Measurements of muonic X-rays and gammas from Al and Ti

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Outline

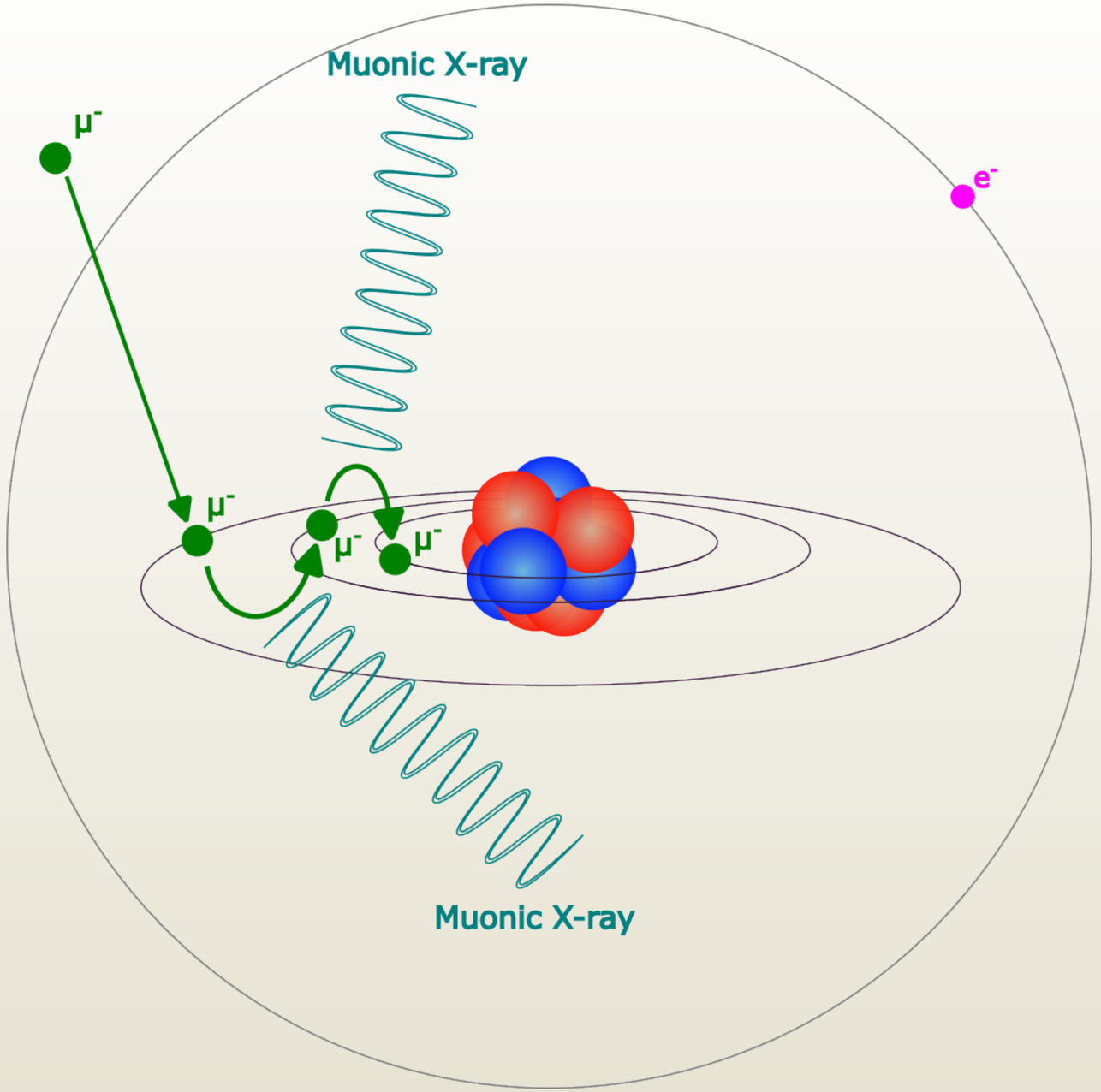
- Motivation and reminder
- Experimental setup
- Measurements
- Results

Motivation

- Mu2e and COMET experiments aim to search for neutrinoless muon decay to electron
- Need to know the number of stopped muons in their target (primary is Al, secondary is Ti)
- Both experiment plan to use muonic X-rays and gammas from nuclear muon capture to calculate the number of stopped muons
  - join force to form AlCap experiment to measure photons (and charged particles, neutrons) after muon capture on Al and Ti
- In general, we want to use Kα lines from Al and Ti
  - Al: 347 keV
  - Ti: 932 keV

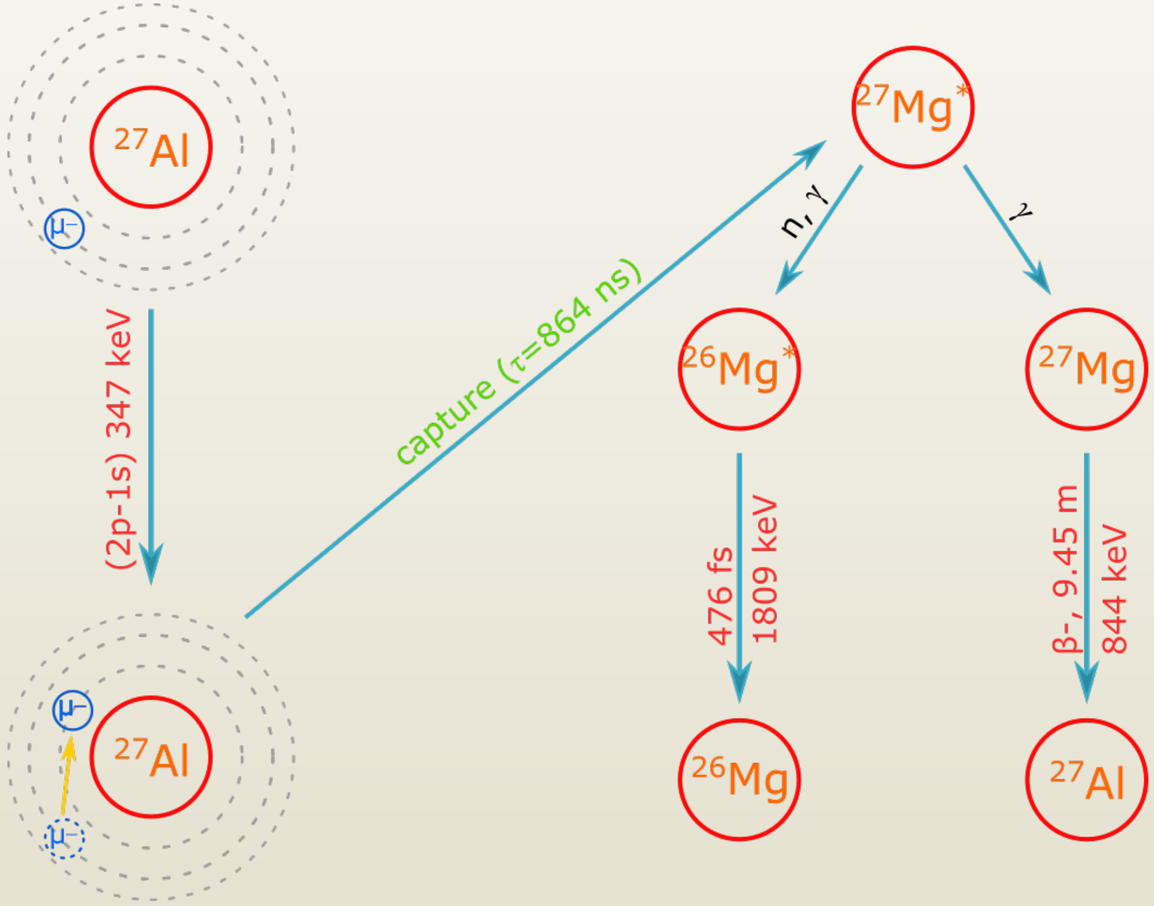
What is muonic X-ray?

