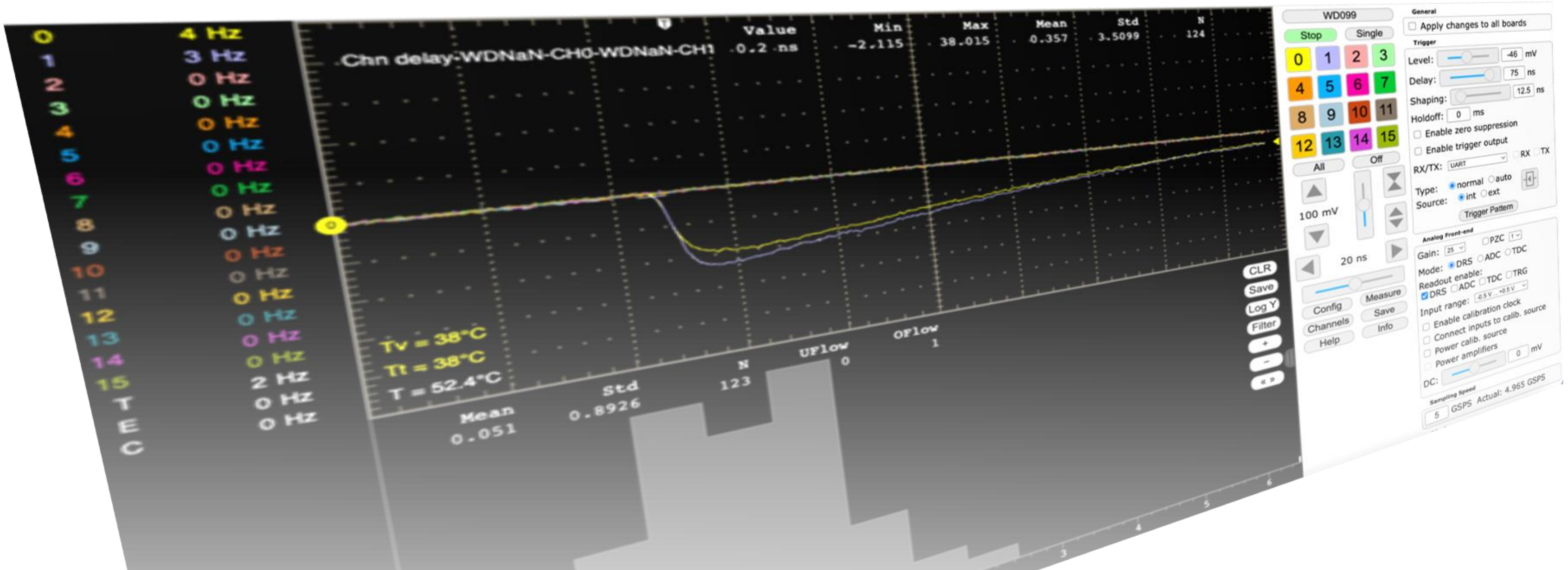

Time-of-Flight Lab Introduction

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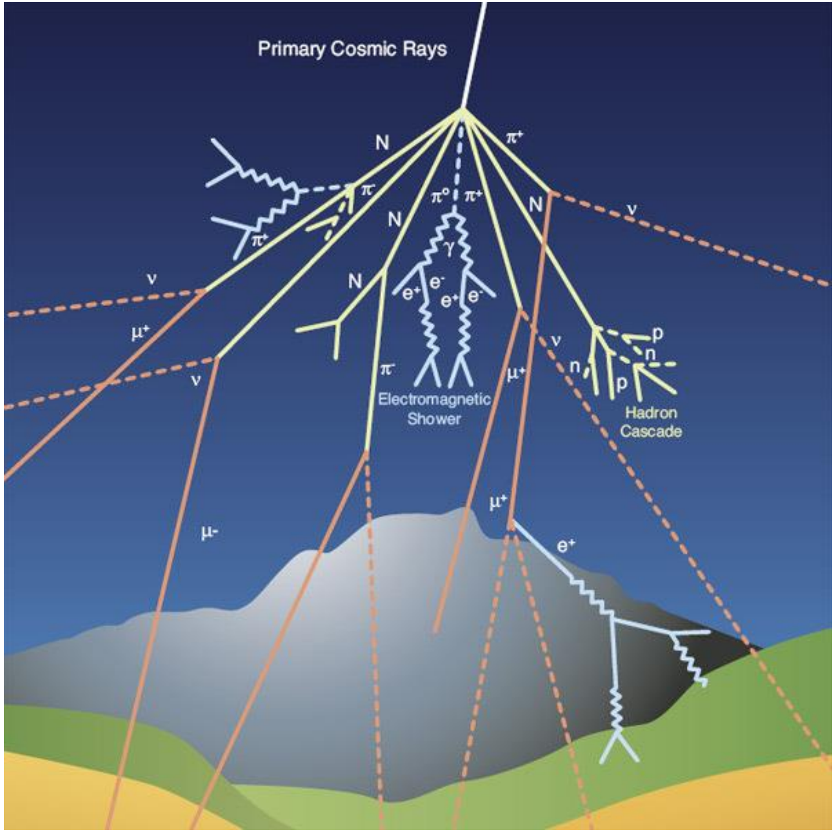
Cosmic rays

