

Team Project - Measurement of cosmic-ray flux with the Cosmic Watch

Bożena Poncyljusz, Michalina Borczyńska, Paulina Tomkiel,
Mikołaj Mrozowski, Bartosz Sójka

Abstract

The goal of the project was to check whether the dependence of the cosmic muon flux on the zenith angle is consistent with the relation $\left| \overrightarrow{j(\theta)} \right| = j_0 \cos^2 \theta$ and also to find the total cosmic muon flux for the horizontal surface. For that purpose, we used six Cosmic Watches as detectors. There was noticed an asymmetry in the dependence of the cosmic muon flux on the zenith angle, which was most likely the result of location of a wall on one side of the measurement system and windows on the other. However, this asymmetry turned out to be negligible. The obtained total cosmic ray flux for the horizontal surface is

$$j_H = (174 \pm 17) \text{ m}^{-2} \text{ s}^{-1},$$

which is consistent with the expected value $\hat{j}_H = 180 \text{ m}^{-2} \text{ s}^{-1}$ [3].

1 Introduction

Cosmic radiation is the high-energy flux of particles and radiation that originates from space. Due to the interaction of cosmic rays with the matter in the atmosphere, mainly interaction with nitrogen or oxygen nuclei, particle cascades are formed. These particle cascades created in the atmosphere are also called air showers. They are composed of electromagnetic, muonic, and hadronic cascades. According to the [3] muons are the major part of the charged particles of the air showers at sea level. The registration and analysis of air showers, especially their muonic part, is the basic method of detection of cosmic rays. Therefore it is instructive to measure and analyse the muon flux at the ground. In this report, we present the results of the measurement of the angular distribution of the cosmic-ray flux using the Cosmic Watch detectors. It is expected (see [3]) that the angular distribution of muons should be proportional to the $\cos^2 \theta$, where θ is the zenith angle, and the total horizontal flux should be equal to $\hat{j}_H = 180 \text{ m}^{-2} \text{ s}^{-1}$.

2 Equipment and Measurements

2.1 Cosmic Watch

As detectors, CosmicWatch devices from [1] were used. They work based on wrapped in the aluminium foil and the insulator tape solid body scintillators, coupled with silicon photo-multiplier (SiPM). Photomultiplier produces measurable electrical signals having a source in photons falling on the photocathode of the SiPM. We can assume that those initial photons arise only as a result of interaction either of gamma rays or muons with the scintillator material. A number of photons emitted in the scintillator is proportional to the energy deposited in the material, which in turn depends on the energy of the initial particle - gamma photon or muon. The signal produced by the photomultiplier is processed by an amplifier and then the peak detector.

As an embedded system in CosmicWatch Arduino Nano is used. It starts data acquisition, when the value obtained by the analog-to-digital converter (ADC) is above a software-defined threshold and finishes when the obtained ADC value is below the defined reset value. Data recorded in the mentioned time interval correspond to one event. Data from the CosmicWatch were collected directly to a computer through a mini-USB cable by running the program "import_data.py" provided in [1].

For each event the recorded data are:

- The date and the time stamp given by the computer;
- The number of the event;
- The total elapsed Arduino time (measured in milliseconds);

- Measured ADC value for the peak corresponding to that event, where the possible values are integer numbers from 0 to 1023;
- Voltage value in mV corresponding to the detected peak in that event, calculated from the measured ADC value - amplitude of the pulse in mV is 11th polynomial function of measured ADC value. It is proportional to the number of photons incident on the SiPM;
- The total dead-time of the detector, got from the subtracting from the total time, the entire time it had taken the Arduino to perform each operation for that event and also previous ones;
- The measured temperature of the detector;
- The detector name.

Detectors were assembled by the team of authors of this report. They were respectively named: MuonoLapka, Iwar, Pan Gruszka, Aurelia and Latenna. In the project we also were using detectors that had been built before, not by the authors of the report: DC_2020, Muon Eater, JK, Louis, oboze, Adler, Grudzień_2020.

2.2 Calibration

Each detector has been built by a different person, so every detector is to some extent different. Also, some of the used scintillators are made from a different material than the others. That is why every detector catches a different number of particles per given time. Moreover, the energy calibration might be different for each detector. Therefore we operated every detector for, approximately, the same time interval and collected data in order to draw for every detector a histogram showing the dependence of the number of counts on the registered signal amplitude. We set the trigger threshold and the reset value on ADC to be respectively 50 (15,67 mV) and 25 (11,02 mV) for each detector.

The histogram in the figure 1 shows an amplitude distribution for the grudzień_2020 detector. The first counts are recorded for approximately 22 mV. It was found that other values were chosen in the detector during calibration. This detector was not used in the subsequent stages of the experiment. Figure 2 shows histograms of amplitude distribution for the MuonoLapka detector, each histogram plotted with different bins width, as the example of how such distributions look like. On the histograms we should see two peaks: the first, bigger one for lower voltages, corresponding to the caught gamma photons and the second, smaller one for higher voltages, corresponding to the detected muons [2]. We decided to work with histograms with a bin width equal to 3 mV, thanks to which both peaks are visible.

Figure 3 shows amplitude distributions measured by Aurelia, MuonoLapka, Iwar, Pan Gruszka, Louis and Latenna detectors. Analogical histograms for the rest of the detectors are included in the Appendix. We see that the shapes of those histograms are similar, but number of counts in the particular voltage range for different detectors might not be the same.

In further measurements we would like ADC threshold value of each detector to correspond to the same energy of the initial particle. In order to find such ADC threshold values, we singled out the representative detector - MuonoLapka and then chose for it the voltage value for which the ADC would be the threshold one. We have called such voltage value as cut off voltage value. Because we are interested in the detection of muons only, the chosen cut-off voltage value was tuned such allowed to discard photons. Therefore the amplitude distribution, as presented in the Figure 4, was fitted with two Gaussian functions: G_1 describing the contribution of photons (violet line) and G_2 - the contribution of muons (green line). Then, the intersection of both fits was chosen for a cut-off value. Our chosen cut-off voltage value for MuonoLapka detector was set to 55mV and presented with a red vertical line in the Figure 4.

Then we calculated the ratio R of the fitted G_1 function value in the cut-off point to its maximum. Figures 5-9 and figures 14-18 in the Appendix show amplitude distributions respectively for Pan Gruszka, Latenna, Iwar, Aurelia, Louis, Adler, DC_2020, oboze, Muon Eater and JK detectors together with drawn violet points which in a good approximation correspond to the counts of the gamma photons, green points which in a good approximation correspond to the counts of the muons and also two fitted Gaussian functions respectively to the violet and green points. Afterwards, for each of the detectors (besides MuonoLapka), we multiplied the maximum of the fitted Gaussian function to violet points by the ratio R and chose obtained values as cut-off voltage values. In the figures 5-9 and 14-18 we drew red vertical lines which positions correspond to the obtained cut-off voltage values.

Table 1 and 2 show for each detector the time which have elapsed since the first detected event to the last one, number of counts, value of the voltage cut off, ADC value corresponding to the voltage cut off, number of events for which peak amplitude was higher than the cut of voltage value and also efficiency.

