Applied Physics: Muon Absorption Tomography

Muon Radiography at Palazzone Necropolis Perugia

27/10/2022

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Università di Perugia

Università degli Studi di Firenze

INFN
PG,FI

Report of the PhD project activity (second year)

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- The aim of the P.h.D project:
  - Application of muon radiography technique at the Palazzone Necropolis for the search of hidden cavities/tombs

- Status of PhD project:
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  - Installation at the Palazzone
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  - Freesky measurement at INFN of Florence
  - 2D muon transmission map, 2D density map and simulations
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- Educational Activities: courses, school, conference, publications

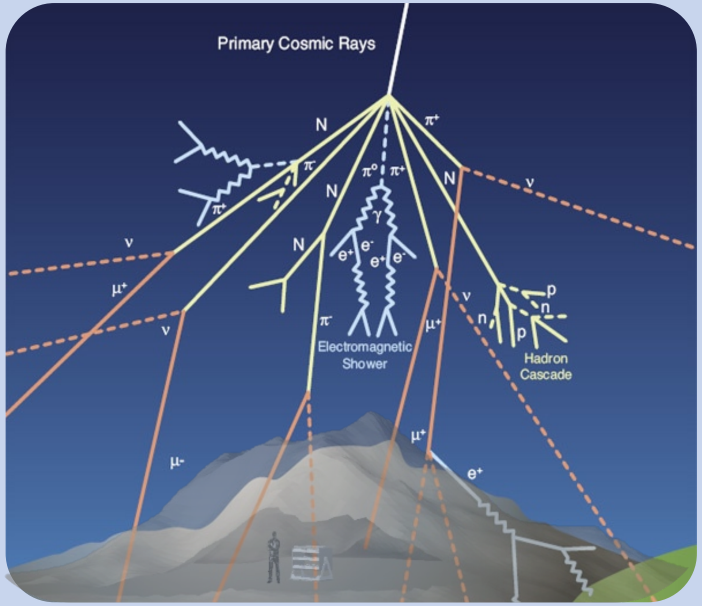
Report of the PhD project activity (second year)

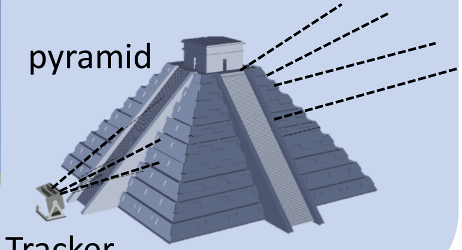
Muon radiography technique

Muon radiography is an ***imaging technique*** that allows to create 2D or 3D images of the internal density distribution of the object under study (target) through *transmission measurements of cosmic muons*. The detectors used are charged particle **trackers.**

Muon radiography technique

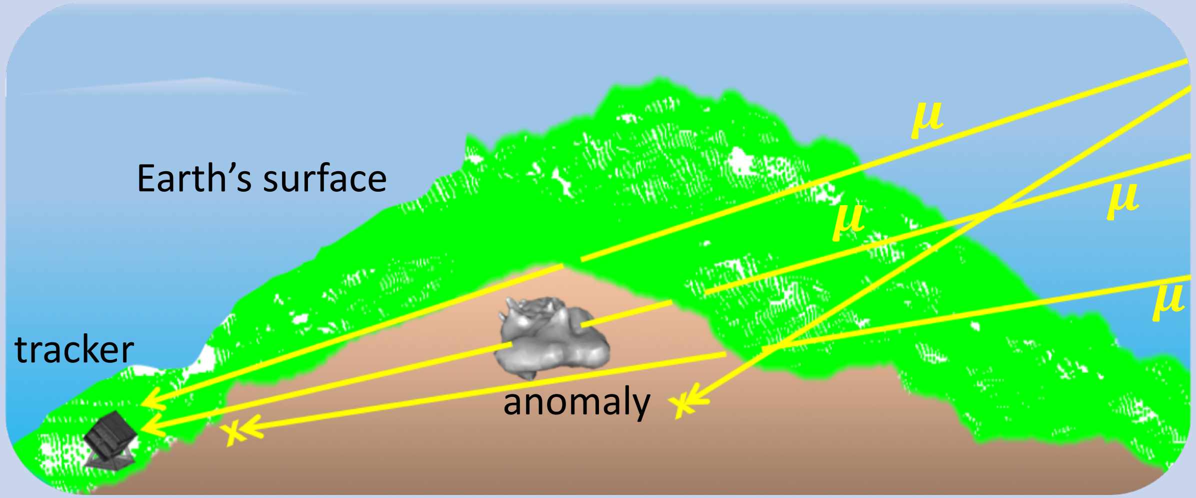
- ✓ Non-invasive technique
- ✓ Possibility of installing the detectors in small and difficult to access places
- ✓ Various fields of application: archaeological, geological, civil engineering and nuclear safety, industrial field, monitoring of large structures





Search for low density anomalies within an archaeological site

- ✓ mapping of cavities in the areas
- ✓ possibility of finding unknown cavities
- ✓ important from an archaeological point of view



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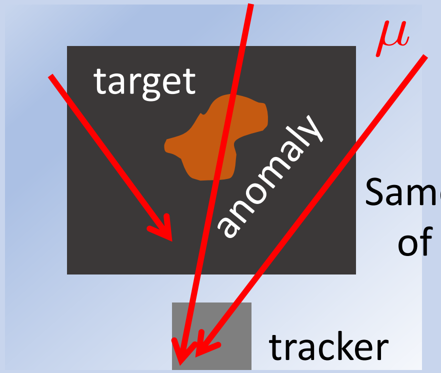
Muon radiography: imaging methodology

The <u>number of muons is measured</u> in a given acquisition time t as a function of the observation angles $N_{\mu}(\theta, \phi)$. It depends on the density and shape of the target, the flux of cosmic muons on the ground and detector acceptance and efficiency.

2D target density map, three steps are required:

1. Target measure

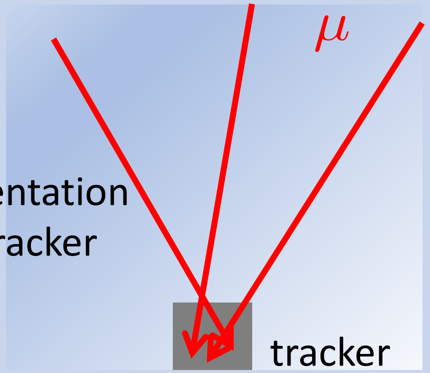
$N_{\mu_{target}}(\theta, \phi)$



Same orientation of the tracker

2. *Freesky* measure

$N_{\mu_{freesky}}(\theta, \phi)$



Transmission of μ measured

$$T_{misu}(\theta, \phi) = \frac{N_{\mu\_target}}{N_{\mu\_freesky}} \cdot \frac{t_{freesky}}{t_{target}}$$

3. Simulation in the case of absence of anomalies

Simulated transmission of μ

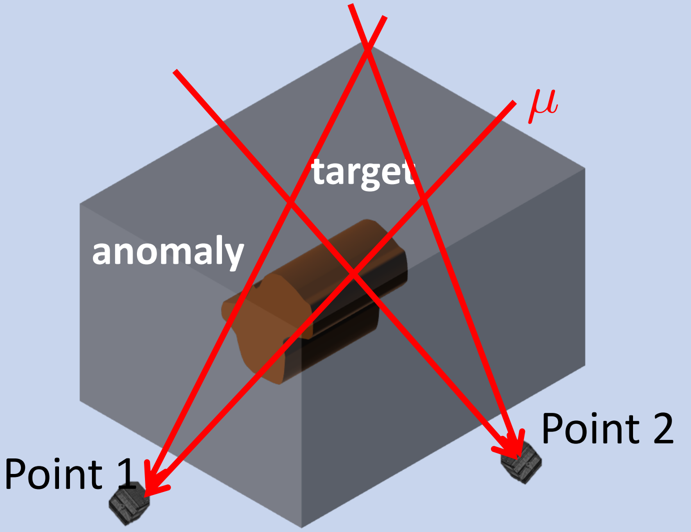
$$T_{simu}(\theta, \phi, \bar{\rho})$$

Varying $\bar{\rho}(\theta, \phi)$: $T_{misu}(\theta, \phi) = T_{simu}(\theta, \phi, \bar{\rho})$ → **2D angular density map** $\boldsymbol{\rho_{target}}(\theta, \phi)$

3D target density map

- <u>Triangulation technique</u>

  For a **stereoscopic vision** it is possible to install the detectors in several points:



- <u>Backprojection technique</u>: estimate the distance to the anomaly using data acquired from a single measure (applicable only under some conditions).

Report of the PhD project activity (second year)

Muon radiography at Palazzone Necropolis (PG)

The aim of the PhD project is the imaging of a zone of the archaeological area «Necropoli del Palazzone» (Perugia) using the muon radiography technique for the search of unknown tombs

The necropolis (of Etruscan era) is an archaeological site containing about 200 tombs, the largest and best known is the Hypogeum of the Volumni. The necropolis is partly visited by tourists.

