Atmospheric Muon Flux Measurements and Applications

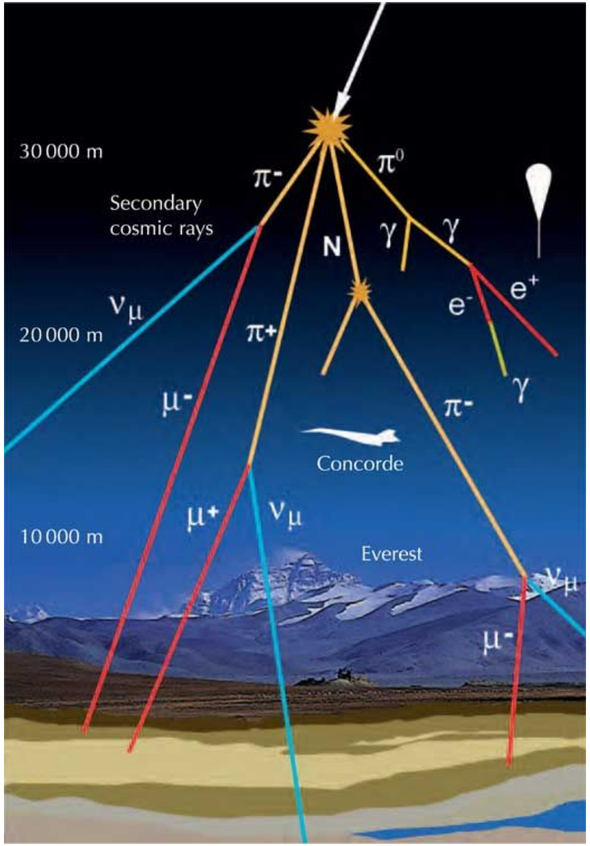
V Uniandes Particle Detector School
Universidad de los Andes

Cristian Borja
cm.borja10@uniandes.edu.co

What are muons (μ) and where they come from?

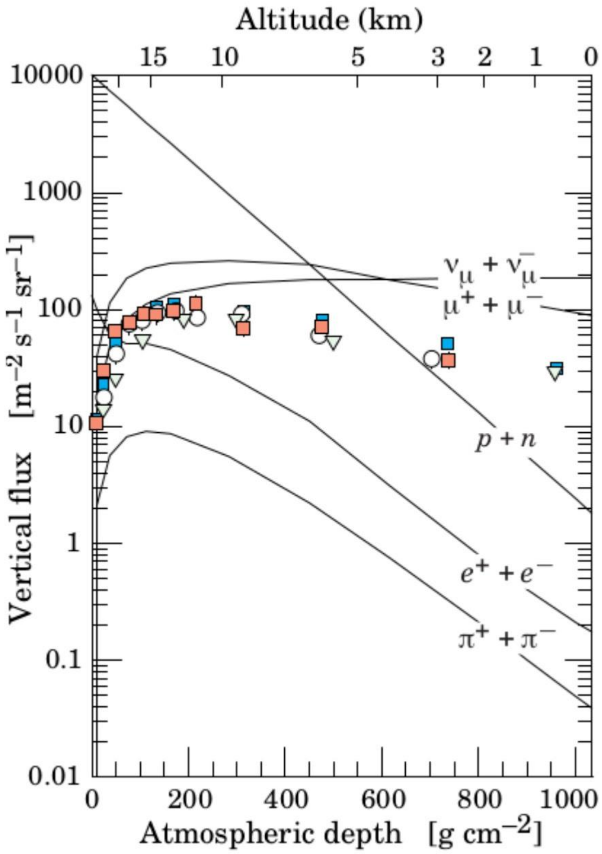
- Fundamental particles
- Muons are the heavy cousins of electrons **m_μ = 200 m_e**
- They have a life-time of **τ = 2.2μs**

- Cosmic Rays are radiation from outer space
- Atmospheric muons are produced when Cosmic Rays interact with the atmosphere.



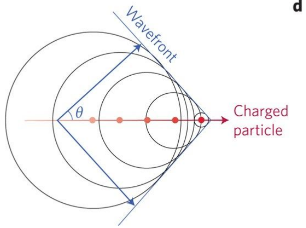
Why do we measure muons?

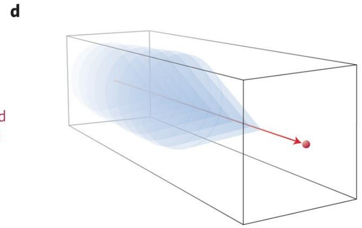
- Its production is closely related to neutrino production
- Imaging applications
- Unlimited radiation, free and naturally produced
- Non invasive. (No health effects)
- Long life-time and high mass, they reach Earth surface.
- Produced at 15 km height. (relativistic factor $\gamma \approx 20$, they can travel 24 km before decay)
- Highly penetrating. Energy loss (Bremsstrahlung radiation) is proportional to $1/m^2$



How can we detect muons?

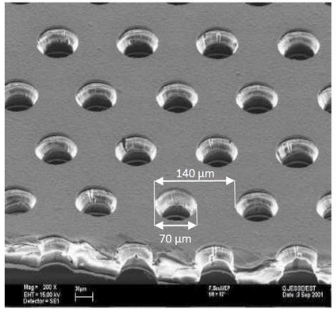
- Plastic Scintillators
- Cherenkov Effect
- Emulsion Films
- Gaseous Detectors (GEM)

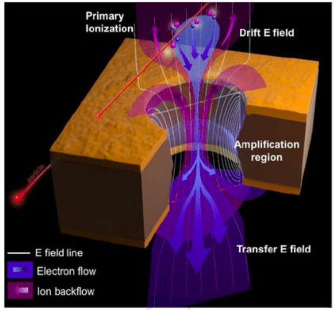


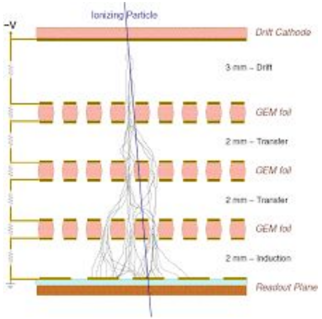


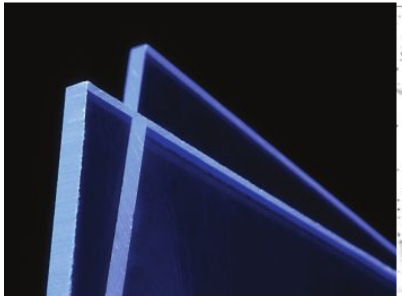
Detection techniques are usually combined with computer simulations

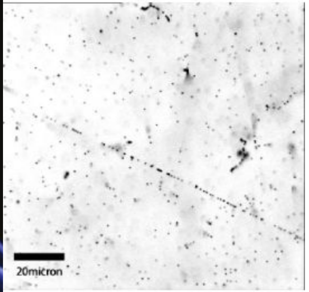
- CORSIKA (COsmic Ray SImulations for KAscade)
- MUSIC (MUon SImulation Code)
- GEANT4 (GEometry And Tracking)





