IEEE NPSS
Real Time School

Time-of-Flight
Data Acquisition Lab

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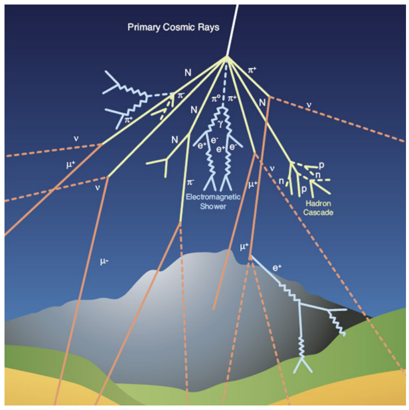
1 Introduction



This lab teaches you how to measure the speed and direction of cosmic muons generated in the upper atmosphere of the earth with the Time-of-flight (ToF) technique. Two scintillator plates are read out by silicon photomultipliers (SiPM) each on two sides. In a first measurement, the time difference between the signals on both plates is measured to determine the speed of the muons, while in a second measurement the two plates are rotated to measure the direction of the muons.

2 Equipment

2.1 Silicon Photomultiplier (SiPM)

SiPM are photon-counting devices made up of multiple avalanche photodiodes (APD) working in Geiger mode. A photon impinging on the silicon surface creates an electron-hole pair through ionization. These carries are then accelerated by a high voltage and create secondary electron-hole pairs (avalanche effect). This process continues and give a gain of 10^5-10^6, so a single photon can generate a measurable electrical signal.

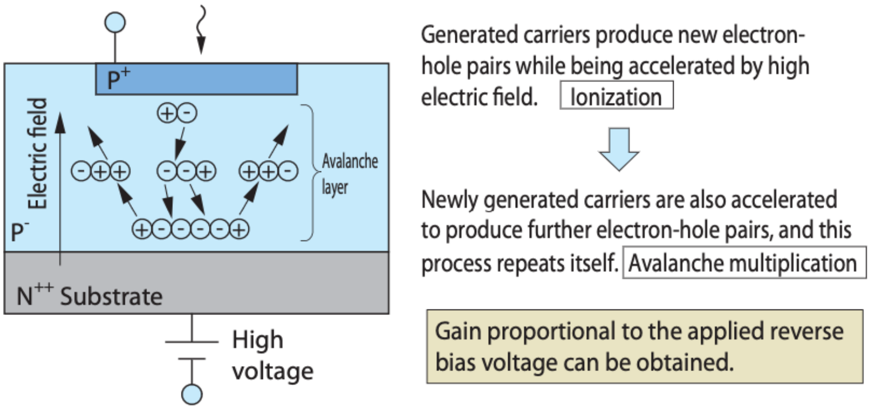


Figure 1: Working principle of an avalanche photodiode (source: Hamamatsu MPPC Data Sheet)

The APD is operated in Geiger mode, so the device goes in breakdown mode where it becomes conductive even if operated in reverse polarity. To prevent damage of the diode, a quench resistor is used to in series (see Figure 2). If the current goes above a certain limit, the voltage drop across the resistor becomes so big that the voltage across the diode drop below the breakdown voltage and the avalanche stops. After a certain recovery time, the diode becomes sensitive again. A single diode goes into breakdown independent from the number of primary photons and is therefore not suited to measure the amount of light and therefor the energy a particle deposits in a scintillator. To overcome this problem, several APDs are combined on a single chip. This arrangement is called Silicon Photomultiplier (SiPM) or Multi-Pixel Photo Detector (MPPC).

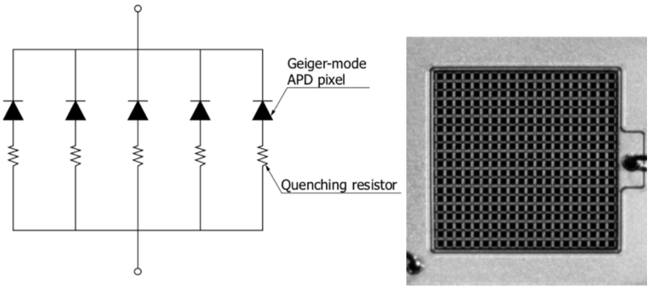


Figure 2: SiPM with many APDs each having its own quench resistor. The right picture shows a photograph of a real SiPM.

