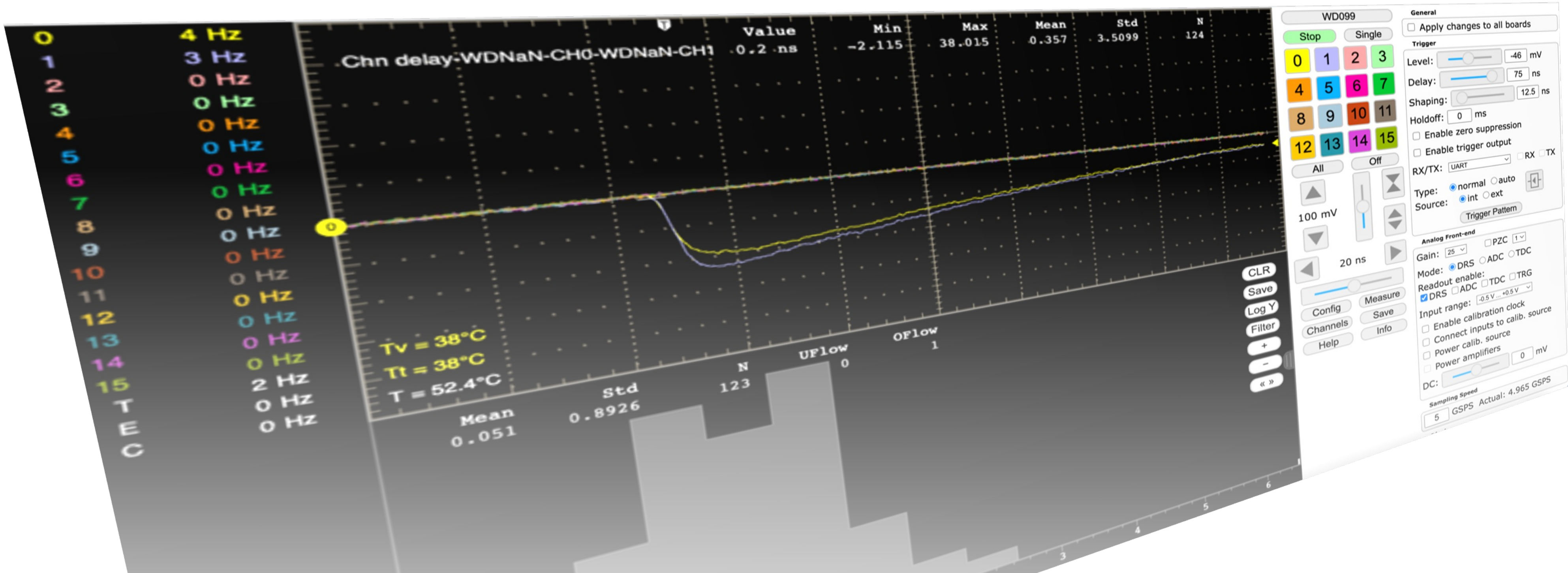


# Time-of-Flight Lab Introduction

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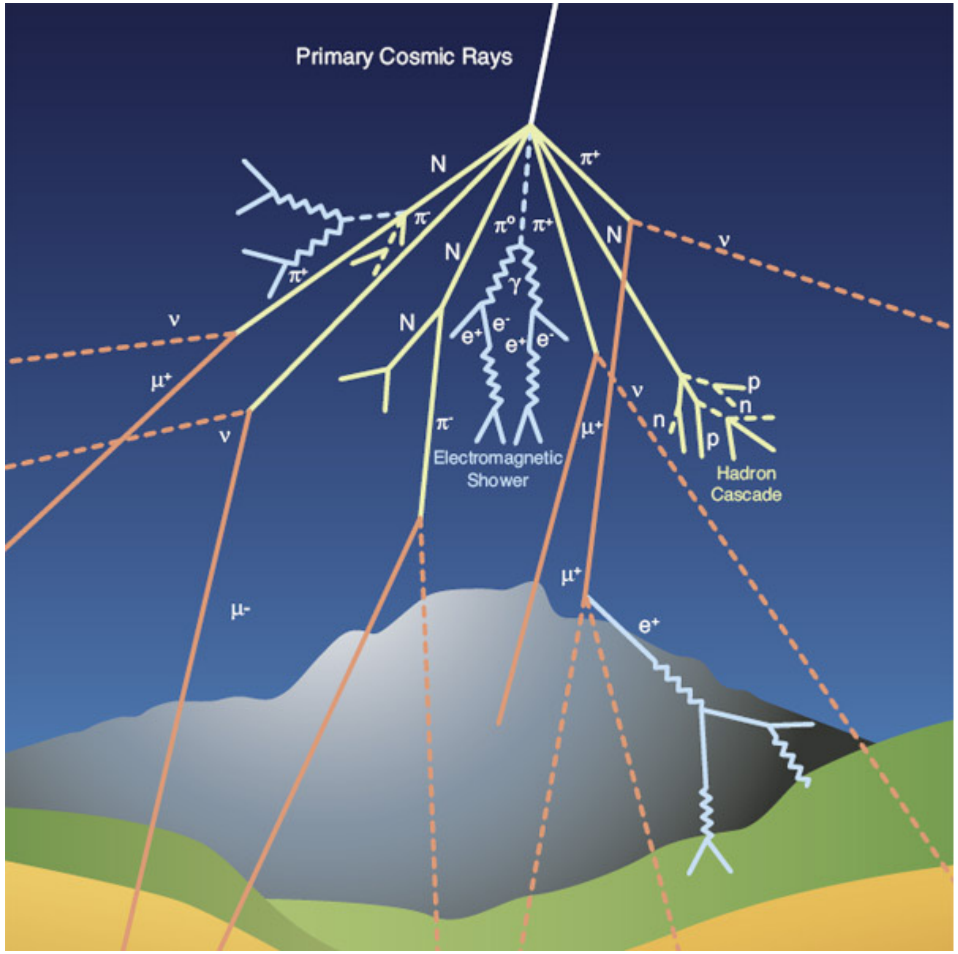
*IEEE NPSS Workshop on Applicatioins of Radiation Instrumentation*
*November 2022, Dakar, Senegal*

# Cosmic rays

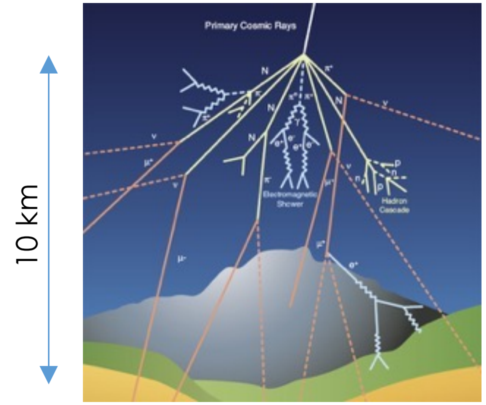
- **Energetic particles** (mainly protons and alpha particles) generated in solar eruptions and astrophysical processes even **outside our Milky Way**
- Some particles have much **higher energies** than those possible with the biggest man-made accelerators.
- Used as **messengers** to understand cosmic processes such as **supernovae**
- **Primary** cosmic rays generate **secondary** rays in the upper earth atmosphere
- Most showers are **absorbed** by atmosphere
- Some **muons** ($\mu$) make it down to **earth**



