International Center for Interdisciplinary Science and Education

LED Optical Fiber Profile measurement and Cosmic ray Muons with MPPC arrays

HARDWARE CAMP
FOR FAST AND LOWLIGHT DETECTION

GROUP B

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1. Introduction

In this scientific report, we delve into the comprehensive exploration of experiments undertaken at the Hardware Camp for Swift and Dim Light Detection. The focal point of our endeavors revolves around swift light detection, concerning the prompt discernment of light signals occurring within a fleeting timeframe. Complementarily, our pursuits extend to the realm of low light detection, emphasizing the capacity to detect and quantify exceedingly faint levels of luminosity.

Throughout the duration of the camp, our endeavors were concentrated on furnishing participants with immersive hands-on encounters, predominantly centered around the utilization of Multi-Pixel Photon Counters (MPPCs). These endeavors aimed to equip participants with adeptness in employing MPPCs to identify and gauge minute levels of luminance effectively.

Muons, akin to electrons albeit considerably weightier, are elemental particles spawned within cosmic ray cascades. They serve as invaluable probes for scrutinizing an array of physical phenomena, spanning from atmospheric physics to high-energy particle physics. The detection of muons necessitates the deployment of highly responsive detectors capable of singling out individual particles. In this context, MPPCs have emerged as a promising technological avenue. Harnessing MPPCs for muon detection harbors the potential to furnish novel insights into the rudimentary realms of physics while facilitating the evolution of pioneering technologies tailored for particle detection endeavors.

Furthermore, LED optical fiber profile measurement epitomizes a methodology engineered to ascertain the optical attributes emanating from an LED through an optical fiber conduit. This meticulous measurement regimen stands as a linchpin in myriad applications wherein meticulous oversight and delineation of luminous output prove indispensable. These applications span across the spectrum, encompassing telecommunications, medical apparatus, illumination infrastructure, and optical sensing frameworks.

The cumulative outcomes stemming from these multifaceted experiments are poised to underpin enhancements in the design and efficacy of particle detectors. Such advancements are poised to resonate across a diverse array of applications, spanning from foundational particle physics explorations to the frontiers of medical imaging innovation.

2. Materials

2.1. MPPC arrays.

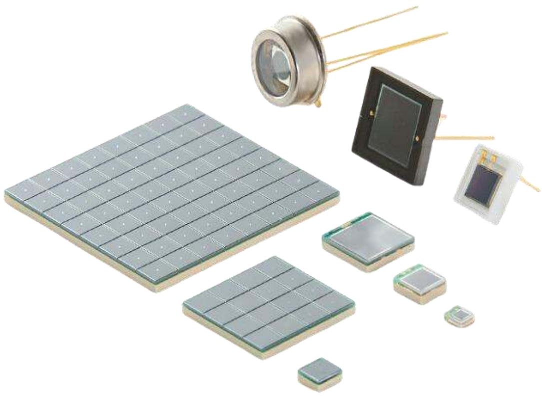

Figure 2.1. The configuration of MPPC arrays

MPPC is short for Multi-Pixel Photon Counter, and this detector is also known as silicon photomultiplier (SiPM). It is a solid state photodetector that uses multiple avalanche photodiode (APD) pixels operating in Geiger mode. MPPCs are for precision measurement featuring high photon detection efficiency as well as low crosstalk, low afterpulses, and low dark count.

MPPC arrays are a system of wavelength separators consisting of multiple MPPCs set up and interconnected into an array in a specific manner on a common surface. Each MPPC in the array operates independently to detect individual photons of light.

In this experiment, we used an MPPC array of the model Hamamatsu S13361-3050AE-04. Our MPPC Array contains 16 pixels which can be connected to 16 channels. However, we only use 4 pixels at a time: 1, 5, 9, 13.

