DETECTOR CHARACTERISATION AND READOUT DEVELOPMENT FOR THE REAL-TIME RADON-222 MONITORING SYSTEM

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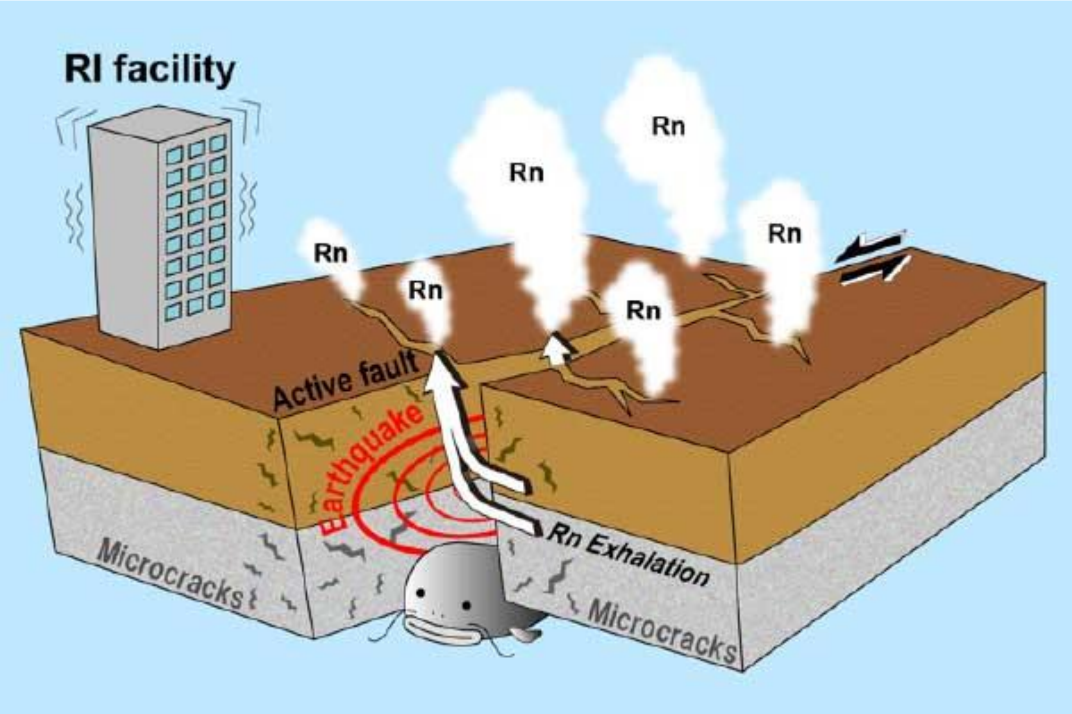
BACKGROUND

- Past studies suggest that there exists a correlation between tectonic activities and changes in the radon concentration.
- Rn-226, usually found in rocks such as limestone, decays into Ra-222. The radon gas escapes through cracks and pores due to seismic activities.
- Question: What is the relationship between the change in radon concentration with seismic activity?

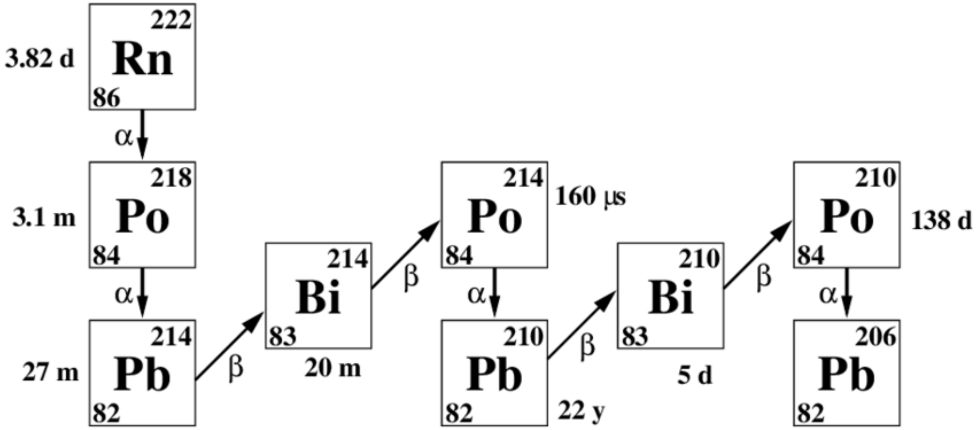


THE RADON DECAY CHAIN

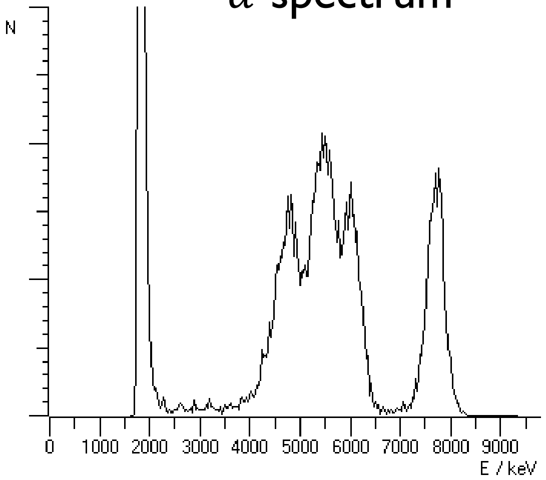
- Most studies measure the change in concentration of Radon gas by capturing and counting the alpha particles produced in the decay chain:
  - Ra-226, Po-210, Rn-222, Po-218, Po-214

- Our method counts the number of photons emitted from the excited states of the nucleus present in the decay chain.
  - Rn-222:186 keV
  - Bi-214: 242 keV, 295 keV, 352 keV
  - Po-214: 609 keV

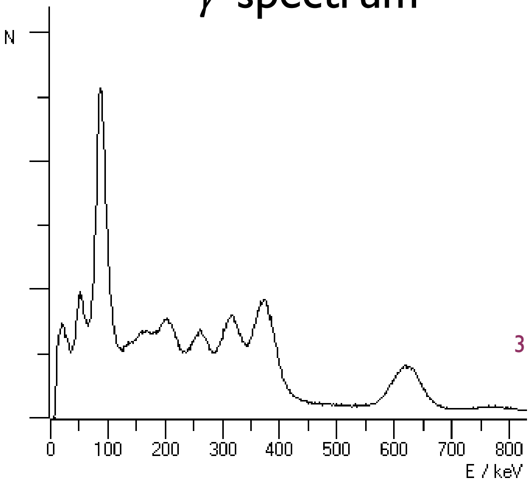
- This method is "real-time" in the sense that we do not need any collection system to trap the particles in the air and then do the counting.
  - The Lucas cell method for alpha particles takes around 2-3 hours per measurement.



α spectrum



γ spectrum



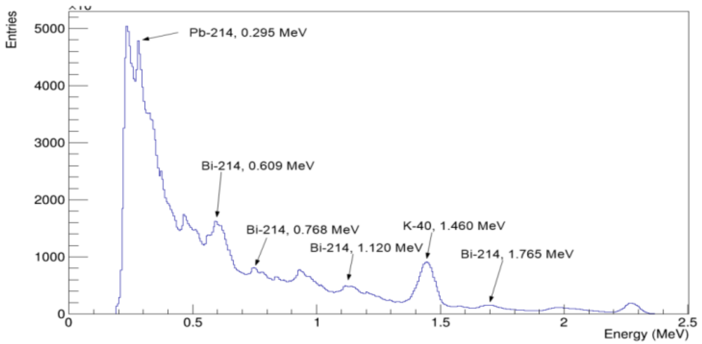
THE GOALS OF THE DETECTOR

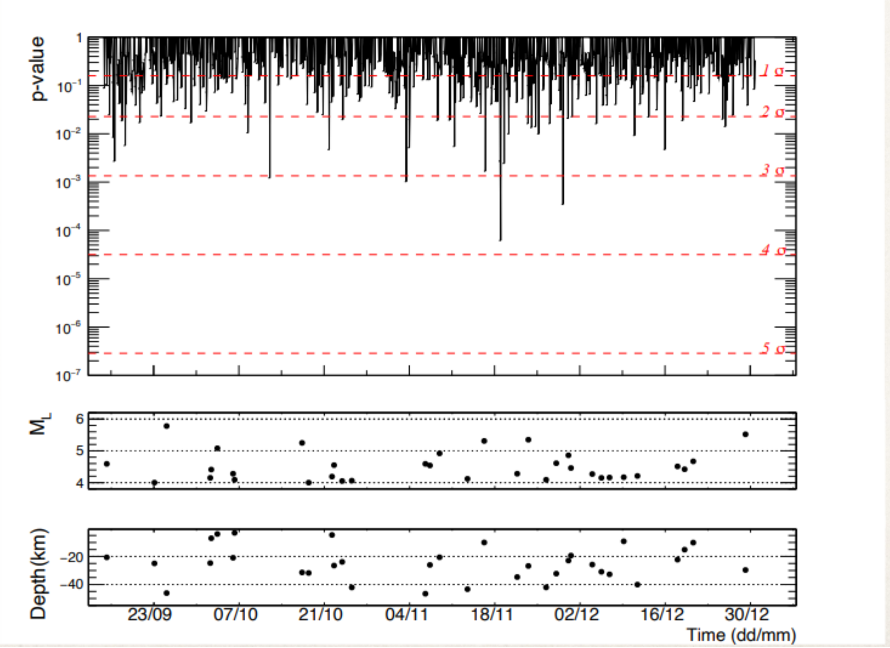
- To have a spectrometer that is sensitive to changes in radon concentration in air.
- Requirements:
  - High processing rate
  - Good energy resolution
- Three different methods:
  - Single PMT
  - Two single PMTs not in coincidence
  - Two PMTs in coincidence

New!

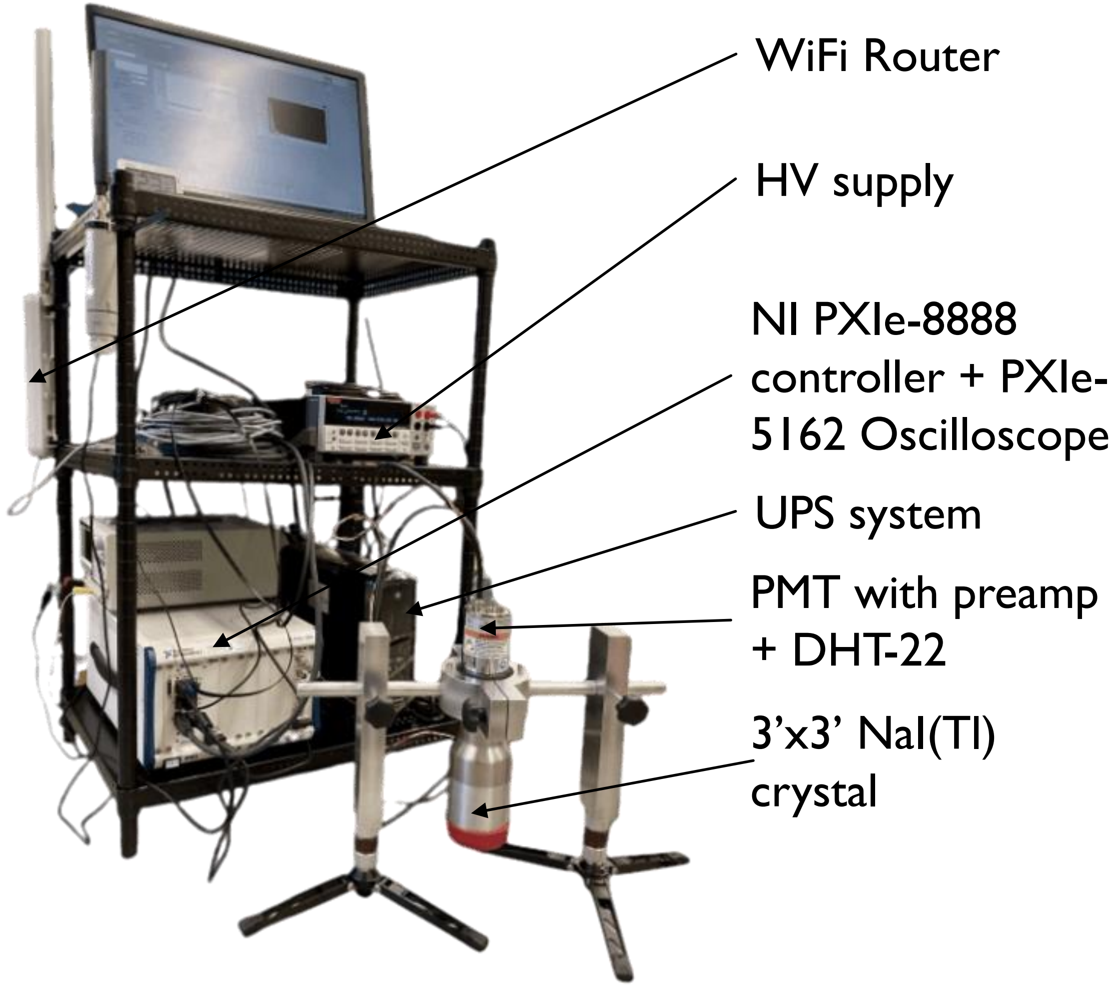
FIRST DEPLOYMENT HUALIEN DEPLOYMENT

- Deployment during the "earthquake swarm", in the summer of 2021—a perfect time to put the system to test.
- The detector managed to capture the gamma spectrum of the Ra-226 decay chain.
- With the dates when the earthquakes happened, a significant test can be done with any identified Ra anomalies to see if an earthquake happened within that period.
- Challenges:
  - Difficulty in modelling the background: no standard "template" to fit.
  - Pile-up due to preamplifier.
  - Noisy background due to the intrinsic radiation present in the crystal.
  - Calibration to correct the effects of temperature.
  - Concern with hardware: NI chassis + High Voltage Supply (costly!)

