FAMU: study of the energy dependent transfer rate $\Lambda_{\mu p \to \mu O}$

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on behalf of the FAMU Collaboration

International Conference on Precision Physics of Simple Atomic Systems

Wien – 14/18 May 2018

Outline

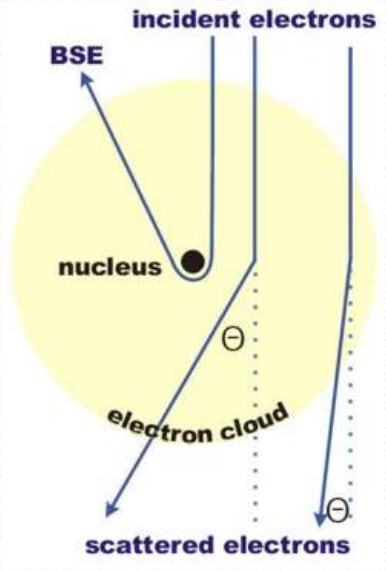
- Introduction
- The FAMU experiment
- Apparatus setup
- Measurement of the transfer rate $\Lambda_{\mu p \to \mu O}$ (a.k.a. Λ_{pO}):
  - Data selection and selection efficiencies
  - Background evaluation
  - Time dependence fit
- Results
- Summary

Introduction

FAMU: HFS of $\mu^- p$ ground level

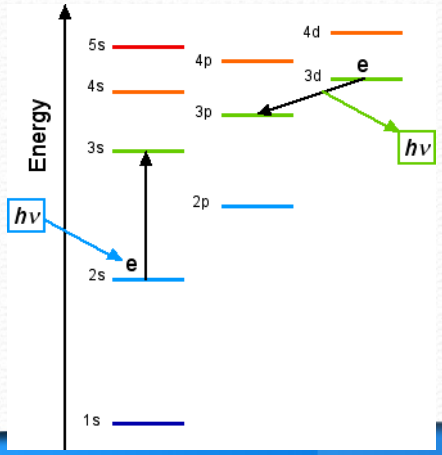
Study of the properties of the proton

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

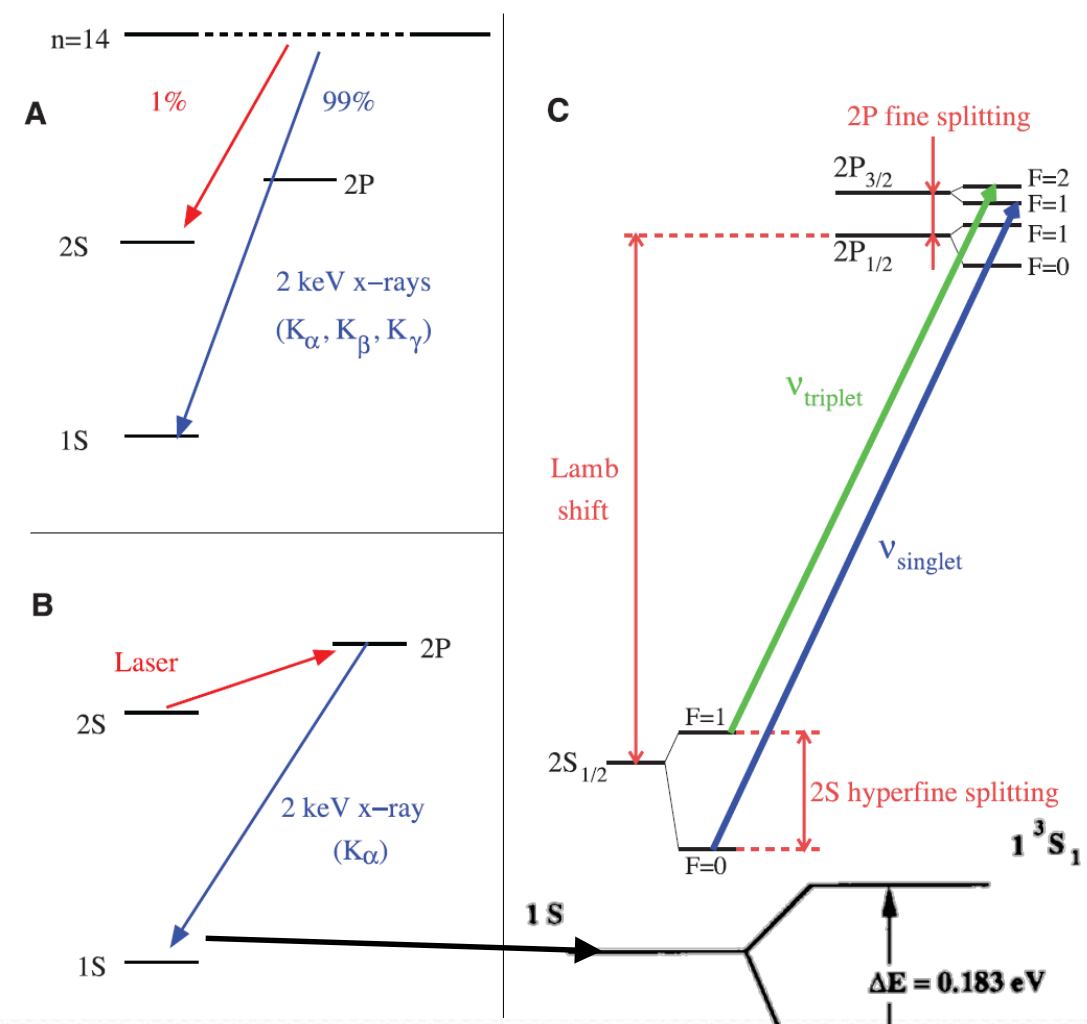


3) spectroscopy: electronic atoms and ions
4) spectroscopy: exotic atoms

HFS of muonic hydrogen ground level



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
- **Laser developement**
- **Muon transfer** studies

hyperfine structure

The FAMU experiment

Fisica Atomi MUonici (Physics with muonic atoms)

FAMU: $\mu^- p$ spectroscopy

"Usual" spectroscopic flow:

1) create muonic hydrogen
2) laser excitation
3) count triplets

repeat varying laser frequency to find resonance value.

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

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

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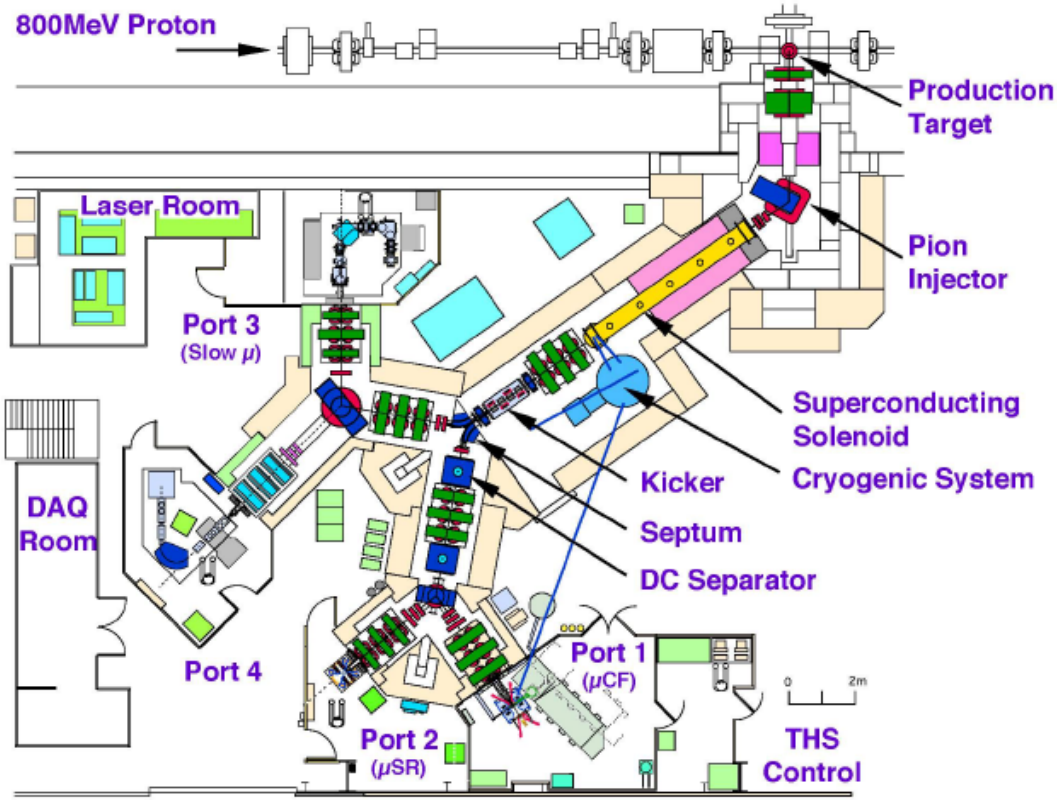
- H. Schneuwly, Z. Phys. C - Particles and Fields 56, 280 (1992).
- R. Jacot-Guillarmod, Muon transfer from thermalized muonic hydrogen isotopes Phys. Rev. A51, 2179 ~1995.
- F. Mulhauser and H. Schneuwly, J. Phys. B 26, 4307 ~1993.
- L. Schellenberg, P. Baeriswyl, R. Jacot-Guillarmod, B. Mis- chler, 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.

Apparatus setup

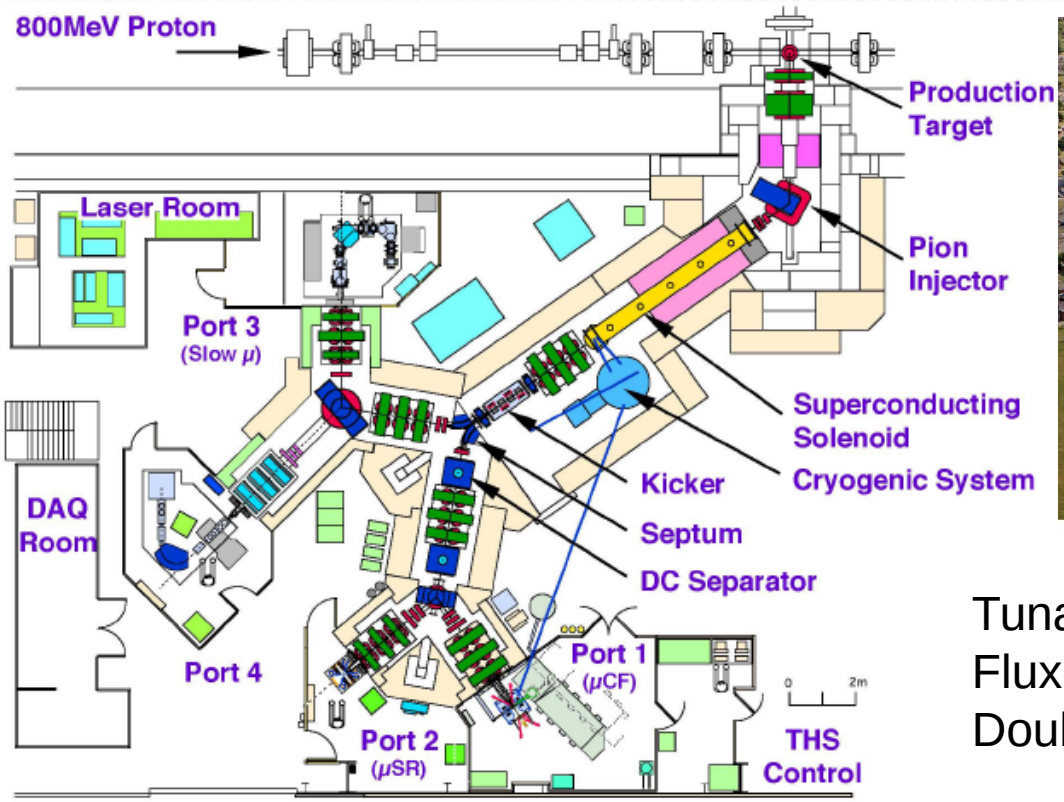
RIKEN – RAL muon facility

Rutherford Appleton Laboratory – Oxfordshire UK



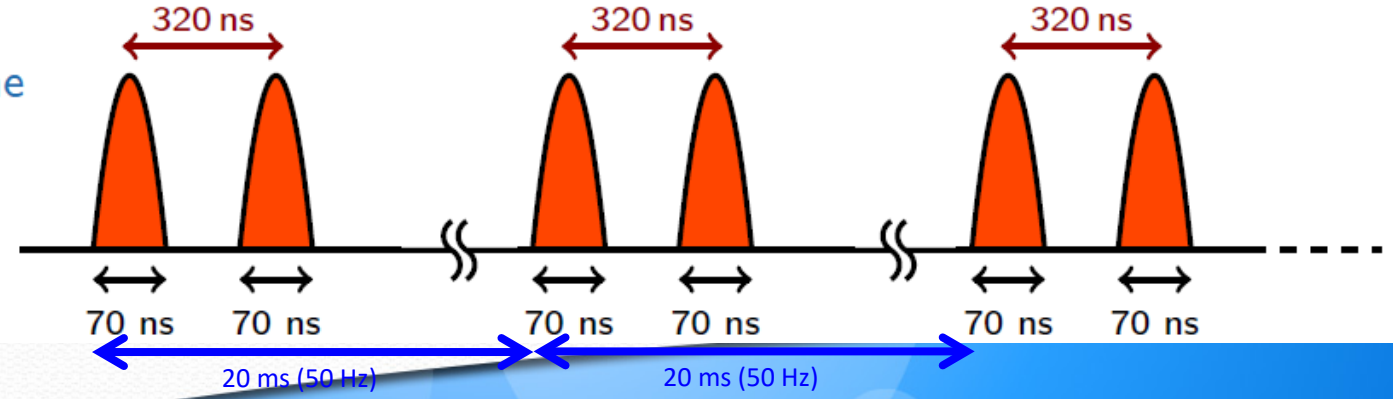
The brightest pulsed muon beam facility in the world!

