Muon Tomography using Micromegas detectors

From Archeology to Nuclear Safety Applications

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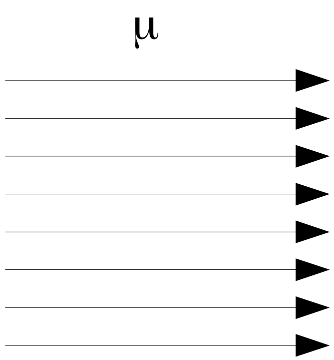
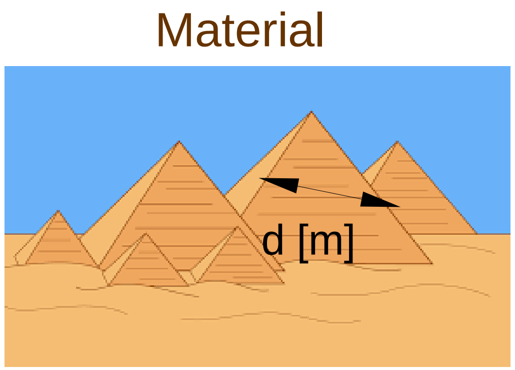
Outline:

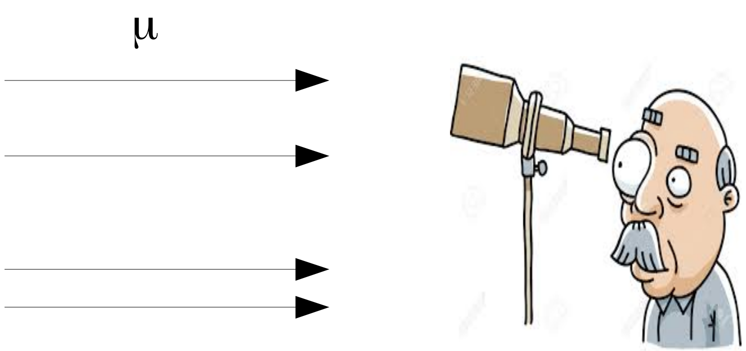
- Muon tomography: General aspects
- A Micromegas-based muon telescope
- Applications and results
- A muon tomography simulation tool
- What is next?

- Use of the ***atmospheric muons*** for the scanning of the ***internal structure of "big" objects*** (from few meters to hundreds of meters scale)

- Main methods: ***Transmission***







Initial flux ϕ_i

Dependant on the μ energy and incident angles (E, θ, φ)

Density: ρ [g/cm3]

Opacity: **δ [g/cm²]** = ρ d

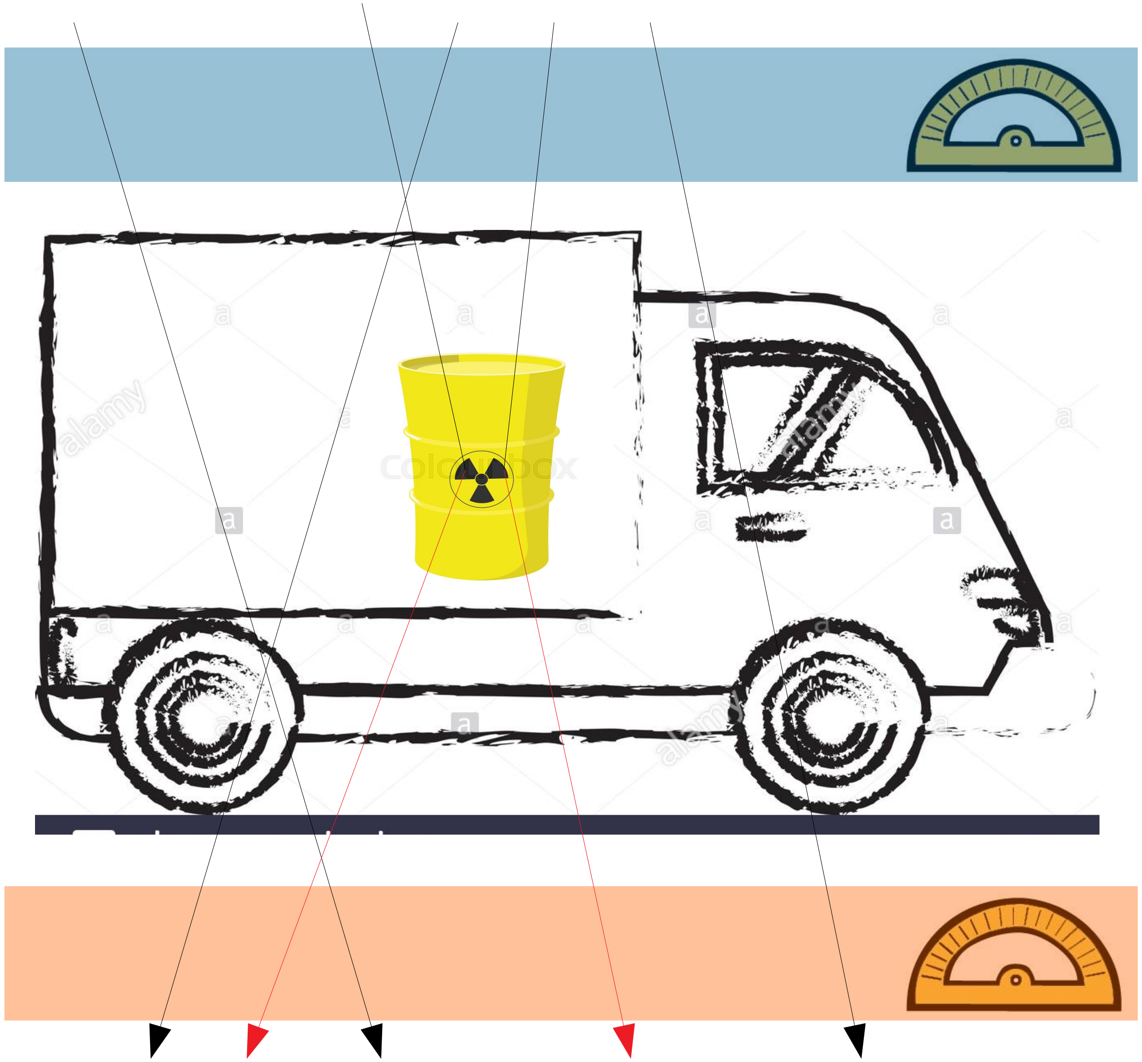
Final flux ϕ_f

Detected muons for a given direction

- Ratio between initial and final fluxes is directly related with Opacity
- Differences in final flux (after normalization) for different directions also points to Opacity differences
    - Precise knowledge of the atmospheric muons flux is advisable

