Alma Mater Studiorum · University of Bologna

School of Science
Department of Physics and Astronomy

Measurement of Muon Lifetime

Supervisors:

Prof. Luigi Guiducci
Dott. Marco Garbini
Dott. Federica Primavera
Dott. Marco Selvi

Submitted by:

Danish Alam
Robin Pelkner
Daniele Rossi

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Abstract

Muons are elementary particles which are naturally produced in the upper atmosphere of the earth due to cosmic rays. This experiment aims to determine the average lifetime using a plastic scintillator and photomultipliers to detect them and a triggering system for the time measurement.
HERE ARE THE RESULTS OF THE ANALYSIS!

Contents

Chapter 1

Introduction

This experiment aims to determine the lifetime of muons. Muons are produced by cosmic ray showers in the higher atmosphere. Incoming Protons react with the hadrons of the atmosphere and produce pions, which can decay into muons. Due to the high, relativistic velocities of the muons, they can reach the surface of the earth.

In this experimental setup, the incoming muons are slowed down and stopped by layers of iron and then detected with a plastic scintillator. A trigger logic is used to determine the lifetime of the various incoming muons.

This report is structured as follows: in this chapter, an introduction to the physical aspects of muons is given. Chapter 2 describes the used components and the experimental setup. In Chapter 3 the preliminary measurements for the calibration of the setup are described and their results are discussed. Chapter 4 discusses the composition of the experiment and the process of data taking, while Chapter 5 presents the data analysis. Chapter 6 concludes this report.

1.1 General introduction to muons

The standard model of elementary particles differentiates between quarks, leptons, and bosons. Quarks, as well as leptons, can be divided into three generations. The muons and the antimuon respectively are the second generation of leptons together with their each associated neutrinos. Like the electron, muons have an spn 1/2 and a negative elementary charge (a positive elementary charge for the antimuon). Although the similarities, both leptons differ concerning their masses and their lifetimes.
While the electron is a stable particle, the muon has a finite lifetime, which this experiment is supposed to detect. The lifetime, given as an average result of past measurements, is $\tau = (2.196\,981\,1 \pm 0.000\,002\,2)$ µs. Their mass is given as $m_\mu = (105.658\,374\,5 \pm 0.000\,002\,4)$ MeV, which is 206 times the mass of the electron [2].

1.2 Muons from cosmic ray showers

Muons are naturally produced in cosmic ray showers. When a particle strikes the hadrons in the upper atmosphere, they interact and produce a hadronic shower. These particles originate in various galactic and intergalactic sources like the sun, the Milky Way, and other galaxies. The cosmic ray is mostly protons, but also electrons and atomic nuclei. The protons hadronize mostly into π mesons, because they are the lightest mesons, but also into K mesons and other hadrons. The primary cosmic rays are completely hadronized at altitudes of 20 km. Because π mesons and K mesons are not stable with lifetimes in the order of magnitude of 10^8 s they decay very fast. For the decay into muons, the π mesons have a branching ratio of $\Gamma = (99.98770 \pm 0.00004)\%$, while the K mesons have a branching ratio of $\Gamma = (63.56 \pm 0.11)\%$ [2]. It should be noted that these decays into muons only occur with charged π and K mesons. Neutral Mesons are also produced in these showers, but they do not decay into charged muons. The decay of the π mesons takes place via the weak interaction

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\pi^- \to \mu^- + \bar{\nu}_\mu.$$

This process is analogous to K mesons. The muons also only decay via the weak interaction as follows

$$\mu^- \to e^- + \bar{\nu}_e$$
$$\mu^+ \to e^+ + \nu_e.$$

Because the muons have a longer lifetime, they can reach the surface of the earth and can be detected through their decay. A schematic with typical processes, which lead among other things to the production of muons, can be seen in Figure 1.1. Now that the particle is produced in the high atmosphere, even if their lifetime will not let them reach the ground, thanks to their relativistic speed time dilatation is enabled which extends their lifetime enough to let them arrive on the earth.
Suppose a factor $\beta = 0.999c$ and a muon lifetime $\tau = 2 \times 10^{-6}$ s, classically this is not enough. But since the beta factor is high enough we end up in the relativistic regime and we can calculate

$$\tau' = \frac{1}{\sqrt{1-\beta^2}}\tau = 1.4 \cdot 10^{-4}$$

which is a lot longer than the classical result would allow. Once they arrive we can prepare an apparat to detect them. The basic idea is that when a particle passes through matter they release part of its

