Muon Tomography with MPGDs

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

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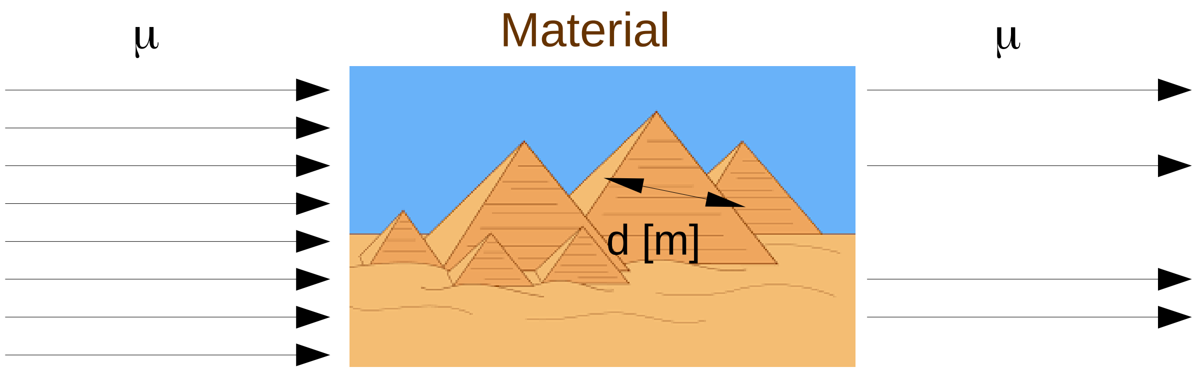
Outline

- Muon tomography:
  - → General aspects
  - → What do we need?
- A Micromegas-based muon telescope
  - → Autonomy, portability, stability …
- Some applications and results
- A muon tomography simulation tool
- What is next?
  - → TPCs for 3D muography
- Summary and conclusions

- 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 [g/cm³] x d [L]

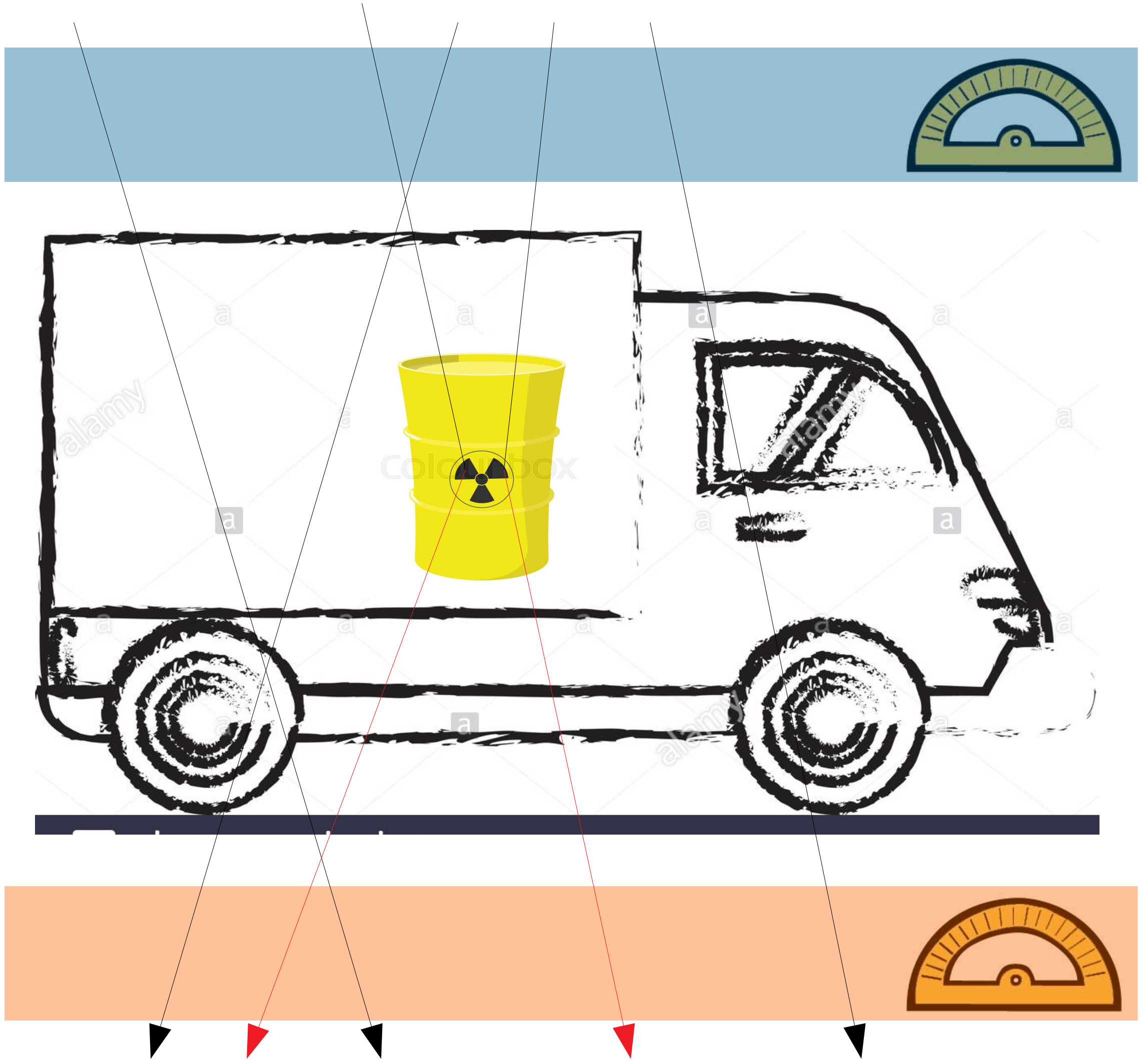
Final flux ϕ_f

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.

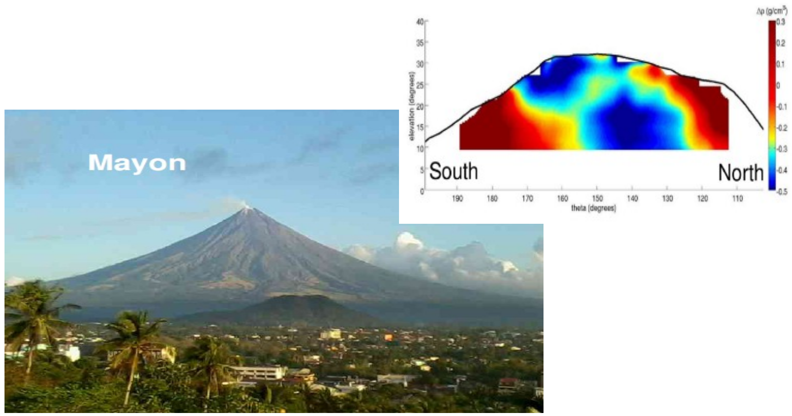
Mat.	Thickn.	δ (g/cm²)	θ (deg)	P_{abs}
Air	100 m	**0.123**	0.094	0.78 %
Water	1 m	**1**	0.35	2.9 %
Lead	10 cm	**113**	1.01	4.2 %
Soil	100 m	**230**	-	99 %

✔ Faster

✔ For smaller objects with no big opacities

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

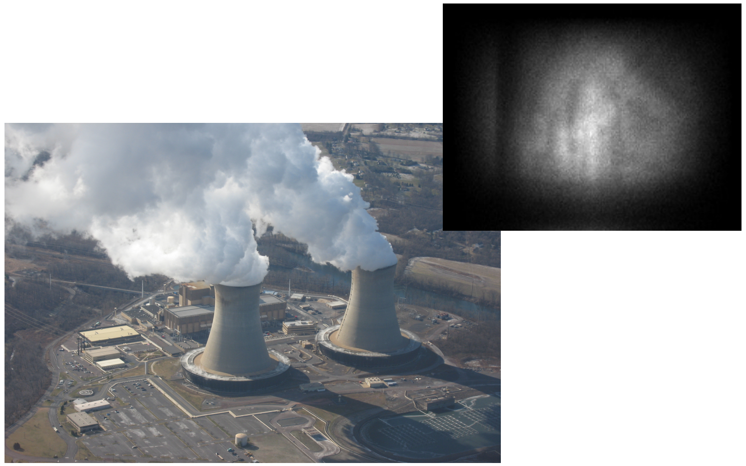
Deviation



Volcanology

Archeology

Transmission



Nuclear control and safety

Homeland security

What do we need?

Muon tomography requires:

- 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

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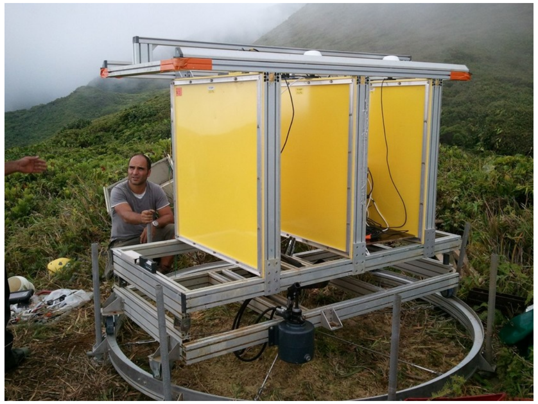
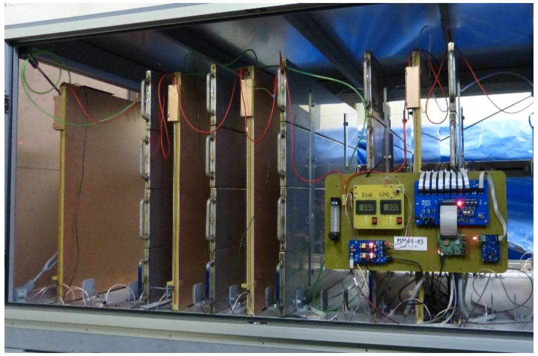
Emulsion Plates