- Use of the ***atmospheric muons*** for the scanning of the ***internal structure of "big" objects*** (from few meters to hundreds of meters scale)

- Main methods: ***Deviation***



- Muon trajectory deviation is related with the material density (Moliere Theory)

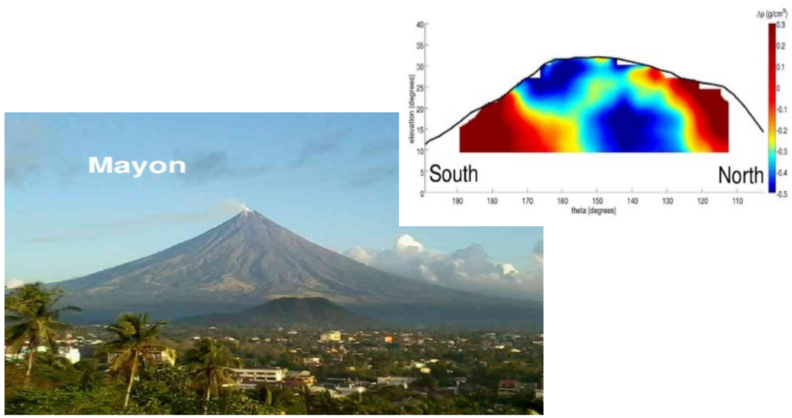
- Comparing ***initial vs final*** directions for each point of the studied object, a mean deviation angle can be obtained, then a density map.

✔ Faster

✔ For smaller objects with no big opacities

- Cheap, ***non-invasive***, ***versatile***, hazard-less imaging method.
- Specially interesting for ***big objects***