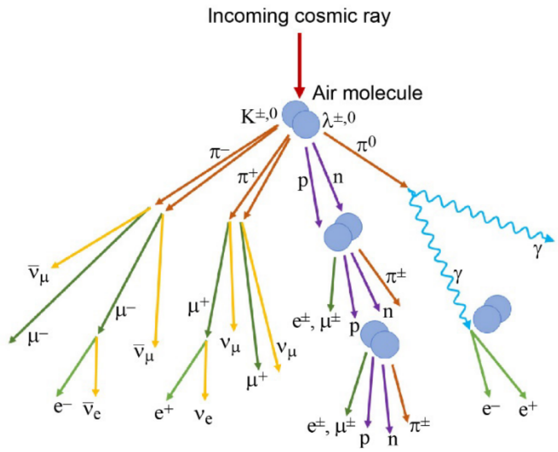


Figure 1.1: Typical shower processes after an incoming cosmic ray. The primary rays induce secondary particles by scattering with the molecules of the atmosphere. These secondaries can decay or scatter again with the atmosphere and produce more particles in the process. This is called a decay chain or a cosmic ray shower[1].

energy which is converted into new particles or radiation. The amount of released energy is explained by the Bethe Bloch Formula:

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{z^2}{\beta^2}[ln(\frac{2m_e\gamma^2 v^2 W_{max}}{I^2} - 2\beta^2 - \delta 2\frac{C}{Z})]$$

In general, a heavy, charged particle passing through matter loses energy through five mechanisms

1. Inelastic collision from atomic electron
2. Elastic scattering from nuclei
3. Cherenkov radiation
4. Nuclear reaction
5. Bremsstrahlung.

The last three are usually not included in the calculation because the cross-section of their reaction is really low. The transferred energy from the particle to the atom will cause ionization or excitation of them and we can construct an apparatus with specific material to take advantage of this process. In this case, a scintillator coupled with a photomultiplier is used.
A Scintillator is a device constructed with particular materials that exhibit a propriety called *luminescence* which consists of the ability to convert a certain form of energy in visible light. The characteristics of a good scintillator are

1. high efficiency for conversion of energy into fluorescent radiation

2. transparency to its fluorescent radiation so it can permit the transmission of the produced light
3. short decay constant
4. emission in a spectral range consistent with the spectral response of existing photomultipliers.

So thanks to this we can translate an unknown particle into something known. Since we want a signal out of this we can use the radiation emitted to create a current employing the photoelectric effect.
Then once these photoelectrons are produced they can create a current which usually is very weak and we want a device that can amplify it using a photomultiplier.
A photomultiplier consists of a cathode made of photosensitive material followed by an electron collection system, an electron multiplier section (or dynode string as it is usually called) and finally, an anode from which the final signal can be taken. When photons hit the photocathode electrons are released which are accelerated towards the next dynode causing more electrons to be released and so on till they reach the anode where the signal is produced. The photocathode is a device that converts incident light into a current of electrons by the photoelectric effect. To facilitate the passage of this light, the photosensitive material is deposited in a thin layer on the inside of the photomultiplier window which is usually made of glass or quartz. The process is modeled by the Einstein formula

$$E = hv - \phi$$

where E is the kinetic energy of emitted electrons, v is the frequency of incident light and ϕ the work function. It is clear that a certain minimum frequency is required before the photoelectric effect may take place.

Chapter 2

Experimental Setup

In our experiment, we are detecting mostly cosmic muons slowed down by an iron block, using three layers of scintillating detector attached to photomultiplier tubes (PMTs) via a light guide. The top two scintillators form a sandwich and are required to fire in coincidence. The choice to use an iron block was made due to its relatively high density, which makes muons suffer larger energy losses compared to the scintillator. Because of the many collisions experienced as the muons travel through the metal, some muons lose sufficient energy that they slow down until they can be *captured* by one of the atoms in the scintillator. The captured muon will eventually decay into an electron or positron and two neutrinos. The goal is to select only the muons that cross the top two scintillators, slow down in the metal and then stop and decay in the bottom scintillator. These charged muons passing through a scintillating material excite the vibrational motion of the molecules which, when de-energized, emit visible light photons (approximately one photon for every 100 eV deposited). The number of photons produced by scintillation is proportional (within statistical considerations) to the energy loss of the passing particle. Those photons will enter the PMT and produce electrons that form the electrical pulse we measure. The size of the electrical pulse in a PMT is proportional to the number of photons detected. To maximize the number of photons that reach the photocathode it is necessary that the scintillator, light guide, and photomultiplier tube all be wrapped in reflective foil. Also, to block external light the assembly is then covered by black tape.