High intensity muon beam

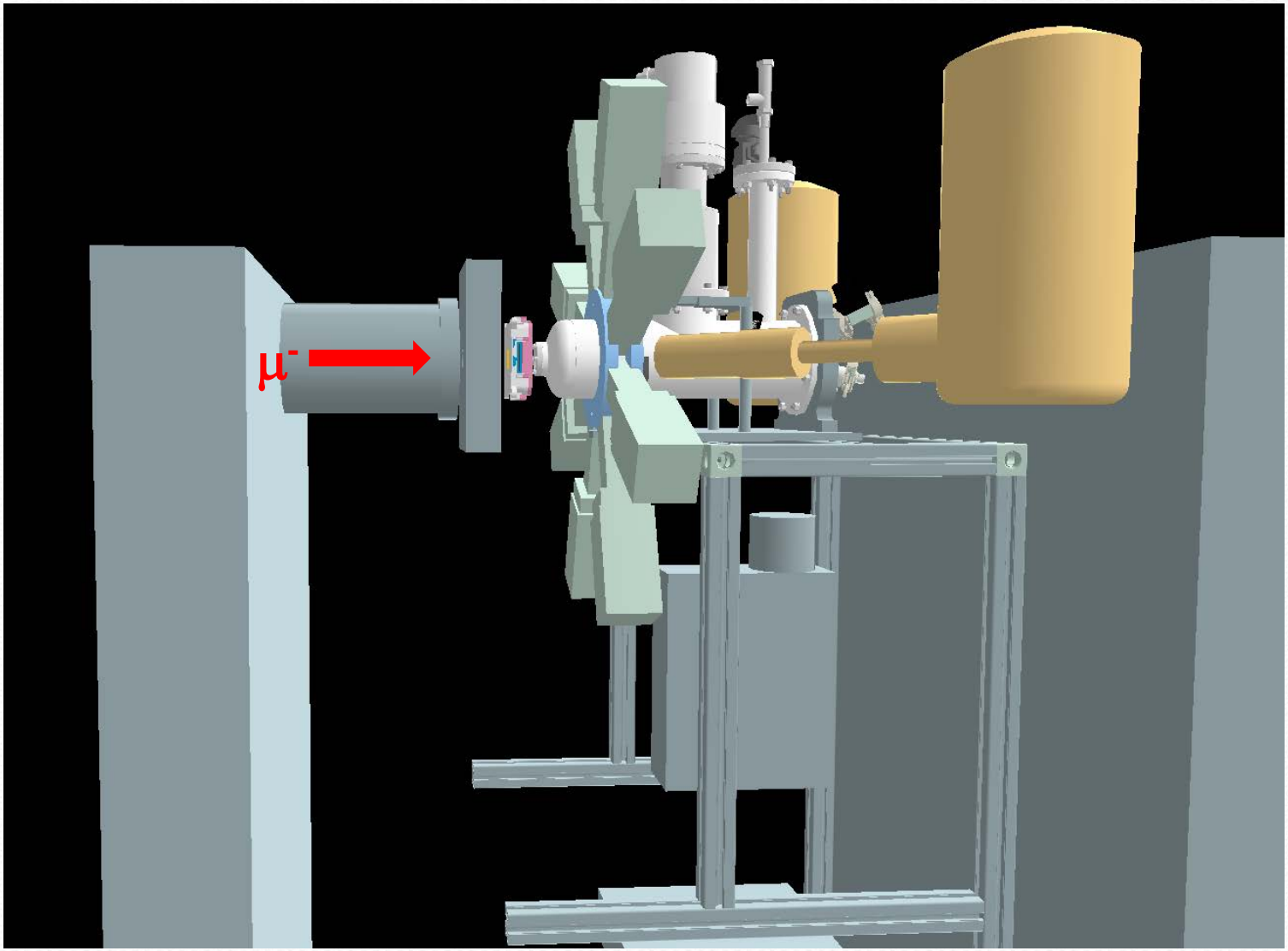


Tunable momentum: 20 – 120 MeV/c
Flux μ^- : 7 x 10^4 muons/s
Double pulsed beam

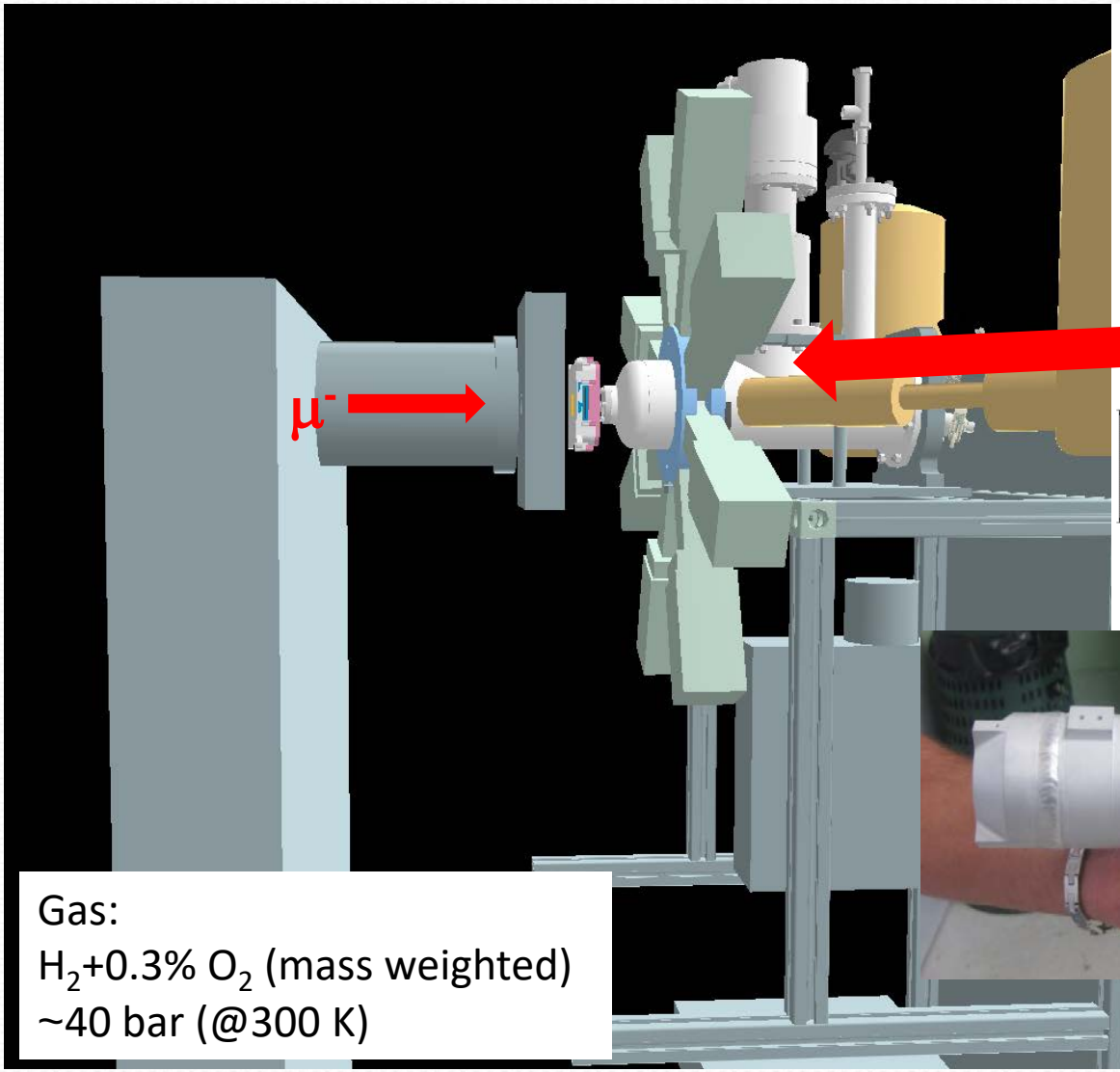
Beam time structure

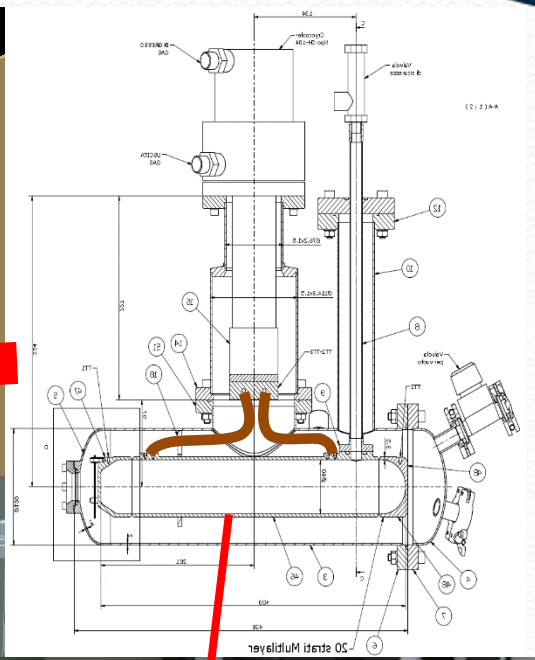


2016: experimental setup



Cryogenic thermalized target

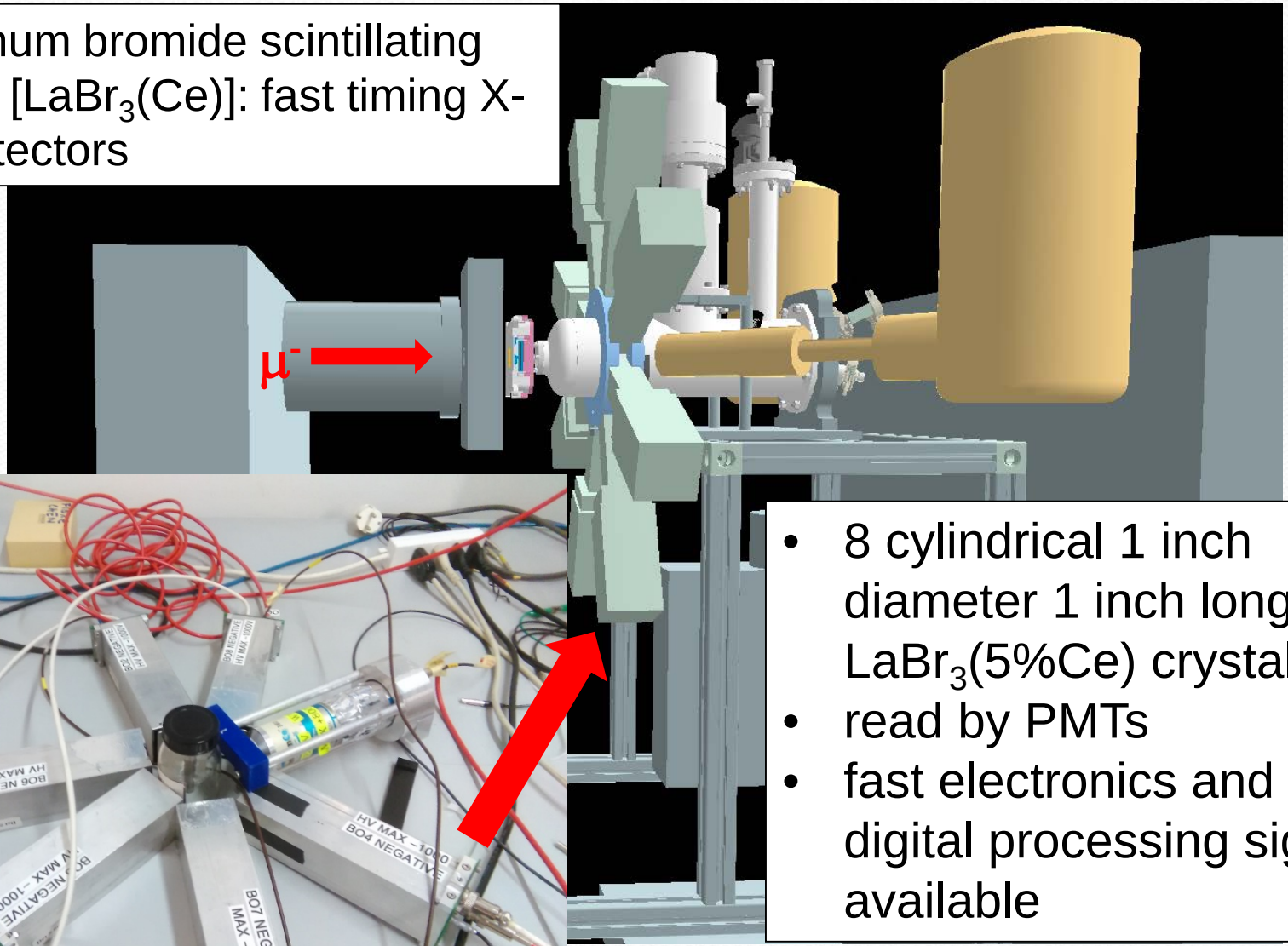




Gas:
H_2+0.3% O_2 (mass weighted)
~40 bar (@300 K)

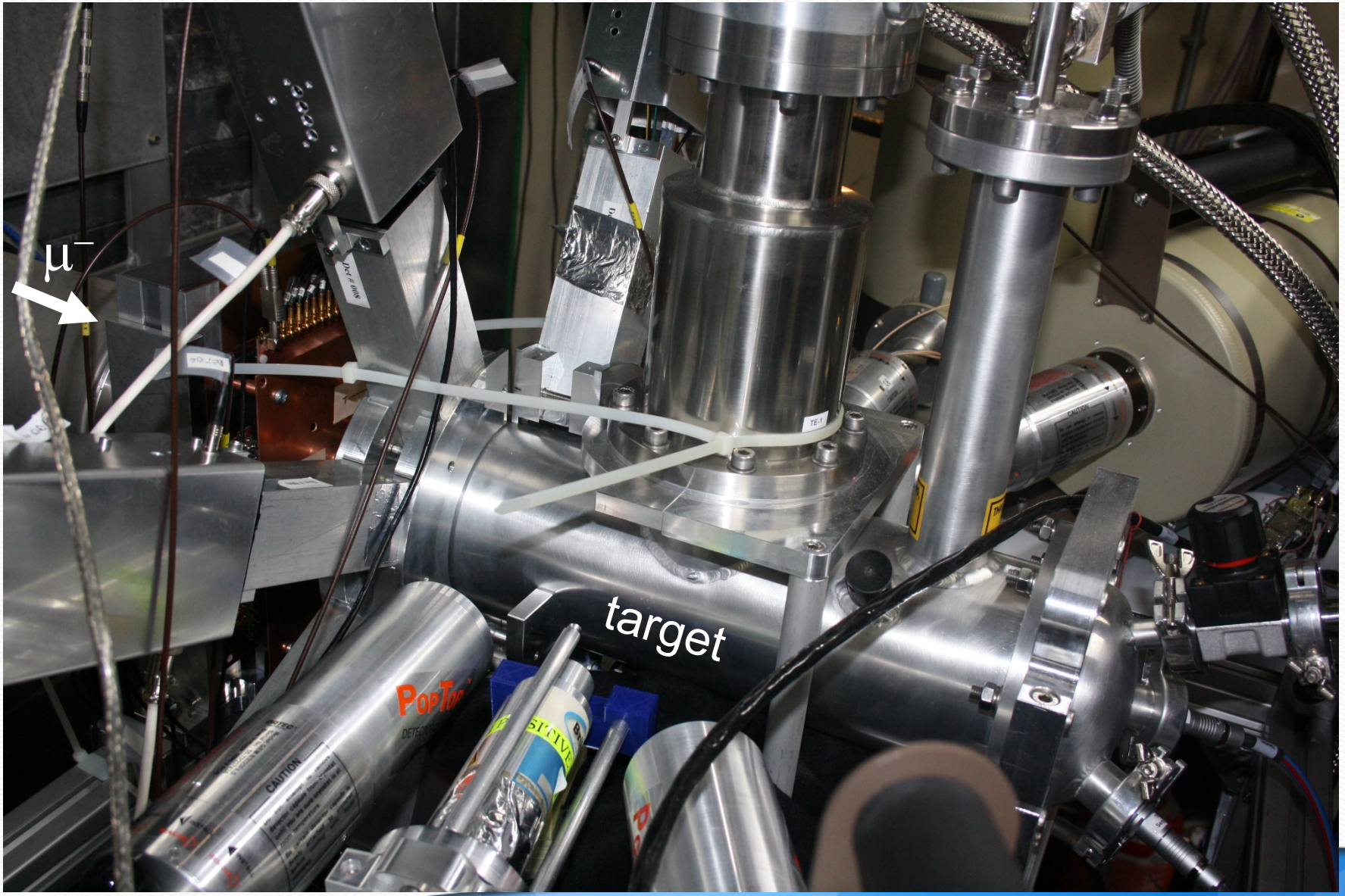
2016: experimental setup

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



- 8 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



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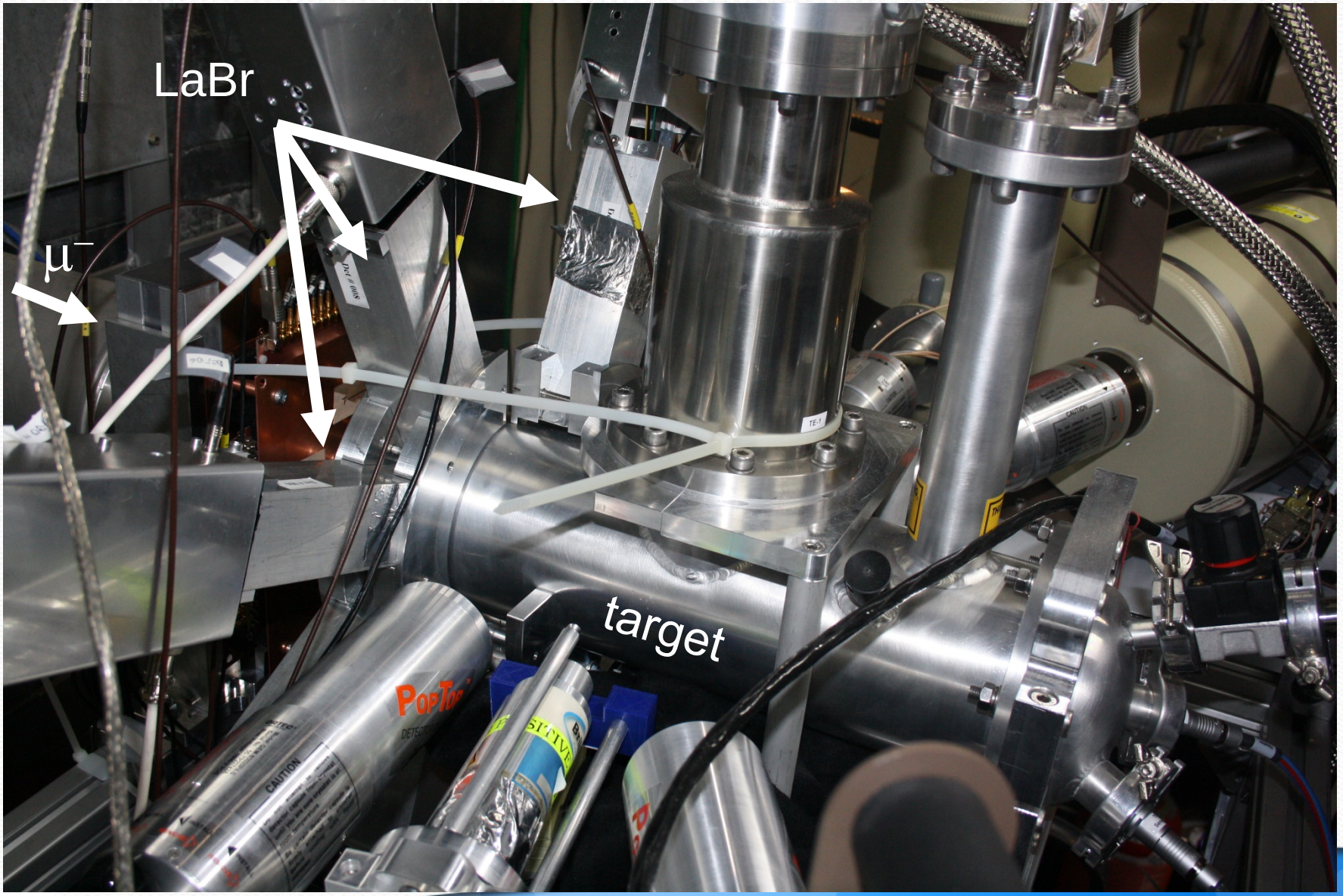