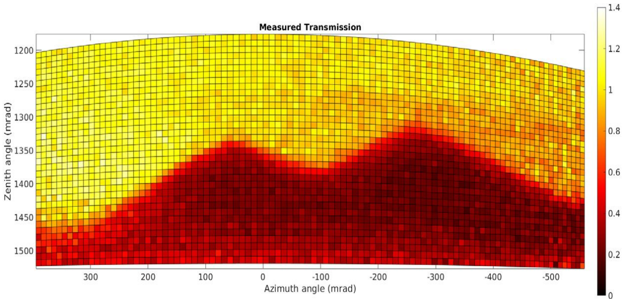


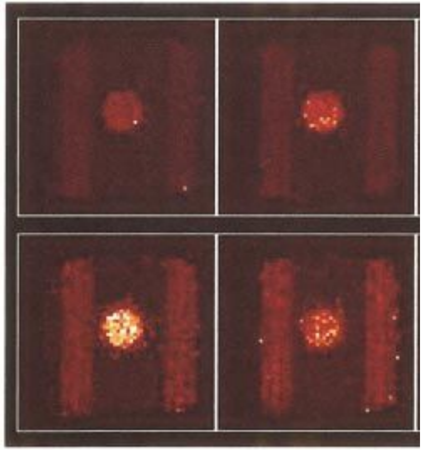


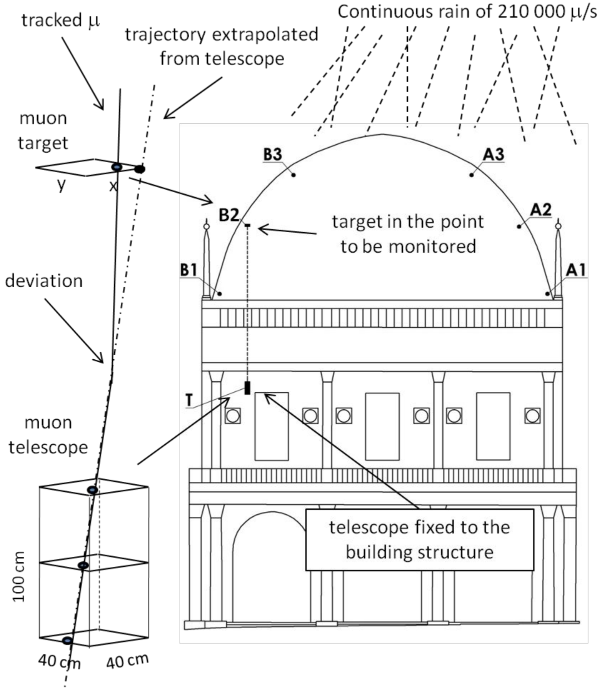


Atmospheric Muon Applications

- Muon imaging radiography / tomography of geological and archaeological structures.
- Monitoring of mechanical stability of buildings, radioactive material and blast furnaces processes.



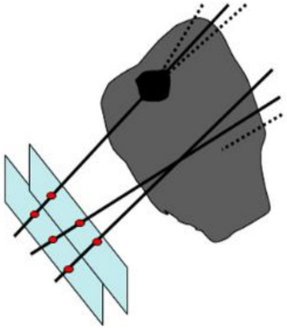


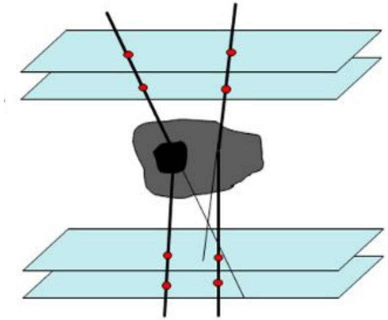


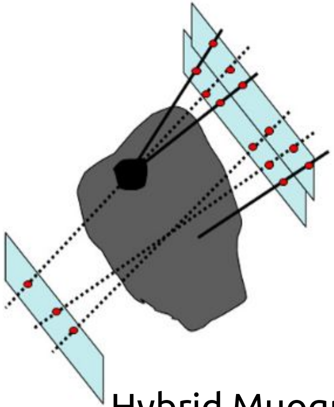
(2018) L. PrestiThe MEV project: Design and testing of a new high-resolution telescope for muography of Etna Volcano
(2003) Priedhorsky - Detection of high-Z objects using multiple scattering of cosmic ray muons
(2019) Bonomi - A Cosmic Rays Tracking System for the Stability Monitoring of Historical Buildings

Muon Imaging (Muography)

- Measuring flux change: open sky flux vs. flux through a target. Imaging of objects from hundred meters to km.
- Measuring change of trajectories due to scattering with a target. Only useful for high Z targets and in mm to cm scale.
- Hybrid techniques for intermediate objectives

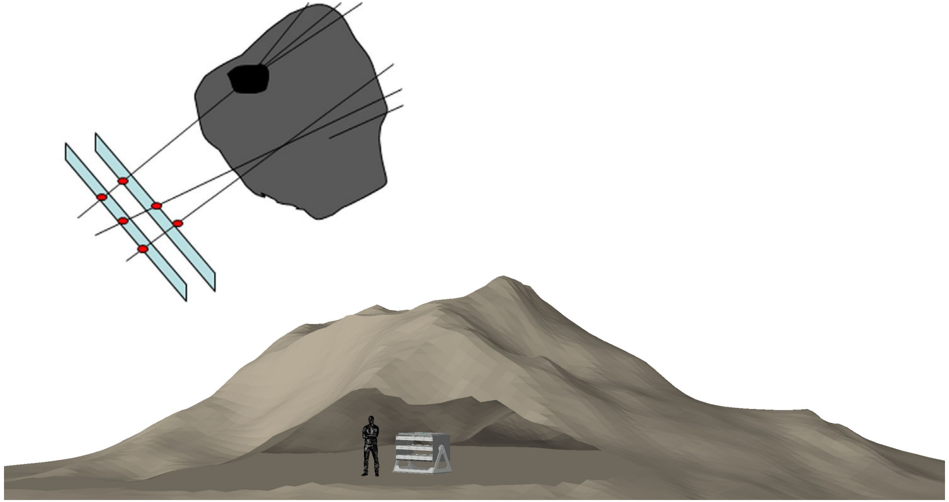

Attenuation Muography

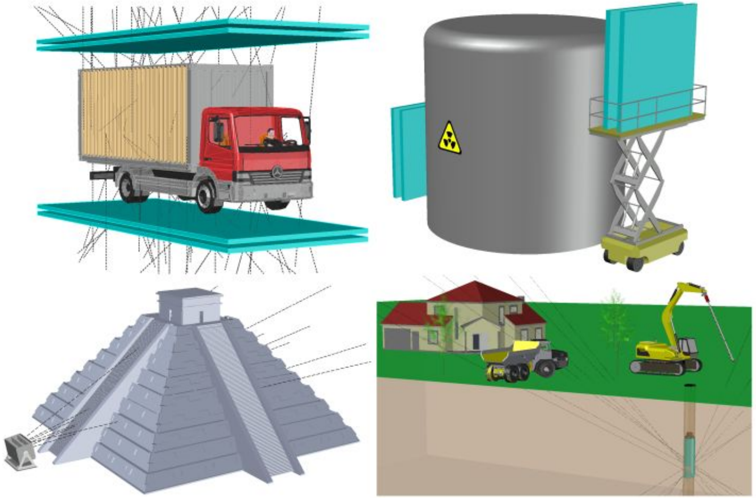

Scattering Muography


Hybrid Muography

Absorption/Attenuation/Transmission Muography

- For monitoring of large objectives.
- Based on the probability of a muon to cross the target (depends on the muon energy).
- Muon flux attenuation compared with open sky flux.





Diagrams taken from
(2019) L, Bonechi, Atmospheric muons as an Imaging Tool
(2018) S, Procureur, Muon Imaging: Principles, techniques and applications.