2.2 Scintillator

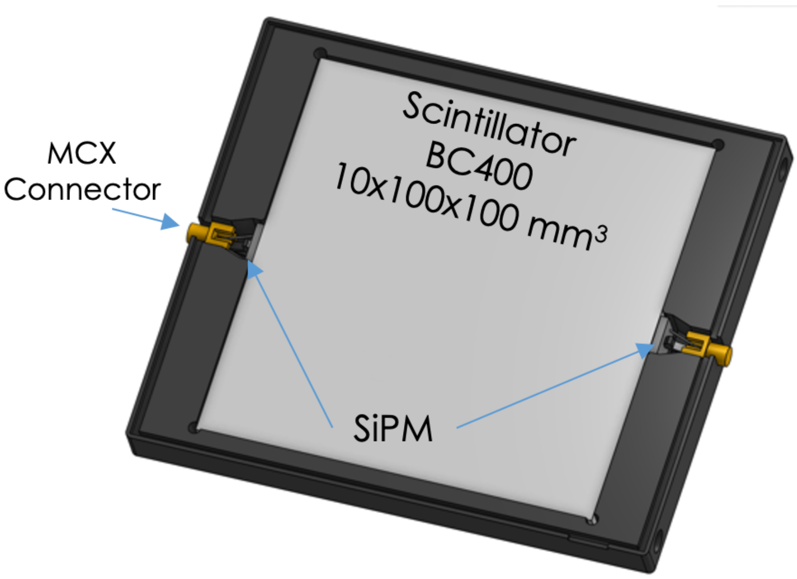


Figure 3: Scintillator coupled to two SiPMs

2.3 WaveDREAM Board

The WaveDREAM board is an integrated data acquisition board developed at the Paul Scherrer Institute, Switzerland. It contains 2 x DRS4 chips which sample the input signal with up to 5 GS/s. It has amplifiers with variable gain for each channel to digitize directly signals from silicon photomultipliers (SiPM). An integrated high voltage board devlivers the ~50 V bias voltage for the SiPMs. The board is read out via Gigabit Ethernet to a PC or a RaspberryPi computer.