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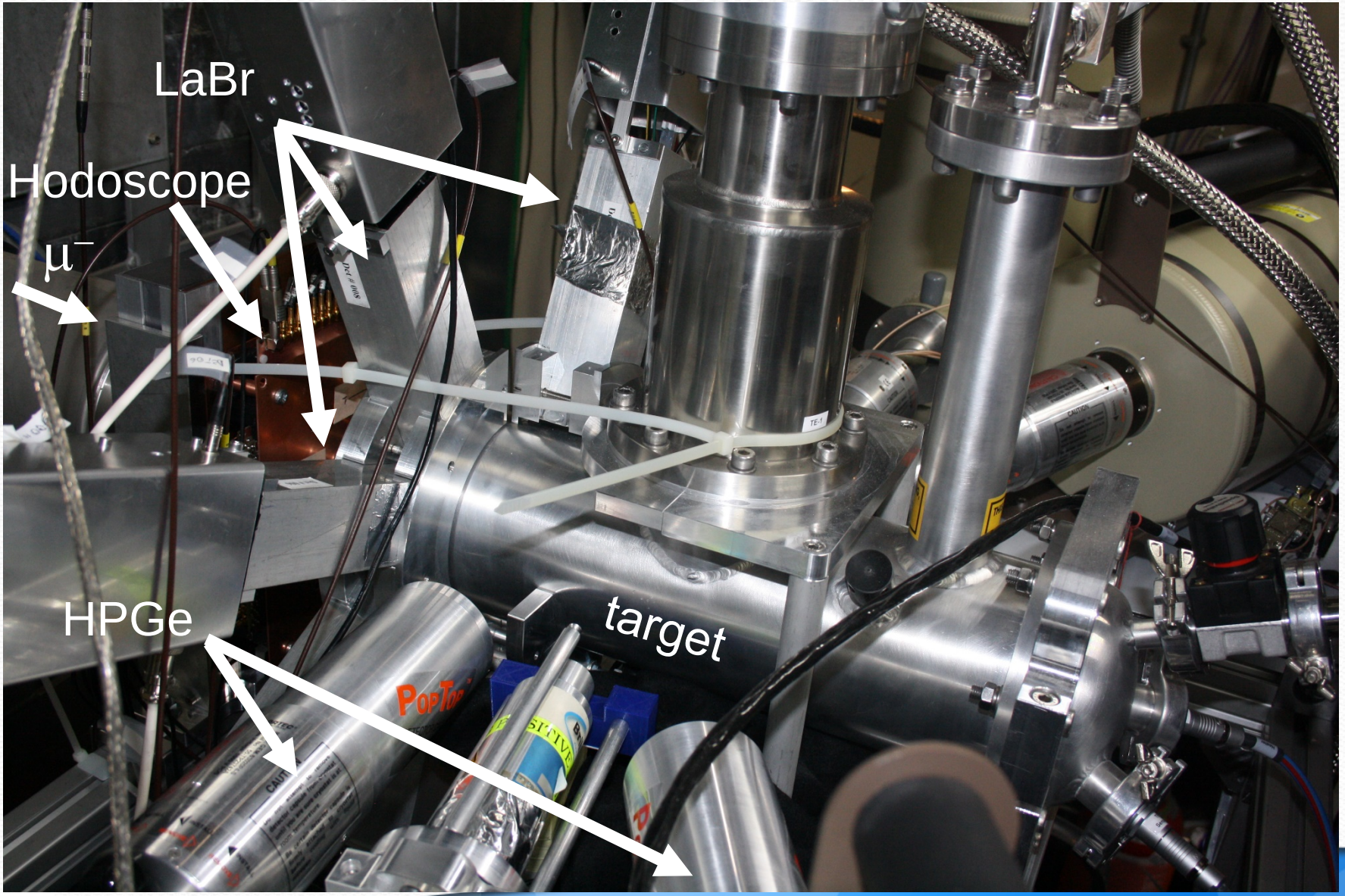
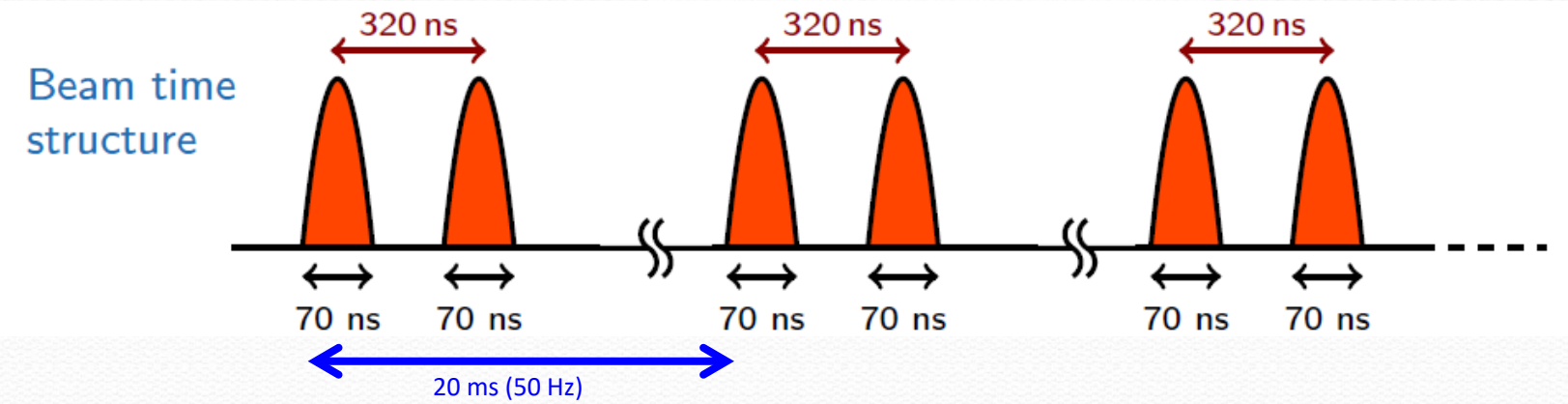
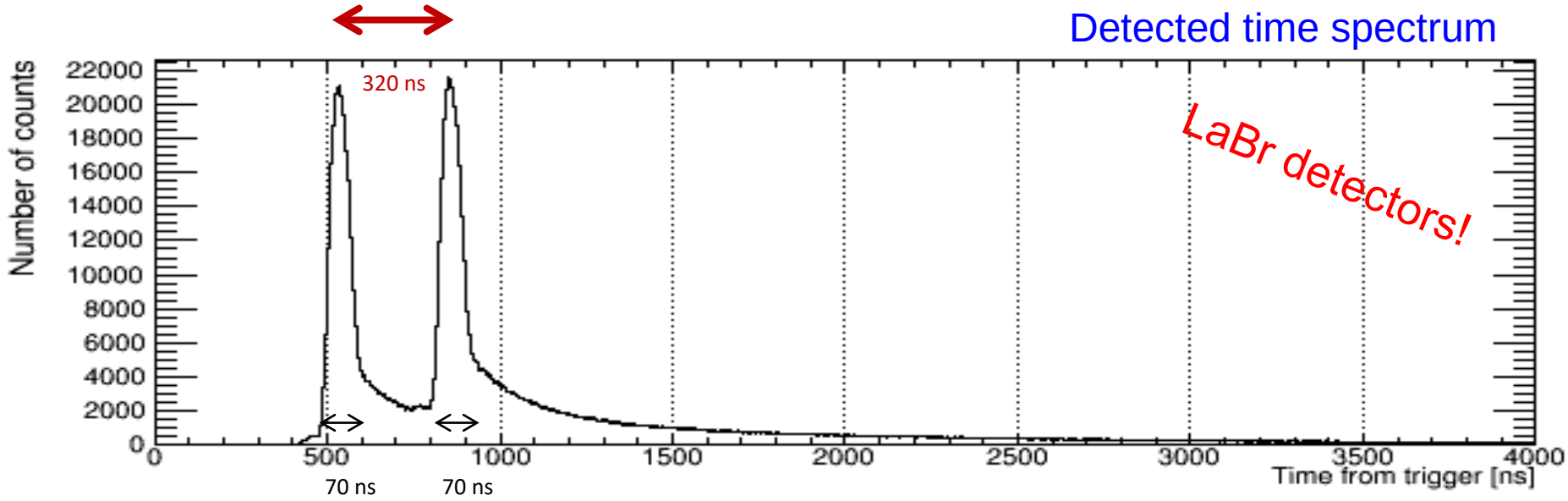


Measurement of the transfer rate $\Lambda_{\mu p \to \mu O}$

Time spectrum: peaks and tails





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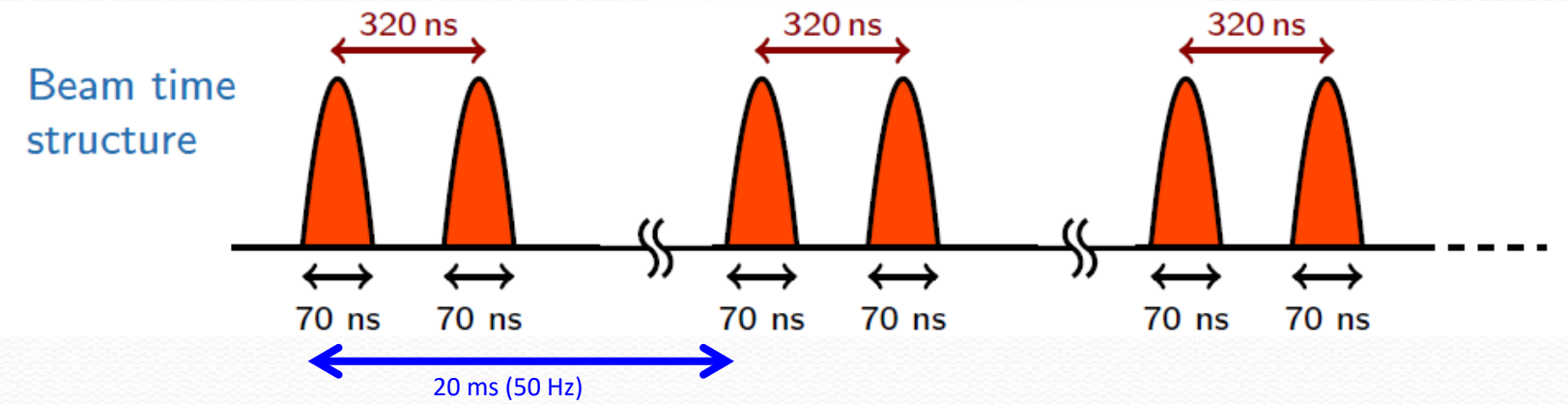

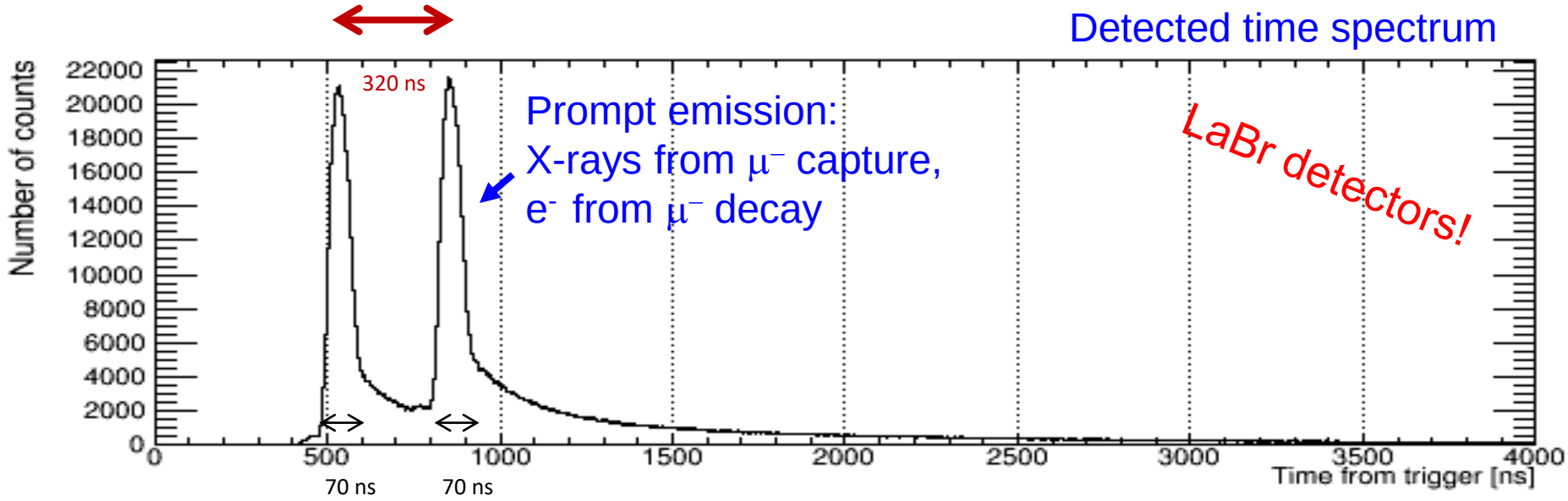

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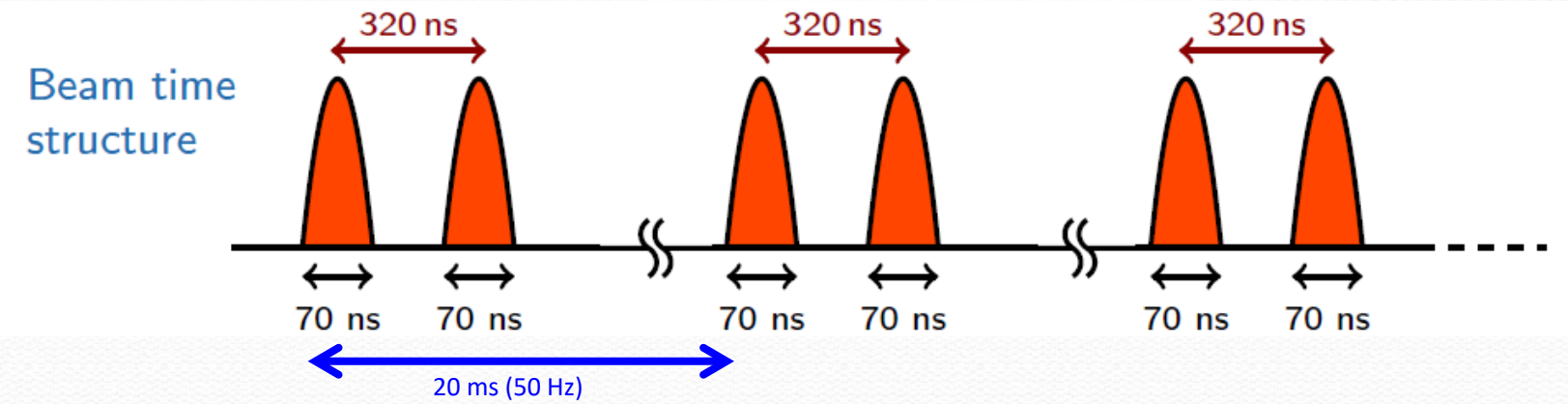
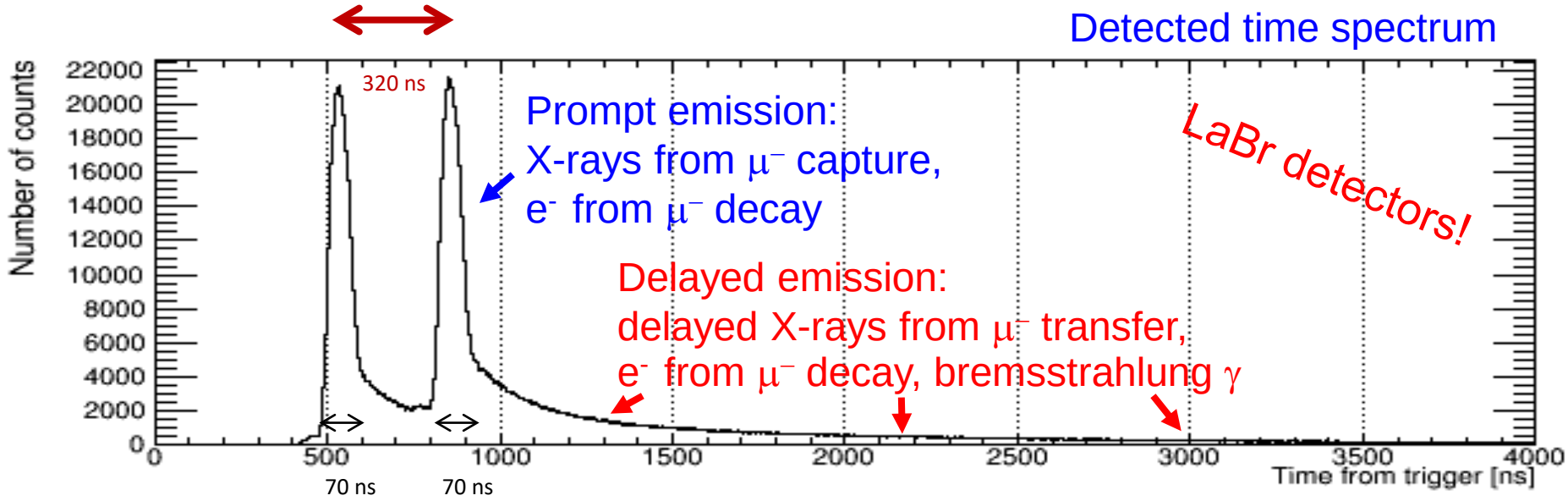