Plastic scintillator

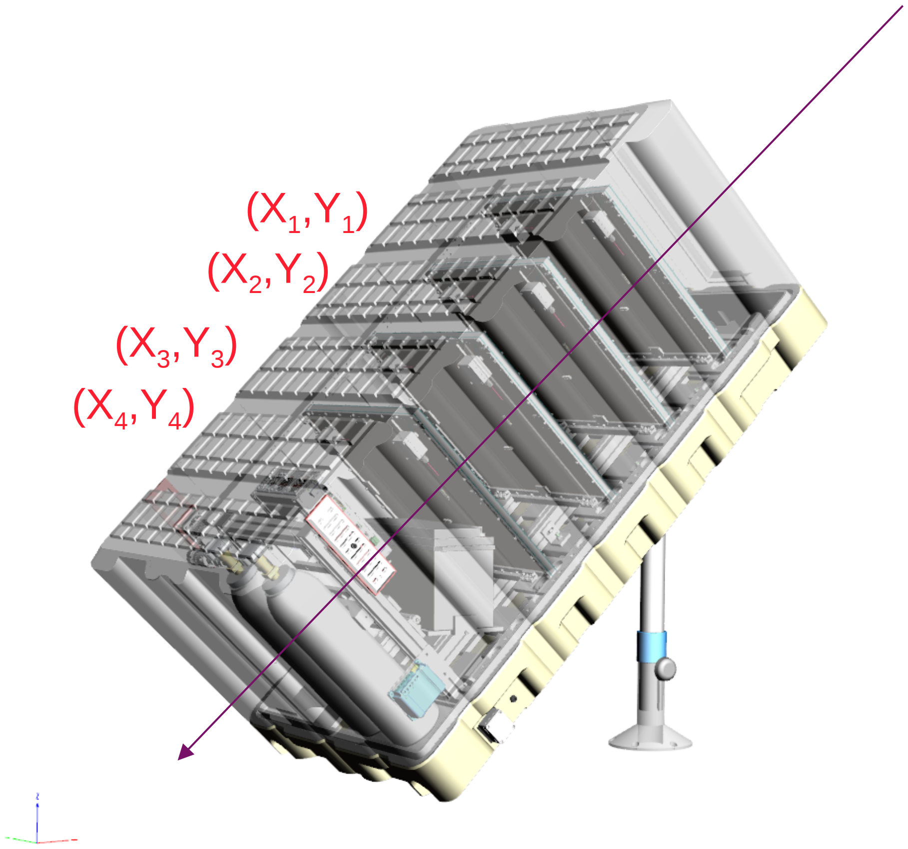


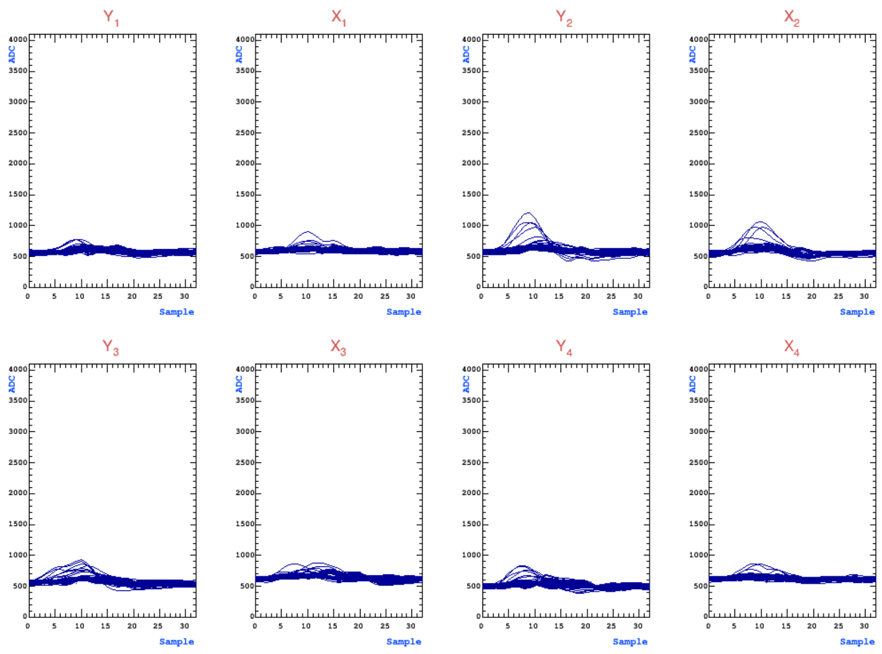
Micromegas

MWPC



A Micromegas-based muon telescope





Basic operation principle:

Micromegas distributed in parallel planes

When a muon crosses the planes, the (X, Y) interaction point is reconstructed

The set of interaction points returns the muon incident direction

A Micromegas-based muon telescope

Bulk Micromegas

Robust, well-known

Big surface (50 x 50 cm^2)

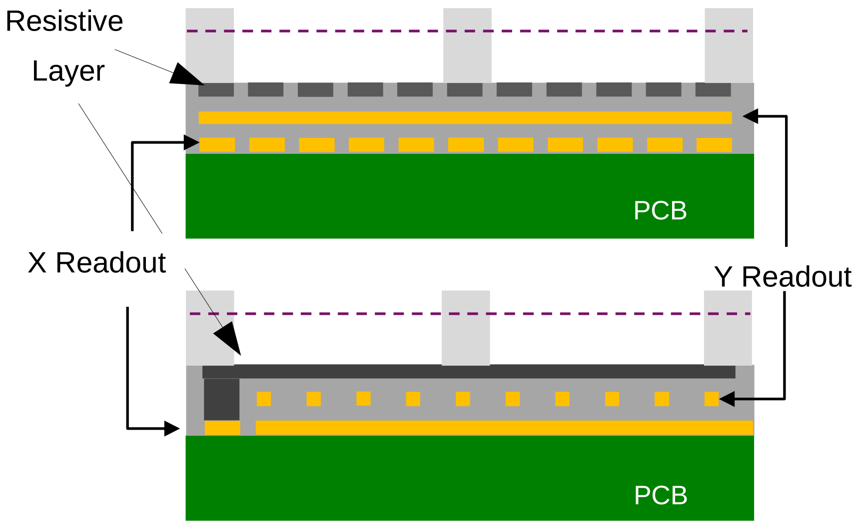
1037 strips (X and Y) → 482 μm pitch

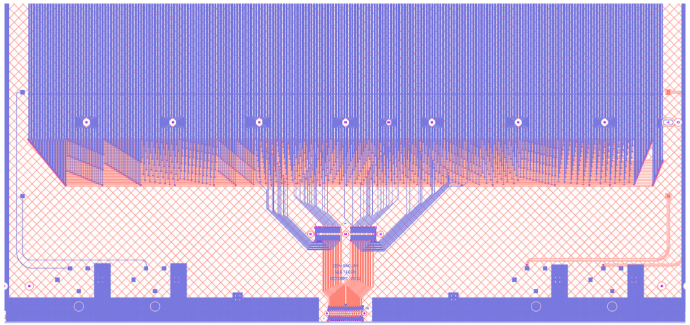
Resolution:

~100 μm spatial

~10 mrad angular

~10 ns temporal





Resistive Strips

Avoid sparks → Detector protection

Charge Diffusion → Better 2D spatial resolution

→ Multiplexing possibility

Multiplexed Readout

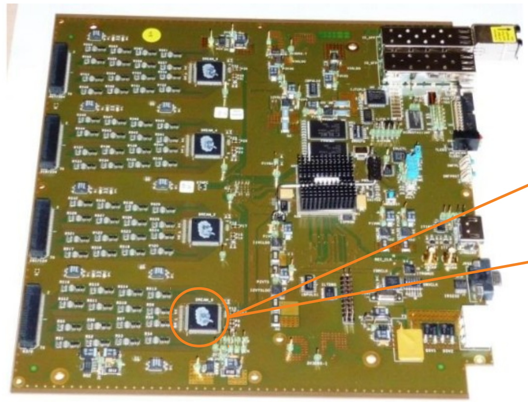
From 1037 to 61 channels both X and Y

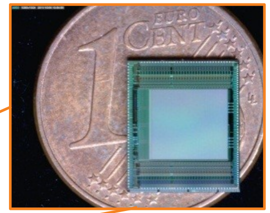
→ 1/34 lines reduction

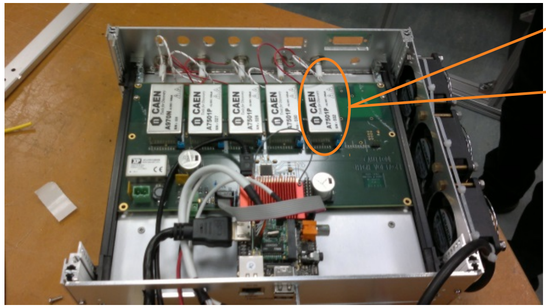
→ Simpler DAQ

A Micromegas-based muon telescope

- *Front-End Unit (FEU) cards*
  - Based on DREAM chip (IRFU)
  - 2 Chips per Micromegas
  - Possibility of self or external trigger
- *HV card*
  - Based on CAEN HV DC-DC Modules
  - Miniaturized @ IRFU
- *Hummingbird Nano-PC*
  - Accessible via 3G/4G
  - Modules control and monitoring, data transfer
  - Online Analysis







~35 W consumption @ 12 V DC together with all ancillary systems

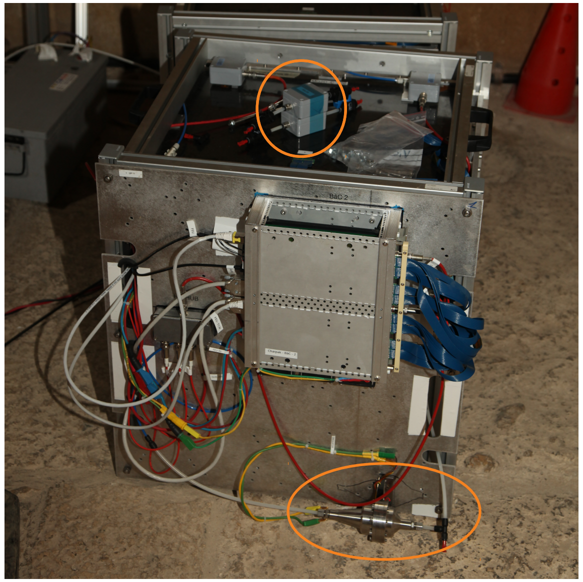
Possibility to supply by batteries or solar panels