WaTo Experiment, Saclay France 2016

Micromegas Detector (Micro-MEsh Gaseous Detector)

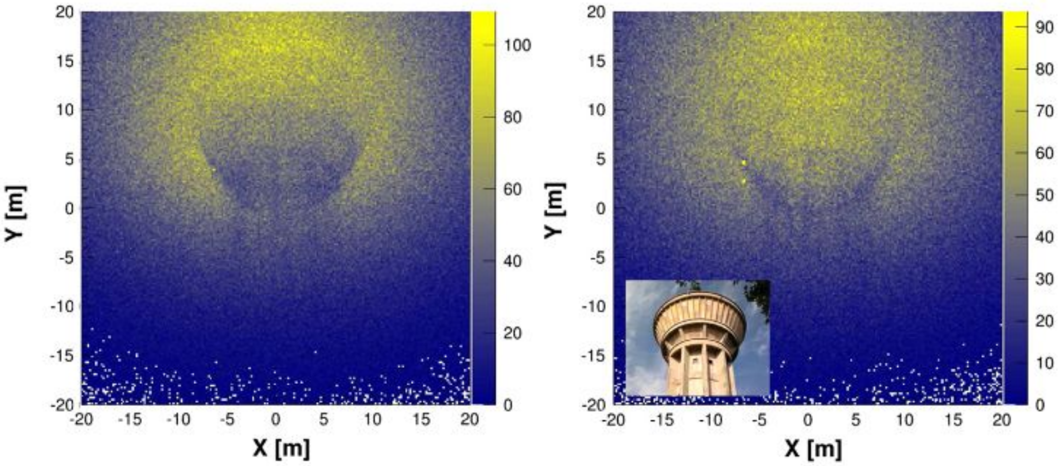
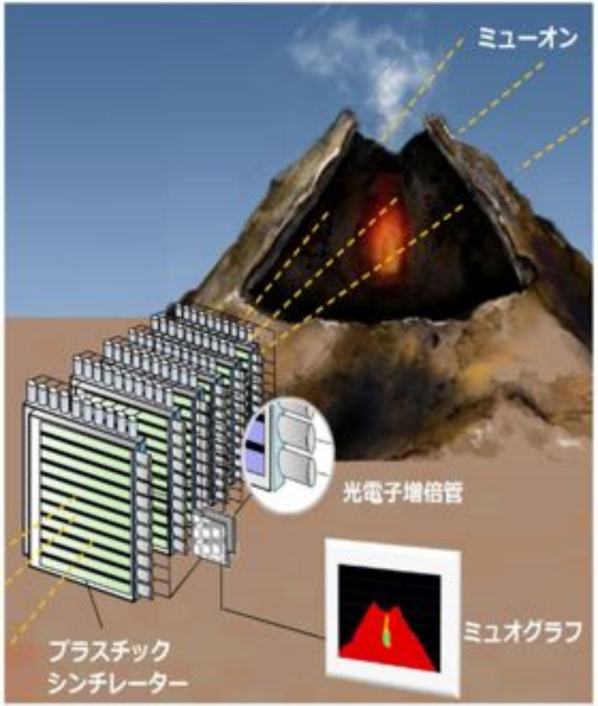


Fig. 5. Muography of the Saclay water tower with 4 days of data during the phase 2, with the water (left) and during the emptying (right).

Images taken from:
(2016) S, Bouteille - *A Micromegas-based telescope for muon tomography: The WatTo experiment*

Muography of Satsuma-Iwojima Volcano, Japan 2014



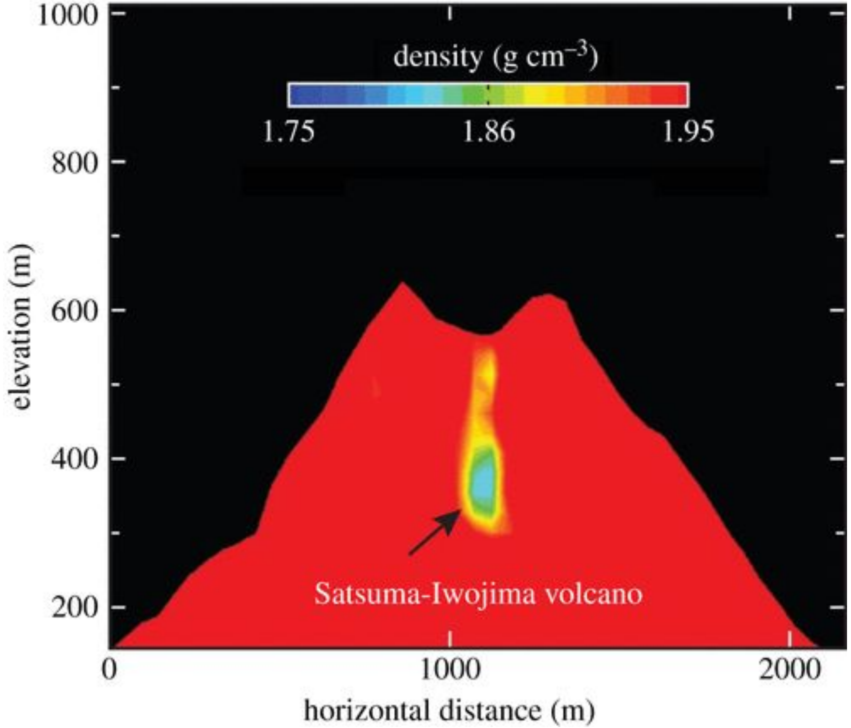
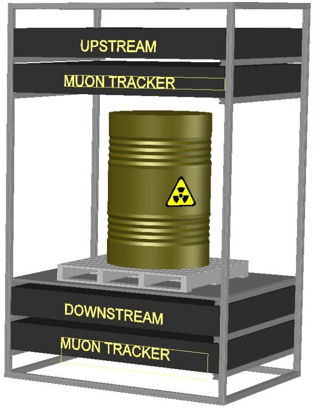
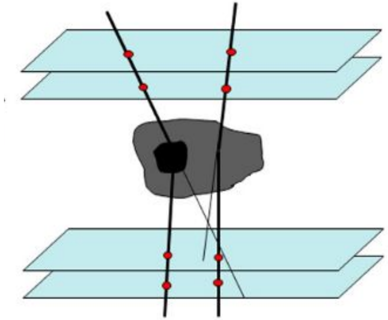


Image taken from:
(2019) Tanaka - Japanese volcanoes visualized with muography

Scattering Muography

- For monitoring of containers or small targets.



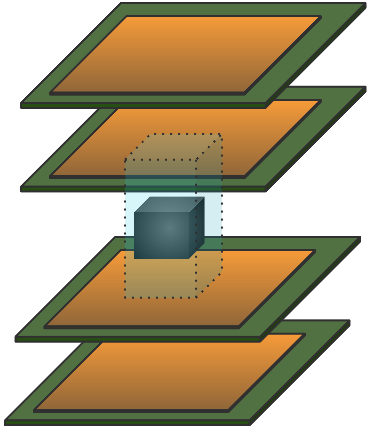


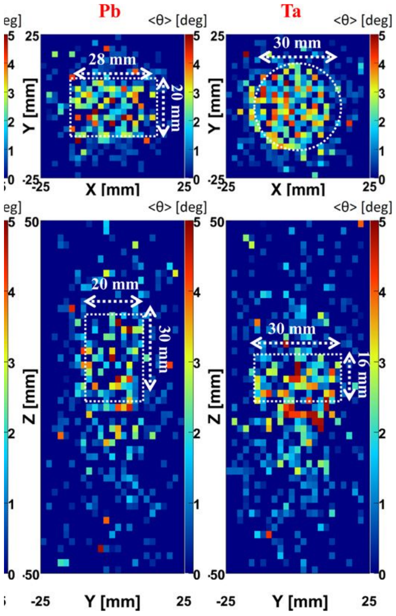
Diagrams taken from
(2019) L, Bonechi, Atmospheric muons as an Imaging Tool
(2018) S, Procureur, Muon Imaging: Principles, techniques and applications.