- **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** (μ) 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:

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

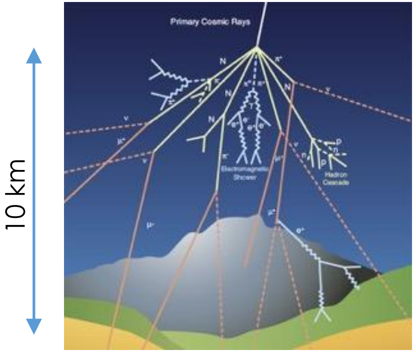
- Muon lifetime @99.9% of c:

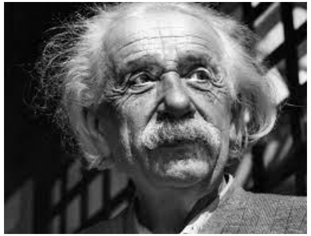
  $t'_{1/2} = 2.2 \times 10^{-6}$ s / sqrt$(1-0.999^2) = 49 \times 10^{-6}$ s

  Lorentz factor $\gamma = 22.4$

- Modified travel distance:

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

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

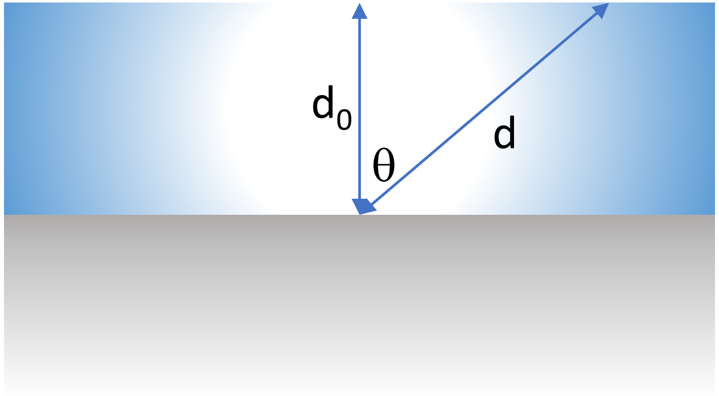
$$d = d_0 / \cos(\theta)$$

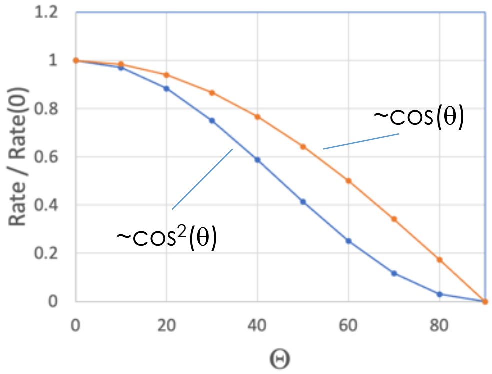
$$r(\theta) = r_0 / d = r_0 * \cos(\theta)$$