Report of the PhD project activity (second year)

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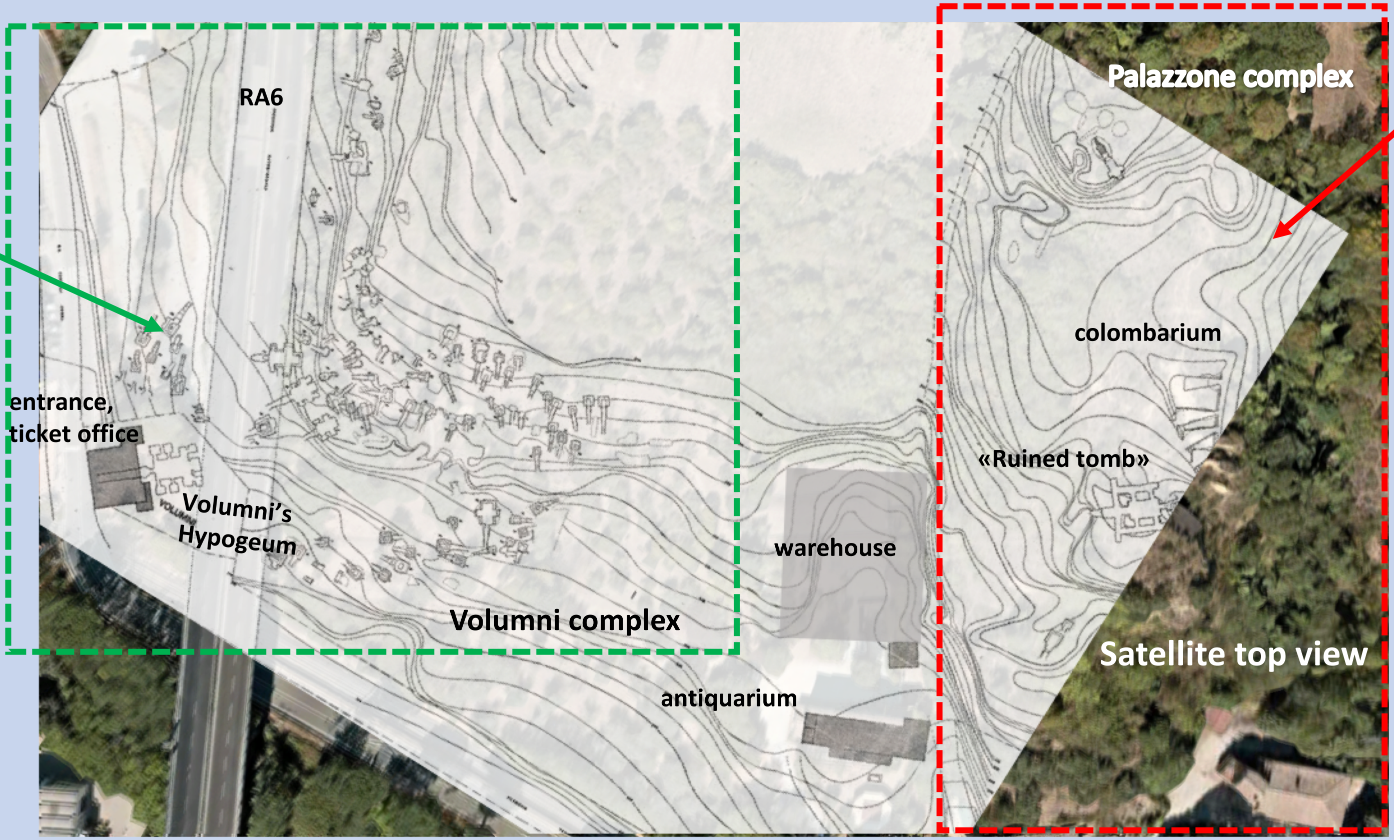


Ruined Tomb

Interesting area for muographic measurements:

-is not open to the tourist route

-is not fully inspected

-possibility of the existence of other tombs

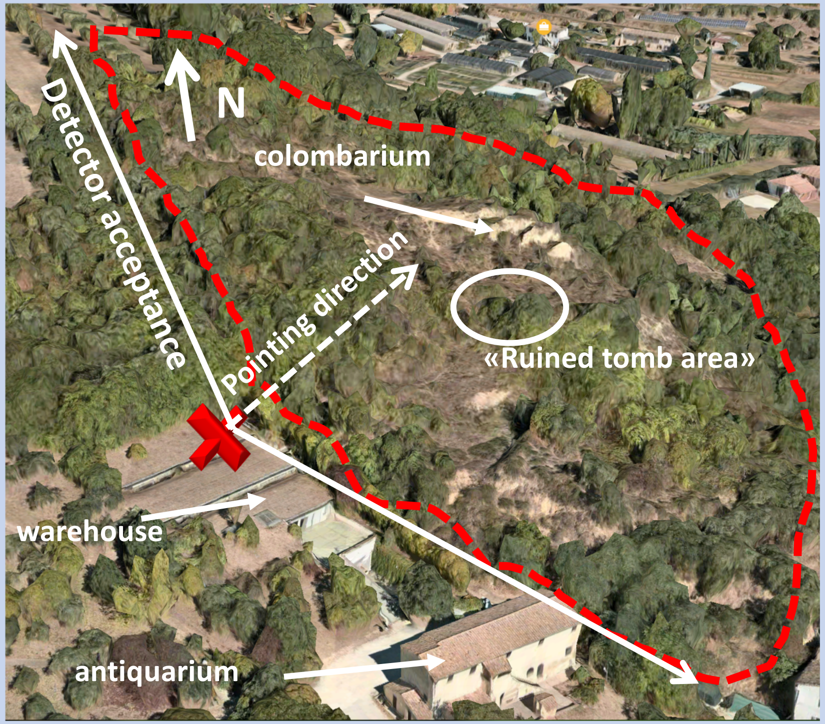
Choice of installation point and preliminary simulation

Choice of installation point

Main requirements related to the flux of cosmic rays:

- the installation point must be lower in altitude than the area to be observed;
- the elevation angles under which the area of interest is viewed must be as high as possible

Satellite view

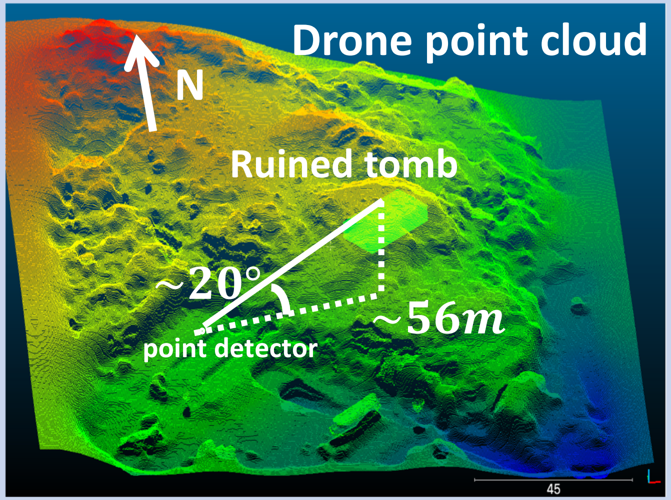


detector acceptance cone about $\pm 65°$ relative to the pointing direction

Installation point:
Inside the warehouse

the «Ruined tomb» represents, being known, the test cavity

Preliminary simulations



Geometry:

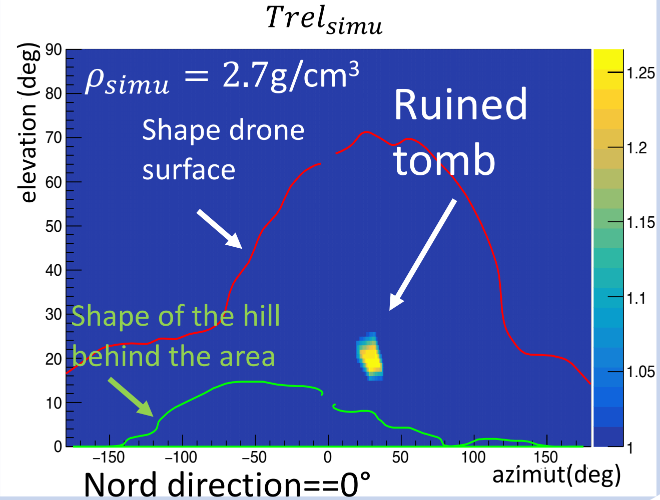
- Drone point cloud for the hill;
- Fictitious volume that reproduces the dimensions of the «ruined tomb»

- Simulation1 with tomb →transmission1 with tomb (T_1)
- Simulation2 without tomb →transmission2 without tomb (T_2)

$$Trel_{simu} = T1/T2$$

The tomb is seen at 20 degrees of elevation.

