Measurement of the transfer rate from muonic hydrogen to oxygen with FAMU

Emiliano Mocchiutti
on behalf of the FAMU Collaboration

ECSAC2019 – The Proton Radius

Veli Lošinj – 16/20 September 2019

INFN FAMU

Outline

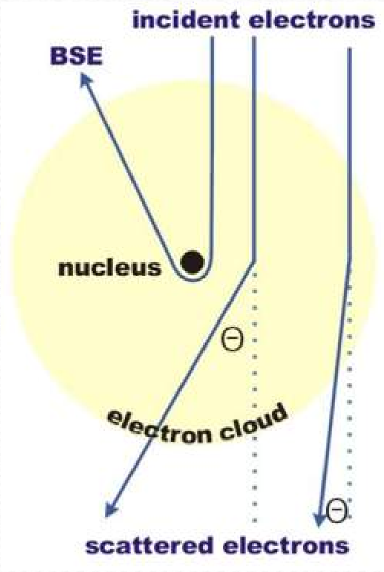
- Introduction
- The FAMU experiment
- Apparatus setup
- Measurement of the transfer rate $\Lambda_{\mu p \to \mu O}$ (a.k.a. Λ_{pO}):
  - Data selection and selection efficiencies
  - Background evaluation
  - Time dependence fit
- Results
- Summary

Introduction

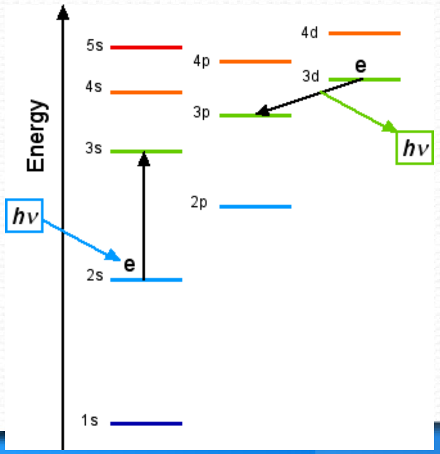
FAMU: HFS of $\mu^{-}p$ ground level

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

The FAMU experiment

Fisica Atomi MUonici (Physics with muonic atoms)

FAMU: μ^-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...

Summary of muon atomic capture physics (in H gas)

1. Hydrogen gas at room temperature (i.e. H_2 molecules mean kinetic energy 30 meV – 0.03 eV)

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5. The system muon-proton (muonic hydrogen) gains kinetic energy (average energy about 2 eV !)
6. The muonic hydrogen thermalizes due to collision with other molecules (thermalization time depends on density and temperature, order of 100 ns @ 40 bar 300 K)
7. The muon decays OR it is transferred OR it undergoes nuclear capture ($\mu^- + p \rightarrow n + \nu_\mu$)

FAMU: $\mu^- p$ spectroscopy

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HFS de-excitation: $\mu^{-}p$ gains kinetic energy

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... but in the triplet to singlet transition muonic hydrogen gains kinetic energy (~120 meV, 0.12 eV)

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

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Key point:

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

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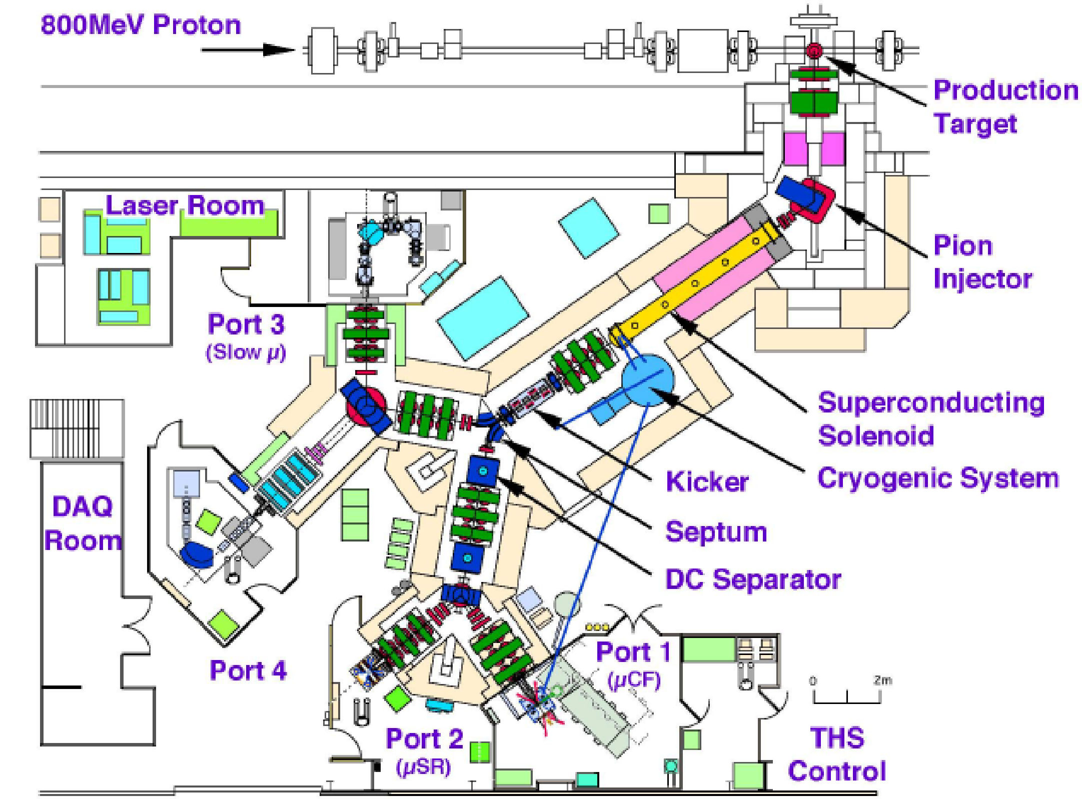
Many indications, no accurate and comprehensive study of this effect!

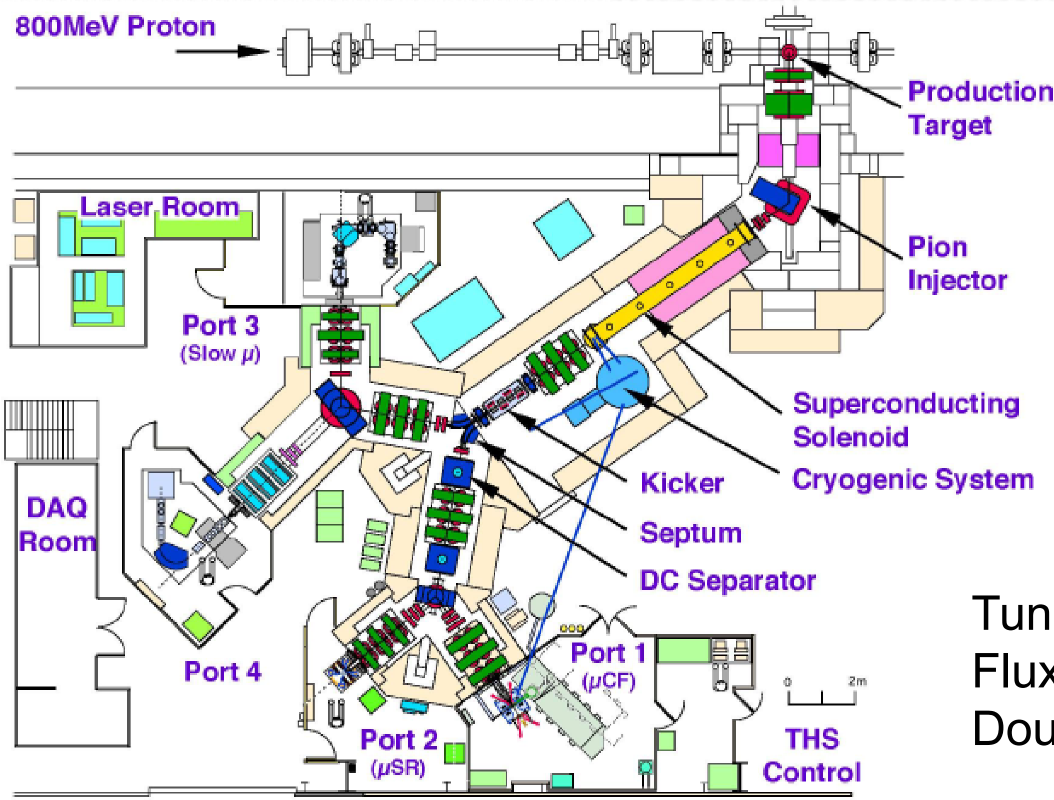
Apparatus setup

RIKEN – RAL muon facility

Rutherford Appleton Laboratory – Oxfordshire UK



High intensity muon beam

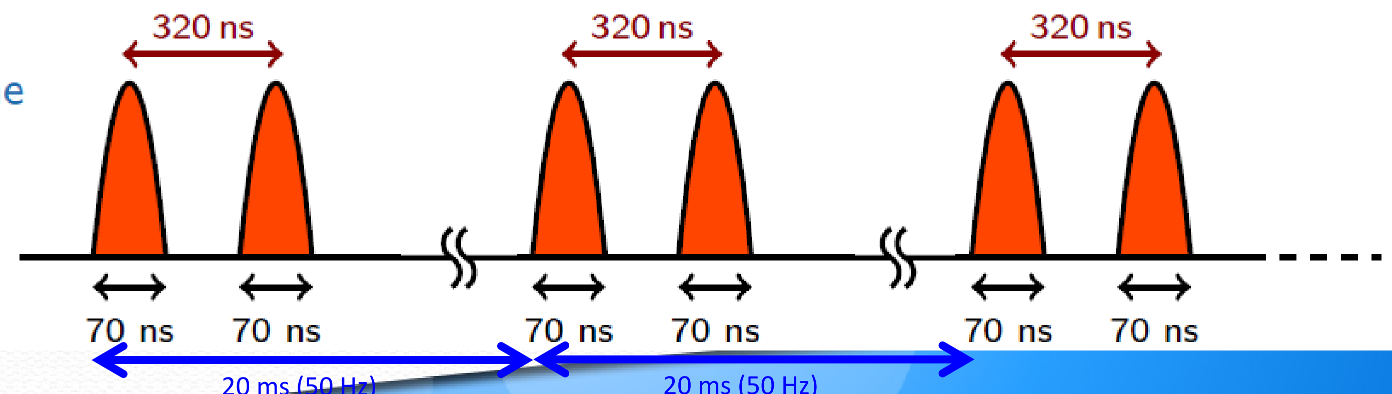


Tunable momentum: 20 – 120 MeV/c

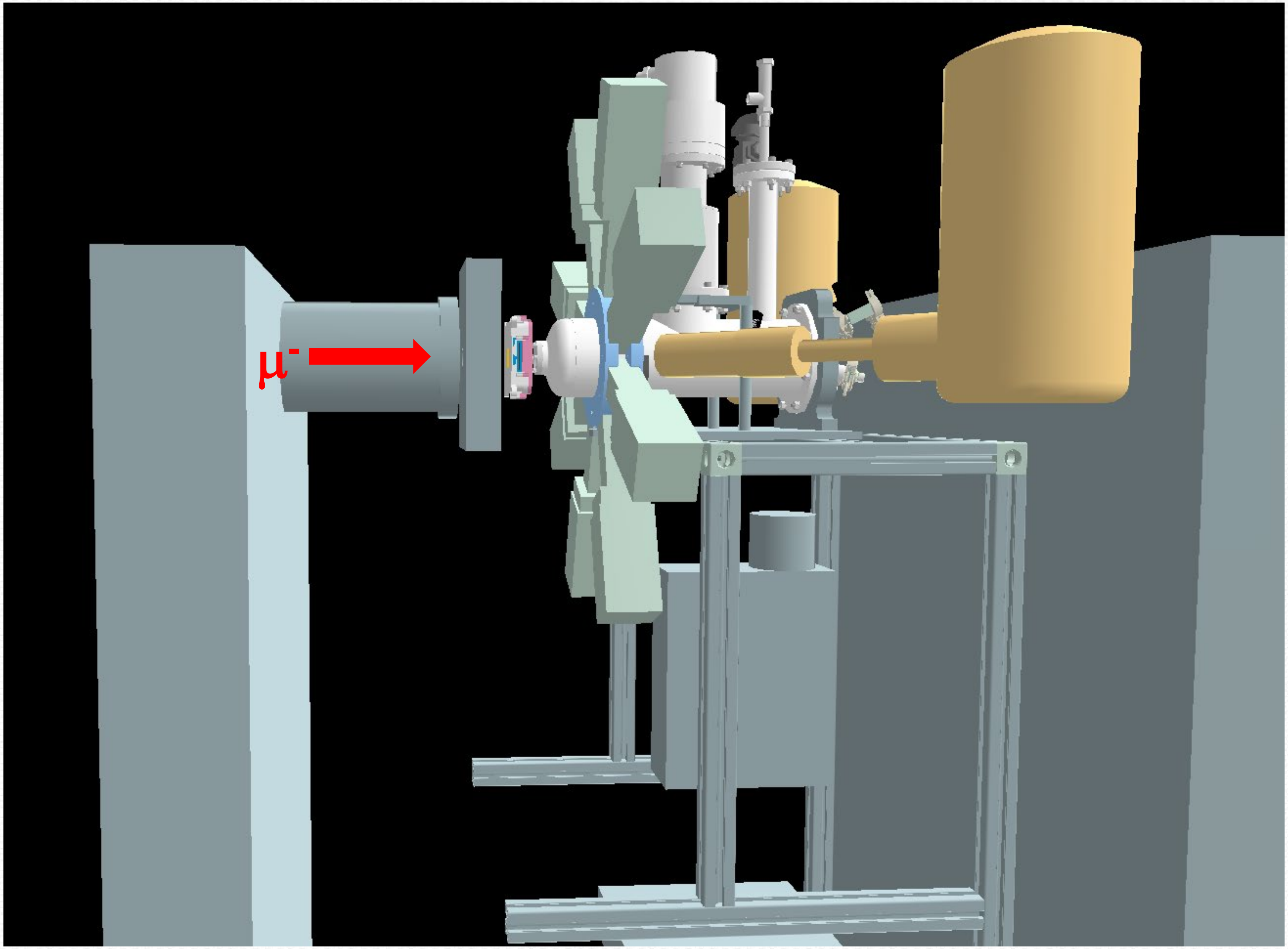
Flux μ^- : 7 x 10^4 muons/s

Double pulsed beam

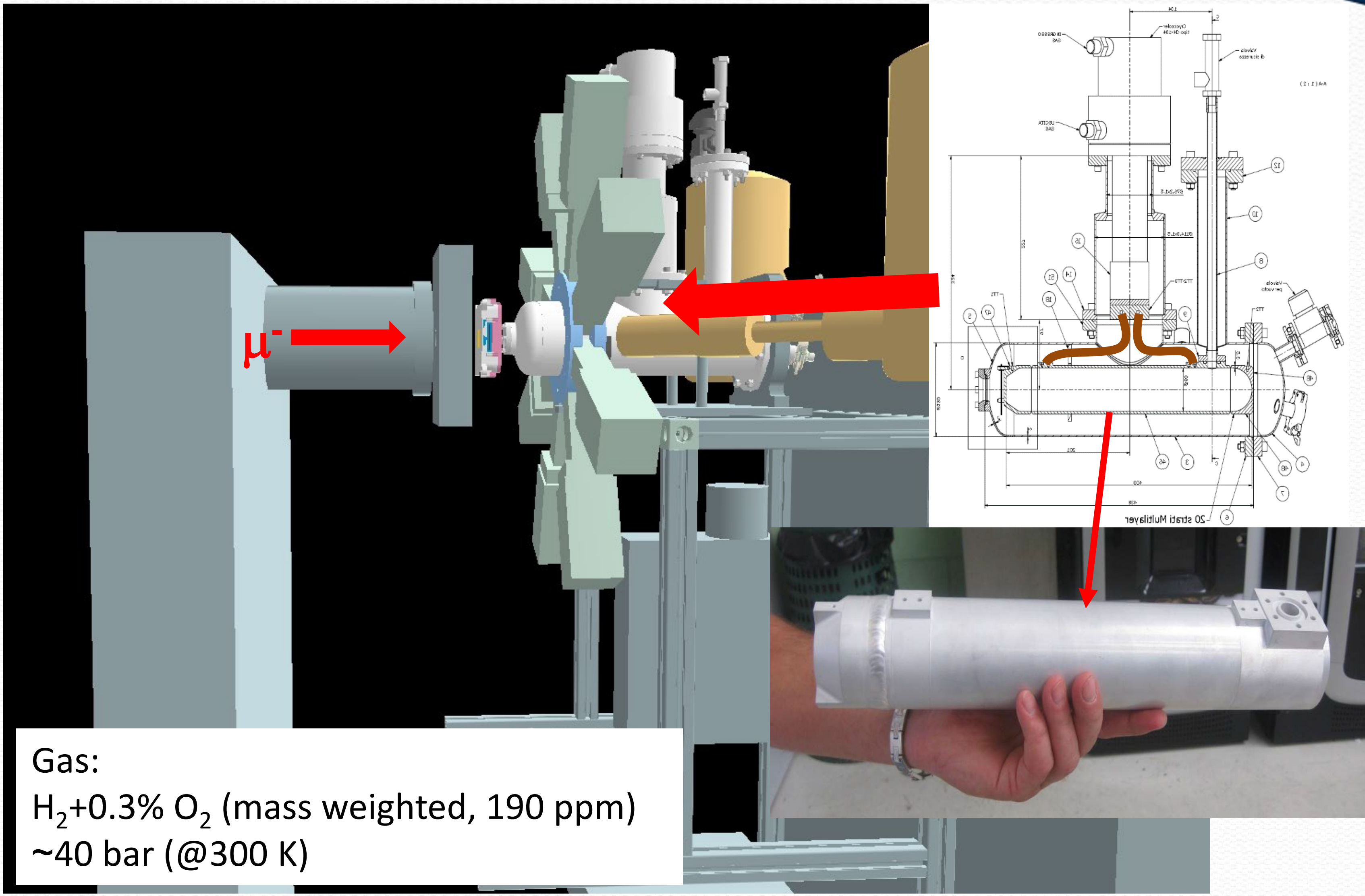
Beam time structure



2016: experimental setup

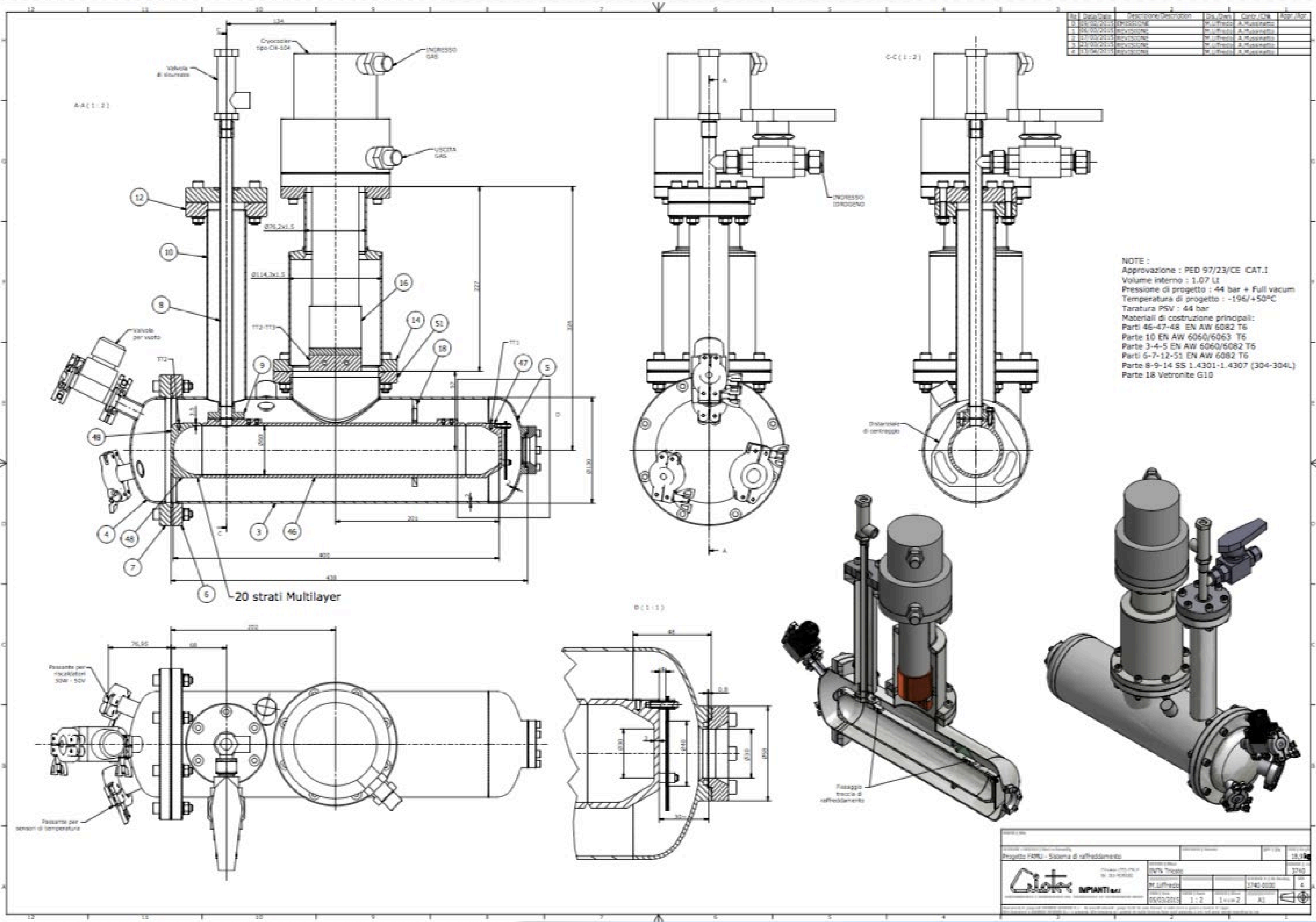


Cryogenic thermalized target

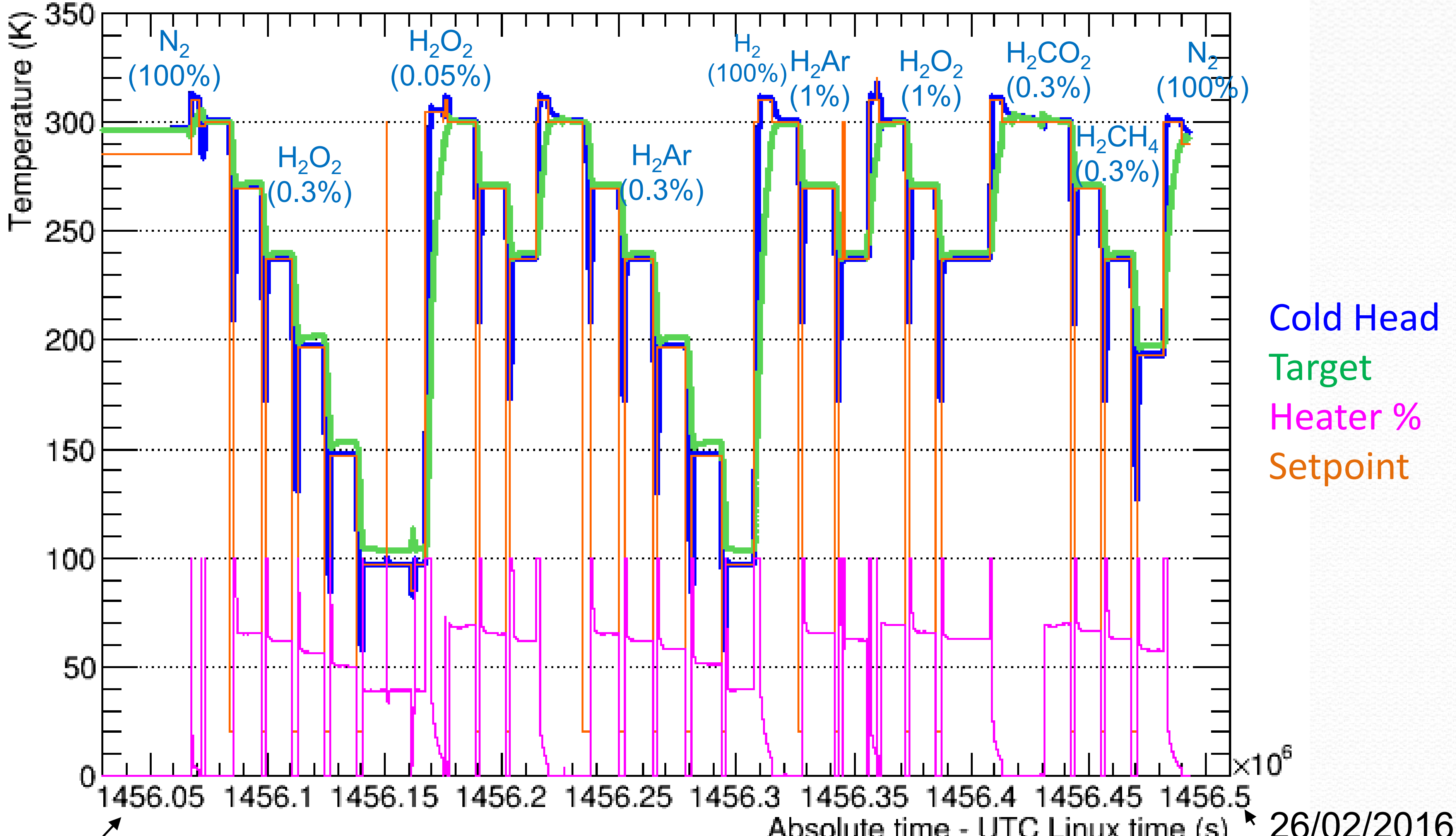


Gas:
H_2+0.3% O_2 (mass weighted, 190 ppm)
~40 bar (@300 K)

2016 cryogenic target



Thermal cycles 2016



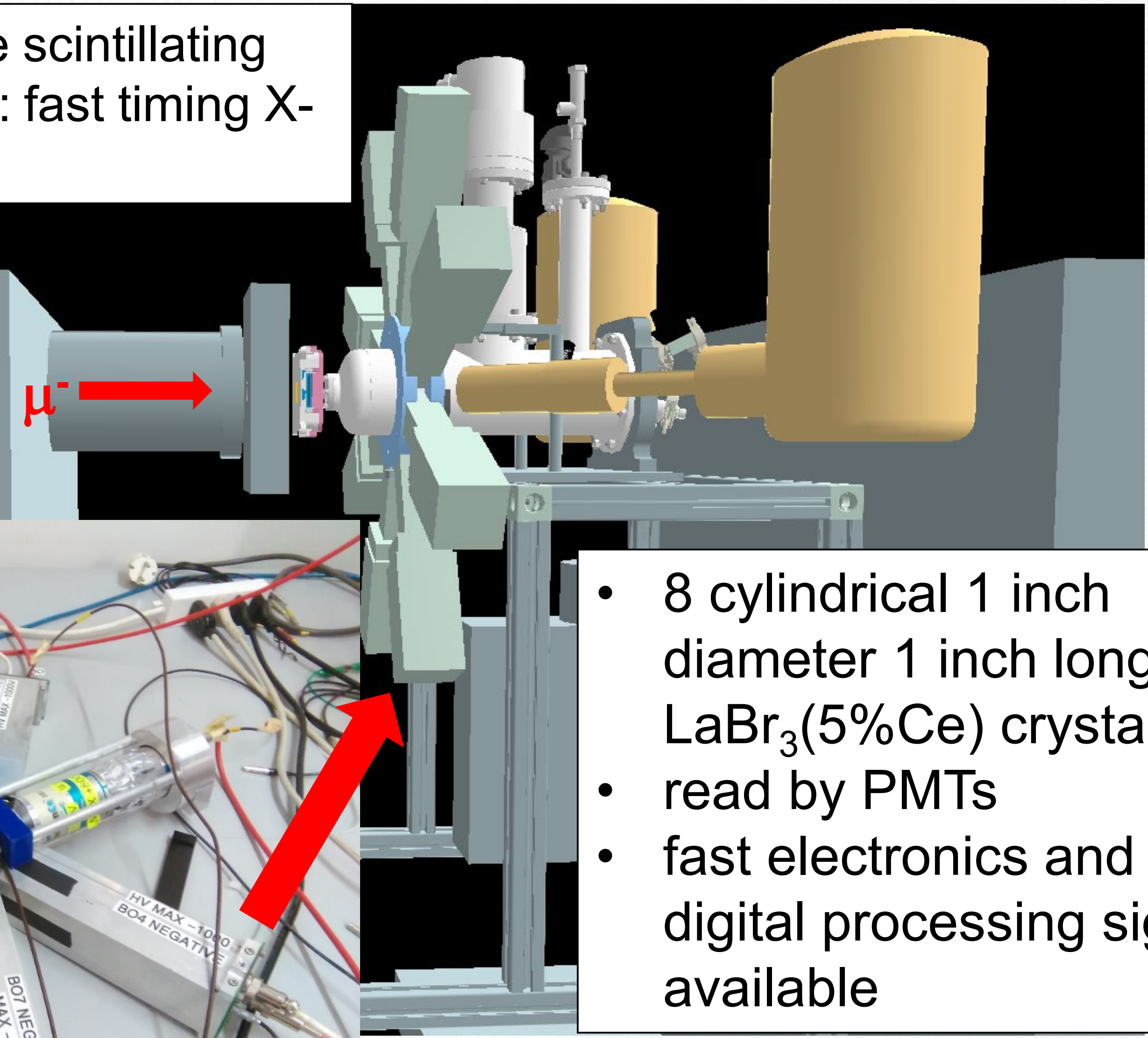
21/02/2016

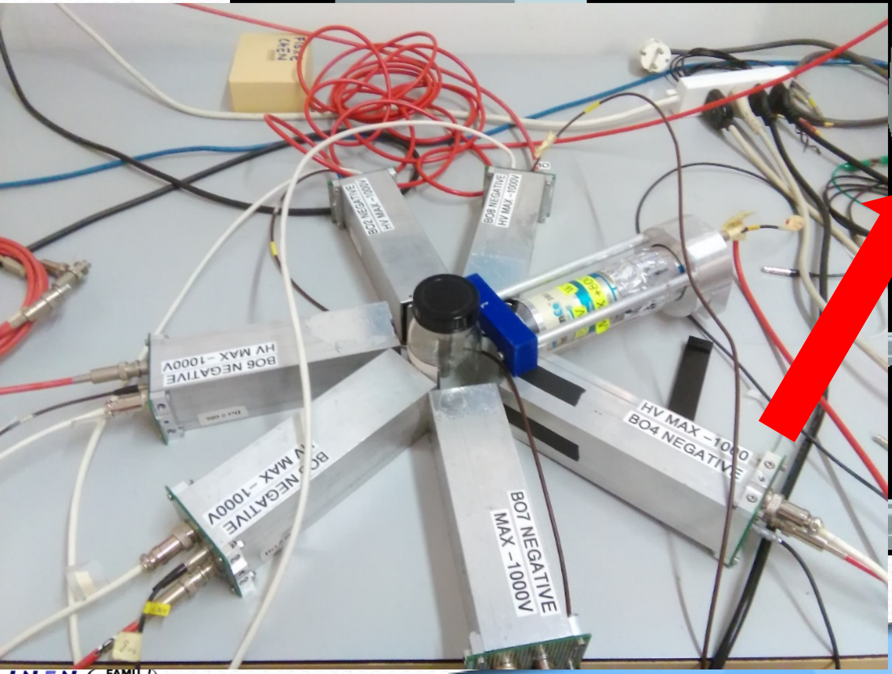
26/02/2016

5 days: Feb 2016 measurements run

2016: experimental setup

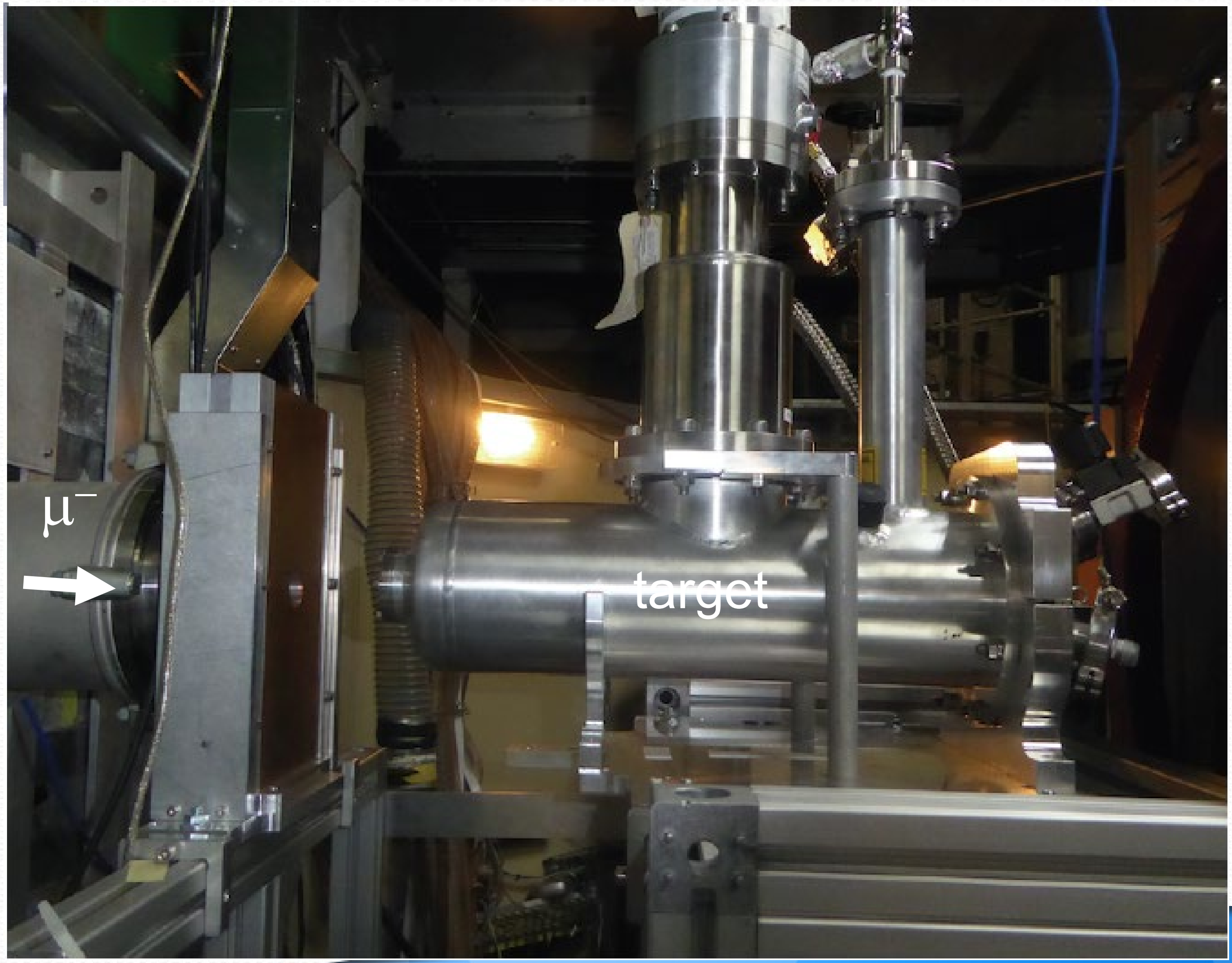
Lanthanum bromide scintillating crystals [$LaBr_3(Ce)$]: fast timing X-rays detectors





- 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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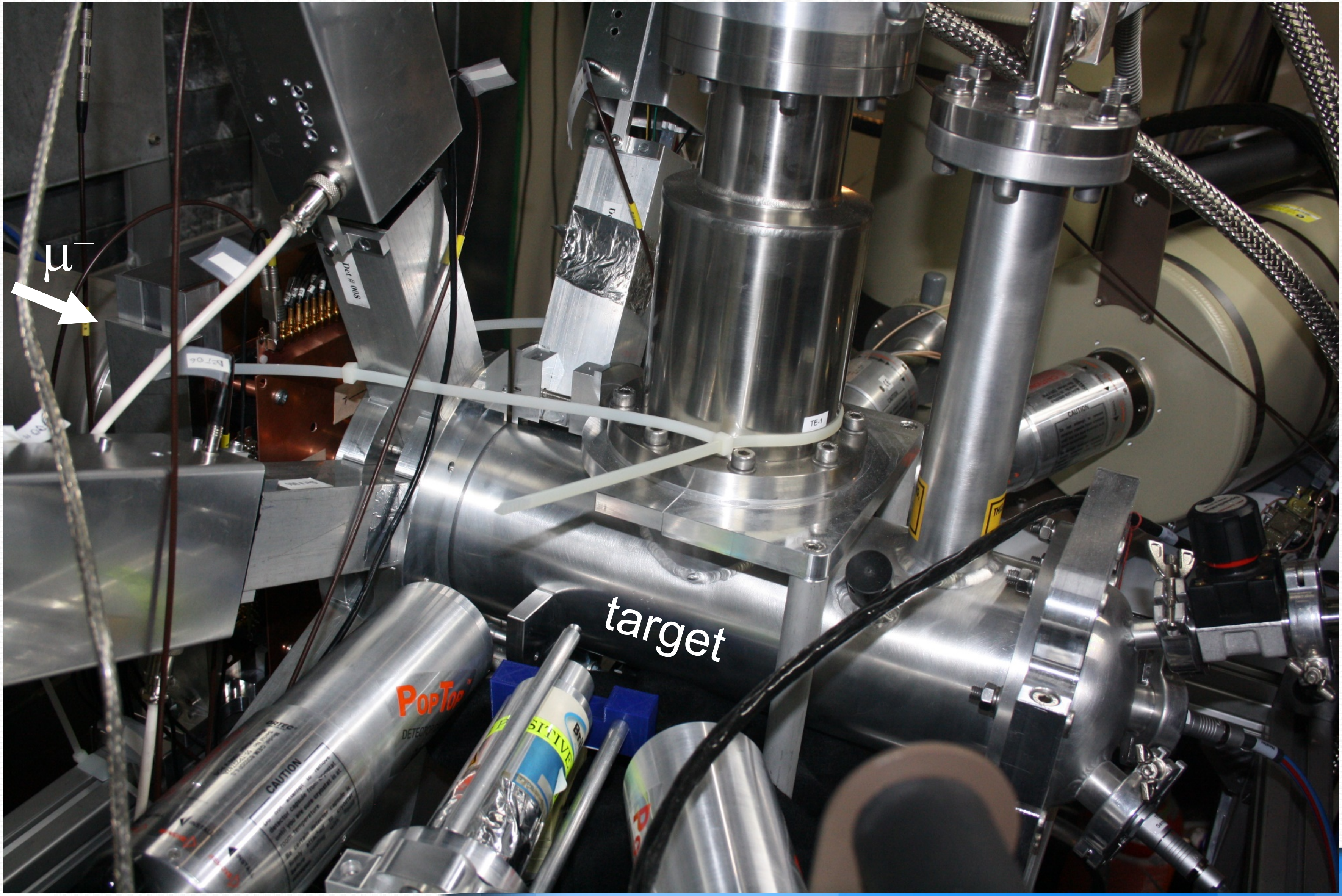

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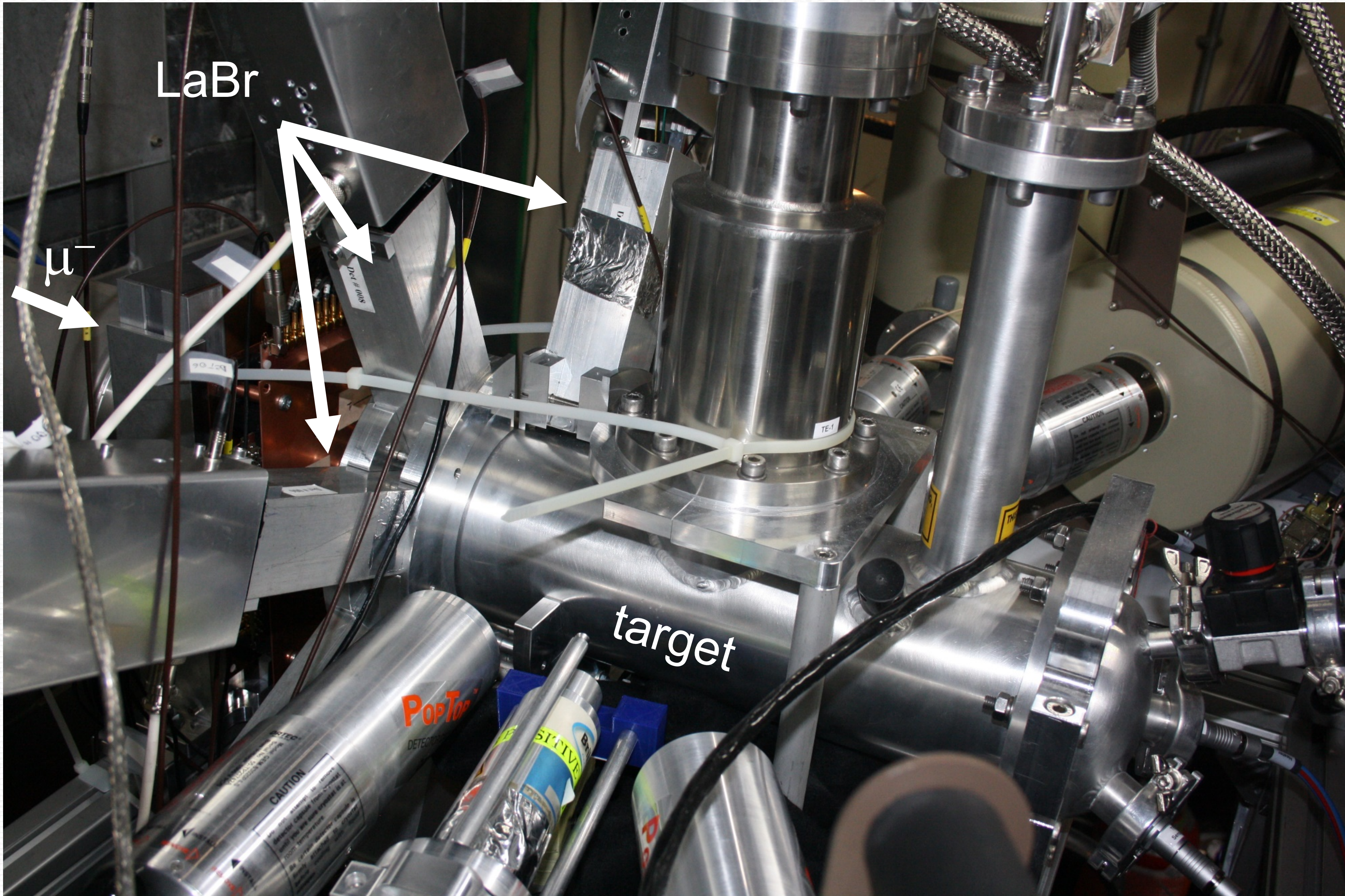