# Fun fact: Time dilation

- Muon lifetime: $t_{1/2} = 2.2 \times 10^{-6}$ s
- Thickness of earth atmosphere: **~10 km**
- Average travel distance of a muon having speed of light:

  $d = t_{1/2} * c = 2.2 \times 10^{-6}\text{s} * 3 \times 10^{8}\text{ m/s} = \mathbf{660\ m}$




- Special relativity predicts time dilation

$$t' = \frac{t}{\sqrt{1 - \frac{v^2}{c^2}}}$$

t' Time measured from an observer outside the frame of reference.
t Time measured from an observer inside the frame of reference.
v Speed of the object.
c Speed of light

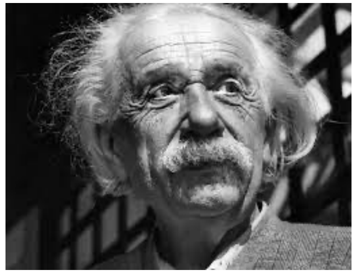
- Muon lifetime @99.9% of c:

  $t'_{1/2} = 2.2 \times 10^{-6}\text{ s} / \text{sqrt}(1-0.999^2) = 49 \times 10^{-6}$ s

  Lorentz factor $\gamma = 22.4$

- Modified travel distance:

  $d = t'_{1/2} * 0.999 * c = 49 \times 10^{-6}\text{s} * 3 \times 10^{8}\text{ m/s} = \mathbf{14.7\ km}$



# Direction of cosmic muons (CM)

- CM are **anisotropic**
- CM loose energy proportional to thickness **d** of atmosphere
- At q=**90 deg**. rate goes to **zero** (flat earth approximation)

$d_0/d = \cos(\theta)$

→

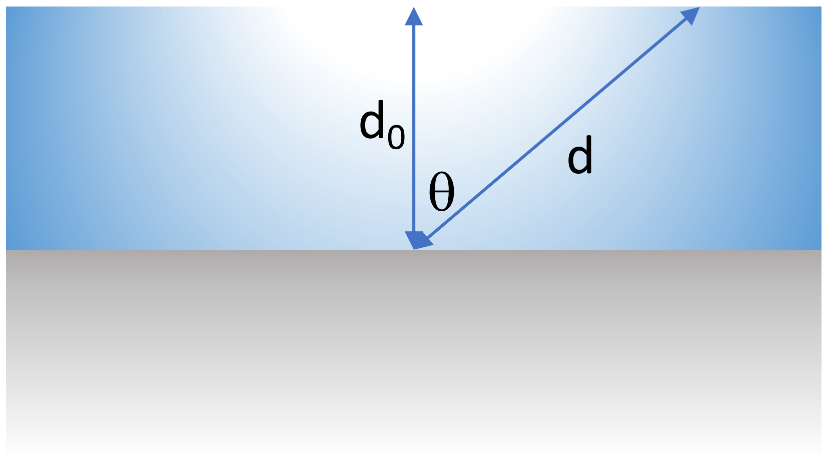
$d = d_0 / \cos(\theta)$

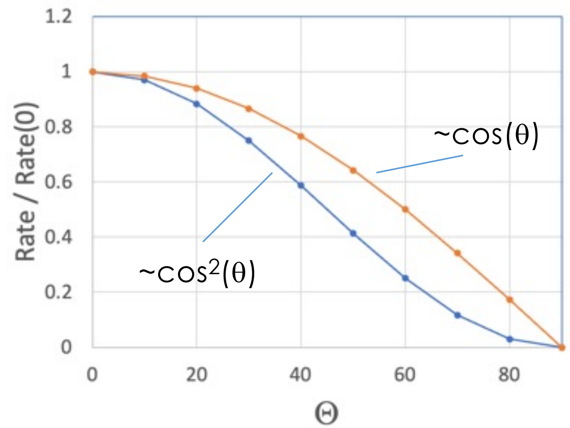
$r(\theta) = r_0 / d = r_0 * \cos(\theta)$

- **Better approximation** (earth curvature, inhomogeneous atmosphere, muon scattering, …)

