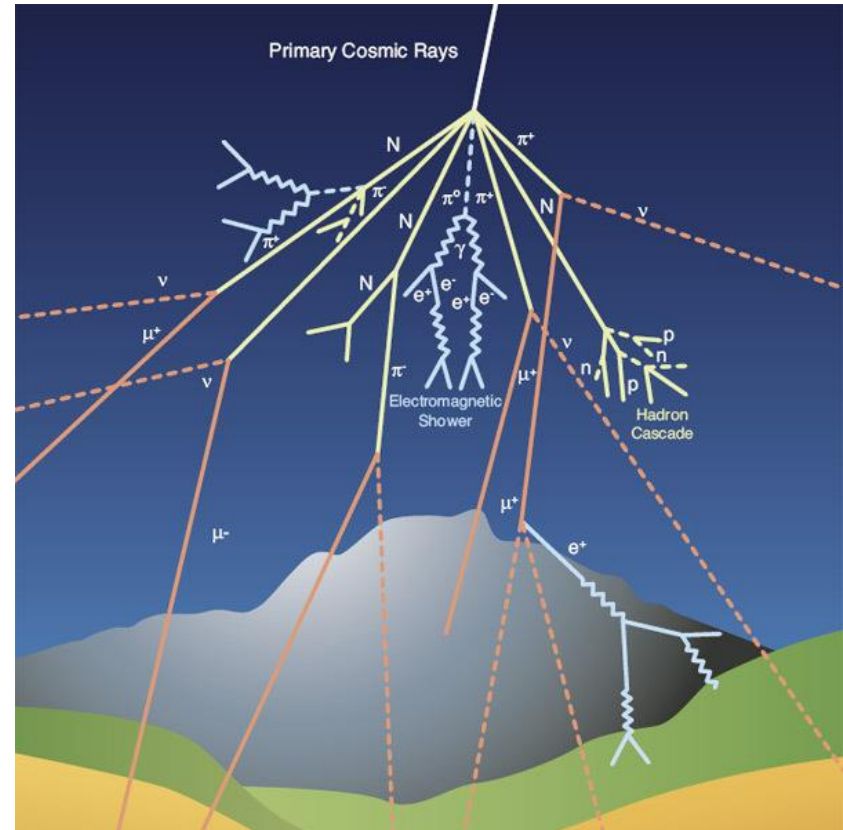


# Time-of-Flight Lab Introduction

*Stefan Ritt, Paul Scherrer Institute, Switzerland  
 IEEE NPSS Workshop on Applications of Radiation Instrumentation  
 November 2022, Dakar, Senegal*

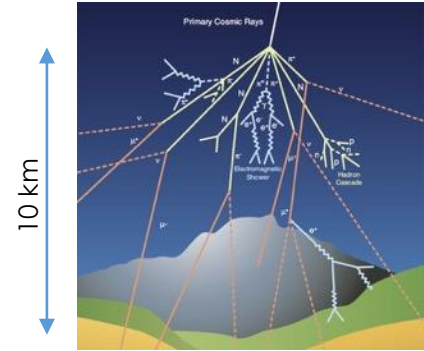
# Cosmic rays

- ▶ **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

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

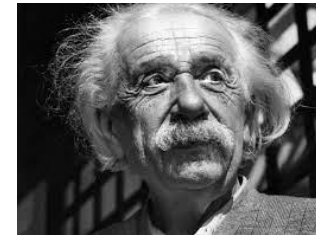
- t' Time measured from an observer outside the frame of reference.
- t Time measured from an observer inside the frame of reference.
- v Speed of the object.
- c Speed of light

- ▶ Muon lifetime @99.9% of c:

$$t'_{1/2} = 2.2 \times 10^{-6} \text{ s} / \underbrace{\text{sqrt}(1-0.999^2)}_{\text{Lorentz factor } \gamma = 22.4} = 49 \times 10^{-6} \text{ s}$$