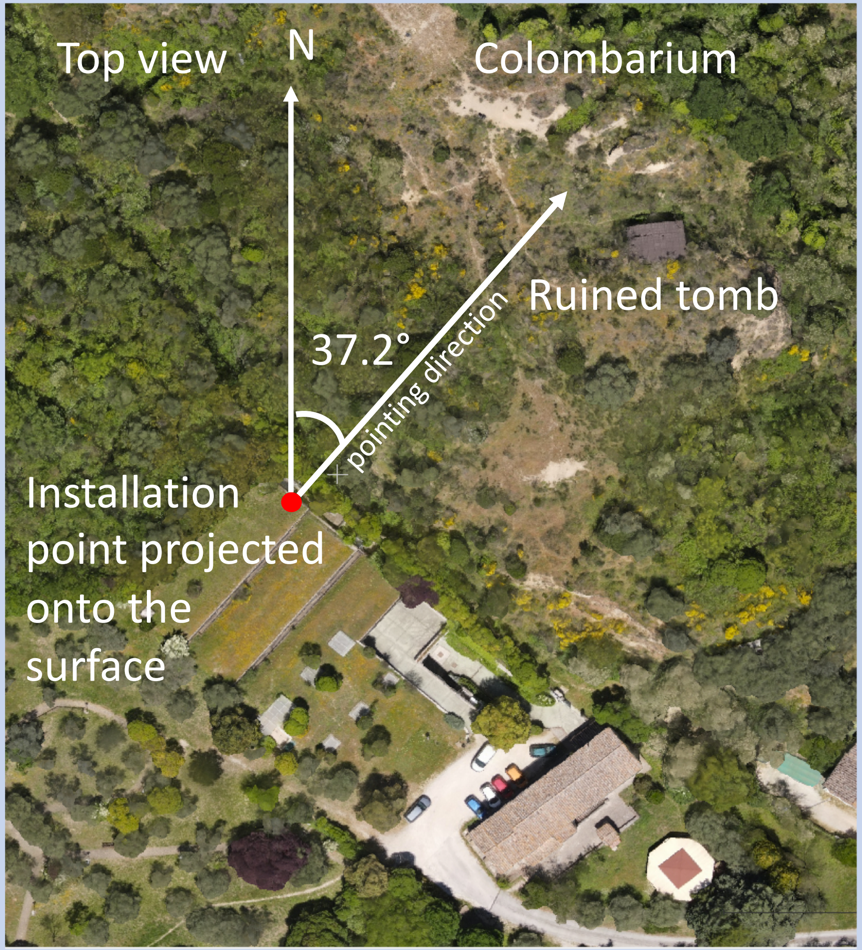
Transmission with tomb is greater than ~25%.



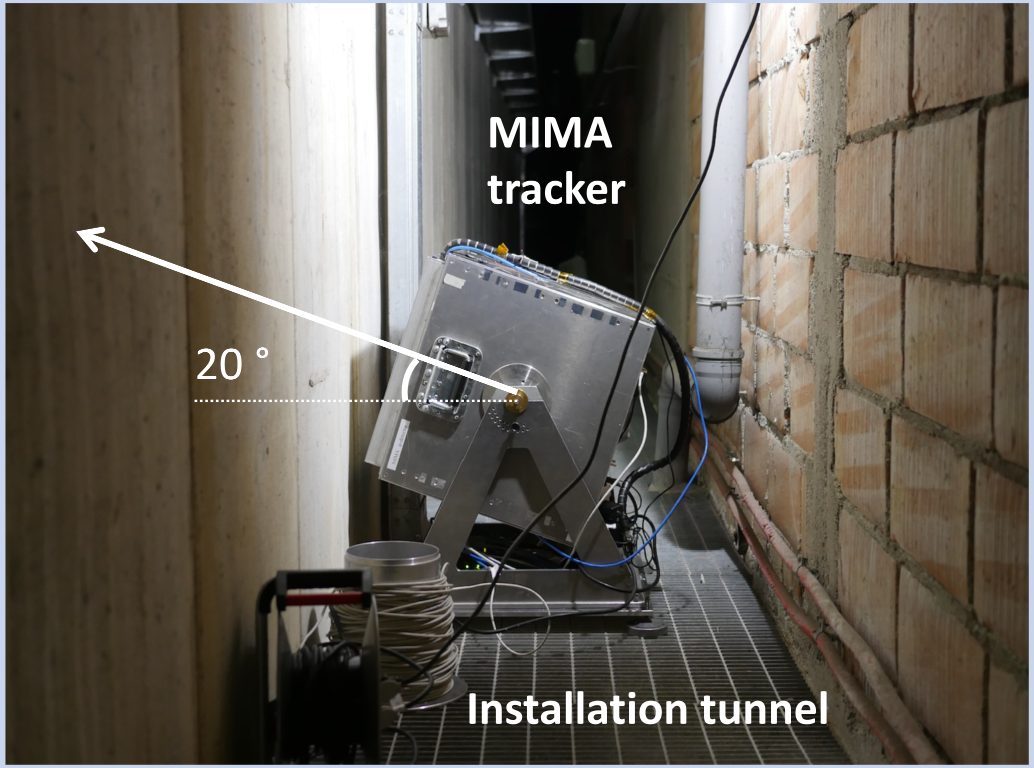
Installation

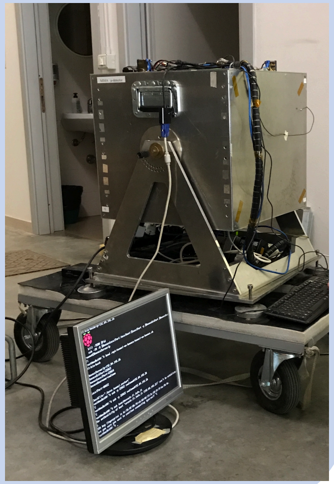
Installation: 13/05/2022, **Disinstallation**: 20/07/2022

Azimuth: perpendicular to the warehouse wall →azimuth 37.2°, **Elevation**: 20 °



Top view from the drone





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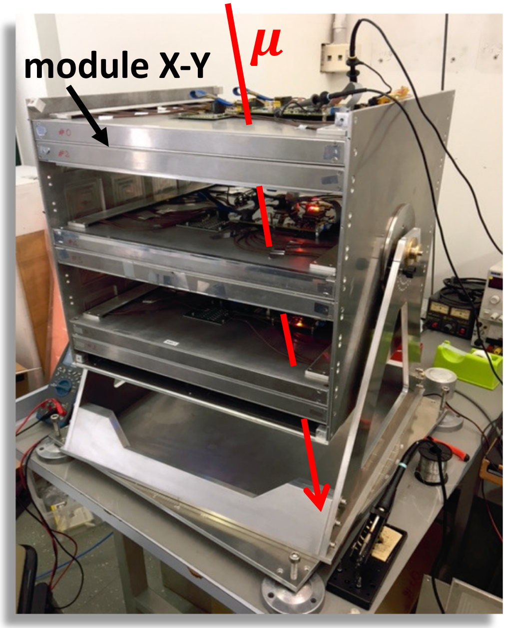
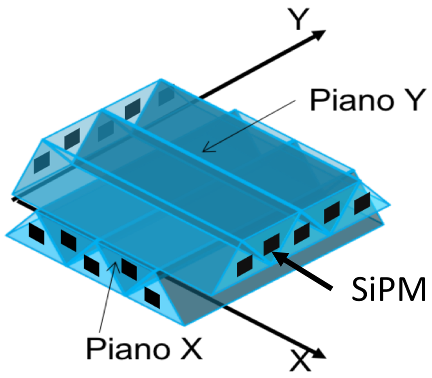
MIMA tracker for muographic measurement and detector monitoring

MIMA (**M**uon **I**maging for **M**ining and **A**rchaeology)



Module X-Y
simplified scheme



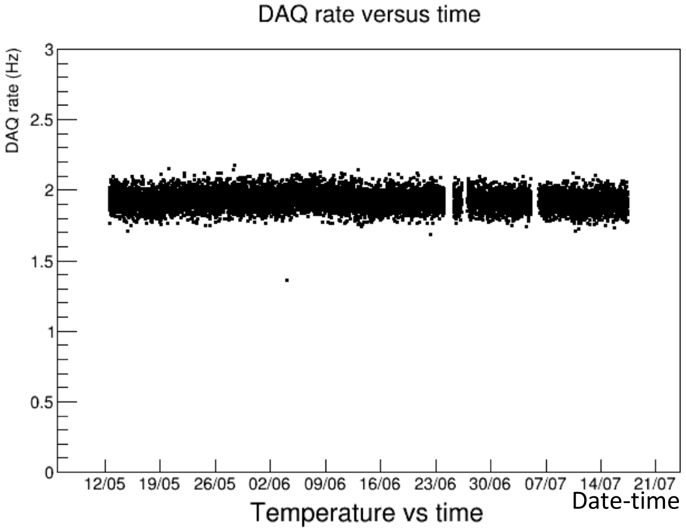
Cubic dimension (50x50x50) cm^3 based on a rotating platform.

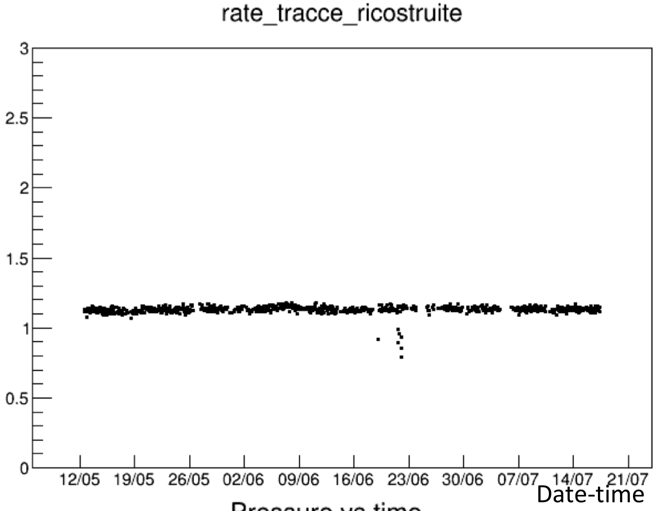
Material: Triangular section plastic scintillator (4x2x40) cm.