- Similar to X-ray, but with muonic levels
- Characteristic to each element
  - Higher energy than normal X-ray due to the mass of muon
  - K-line energy is ~2 keV for H, up to ~6000 keV for Pb
- Prompt with atomic muon capture process
  - 10^{-14} s for muons to cascade from the highest state to 1S



And gammas?

- From unstable products of the nuclear muon capture process
- For example: $\mu^- + {}^{27}\mathrm{Al} \rightarrow {}^{27}\mathrm{Mg}^*$
  - 1809 keV line has life time of 864 ns
  - 844 keV line has life time of 9.45 min



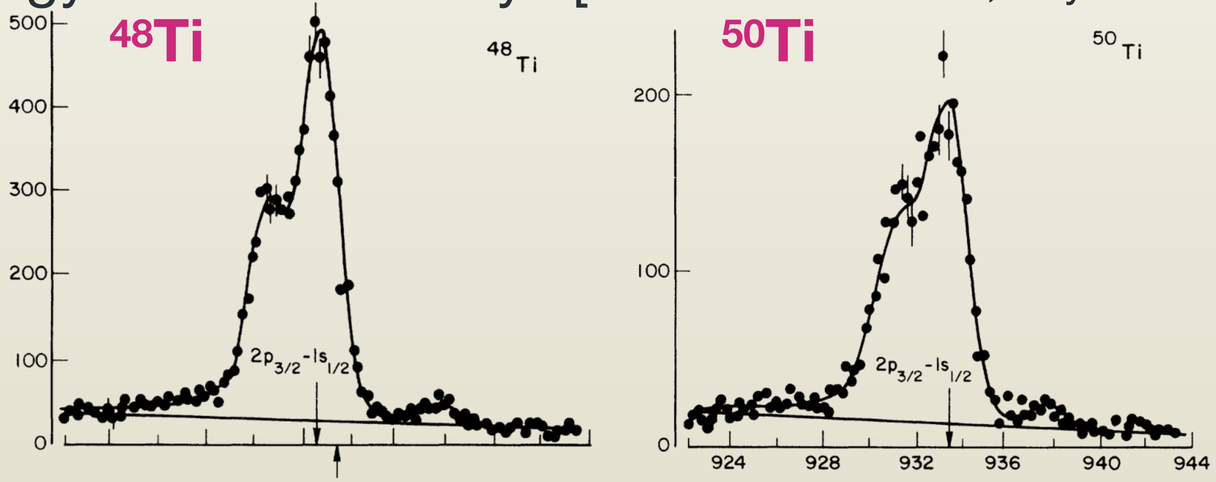
Literature on photons on muon capture

- Measday and Stocki [Phys. Rev. C 76, 035504 (2007)] measured the muonic X-rays and gammas from Al to details

μ x ray	Energy (keV) (this exp.)	Energy (keV) [5–7]	Intensity (%) (this exp.)	Intensity (%) [8]
$2p$-$1s$	346.828[a]	346.828(2)	79.8(8)	79.65(60)
$3p$-$1s$	412.87(5)	412.877(10)	7.62(15)	7.43(29)
$4p$-$1s$	435.96(10)	435.981(12)	4.87(10)	4.72(20)
$5p$-$1s$	446.61(10)	446.65(4)	3.86(10)	3.89(17)
$6p$-$1s$	452.38(10)	452.45(5)	2.20(10)	2.35(11)
(7 to ∞) p-$1s$			1.63(15)	1.96(20)

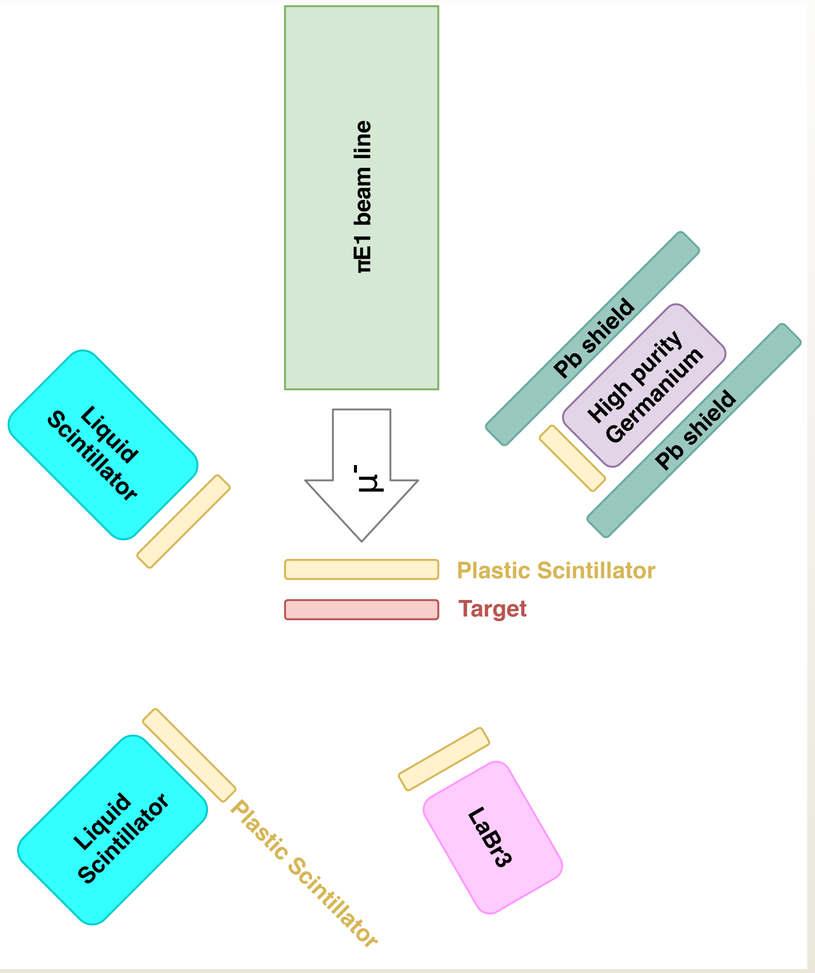
Level in ^{26}Mg (keV)	J^π	Transition branching ratio (%)	Transition energy (keV)	Observed γ-ray yield (%)
1808.73	2^+	100	1808.66	51(5)
2938.34	2^+	9	2938.16	1.1(2)
		91	1129.58	14.8(15)