A Micromegas-based muon telescope

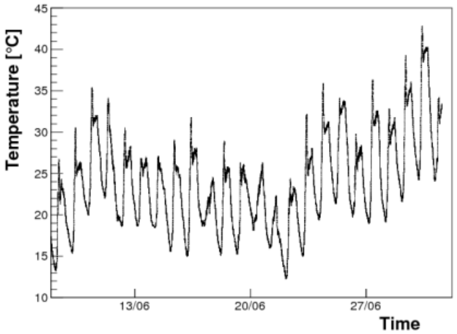
Autonomy / Portability



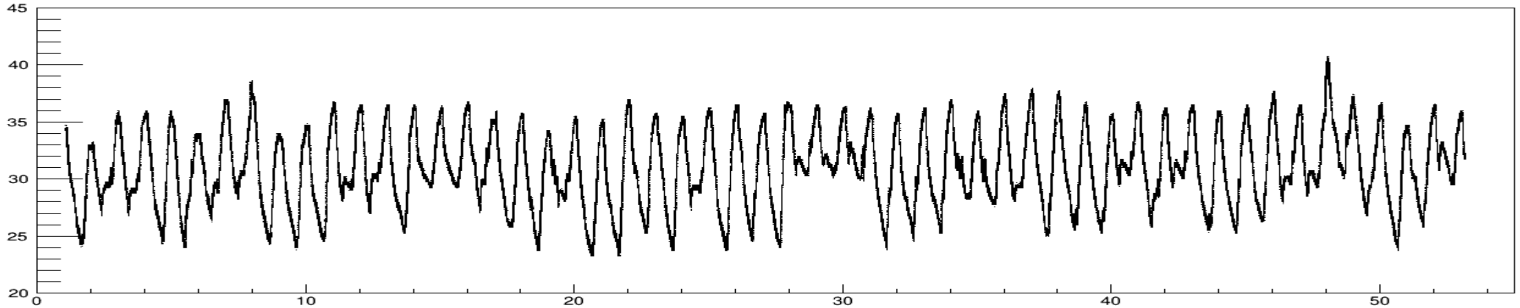
- *Materials*
  - Mostly light: Aluminium structure, plastic case...
  - Overall weight ~130 kg
- *Gas*
  - Ar – isoC_4H_{10} – CF_4 (95 – 2 – 3): No flammable → Safe
  - Recirculation system + filters → Low flux and gas consumption
  - Input/output flow-meters to monitor and control



- *Environment monitoring*
  - Yoctopuce® sensors:
    - Temperature, Pressure, Humidity
    - Also accelerometer/inclinometer → Movement / position

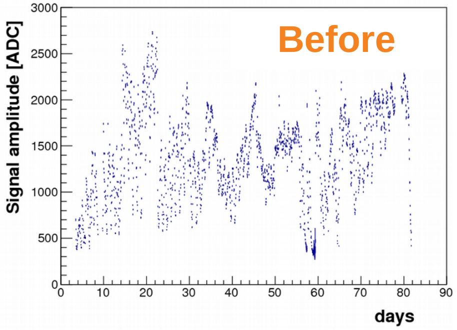


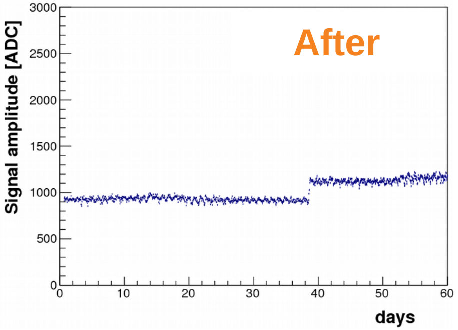
Saclay: T = 12 - 42^{o}C



Egypt: T = 23 - 44^{o}C

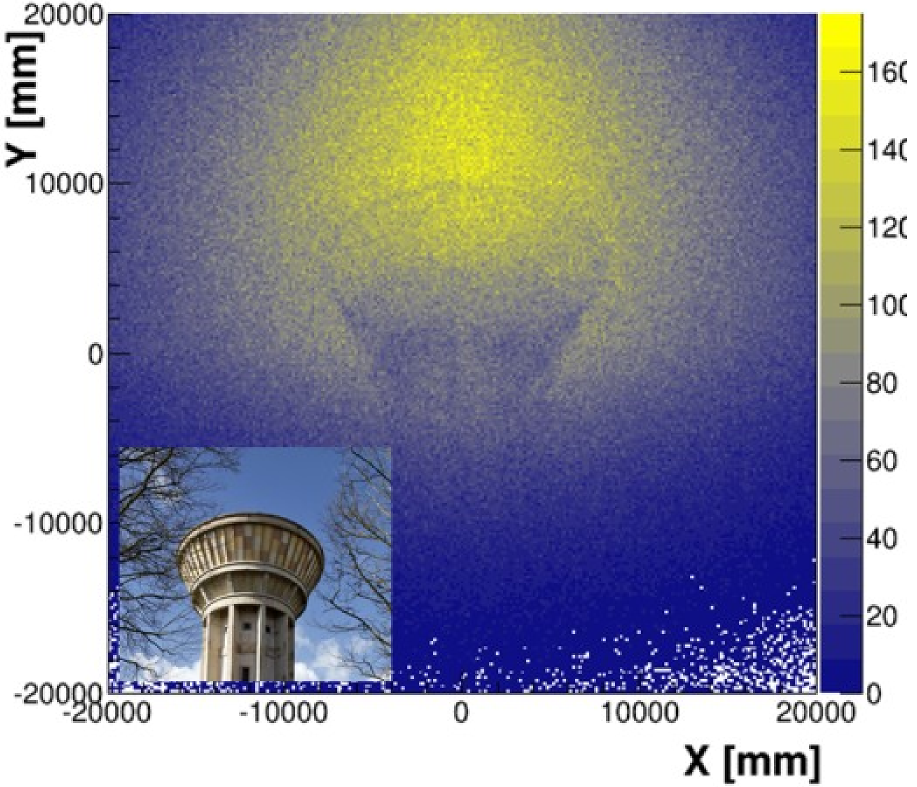
- *Stability system*
  - Micromegas HV tuned depending on Amplitude feedback
  - HV vs Amp based on calibration measurements

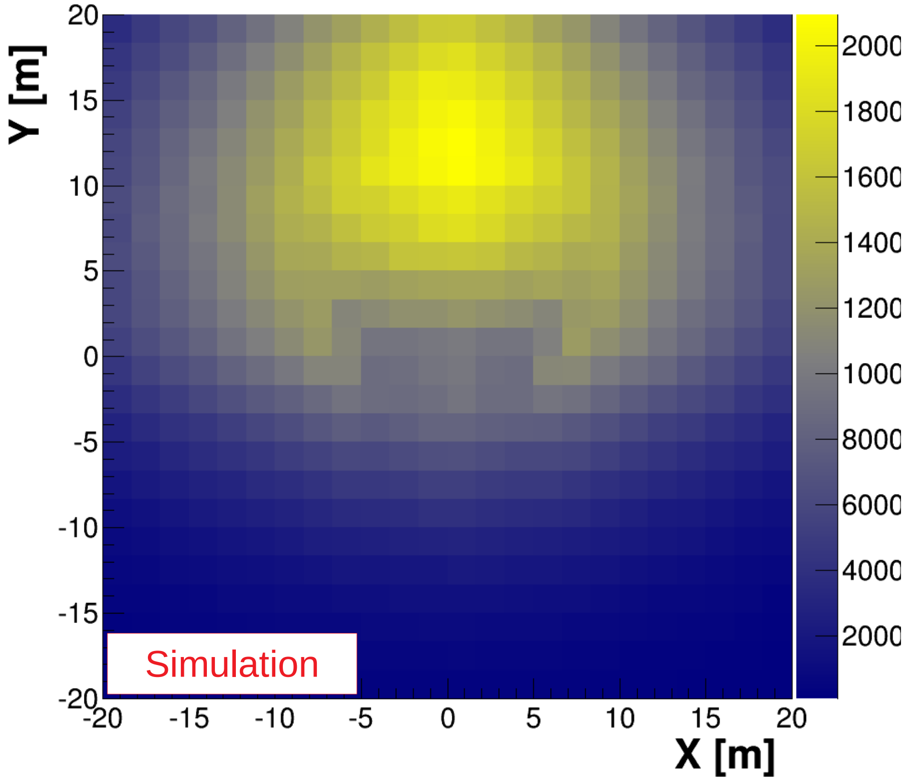




- Muography ***static*** photograph of ***Chateau d'eau*** (CEA-Saclay)

NIM A 834 (2016) 223 - 228





- ***Micromegas*** telescope
    - Raw experimental data:
        - 4 weeks; ~30^{o} elevation
    - No flux or acceptance corrected

- ***Plastic scintillator*** telescope
    - Same size / position as μMs one
    - Simulated data: 4 weeks

1st application: WatTo

- Muography ***dynamic survey*** of ***Chateau d'eau*** (CEA-Saclay)

