Muon Tomography with Micromegas:

Archaeology, Nuclear Safety and new developments for Geotechnics

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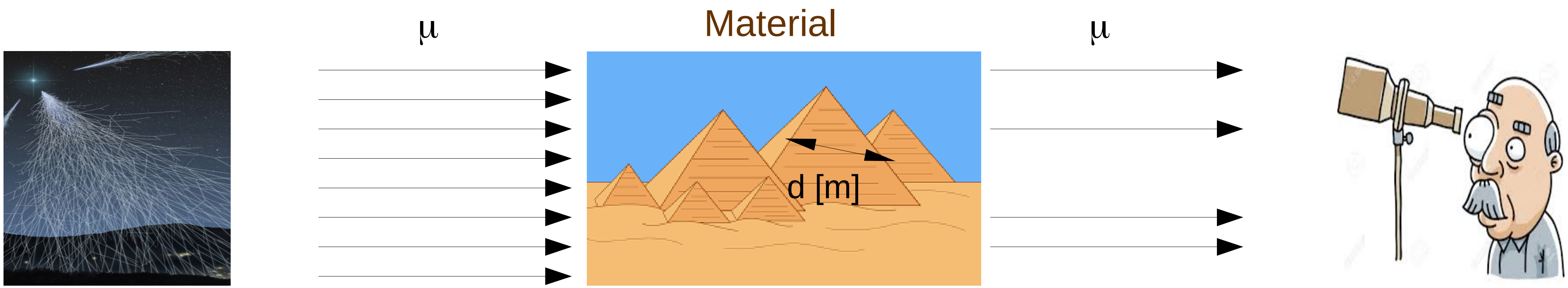
Outline

- Muon tomography:
  - → General aspects
  - → What do we need?
- A Micromegas-based muon telescope
  - → Autonomy, portability, stability …
  - → Some applications and results
- D3DT: A TPC for 3D muon tomography
  - → Simulations and Analysis
  - → First Pre-Prototype and Results
- What is next?
- 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]

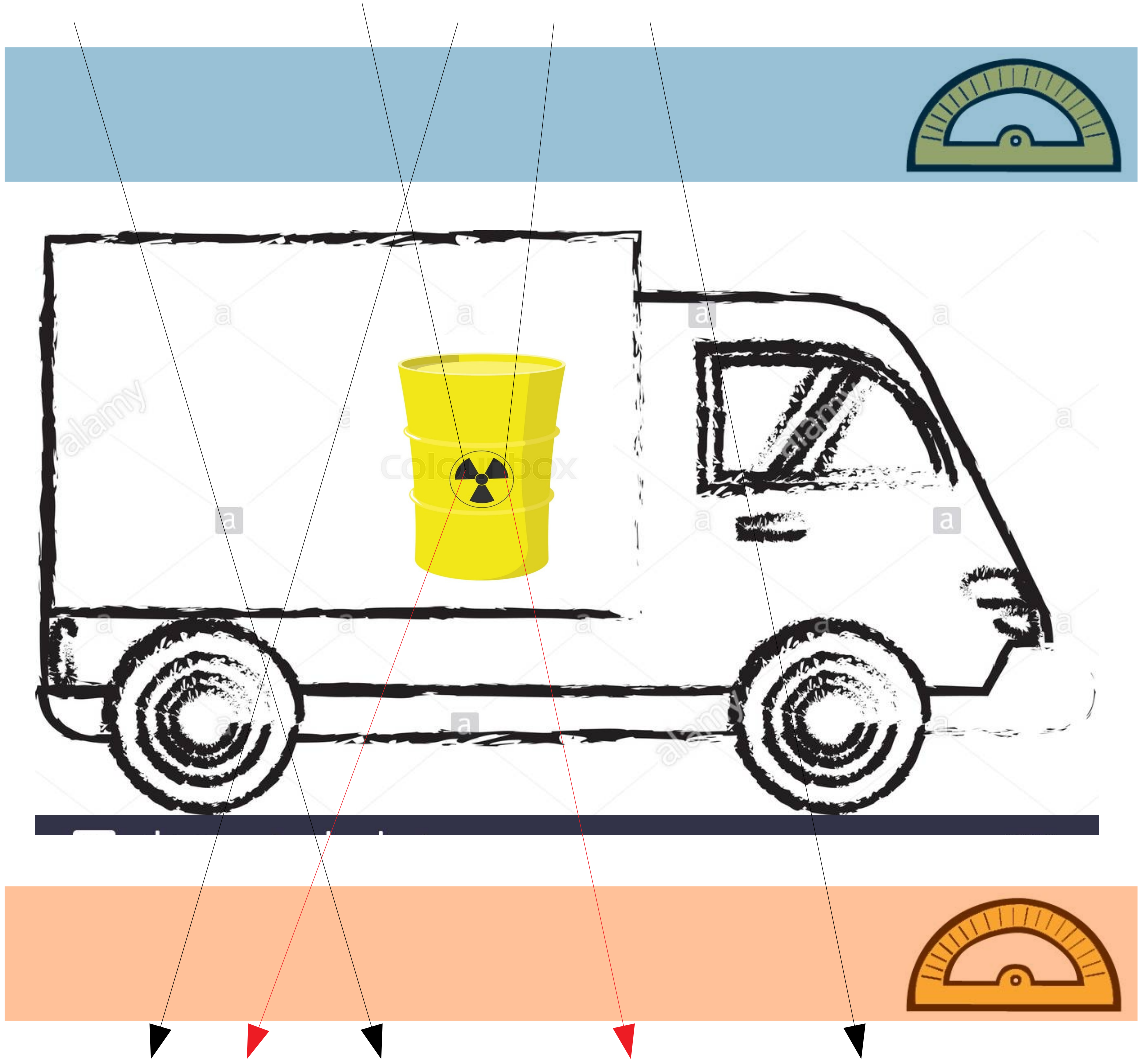
Final flux ϕ_f

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.

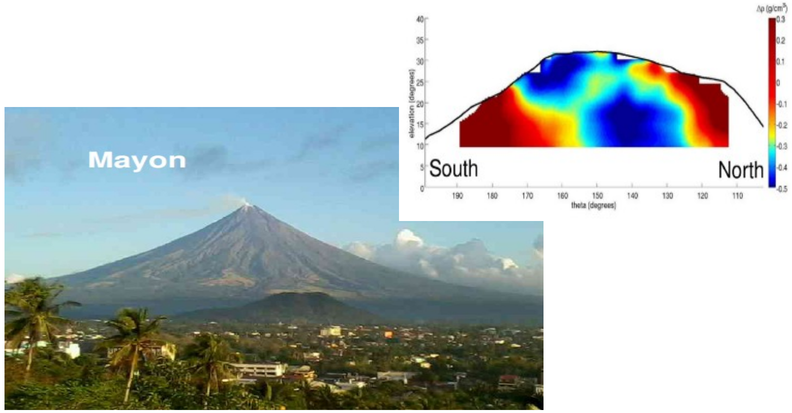
Mat.	Thickn.	δ (g/cm²)	θ (deg)	P_{abs}
Air	100 m	**0.123**	0.094	0.78 %
Water	1 m	**1**	0.35	2.9 %
Lead	10 cm	**113**	1.01	4.2 %
Soil	100 m	**230**	-	99 %

✔ Faster

✔ For smaller objects with no big opacities

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

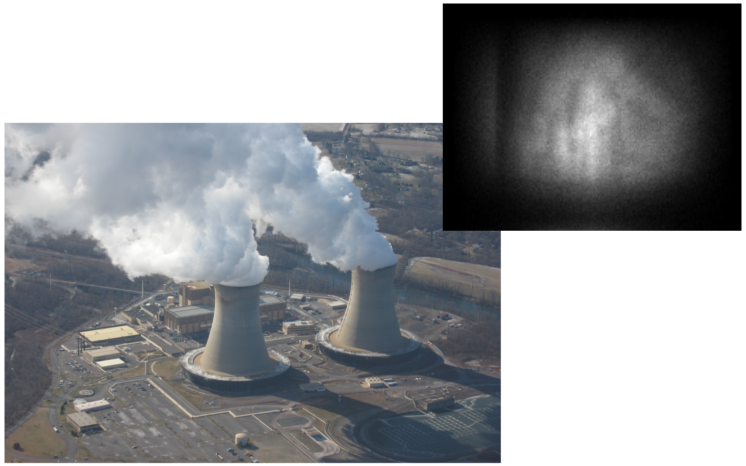
Transmission



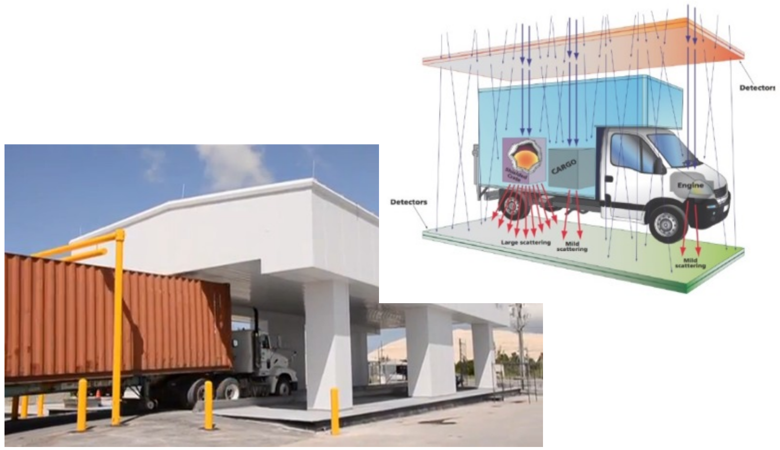
Volcanology

Archeology

Deviation



Nuclear control and safety



Homeland security

Muon Tomography

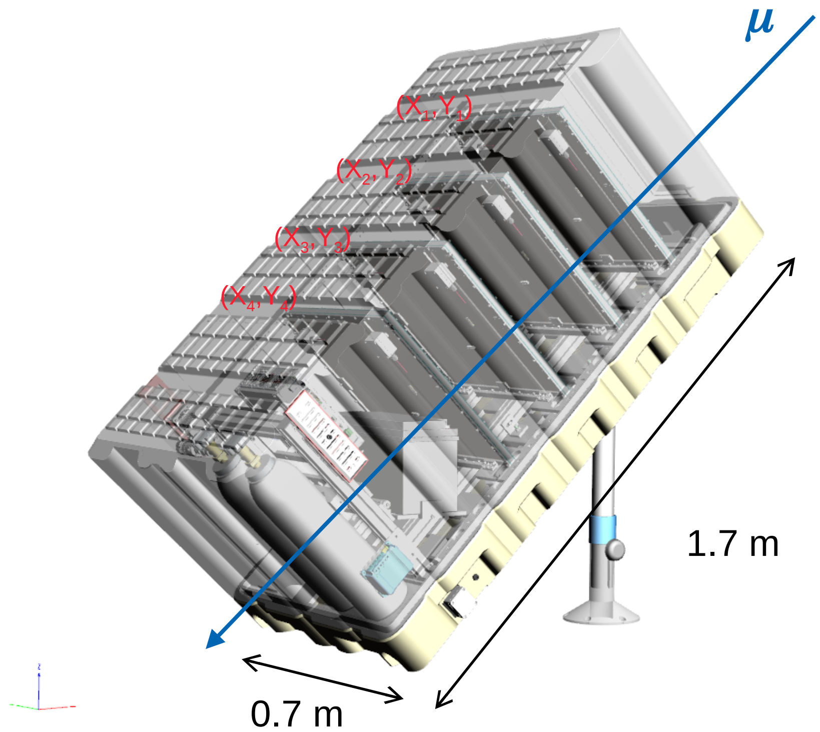
What do we need?

