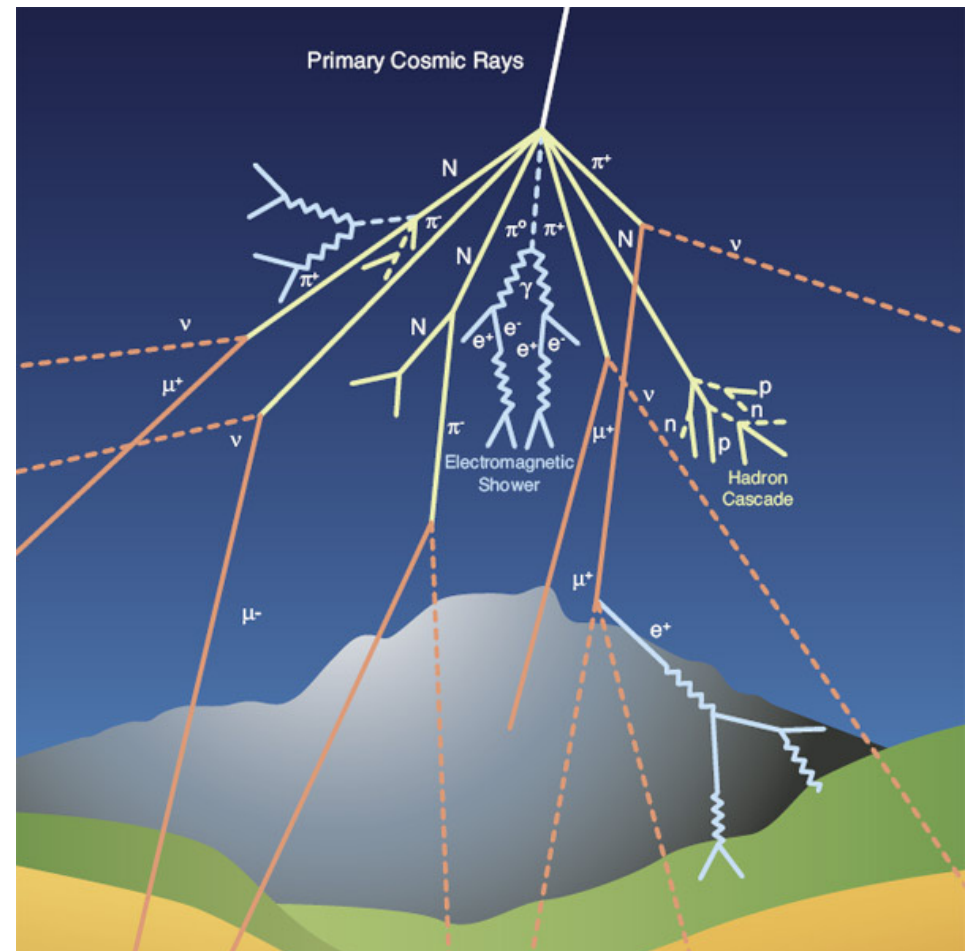


# Time-of-Flight Lab Introduction

*Stefan Ritt, Paul Scherrer Institute, Switzerland  
IEEE NPSS Workshop on Applications 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:  $t_{1/2} = 2.2 \times 10^{-6} \text{ s}$
- ▶ Thickness of earth atmosphere: **~10 km**
- ▶ Average travel distance of a muon having speed of light:

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

- ▶ Special relativity predicts time dilation

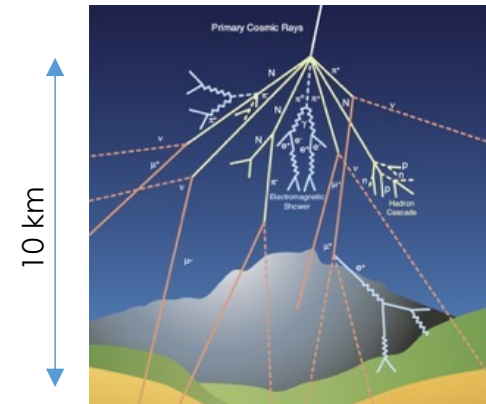
- ▶ Muon lifetime @99.9% of c:

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

$\underbrace{\hspace{10em}}$   
 Lorentz factor  $\gamma = 22.4$

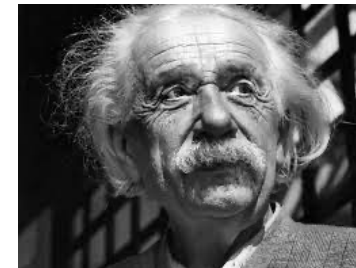
- ▶ Modified travel distance:

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



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

- $t'$  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



# Direction of cosmic muons (CM)

- ▶ CM are **anisotropic**
- ▶ CM lose energy proportional to thickness **d** of atmosphere
- ▶ At  $\theta=90$  deg. rate goes to **zero** (flat earth approximation)

