



DESIGN, CONSTRUCTION AND IN SITU TESTING OF A MUON CAMERA FOR EARTH SCIENCE AND CIVIL ENGINEERING APPLICATIONS.

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Thesis defense for the degree of Ph.D. in Earth & Universe Sciences

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OUTLINE

1. Introduction
 - Context
 - Muons
2. MUST² camera
 - Principle
3. Signal
 - Formation
 - Trajectory reconstruction
4. Experimental results
 - Calibration tests
 - Study case
5. Considerations towards industrialization
6. Conclusions & outlook

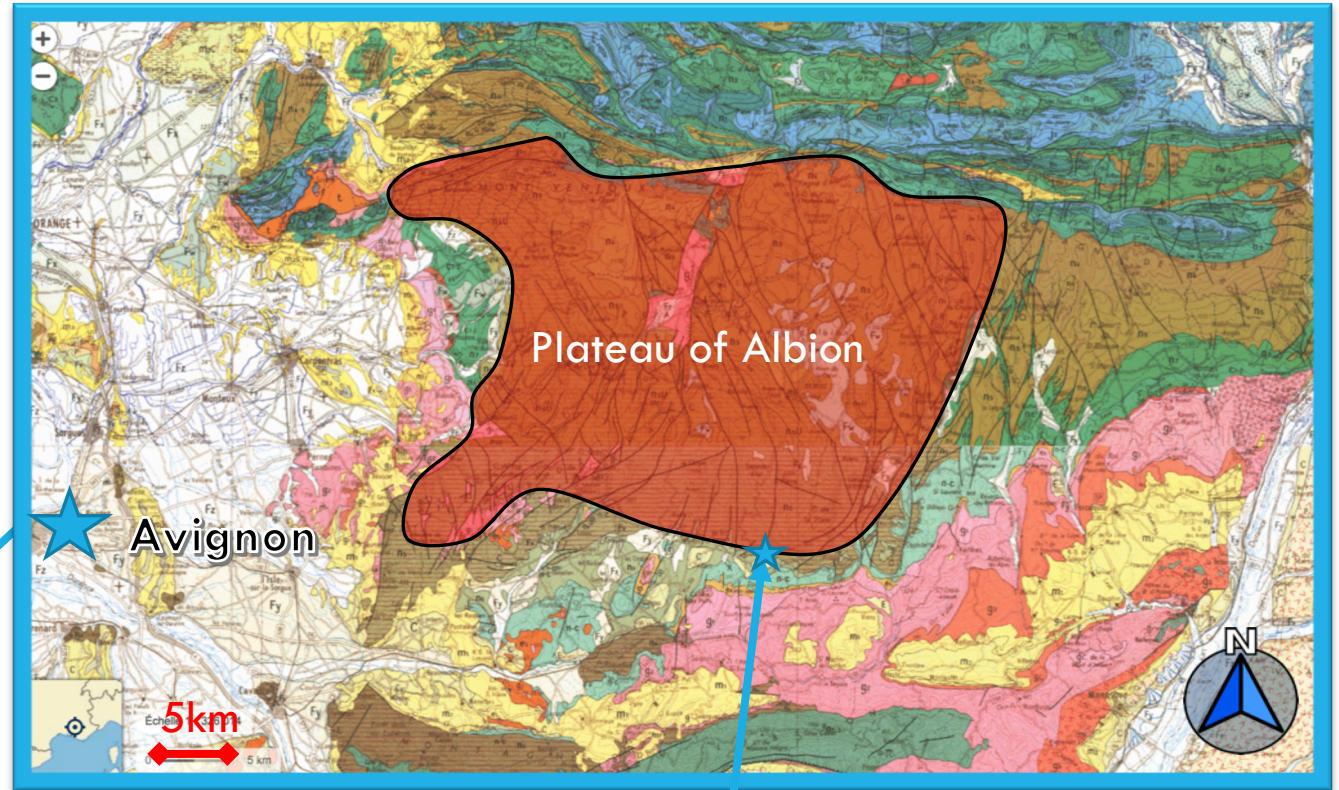


INTRODUCTION - Context



Figure from MODIS project by NASA.

Figure from Géoportail, source BRGM.





INTRODUCTION - Context

Project framework

- The fluid flows across the unsaturated zone
 - This mass motion results into volumetric mass fluctuations: **local density variations**
 - Hydraulic timescale?**
 - Hydraulic volumetric?**
 - Strong porosity and permeability **heterogeneities**
- Experimental site: carbonate reservoir
 - Access to the non saturated zone in LSBB
 - Fontaine de Vaucluse water catchment

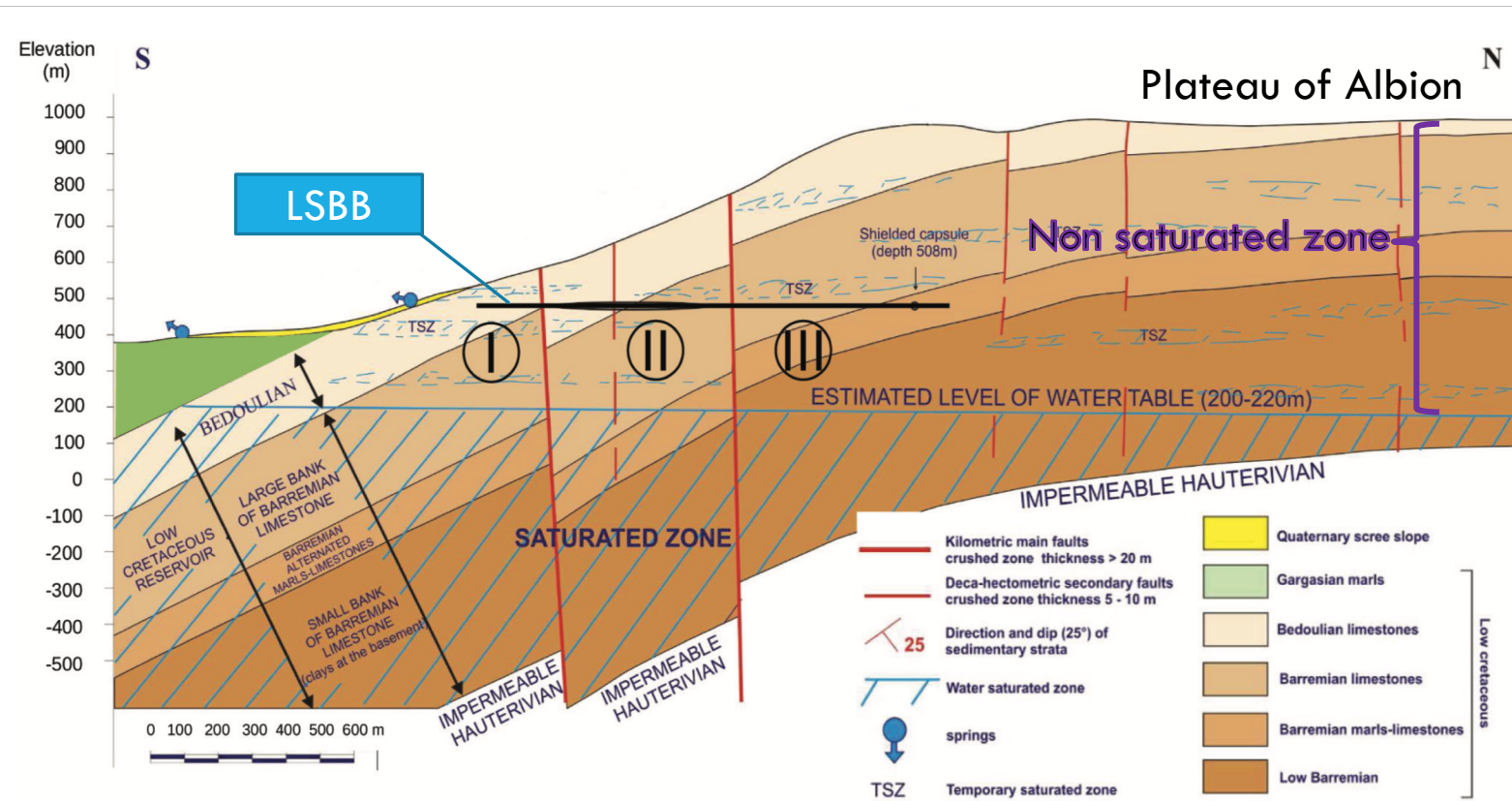
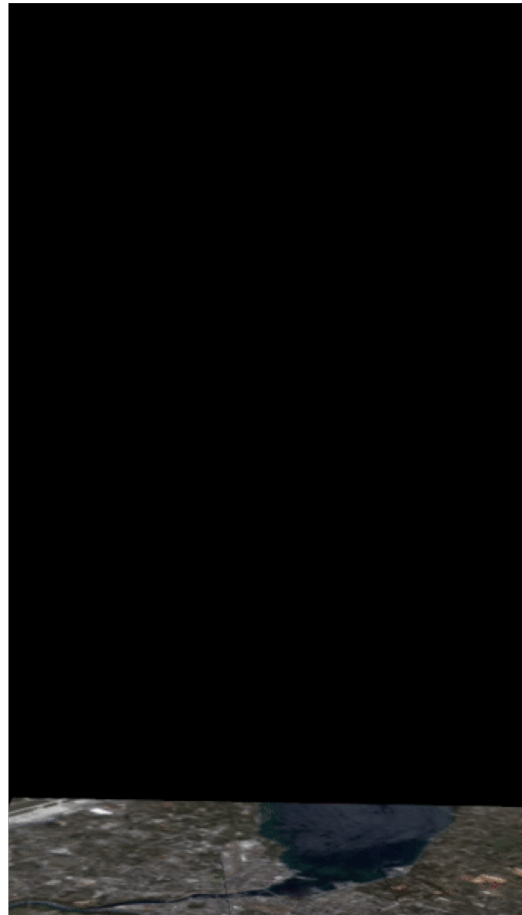


Figure from Sénéchal, (2013)

INTRODUCTION - Context

How to measure temporal density variations?

- The muon flux decreases progressively, with an absorption correlated with the medium opacity*
- Cosmic muons are able to **penetrate up to several hundreds of meters** underground
- **Muographic measurements in transmission** do not require a direct contact between the target volume and the detector
- Provides **complementary information** to other techniques
- Cosmic muons are a natural, permanent, passive source
- Muons average flux at sea level $\sim 10.000 \mu / (\text{m}^2 \cdot \text{min} \cdot 2\pi\text{sr})$

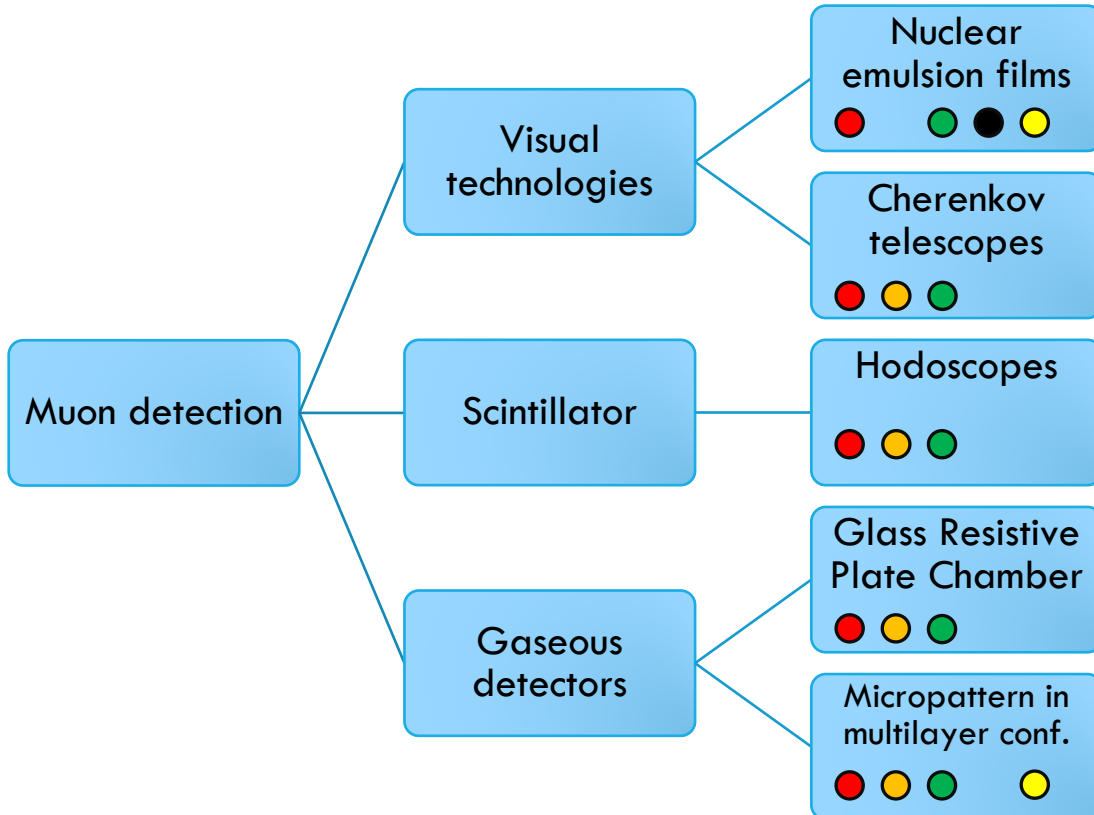


*Opacity is the density integrated over the path length



INTRODUCTION - Muons

Which muon detection technology?



- Requirements for the targeted application:
 - Retrieve the particle trajectory (zenith and azimuth angles)
 - Temporal information of the detected muons
 - Angular resolution compatible with geophysical techniques
 - Big angular acceptance
 - Compact and transportable for narrow operation

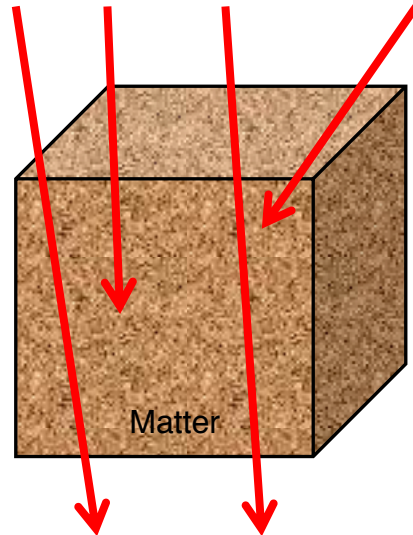
There was no muon detection technology capable of fulfilling all the requirements:

Need for a new technology

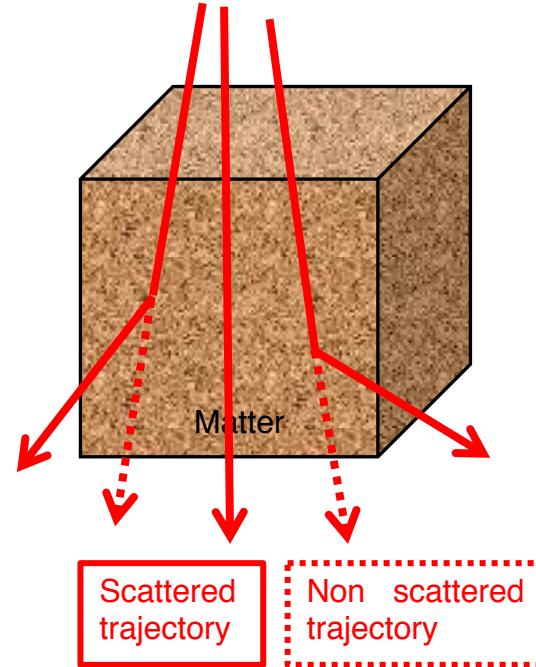
INTRODUCTION - Muons

What should we measure?

Muon transmission



Muon flux attenuation
due to energy loss



Muon scattering

- Two kinds of approaches depending on the muon interaction
- Based on the screening effect of matter on the natural flux of cosmic muons
- Both interactions take place **simultaneously**
- Their contribution varies depending on the case, **transmission** is more sensitive to absorption when imaging big rock volumes



INTRODUCTION - Muons

How to quantify the flux attenuation?