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

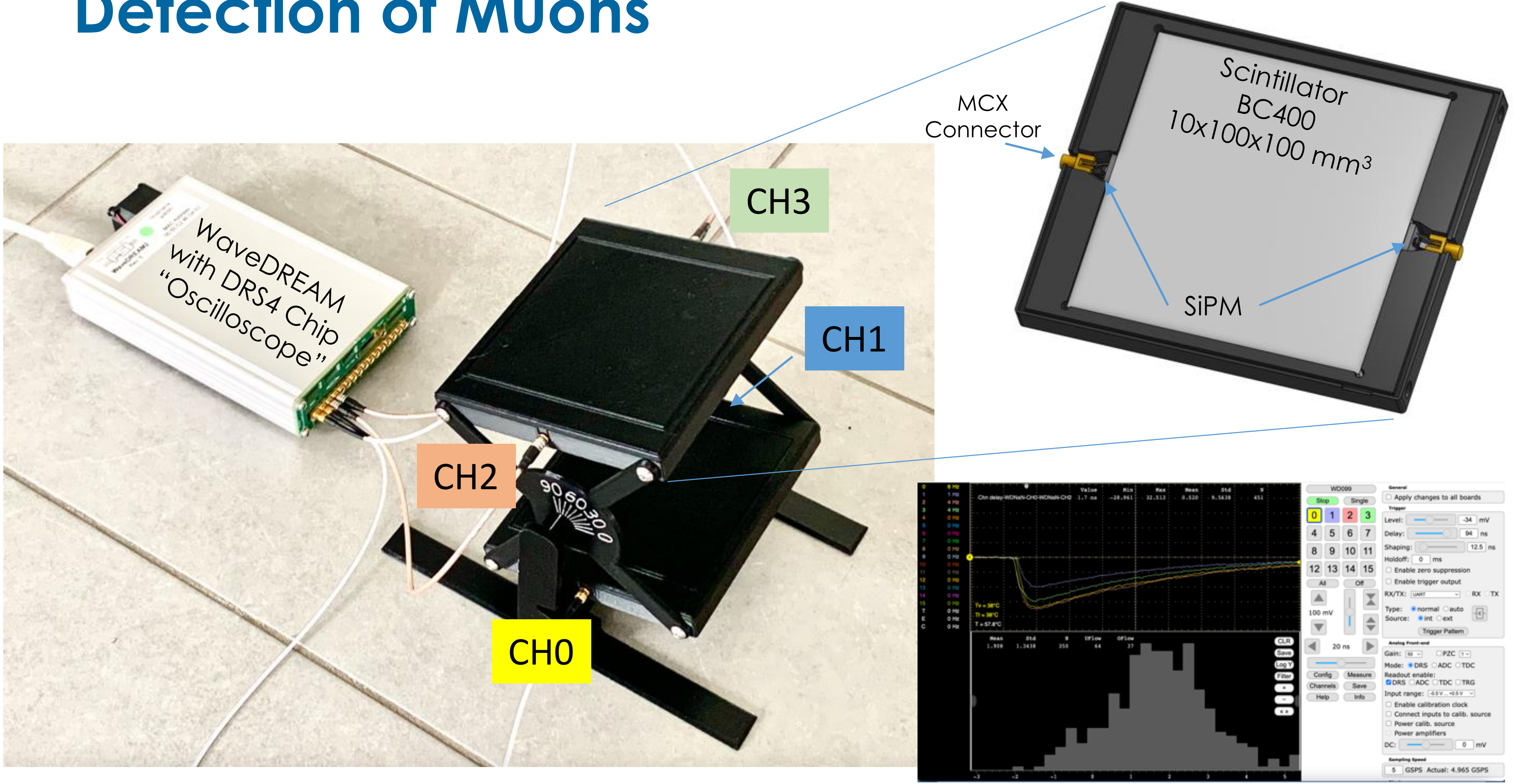
$$r(\theta) = r_0 * \cos^2(\theta)$$

- **Empirical** formula, not exactly derived





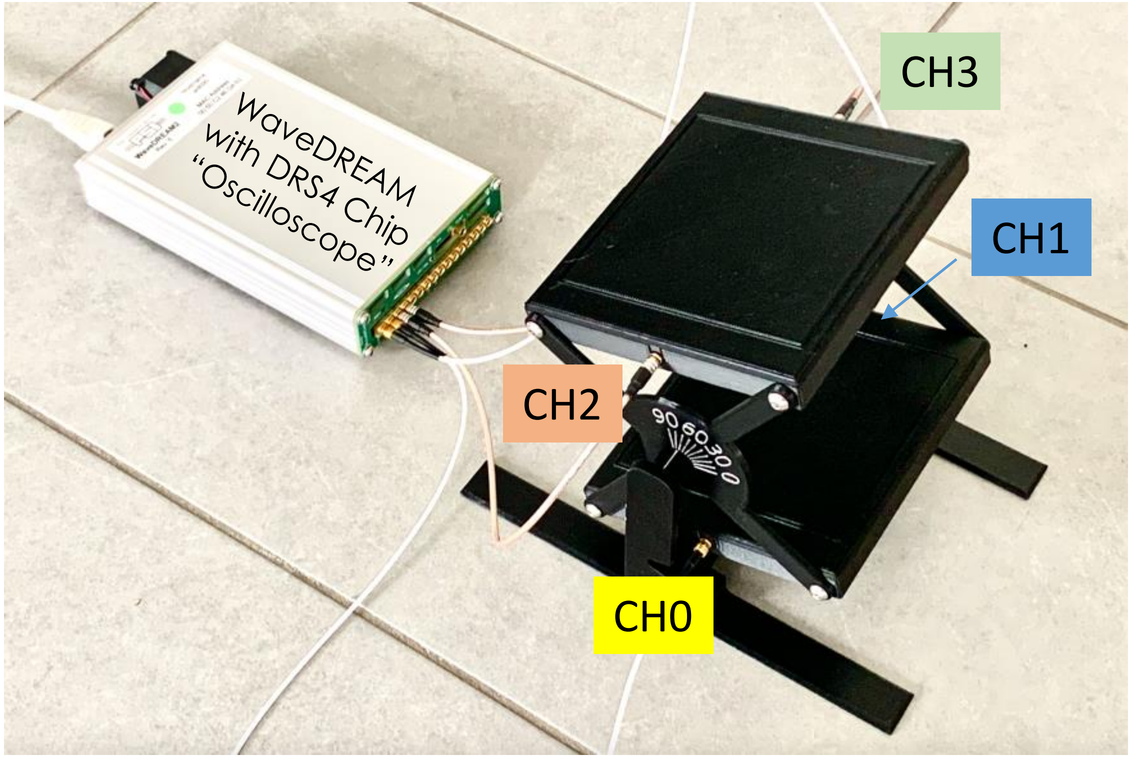