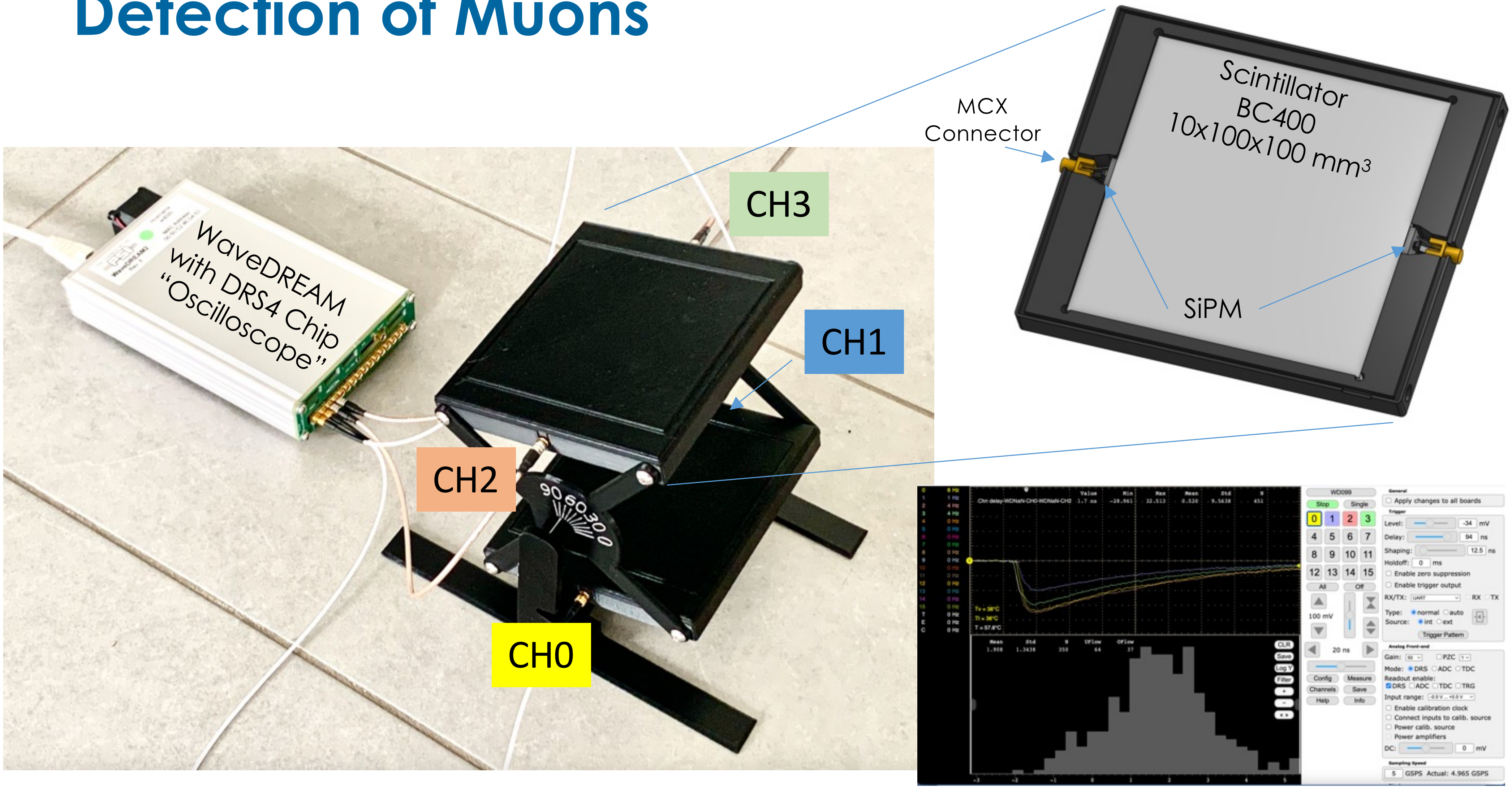
$r(\theta) = r_0 * \cos^2(\theta)$

- **Empirical** formula, not exactly derived



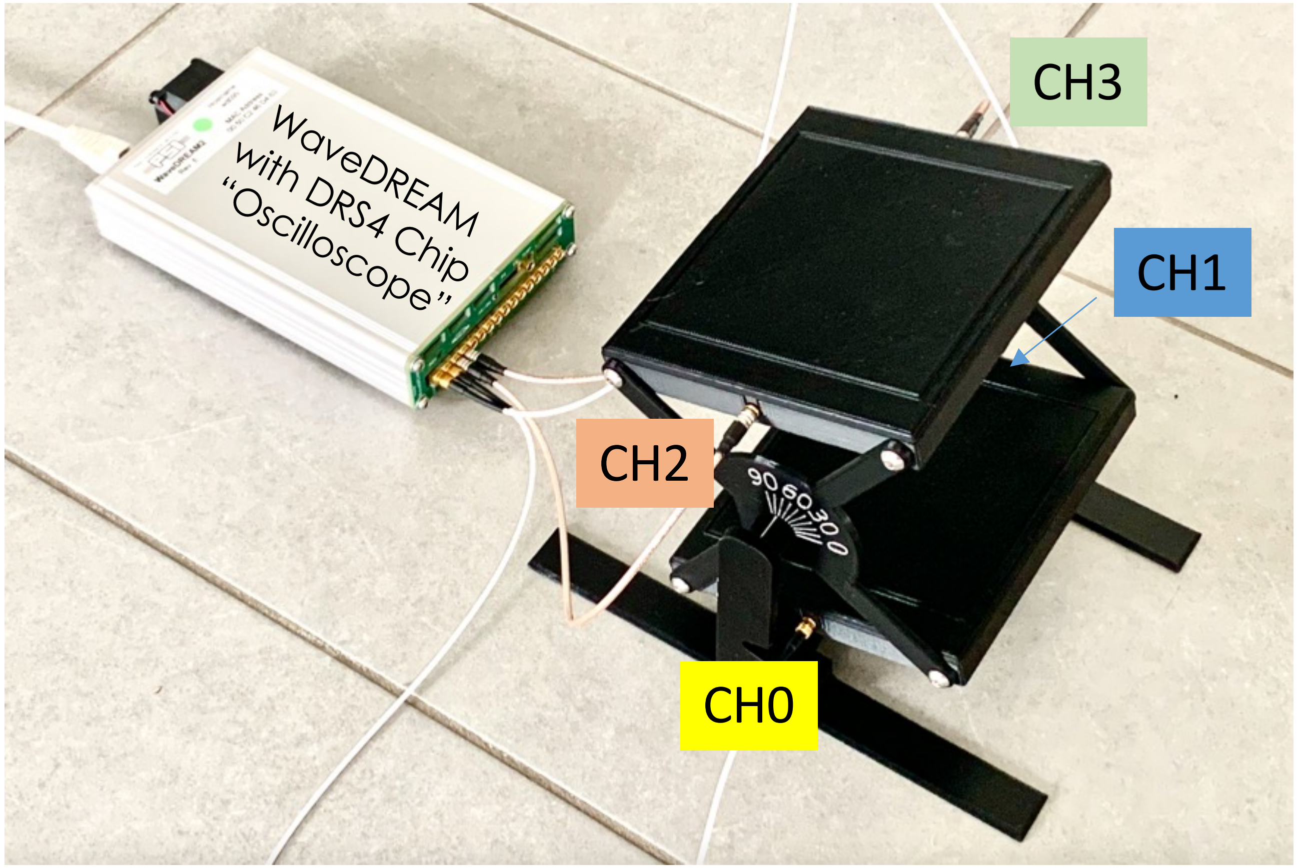
# Detection of Muons



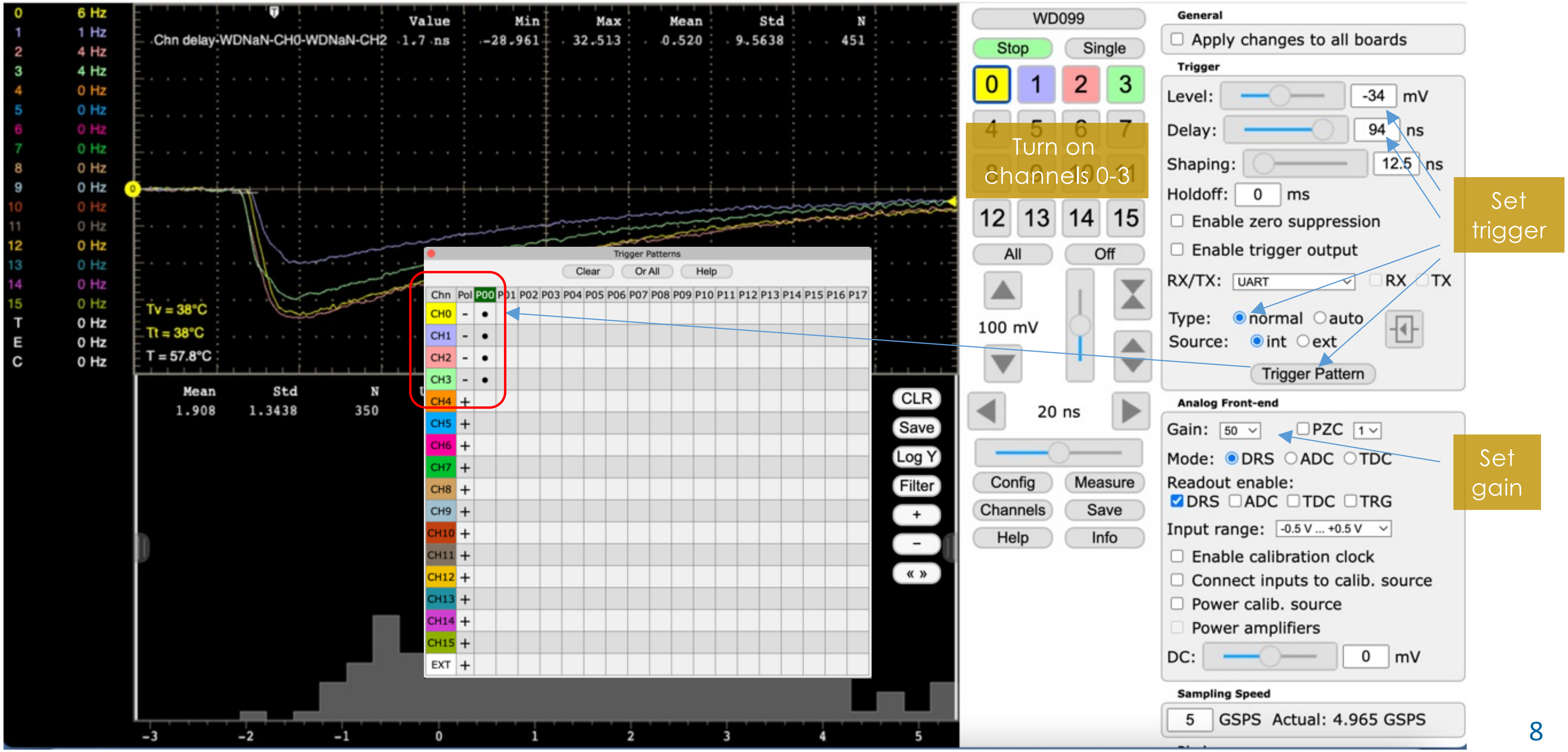
# Lab goals

1. Configure measurement