Muon flux Surface at sea level

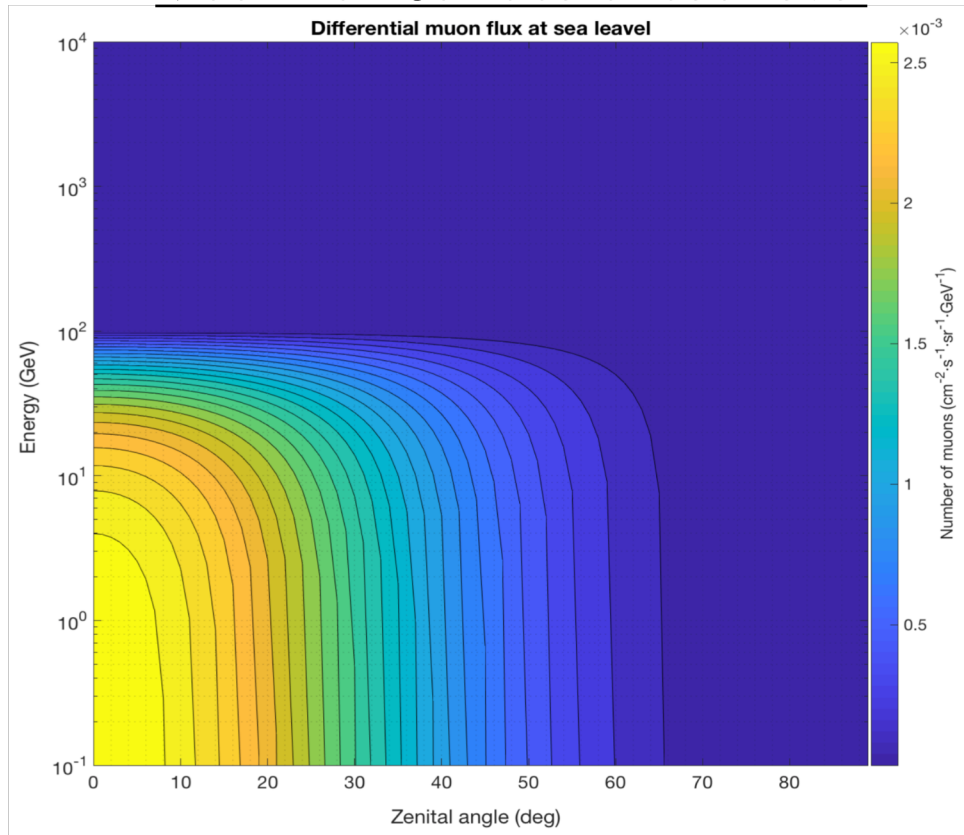
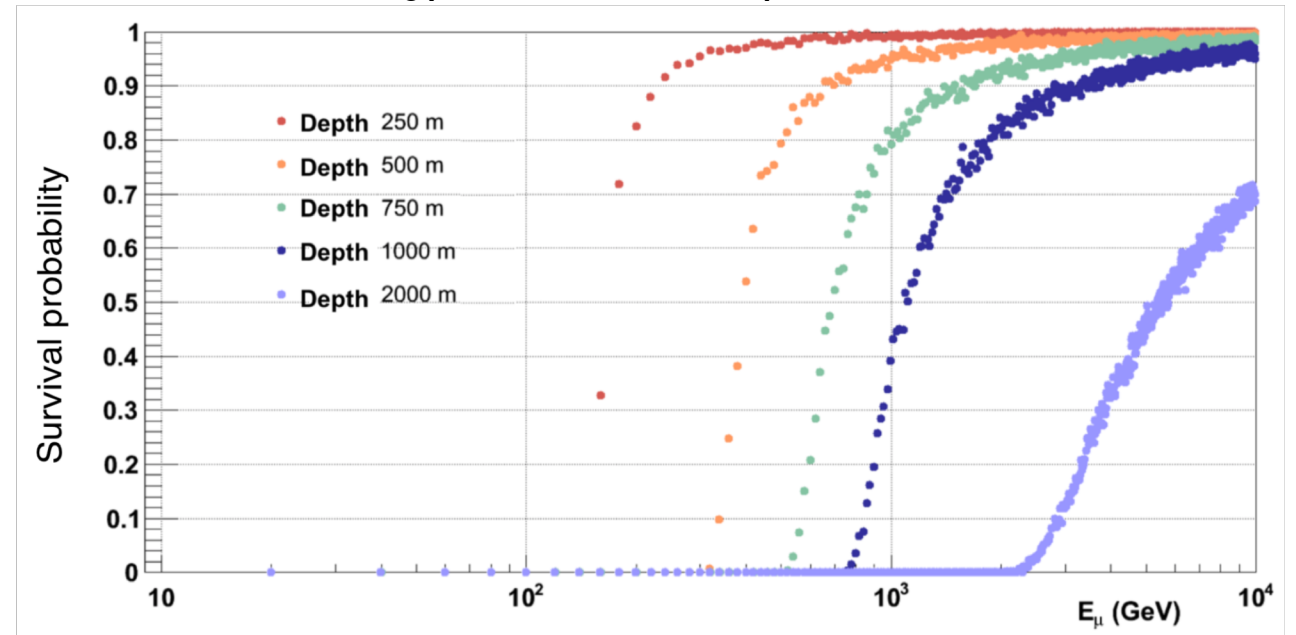


Figure of Angular and energy distribution of the differential muon flux at sea level obtained with the Gaisser's model with Tang parameters [Tang, 2006].

Underground

Muon survival probability of muons according to their energy for different depths of standard rock*.

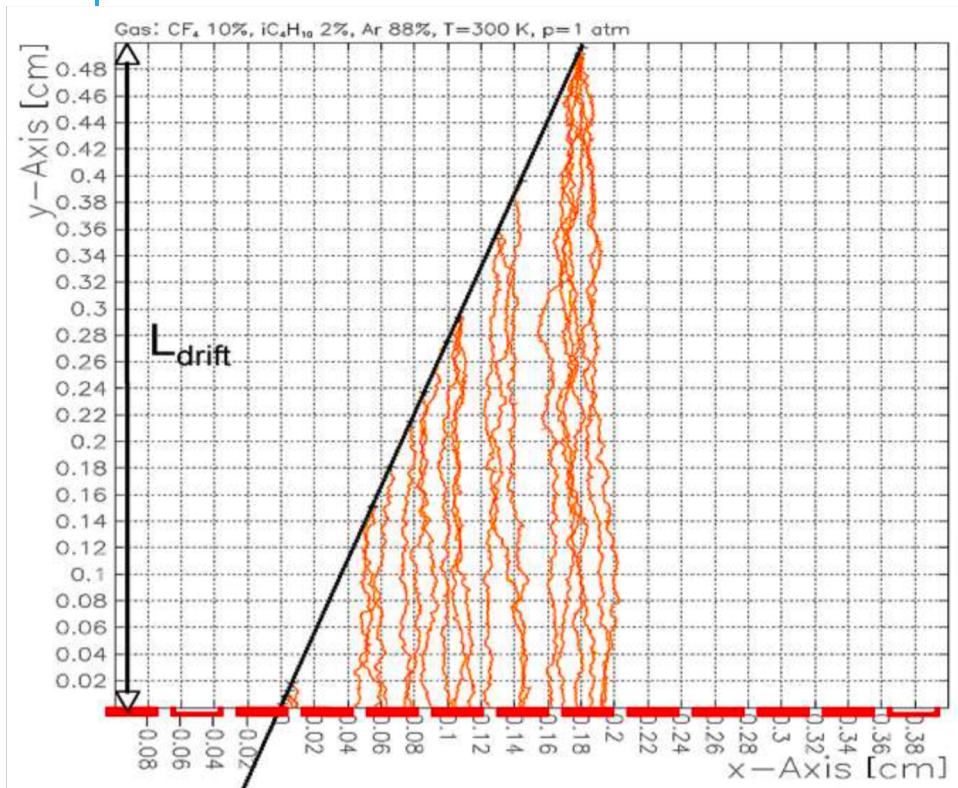


Simulation made with MUSIC code and 10.000 muons per depth.

*Standard rock ($A=22, Z=11, \rho=2,65g/cm^3$)

Figure from [Hivert, 2017].

MUST² CAMERA – Principle



Simulation of the passage of a muon inside a detector made with Garfield++ code by R. Veenhof [Veenhof, 2010].

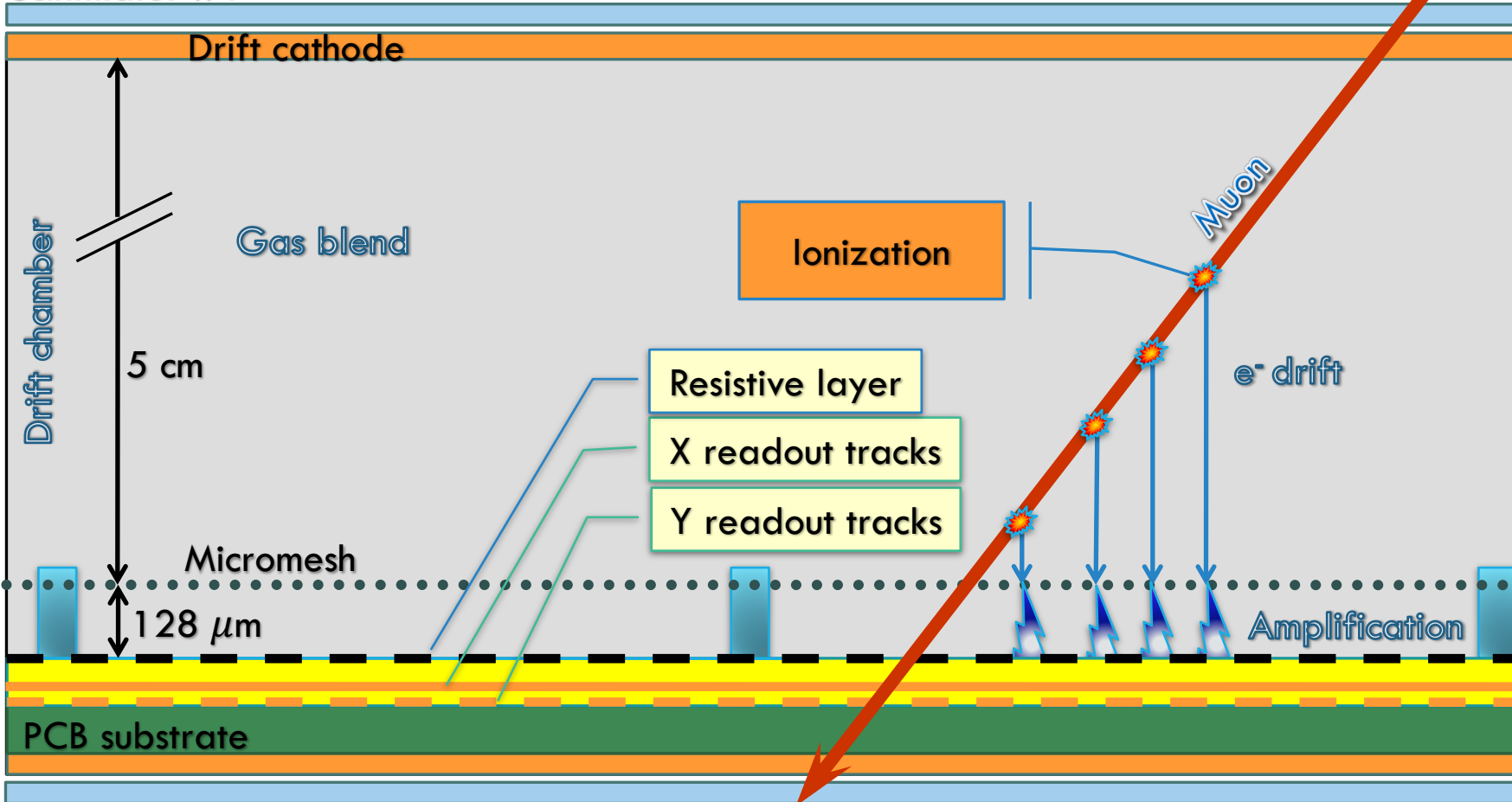
How to measure the trajectory of a muon?

- Conversion of the incident radiation into primary e⁻ and ions.
- Ionizations generated randomly, stochastic process
- The primary electrons drift towards the amplification zone
- The longitudinal and transverse diffusion should be minimized

MUST² CAMERA – Principle

MUon Survey Tomography based on Micromegas detectors for Unreachable Sites Technology

Scintillator #1



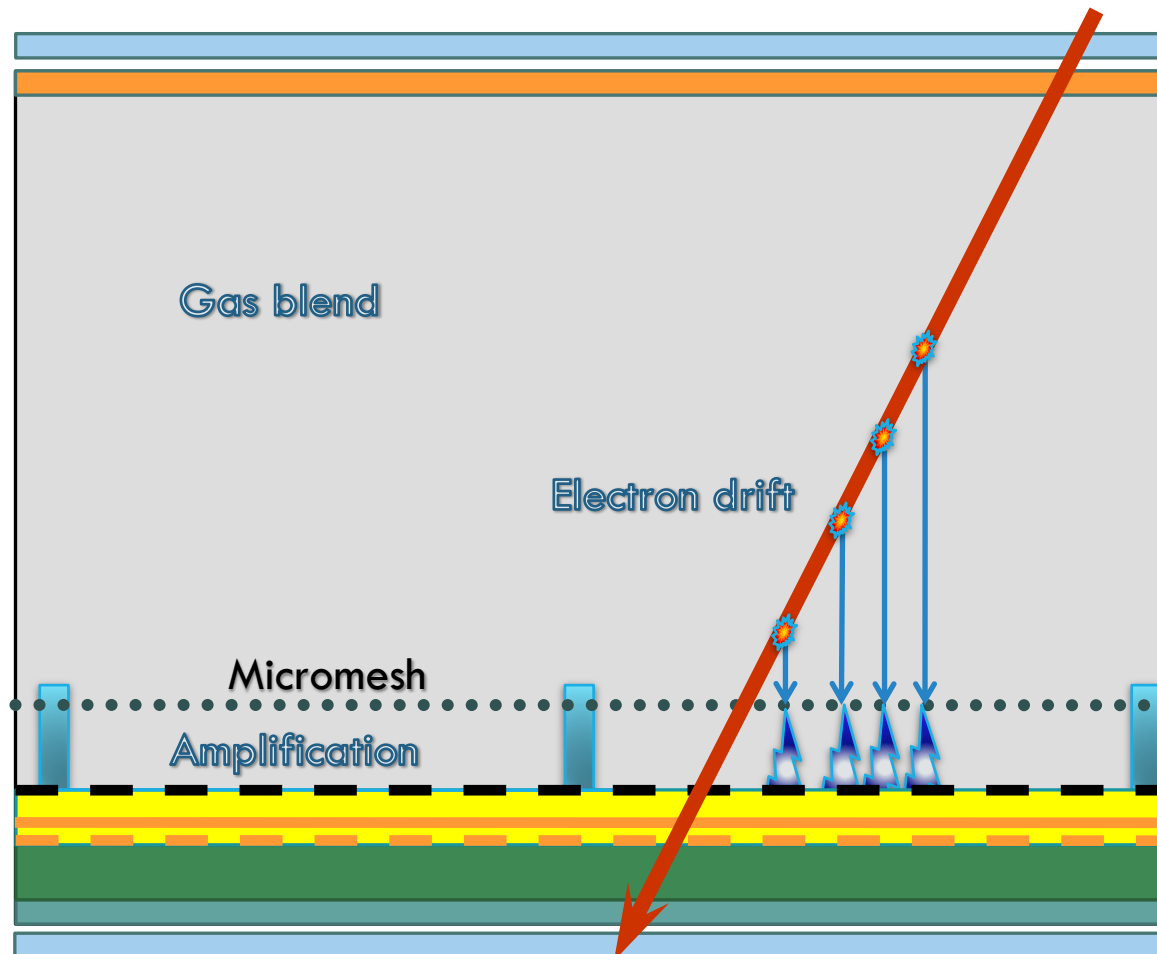
- Thin time projection chamber
- Bulk Micromegas with resistive layer [Giomataris, 2006]
- Accessory scintillators

Scintillator #2

MUST² CAMERA – Principle

Considerations towards TPC operation

- Gas choice
- Adequate projection of primary electrons
- Minimize neutralization of e^- by the micromesh
- Enough signal amplification
- Reliable trigger