2.2. PBA116 Amplifier

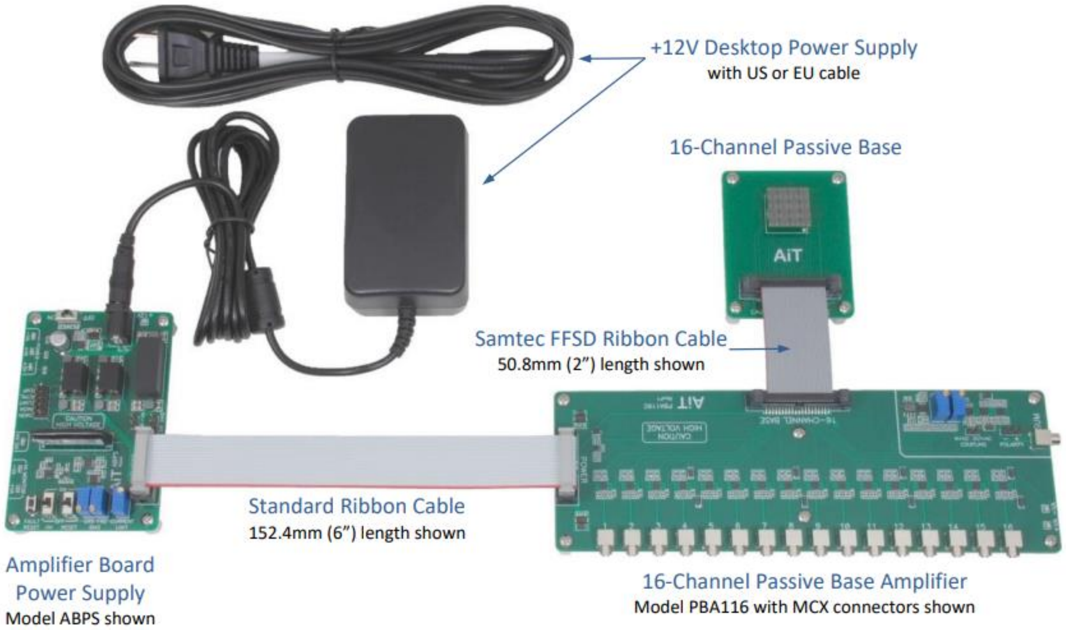

Figure 2.2. 16-Channel Passive Base Readout Kit

The PBA116 amplifier is a specific type of amplifier designed for use in various electronic applications, particularly in instrumentation and measurement systems.

Applications:

- Instrumentation: The PBA116 amplifier is commonly used in instrumentation systems for amplifying signals from sensors, transducers, or other measurement devices.
- Data Acquisition: It plays a crucial role in data acquisition systems where weak signals need to be amplified before processing or recording.
- Communication Systems: In some cases, the amplifier may be used in communication systems to boost signal strength or improve signal-to-noise ratio.
- Testing and Measurement: It is employed in various testing and measurement applications, including laboratory experiments, industrial testing, and scientific research.

2.3. Optical Fibers

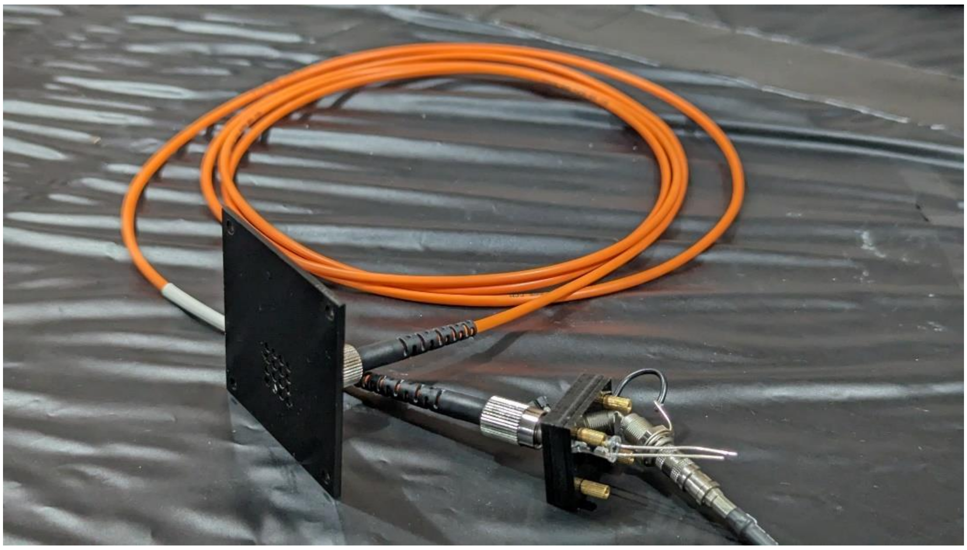

Figure 2.3. An image of the Optical Fiber.

Fiber optic is a modern communication and data transmission technology that uses light as a medium for communication. Optical fiber consists of a central conducting core made of transparent glass or plastic fiber, refined to allow maximum transmission of light signals. The fiber optic cable is the outer protective layer comprising various layers depending on the structure and properties of each type of cable.

The advantages of Optical Fiber:

- Large bandwidth, small size, and lightweight, making it easy to install.
- Immunity to electrical signals, electromagnetic interference, or even light radiation.
- Insulating property due to being made of glass, containing no conductive material, thus ensuring safety.
- High security, capable of withstanding harsh temperature and humidity conditions.
- Flexibility as optical information systems are available for most forms of data, voice, and video transmission.

3. Theoretical Background

3.1. Muon

Muon is a fundamental particle belonging to the lepton family, along with the electron, tau, and their associated neutrinos. It is denoted by the symbol μ. Muons are similar to electrons but are much heavier, with a mass of approximately 207 times that of an electron. Like electrons, muons are elementary particles, meaning they are not composed of smaller constituents.

The muon was first discovered by Carl D. Anderson and Seth Neddermeyer in cosmic ray experiments in 1936. Initially, it was thought to be the particle predicted by physicist Hideki Yukawa, who proposed the existence of the meson as a mediator of the strong nuclear force. However, it was later determined that muons are not mesons but rather a distinct type of lepton.