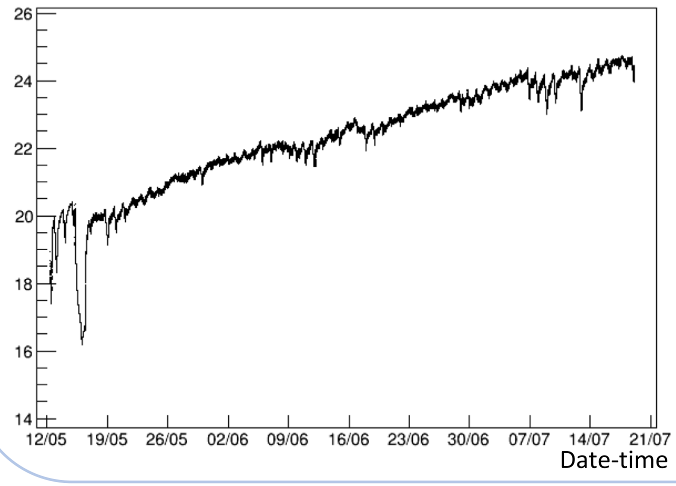
- Acceptance: about $\pm 65°$;
- Spatial resolution 1.6mm, angular resolution 6.7mrad;
- weight about 60 kg;
- Power consumption 30W

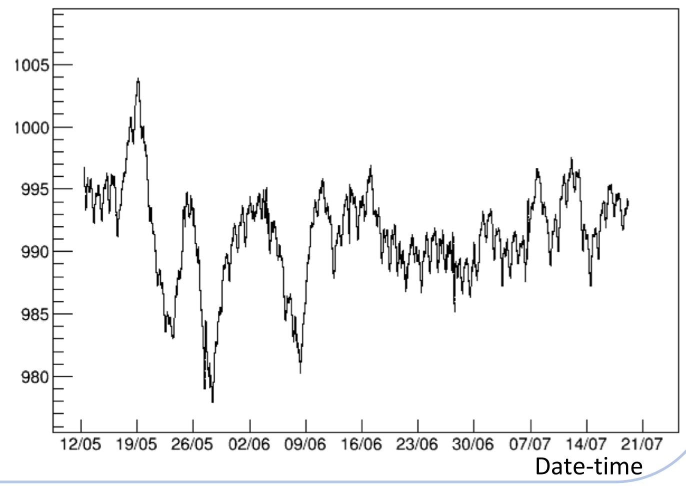
Detector monitoring

Tot: 58 days of data acquisition (subtracting dead times)







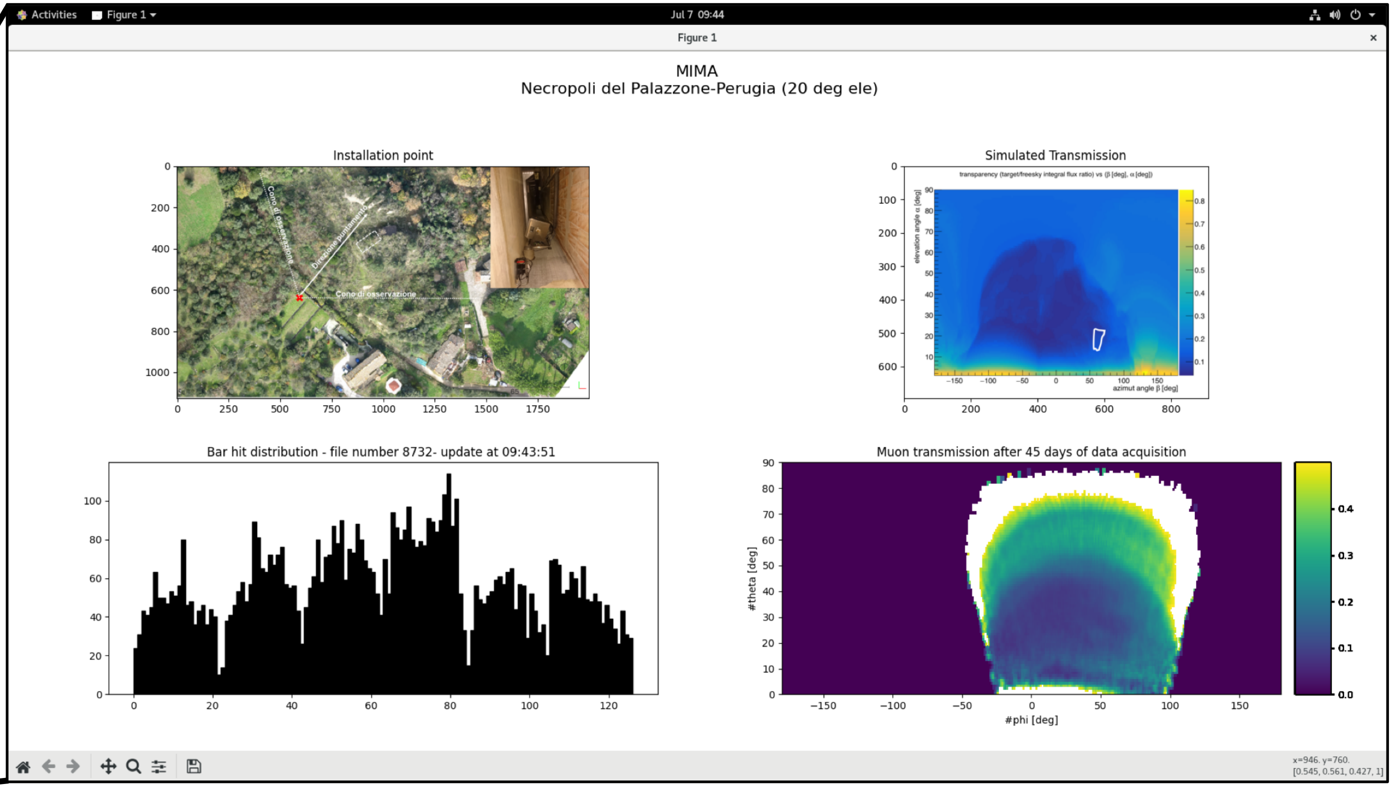


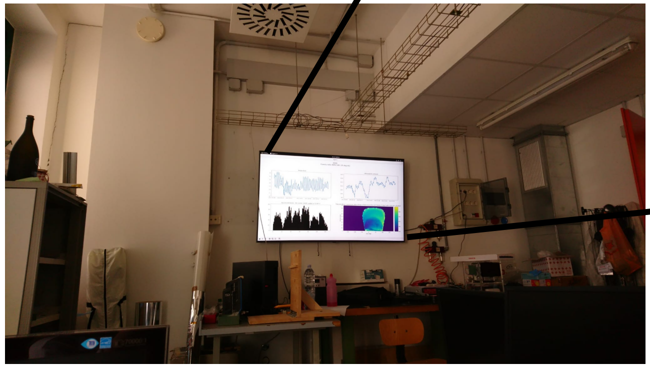
Report of the PhD project activity (second year)

MIMA tracker for muographic measurement and detector monitoring

I developed a software that can monitor online the status of the detector

Screenshot of the computer screen used for monitoring in Florence





Lab at INFN-FI

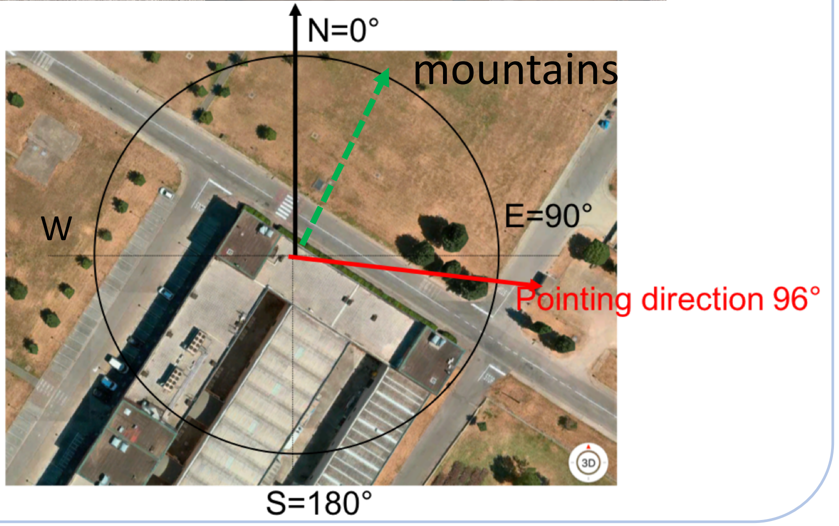
Report of the PhD project activity (second year)

Freesky measurement

Due to the presence of hills and distant reliefs in the area of the Palazzone, it was decided to make the measurement of free sky at 20° elevation at the INFN in Florence where the horizon is more free.