SIGNAL – Formation

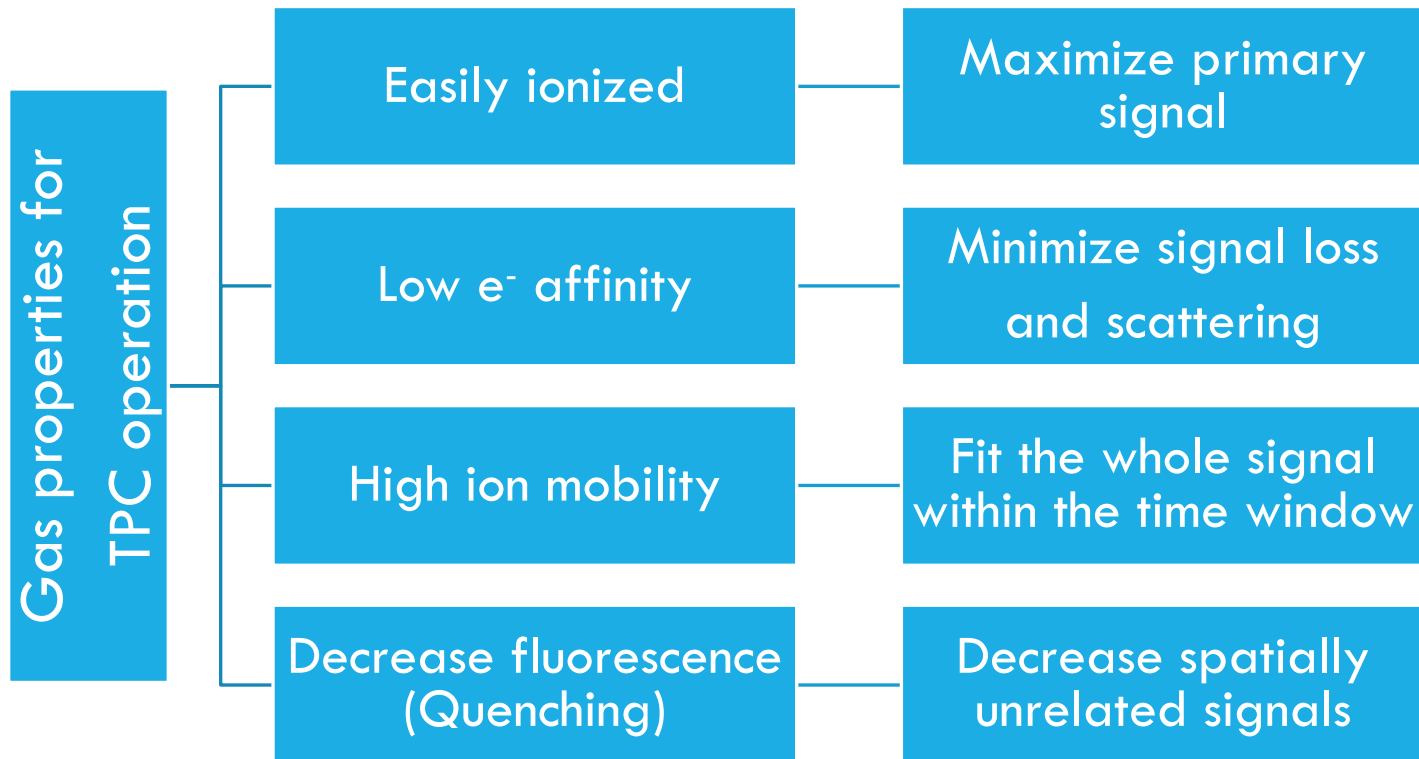
How to optimize the signal?

$$\text{Signal strength} = \underbrace{N_T \cdot (1 - R) \cdot (1 - A) \cdot T \cdot G}_{\text{Physical processes of the detector}} \cdot k$$

- N_T = total ionization per path length (Gas choice)
- R = Recombination after primary ionization (\vec{E}_{drift})
- A = attachment to gas constituents during scattering (Gas contaminants)
- T = Micromesh e^- transparency (Micromesh geometry and $\vec{E}_{drift} / \vec{E}_{amp}$ ratio)
- G = detector gain (\vec{E}_{amp})
- k = conversion factor between the charge generated and the signal read by the electronics (readout design and electronics configuration)

SIGNAL – Formation

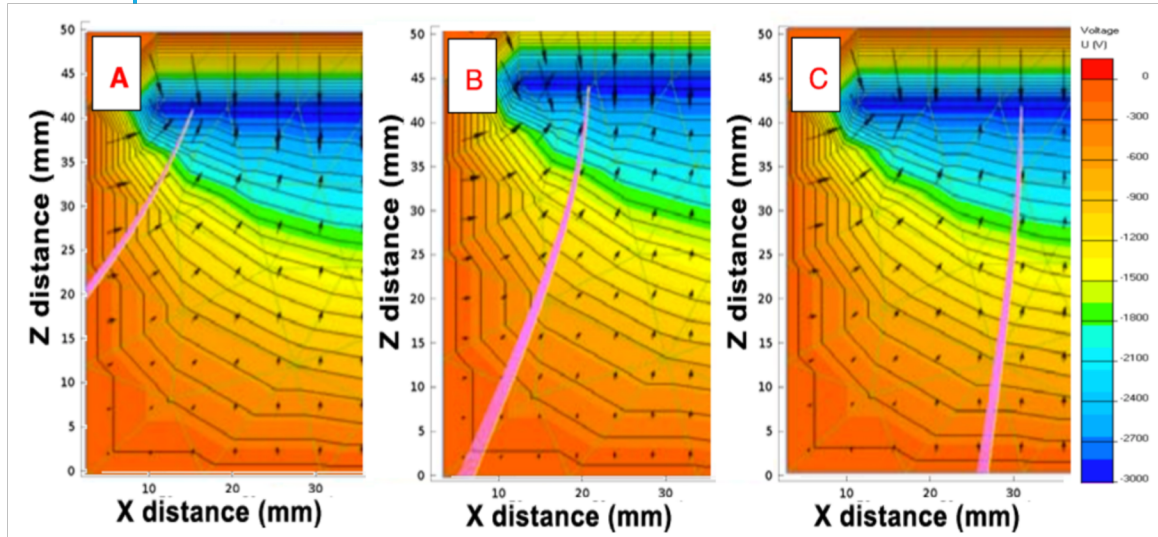
How to choose the gas?



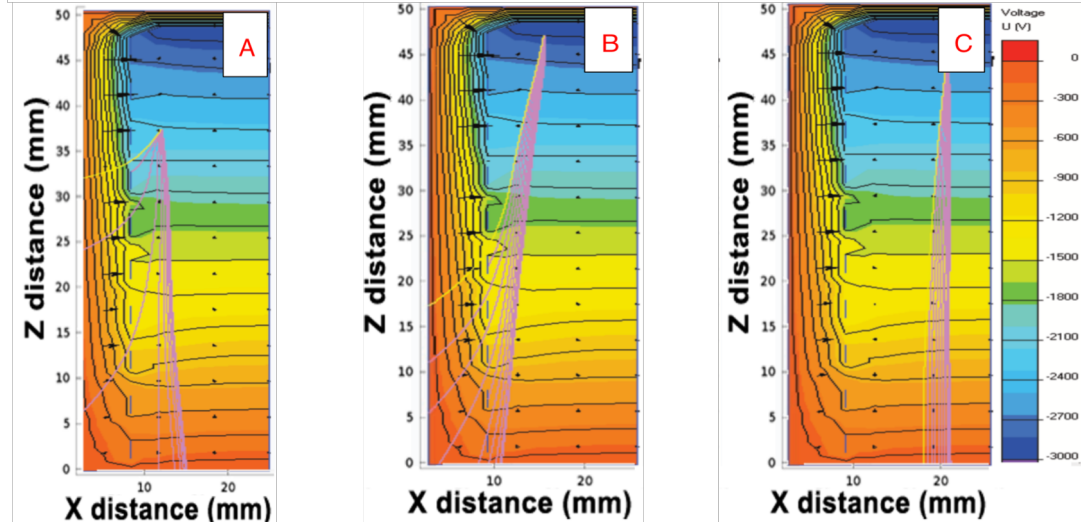
- TPC operation requires a gas with conflicting properties.
- Specific gas blend combining complementary features.
 - Argon (88%), easily ionized and low electron affinity
 - CF₄ (10%) increases ion mobility
 - iC₄H₁₀ (2%) quenching gas



SIGNAL – Formation



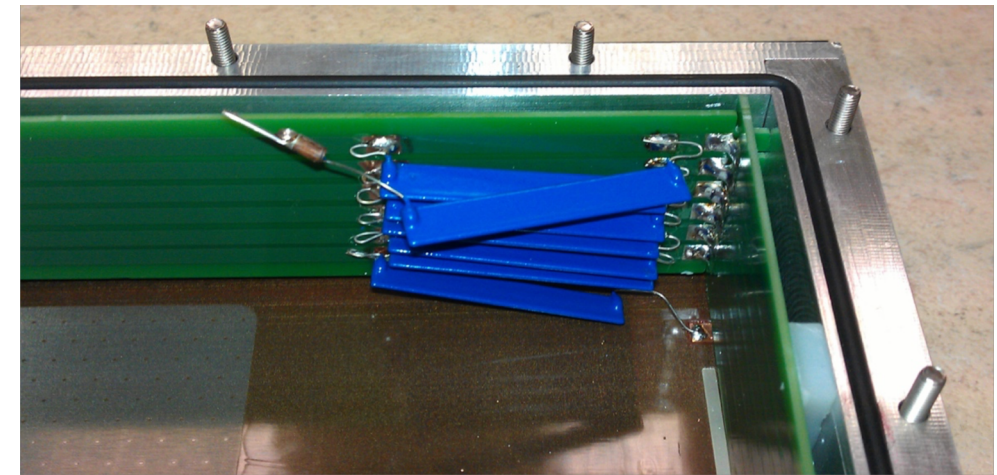
Without field cage



With field cage

How to obtain a straight projection in a TPC?

- Simulations of the electron drift within the TPC reveal **deviations** from straight path near the frame perimeter.
- Electric field cage reduces this unwanted effect

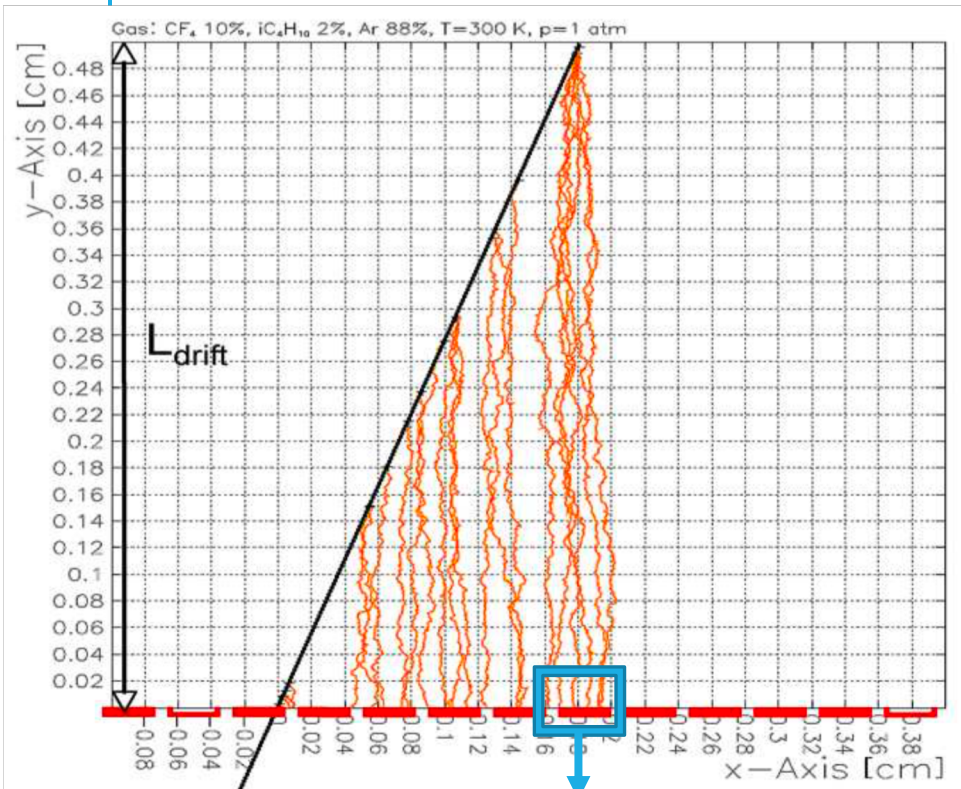


Figures show the most probable path of the electron inside the TPC drift chamber according to their position. Simulation are made for 10 electrons each with QuickField code.



SIGNAL – Formation

How is the signal formation near the amplification zone?



Zoom of amplification zone



Micromesh

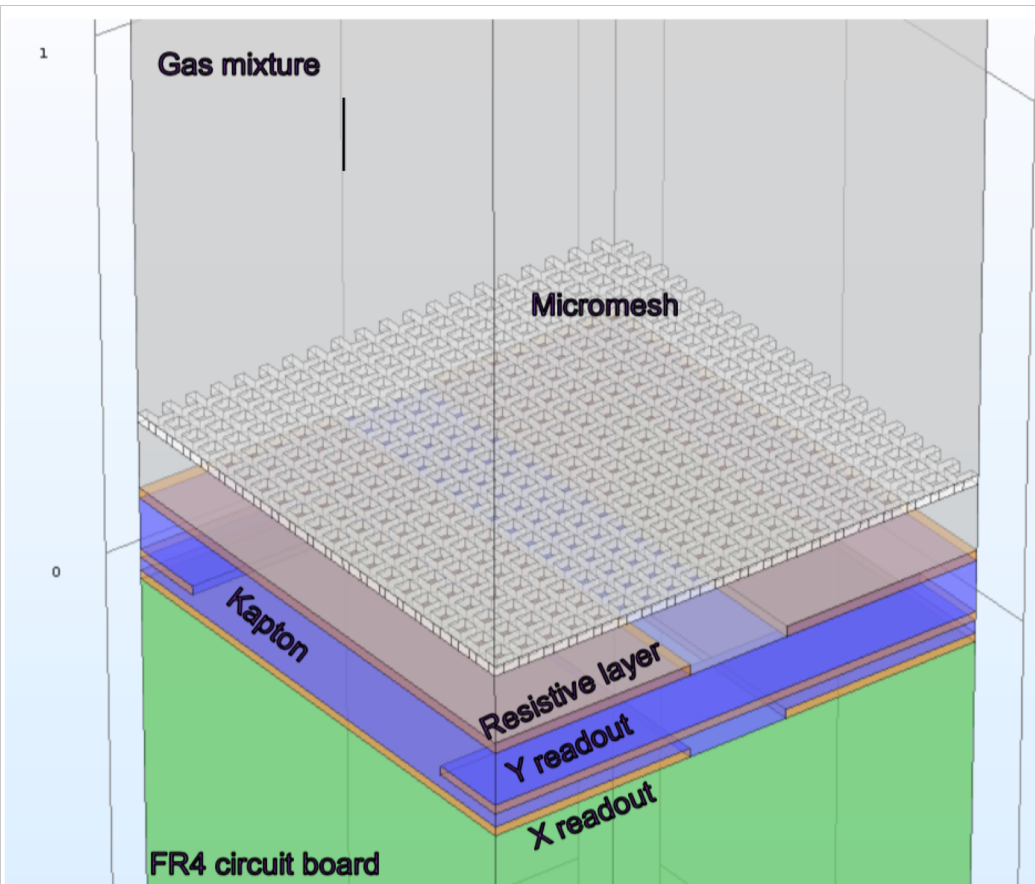
- Primary electrons arrive near the micromesh
- A small fraction of electrons is neutralized against the micromesh [Nikolopoulos, 2011]
- The stronger electric field accelerates the electrons and causes avalanches (Gain $\sim 10^4$)
- The displacement of charges induces signal into the micromesh and the readout tracks

Simulation of the passage of a muon inside the MUST² camera made with Garfield++ code by R. Veenhof [Veenhof, 2010].

SIGNAL – Formation

Which readout suits better?

- The big active surface and angular resolution required results into a high granularity readout
- Pixel-based detectors lead to high number of channels (n^2 channels)
- Strip based detectors require less electronics ($2n$ channels)
- The price to pay:
 - Heterogeneity in terms of charge induced in the X and Y planes



Scheme of the unit cell of the Micromegas detector. Performed with COMSOL multiphysics®.



SIGNAL – Formation

How to quantify the signal amplification?