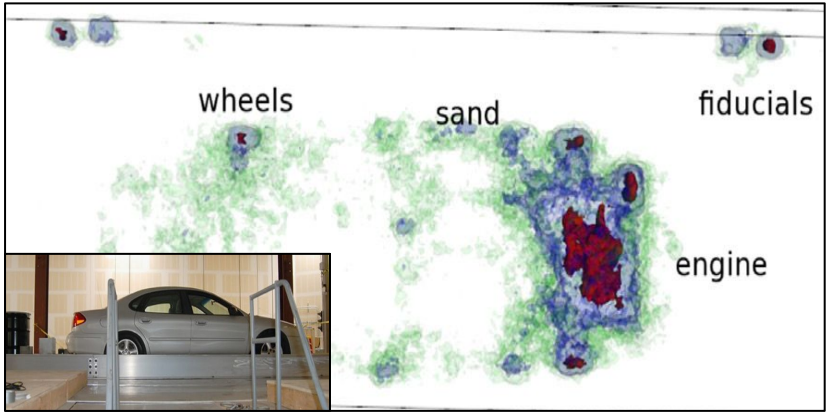
Scattering Muography and Hybrid techniques

(2010) Gnavo - *Imaging of high-Z material with a muon tomography station based on GEM detectors.*

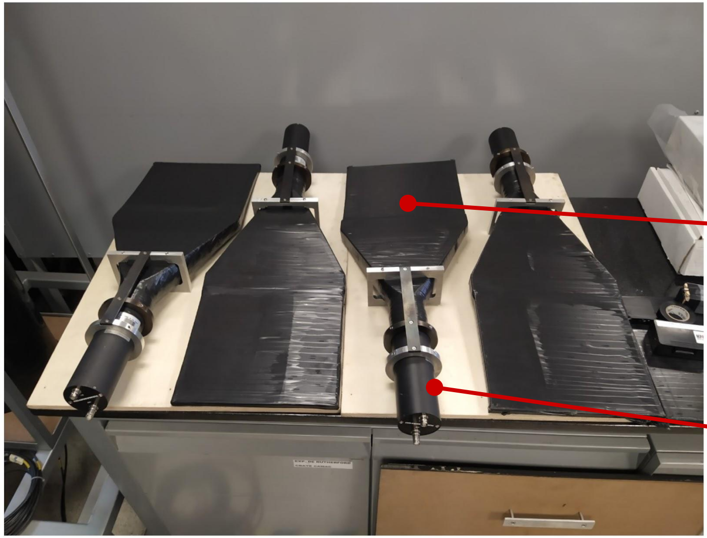
(2015) Blanpied - *Material discrimination using scattering and stopping of cosmic ray muons and electrons: Differentiating heavier from lighter metals as well as low-atomic weight materials*

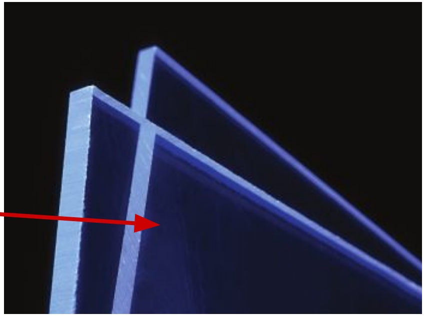






The μ-niandes Muon Detector





Each detector is composed of:

- Plastic Scintillator
- Photo multiplier tubes (PMT)
- Mechanical support

How a PMT works?

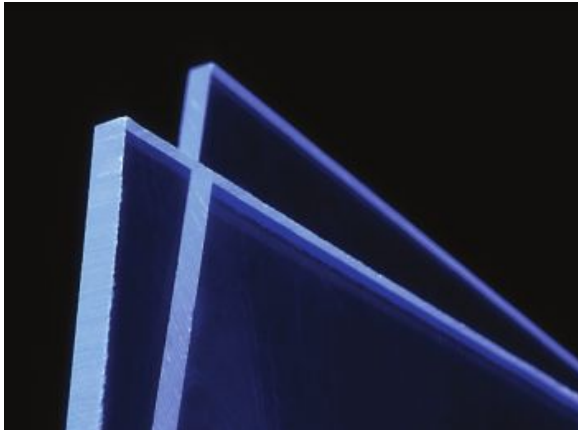
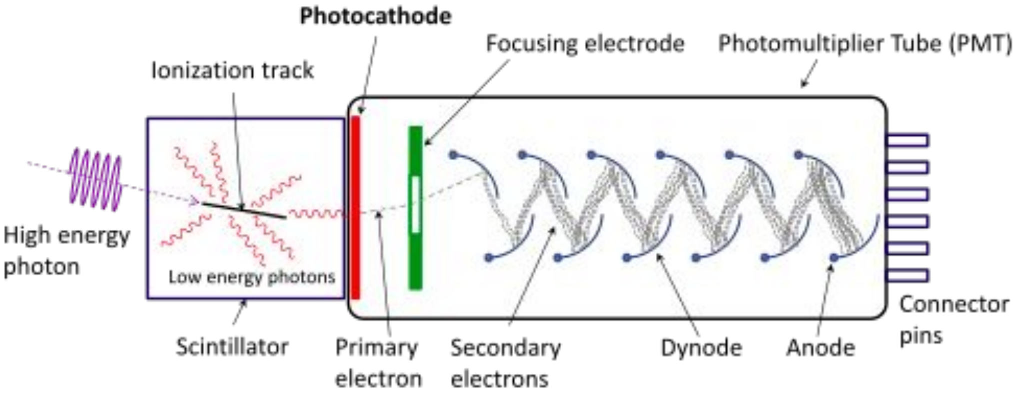


Photo-electric effect



µ-niandes Data Acquisition Electronics

High Voltage Source

4 Channels
Polarity +/-
Range from 0 to 5 kV
(Detector power supply)

Fan In/Out

4 Channels
Reply Signals
(For monitoring and clone signals)

Discriminator

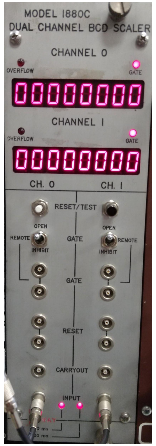
8 Channels
Controllable pulse width (from 4ns to 75ns) and thresholds levels
(Signal digitization)

Delay Generator

4 Channels
Delays from ns to s scale
(Allows acquire data after triggering signals)

Logic Unit

From 1 to 4 input.
Coincidence levels: OR/2-AND/3-AND/ Majority
(Triggering signal)



BCD Counter

2 Channels
(Count number of coincidences)

μ-niandes Data Acquisition Electronics

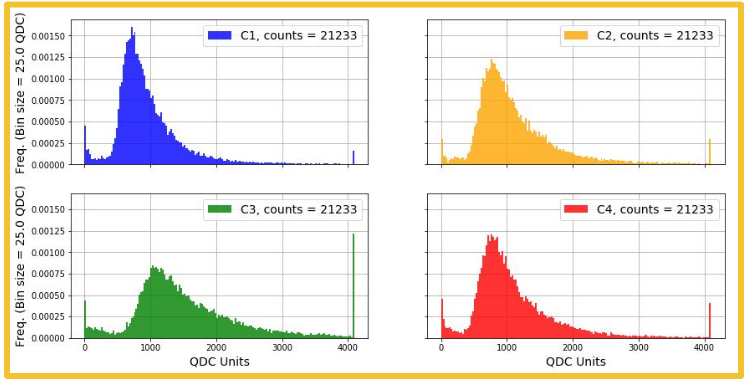
Camac BUS
(Allows PC-Electronics communication)