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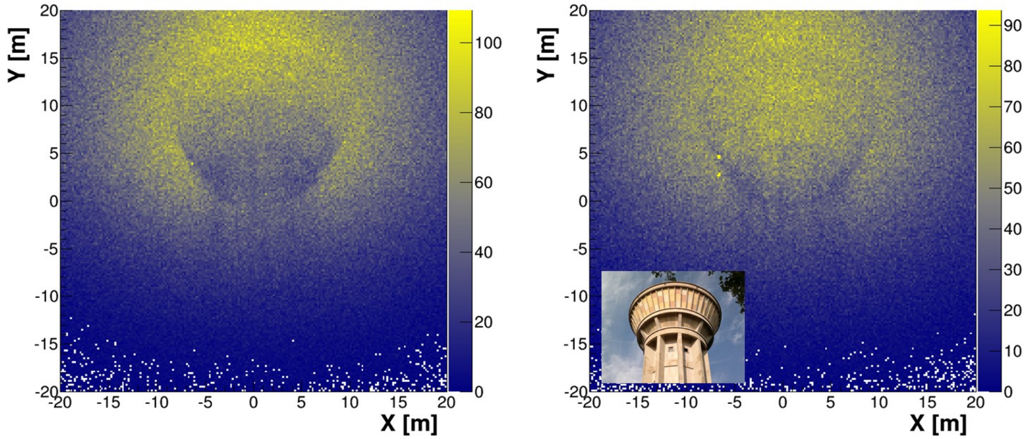
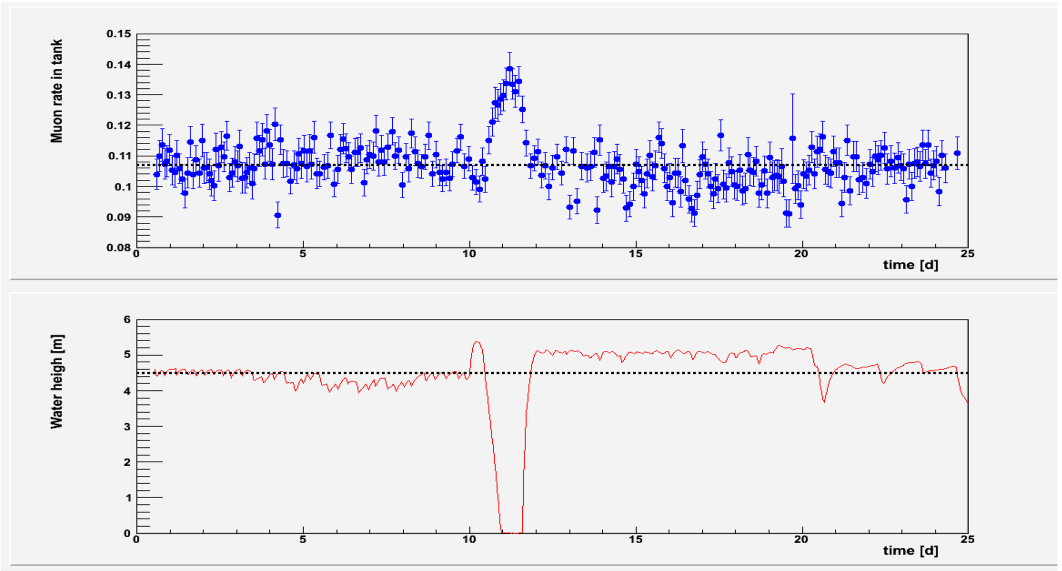
Water Filled | Water Empty



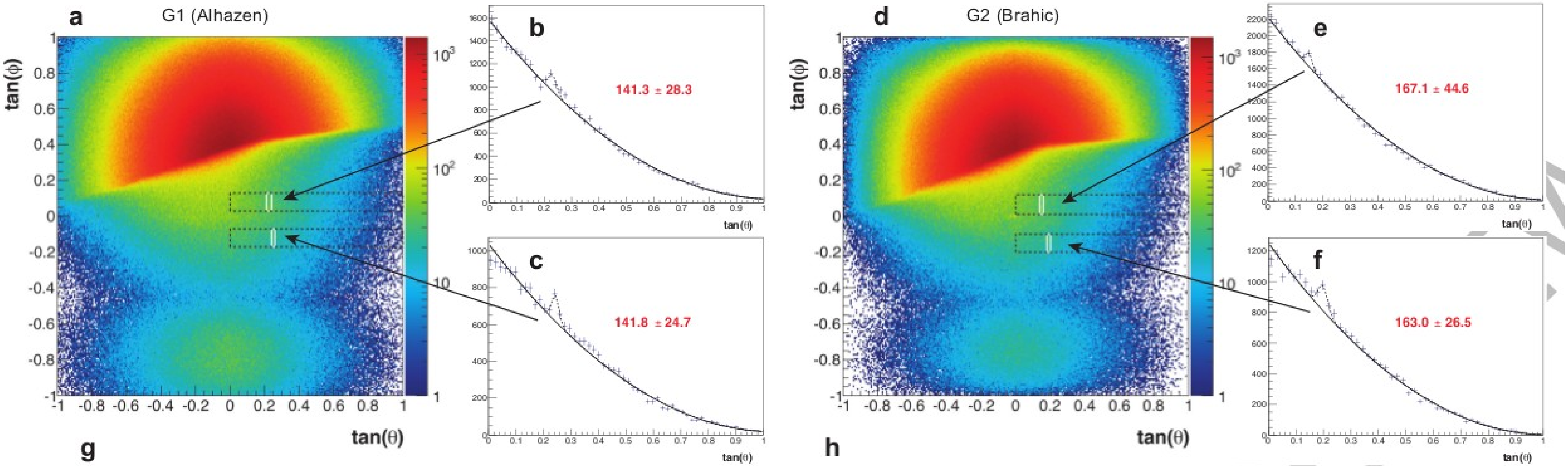
Muon flux @ water tank



Water level @ water tank

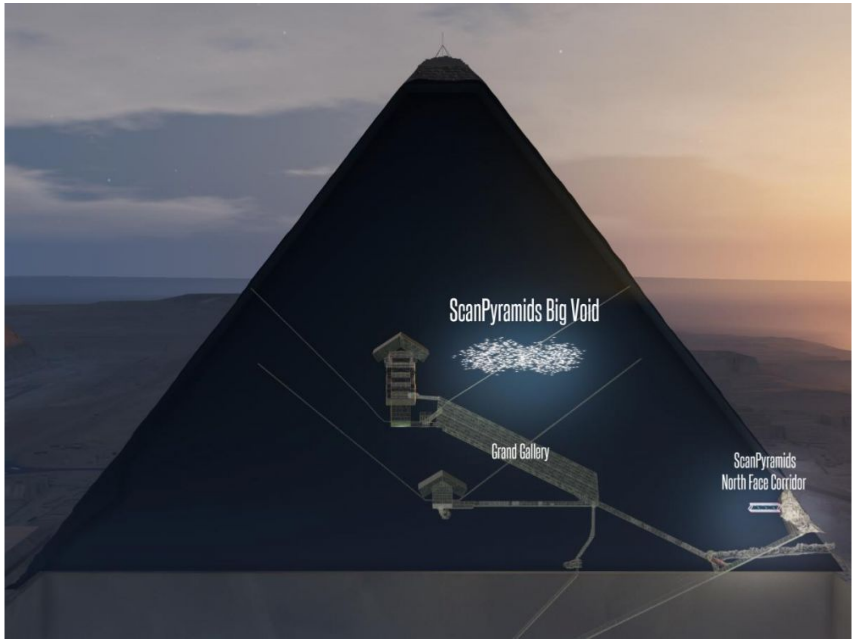
- ***Micromegas*** telescope
  - Raw experimental data:
    - 4 days each; ~45° elevation
  - No flux or acceptance corrected

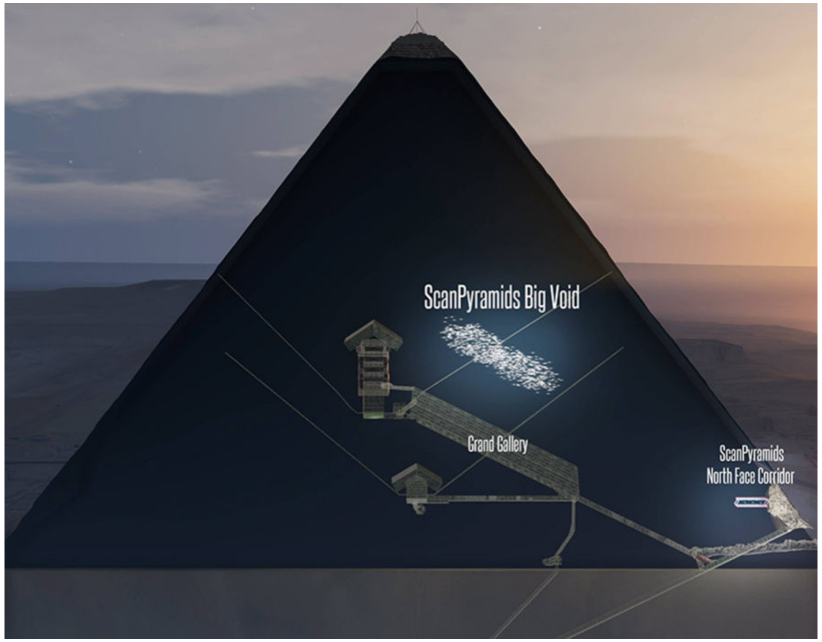
- Exploration of the ***Khufu (Kheops) pyramid***
- 2 Micromegas telescopes outside the pyramid
  - Different positions over 3 campaigns
- ~2 months of data for the last campaign
- Raw-data analysis dividing data in constant zenith angle "slices"
  - ***No data correction***: Muon flux, detector acceptance...