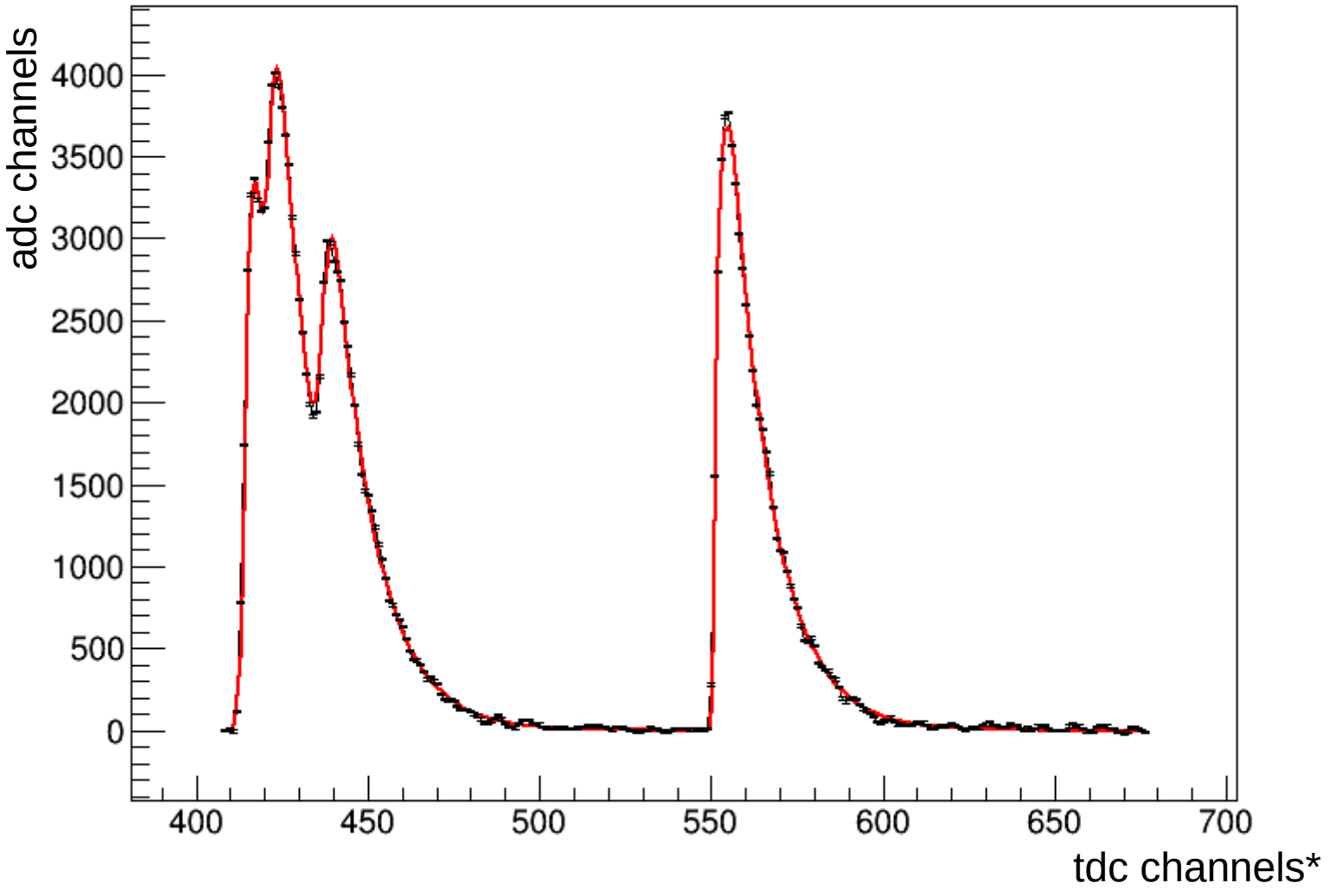


Transfer rate measurement

Steps:

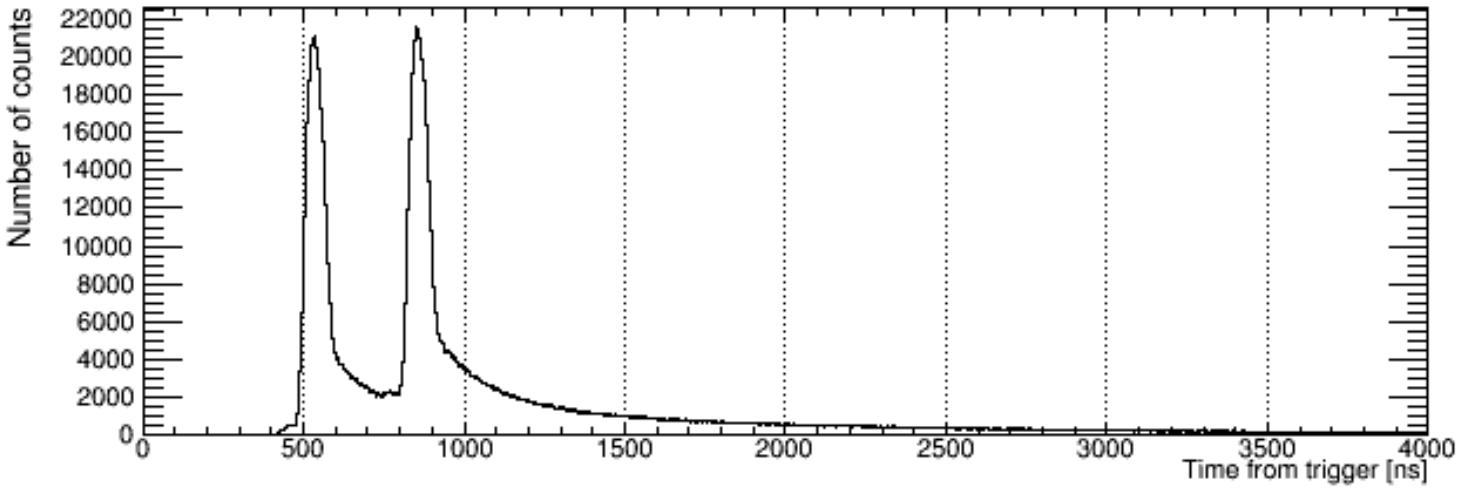
1) fix a target temperature (i.e. mean kinetic energy of gas constant)
2) produce μp and wait for thermalization
3) study time evolution of Oxygen X-rays
4) repeat with different temperature

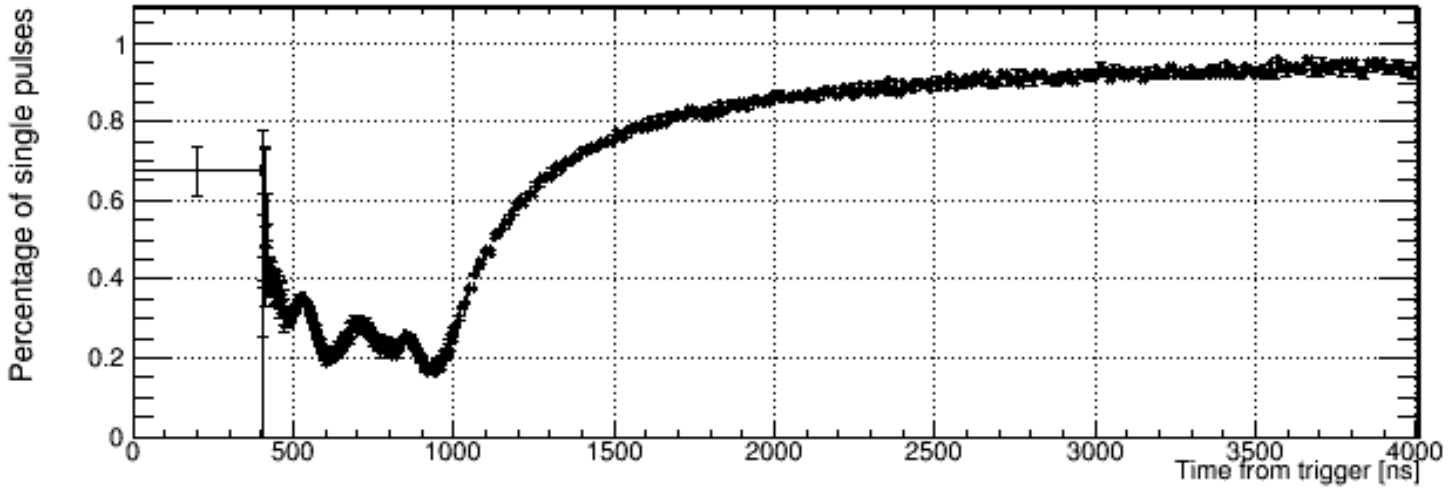
Waveforms fit



* 1 tdc = 2 ns

Mostly single pulses in delayed phase





Data selection

1. “Reasonable” reduced chi2 from the fit

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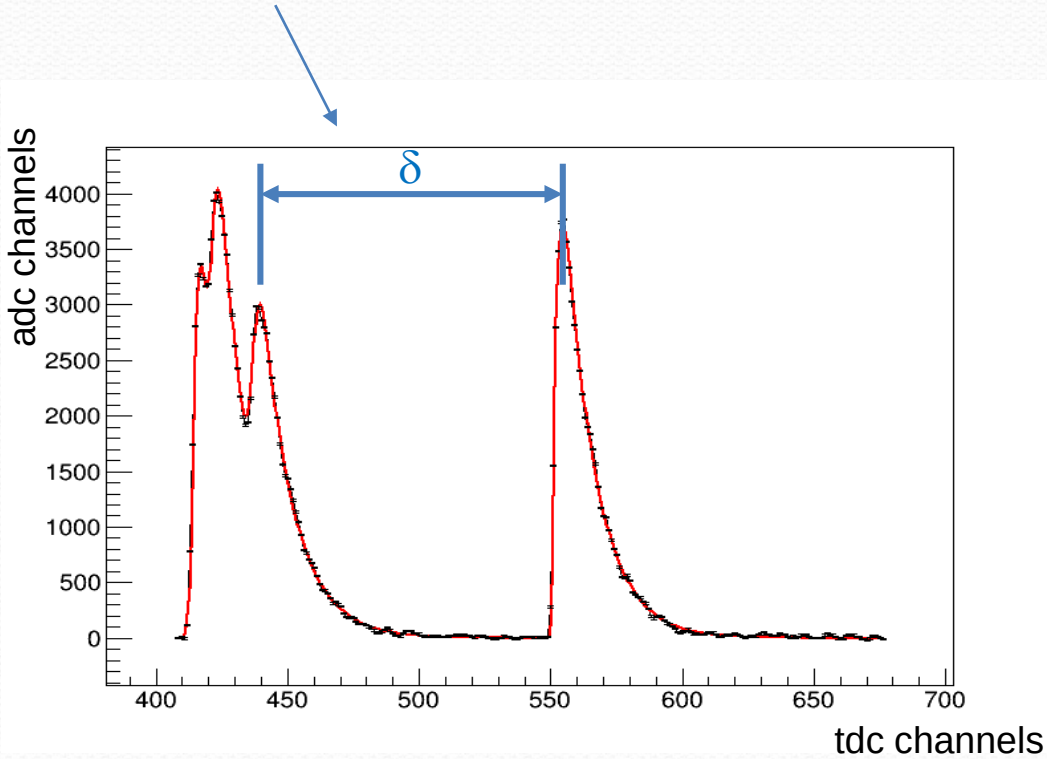
2. Distance (δ) between pulses > 30 ns