The most common decay mode of the muon is known as muon decay or muon decay to an electron and two neutrinos. The decay is mediated by the weak force, one of the fundamental forces of nature responsible for processes such as beta decay. The decay process violates conservation of lepton flavor, as a muon, a member of the muon lepton family, transforms into an electron, a member of a different lepton family.

3.2. Crosstalk

Crosstalk is a phenomenon that occurs in certain optical devices, such as MPPCs (Multi-Pixel Photon Counters), where the detection of a light signal in one pixel can result in the generation of secondary photons that are detected by neighboring pixels. These secondary photons are produced during the avalanche multiplication process within the pixel, leading to an unintended signal in adjacent pixels. This phenomenon is commonly referred to as optical crosstalk.

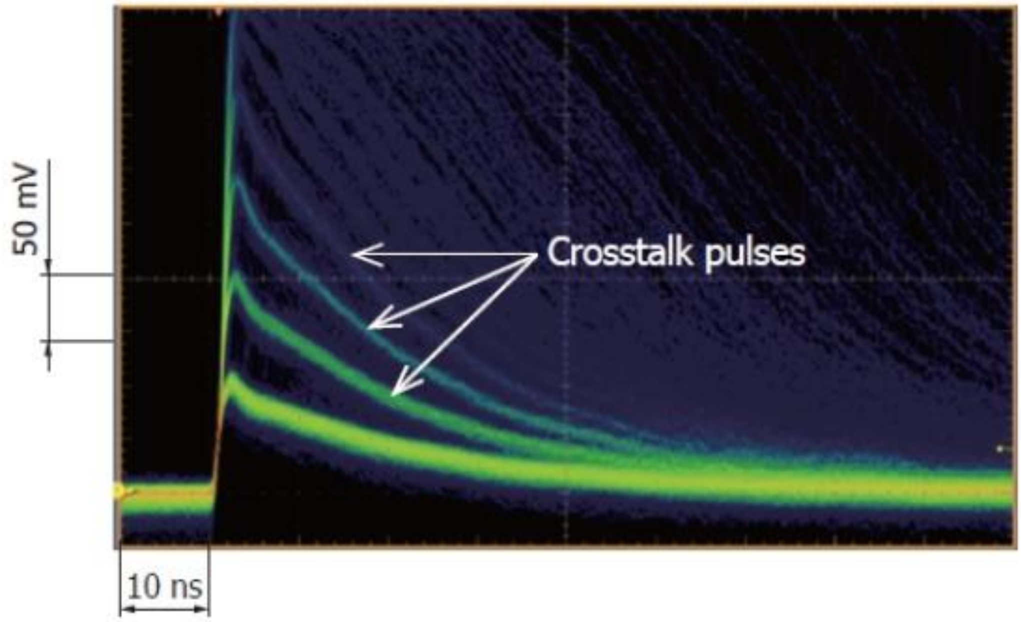

Figure 3.1. Crosstalk pulse waveforms.

Optical cross-talk can occur due to various mechanisms, including photon diffusion, scattering, or reflections within the device. When a primary photon is detected by a pixel, it can trigger the release of secondary photons, either through the re-emission of absorbed photons or the generation of new photons through optical processes. These secondary photons can travel and be detected by neighboring pixels, leading to false or additional signals.

The formula to determine the probability of Crosstalk:

$$P_{crosstalk} = \frac{N_{1.5p.e}}{N_{0.5\ p.e}}$$

The $P_{crosstalk}$ has almost no dependence on the temperature.

3.3. Electric gain

The MPPC gain is defined as the charge (Q) of the pulse generated from one pixel when it detects one photon, divided by the charge per electron ($q = 1.602 \times 10^{-19}$).

$$M = \frac{Q}{q}$$

The charge Q depends on the reverse voltage (V_R) and breakdown voltage (V_{BR}) and is expressed by equation.

$$Q = C \times (V_R - V_{BR})$$

with M as the gain and C as the capacitance of a pixel.

4. Experiment

4.1. Single photoelectron

A single photoelectron signal is the signal generated by one photon when it hits an MPPC pixel. The signal we observe has been pre-amplified (multiplied with gain) before entering the Oscilloscope.

Experiment setup:

Connect MPPC pixels to the Oscilloscope channels in a specific order:

Pixel 1	Pixel 5	Pixel 9	Pixel 13
Channel 1	Channel 2	Channel 3	Channel 4

- Power on in sequence.
- In the function , select EDGE, then adjust the trigger to a level of 0.5pe for low and 1.5 pe for high (average 1024)
- After completion, press save.

The result obtained is the area of the signal corresponding to the charge of each channel.