- Not much on Ti apart from the energy of muonic X-rays [H. D. Wohlfahrt et.al, Phys. Rev. C 23, 533 (1981)]
  - ~932 keV for natural Ti



Experimental setup

- Done at PSI in 2015
- High purity germanium detector (HPGe) was used for photons measurement
- A LaBr3 detector was tested
- 2 liquid scintillators used for neutron detection
- Muon momentum was tuned to stop in middle of targets

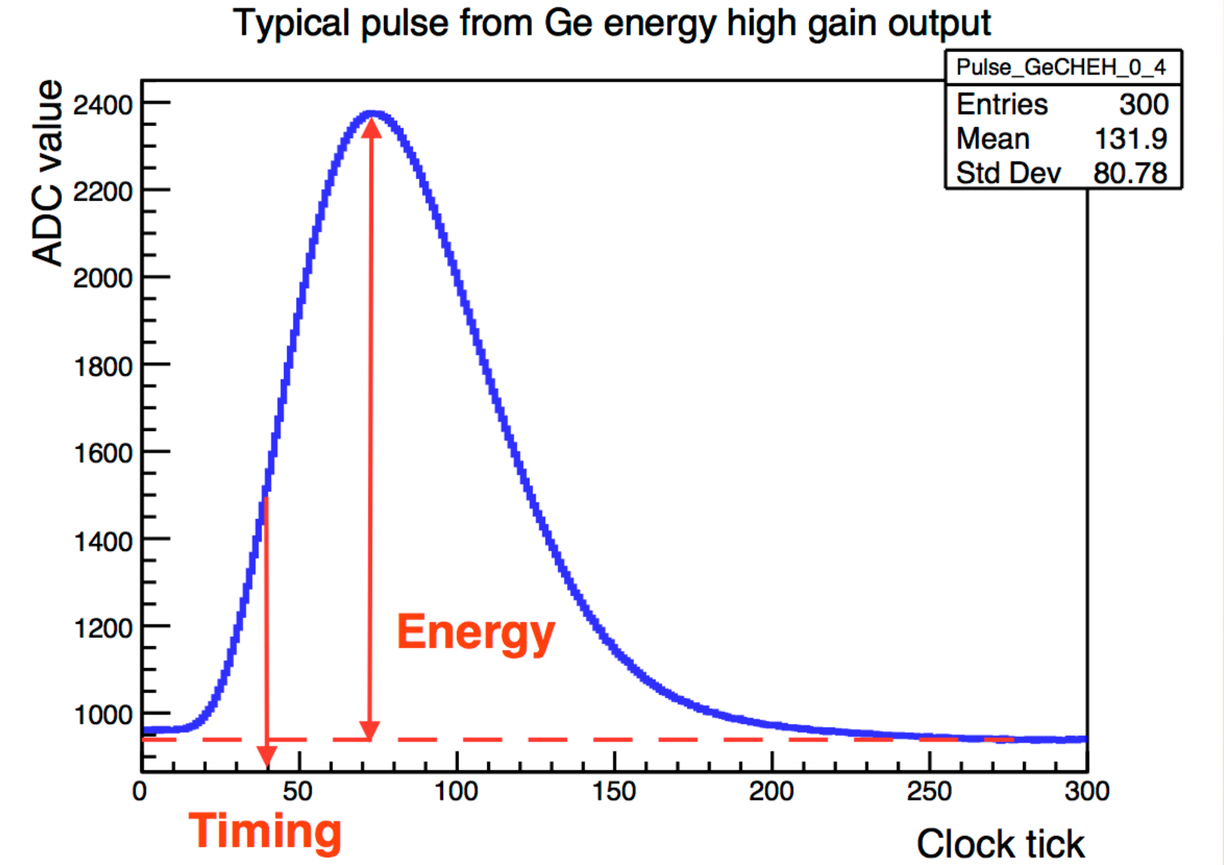


Targets

Target	Thickness [mm]	Muon momentum [MeV/c]	Number of muons	Comments
Al	2	33, 36	3.04×10^{8}	Primary target for Mu2e and COMET
Ti	1.3	36	2.07×10^{8}	Secondary target for Mu2e and COMET
Pb	1.5	36	9.03×10^{7}	Shielding material
W	0.5	36	1.73×10^{7}	Wires holding muon stopping target in Mu2e
Stainless steel	0.9	36	2.51×10^{7}	Various structure components
Mylar	3	36	2.95×10^{7}	Various structure components
Polyethylene	5	36	2.77×10^{7}	Various structure components