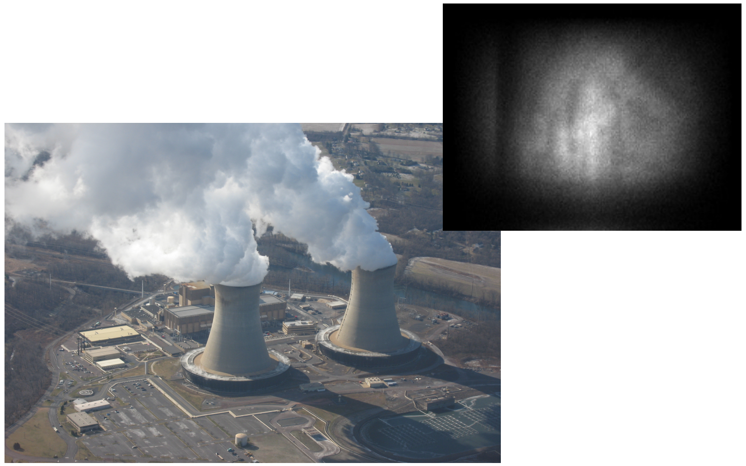
Deviation



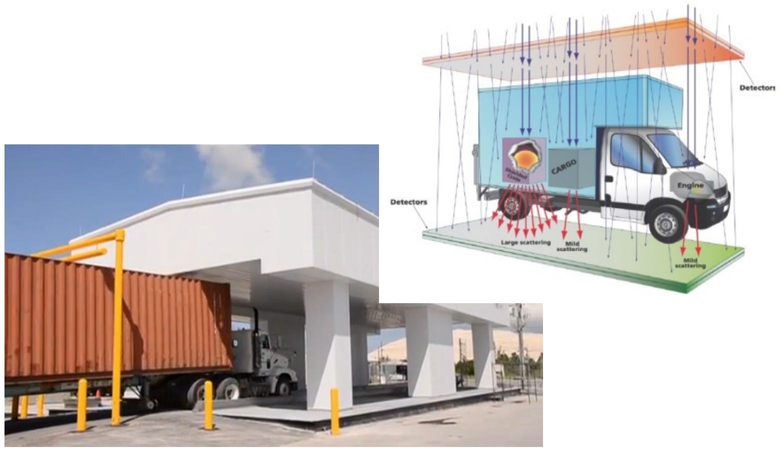
Volcanology

Archeology

Transmission



Nuclear control and safety



Homeland security

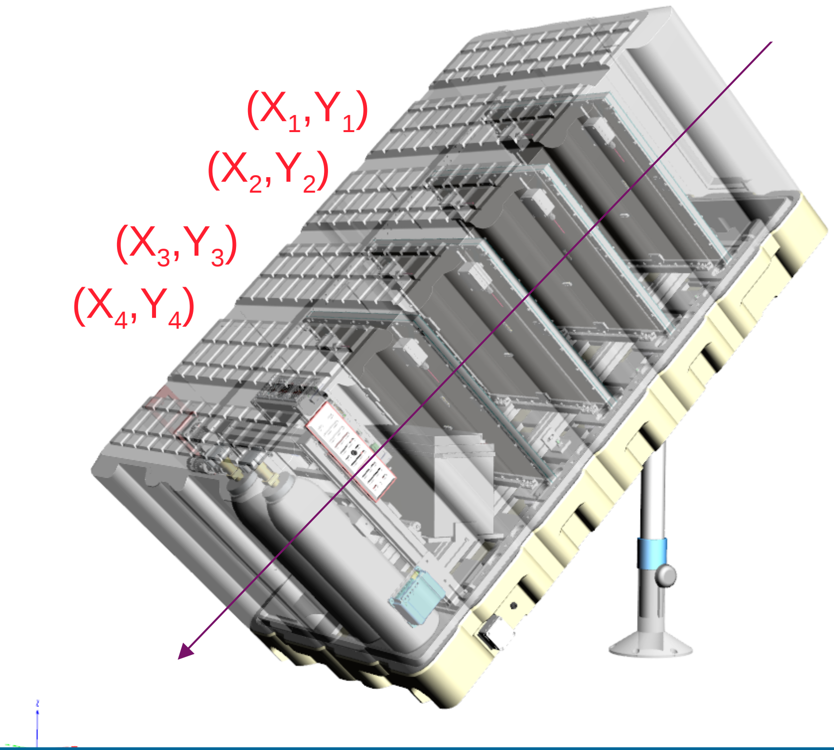
A Micromegas-based muon telescope

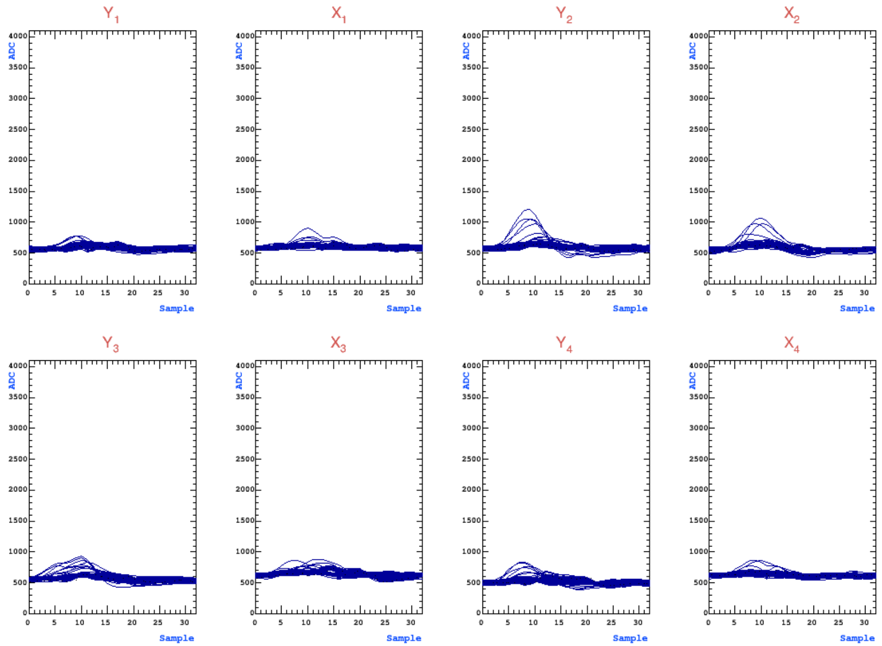
Muon tomography needs:

- Reconstruct muon track direction
- Continuously operates over ~months
- Operates @ studied object location
  - Outside
  - Varying environmental conditions

Muon telescope must be / have:

- Excellent angular resolution
- Performing and robust technology-based
- Portable
- Autonomous
- Protected from environment





Bulk Micromegas

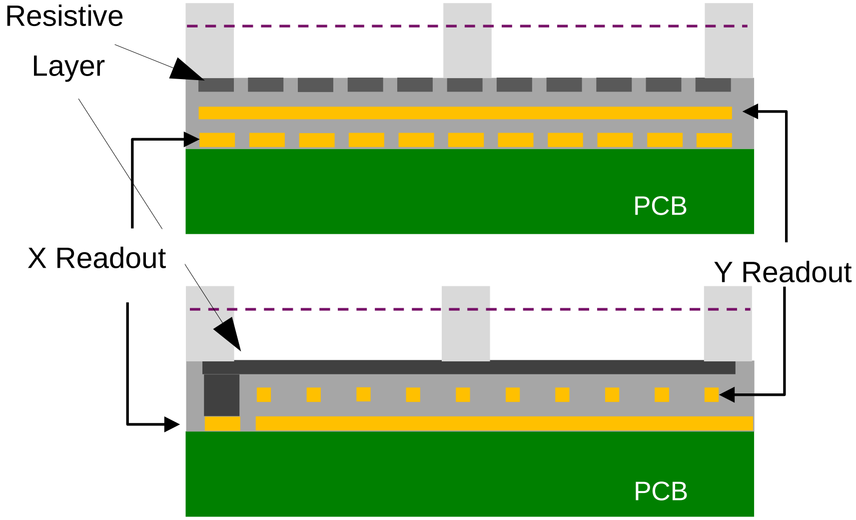
Robust, well-known

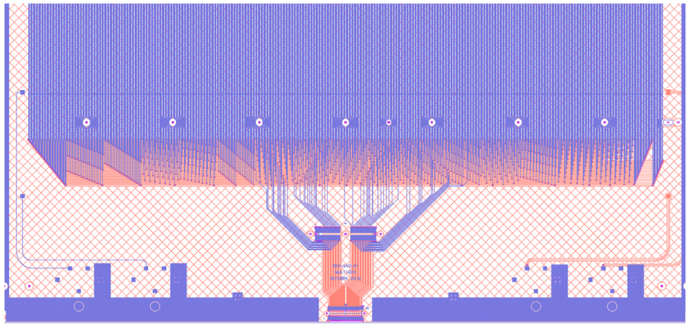
Big surface (50 x 50 cm^2)

Resolution:

~100 μm spatial

~10 mrad angular





Resistive Strips

Avoid sparks → Detector protection

Charge Diffusion → Better spatial resolution

→ Multiplexing possibility

Multiplexed Readout

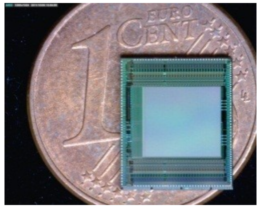
From 1037 to 61 channels both X and Y

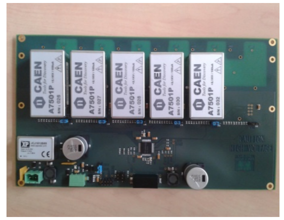
→ 1/34 lines reduction

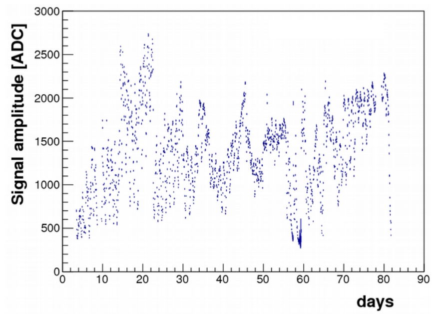
→ Simpler DAQ

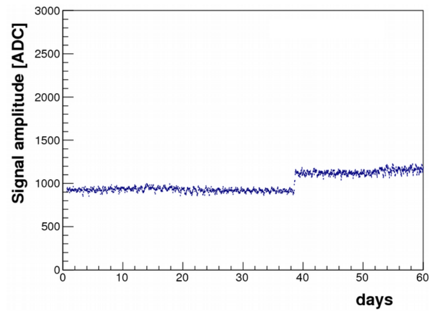
Autonomy / Portability

- Light materials: Aluminium structure, plastic case …
- Reduced size with low power consumption DAQ components
  - Miniaturized ASIC and HV modules
  - ~35 W power consumption (solar panels, batteries…)
- Auto-tunable gain → Stability
- Hummingbird nano-pc (as your smartphone) → Online analysis
- 3G/4G connection for remote control and data transfer