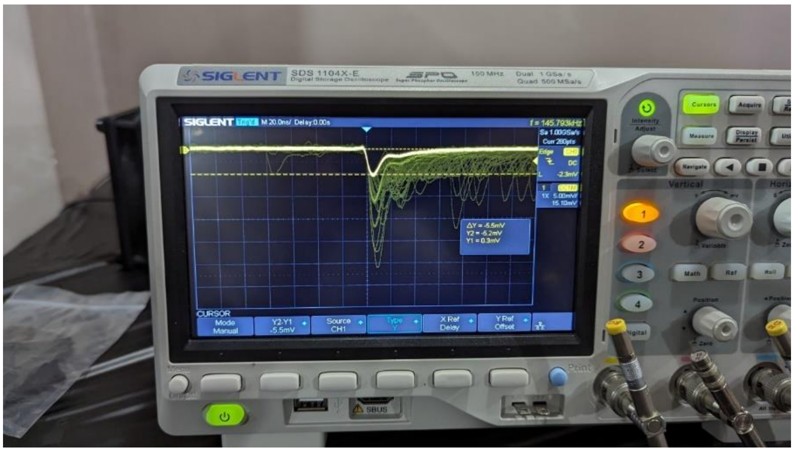

Figure 4.1. The signal of a single photon – electron

Figure 4.2. The signal of two photons – electron

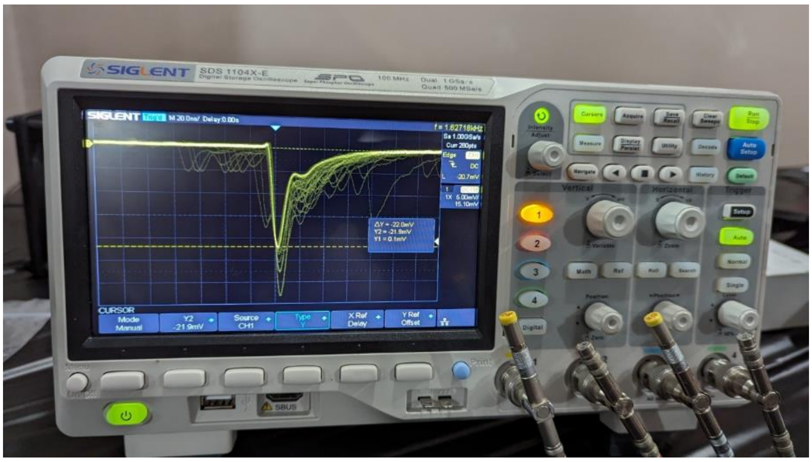

Figure 4.3. The signal of three photons - electron

4.2. Coincident rate

The coincidence rate is the rate at which multiple pixels within the MPPC detect photons simultaneously or within a short time window.

Select Pattern on the Oscilloscope, adjust CH1 and CH2 to low trigger. The purpose is to measure the coincidence rate of two, three, and four channels.

4.3. Electrical gain

Electric gain refers to the amplification factor applied to the signals generated by the photodetection process within the MPPC.

Experiment setup:

- Connect the LED lamp to the optical fiber and MPPC arrays.
- Adjust the trigger EDGE level to 0.5 p.e (Average 128).
- Tune the voltage from 3.0V to 3.2V, frequency 100kHz, duty cycle 0.4%.

The purpose of this step is to convert the area of each channel to the gain of MPPCs and connect the light source to each channel to observe the signal.

Table 4.1. The charge value of a single photon-electron after amplification

Single photon electron Charge Results			
CH1 – 1	CH2 – 5	CH3 – 9	CH4 – 13
$-1.3. 10^{-10}$	-1.2×10^{-10}	-2.5×10^{-10}	-1.3×10^{-10}

Table 4.2. Electric gain.

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CH1 – 1	CH2 – 5	CH3 – 9	CH4 – 13
8.00×10^7	7.54×10^7	1.56×10^7	7.89×10^7

4.4. LED optical fiber profile measurement with 4 channels.

Setup procedure:

- Gather all necessary equipment.
- Connect MPPC pixel to Oscilloscope channel in specific order:

Pixel 1	Pixel 5	Pixel 9	Pixel 13
Channel 1	Channel 2	Channel 3	Channel 4

- Note the charge of one photoelectron for each pixel (if already calculated at Task 1. If haven't re-measure and calculate).
- Connect function generator to the LED, using optic fiber to transmit light from LED, make sure that the connection between LED and optic fiber is steady.
- Setup a constant distance between the end point of optic fiber and MPPC (44mm), using black plastic plate and copper pillar.
- Cover the MPPC, wire and optic fiber connection with a black blanket (the purpose is to block all light from outside to the MPPC).
- Turn on MPPC in order, turn on Oscilloscope, make sure that all channels are visible.
- Turn on function generator at CMOS, using 3.3V, frequency 100kHz, duty cycle 0.4%. Observe the signals on oscilloscope to make sure that MPPC is receiving photon from the optic fiber.