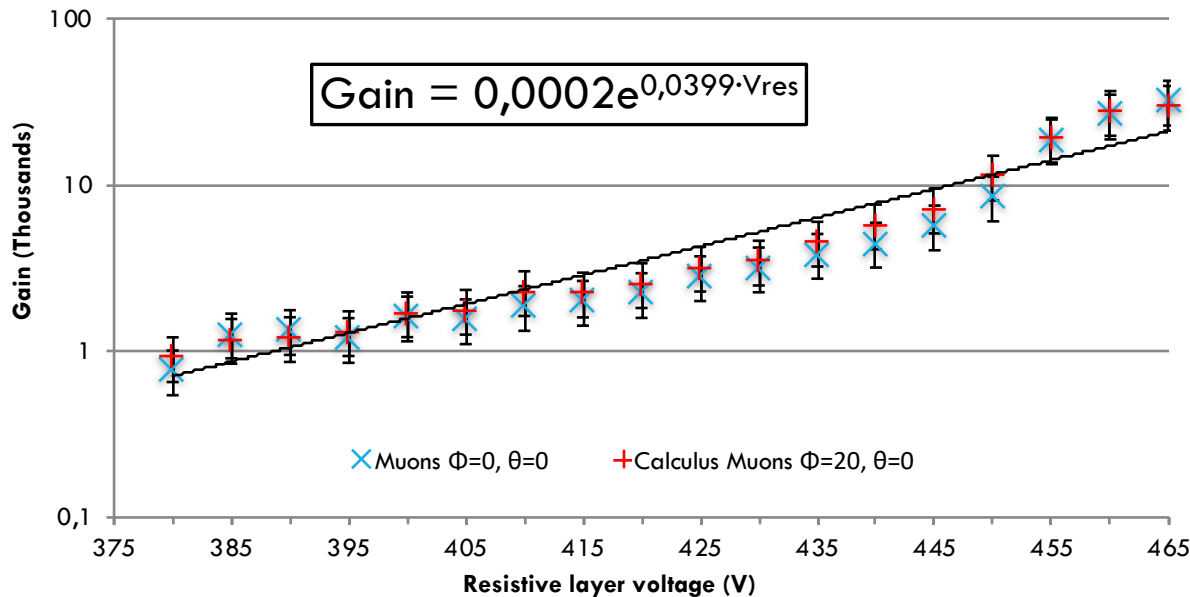
$$Gain = \frac{\Delta I}{N_T \cdot d \cdot \mu/s \cdot charge\ of\ e^-}$$

ΔI = Average variation of the current consumption between spills and breaks (nA)

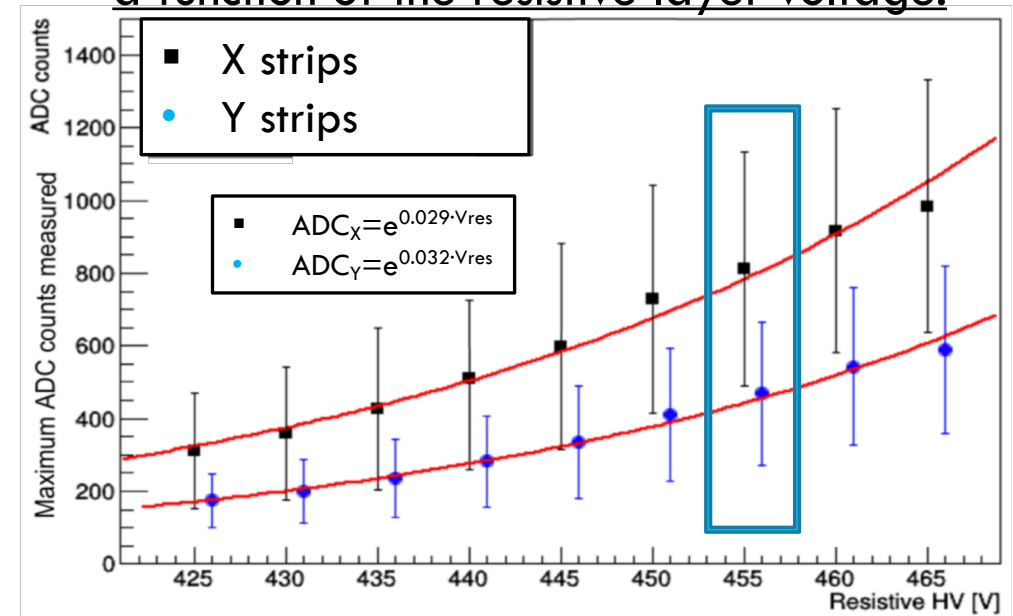
$N_T \cdot d$ = Number of electron-ion pairs induced by the muon

μ/s = Number of muons per second during the measurement (Muons per spill/spill length).

Calculated gain as a function of the resistive voltage

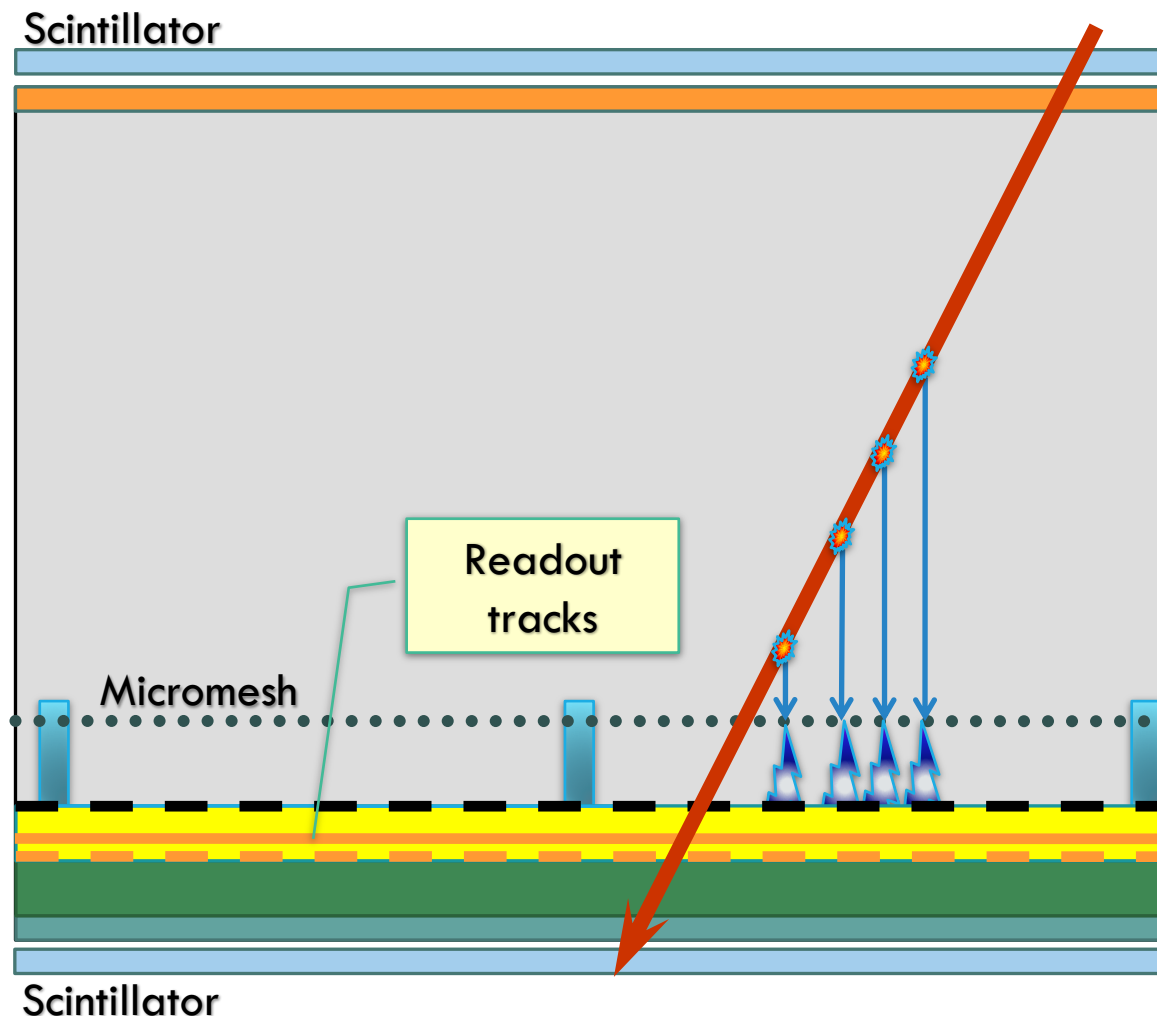


Signal amplitude of the MUST² camera as a function of the resistive layer voltage.



SIGNAL – Formation

How to trigger the acquisition?



- 1. Auxiliary scintillators in coincidence**
 - Reduces the false positives due to random coincidences or instrumental noise
 - Increases price and volume
- 2. Self-trigger from the mesh**
 - Doesn't need auxiliary equipment
 - Sensible to instrumental noise
 - Hard to calibrate
 - Gain dependent
- 3. Signal over threshold track trigger**
 - Doesn't need auxiliary equipment
 - Allows customization
 - Sensible to instrumental noise
 - Gain dependent



SIGNAL – Formation

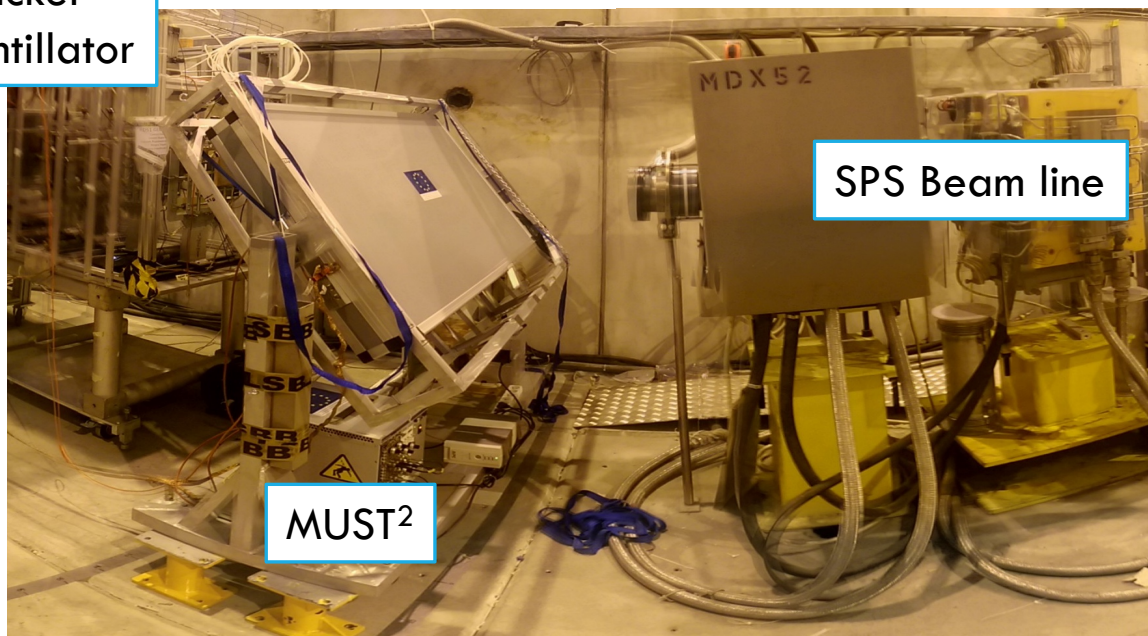
Trigger validation

Tracker scintillator

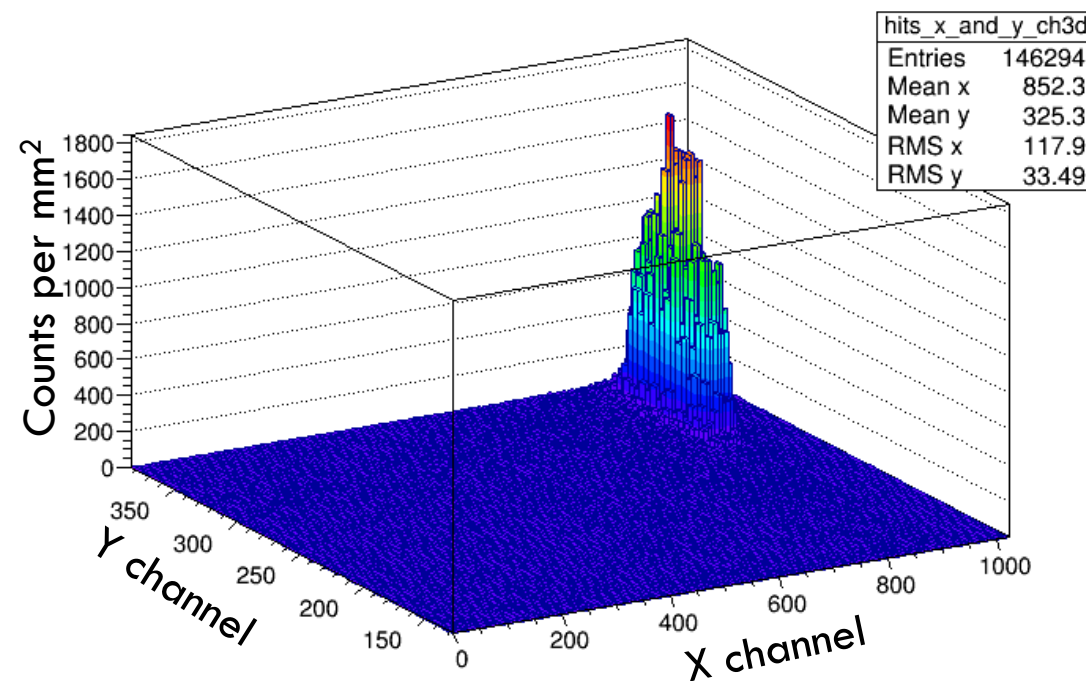
Tracker scintillator

SPS Beam line

MUST²



Muon beam test at CERN thanks to RD51 collaboration

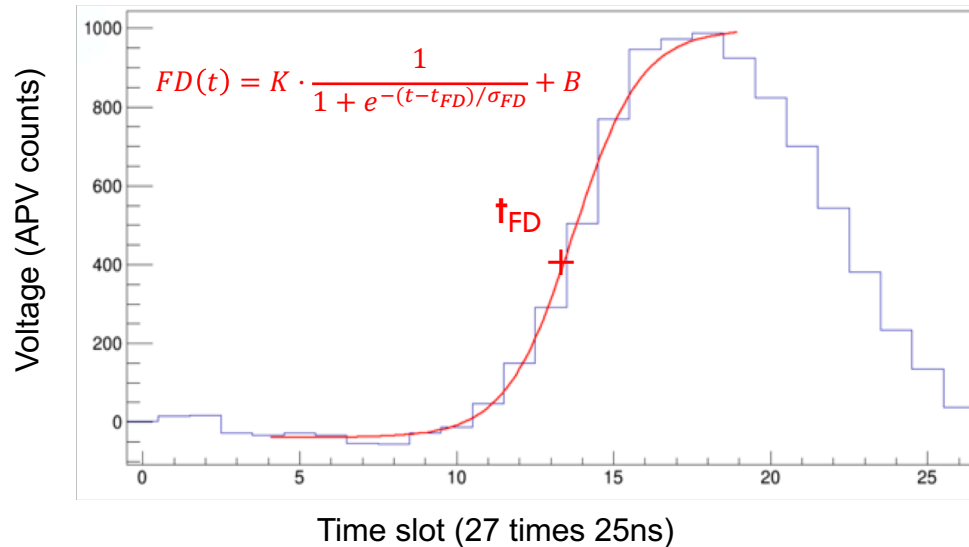


Histograms with the detected events per mm² for different positions

SIGNAL – Trajectory reconstruction

How to retrieve temporal information?

Example of signal fit with a Fermi-Dirac function for 1 isolated channel

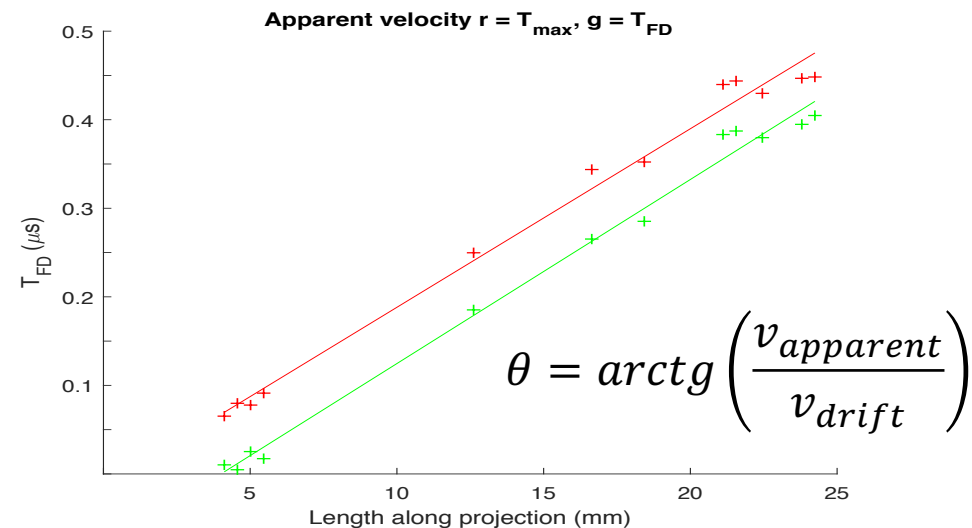
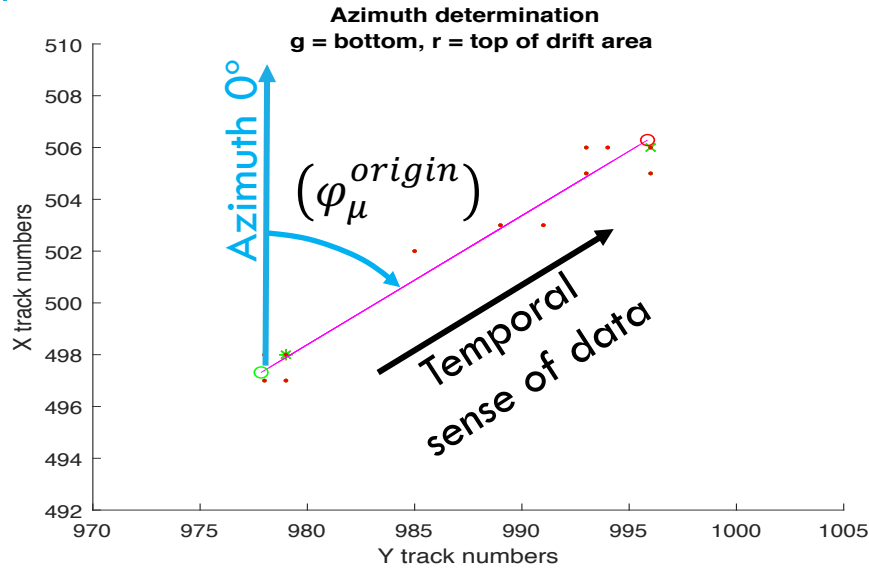


