MUon RAdiography of VESuvius (MURAVES)

Imaging Mt. Vesuvius with cosmic muons

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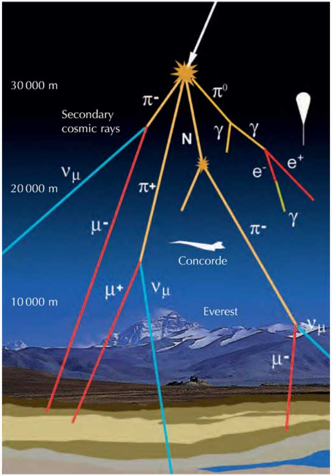
Outline

1. Muon Tomography
2. Mt. Vesuvius
3. MURAVES
4. Preliminary results
5. On-going and future work

Muon Tomography

Muography

Muon Tomography (Muography) : Imaging techniques based on the absorption or scattering of cosmic ray muons (μ)



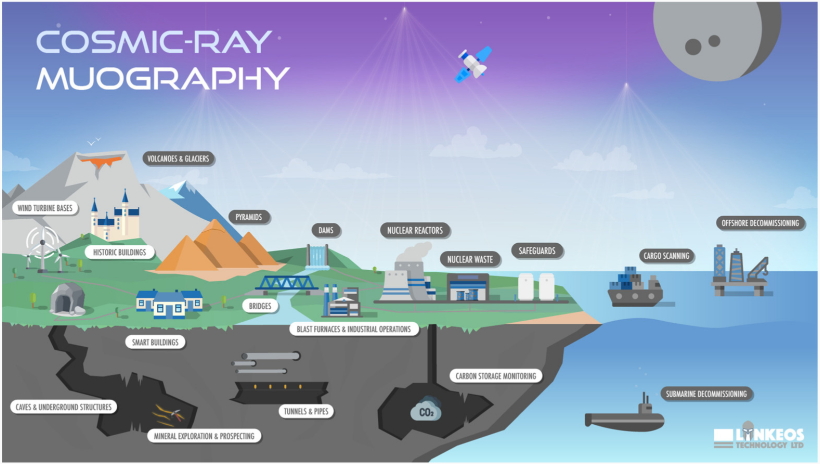
Cosmic muon cascade

Why cosmic muons?

- Natural source and a well-known constant flux (1 muon/minute/cm^2)
- No strong interaction and low probability of generating electromagnetic cascades
- Minimal energy loss due to ionization up to very high momenta
- Most penetrating part of the cosmic shower ($\sim$ O(100m) in rock)

Muography

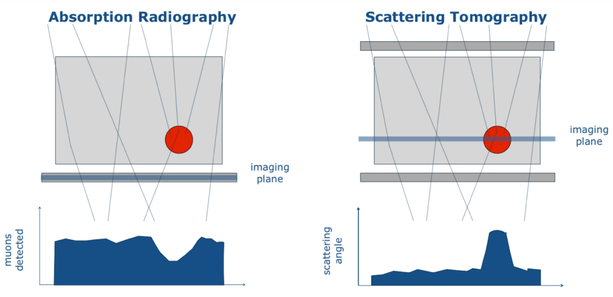
In recent times, muography has become popular in the fields of geosciences, archeology, civil engineering, nuclear safety and security etc



Schematic infographic illustrating various muography applications ([1])

Muography

Muon Tomography (Muography) : Imaging techniques based on the absorption or scattering of cosmic ray muons (μ)



Schematics showing absoprtion vs scattering muogrpahy ([1])

- "Opacity" along the line of sight measurement via energy loss:

$$-\frac{dE}{dx} \propto \frac{Z}{A} \cdot \rho \cdot \frac{1}{\beta^2} \cdot [...] \quad (1)$$

- Slow and applicable mostly for very large targets e.g. volcanoes

- Z measurement via angle of deflection, $\Delta\theta$:

$$\sigma(\Delta\theta) \propto \frac{13.6\mathrm{MeV}}{\beta \cdot c \cdot p}\sqrt{\frac{L}{X_0}} \cdot [...] \quad (2)$$