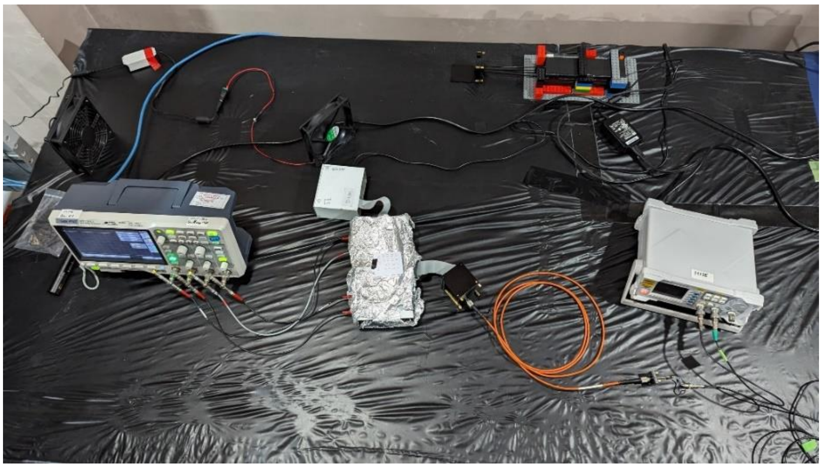

Figure 4.4. The experimental setup for measuring the LED optical fiber profile.

At this step, we assured that the experiment setup is complete and working as we wanted. We can start investigating the optic fiber profile now.

We'll point the optic fiber directly to each pixel one by one (only 4 pixel we are using) and gather average signal of each channel for each times. In the end, we should have 4 sets of data, each has 4 data for each channel.

Table 4.3. The charge of each pixel with each channel connected to the optical fiber.

Charge of each		CH1	CH2	CH3	CH4
Optic fiber pointed at	CH1	-6.01E-09	-2.80E-09	-9.20E-10	-4.50E-10
	CH2	-3.91E-09	-6.30E-09	-6.50E-09	-7.00E-10
	CH3	-4.61E-09	-1.10E-08	-2.70E-09	-2.70E-09
	CH4	-3.63E-10	-1.70E-09	-9.90E-09	-5.50E-09

To convert these 4 datasets of charge to number of photoelectrons each channel received, we must divide each to its single photoelectron charge data that we already noted. The results is shown below:

Table 4.4. The number of photons for each pixel with each channel connected to the optical fiber.

No. Photon at each		CH1	CH2	CH3	CH4
Optic fiber pointed at	CH1	46.94	23.29	3.69	3.57
	CH2	30.54	52.57	26.01	5.53
	CH3	36.02	92.1	10.76	21.29
	CH4	2.84	14.41	39.58	43.7

With these datasets, we can draw the optic fiber profile by now and find out where is the middle position and what is the width of the profile. Due to the limited time, we only used data when optic fiber pointed at CH1 and CH4. Before plugin the data and start fitting it with a gaussian function, we first must normalize it by dividing all with its maximum. After that, we can plot a scatter graph, and fit it.

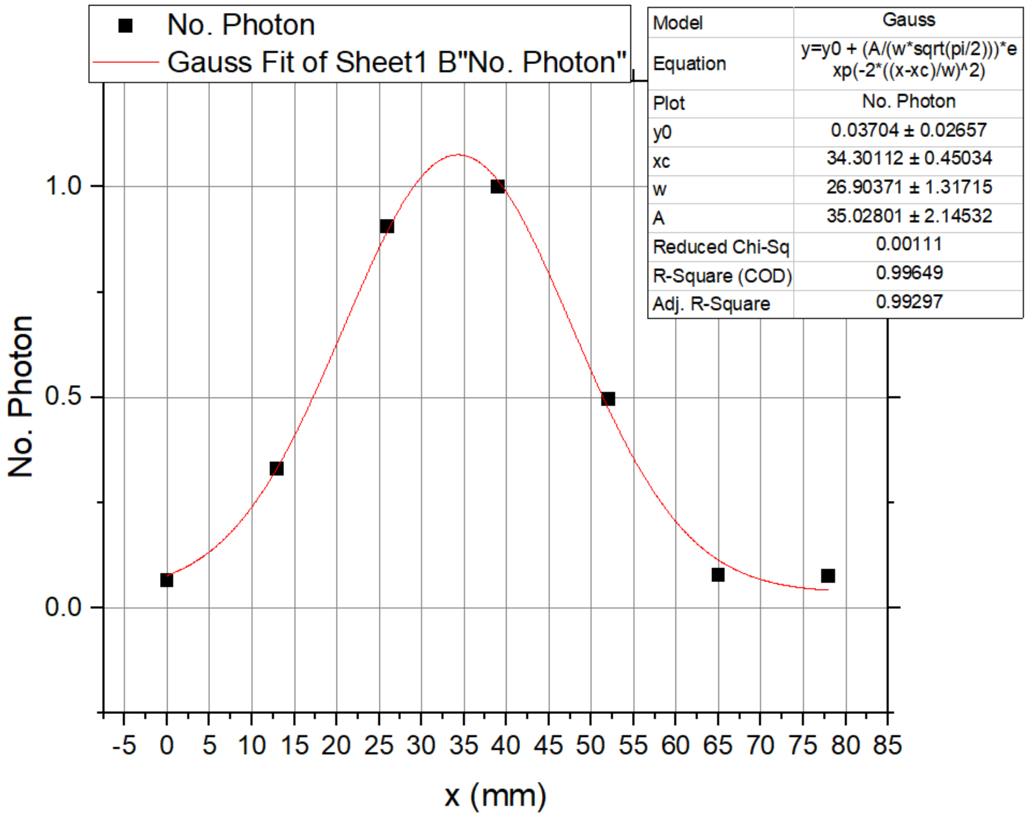

Figure 4.5. Graph of optical fiber profile and Gauss fit function.

