Cosmic rays & applications from the study of volcanoes to building stability monitoring

Chiara Pinto* for the EEE Collaboration

*Centro Fermi, Rome; University and INFN, Catania

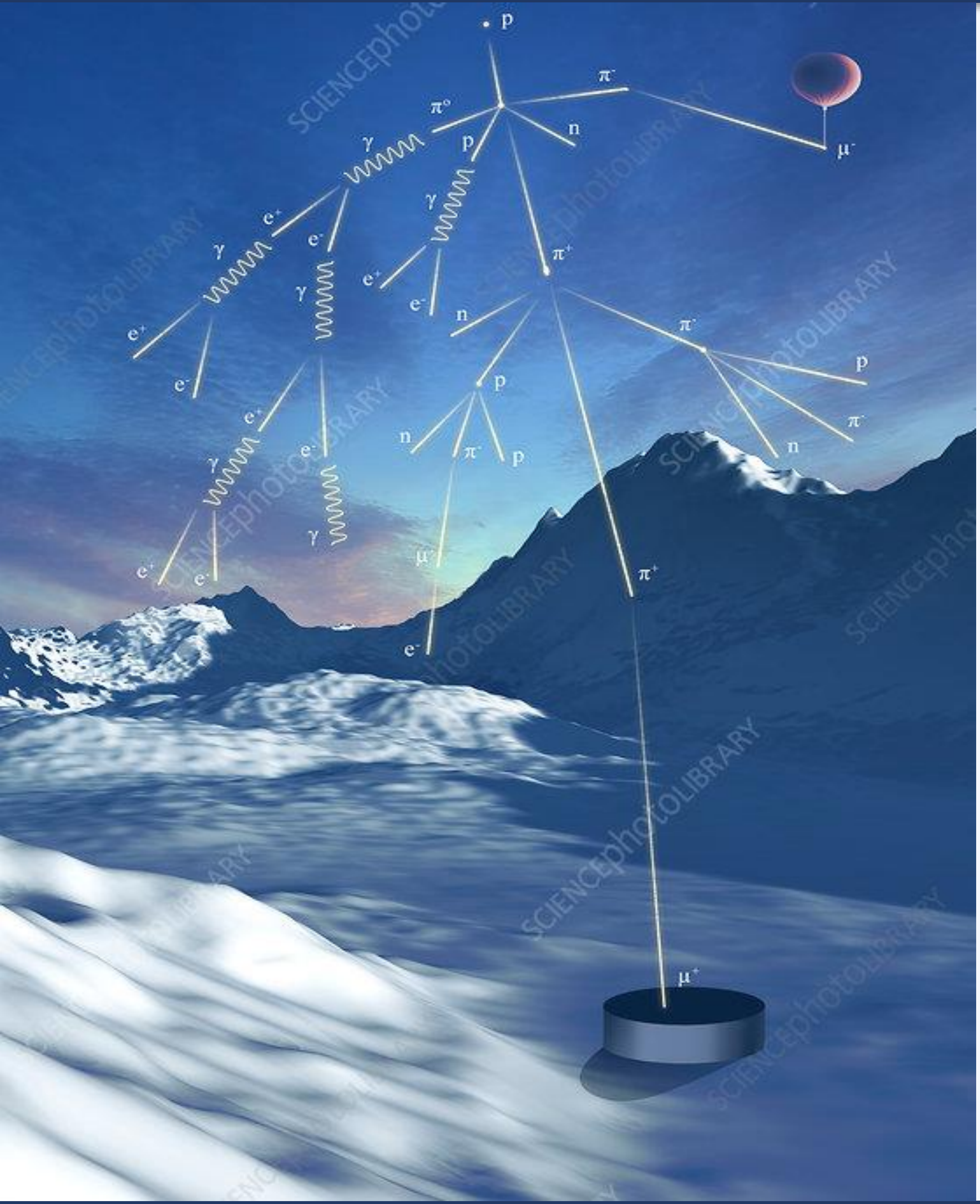
INFN Istituto Nazionale di Fisica Nucleare

Dipartimento di Fisica e Astronomia "Ettore Majorana"

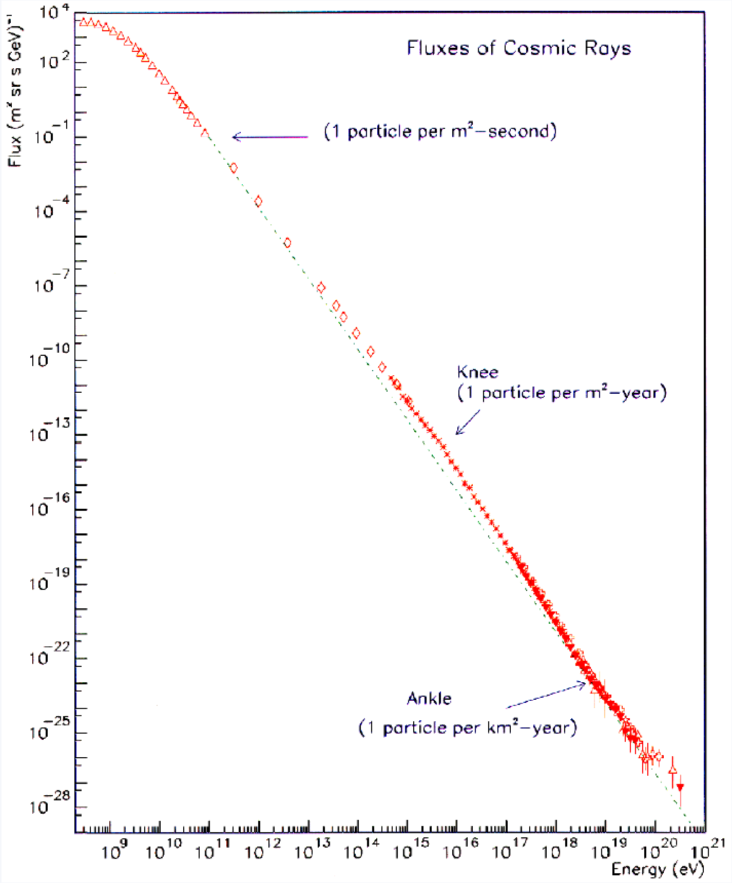
Centro Fermi — Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi

Extreme Energy Events — Science inside Schools

Cosmic radiation



- Primary radiation: H, Li, Be, B, … up to Fe → energies: $10^8 – 10^{20}$ eV
- Secondary cosmic rays a.s.l.: **muons**, e-, neutrinos… → energies: ~ 10^9 eV



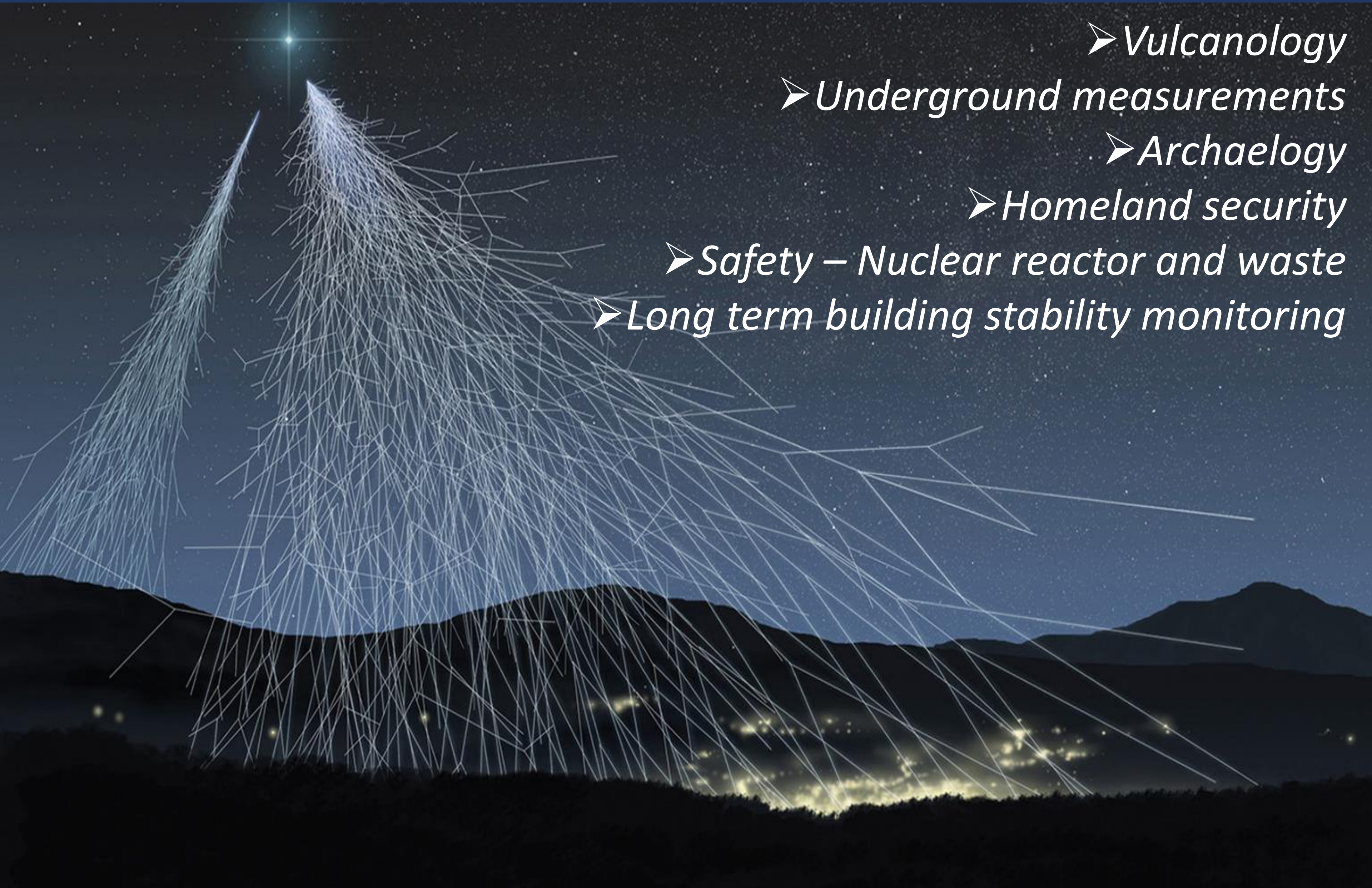
Why using muons?

- Free natural source of radiation
- Limited invasiveness
- μ are highly penetrating walls and floors are easily traversed
- Relatively high muon flux ~ 1 cm^{-2} min^{-1}
- Energy and direction distributions are well known
- Muon scattering strongly depends on atomic number Z

Application techniques are based on
- *Muon scattering*
- *Muon absorption*

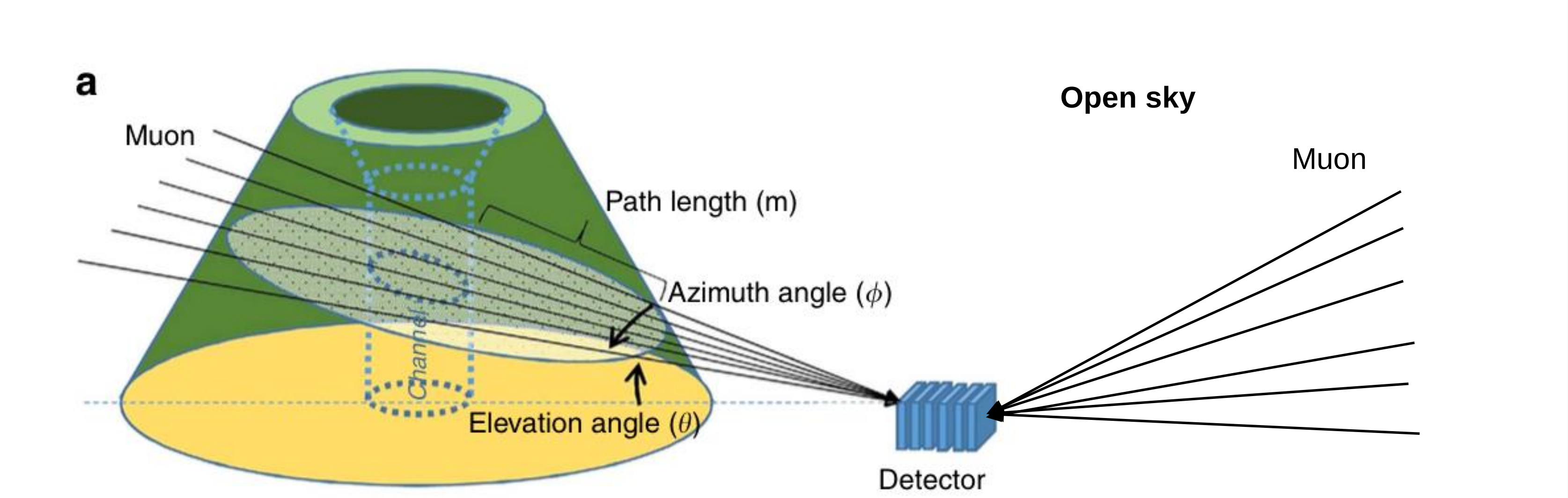
Applications of secondary cosmic rays

- *Vulcanology*
- *Underground measurements*
- *Archaelogy*
- *Homeland security*
- *Safety – Nuclear reactor and waste*
- *Long term building stability monitoring*