Other than the detector itself, we use a NIM (Nuclear Instrument Modules) and a CAMAC (Computer Automated Measurement And Control) crate with appropriate cards and modules. All algorithms and tunings of the experiment are done within the NIM crate and CAMAC is used for the read-out. The NIM modules which are used can be summarized as follows:

HV power supply:
CAEN N470 Quad Channel NIM Programmable High Voltage Power Supply ($\pm 8\,\mathrm{kV}, 1\,\mathrm{mA}, \pm 3\,\mathrm{kV} 3\,\mathrm{mA}$). This module is the power supply to the photomultiplier tubes. Using the correct functions, we can select the channel and set the HV for each PMT.

Discriminator:
CAEN N840 Octa Channel Leading Edge Discriminator module; pulse width: 5-40 ns, and threshold 1-255 mV.
Given an analog input signal, the discriminator compares the amplitude with a threshold (in mV since it is amplitude). If the falling edge of the input signals overcomes the threshold then a LOGIC 1 signal is

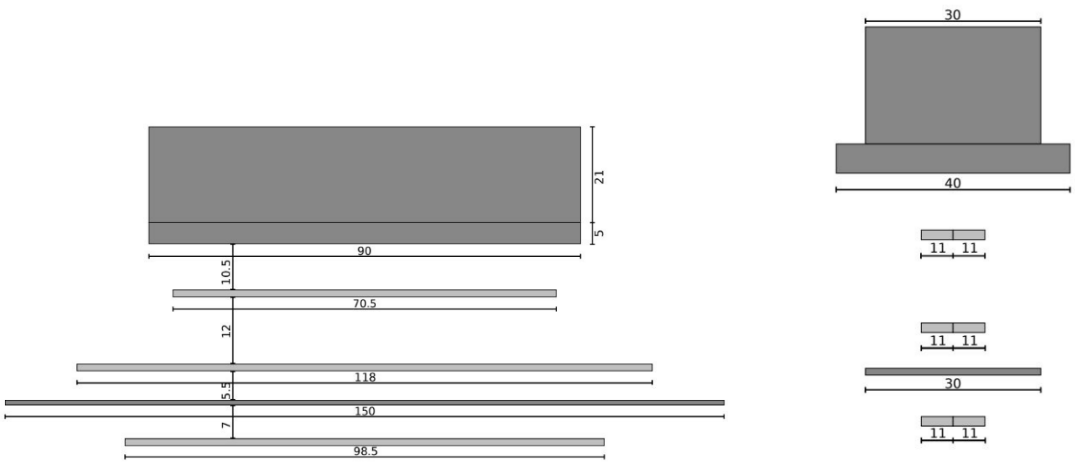


Figure 2.1: The experimental setup where it is shown in lateral and front view the absorber layers (dark grey) and the scintillator planes (light grey) with the dimensions in cm.

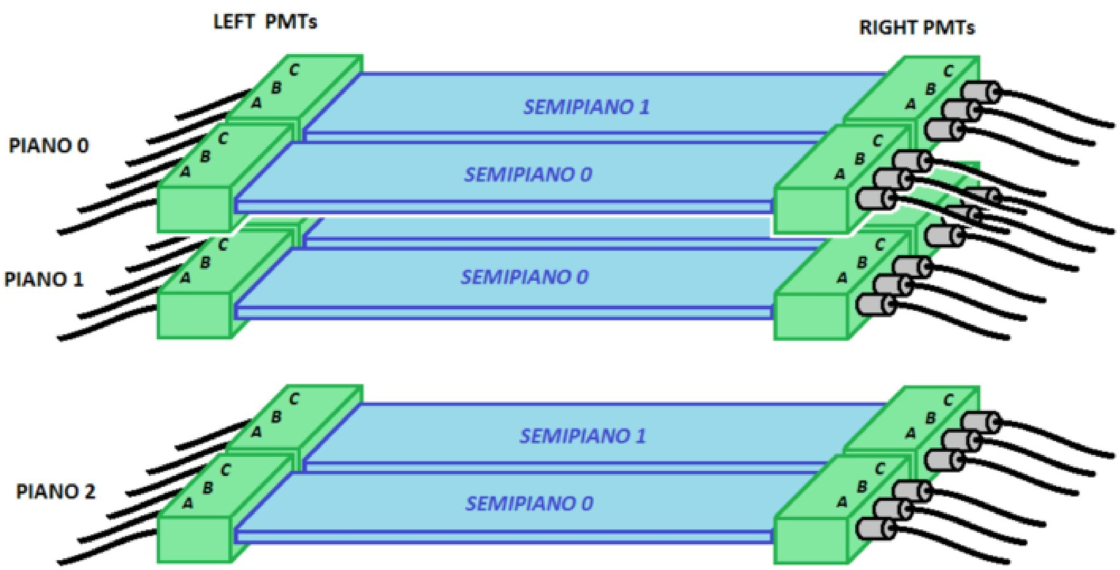


Figure 2.2: The experimental setup where it is shown in lateral and front view the absorber layers (dark grey) and the scintillator planes (light grey) with the dimensions in cm.

produced as output. If the signal is lower than the threshold, a LOGIC 0 is generated. The Standard LOGIC used by this module is the Nuclear Instrument Module Logic (NIM).