By measuring the distance between each pixel (the width of each pixel) we know how far each datapoint is so we can plot the above scatter graph.

- The middle position is $x_c = 34.3 \pm 0.5$ mm.
- The width of the profile is $w = 36.9 \pm 1.3$ mm.

4.5. Cosmic ray muons

4.5.1. Coincident detection.

When a muon passes through a detection system consisting of multiple detectors arranged in an array, it can generate coincidence signals in more than one detector simultaneously. This phenomenon is known as "coincidence detection" and is a key principle used in particle detection experiments, particularly in experiments involving cosmic ray detection or other high-energy particle studies.

If you have a setup with at least three detectors arranged in a way that they can detect the passage of a muon, it's common to observe coincidence signals in three or more detectors when a muon passes through the system. This is because muons are highly energetic particles that can traverse through multiple layers of detectors in quick succession.

In some experiments, especially those requiring higher levels of precision or background rejection, a coincidence signal in four or more detectors may be used to further confirm the presence of a muon event and reduce the likelihood of false positives due to noise or other sources of interference.

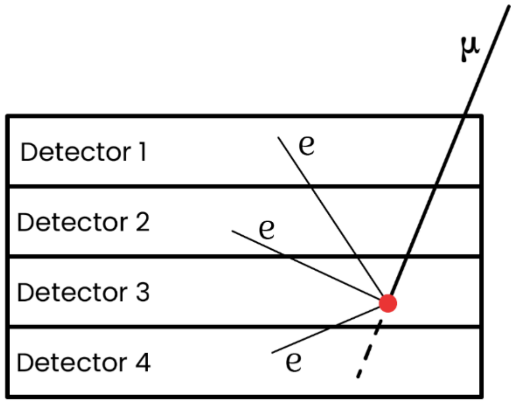

Figure 4.6. Coincident event of 3 plastic scintillators.

The requirement for the rate of muon signals to be at least 100 times higher than the rate of noise (dark count) in a detection system is primarily due to the need to ensure a reliable and accurate detection of muons while minimizing false positives caused by noise. Dark count, or noise, refers to the random signals generated by the detection system even in the absence of external stimuli. These noise signals can sometimes be indistinguishable from signals produced by muons. By requiring the muon signal rate to be significantly higher than the noise rate, false positives due to noise can be minimized, leading to more accurate results.

4.5.2. Examine the noise to find the suitable threshold (trigger).

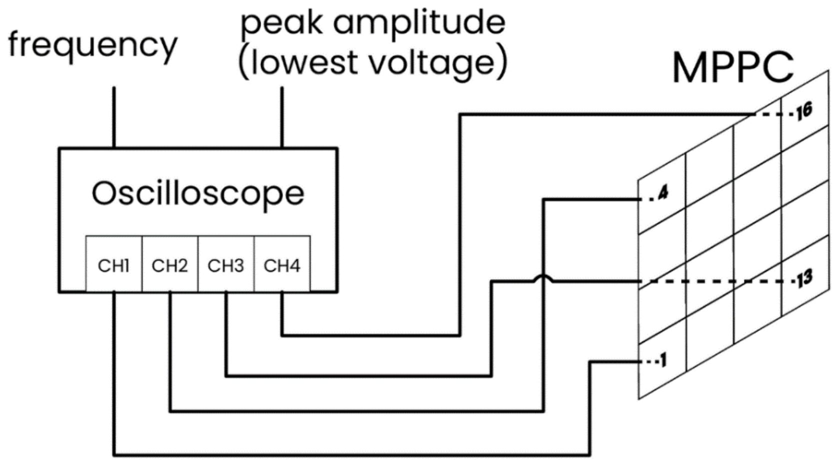

Figure 4.7. Diagram of the Dark Count Measurement System Setup.

Firstly, to identify the muon signal, we need to determine the threshold voltage values corresponding to 1 p.e, 2 p.e, 3 p.e for each channel, aiming to eliminate background noise from dark counts.

Table 4.5. The coincident frequency of each channels corresponding to 1, 2, 3 p.e

The coincidence frequency of each channel (kHz)			
Number of Photoelectron	1	2	3
CH1 - 1	619.8	80.11	9.85
CH2 - 4	720.1	80.39	10.66
CH3 - 13	673.6	73.05	10.01
CH4 - 16	531.7	57.34	7.06

Table 4.6. The peak voltage of the 4 channels corresponding to 1, 2, 3 p.e, respectively.