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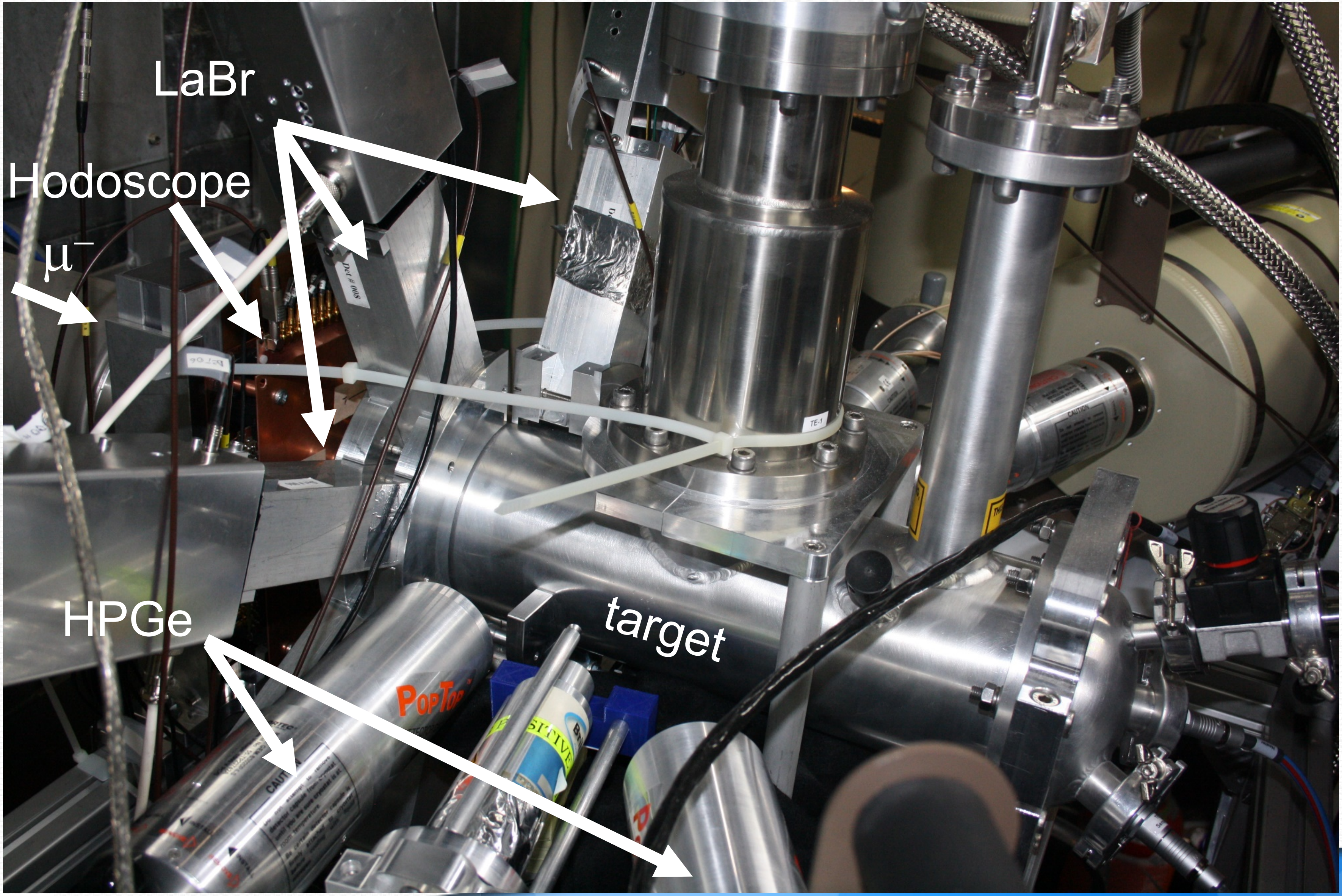
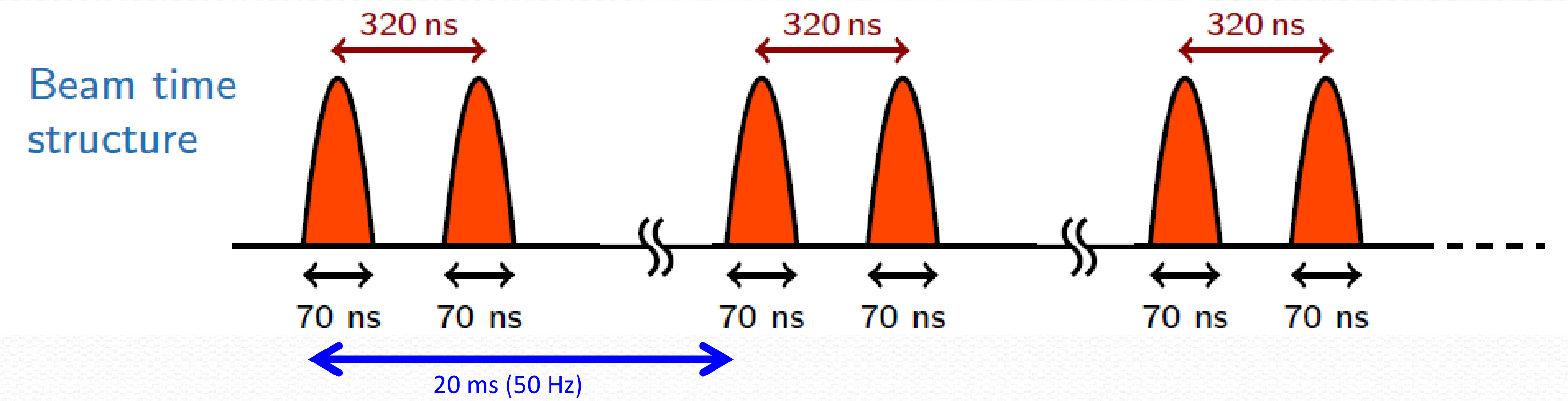
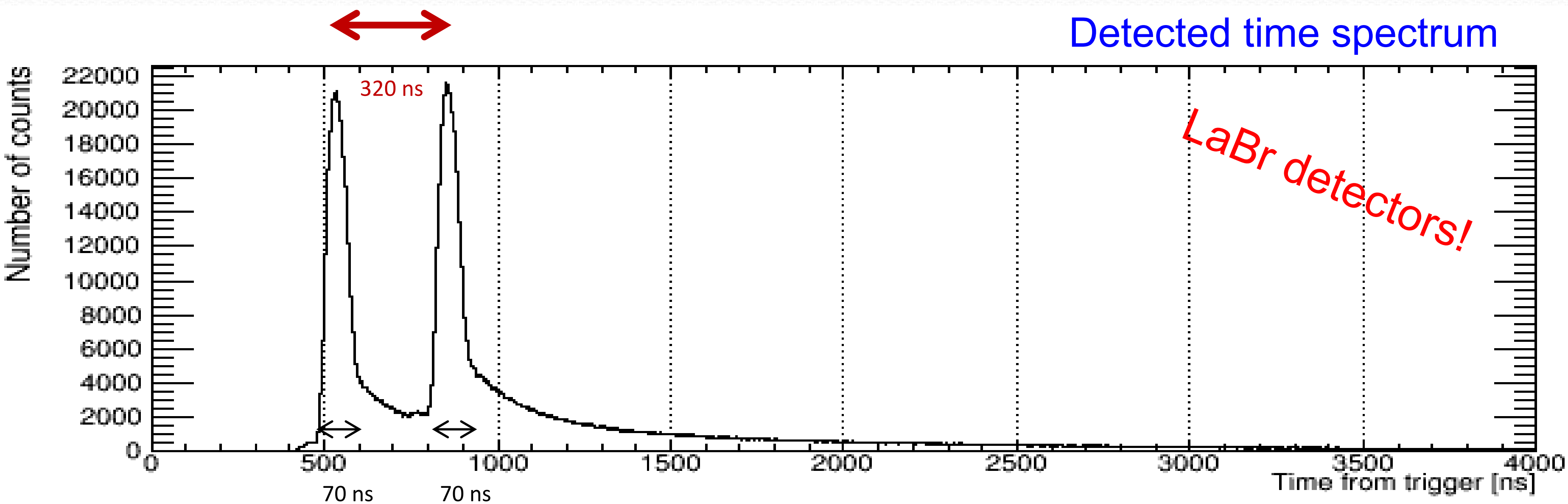


Measurement of the transfer rate $\Lambda_{\mu p \rightarrow \mu O}$

Time spectrum: peaks and tails





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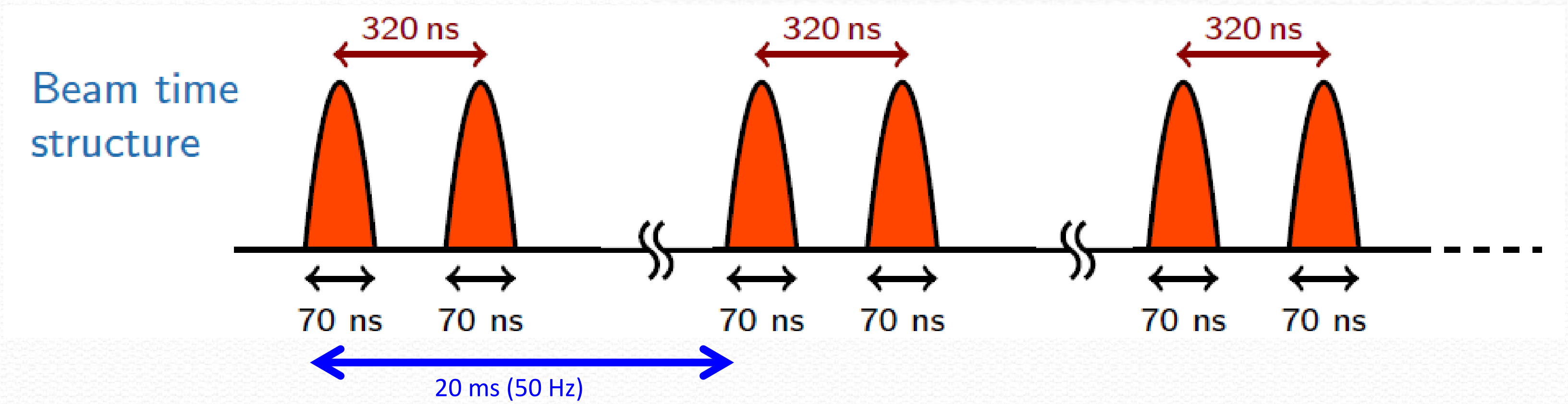

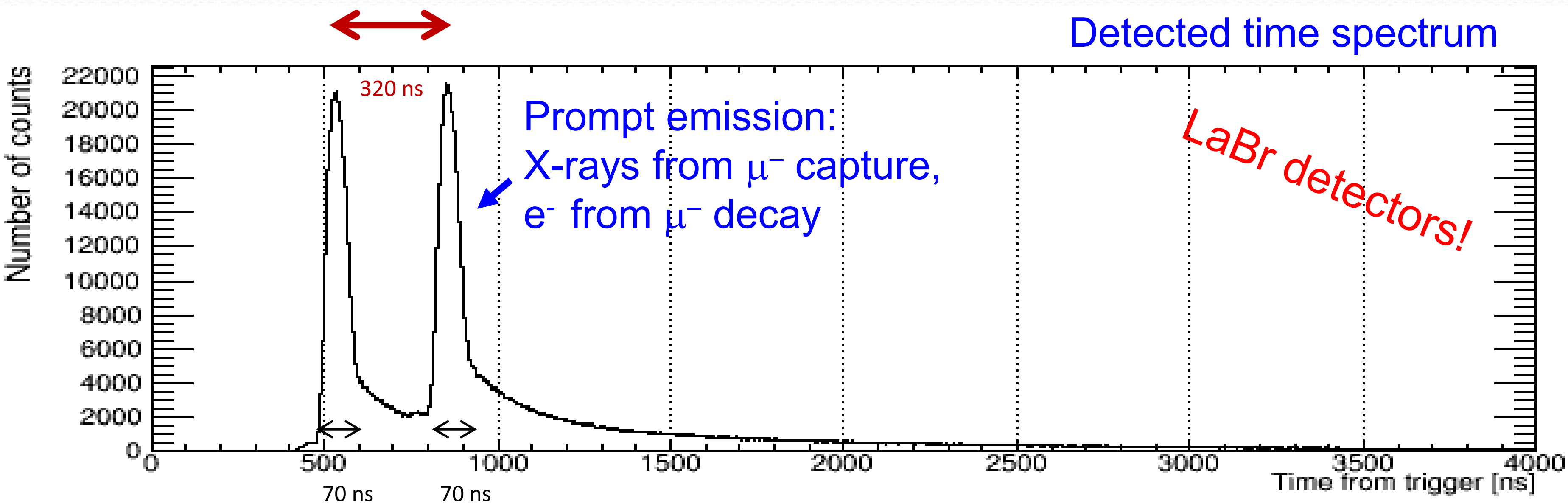

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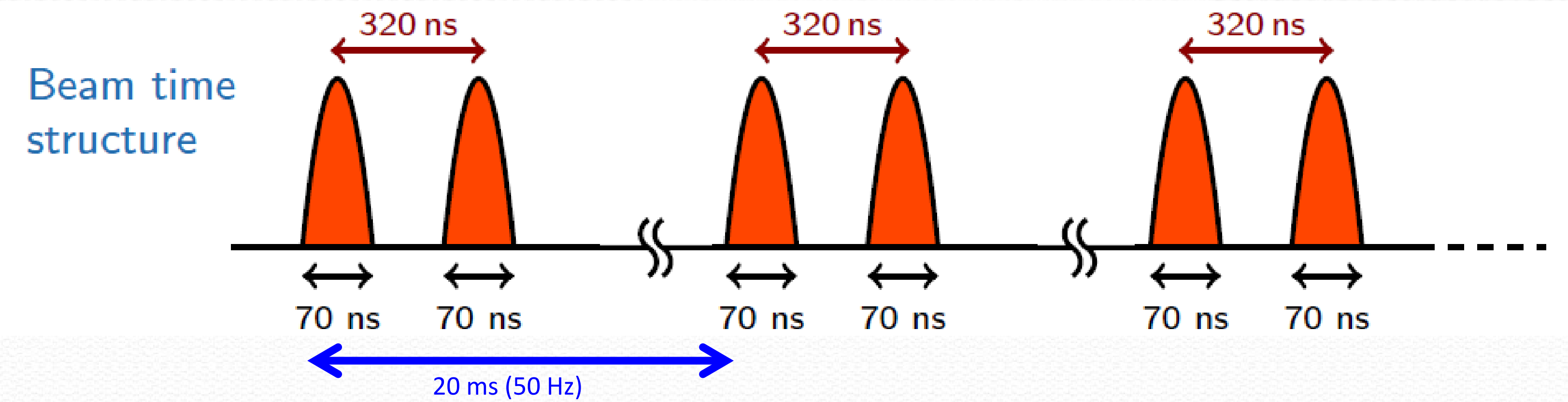
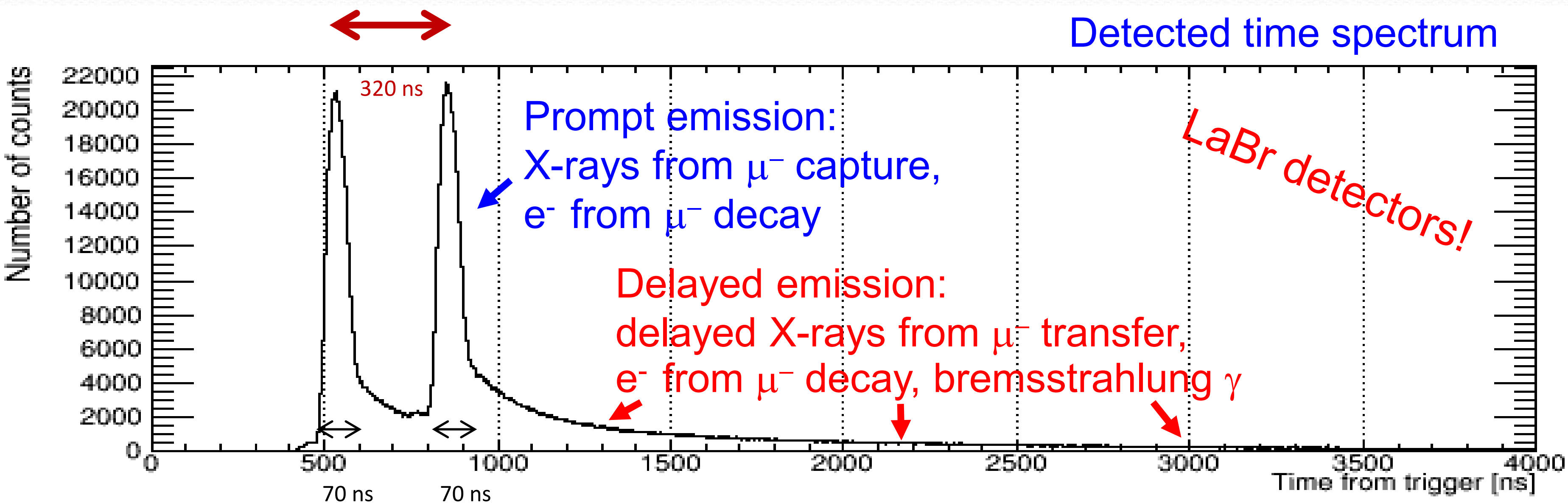


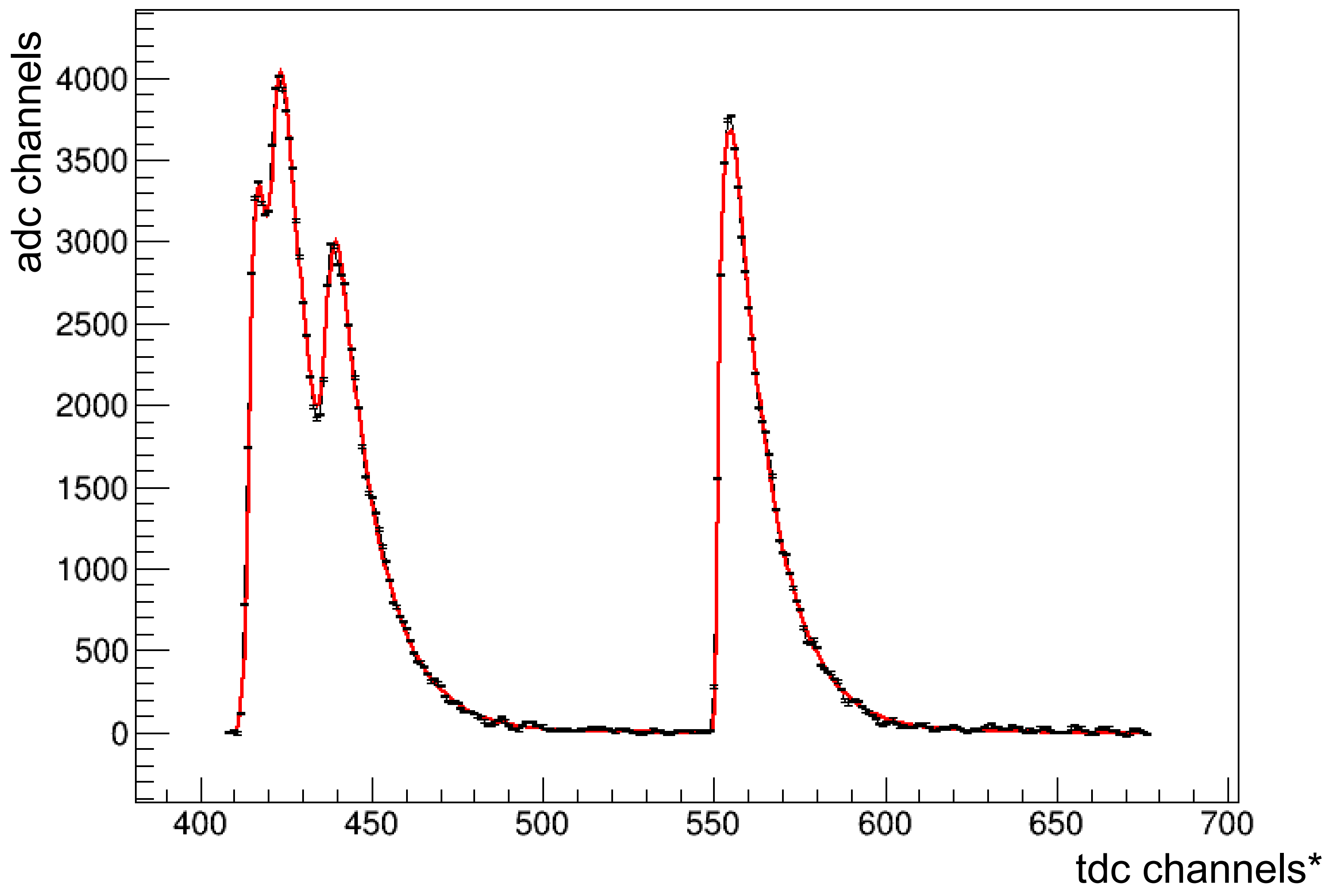


Transfer rate measurement

Steps:

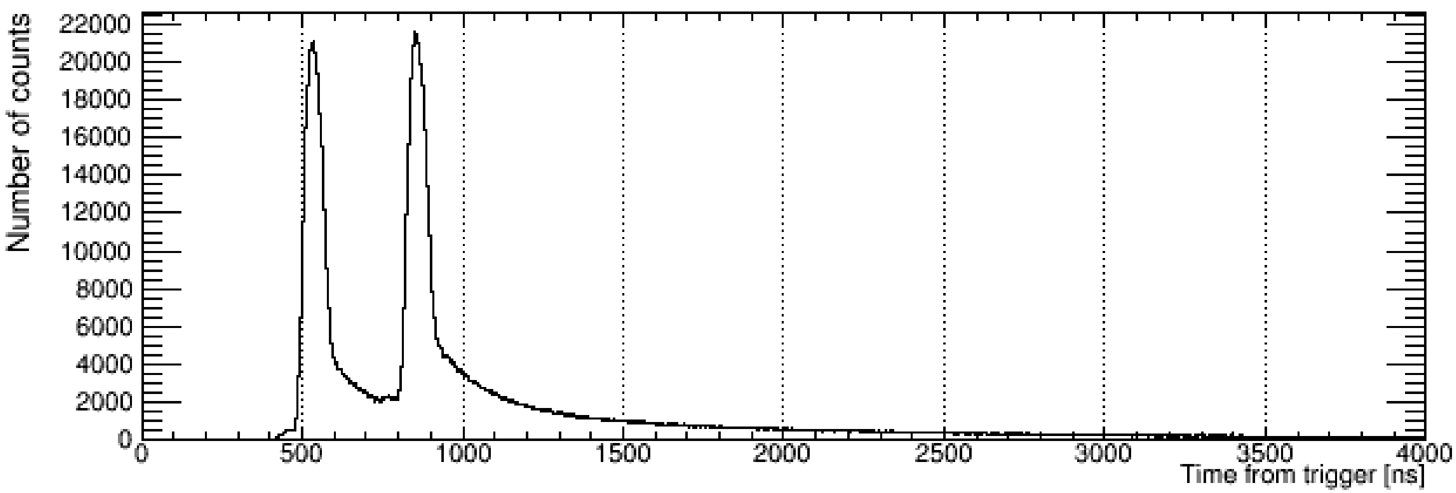
1) fix a target temperature (i.e. mean kinetic energy of gas constant)
2) produce μp and wait for thermalization
3) study time evolution of Oxygen X-rays (133 keV/~160 keV)
4) repeat with different temperature

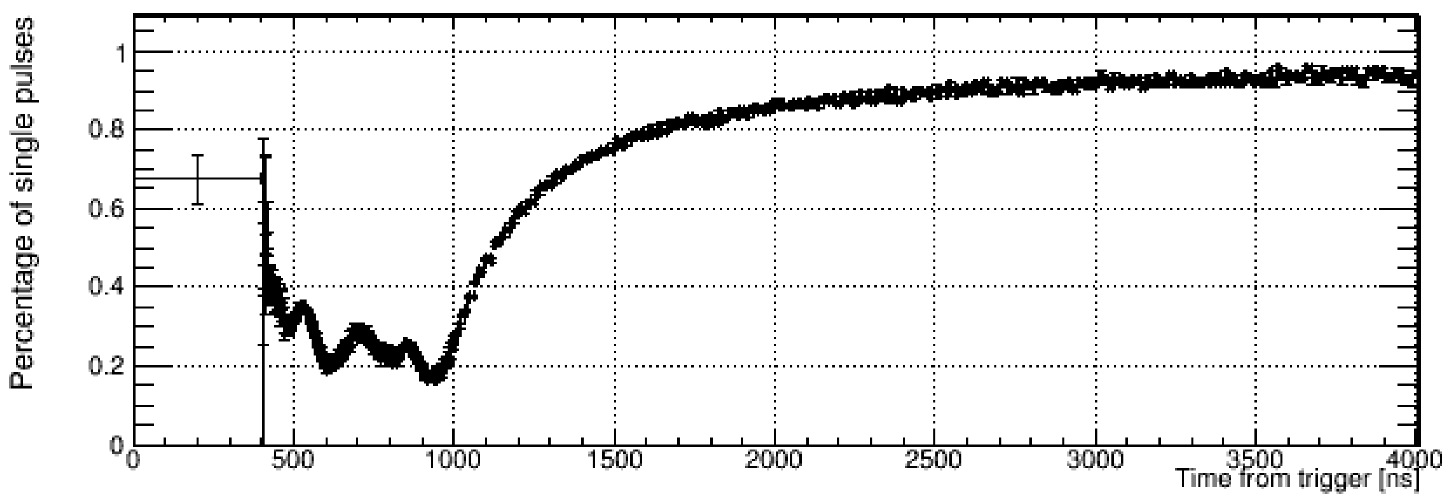
Waveforms fit



* 1 tdc = 2 ns

Mostly single pulses in delayed phase





Data selection

1. “Reasonable” reduced chi2 from the fit

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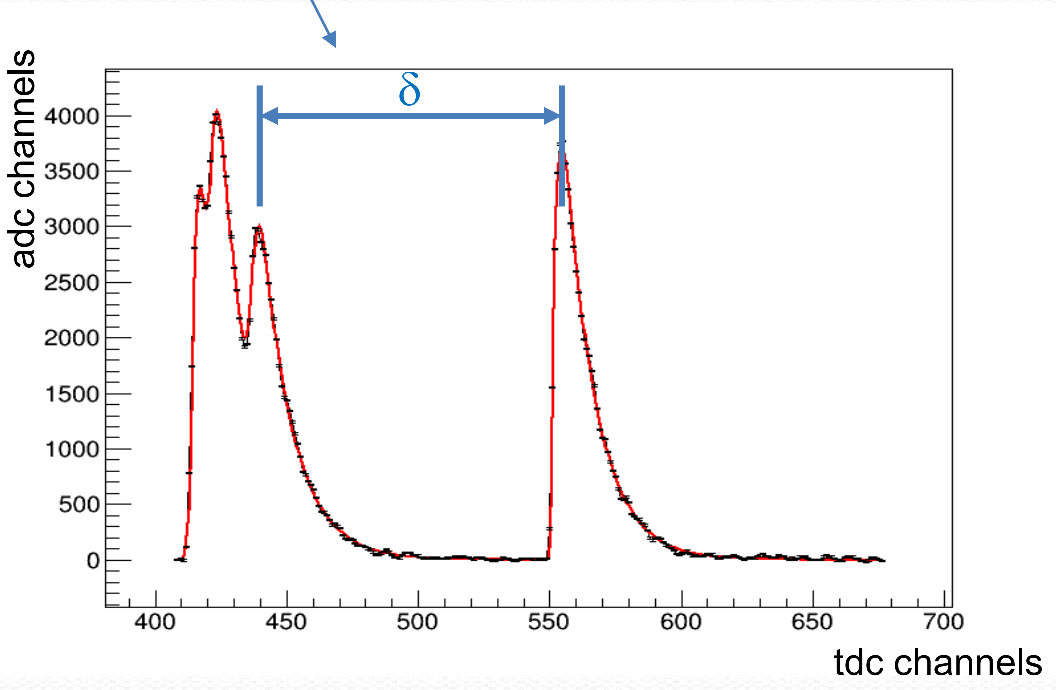
2. Distance (δ) between pulses > 30 ns

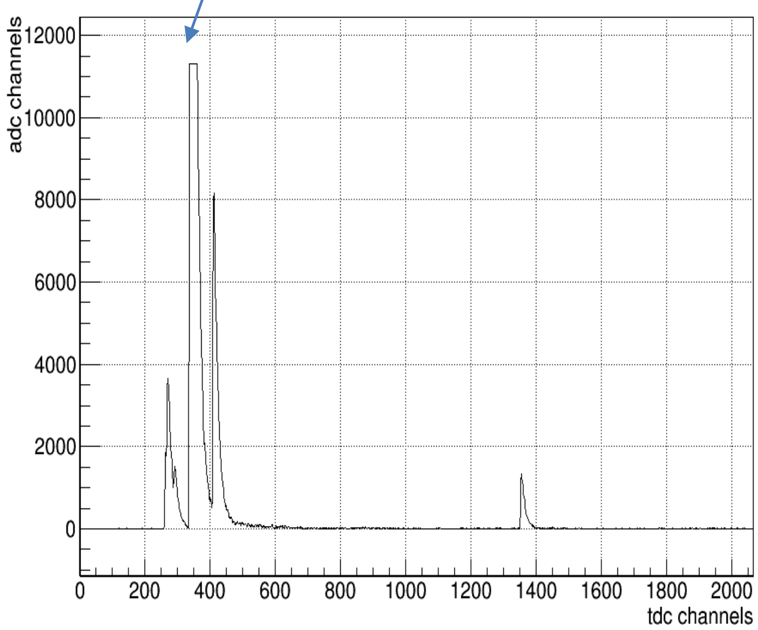


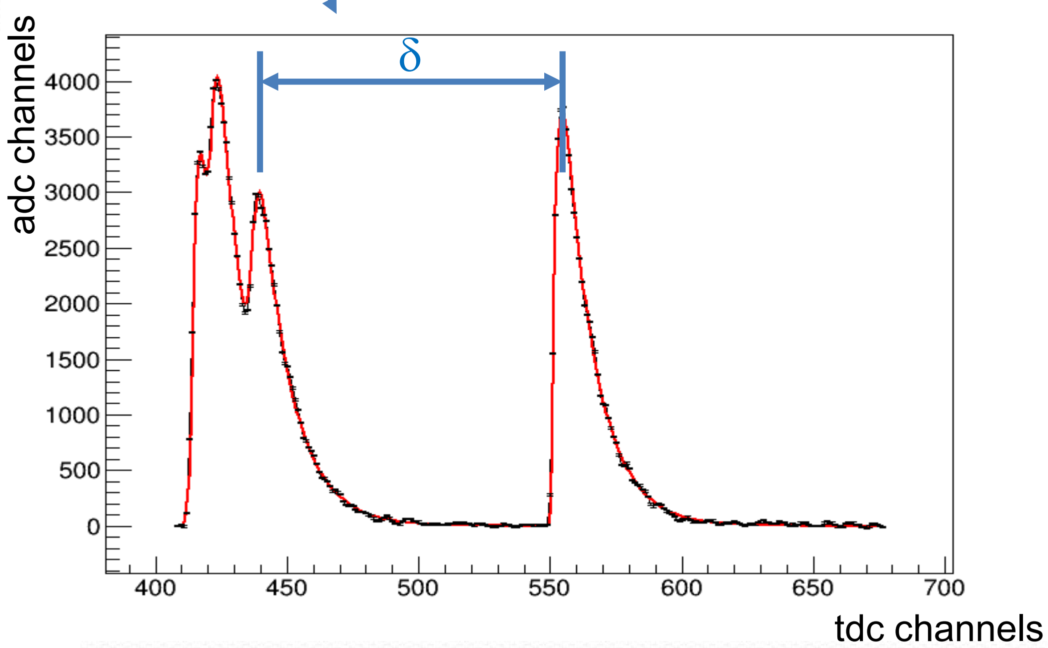
Data selection

1. “Reasonable” reduced chi2 from the fit

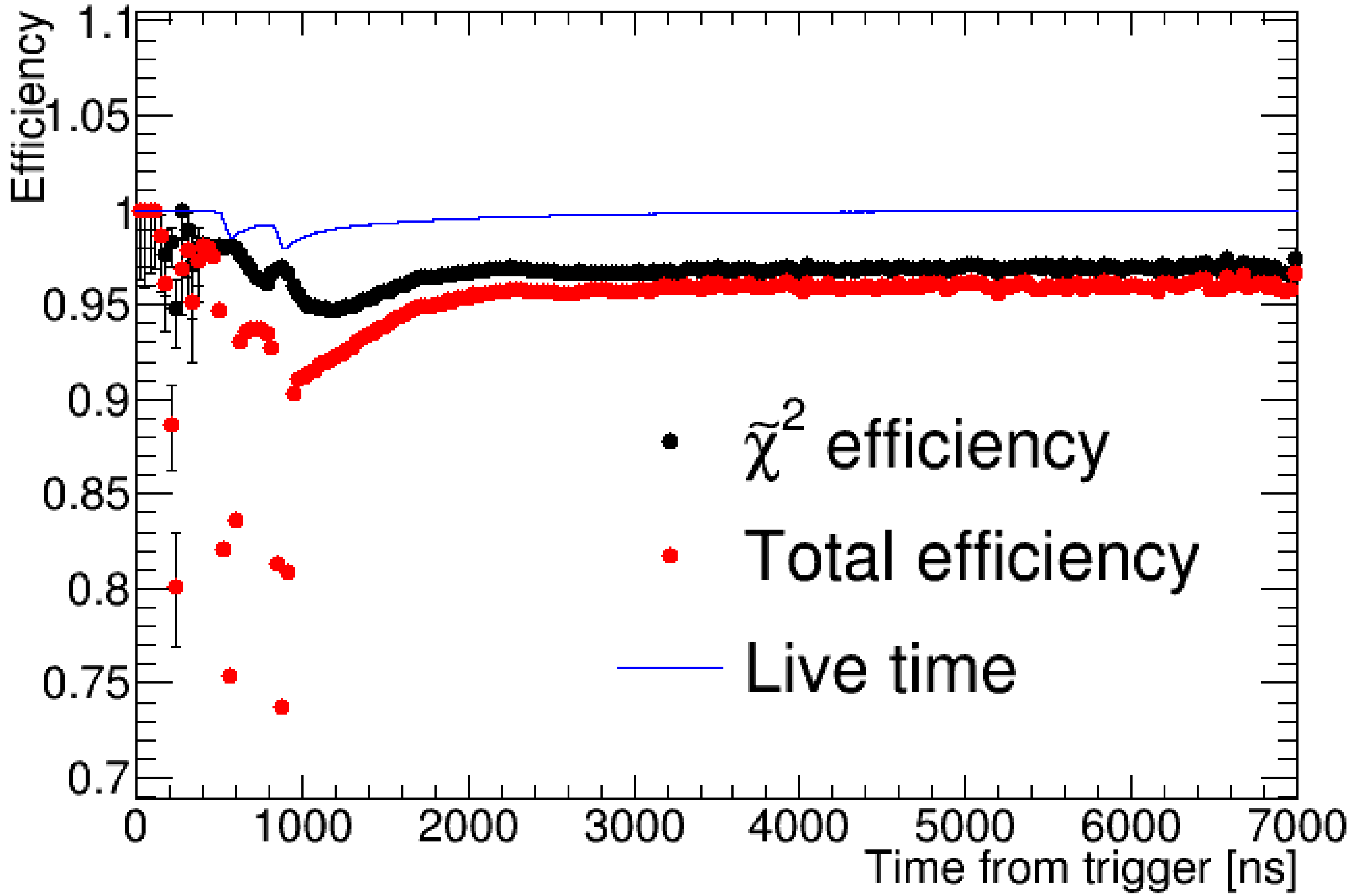
2. Distance (δ) between pulses > 30 ns

3. No saturated events





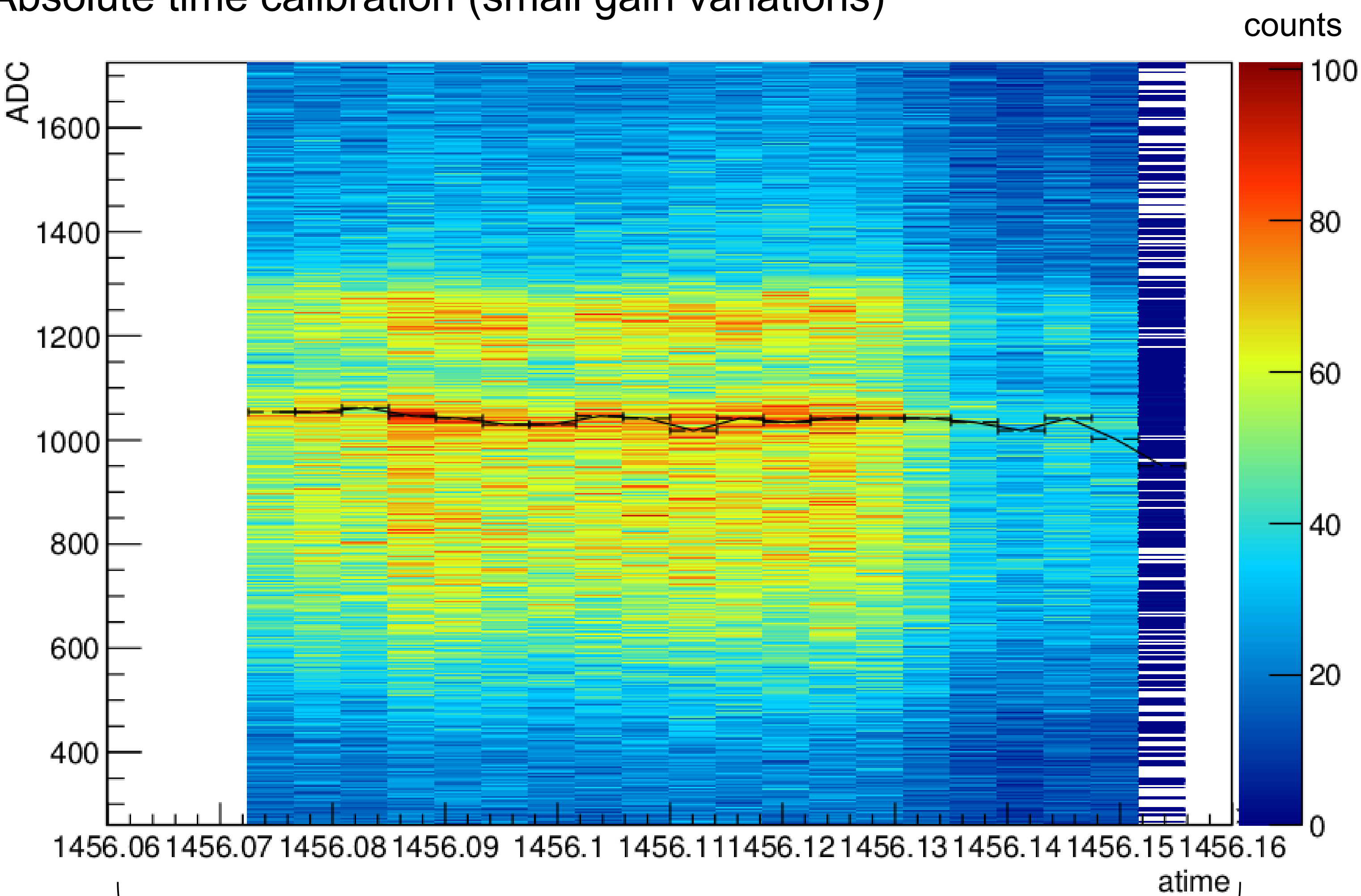
High selection efficiencies



Calibrations

LaBr3 detectors calibration

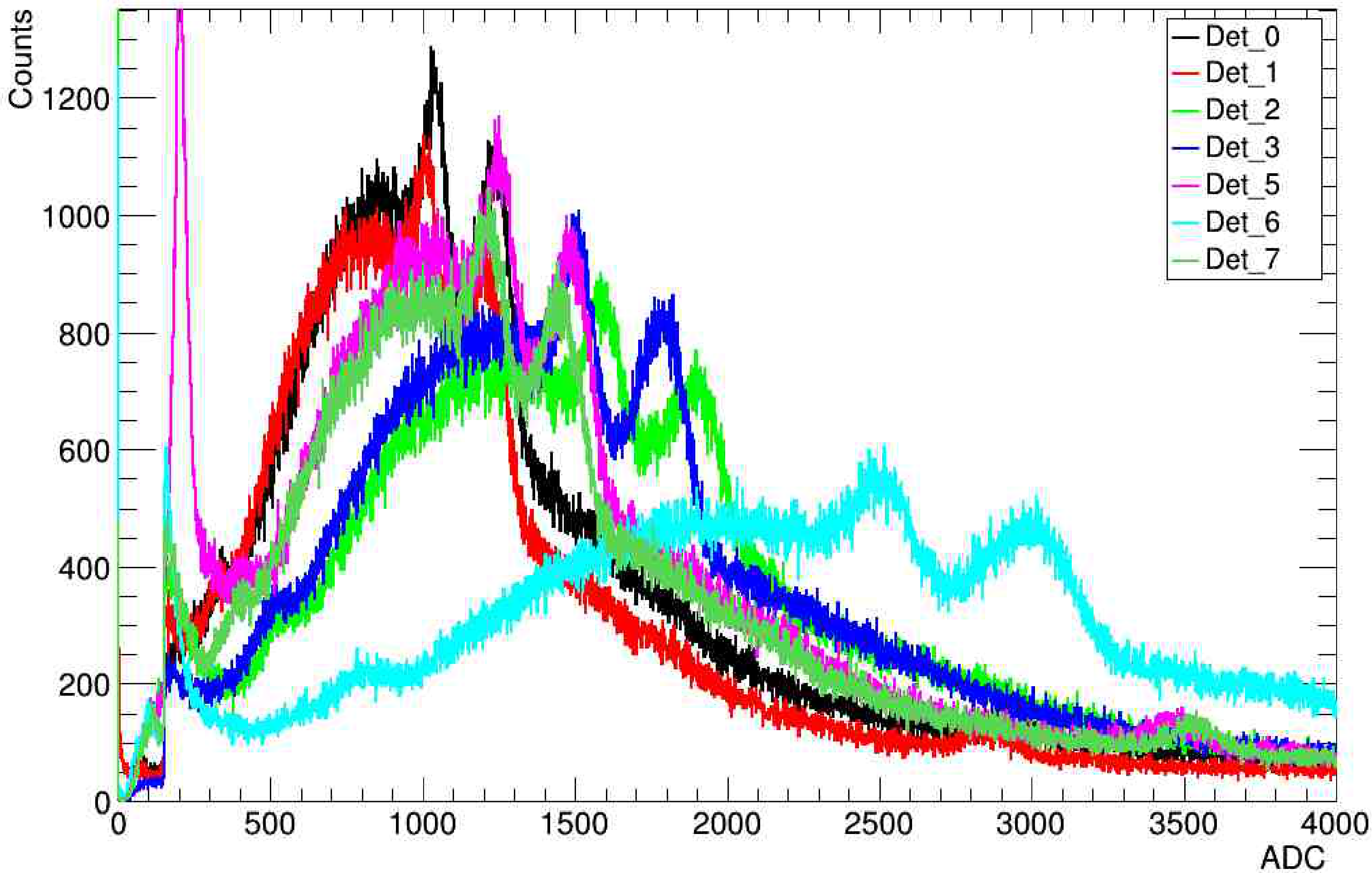
Absolute time calibration (small gain variations)