Logic Unit:
CAEN N405 3-fold logic unit module having 3 independent sections to perform logic AND/OR up to 4 logic signals in input.
It provides 1 linear OUT (width of the signals depending on input signals superposition), 2 fixed width (adjustable) OUT signals, 1 ANTI OUT signal, and 1 VETO input.
The first signal enters the LOGIC unit. During this time it is "1" the other signal arrives so there is Δt during which both signals are "1". This means the signals coincide and an AND signal is produced.

FI/FO:
CAEN N625 Quad Linear FAN-IN FAN-OUT module
The module has 4 identical sections. Each section has 4 inputs that can be fed with analog signals. Then for each section, there are 4 identical OUT signals. If only one IN is used the 4 OUT are the replica of the IN signal. If more than one IN is connected then the OUTs provide the sum of the IN signals. So each of the 4 sections of this module can be used to replicate a signal 4 times (4 OUT).

Counter/Scalar:
CAEN N1145 Quad Scaler and Preset Counter/Timer
Count 4 NIM or TTL level signals for a given time interval defined by the user. The user can follow the countdown and read the number of counts on displays.

Chapter 3

Preliminary Measurements

3.1 Working Voltage for the Photomultipliers

As a first step, the optimal working voltages for the photomultipliers (PMTs) have to be found. Two PMTs were chosen for this measurement as a sample from the whole detector, `R10B` and `R20A`. It is important to choose PMTs from different planes to make sure the measured signal is due to a particle crossing the detector. A schematic for the measuring circuit is shown in Figure 3.1.

Only signals measured with both PMTs are taken into account. To determine these coincidences logic

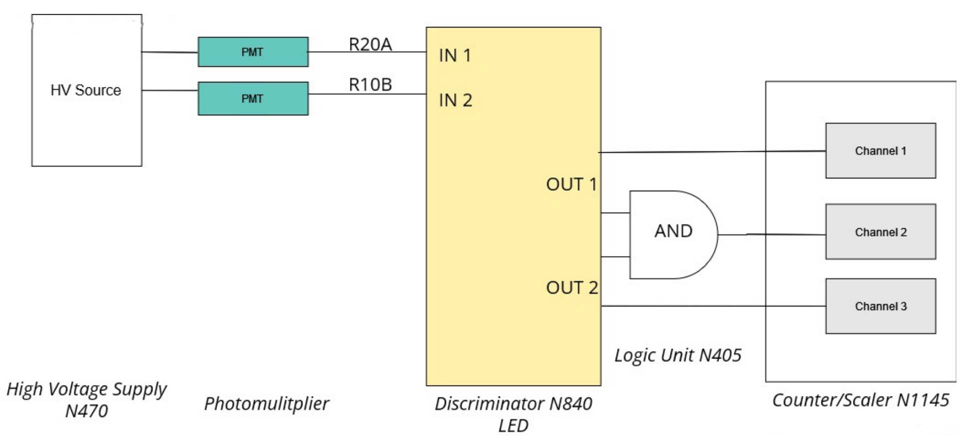
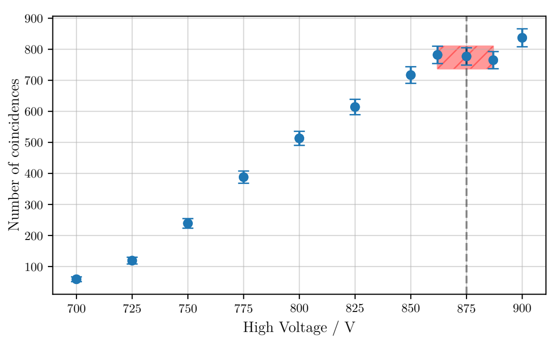


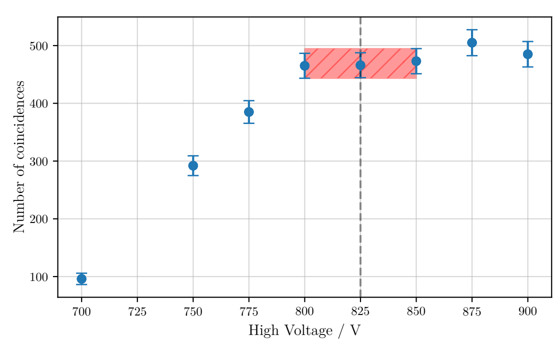
Figure 3.1: Schematic representation of the coincidence counting circuit for varying high voltage for the PMTs. The signal propagation is from left to right starting with the PMTs and their high voltage supply and ending with the scaler.