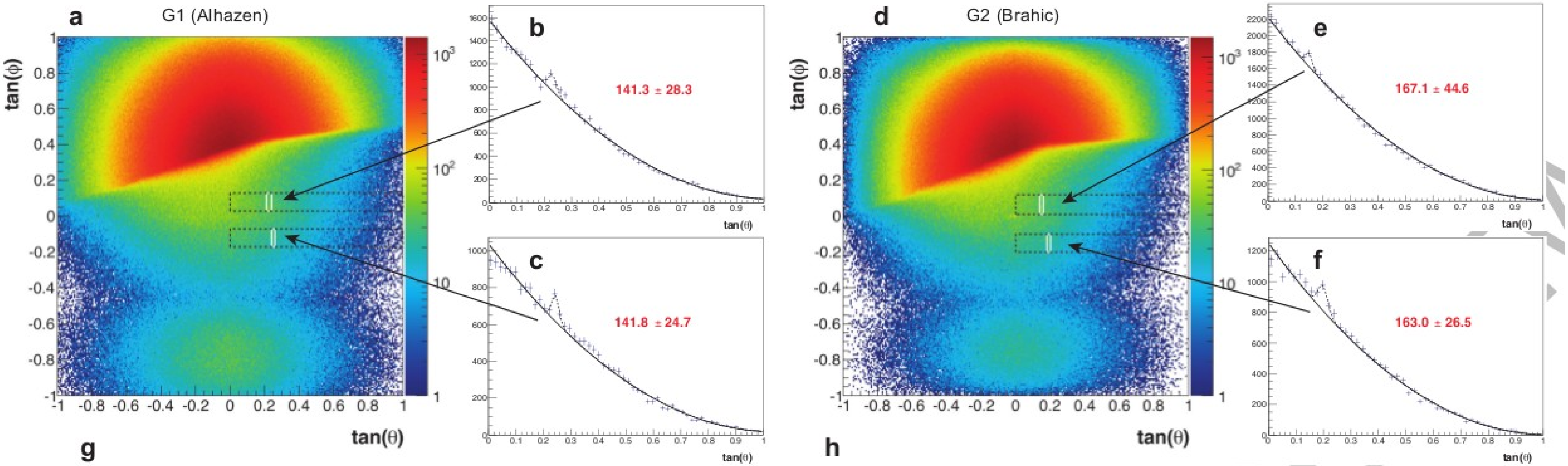






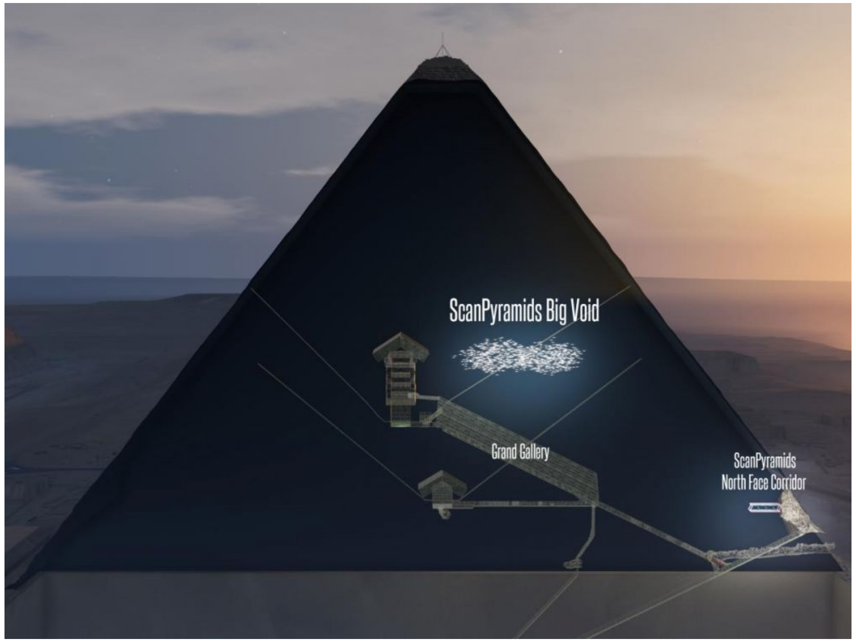


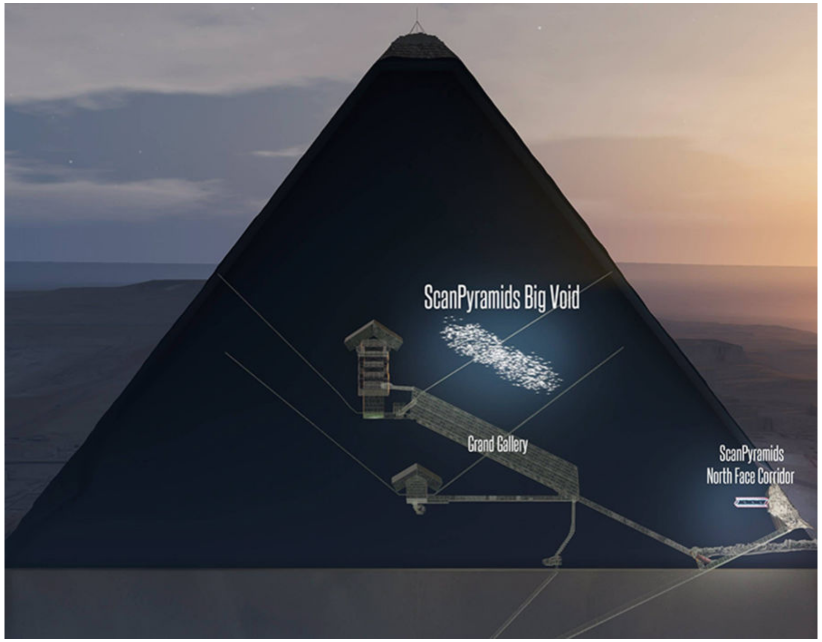
- Exploration of the ***Khufu (Kheops) pyramid***
- 2 Micromegas telescopes outside the pyramid
  - Different positions over 3 campaigns
- ~2 months of data for the last campaign
- Raw-data analysis dividing data in constant zenith angle “slices”
  - ***No data correction***: Muon flux, detector acceptance...



Full information (not only mMs results) @ Nature 552 (2017) 386 -390

- All three detector technologies (emulsion plates, plastic scintillators and Micromegas) revealed an anomaly at the same position
  - At least 30 m long and 21 m above ground level





- Some questions to clarify:
  - Horizontal or sloped?
  - One big void or a series of smaller chambers?

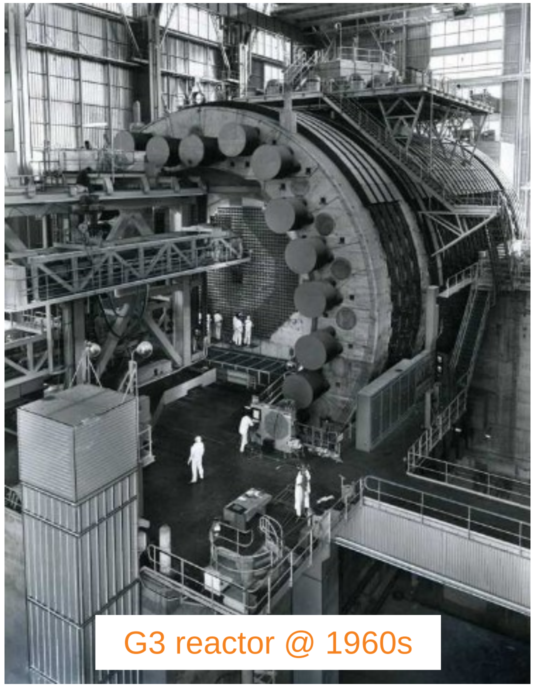
Further dedicated measurements planned

Full information (not only mMs results) @ Nature 552 (2017) 386 -390

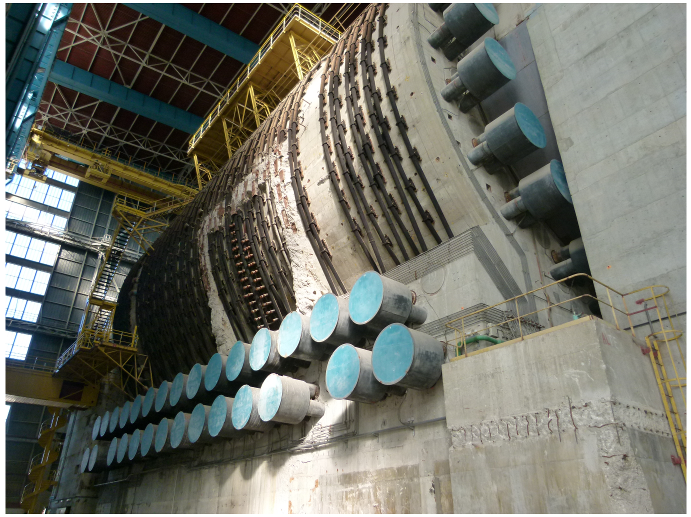
Main Goal:

- Surveillance of the G2 and G3 nuclear reactors, located at CEA – Marcoule (South France), by muon tomography to:
    - Cross-check the validity of the existing plans / designs (they date from the 60's)
    - Check the internal structure and ageing of the reactors → ***Reactor Body***
    - Look for possible damages (e.g. fissures) inside the concrete

G2 – G3 buildings @ CEA Marcoule



G3 reactor @ 1960s



G3 reactor @ 2018

Main Goal:

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First Phase:

- Feasibility study by Monte Carlo simulations of the muon tomography capabilities

Second Phase:

- On-site measurements

A muon tomography simulation tool

- ***Simulations*** represent a ***useful tool*** in muon tomography to:
  - Perform feasibility studies
  - Choose best detector position
  - Data analysis and interpretation
    - Better understanding of the detector behaviour

  Improve measurement sensitivity

- To achieve that, the simulation framework ***requires***:
  - The precise implementation of :
    - The studied geometry
    - The muon parametrization at Earth surface
  - Consider all the muon physics processes
  - Definition of the used detector features and performance