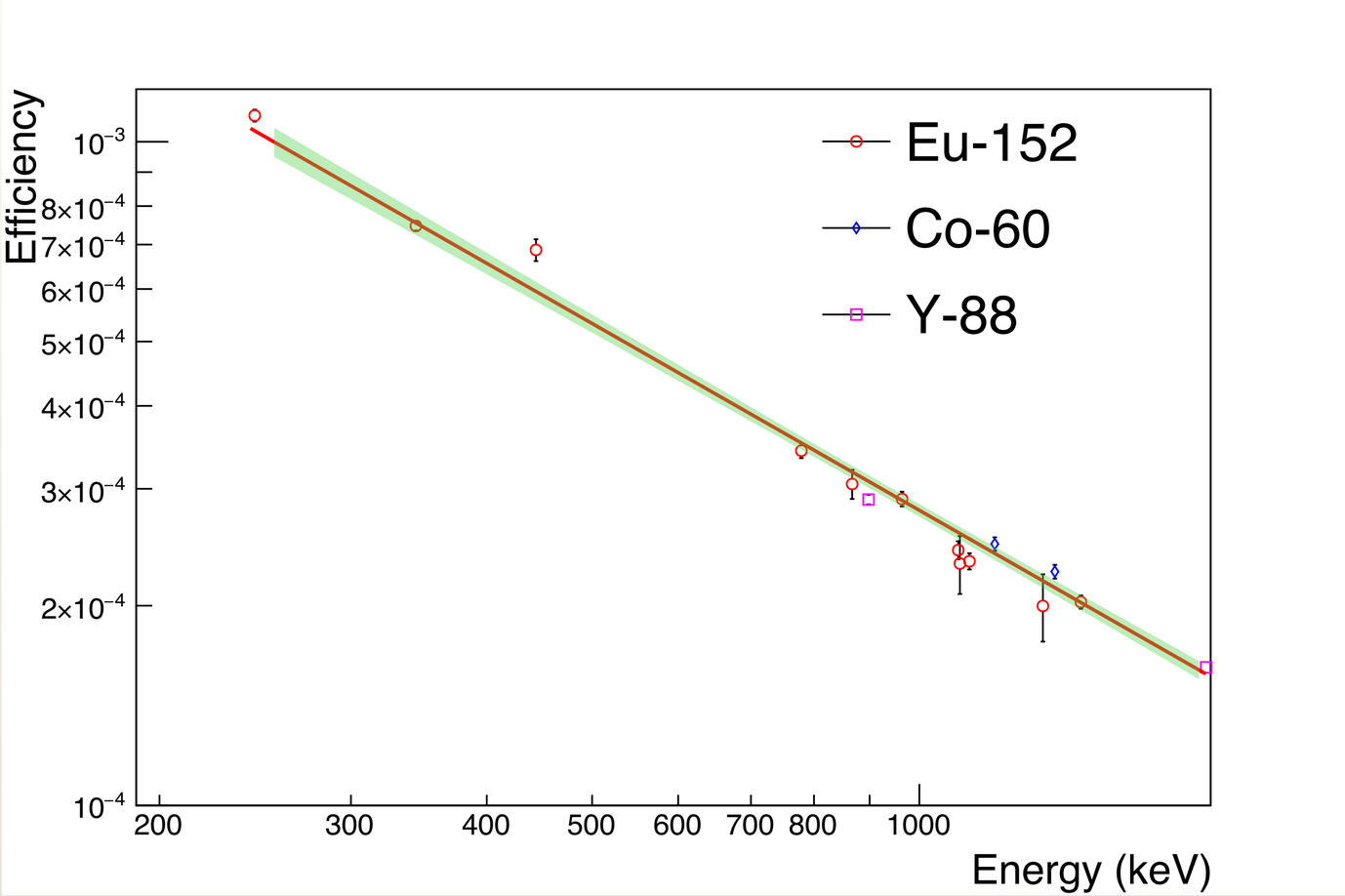
Analysis - Digital pulse processing

- HPGe pulse processing:
  - Energy is proportional to amplitude of the pulse
  - Timing is the clock tick where the traces pass 30% of the amplitude (230 ns resolution)



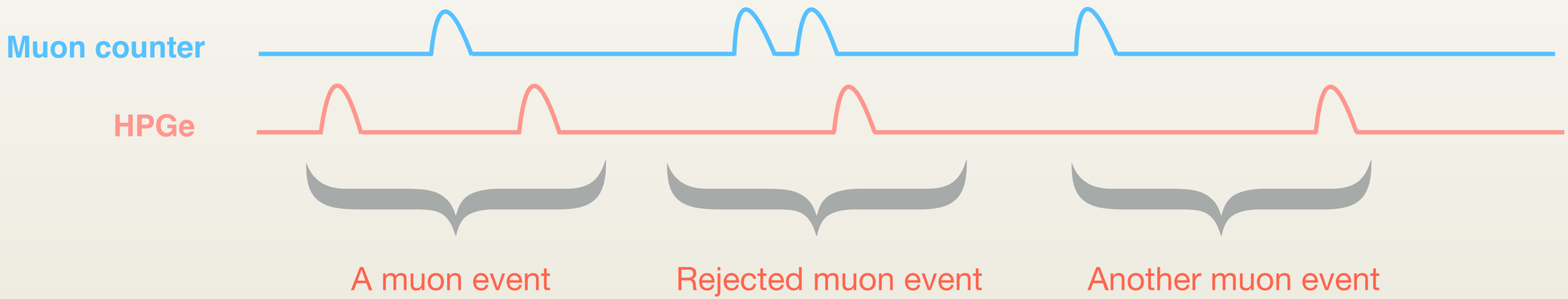
Analysis - Acceptance calibrations

- Calibrated with sources ^{152}Eu, ^{60}Co, and ^{88}Y
  - Acceptance: $A(E) = c_1 \times E^{c_2}$