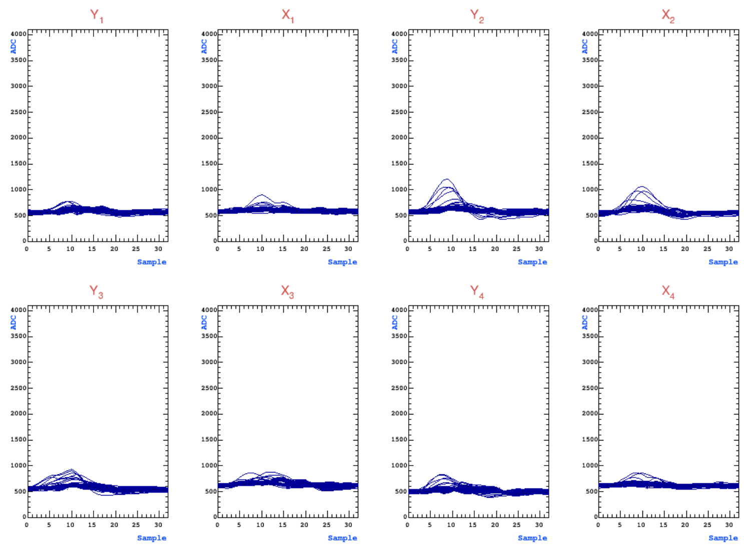
Muon tomography requires:

- 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





A Micromegas-based muon telescope

Bulk Micromegas

Robust, well-known

Big surface (50 x 50 cm^2)

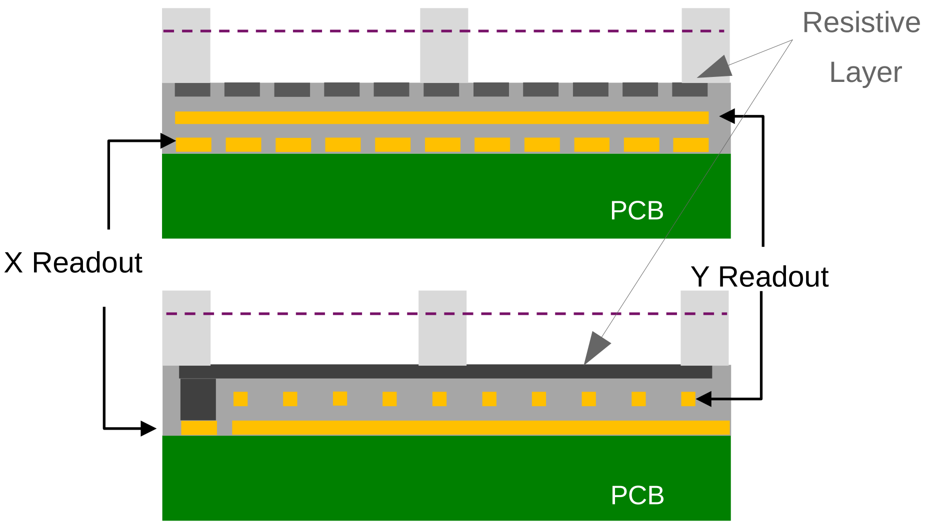
1037 strips (X and Y) → 482 μm pitch

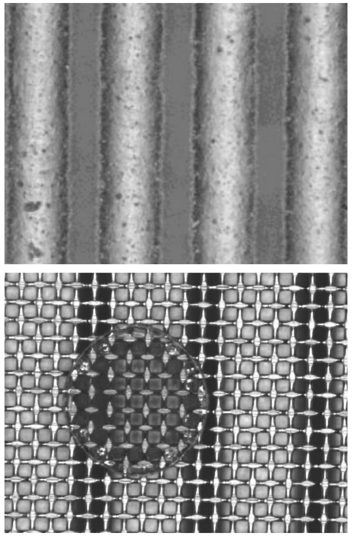
Resolution:

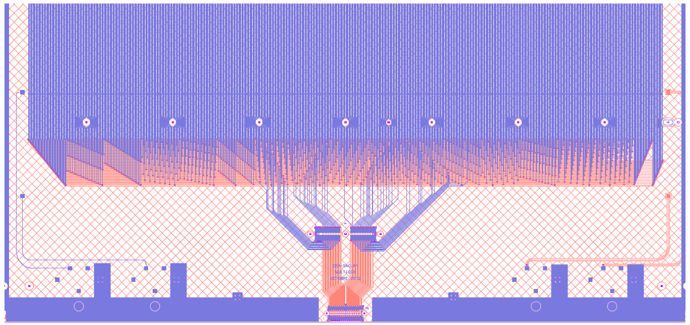
~100 μm spatial

~10 mrad angular

~10 ns temporal







Nucl. Instrum. Meth. A 729 (2013) 888

Resistive Strips

Avoid sparks → Detector protection

Charge Diffusion → Better 2D spatial resolution

→ Multiplexing possibility

Multiplexed Readout

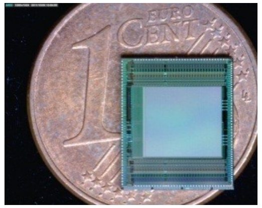
From 1037 to 61 channels both X and Y

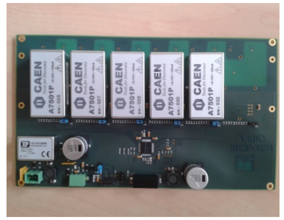
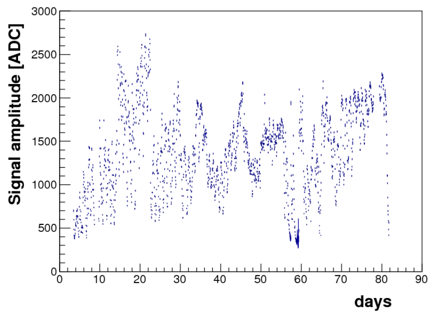
→ 1/34 lines reduction

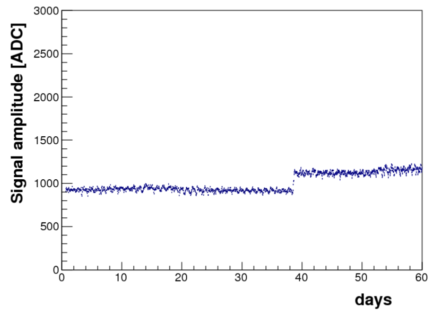
→ Simpler DAQ

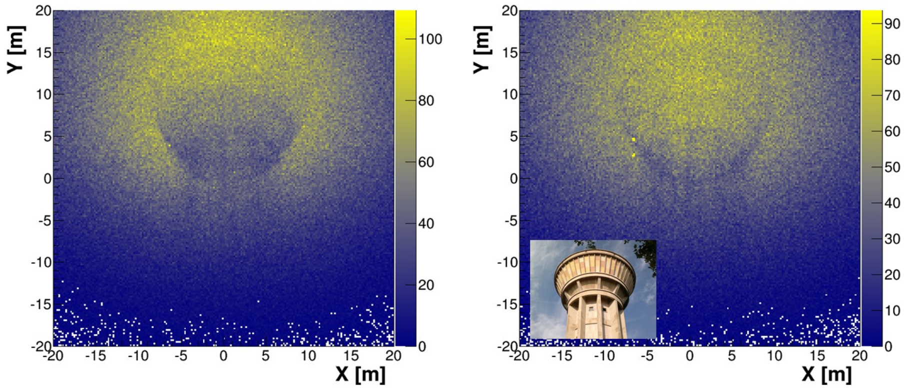


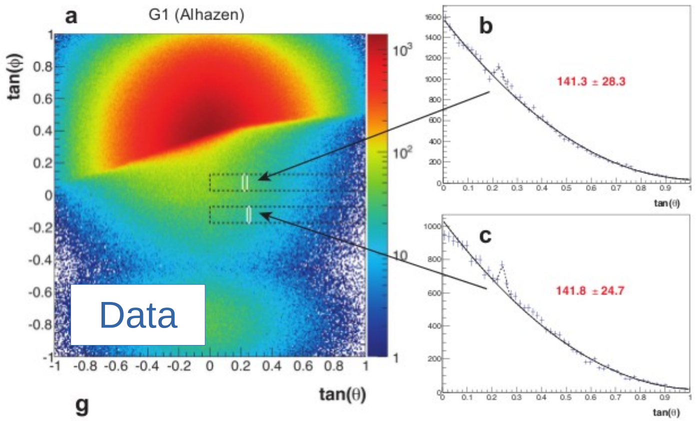
- Light materials: Aluminium structure, plastic case …
- Reduced size with low power consumption DAQ components
  - Miniaturized ASIC and HV modules
  - ~35 W power consumption (solar panels, batteries…)
- Auto-tunable gain → Stability
- Hummingbird nano-pc (as your smartphone) → Online analysis
- 3G/4G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

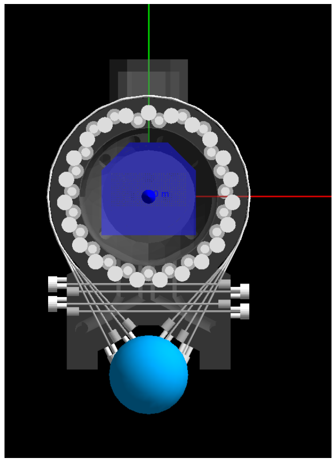


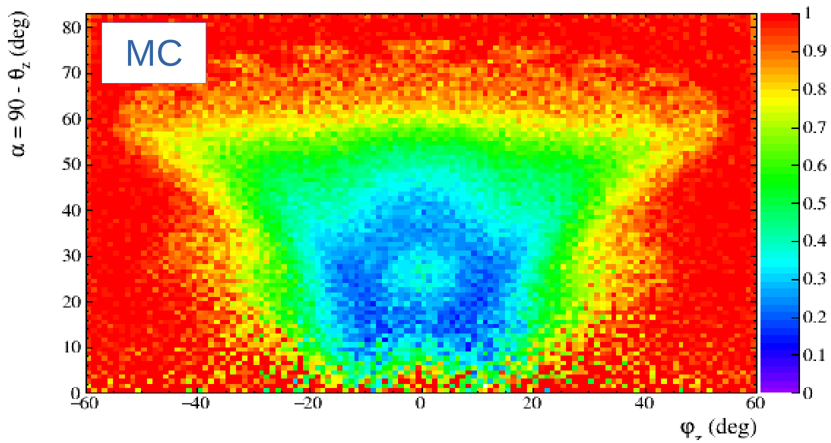














WatTo → NIM A 834 (2016) 223 - 228

- Scanning of "Chateau d'eau" @ Saclay (2015)
- First outdoor measurement: Proof of concept
- Capable to monitor water level

ScanPyramids → Nature 552 (2017) 386 -390

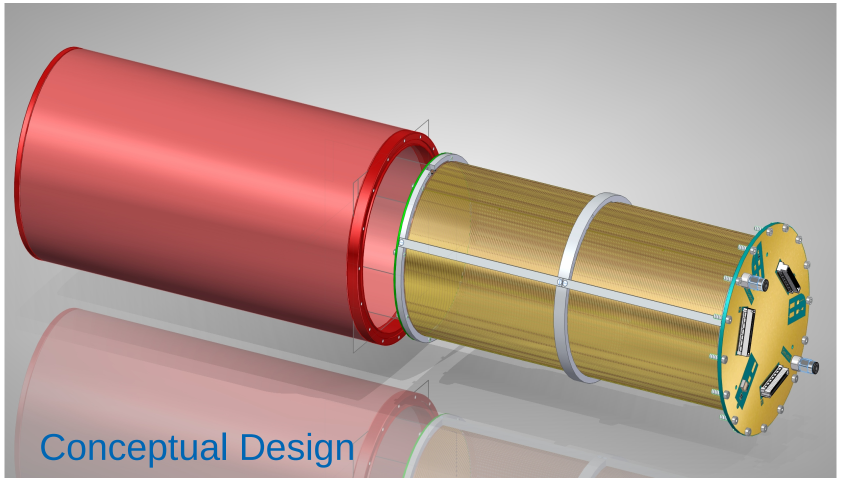
- Scanning of Khufu's Pyramid
- Discovery of a void over Grand Gallery
- Ongoing measurements for more information

G2G3 → https://doi.org/10.1016/j.nima.2018.10.011

- Scanning of Nuclear Reactors @ CEA – Marcoule
- Feasibility studies by MC simulation (Geant4)
- Development of a devoted simulation framework

We didn’t say a word about TPC’s so far….