- Fast and applicable for smaller targets e.g. radioactive material detection

Absorption Mougraphy

Imaging large structures e.g. volcanoes $\rightarrow$ Absorption muography

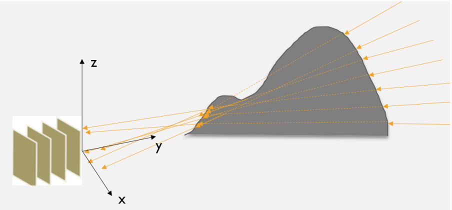
- As muons pass through the rock, they undergo various interactions such as ionization and *brehemstrahalung*
- Energy loss via such interactions, for standard rock, can be approximated as:

$$-\frac{dE}{dx} = aE + b, \tag{3}$$

where $a \sim 2\text{MeV g}^{-1}\text{ cm}^2$ and $b \sim 4 \times 10^{-6}\text{g}^{-1}\text{ cm}^2$

- The range (i.e., rock thickness) a muon can pass without being absorbed depends on its initial energy:

$$R = \int_0^E -\frac{dE}{dx}dx \tag{4}$$



Schematic of the passage of muon to the detector ([2])

For typical rock thickness (O(km)), high energy muons are required for imaging:

- Lower flux :(
- Dominate the near horizontal angles :)

Energy	10 GeV	100 GeV	1 TeV	10 TeV
Range	19 m	115 m	0.9 km	2.3 km

Absorption Muography

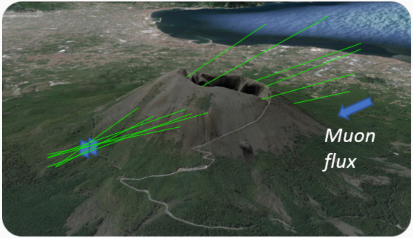
- The integrated flux along the muon path exiting the target that is dependent on rock thickness and integrated density is measured:

$$N(\theta, \phi) = \Delta T \cdot \varepsilon \cdot A \int_{E_{min}}^{\infty} \Phi(E; \theta, \phi) dE \quad (5)$$

- The integrated flux without the target, the so-called free-sky (FS) flux is also measured:

$$N^{FS}(\theta, \phi) = \Delta T^{FS} \cdot \varepsilon \cdot A \int_{E_{det}}^{\infty} \Phi(E; \theta, \phi) dE \quad (6)$$

- Then, the transmission (T), which is naturally independent of detector efficiency and other acceptance effects, is obtained by simply dividing the survival flux by the free-sky flux (Equation 7)



Muon flux through the target ([2])

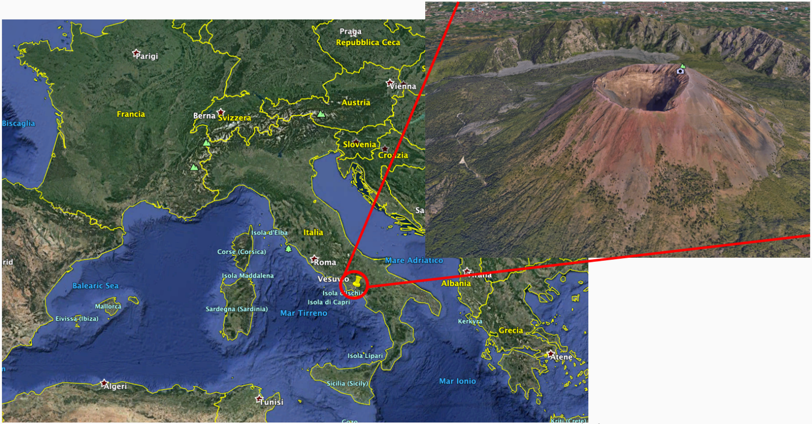
$$T(\theta, \phi) = \frac{N(\theta, \phi) \cdot \Delta T^{FS}}{N^{FS}(\theta, \phi) \cdot \Delta T} \quad (7)$$