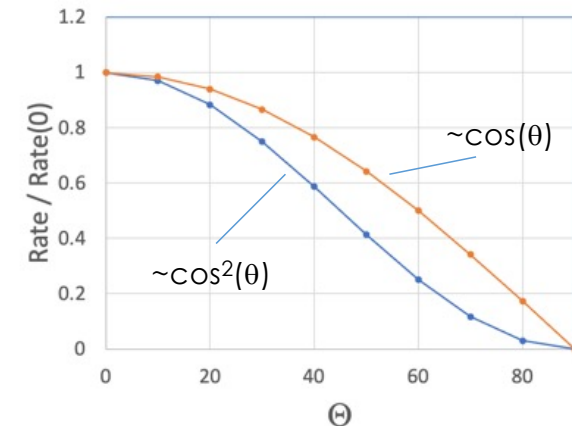
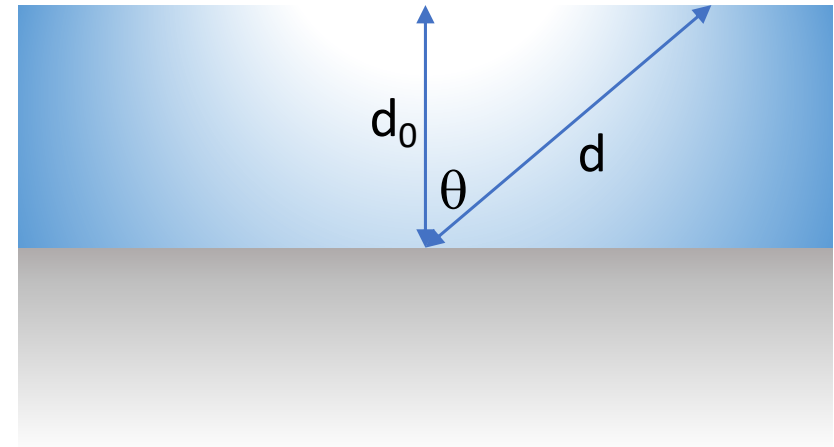
$$\begin{aligned} & d_0/d = \cos(\theta) \\ \rightarrow & d = d_0 / \cos(\theta) \end{aligned}$$

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

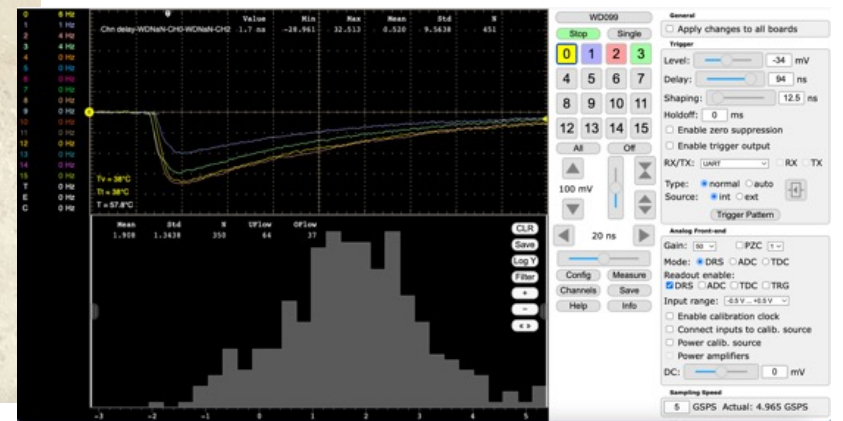
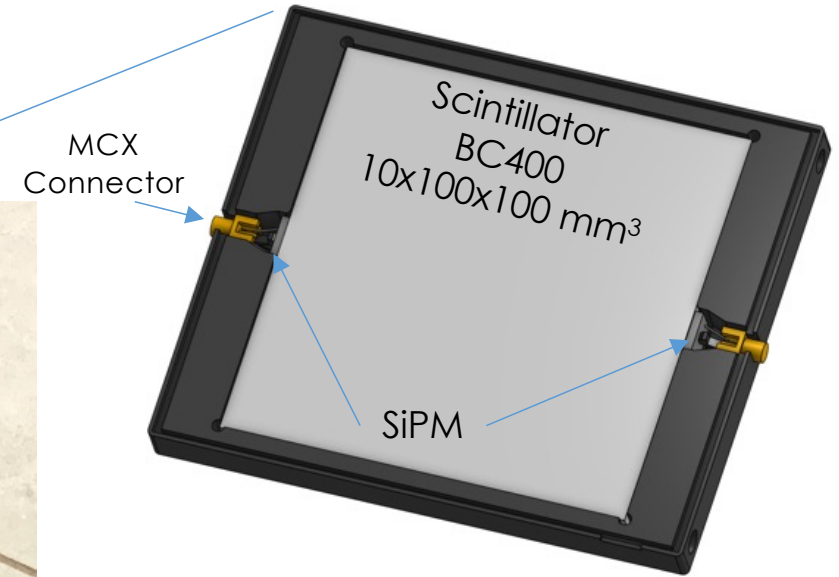
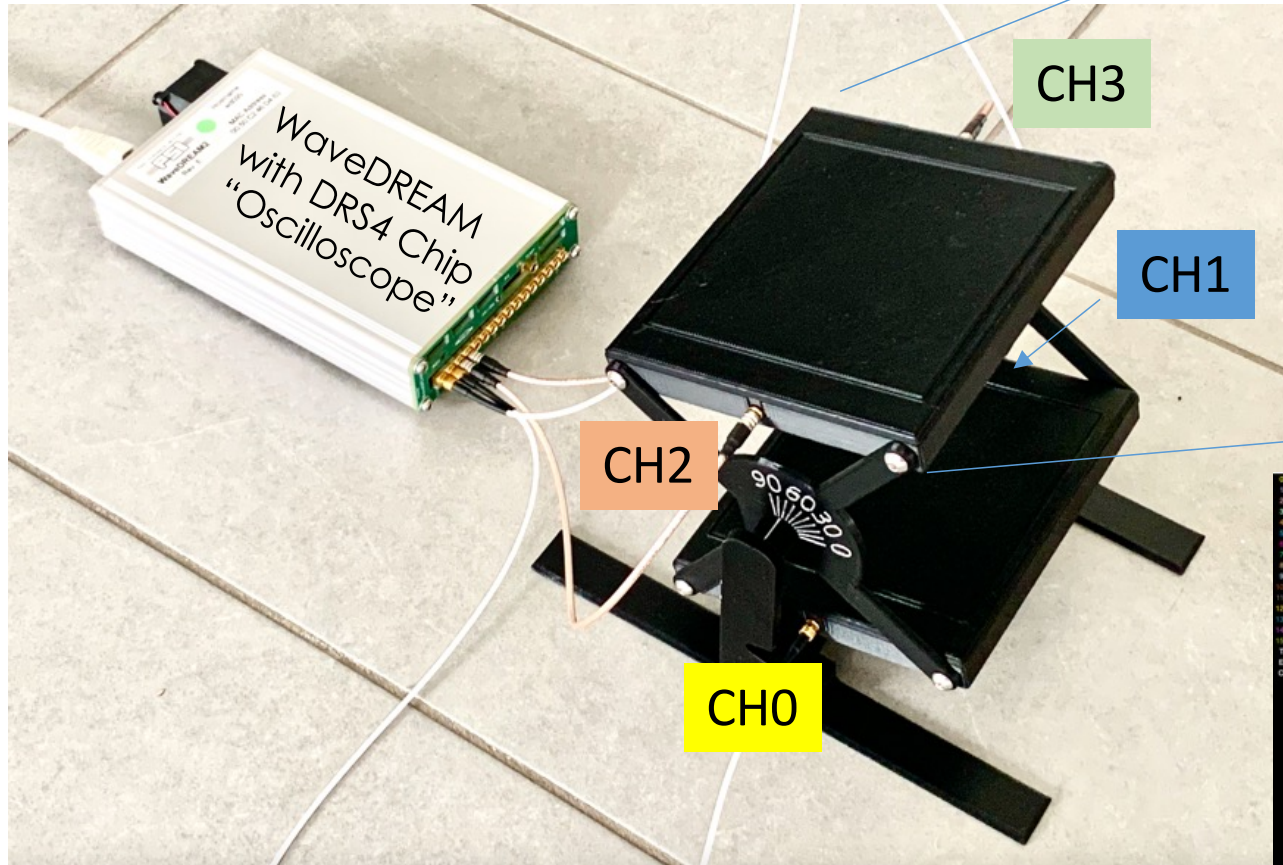
- ▶ **Better approximation** (earth curvature, inhomogeneous atmosphere, muon scattering, ...)