signals are needed. For those discriminators with a threshold of 40 mV are used. They convert the analogous signals of the PMTs into NIM standard signals. Using a logic unit module, the coincidences can be defined as the logic `AND` of both PMT signals. The NIM signals last for 40 ns each so the signals do not have to arrive at the same time but within 40 ns of each other. This is important because the muons arrive in the different planes at different times and not necessarily at the same distance from the

PMTs. Furthermore, the PMTs may have different delay times as well.
For the measurement, the `R10B` PMT works on a fixed high voltage of 775 V while the high voltage of `R20A` is varied from 700 V to 900 V. Each measurement lasts 200 s. The taken data is shown in Figure 3.2. A plateau can be found with 875 V corresponding to the middle value of it. This value is used as a fixed value for the `R20A` PMT when the threshold of the `R10B` PMT is varied in the same range of high voltages. The measurements for this PMT were each taken in 100 s due to time limitations. The central value of the plateau for this PMT is 825 V. Both measurements were also stopped when the PMTs are operating in the discharge region due to the high voltage to avoid damaging the PMTs.
The results are shown in Figure 3.2a and Figure 3.2b. All uncertainties are obtained assuming a Poissonian distribution, meaning $\sigma \propto \sqrt{N}$, where N is the number of coincidences. Because the output of the high voltage sources can fluctuate, the central values of the plateaus, 875 V for the `R20A` PMT and 825 V for the `R10B` PMT, can be used as the optimal working voltages to ensure a voltage output in the region of the plateau. Both results are slightly higher than the voltages used in the experiment because there are always three PMTs powered with the same voltage. For the `R20` PMTs a voltage of 830 V is used which is a deviation of 5.4% and for the `R10` PMTs a voltage of 780 V is used which corresponds to a deviation of 5.8%. Because of that, both measurements can be seen as successful measurements.



(a) Data of the `R20A` PMT. The central value of the plateau is 875 V.



(b) Data of the `R10B` PMT. The central value of the plateau is 825 V.

Figure 3.2: Measured number of coincidences regarding varying high voltages of the `R10B` PMT and the `R20A` PMT. The dashed line indicates the central values of each plateau. The striped red areas mark the found plateaus.

3.2 Threshold measurements

After obtaining the optimal working voltages was found, the determination of the optimal threshold voltage of the chosen PMTs started. A good determination of the threshold is necessary to suppress electronic noise on the one hand, but also to make sure that real signals are not filtered as well on the other hand. So the threshold can neither be too low nor too high.
It should be noted that it is not possible to use only one PMT, but always the sum of the three PMTs of each halfplane. Similar to the step before, a counting experiment of coincidences concerning the threshold voltages is conducted. This time the circuit arrangement is shown in Figure 3.3 is used. The

PMTs are powered using the working voltages given in the laboratory as an average optimal working voltage for three PMTs.
In principle, the threshold of the discriminator of one plane is kept fixed at 15 mV, while the threshold of

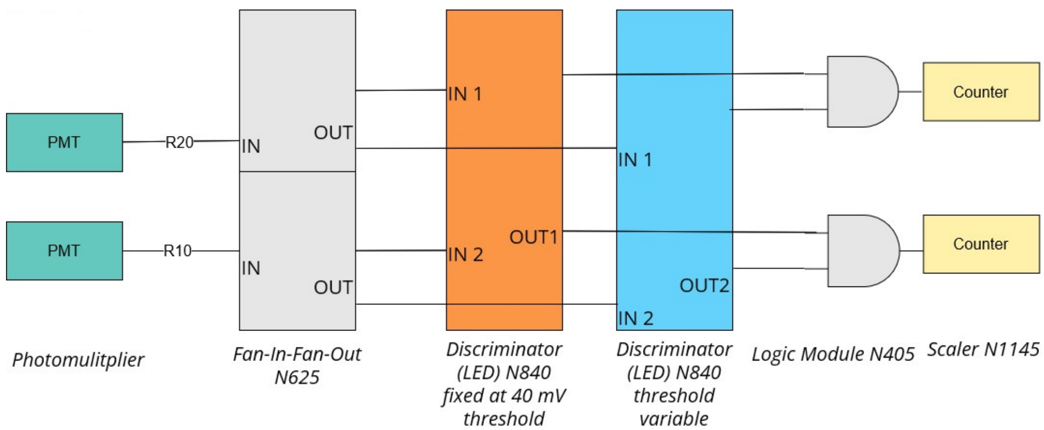


Figure 3.3: Schematic representation of the electronic circuit used to find the optimal threshold voltage .The signal flows from left to right, starting with the PMTs and Ending with the scaler.