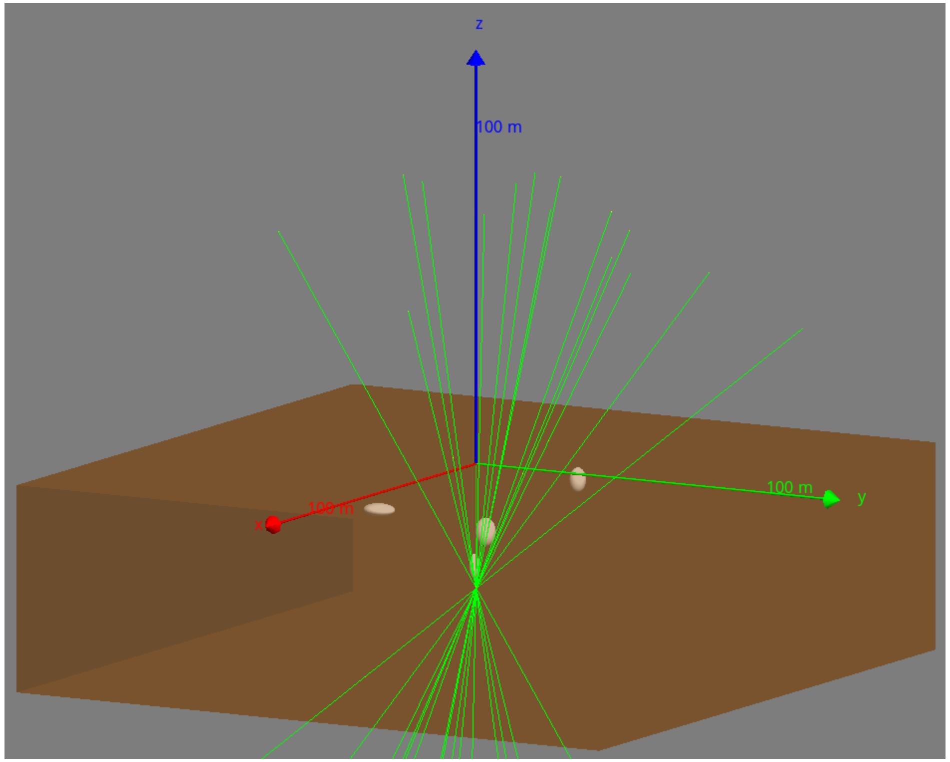
A TPC for 3D Muon Tomography



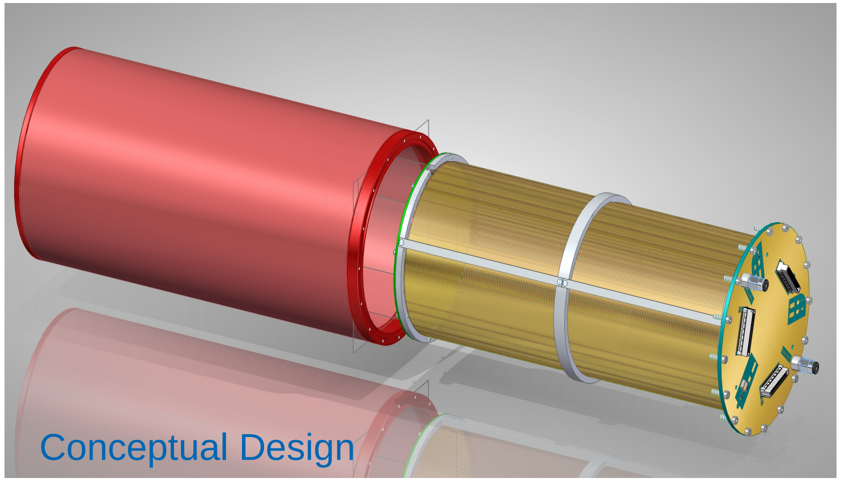
- Components:
  - Cylindrical TPC (~40 cm long, 15 cm Ø)
  - Readout by circular Micromegas with 2D pads multiplexed
    → 1344 pads to 192 (3 x 64) lines

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

3D resolution with a detector network



- TPC placed at the bottom of a borehole
- Scanning by muography of the surroundings
- Possible applications:
  - Mining exploration
  - Geothermal fields sounding
  - Civil engineering (tunnels …)
  - Monitoring: buildings, dykes, bridges
  - Geophysics ?


Conceptual Design

- Components:
  - Cylindrical TPC (~40 cm long, 15 cm Ø)
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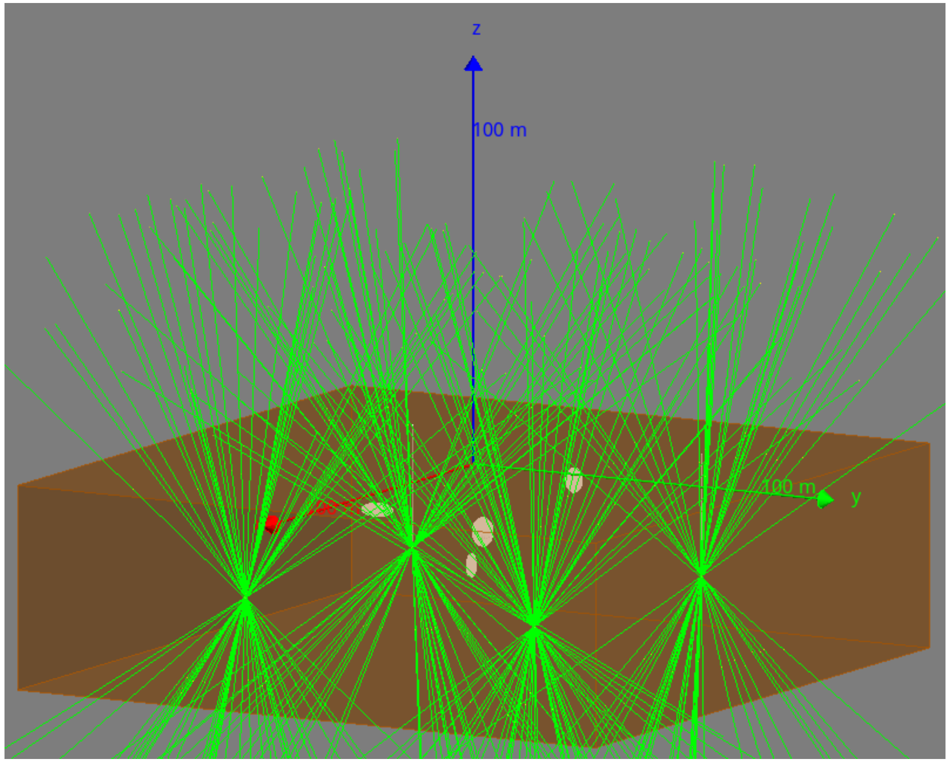
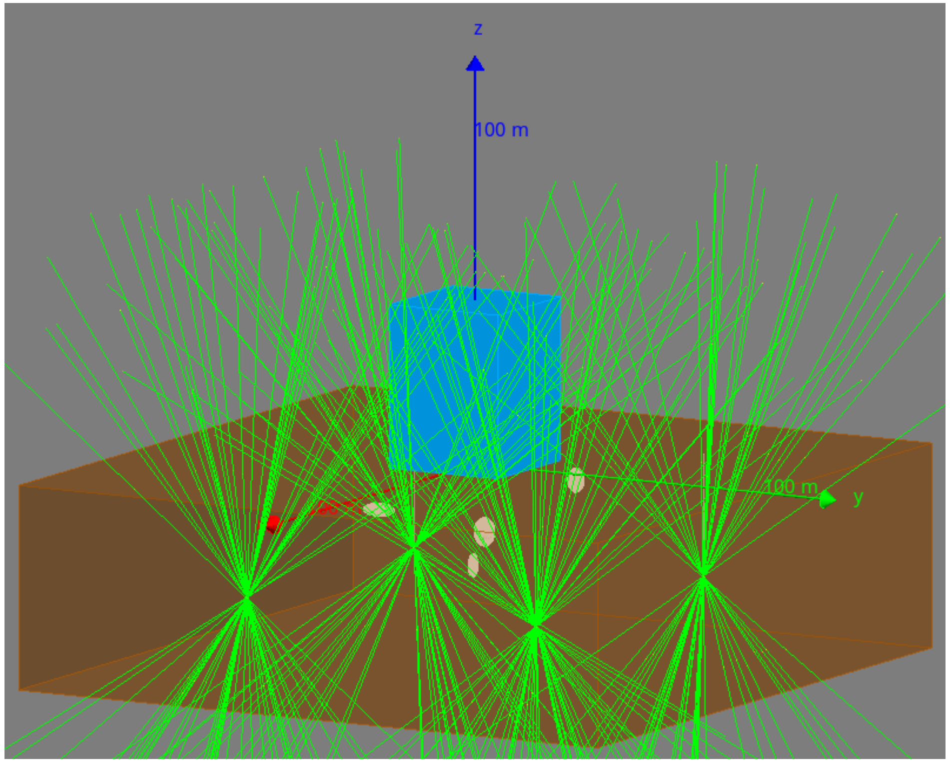




Active Surface: 12 cm Ø
1344 pixels
(2.997 x 2.897 mm^2)