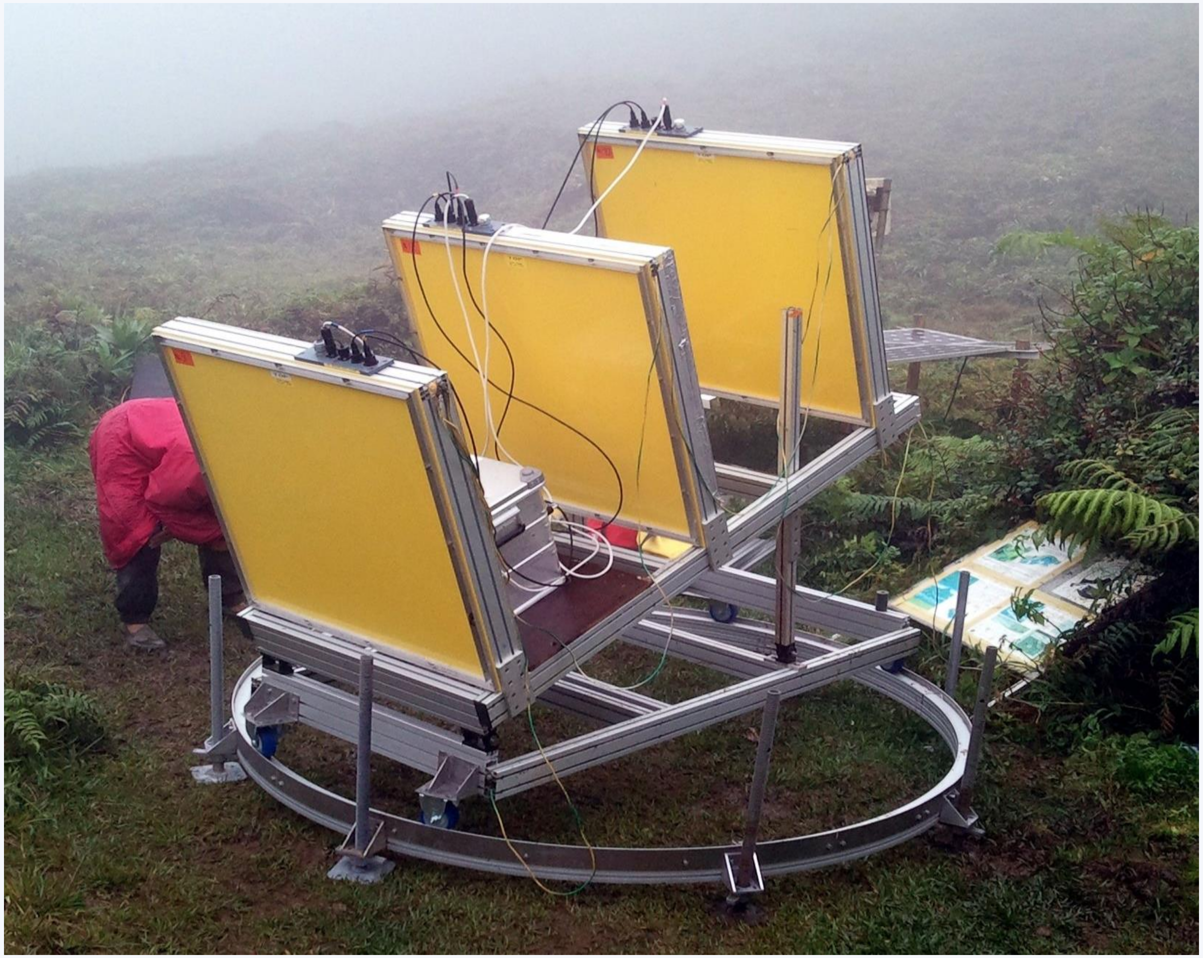
Vulcanology

Absorption muon tomography – possibility of exploring the hidden part of mountains, like (potentially) active volcanoes, by means of cosmic muons traversing part of their solid structure and being partially absorbed with respect to those coming from the open sky



Exploring volcanoes using cosmic rays

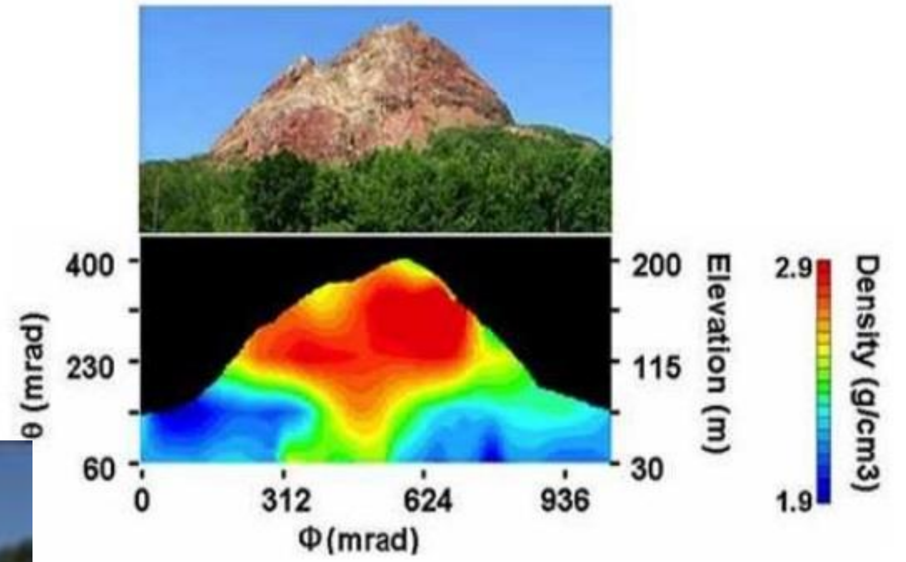
Detector used by french researchers to perform the radiography of a volcano using cosmic rays

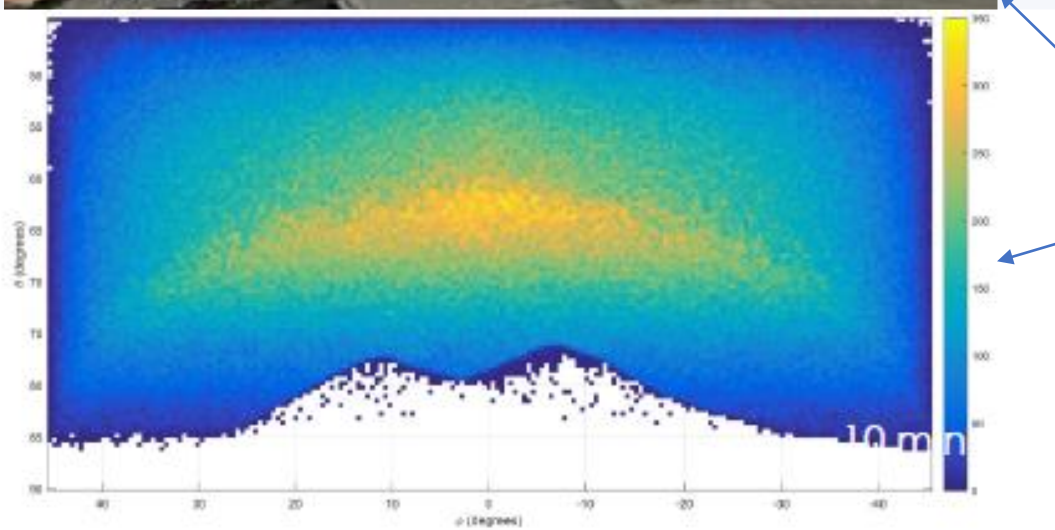


Structural imaging of mountains

Such studies allow to make a structural imaging of the mountain

The colour scale indicates the density of the structure



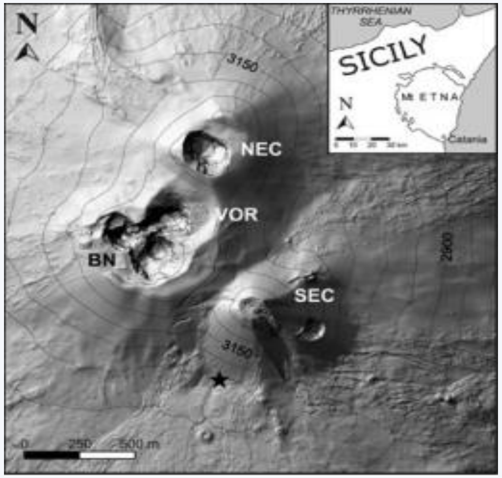


Do you see any difference between

- Picture
- Transmission muons image

of Mt. Rossi in Catania?

Study of Mt. Etna in Catania



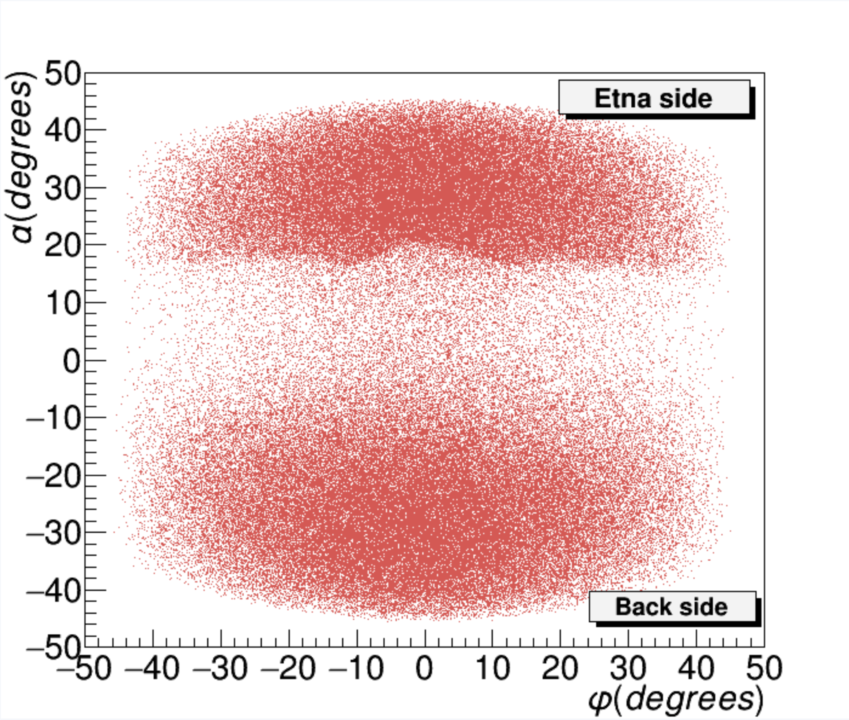
A telescope made of 3 scintillator layers (1 x 1 m^2 each) has been built and it is installed on Mt. Etna territory, taking data since 2017

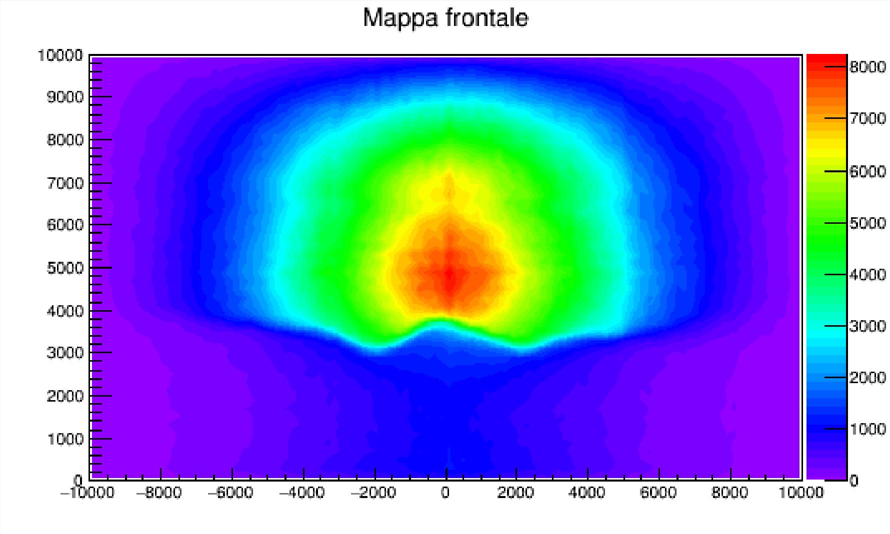
Goal: carry out detailed muographic inspections of the interior of the top craters of Mt. Etna (about 3300 m)