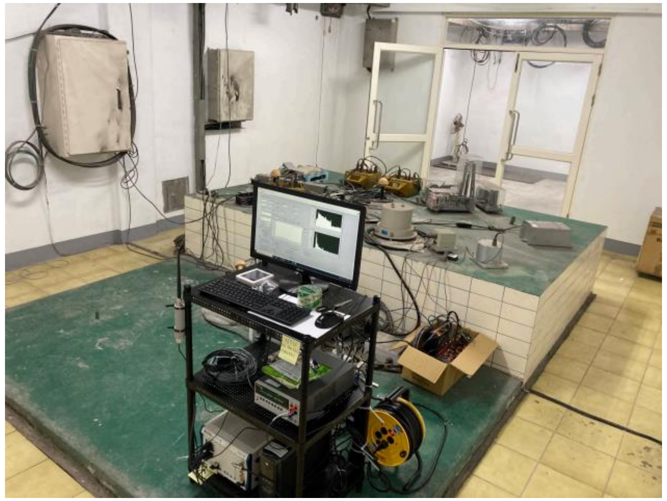




THE SYSTEM

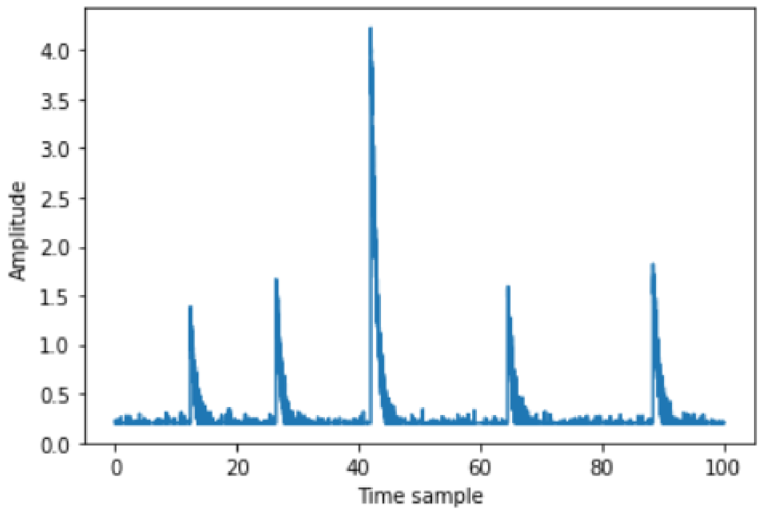


- The system was deployed in the seismic room of the Hualien weather station from April 18 to June 7, 2021.
- Additional equipment:
  - UPS system: Supplies 15 mins of electricity during a power outage.
  - WiFi Router: Provides internet access for remote access and to monitor the system.
  - DHT-22 temperature and humidity sensor: To monitor the change in temperature.



NEW READOUT DEVELOPMENT

AN OVERVIEW OF THE READOUT

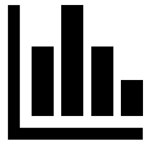


EITHER

Save all the waveform for each capture

OR

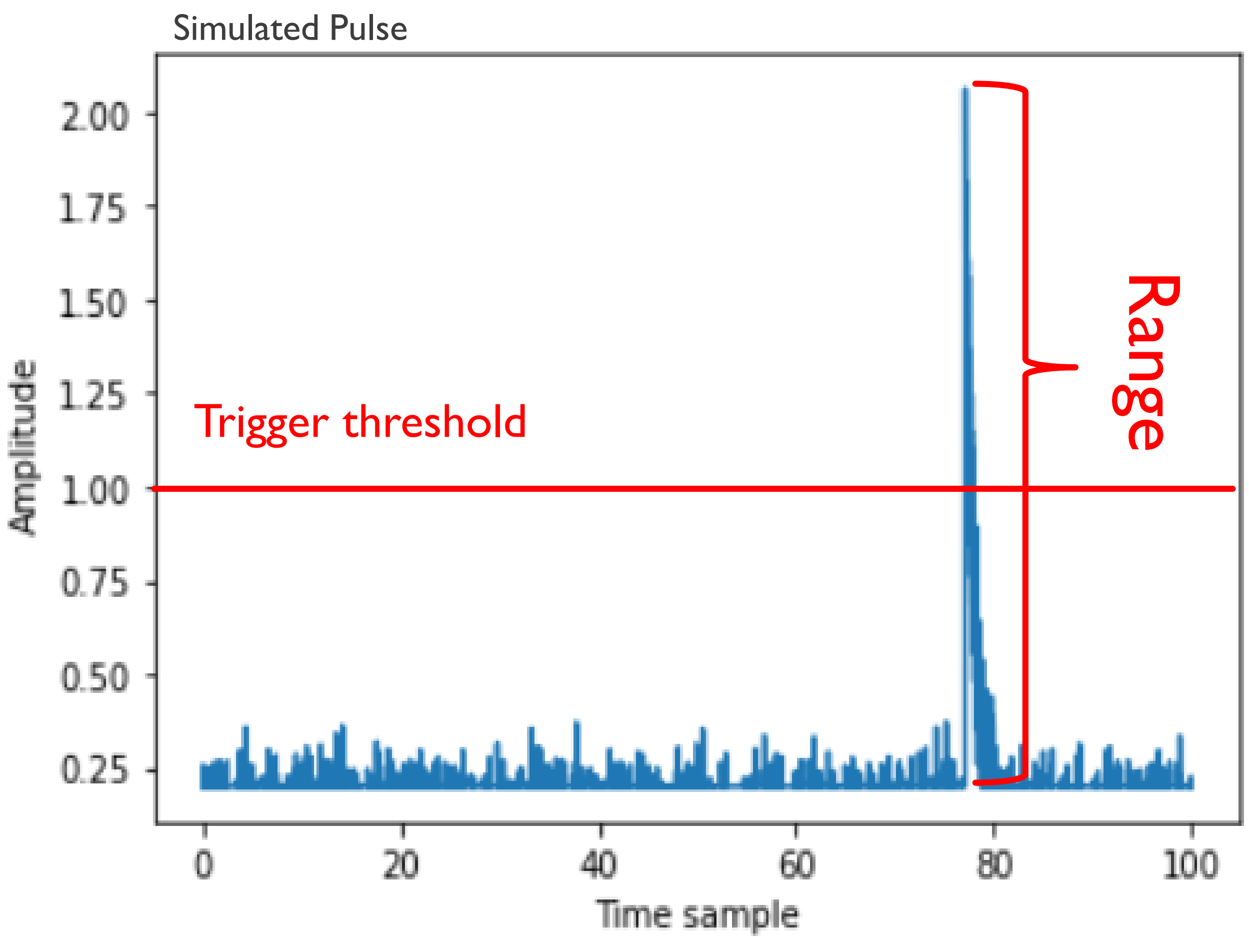
Save the characteristic features of every capture



Assumptions

1) The range of energy of interest is linear.
2) The recorded output is proportional to the energy of the incident gamma rays.

THE OLD READOUT SYSTEM

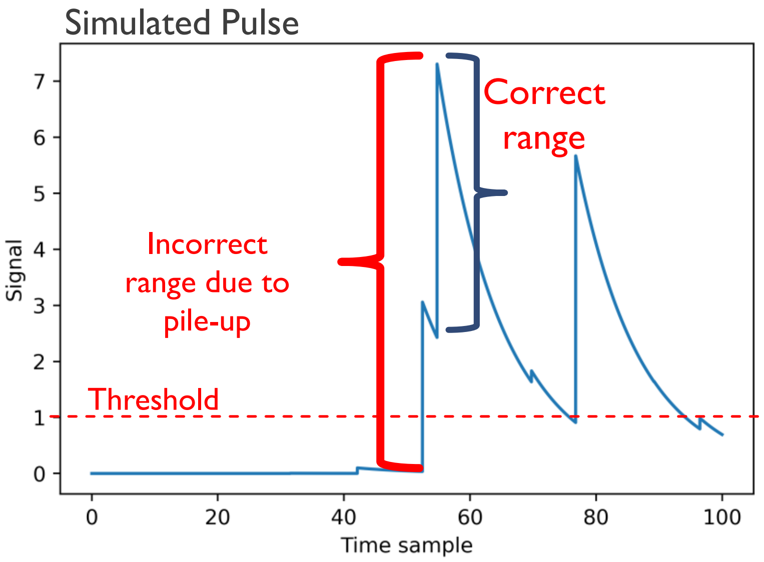


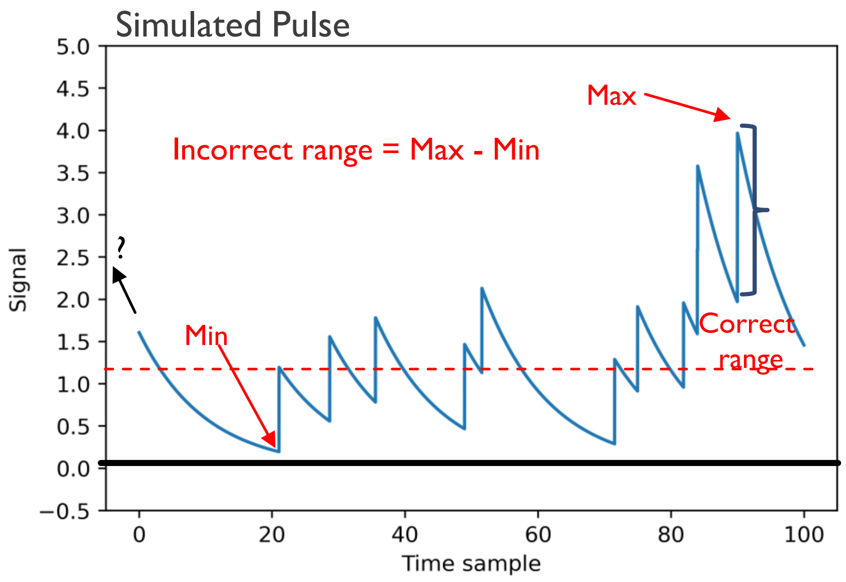
1) A capture that has samples crossed the trigger threshold is detected.
2) The maximum and minimum amplitude (e.g., voltage or ADC) in the capture is determined.
3) Range = Maximum amplitude – minimum amplitude.
4) The range is recorded and stored.

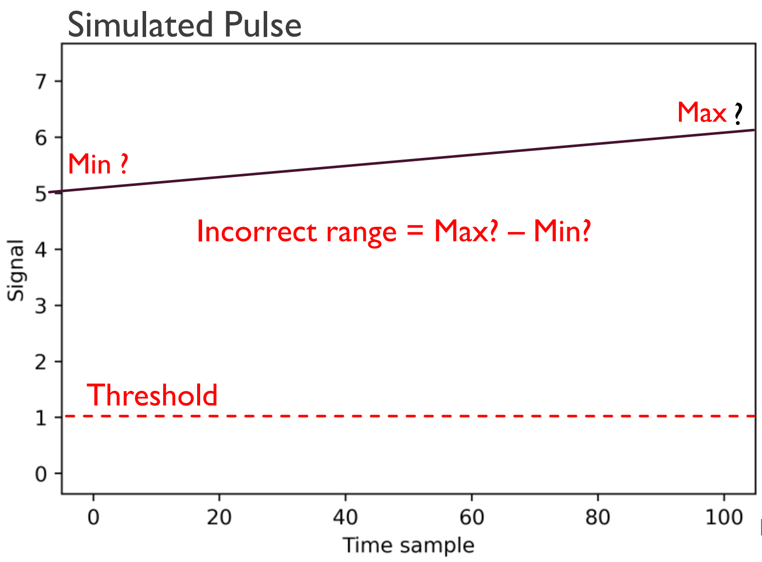
PROBLEMS OF ELECTRONICS PILE-UP (WITH PREAMP)

- Advantages of the old readout
  - Simple to compute, hence fast
  - Simple data points: the output is smaller in size

- Disadvantages of the old readout
  - Susceptible to pile-up
  - Only works with a rising edge trigger (but falling edge is not guaranteed→ incomplete determination of signal range)
  - Not an ideal system for coincidence technique (due to the reason above)

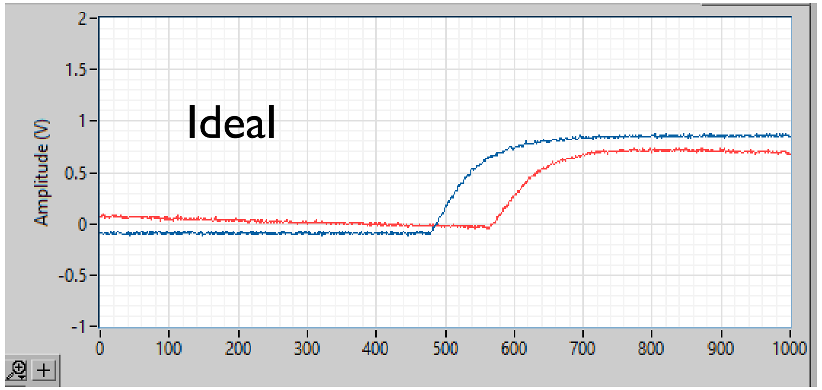


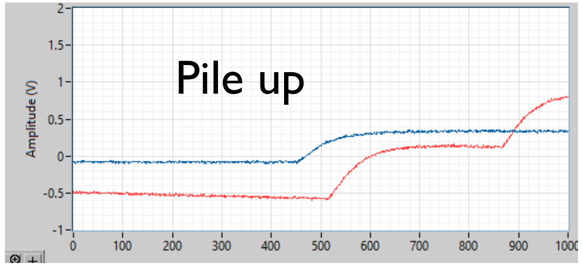


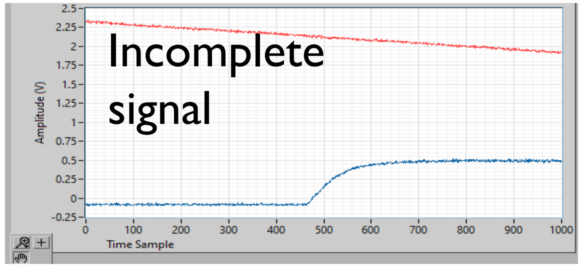


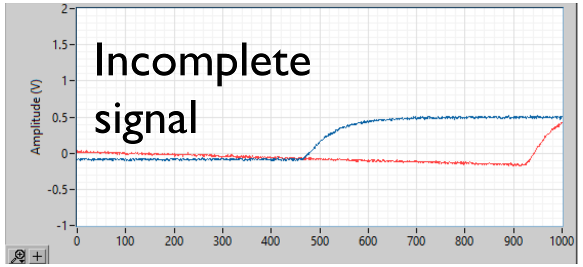
MITIGATING THE PROBLEM: REDUCING WINDOWS

- One way to mitigate the pile-up is to look at a smaller window per capture (2us, 0.0002% of one capture).
- Within the 2us window we still observed pile-up and incomplete signal from time to time.
- How can we study the effects of these “unwanted” signals on the resolution of the peaks?
    - The need for a new readout system that is affected minimally by the “unwanted” effects!
    - Compare the two systems and decide the best.