A muon tomography simulation tool

***G4TomoMu** (Geant4)*

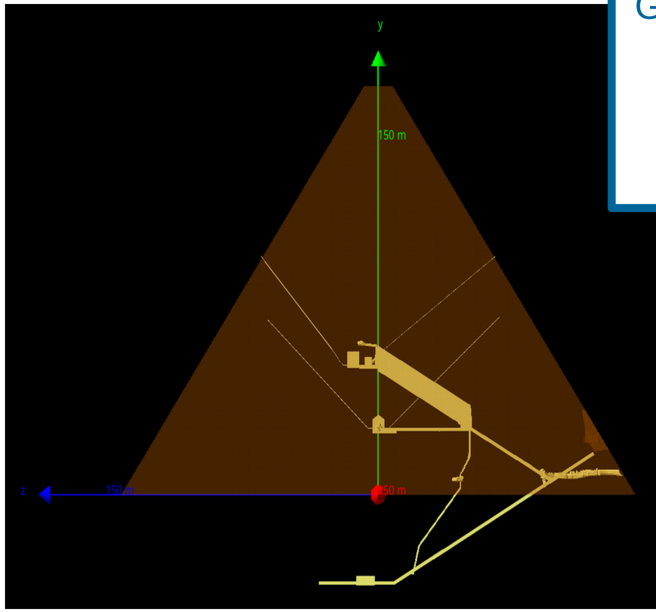
- Simulations of muons through the object
  - Muon parametrization
  - Object geometry (GDML)
  - Detector position (generic sphere)

***G4TomoDet** (Geant4)*

- Muon event generation @ detector
  - Detector main features
  - Other details (i.e. structure) not required

***TomoResp** (C++ / Root)*

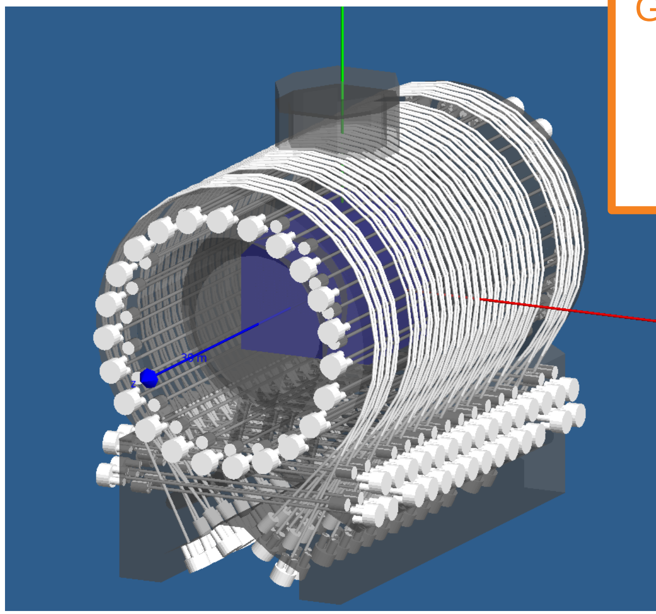
- Signal generation
  - Type / Properties of the gas (diffusion …)
  - Micromegas properties (resistivity, path ...)



GDML Model:

4 files

8.1 Mb



GDML Model:

22141 files

3.4 Gb

A muon tomography simulation tool

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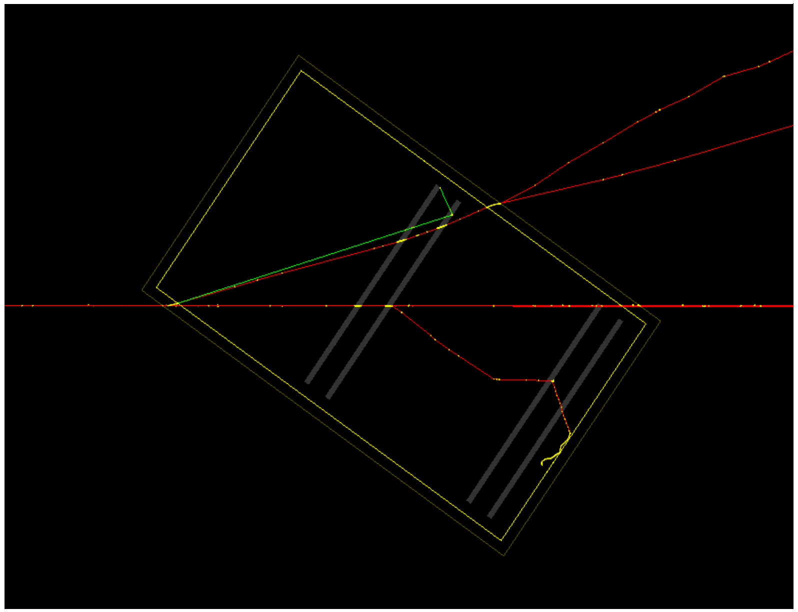

Any detector can be implemented

A muon tomography simulation tool

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  - Muon parametrization
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  - Detector position (generic sphere)