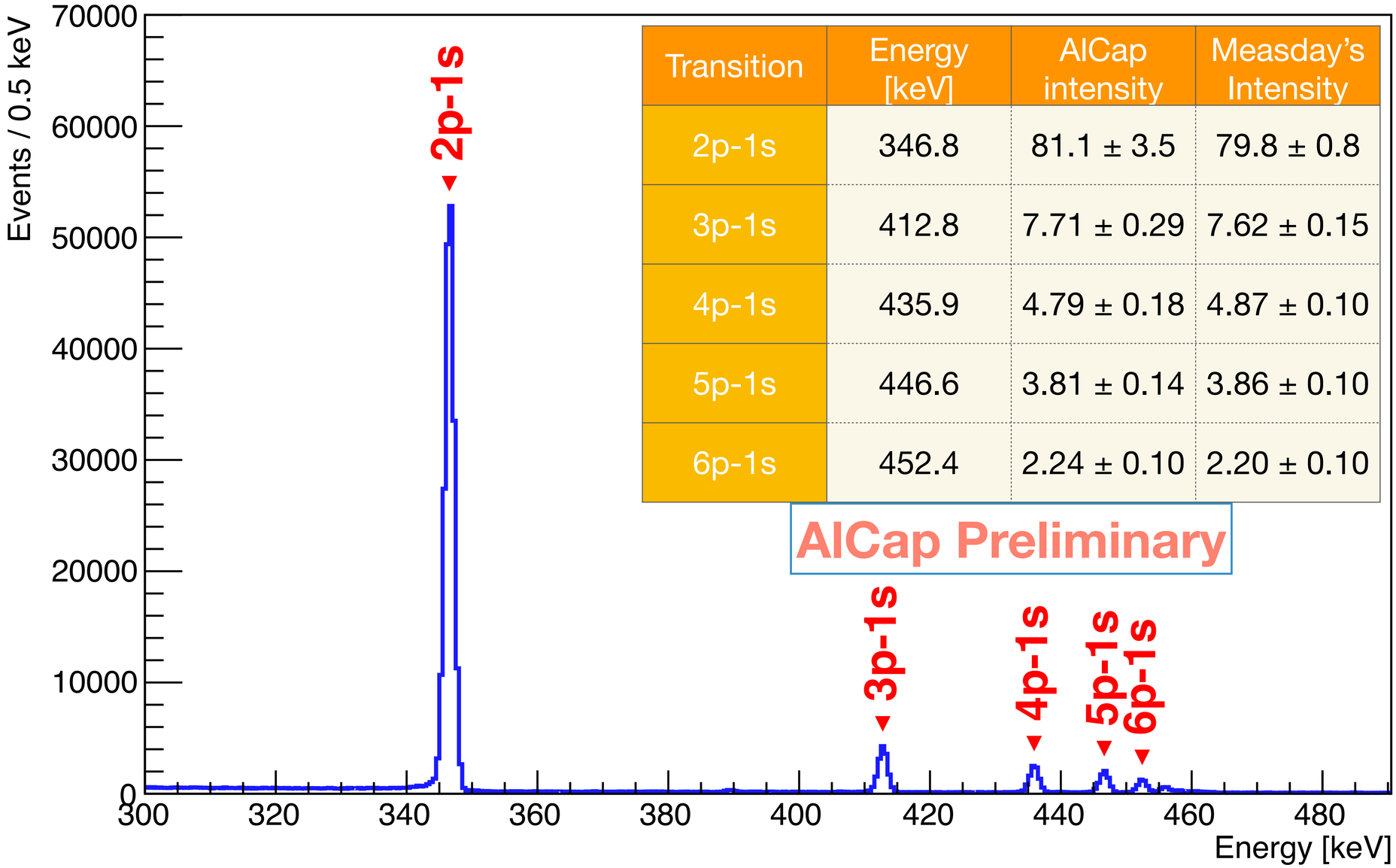
Analysis - Muon event

- Digitized pulses are organized into muon events:
  - A hit on the muon counter
    - if there is another hit on muon counter within +/- 5 μs, reject both
  - All hits on HPGe detector within 10 μs around the hit on muon counter



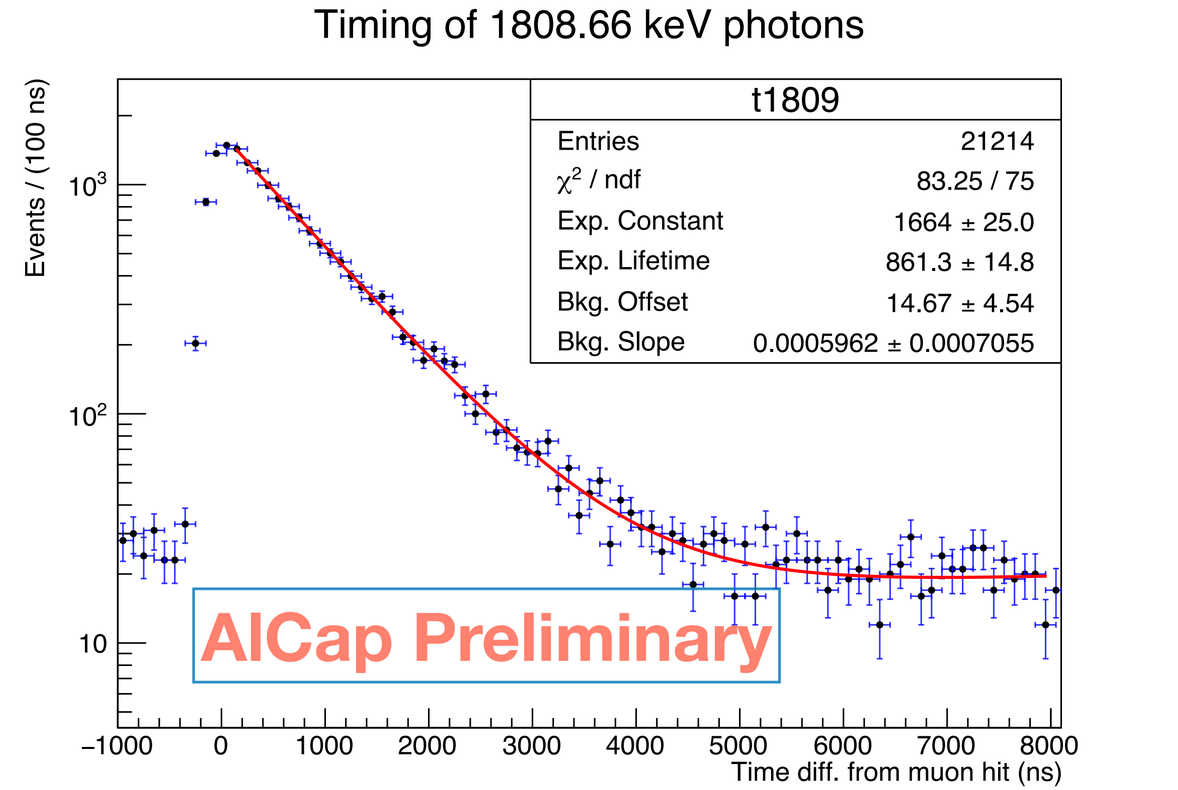
- Timing cuts
  - Muonic X-ray: +/- 300 ns around a muon counter hit
  - Delayed gamma: -300 - 5000 ns around a muon counter hit