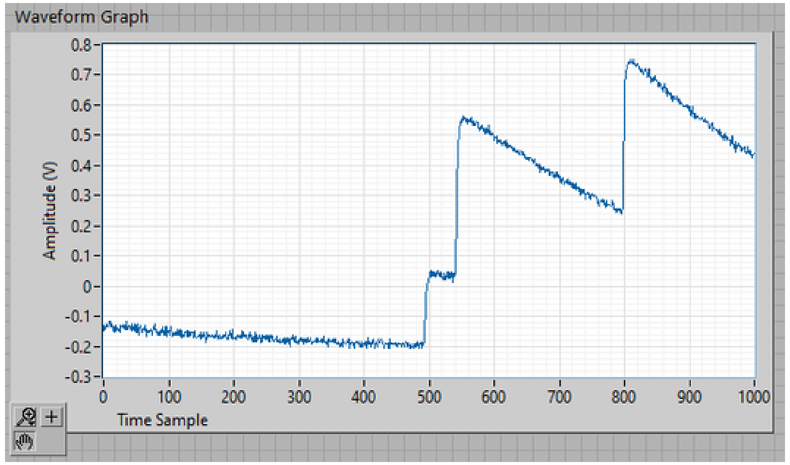






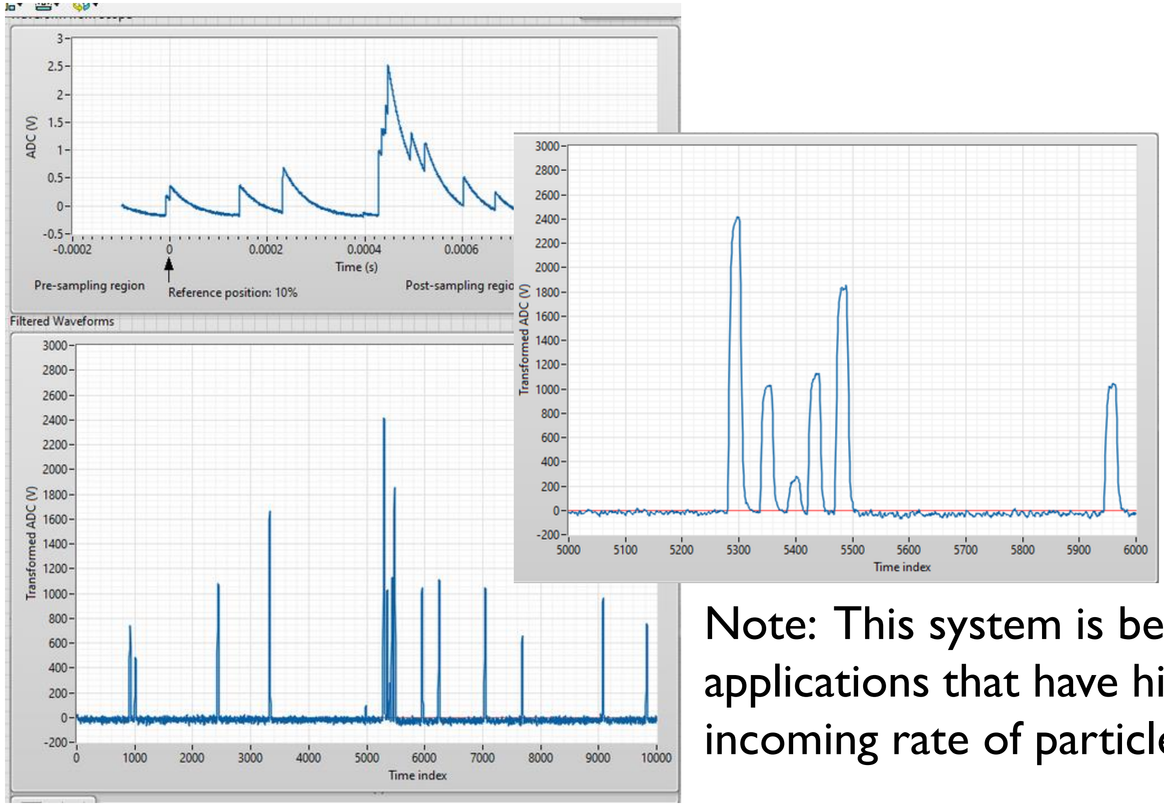
THE OLD VS NEW READOUT SYSTEM

Old Readout



Time resolution: 4ns
Per capture width: 4us

New Readout

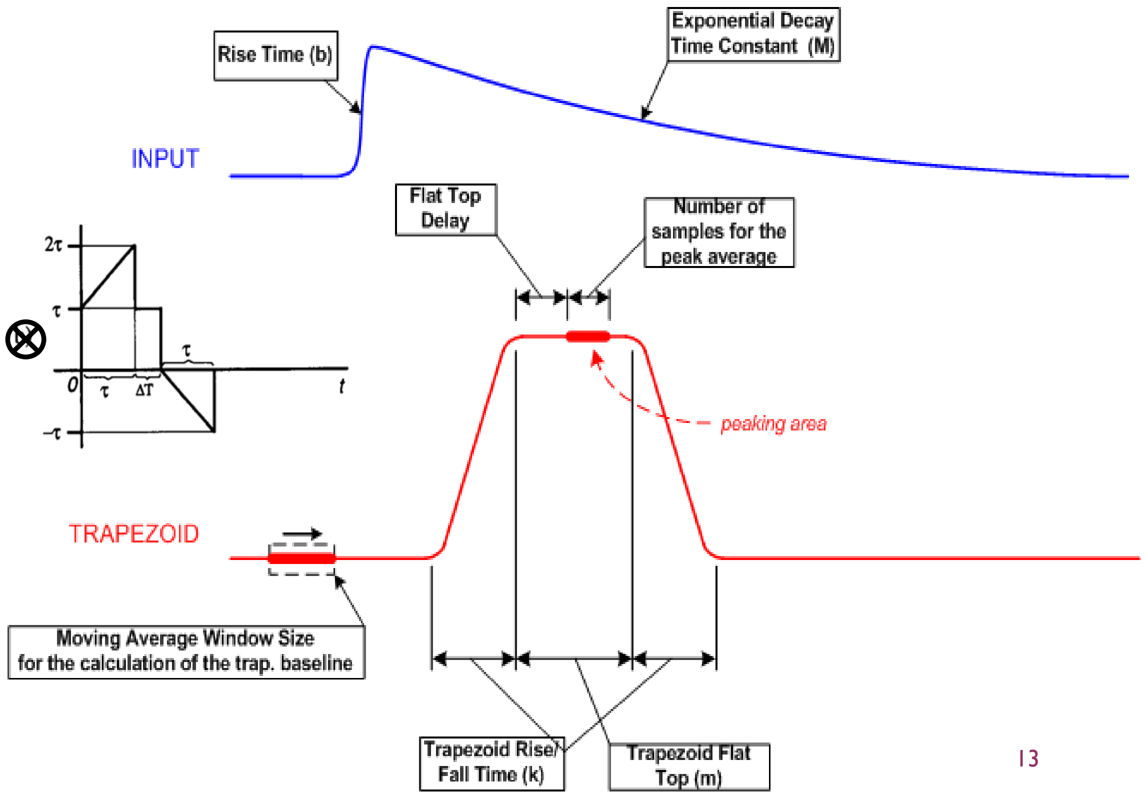


Note: This system is best for applications that have high incoming rate of particles.

Time resolution: 100ns
per capture width: 1ms

THE WORKING PRINCIPLE

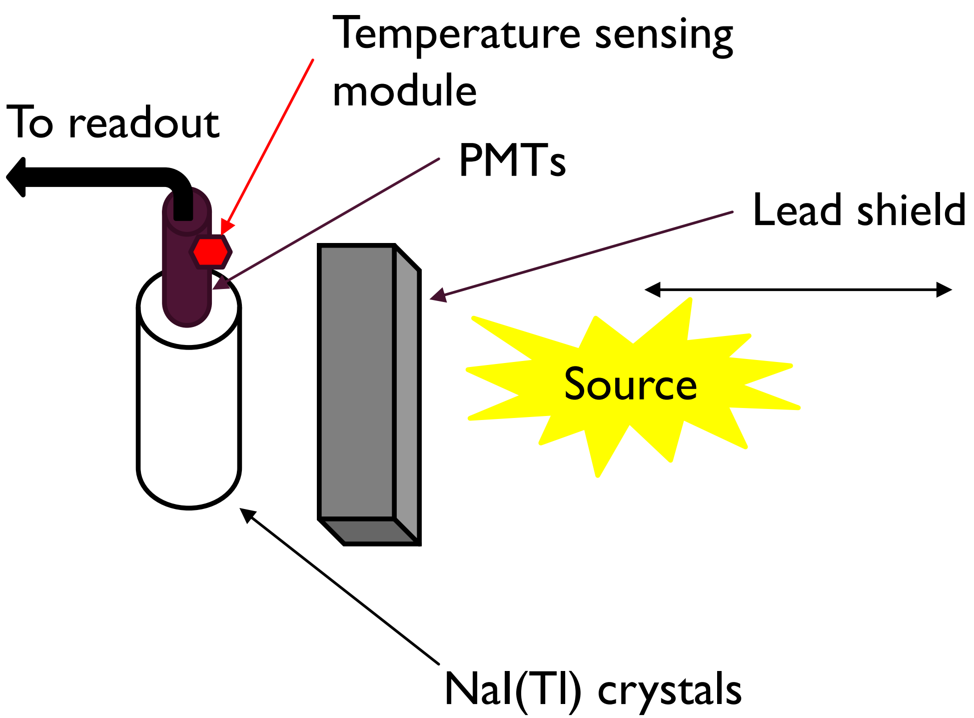
- The long-tailed exponential signal convolutes with a trapezoidal shaper impulse function to form a trapezoidal-like signal, in which the height of the trapezoid is proportional to the energy of the signal [a].
- The trapezoidal signal is guaranteed to have a baseline of zero.
- Three adjustable parameters:
  - K: trapezoidal signal rise time
  - L: trapezoidal signal hold time (flat top)
  - M: trapezoid height
- K, L, and M depend on the input signal parameter, so changing the timing resolution will change the KLM as well
  - needs to be calibrated and fixed for the whole experiment.
- At least a rising edge is guaranteed in each capture
  - The possibility of triggering on either channel.



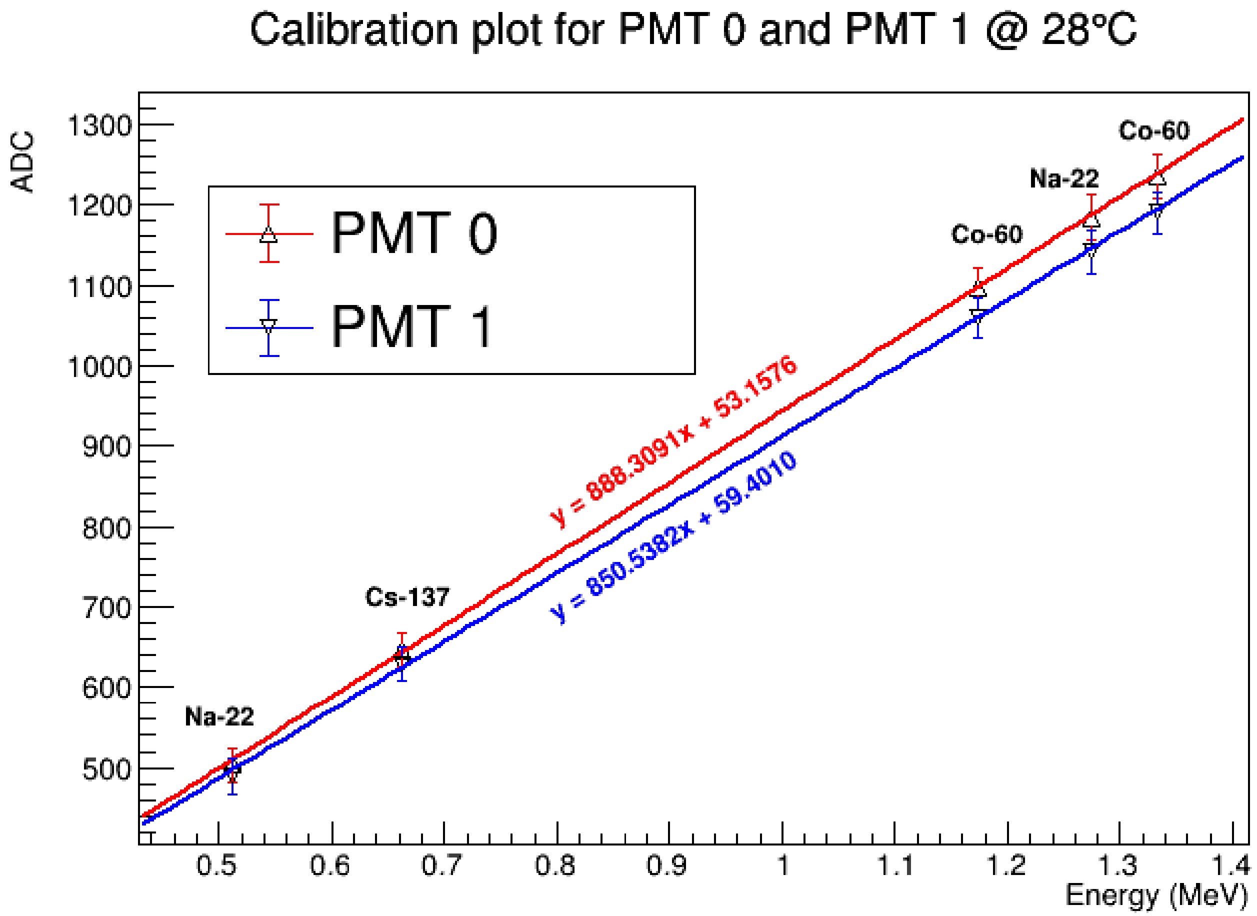
a. Appreciation to Alexander Becker (KIT) for sharing his code for the trapezoidal filter.