As for the efficiency of the detector, we defined the ratio between the number of counts above the cut-off voltage registered by each detector with respect to the same value obtained with a reference one. The efficiency was calculated with respect to the Latenna detector, marked with a green, for which 100% efficiency was assumed. Results obtained for the MuonoLapka detector were colored blue as it was a representative detector for establishing cut-off values.

For further measurements we chose MuonoLapka, Latenna, Aurelia, Pan Gruszka, Iwar and Louis detectors as they were six detectors with the highest calculated efficiency.

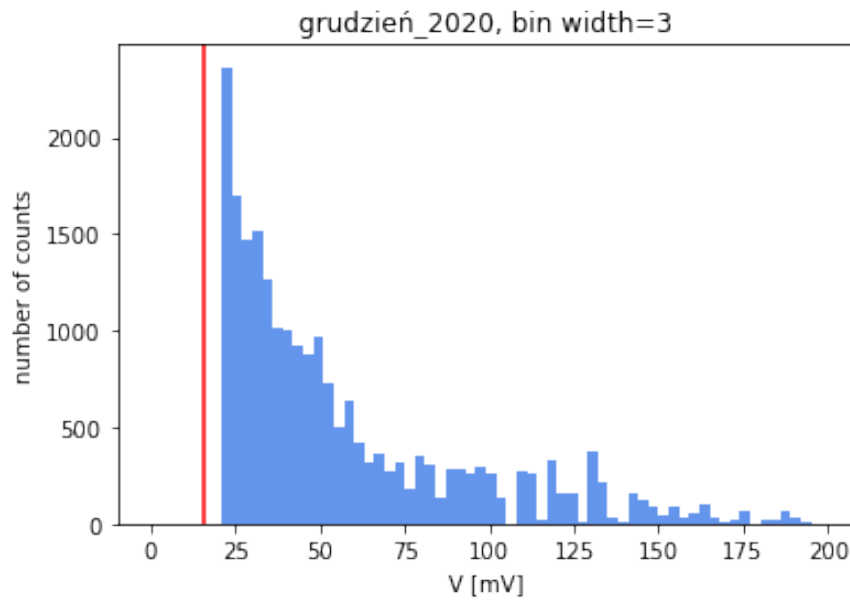


Figure 1: Amplitude distribution of signals registered by grudzień_2020 detector; bin width = 3mV.

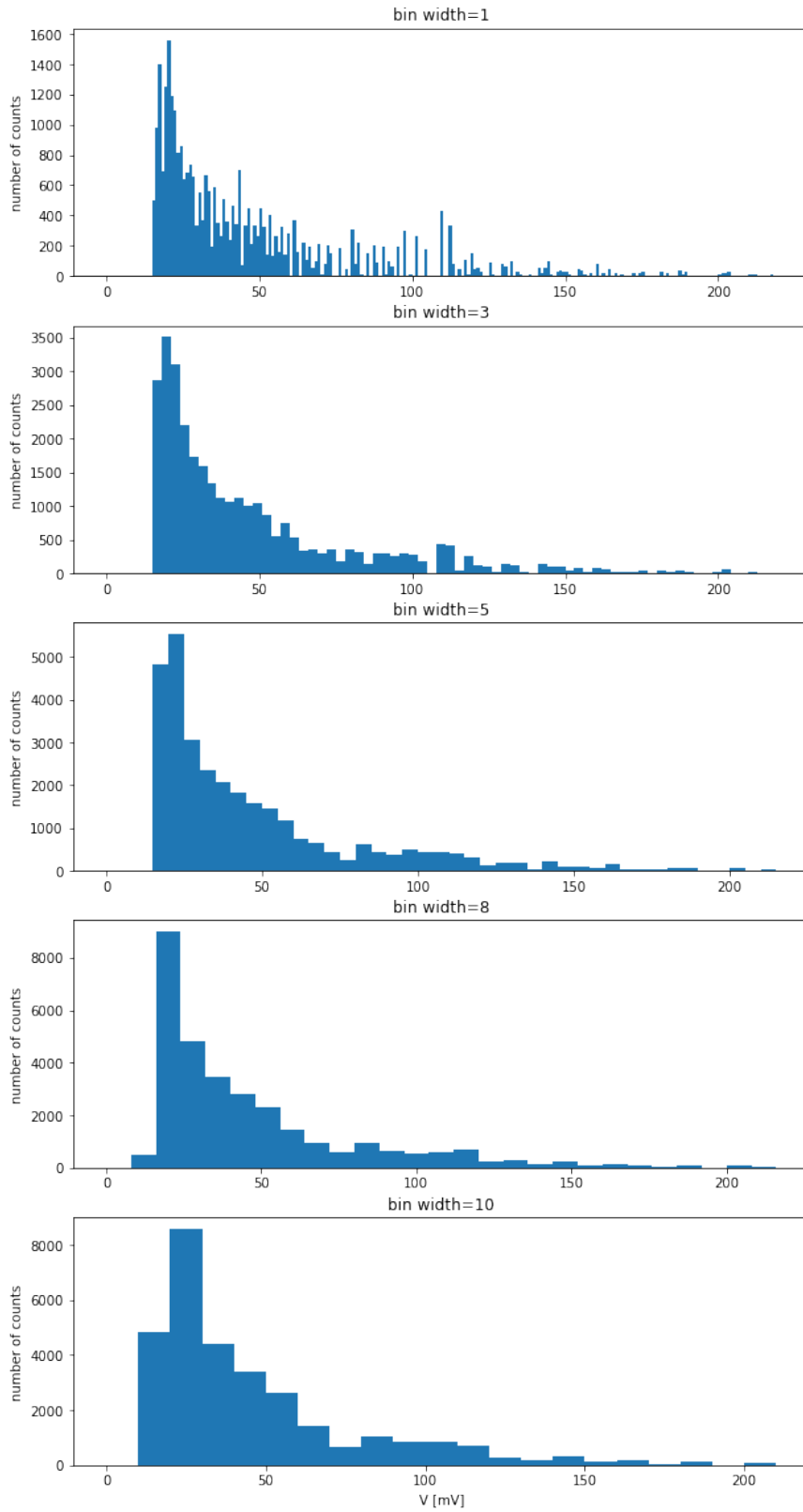


Figure 2: Amplitude distribution of signals registered by MuonoLapka detector with bin width respectively equal to 1 mV, 3 mV, 5 mV, 8 mV and 10 mV.