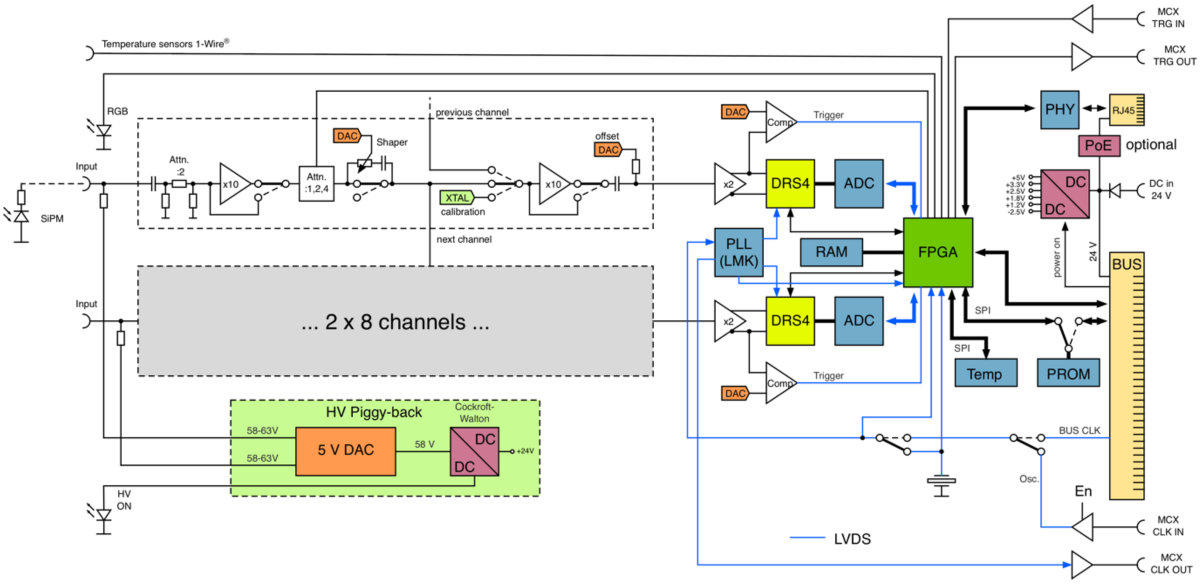


Figure 4: Schematics of the WaveDREAM Board with 16 input channels, ADC, DRS4 and FPGA

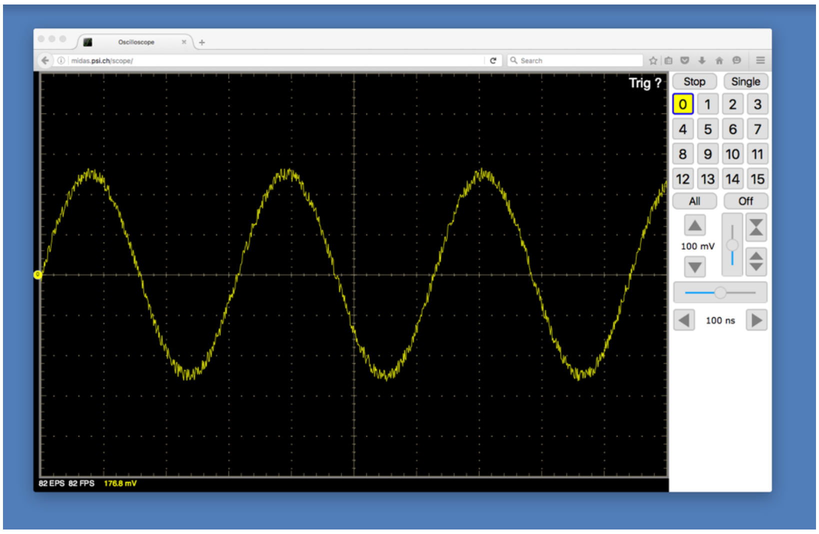
Figure 5: [Left side]: WaveDREAM board (bottom) with 240V high voltage Cockroft-Walton Generator piggy-back (top). [Right side]: Boxed WaveDREAM boards

2.4 RaspberryPi

Figure 6: PaspberryPi Computer

The RaspberryPi Computer runs the WaveDREAM Server Program (wds) to receive the individual data packets from the WaveDREAM board and make the waveforms available to a web browser based oscilloscope application.

2.5 WDS Oscilloscope



The oscilloscope application has built-in measurement functions with which one can analyze the signals coming from particle detectors.

2.6 I-V Curve

The current flowing through a SiPM depends on the voltage. The higher the voltage, the more ionization inside the silicon and the higher the current. At a certain voltage, the Geiger-Mueller region starts, where we have full ionization of a SiPM pixel. This is called the "breakdown-voltage" V_b. One can measure this breakdown voltage by recording a curve of current vs. voltage (see Figure 7). If time is left, the I-V curve can be recorded by changing the high voltage and reading the current for each channel as described later. The typical operation voltage is the $V_{op} = V_b + 3V$. Please make sure not to exceed a current of 1.5 uA!