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
  - Above and along the Grand Gallery





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

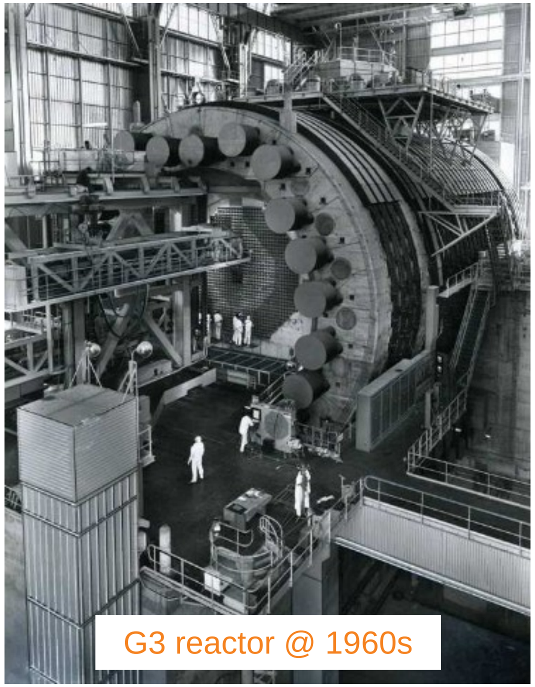
Further dedicated measurements (inside Pyramid) ongoing since July'18

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

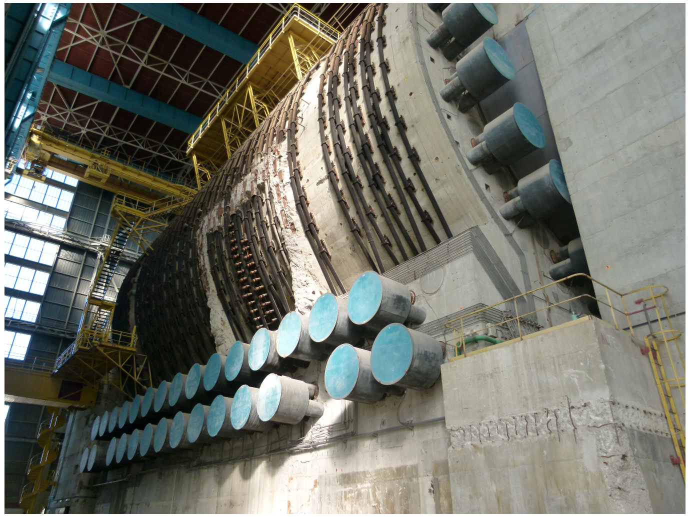
Main Goal:

- 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:

- 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

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)*

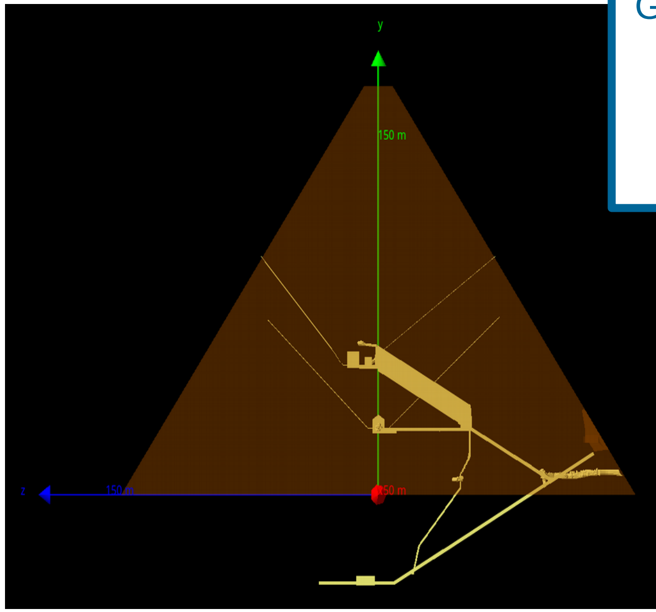
- Simulations of muons through the object
  - Muon parametrization
  - Object geometry (GDML)
  - Detector position (generic sphere)

G4TomoDet *(Geant4)*

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

TomoResp *(C++ / Root)*

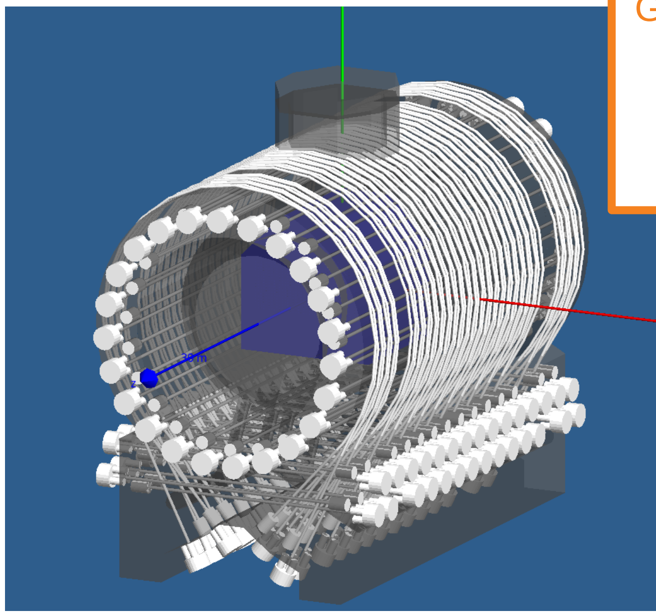
- Signal generation
  - Type / Properties of the gas (diffusion …)
  - Micromegas properties (resistivity, path ...)



GDML Model:

4 files

8.1 Mb



GDML Model:

22141 files

3.4 Gb

A muon tomography simulation tool

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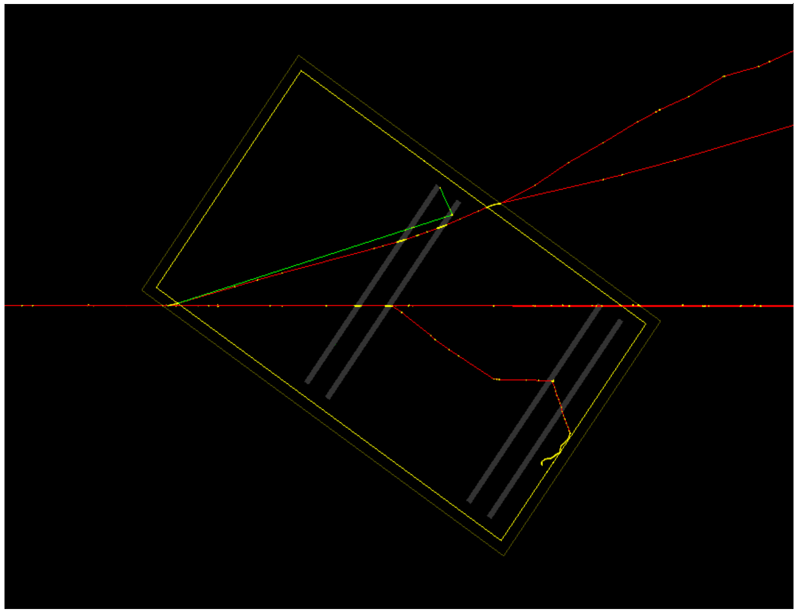