- Reconstruction of a single channel signal
- Signal fit
 - Allows determining the signal rise time (t_{FD}) with a few ns resolution
 - Determines the hit tracks in X and Y axes

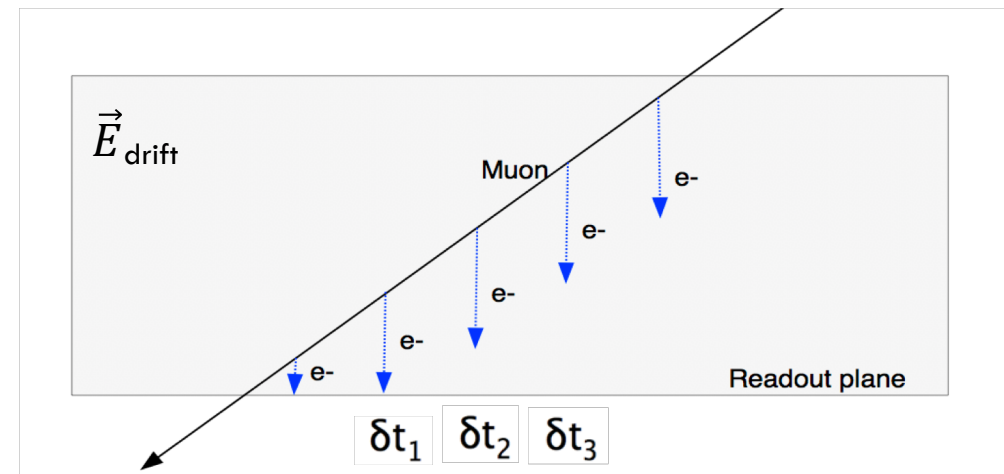


SIGNAL – Trajectory reconstruction

How to retrieve the muon trajectory?

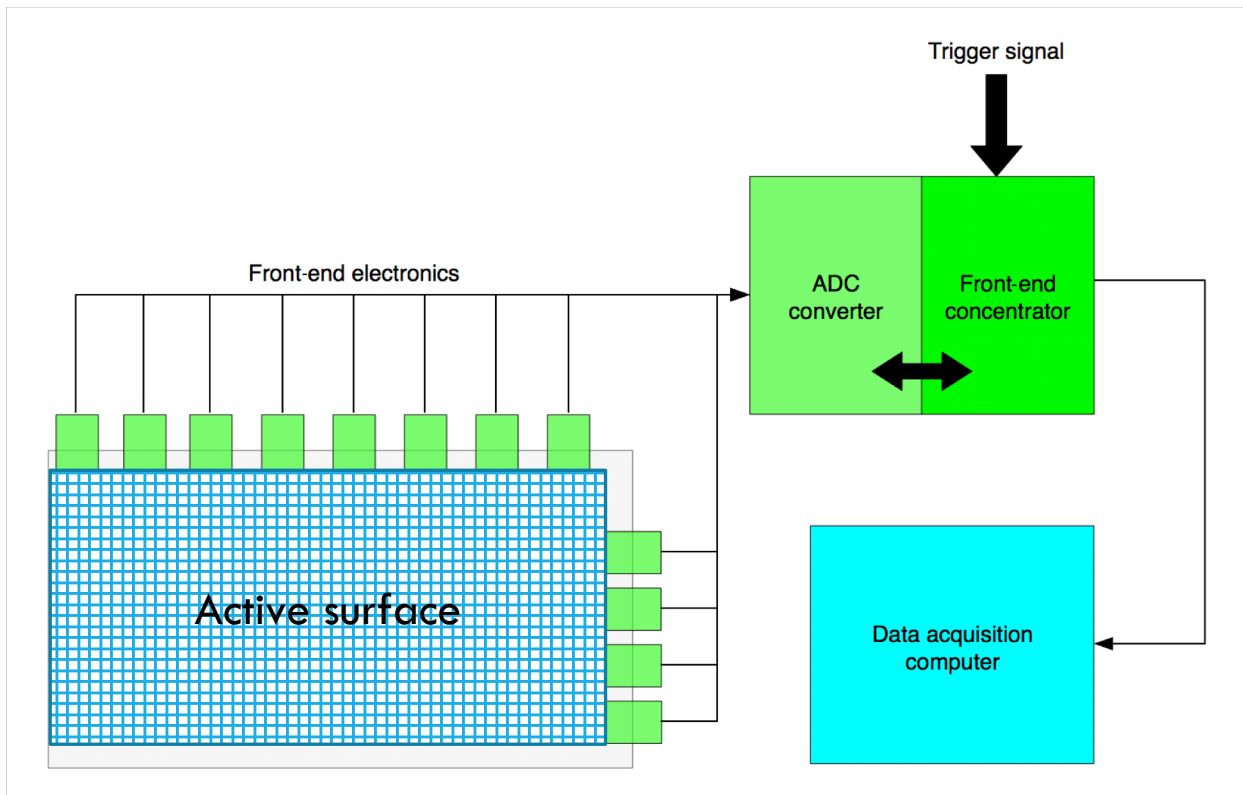


- The arrival time of e^- is distance-dependent
- The e^- drift speed is known and constant for a given \vec{E}
- The time difference provides information about the original height of the ionization point
- The azimuth angle can be calculated by the orientation of points along the readout plane
- The zenith angle is related to the length of track and time interval between points



SIGNAL – Trajectory reconstruction

How to instrument the camera?



- Requirements:
 - ❑ Good enough temporal resolution
 - ❑ Highly scalable
 - ❑ Modular
 - ❑ Relatively inexpensive (big number of channels)
- Challenges:
 - ❑ Network configuration, distance between elements
 - ❑ Adapt existing or develop new software tools for data acquisition
 - ❑ Live data management and analysis



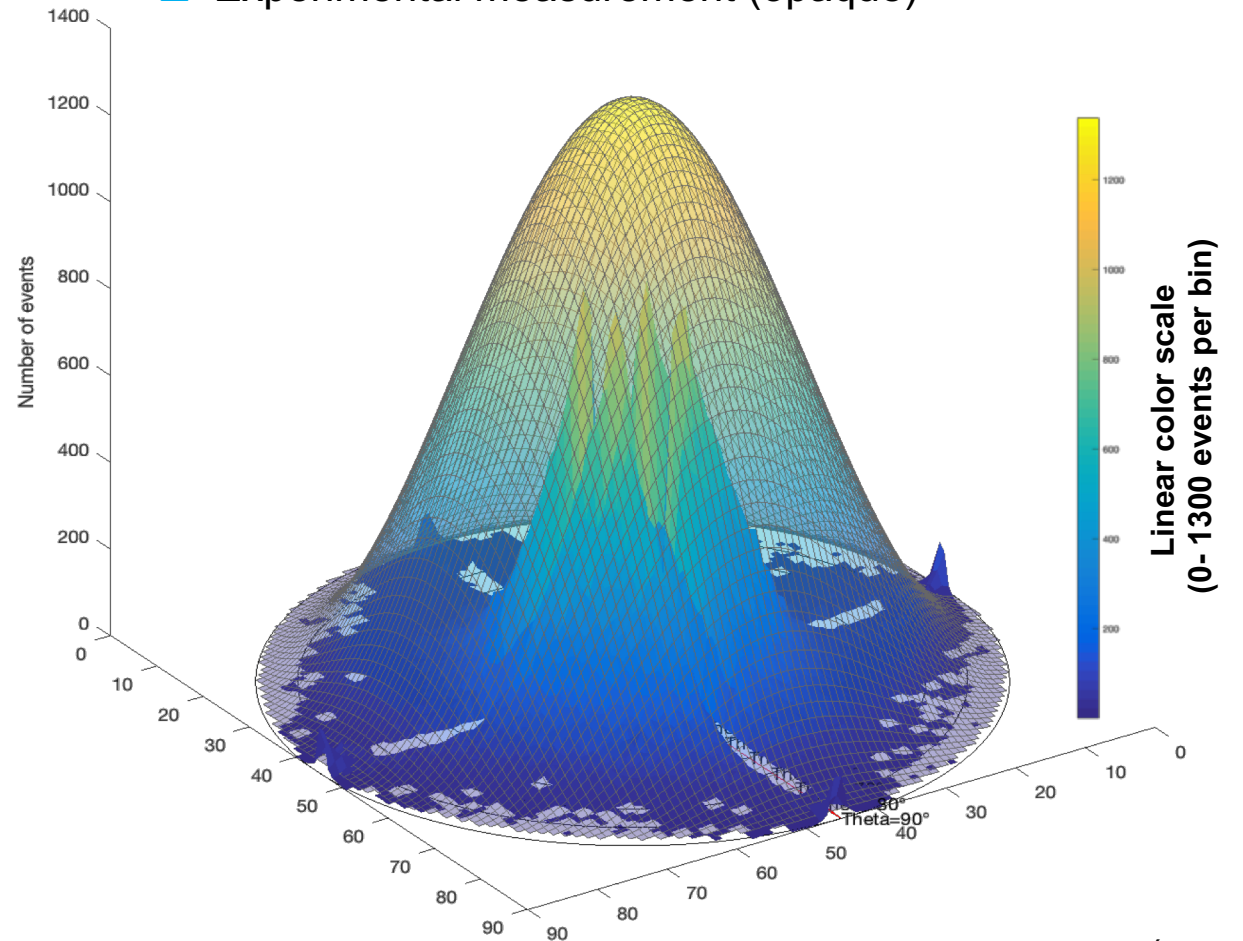
EXPERIMENTAL RESULTS – Calibration tests : response characterization

Aerial view of the top of the mountain hosting the LSBB, test site for open air measurements.



Number of muons:

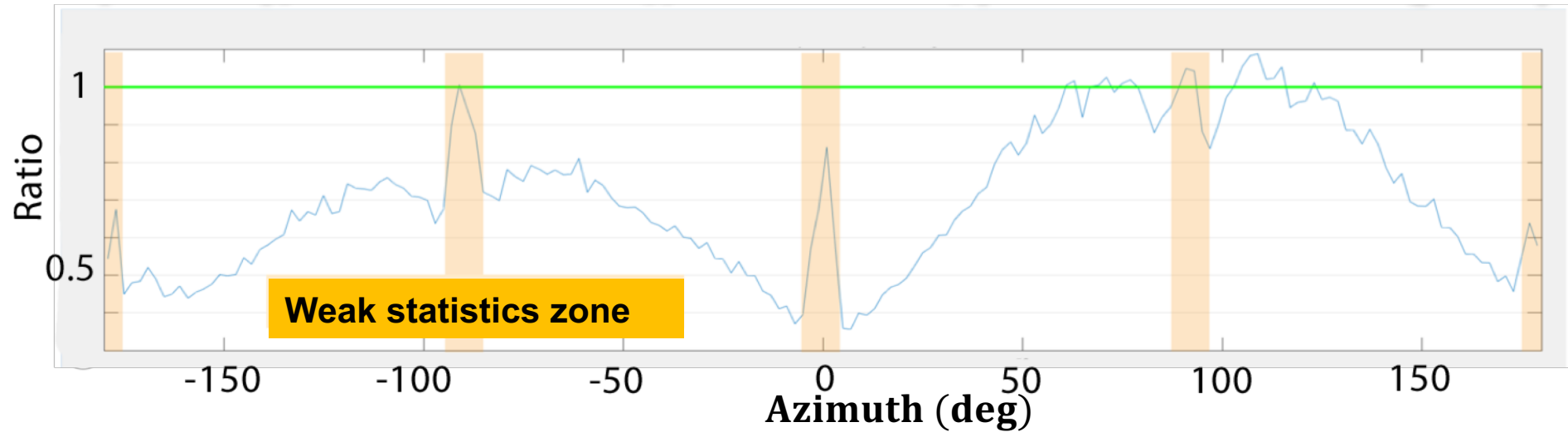
- Expected according to Tang, (2006) model (translucid)
- Experimental measurement (opaque)





EXPERIMENTAL RESULTS – Calibration tests : first qualitative measurements

$$\text{Ratio} = \frac{\text{Muons per azimuth deg } OPEN\ SKY}{\text{Muons per azimuth deg } EXP. MEASUREMENT}$$



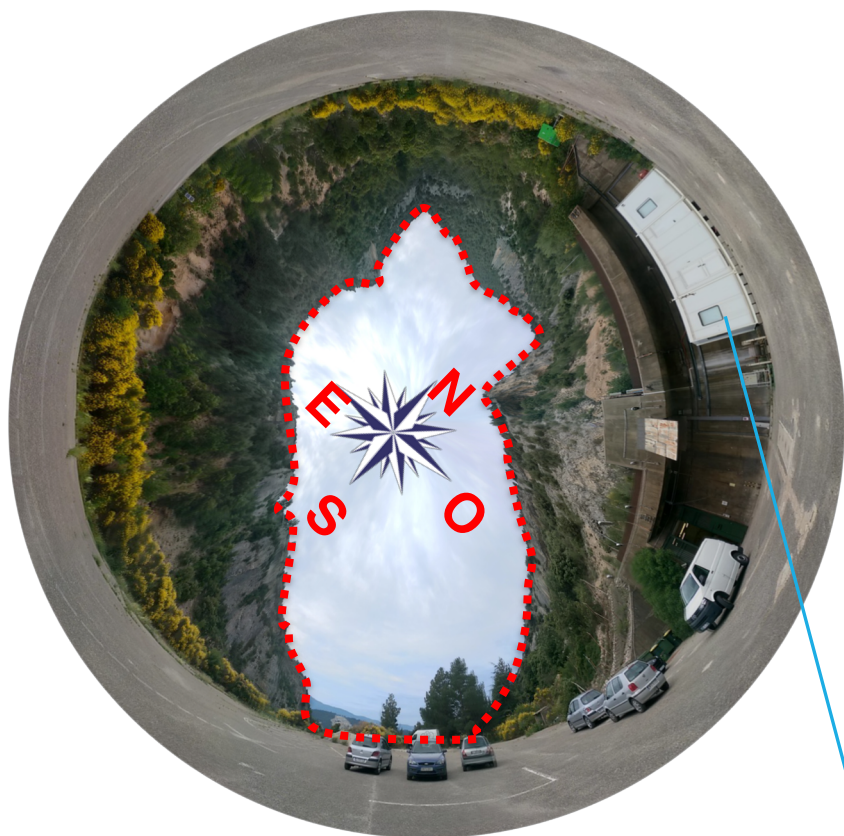
360° view around the camera with the same orientation as the upper graphic



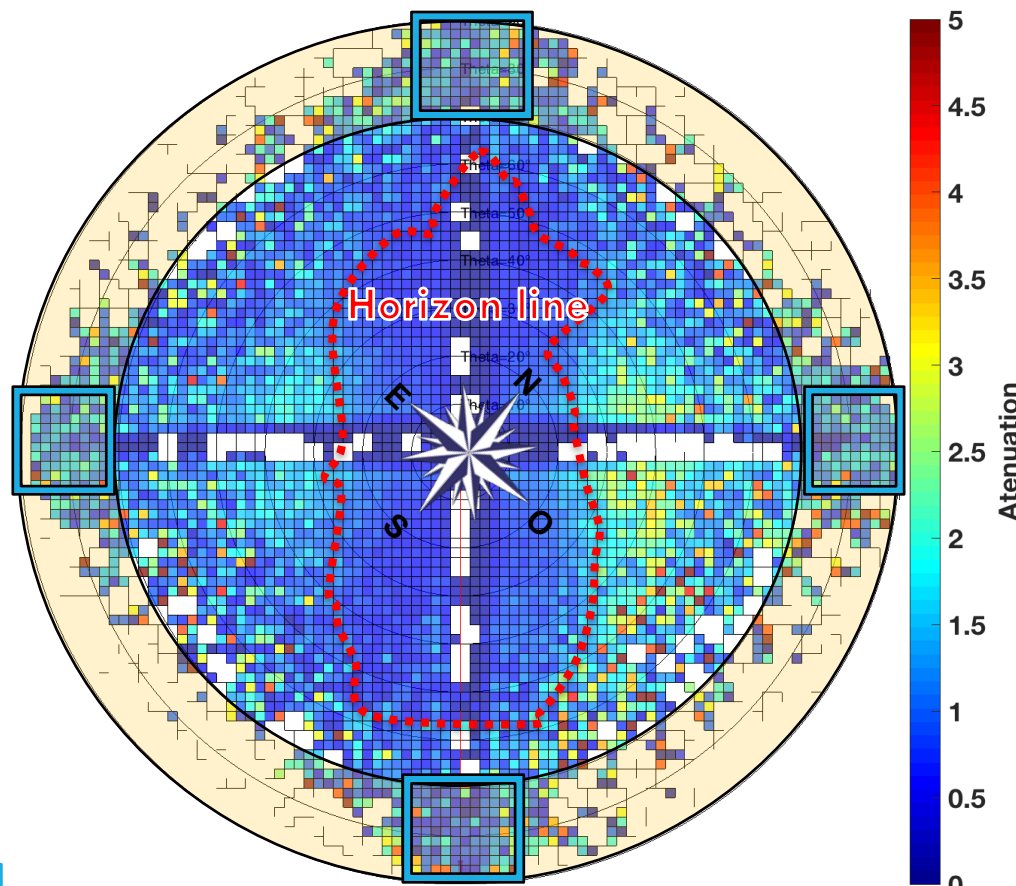


EXPERIMENTAL RESULTS – Calibration tests : first qualitative measurements

360° view around the camera



Camera location



Artefacts created by the reconstruction algorithm

Weak statistics zone

EXPERIMENTAL RESULTS — Study case



▪ Monitored parameters:

- Temperature, humidity and atmospheric pressure inside the valve house
- Level, temperature and conductivity of reservoir's water
- Precipitations (only known water source)

Known topology



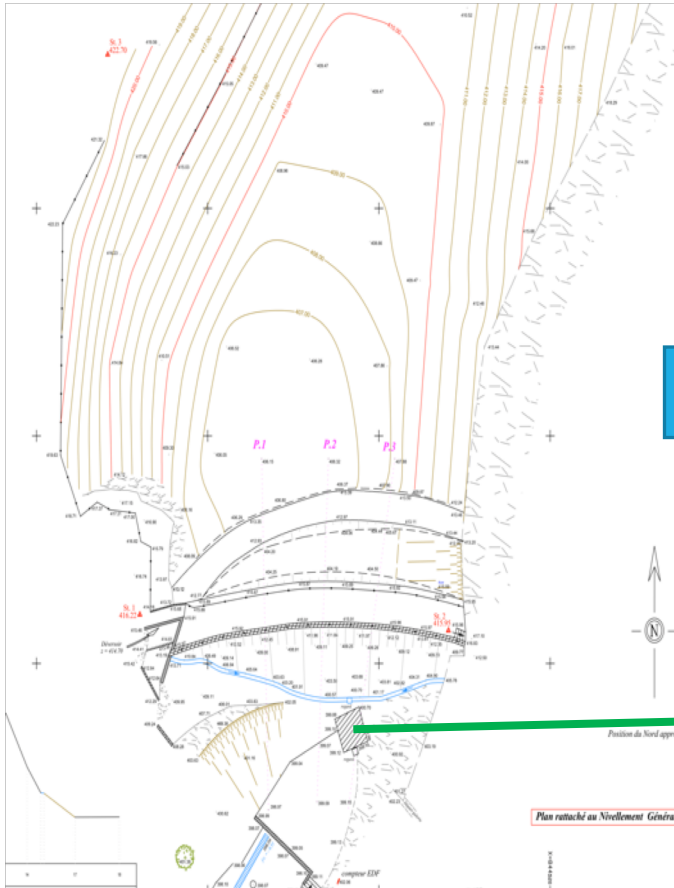
Risk monitoring





EXPERIMENTAL RESULTS – Study case

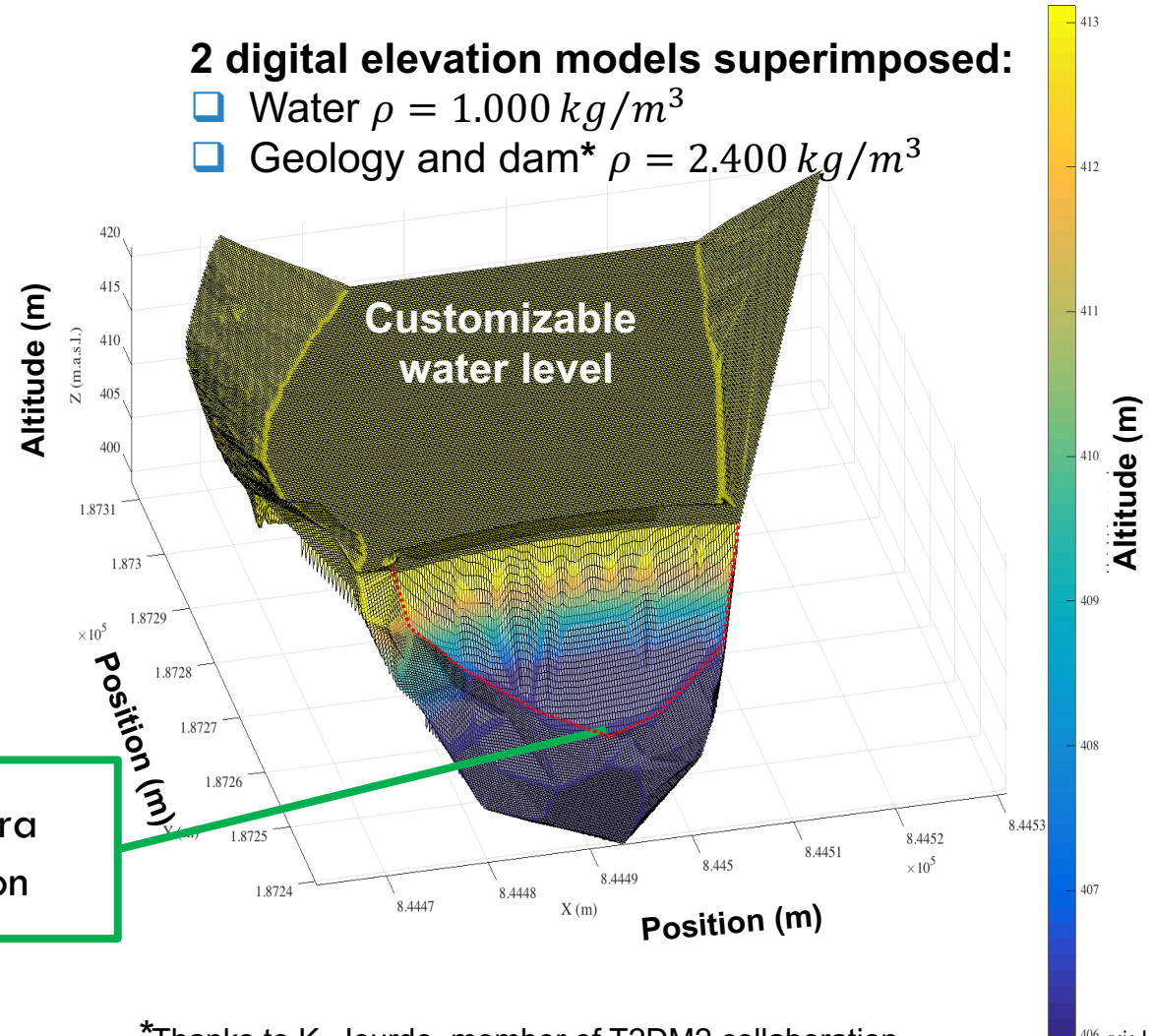
Topographic data



Camera location

2 digital elevation models superimposed:

- Water $\rho = 1.000 \text{ kg/m}^3$
- Geology and dam* $\rho = 2.400 \text{ kg/m}^3$

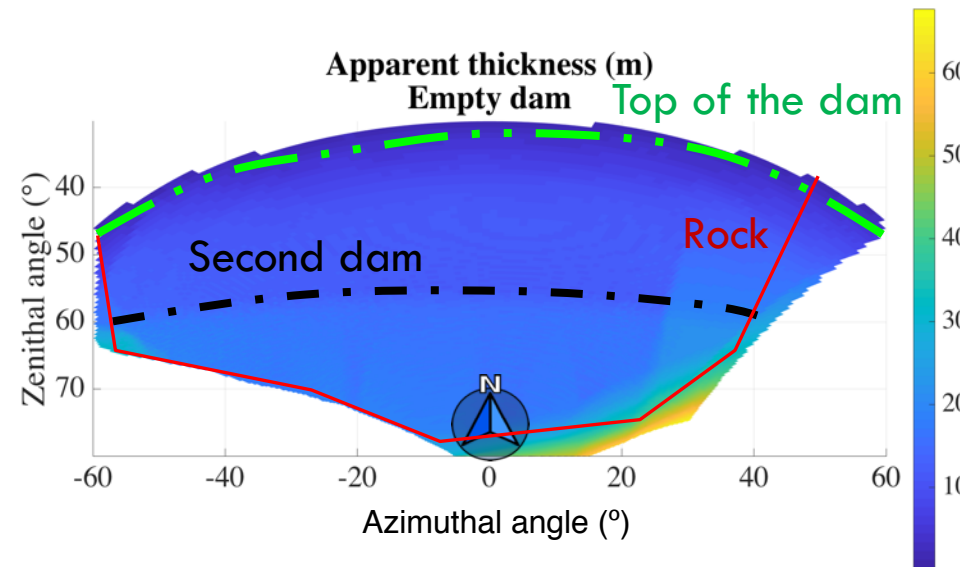
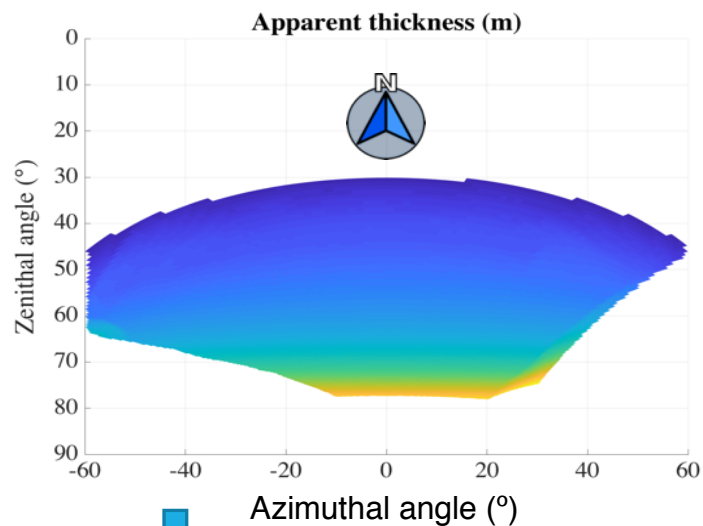


Source: Société du canal de Provence

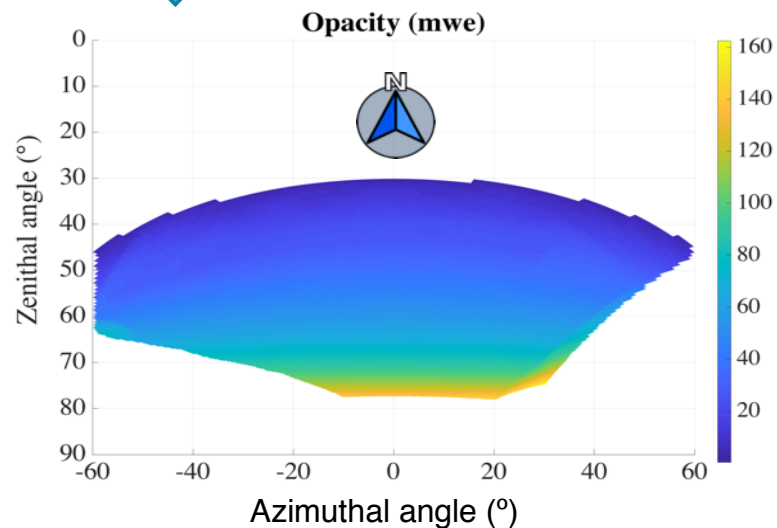
*Thanks to K. Jourde, member of T2DM2 collaboration