~1 day of data

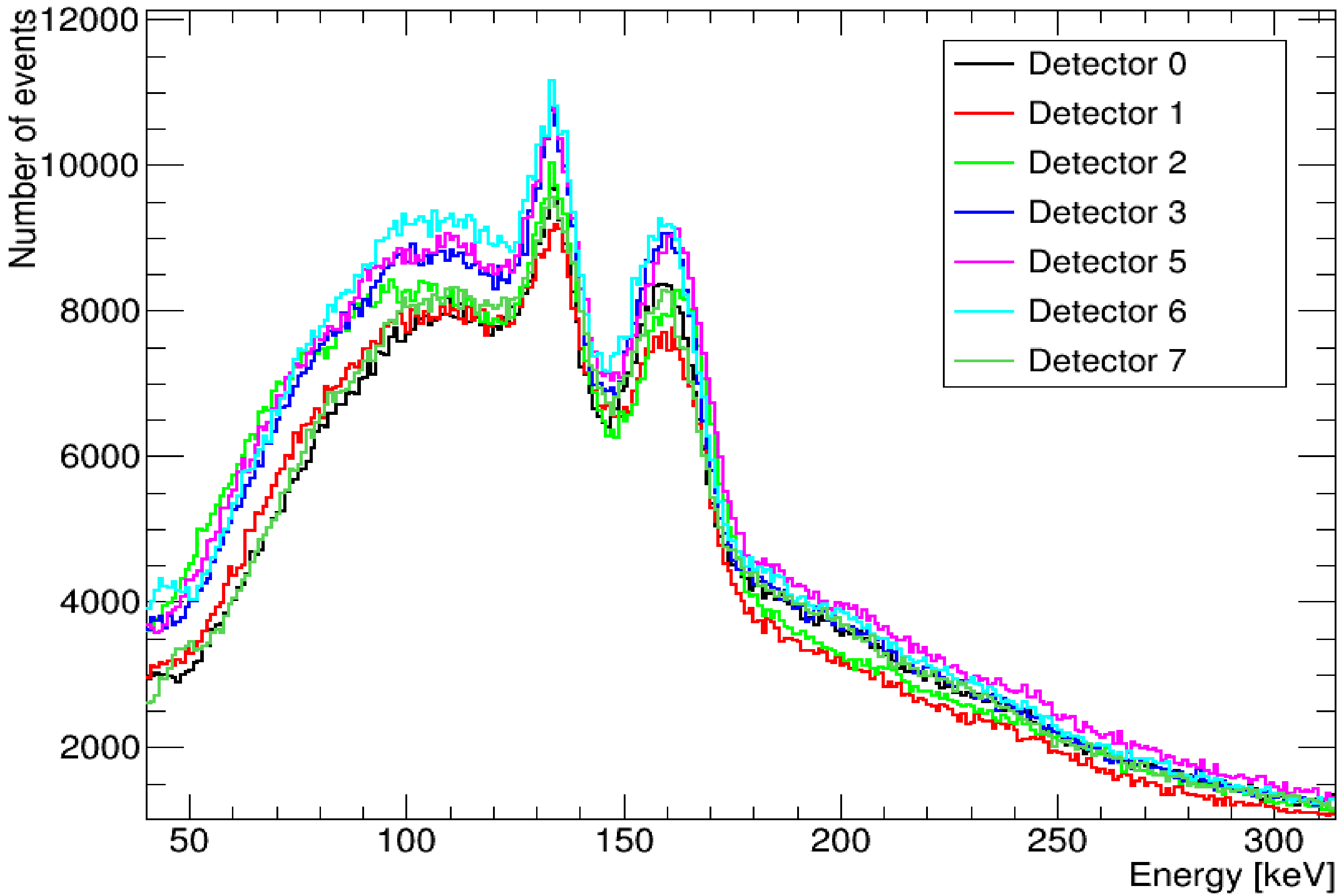
LaBr3 detectors calibration

Oxygen lines (uncalibrated)

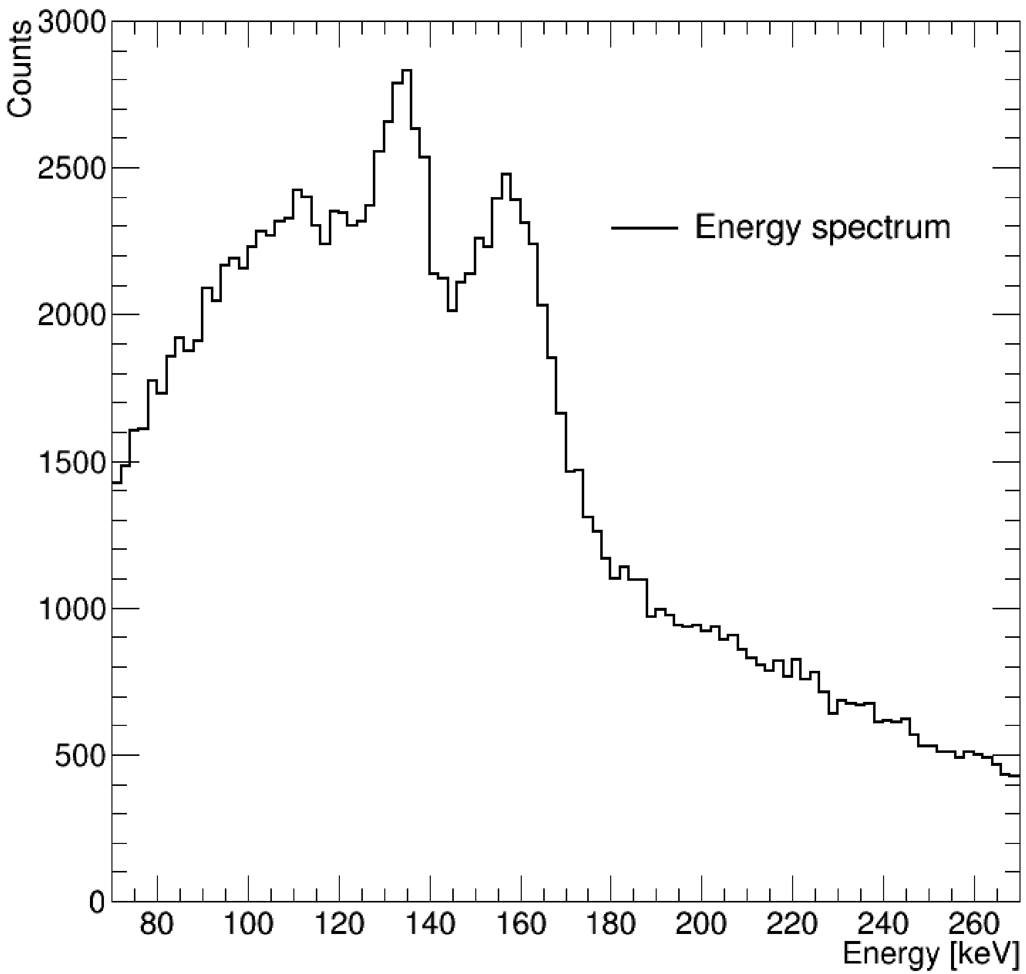


LaBr3 detectors calibration

Oxygen lines (calibrated)

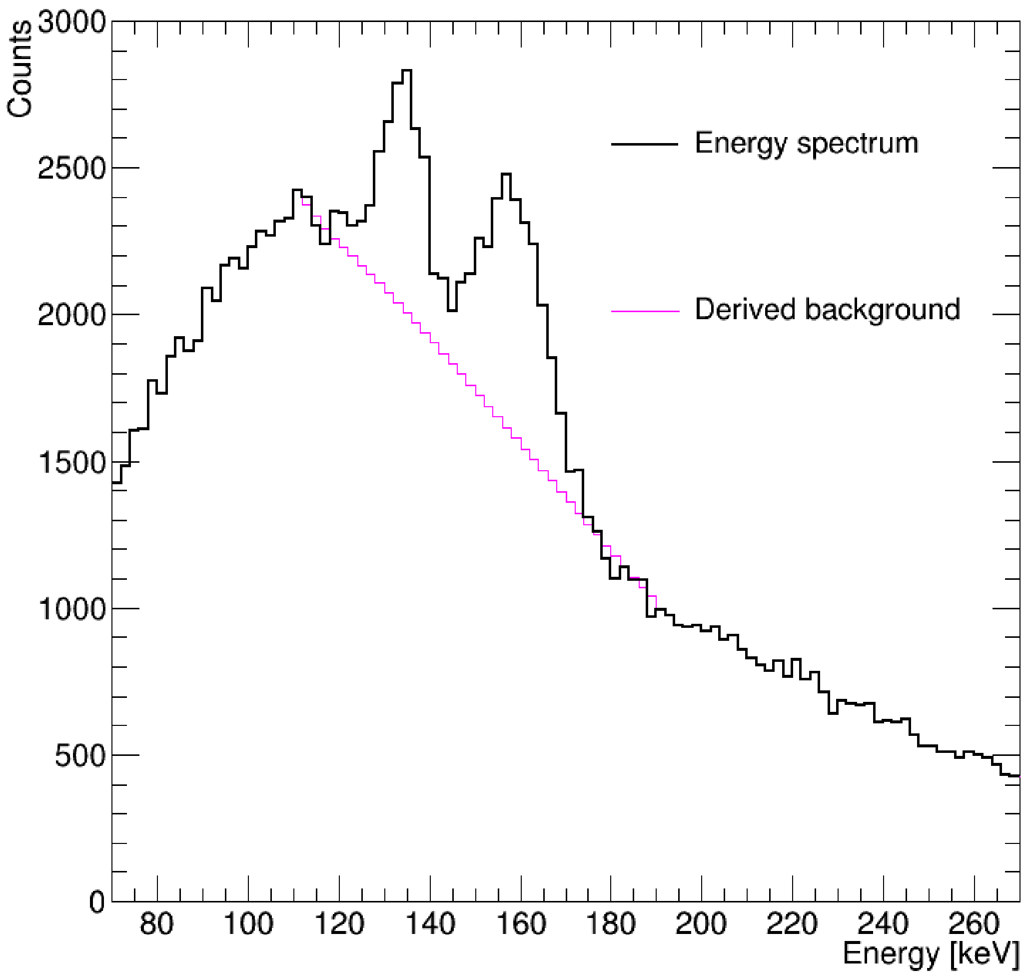


The background problem…



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

Simplest solution: "straight line"

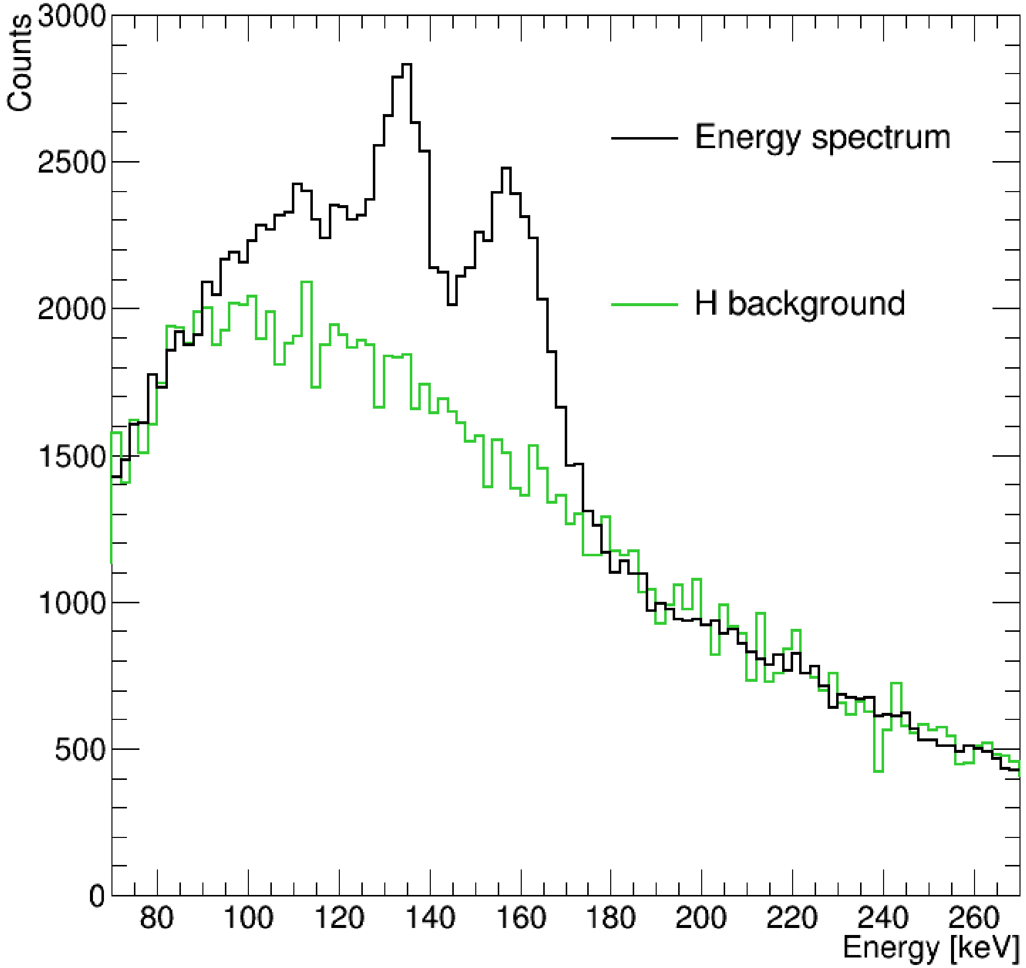


T = 300 K
Time bin = [1450,1650] ns

Using ROOT/"TSpectrum" class – spectroscopic algorithms

Problem: unstable results…

Better solution: pure hydrogen

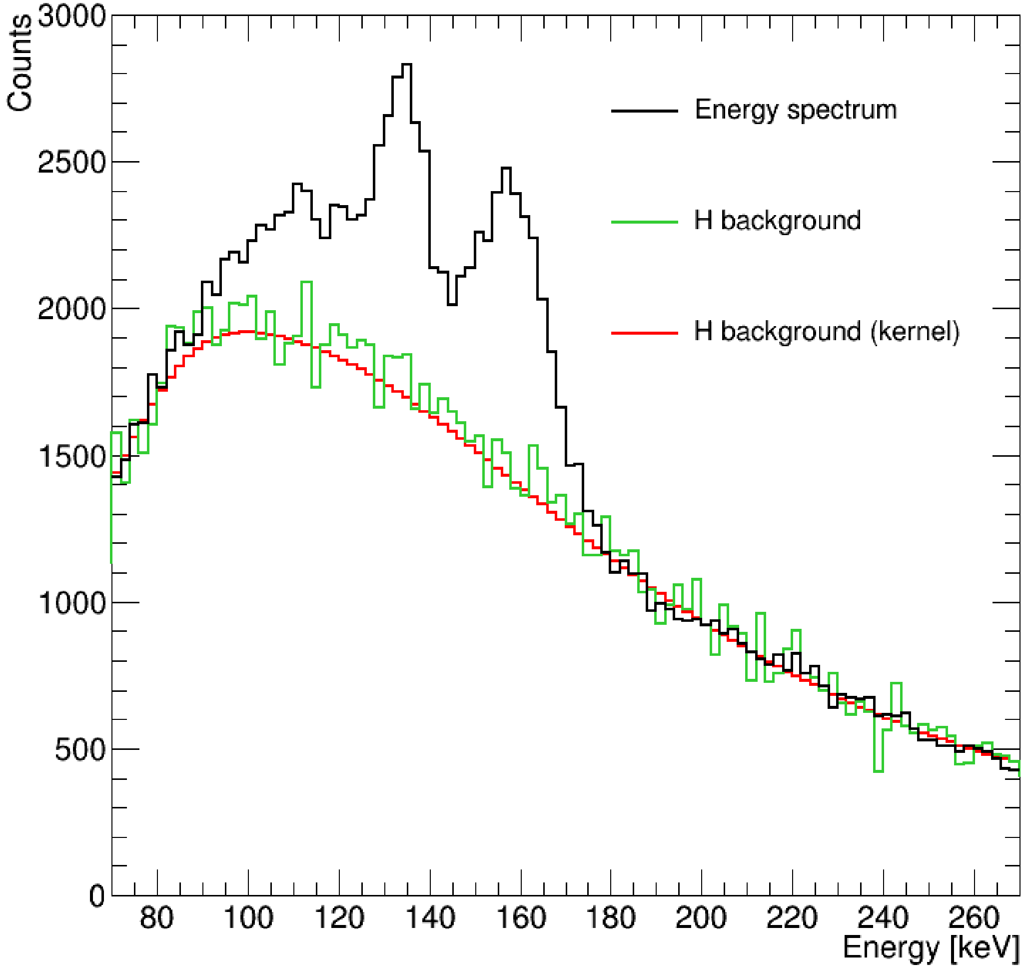


T = 300 K
Time bin = [1450,1650] ns

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

However: poor statistics…

Best solution: pure H smoothing



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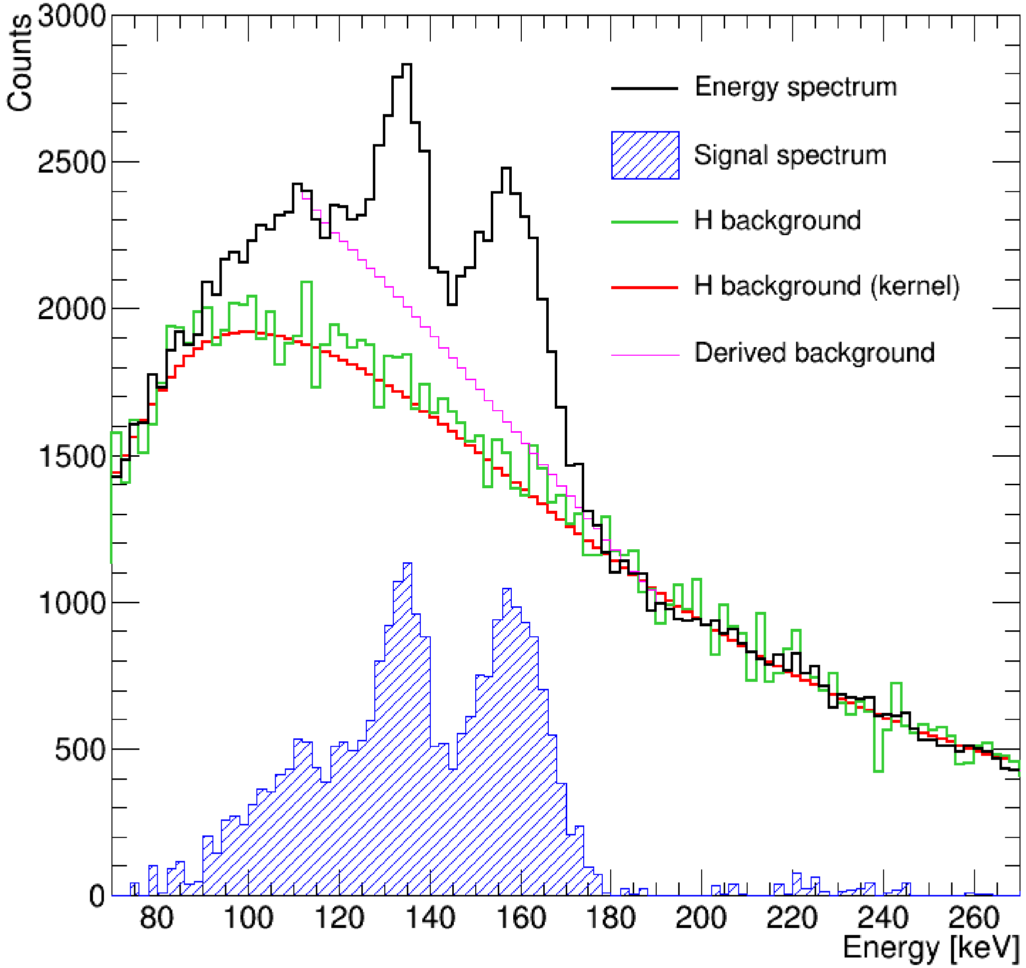

T = 300 K
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Simulation studies

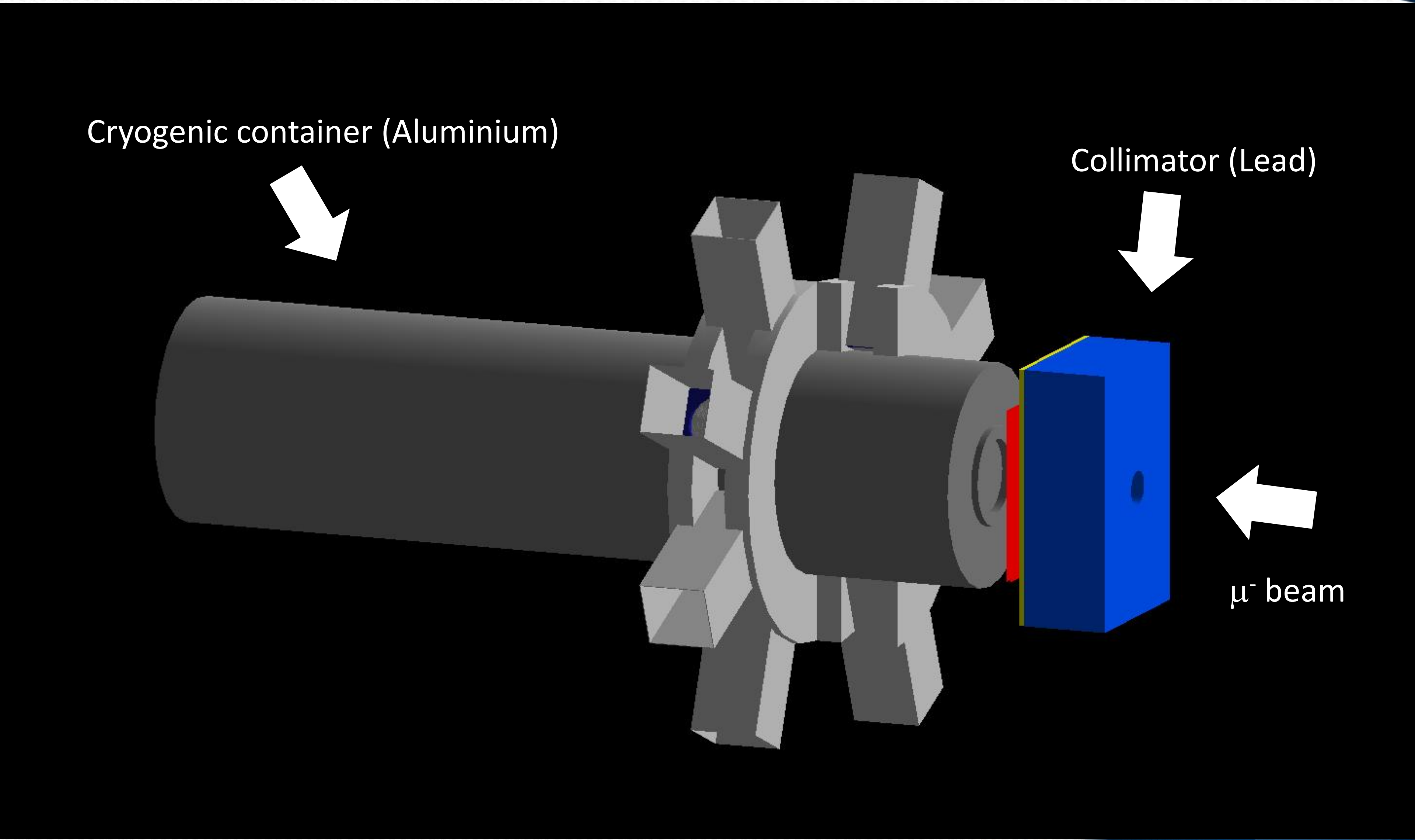
GEANT4 simulation with tuning

FAMU 2016 apparatus and detectors simulation:
- Geometry
- Digitization
- Reconstruction using the same programs used for real data

GEANT4 physics tuning, corrections and add-ons:
- Muonic X-ray lines not reproduced correctly
- Transfer rate process not implemented

Custom physics-list which solves (partially) these missing items

FAMU simulated geometry



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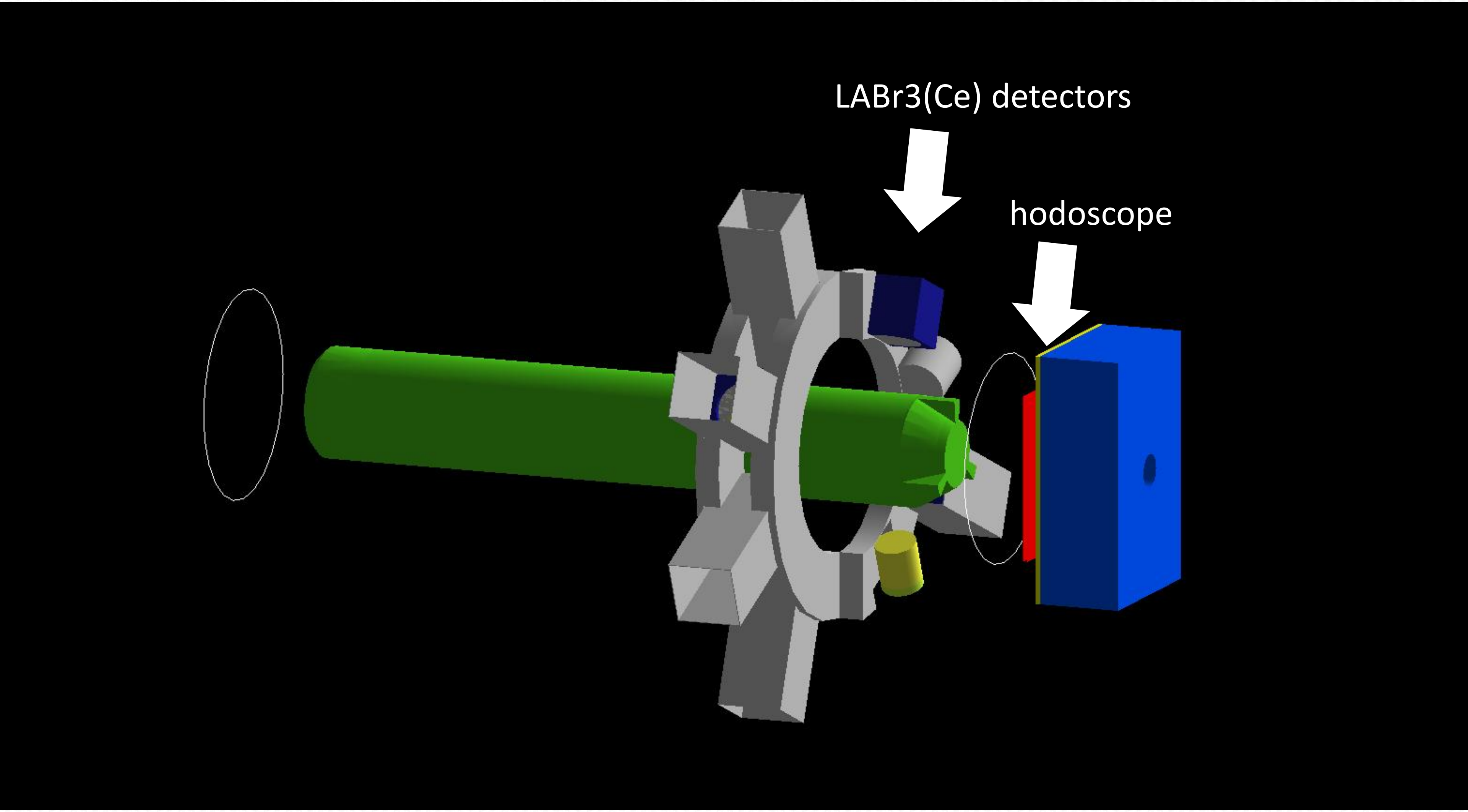

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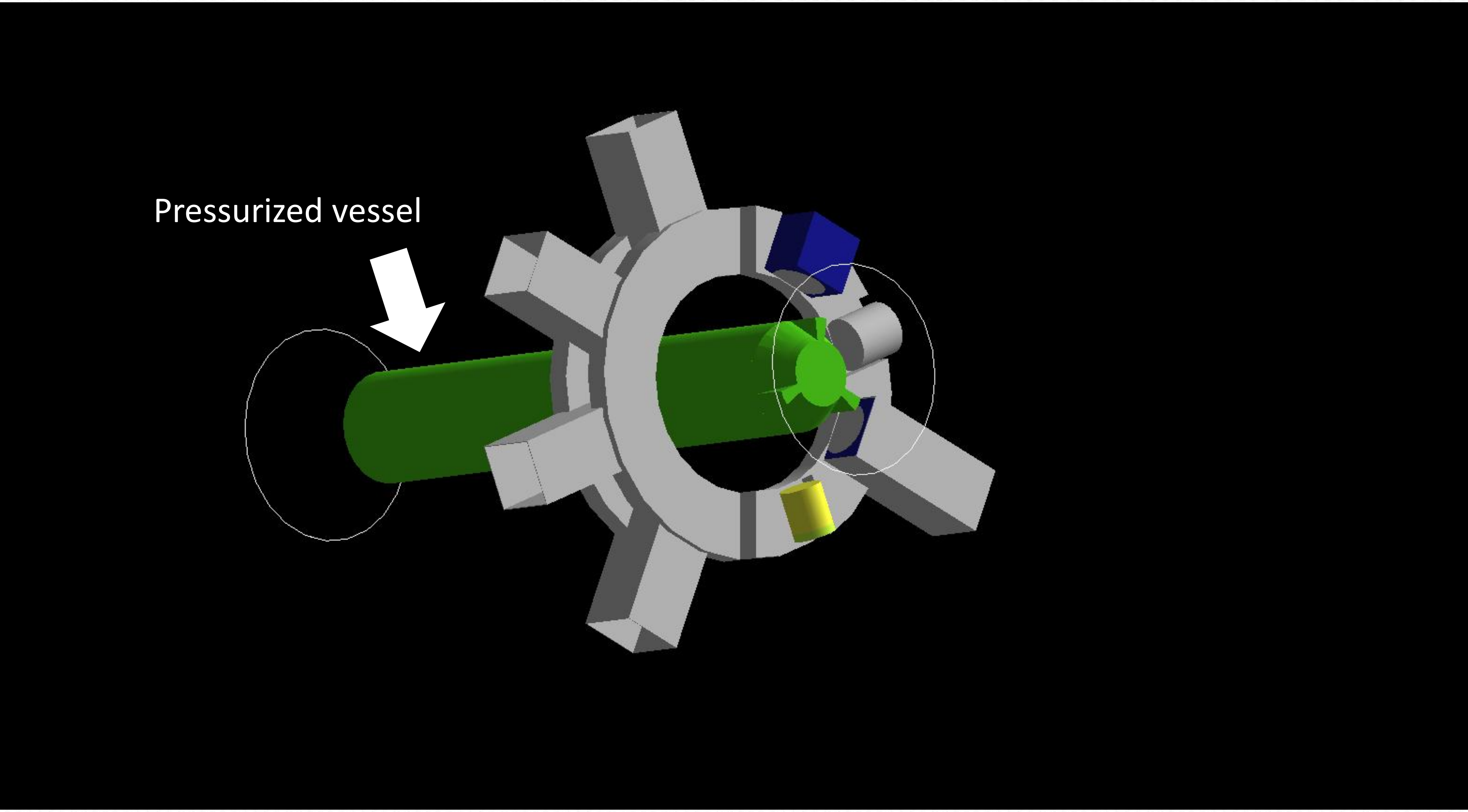