- The density distribution along the body of the target is evaluated by exploiting the direction and thickness information

Mt. Vesuvius

Mt. Vesuvius

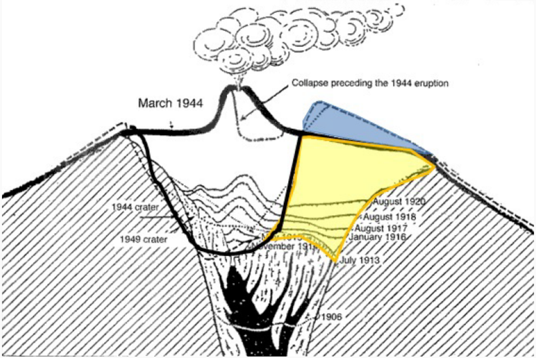
- Located in the south of Italy near Naples
- One of the most dangerous active volcanoes in the world; more than half a million people live in the ”red zone” of Mt. Vesuvius



Last eruption in 1944

Observations of the Upper Part of Mt. Vesuvius

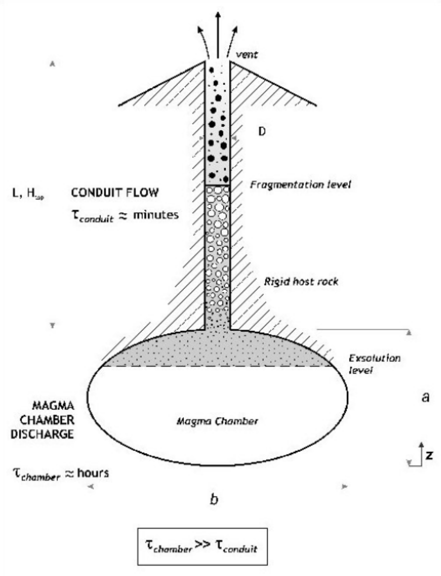
Several eruptions from 1906 to 1944 generated a complex layered structure



Crater in 1944

Crater today

Simplified Scheme of a Volcano



A simple model of a volcano [3]

The eruption dynamics depends on:

- Gas content
- Chemical composition of the magma
- **Dimension and the shape of the conduit**

In the case of Mt. Vesuvius, muography is expected to shed some light on the density distribution along the body of the volcano, providing direct image of the layers that form the structure of Mt. Vesuvius

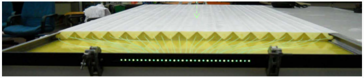
MURAVES

Collaboration

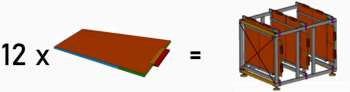
- Founding member institutes:
  - Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Napoli, Naples, Italy
  - Istituto Nazionale di Geofisica e Vulcanologia (INGV), Osservatorio Vesuviano, Naples, Italy
  - Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Firenze, Sesto Fiorentino, Florence, Italy
  - Università di Napoli “Federico II”, Dipartimento di Fisica, Naples, Italy
  - Università di Firenze, Dipartimento di Fisica e Astronomia, Sesto Fiorentino, Florence, Italy
- Recent involvement:
  - Université Catholique de Louvain, Belgium. (since 2019)
  - Universiteit Gent, Ghent, Belgium (since 2020)

Mu-Ray: the Prototype

- INFN prototype (2009-2013) of the MURAVES project
- Tracker with 3 X-Y tracking planes, assembled with 12 modules
- Based on:
    - Plastic scintillator bars with triangular section
    - Wavelength shifting (WLS) fibers
- Each module consists of 32 bars $\rightarrow \sim 0.5 \times 1$ m^2
- SiPM front-end based on EASIROC1B chip by OMEGA