DETECTOR CHARACTERISATION

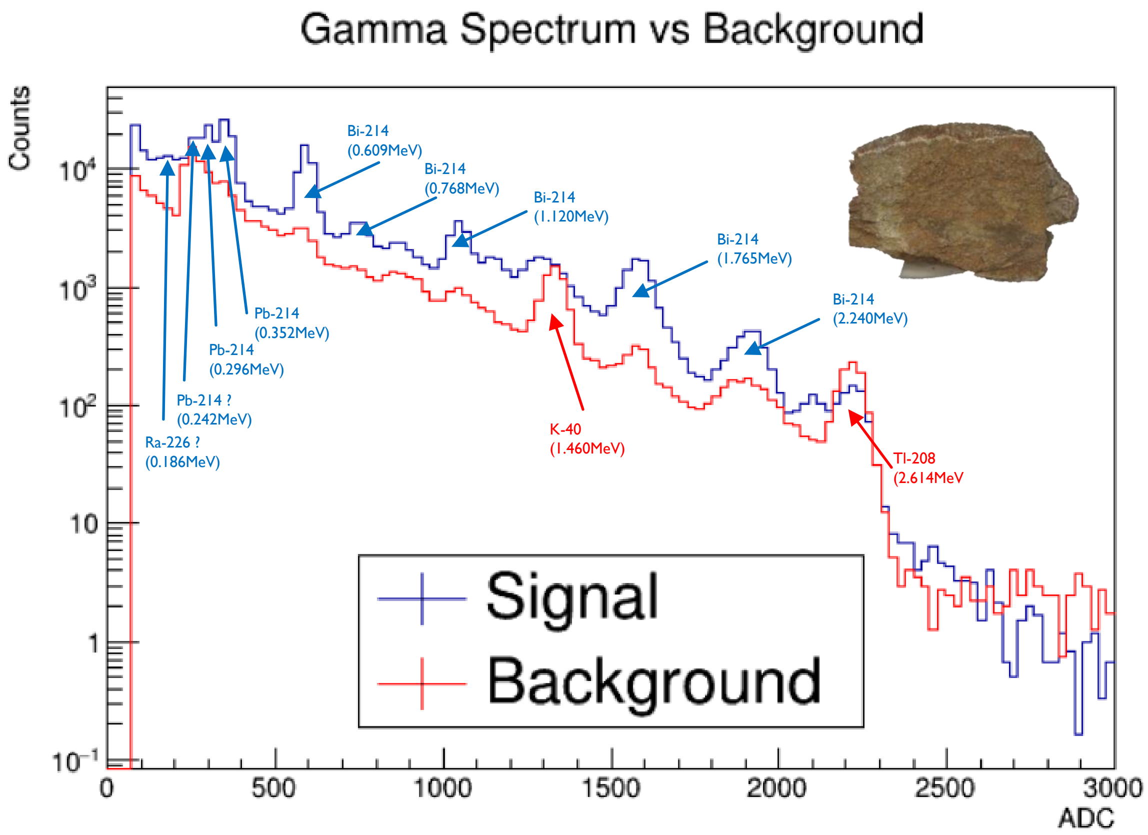
ENERGY CALIBRATION

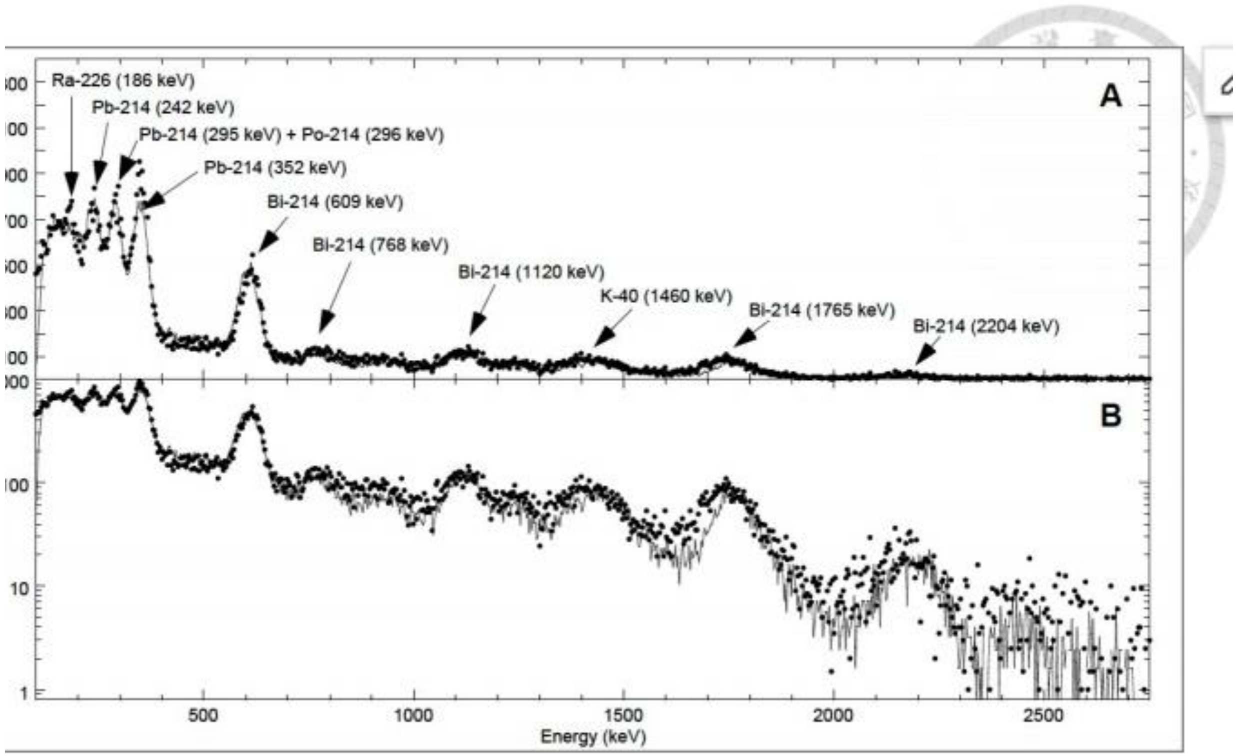


Varying the source distance/adding a lead shield to optimize the rate so the resolution will not be affected.



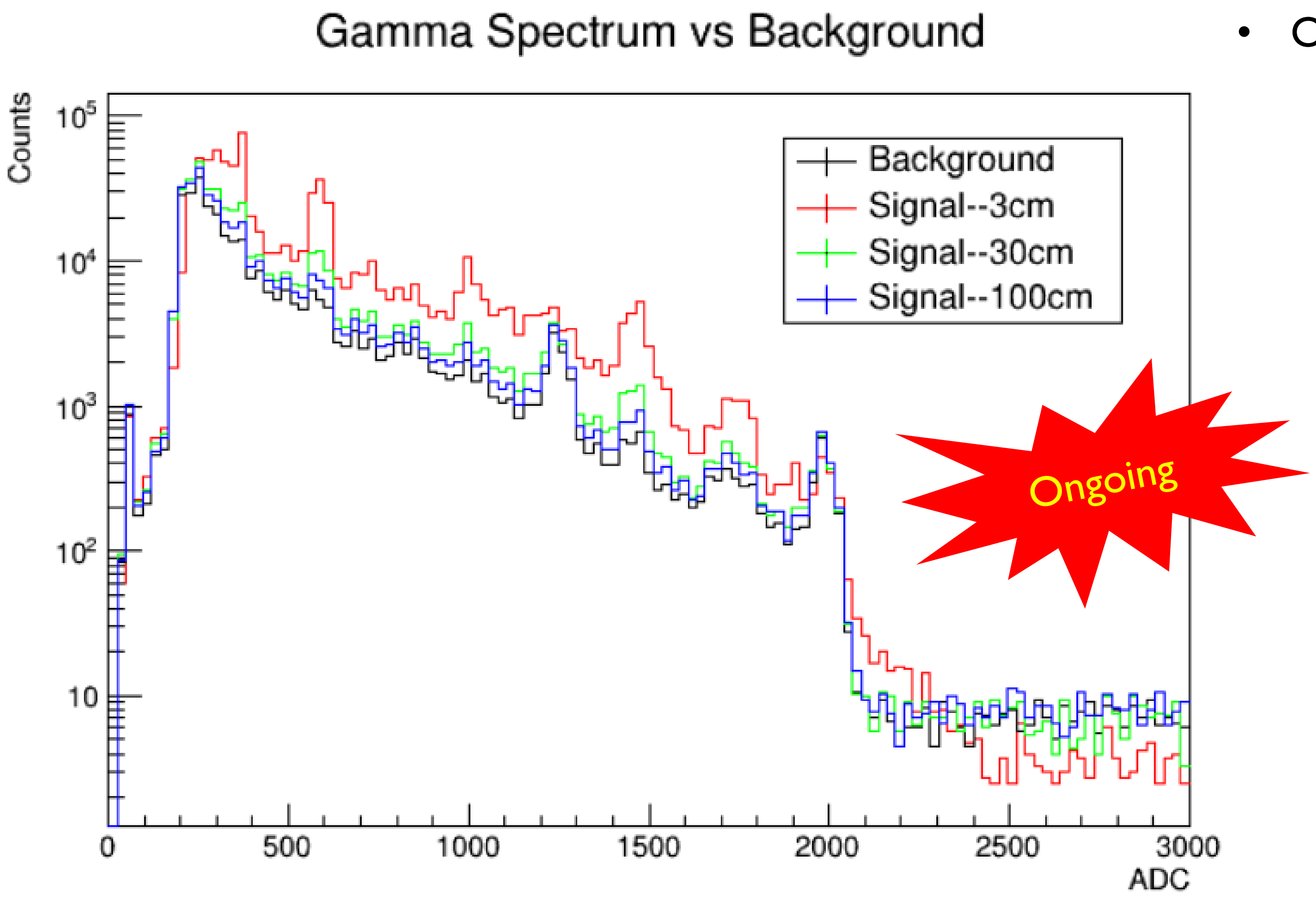
THE GAMMA SPECTRUM OF THE RN-222 DECAY CHAIN





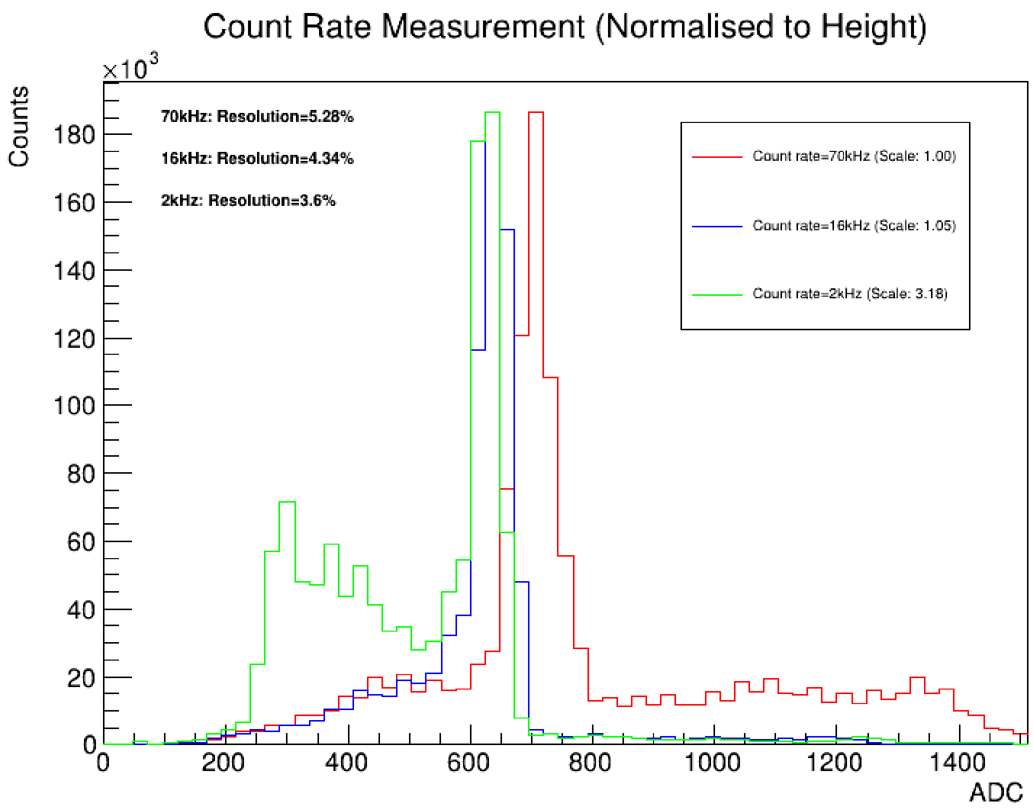
- Note: This is when source is close to the PMTs.

SENSITIVITY TO CHANGE IN RADON CONCENTRATION



- One of the proposals: the bin counting method:
  1. Run background run for a long time, and identify the "signal-bins", e.g. 609keV and its fluctuation.
  2. For every hour, count the number of signals in the dedicated bins (after correcting for temperature shift).
  3. Perform a Poisson test to check if the change in counts is significant.
  4. If anomalies are found, correlate with any significant seismic activities that happened within a certain period.