Detection of Muons



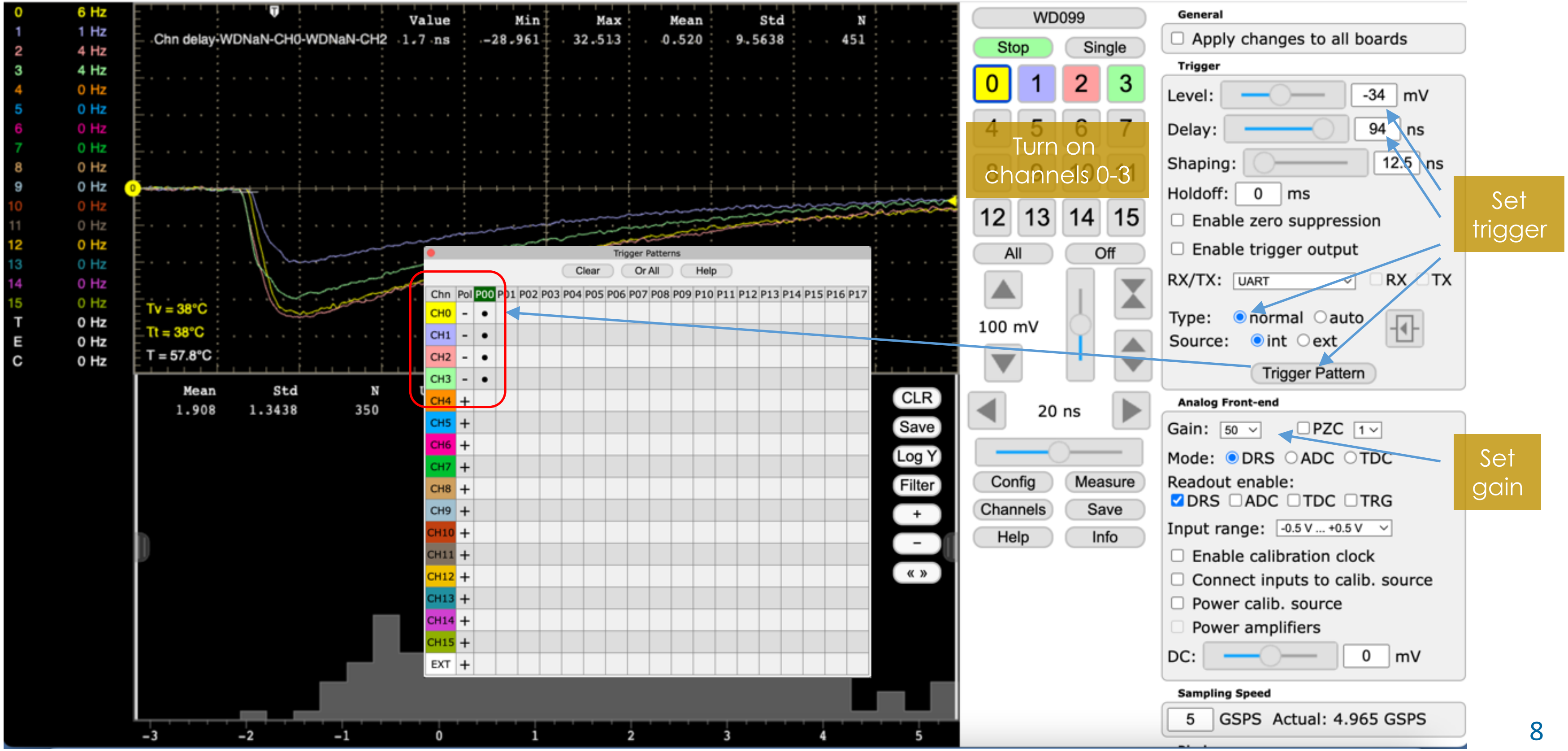
Lab goals

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

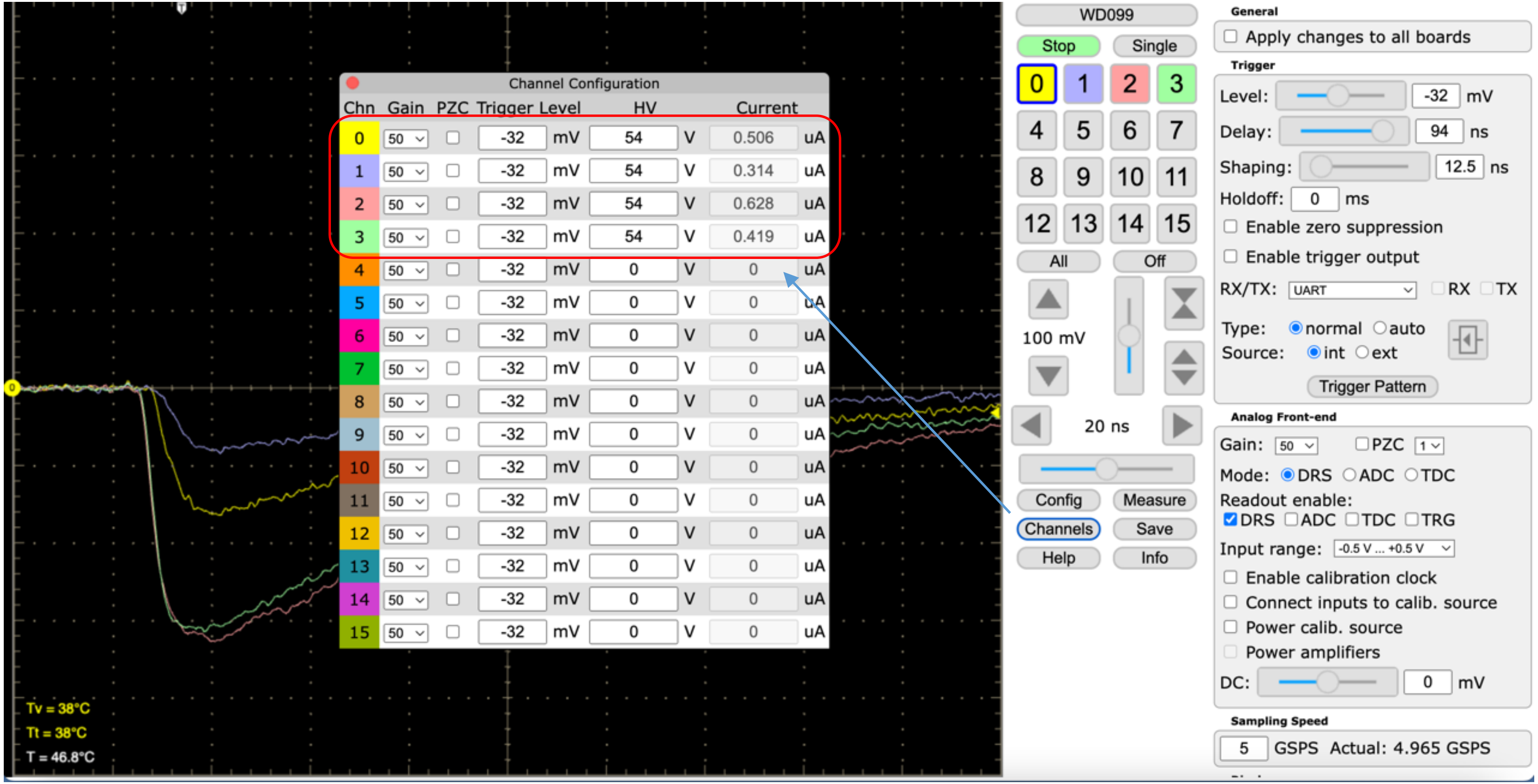
Connect oscilloscope



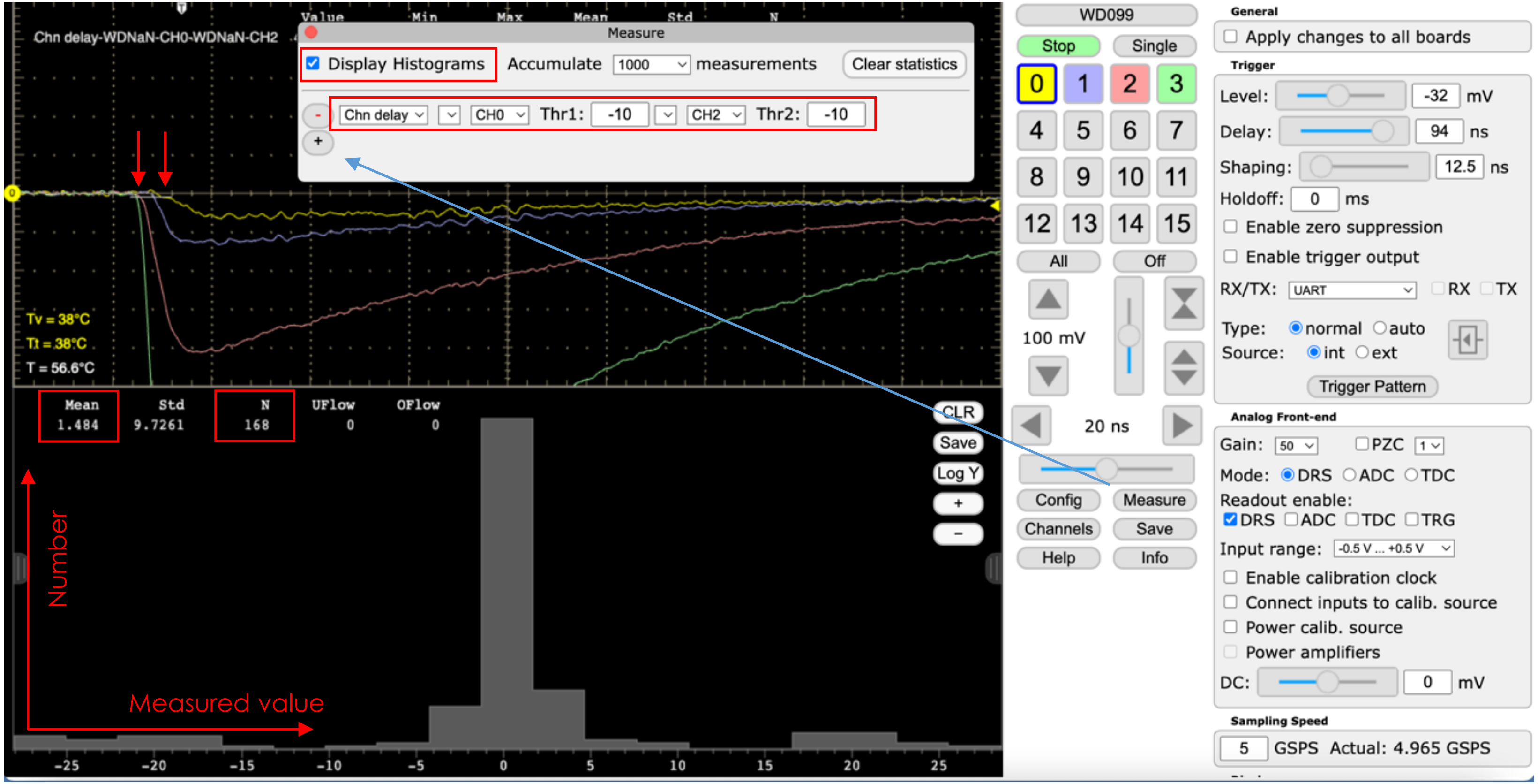