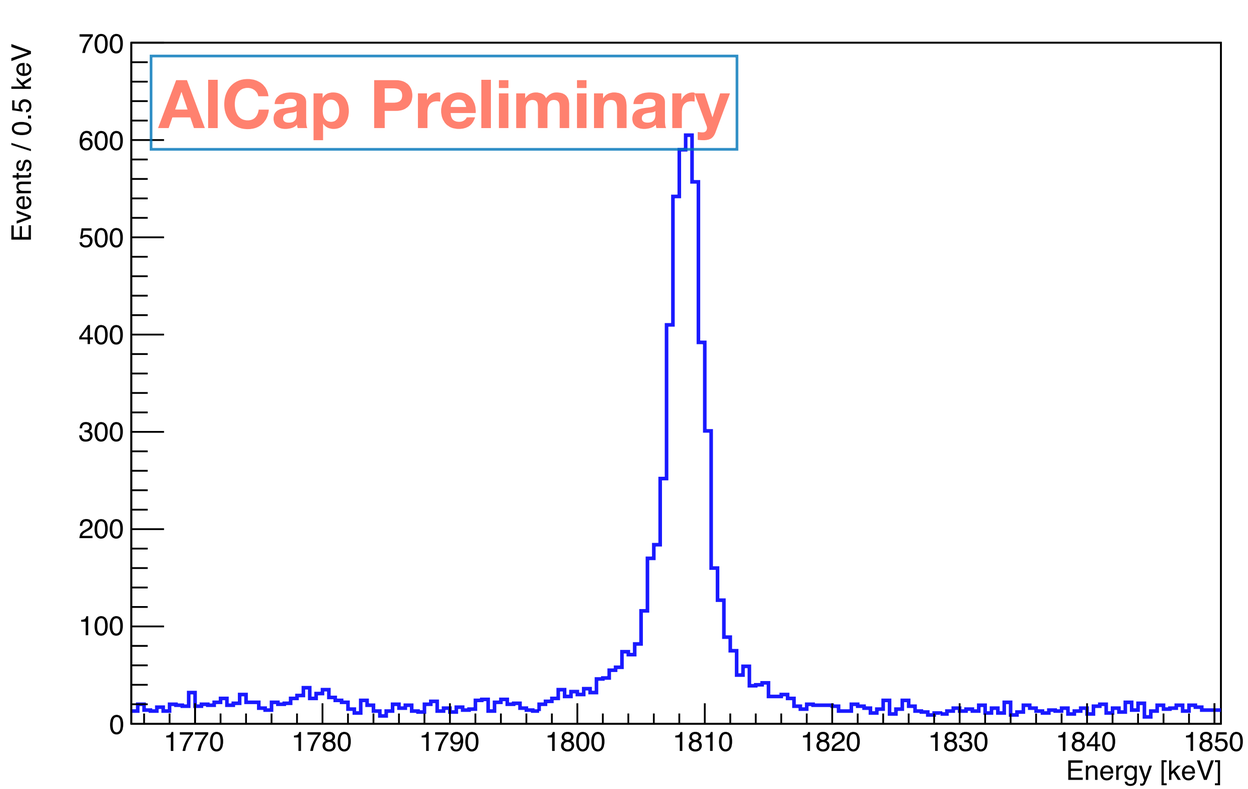
Muonic X-rays from aluminum



Transition	Energy [keV]	AlCap intensity	Measday's Intensity
2p-1s	346.8	81.1 ± 3.5	79.8 ± 0.8
3p-1s	412.8	7.71 ± 0.29	7.62 ± 0.15
4p-1s	435.9	4.79 ± 0.18	4.87 ± 0.10
5p-1s	446.6	3.81 ± 0.14	3.86 ± 0.10
6p-1s	452.4	2.24 ± 0.10	2.20 ± 0.10

1809 keV gamma line from aluminum



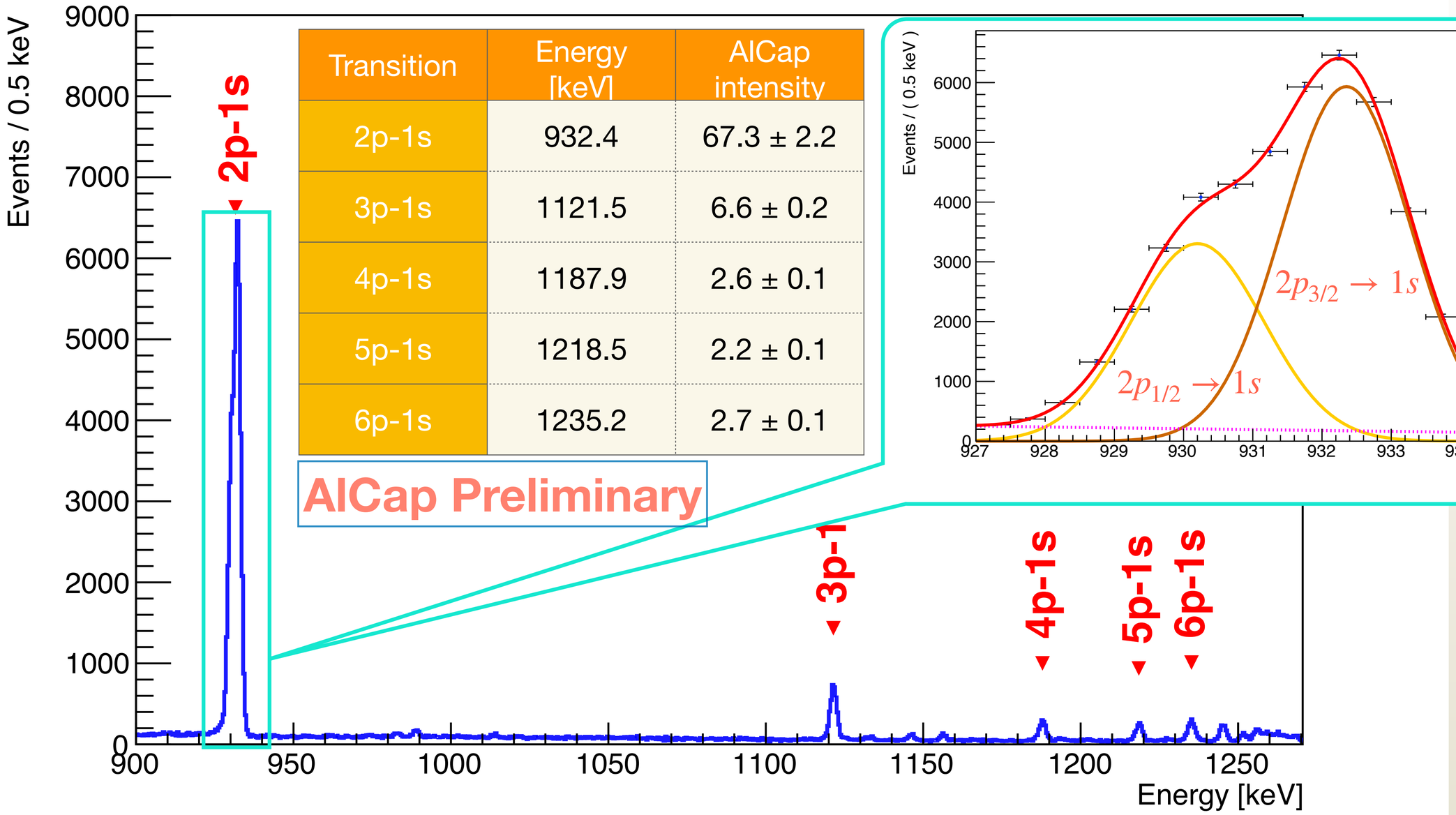


- Fitted lifetime: 861(14) ns
  - Lifetime of muons in aluminum 864(4) ns
- Emission rate: $53.8 \pm 2.6\,\%$ per muon capture
  - Consistent with previous value at $51 \pm 5\,\%$