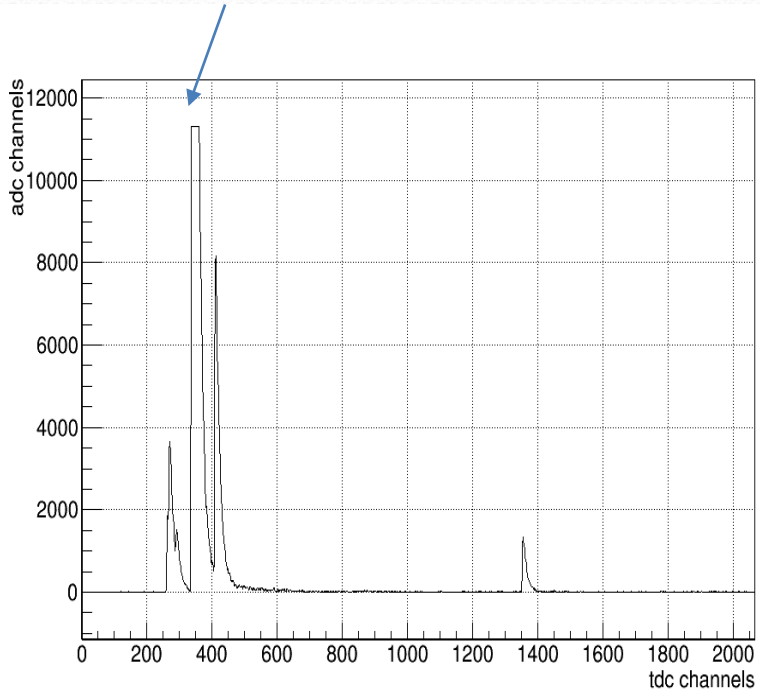


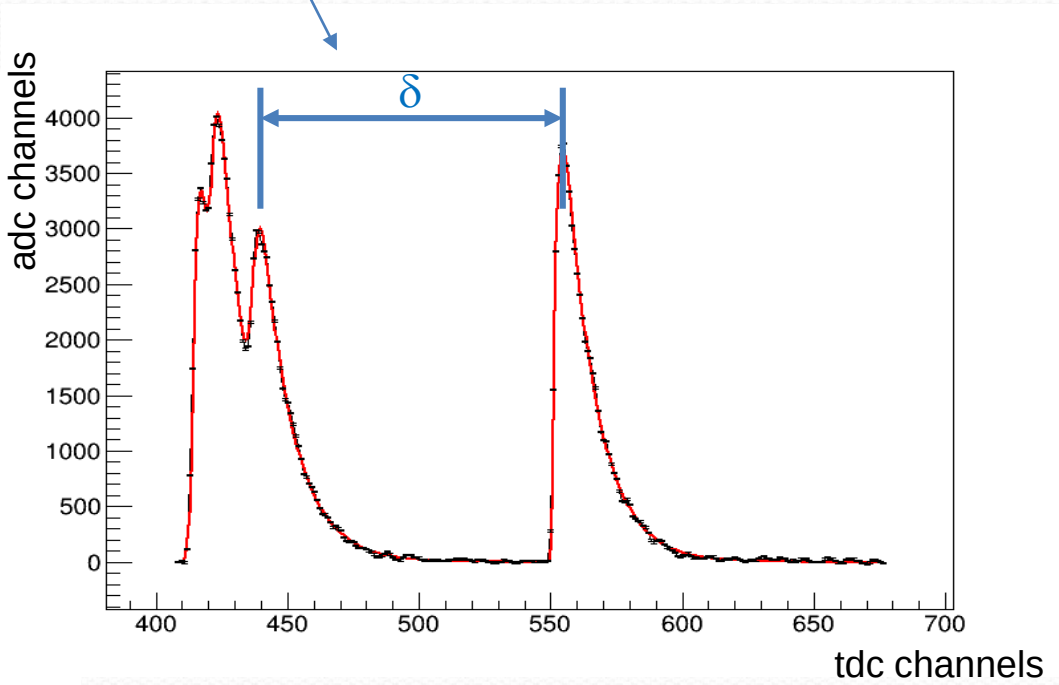
Data selection

1. “Reasonable” reduced chi2 from the fit

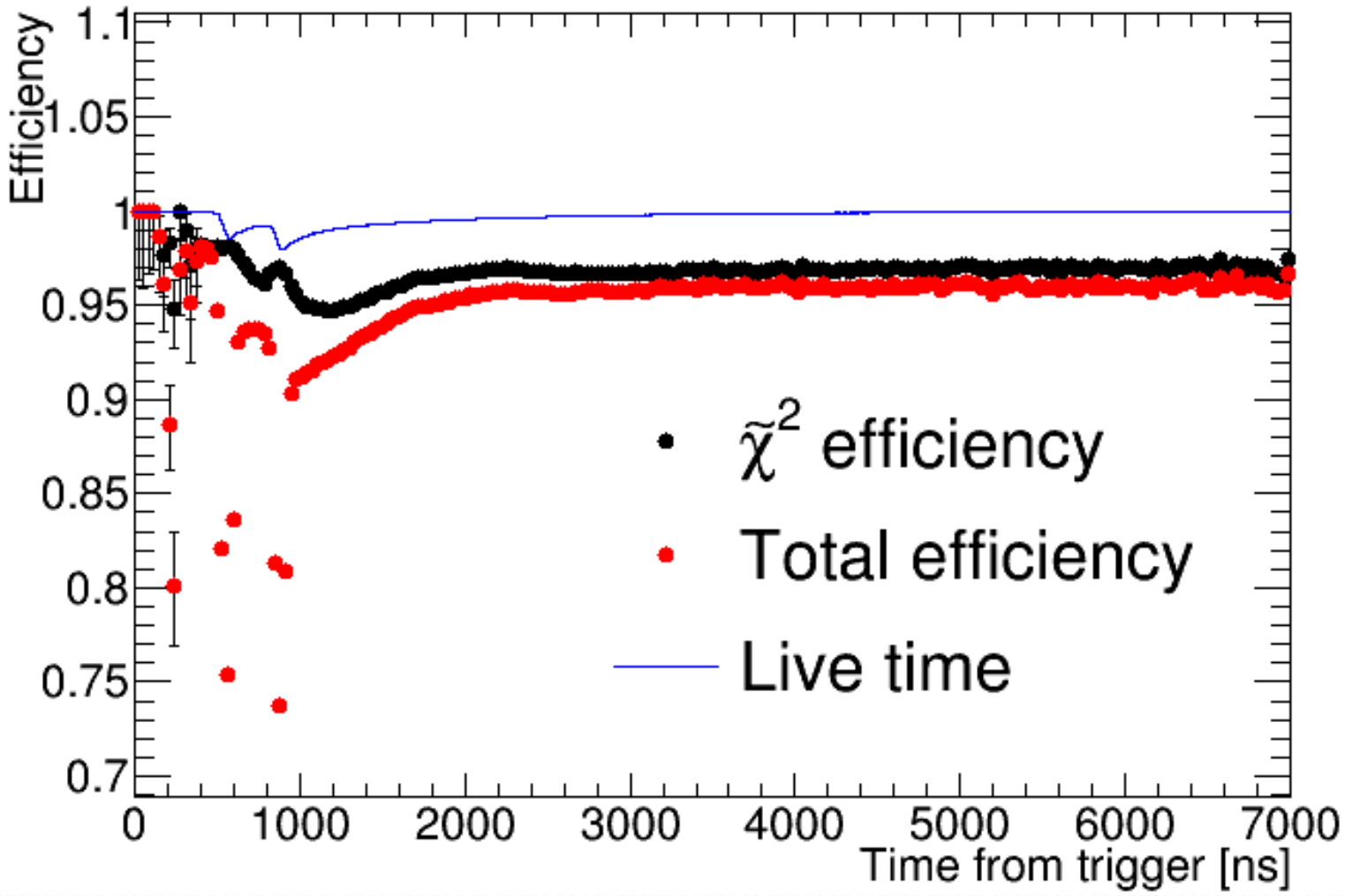
2. Distance (δ) between pulses > 30 ns

3. No saturated events

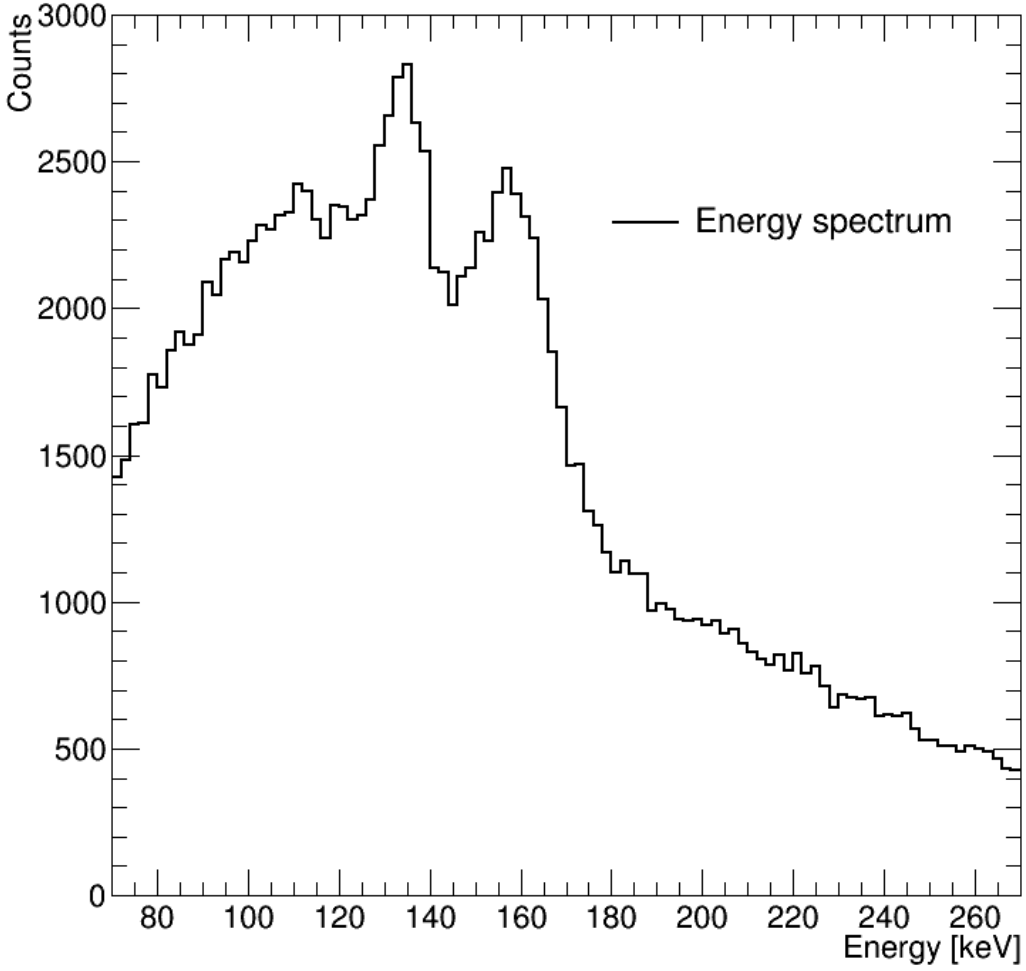




High selection efficiencies

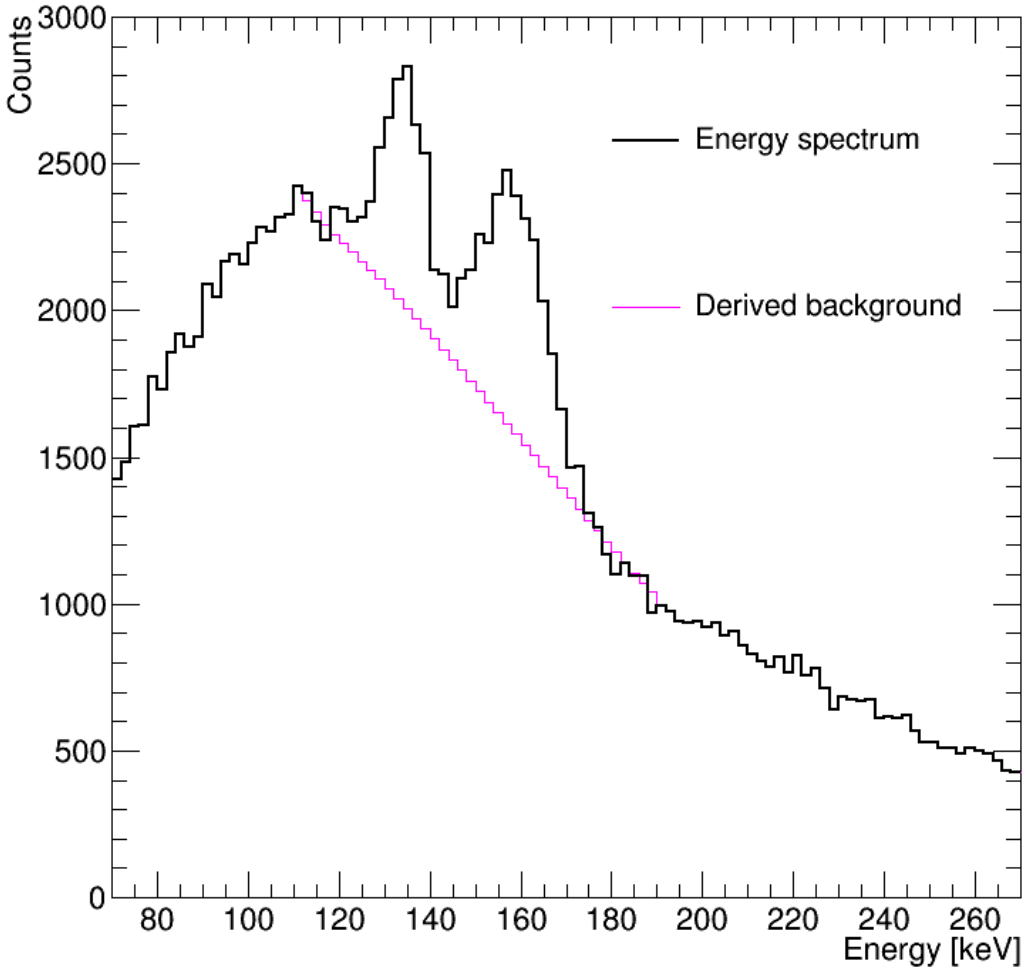


The background problem…



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

Simplest solution: “straight line”

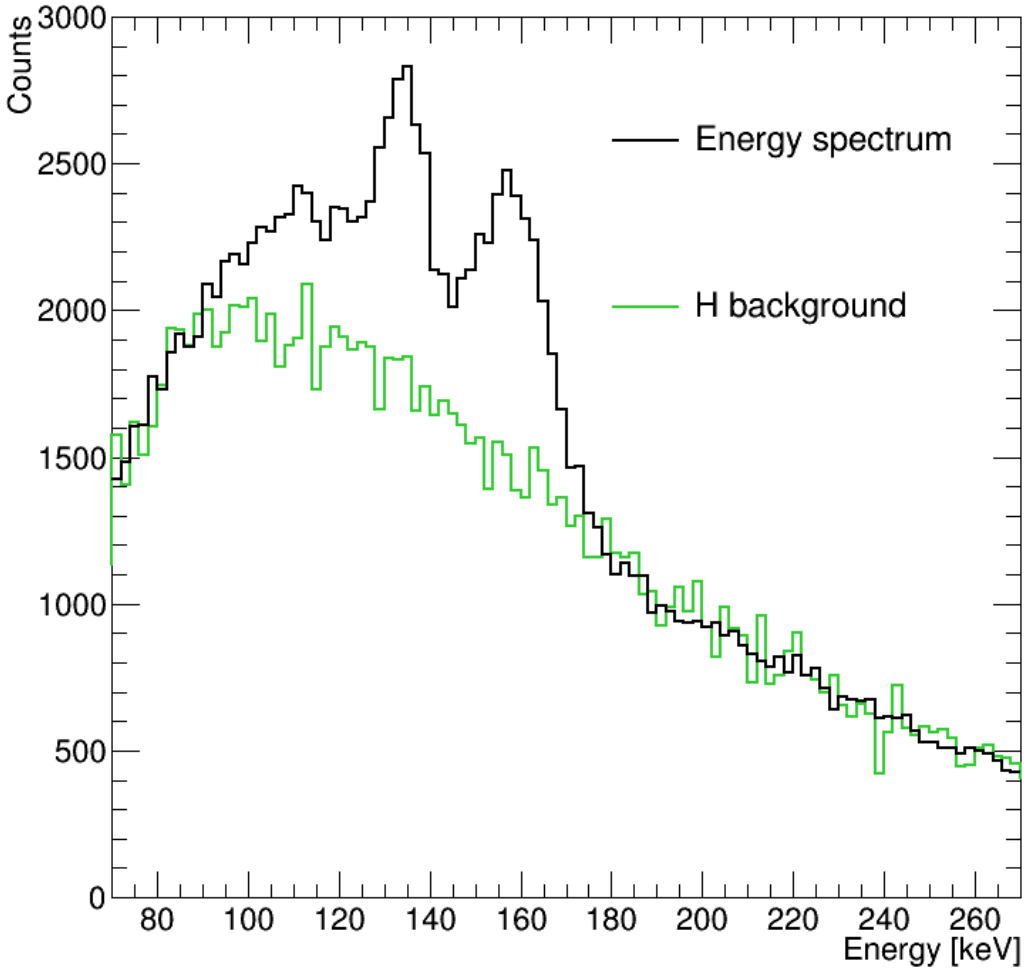


T = 300 K
Time bin = [1450,1650] ns

Using ROOT/“TSpectrum” class – spectroscopic algorithms

Problem: unstable results…

Better solution: pure hydrogen

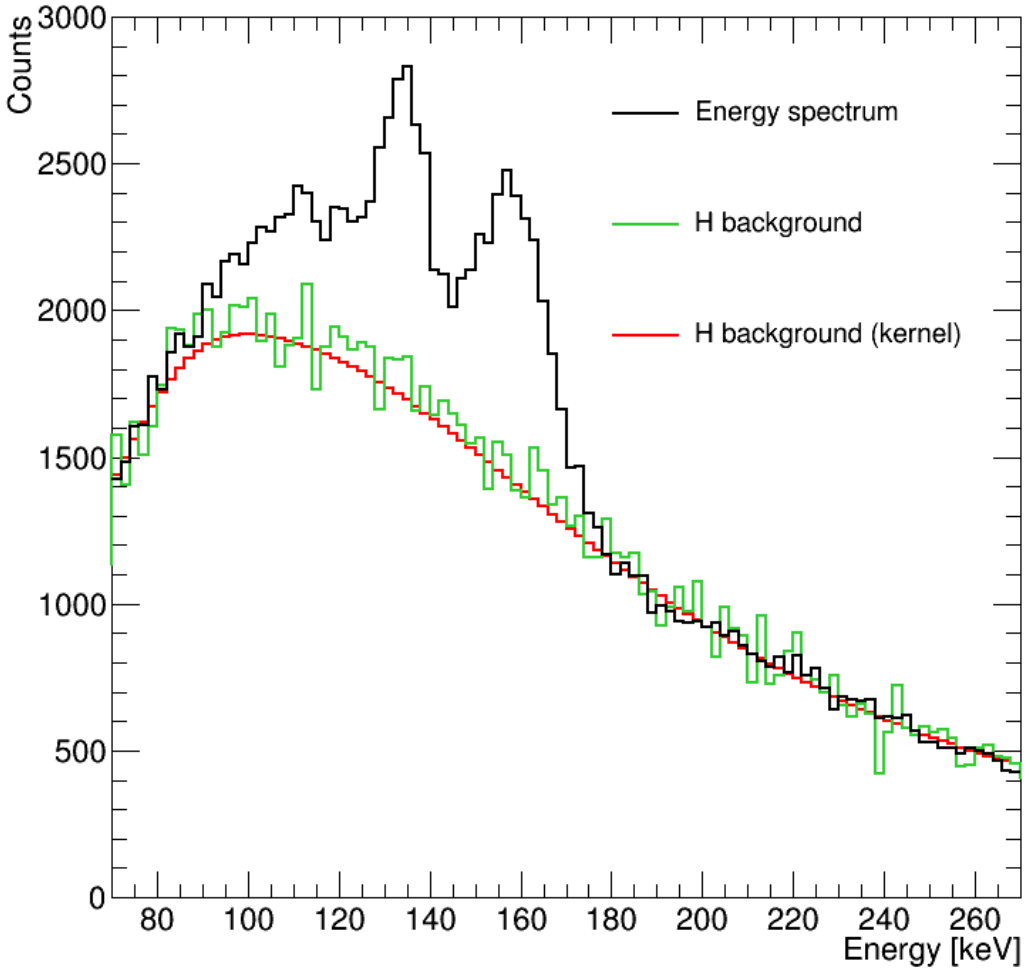


T = 300 K
Time bin = [1450,1650] ns

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

However: poor statistics…

Best solution: pure H smoothing



T = 300 K
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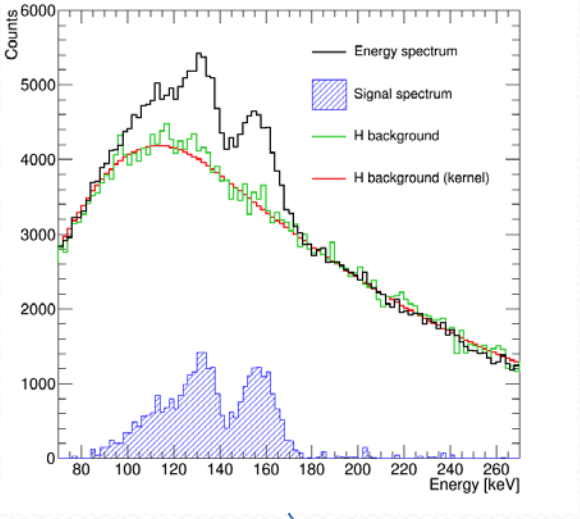
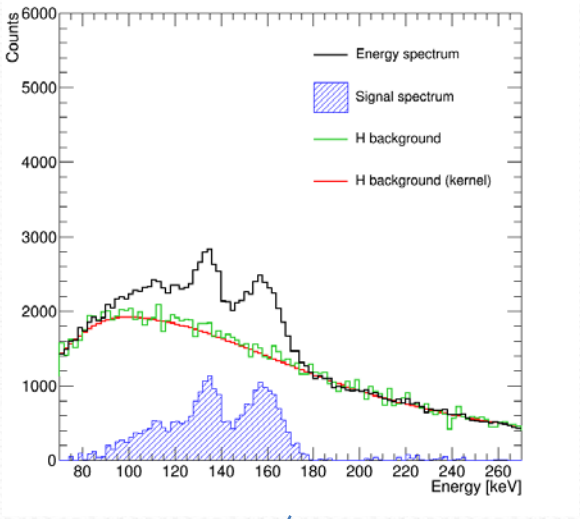
Pure hydrogen data taking within the same beam time and with the same pressure and temperatures.