Peak voltage (mV)			
Number of Photoelectron	1	2	3
CH1 - 1	6.24	11.72	16.6
CH2 - 4	5.96	11.8	16.8
CH3 - 13	11.2	22.3	32.4
CH4 - 16	6.08	12	18.2

The coincidence frequency tends to be lower when detecting multiple photons simultaneously compared to detecting only one photon because the probability of two or more photons arriving simultaneously at multiple detectors is usually lower than the probability of a single photon arriving at a single detector. When detecting multiple photons at once, the likelihood of all photons coinciding in time and activating multiple detectors simultaneously decreases, leading to a lower coincidence frequency.

Table 4.7. The coincidence frequency recorded for 1 p.e, 2 p.e, 3 p.e
when combining channel 1 with channel 2, and when combining all 3 channels.

	Frequency of coincident		
Number of photon - electron	1	2	3
CH1 & 2	1346 kHz	61.73 kHz	403 mHz
CH1 & 2 & 3	91.81 Hz	20 mHz	< 0.1 mHz

When using both channel 1 and channel 2 to record coincidence signals from photon-electron events, the detection efficiency will progressively decrease if we aim to record more photon-electron events.

4.5.3. Muon decay.

Through the oscilloscope, we can observe the appearance of coincidence signals. However, for experiments recording from 2 pe or 3 pe onwards, along with the utilization of multiple channels simultaneously to capture more coincidences, it becomes increasingly challenging to detect coincidence signals, as mentioned above. Therefore, we established the muon detection system for an extended period, specifically from 10 AM on March 7th to nearly 3 AM on March 8th. We recorded over 19,000 events with a muon rate of 0.293 ± 0.002 (muons/cm^2/min). The size of the scintillator we used is 2.5 x 25.5 cm^2.

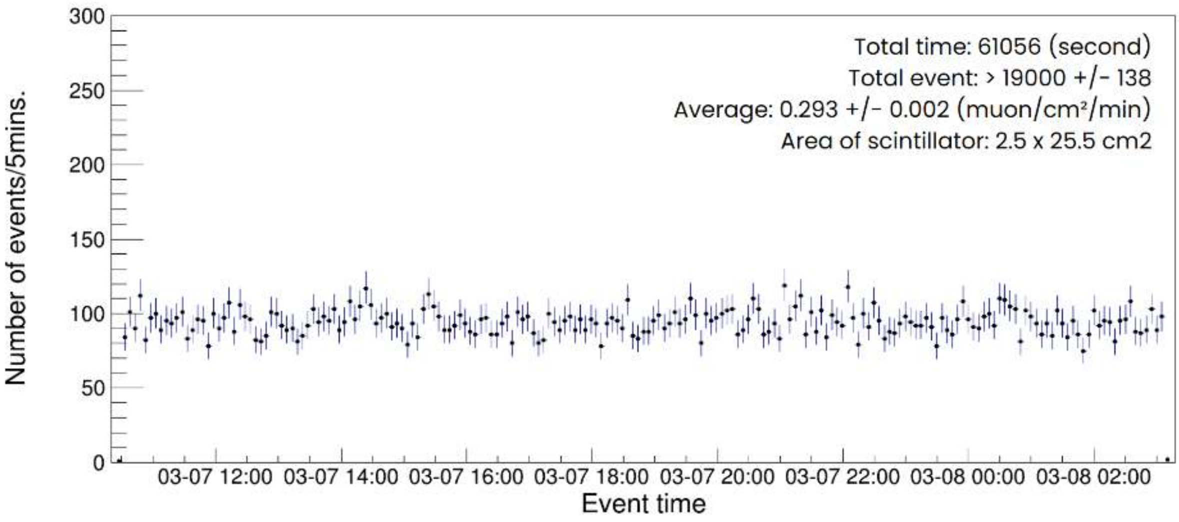

Figure 4.8. The number of muon decay events recorded
from 10 AM on March 7th to 3 AM on March 8th.

Additionally, we set up an outdoor muon detection system on the rooftop of the third floor at ICISE (International Centre for Interdisciplinary Science and Education) within a one-hour period, using a plastic scintillator measuring 2.5 x 25.5 cm^2, and recorded 2077 events.