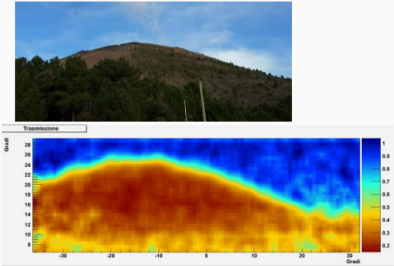
One of the modules without the aluminum casing



Final installation of Mu-Ray at Puy de Dome (2013)

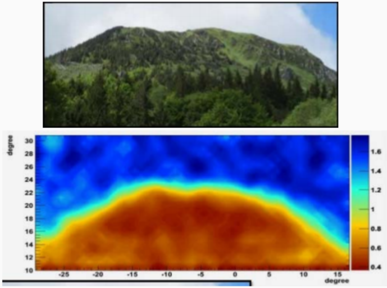
Proof of Principle from Mu-Ray

One week of data-taking in April 2013



F. Ambrosino et al.
The MU-RAY project: detector technology and first data from Mt. Vesuvius
2014 JINST 9 C02029

June-December 2013

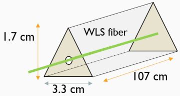


F. Ambrosino et al.
Joint measurement of the atmospheric muon flux through the Puy de Dôme volcano with plastic scintillators and Resistive Plate Chambers detectors
Journal of Geophysical Research: Solid Earth
10.1002/2015JB011969

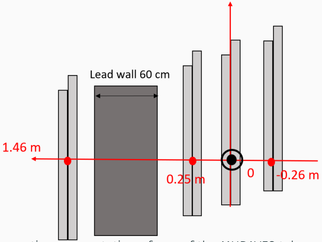
Mu-Ray was used for two different volcanoes, Mt. Vesuvius and Puy de Dome. For Puy de Dome, two different detectors were used and the results from Mu-Ray is consistent with those from RPC-based TOMUVOL

MURAVES: The Detector

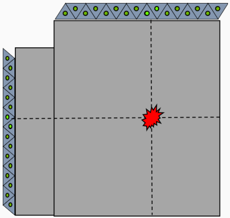
- Based on the same technology as the prototype, Mu-Ray, i.e., triangular scint. and SiPMs
- Three identical detectors, namely ROSSO, **NERO**, and BLU, with 4 stations each
- Active area for a station $\sim 1\ \text{m}^2$
- $24\ \text{m}^2$ of plastic scintillators and 2 km WLS used in total
- 1536 SiPMs as well as the readout channels
- Also contains 60cm wide lead block for better background suppression, recycled from the OPERA experiment



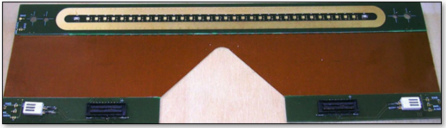
Triangular scint. bars dimensions



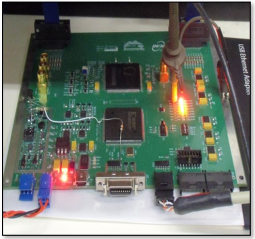
Schematic representation of one of the MURAVES telescopes


A station consisting X and Y planes that are orthogonal to each other

MURAVES: Readout System

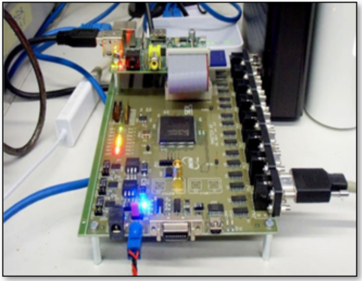


SiPMs hybrid board: 32 channels conneted to a SLAVE board



Slave board

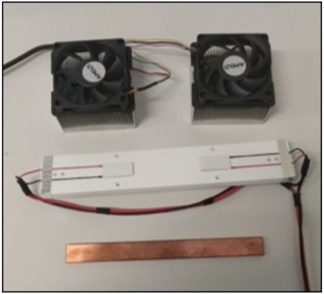
- Omega ASIC EASIROC1B to handle 32 channels with HV on board and 3W power consumption used as “slave” boards
- For trigger and DAQ, a combination of FPGA and Raspberry-pi used as “master” board; can handle up to 32 FEE boards
- 16 modules read by 16 “slave” board connected to the “master” board