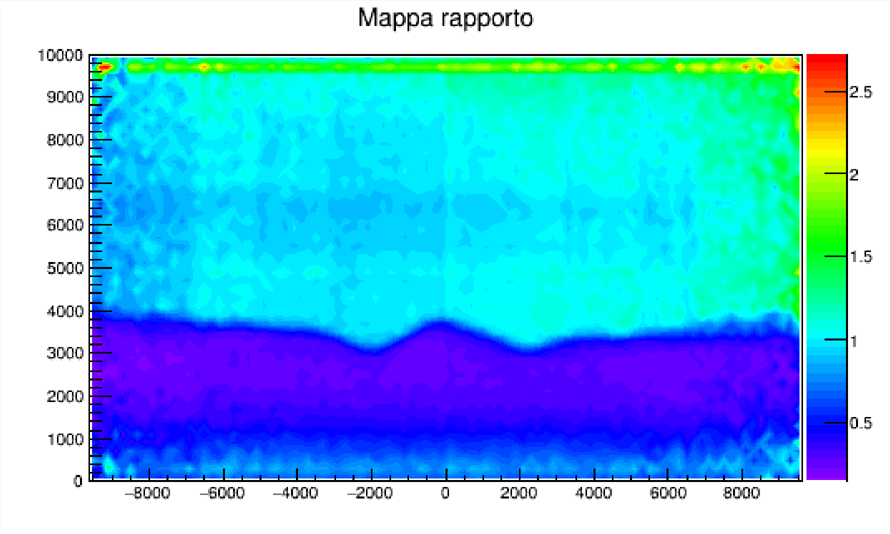
Study of Mt. Etna in Catania

The MEV telescope installed close to the top of Mt. Etna, since August 2017

Imaging of Mt. Etna







Structural imaging of Mt. Etna exploiting the absorption of muons in the rock and those coming from the open sky

Archaeology

Absorption muon tomography – One of the first applications in this field was made by Alvarez and his collaborators, who employed a muon detector inside an Egyptian pyramid to search for possible hidden chambers.

Luis Alvarez, Nobel Prize 1968

A big empty space (30 m length) was found in Cheope's Pyramid

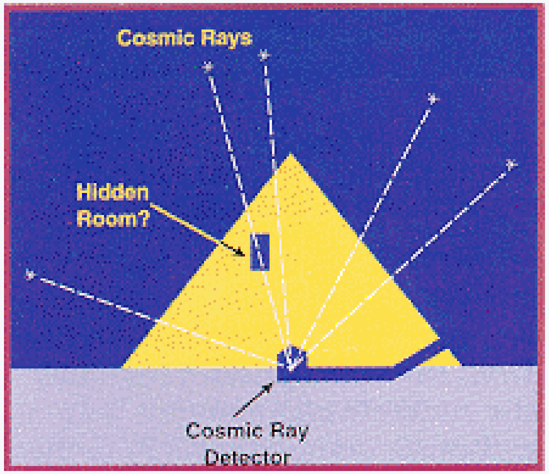


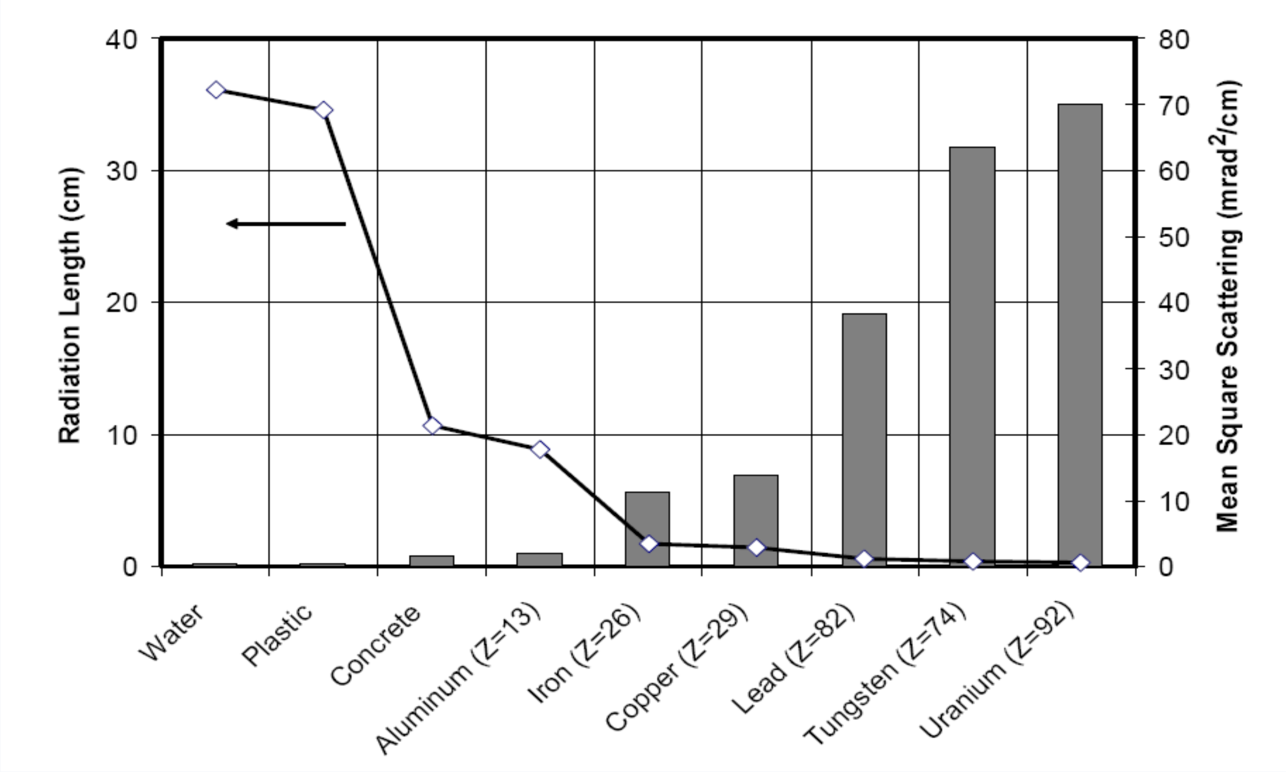
Figure 5 - Schematic of the Alvarez cosmic ray technique used to search for possible hidden chambers in the Pyramid of Kephren. It can be applied to locate voids in very thick sections such as highway bridges.

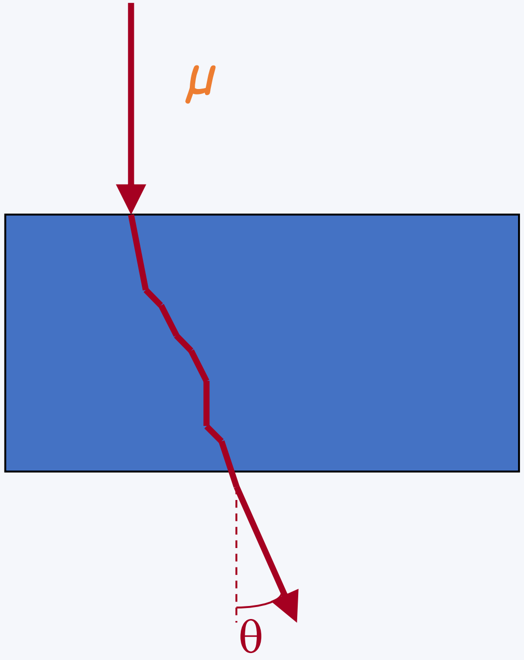
Alvarez, L.W. et al., Search for Hidden Chambers in the Pyramids, Science, 167(1970),832

Muon scattering – based methods

Muon scattering strongly depends on atomic number Z

Multiple scattering of muons – Particularly useful to detect the presence of Uranium, Plutonium or Lead





Applications: Homeland security & Imaging of nuclear reactors and waste

Homeland security

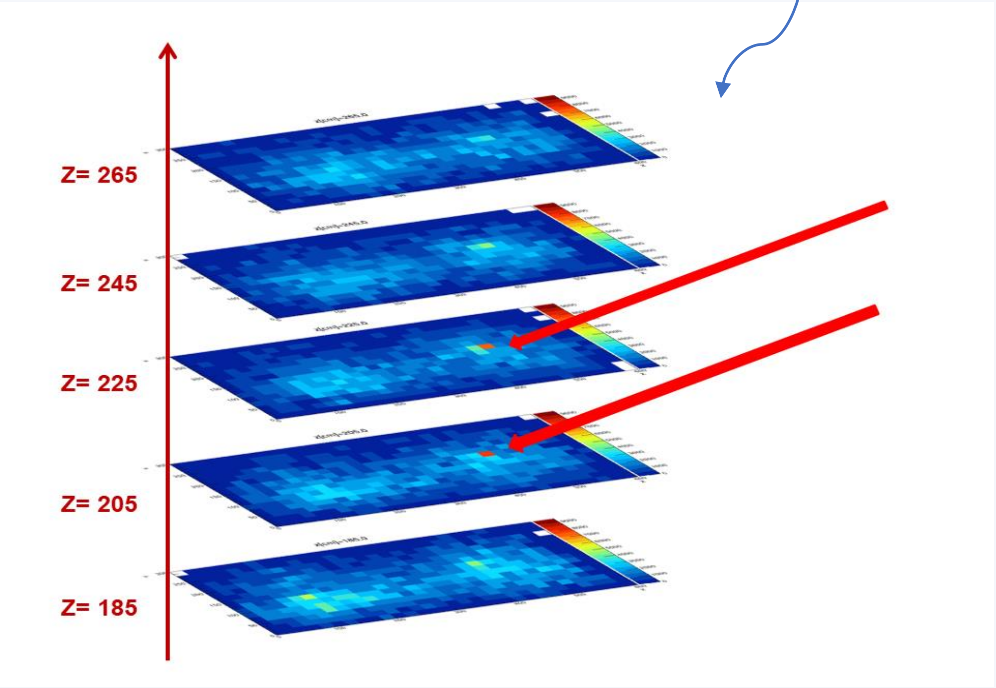
Multiple scattering – Inspect the inside of a container to search for illicit fissile elements.

The technique requires two muon tracking detectors, one placed above and the other placed below the container, used to reconstruct muon tracks before and after traversing the container content.

Homeland security

In Catania a prototype was built for this purpose (3 x 6 x 7 m)

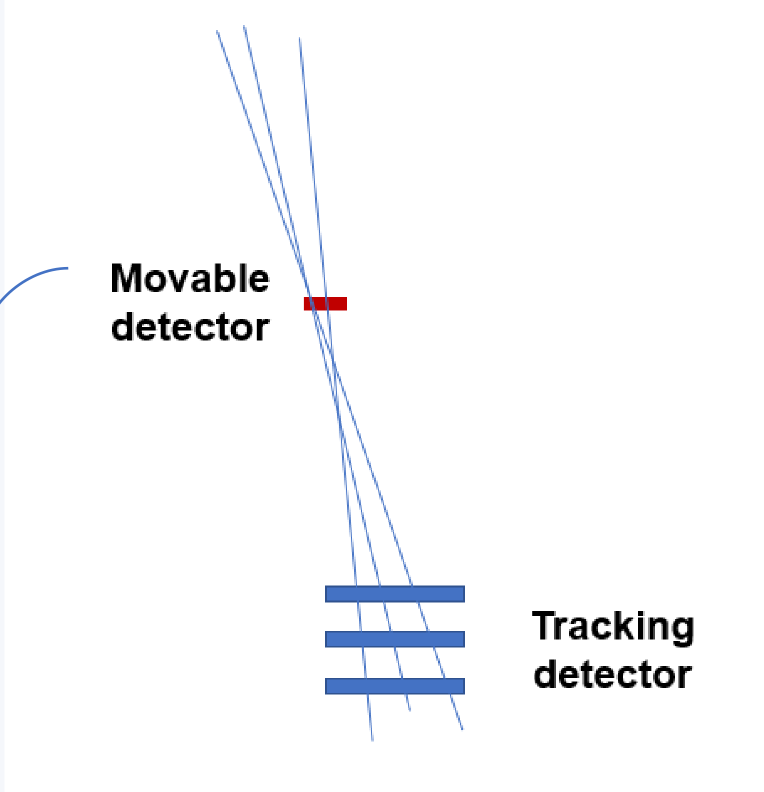
Several scanning planes at different heigths z