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

- ▶ **Empirical** formula, not exactly derived



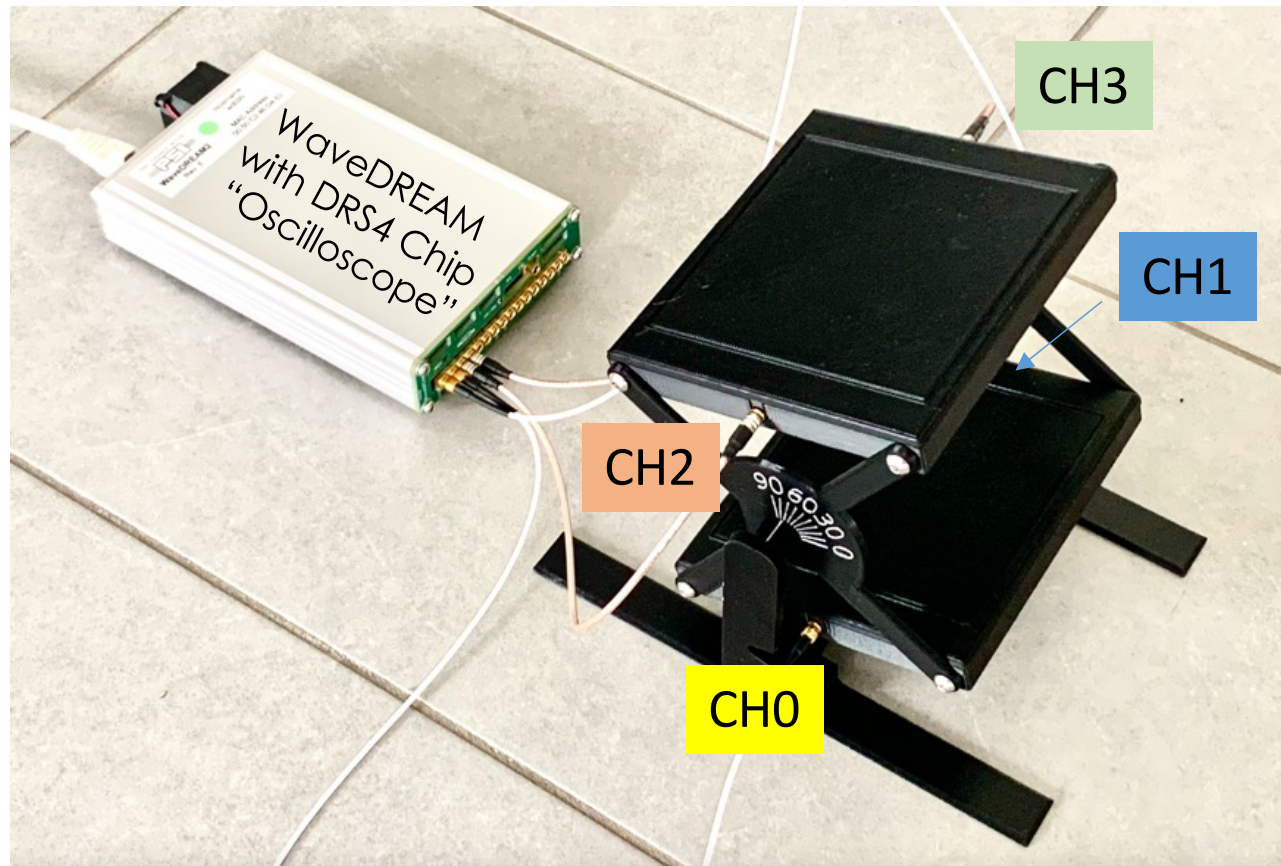
# Detection of Muons



# Lab goals

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

# Connect oscilloscope



# Setting up the oscilloscope

**Waveform Data:**

Value	Min	Max	Mean	Std	N	
Chn delay: WDNaN-CH0-WDNaN-CH2	.17 ns	-28.961	32.513	0.520	9.5638	451