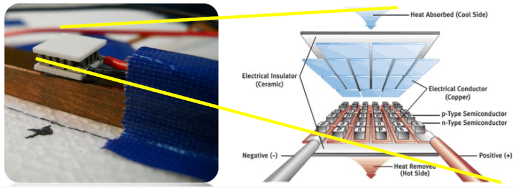
Master board

MURAVES: Temperature Stability

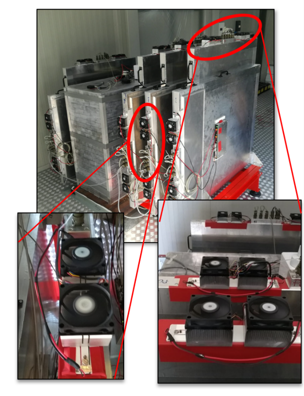
A cooling system was installed since the scint. performance is dependent on the temperature



Peltier system with fan for cooling and a copper strip for uniform coupling



Close-up view of a typical Peltier system



Placement of cooling system in the detector

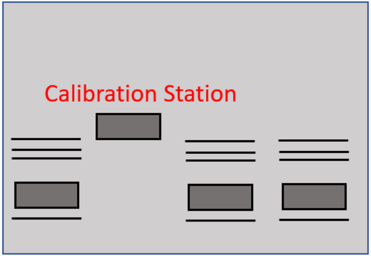
Unlike usual experiments in the lab, the temperature variation is significant for a detector in the wild!!

MURAVES: Detector Installation @ The Vesuvius

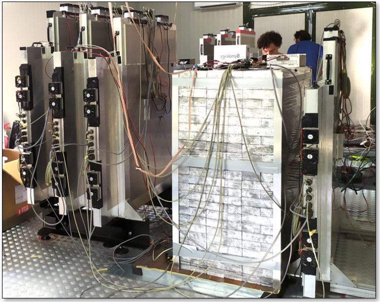
Selected site: Casina Amelia @ an altitude of 600m, few kms away from Mt. Vesuvius

MURAVES: Detector Installation @ The Vesuvius

A small hut for housing the detectors for data-taking



Installation of the detector at the Vesuvius location



Four slots for detectors; only three facing Vesuvius

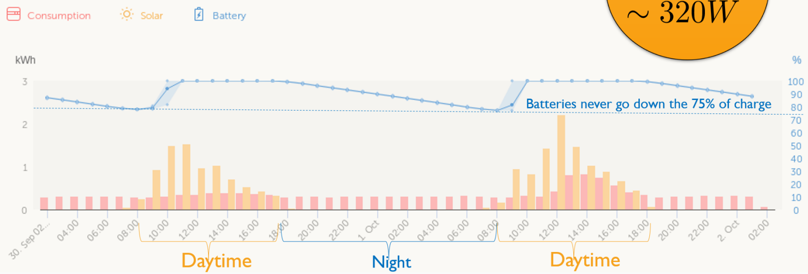
- Small hut with $\sim$45 m^2 total surface area
- Solar panel on the roof for power supply
- 4 cement stations for the placement of lead block
- 35 tons of lead (3 walls of 60 cm)
- Installation of all three detectors completed