Fixed temperature: time evolution

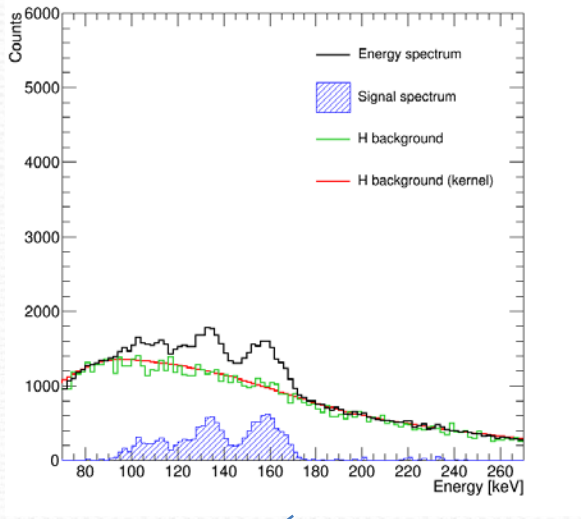
time bin 2

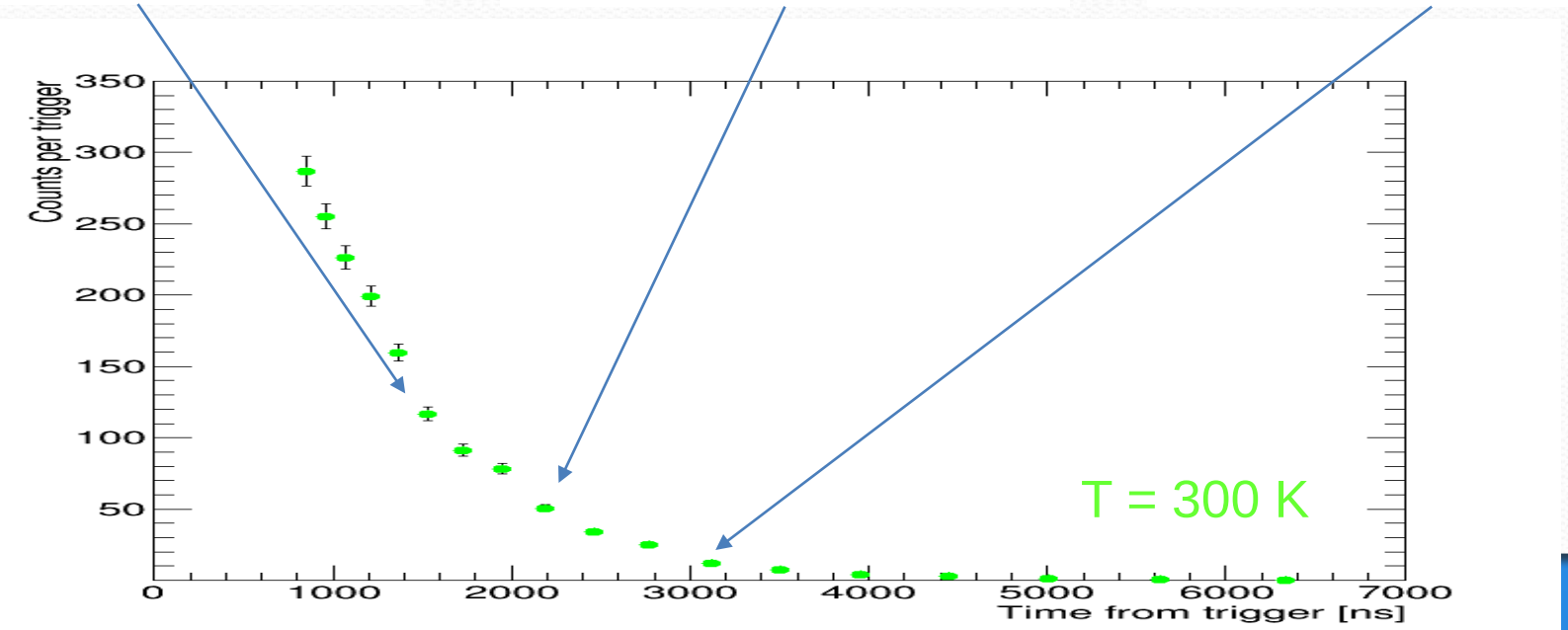


time bin 5

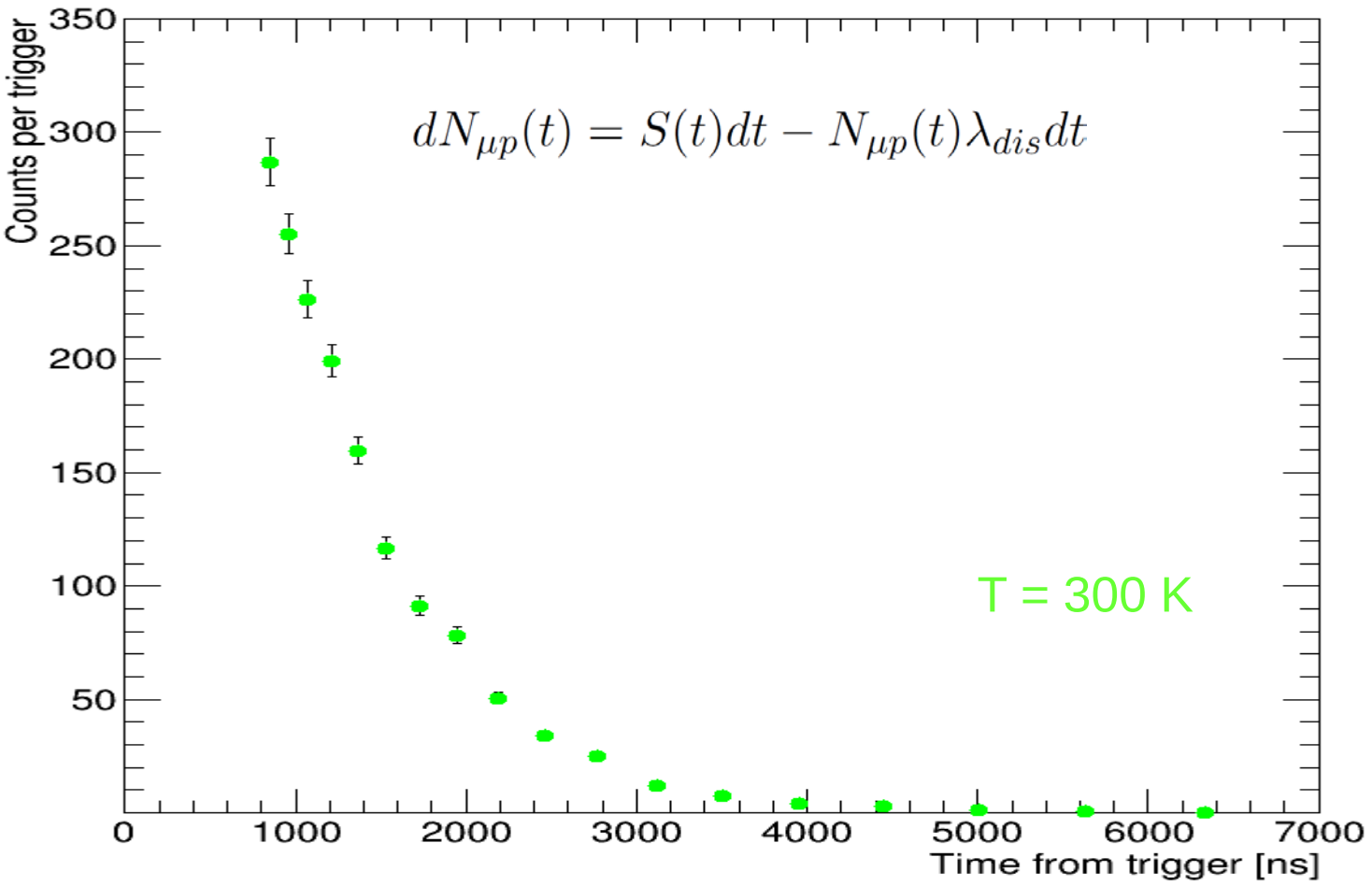


time bin 8





Temperature and time evolution



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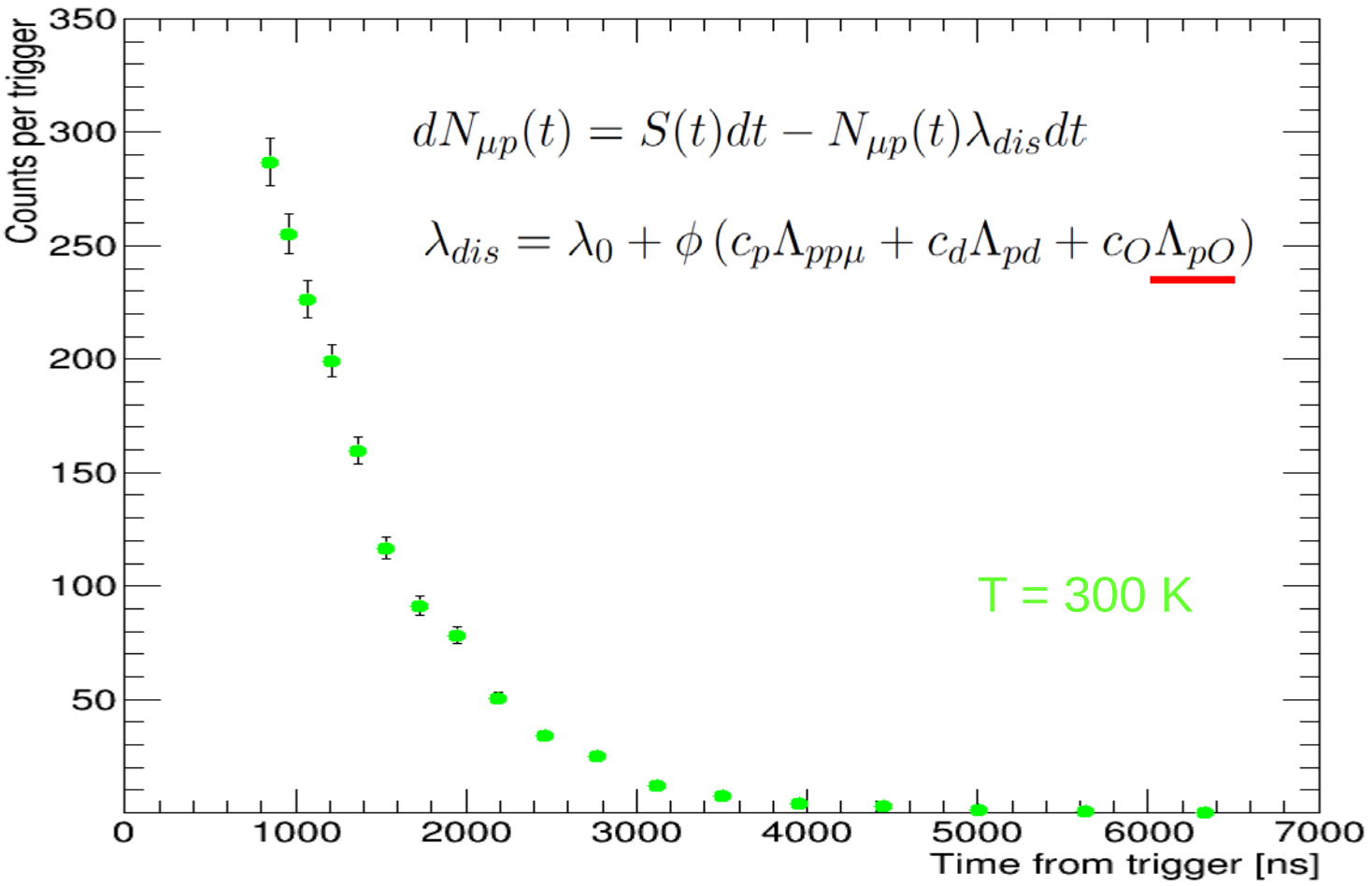

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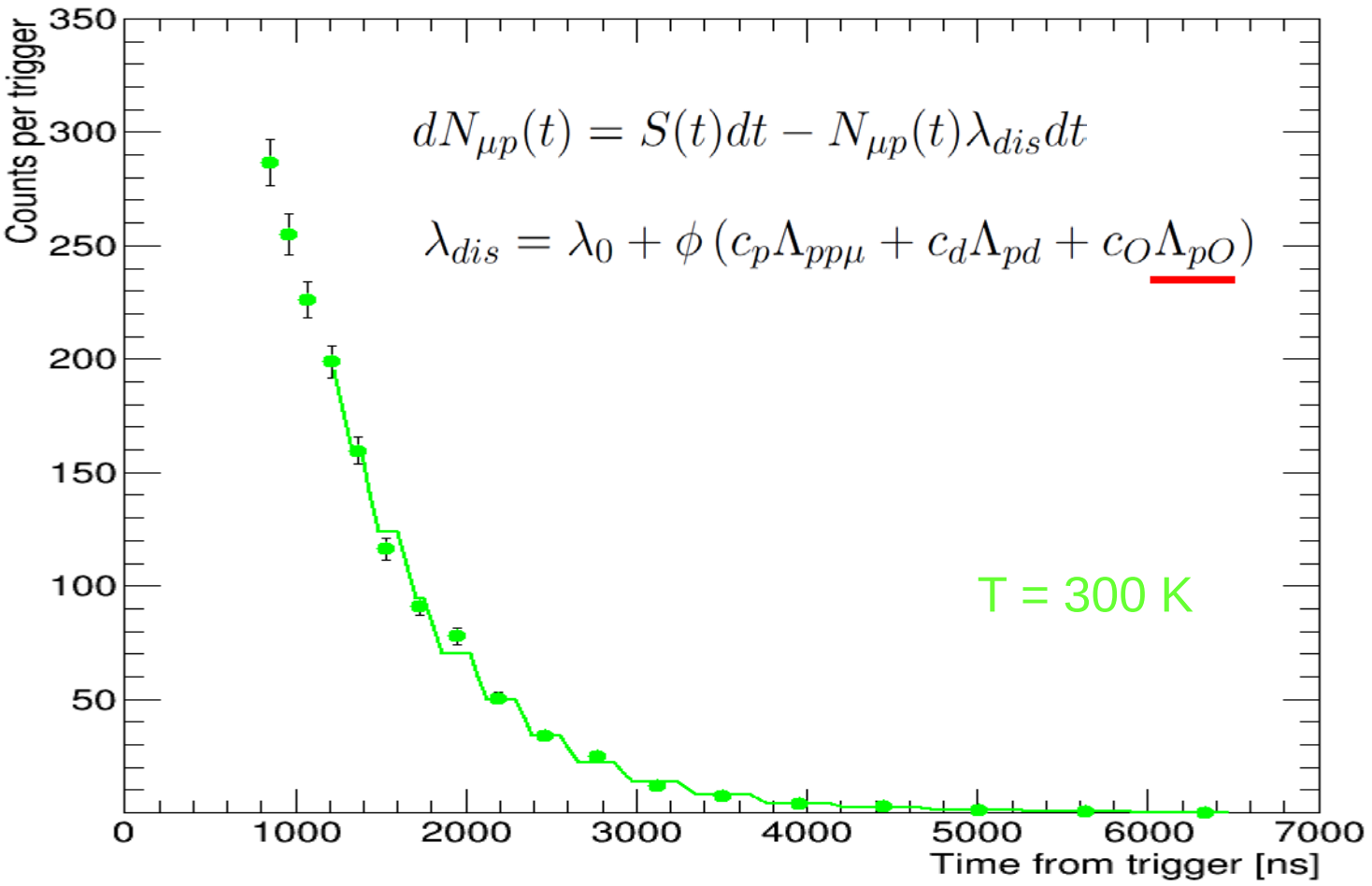
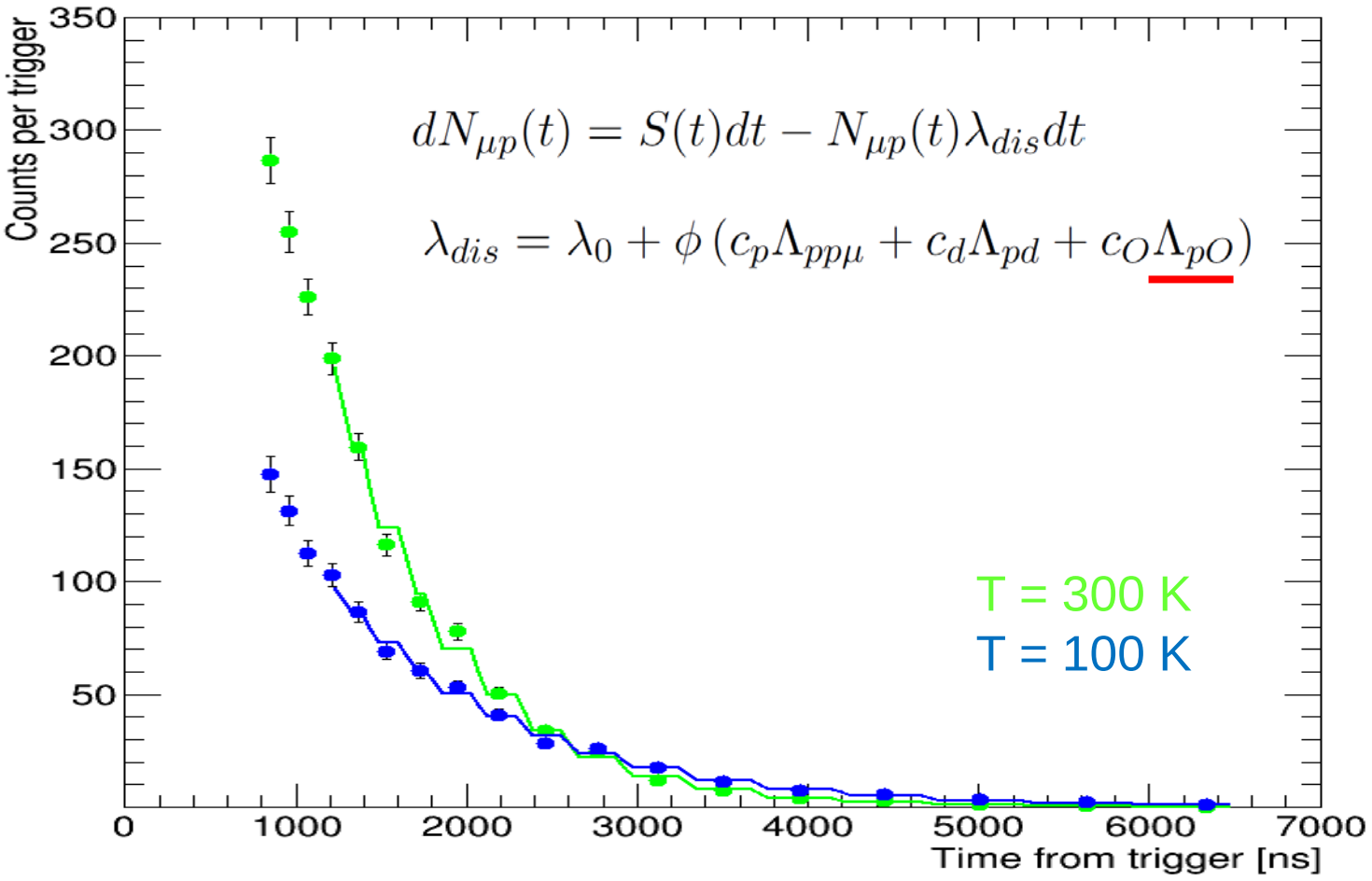