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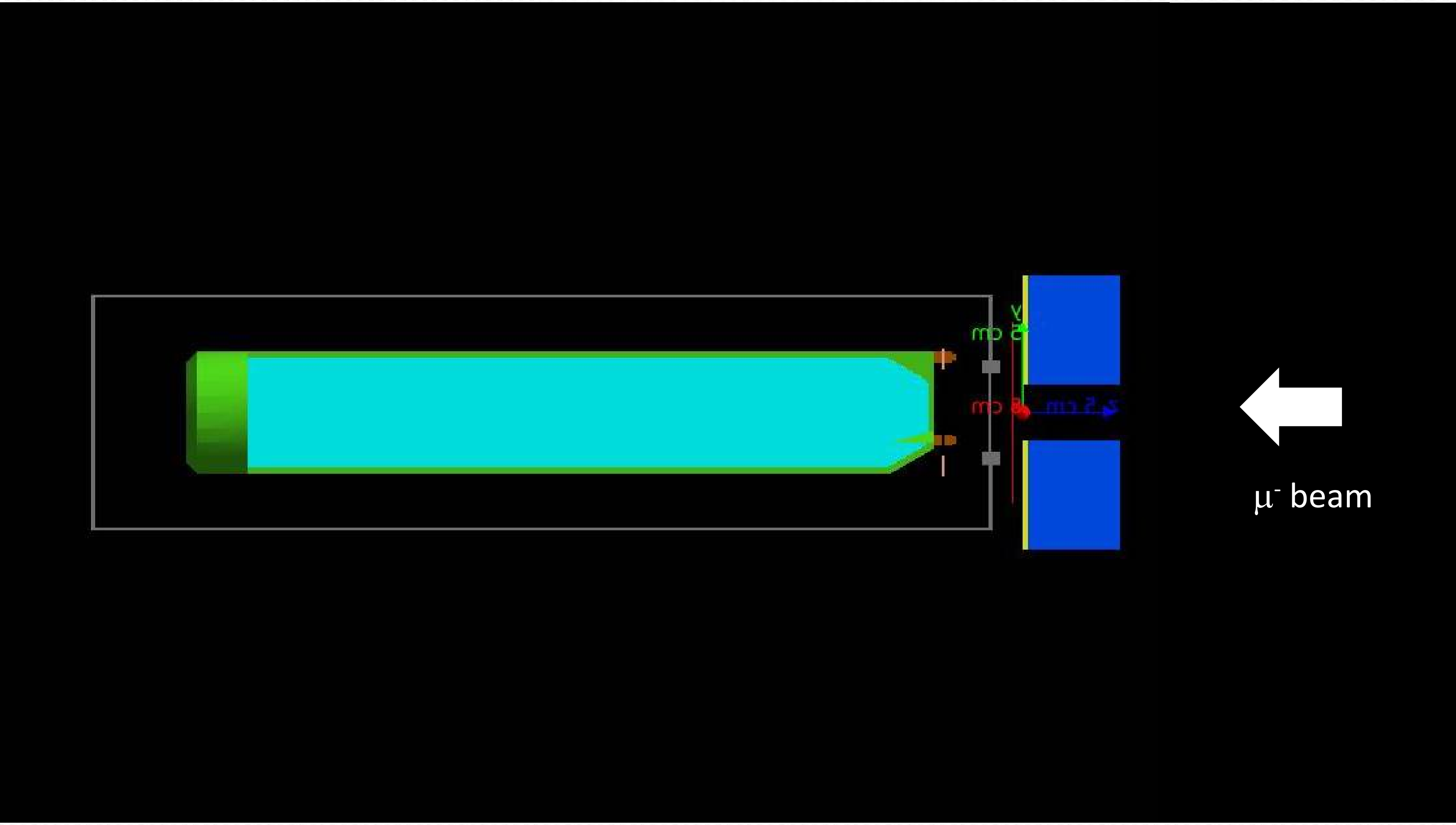
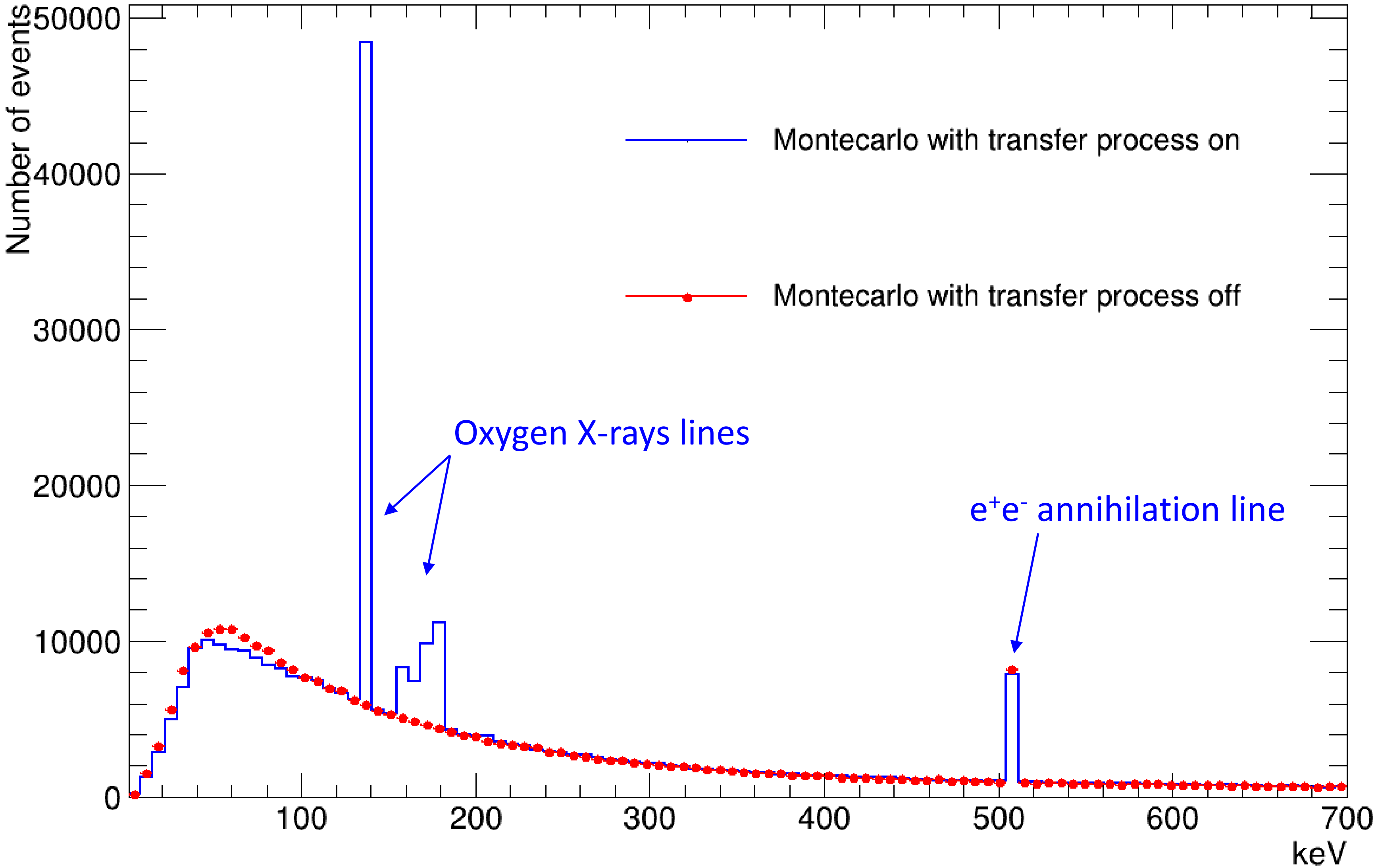
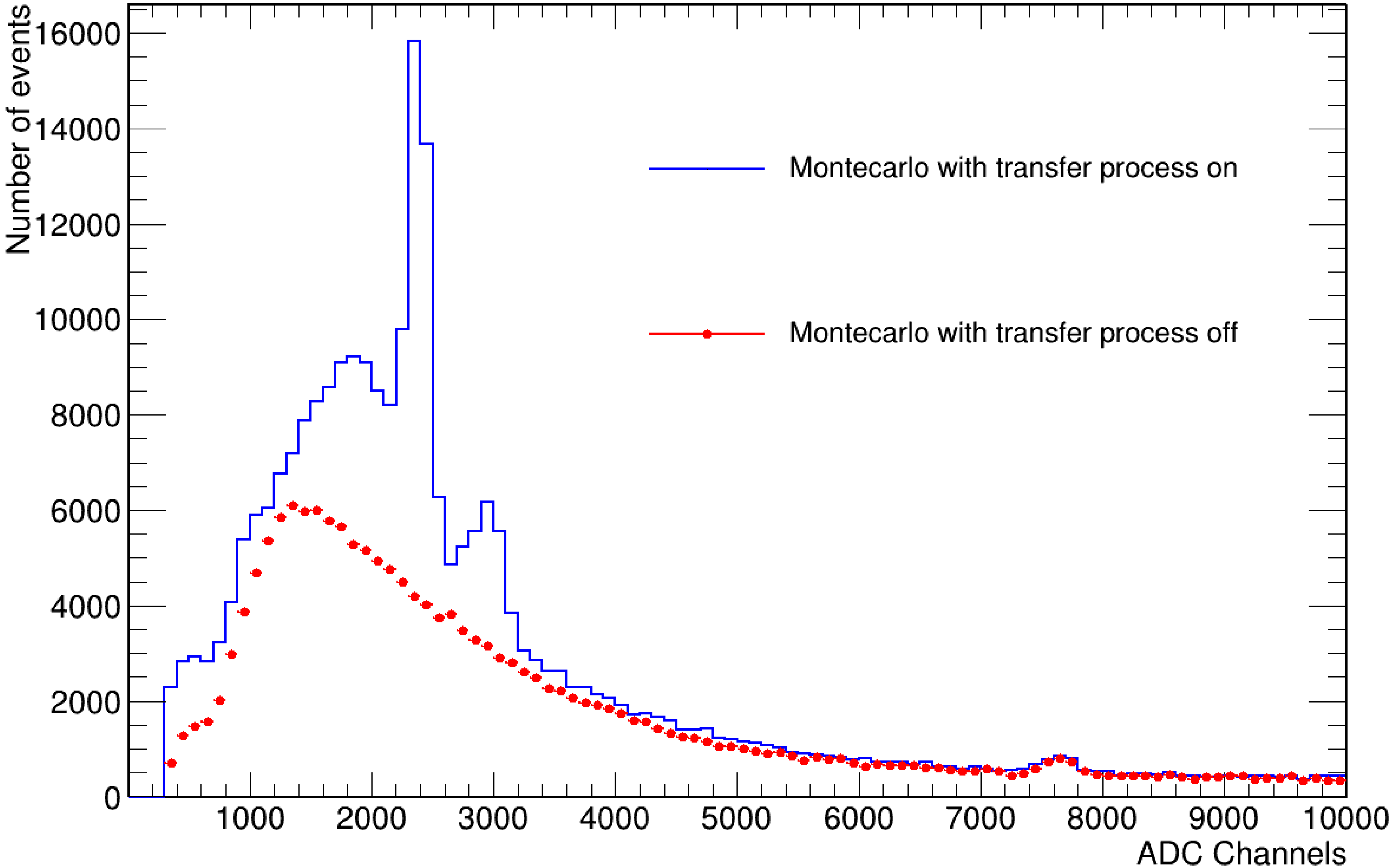


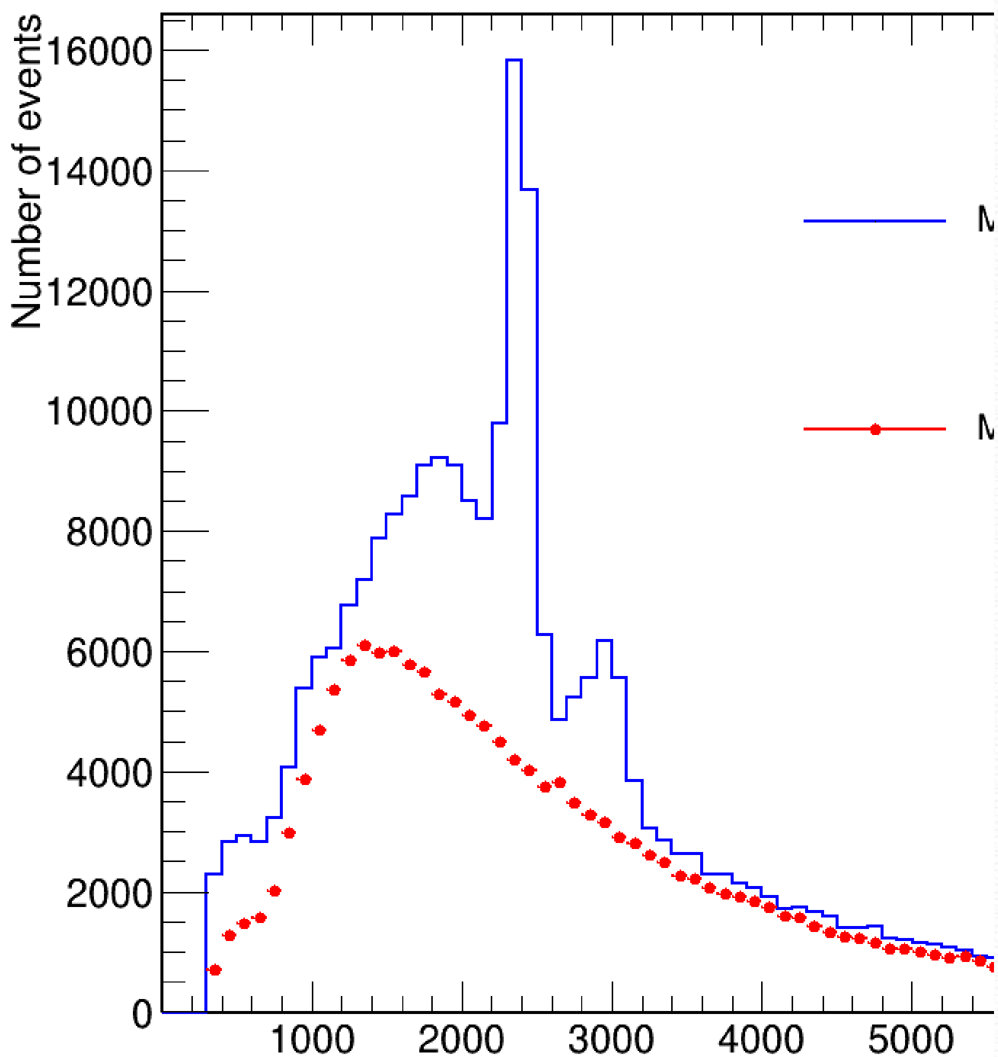
Simulation: energy at generation time of particles entering the detectors

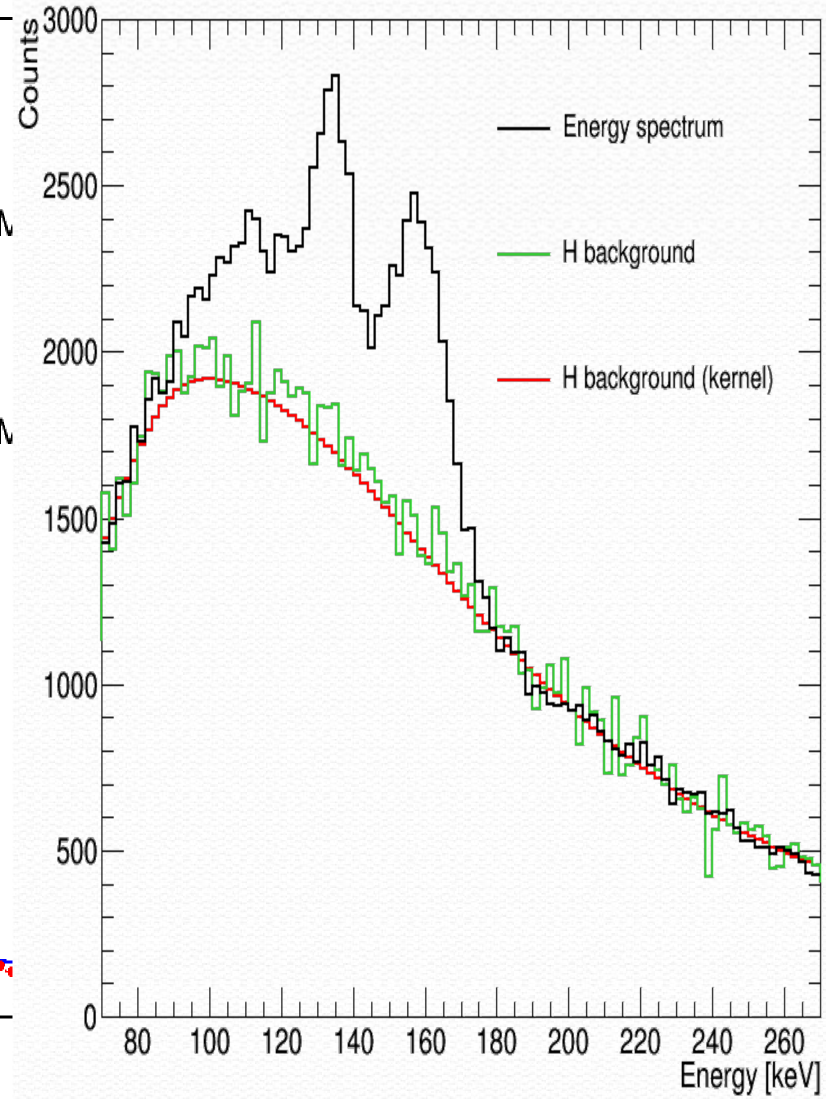


Simulation: energy measured by the detectors (after digitization)

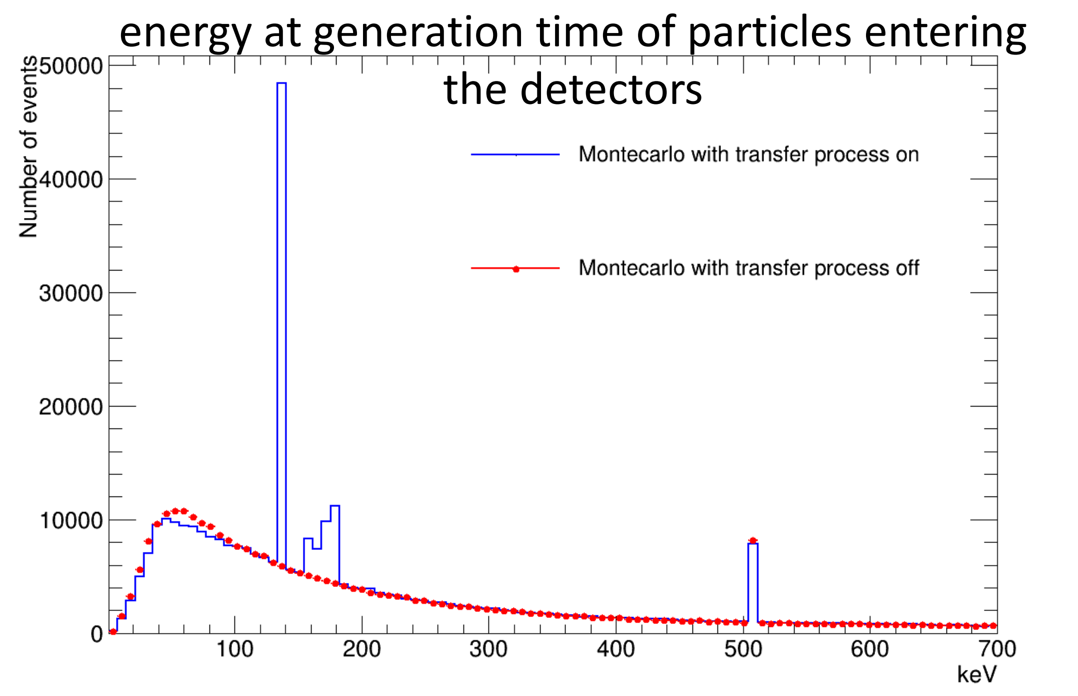


Simulation vs data: pretty similar!





Simulation: energy released in the detector for 133 keV line



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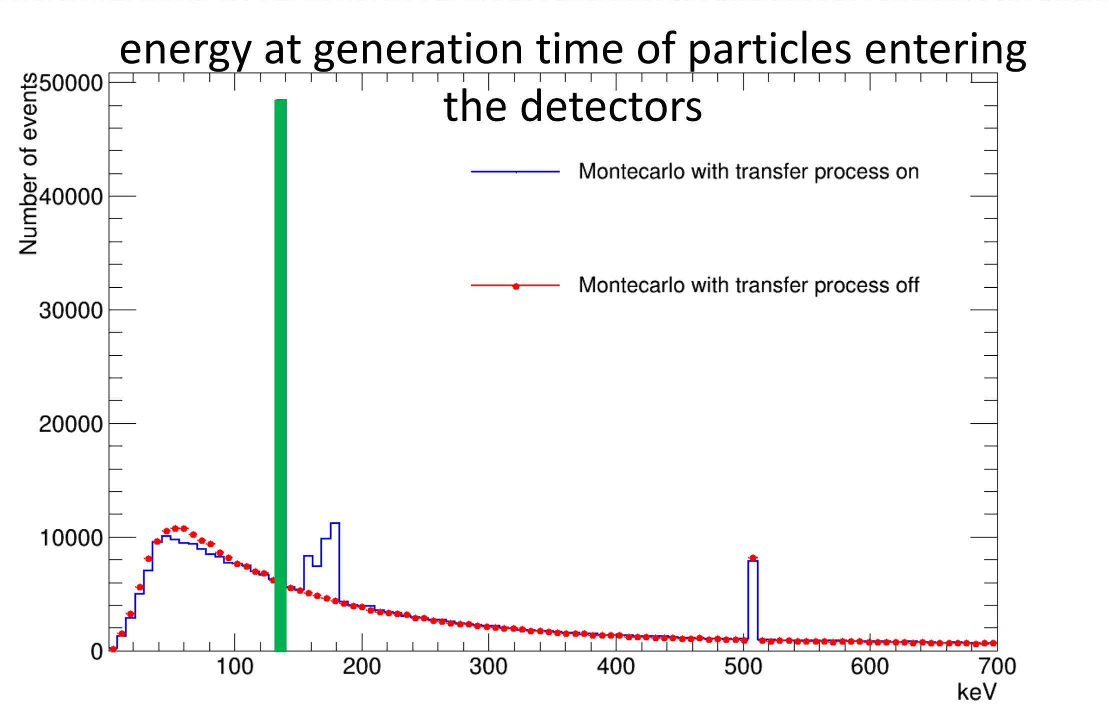
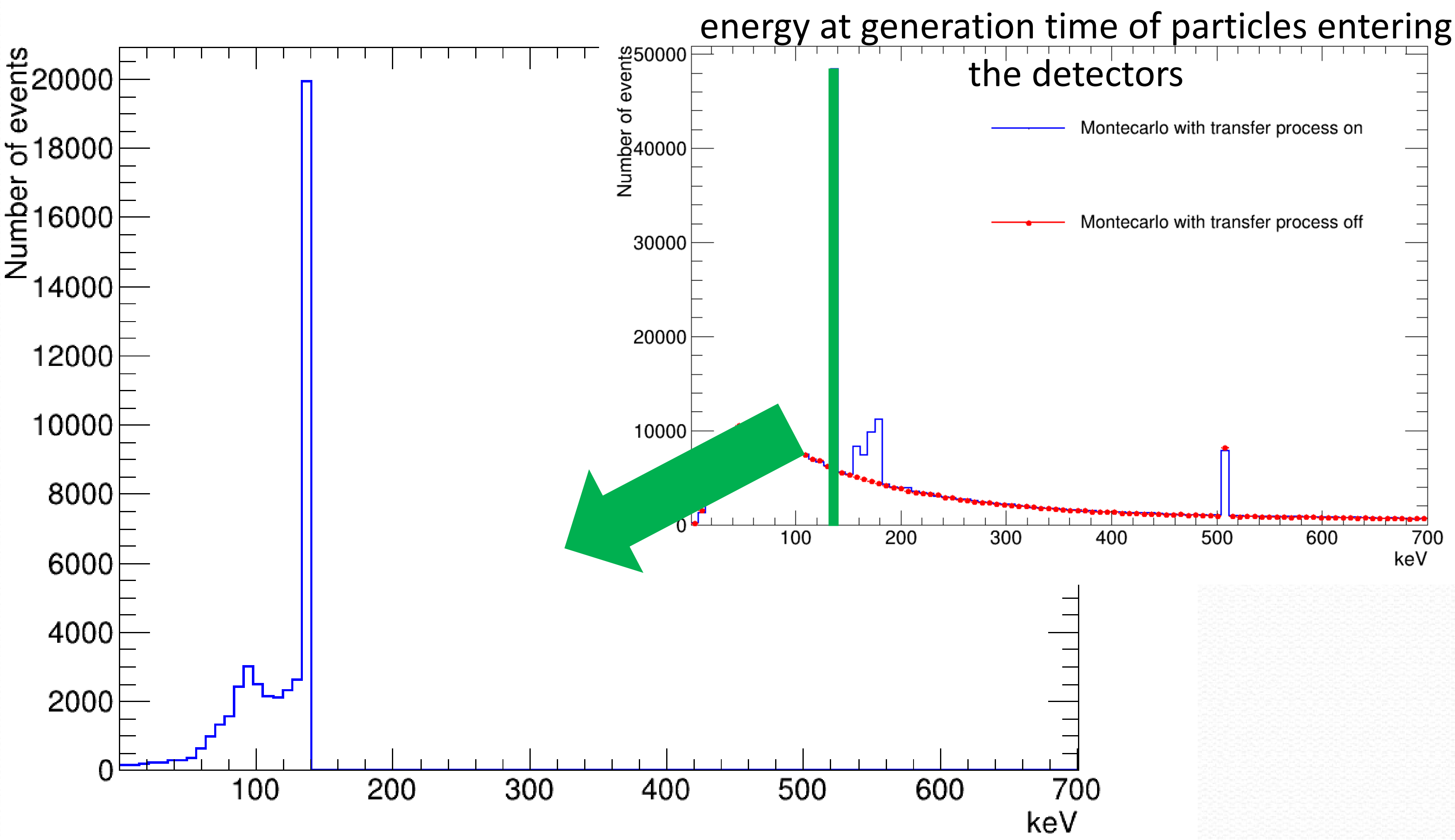
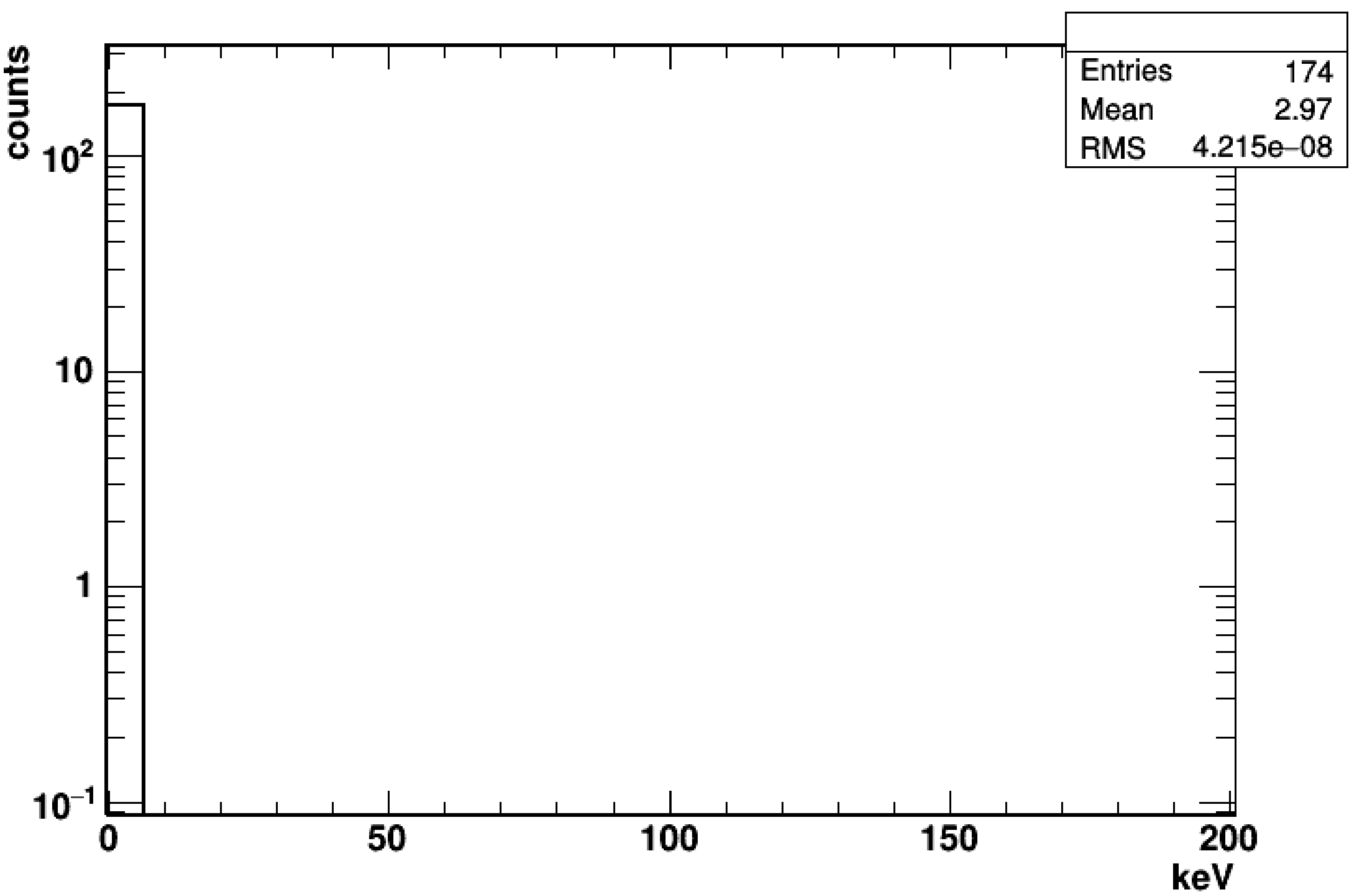


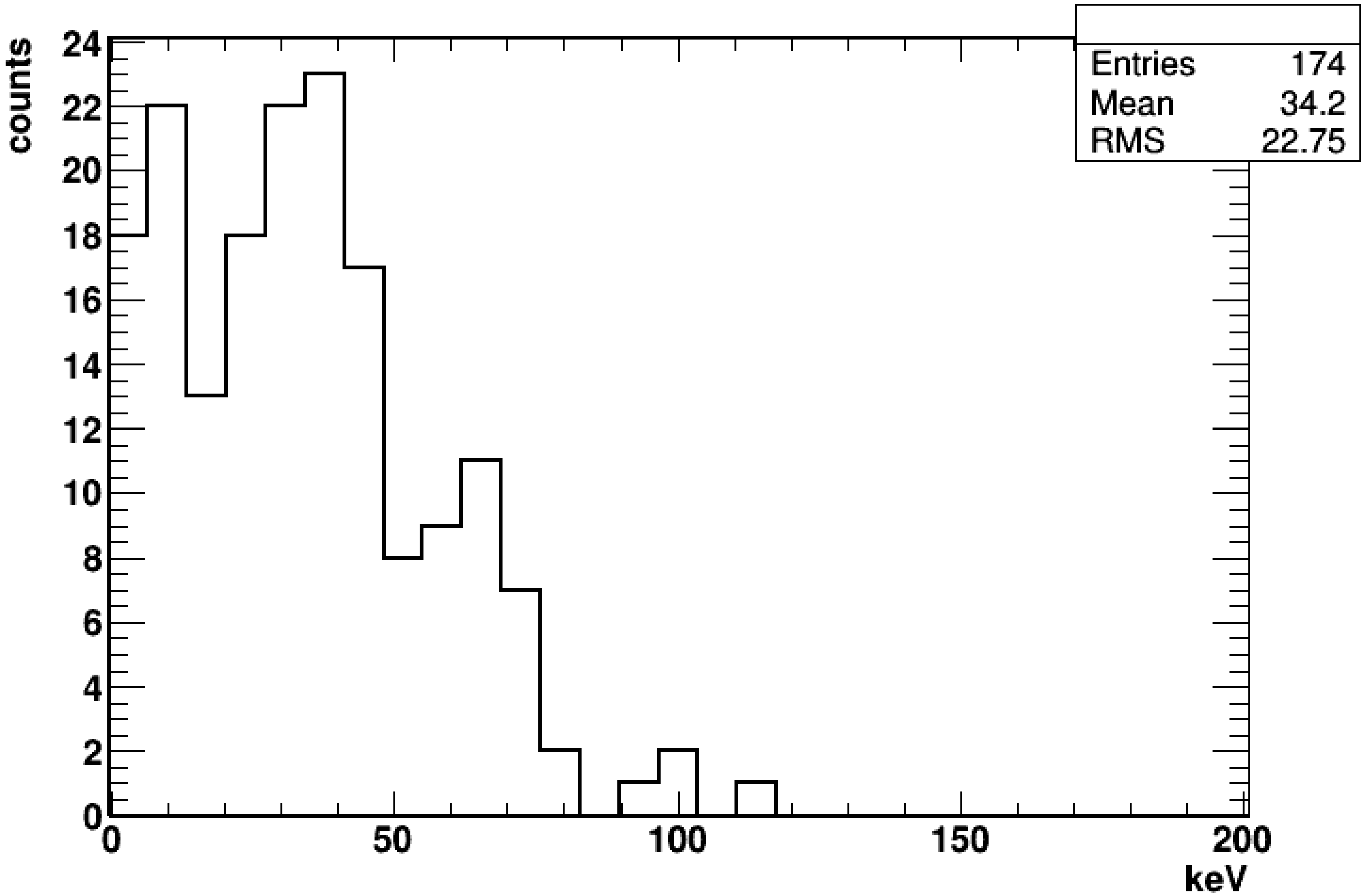
Simulation: energy released in the detector for 133 keV line



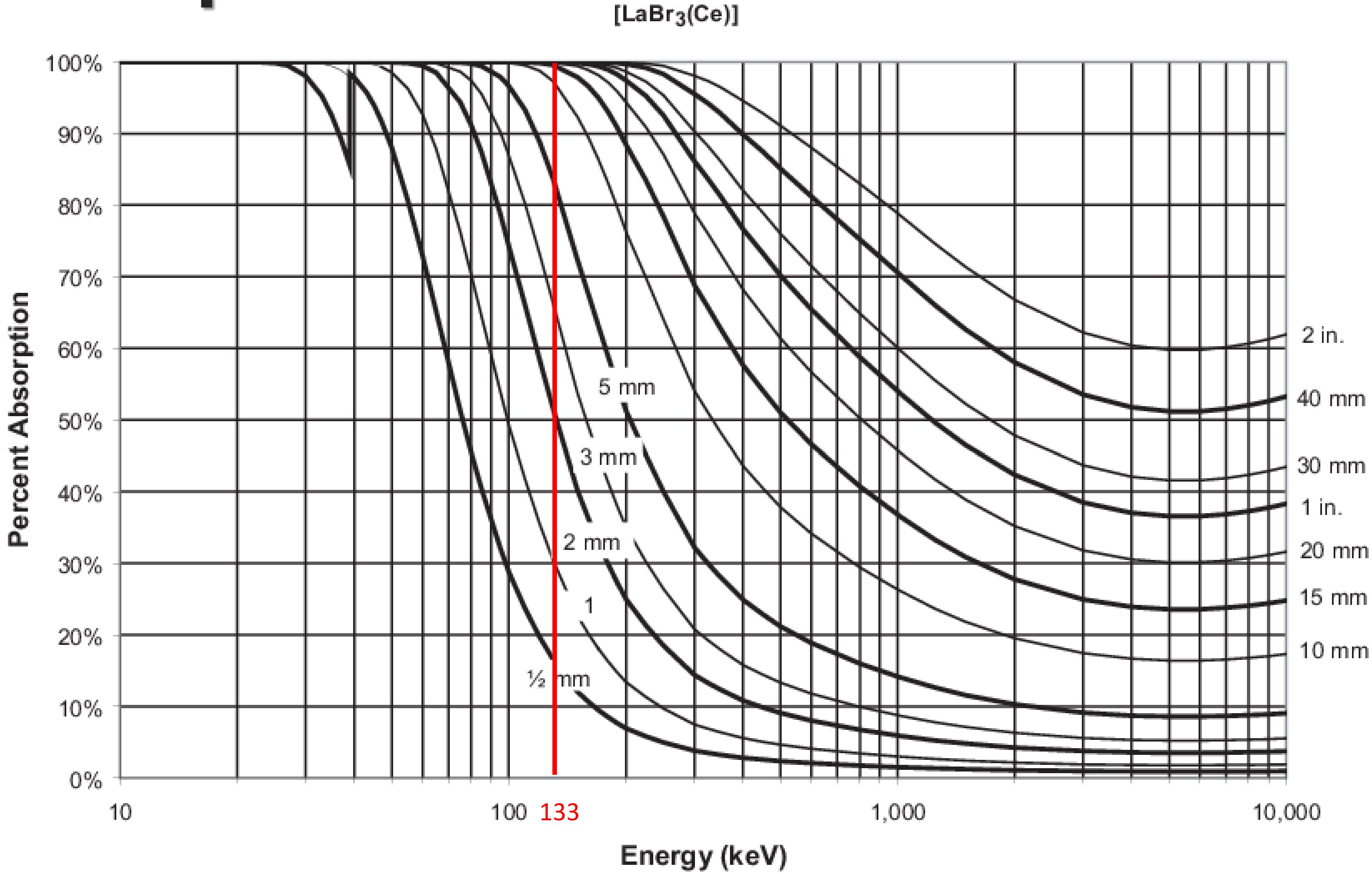
Simulation: energy loss by particles BEFORE entering the crystal



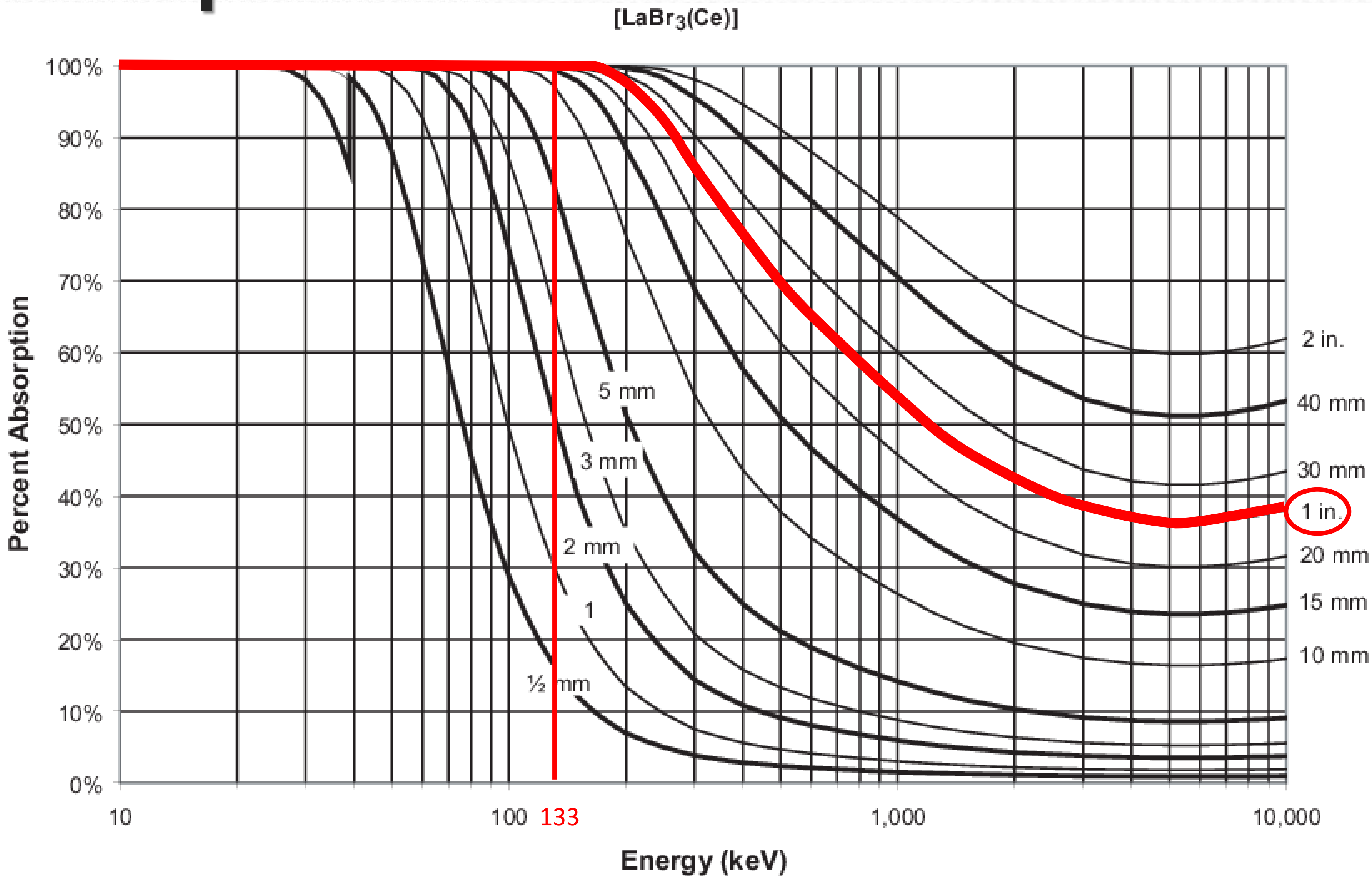
Simulation: energy deposit outside the crystal after the first interaction (leakage)



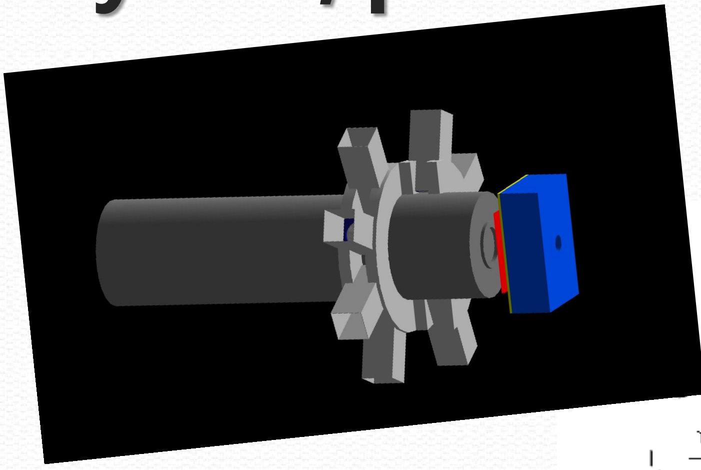
LaBr3(Ce) absorption graph: 133 keV photon: 80% in 5 mm