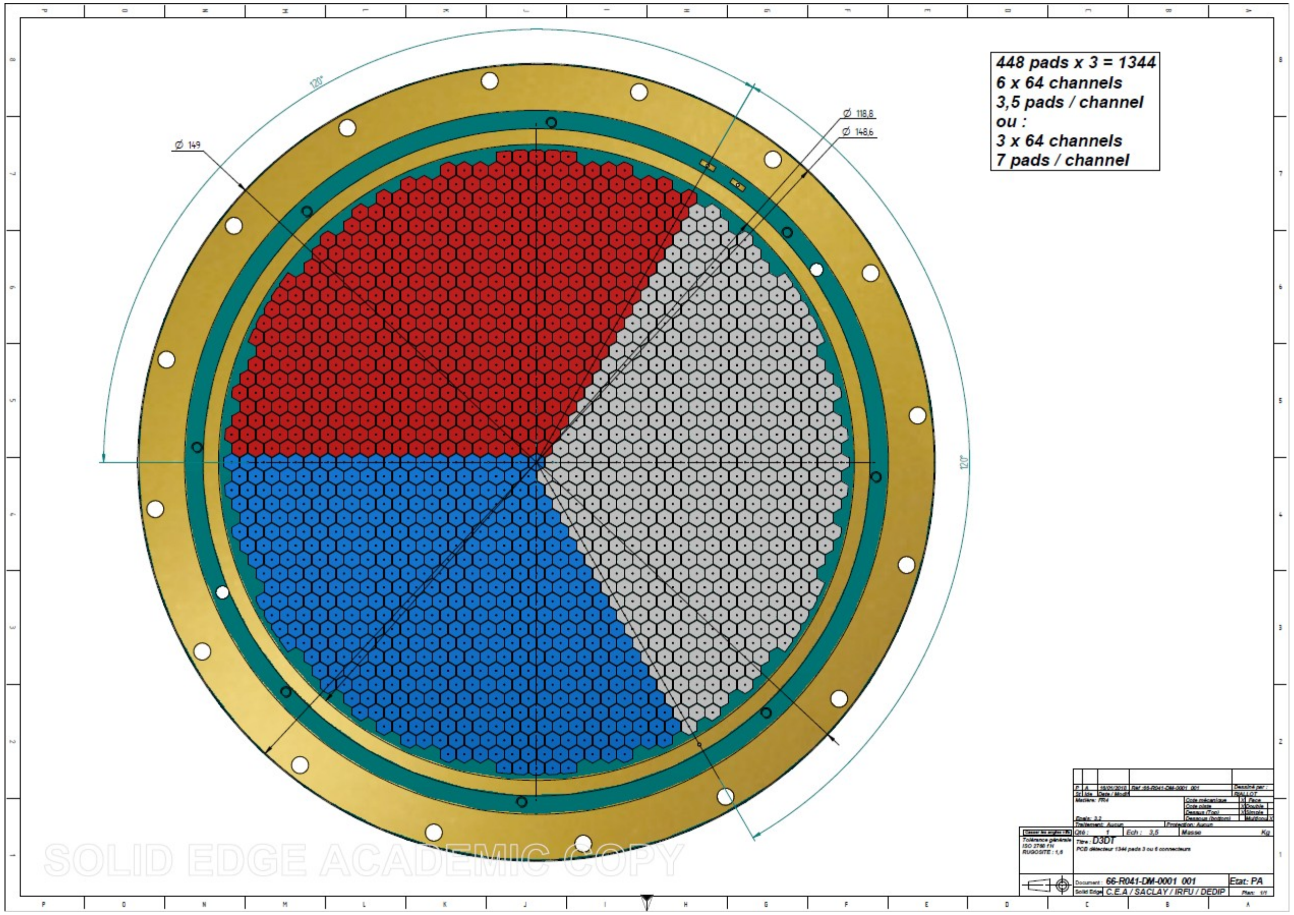
2D Multiplexing:
7 pixels per channel

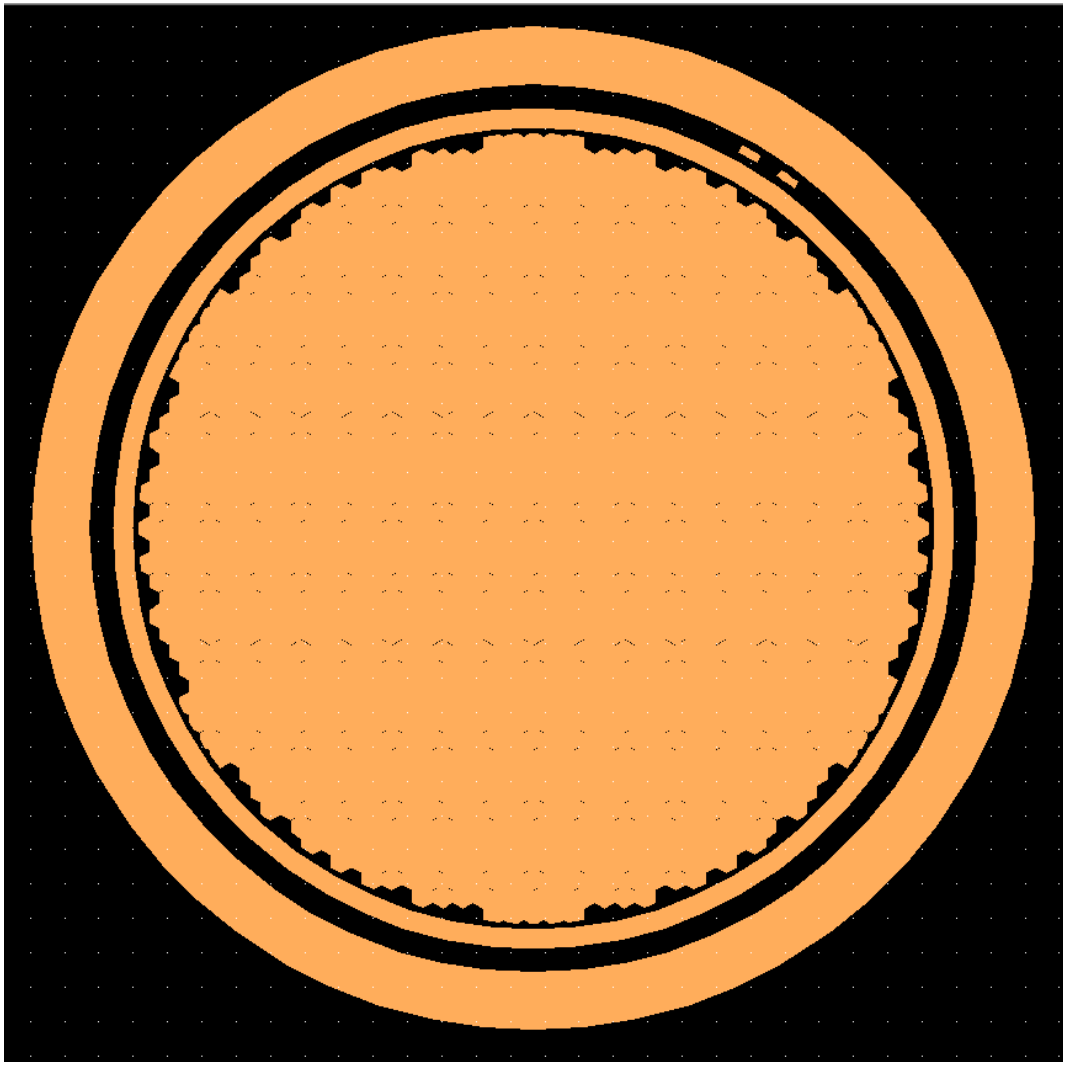
192 readout channels

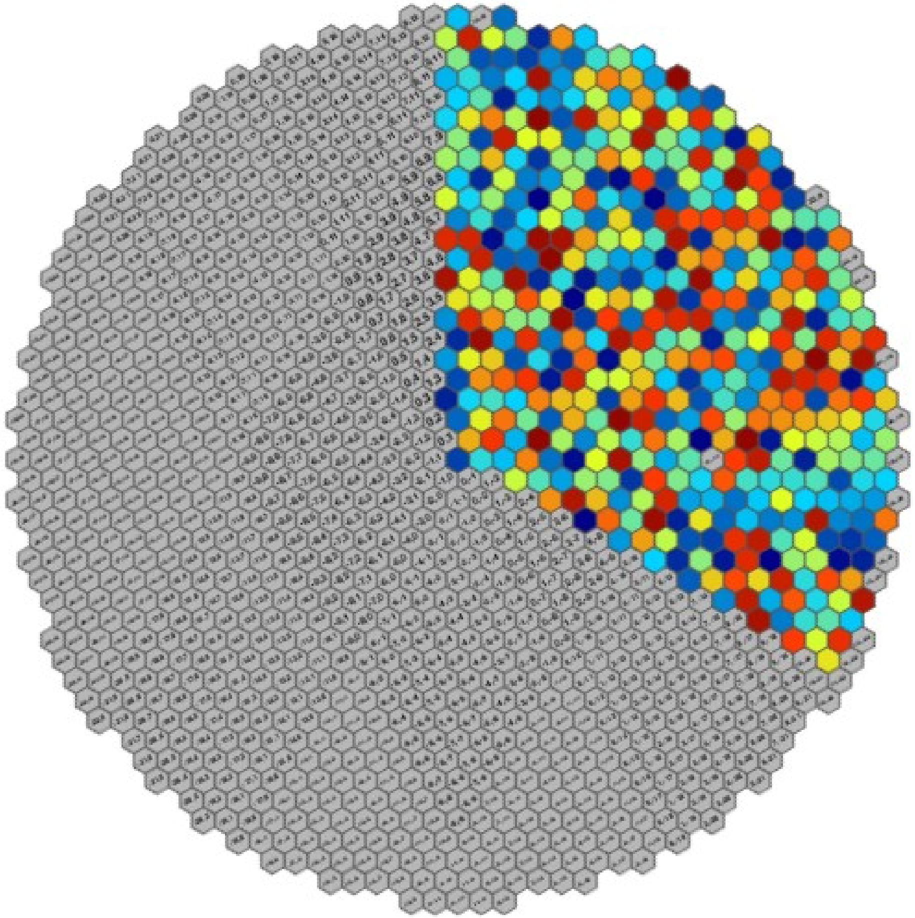
Channels divided in
3 sectors

64 Channels per sector

1 ASIC per sector

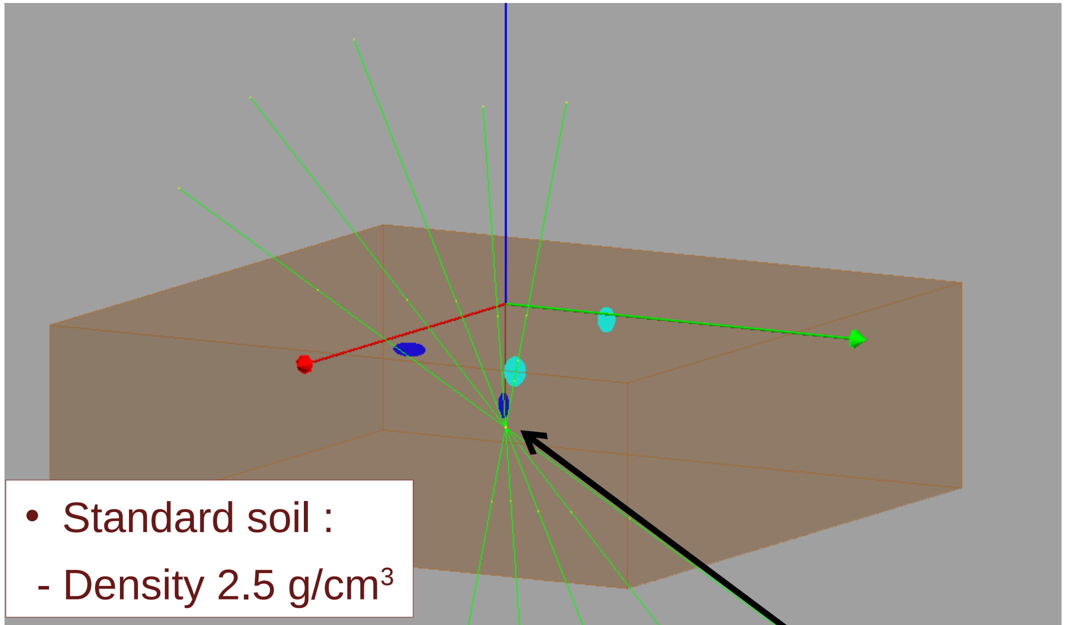






12 layers PCB: 3.2 mm thick

- 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/cm^3

- Typical cavities :
  - 2 filled of water and 2 of air
  - Depth between 5 et 25 m
  - Volume between 18 et 92 m^3