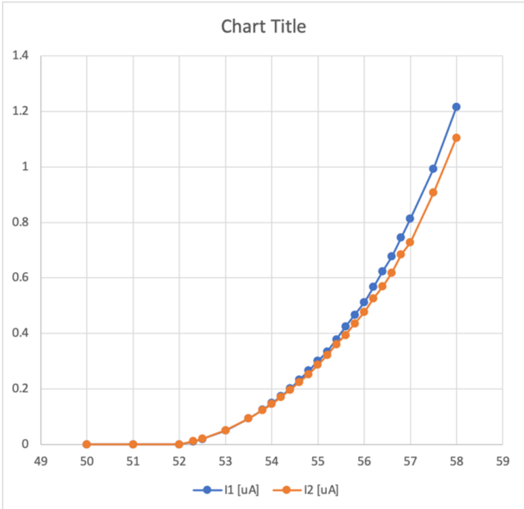
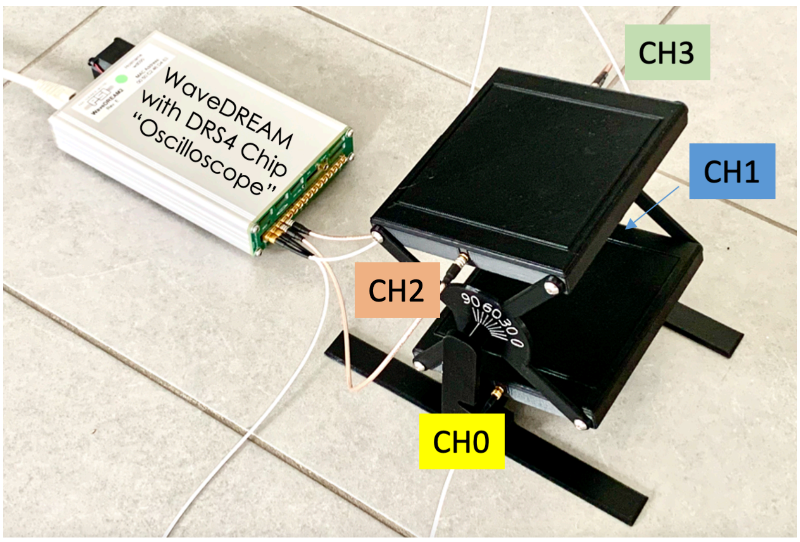