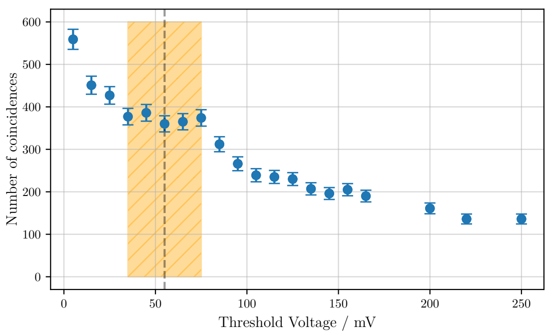
the other discriminator is being varied from 5 mV to 250 mV in irregular steps. Using a discriminator and a Fan-in-Fan-out system as shown in Figure 3.3, it is possible to vary the threshold of the discriminators of both PMT planes at the same time and therefore cutting the measurement time in half. Each counting measurement was conducted in 60 s.
The results for the `R10` and `R20` planes can be seen in Figure 3.4. Results from other planes have to be taken from Appendix A, figures Figure A.1 to Figure A.6.

The data shows a higher number of coincidences at low threshold voltages, which declines with

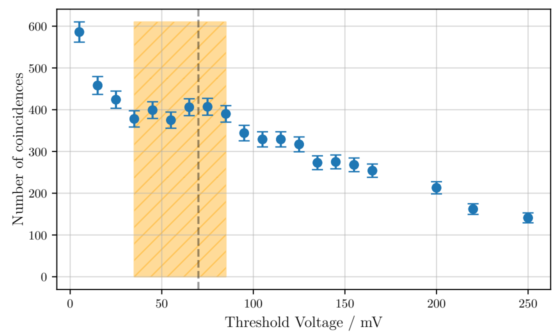
Table 3.1: Overview of optimal threshold voltages for each plane.

Plane	Voltage / mV	Plane	Voltage / mV	Plane	Voltage / mV
R00	50	R20	55	L01	55
R10	70	R21	55	L11	75
R10	*45*	L00	30	L20	50
R01	55	L10	35	L21	50
R11	60	*L10*	*60*		

rising voltages. This behavior is the same for all PMTs although not all curves show it that clearly. Also, a plateau of optimal threshold voltages can be seen. From the middle of this plateau, a threshold voltage has to be chosen as the optimal threshold value. As before the uncertainties will be taken into consideration using the Poissonian error. The optimal threshold voltages of all PMTs are shown in Table 3.1. Note that for the `L10` PMTs and the `R10` PMTs two measurements were taken. Thus, in these cases, only the value from the curve where it is easier to detect where the plateau is will be taken into consideration. The other values are marked italic in the tabular.



(a) Data of the `R20` PMTs. The central value of the plateau is 55 mV.



(b) Data of the `R10` PMTs. The central value of the plateau is 70 mV.

Figure 3.4: Measured number of coincidences concerning varying threshold voltages of the `R10` PMTs and the `R20` PMTs. The dashed line indicates the central values of each plateau. The striped orange areas mark the found plateaus.

3.3 TDC callibration

Chapter 4

Trigger Logic and Data Taking

Chapter 5

Data Analysis

Chapter 6

Final Results and Conclusions

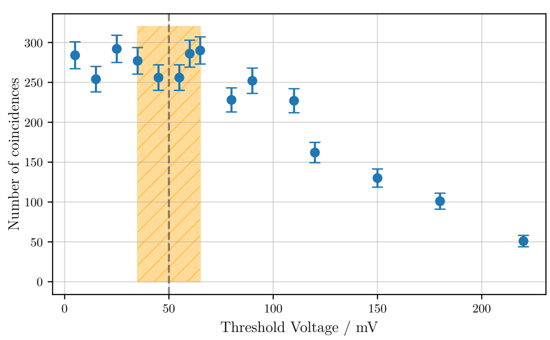
Bibliography

[1] J.D. Wrbanek and S.Y. Wrbanek. “Space Radiation and Impact on Instrumentation Technologies”. In: (2020).