- ▶ Modified travel distance:

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



# 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)

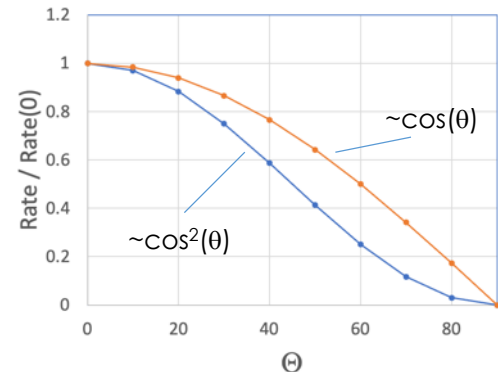
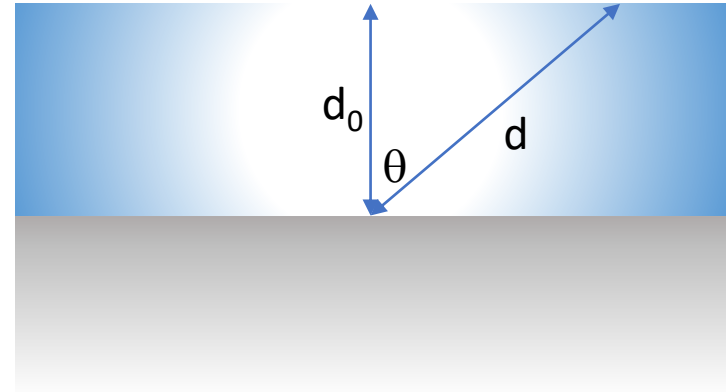
$$\begin{aligned} & d_0/d = \cos(\theta) \\ \rightarrow & d = d_0 / \cos(\theta) \end{aligned}$$