Temperature and time evolution



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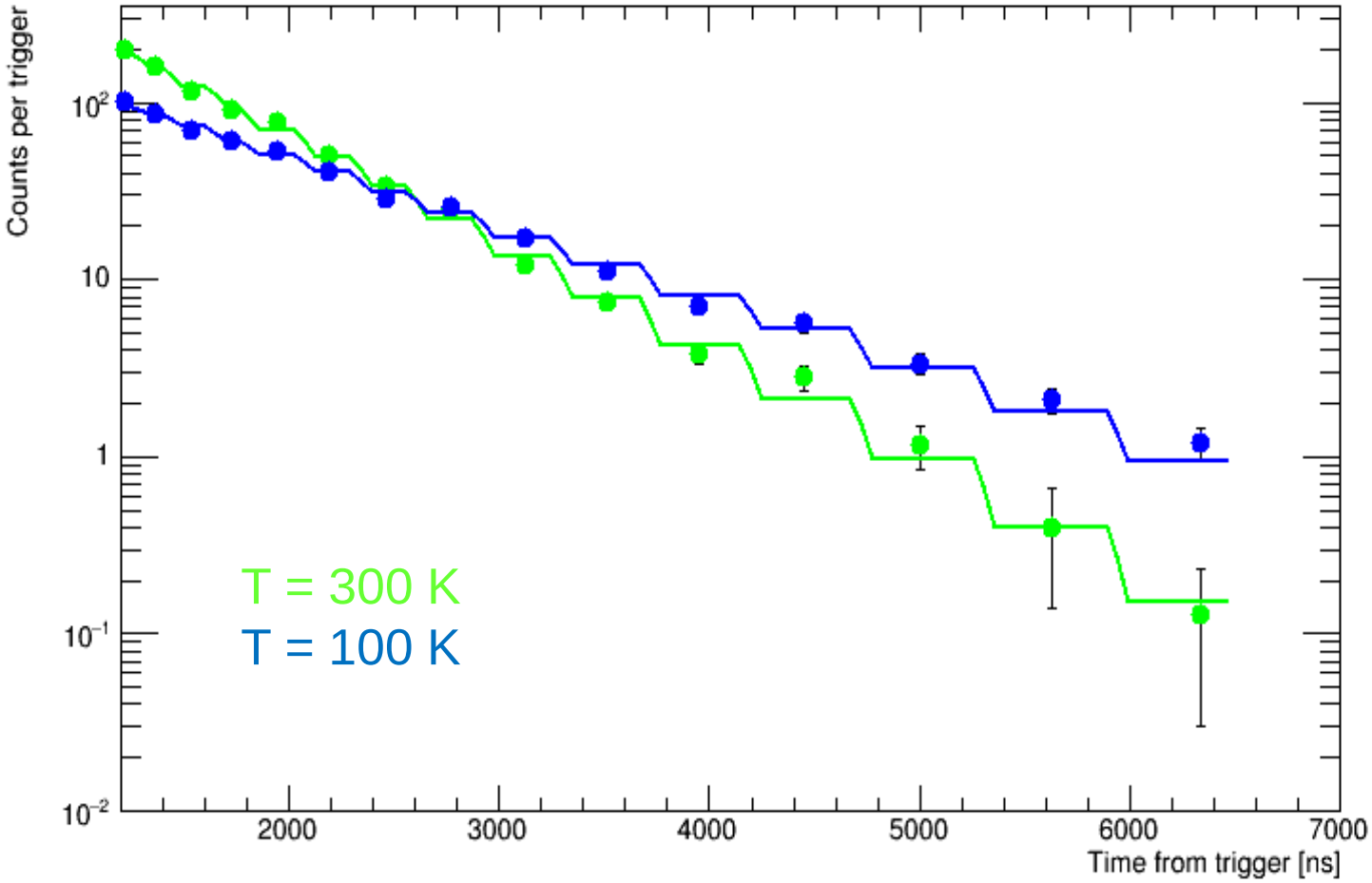
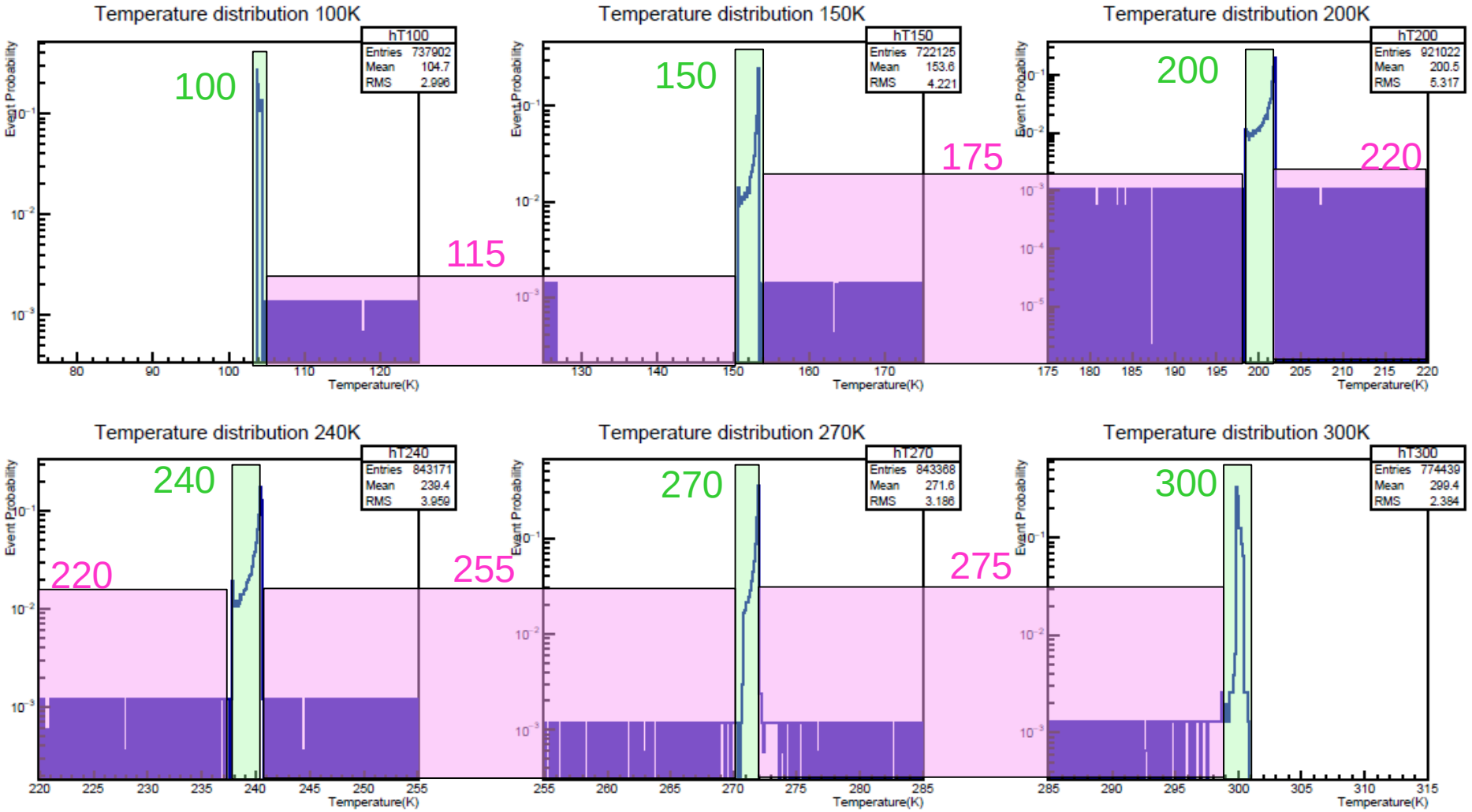
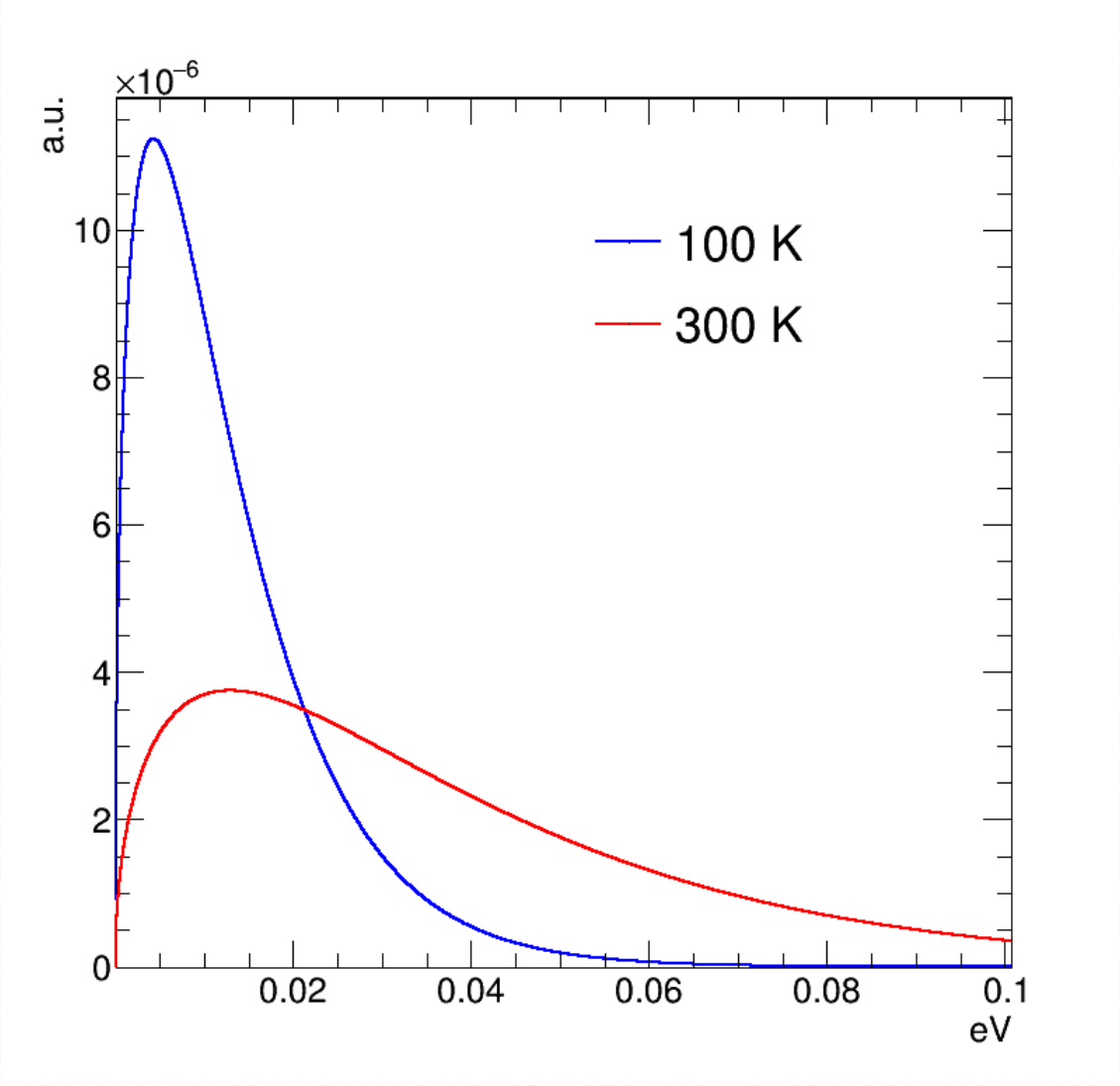


Temperature bins

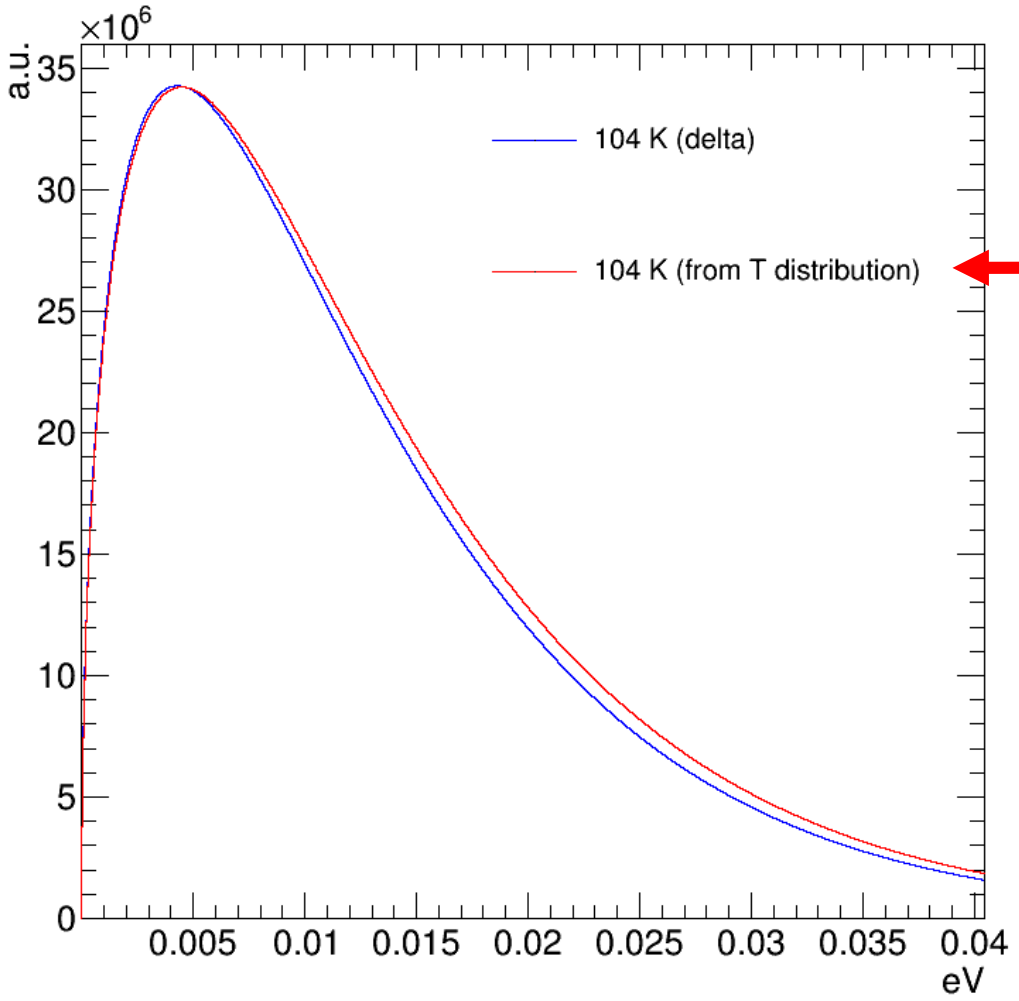
6 fixed steps + 5 intermediate temperatures