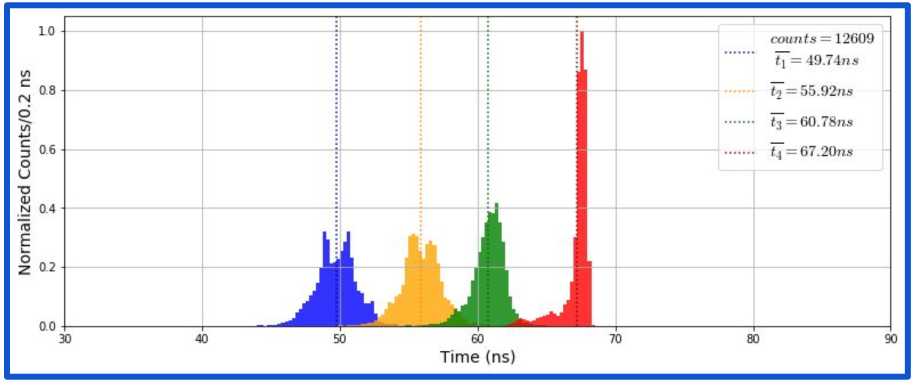
QDC (Energy-Like Data)

4095 digital units
Integrates with a GATE signal
16 Channels
(Deposited Charge Measurements)

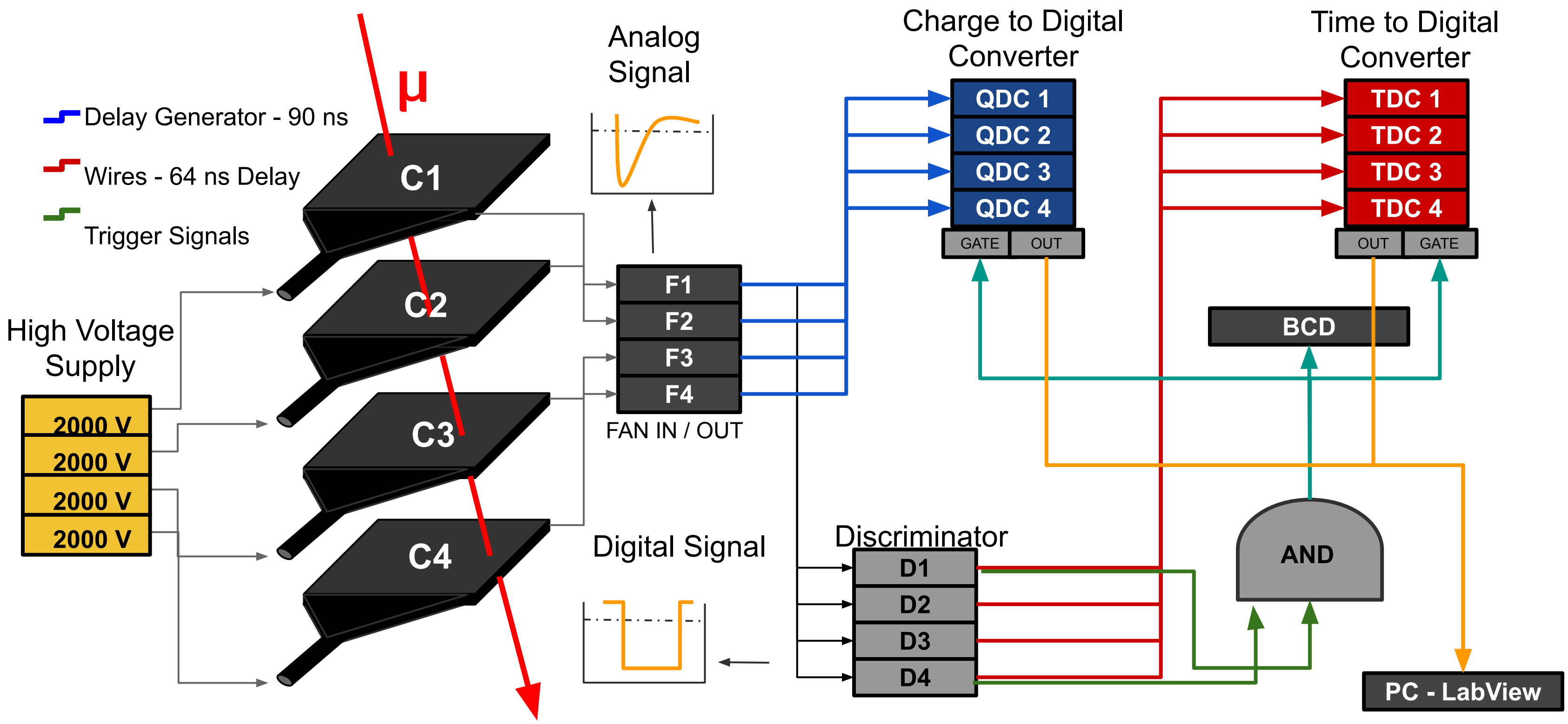
TDC (Time Data)

4095 digital units (25ps res.)
Measure with a START signal
16 Channels
+20ns offset
(Timing Measurements)