Building stability

THE IDEA → **Muons passing through a tracking detector and additional detectors are used as a tool to monitor small (mm) shifts of parts of the structure over long time periods.**

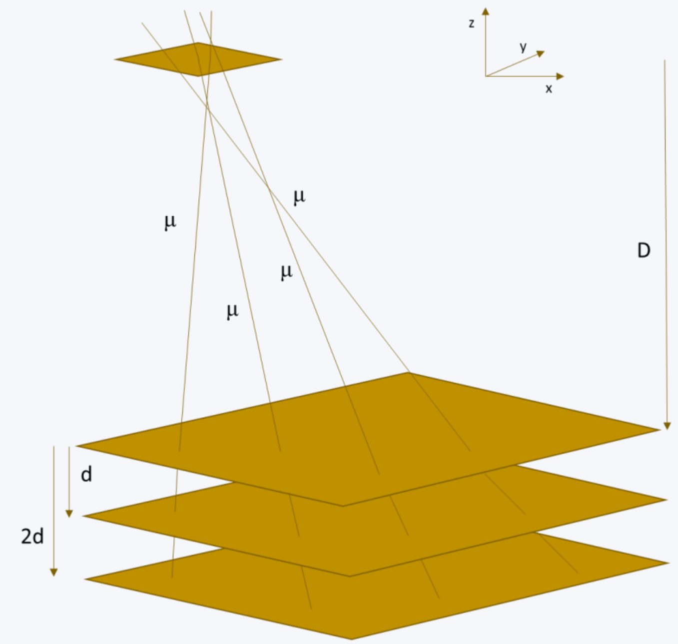
Moved to mimic possible deformations of the building



Depend on: capability of the main tracking detector, geometry and position of the additional detectors, constant response of detectors, acquisition time,.. ← ***PERFORMANCE***

Pros & Cons

Usually other techniques are used to control the stability of a structure, namely mechanical methods such as metal wires stretching or optical systems such as laser alignments…



WHY USING COSMIC MUONS TO MONITOR THE BUILDING STABILITY?

- 👍 limited invasiveness
- 👍 use of a free natural source of radiation
- 👍 μ are highly penetrating walls and floors are easily traversed
- 👍 no need of visibility or empty spaces (VS optical systems)
- 👍 possibility to design a global monitoring system
- 👎 low rate of cosmic muons (relatively) long data taking

Experimental setup to monitor the building stability

In Catania → experimental setup to test the possibility of monitoring the long term building stability

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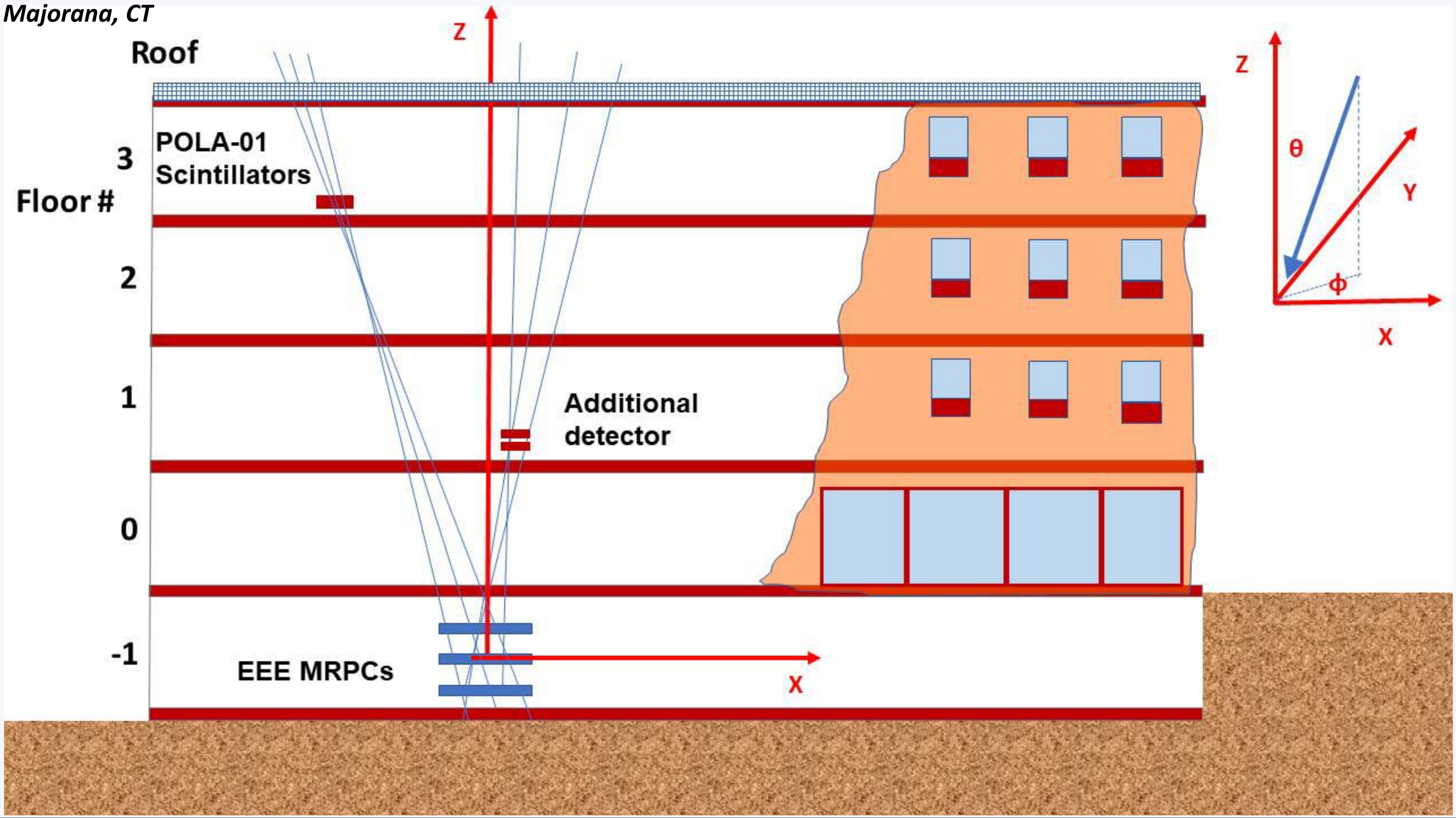
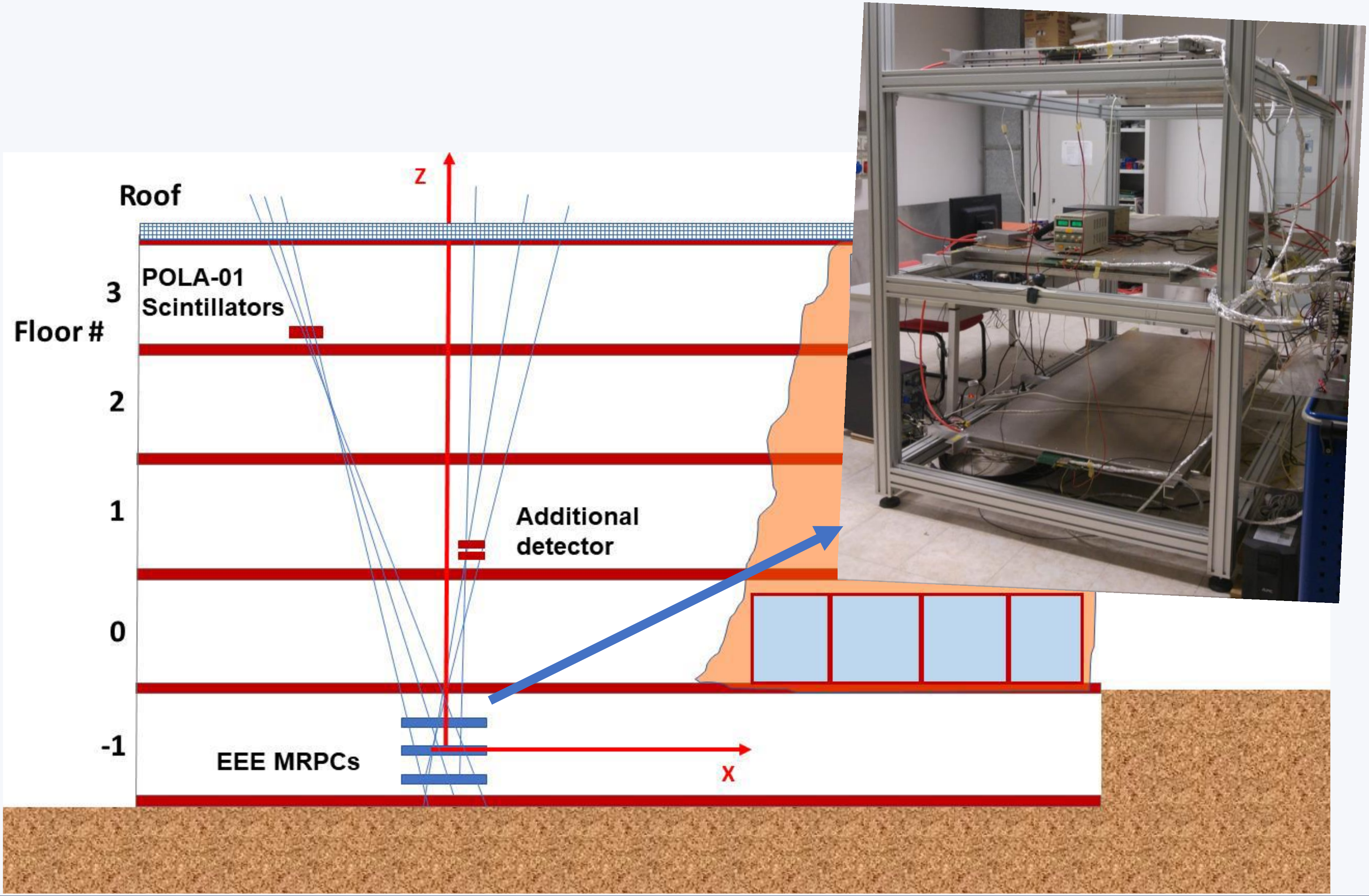
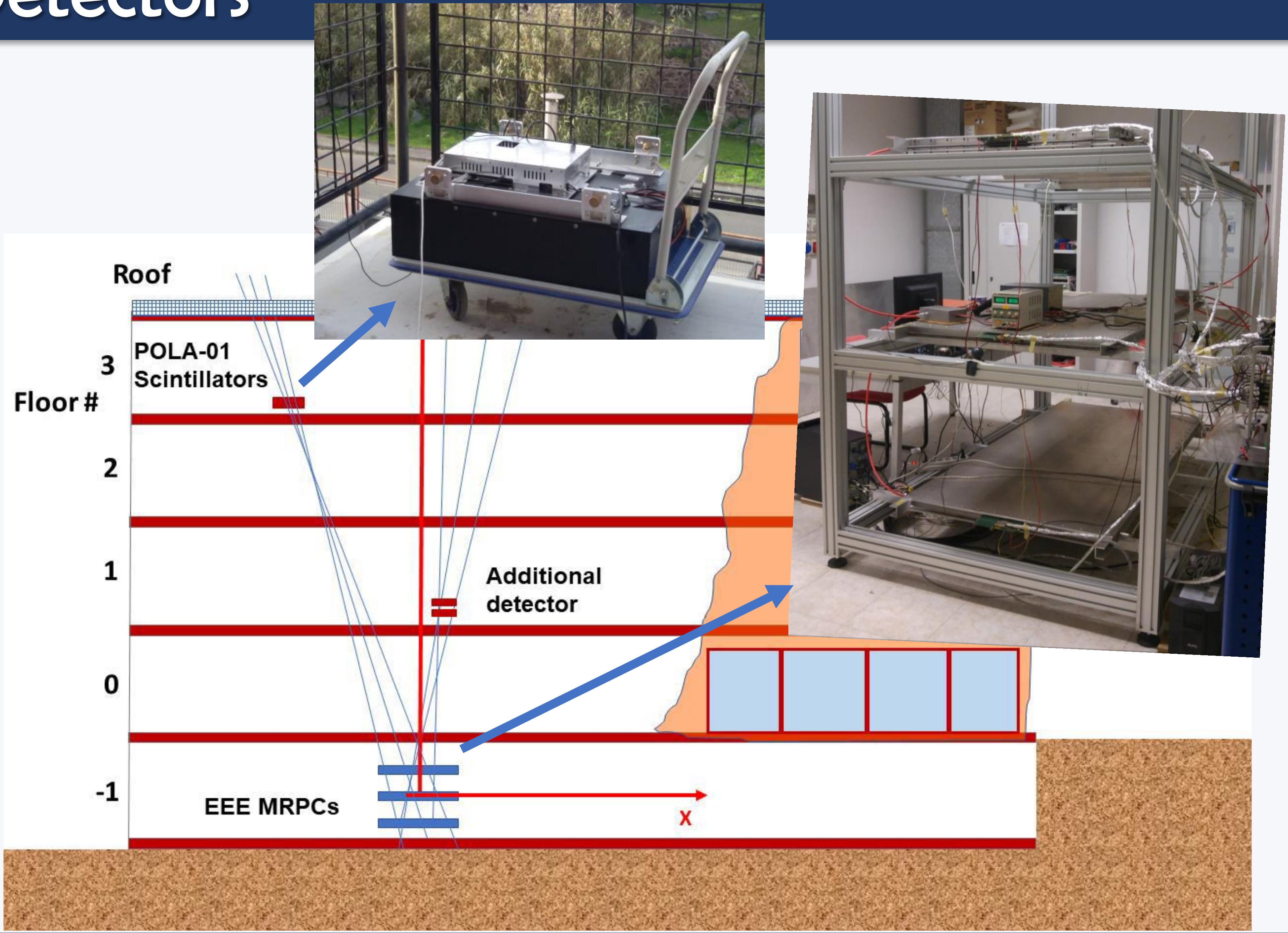