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

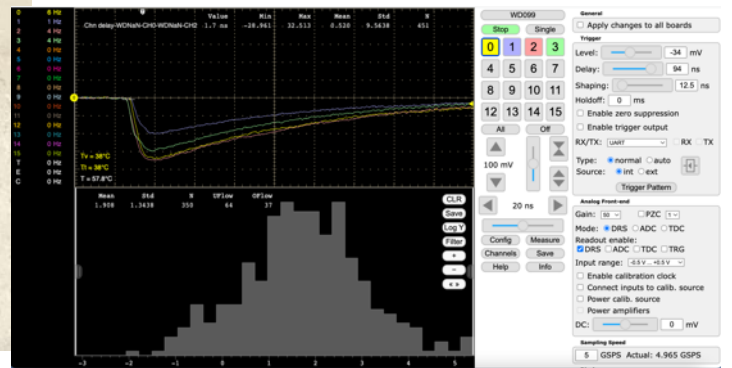
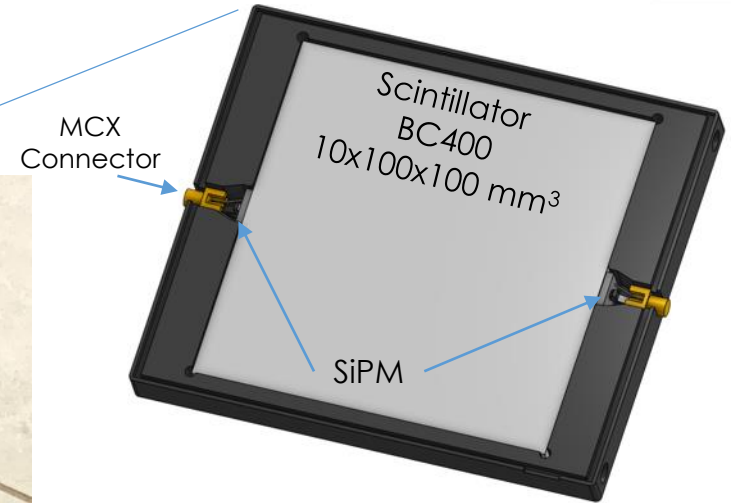
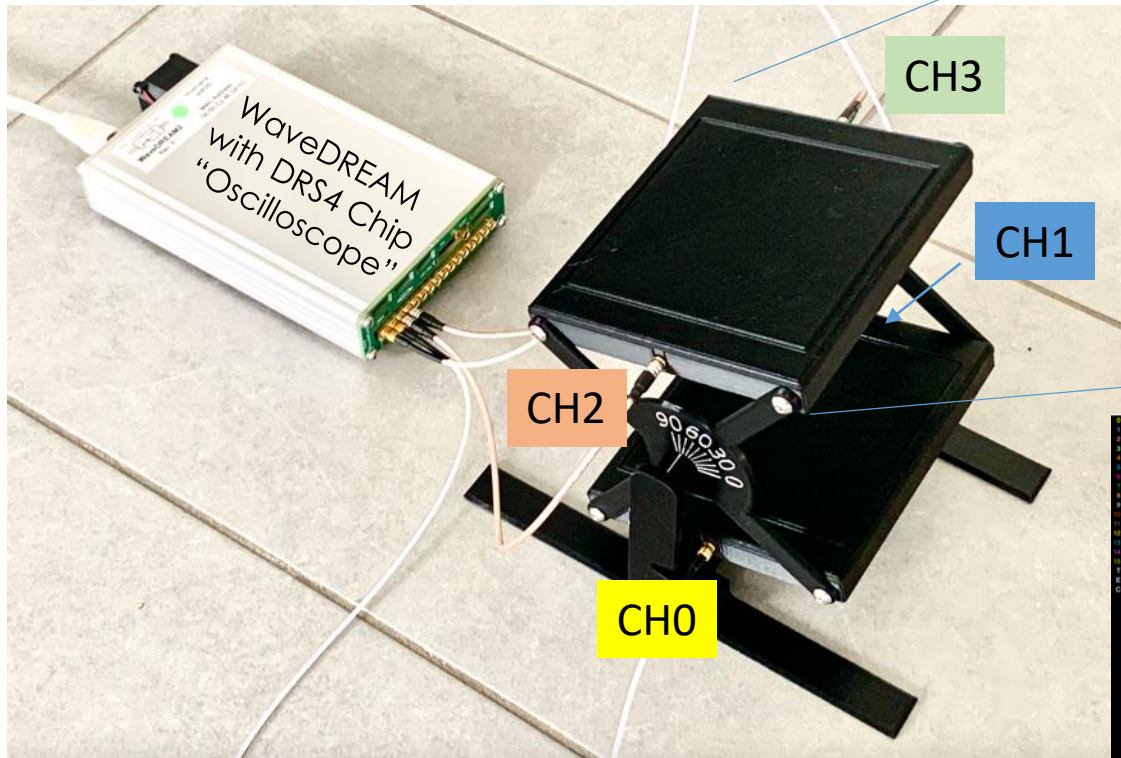
- ▶ **Better approximation** (earth curvature, inhomogeneous atmosphere, muon scattering, ...)