μ-niandes Data Acquisition Electronics

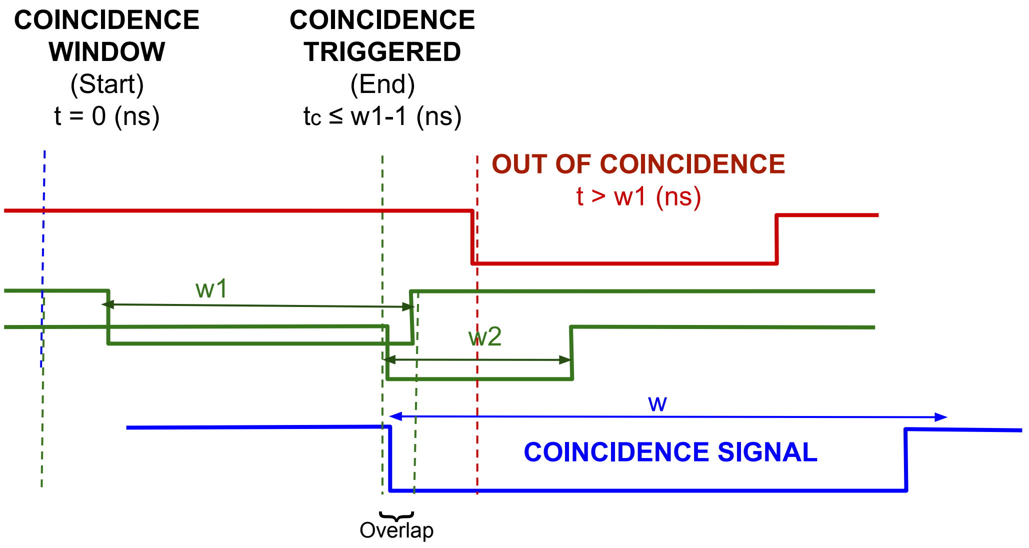


µ-niandes Triggering System

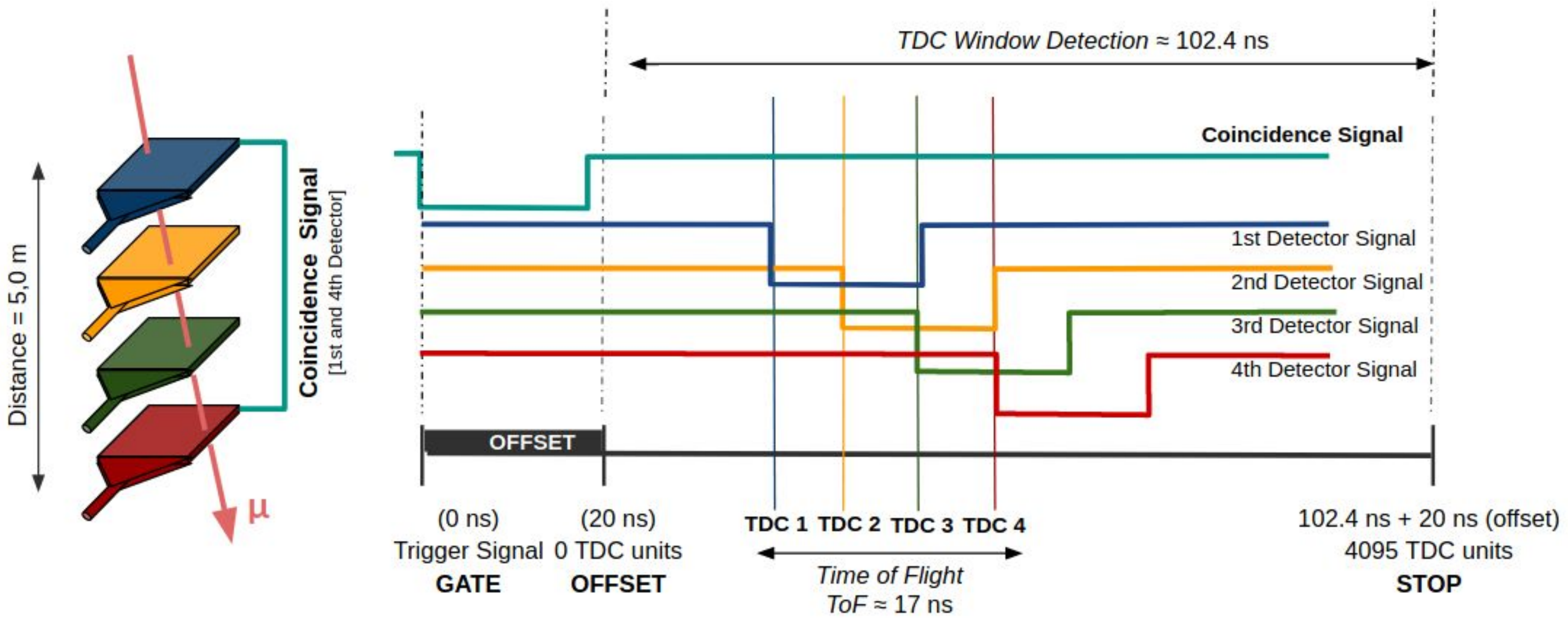
The “trigger” is the signal that determines if an event is of physical interest.

- Voltage Discriminator Threshold Levels
- Trigger Signal - Coincidence C1.C4 within a time-window
- Off-line event discrimination (cleaning QDC and TDC data)