Detectors


Roof
Z
POLA-01
Scintillators
3
Floor #
2
1
Additional
detector
0
-1
EEE MRPCs
X

Detectors

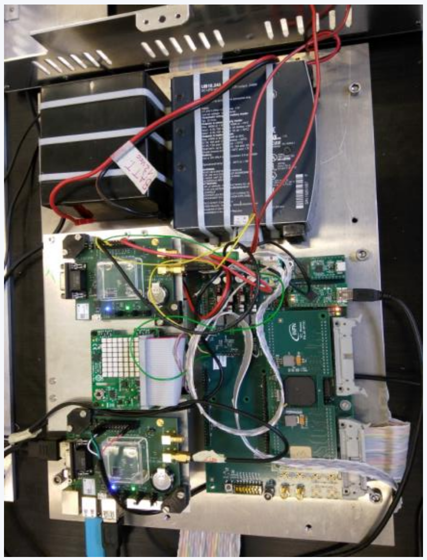


Roof
3
Floor #
POLA-01
Scintillators
2
1
Additional
detector
0
-1
EEE MRPCs
X

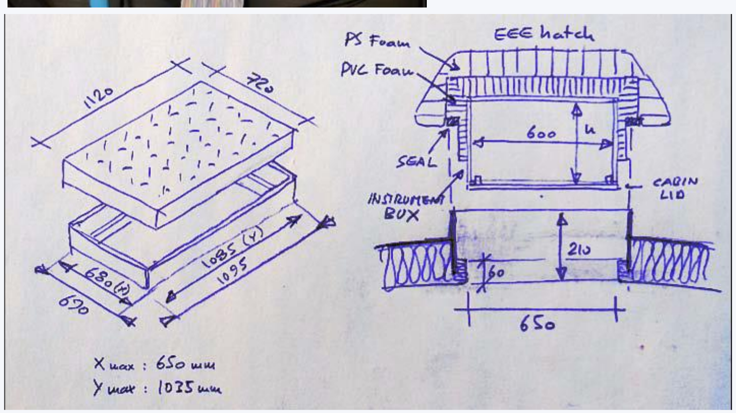
POLAR detector

Polar is one of the three detectors of the PolarquEEEst project by Centro Fermi

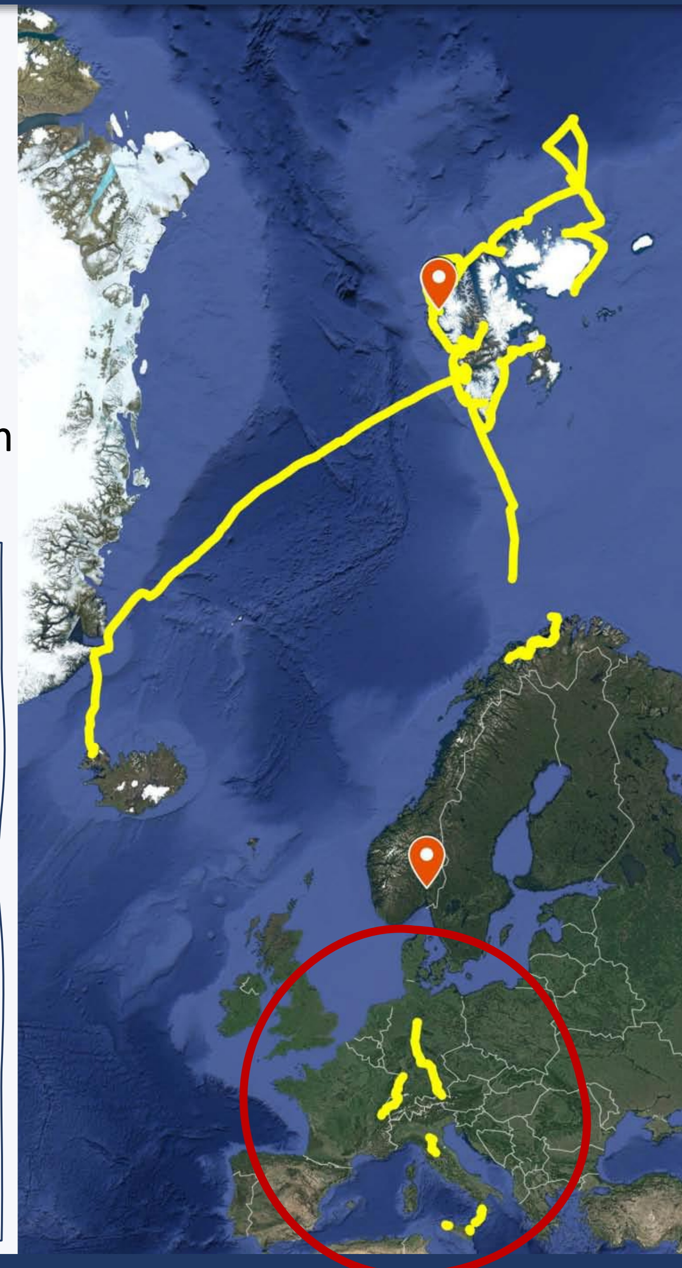
Assembled at CERN by high school students



- 2 Plastic scintillator planes
- Distance between planes: 11 cm
- 4 Tiles for each plane: 30 cm x 20 cm
- 2 SiPMs per tile (16 SiPMs in total)



- ✓ Nanuq
- ✓ Genova
- ✓ Vigna di Valle (Rome)
- ✓ Cosenza
- ✓ Messina
- ✓ Cefalù (Palermo)
- ✓ Erice (Trapani)
- ✓ Catania-Etna
- ✓ Lampedusa
- ✓ Bologna
- ✓ Munich
- ✓ Hannover
- ✓ Frankfurt am Main
- ✓ CERN



POLAR detector

- ✓ Nanuq
- ✓ Genova
- ✓ Vigna di Valle (Rome)
- ✓ Cosenza
- ✓ Messina
- ✓ Cefalù (Palermo)
- ✓ Erice (Trapani)
- ✓ Catania-Etna
- ✓ Lampedusa
- ✓ Bologna
- ✓ Munich
- ✓ Hannover
- ✓ Frankfurt am Main
- ✓ CERN

Ny Alesund

POLAR started its trip in Ny Alesund and for some time stopped in Catania

Catania

Experimental setup @ DFA- UniCT

No visibility between detectors (4 layers of concrete)

- GPS time tagging of events
- Average count rate a.s.l. ~30 Hz

Detectors take data independently, then correlated by GPS information

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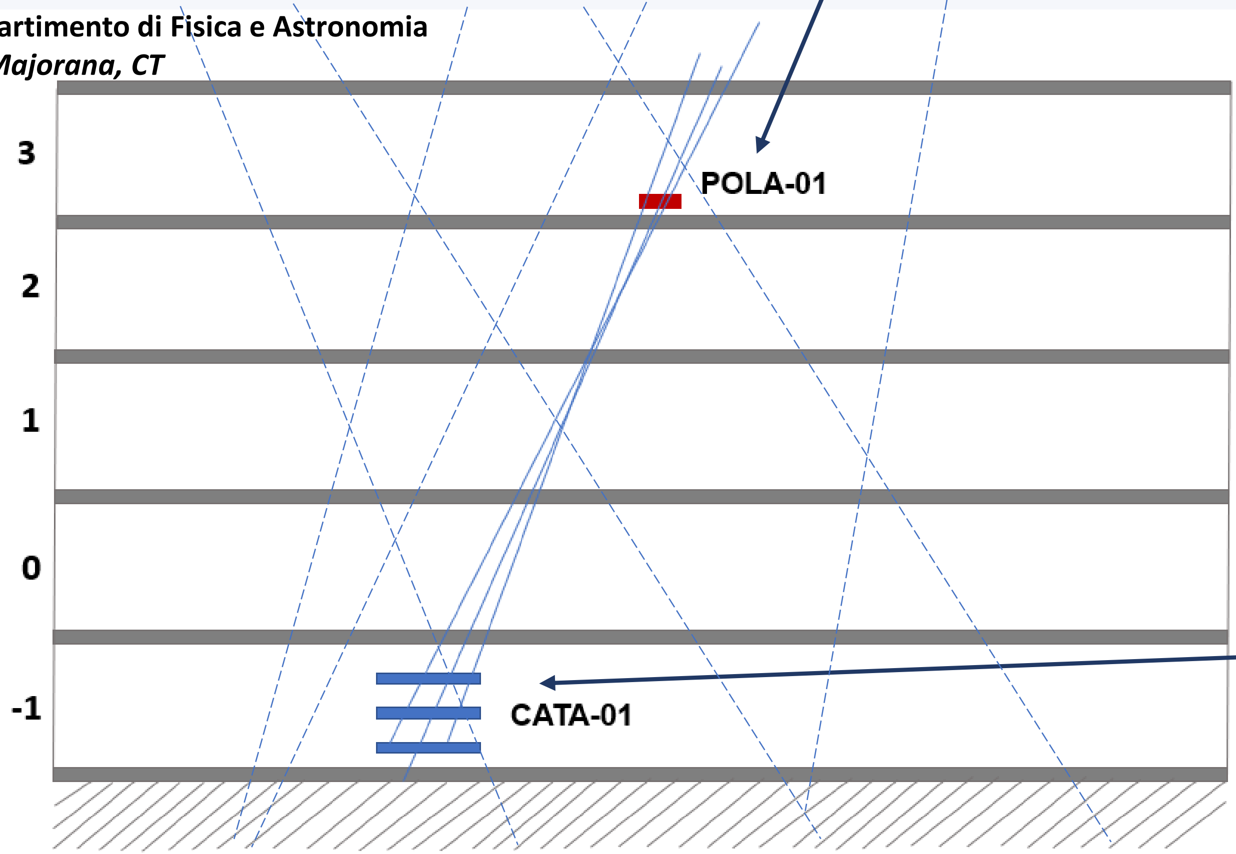
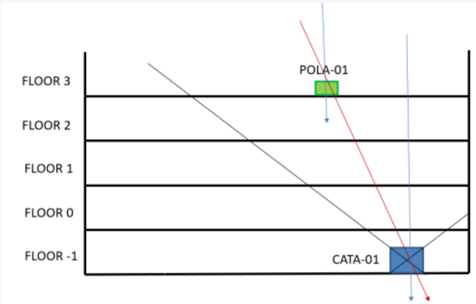