COUNT RATE MEASUREMENT USING CS-137



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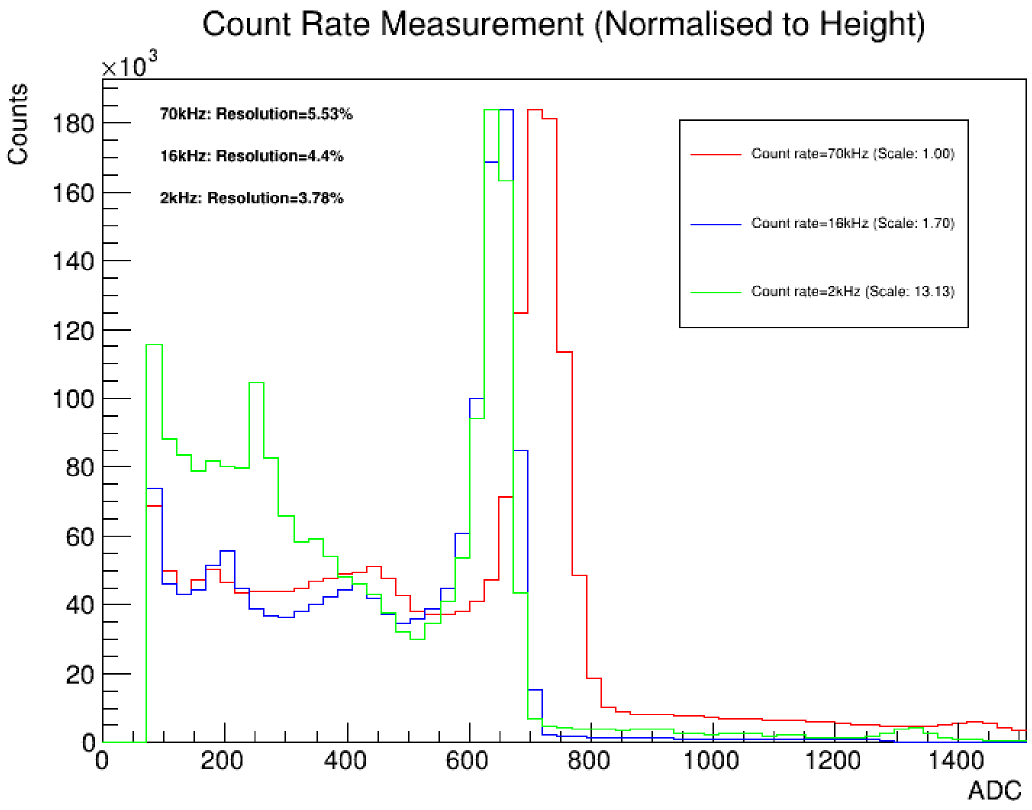
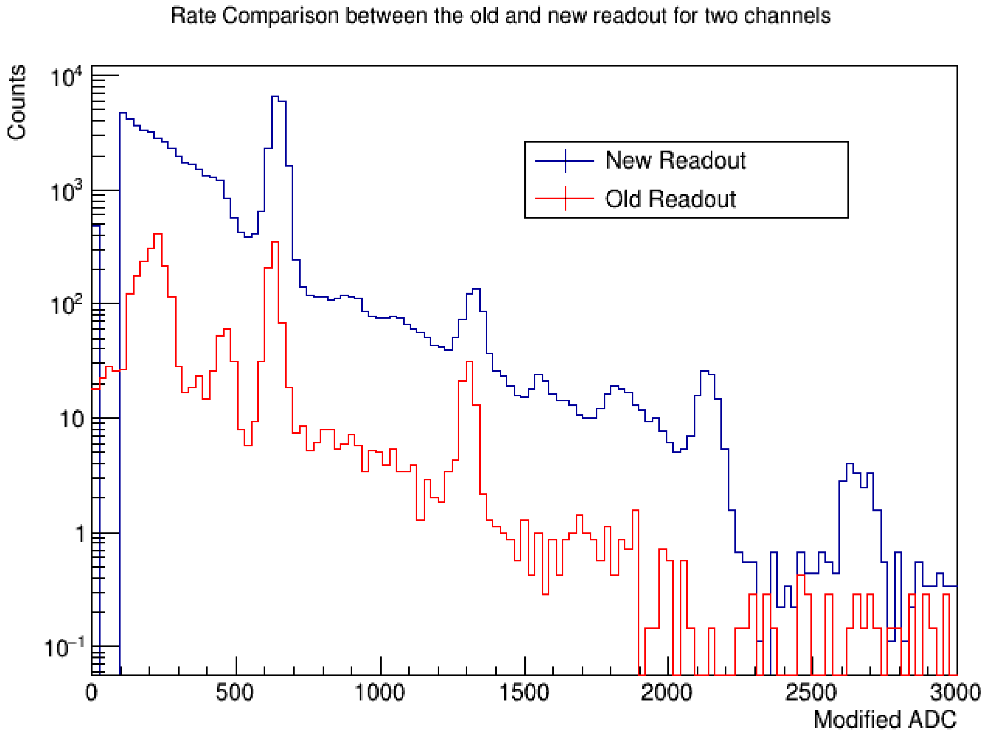
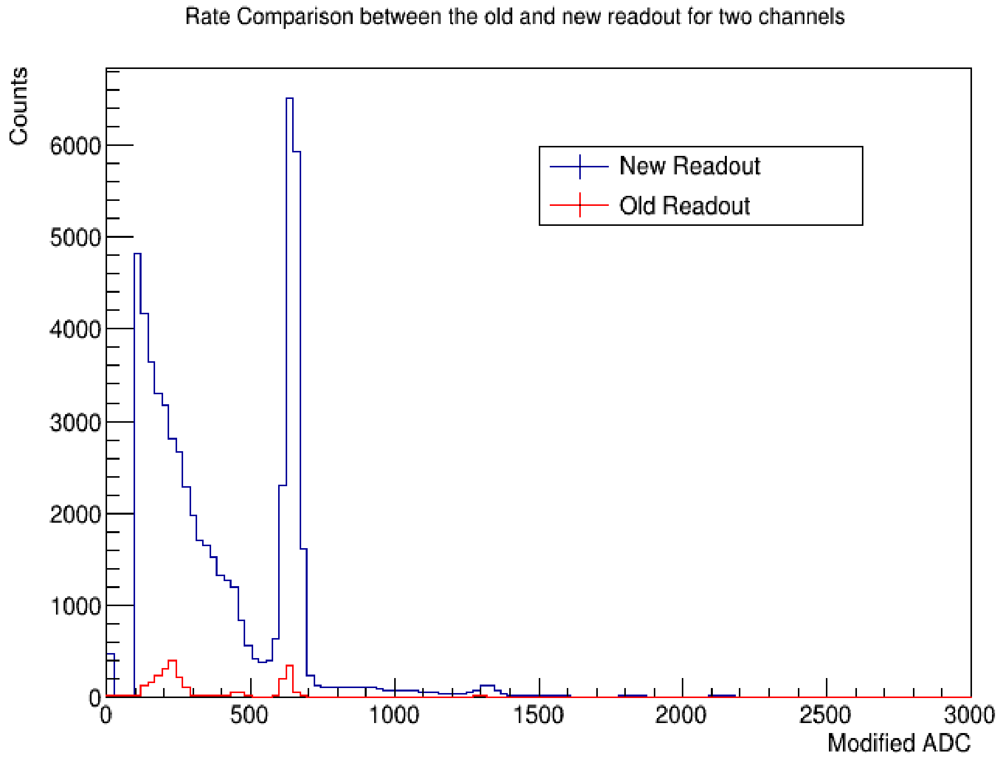


- By varying the distance between Cs-137 and the crystal, we measured that the resolution of both readout are similar, and the old readout provides slightly better resolution due to higher statistics.
- Despite the presence of undesired effects, most of the pulses are still being considered as “good” pulses.

THE NEED FOR TWO PMTS?



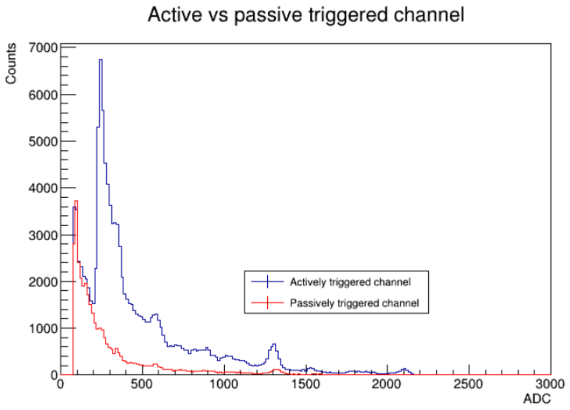


The average event recorded per second

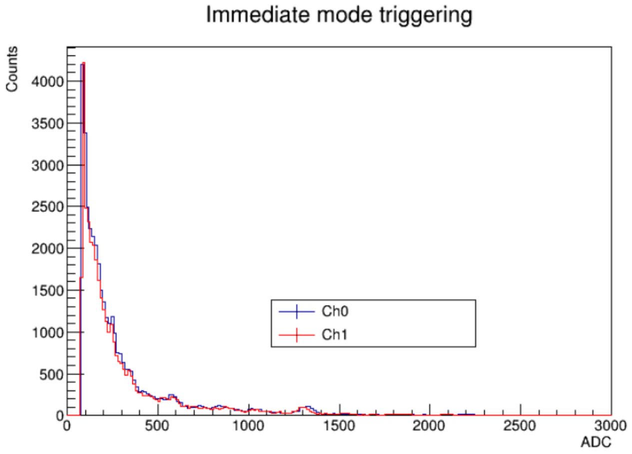
- old readout: 0.80Hz (by forcing two rising edges to be detected at the same time.)
- new readout: 17.4Hz

THE "OR" TRIGGERED OSCILLOSCOPE

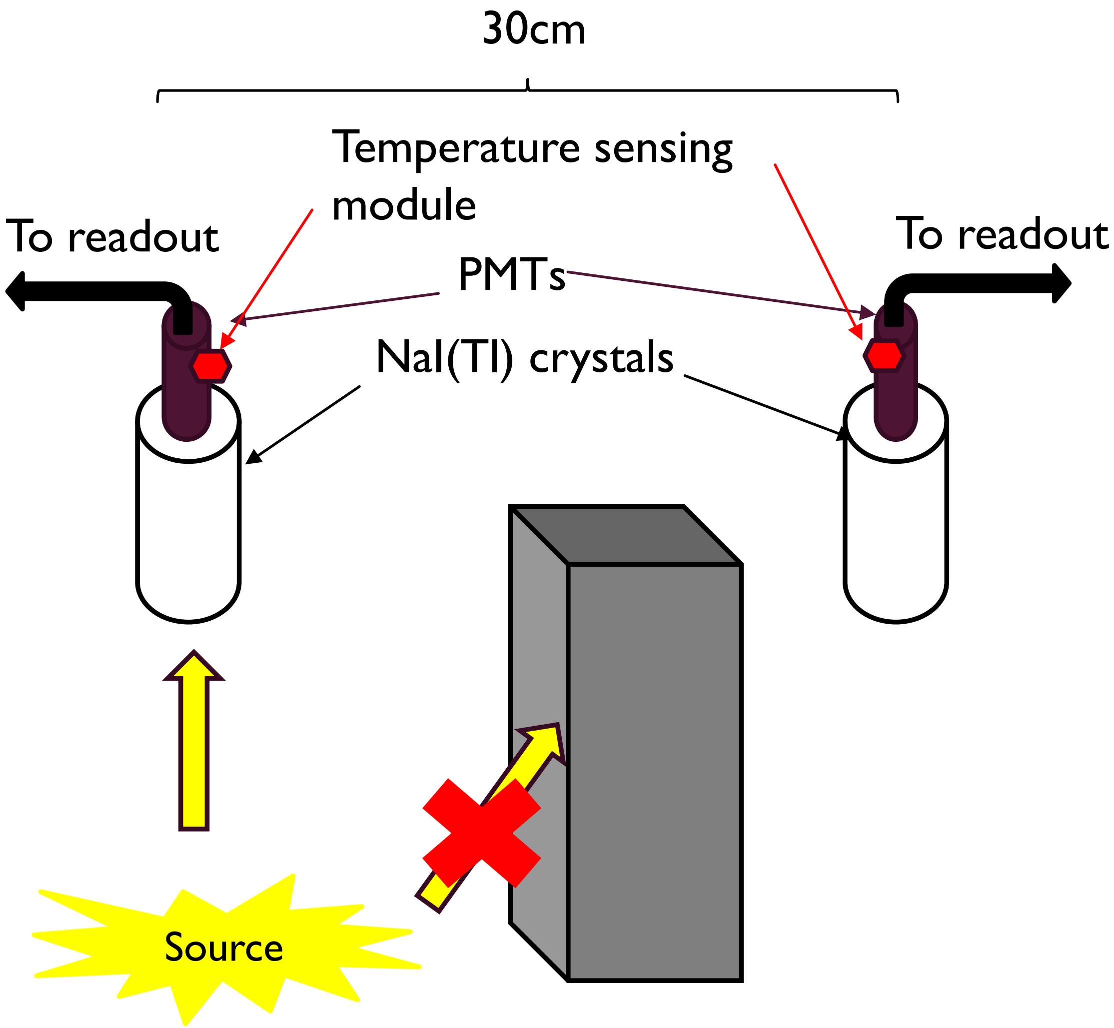
- Avoid biases in triggering, but at the cost of speed and amount of data.
- The intermediate mode has no hard trigger, but it's a feature which the system will trigger whenever it is ready to take a new capture. (A feature of NI's Niscope application.)
- This is only possible if there are multiple pulses per window, which the new readout is capable of doing.



Ongoing

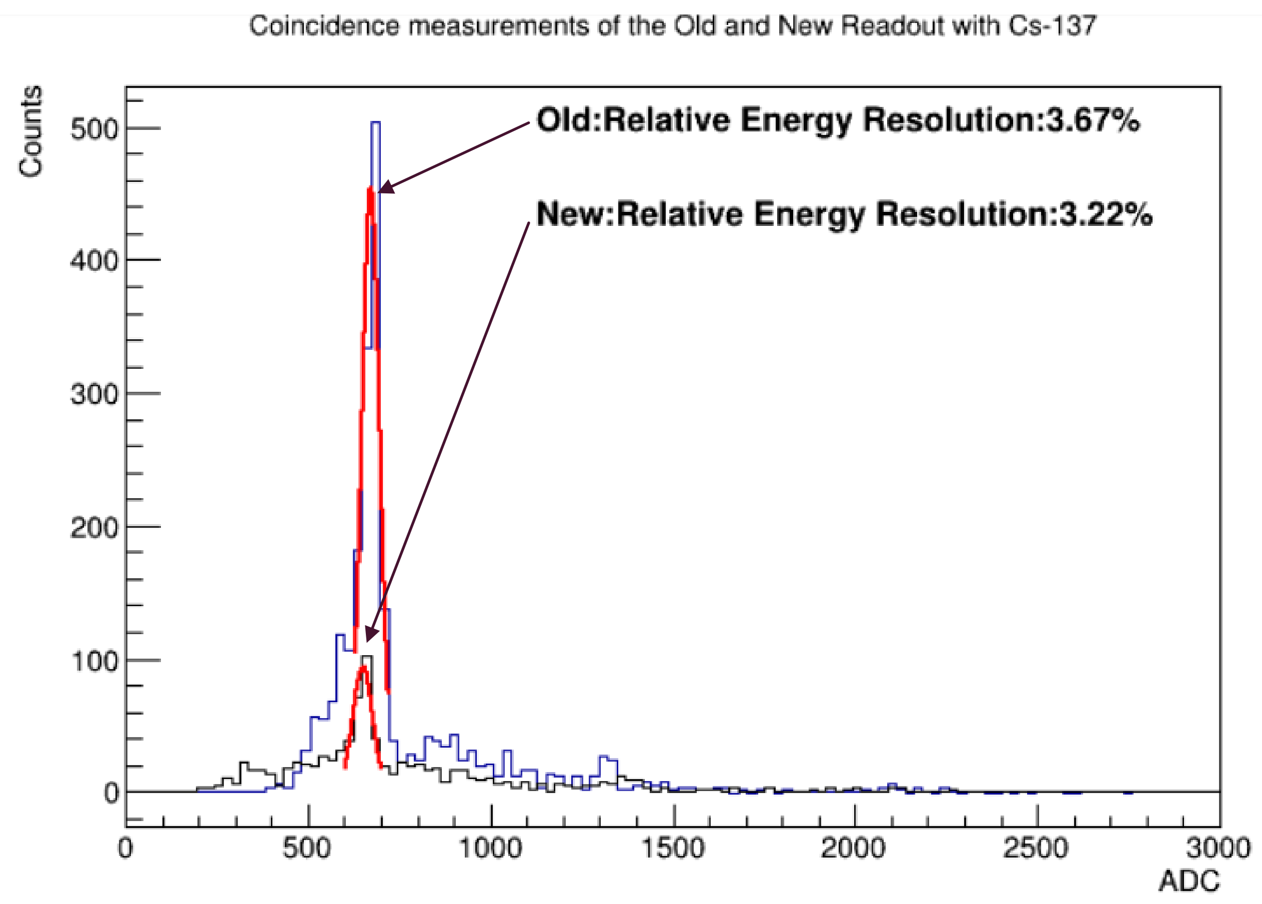


PHOTOMULTIPLIER TUBES IN COINCIDENCE



- As the gammas of interest have energy that mostly interacts with the medium through Compton scattering, we can use this method to obtain a relatively “clean” background.
- The scattered photon can be captured with two crystals running in a coincidence mode.
- The old readout has a fixed coincidence window of 2us while the new readout has a variable size of coincidence window, the smallest being 0.1us.