Figure 7: Typical I-V curve of a SiPM

3 Measurement

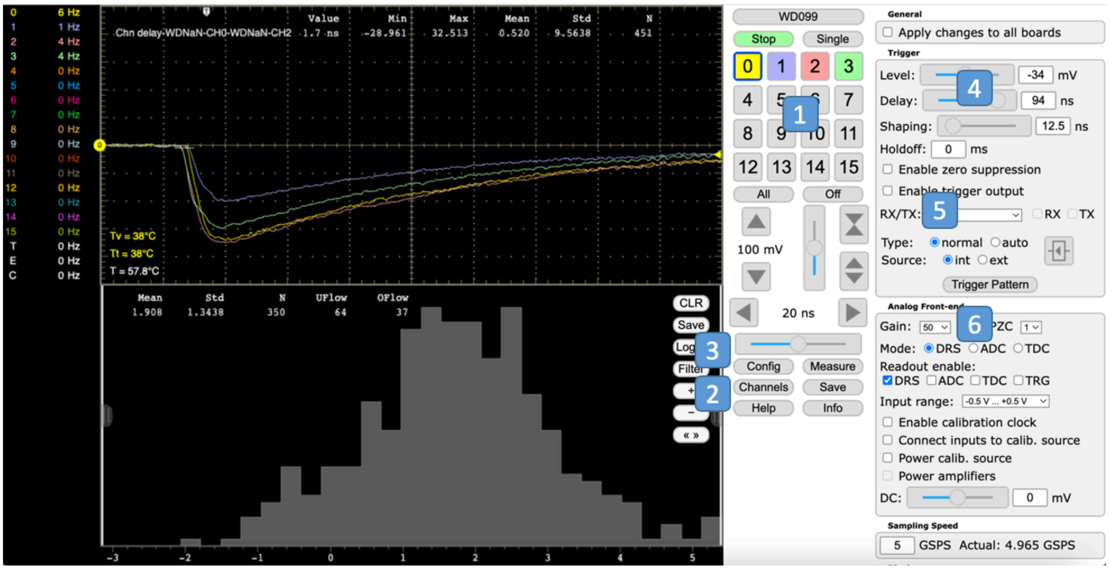
3.1 Preparation

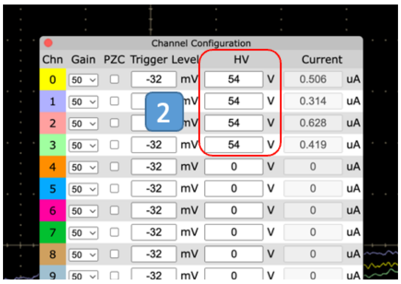
Please make sure all cables and devices are connected as shown in the following picture. The lower scintillator plate should be connected to channel 0 and 1 (CH00, CH01) to the silver data acquisition board, and the upper plate must be connected to CH02 and CH03.



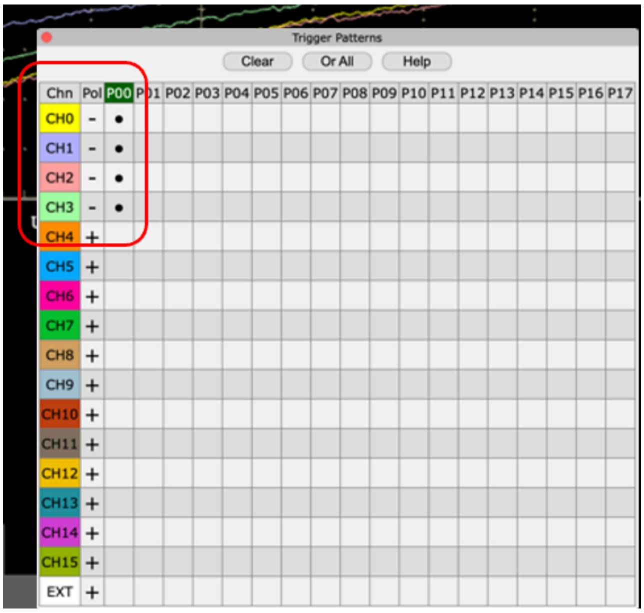
Now connect your browser to the RaspberryPi computer of your setup using the URL printed on the cover page of this manual. Make sure not to connect to the Pi of your neighbour! Then, configure the DAQ board according to following scheme (note the blue labels on the pictures below):

1. Turn channel 0, 1, 2, 3 on, all other channels off (must be grey)
2. Click on "Channels" to reveal the channel configuration panel. Set the HV of the first four channels to the value printed on the detectors. Usually either 54 V or 56 V. Make sure to have some current flow of 0.2-0.7 µA. If there is no current, report to your instructor.
3. Click on "Config" to reveal the configuration panel
4. Set the Trigger Level to -45 mV and the Delay to 94 ns
5. Set the Trigger Type to "normal"
6. Set the Gain to 50



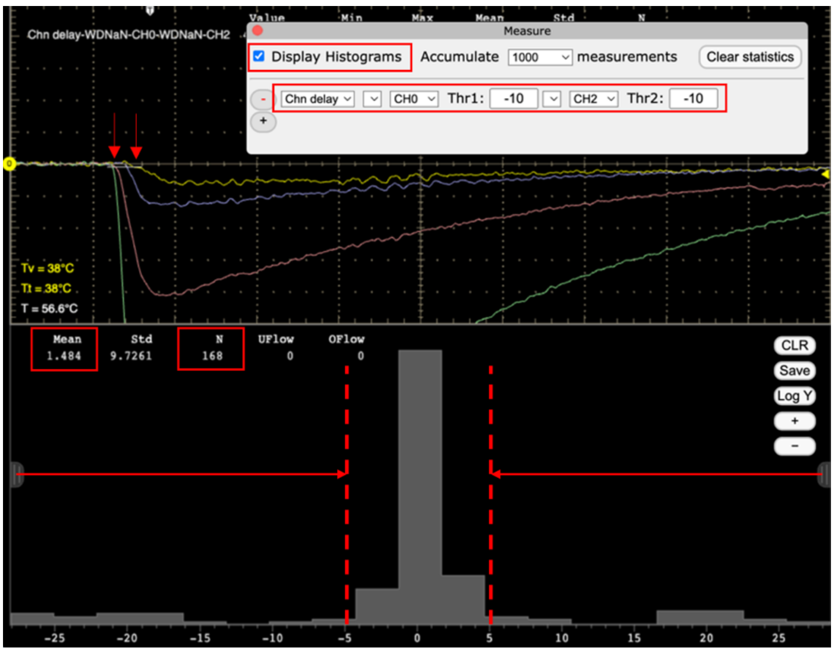


Next configure the trigger. Click on "Trigger Pattern" to reveal the trigger configuration page blow.