Setting up the oscilloscope



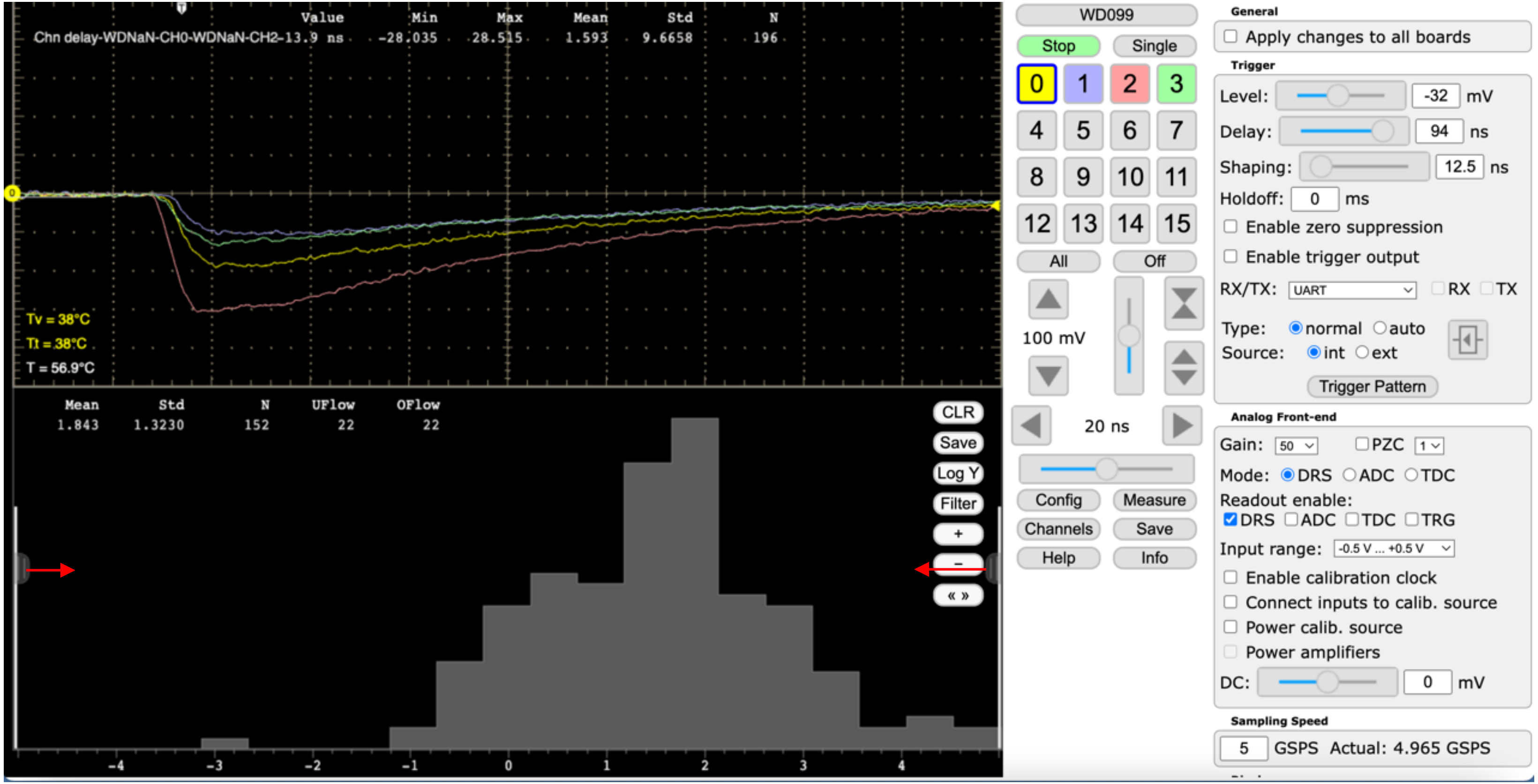
Setting high voltage for SiPM to 54 V



Define time measurement

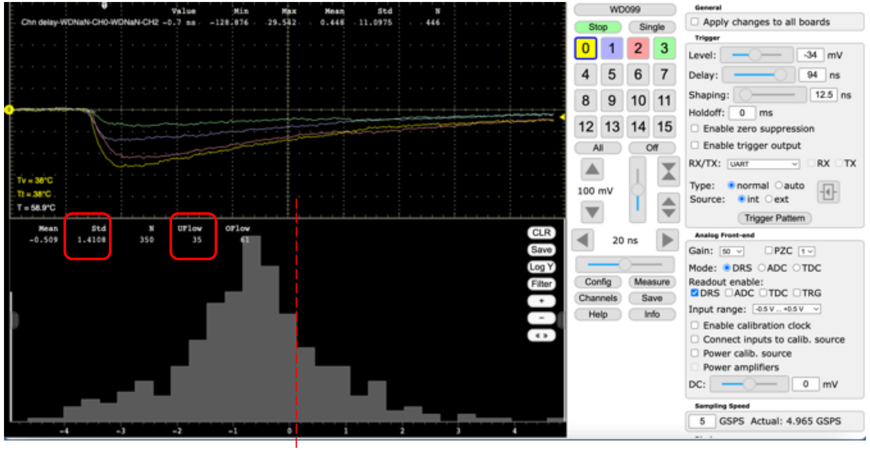


Zoom to -5 ns to +5 ns