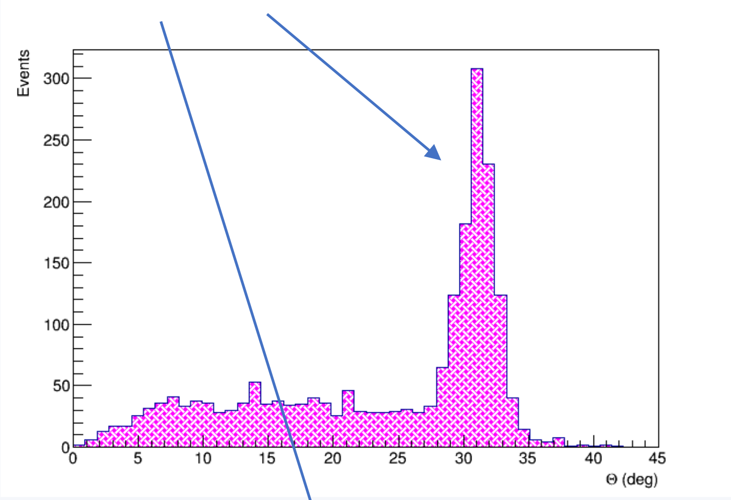
- GPS information

Commissioning measurements

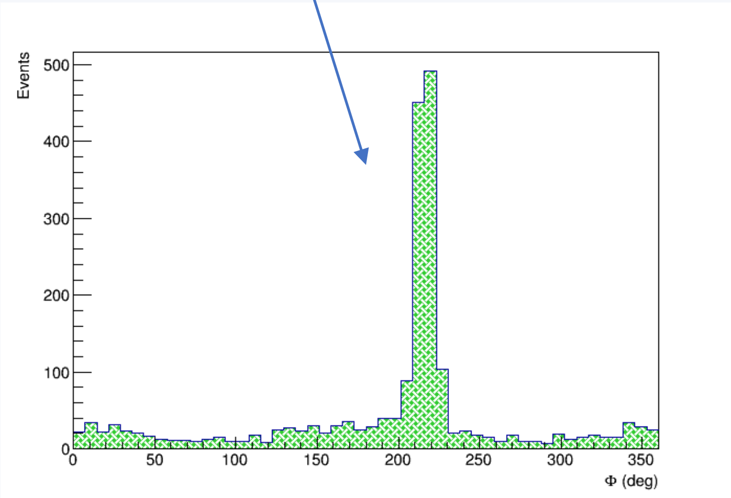


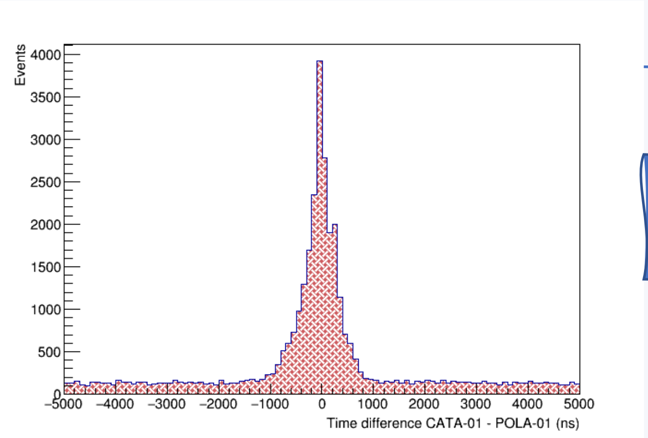
Same muons passing through both detectors.

Inside the acceptance cone: ~ **47 days** data acquisition in total



- The track orientation (θ,ϕ) — as reconstructed by the MRPC EEE telescope — is considered
- These distributions depend on the relative position of the movable scintillator w.r.t. the EEE telescope





Coincidence: 600 ns time window

M. Abbrescia *et al* 2019 *JINST* **14** P06035

«Simulating» the building shifts

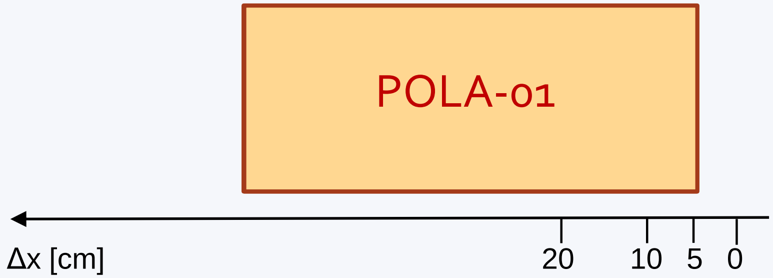
The scintillator was moved to mimic the building shift

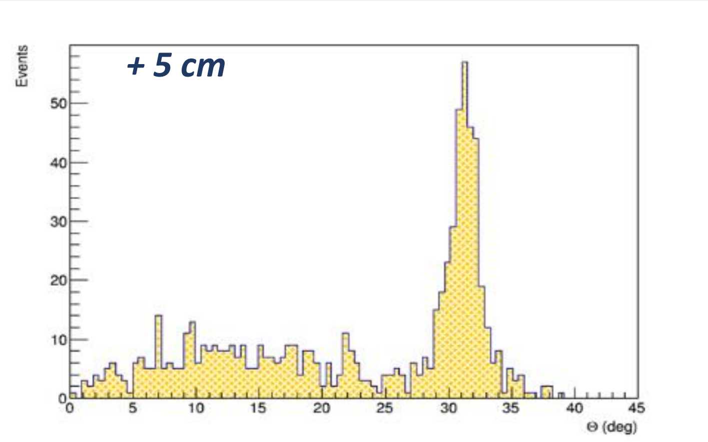
Four sets of measurements:

- Reference -> 0 cm

«Simulating» the building shifts

The scintillator was moved to mimic the building shift



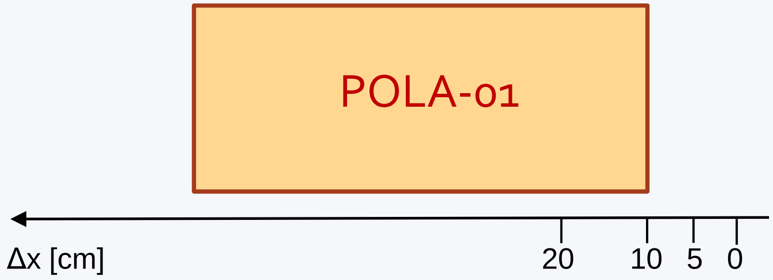


Four sets of measurements:

- Reference -> 0 cm
- First shift -> 5 cm

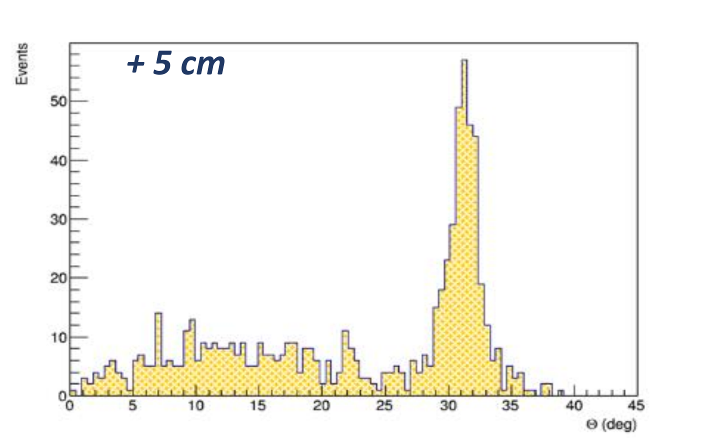
«Simulating» the building shifts

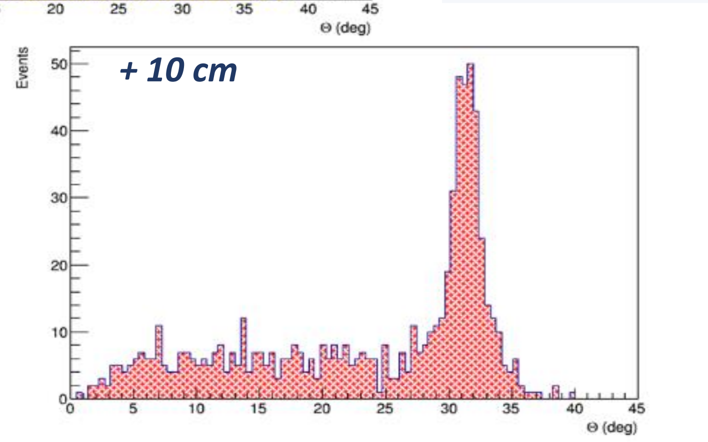
The scintillator was moved to mimic the building shift



Four sets of measurements:

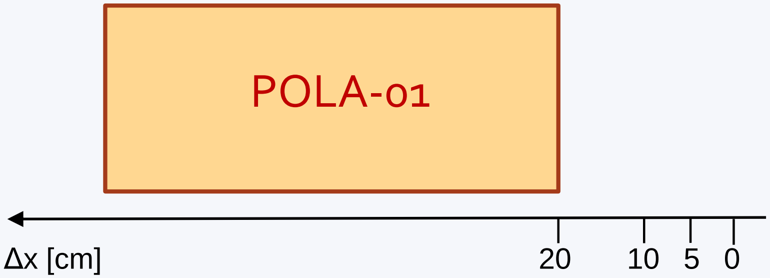
- Reference -> 0 cm
- First shift -> 5 cm
- Second shift -> 10 cm





«Simulating» the building shifts

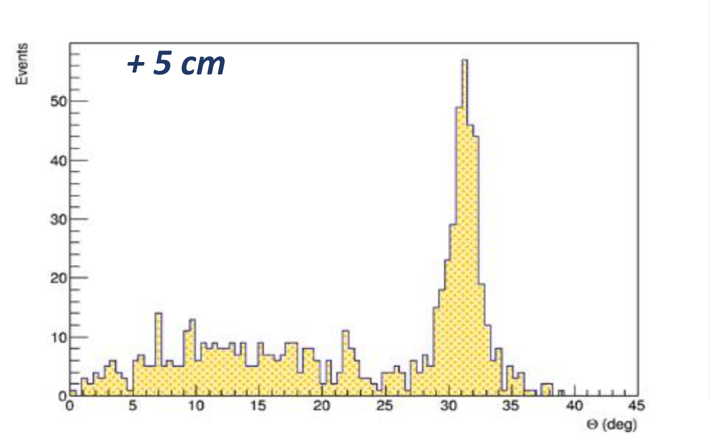
The scintillator was moved to mimic the building shift

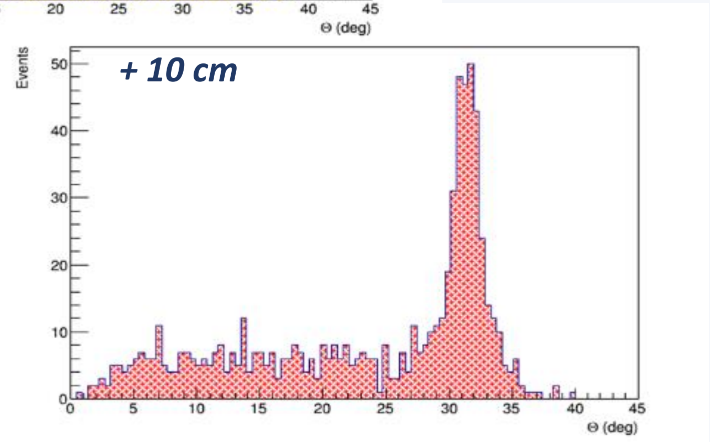


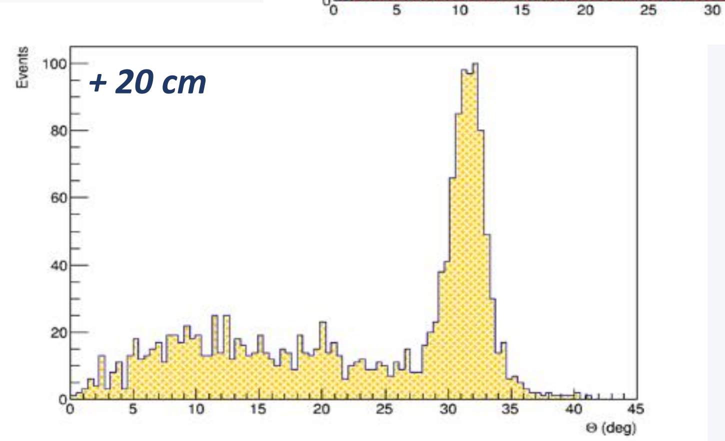
Four sets of measurements:

- Reference -> 0 cm
- First shift -> 5 cm
- Second shift -> 10 cm
- Third shift -> 20 cm

Gaussian fit		
x [cm]	**< θ > ± Δ<θ>**	**< ϕ > ± Δ<ϕ>**
0	31.03° ± 0.05°	216.39° ± 0.16°
+5	31.18° ± 0.07°	215.88° ± 0.33°
+10	31.36° ± 0.08°	215.98° ± 0.30°
+20	31.45° ± 0.06°	215,67° ± 0.20°