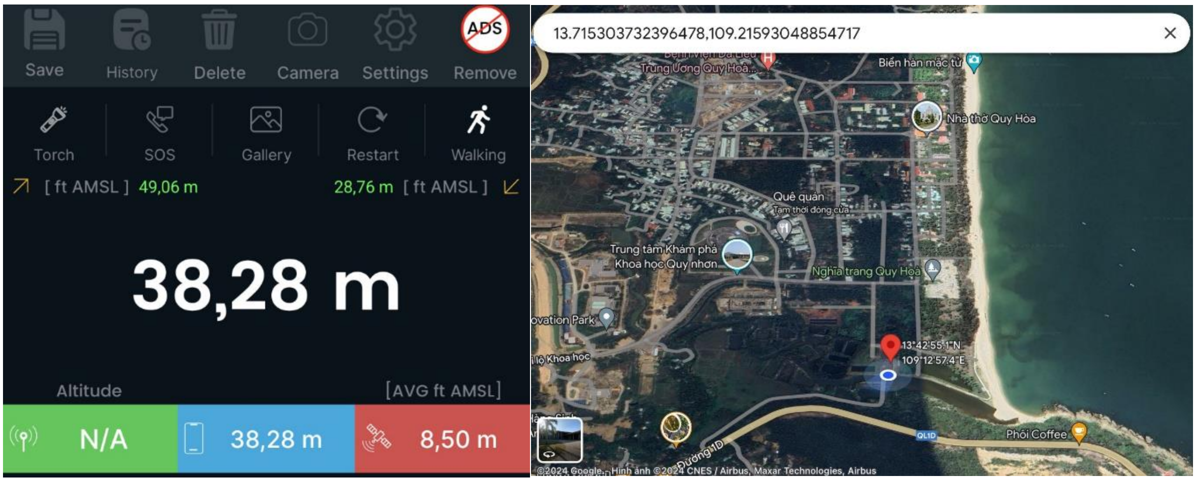

Figure 4.9. The measurement location and elevation relative to the ground.

With the data we have collected, we can now calculate the muon rate at that location as follows.

$$2077 : 60 : (2.5 \times 25.5) = 0.543\ (\text{muon/cm}^2/\text{min})$$

Here are a few coincidence events that we have collected during the 17-hour muon detection experiment

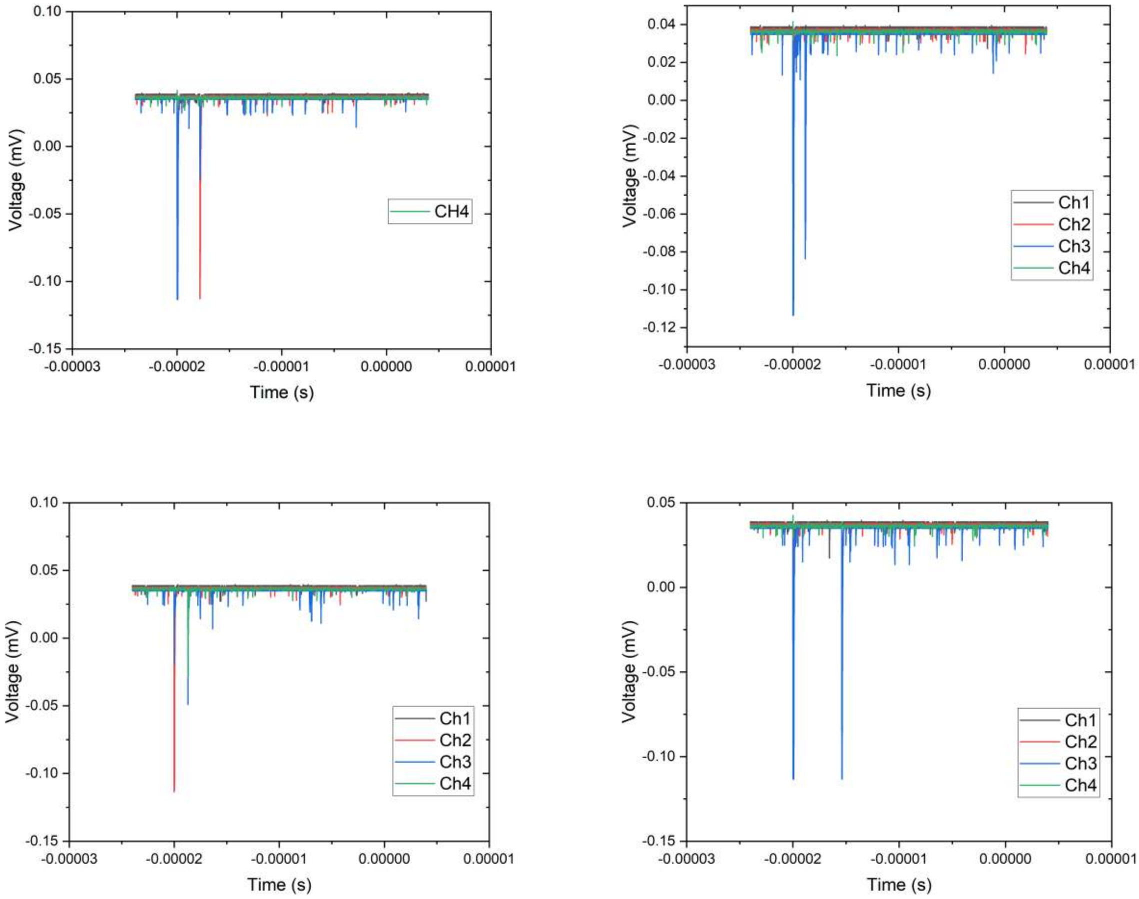

Figure 4.10. Data retrieved on remote PC

5. Conclusion

- Measured muon rate is lower than expected. The Expected muon rate is 1muon/min/cm2.
- The setup geometry can't cover all muon passing through.
- Due to the limited time and when working as a group, we want to make sure all members can study together, understand well so we can't cover every problem deeply.