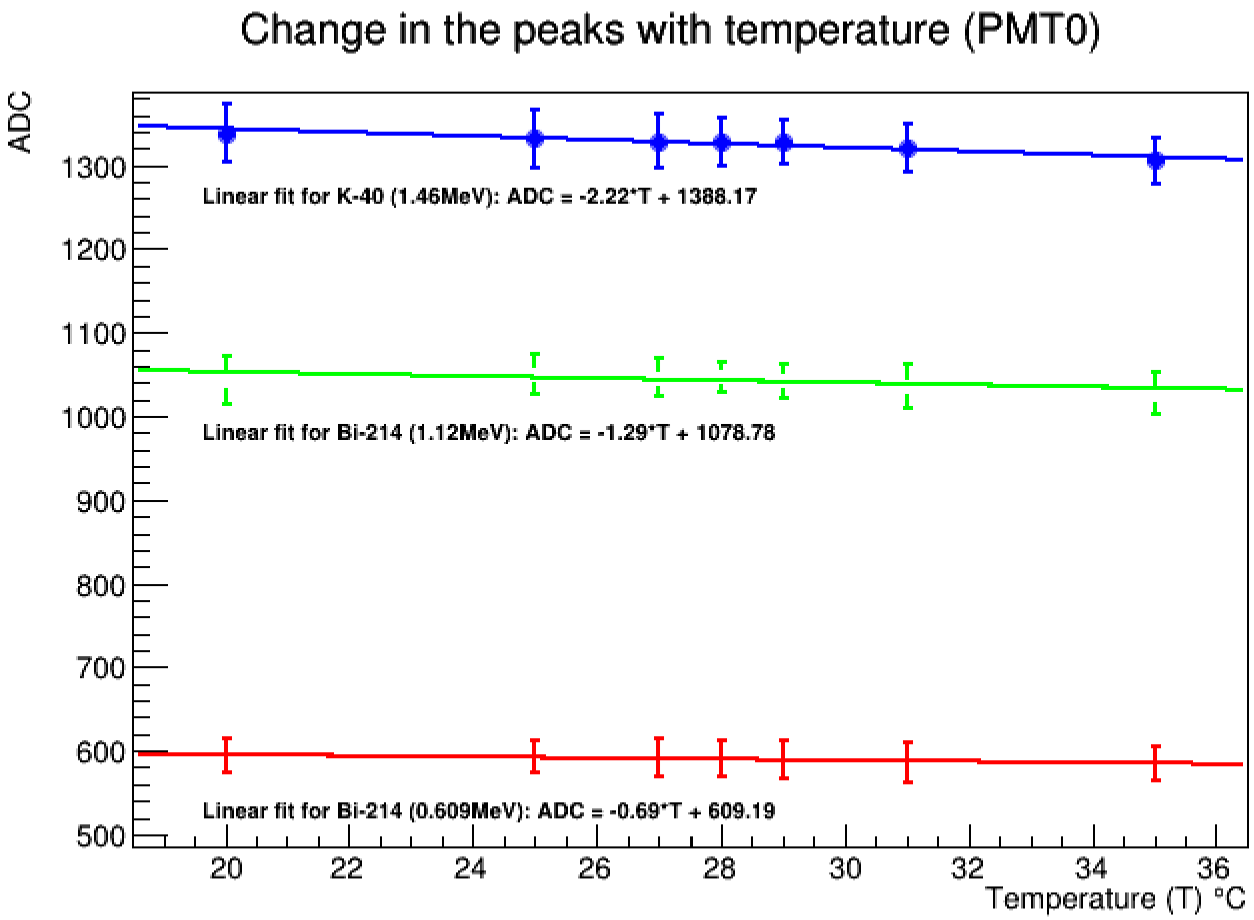
COMPARING THE COINCIDENCE RESULTS



- It is found that despite a lower data rate, the new readout has a similar resolution performance as the old readout.
- Both the readout demonstrated their ability to do coincidence measurement.

TEMPERATURE EFFECT

- The gains of different energies decreased as temperature increased. This is consistent with the literature.
- We note that the relative change of peaks with temperature is different for each energy. Hence, each peak has to be corrected individually instead of applying a global correction factor.
- The calibration can be done in situ.
- The reasons for this are unclear, and further study is needed to understand why the change in gain is different for each peak.

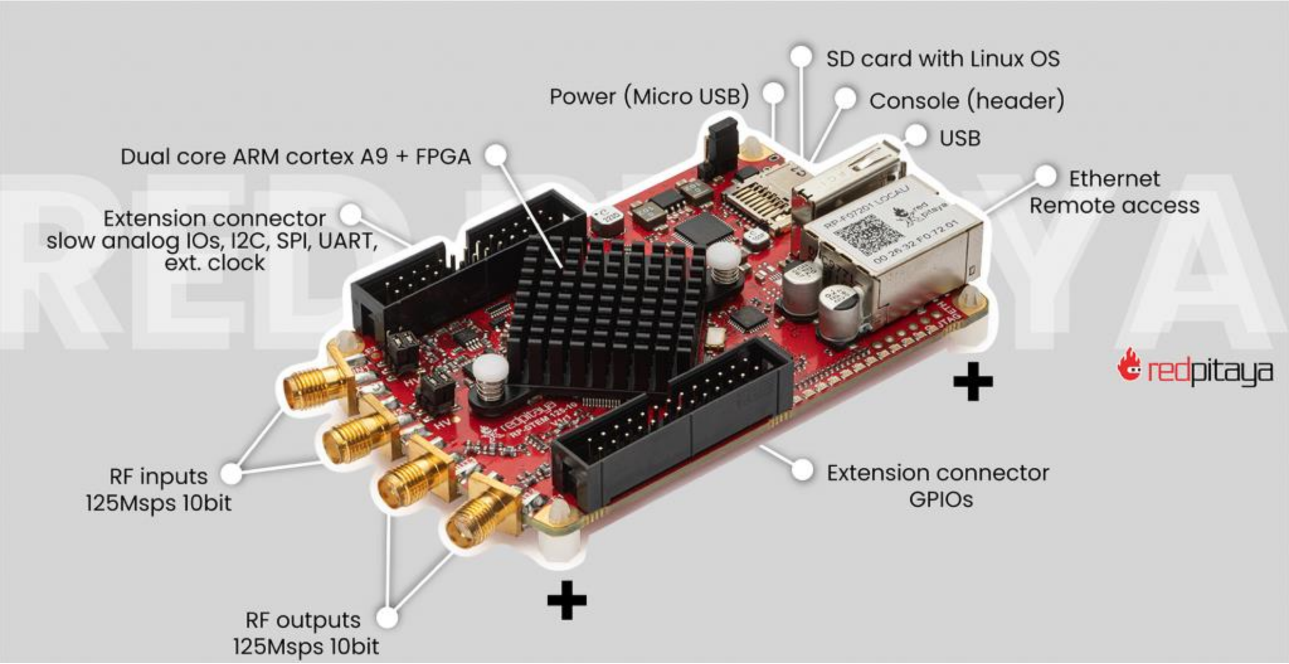


DEVELOPMENT OF NEW DAQ SYSTEM

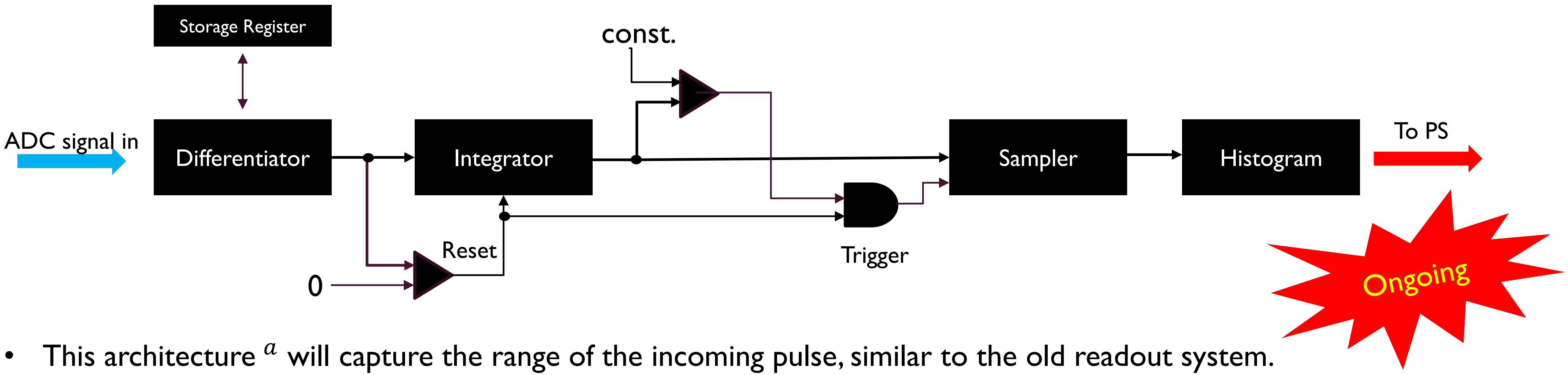
THE NEED OF A NEW DAQ STRATEGY

- Both readout systems use the NI PXIe-5162 oscilloscope which has 5Gs/s sampling speed.
- However, due to pile-ups caused by the preamp and limited by the computing speed of the PXIe-8880 controller/computer, it's difficult to utilise the oscilloscope to its full power.
- Questions to ponder:
  - Do we need such a high-speed oscilloscope?
  - How can we improve the system throughput?
  - Do we want to deploy such a costly system?
- Solutions:
  - Use a base without preamplifier
  - By using FPGA

The solution: Red Pitaya Development Board



THE FPGA ARCHITECTURE



- This architecture [a] will capture the range of the incoming pulse, similar to the old readout system.
- It detects a rising edge/falling edge that crosses a certain defined threshold.
- The future detector will be of the combination of a new PMT base without a preamp and the FGGA as the DAQ.

a. Appreciation to Alexander Becker (KIT) for proposing the architecture.

ANY QUESTIONS?

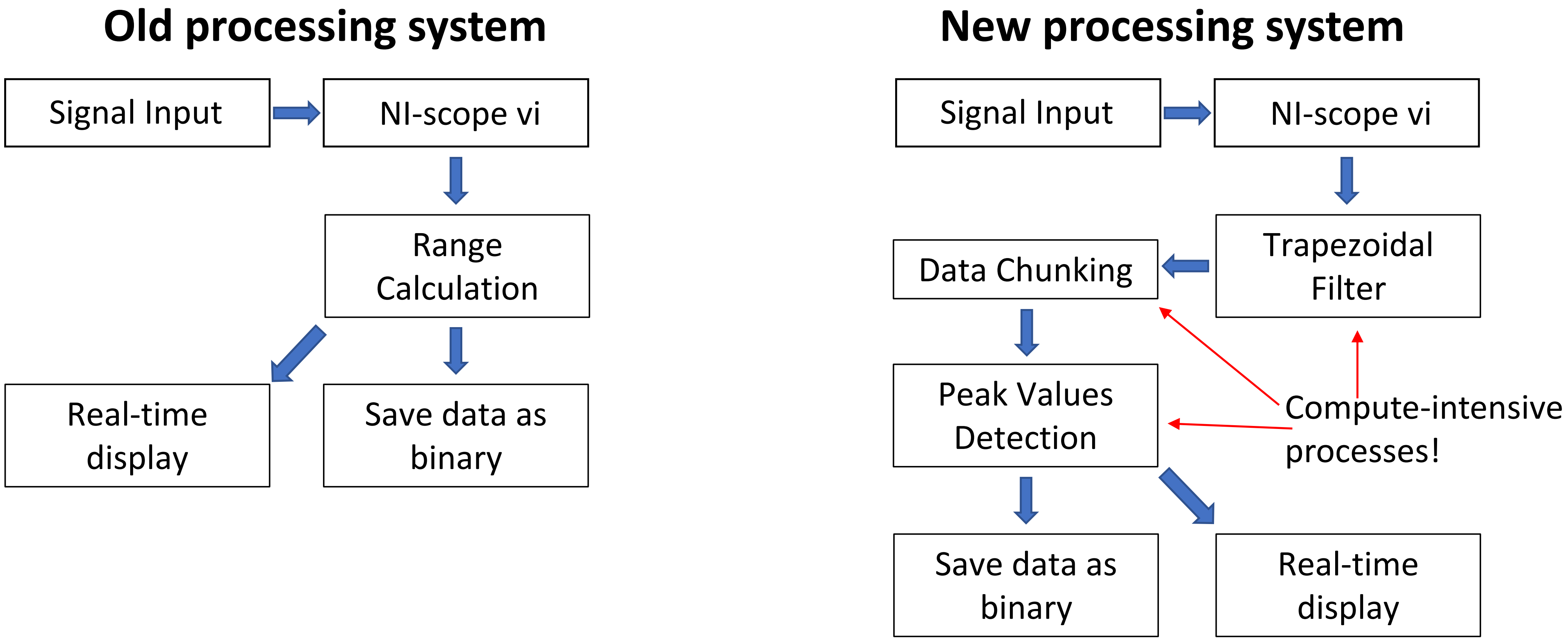
THANK YOU ☺

BACKUP SLIDES

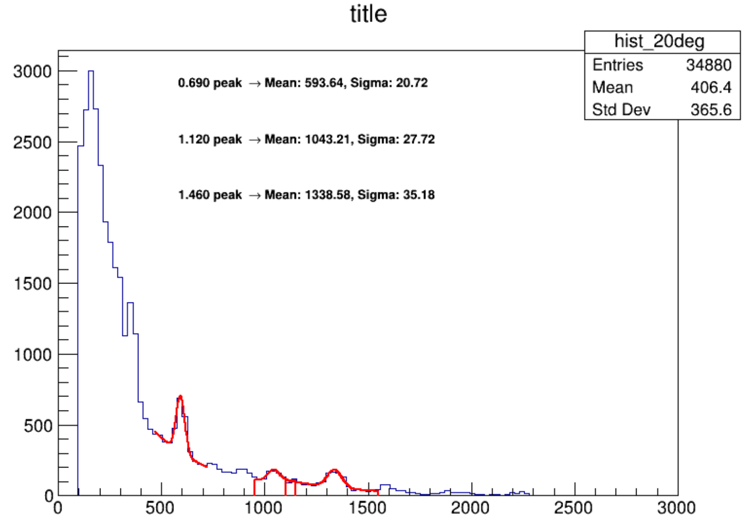
TRIGGER MODE: IMMEDIATE VS ANALOG EDGE

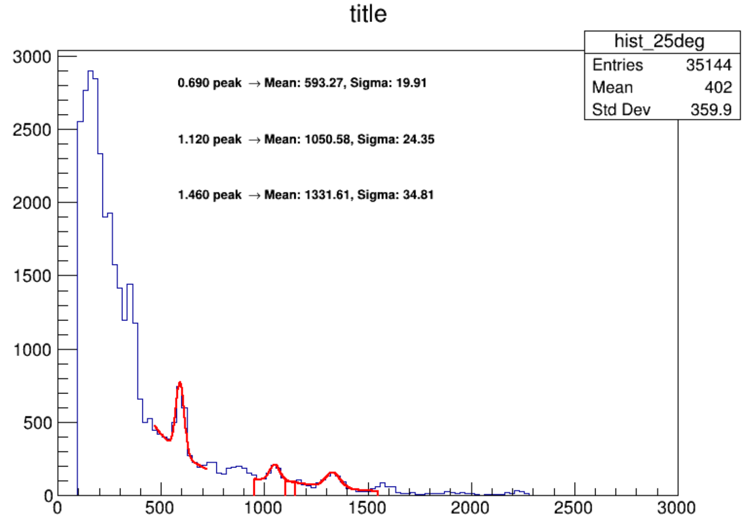
- In Analog edge mode
  - Digitiser triggers over the threshold set in the "Trigger level" input.
  - The system then captures and processes the pulses.
  - Guaranteed always seeing the first pulse at the "reference position".
- In immediate mode
  - No trigger over a certain threshold.
  - The system captures the upcoming pulses once it finished processing the pulses.
  - First pulse not guaranteed at the reference position. It can be anywhere within the window.
- Dead time: When the system is processing the pulses, i.e. calculating the ranges and will not be able to process incoming signals.