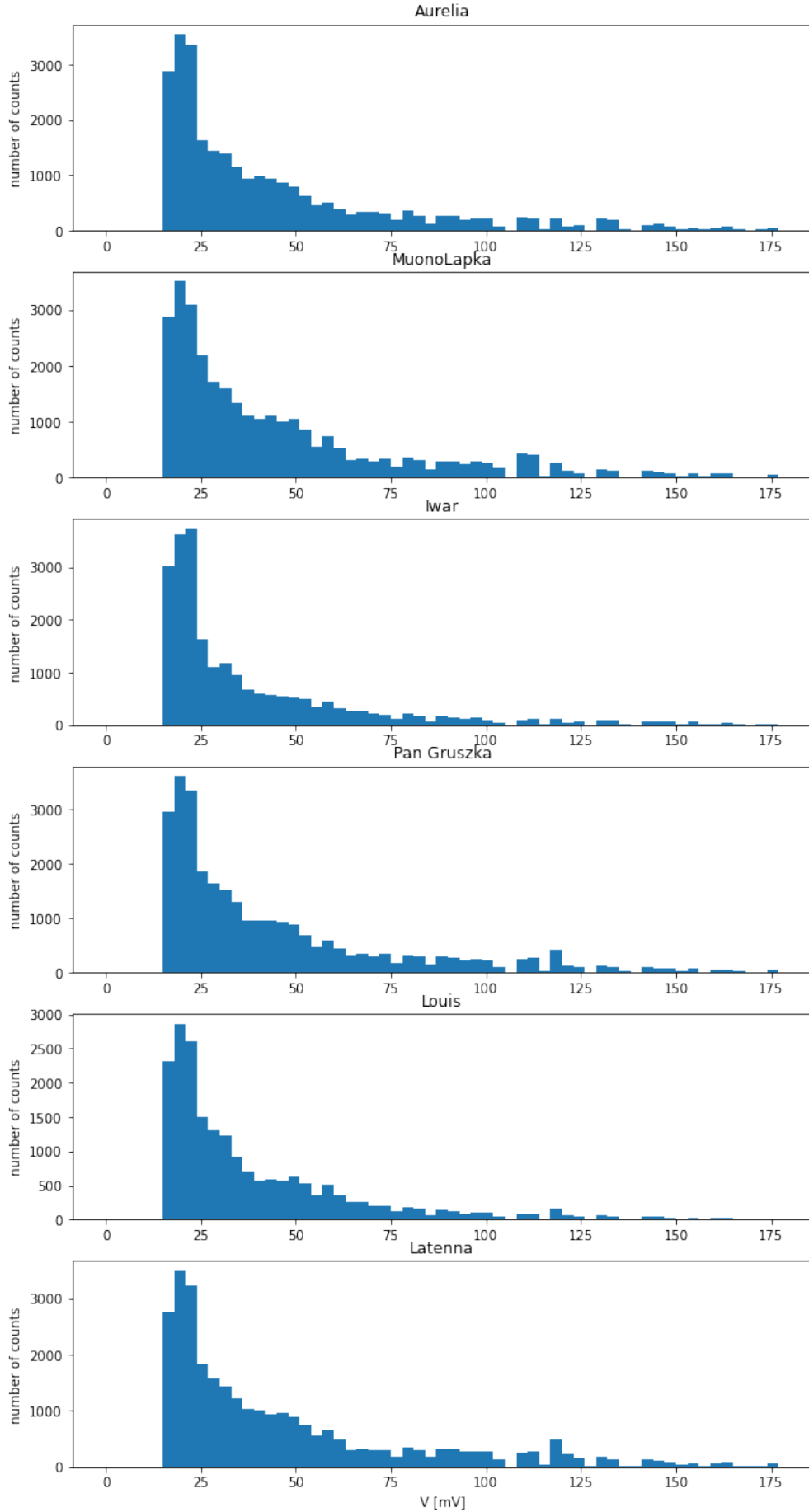


Figure 3: Amplitude distribution of signals registered by six representative detectors: Aurelia, Latenna, Iwar, Pan Gruszka, Louis, MuonoLapka.

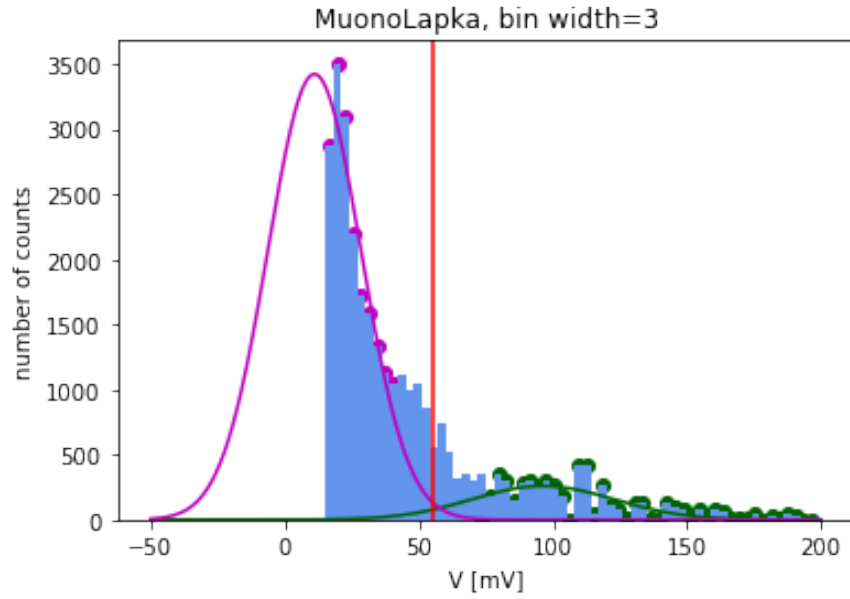


Figure 4: Histogram with amplitude distribution and fitted Gaussian functions for the counts for the energy corresponding to the photons (violet) and the energy corresponding to the muons (green) along with cut-off value (a vertical red line) for the MuonoLapka detector.

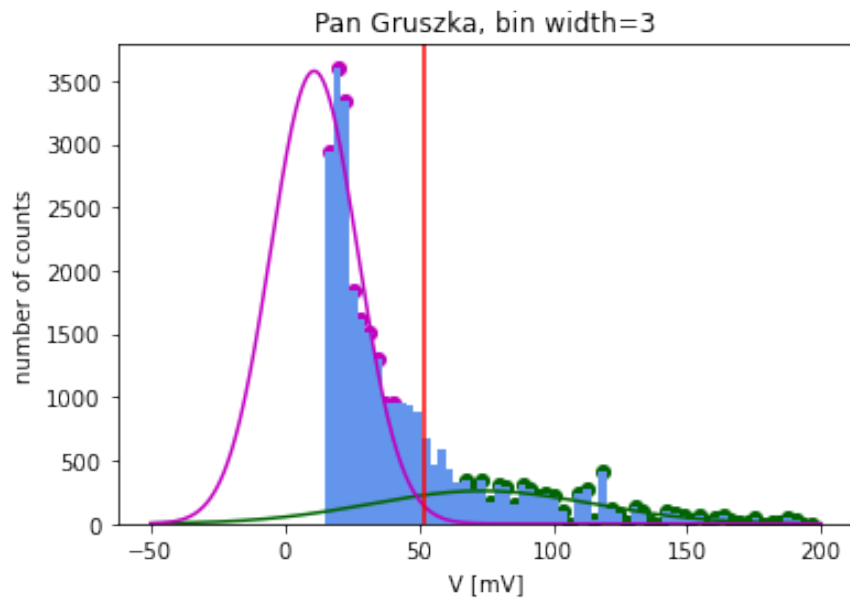


Figure 5: Histogram with amplitude distribution and fitted Gaussian functions for the counts for the energy corresponding to the photons (violet) and the energy corresponding to the muons (green) along with cut-off value (a vertical red line) for the Pang Gruszka detector.