Any detector can be implemented

A muon tomography simulation tool

G4TomoMu *(Geant4)*

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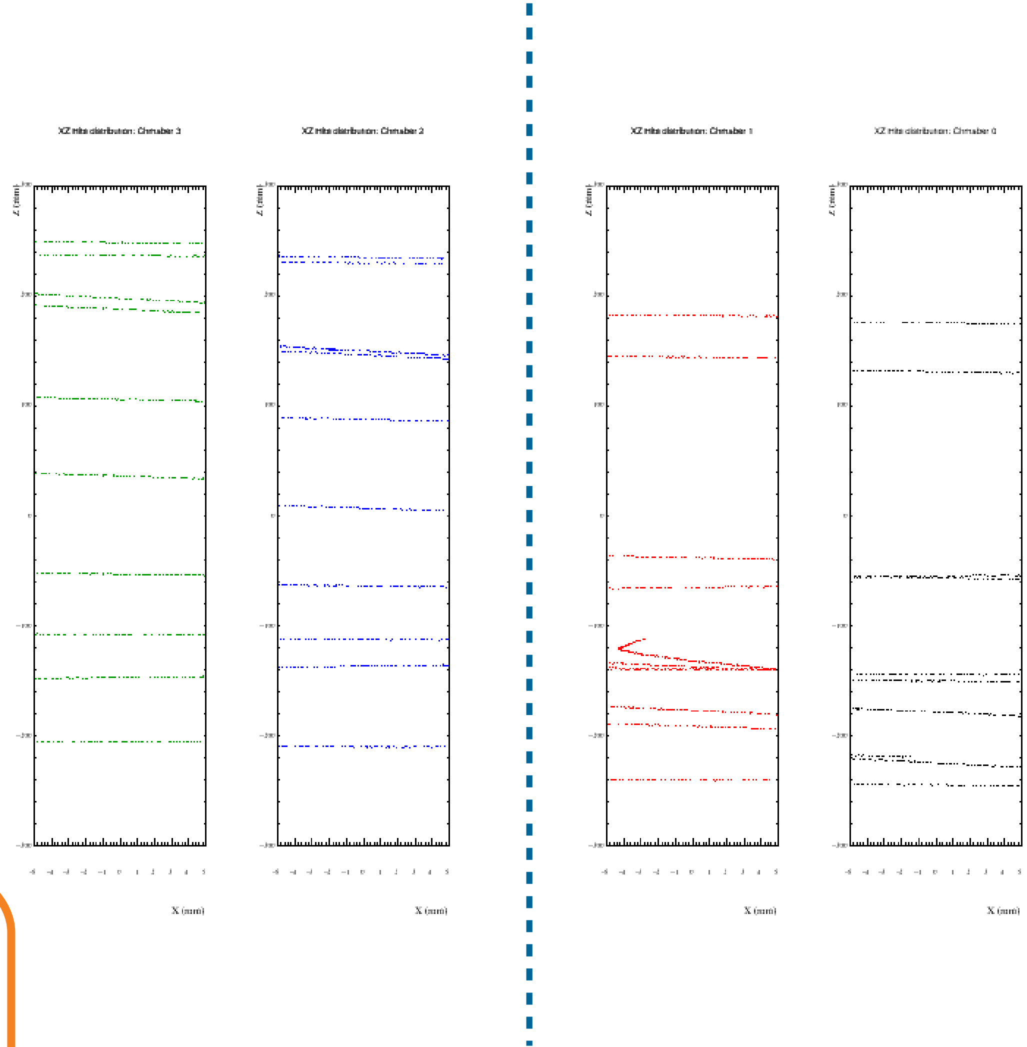
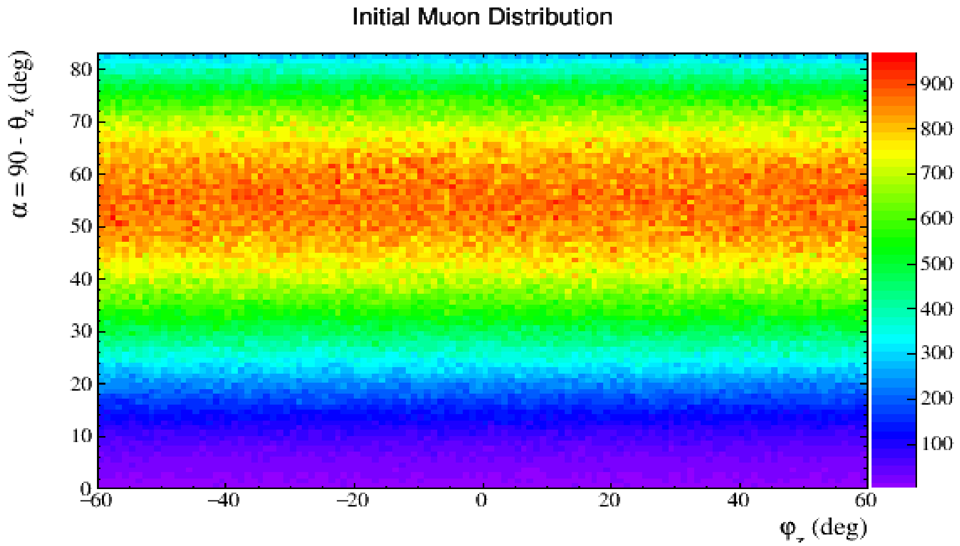
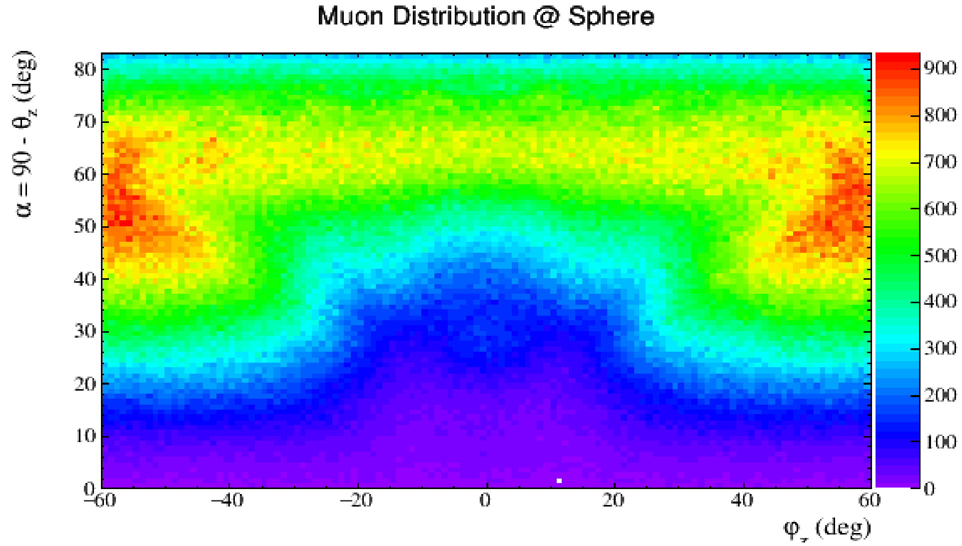


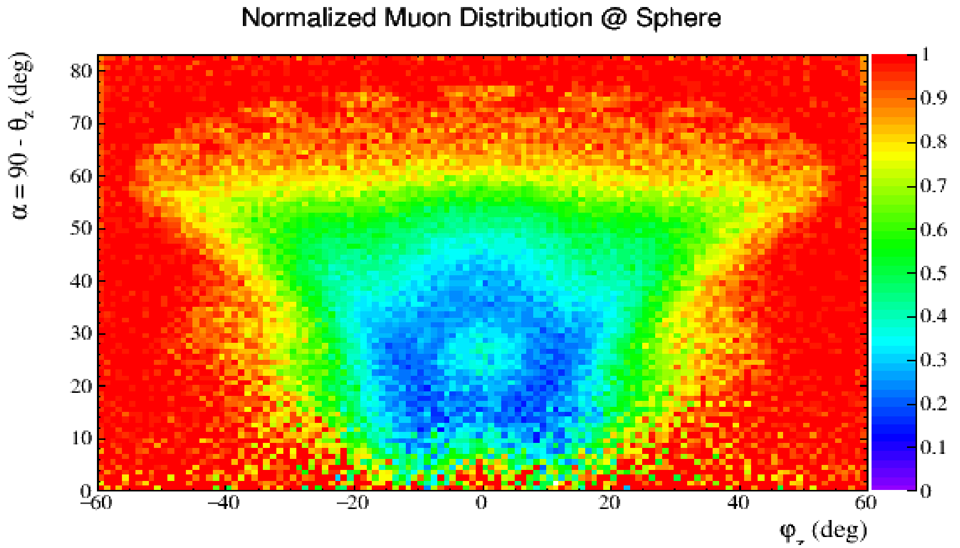
TomoResp *(C++ / Root)*

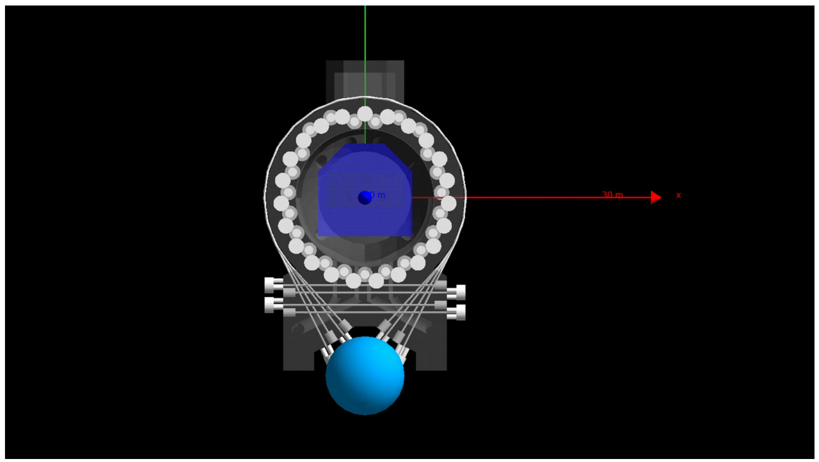
- Signal generation
  - Type / Properties of the gas (diffusion …)
  - Micromegas properties (resistivity, path ...)

Previous activities for MPGDs can be useful



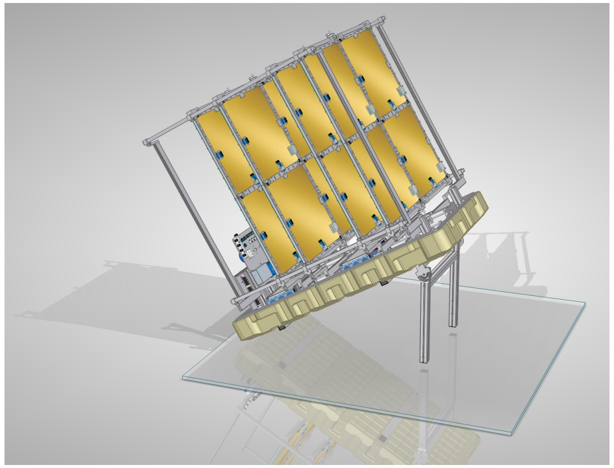


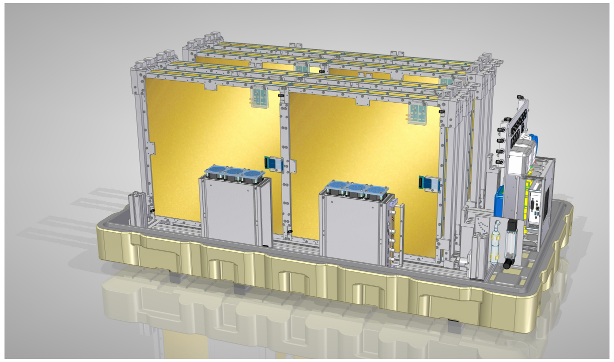


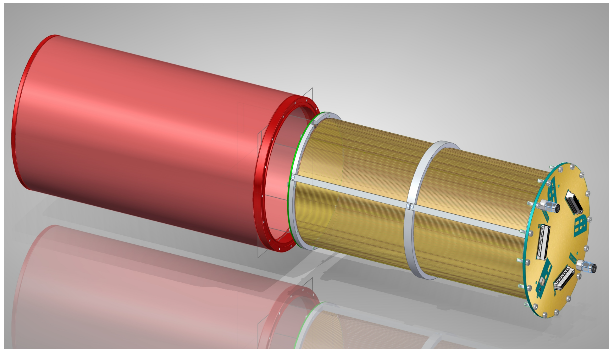


Other features to implement in the analysis: Object length traversed by muons, detector acceptance (rather @ G4TomoDet), ...

What is next?