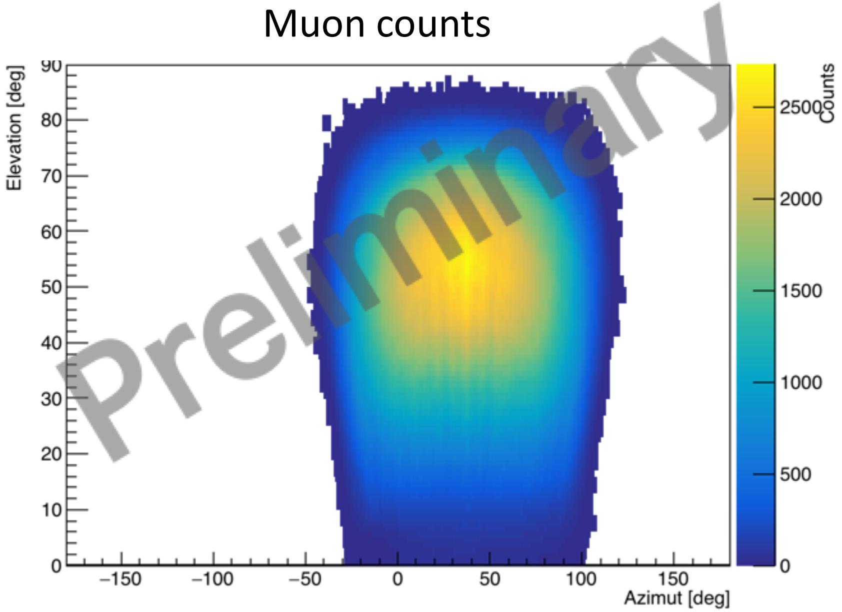
The detector was installed on the roof

Elevation: 20°

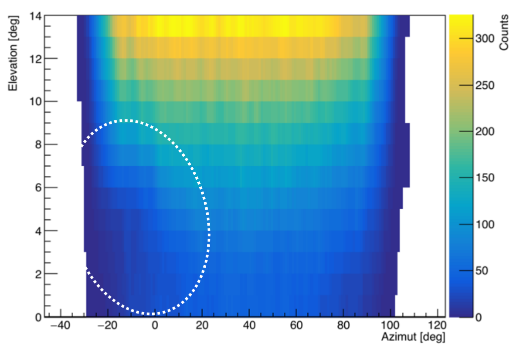


Tot: 38 days of data acquisition having subtracted the dead times (from 25/07/2022 to 09/09/2022)

Muon counts

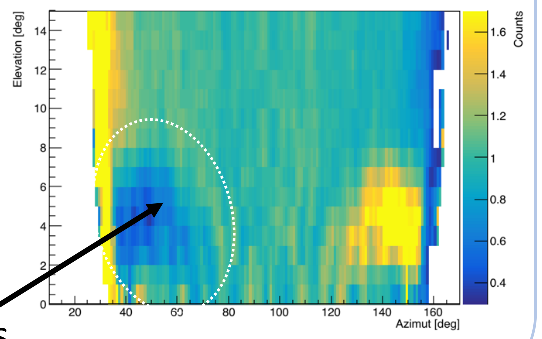


Zoom



the presence of reliefs on the left is visible

freesky / freesky_flipped



A new freesky measurement is underway pointing south where there are no mountains

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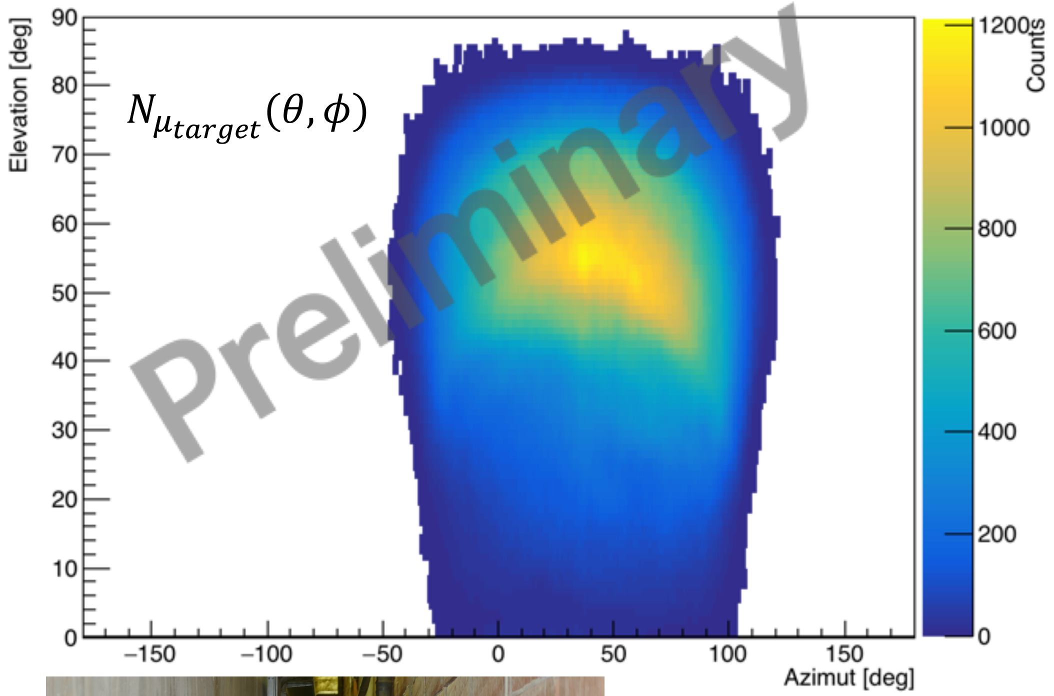
Muon counts: target and freesky configuration