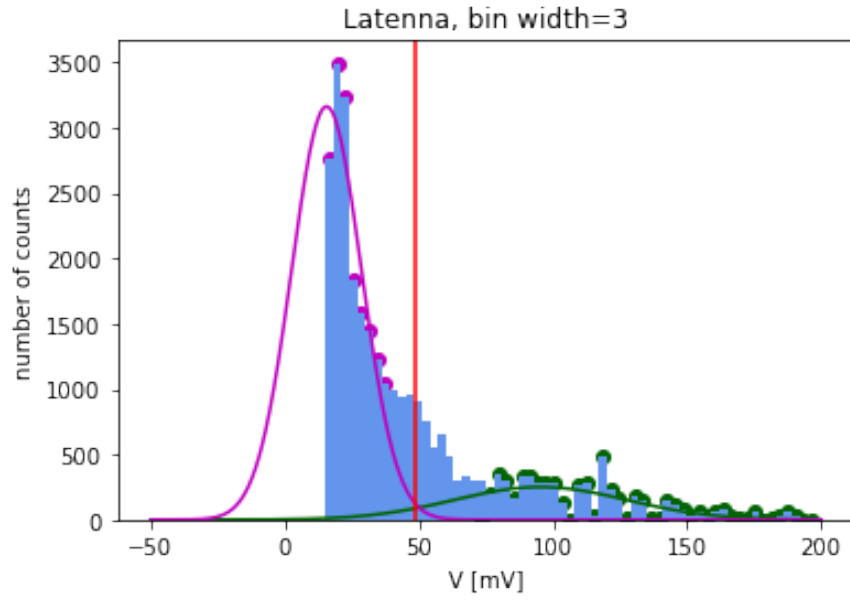


Figure 6: Histogram with amplitude distribution and fitted Gaussian functions for the counts for the energy corresponding to the photons (violet) and the energy corresponding to the muons (green) along with cut-off value (a vertical red line) for the Latenna detector.

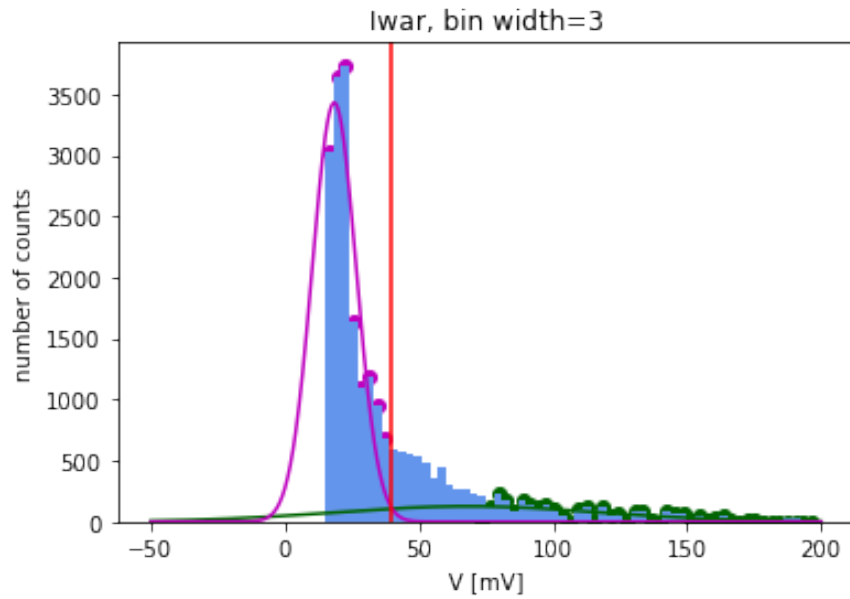


Figure 7: Histogram with amplitude distribution and fitted Gaussian functions for the counts for the energy corresponding to the photons (violet) and the energy corresponding to the muons (green) along with cut-off value (a vertical red line) for the Iwar detector.

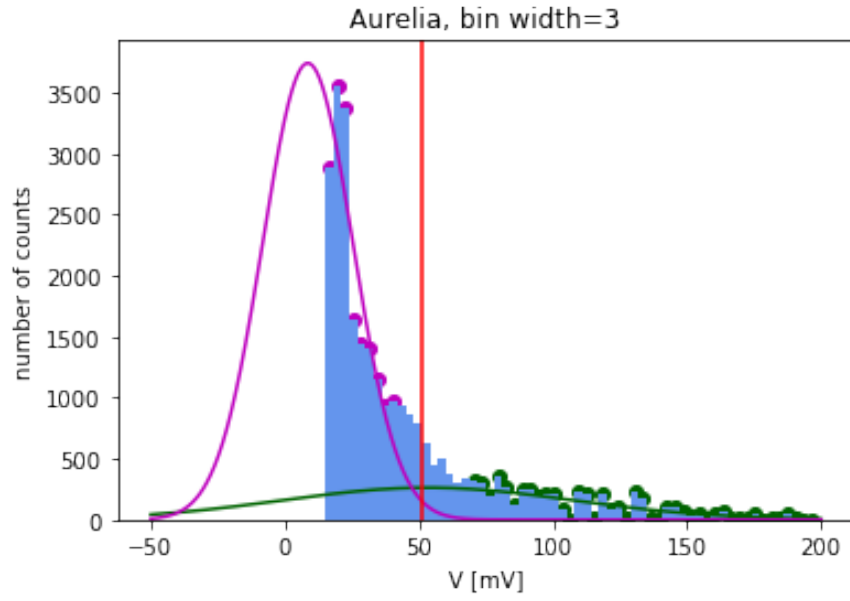


Figure 8: Histogram with amplitude distribution and fitted Gaussian functions for the counts for the energy corresponding to the photons (violet) and the energy corresponding to the muons (green) along with cut-off value (a vertical red line) for the Aurelia detector.

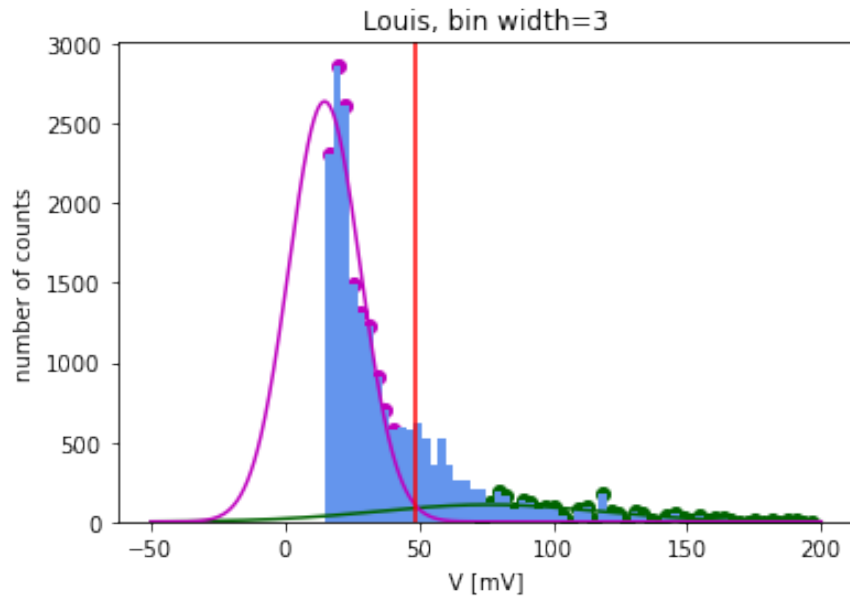


Figure 9: Histogram with amplitude distribution and fitted Gaussian functions for the counts for the energy corresponding to the photons (violet) and the energy corresponding to the muons (green) along with cut-off value (a vertical red line) for the Louis detector.