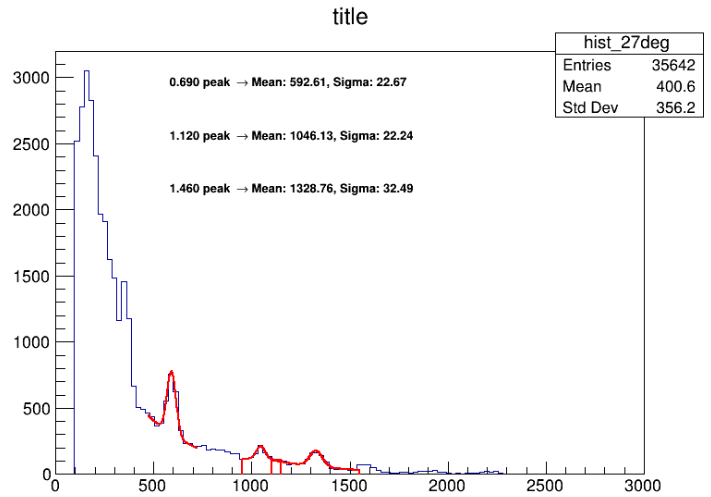
COMPARISON OF THE OLD AND NEW PROCESSING SYSTEM

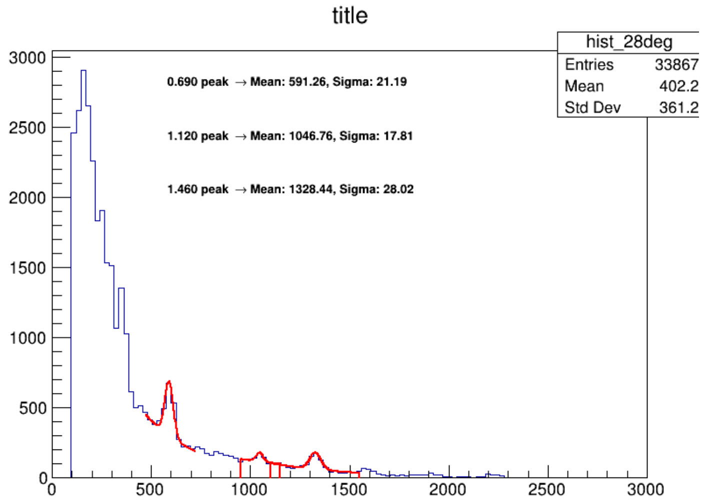


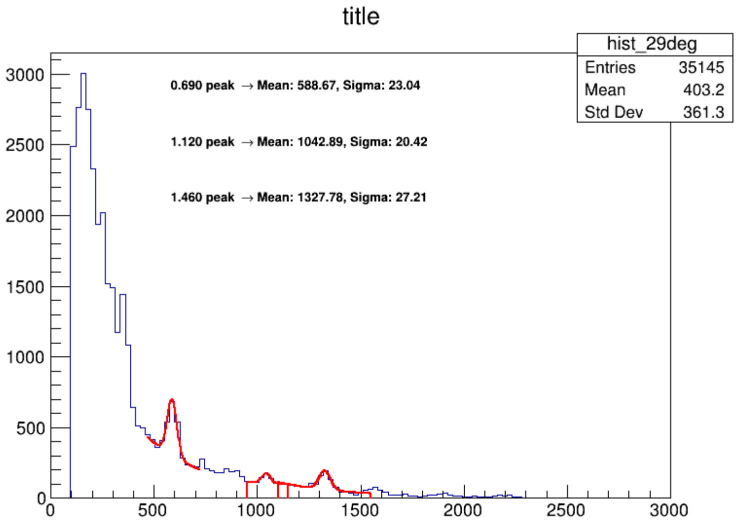
Take away: Both systems work because the energy is proportional (to some extent) to the energy deposited in the crystals. Just that the constant of proportionality is different for both systems.

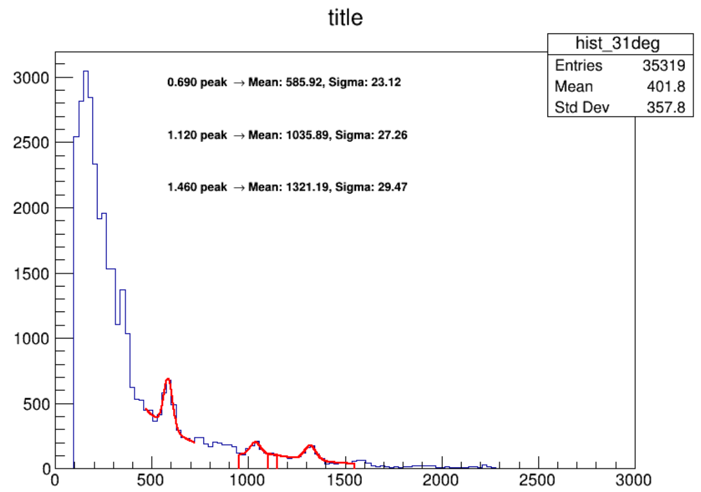

title
hist_20deg
Entries 34880
Mean 406.4
Std Dev 365.6
0.690 peak → Mean: 593.64, Sigma: 20.72
1.120 peak → Mean: 1043.21, Sigma: 27.72
1.460 peak → Mean: 1338.58, Sigma: 35.18

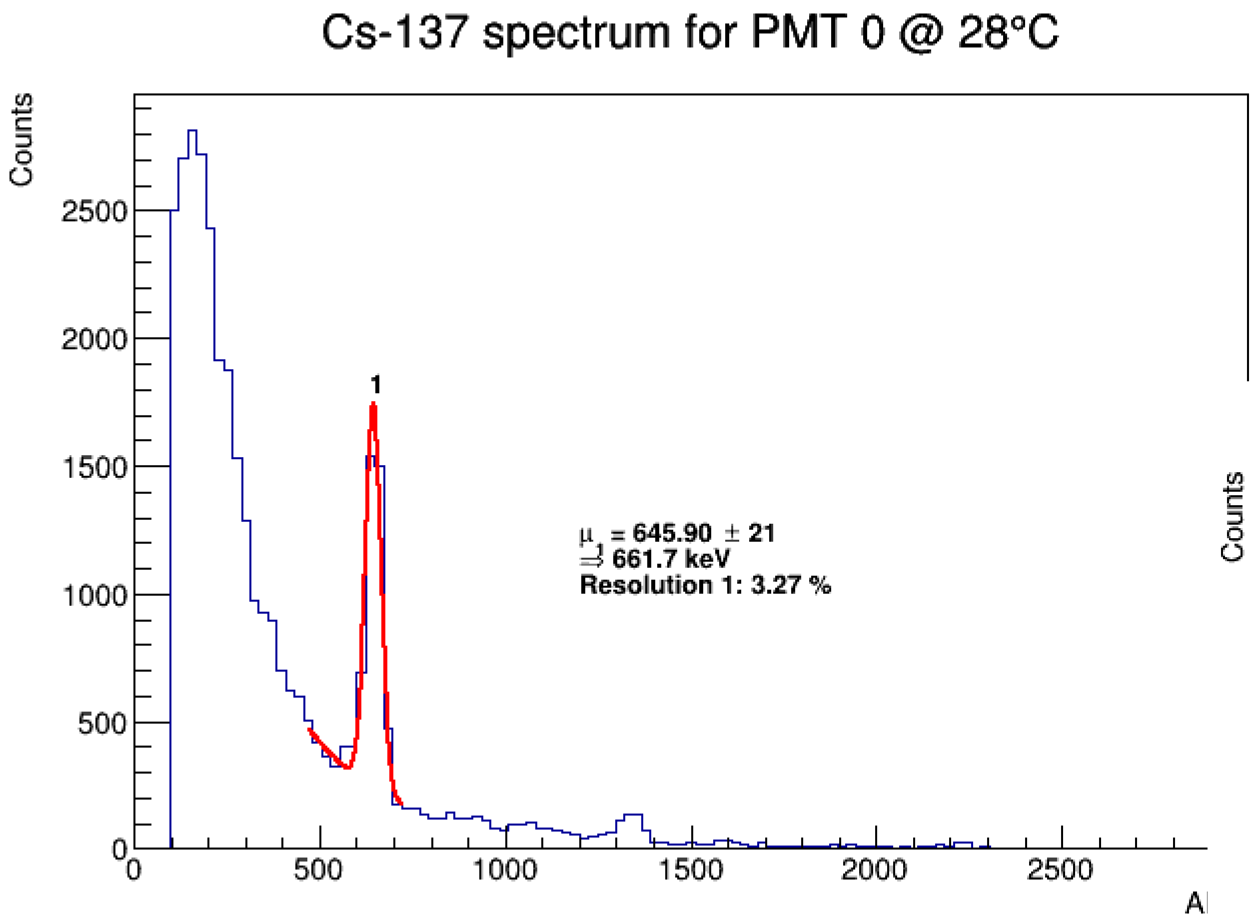

title
hist_25deg
Entries 35144
Mean 402
Std Dev 359.9
0.690 peak → Mean: 593.27, Sigma: 19.91
1.120 peak → Mean: 1050.58, Sigma: 24.35
1.460 peak → Mean: 1331.61, Sigma: 34.81

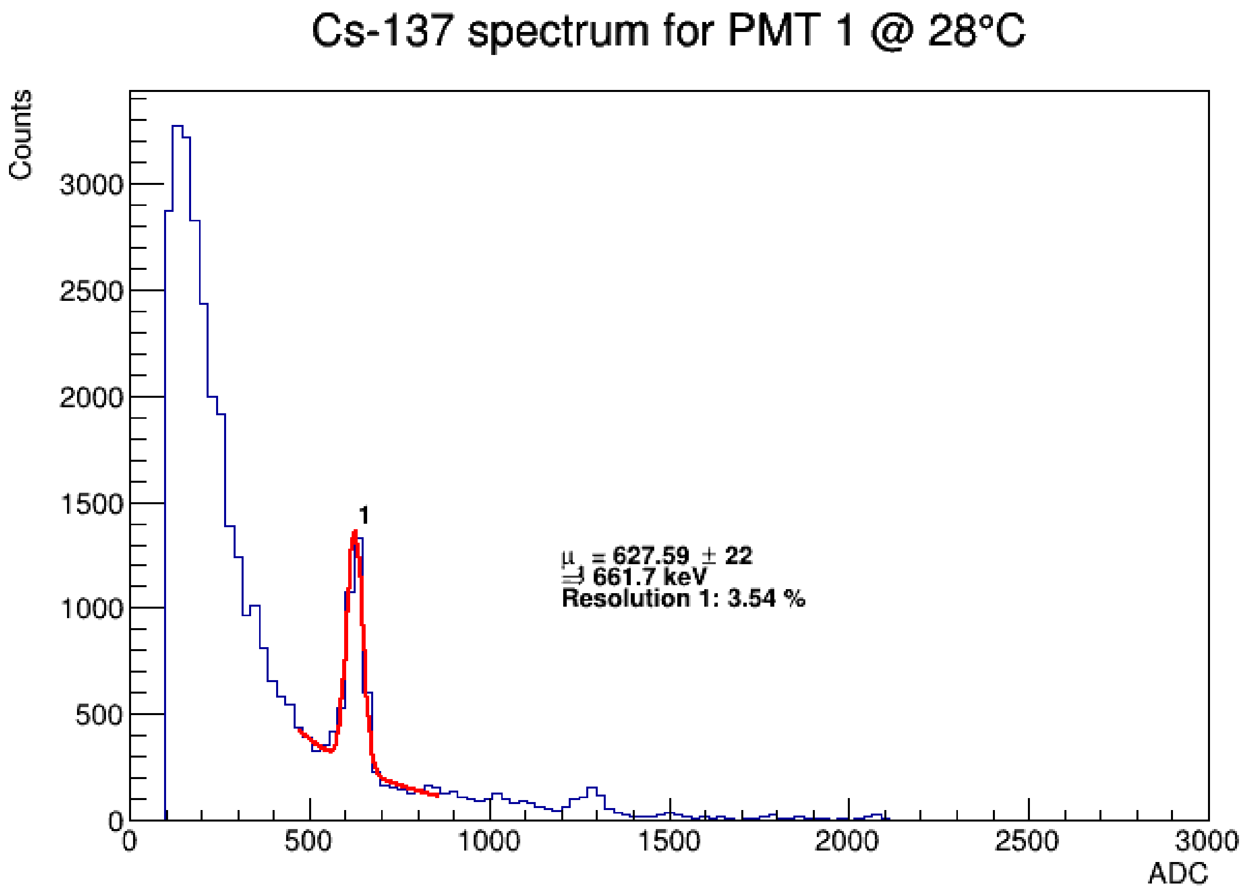

title
hist_27deg
Entries 35642
Mean 400.6
Std Dev 356.2
0.690 peak → Mean: 592.61, Sigma: 22.67
1.120 peak → Mean: 1046.13, Sigma: 22.24
1.460 peak → Mean: 1328.76, Sigma: 32.49


title
hist_28deg
Entries 33867
Mean 402.2
Std Dev 361.2
0.690 peak → Mean: 591.26, Sigma: 21.19
1.120 peak → Mean: 1046.76, Sigma: 17.81
1.460 peak → Mean: 1328.44, Sigma: 28.02