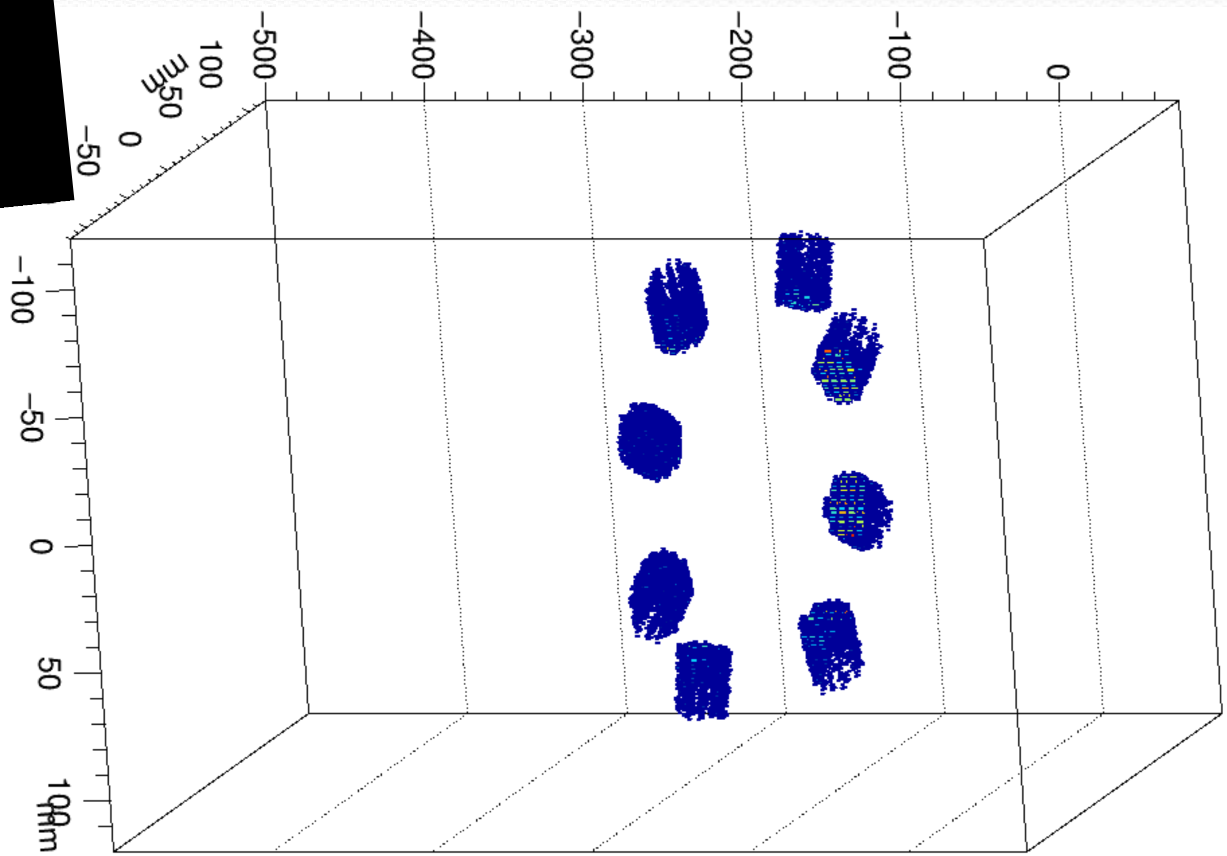


LaBr3(Ce) absorption graph:
133 keV photon: 80% in 5 mm

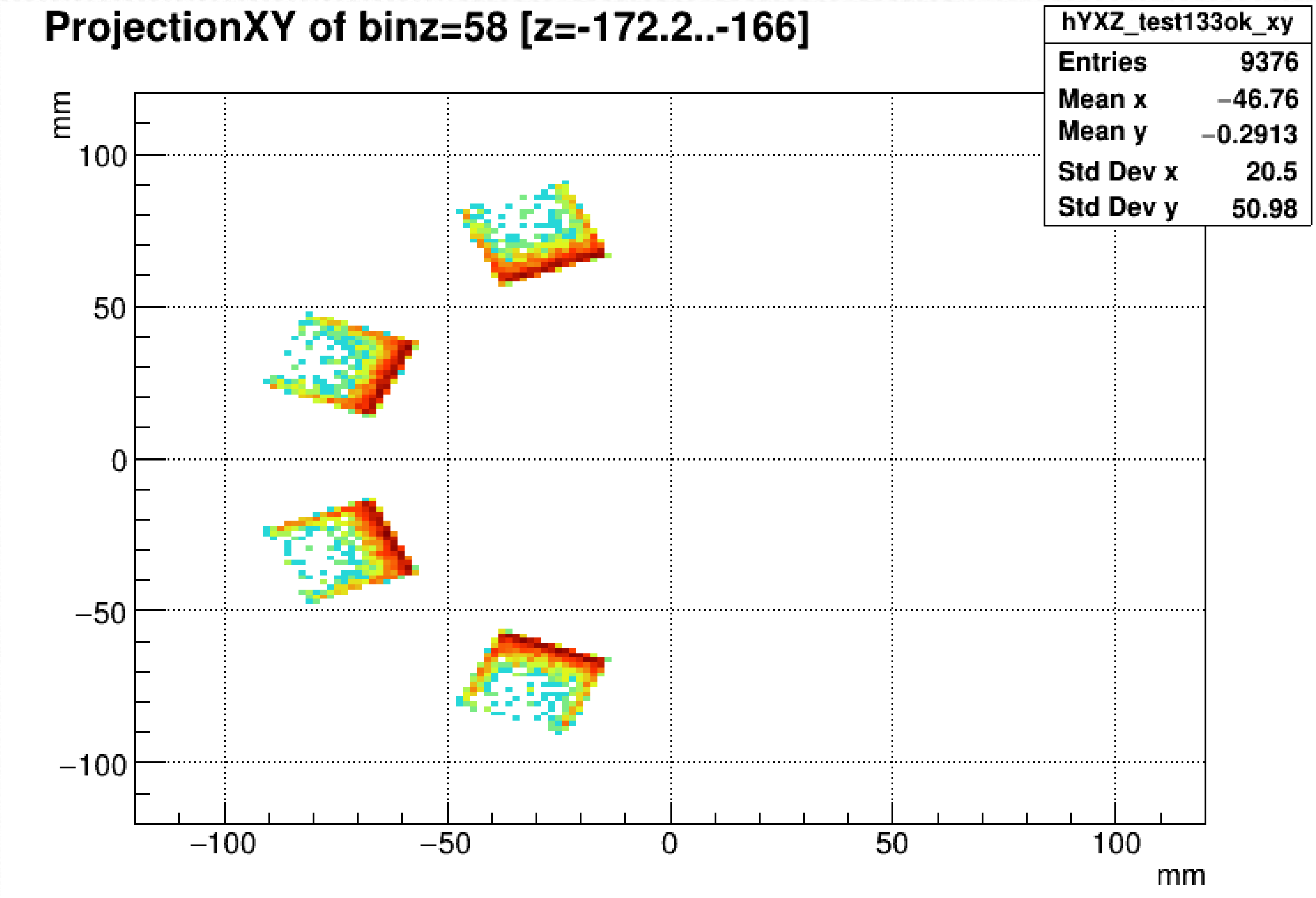


Simulation: impact point in the crystals, particles at any energy

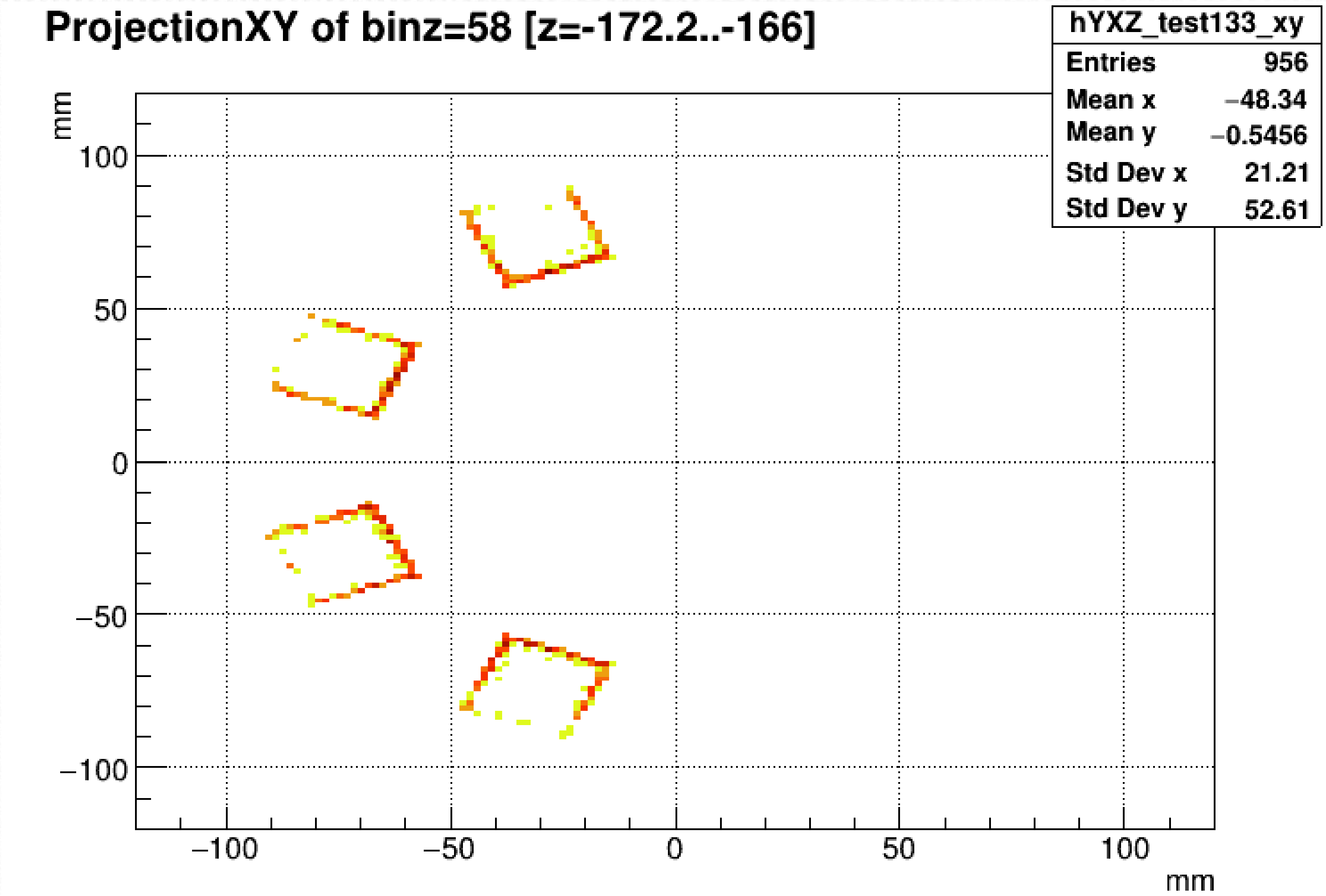




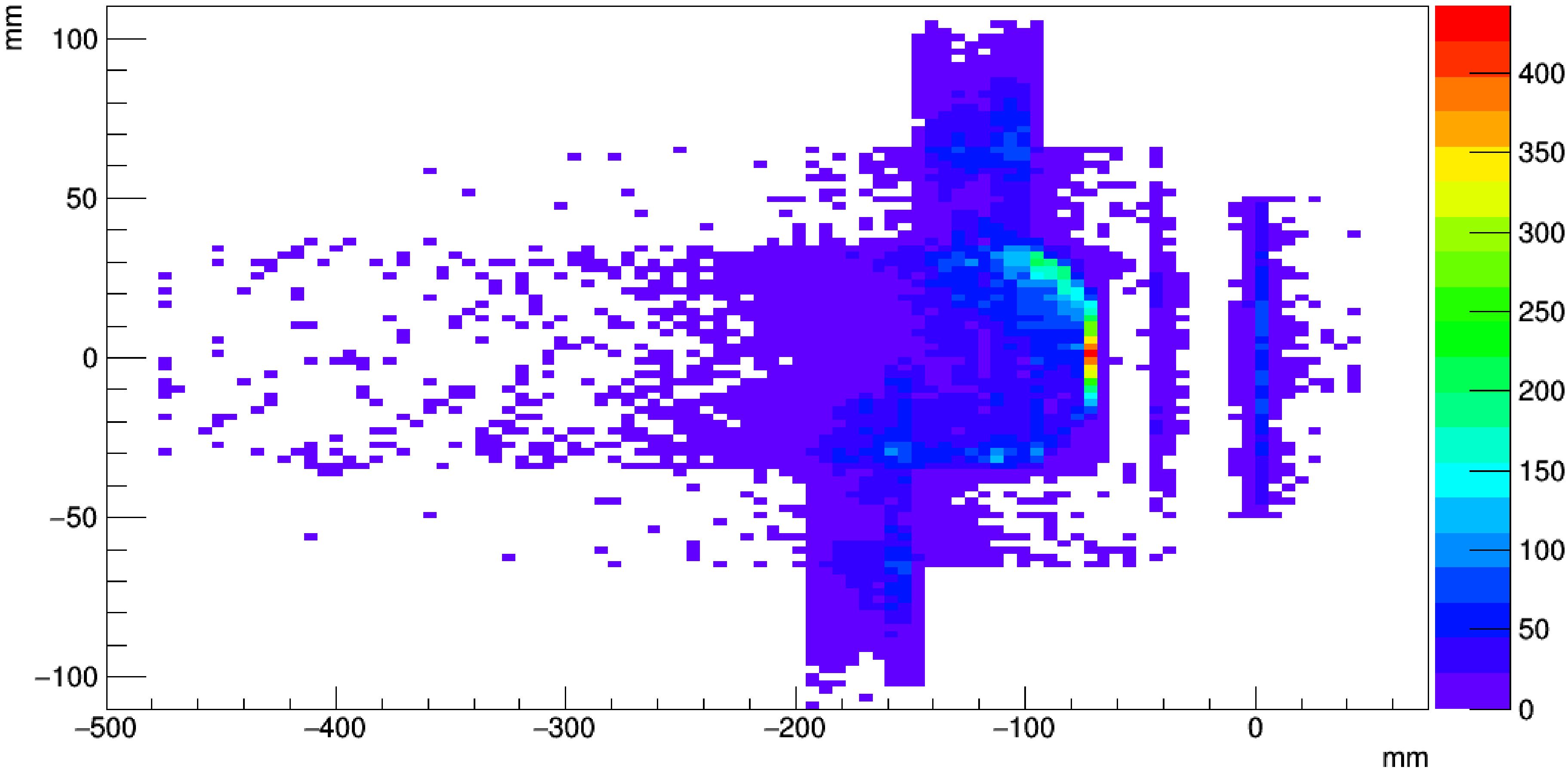
Simulation: impact point in the crystals, 133 keV energy deposit



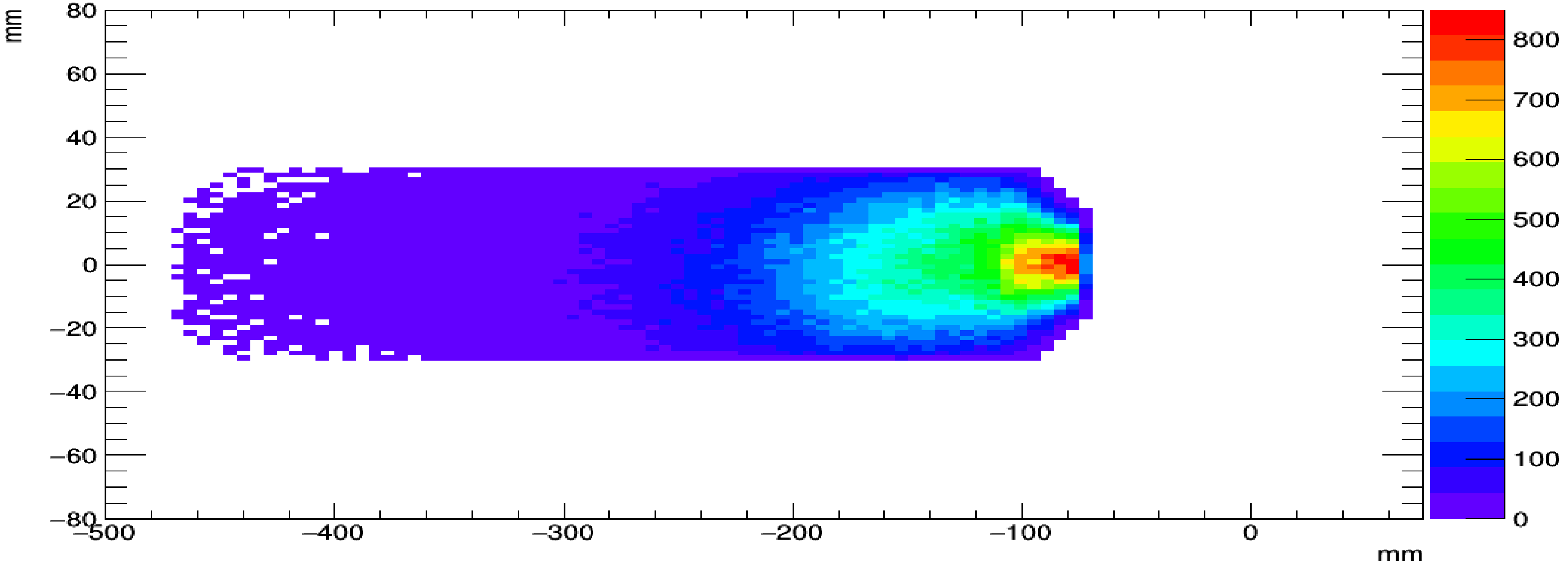
Simulation: impact point in the crystals, <133 keV energy deposit



Simulation: origin of X-rays (not coming from gas)



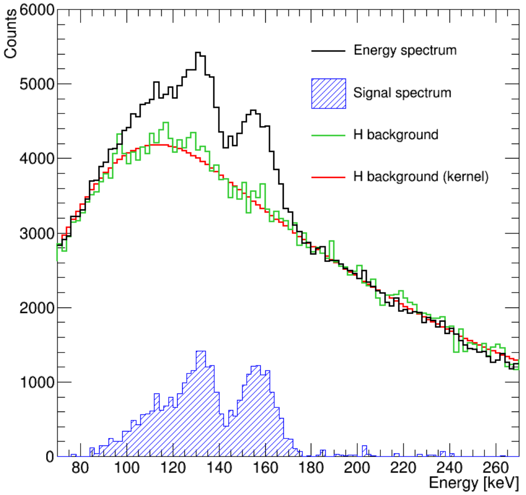
Simulation: origin of X-rays coming from gas



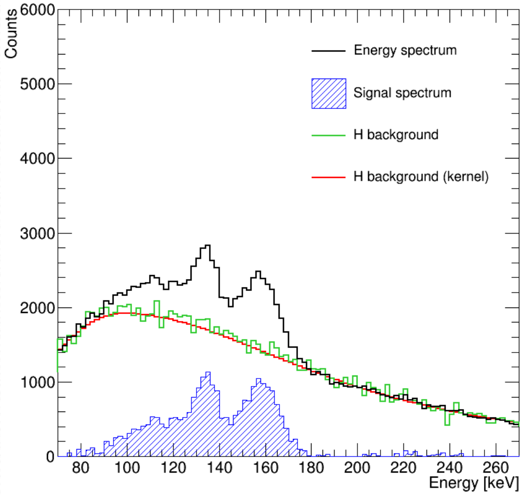
Transfer rate evaluation

Fixed temperature: time evolution

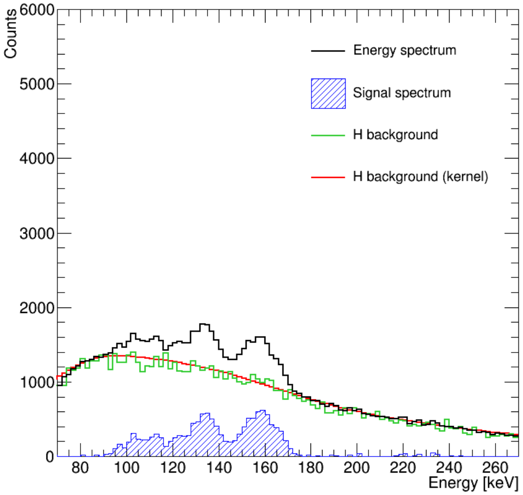
time bin 2

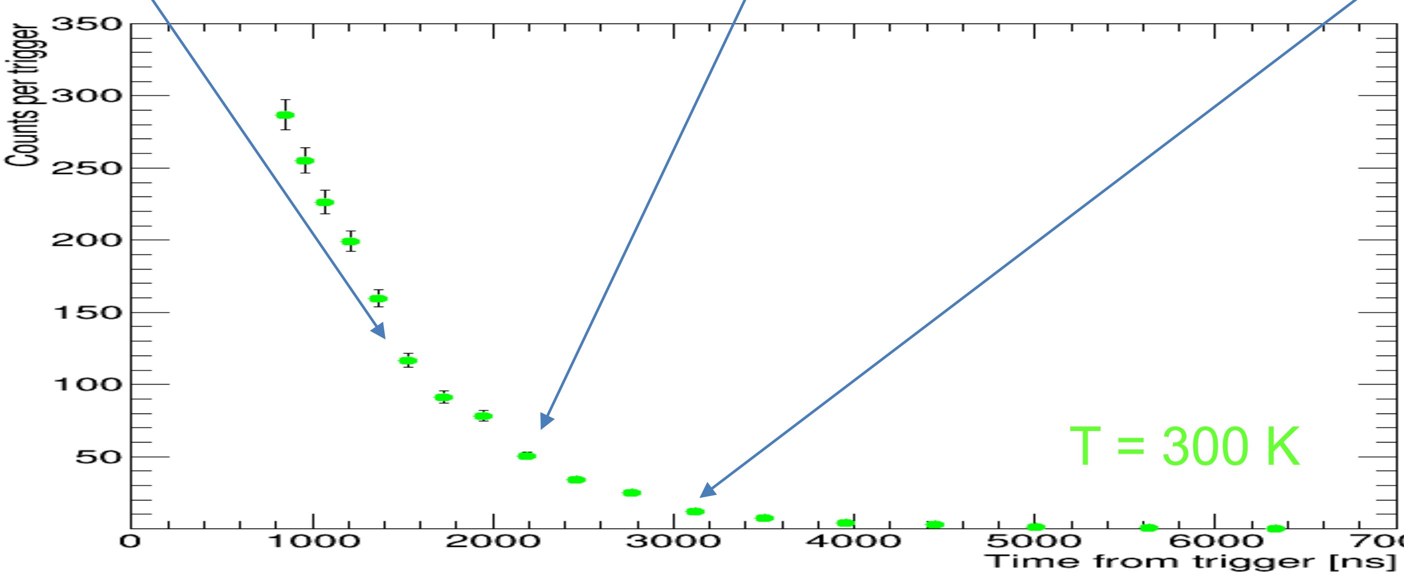


time bin 5

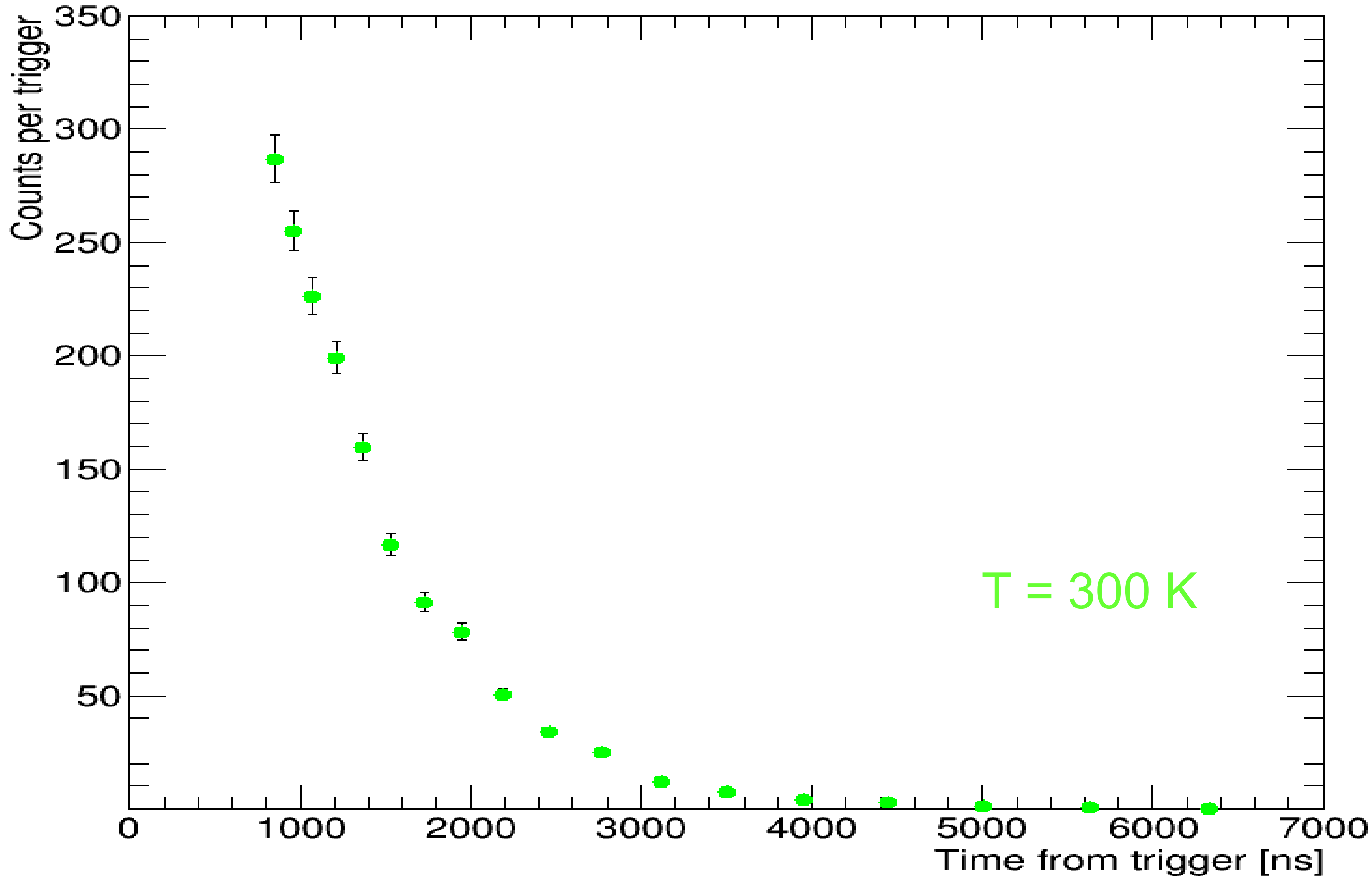


time bin 8

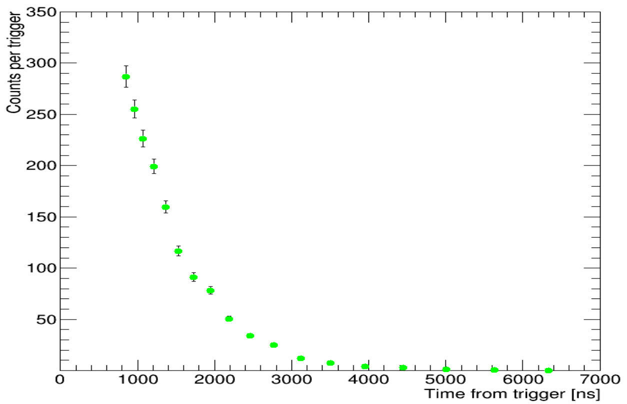




Temperature and time evolution



Temperature and time evolution



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

Disappearence rate

$$\lambda_{\mathrm{dis}}(T) = \lambda_0 + \phi\left[c_{\mathrm{p}}\Lambda_{\mathrm{pp}\mu} + c_{\mathrm{d}}\Lambda_{\mathrm{pd}}(T) + c_{\mathrm{O}}\Lambda_{\mathrm{pO}}(T)\right]$$

UNKNOWN TERM

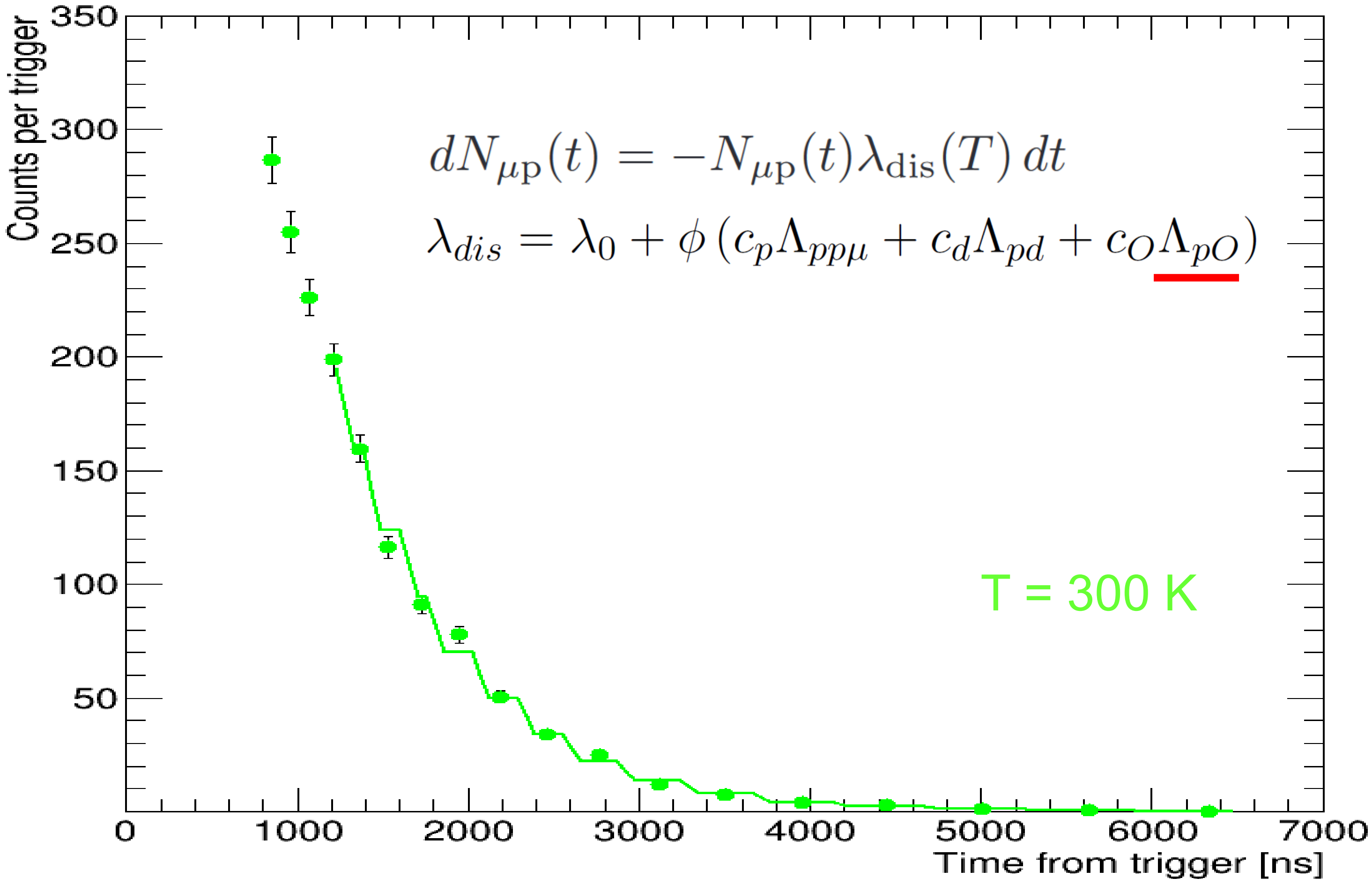
Rate of disappearance of muons bounded to p (decay, ..)

$\Lambda_{pp\mu}$, Λ…, transfer rates

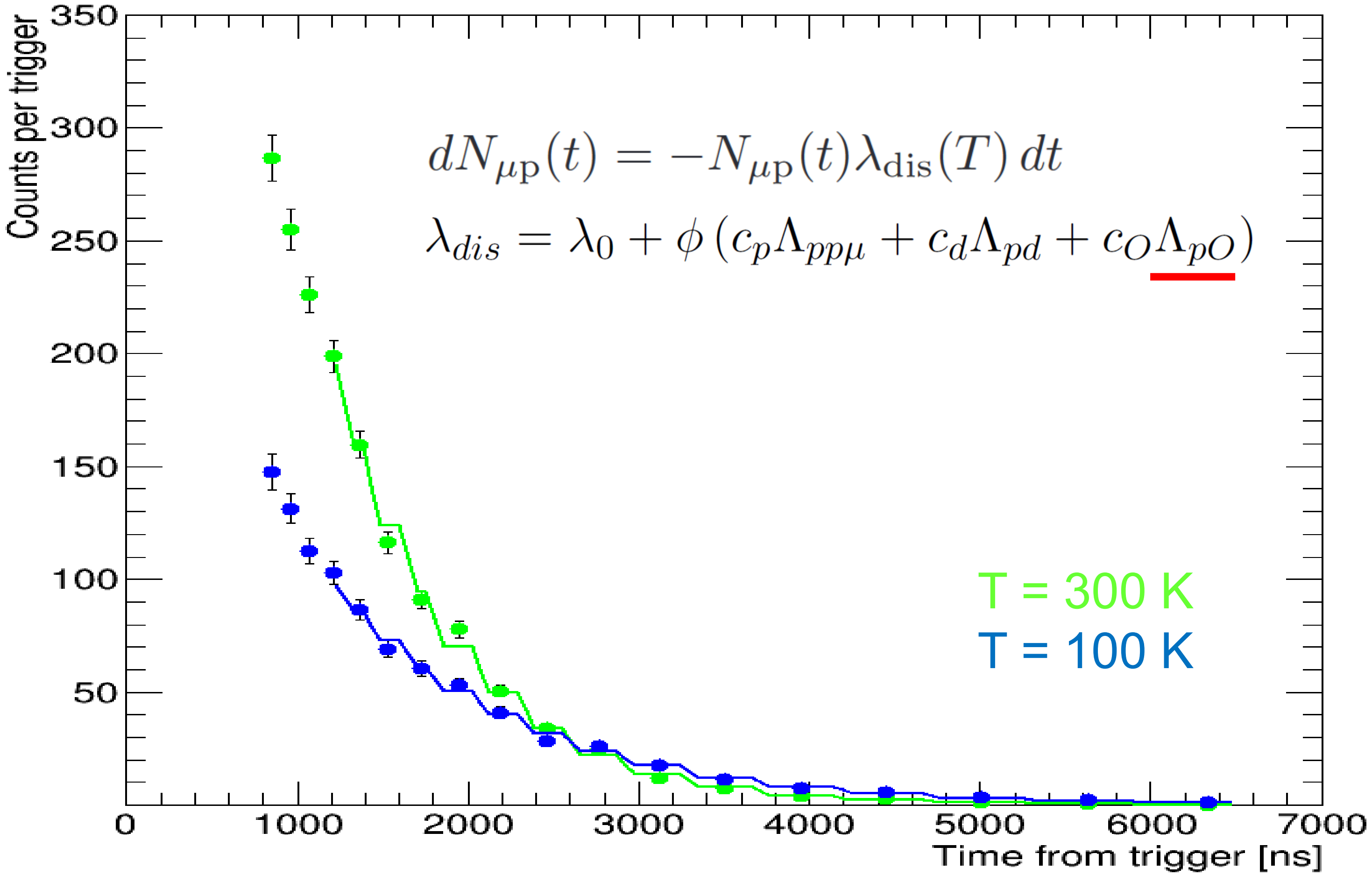
c_p, c… concentrations of hydrogen, deuterium, oxygen

ϕ number density of atoms in the gas target

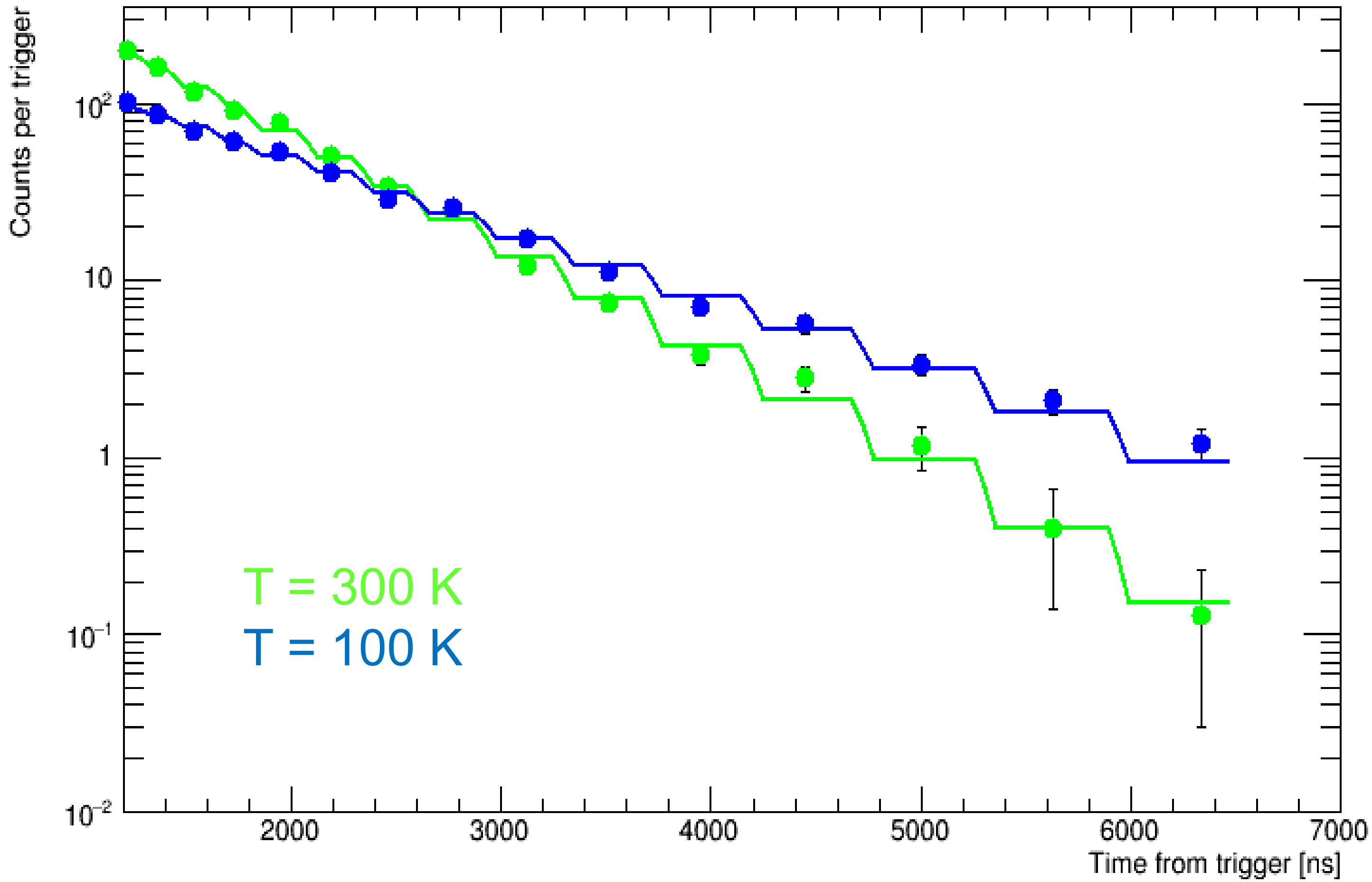
Temperature and time evolution



Temperature and time evolution

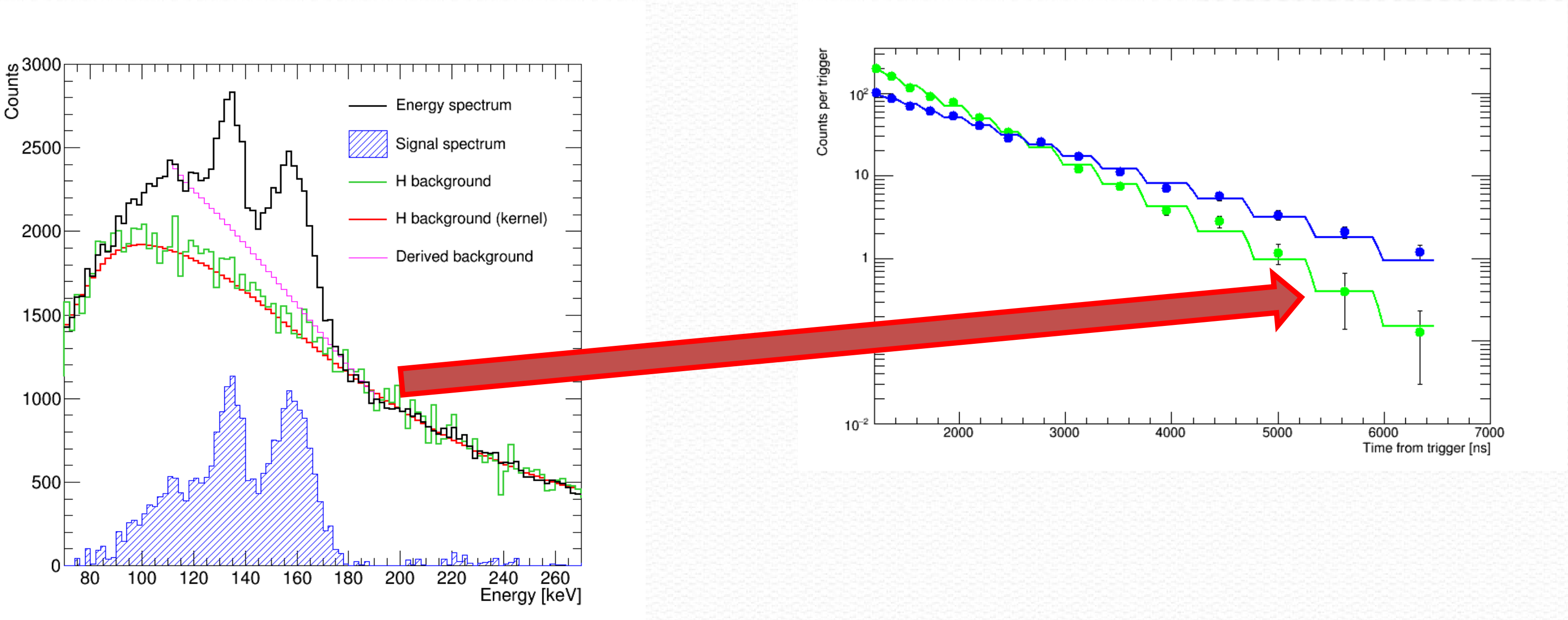


Temperature and time evolution



Systematics

1. Background estimation and normalization



Effect: fluctuations (5÷20%) of points used in the fit
➡ fluctuations of the transfer rate results
This uncertainty was quadratically summed to statistical errors

Systematics

1. Background estimation and normalization

2. Uncertainty on the density (ϕ) ➧ ~3% effect on transfer rate (solid shift of points)

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

$$\lambda_{dis} = \lambda_0 + \underline{\phi}\,(c_p\Lambda_{pp\mu} + c_d\Lambda_{pd} + c_O\Lambda_{pO})$$

Systematics

1. Background estimation and normalization

2. Uncertainty on the density (ϕ) ➧ ~3% effect on transfer rate (solid shift of points)

3. Uncertainty on oxygen concentration (c_O) ➧ ~3% effect on transfer rate (solid shift of points)

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

$$\lambda_{dis} = \lambda_0 + \phi\left(c_p\Lambda_{pp\mu} + c_d\Lambda_{pd} + \underline{c_O}\Lambda_{pO}\right)$$