MURAVES: Power Supply

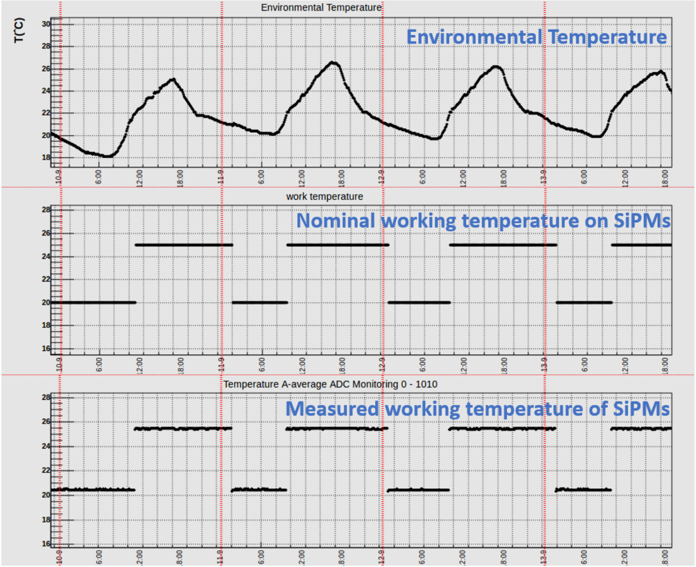
Solar panels charge the batteries → Batteries provide power to the system

2 detectors + data storage, internet, consumption

$\sim 320W$

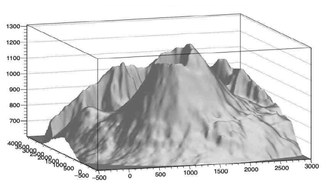


MURAVES: Temperature Monitoring



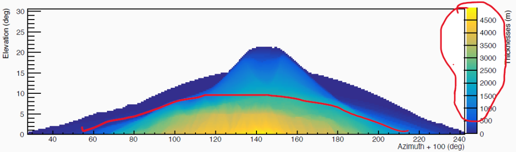
Preliminary results

Simulation

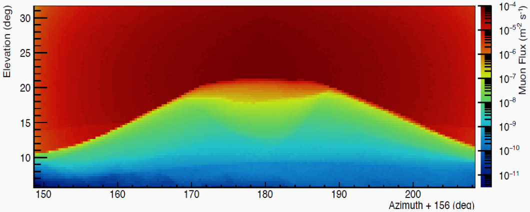


Original DEM of Mt. Vesuvius

- A digital elevation model (DEM) is used to gain information about the topology of the target
- Rock thickness crossed vs direction is evaluated using TURTLE [4]
- Expected muon flux simulated with a backward monte-carlo called PUMAS [5]

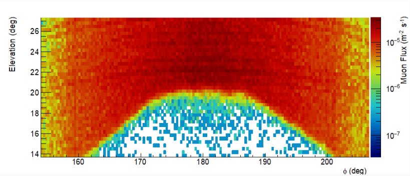


Angular distribution as a function of thickness via TURTLE

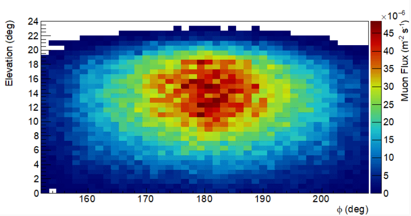


Expected muon flux with PUMAS taking into account the detector acceptance

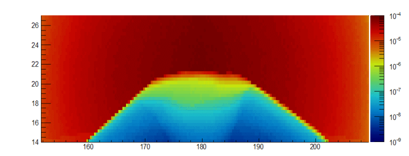
“very” Preliminary Results



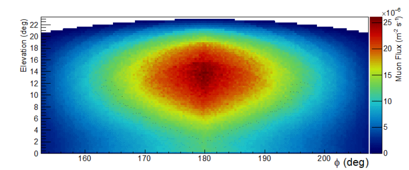
Observed muon flux through Mt. Vesuvius



Observed free-sky muon flux



Expected muon flux through Mt. Vesuvius



Expected free-sky muon flux

Observed results are obtained from 52 days of data acquisition from one detector but we have been running for more than a year and half now and the analysis of those data is currently underway

On-going and future work

Time of Flight (ToF)