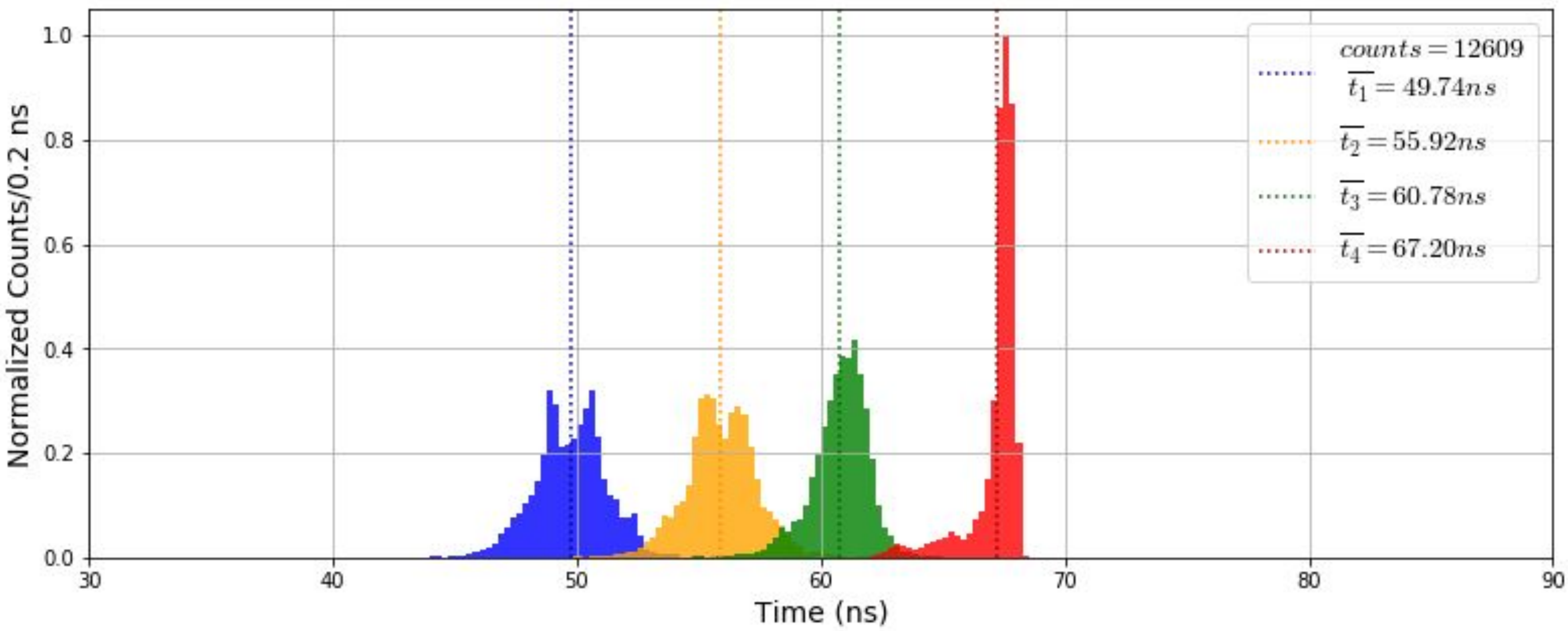
Coincidence Diagram



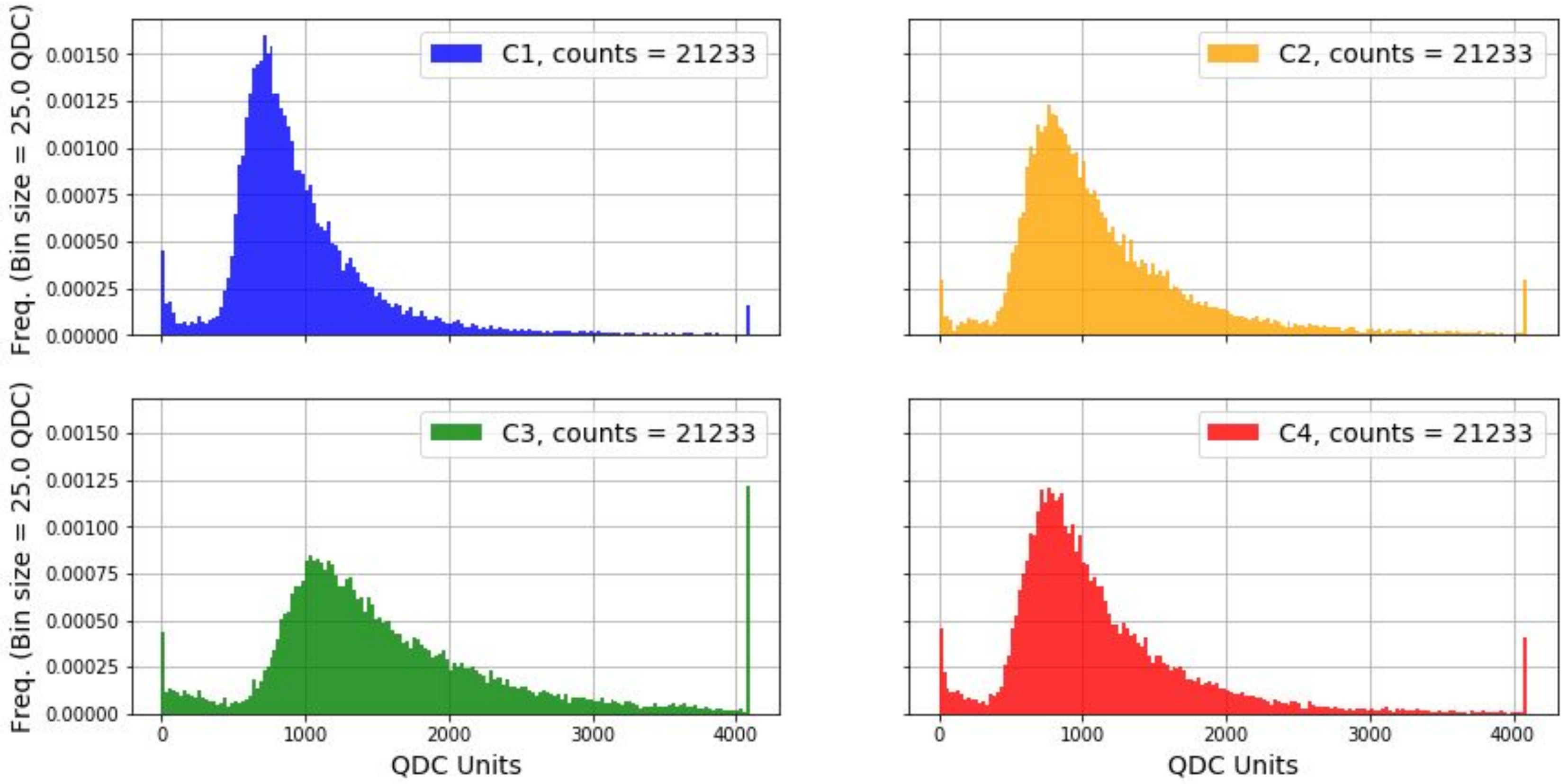
μ-niandes Timing Diagram



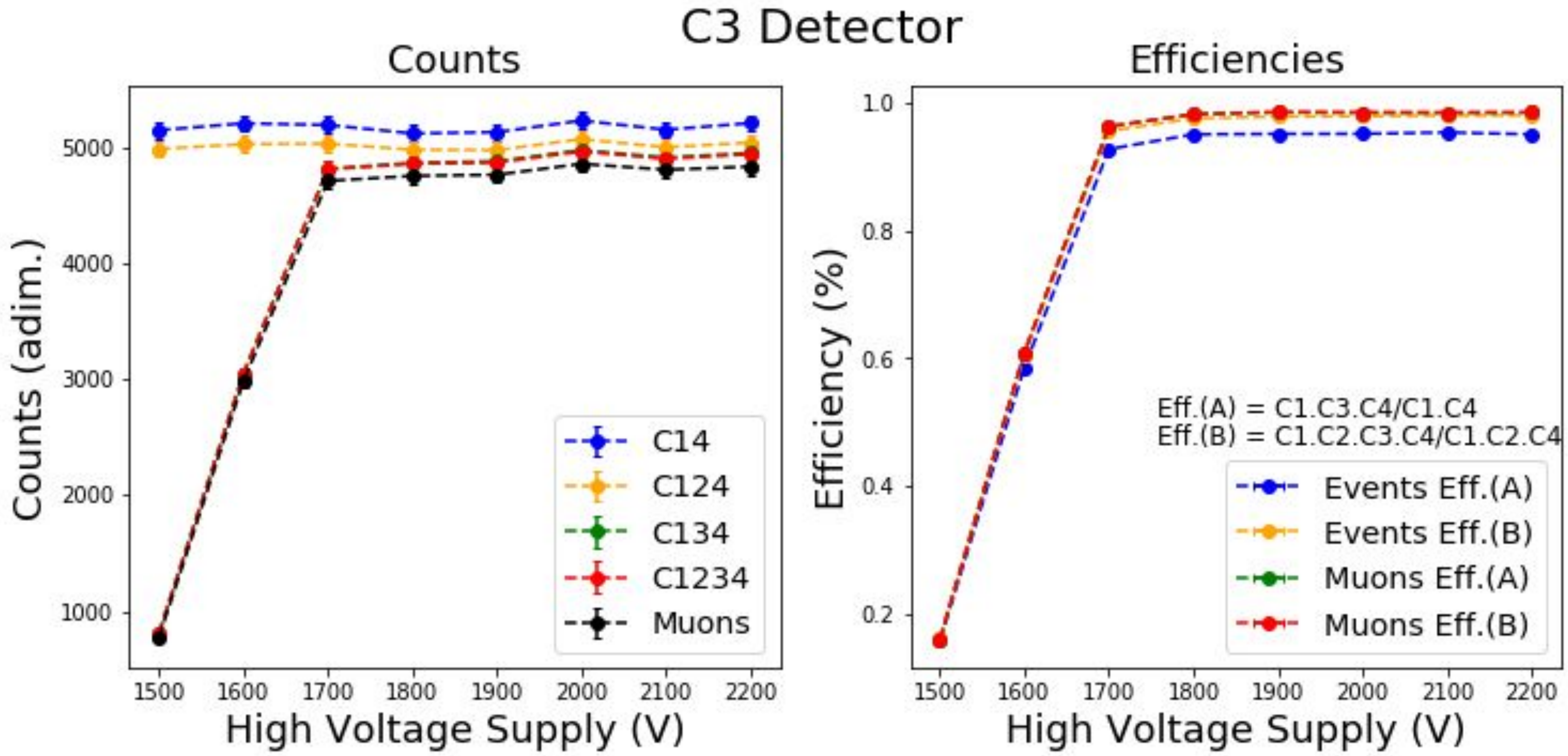
μ-niandes Timing Data (TDC)



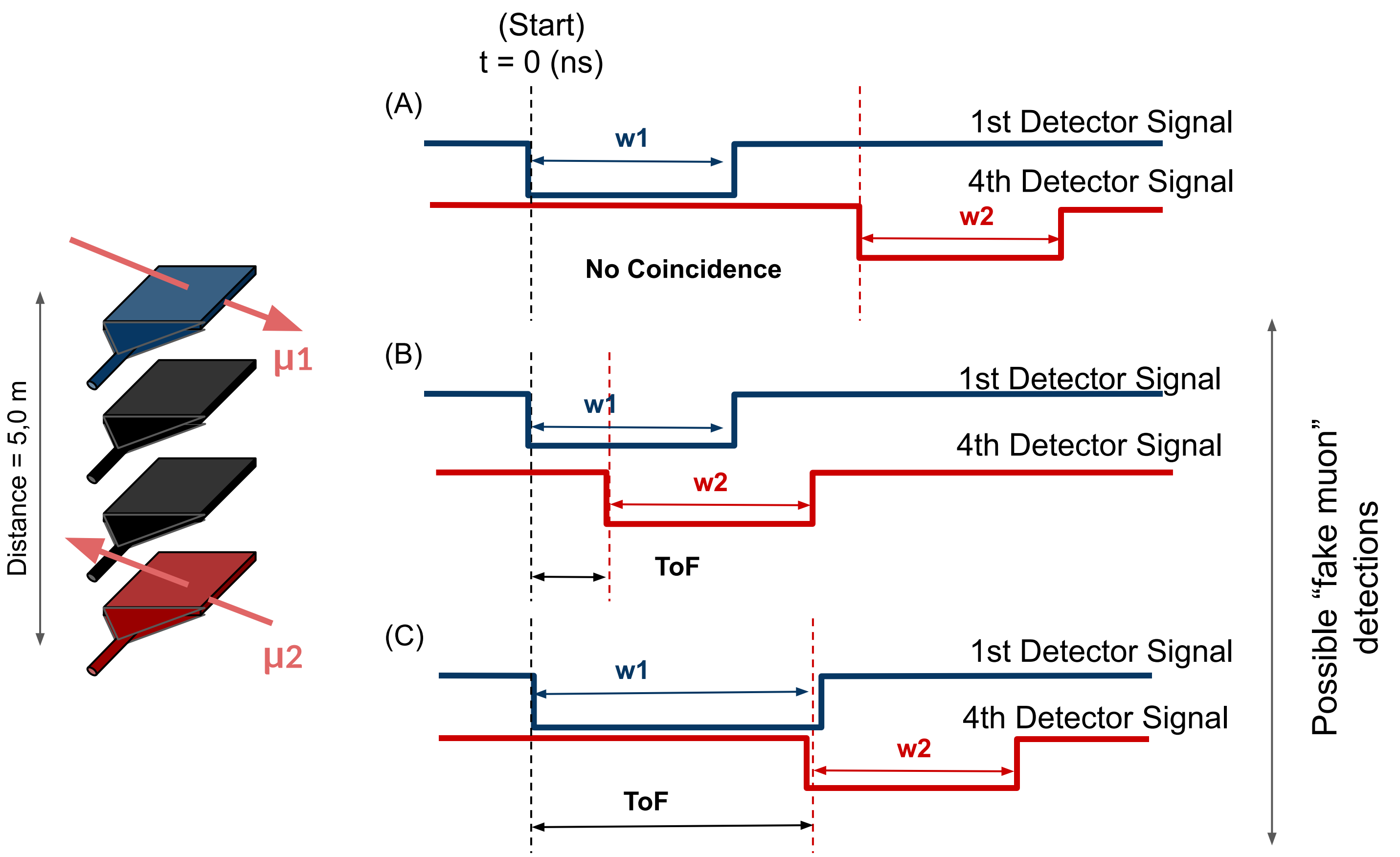
μ-niandes “Energy” Data (QDC)