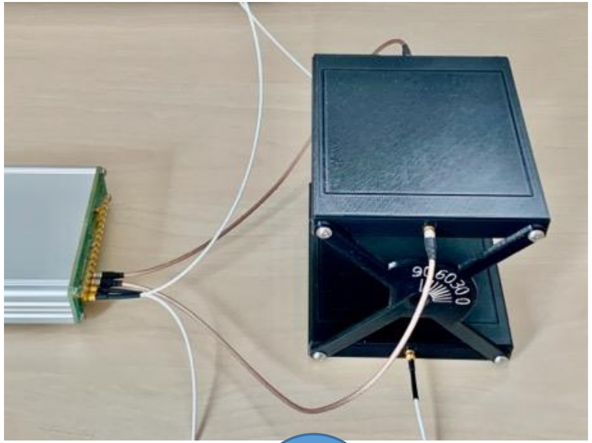
Measure Speed of Cosmic Muons

Measure speed of muons

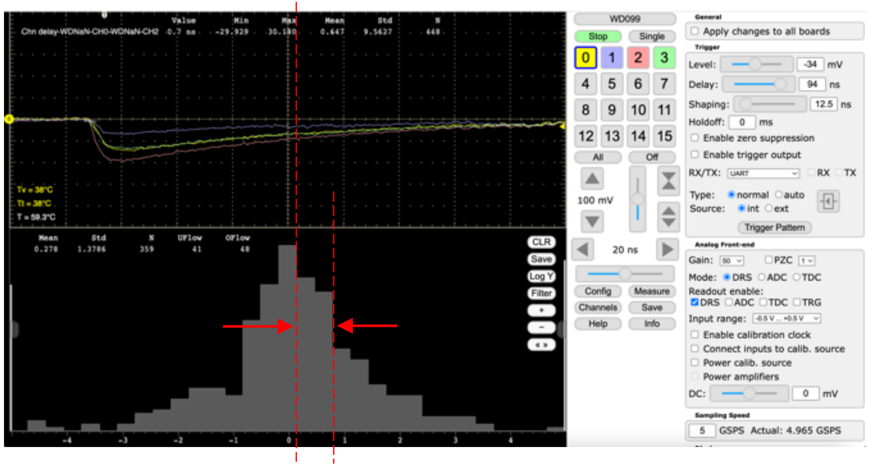


Case A

Measure 300-500 events
write down mean

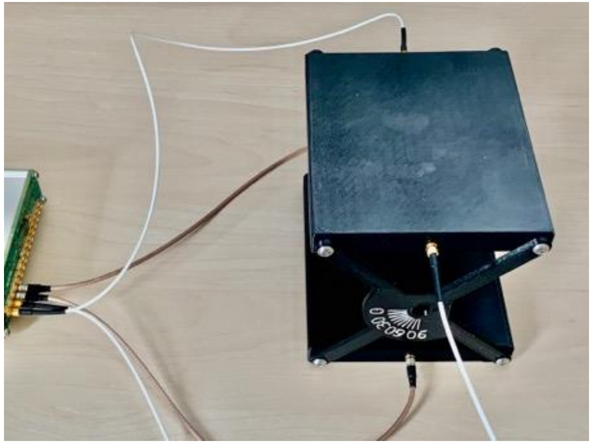