Table 1: Summary of the detector operation time and the number of counts at that time.

Detector Name	counting time (hours: minutes: seconds)	number of counts
DC_2020	08:14:38	2954
Pan Gruszk	08:15:27	29089
Muon Eater	08:17:04	16539
JK	08:17:46	21655
MuonoLapka	08:18:04	31241
Aurelia	08:18:28	27634
Iwar	08:19:01	23500
Louis	08:19:24	20650
oboze	08:28:23	1266
Adler	08:21:10	16703
Latenna	08:16:03	30012

Table 2: Summary of cut-off values and efficiencies for each detector.

Detector Name	cut-off [mV]	cut-off [ADC]	number of counts above cut off point	efficiency [%]
DC_2020	34,09	200	422	4,61
Pan Gruszk	51,90	296	7990	87,26
Muon Eater	46,67	270	3801	41,51
JK	49,43	284	5418	59,17
MuonoLapka	55,00	309	8589	93,80
Aurelia	51,31	293	7705	84,14
Iwar	41,18	240	7174	78,34
Louis	48,65	280	5463	59,66
oboze	37,98	222	2141	23,38
Adler	48,25	278	3739	40,83
Latenna	53,21	301	9157	100

2.3 Measuring Stand

In order to measure the θ dependence of the muon flux it is necessary, to have measurements from different θ angles. To achieve this, a measuring stand was built. It consists of the central rod on two supporting rods, screwed to the base plate and some number of the module consisting of the rod with two CosmicWatches at its ends. In the performed measurements there were three modules used.

Parts holding rods were 3D printed. The base plate is made from plywood and supporting plates below detectors from polycarbonate. Assembled measuring stand is presented in the figure 10.

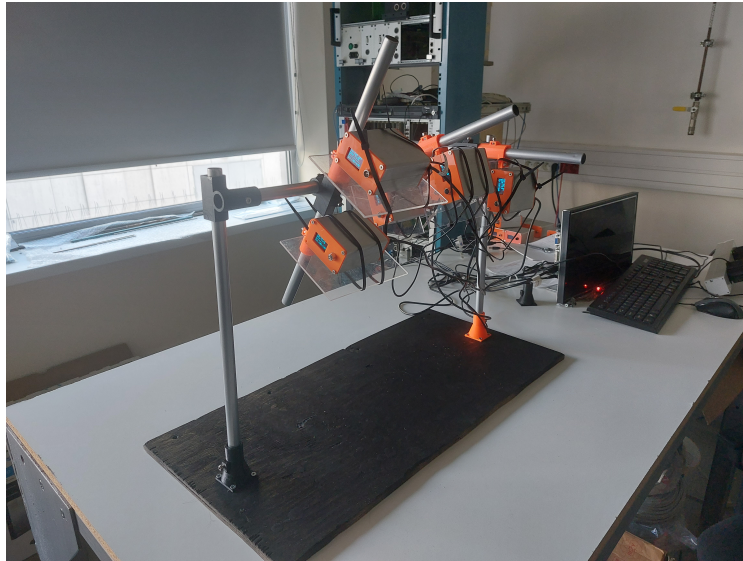


Figure 10: Measuring stand with three modules.

2.4 Measurement of Cosmic-Ray Flux

During measurement, detectors were working in pairs in so-called master-slave mode. In this mode, one detector (slave) counts a detection only when the other from its pair (master) also does so in the $30\mu\text{s}$ window. This allows us to have detections only on events where a muon passes two detectors nearly simultaneously. The time that takes a muon to travel between two CosmicWatches is significantly lower than $30\mu\text{s}$ (about 10^4 times smaller). We treat all events of detection of a muon in two detectors in a $30\mu\text{s}$ window as an event of one muon passing two detectors, as the probability of having two different muon passing in a $30\mu\text{s}$ window through two detectors is very low.

The master-slave mode is also essential for the measurement of the spectral density of the muon flux. Especially, it plays a significant role in the assessment of the solid angle of the incident muons. Since the cosmic ray flux is defined as

$$\vec{j} = \frac{dN}{dS dT d\Omega} \hat{e}_r, \quad (1)$$

where $\hat{e}_r$ is the unit vector along the muon velocity and dN is the number of muons reaching the infinitesimal surface dS in dT period, originated from the solid angle $d\Omega$. We need to integrate over the solid angle to obtain the total cosmic ray flux approaching the horizontal surface

$$j_H = \int_{\Omega} \vec{j} \cdot \hat{e}_z d\Omega, \quad (2)$$

where $d\Omega = \sin\theta d\theta d\phi$ and $\phi \in [0, 2\pi]$ is the azimuthal angle and also $\theta \in [0, \pi/2]$ is the polar angle, $\hat{e}_z$ is the unit vector in the zenith direction. The θ range covers only half of the sphere, because we assume that muons originate only from the atmosphere, not the ground. As mentioned in the Introduction we expect that the cosmic ray flux strongly depends only on the polar angle θ and this dependence has the following form

$$|\vec{j}(\theta)| = j_0 \cos^2\theta, \quad (3)$$

where j_0 is a constant. Thus, we need to collect muons from the well-defined solid angle. For this purpose, we have chosen the bottom detector in the detector pair to be the slave one. In this way, the solid angle Ω of muons reaching the bottom detector is completely determined by the surface of the upper (master) detector.

In order to perform a measurement of the polar angle dependence of the cosmic ray flux, we have firstly tested the compatibility of each pair of detectors. We have counted muons in the zenith direction using each pair of detectors and then compare results taking into account different efficiencies of detectors, i. e. we divided measured counts by the efficiencies of detectors used in the measurement (see Tabel 1). The obtained results were in excellent agreement (Table 3), therefore, we could perform the measurement for other polar angles simultaneously setting each detector pair at a different angle. In the analysis, we have assumed that the uncertainty of time measurement and efficiency is negligible compared to event counting. We have also assumed that the distribution of detected events may be approximated by the Poisson distribution. Hence, the uncertainty of measured n counts is given by $u_n = \sqrt{n}$.

Table 3: Results for the polar angle $\theta = 0^\circ$, where n - counts, t - time duration of measurement (without the dead time of detector), f - frequency taking into account the efficiency of detectors (i. e. we divided measured counts by the efficiencies of detectors used in the measurement).