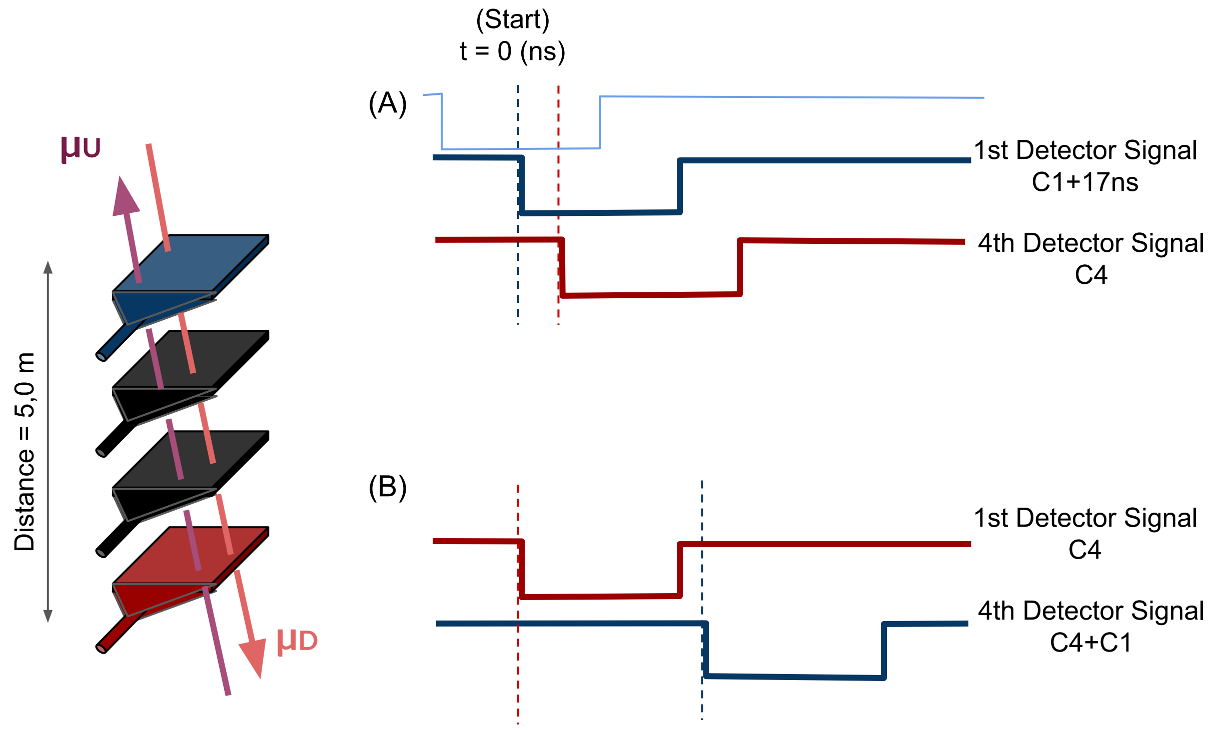
Detector Performance



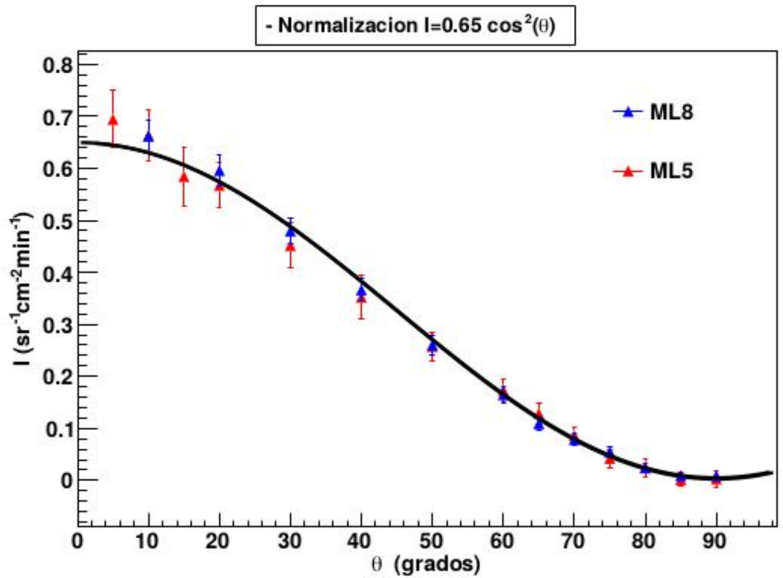
(Fake detections) Independent Muon Coincidences



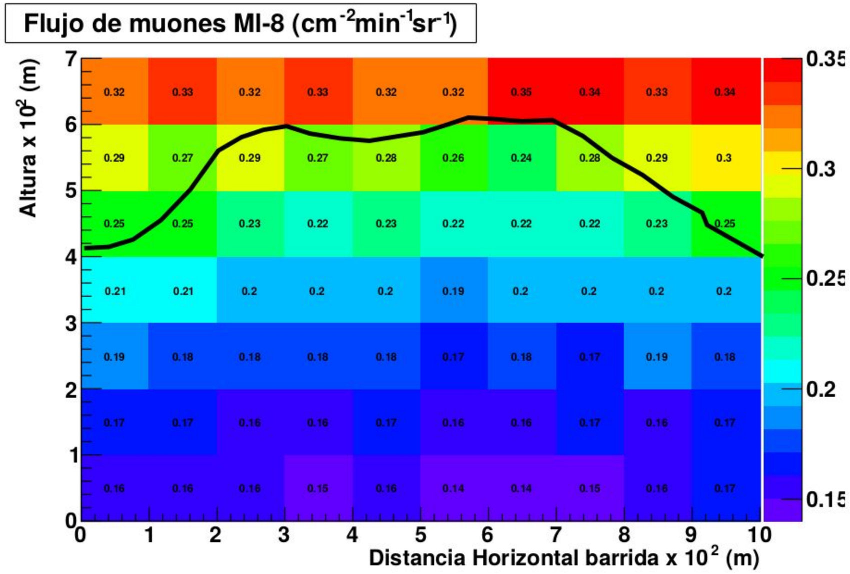
Directional Filter for Muon Detection



First Muography of Monsterrate Mountain



Open sky muon flux measurement
(2018) Jairo Fajardo



Monserrate density mapping
(2018) Jairo Fajardo

¡Thanks for your time!