Systematics

1. Background estimation and normalization

2. Uncertainty on the density (ϕ) ➧ ~3% effect on transfer rate (solid shift of points)

3. Uncertainty on oxygen concentration (c_O) ➧ ~3% effect on transfer rate (solid shift of points)

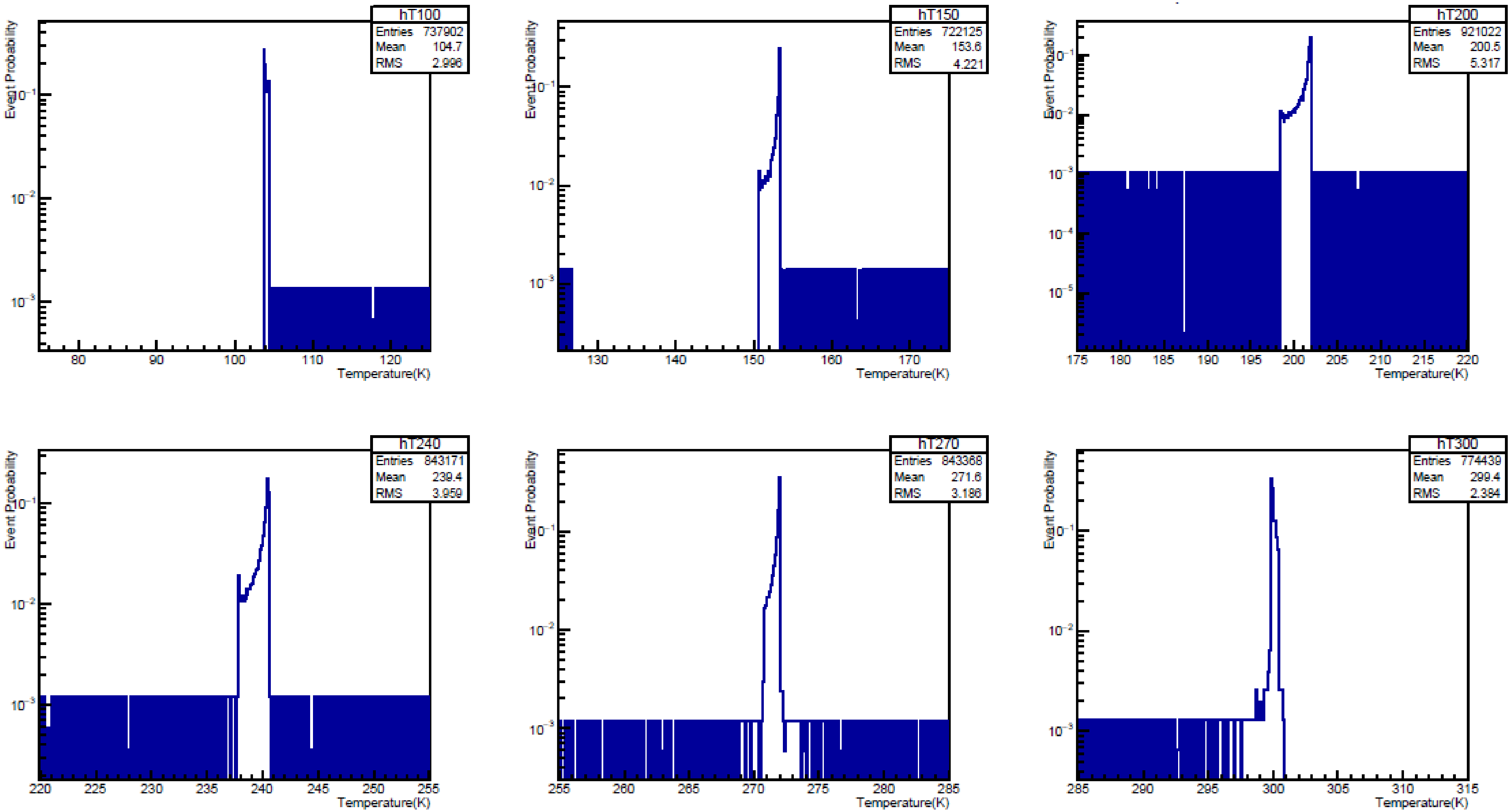
4. Other uncertainties, negligible (<< statistical error)

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

$$\lambda_{dis} = \underline{\lambda_0} + \phi\left(\underline{c_p\Lambda_{pp\mu}} + \underline{c_d\Lambda_{pd}} + c_O\Lambda_{pO}\right)$$

Temperature bins

6 fixed steps + 5 intermediate temperatures



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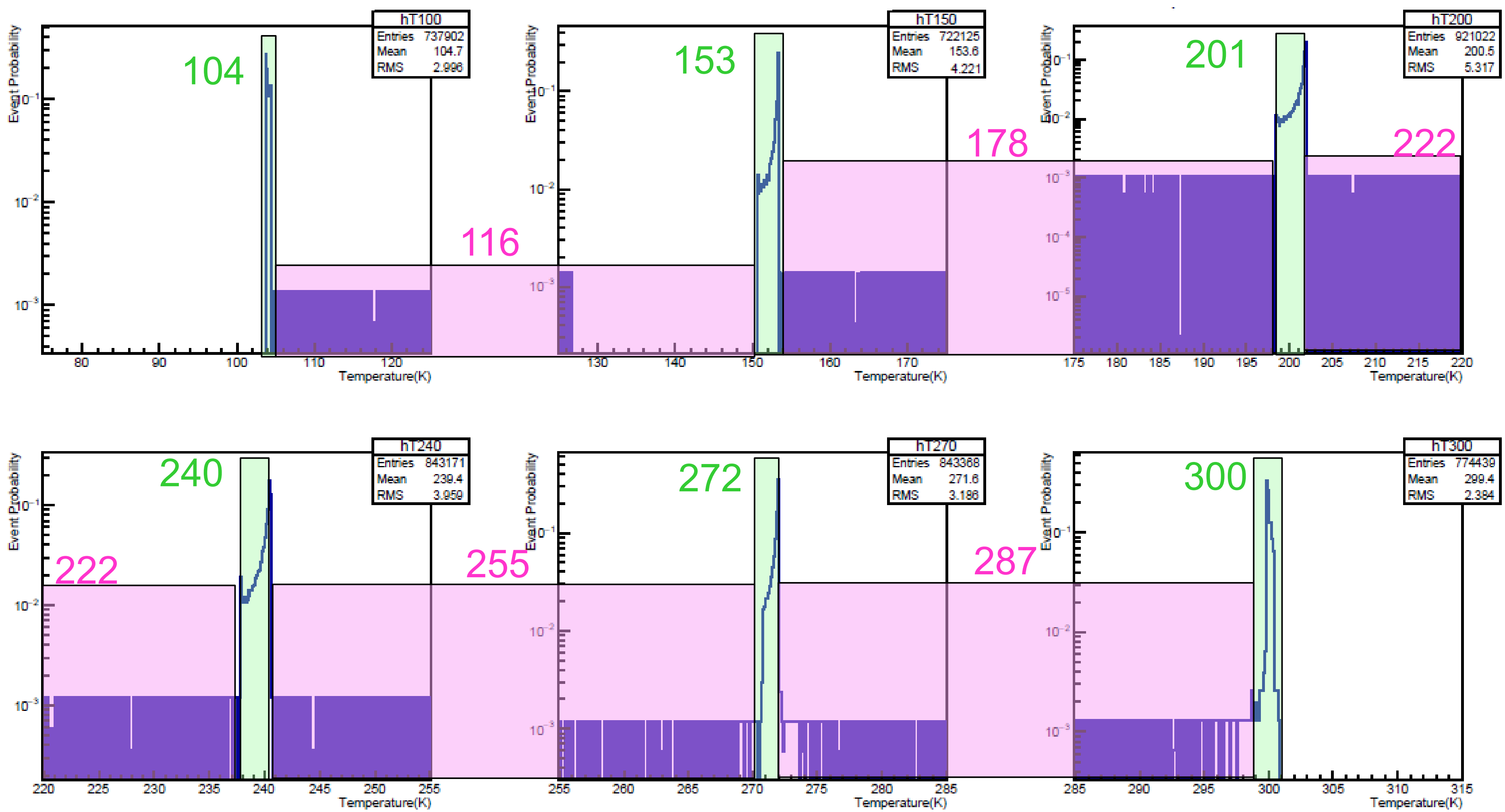
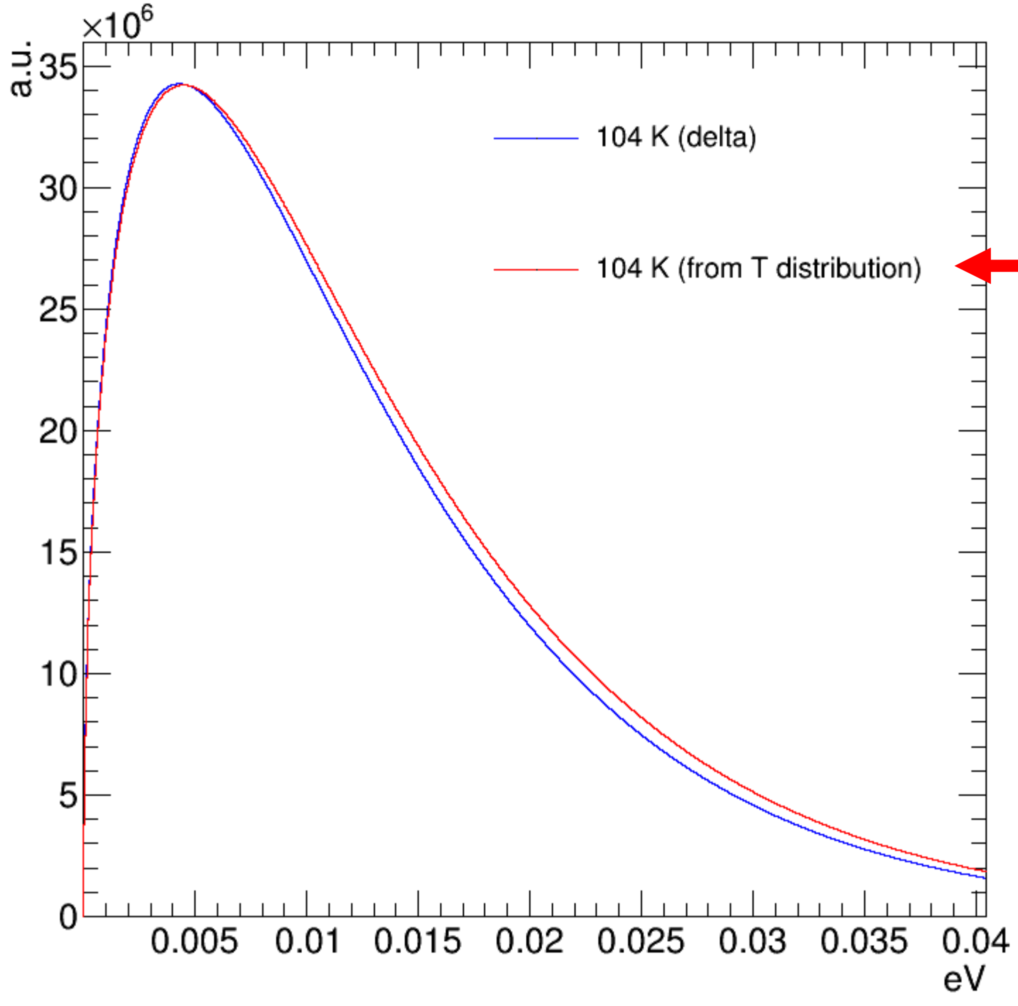
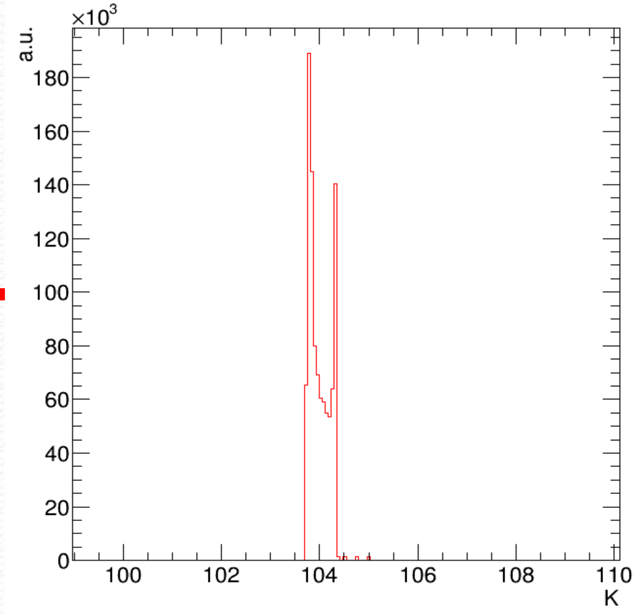


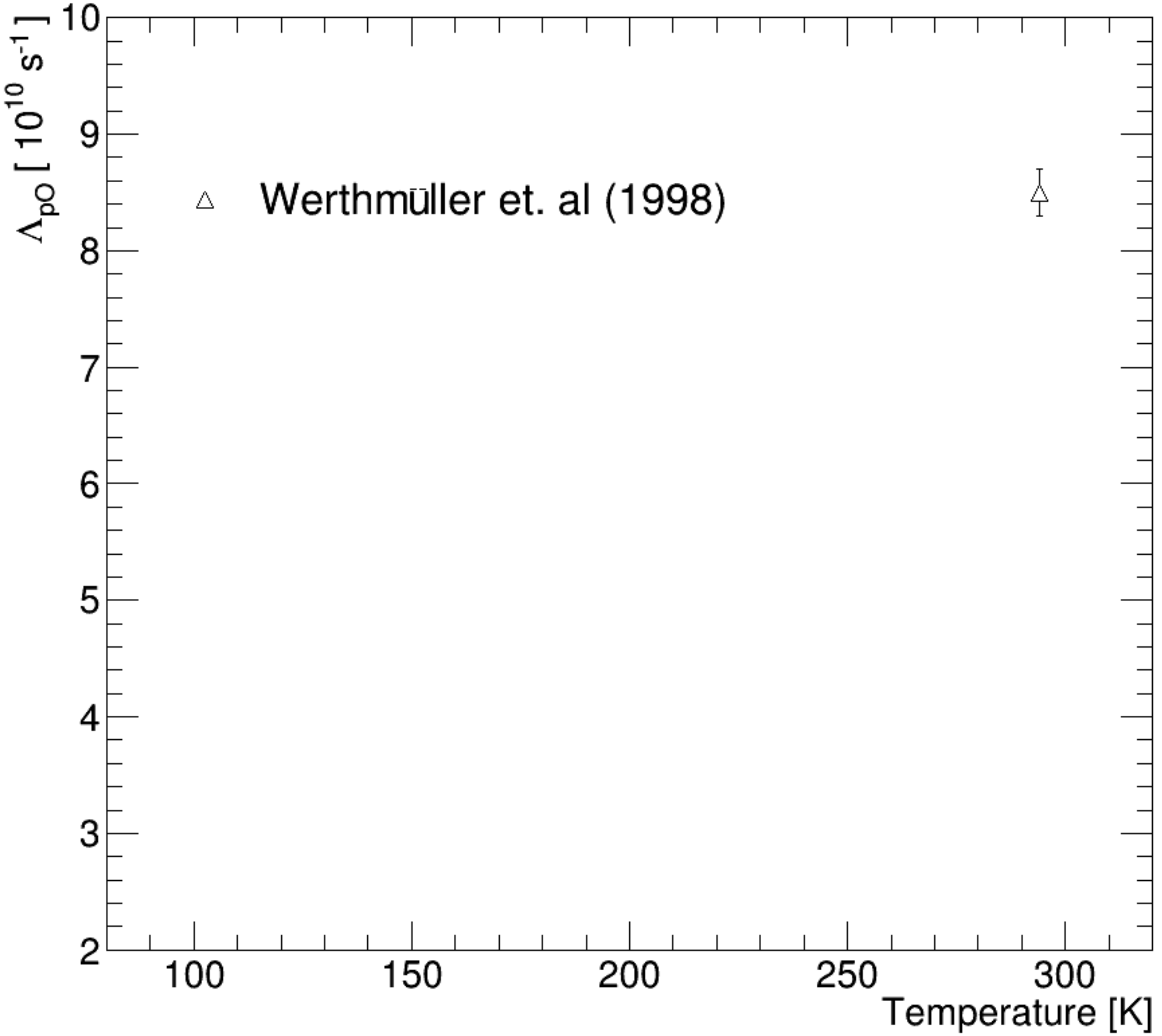
Very close to Maxwell-Boltzman distribution



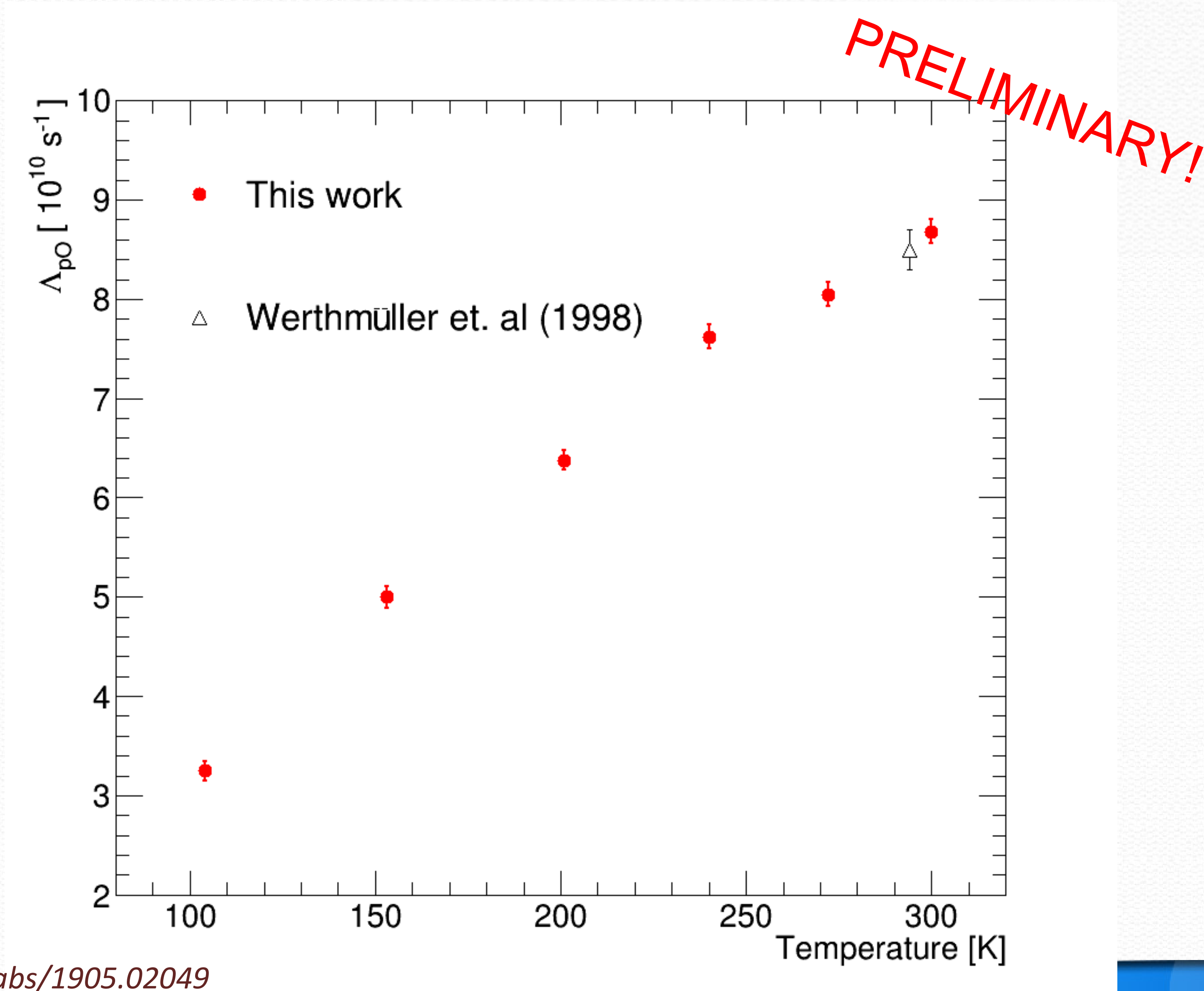


Results

Transfer rate measurement

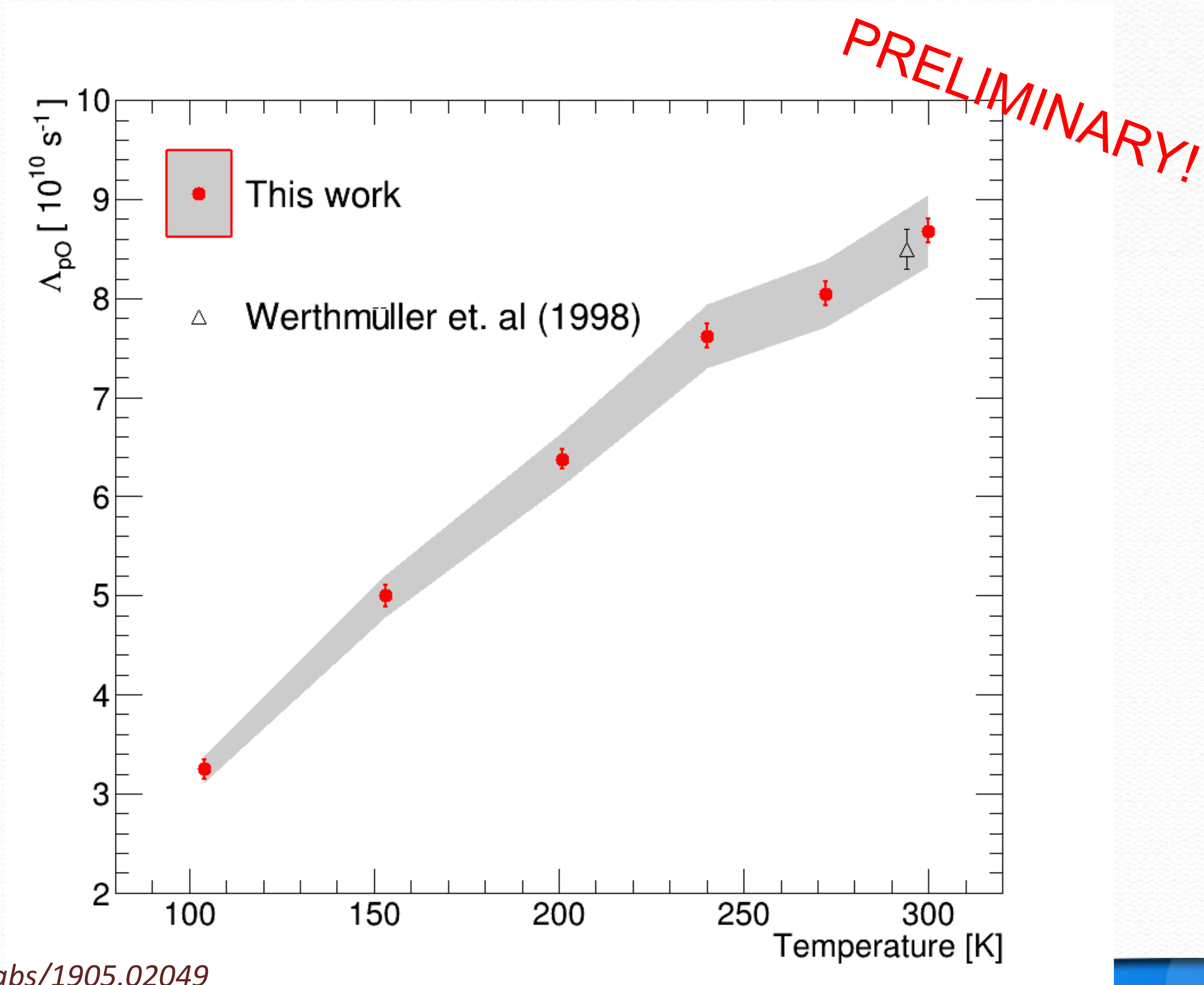


Transfer rate measurement



http://arxiv.org/abs/1905.02049

Transfer rate measurement



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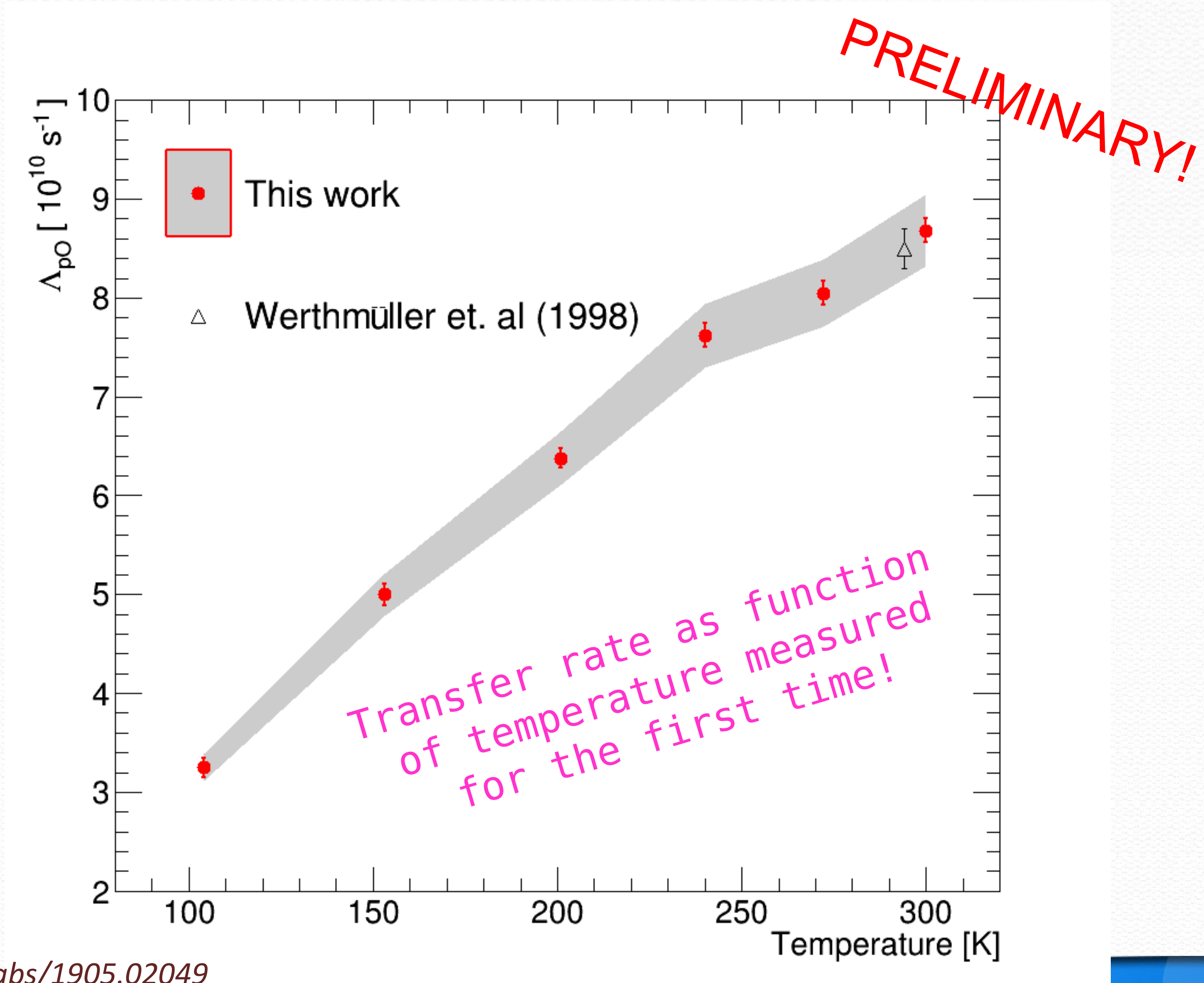

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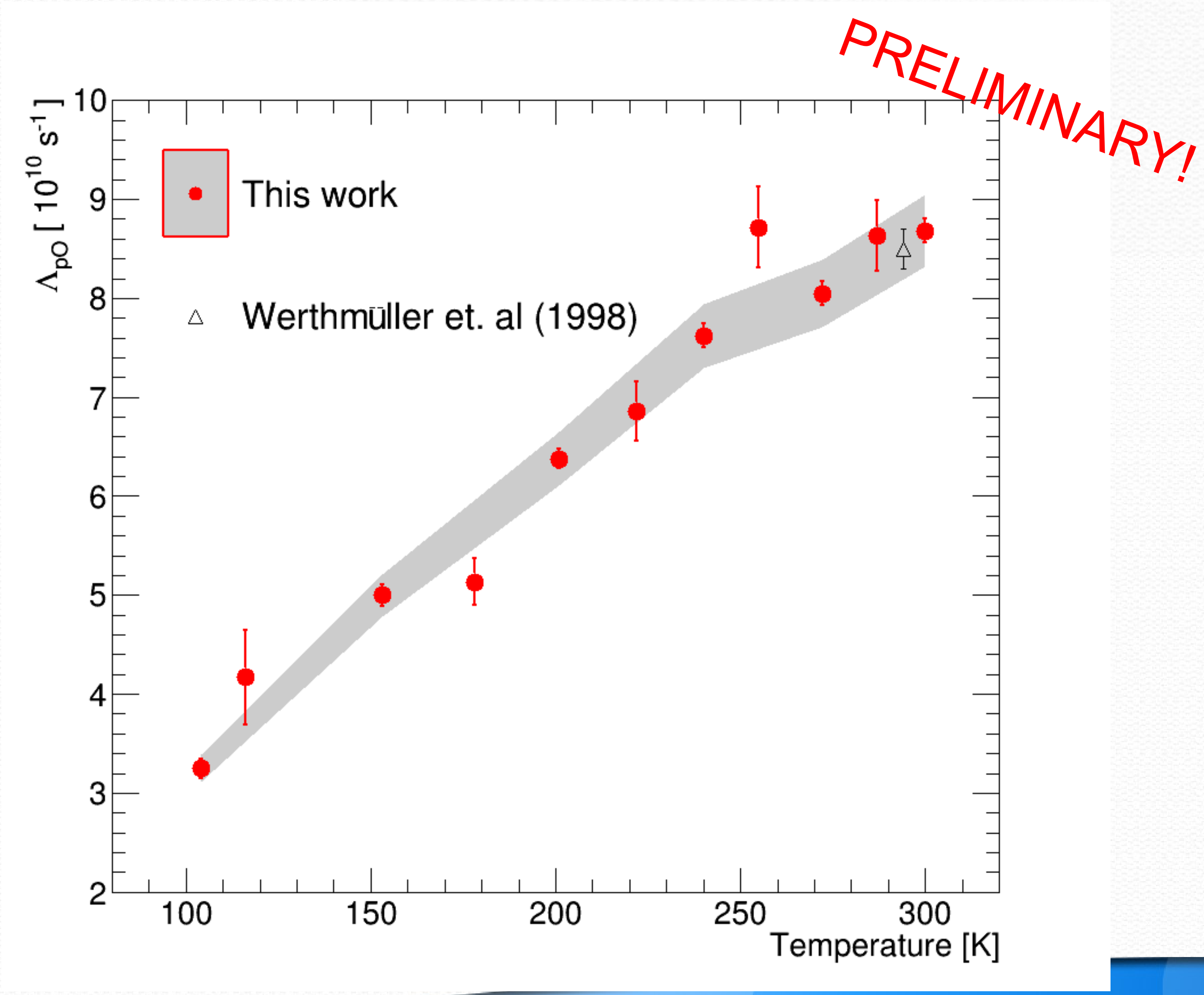
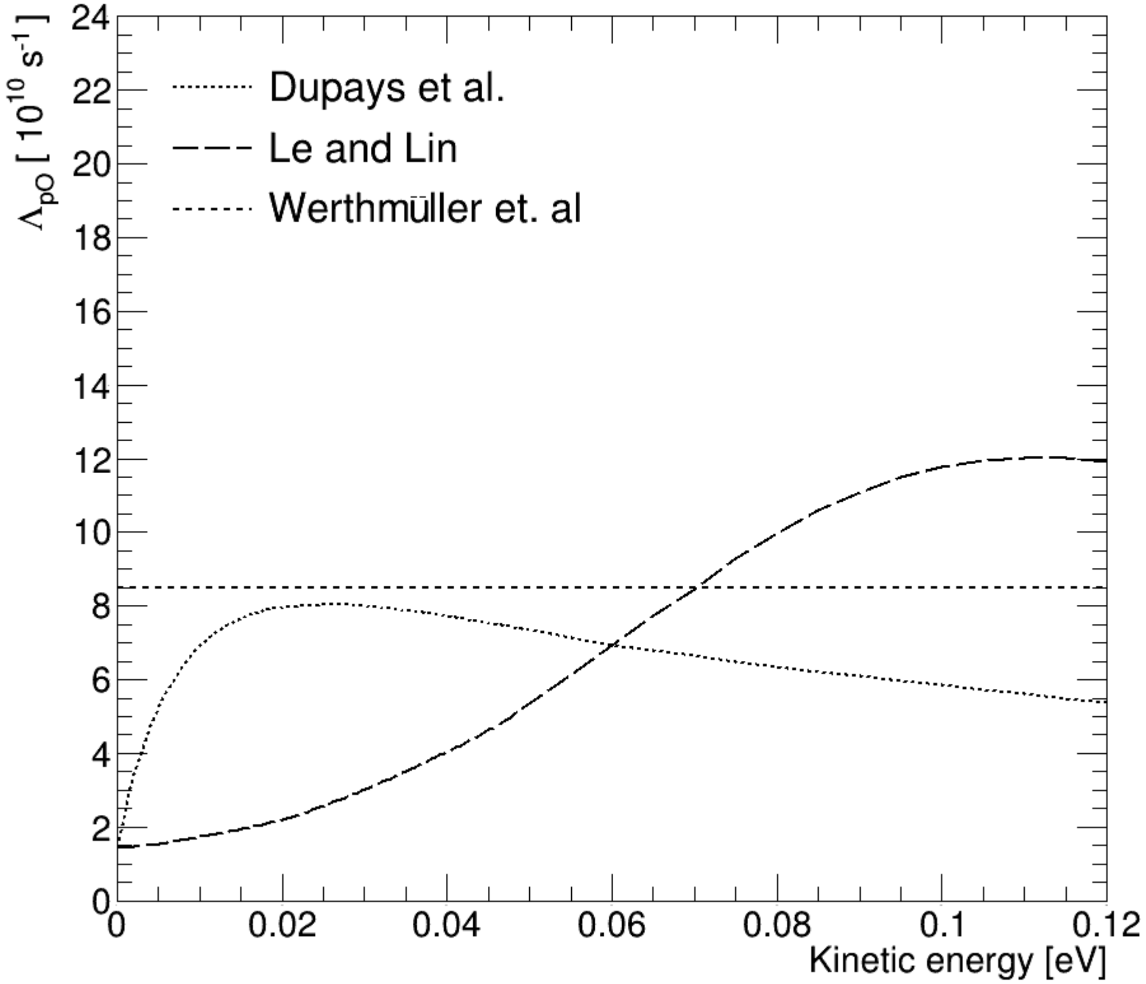


Transfer rate measurement



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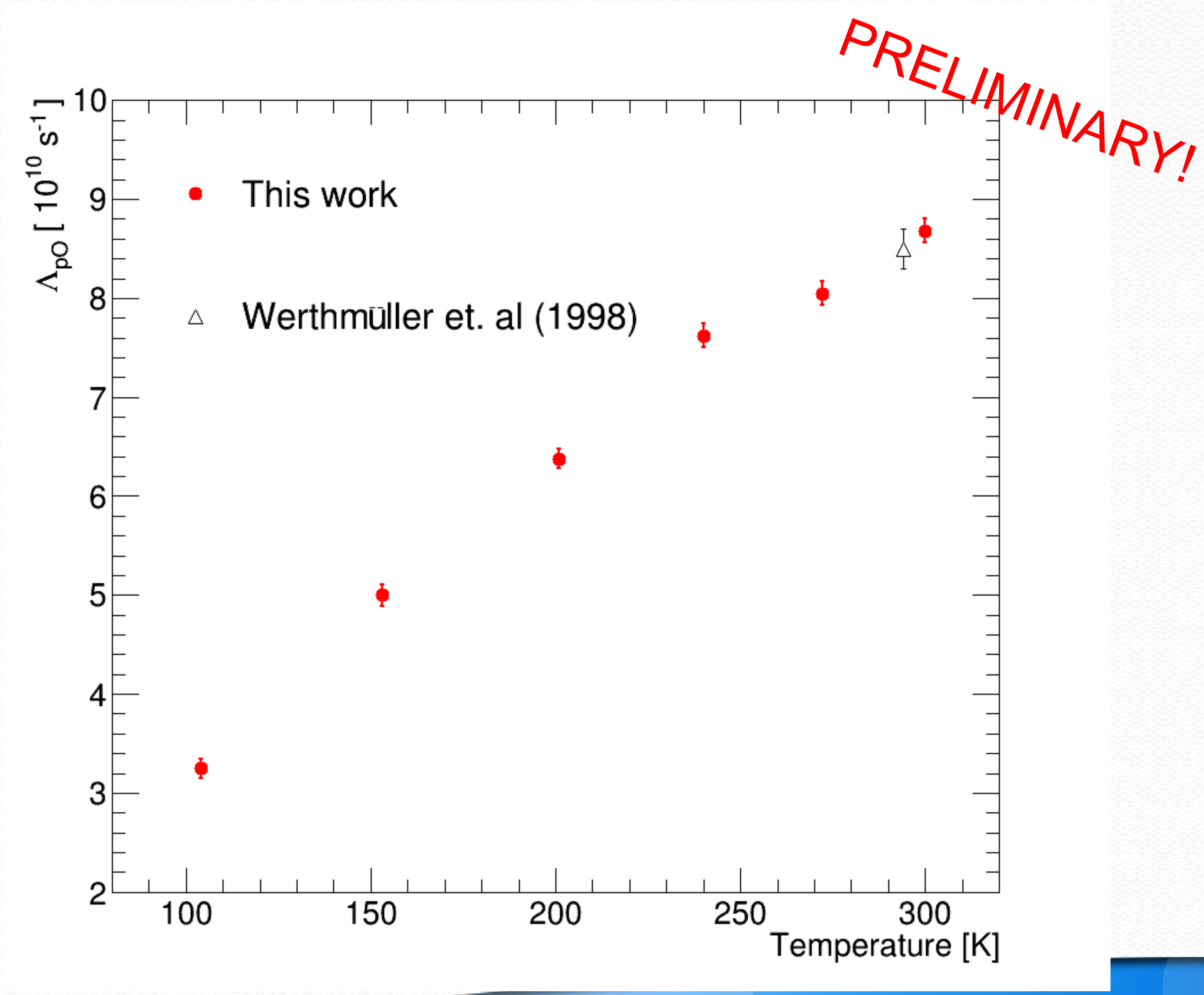
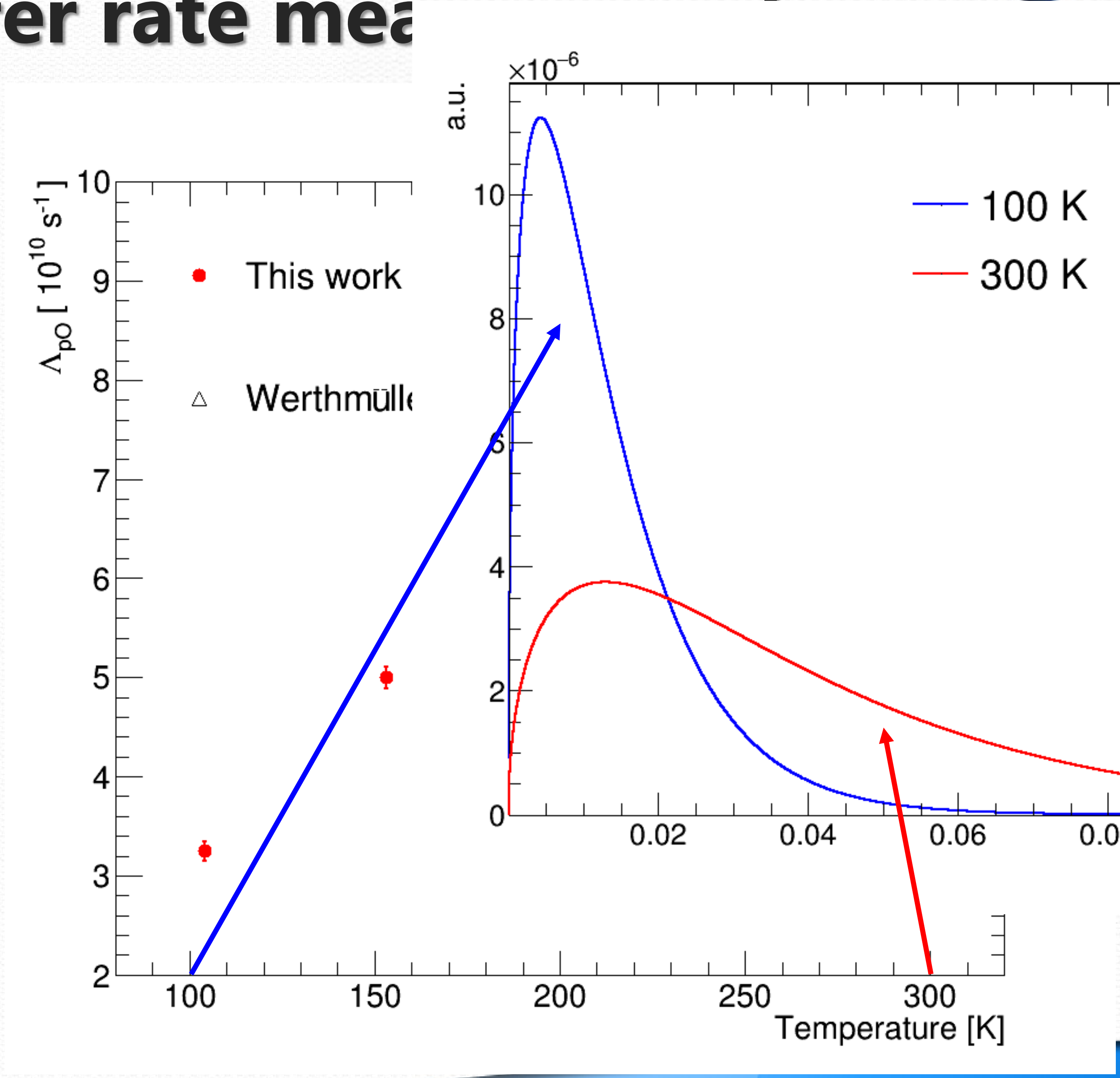