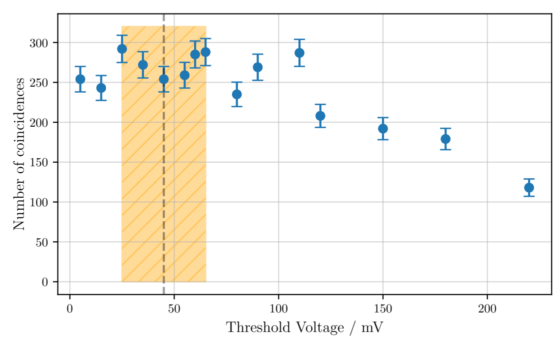
[2] P.A. Zyla et al. “Review of Particle Physics”. In: *PTEP* 2020.8 (2020). and 2021 update. DOI: `10.1093/ptep/ptaa104`.

Appendix A

Threshold voltages of the PMTs

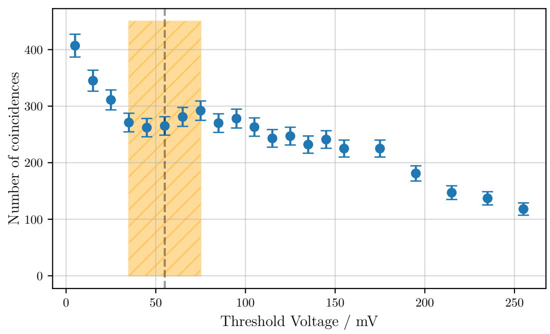


(a) Data of the `R00` PMTs. The central value of the plateau is 50 mV.

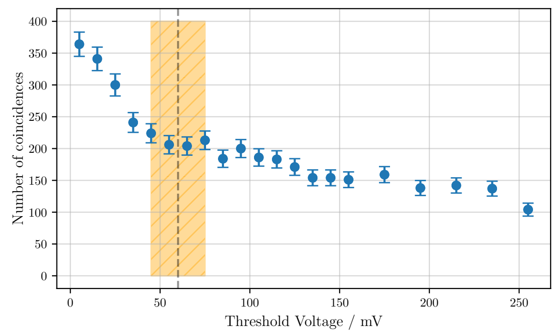


(b) Data of the second measurement of the `R10` PMTs. The central value of the plateau is 45 mV.

Figure A.1: Measured number of coincidences concerning varying threshold voltages of the `R00` and `R10` PMTs. The dashed line indicates the central values of each plateau. The striped orange areas mark the found plateaus.

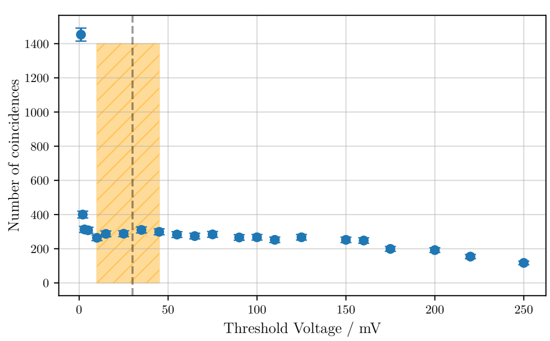


(a) Data of the `R01` PMTs. The central value of the plateau is 55 mV.

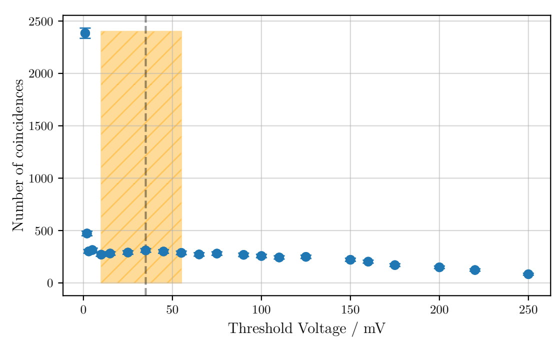


(b) Data of the `R11` PMTs. The central value of the plateau is 60 mV.

Figure A.2: Measured number of coincidences concerning varying threshold voltages of the `R01` and `R11` PMTs. The dashed line indicates the central values of each plateau. The striped orange areas mark the found plateaus.

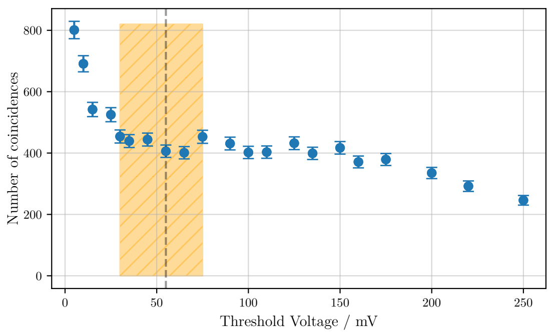


(a) Data of the `L00` PMTs. The central value of the plateau is 30 mV.