58 days of data acquisition
Muon counts

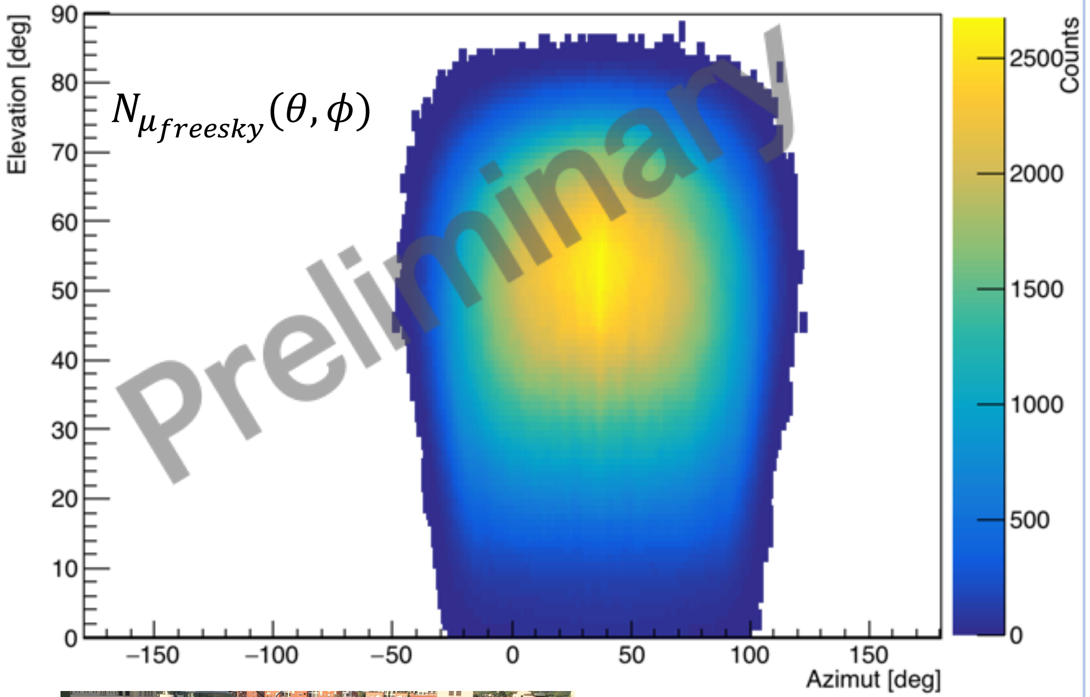


Target MIMA – 2022
Palazzone

Elevation 20°

Target configuration

measure in progress, currently 45 days
Muon counts



freesky MIMA – 2022
INFN-FI

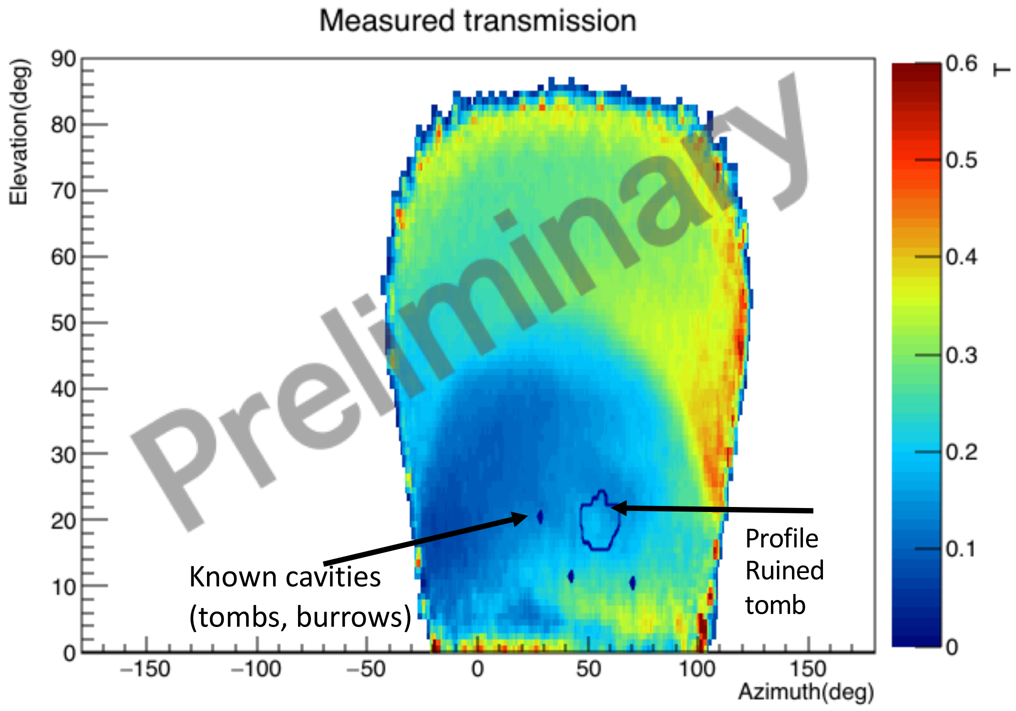
Elevation 20°

freesky configuration

Report of the PhD project activity (second year)
Muon transmission

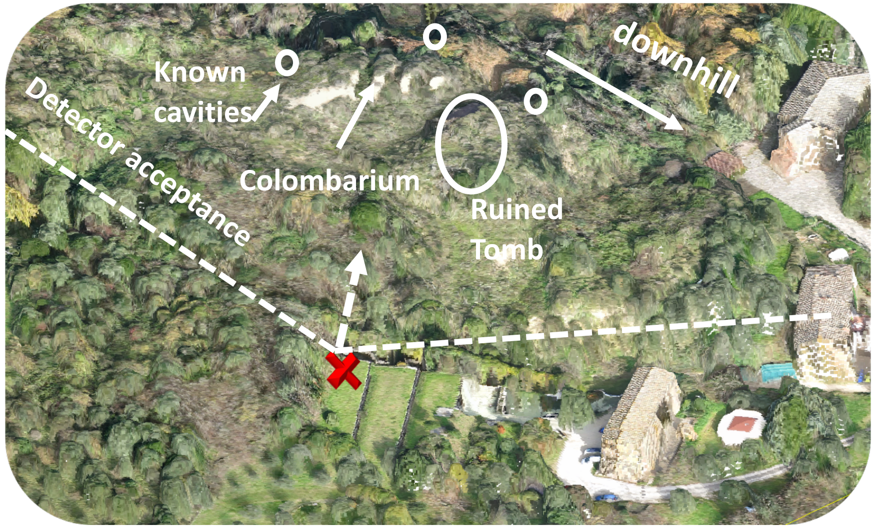
Measured transmission

$$T_{misu}(\theta,\phi) = \frac{N_{\mu\_target}}{N_{\mu\_freesky}} \cdot \frac{t_{freesky}}{t_{target}}$$



Considerations:

- The measured transmissions increases to the right consistently with the decrease in the thickness of the hill
- Known voids are located around areas with higher transmission



The dependence on the conformation of the hill remains →comparison with simulations to find unknown cavities

Simulated Transmission

Simulated transmission

Custom software

$$T_{simu}(\theta,\phi,\rho) = \frac{\Phi_{simu\_target}(\theta,\phi,\rho)}{\Phi_{simu\_freesky}(\theta,\phi,\rho)}$$

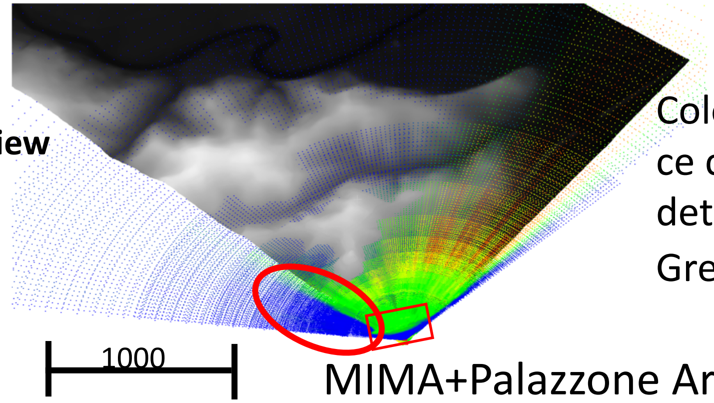
$$\Phi_{simu}(\theta,\phi,\rho) = \int_{E_{min}(X)}^{\infty} \varphi_{ADAMO}((\theta,\phi,E))dE$$

- φ_{ADAMO} differential flux of ADAMO (INFN FI) magnetic spectrometer
- $X(\theta,\phi) = \int \rho(l,\theta,\phi)\cdot dl$ opacity along the line-of-sight
- $E_{min}(X)$, the minimum energy that a muon must have to reach the detector assuming a uniform density

Geometry:

Drone 20x20 cm (warehouse)+DTM 1mx1m (Palazzone's Hill+ hill on the background)