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

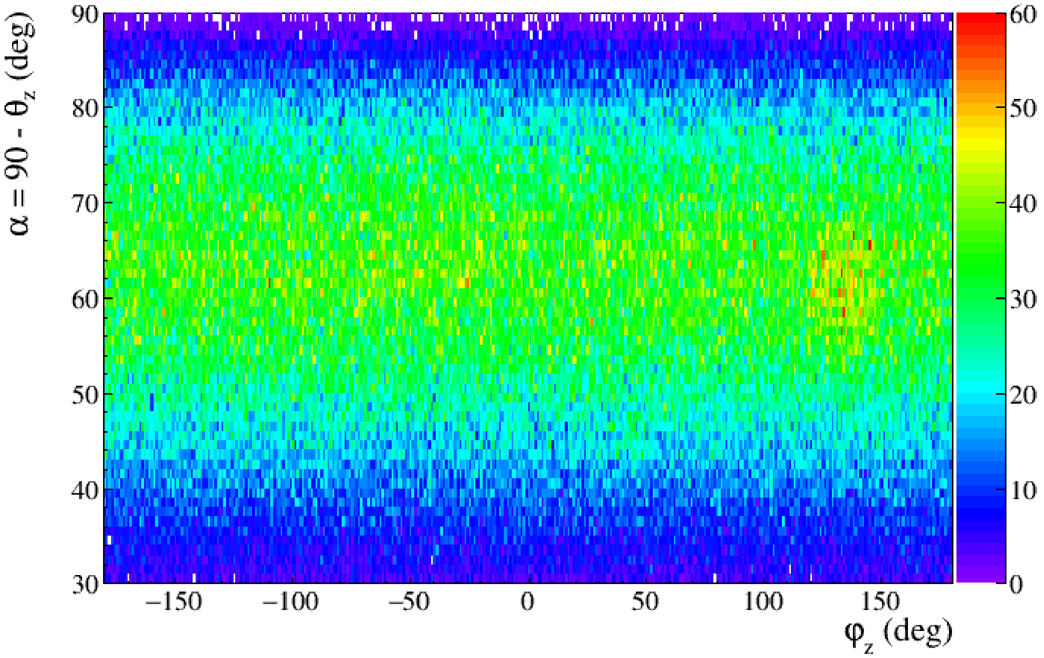
Comparison between simulations with (1) and without (2) cavities

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

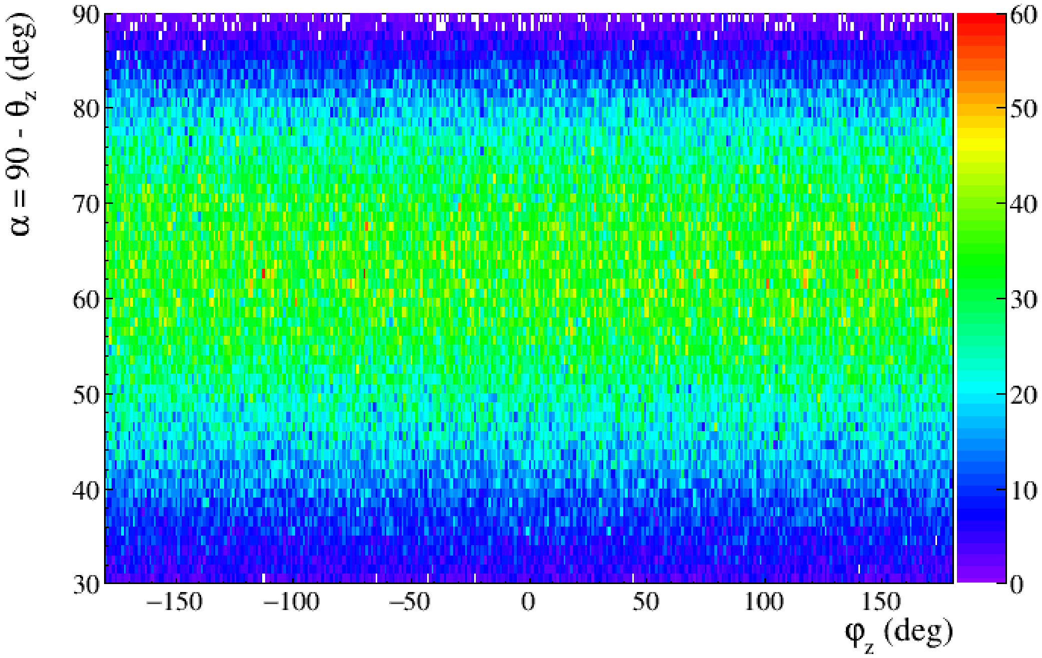
Or direct analysis of “raw measurements”

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

Raw simulation with cavities



Raw simulation without cavities

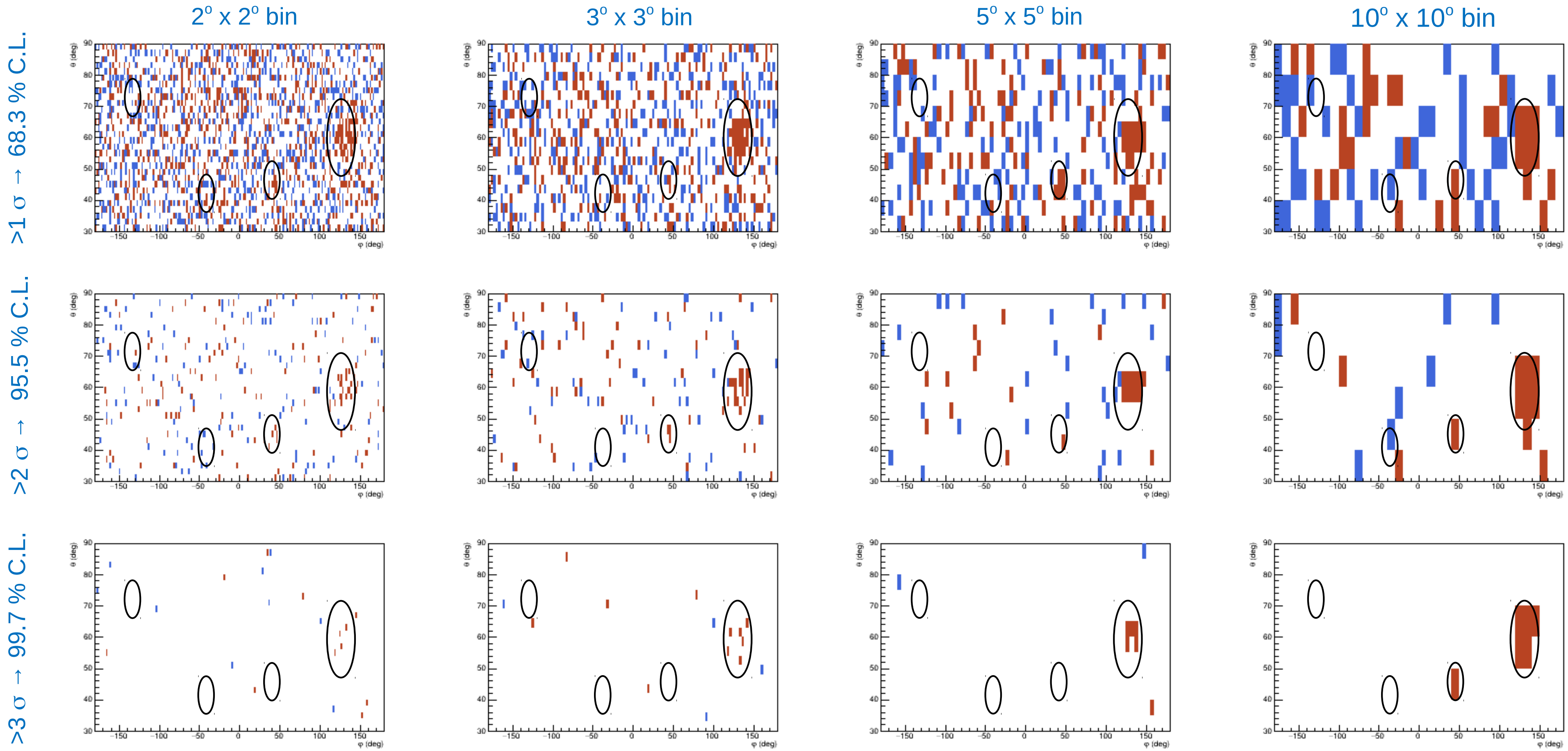


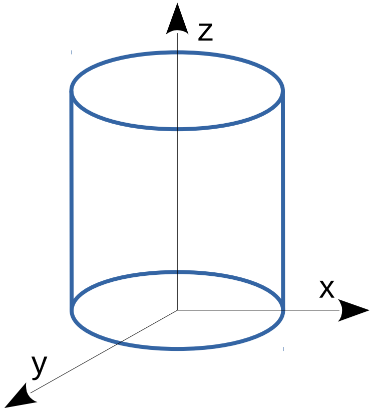
Simulated events corresponding to ~1 month measurement