**Temperature Data:**

Parameter	Value
Tv	38°C
Tt	38°C
T	57.8°C

**Trigger Patterns Table:**

Chn	Pol	P00	P01	P02	P03	P04	P05	P06	P07	P08	P09	P10	P11	P12	P13	P14	P15	P16	P17
CH0	-	•																	
CH1	-	•																	
CH2	-	•																	
CH3	-	•																	
CH4	+																		
CH5	+																		
CH6	+																		
CH7	+																		
CH8	+																		
CH9	+																		
CH10	+																		
CH11	+																		
CH12	+																		
CH13	+																		
CH14	+																		
CH15	+																		
EXT	+																		

**Configuration Panels:**

- General:**
  - Apply changes to all boards:
- Trigger:**
  - Level: -34 mV
  - Delay: 94 ns
  - Shaping: 12.5 ns
  - Holdoff: 0 ms
  - Enable zero suppression:
  - Enable trigger output:
  - RX/TX: UART (selected), RX, TX
  - Type: normal (selected), auto
  - Source: int (selected), ext
- Analog Front-end:**
  - Gain: 50 (selected), PZC 1
  - Mode: DRS (selected), ADC, TDC
  - Readout enable:  DRS,  ADC,  TDC,  TRG
  - Input range: -0.5 V ... +0.5 V
  - Enable calibration clock:
  - Connect inputs to calib. source:
  - Power calib. source:
  - Power amplifiers:
  - DC: 0 mV
- Sampling Speed:**
  - 5 GSPS Actual: 4.965 GSPS



# Setting high voltage for SiPM to 54 V

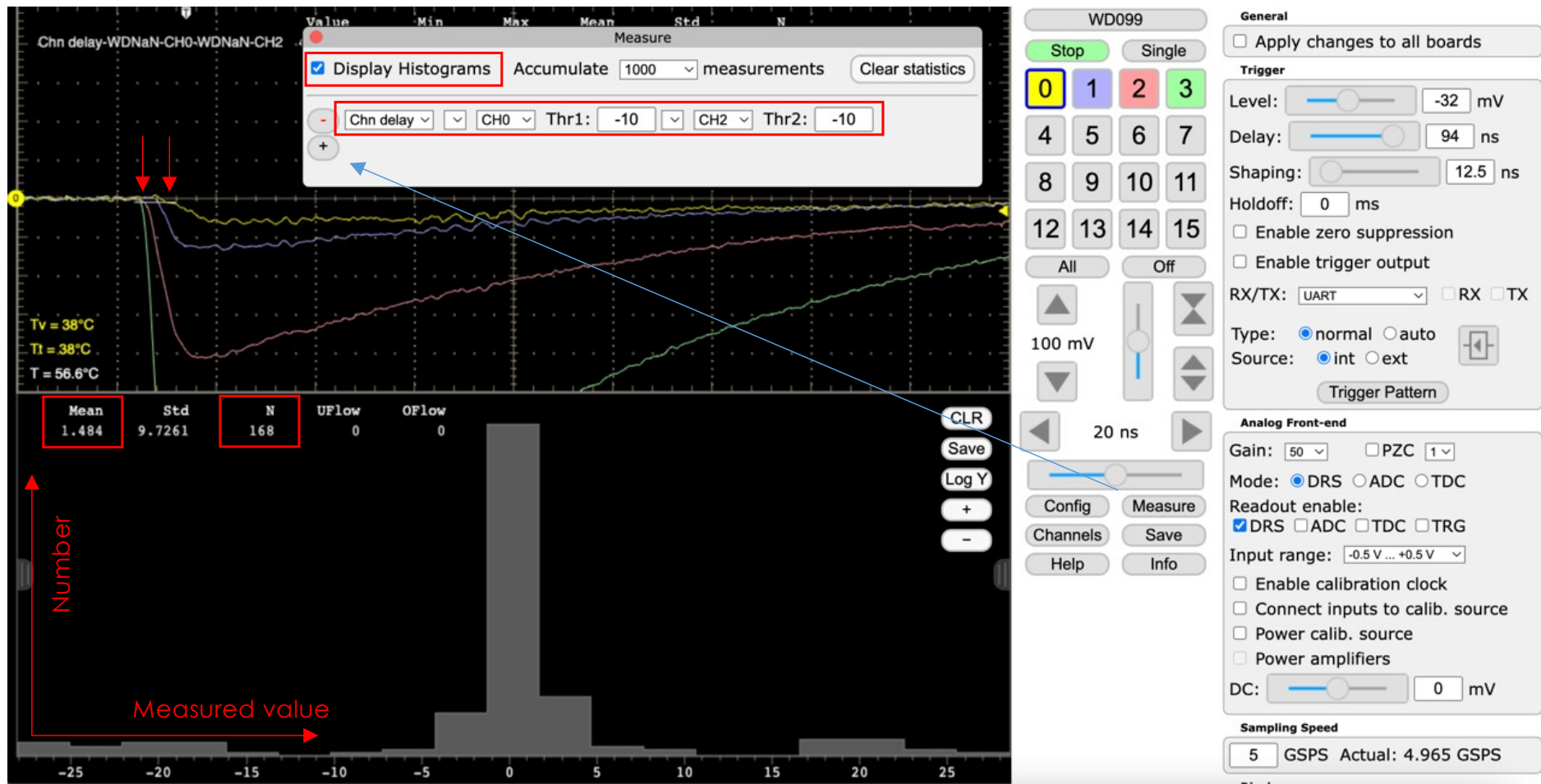
The screenshot displays the 'Channel Configuration' table and the 'Analog Front-end' settings. The table shows that channels 0-3 are configured with a high voltage (HV) of 54 V, while channels 4-15 are set to 0 V. The 'Analog Front-end' settings are configured for DRS mode with a gain of 50 and an input range of -0.5 V to +0.5 V.