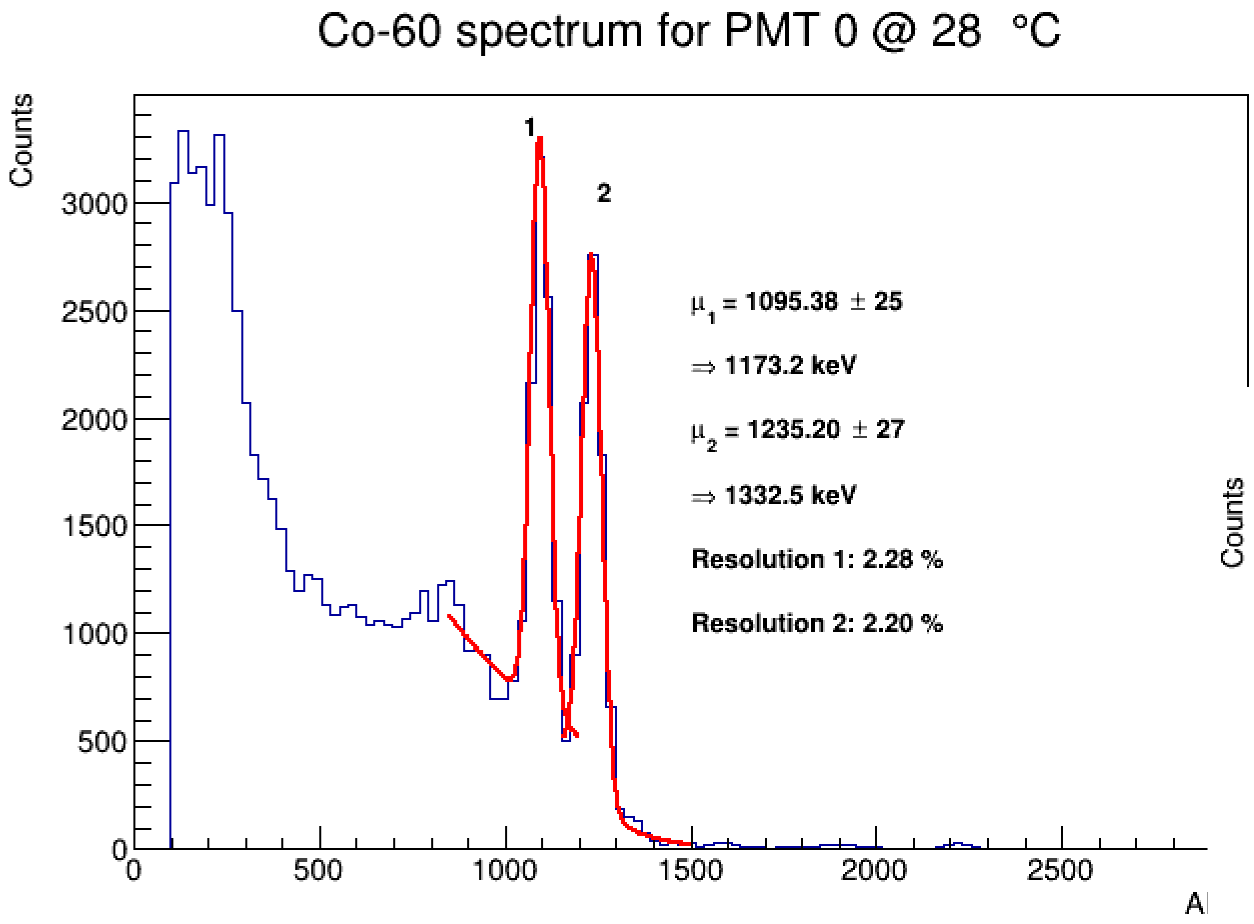

title
hist_29deg
Entries 35145
Mean 403.2
Std Dev 361.3
0.690 peak → Mean: 588.67, Sigma: 23.04
1.120 peak → Mean: 1042.89, Sigma: 20.42
1.460 peak → Mean: 1327.78, Sigma: 27.21

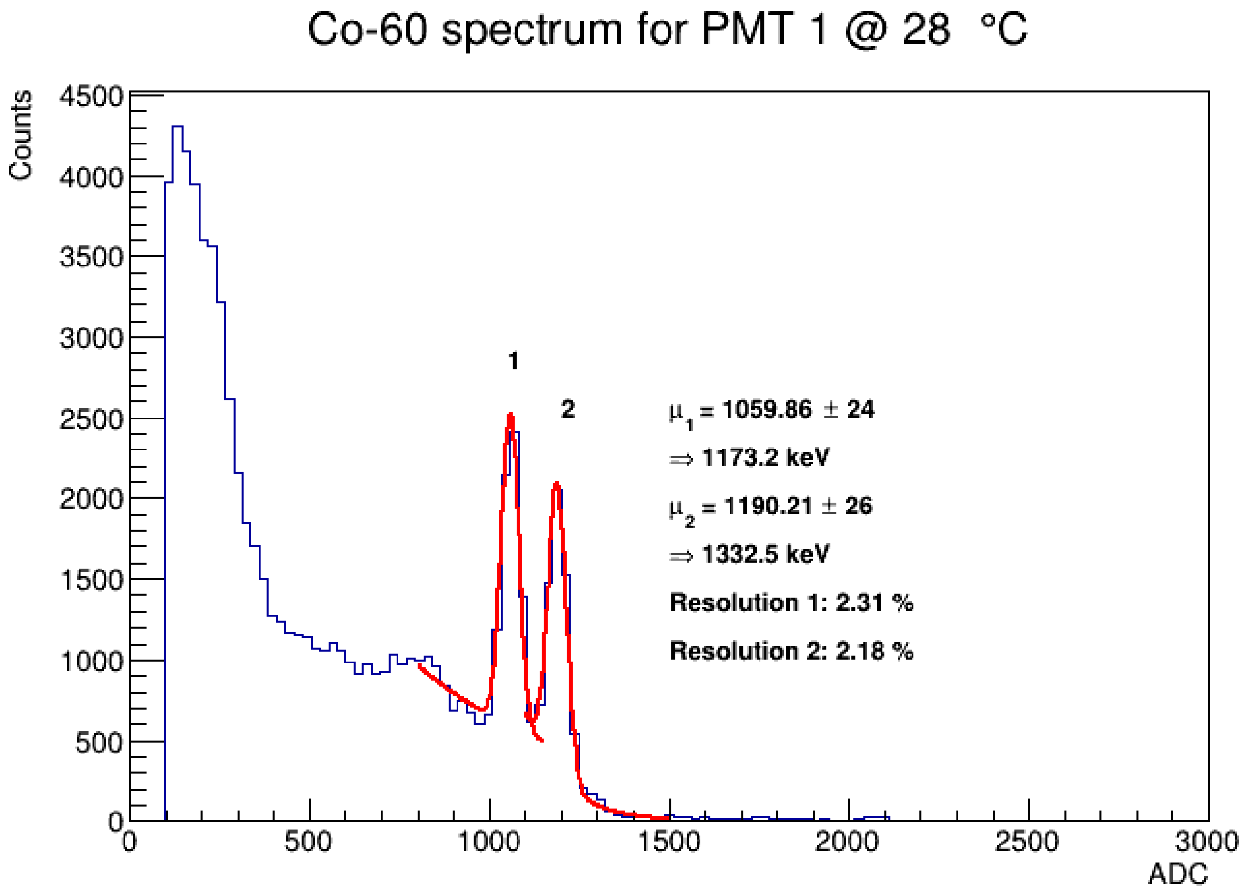

title
hist_31deg
Entries 35319
Mean 401.8
Std Dev 357.8
0.690 peak → Mean: 585.92, Sigma: 23.12
1.120 peak → Mean: 1035.89, Sigma: 27.26
1.460 peak → Mean: 1321.19, Sigma: 29.47

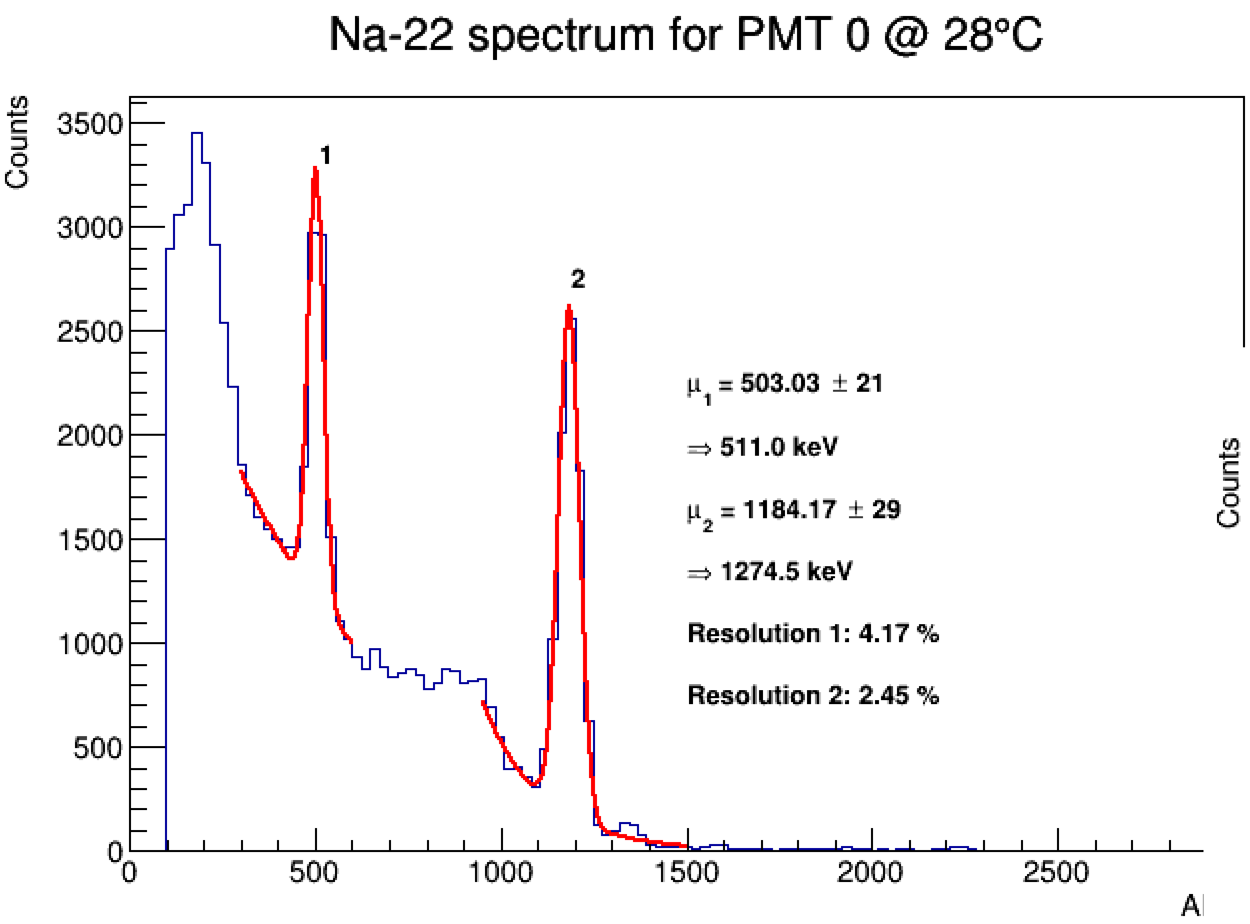


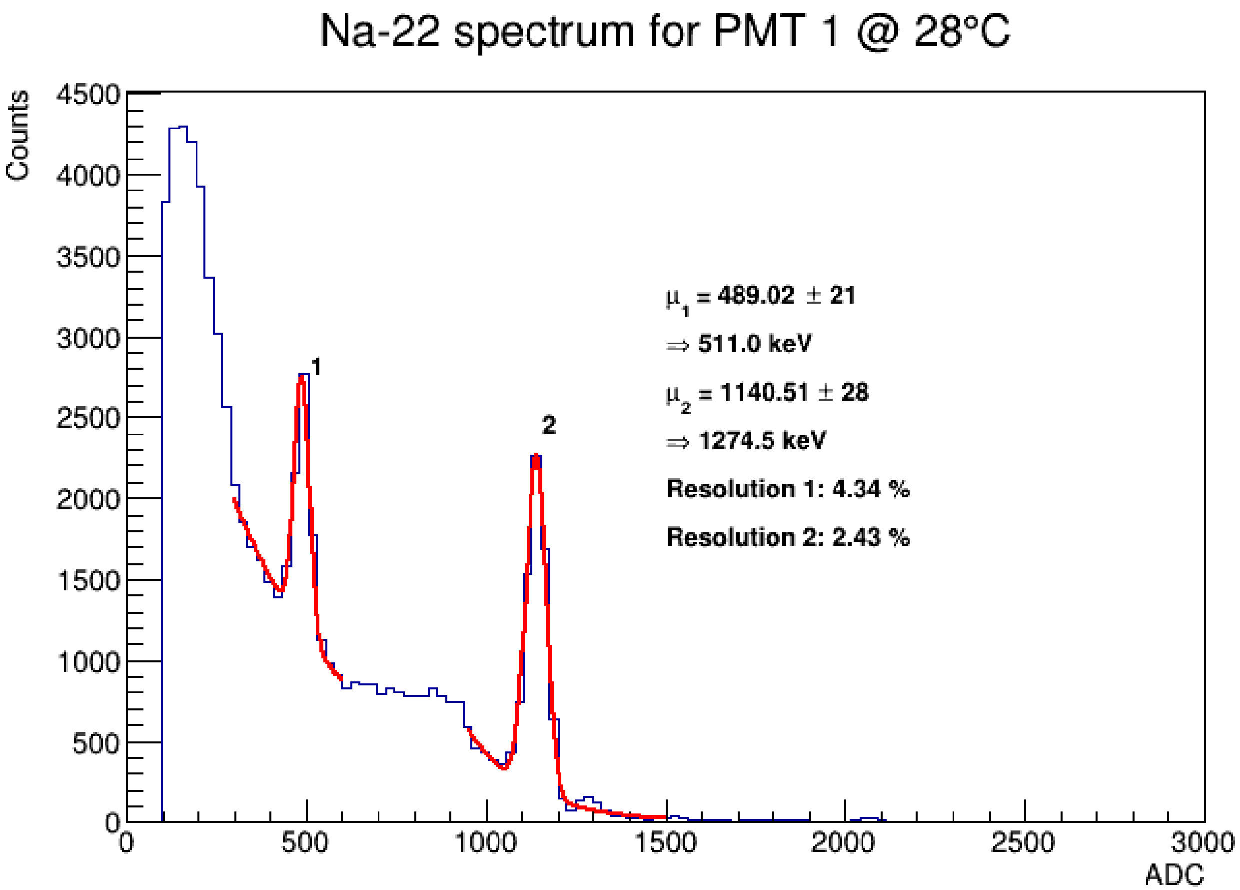


- The binning is determined using the Freedman-Diaconis rule, which is resilient to outliers and also suitable for tailed distribution.
- We reduced the count rate to mimic the condition where there's large background noise at low energy regions.


Co-60 spectrum for PMT 0 @ 28 °C
Counts
1
2
μ1 = 1095.38 ± 25
⇒ 1173.2 keV
μ2 = 1235.20 ± 27
⇒ 1332.5 keV
Resolution 1: 2.28 %
Resolution 2: 2.20 %
0
500
1000
1500
2000
2500
3000
0
500
1000
1500
2000
2500


Co-60 spectrum for PMT 1 @ 28 °C
Counts
1
2
μ1 = 1059.86 ± 24
⇒ 1173.2 keV
μ2 = 1190.21 ± 26
⇒ 1332.5 keV
Resolution 1: 2.31 %
Resolution 2: 2.18 %
0
500
1000
1500
2000
2500
3000
3500
4000
4500
0
500
1000
1500
2000
2500
3000
ADC


Na-22 spectrum for PMT 0 @ 28°C
Counts
1
2
μ1 = 503.03 ± 21
⇒ 511.0 keV
μ2 = 1184.17 ± 29
⇒ 1274.5 keV
Resolution 1: 4.17 %
Resolution 2: 2.45 %


Na-22 spectrum for PMT 1 @ 28°C
Counts
ADC
1
2
μ1 = 489.02 ± 21
⇒ 511.0 keV
μ2 = 1140.51 ± 28
⇒ 1274.5 keV
Resolution 1: 4.34 %
Resolution 2: 2.43 %