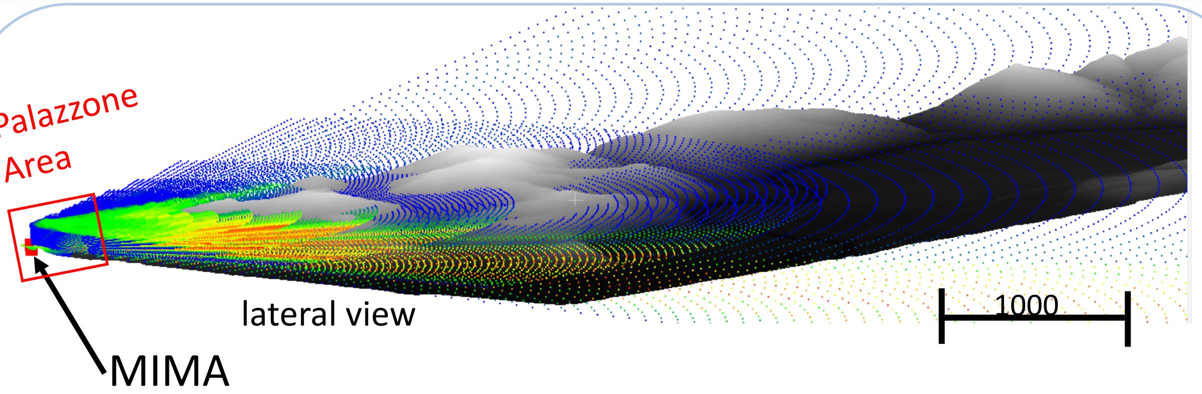
top view



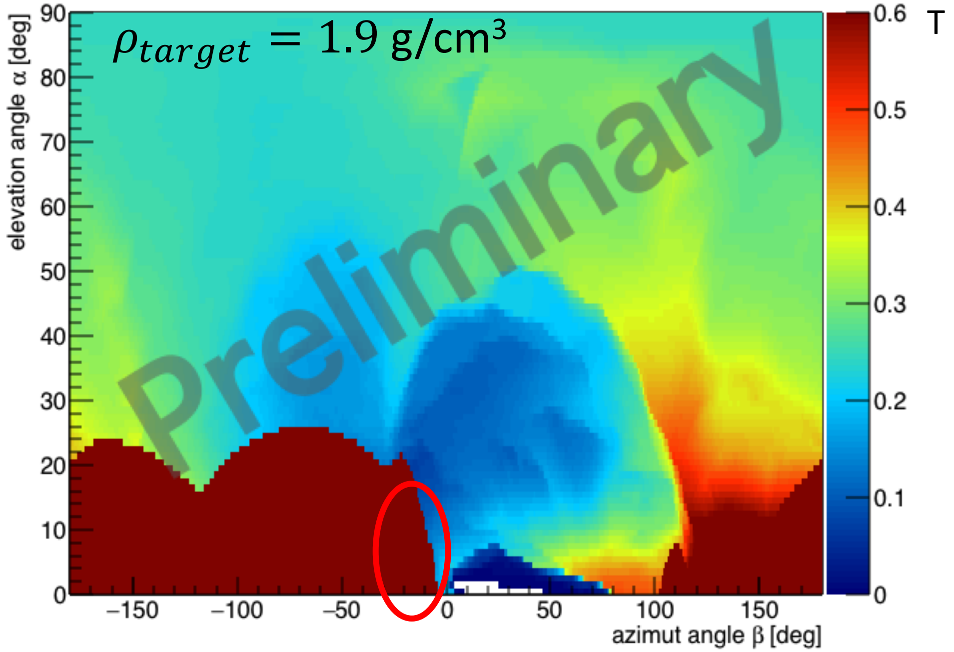
MIMA+Palazzone Area

Colours=acceptance cone of the detector

Grey=DTM



Simulated Transmission -homogeneous target



- Redo a simulation with a larger clipped DTM

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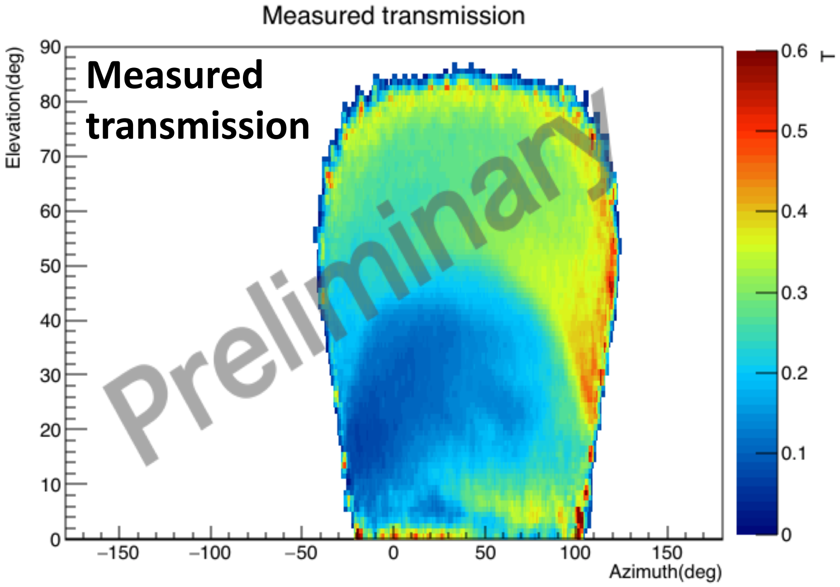
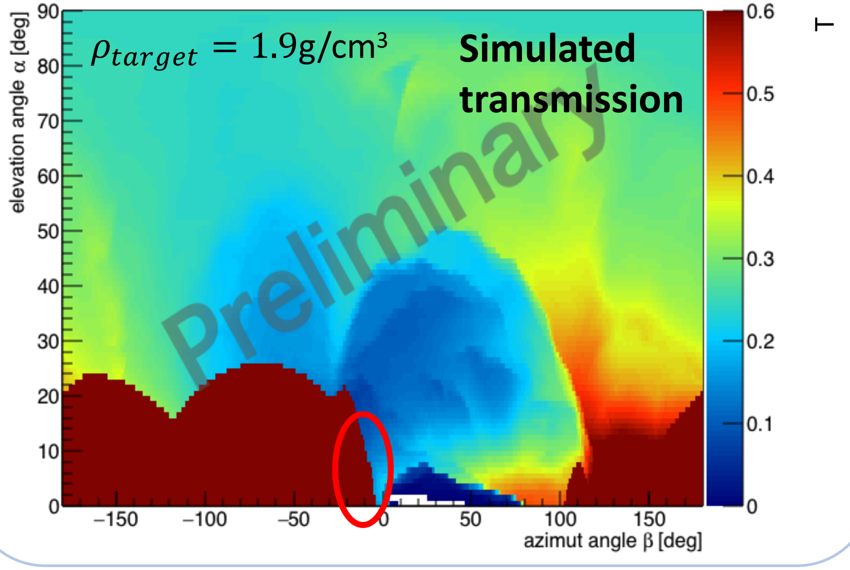
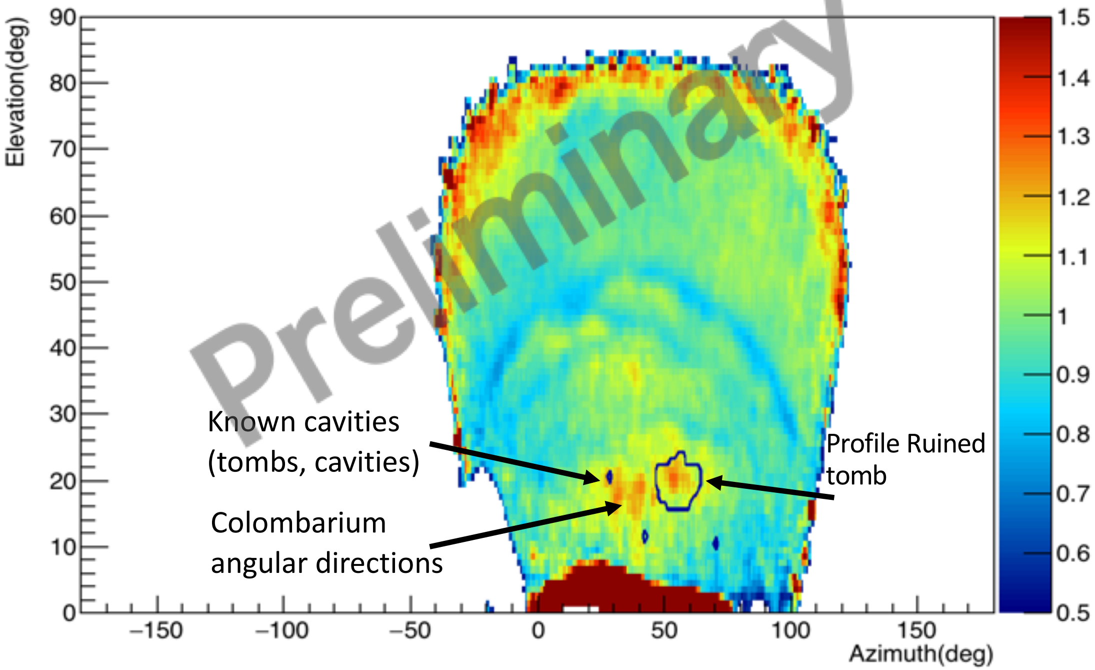
Relative Transmission





$$T_{rel}(\theta, \phi) = \frac{T_{measured}(\theta, \phi, \rho)}{T_{simulated}(\theta, \phi, \rho)}$$



-the known voids are in a higher relative transmission zone, but:

- but there are high transmission arcs that look like artifacts
- there are red zones that correspond to the angular directions in which the columbarium is located

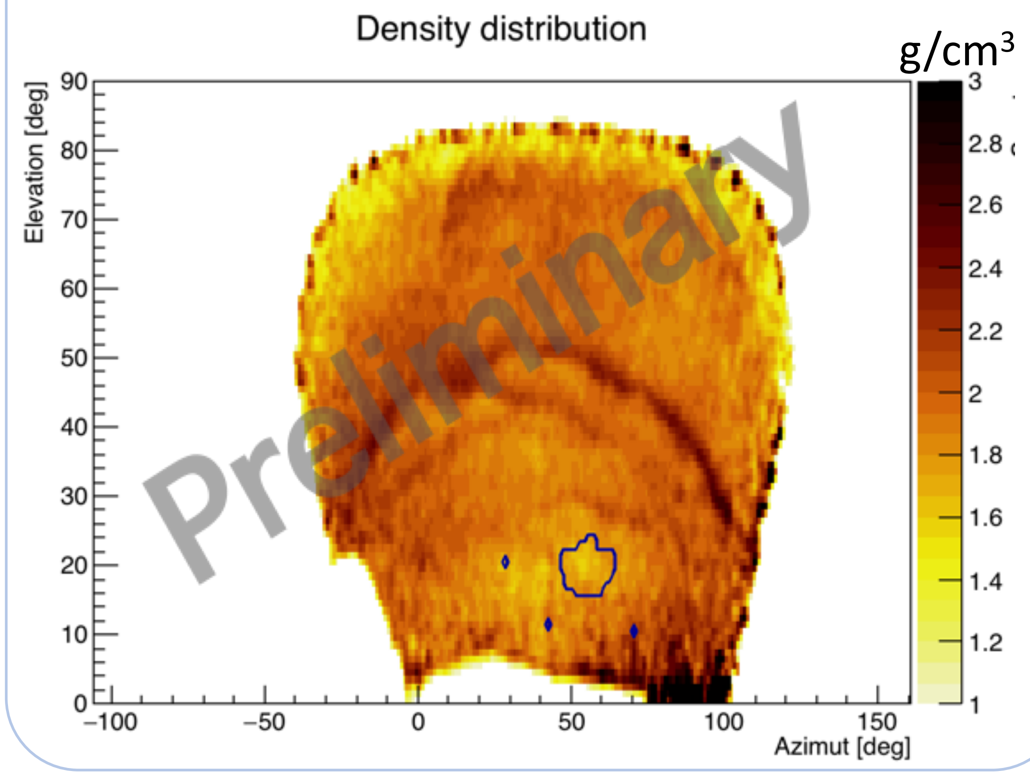
⬇

possible misalignments between measurement-simulation or not perfect geometry of the hill in the simulation

Report of the PhD project activity (second year)

Density map

Density angular distribution



Considerations:

The average density values are compatible with the material densities of the Palazzone hill 1.8-2.1 g/cm^3

Issues:

We have the same artifact of the relative trasmisision in the density map

Possible explanations:

- Misalignment of the MIMA position between measurement and simulation
- We don't have a good enough description of the hill in the simulation
- the geometry in the simulation is misaligned with respect to the actual development of the hill

How can we solve:

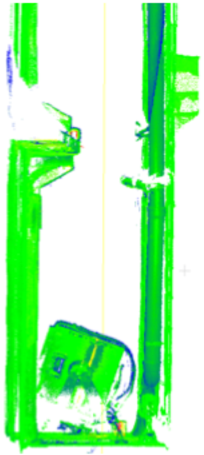
➢ try to have a description of the known geometry (detector position, conformation of the hill without trees, tomb in ruins) more detailed

Report of the PhD project activity (second year)

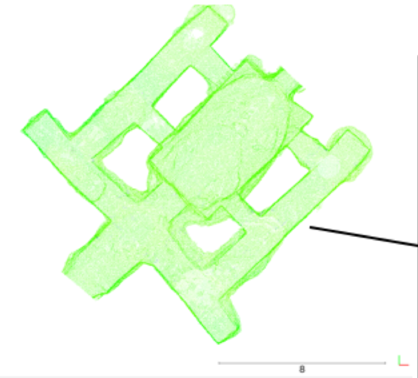
laser scanner campaign

- a laser scanner campaign was carried out during the disinstallation useful for:

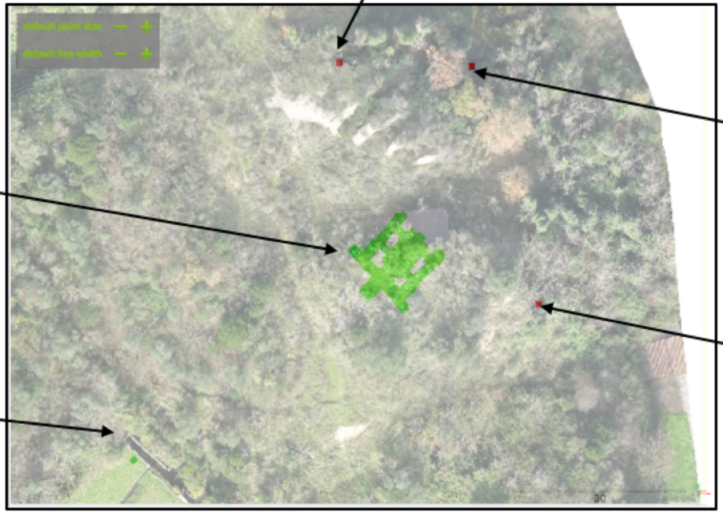
- geolocate MIMA with greater precision (including MIMA in the point cloud),
- have a geolocated point cloud of the ruined tomb,
- control cloud to verify the correctness of the dtm clouds used for simulation



known cavities



Ruined tomb



MIMA position:
EPSG3004
X=2310490.461312
Y=4774089.372198
Z=225.22

Laser scanner and point cloud drone: thanks to Tommaso Beni and Luca Lombardi (UNIFI) Department of Earth Sciences