- ***Detectors:***
    - Optimize resistive Micromegas construction and performance
    - Construct 1m^2 active surface telescopes:
        - Bigger aperture → Shorter measurements
    - Development of a Micromegas-read cylindrical TPC for muography

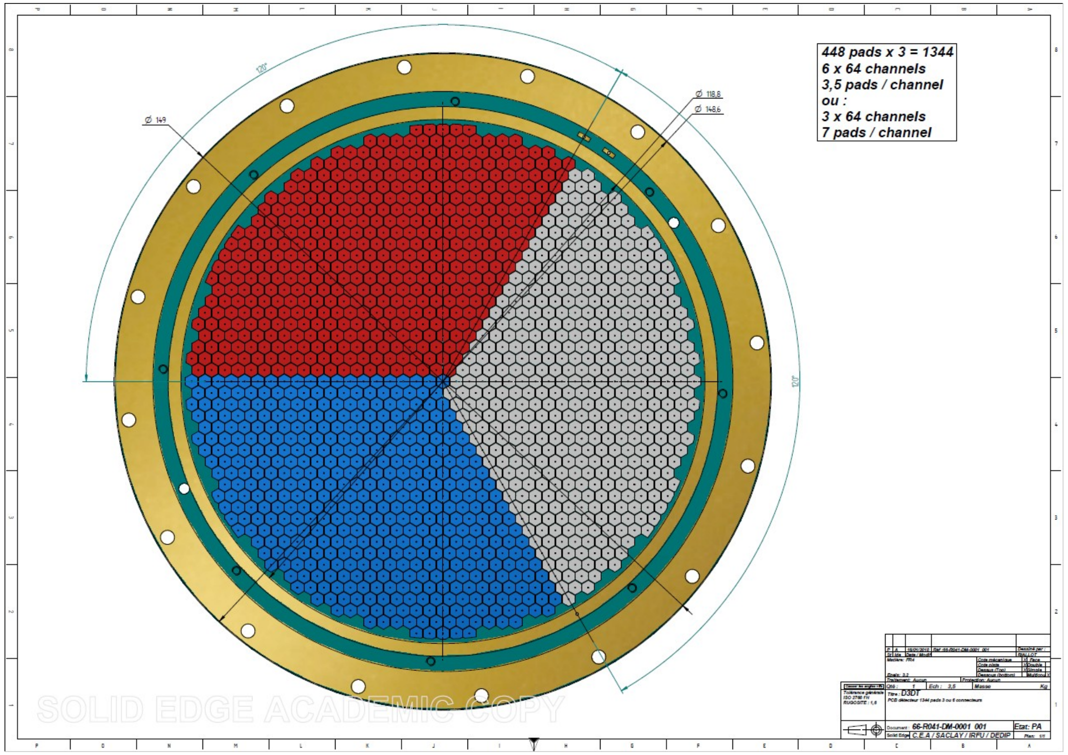
What is next? — *Cylindrical TPC*

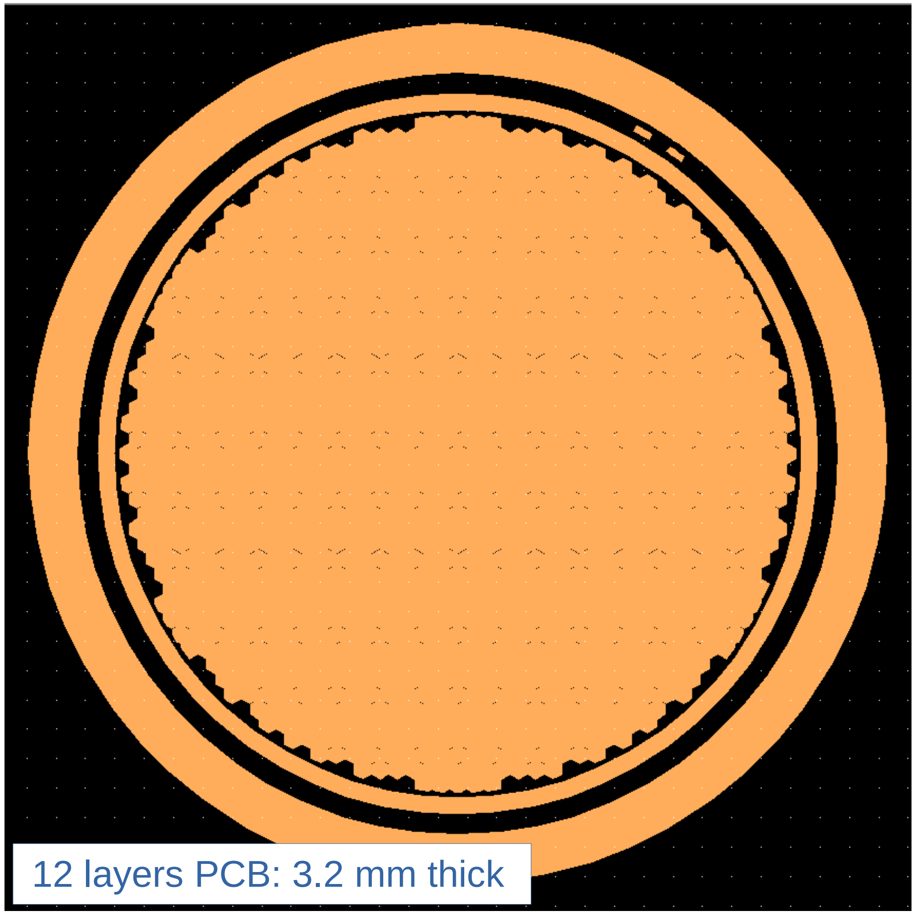
D3DT project: *(Détecteurs 3D pour la Tomographie)*

- Components:
  - Cylindrical TPC (50 cm long, 15 cm Ø)
  - Readout by circular Micromegas with 2D pads multiplexed → 1344 pads to 192 (3 x 64) lines

Measurement coverage
$\Omega = 2\pi$ with a single detector

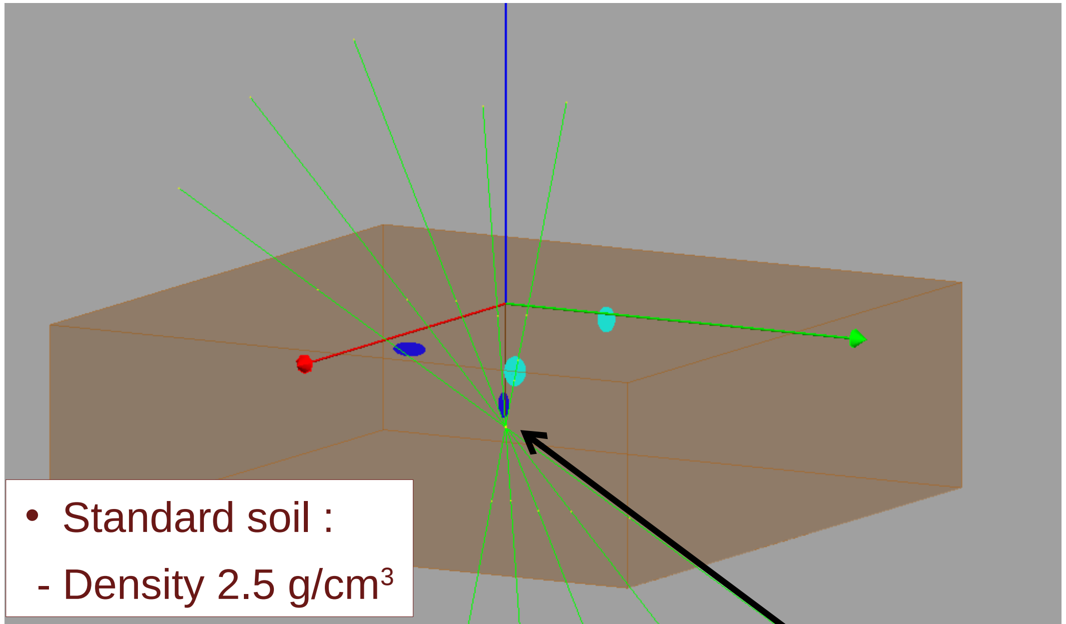
3D resolution with a detector network





D3DT project: *(Détecteurs 3D pour la Tomographie)*

- Preliminary simulations:
  - Rough demonstration of the potential with a single detector
  - More precise studies depending on the upcoming projects



- Standard soil :
  - Density 2.5 g/cm³

Comparison between simulations with (1) and without (2) cavities

$$Res = \frac{\frac{c_1}{t_1} - \frac{c_2}{t_2}}{\sqrt{\left(\frac{\sqrt{c_1}}{t_1}\right)^2 + \left(\frac{\sqrt{c_2}}{t_2}\right)^2}}$$

- Typical cavities :
  - 2 filled of water and 2 of air
  - Depth between 5 et 25 m
  - Volume between 18 et 92 m³