EXPERIMENTAL RESULTS – Study case



Opacity = Density · Distance

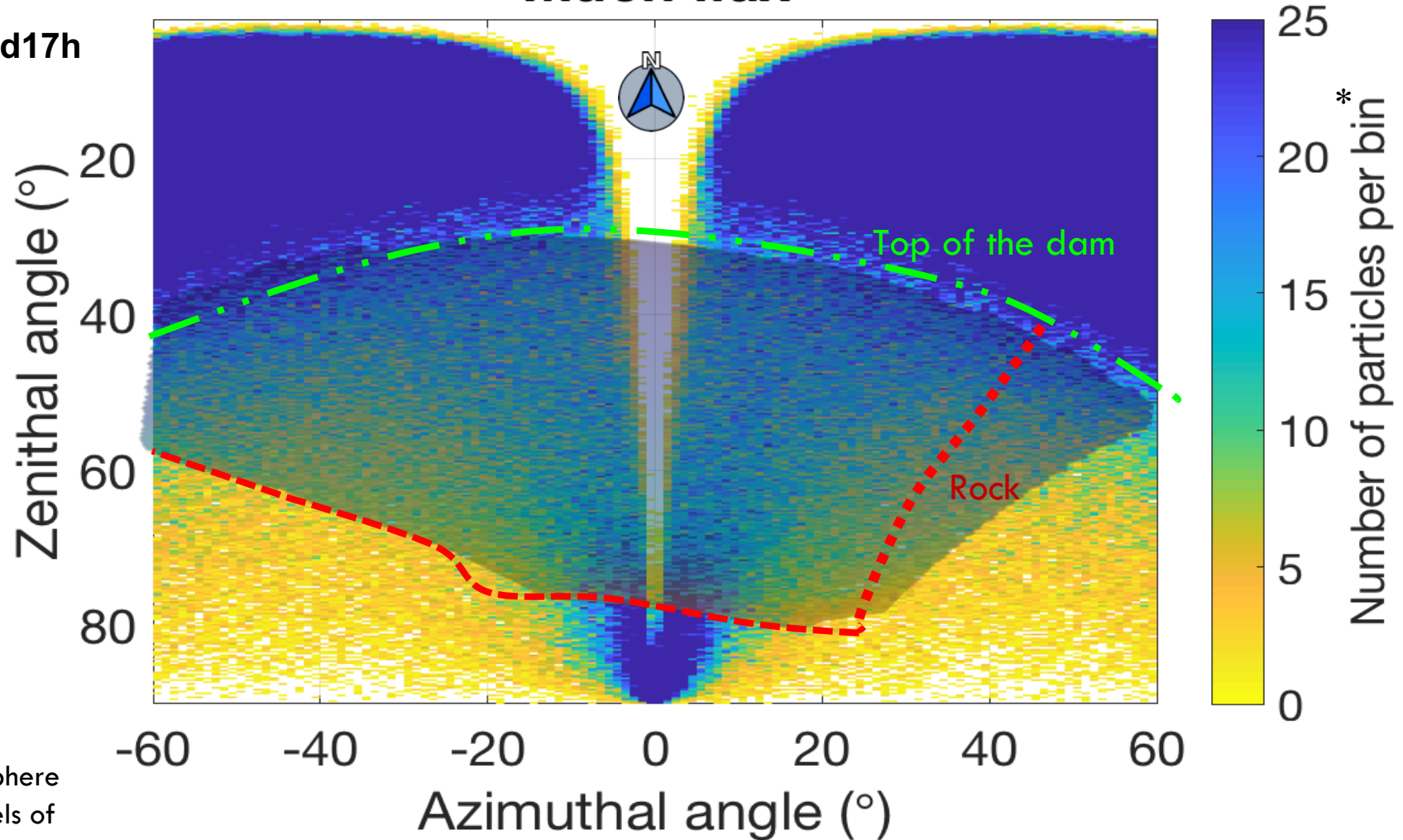




EXPERIMENTAL RESULTS – Study case

Muon flux

Integration time = 3d17h

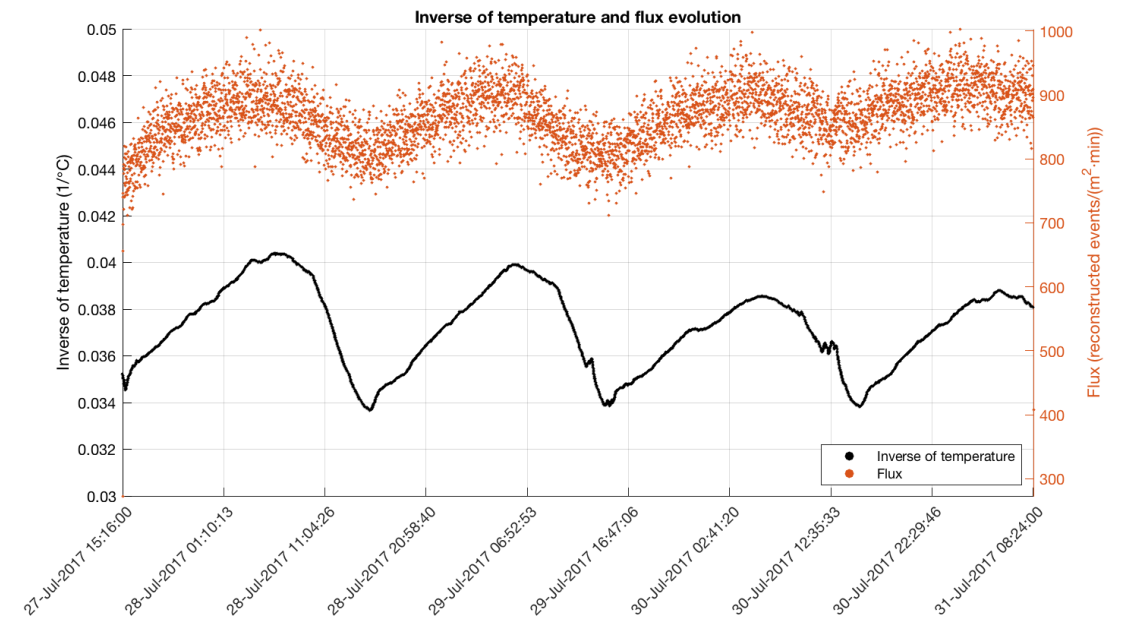
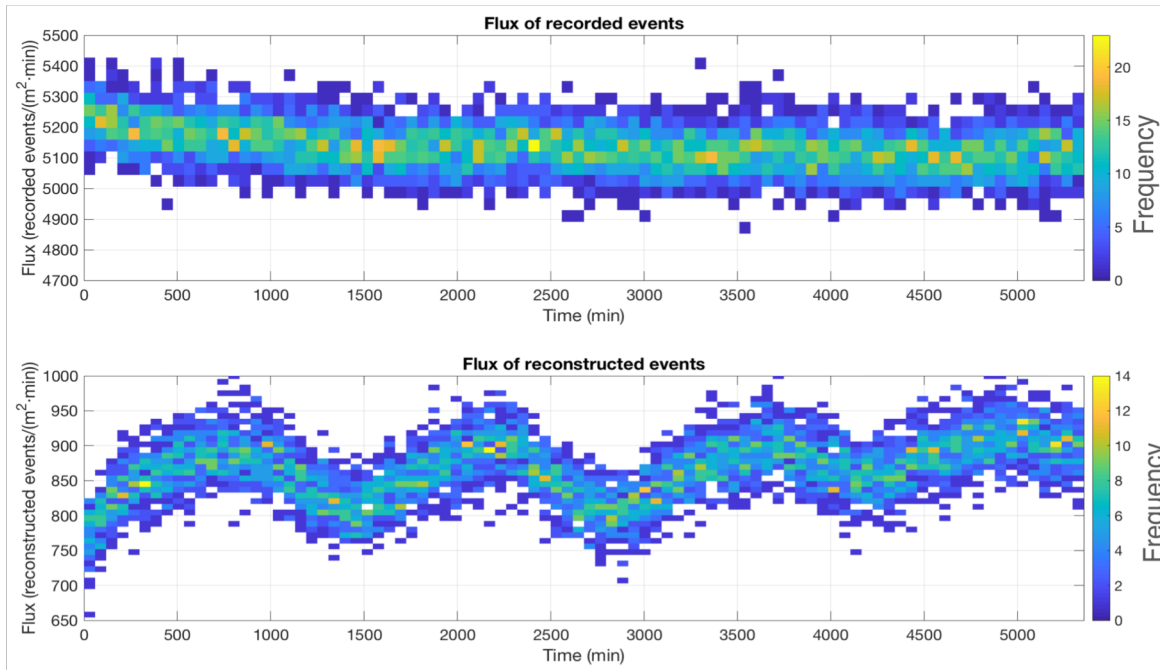


*Bin = Representation of the hemisphere over the camera in a matrix of pixels of dimension 360x360



EXPERIMENTAL RESULTS – Study case

Temperature influence on the muon flux measurement



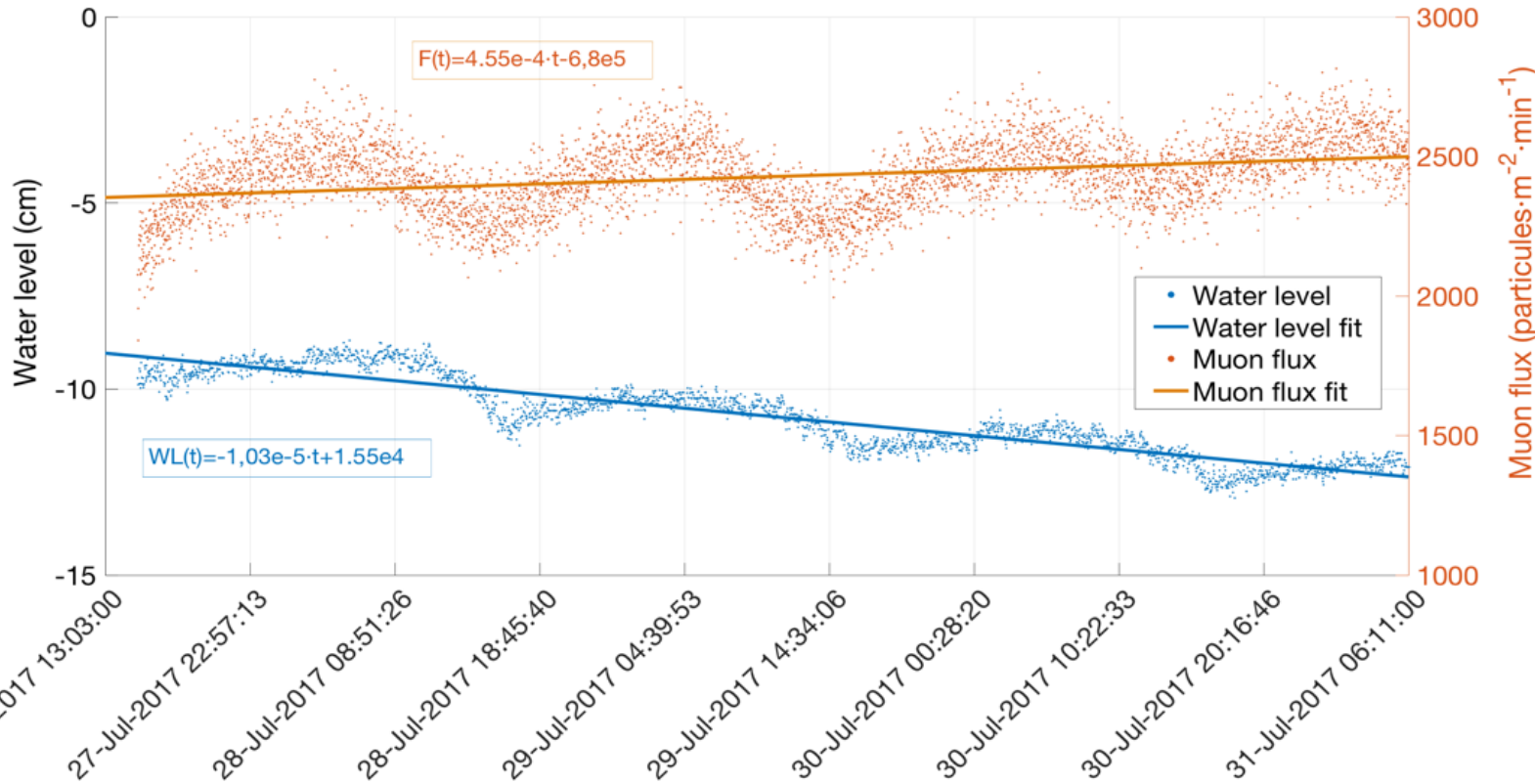
- 2 well differentiated behaviors:
 - Small variations in events triggered by the scintillators
 - Sinusoidal shape for reconstructed events with MUST²

- Influence of the inverse of temperature in the signal reconstruction performance



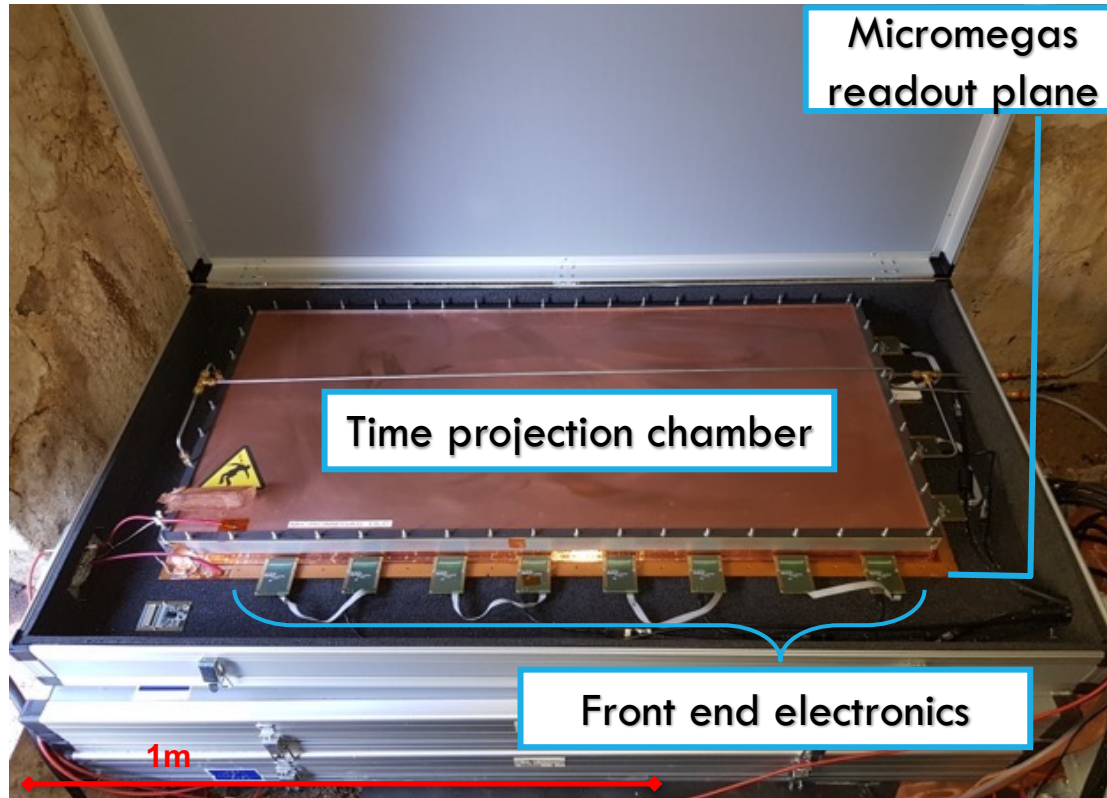
EXPERIMENTAL RESULTS – Study case

Temporal evolution of muon flux and water level



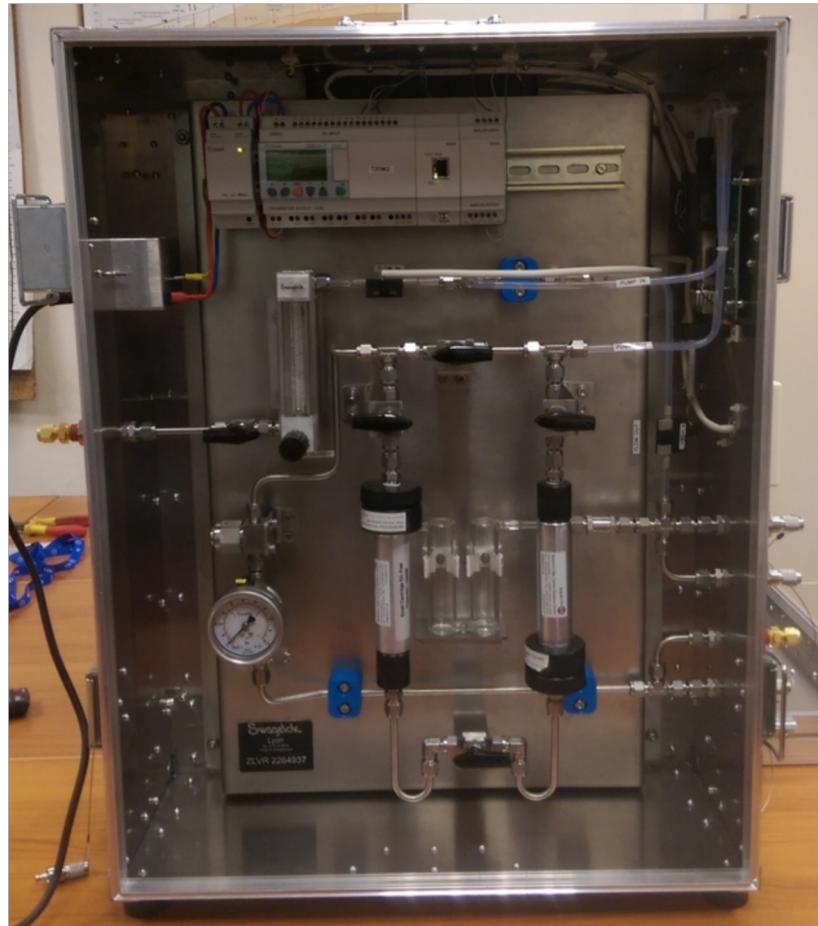
- Strong sine-wave behaviour due to the effect of the temperature in both the barometer used to determine the water level and the MUST² camera
- The linear regression of the whole data shows that the emptying trend of the dam is related to a rise of the muon flux

CONSIDERATIONS TOWARDS INDUSTRIALIZATION

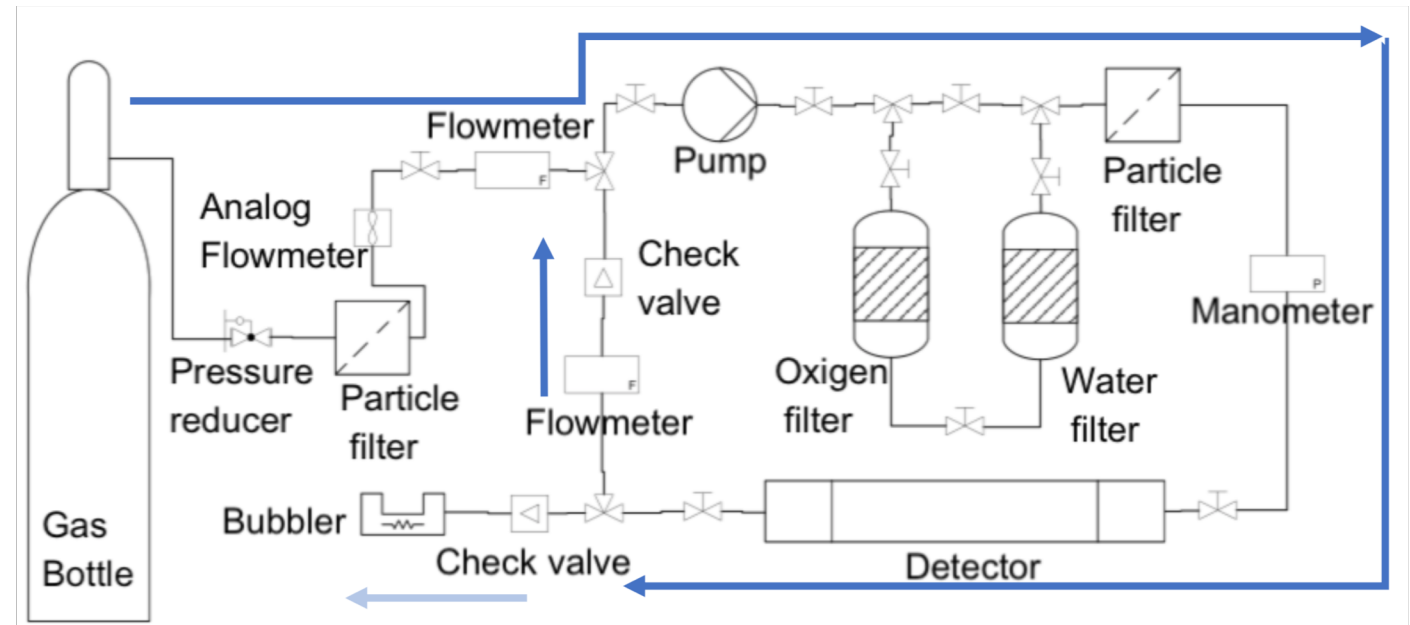


- Max. external dimensions 144 x 79 x 12 cm
- Weight ~28 kg
- Angular acceptance up to 80° when triggered with external scintillators
- Angular resolution better than 1° for particles with angles of incidence over 17°
- Patented in 2016 [Lázaro, 2016]