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

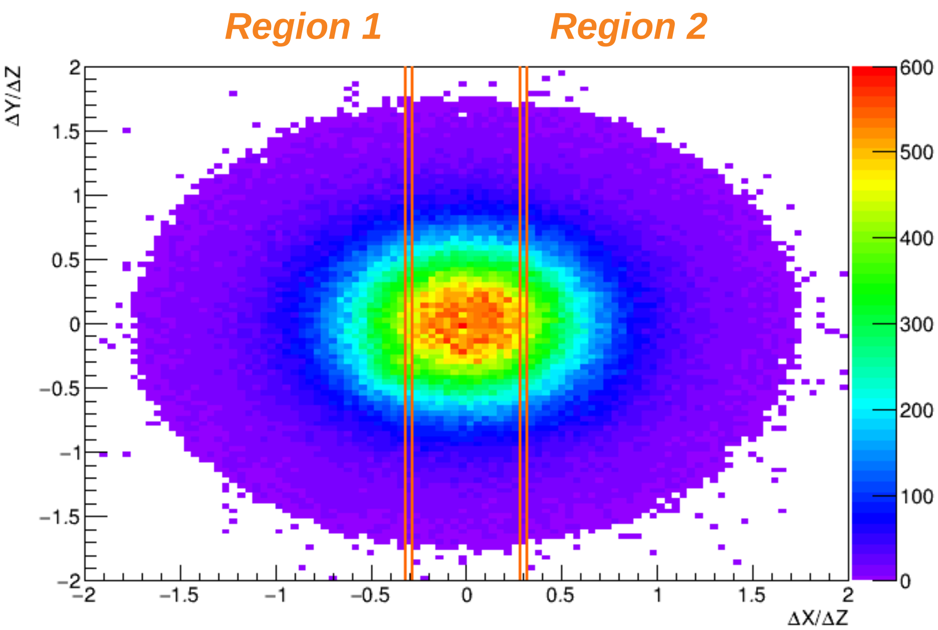
Excess of muons

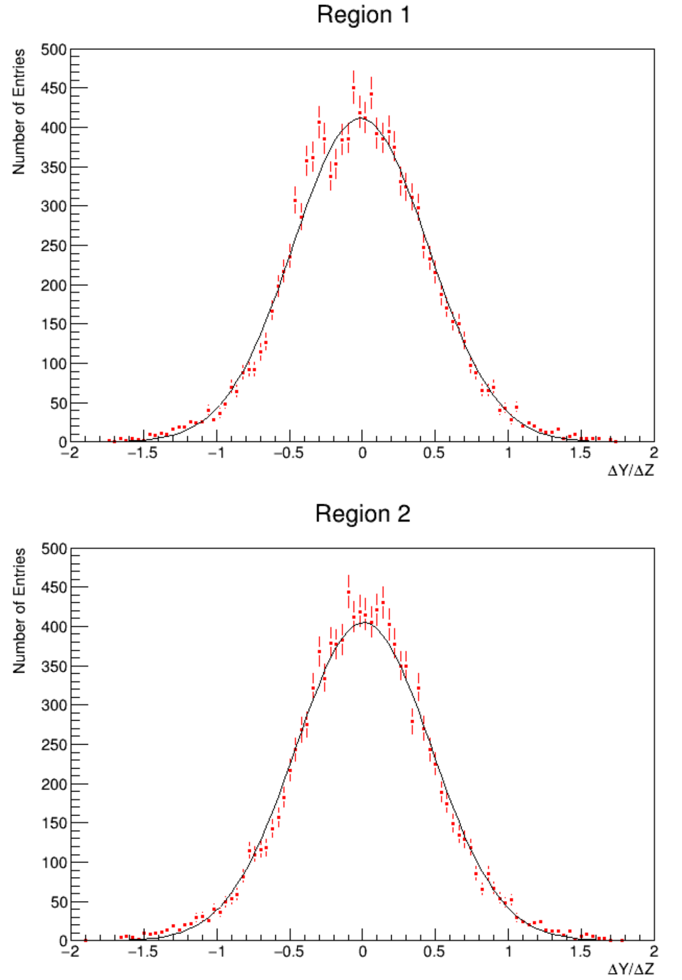
Lack of muons





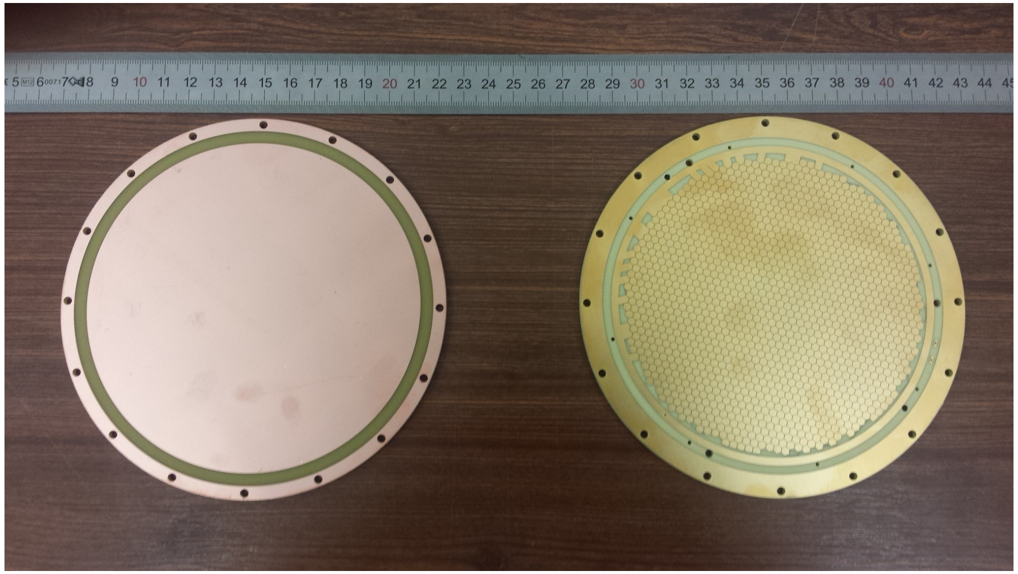
- ***Analysis of the "Raw measurements"***
    - Plot of "displacement" of a muon @ TPC rather than incident angles

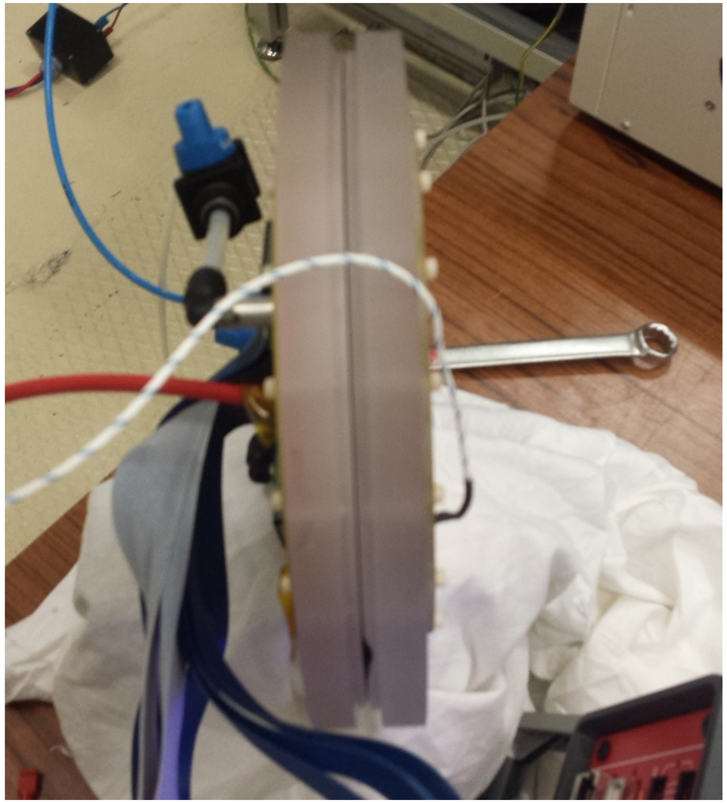


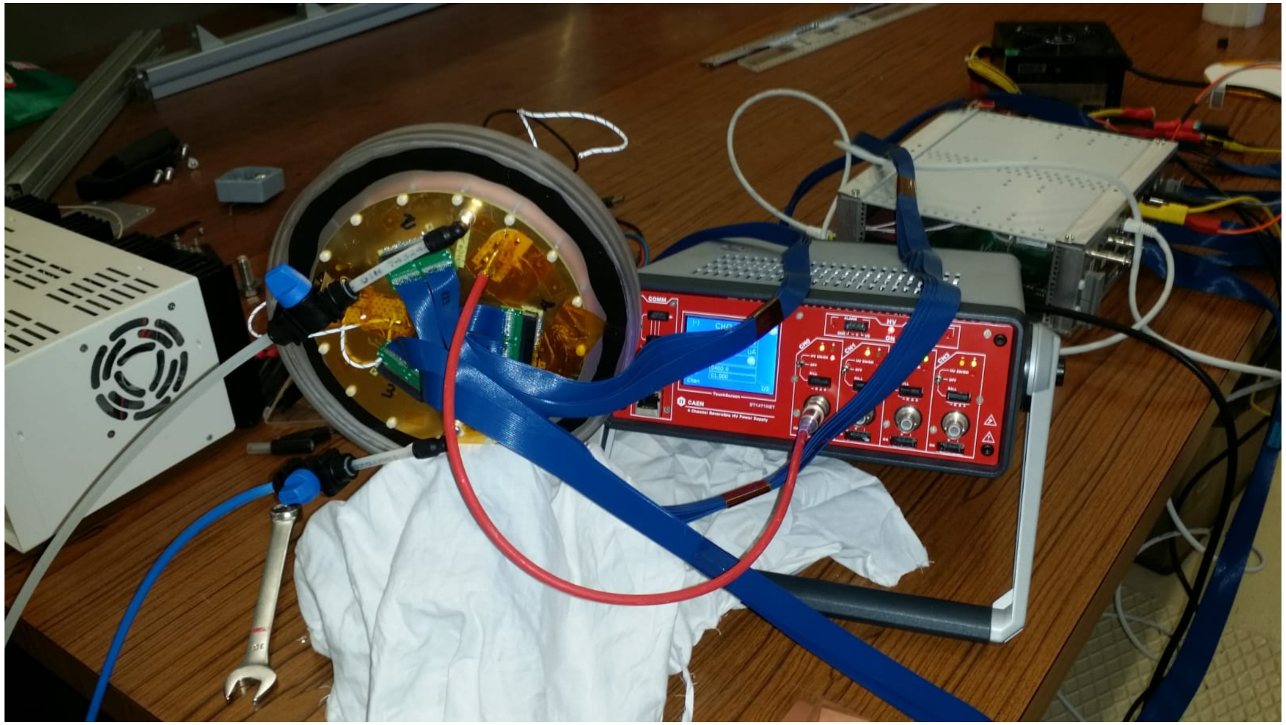


First Pre-Prototype and Results

- For fast test of Micromegas performance
  - Drift volume: 12 cm Ø; 3 cm length
  - No field cage





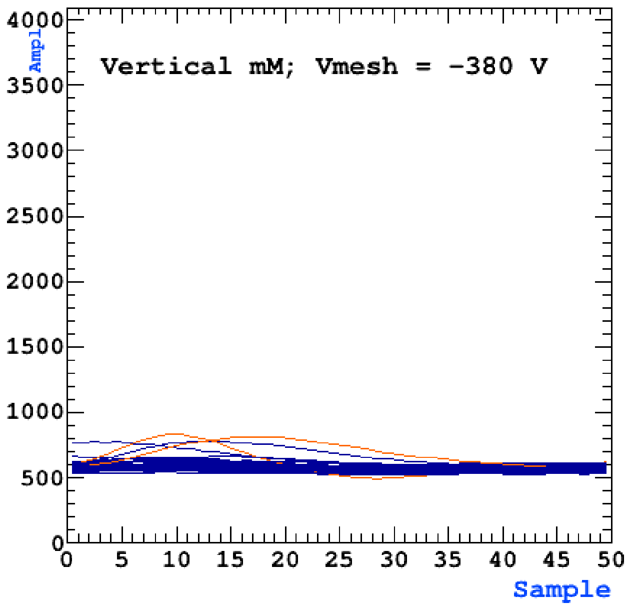


First Pre-Prototype and Results

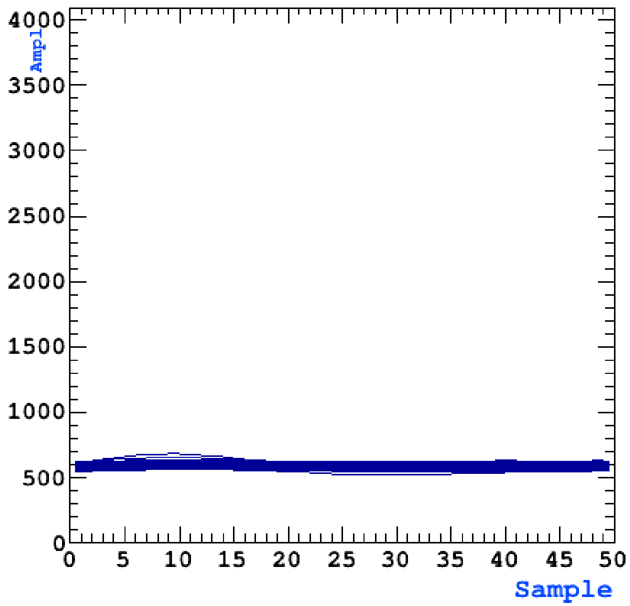
- First Data Taking
  - Ar – iC_4H_{10} – CF_4 (95:2:3) @ P_{atm}
  - V Cathode = -1000 V
  - V Mesh = -380 – -400 V
  - Detector Vertical and Horizontal