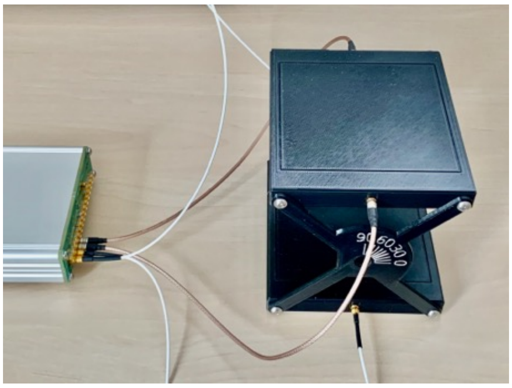
Here, switch the polarity of CH0-CH3 to negative ("-") and turn the coincidence on (solid dot under the "P00" header). This requires all four channels to carry a signal to trigger the board. Make sure all other Pxx columns are grey (inactive).

Now define the time measurement. Click on "Measure", then click on "+" to add a new measurement. Select "Chn delay", then "CH0", Thr1: -20, "CH2", Thr2: -20. This defines a channel delay measurement between channels 0 and 2 (not 1!) which are the lower and upper scintillator plates. The threshold for the time measurement is set to -20 mV. Turn on "Display Histograms". If everything works correctly, you should see a peak around "0" in the bottom histogram after a few minutes. Now use the "handles" left and right of the histogram to restrict the X-axis from -5 to +5 ns. This eliminates any wrong pulses coming from electrical noise etc. Please note the "Mean" of the histogram which is 1.484 ns in the example below and the number of events "N" which is 168 in the example. You will use your values to do the following measurements.

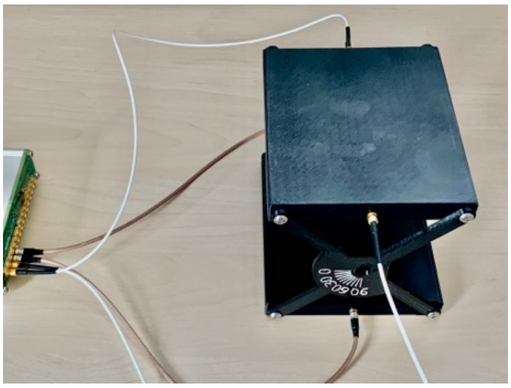


3.2 Measurement 1: Speed of Cosmic Muons

To measure the speed of cosmic muons, the time of the signal of the lower plate can be subtracted with the time of the signal on the upper plate. This is effectively done in the histogram above and can be read under "Mean". Unfortunately, the cables do not have exactly the same length, which adds to the time measurement and causes a large uncertainty. To cancel this errors, two measurements must be made, one with a normal orientation of the detector, and one with the "upside-down" orientation, see below:



Normal orientation



Inverted orientation

For each measurement, take at least 200 events and note the "Mean" of each histogram. This takes about 15 minutes. To avoid any noise events far at left or right, restrict the X-axis to -5 ns to +5 ns by dragging the handles on the left and right of the histogram towards the middle.