- In high energy physics, ToF is typically used as a means to separate particles by mass
- For MURAVES, the detector is oriented quasi-horizontally so soft muons scattering off the ground behind the detector can enter from its rear
- These backward muons may even overwhelm the muons that carry information about the target and thus have to be rejected
- ToF of the detected muons between front and rear layer of the telescope can be used to reject these backward muon background

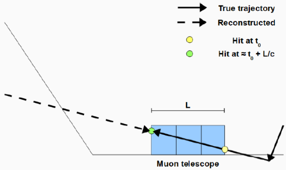
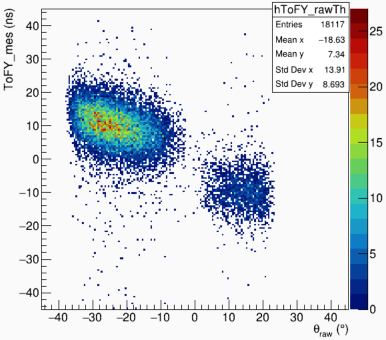
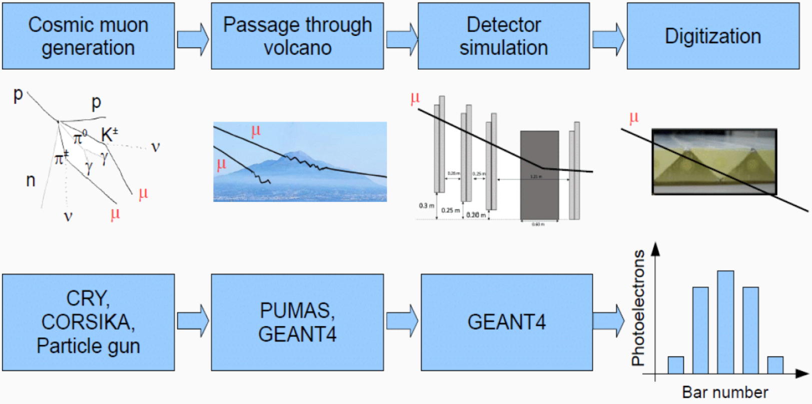


Figure illustrating backward muon [6] – ToF to be used to reject these



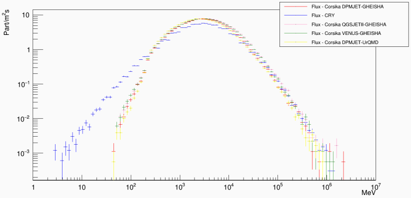
ToF vs θ_{recons} – two represent forward and backward muons

End-to-end simulation for MURAVES

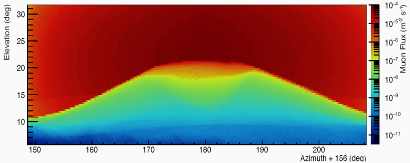


Simulation chain starting with muon generation in the upper atmosphere to the formation of signals in the SiPM coupled to the MURAVES scintillating bars

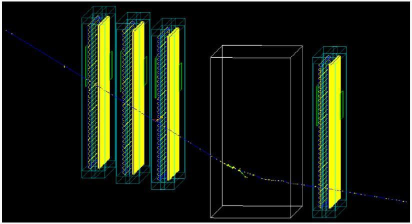
End-to-end simulation for MURAVES



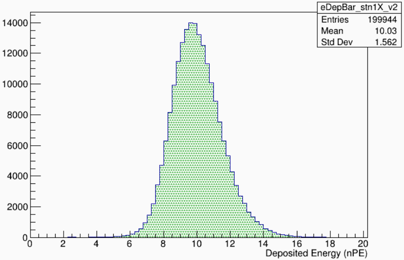
CRY vs CORSIKA – muon generators comparison



Expected muon flux through Mt. Vesuvius with PUMAS



Interaction of 1 GeV muon with the MURAVES simulated using Geant4



Conversion of the deposited energy from MeV to photoelectrons

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Questions?