Data taken between 7/12/18 and 10/12/18

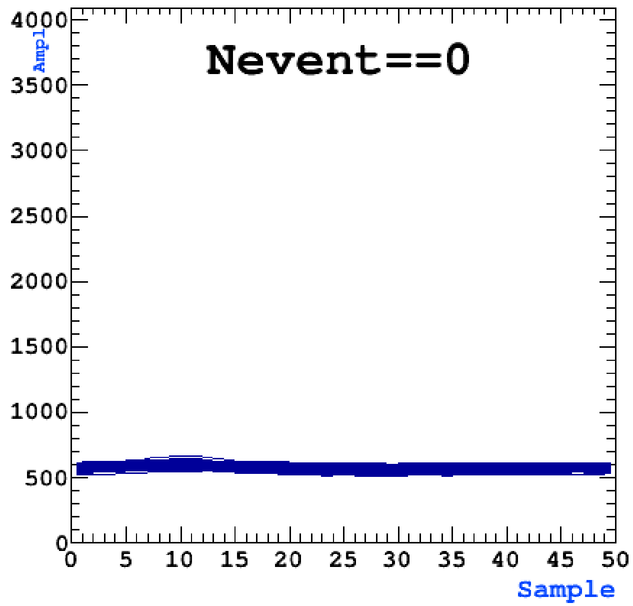
Asic #0



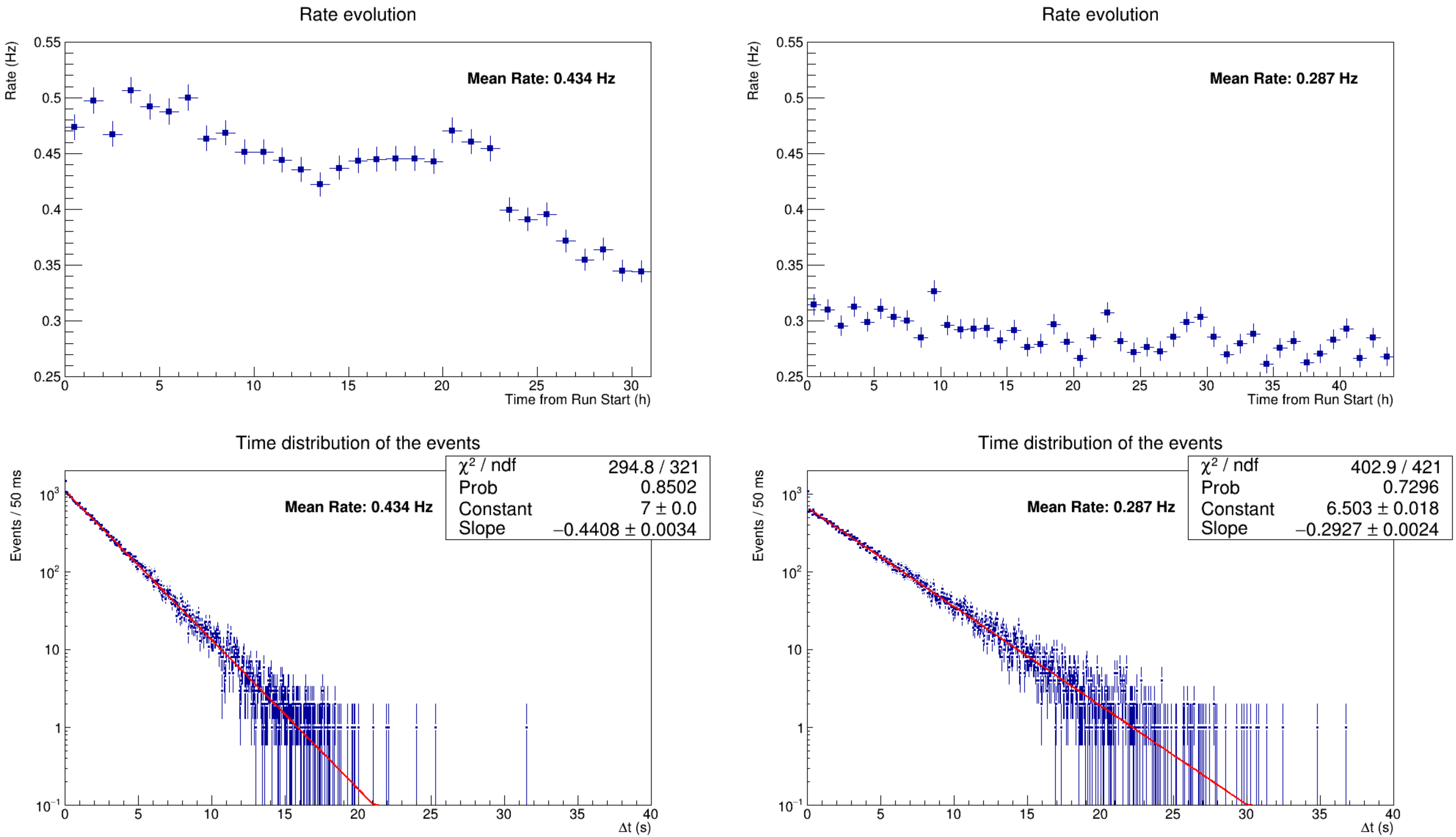
Asic #1



Asic #2



Vertical mMs; Vmesh = -380 V; Vdrift = -1000 V



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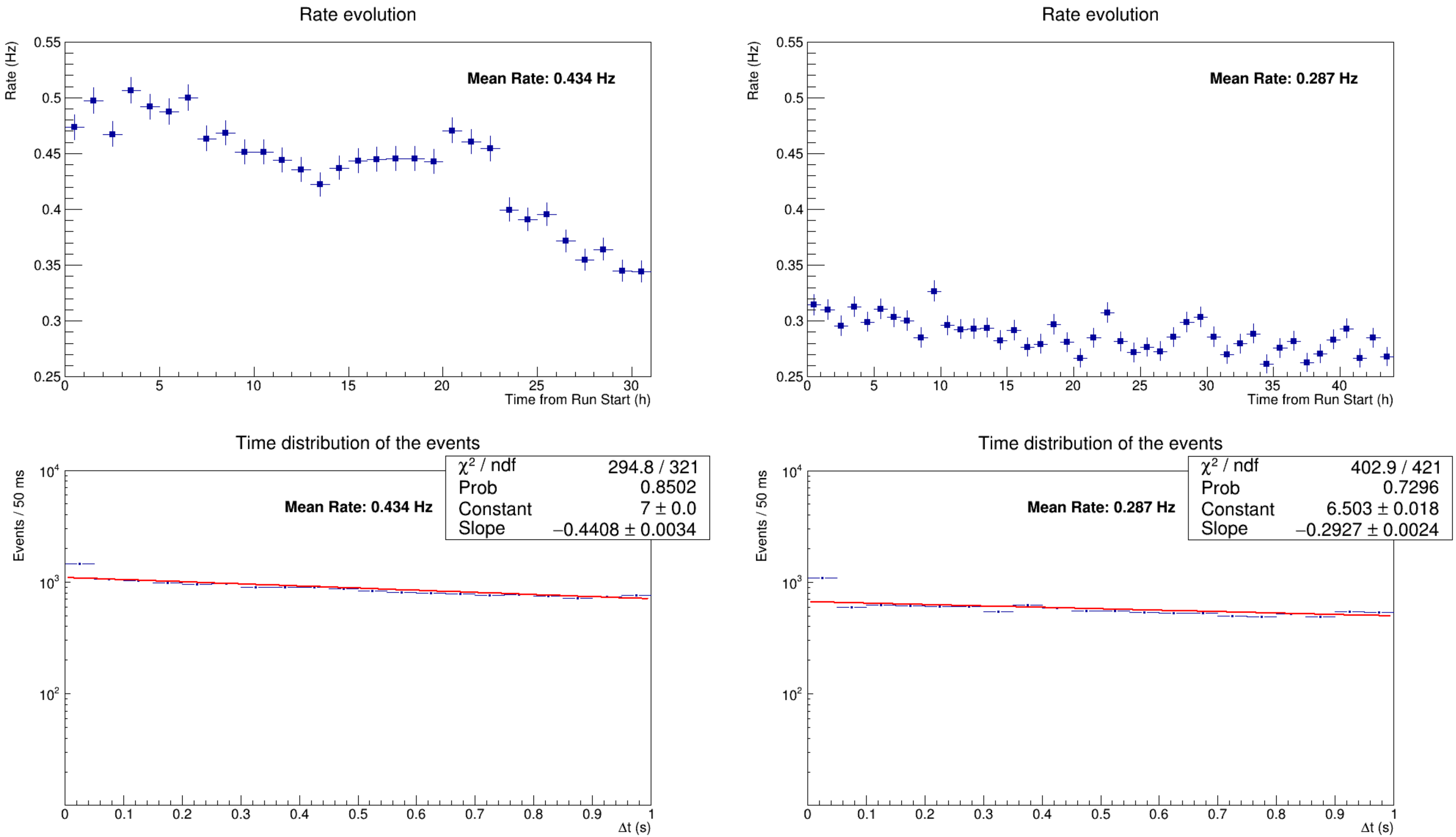
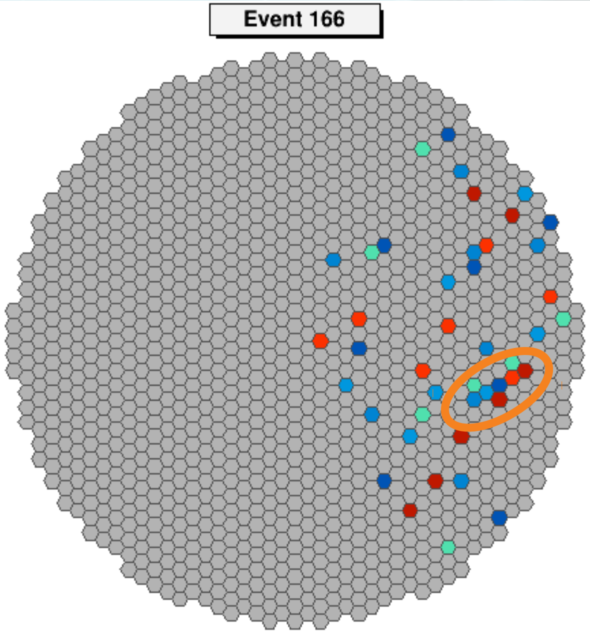