After you wrote down the mean of the histogram, rotate the detector upside-down and clear the histogram bit hitting "CLR". Now repeat the measurement with 200 events and note the new mean. Then calculate the speed of the muons as a percentage of the speed of light (3×10^8 m/s), assuming that the detector plates are 10 cm apart:

Difference Measurement

Case A:

$\Delta t_A = (t_{0,A}+t_{c0}) - (t_{2,A}+t_{c2}) = d / v$

Case B:

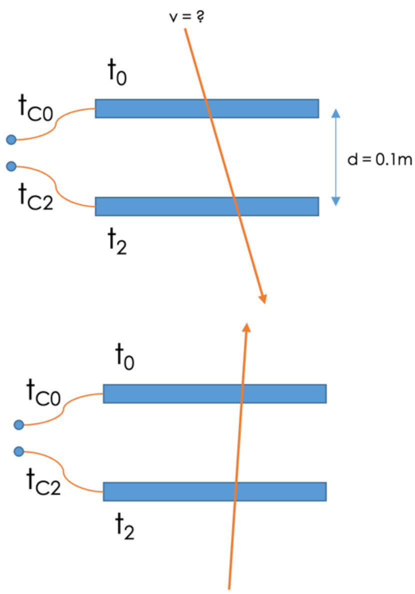
$\Delta t_B = (t_{0,B}+t_{c0}) - (t_{2,B}+t_{c2}) = d / (-v)$

Difference:

$\Delta t_A - \Delta t_B = (t_{0,A}+-t_{0,B})-(t_{2,A}+-t_{2,B}) = 2d / v$

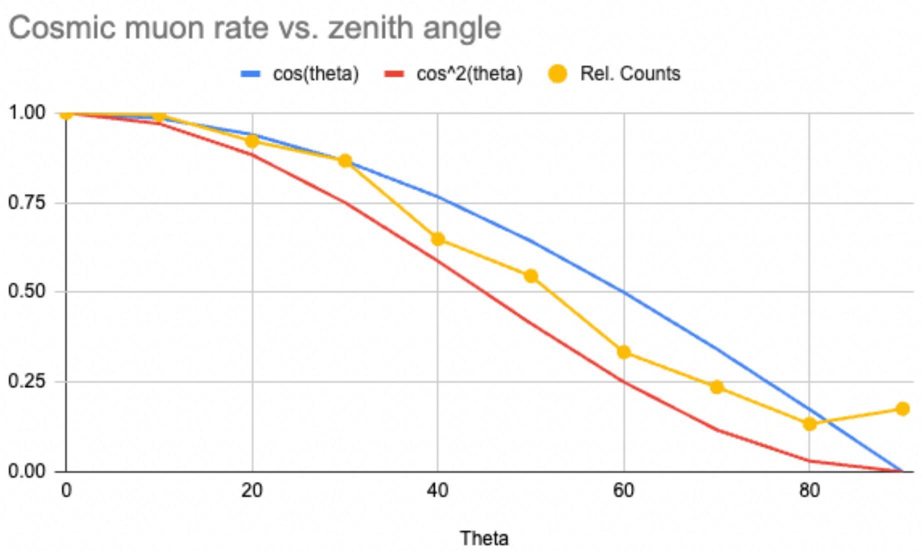
→ $v = 2d / (\Delta t_A - \Delta t_B)$

Task: measure v in % of c (= 3×10^8 m/s)



3.3 Measurement 2: Direction of Cosmic Muons

Measure the direction of cosmic muons. The coincidence between the two scintillator plates effectively selects muons travelling through both plates, so it defines a direction. Let's rotate the scintillator plates in steps of 10 degrees and take events for 5 minutes each. Write down the number of events N_i for each measurement (i=0, 10, 20, … 90). Then normalize your count rates to 0…1 by dividing each N_i by N_0. Then plot the counts vs. angle using some spreadsheet software (like Excel or Google Sheets https://sheets.google.com). Overlay the normalized counts (divide each count with the number of events at zero degrees) with a $\cos(\theta)$ curve and $\cos^2(\theta)$ curve to see which one fits better. You should get a plot similarly to this one:



If you cannot access google sheets, you can draw your measurements in the chart above.

Critically question your data, and think about the following questions:

- Why does the rate not drop to zero at 90 degrees?
- Why are the points not on a smooth line?
- If you measure again, will you get exactly the same points?
- How could the experiment be improved?