- Borehole :
  - Diameter : 30 cm
  - Depth : 30 m
  - TPC at bottom

D3DT project: *(Détecteurs 3D pour la Tomographie)*

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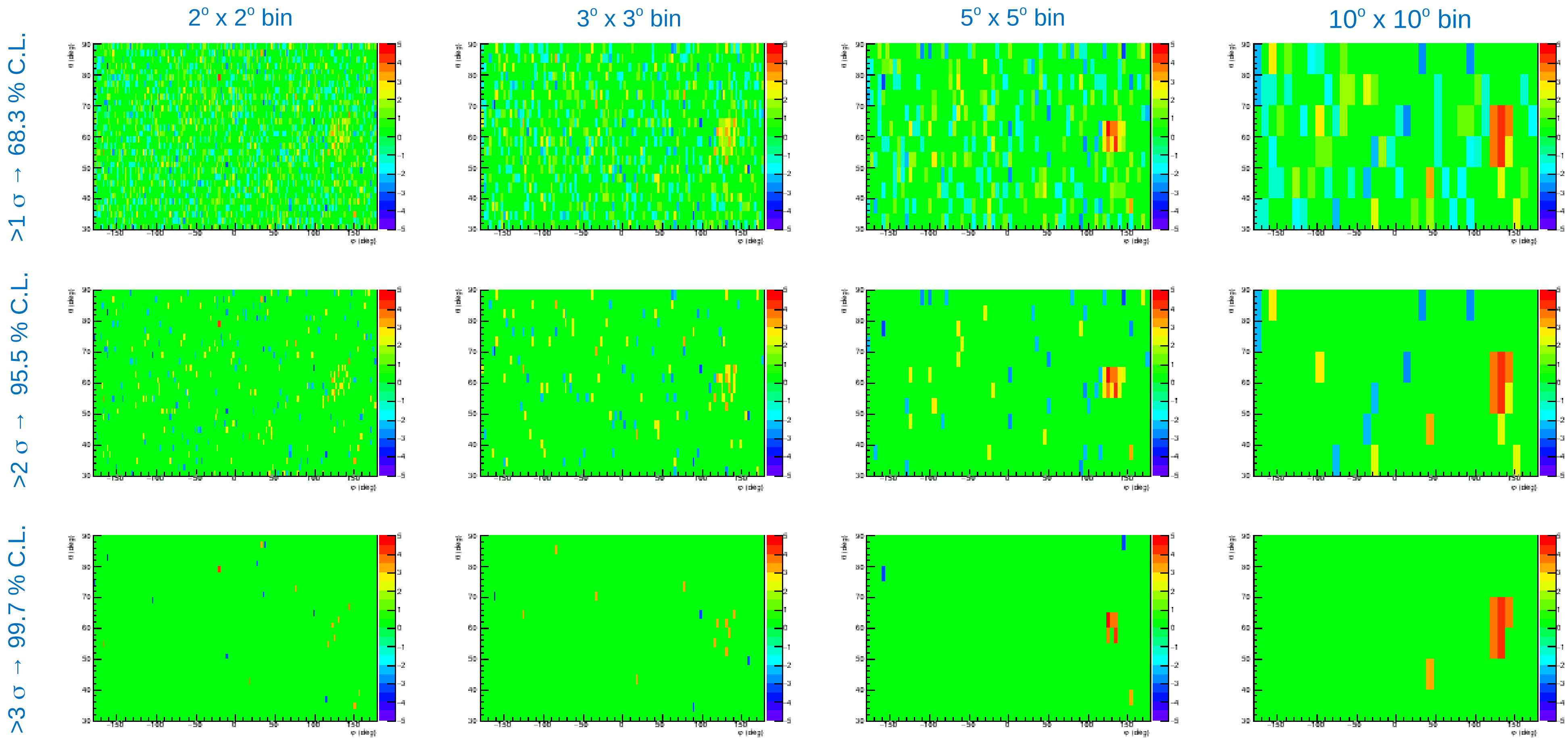

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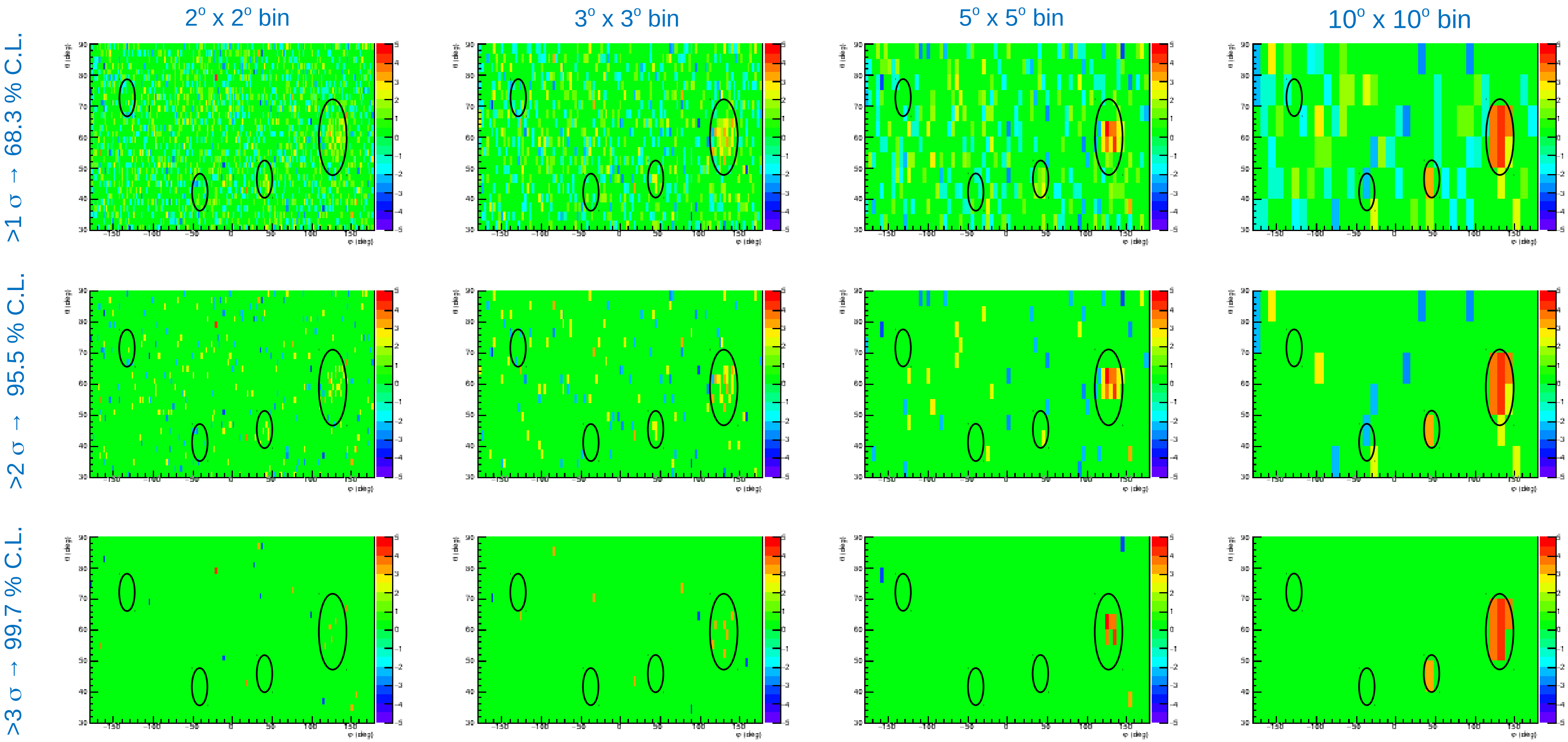
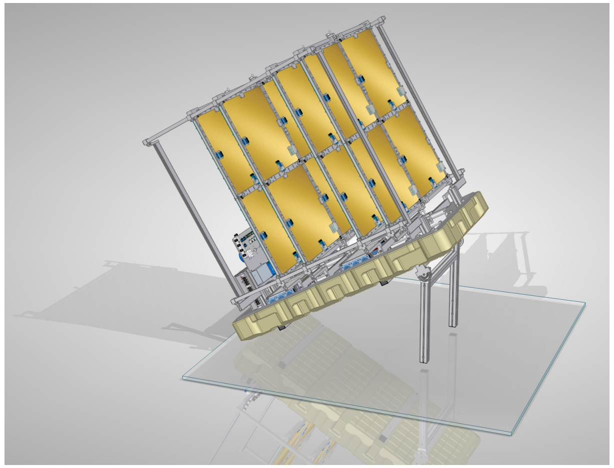
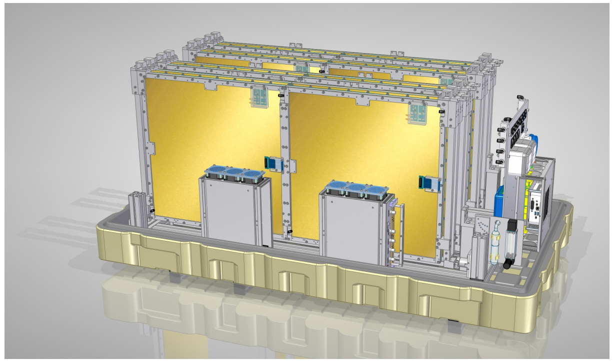
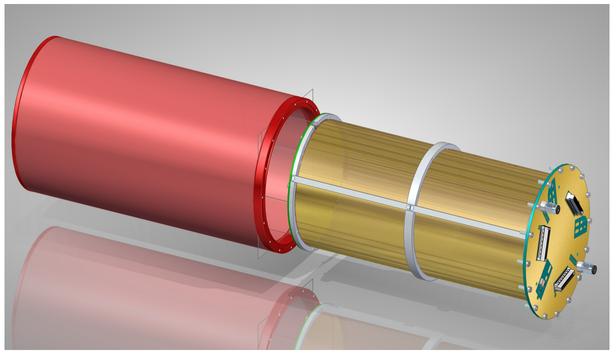


What is next?







- ***Detectors:***
  - Optimize resistive Micromegas construction and performance
  - Construct 1m^2 active surface telescopes:
    - Bigger aperture → Shorter measurements
  - Development of a Micromegas-read cylindrical TPC for muography
- ***Projects:***
  - ***ScanPyramids:***
    - New measurement campaign ongoing (detectors inside the pyramid pointing to the new void)
    - Simulations for data analysis
  - ***G2G3:***
    - Continue feasibility studies
  - ***D3DT:***
    - Construction and commissioning of the first prototype
  - ***Others:***
    - Explore other applications (civil engineering, boreholes...)

Summary and conclusions

- **Muon tomography** reveals as an interesting method for the **internal scanning of big objects**
  - Cheap, non-invasive, versatile, hazard-less
- Among the different techniques to carry out the measurements, **Micromegas-based** telescopes stand out
  - Robust technology, good performance (angular and spatial resolution)
- **CEA/Irfu group** has work in the last years in **different R&D** areas to improve the telescopes performance
  - Multiplexed Micromegas
  - Miniaturized DAQ
  - Gas system

Portability	Autonomy (low consumption)
Stability	Safety

- Different projects and measurements have shown the capabilities of our instrument
- **New ideas** and projects are ongoing
  - Bigger instruments
  - Micromegas-read TPCs
  - Dedicated simulation framework

Muon Tomography with MPGDs MICROMEGAS

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