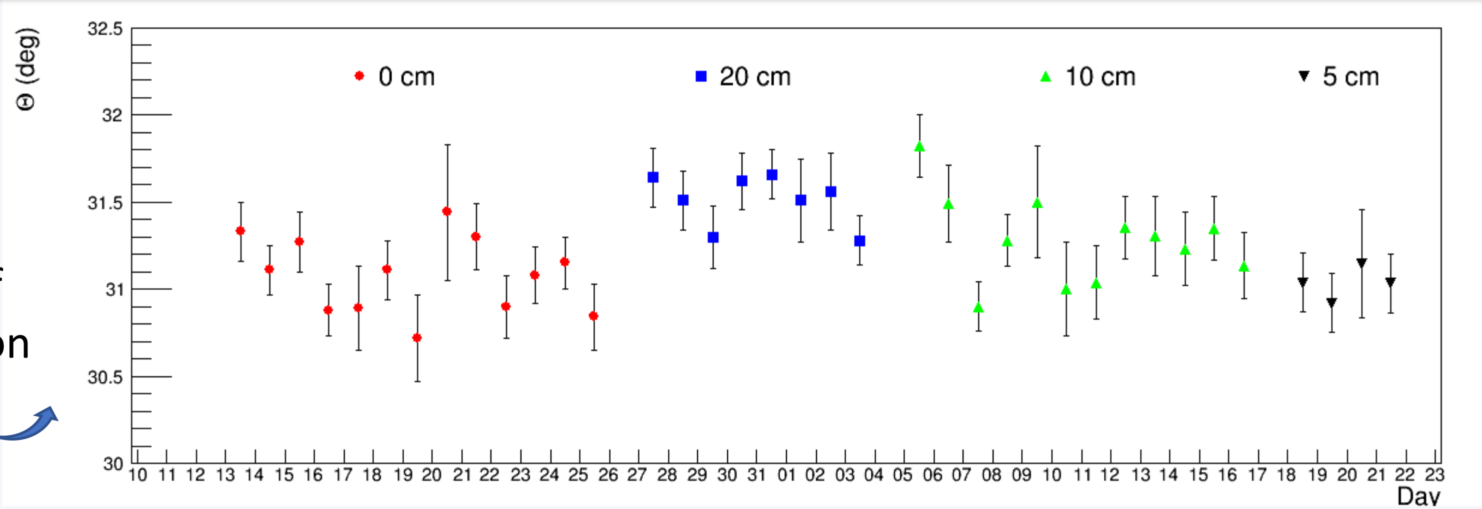






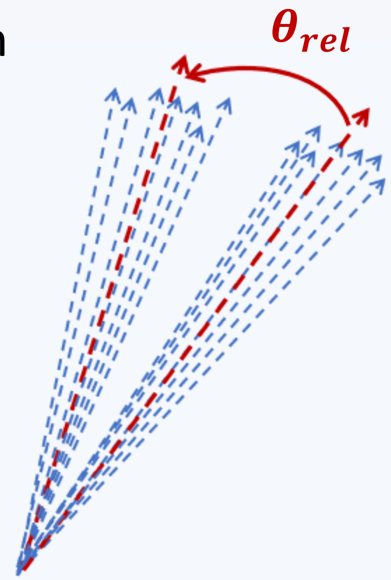
Performance of the method

Day-by-day monitoring of track orientation



CONVERSION INTO A 3D INFORMATION

Estimation of the average direction in space, summing on all the tracks, in 3 configurations (5 cm, 10 cm, 20 cm).



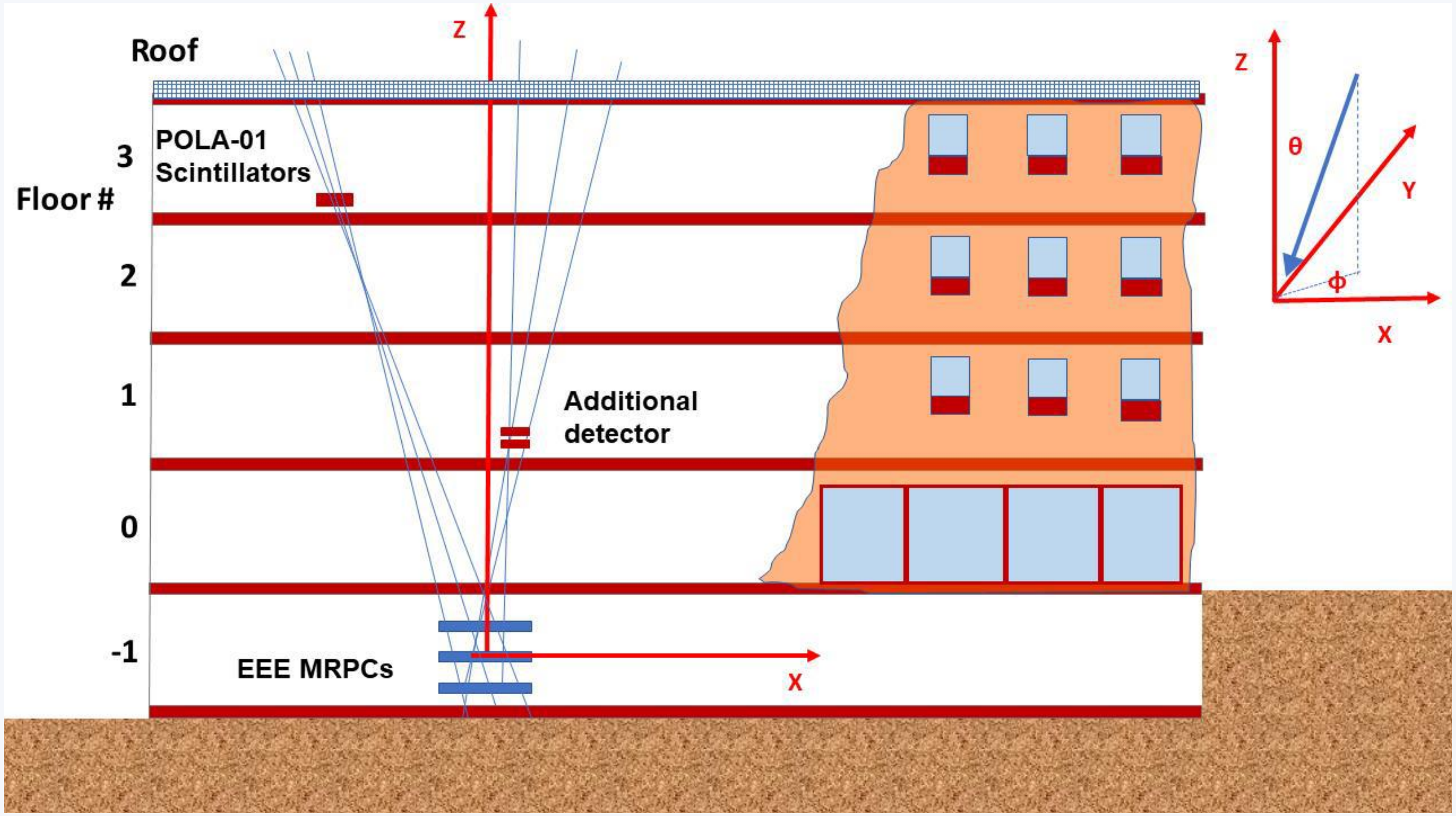
Performance of the method at 2.5 m:

- *few **cm** in 1 day data taking*
- *few **mm** in few months data taking*

How to *monitor* the building stability?

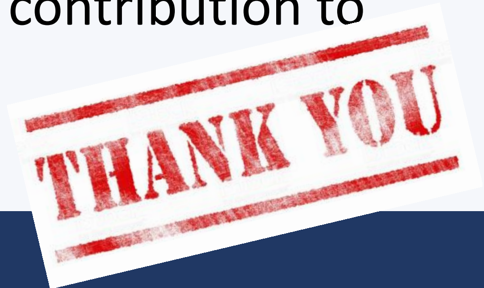
By monitoring the track orientation (θ,ϕ) over long times (of the order of months), it is possible to *see* if the structure is moving.

We are not able to detect fast movements (like earthquakes) but only long time deformations.



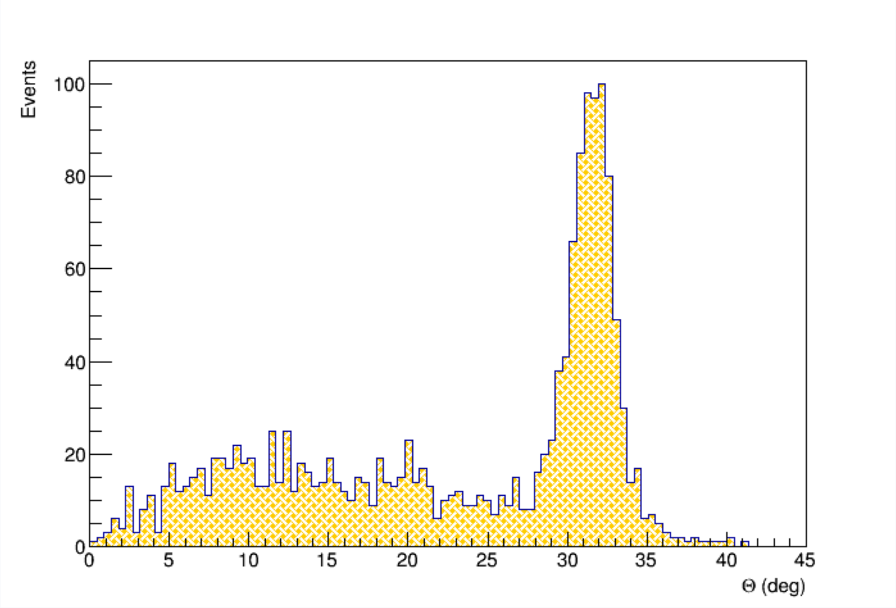
Conclusions

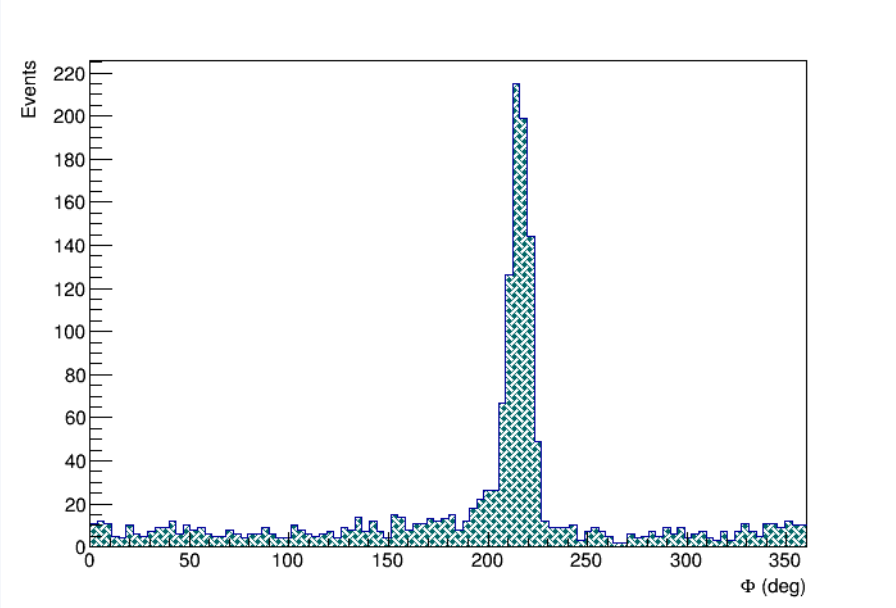
- Cosmic rays are a powerful probe to understand the Universe and also our environment
- Some applications make use of the multiple scattering effect (Homeland security & Imaging of nuclear reactors and waste), others of the muon absorption (Vulcanology & archaeology)
- Possibility of monitoring the long term building stability using coincidence measurements between MRPC EEE telescope & additional detectors
- The additional detector is moved in order to mimic possible deformations of the building
- The sensitivity of the method depends on: capabilities of the main tracking detector, geometry and position of the additional detectors, uniformity over time of detectors response, acquisition time, ...
- Most of the EEE telescopes are presently located inside school buildings → the addition of one or several small scintillators with good capabilities in the same building could offer a further contribution to the EEE activities in the schools