Detectors Pair	n	t [s]	f [Hz]
Louis - Latenna	308	59057.26	(0.00874±0.00050)
Aurelia - MuonoLapka	493	59508.24	(0.01049±0.00047)
Pan Gruszka - Iwar	460	59570.22	(0.01129±0.00053)

3 Results and Their Analysis

In order to describe the spectral distribution of the muon flux, we have measured the muon flux with detectors set at the angles: -90° , -60° , -30° , 0° , 30° , 60° , 90° . Obtained results are shown in the Table 4. Unfortunately, for the larger polar angles such as -90° and 90° we detect muons approaching from both sides of the detector pair. To take this fact into account in the following analysis we have assumed that

the spectral distribution of muons is approximately symmetric. Therefore, we have reduced detected counts by half for the angles -90° and 90° . This assumption is not very accurate, but better analysis requires performing measurements outdoors, which will be explained in the Section 4. From the equation 2 one can derive the relation between the number of counts and the muon flux

$$n = \int_S dS' \int_0^T dt \int_{\Omega_0} \vec{j}(\theta) \cdot \hat{e}_n d\Omega = T \int_S dS' \int_{\Omega_0} \vec{j}(\theta) \cdot \hat{e}_n d\Omega, \quad (4)$$

where n should include the detector efficiency. However, the solid angle Ω depends on the surface element dS' . Therefore, the above-mentioned integral cannot be easily computed. To illustrate this problem we can consider the system of two detectors shown in the Figure 11 rotated in such a way that the normal vector of the detector surface is $\hat{n}_i = (\sin \theta_i \cos \phi_i, \sin \theta_i \sin \phi_i, \cos \theta_i)$. Let us consider the muon reaching the dS_1 surface element of the bottom detector, which previously passed the dS_2 surface element of the upper detector. In this way for the muon moving in the direction $\hat{n} = (\sin \theta \cos \phi, \sin \theta \sin \phi, \cos \theta)$ one can obtain

$$n_i = T \int_{S_1} dS_1 \int_{\Omega} (\vec{j}(\theta) \cdot \hat{n}) (\hat{n}_i \cdot \hat{n}) d\Omega = \frac{3j_0 T_i D^2}{2\pi} \int_{S_1} dS_1 \int_{S_2} \frac{((r_2 \sin \phi_2 - r_1 \sin \phi_1) \sin \theta_i + D \cos \theta_i)^2}{r_{12}^6} dS_2, \quad (5)$$

where the D is the distance between detectors and we have used the equation 3, relations $d\Omega = (\hat{n}_i \cdot \hat{n}) \frac{dS_2}{r_{12}^2}$ and also compute explicitly the dot products according to the Figure 11. The integral in the last equation may be computed only numerically. Thus, to find the estimation for j_0 , we have defined the auxiliary variable

$$\omega(\theta_i) = \frac{2\pi n_i}{3t_i D^2} = j_0 \int_{S_1} dS_1 \int_{S_2} \frac{((r_2 \sin \phi_2 - r_1 \sin \phi_1) \sin \theta_i + D \cos \theta_i)^2}{r_{12}^6} dS_2, \quad (6)$$

. The obtained results and fitting are shown in the Figure 12. From the fitted model we have found that $j_0 = (110 \pm 11) \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. Therefore, the total cosmic ray flux for the horizontal surface is equal

$$j_H = \int_{\Omega} j_0 \cos^2 \theta \cos \theta d\Omega = \frac{\pi}{2} j_0 = (174 \pm 17) \text{ m}^{-2} \text{ s}^{-1},$$

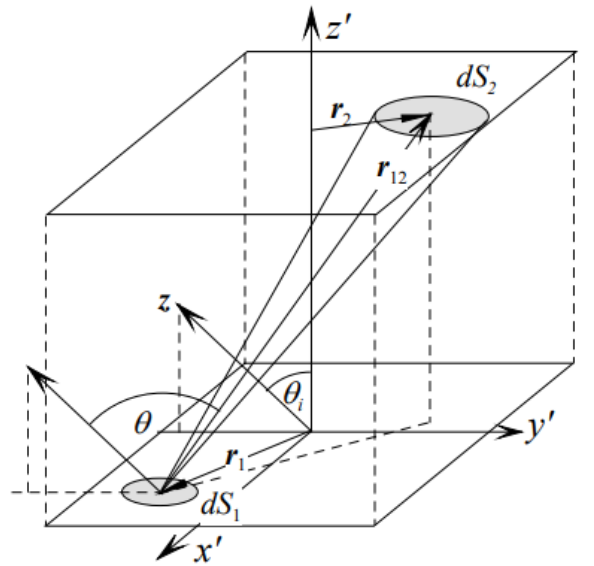


Figure 11: The scheme of the two detectors system rotated by the θ_i angle from the zenith direction, where the z axis is in the zenith direction and the z' axis is along the normal to the detectors surface, the muon is reaching the dS_1 surface element and it is moving along the $\hat{r}_{12}$ direction.

Table 4: The measured spectral distribution of the muon flux, where θ - the polar angle, n - counts, t - time duration of measurement (without the "dead time" of detector), f - frequency taking into account the efficiency of detectors.

θ [°]	n	t [s]	f [Hz]
-90	22	57343.10	0.00024
-60	103	86428.66	0.0017
-30	268	86770.44	0.0052
30	300	61441.62	0.0082
90	13	51353.14	0.0024
60	86	51937.56	0.00016

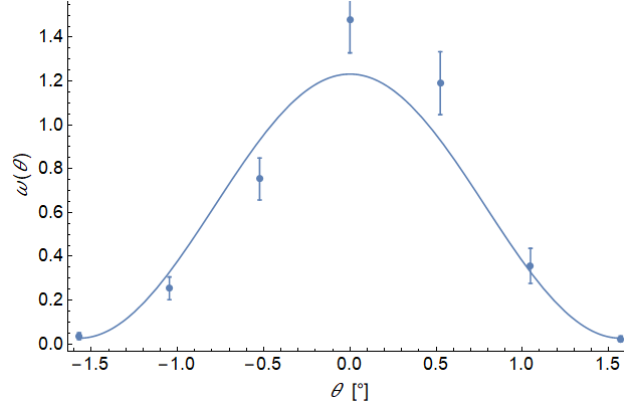


Figure 12: The measured auxiliary variable $\omega(\theta)$ as a function of the polar angle θ and the fitted model according to the equation 6 (blue line).

4 Discussion

Obtained estimation of the total cosmic ray flux for the horizontal surface is in excellent agreement with the expected value $\hat{j}_H = 180 \text{ m}^{-2}\text{s}^{-1}$. However, there is an easily noticeable asymmetry in the $\omega(\theta)$. Therefore, we computed the global asymmetry for this distribution given by the equation

$$a = \frac{f_+ - f_-}{f_+ + f_-}, \quad f_{+/-} = \sum_{\theta} f_{+/-\theta},$$

and its uncertainty is

$$u_a = \frac{1}{f_+ + f_-},$$

where $f_{+/-\theta}$ is the frequency $+/-\theta$, without the angle 0° . We have obtained the value $a = (0.5 \pm 5.2)$, which means that compared to the uncertainties of measured counts the asymmetry is negligible. However, the difference between positive and negative angles may be the consequence of conducting the experiment in the building. More precisely, detectors were aimed at the window for the positive angles and at the wall for the negative angles. This hypothesis may be easily checked, since we have used the portable Cosmic Watch devices as detectors and all experiments may be repeated outside the building. Prepared detectors set and the measurement stand may be also used as the exercise for the students within the Physics Laboratory. The mobile and user-friendly character is the great advantage of used Cosmic Watch devices. Moreover, the obtained accuracy is comparable to the stationary detectors placed in the Physics Laboratory II, which allow to measure the total horizontal flux with the accuracy $j_H = (256 \pm 29) \text{ m}^{-2}\text{s}^{-1}$.