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

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



# Detection of Muons

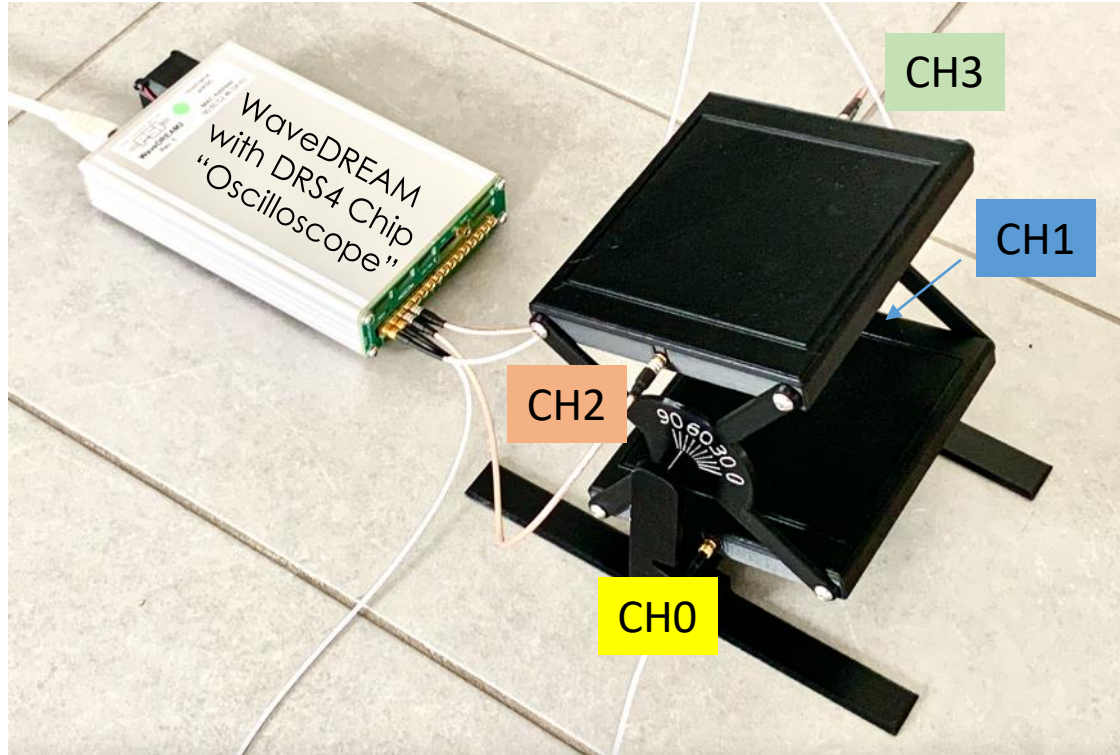


# Lab goals

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



# Connect oscilloscope



# Setting up the oscilloscope

The screenshot displays an oscilloscope interface with a waveform on the left, a statistics table at the top, a Trigger Patterns menu in the center, and control panels on the right. Annotations highlight specific settings.

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

Mean	Std	N
1.908	1.3438	350

Trigger Patterns

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	+																		

WD099

Stop Single

0 1 2 3

4 5 6 7

12 13 14 15

All Off

100 mV

20 ns

Config Measure

Channels Save

Help Info

**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:  RX  TX

Type:  normal  auto

Source:  int  ext

Trigger Pattern

**Analog Front-end**

Gain: 50  PZC 1

Mode:  DRS  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

Turn on channels 0-3

Set trigger

Set gain



# Setting high voltage for SiPM to 54 V

The screenshot displays the configuration interface for a SiPM detector. A central table lists 16 channels, with channels 0-3 highlighted in a red box. Channel 0 is selected, and its HV is set to 54 V. The waveform plot shows a signal pulse for channel 0. The right-hand side contains control panels for 'General', 'Trigger', and 'Analog Front-end' settings.

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

Temperature readings:  $T_v = 38^\circ\text{C}$ ,  $T_t = 38^\circ\text{C}$ ,  $T = 46.8^\circ\text{C}$