BACKUP

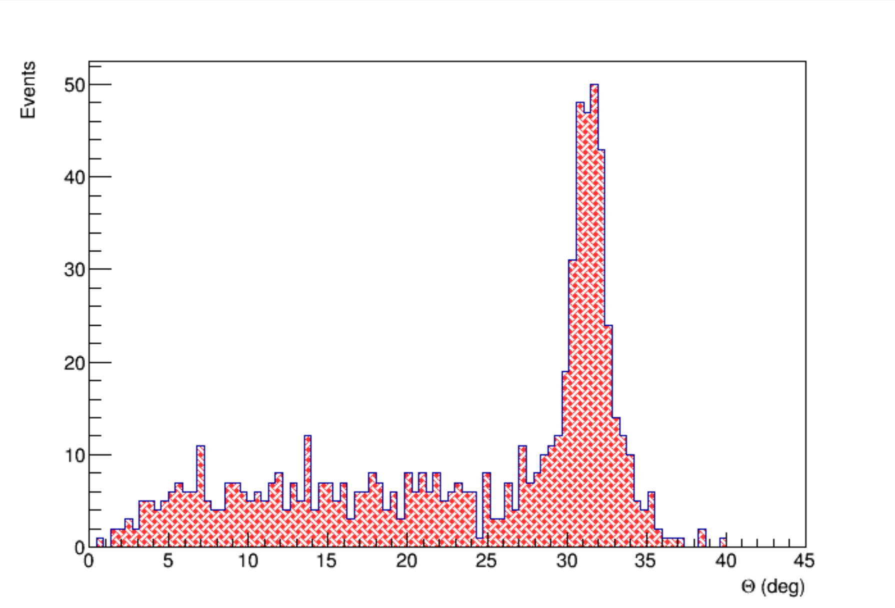
20 cm shift

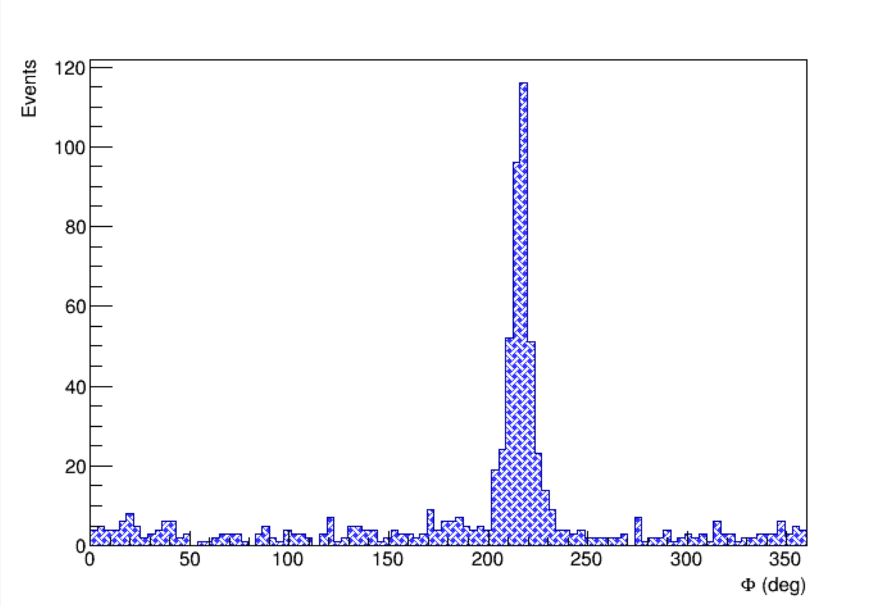




x [cm]	< θ > ± Δ<θ>	< ϕ > ± Δ<ϕ>
0	31.03° ± 0.05°	216.43° ± 0.20°
+20	31.45° ± 0.06°	216.23° ± 0.32°

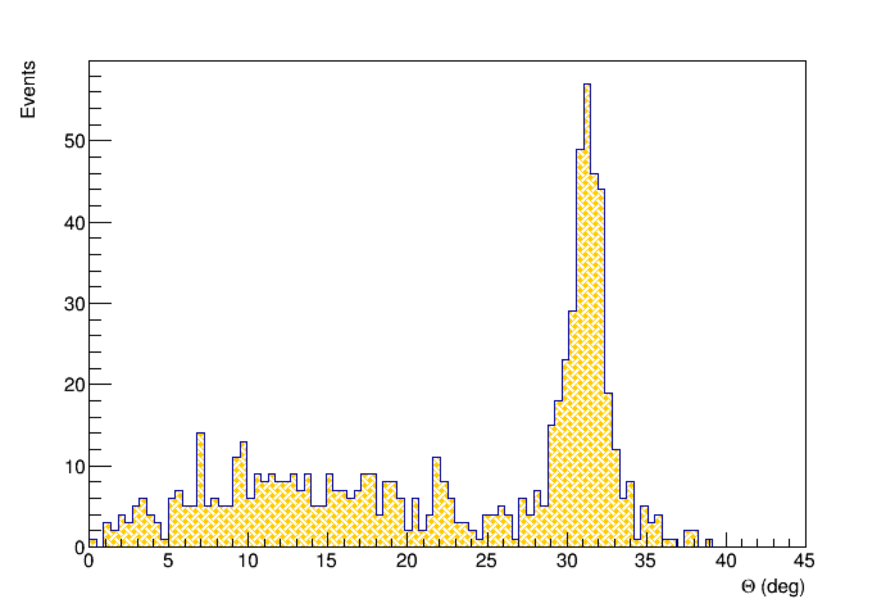
10 cm shift

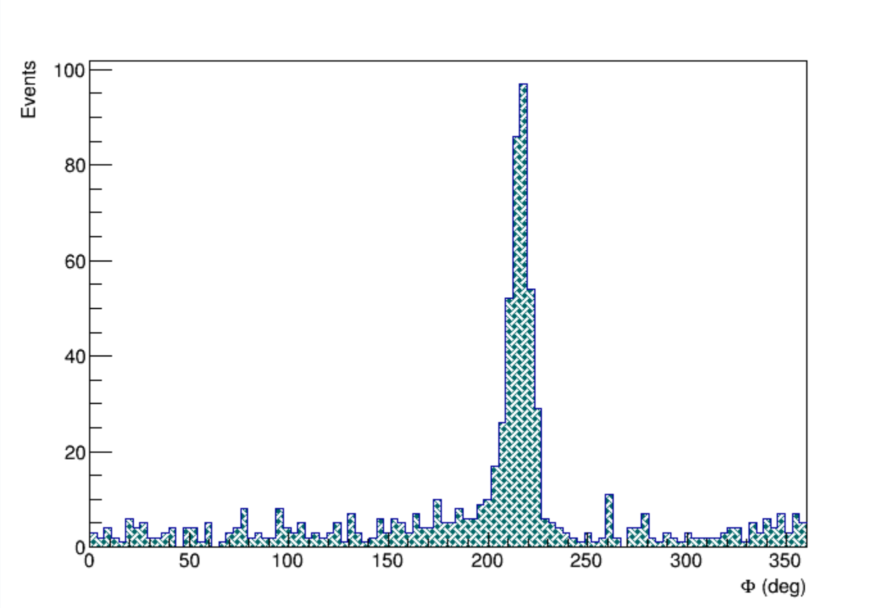




x [cm]	< θ > ± Δ<θ>	< ϕ > ± Δ<ϕ>
0	31.03° ± 0.05°	216.43° ± 0.20°
+10	31.36° ± 0.08°	216.15° ± 0.29°

5 cm shift

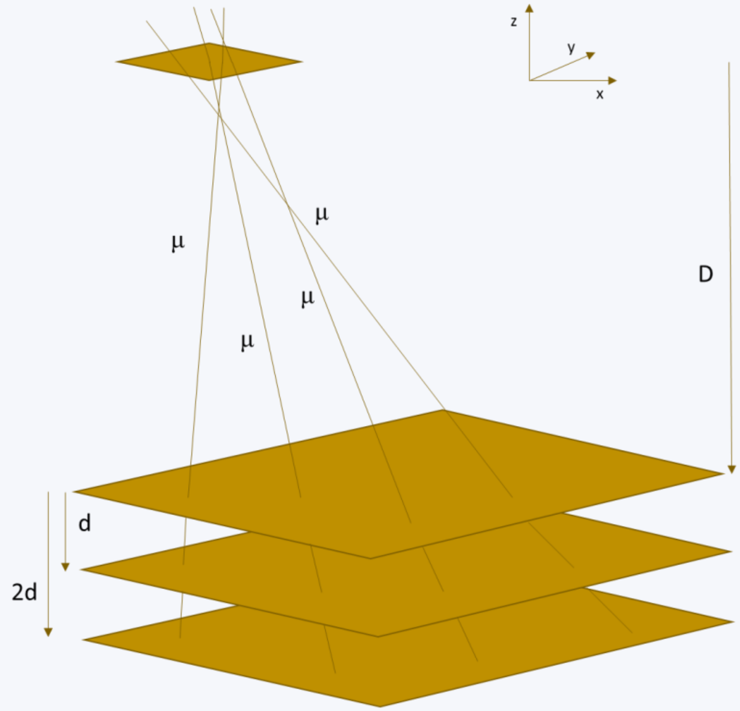


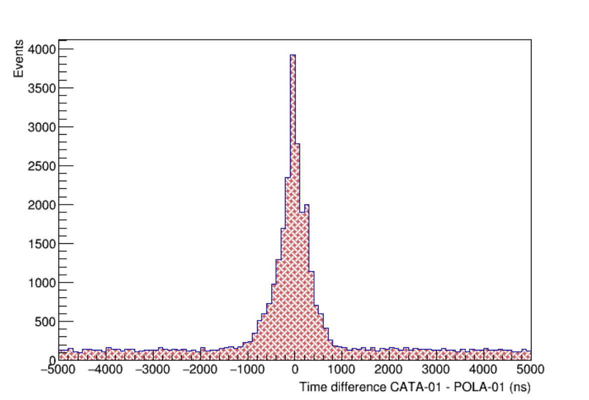


x [cm]	$< \theta > \pm \Delta<\theta>$	$< \phi > \pm \Delta<\phi>$
0	31.03° ± 0.05°	216.43° ± 0.20°
+5	31.18° ± 0.07°	215.88° ± 0.33°

Coincidence measurements

Coincidence window
$\lvert(\Delta t + (t\text{-}int(t)) \cdot 2500 - 1500) - 140\rvert < 600$ ns
Quality cuts
$\chi^2 < 10$
-2 ns < ToF < 10 ns
Number of satellites POLA-01 ≥ 3
Number of satellites CATA-01 ≥ 3
Number of tracks POLA-01 = 1
Number of tracks CATA-01 = 1



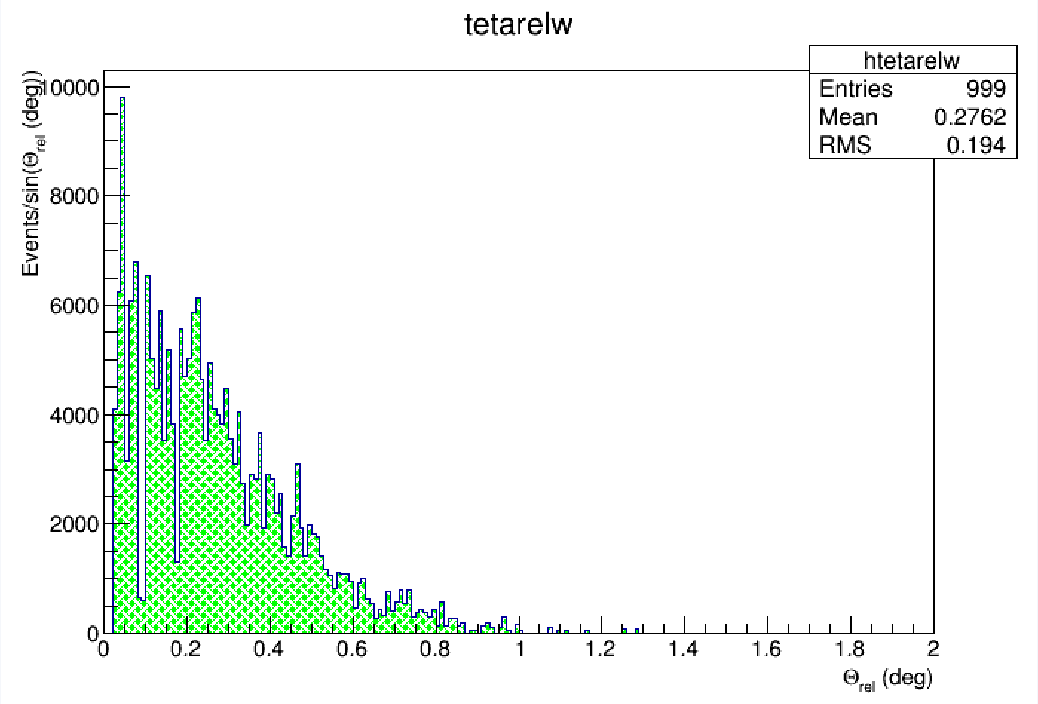


- →Two detectors working separately
- →Coincidence measurement selected using the GPS information in a 600 ns time interval

3D shifts error estimation

To estimate the ***uncertainty in the relative angle***:

- split the overall set of tracks in 2 subsets
- evaluate their average direction
- generate a large number of subsets
- distribution of these differences



3D shifts

Position (x,y)	3D θ	3D ϕ	3D error
(0 cm, 0 cm)	5.926	47.892	0.16
(0 cm, 5 cm)	5.638	49.564	0.13
(0 cm, 10 cm)	5.635	43.573	0.16
(20 cm, 20 cm)	3.901	52.422	0.13

GEANT3 Simulations

→Evaluation of multiple scattering effect due to the interposed material between the two detectors

→60 cm of concrete-equivalent solid for the 4 layers

→For *p* around 3-4 GeV/c → 0.1°-0.2° comparable to the observed uncertainty