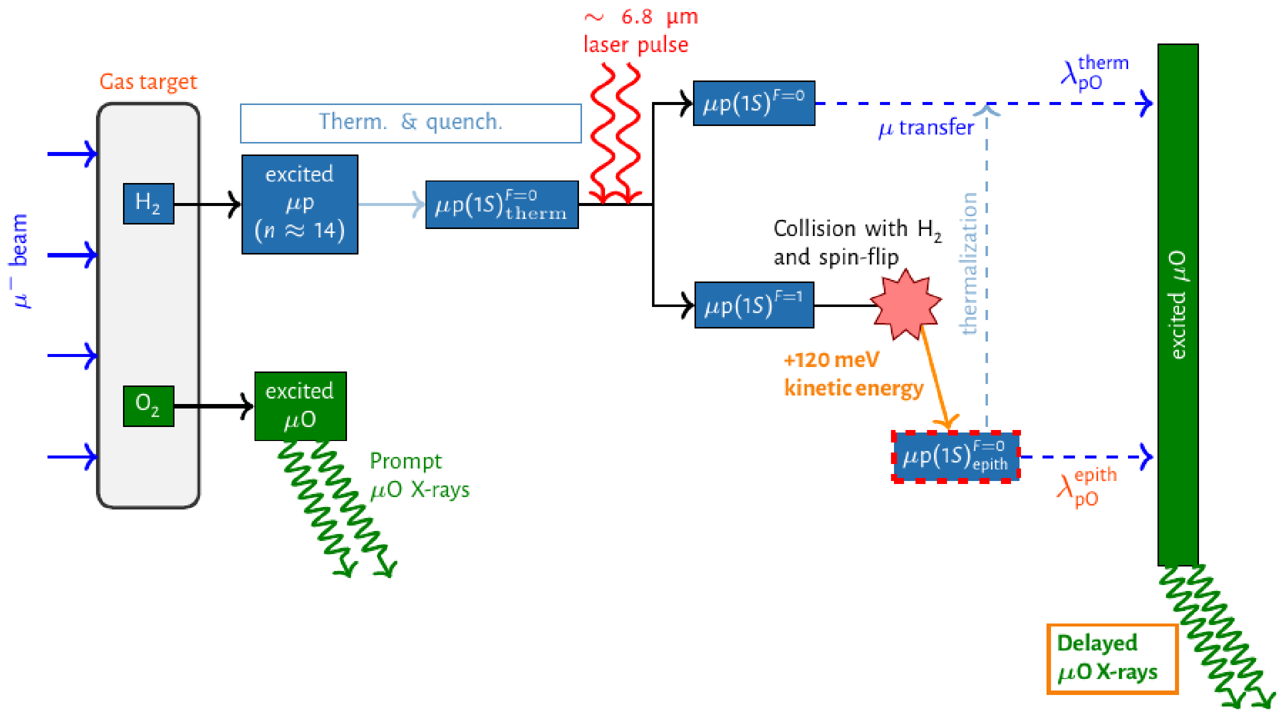
Uncertainty of the fit

Submitted to PRA and http://arxiv.org/abs/1905.02049

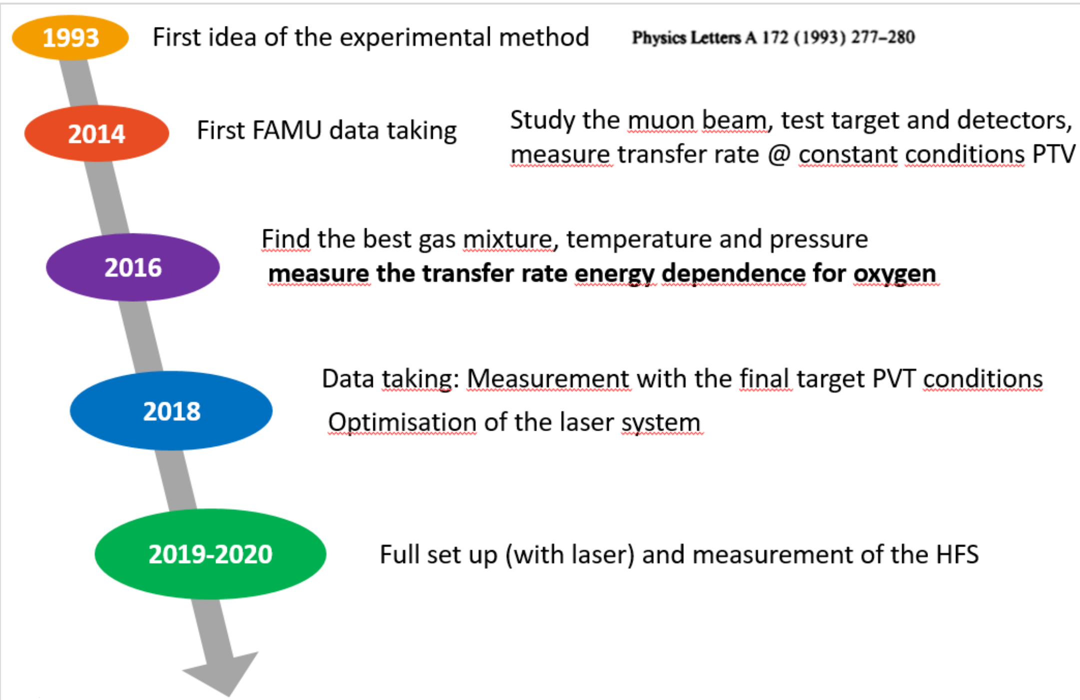
Results

- measured for the first time the **temperature dependence** of the transfer rate for **oxygen** in the range 100-300 K
- the **energy dependence** of the transfer rate **increases by a factor 8** for energies in 0.01-0.08 eV

*This change is **very important** for the FAMU experiment*
*where the **energy dependence** of the transfer rate is used **a signature***



Outlook



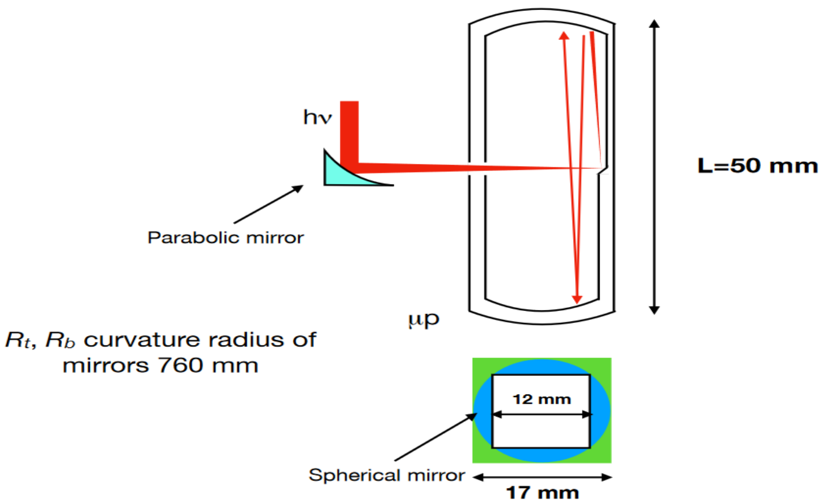