2. Measure speed of cosmic muons
3. Measure direction of cosmic muons

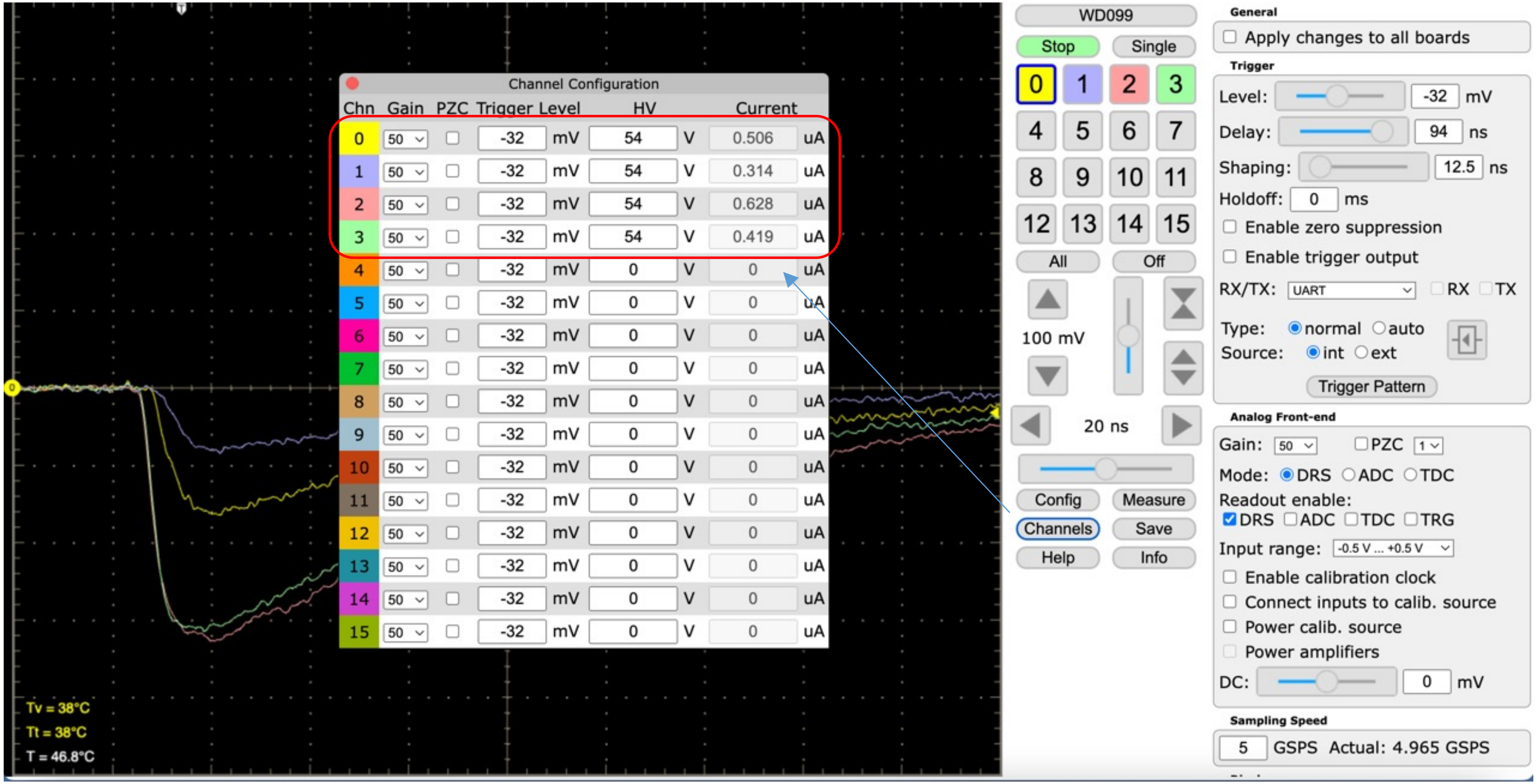
# Connect oscilloscope



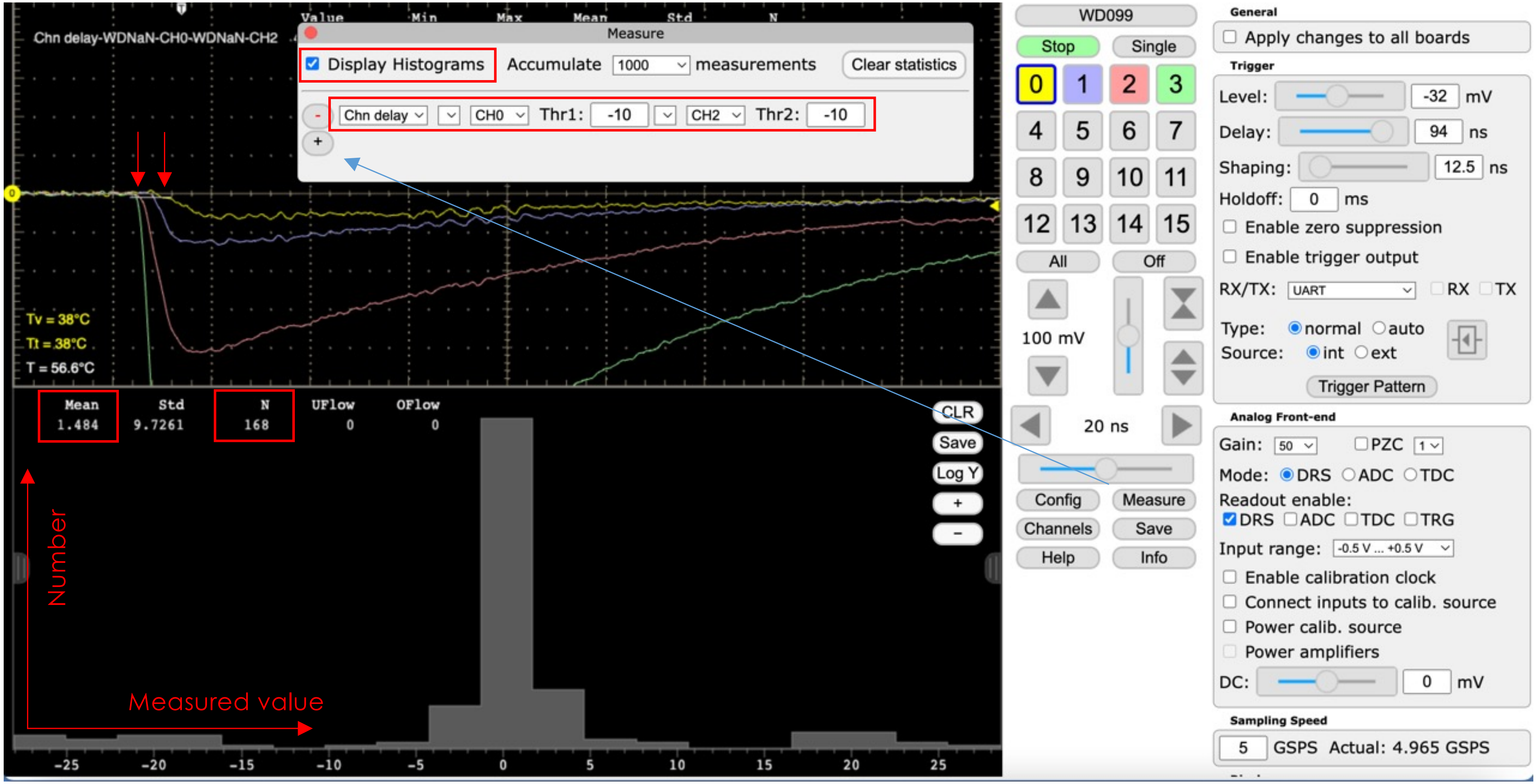
# Setting up the oscilloscope



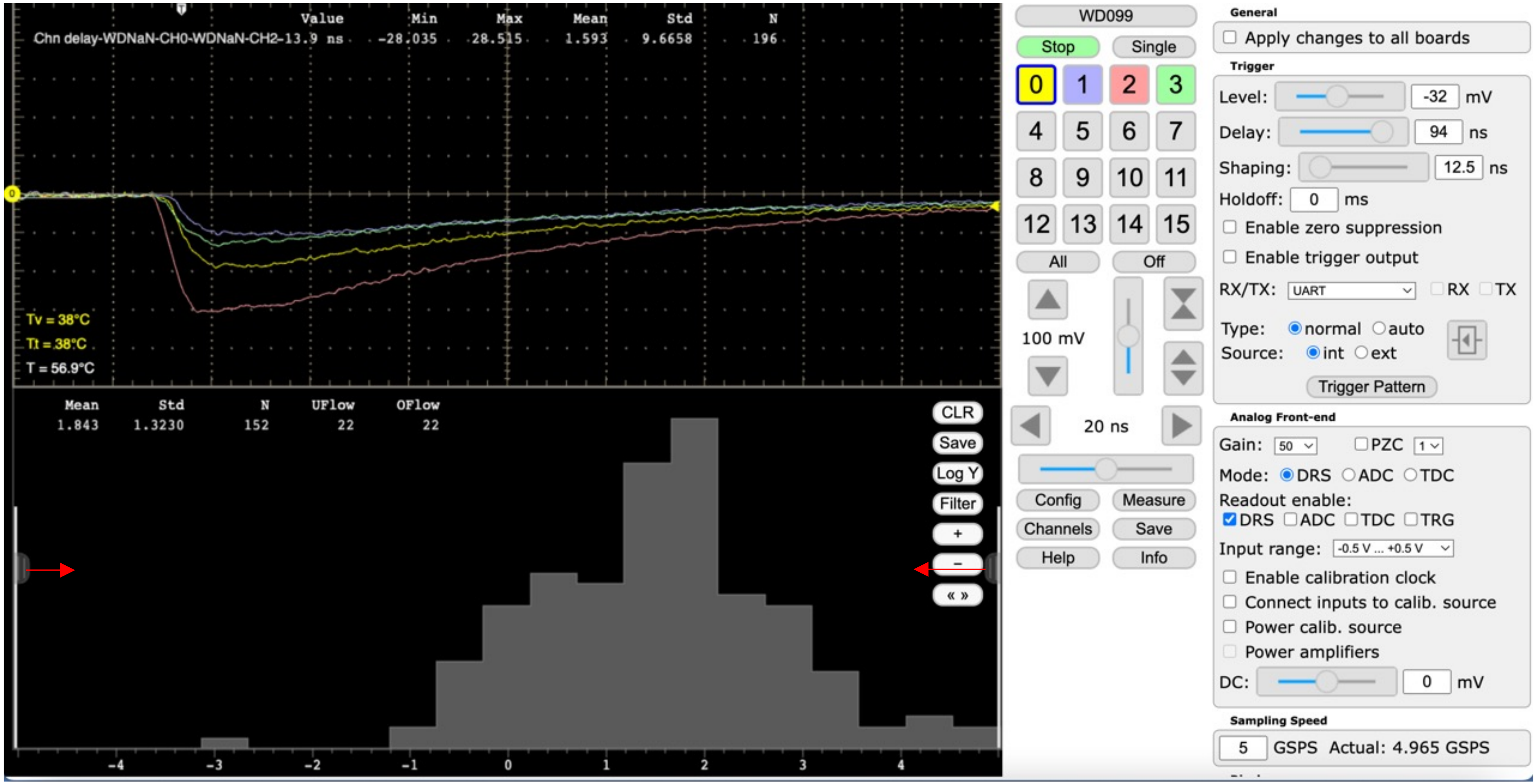