Chn	Gain	PZC	Trigger Level	HV	Current
0	50	<input type="checkbox"/>	-32 mV	54 V	0.506 uA
1	50	<input type="checkbox"/>	-32 mV	54 V	0.314 uA
2	50	<input type="checkbox"/>	-32 mV	54 V	0.628 uA
3	50	<input type="checkbox"/>	-32 mV	54 V	0.419 uA
4	50	<input type="checkbox"/>	-32 mV	0 V	0 uA
5	50	<input type="checkbox"/>	-32 mV	0 V	0 uA
6	50	<input type="checkbox"/>	-32 mV	0 V	0 uA
7	50	<input type="checkbox"/>	-32 mV	0 V	0 uA
8	50	<input type="checkbox"/>	-32 mV	0 V	0 uA
9	50	<input type="checkbox"/>	-32 mV	0 V	0 uA
10	50	<input type="checkbox"/>	-32 mV	0 V	0 uA
11	50	<input type="checkbox"/>	-32 mV	0 V	0 uA
12	50	<input type="checkbox"/>	-32 mV	0 V	0 uA
13	50	<input type="checkbox"/>	-32 mV	0 V	0 uA
14	50	<input type="checkbox"/>	-32 mV	0 V	0 uA
15	50	<input type="checkbox"/>	-32 mV	0 V	0 uA

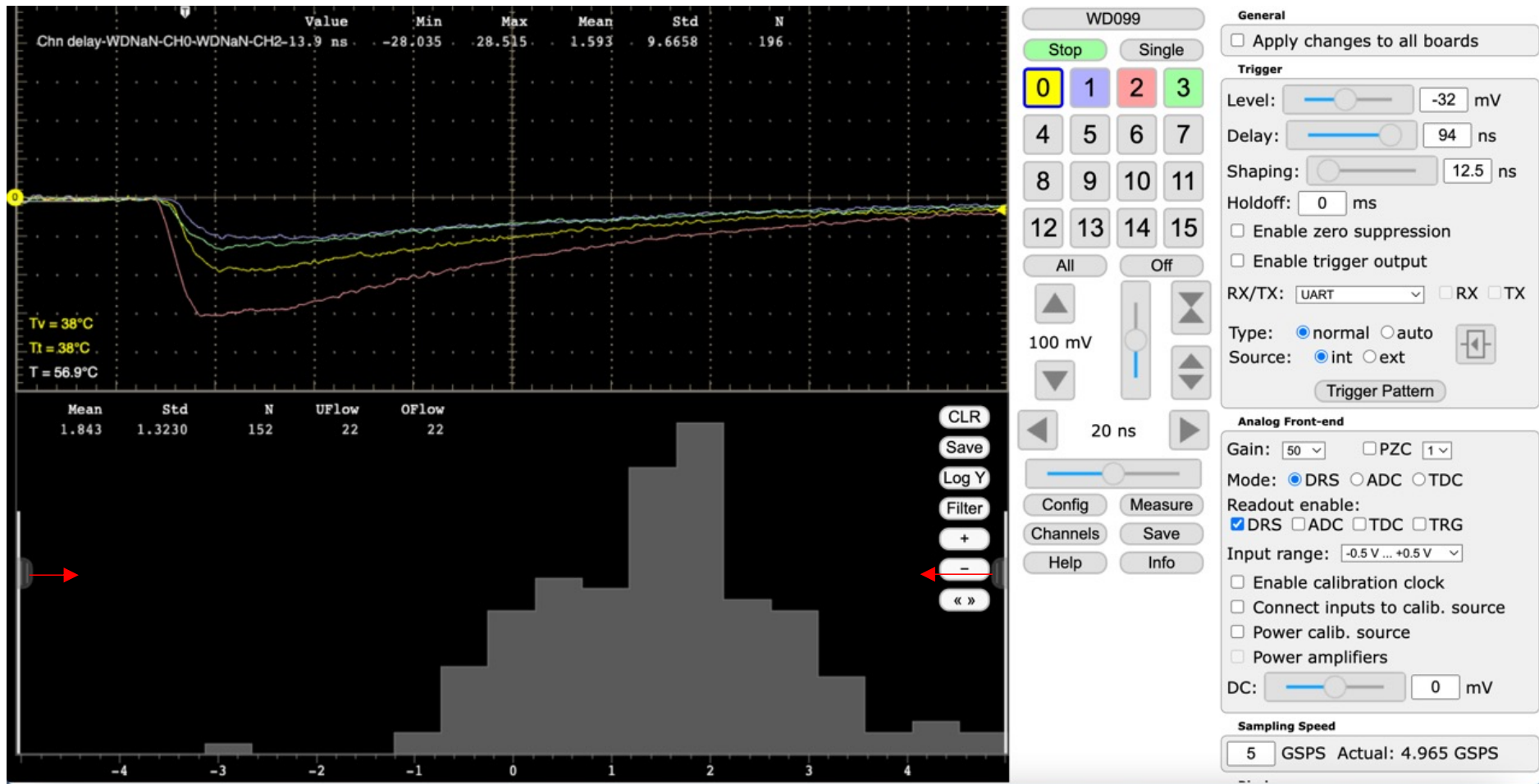
**Analog Front-end Settings:**  
Gain: 50, PZC:   
Mode:  DRS,  ADC,  TDC  
Readout enable:  DRS,  ADC,  TDC,  TRG  
Input range: -0.5 V ... +0.5 V  
DC: 0 mV