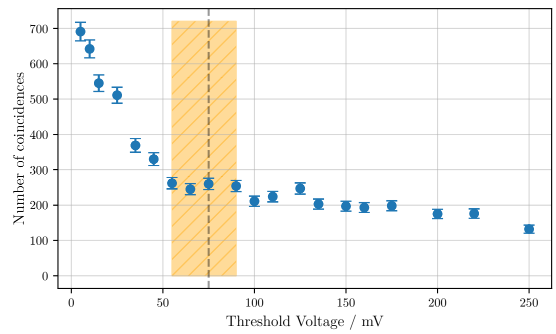


(b) Data of the `L10` PMTs. The central value of the plateau is 35 mV.

Figure A.3: Measured number of coincidences concerning varying threshold voltages of the `L00` and `L10` PMTs. The dashed line indicates the central values of each plateau. The striped orange areas mark the found plateaus.

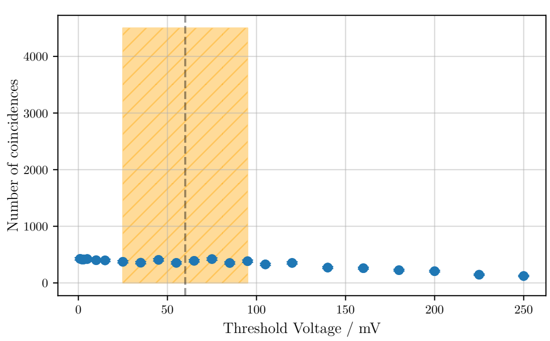


(a) Data of the `L01` PMTs. The central value of the plateau is 55 mV.

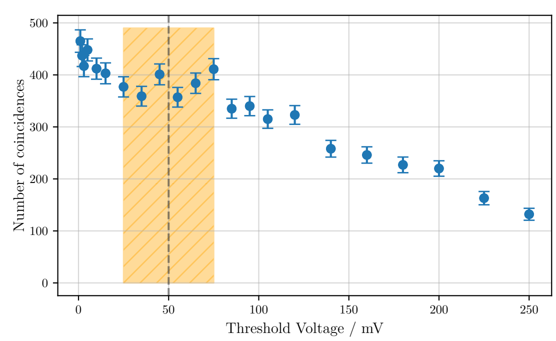


(b) Data of the `L11` PMTs. The central value of the plateau is 75 mV.

Figure A.4: Measured number of coincidences concerning varying threshold voltages of the `L01` and `L11` PMTs. The dashed line indicates the central values of each plateau. The striped orange areas mark the found plateaus.

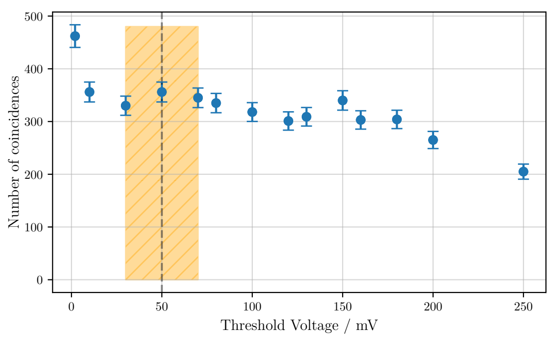


(a) Data of the second measurement of the `L10` PMTs. The central value of the plateau is 60 mV.

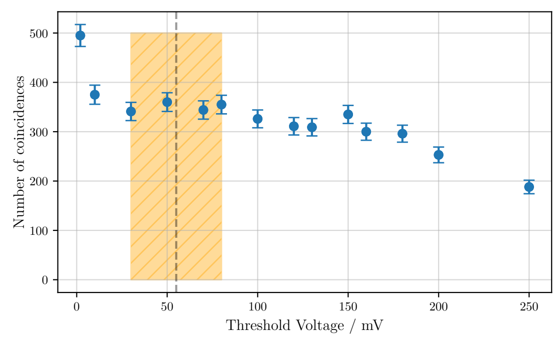


(b) Data of the `L20` PMTs. The central value of the plateau is 50 mV.

Figure A.5: Measured number of coincidences concerning varying threshold voltages of the `L10` and `L20` PMTs. The dashed line indicates the central values of each plateau. The striped orange areas mark the found plateaus.



(a) Data of the `L21` PMTs. The central value of the plateau is 50 mV.



(b) Data of the `R21` PMTs. The central value of the plateau is 55 V.

Figure A.6: Measured number of coincidences concerning varying threshold voltages of the `L21` and `R21` PMTs. The dashed line indicates the central values of each plateau. The striped orange areas mark the found plateaus.