# Setting high voltage for SiPM to 54 V



# Define time measurement

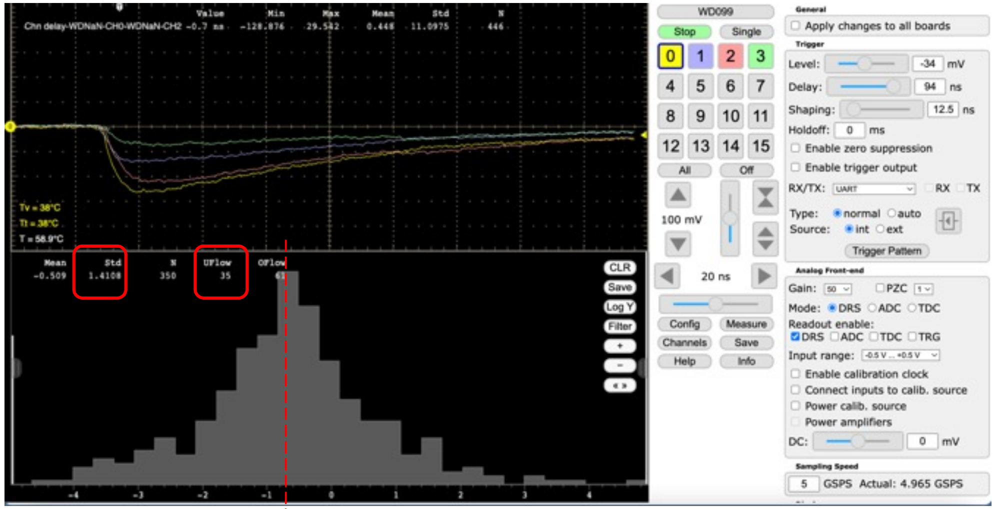


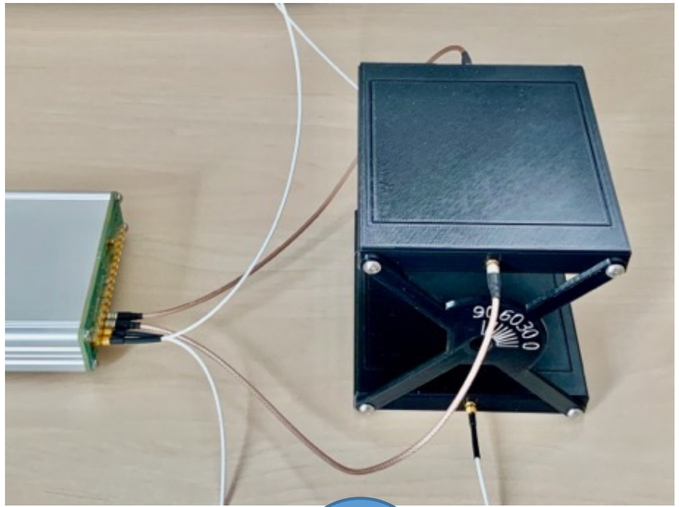
# Zoom to -5 ns to +5 ns



# Measure Speed of Cosmic Muons

# Measure speed of muons

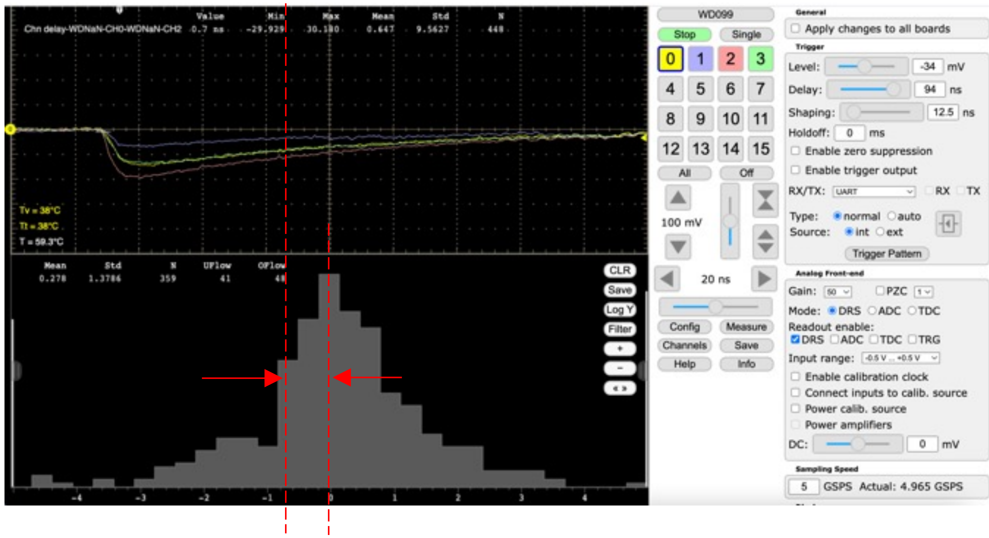