Report of the PhD project activity (second year)

Next steps

- Complete the measurement of freesky
- Re-update the maps with all the statistics of the freesky
- Study the simulation-measurement misalignment
- Do the simulations with the new geo-referenced MIMA point with laser scanner + integrate the geometry with the hill laser scanner and with a larger DTM for the background
- Recreate the density map and identify low density signals

Report of the PhD project activity (second year)

Educational Activities - List

Courses followed:

I semester:

- Introduction to Space Physics – Ph.D in Physics UNIPG, Prof Nicola Tomassetti [1.5 CFU]

II semester:

- Calorimetric techniques at high energies–Ph.D in Physics UNIFI, Prof. Eugenio Berti [3CFU]

Schools:

- Otranto School: «XXXIII International Seminar of Nuclear and Subnuclear Physics-Francesco Romano», 3-10 June 2022

Conference participation:

- International Conference – EGU General Assembly 2022 (23–27 May 2022):

Presentation, D.Borselli et al.: «Identification and three-dimensional localization of cavities at the Temperino mine (Tuscany-Italy) with the muon imaging technique»

Divulgation events:

- International Cosmic Day 22 November 2021:
  -Laboratory activities with high school students
  -Presentation(online): «Muon radiography as an imaging tool»
- ScienzEstate 2022 (16-17 June), Campus Sesto Fiorentino:
  -Laboratory activities
  -Presentation: «Introduction to Cosmic Rays»

Publications:

- D.Borselli et al., *The BLEMAB European project: Muon radiography as an imaging tool in the industrial field*, Il Nuovo Cimento C, Issue 6, Article 201, 11/08/2022
- Bonechi et al. *Blemab European project: muon imaging technique applied to blast fournace,* 2022 *JINST* **17** C04031
- S.Gonzi et al. *Imaging of the Inner Zone of Blast Furnaces Using MuonRadiography: The BLEMAB Project, Journal of Advanced Instrumentation in Science*, vol. 2022, May 2022.

Report of the PhD project activity (second year)

Educational Activities - List

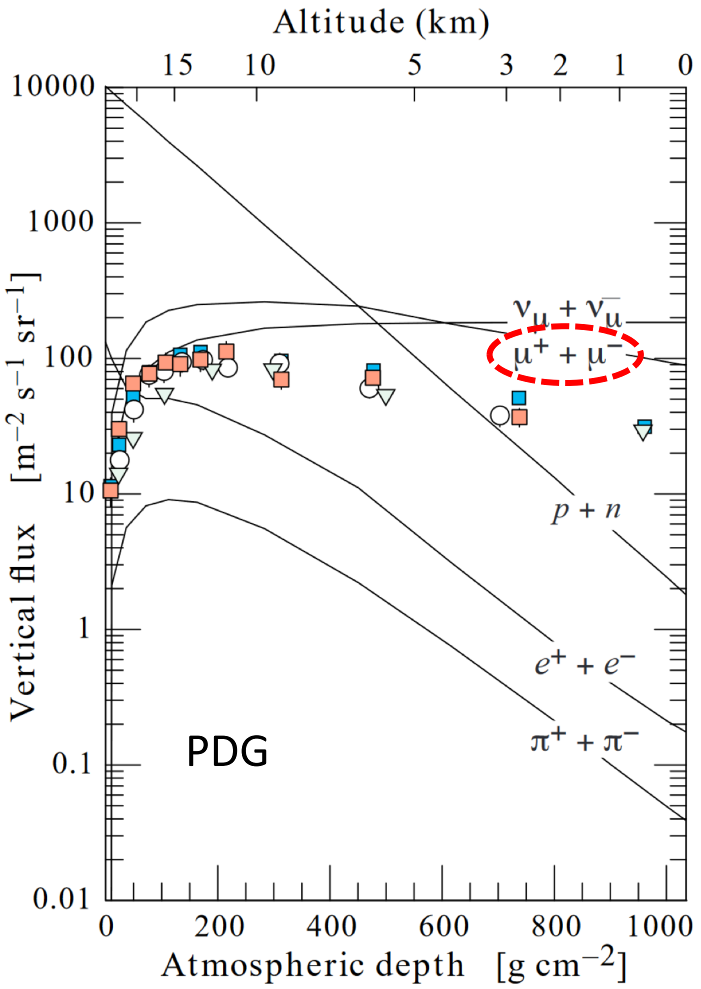
- G.Baccani et al., *The MIMA project. Design, construction and performances of a compact hodoscope for muon radiography applications in the context of archaeology and geophysical prospections*, JINST volume 13 (2018), P11001

Under Review:

- D.Borselli et.al., *Three-dimensional muon imaging of cavities inside the Temperino mine (Italy), Sci. Rep.*

- T.Beni et al., *Transmission-based muography for ore bodies prospecting: a case study from a skarn complex in Italy,* Natural Resources Research, Springer

BACKUP



I **muoni**:

- hanno una vita media di circa 2.2 μs

$$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$$

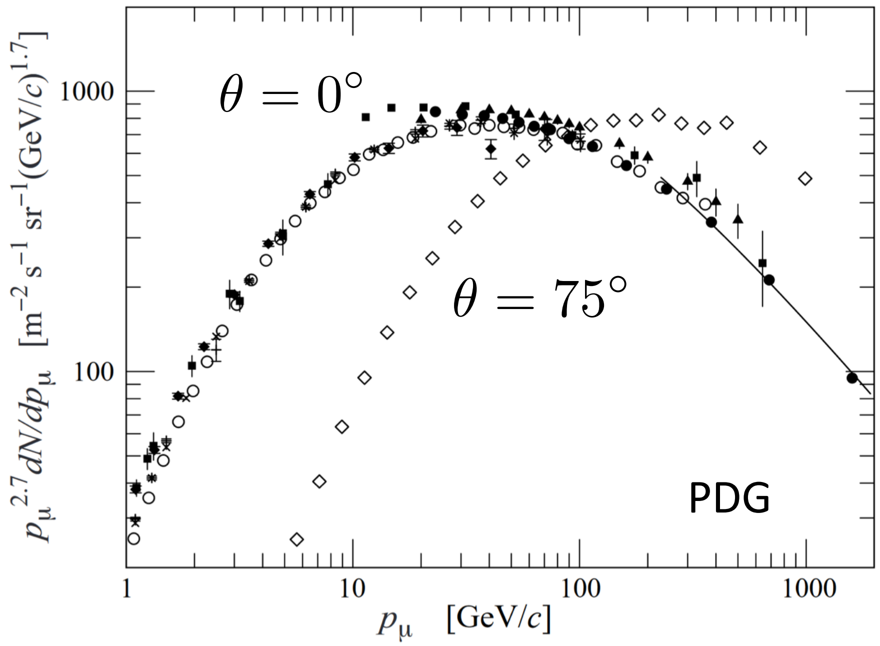
- hanno una massa di circa 105 MeV/c^2 (circa 200 m$_e$)

sono le particelle cariche più abbondanti al suolo

Al livello del mare arrivano in media **70 muoni m^{-2}s^{-1}sr^{-1}** in direzione **verticale**

↓

il flusso non è isotropo ma diminuisce all'aumentare dell' angolo zenitale come $cos^2\theta$ e si sposta ad energie superiori

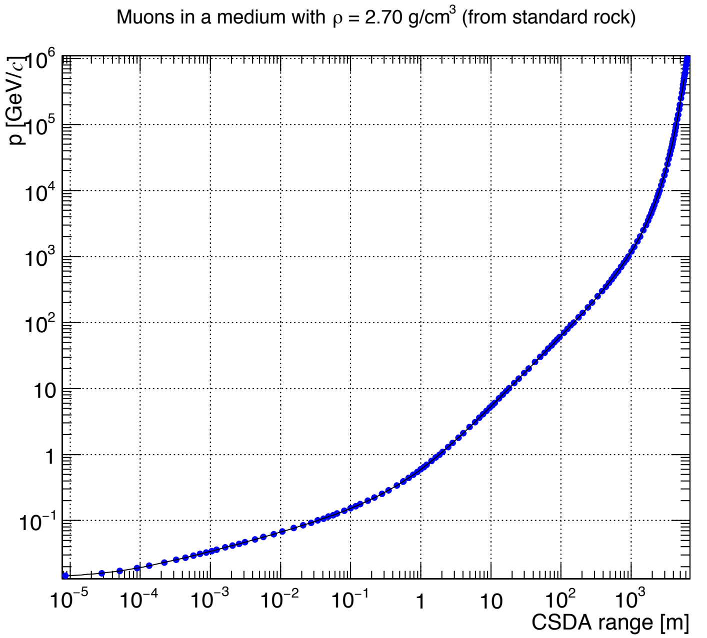


Particelle altamente penetranti

muoni con energie del TeV possono attraversare km di roccia

Report of the PhD project activity (Second year)

Simulation - muRange



(CSDA) Continuous Slowing Down Approximation