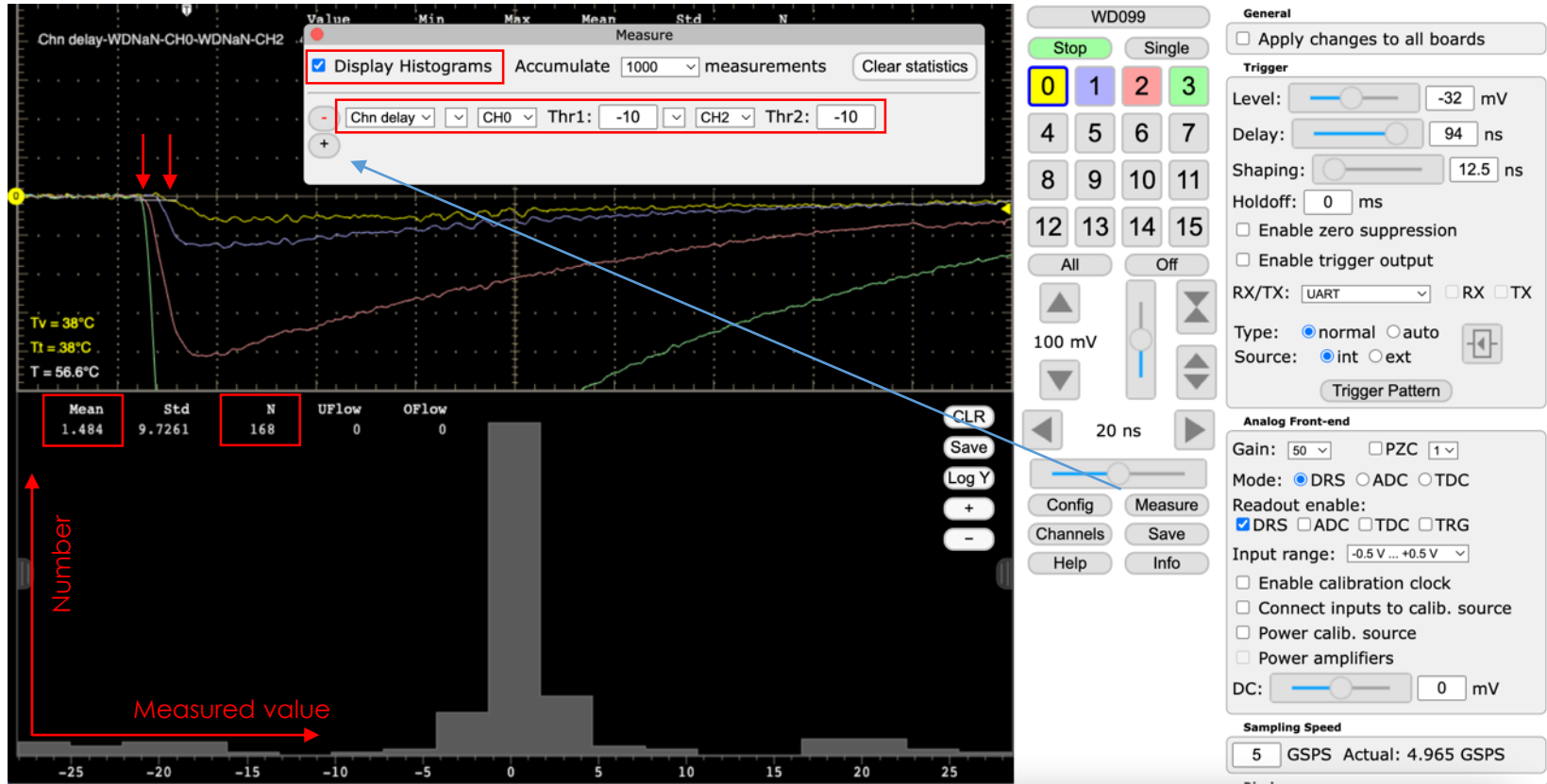
General settings:  Apply changes to all boards

Trigger settings: Level: -32 mV, Delay: 94 ns, Shaping: 12.5 ns, Holdoff: 0 ms,  Enable zero suppression,  Enable trigger output, RX/TX: UART,  RX  TX, Type: normal, Source: int

Analog Front-end settings: Gain: 50,  PZC 1, Mode: DRS, Readout enable:  DRS  ADC  TDC  TRG, Input range: -0.5 V ... +0.5 V, DC: 0 mV