Rotate



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:

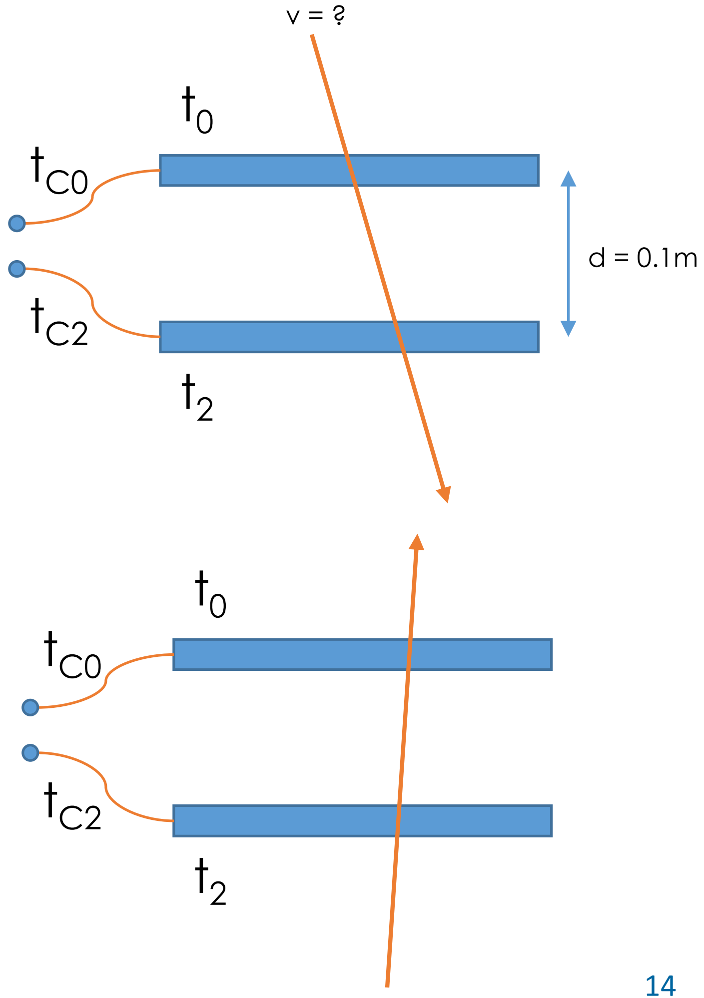
$\Delta t_B = (t_{0,B}+t_{c0}) - (t_{2,B}+t_{c2}) = d / (-v)$

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 (= 3×10^8 m/s)

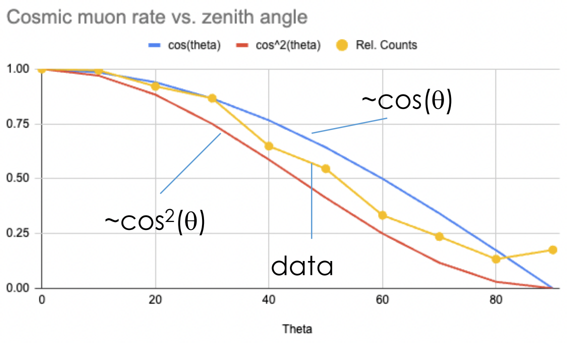


Measure Direction of Cosmic Muons

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

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?