Case A

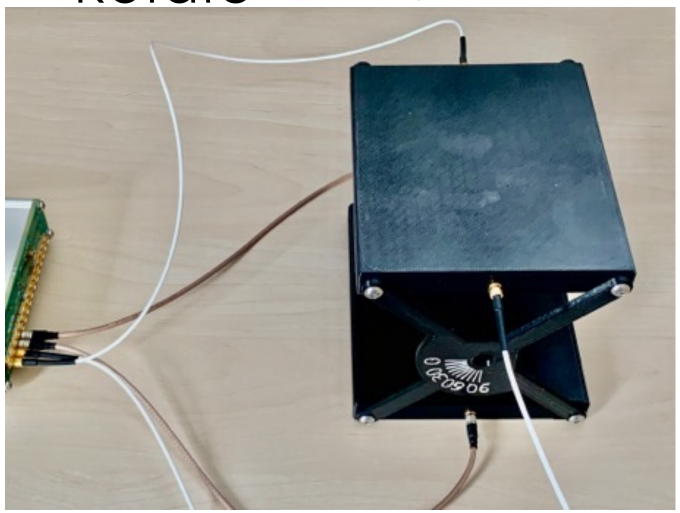
Measure 300-500 events
write down mean

Rotate




Case B

Measure 300-500 events
write down mean



# Difference Measurement

Case A:

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

Case B:

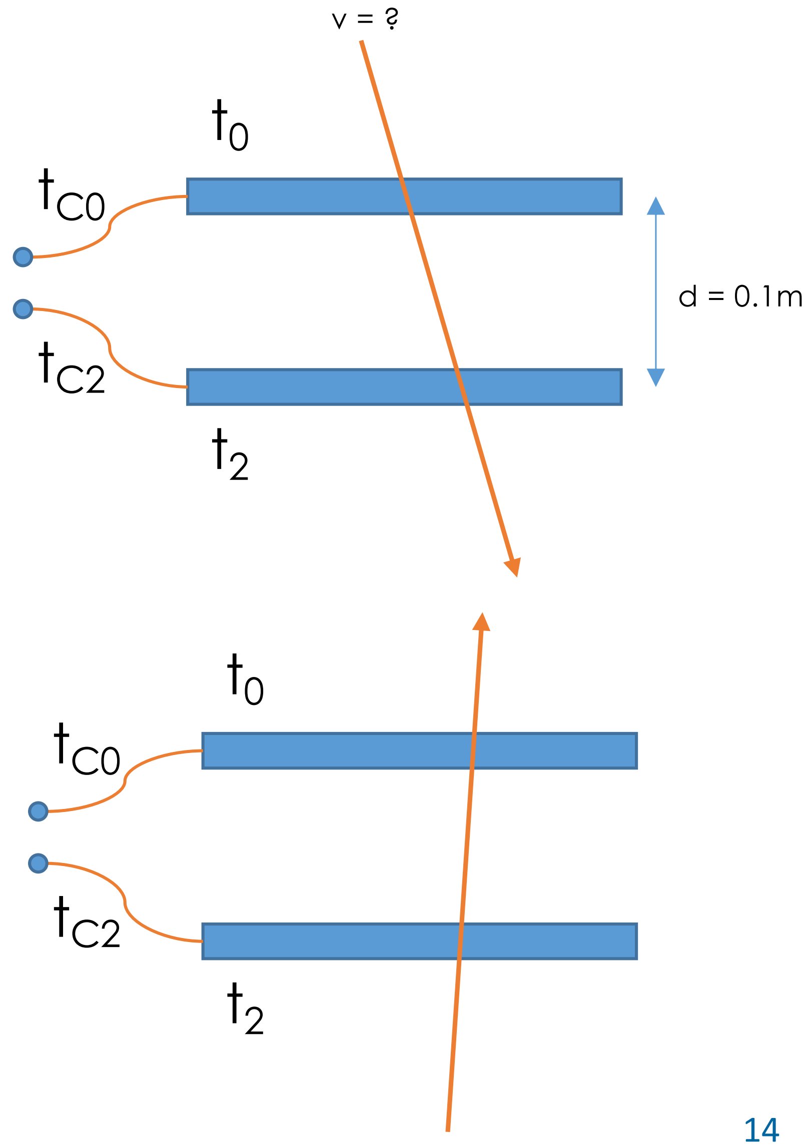
$\Delta t_B = (t_{0,B}+t_{c0}) - (t_{2,B}+t_{c2}) = d / (-v)$