Transfer rate mea



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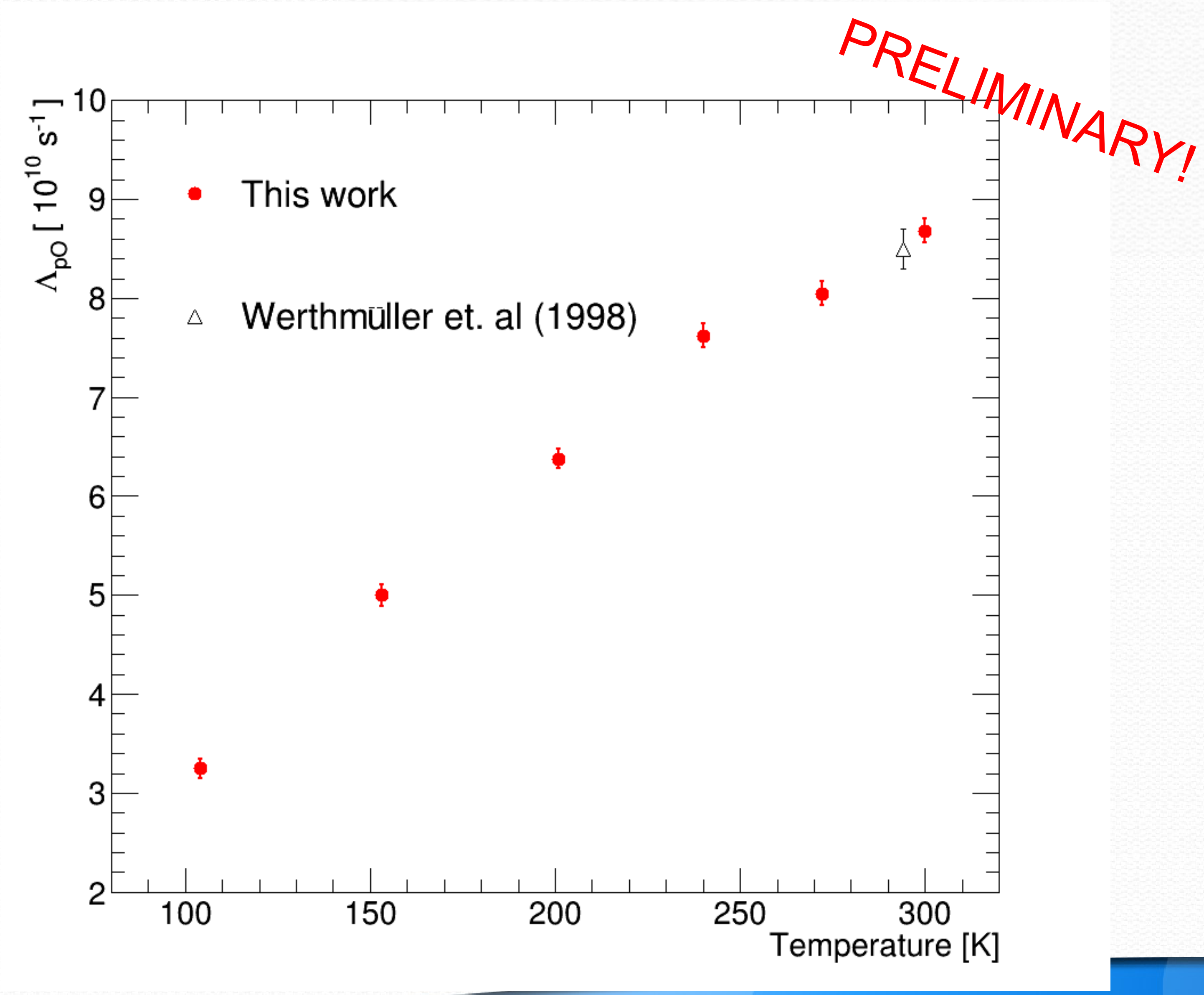
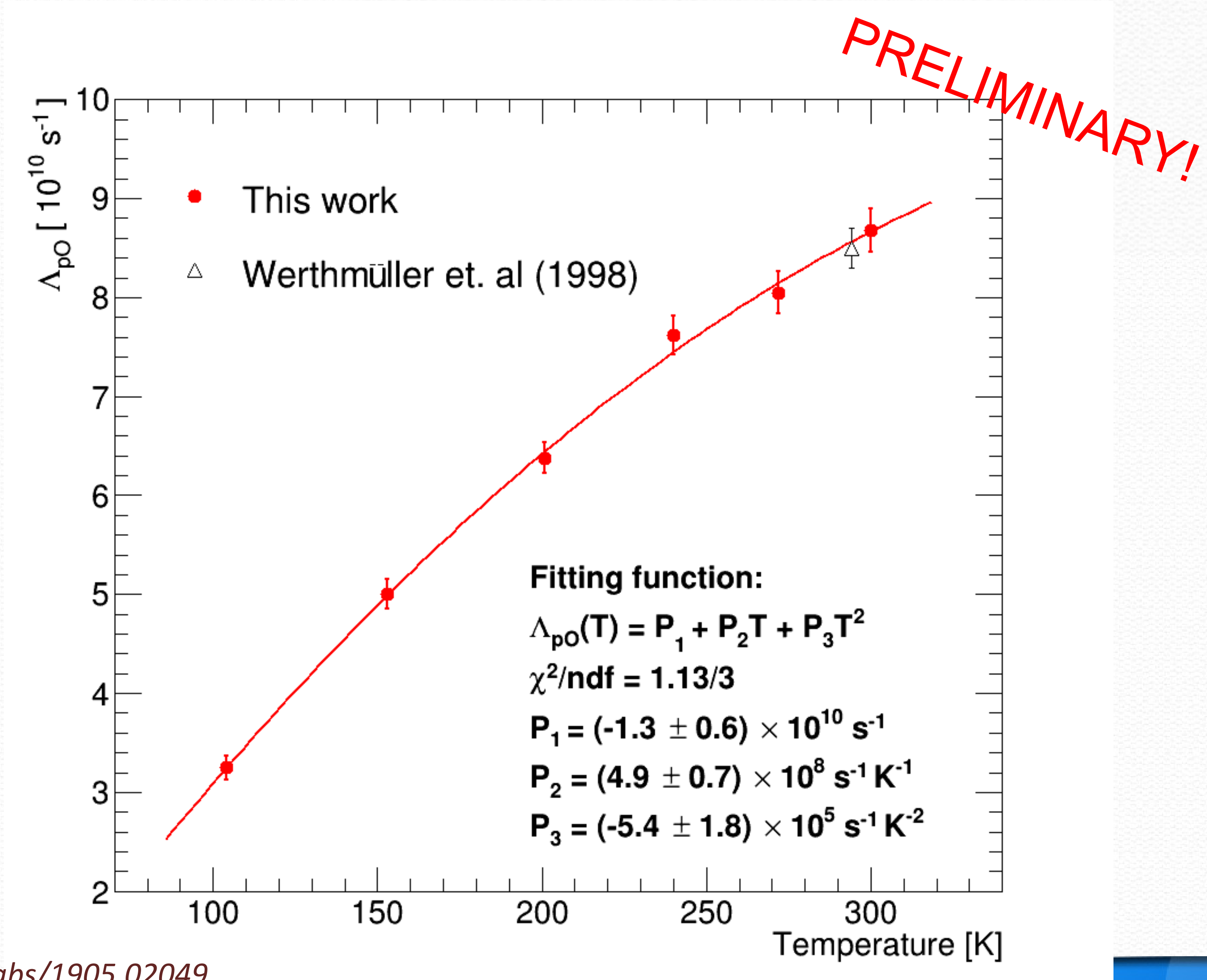
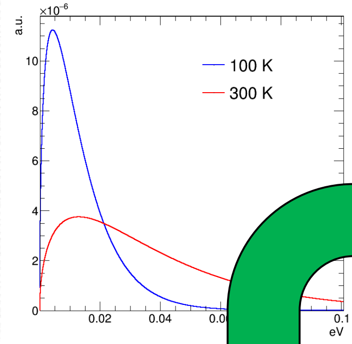


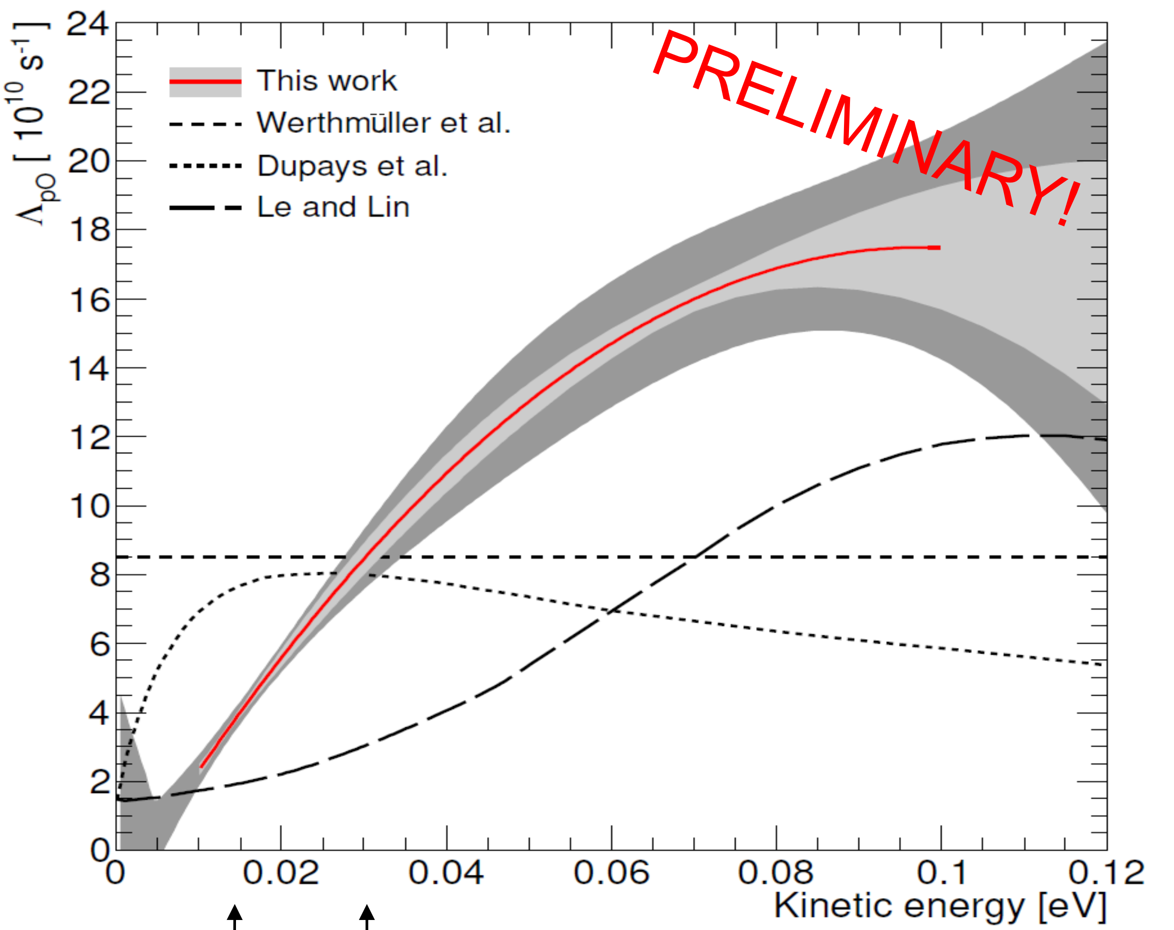
Transfer rate measurement

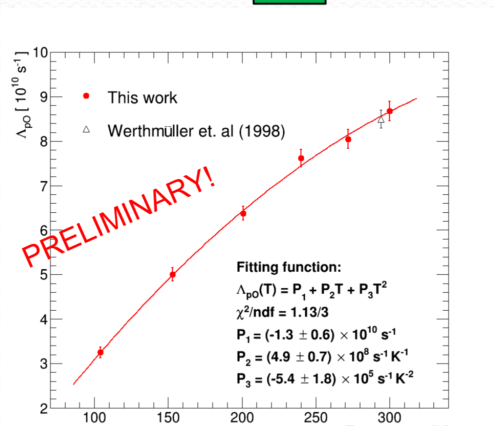


http://arxiv.org/abs/1905.02049

Transfer rate up to 120 meV







~100 K

~300 K

μp energy after de-excitation

http://arxiv.org/abs/1905.02049

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!

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Looking forward to perform the spectroscopic measurement!

Thanks!

Spares

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

... and, of course, all the above within time and cost constraints!

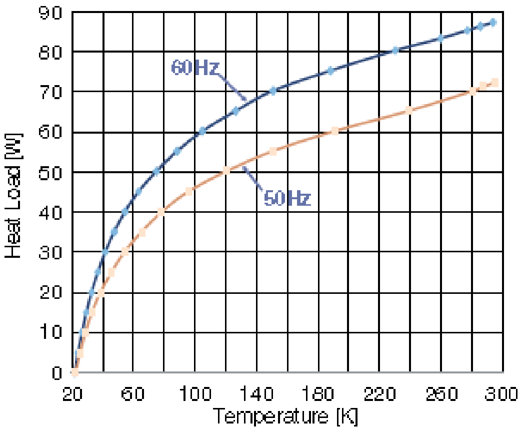
Thermal control

CH-104 77K CRYOCOOLER SERIES

Performance Specifications

Power Supply Hz	50	60
1st Stage Capacity Watts @ 77 K	34	42
Cooldown Time to 20 K Minutes	40	30
Weight kg (lbs.)	7.9 (17.5)	
Maintenance Hours	13,000	

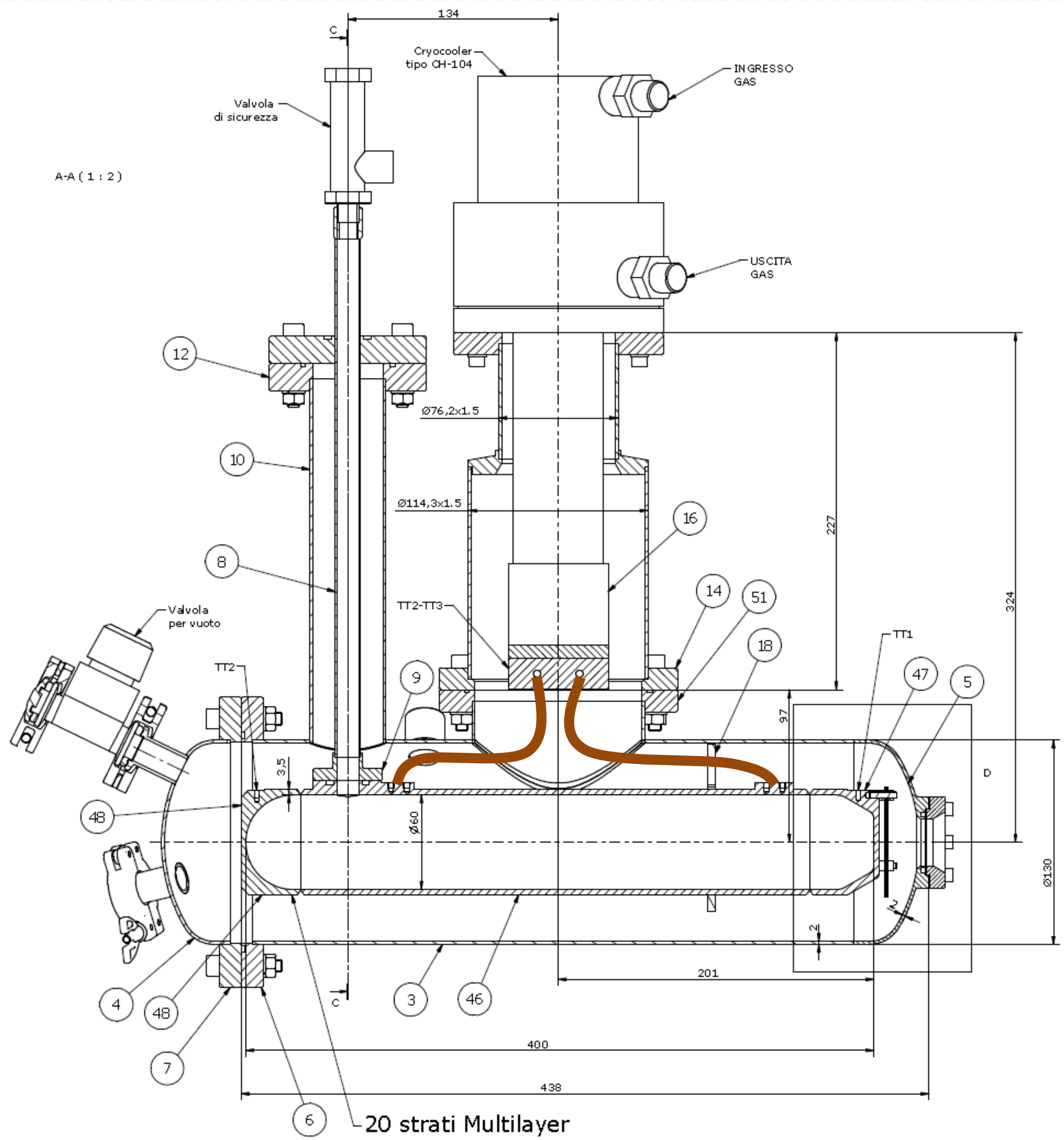
CH-104 Cold Head Capacity Map (50/60 Hz)



Standard Scope of Supply

- CH-104 Cold Head
- Zephyr®, HC-4E1, HC-8E4 or F-70L/H Compressor
- 3 m (10 ft.) Helium Gas Lines
- 3.5 m (11 ft.) Cold Head Cable
- Tool Kit

Best solution



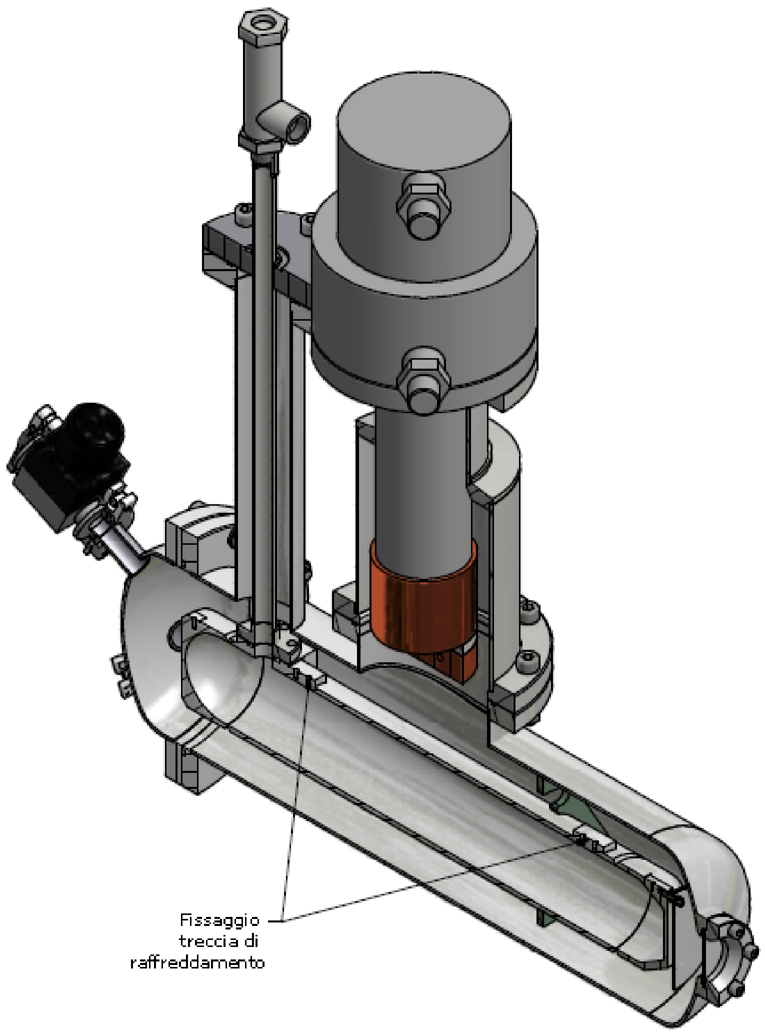
Target= Inner vessel with high P gas (44 bar)

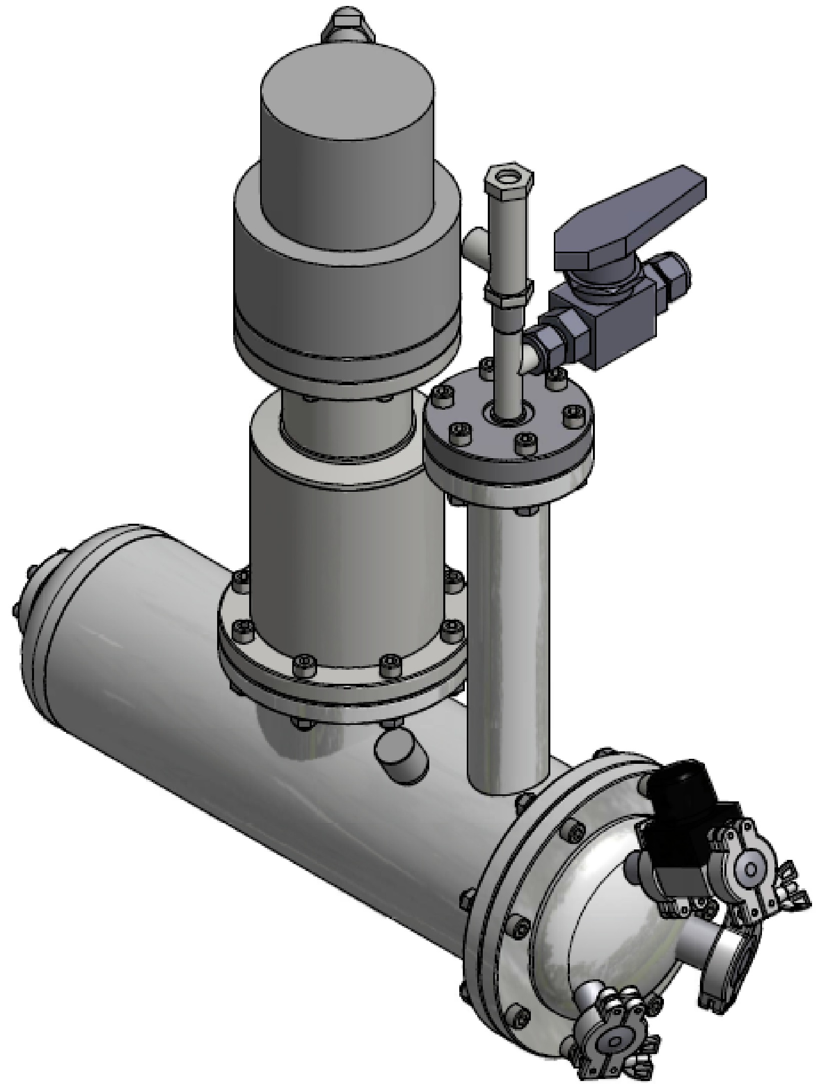
- Al alloy 6082 T6 cylinder D = 60 mm and L = 400 mm, inner volume of 1.08 l
- Internally Ni/Au plated (L = 280 mm)
- Cylinder side wall thickness = 3.5 mm
- Wrapped in 20 layers of MLI
- Front window D= 30 mm 2.85 mm thick
- Three discs of 0.075 mm Al foil for window radiative shield
- 304L SS gas charging tube
- 304L SS cooler cold-end support
- G10 mechanical strut
- Two Cu straps for cooling

Vacuum vessel = outer cylinder (P atm)

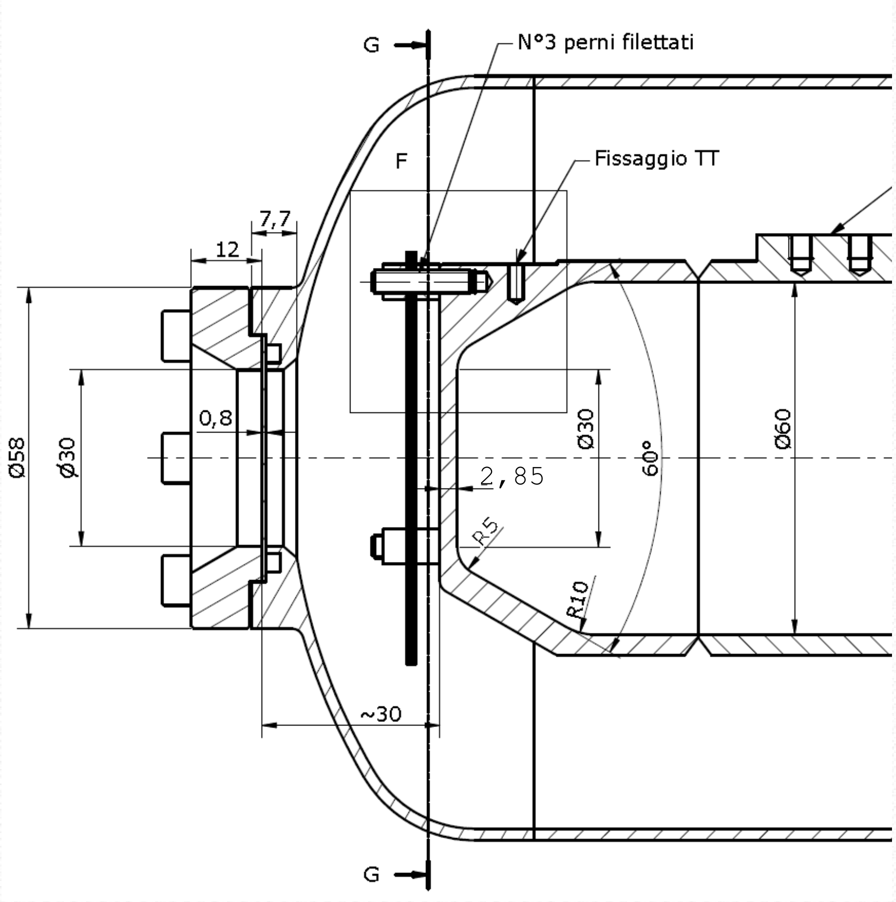
- Al6060 D=130 mm, 2 mm thick walls
- ≈30mm between inner/outer walls
- Flanged Al window 0.8 mm thick
- Pumping valve & harness feed-tru’s

Drawings





Front window



Thickness

Side walls (inner vessel, MLI, outer shell)

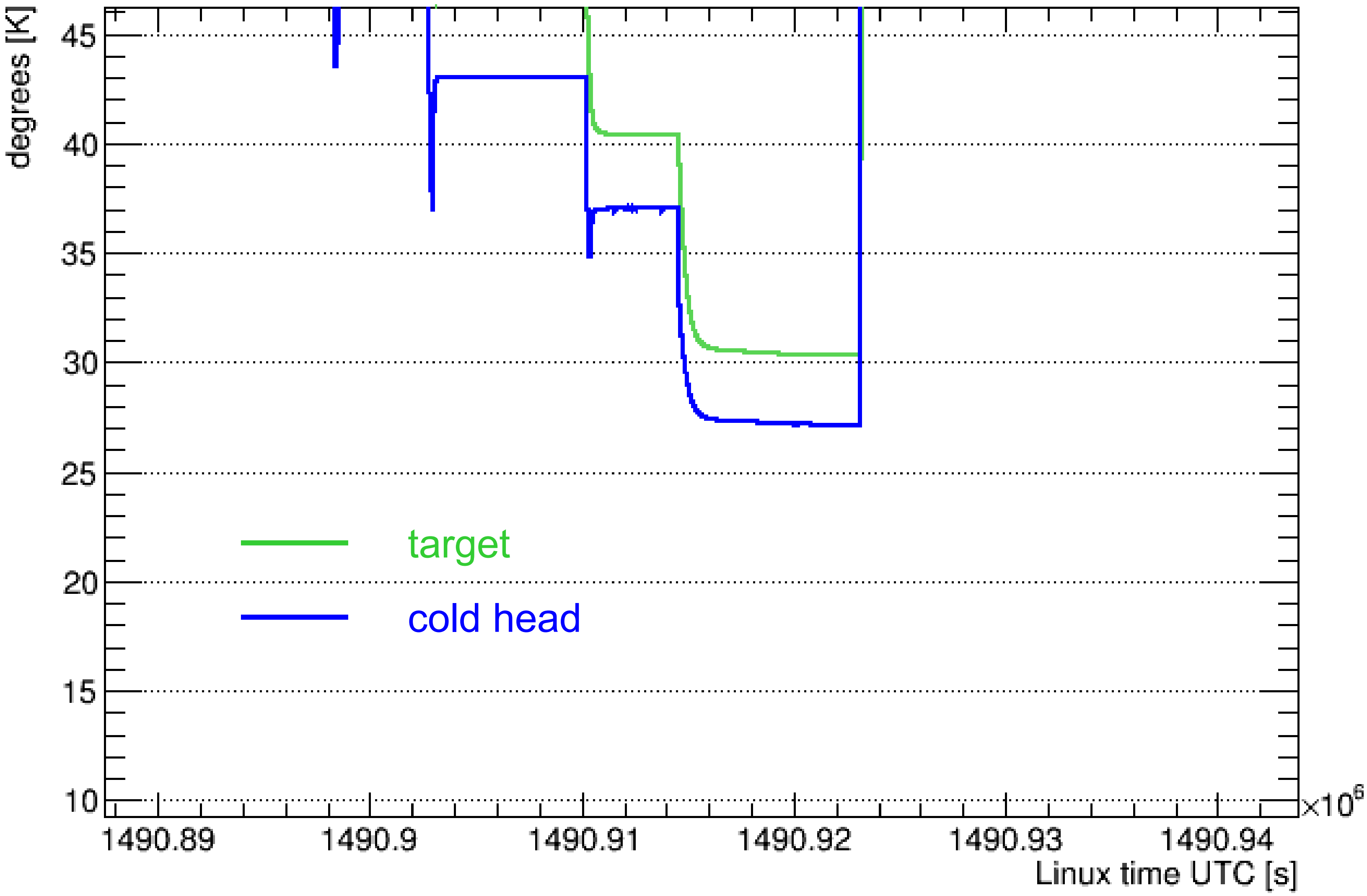
- t_inner = 3.5 mm Al6082
- t_Ni_Au =150 + 10 μm ≈ 0.16 mm
- t_MLI_Al = 1.6 μm pure Al = 0.0016 mm
- t_MLI_Poly < 130 μm Polyester = 0.13 mm
- t_outer = 2 mm Al6060

Windows

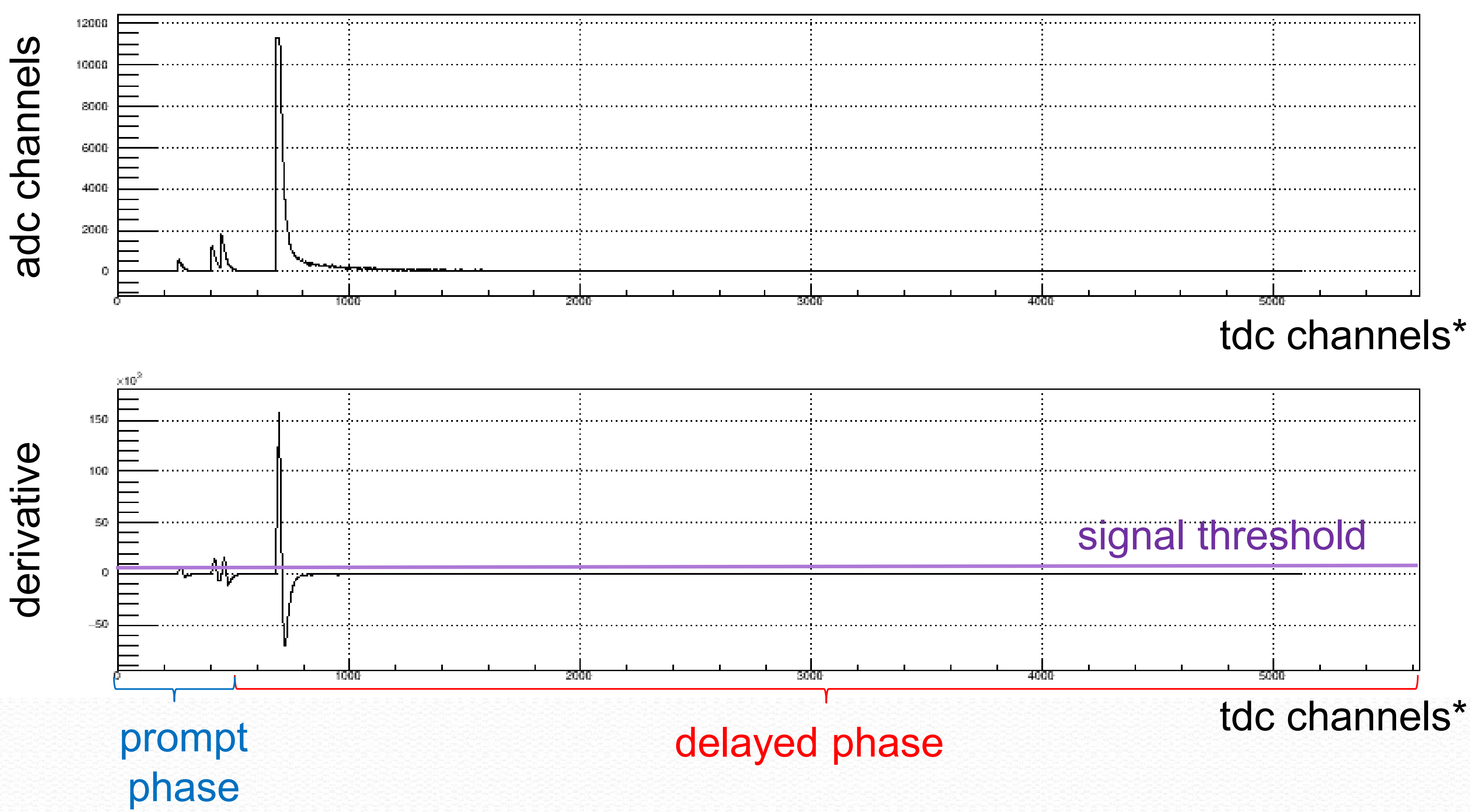
- t_inner_w = 2.85 mm Al
- t_Ni_Au = 0.16 mm
- t_Al_shields = 0.225 mm Al
- t_outer_w = 0.8 mm Al

Target in lab

2017 on beam: lowest temperature

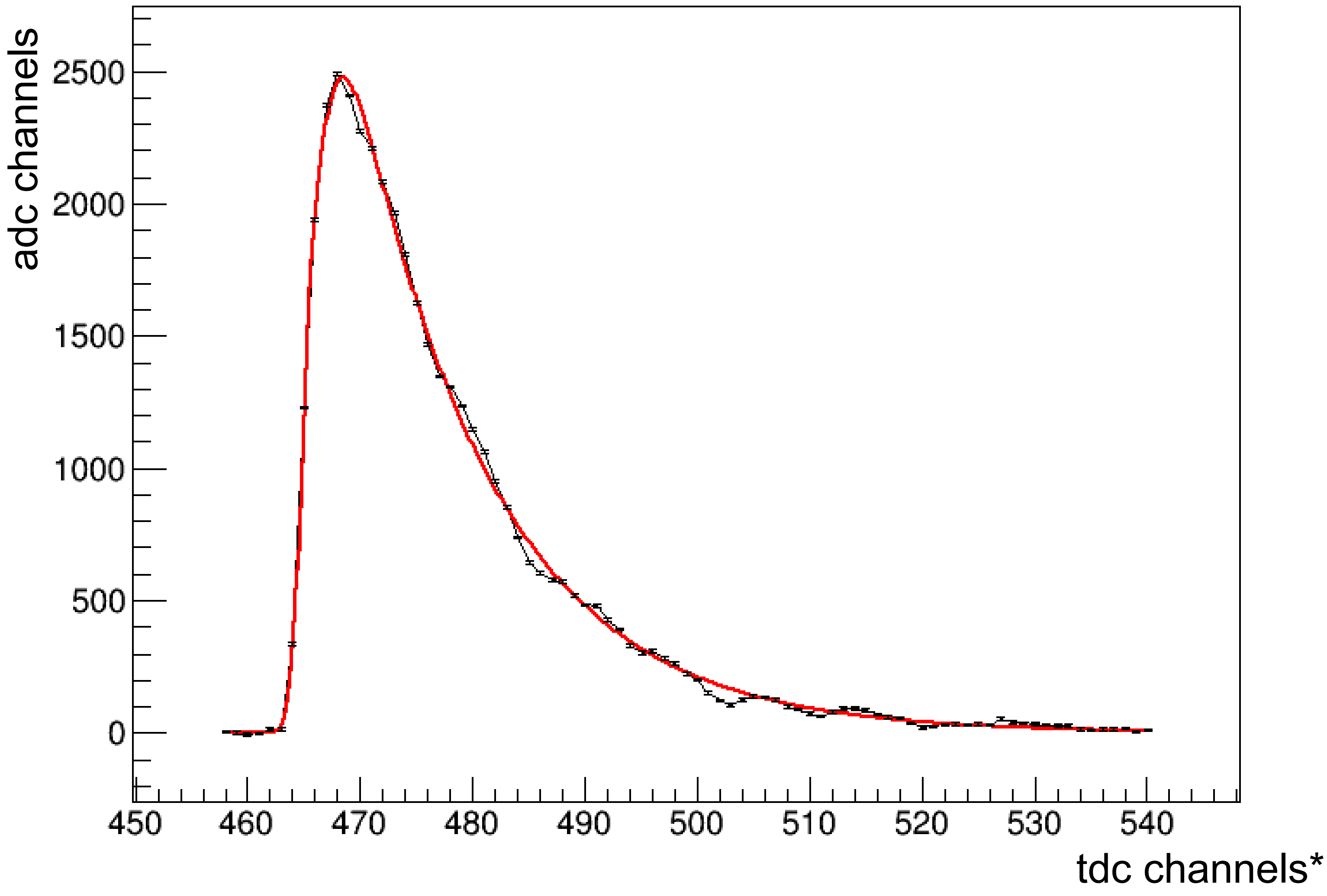


Waveform processing



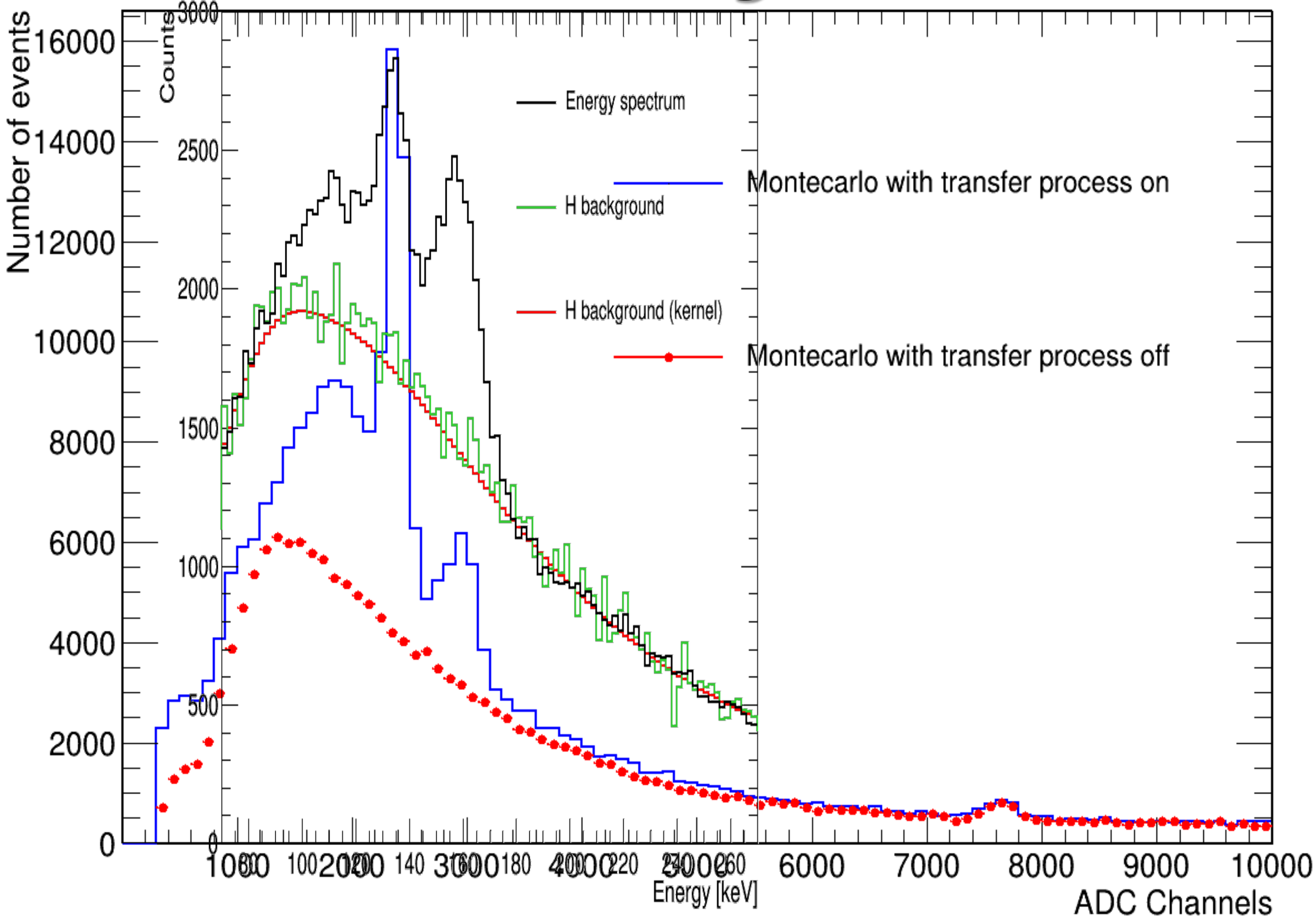
* 1 tdc = 2 ns

Single pulse fit



* 1 tdc = 2 ns

Similar tail!
(even if a better tuning is needed)