Sampling Speed: 5 GSPS Actual: 4.965 GSPS

# Define time measurement



# Zoom to -5 ns to +5 ns

**Value**    **Min**    **Max**    **Mean**    **Std**    **N**  
 Chn delay-WDNaN-CH0-WDNaN-CH2-13.9 ns    -28.035    28.515    1.593    9.6658    196

**Mean**    **Std**    **N**    **UFlow**    **OFlow**  
 1.843    1.3230    152    22    22

**General**  
 Apply changes to all boards

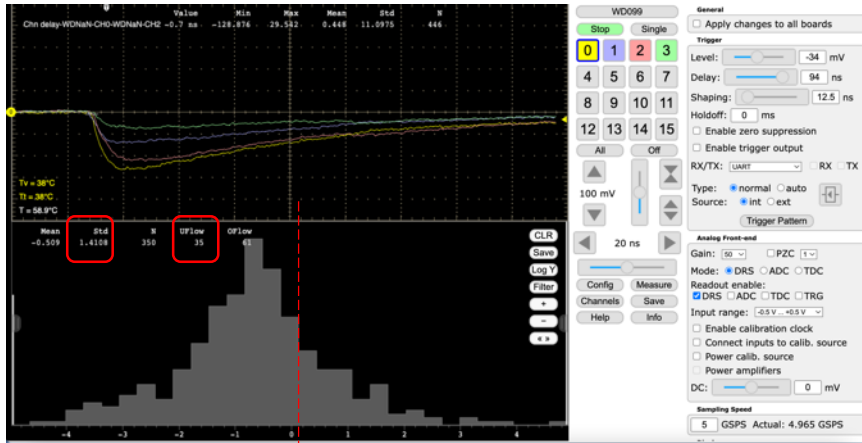
**Trigger**  
 Level:  mV  
 Delay:  ns  
 Shaping:  ns  
 Holdoff:  ms  
 Enable zero suppression  
 Enable trigger output  
 RX/TX:   RX  TX  
 Type:  normal  auto  
 Source:  int  ext  
 Trigger Pattern

**Analog Front-end**  
 Gain:   PZC   
 Mode:  DRS  ADC  TDC  
 Readout enable:  
 DRS  ADC  TDC  TRG  
 Input range:   
 Enable calibration clock  
 Connect inputs to calib. source  
 Power calib. source  
 Power amplifiers  
 DC:  mV

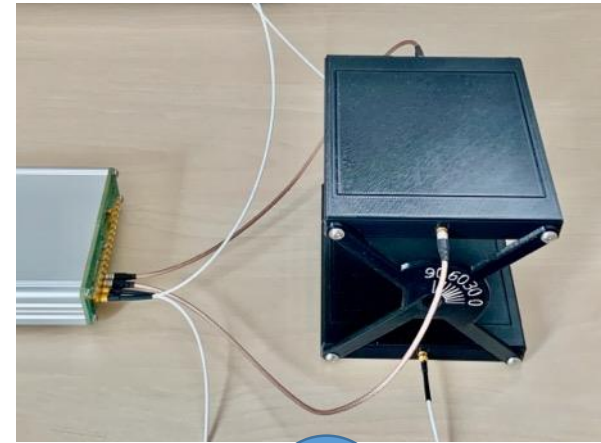
**Sampling Speed**  
 GSPS Actual: 4.965 GSPS