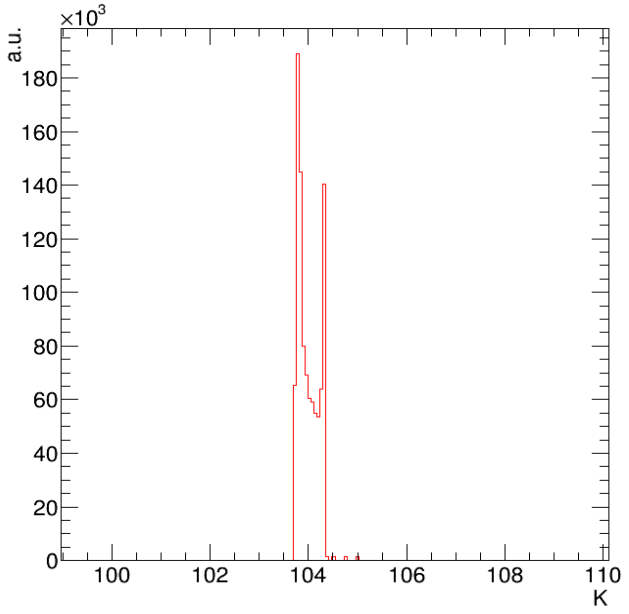


Temperature to energy



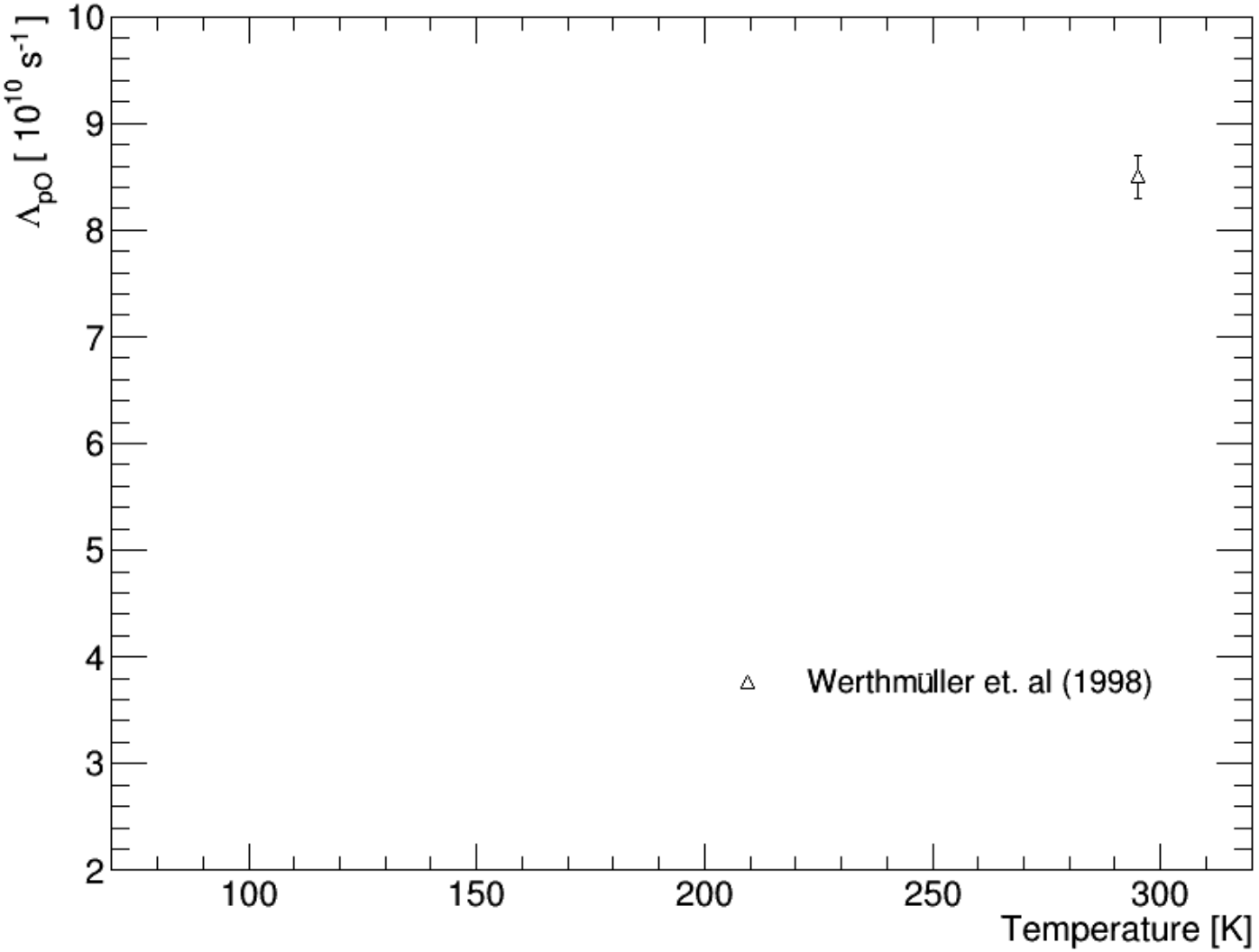
Very close to M-B distribution





Results

Transfer rate measurement



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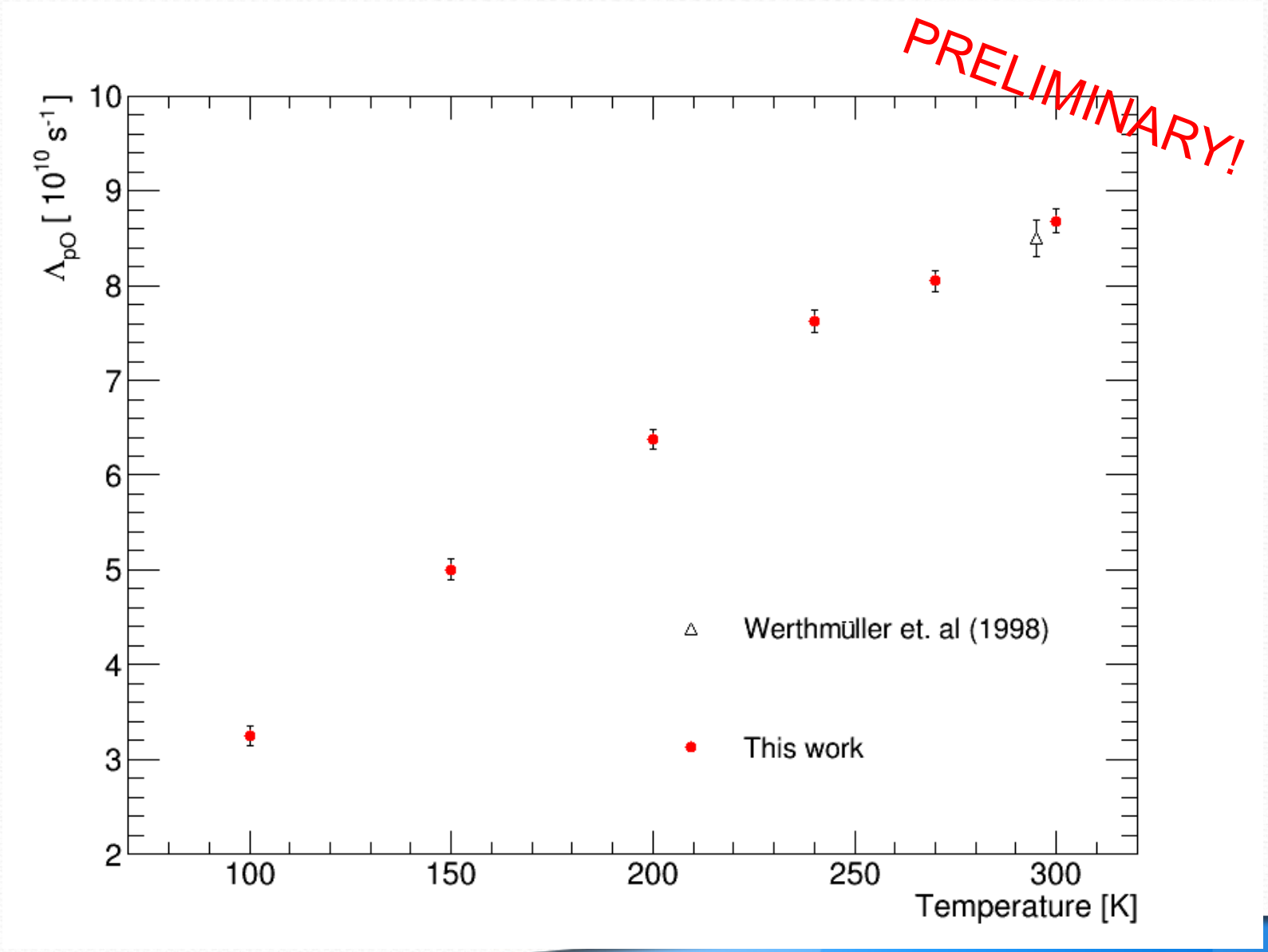

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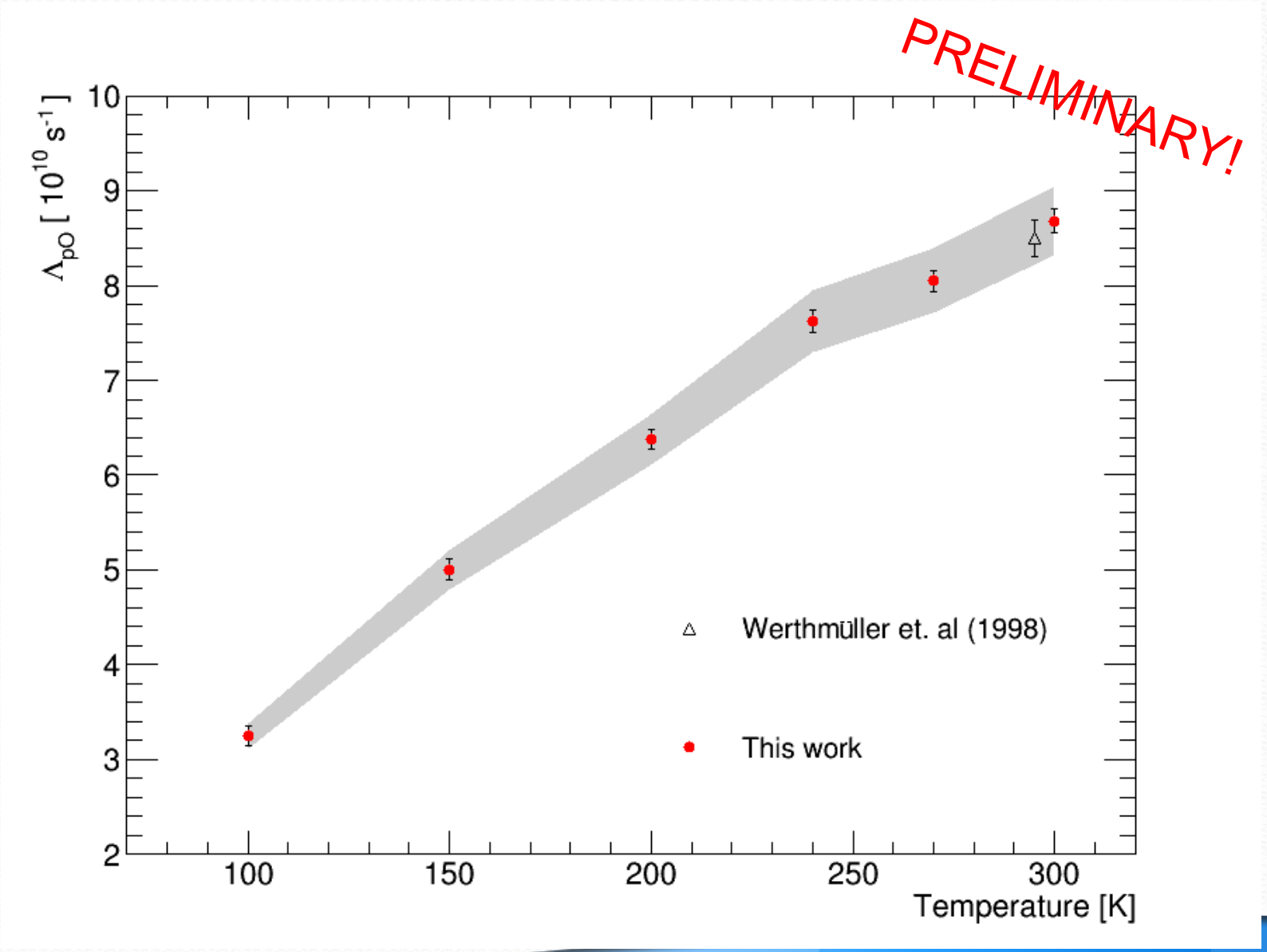

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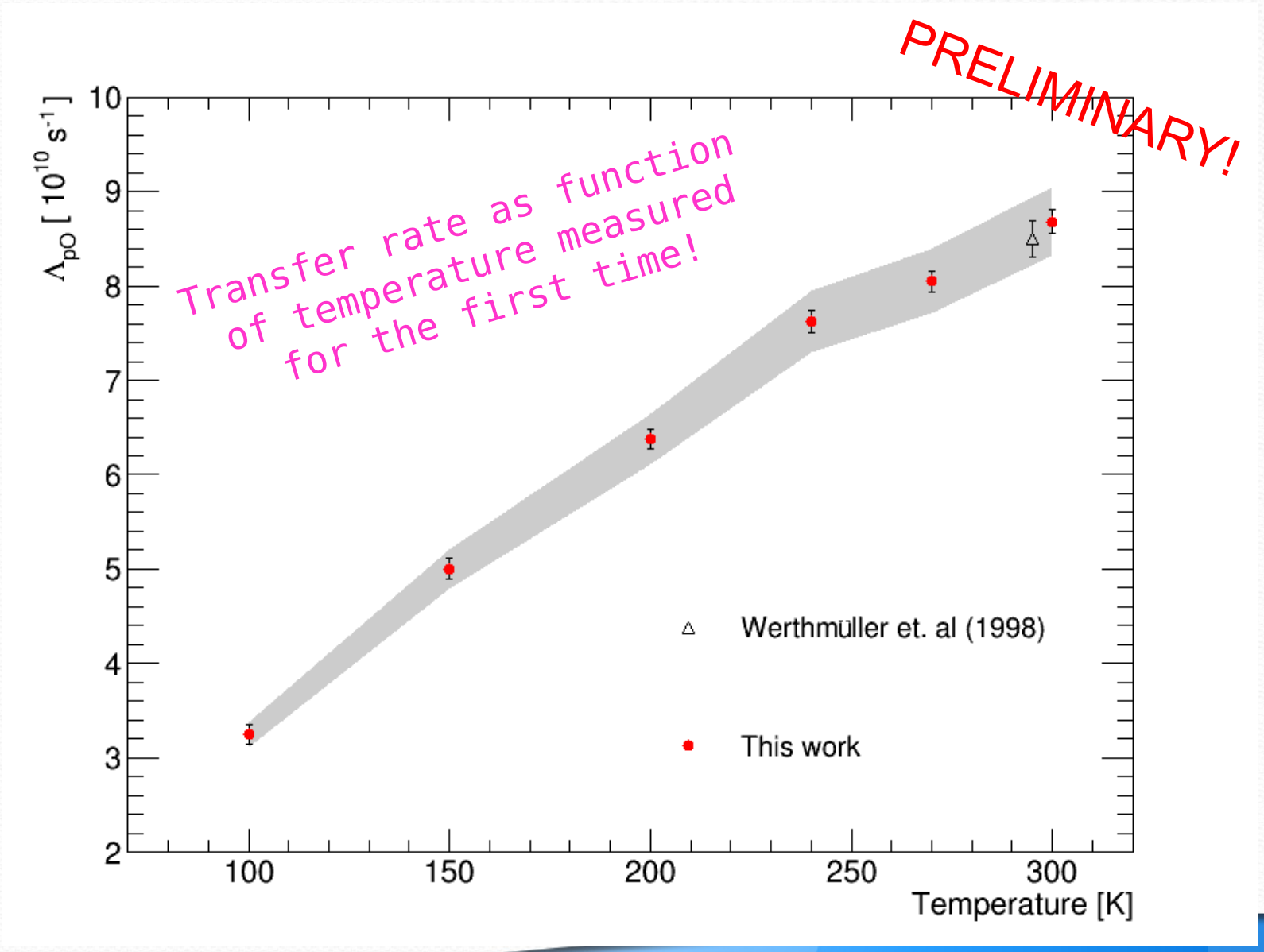


Summary

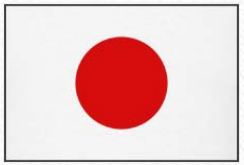
- FAMU: measurement of the $(\mu^- p)_{1S}$ hyperfine splitting

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

Looking forward to perform the spectroscopic measurement!

FAMU Collaboration



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