5 Appendix

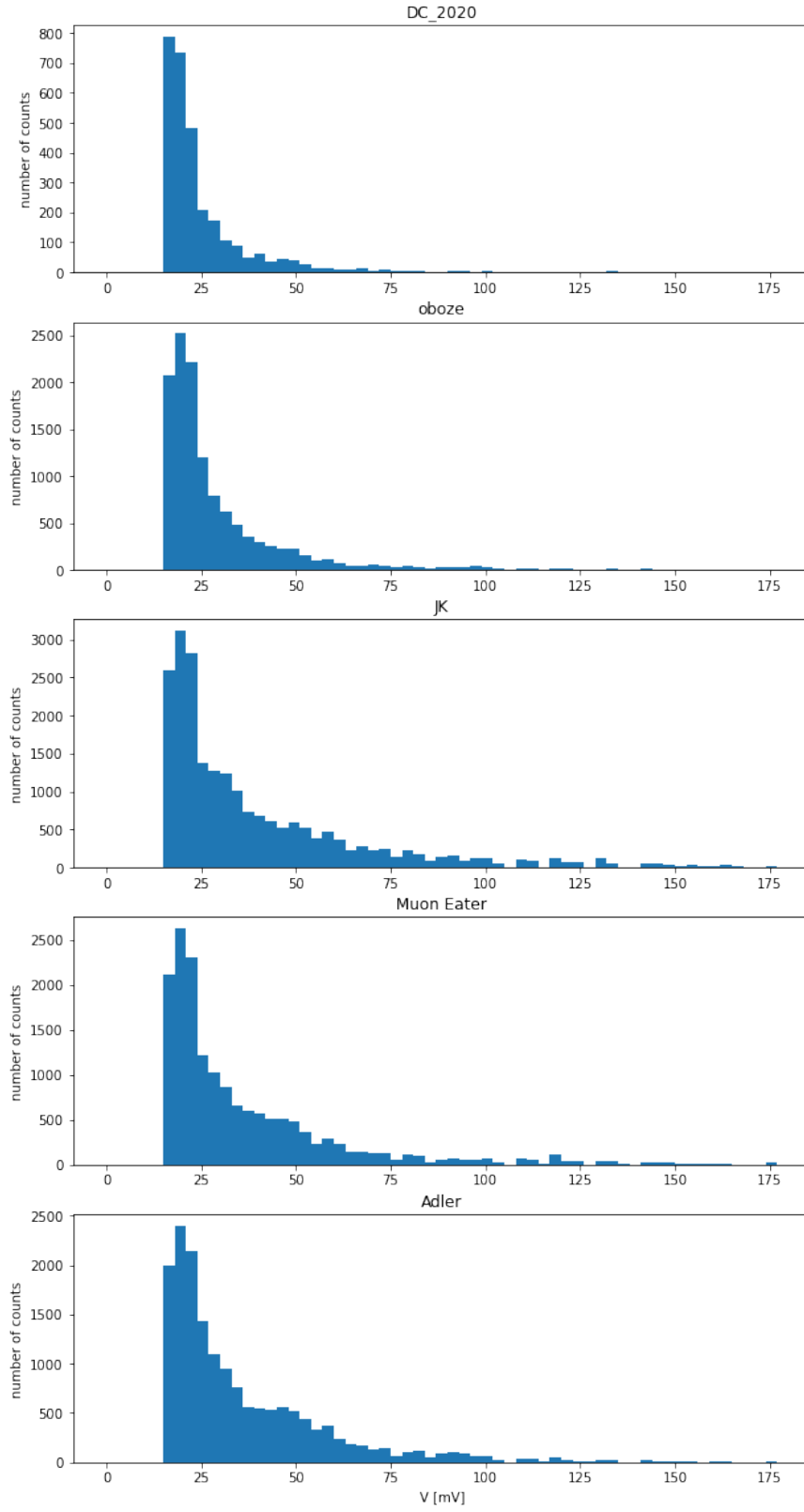


Figure 13: Amplitude distribution of signals registered by detectors: DC_2020, oboze, JK, Muon Eater and Adler.

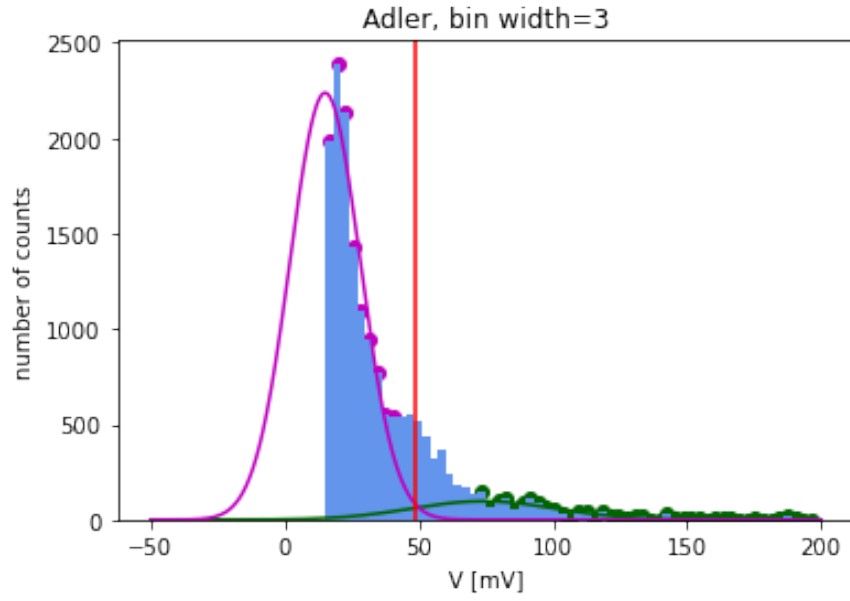


Figure 14: Histogram with amplitude distribution and fitted Gaussian functions for the counts for the energy corresponding to the photons (violet) and the energy corresponding to the muons (green) along with cut-off value (a vertical red line) for the Adler detector.