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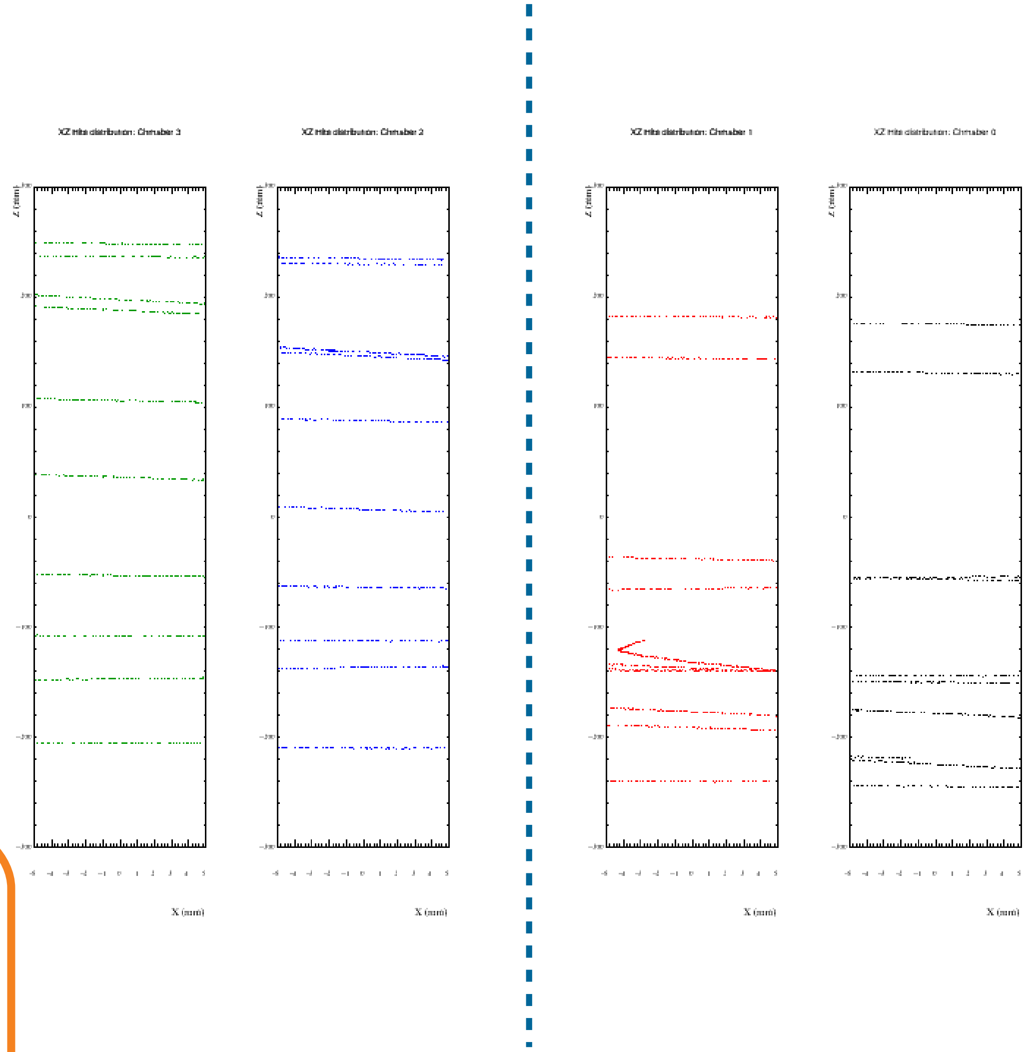
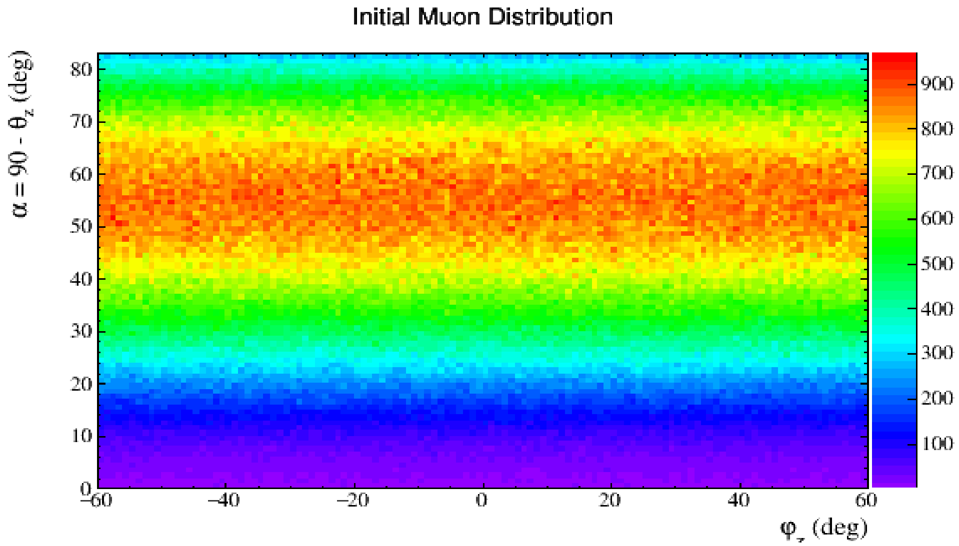
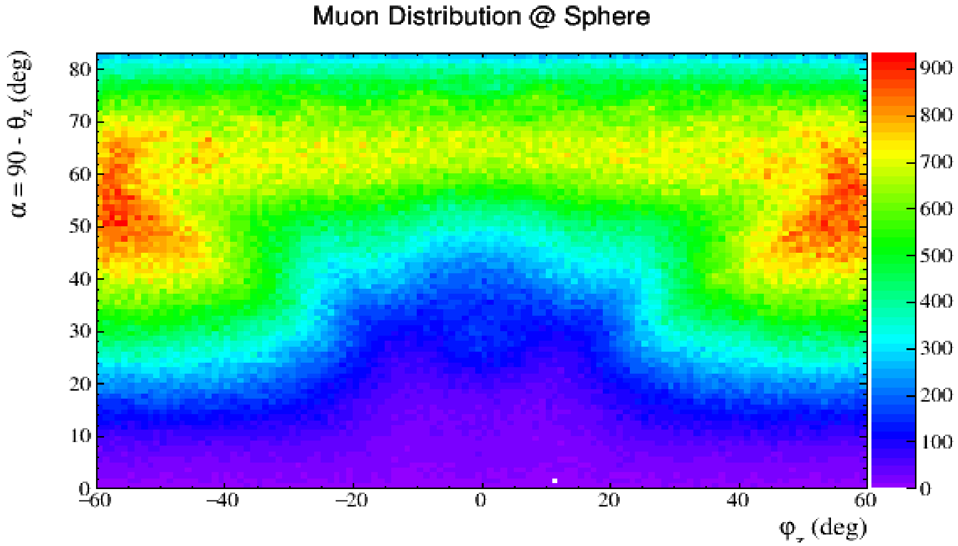
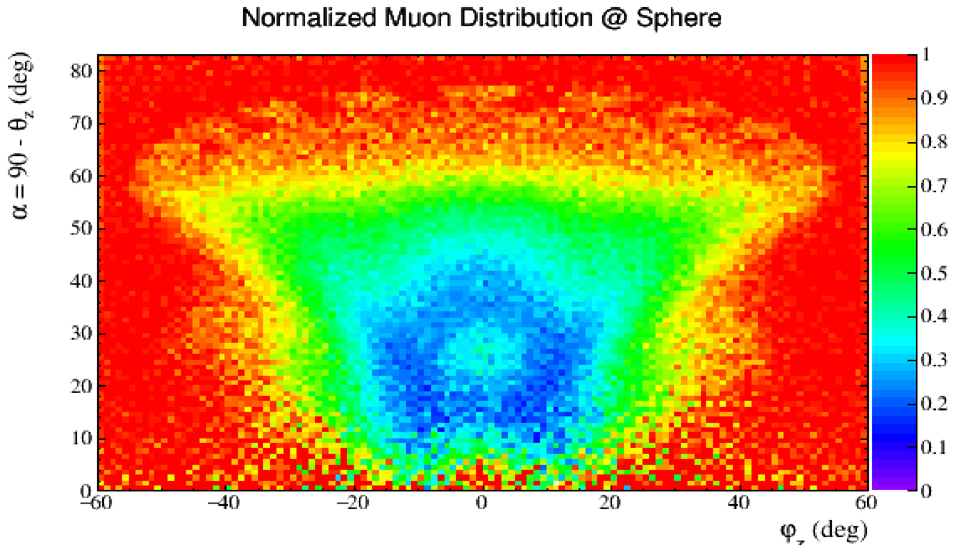
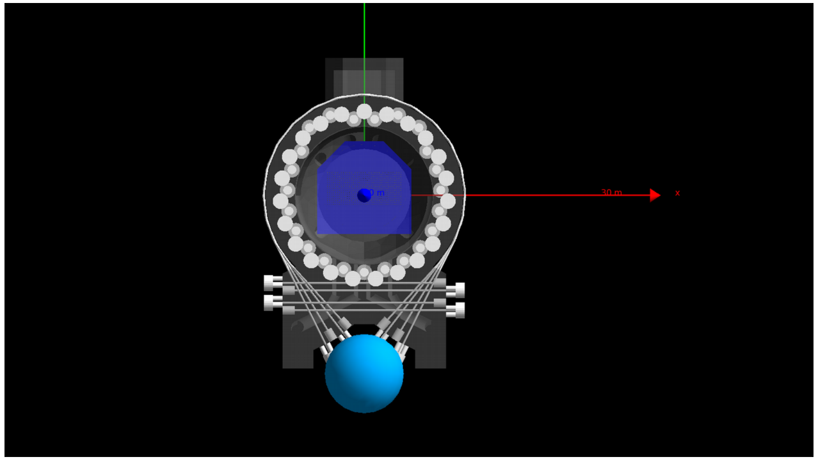