**Temperature Data:**  
Tv = 38°C  
Tt = 38°C  
T = 46.8°C

# Define time measurement

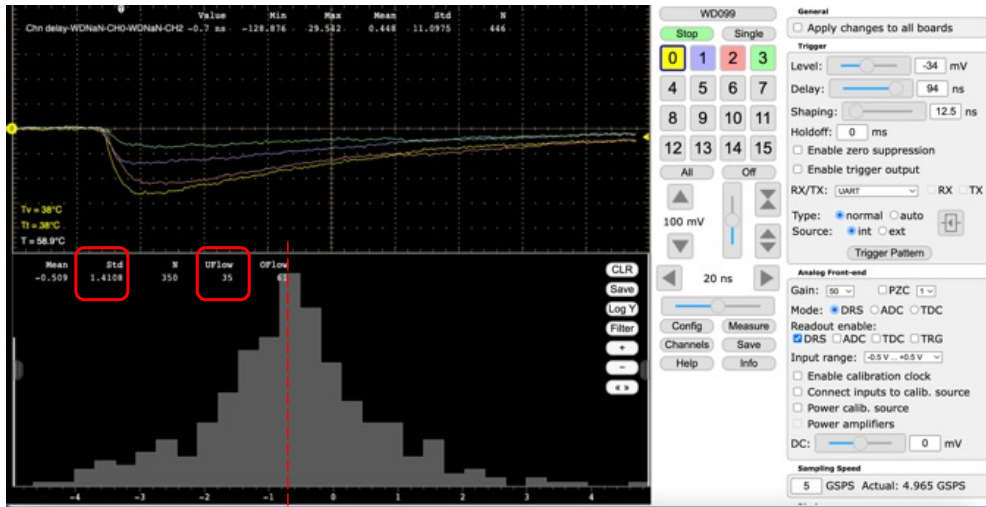


# Zoom to -5 ns to +5 ns

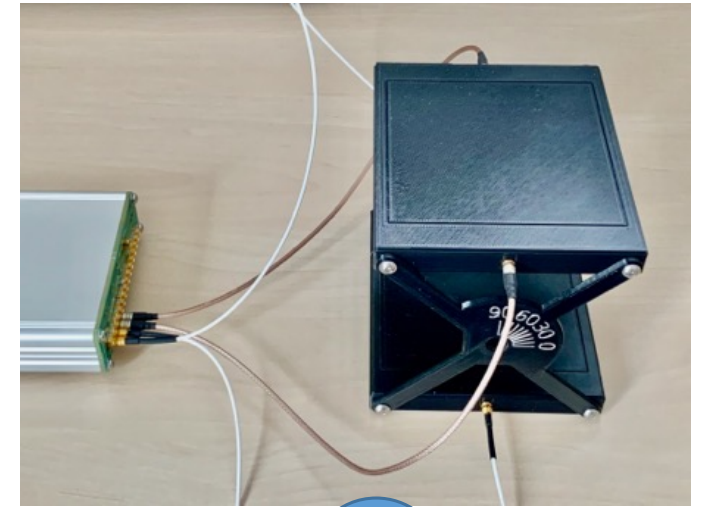


# Measure Speed of Cosmic Muons

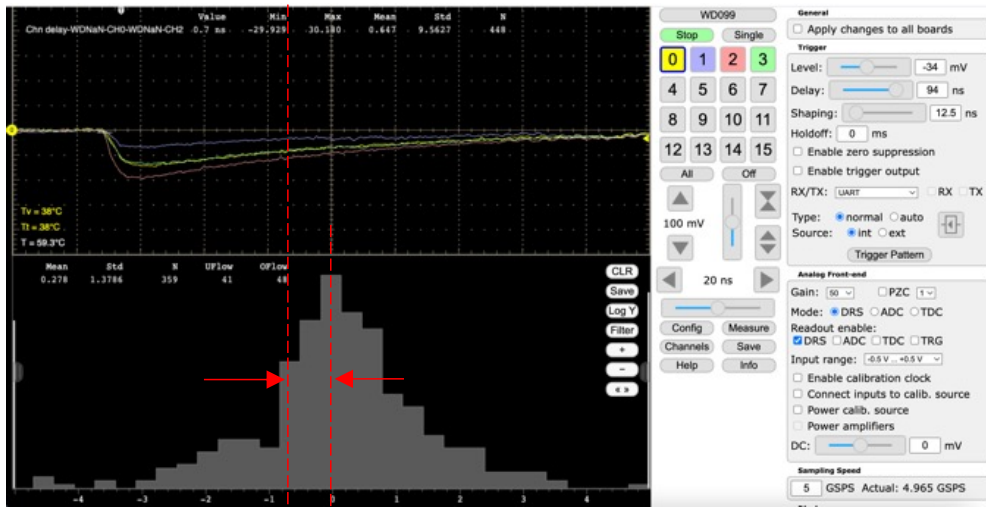
# Measure speed of muons



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:

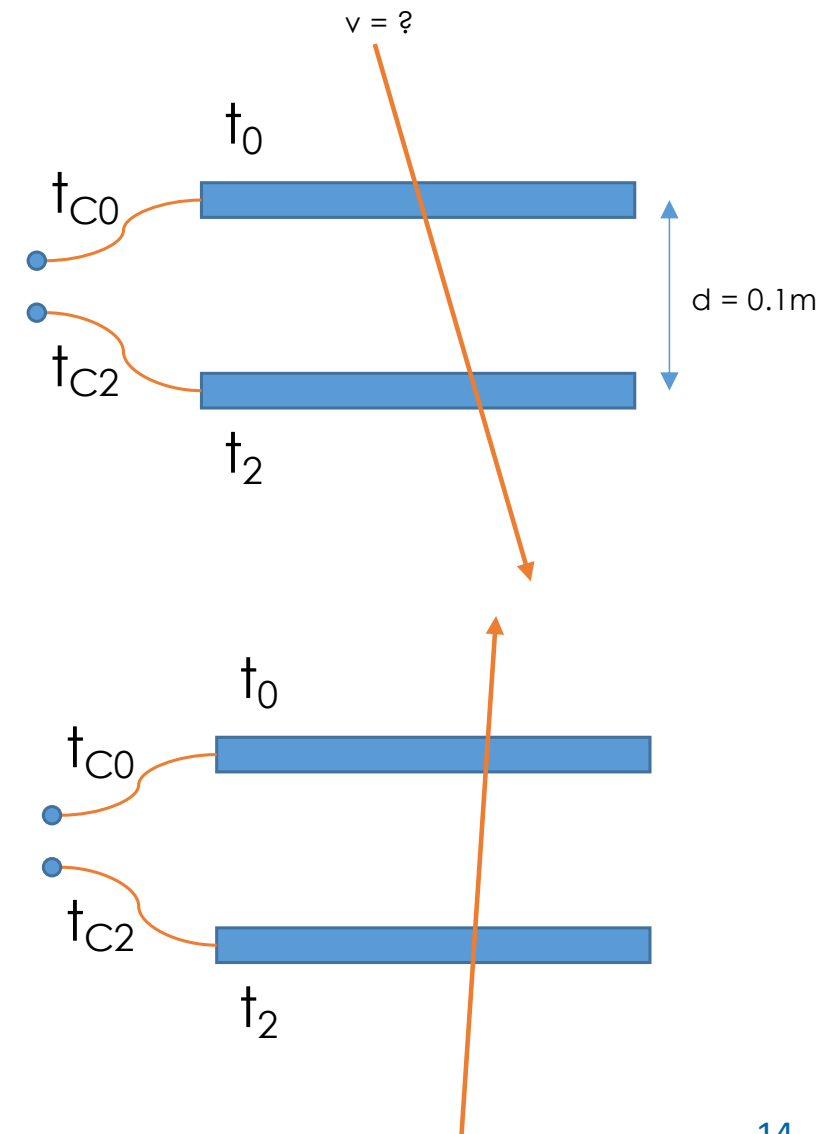
$$\Delta t_B = (t_{0,B} + t_{c0}) - (t_{2,B} + t_{c2}) = d / (-v)$$

Difference:

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

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

**Task: measure v in % of c (=  $3 \times 10^8$  m/s)**

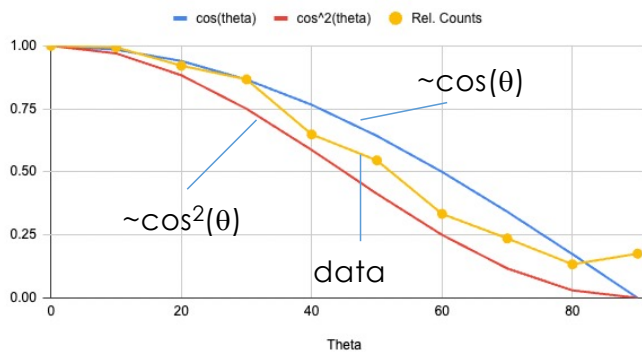


# Measure Direction of Cosmic Muons

# Measure direction of cosmic muons

- ▶ Set angle = 0,10,20...90 deg.
- ▶ Measure 5 minutes
- ▶ Write down counts
  
- ▶ Plot normalized counts vs. angle

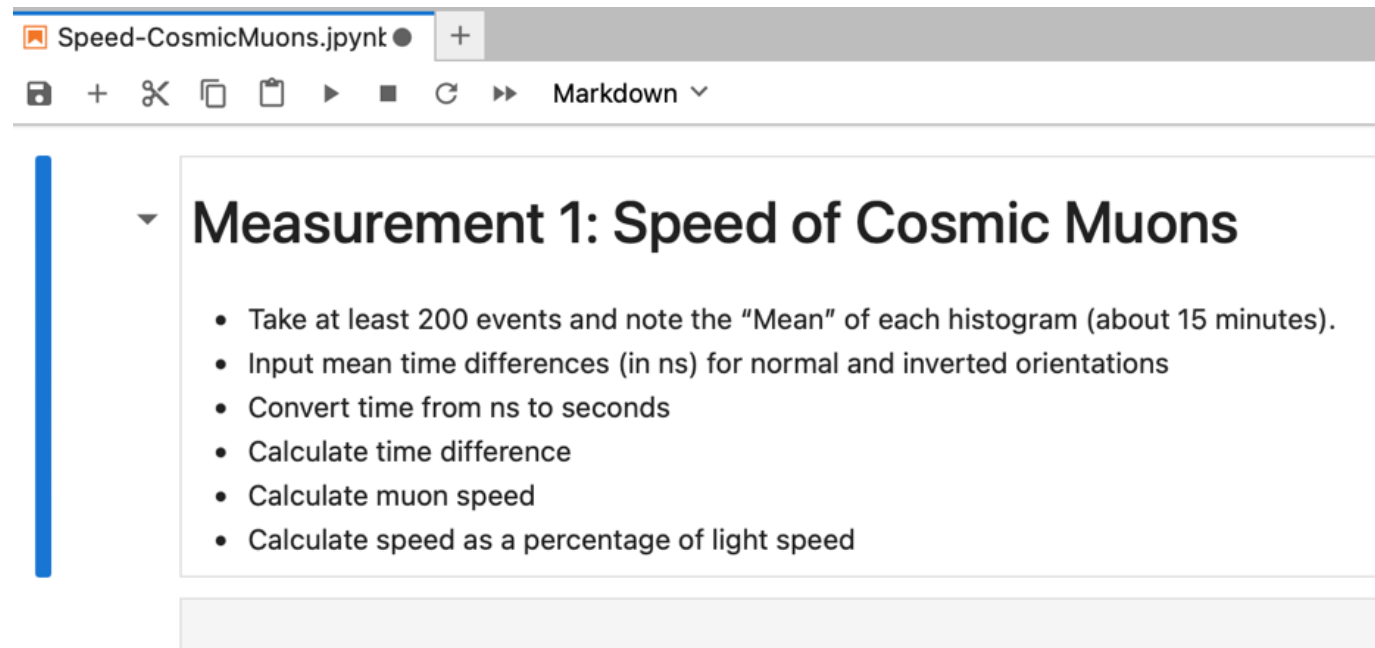
Cosmic muon rate vs. zenith angle





# JupyterLab <https://jupyter.org>

- ▶ Document your measurement!

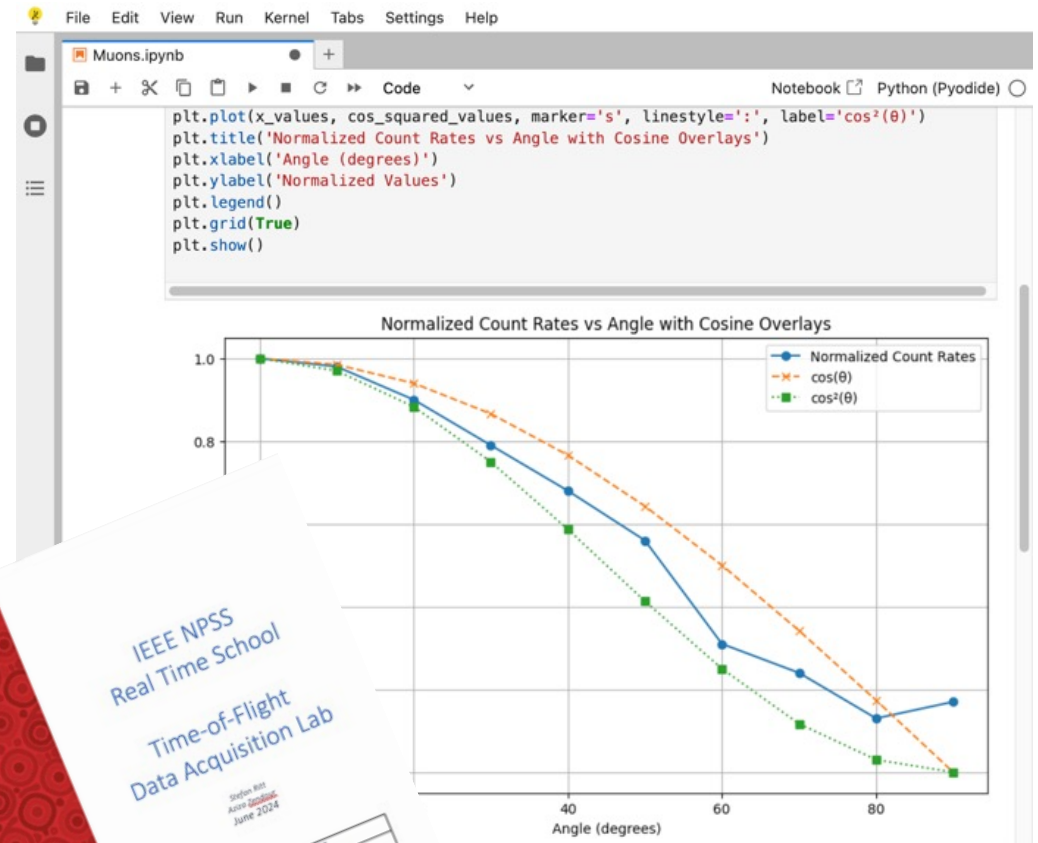


The screenshot shows a JupyterLab notebook window with the title 'Speed-CosmicMuons.jpyn'. The interface includes a toolbar with icons for file operations and a 'Markdown' dropdown menu. The main content area displays a document with a section titled 'Measurement 1: Speed of Cosmic Muons' and a list of instructions:

- ▶ **Measurement 1: Speed of Cosmic Muons**
  - Take at least 200 events and note the "Mean" of each histogram (about 15 minutes).
  - Input mean time differences (in ns) for normal and inverted orientations
  - Convert time from ns to seconds
  - Calculate time difference
  - Calculate muon speed
  - Calculate speed as a percentage of light speed

# 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