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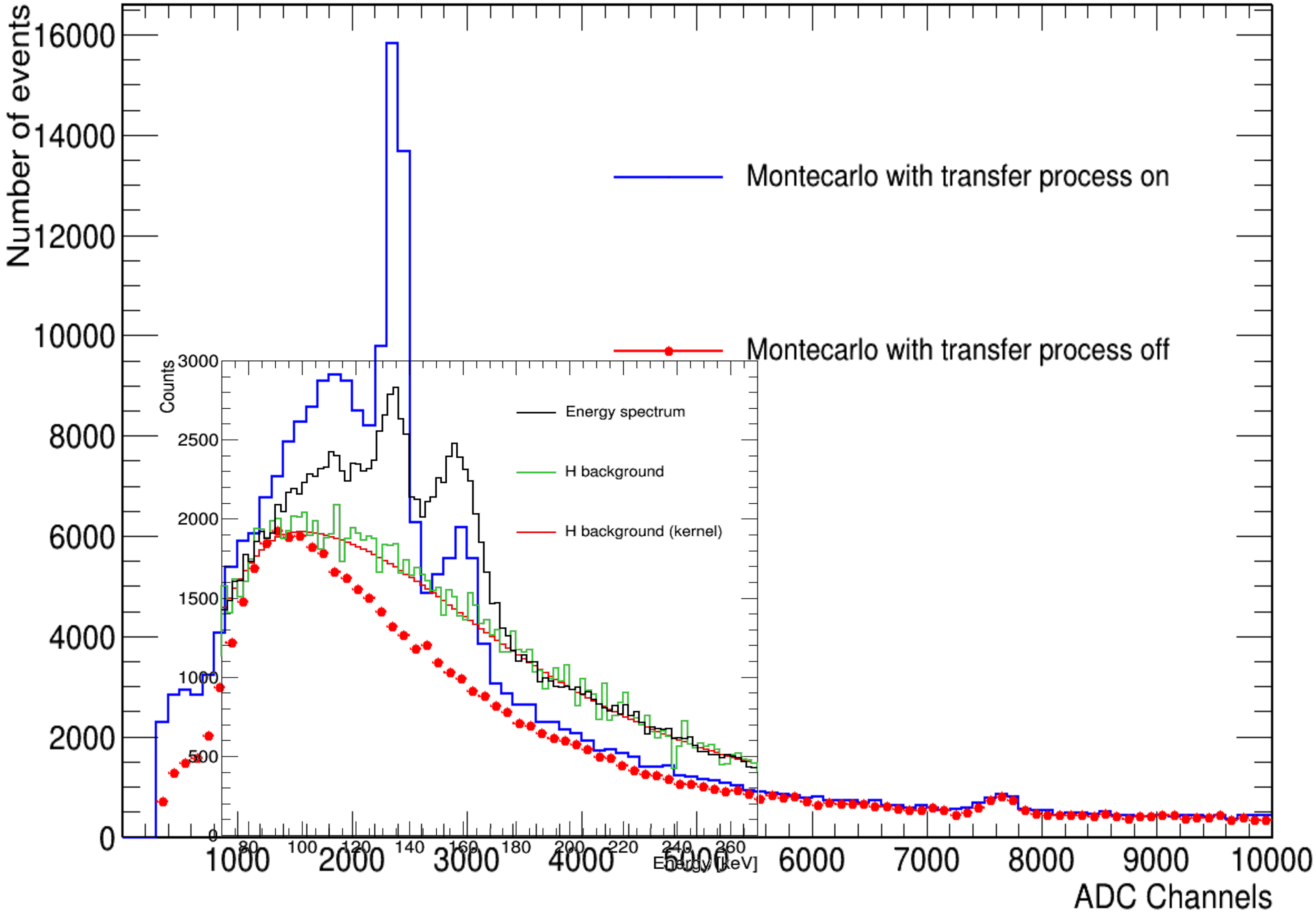


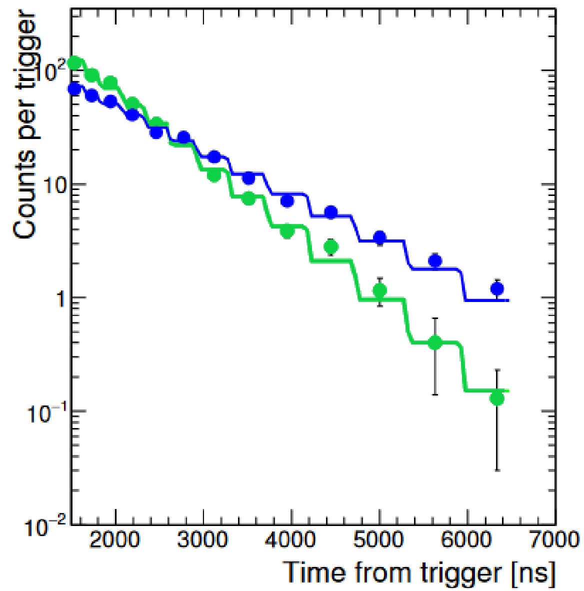
Data Fit

Variation of the number of mu-p atoms in the time dt:

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

Disappearence rate

Fit: numerical integration



$$\lambda_{\text{dis}}(T) = \lambda_0 + \phi\,[c_{\text{p}}\Lambda_{\text{pp}\mu} + c_{\text{d}}\Lambda_{\text{pd}}(T) + c_{\text{O}}\Lambda_{\text{pO}}(T)]$$

UNKNOWN TERM

Rate of disappearance of muons bounded to p (decay, ..)

$\Lambda_{pp\mu}$, Λ..., transfer rates

c_p, c... concentrations of hydrogen, deuterium, oxygen

ϕ number density of atoms in the gas target

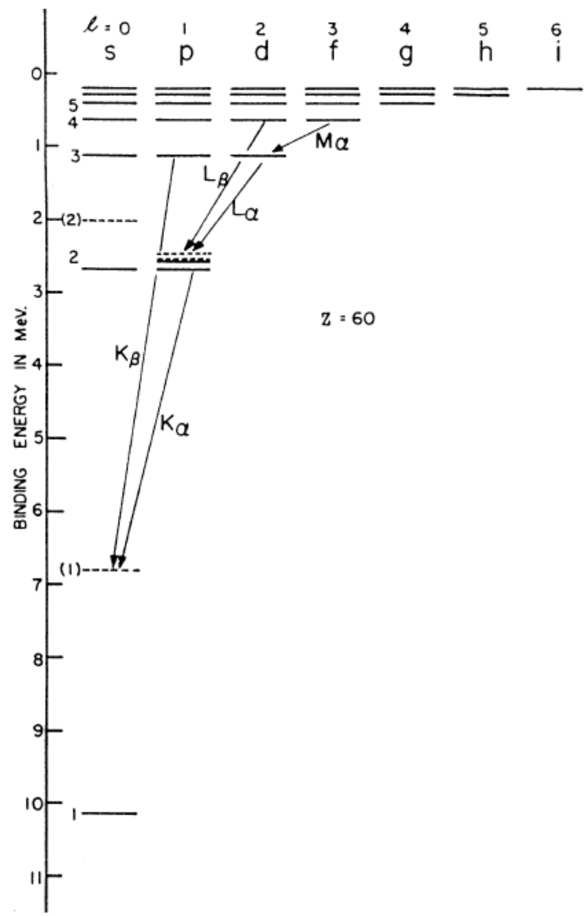
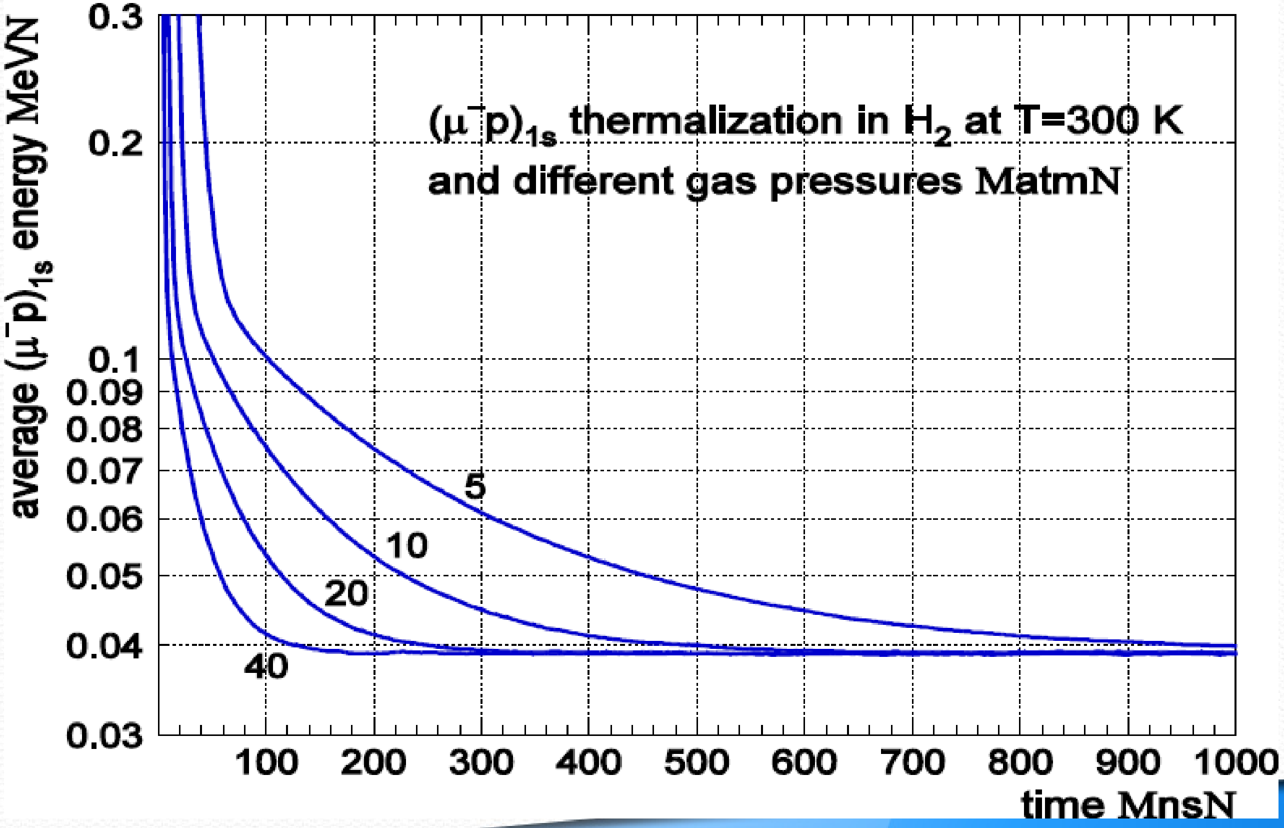
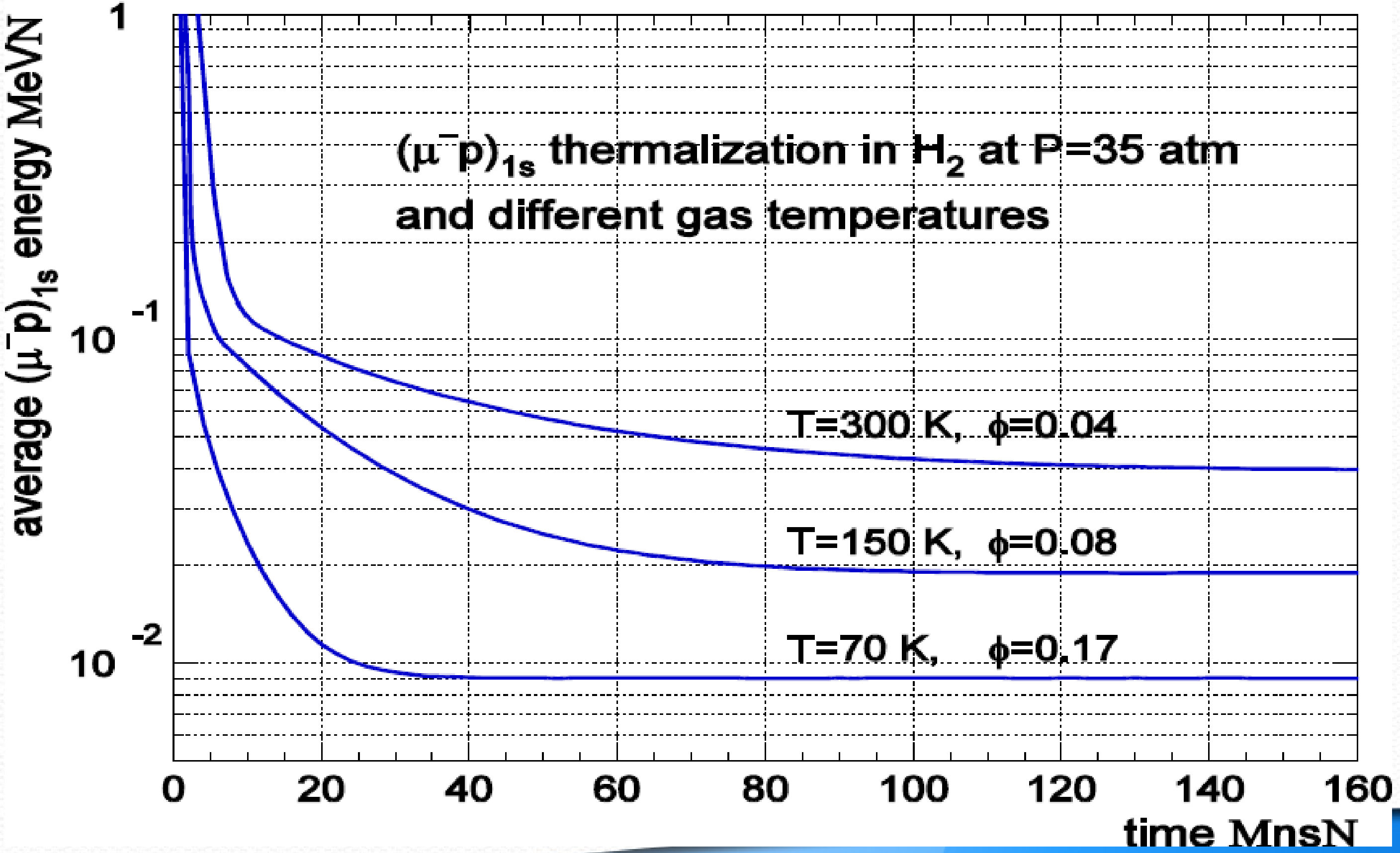


Fig. 3.3. Levels of a muonic atom, showing notation for X-rays. For $Z = 60$ the $1s$ state is raised by 3.3 MeV (dashed level) because of the finite size of the nuclear charge [117].

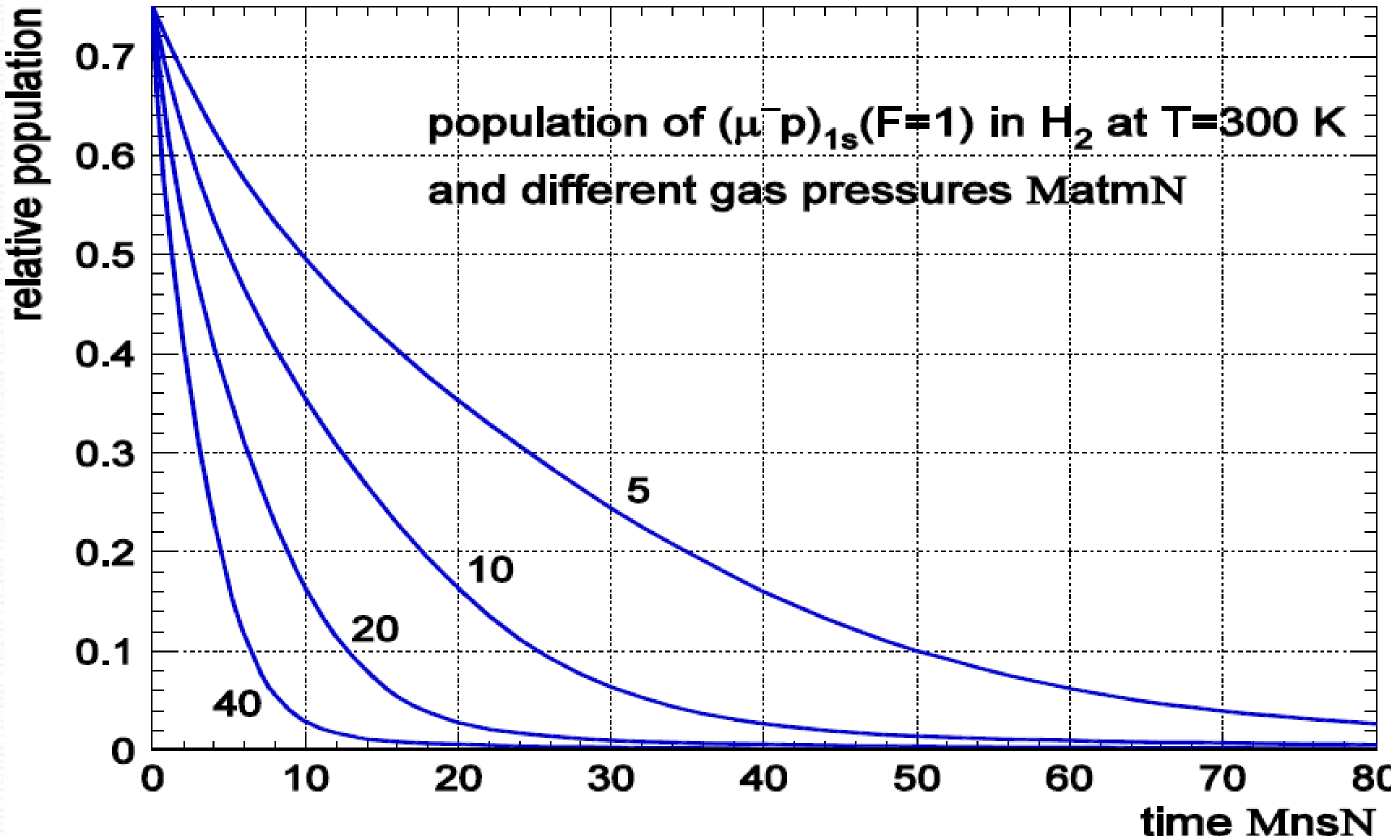
Thermalization of μp



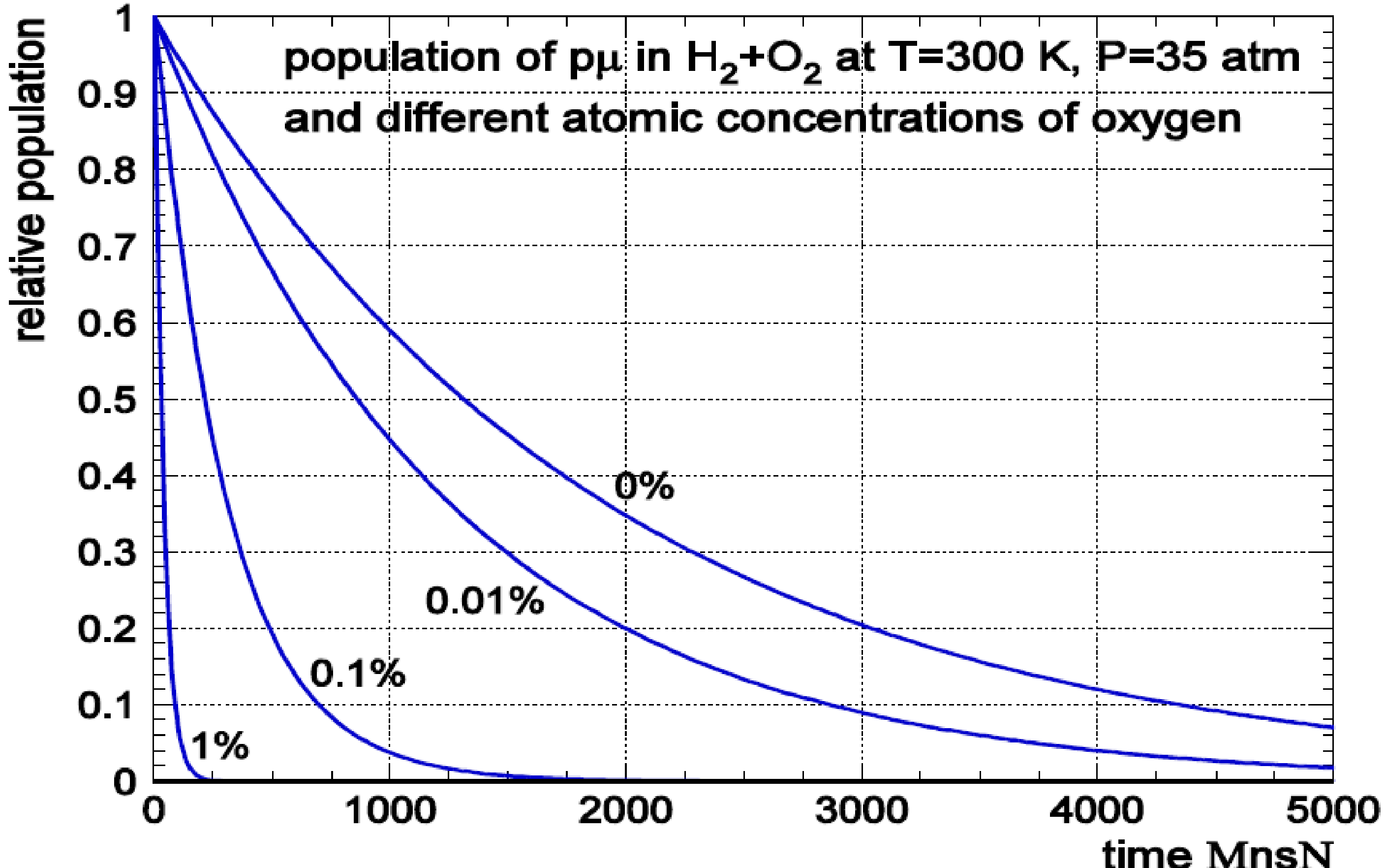
Thermalization of μp



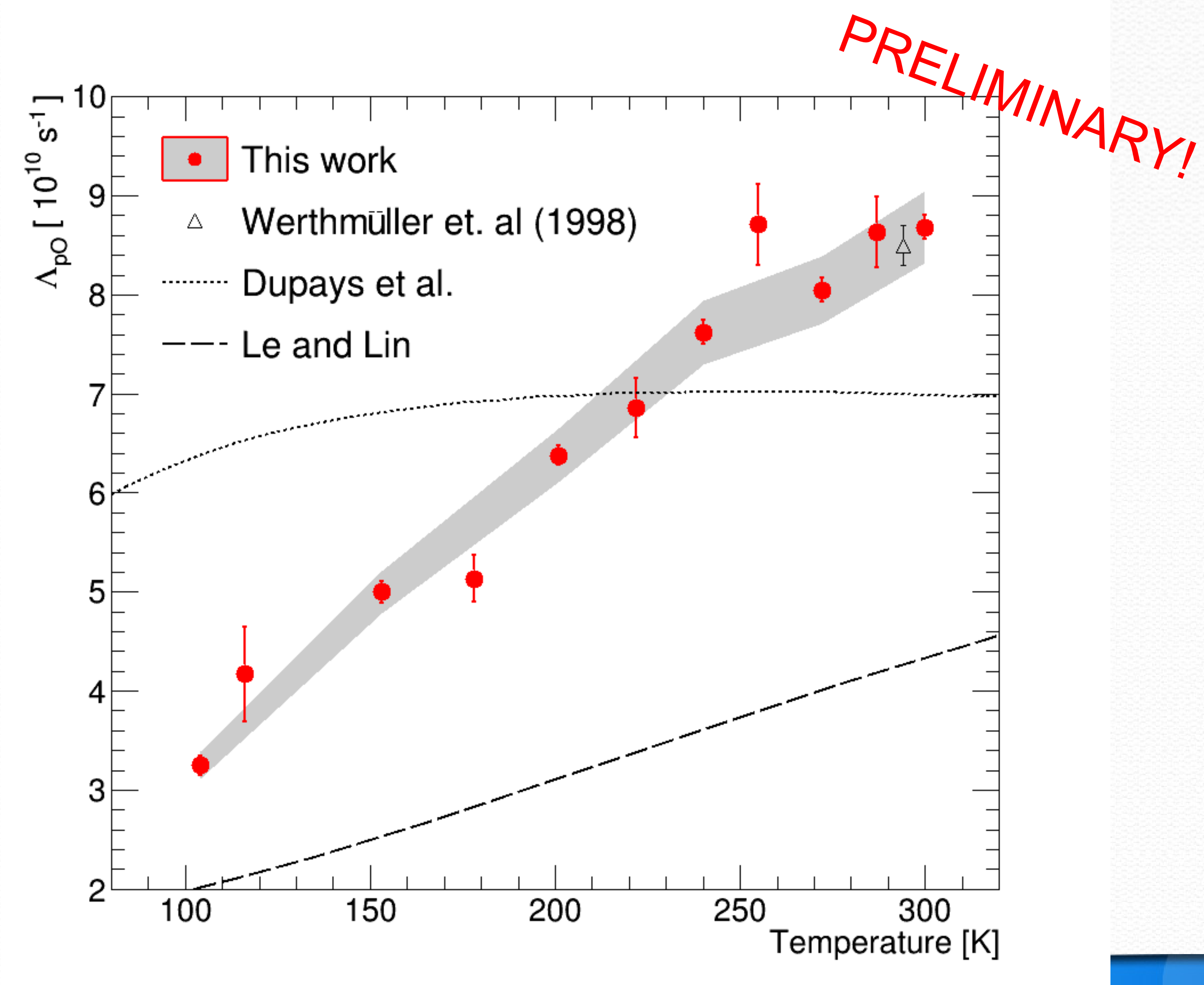
Depolarization of μp



Lifetime of μp and muon transfer

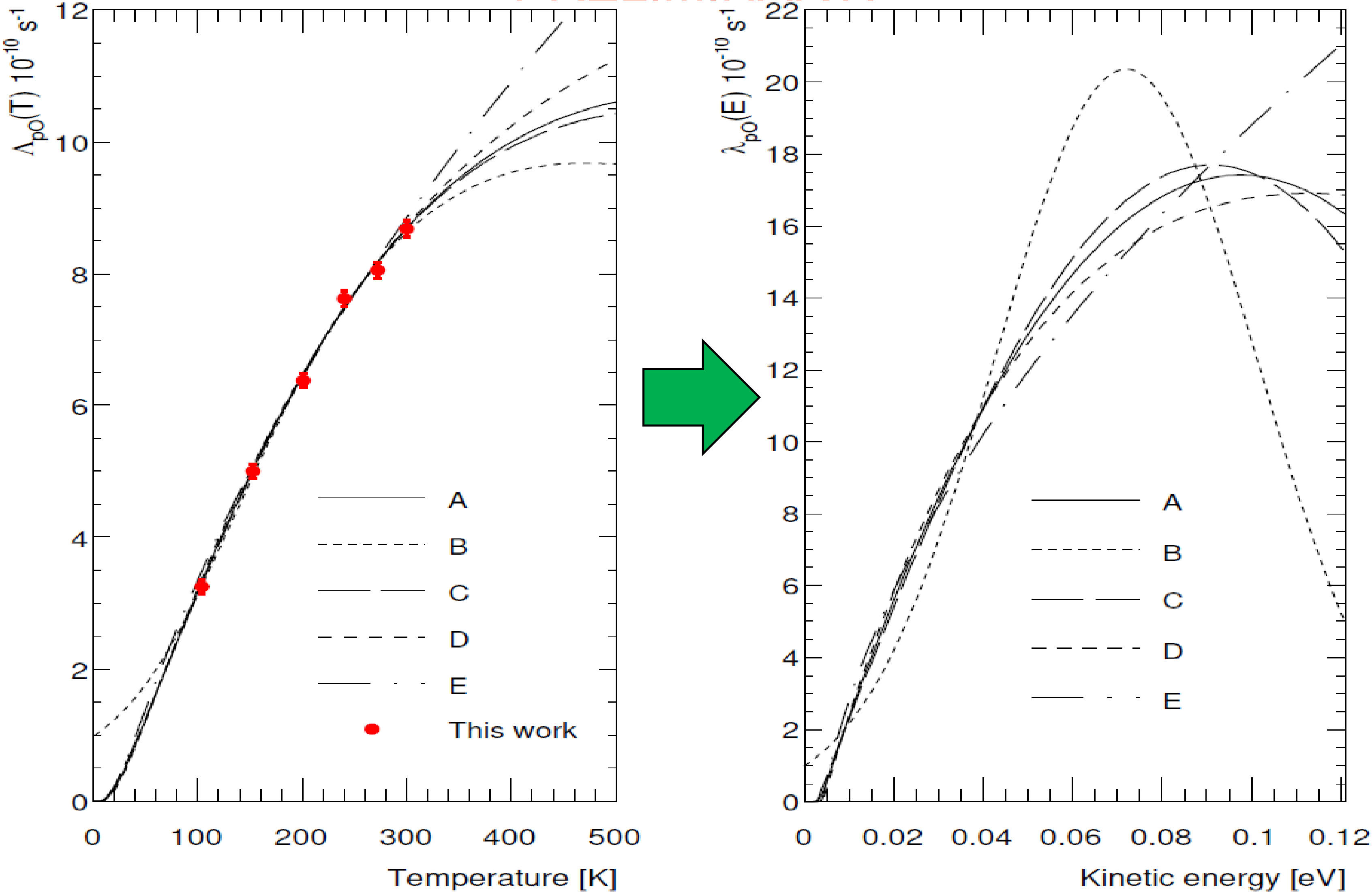


Transfer rate measurement



Transfer rate up to 120 meV

PRELIMINARY!

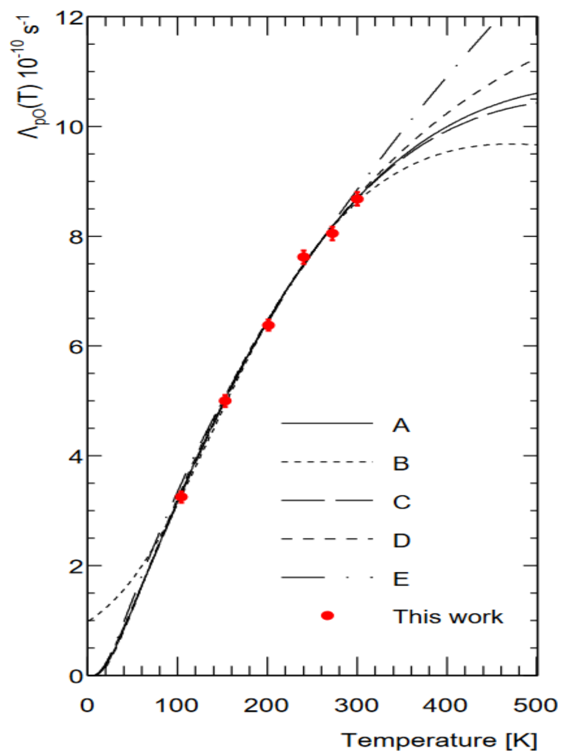


http://arxiv.org/abs/1905.02049

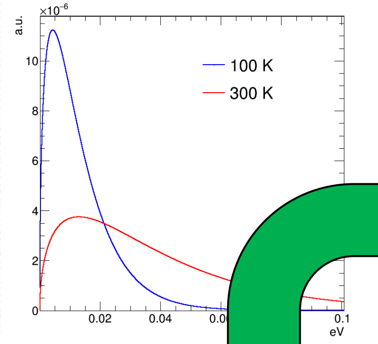
Tested functions transfer rate $\Lambda_{pO}(T)$

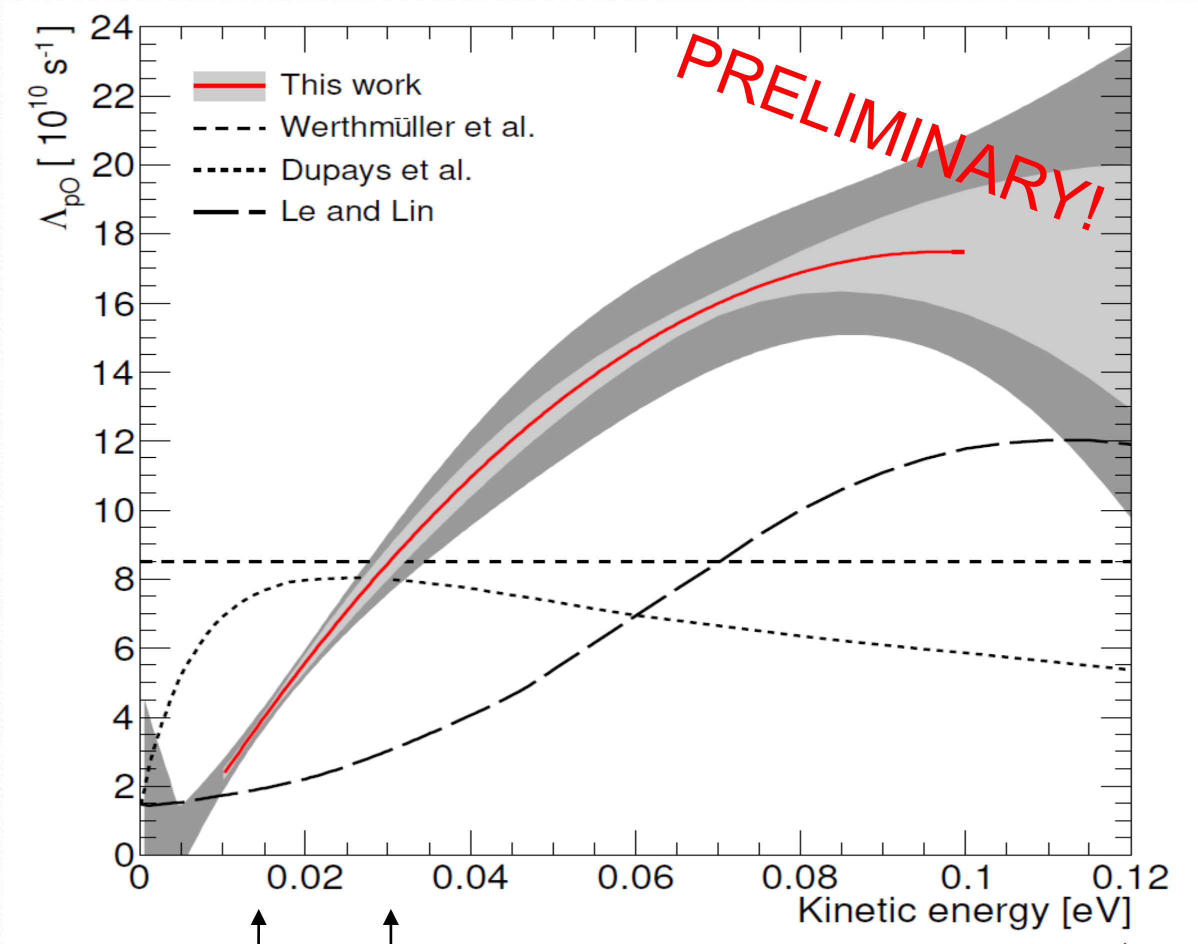
http://arxiv.org/abs/1905.02049

Fit	Analytical expressions and χ^2	Optimal values of the parameters
A	$\lambda_{pO}(E;p) = \sum_{k=1}^{3} p_k E^{k-1}$	$p_1 = (-1.32 \pm 0.61) \times 10^{10}\ s^{-1}$
	$\Lambda_{pO}(T;p) = \sum_{k=1}^{3} (2k-1)!!\, p_k\, (k_B T/2)^{k-1}$	$p_2 = (3.85 \pm 0.54) \times 10^{12}\ s^{-1}\ eV^{-1}$
	$\chi^2/ndf = 1.13/3$	$p_3 = (-1.98 \pm 0.65) \times 10^{13}\ s^{-1}\ eV^{-2}$
B	$\lambda_{pO}(E;p) = p_1 e^{-((E-p_2)/p_3)^2}$	$p_1 = (20.4 \pm 0.97) \times 10^{10}\ s^{-1}$
	$\Lambda_{pO}(T;p) = p_1 \frac{e^{-p_2^2/p_3^2}}{\sqrt{\pi}} \left(\frac{p_3}{k_B T}\right)^{\frac{3}{2}} \left(\Gamma\left(\frac{3}{4}\right) {}_1F_1\left(\frac{3}{4}, \frac{1}{2}, X^2\right)\right.$	$p_2 = (0.0719 \pm 0.0077)\ eV$
	$\left.-2X\Gamma\left(\frac{5}{4}\right) {}_1F_1\left(\frac{5}{4}, \frac{3}{2}, X^2\right)\right),\ X = \frac{p_3^2 - 2p_2 k_B T}{2p_3 k_B T}$	$p_3 = (0.0413 \pm 0.0058)\ eV$
	$\chi^2/ndf = 1.23/3$	
C	$\lambda_{pO}(E;p) = p_1 + p_2 \sin(p_3 E)$	$p_1 = (-0.917 \pm 0.54) \times 10^{10}\ s^{-1}$
	$\Lambda_{pO}(T;p) = (p_1 + p_2 \sin\left(\frac{3}{2} \arctan(p_3 k_B T)\right)$	$p_2 = (18.6 \pm 1.2) \times 10^{10}\ s^{-1}$
	$\times \left(1 + (p_3 k_B T)^2\right)^{-3/4})$	$p_3 = (17.2 \pm 2.8)\ eV^{-1}$
	$\chi^2/ndf = 1.11/3$	
D	$\lambda_{pO}(E;p) = (p_1 + p_2 E) \exp(-p_3 E)$	$p_1 = (-1.8 \pm 0.95) \times 10^{10} s^{-1}$
	$\Lambda_{pO}(T;p) = p_1 \left(1 + \left(p_3 + \frac{2p_2}{2p_1}\right) k_B T\right) (1 + p_3 k_B T)^{-5/2}$	$p_2 = (4.4 \pm 0.94) \times 10^{12}\ s^{-1}\ eV^{-1}$
	$\chi^2/ndf = 1.23/3$	$p_3 = (9.22 \pm 3.24)\ eV^{-1}$
E	$\lambda_{pO}(E;p) = p_1 + p_2\sqrt{E}$	$p_1 = (-4.62 \pm 0.36) \times 10^{10} s^{-1}$
	$\Lambda_p O(T;p) = p_1 + 2p_2\sqrt{k_B T/\pi}$	$p_2 = (74.1 \pm 2.5) \times 10^{10}\ s^{-1}\ eV^{-1/2}$
	$\chi^2/ndf = 2.11/4$	



Transfer rate up to 120 meV

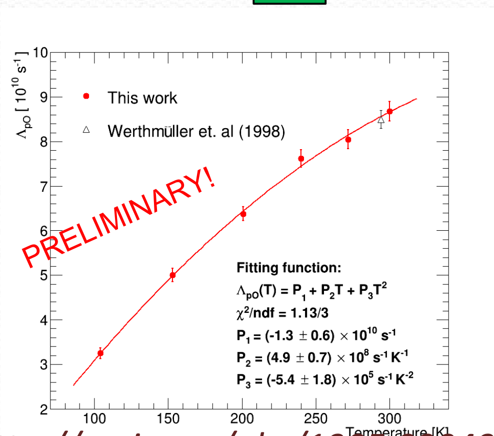




~300 K

~100 K

μp energy after de-excitation



http://arxiv.org/abs/1905.02049

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