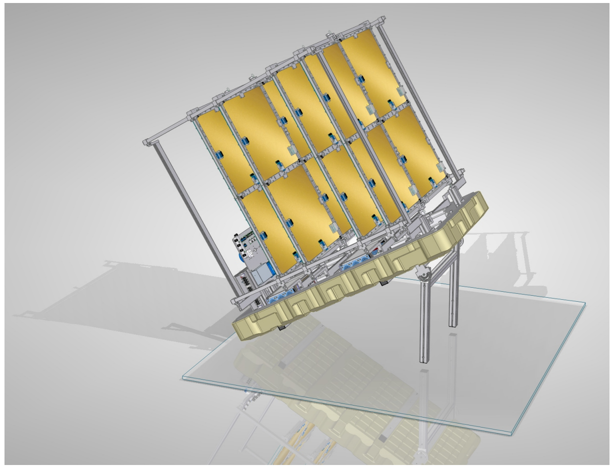


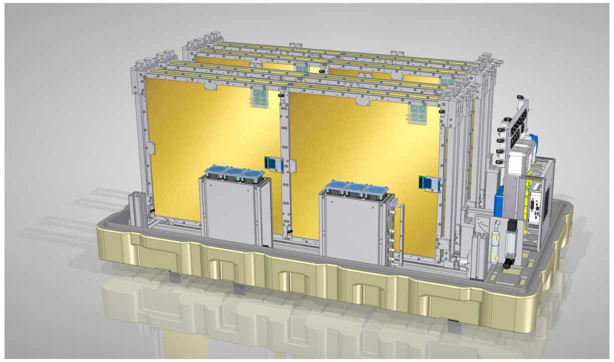


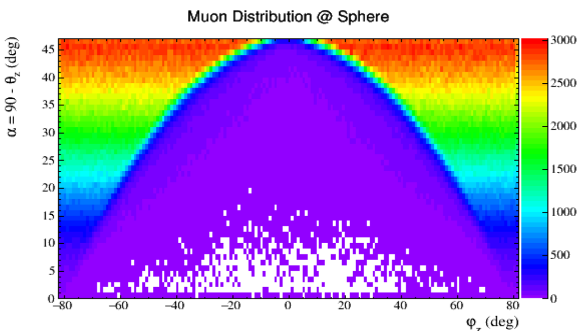


Other features to implement in the analysis: Object length traversed by muons, detector acceptance (rather @ G4TomoDet), ...

What is next?







- ***Detectors:***
  - Optimize resistive Micromegas construction and performance
  - Construct 1m^2 active surface telescopes:
    - Bigger aperture → Shorter measurements
- ***Simulations:***
  - Complete / Tune simulation framework (TomoResp → Signal generation)
- ***Projects:***
  - ***ScanPyramids:***
    - New measurement campaign (detectors inside the pyramid pointing to big void)
    - Simulations for data analysis
  - ***G2G3 Projects:***
    - Continue feasibility studies
  - ***Others:***
    - Explore other applications (civil engineering, boreholes...)

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D. Attie, S. Bouteille, D.Calvet, C. Filosa, B. Gallois, H. Gómez, M. Kebbiri,
P. Magnier, I. Mandjavidze, S. Procureur, M. Riallot

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