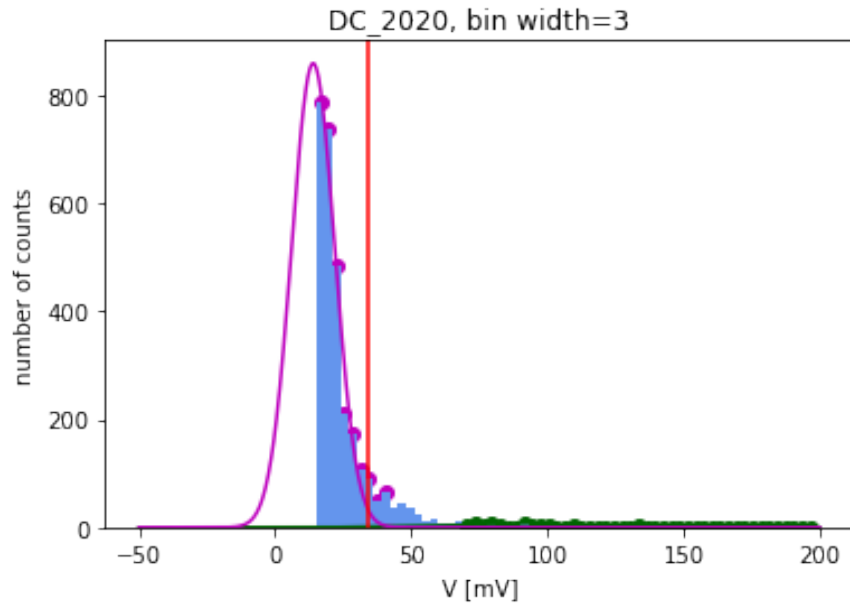


Figure 15: Histogram with amplitude distribution and fitted Gaussian functions for the counts for the energy corresponding to the photons (violet) and the energy corresponding to the muons (green) along with cut-off value (a vertical red line) for the DC_2020 detector.

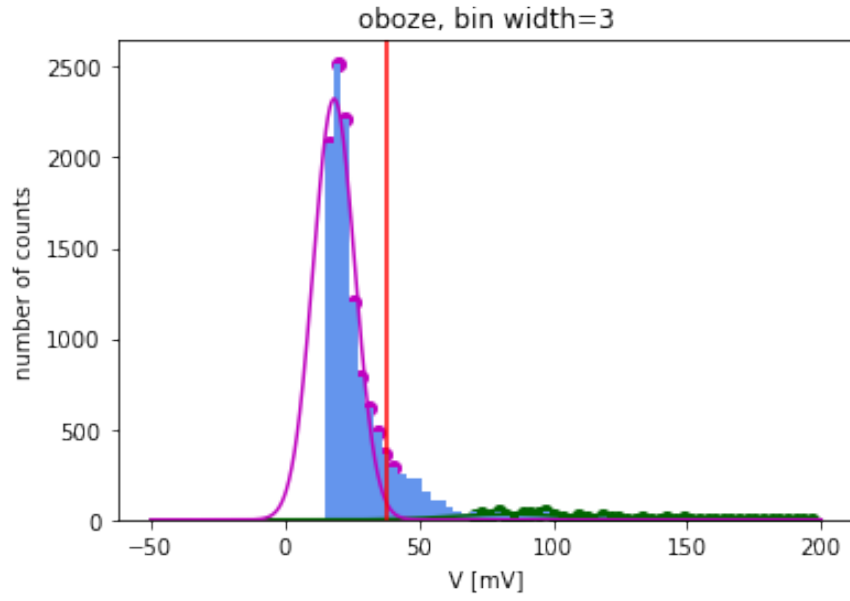


Figure 16: Histogram with amplitude distribution and fitted Gaussian functions for the counts for the energy corresponding to the photons (violet) and the energy corresponding to the muons (green) along with cut-off value (a vertical red line) for the oboze detector.

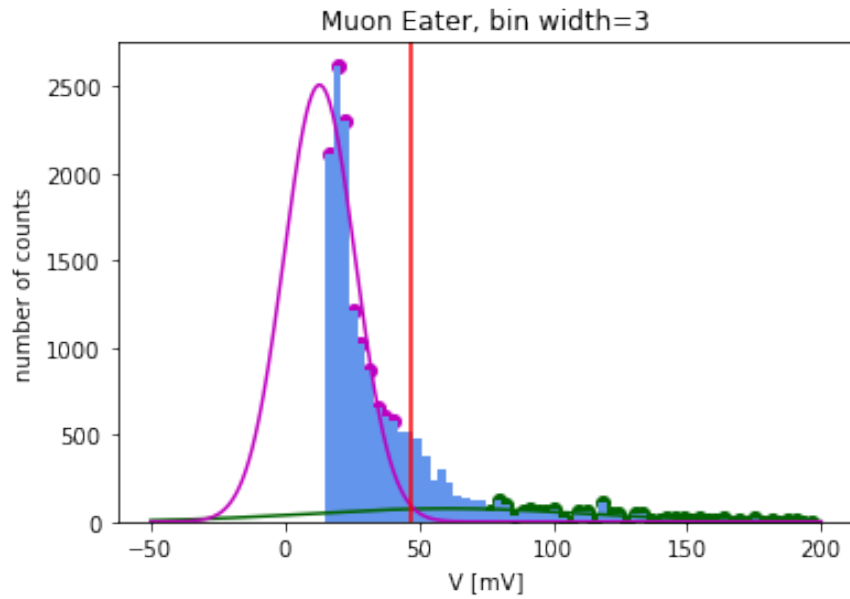


Figure 17: Histogram with amplitude distribution and fitted Gaussian functions for the counts for the energy corresponding to the photons (violet) and the energy corresponding to the muons (green) along with cut-off value (a vertical red line) for the Muon Eater detector.

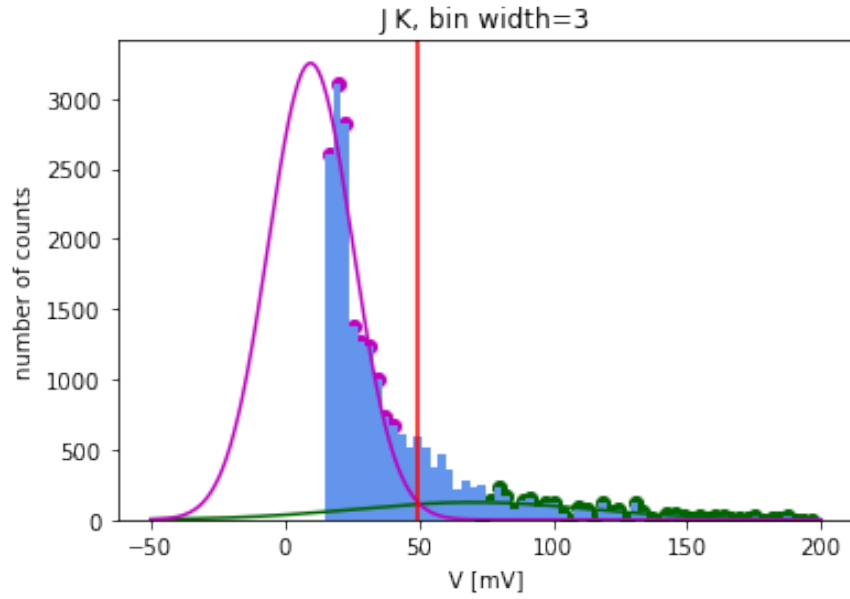


Figure 18: Histogram with amplitude distribution and fitted Gaussian functions for the counts for the energy corresponding to the photons (violet) and the energy corresponding to the muons (green) along with cut-off value (a vertical red line) for the JK detector.

References

- [1] <https://github.com/spenceraxani/CosmicWatch-Desktop-Muon-Detector-v2>
- [2] Axani, Spencer N., The Physics Behind the CosmicWatch Desktop Muon Detectors, 2019
- [3] <https://pdg.lbl.gov/2020/mobile/reviews/pdf/rpp2020-rev-cosmic-rays-m.pdf>