Transfer rate energy dependence for Oxygen ✓

2018 Analysis being finalized
- confirms 2016 results & extends range
- tested final target conditions ✓

Final steps towards the muonic HFS measurement

Towards the final measurement

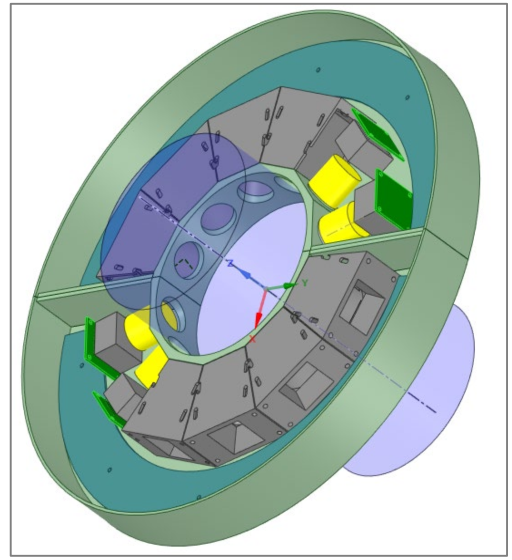
Laser optimisation

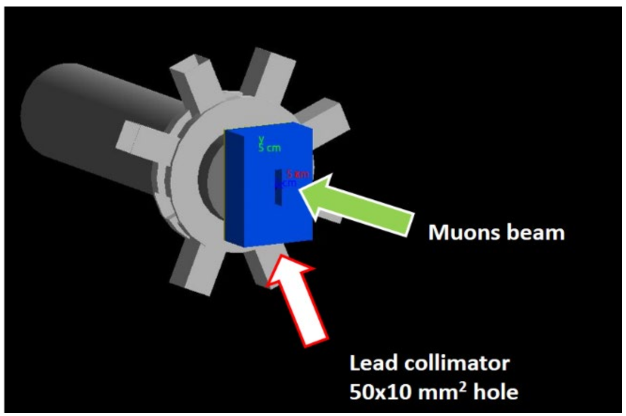


Target & cavity studies

Towards the final measurement

X rays detectors





Dedicated MC simulation

Full set up will be ready

to perform the measurement of HFS in muonic hydrogen

at the end of this year!

Thanks for your attention