# Measure Speed of Cosmic Muons

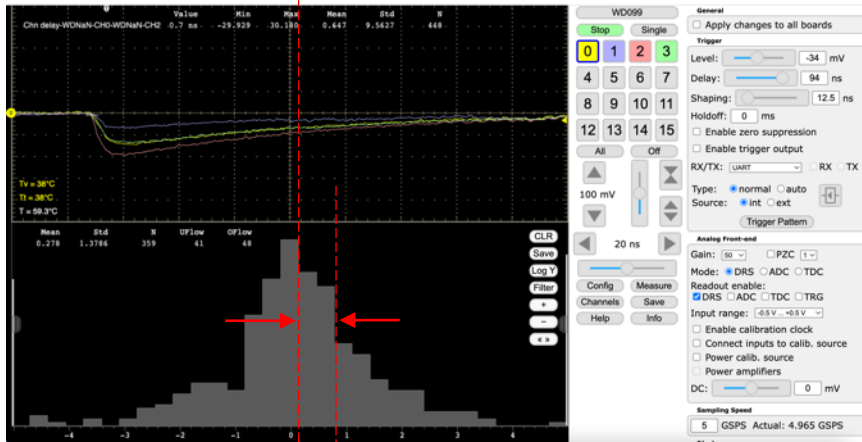
# Measure speed of muons



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:

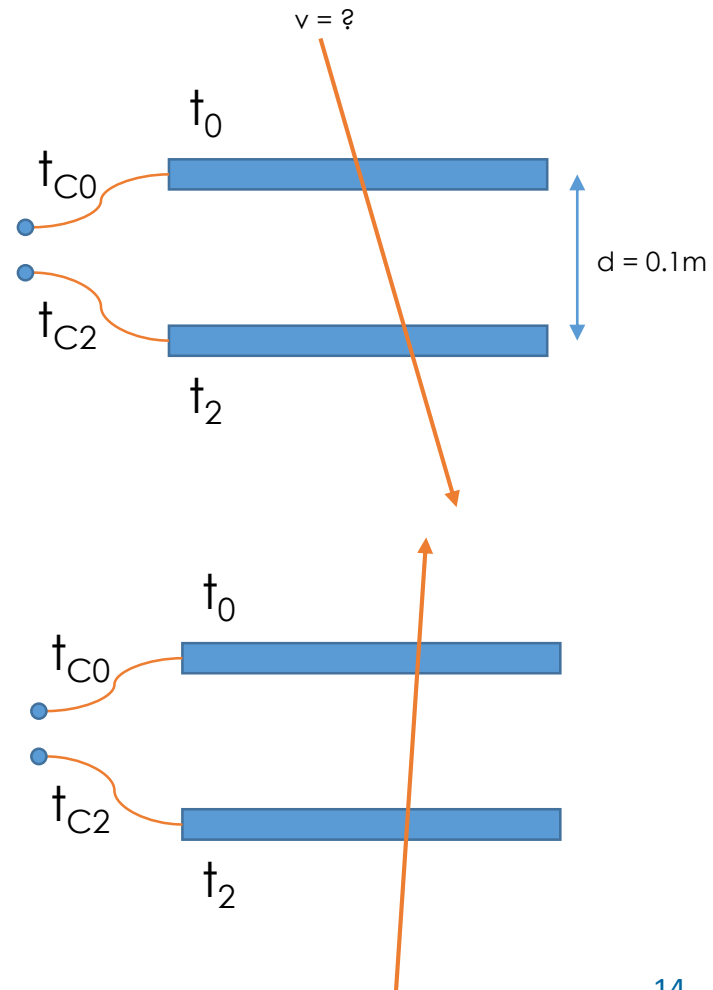
$$\Delta t_B = (t_{0,B} + t_{C0}) - (t_{2,B} + t_{C2}) = d / (-v)$$

Difference:

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

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

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



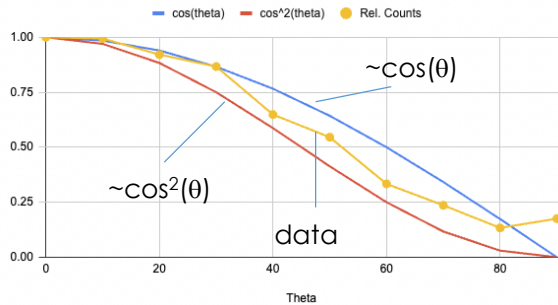


# Measure Direction of Cosmic Muons

# 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



# 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?