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 (= 3x10$^8$ m/s)**

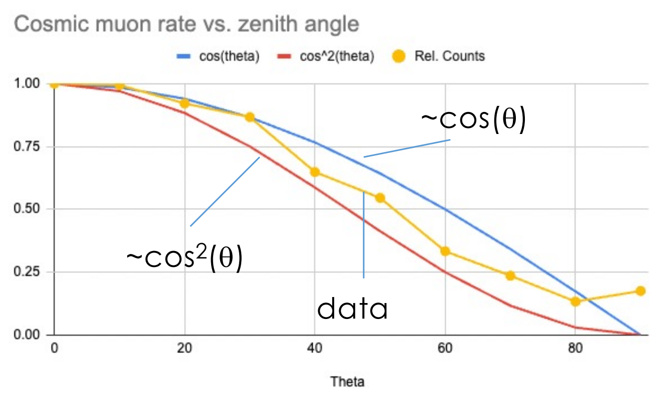


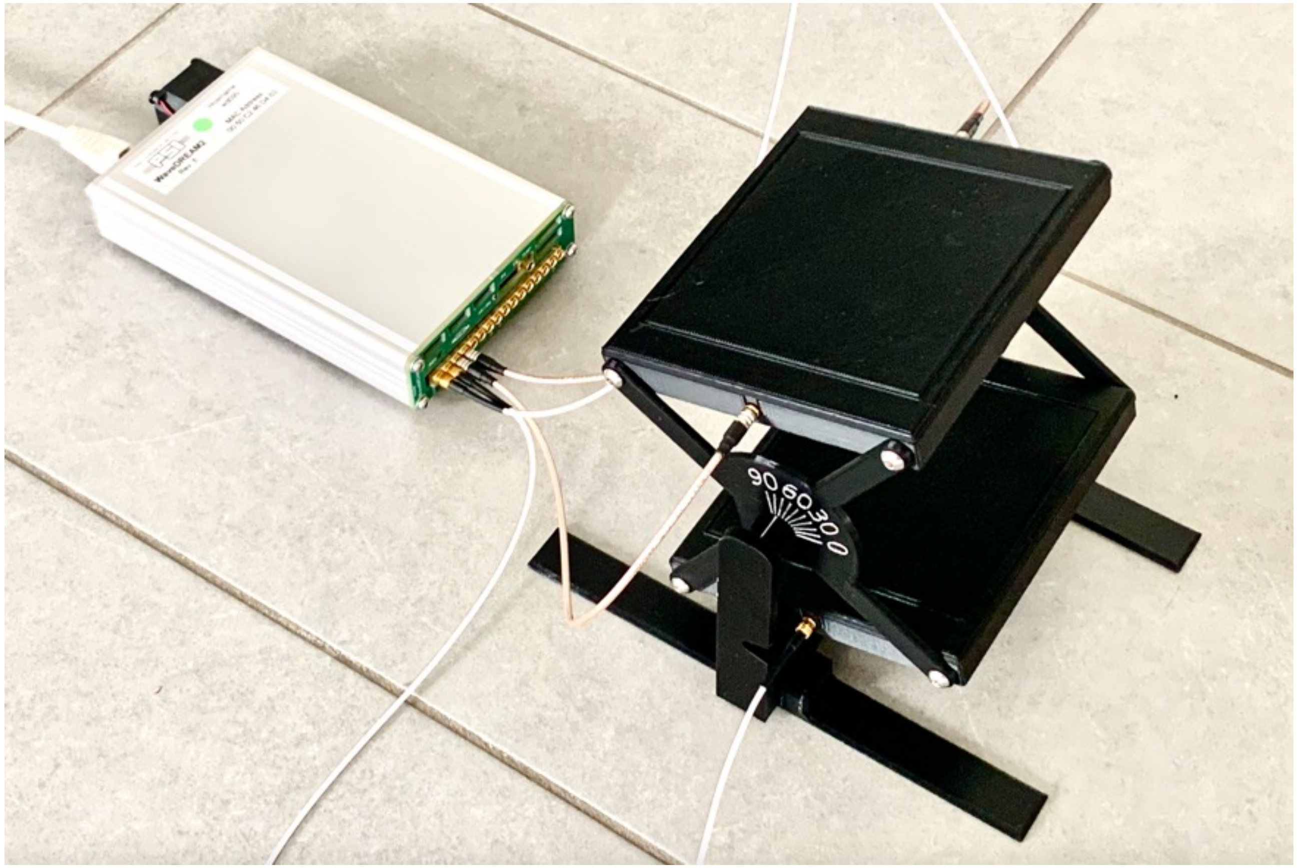
# Measure Direction of Cosmic Muons

# Measure direction of cosmic muons

- Set angle = 0,10,20…90 deg.
- Measure 5 minutes
- Write down counts

- Plot normalized counts vs. angle

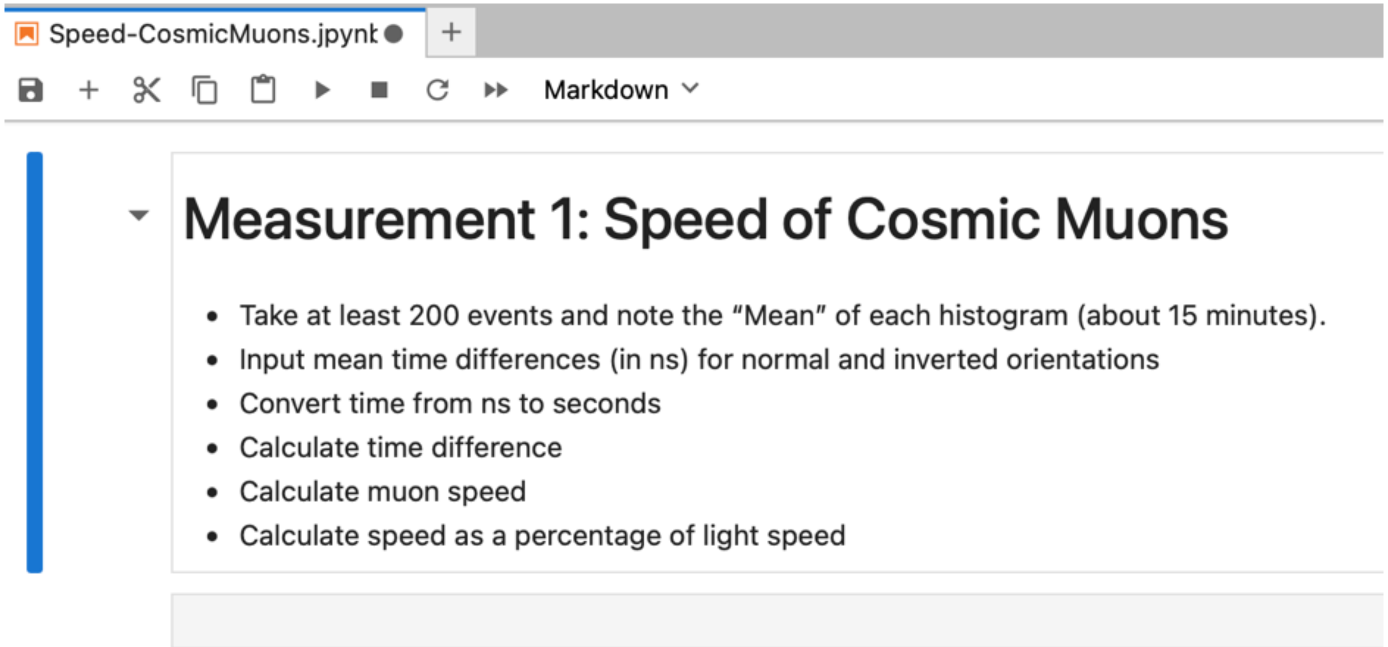



https://docs.google.com/spreadsheets/d/17GKjGK5fU1BGCbbJZV7dLj1fum2MoU38QzSnF404W-o

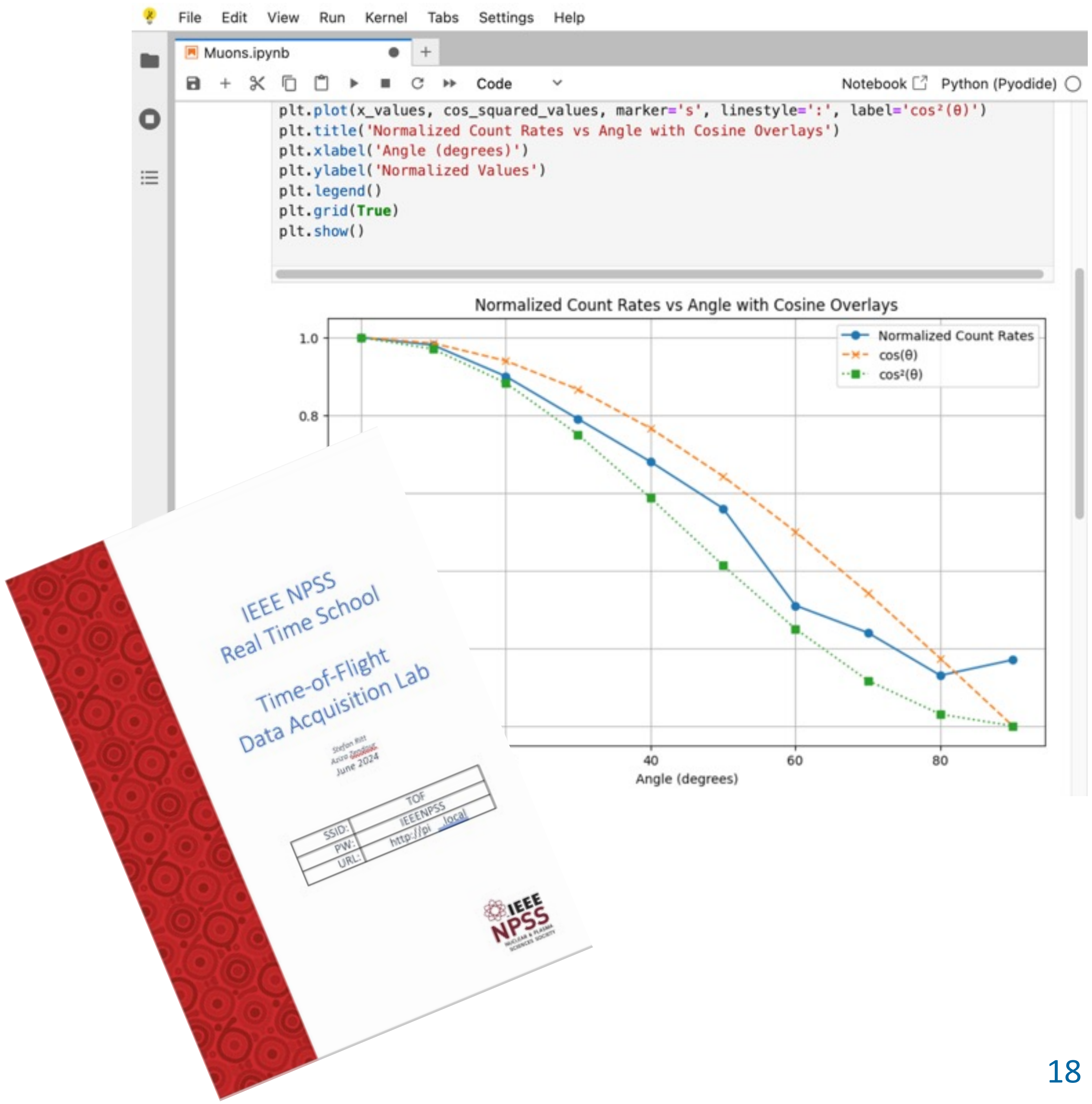
# JupyterLab https://jupyter.org

- Document your measurement!



# Data Analysis

- Write python code to plot your data
- Get help from ChatGPT if necessary
- Double check the code from ChatGPT!
- More details in Lab Script



# Questions to ask yourself

- Why does the rate do not go to zero at 90 deg.?
- Why are the points not on a smooth line?
- If I measure again, will I get exactly the same points?
- How could the experiment be improved?

# Student Presentations

- On Wednesday, every student is supposed to give a ~5 min presentation about one of the four lab courses
- Document your measurements, save results, take pictures
- Wednesday morning time to prepare presentations
- Wednesday afternoon presentations