Muonic X-rays from titanium

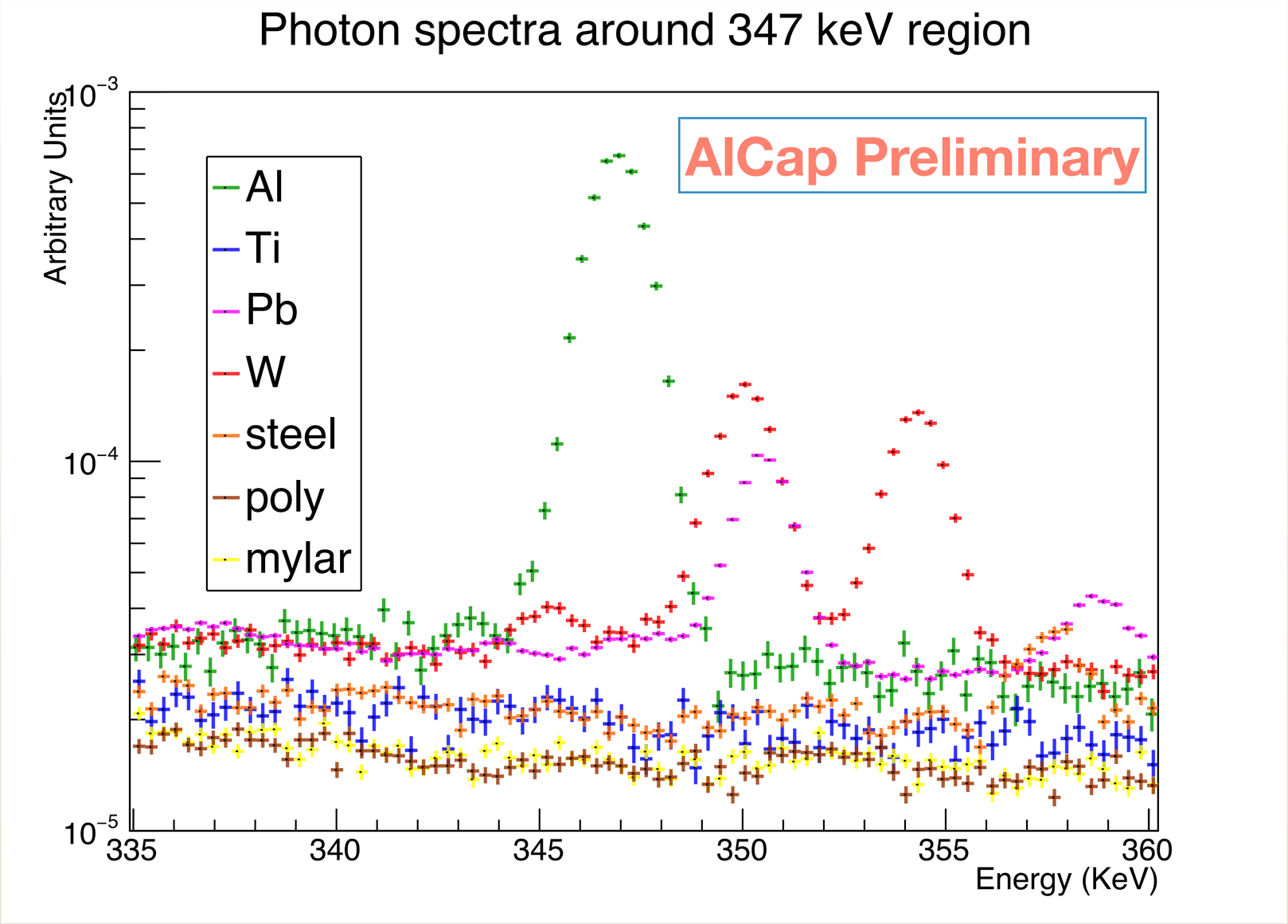
Transition	Energy [keV]	AlCap intensity
2p-1s	932.4	67.3 ± 2.2
3p-1s	1121.5	6.6 ± 0.2
4p-1s	1187.9	2.6 ± 0.1
5p-1s	1218.5	2.2 ± 0.1
6p-1s	1235.2	2.7 ± 0.1