First Pre-Prototype and Results

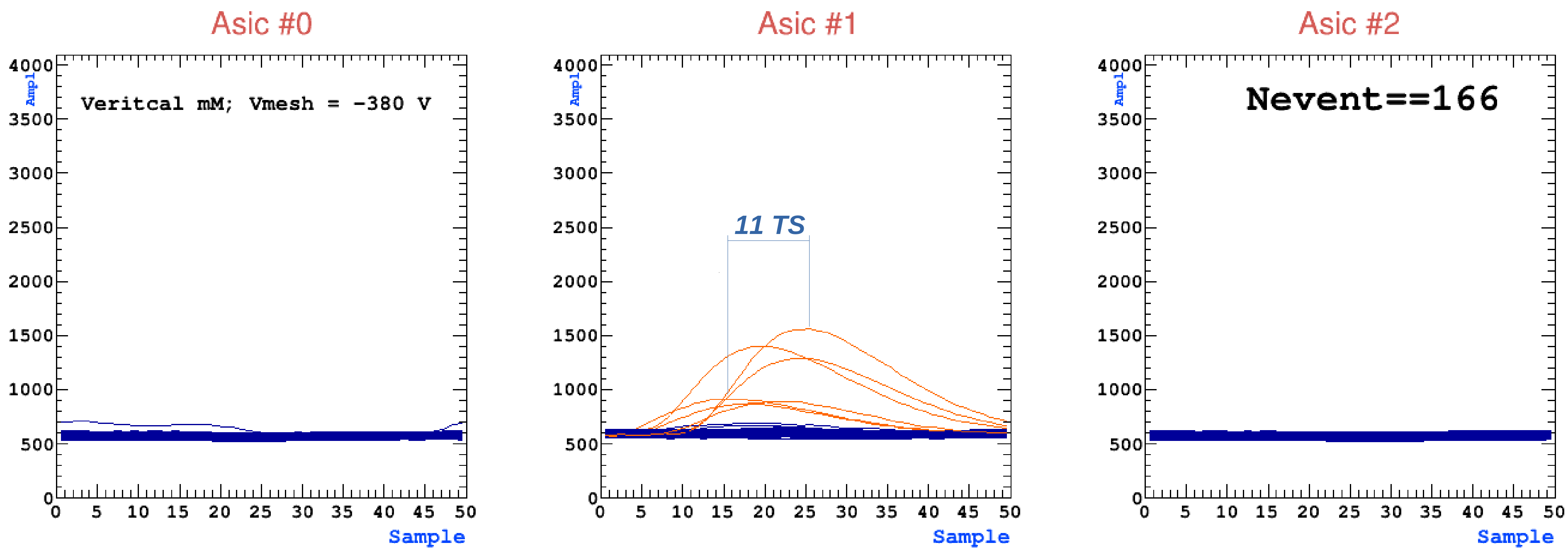


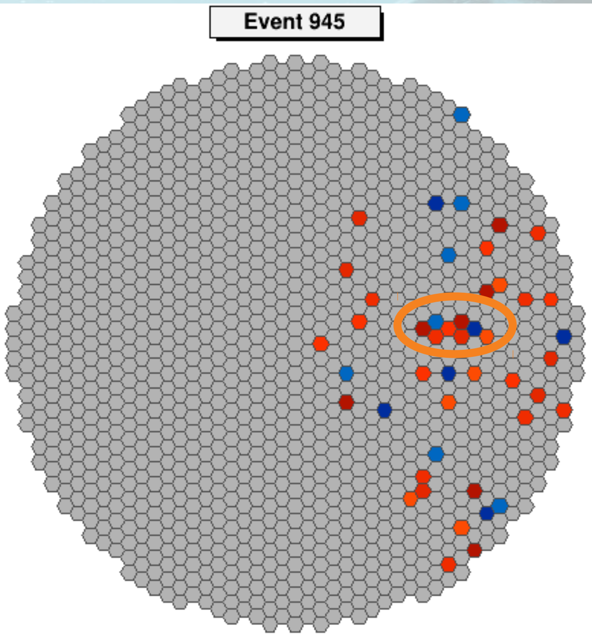
- 6 signals over threshold @ ASIC#1
  - 6 x 7 = 42 fired pixels
- ***1 "long track"*** identified (5 pixels length) → $(\Delta x^2 + \Delta y^2)^{1/2} \sim 15$ mm
- ***11 time samples*** (~ 440 ns) time difference → $\Delta z \sim 30$ mm

Preliminary

Raw Signals

No pedestal subtraction



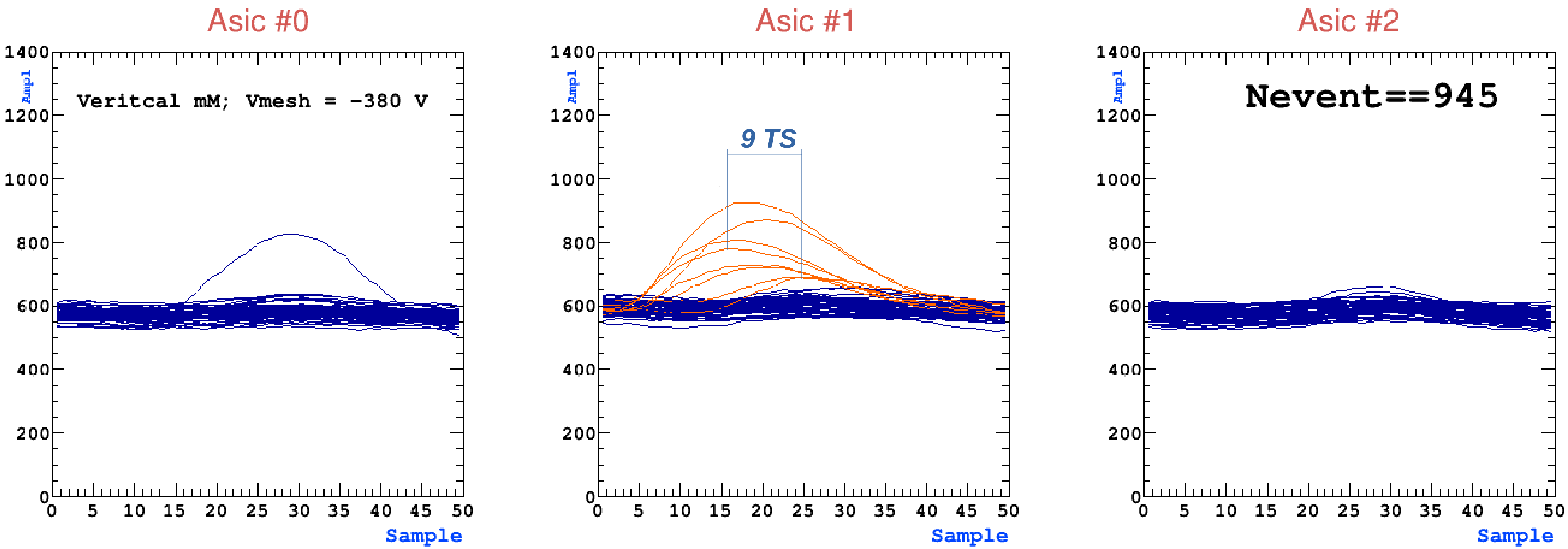


- 8 signals over threshold @ ASIC#1
  - 8 x 7 = 56 fired pixels
- ***1 "long track"*** identified (8 pixels length) → $(\Delta x^2 + \Delta y^2)^{1/2} \sim 18$ mm
- ***9 time samples*** (~ 360 ns) time difference → $\Delta z \sim 25$ mm

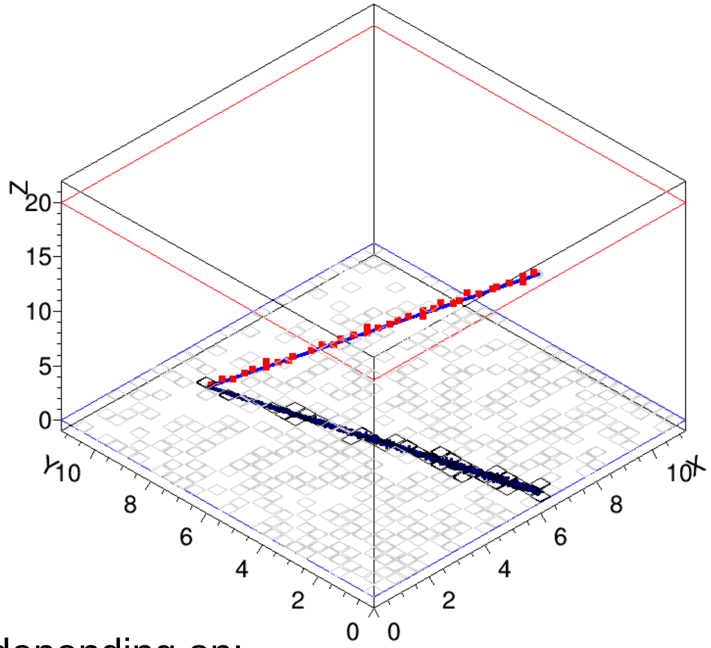
Preliminary

Raw Signals

No pedestal subtraction

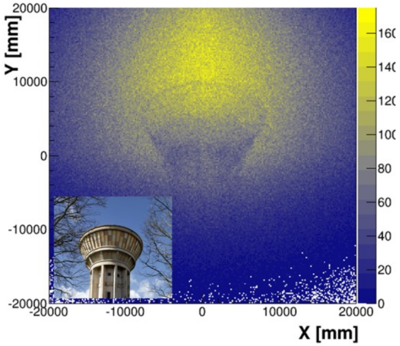


What is next?



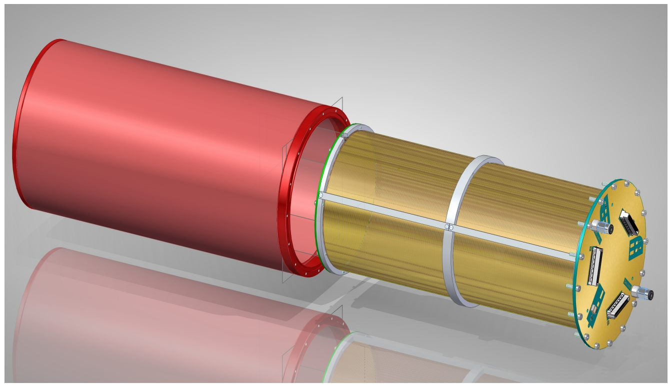
- *Detectors and measurements:*
  - Design and construction of a “Laboratory” prototype
    - First measurements as Proof of Concept
  - Conception and construction of a TPC for “on-site” measurements
    - New design of ancillary systems as DAQ
- *Simulations and analysis:*
  - Sensitivity studies with a single TPC:
    - What kind of anomalies/defaults can we see (and in how much time) depending on:

      → Size, detector depth, relative position, density differences...
  - Simulations corresponding to the performed measurements
  - Simulations measurements with a TPC network:
    - Development of 3D analysis by image combination → ***Muon Tomography***
  - Development of track identification and reconstruction algorithms → Resolution studies
    - Azimuth angle → Triggered Micromegas Pads
    - Zenith angle (relative) → Registered pulses time



- **Muon tomography** reveals as an interesting method for the **internal scanning of big objects**
    - Cheap, non-invasive, versatile, hazard-less ongoing

- Among the different techniques to carry out the measurements, **Micromegas-based** telescopes stand out to carry out the measurements
    - Already successfully used in different projects



- New generation of telescopes is being developed → ***D3DT***
    - **TPC readout by a 2D multiplexed micromegas**
        - New applications possible
    - **More news soon**