AlCap Preliminary



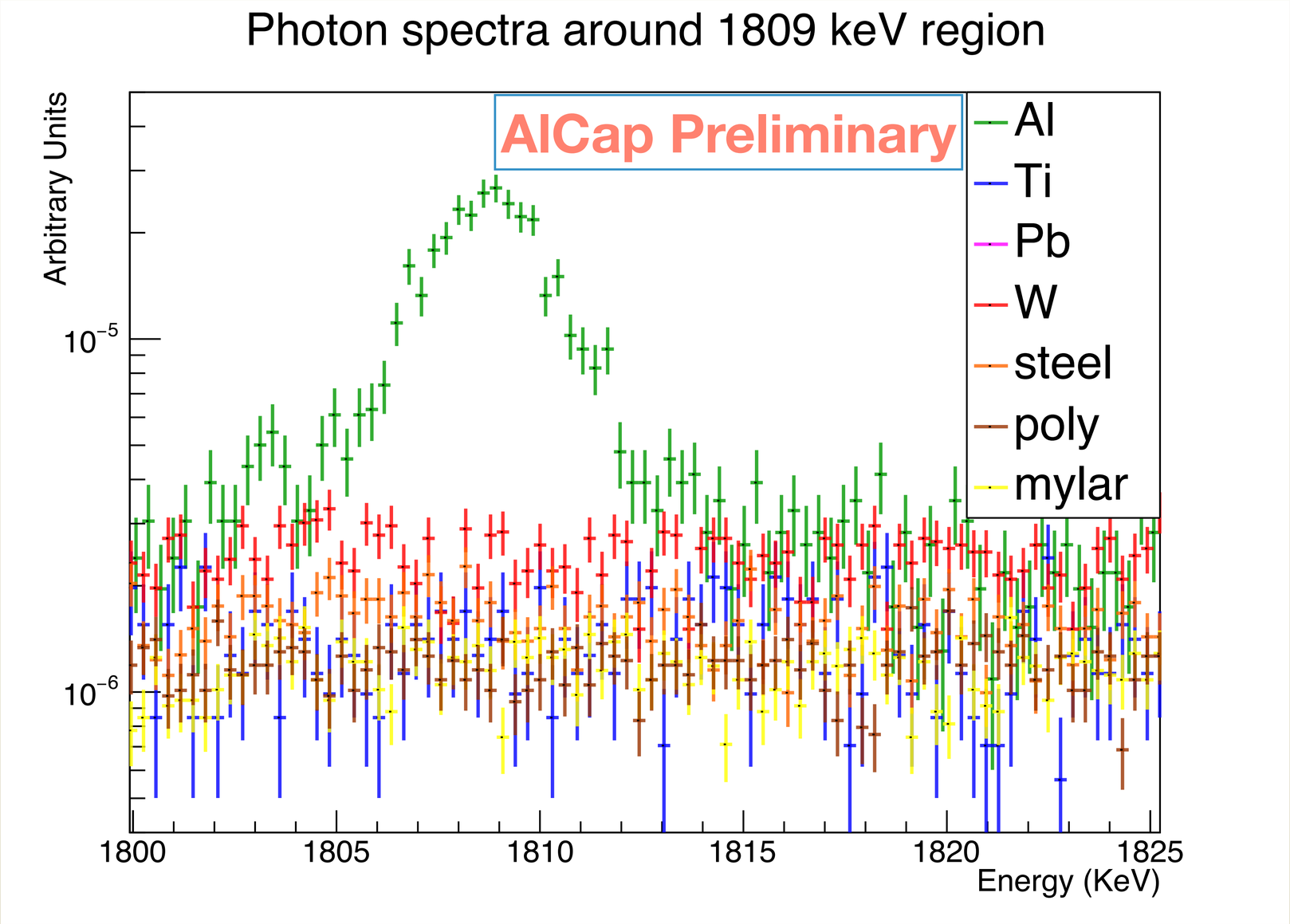
Interference around 347 keV

- W and Pb have lines near 347 keV line from Al



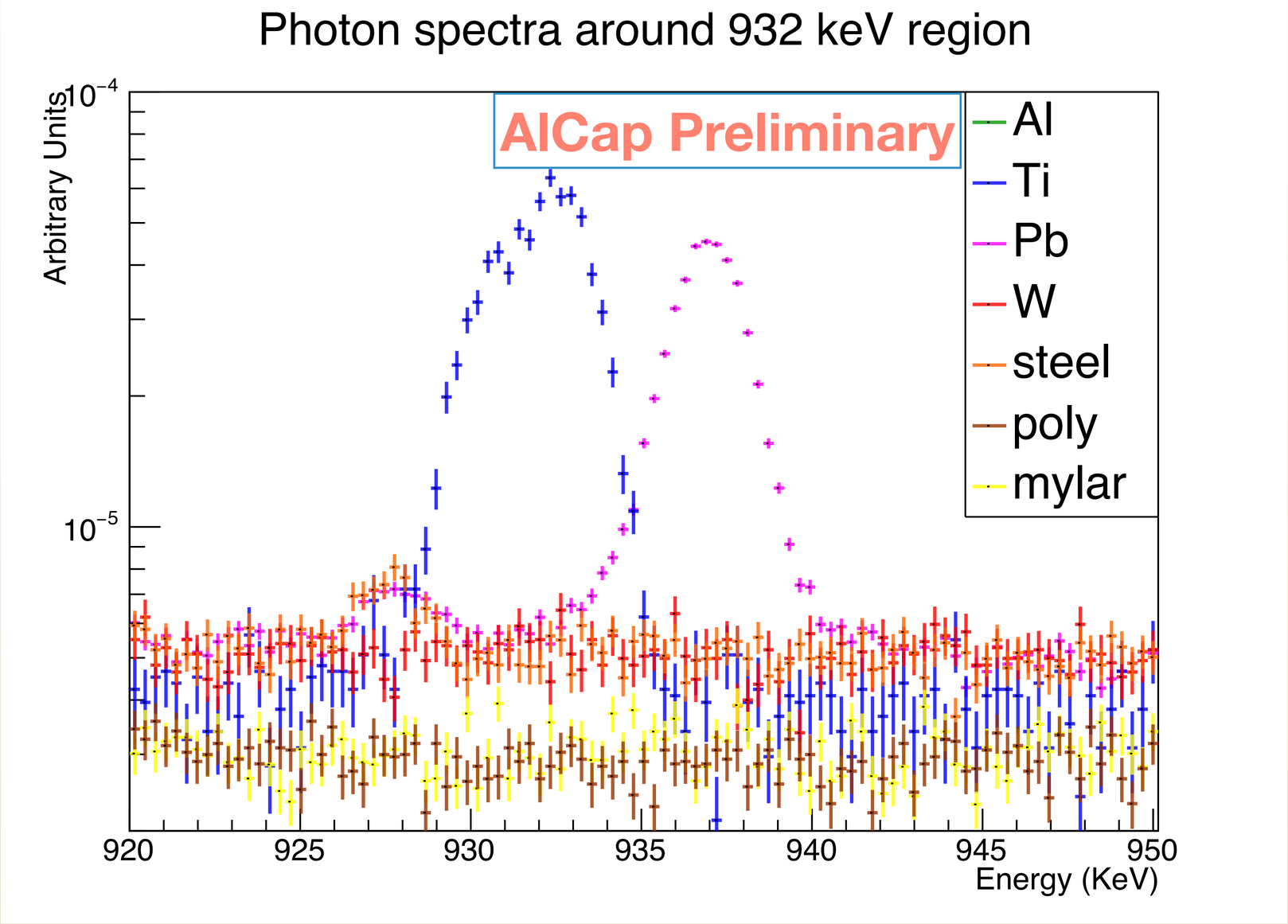
Interference around 1809 keV

- There is no interference around 1809 keV line



Interference around 932 keV

- Pb and stainless steel have lines near 932 keV region



Summary

- AlCap measures charged and neutral particles from muon capture on aluminum & titanium
- Important photons
  - 347 keV X-rays (Al): $79.8 \pm 0.8\,\%$
  - 1809 keV gammas (Al): $53.8 \pm 2.6\,\%$
  - 932 keV X-rays (Ti): $67.3 \pm 2.2\,\%$
- Interferences:
  - 347 keV X-rays (Al) has interferences from W and Pb
  - 932 keV X-rays (Ti) has interferences from Pb, and stainless steel
  - 1809 keV gammas (Al) is clean