CONSIDERATIONS TOWARDS INDUSTRIALIZATION



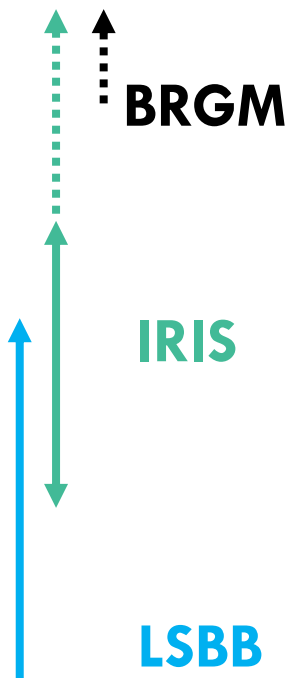
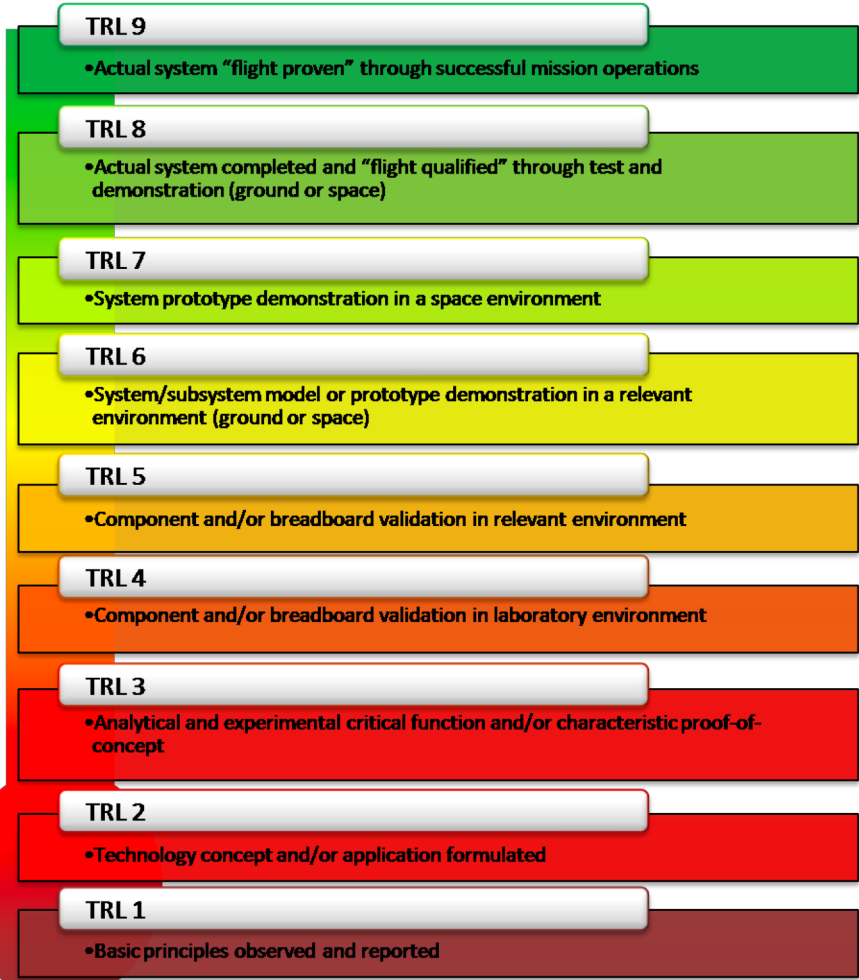
- Gas flow remote control and monitoring
- Filter gas impurities and contaminants
- Custom gas bottle according to context





CONSIDERATIONS TOWARDS INDUSTRIALIZATION

Technology readiness level



Ph.D. complementary partnership

- **LSBB**
 - Original promoter of the project
 - Provides a well-adapted environment for muography
- **IRIS Instruments**
 - Expertise in industrialization
 - Build bridges between the different muographic projects
- **BRGM**
 - National geological survey with vocation of developing new techniques and methodologies for better understanding the subsurface
 - Potential user of the technology

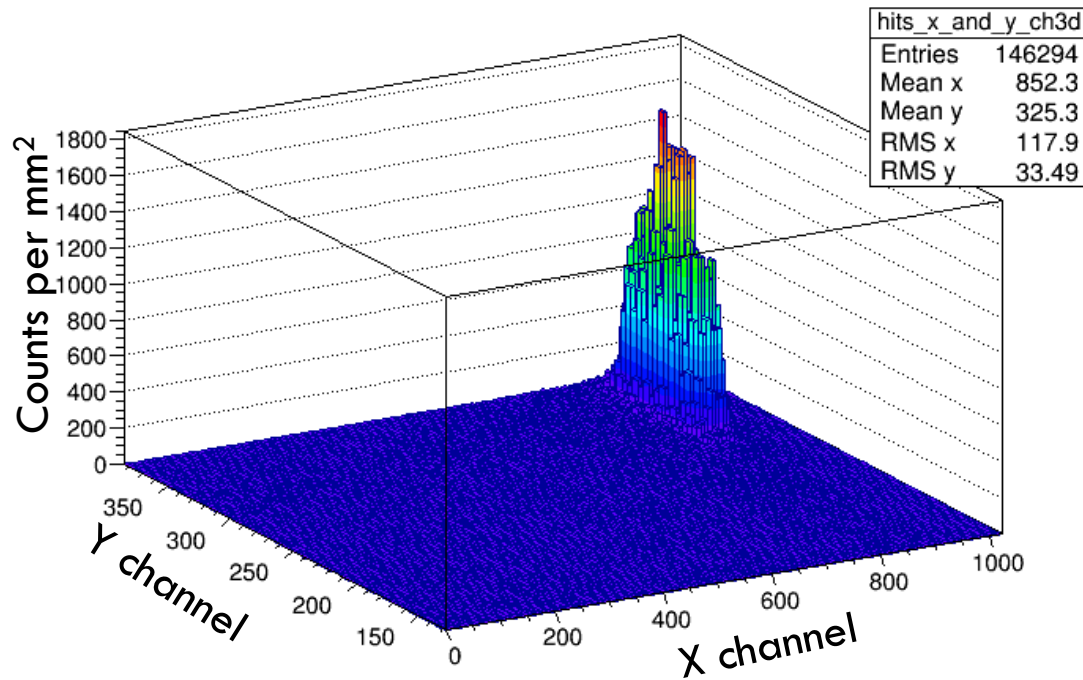
Figure by NASA.



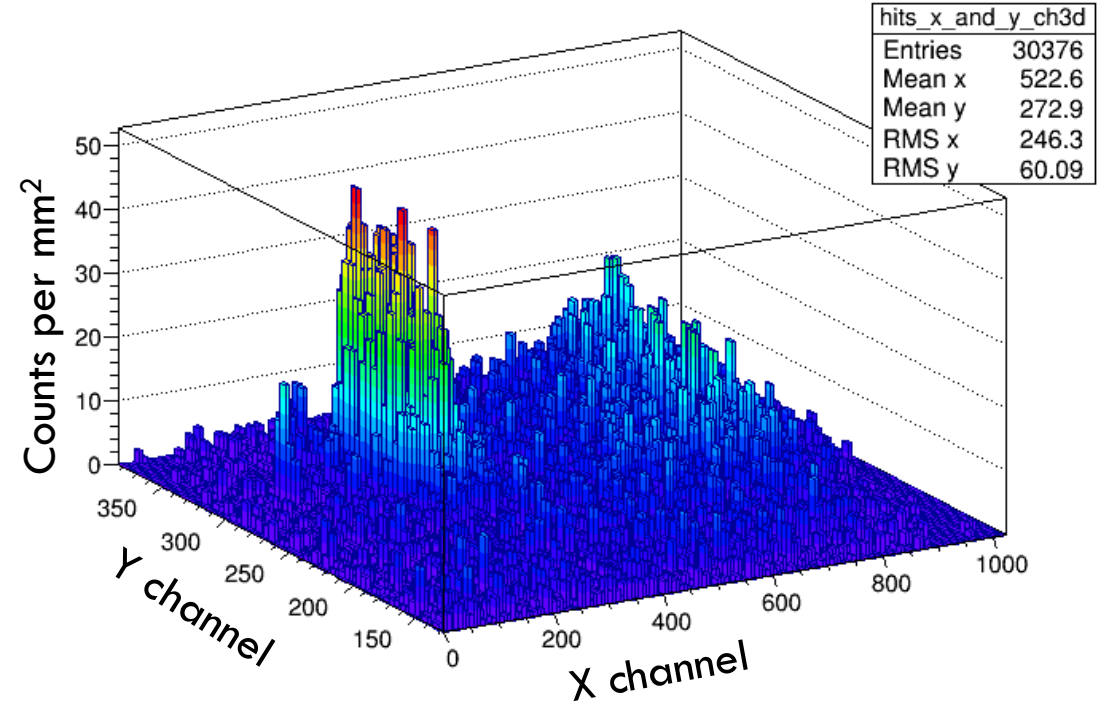
CONSIDERATIONS TOWARDS INDUSTRIALIZATION

Importance of a reliable trigger

Tracker scintillator



Built in scintillators

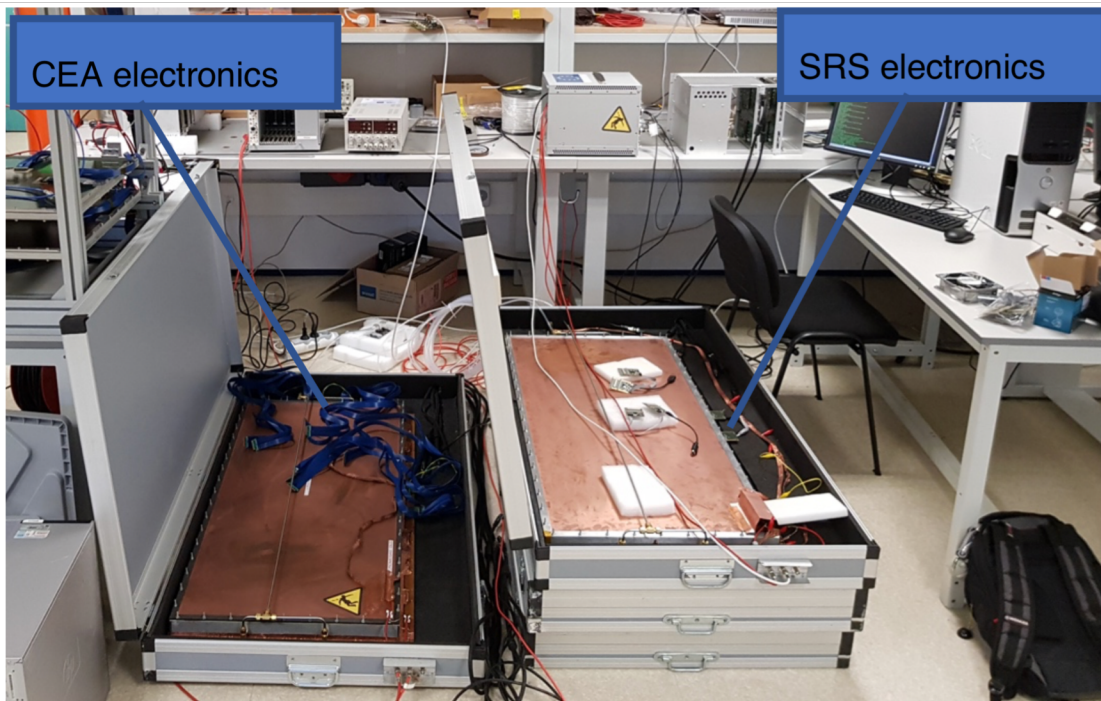


Histograms with the detected events per mm² for different positions

Possibly caused by scintillator damage during transport or operation

CONSIDERATIONS TOWARDS INDUSTRIALIZATION

Electronics alternatives



Experimental setup overview for the electronics comparison.

- Different tested electronics and configurations
 - ❑ 2 independent acquisitions, SRS triggered by 2 scintillator coincidence and DREAM self-triggered by signal over threshold
 - ❑ Trigger signal from 2 scintillators in coincidence mode propagated to SRS and DREAM simultaneously
 - ❑ Dream self-trigger signal propagated to SRS
- All test concluded with successful data acquisition
- A thorough analysis was not possible due to:
 - ❑ Operational parameters optimized for SRS and cloned for CEA
 - ❑ Needs data format adaptation

CONCLUSIONS

- ✓ The technology MUST² is a useful tool for the direction-sensitive measurement of the muon flux
- ✓ The test beam results allowed a good characterization of the performance of the camera
- ✓ The outdoor measurements have validated the field transportability and reliability
 - But gain temperature dependence and only 2 cm water level variation
- ✓ Possibility to do long term campaigns, need to improve the data management and analysis
- ✓ The track reconstruction algorithm has room for improvement in order to enhance the robustness of the results

OUTLOOK – SHORT TERM GOALS

Further development is required :

- ✓ Control the long term stability of the gain
 - Dynamic control of the camera gain as a function of the temperature
- ✓ Remove Blind spots from the reconstruction algorithm
 - New approach for data analysis
- ✓ Software capable of live data acquisition/analysis
- ✓ Minimize the heterogeneity of the camera
 - Modification of the current design



OUTLOOK – FUTURE OF THE PROJECT

- ✓ Construction and deployment at the LSBB of a network of 20 autonomous cameras integrating all the improvements (funded by FEDER LSBB2020)
- ✓ Versatile setup configurations for experiments:
 - Monitoring: network of stand-alone cameras
 - Deep measurements: clustered cameras
 - Multilayer operation: stacked
 - Scatter measurements: tracker upstream/downstream object (different scales)

ACKNOWLEDGEMENTS



Mairie de
Saint-Saturnin-lès-Apt



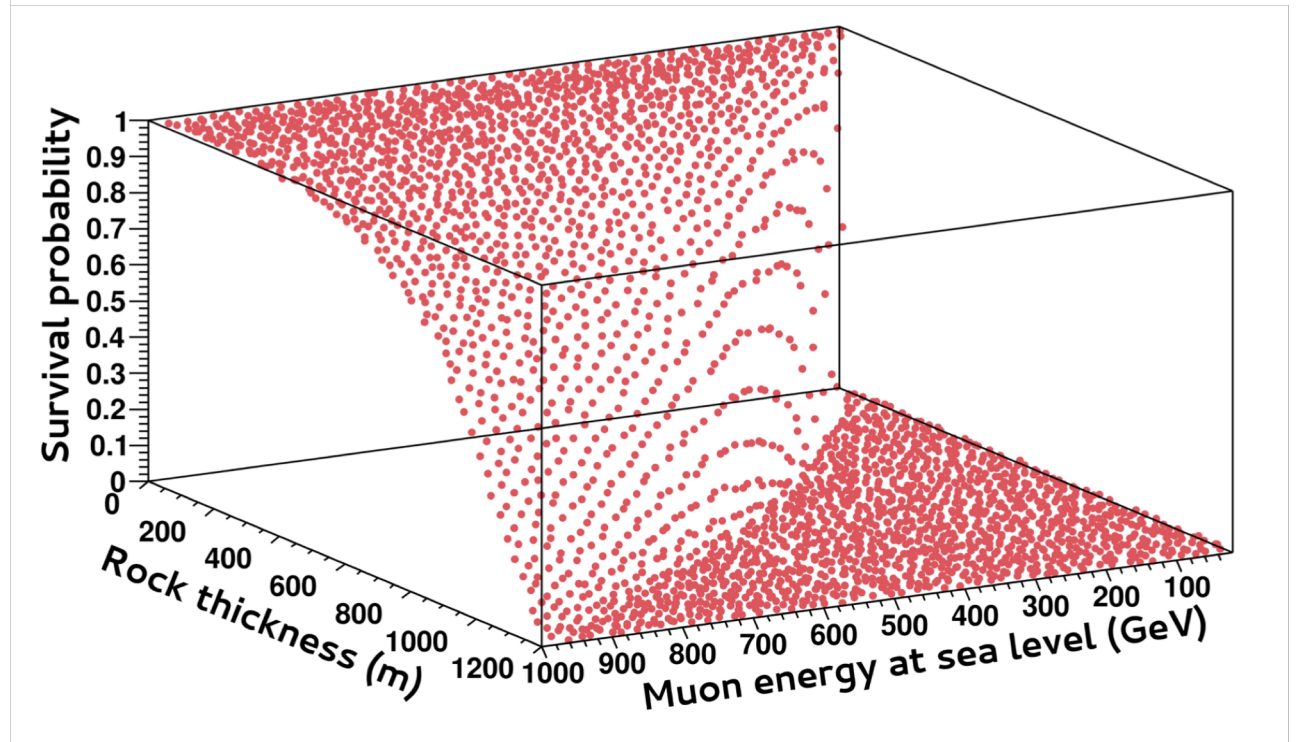
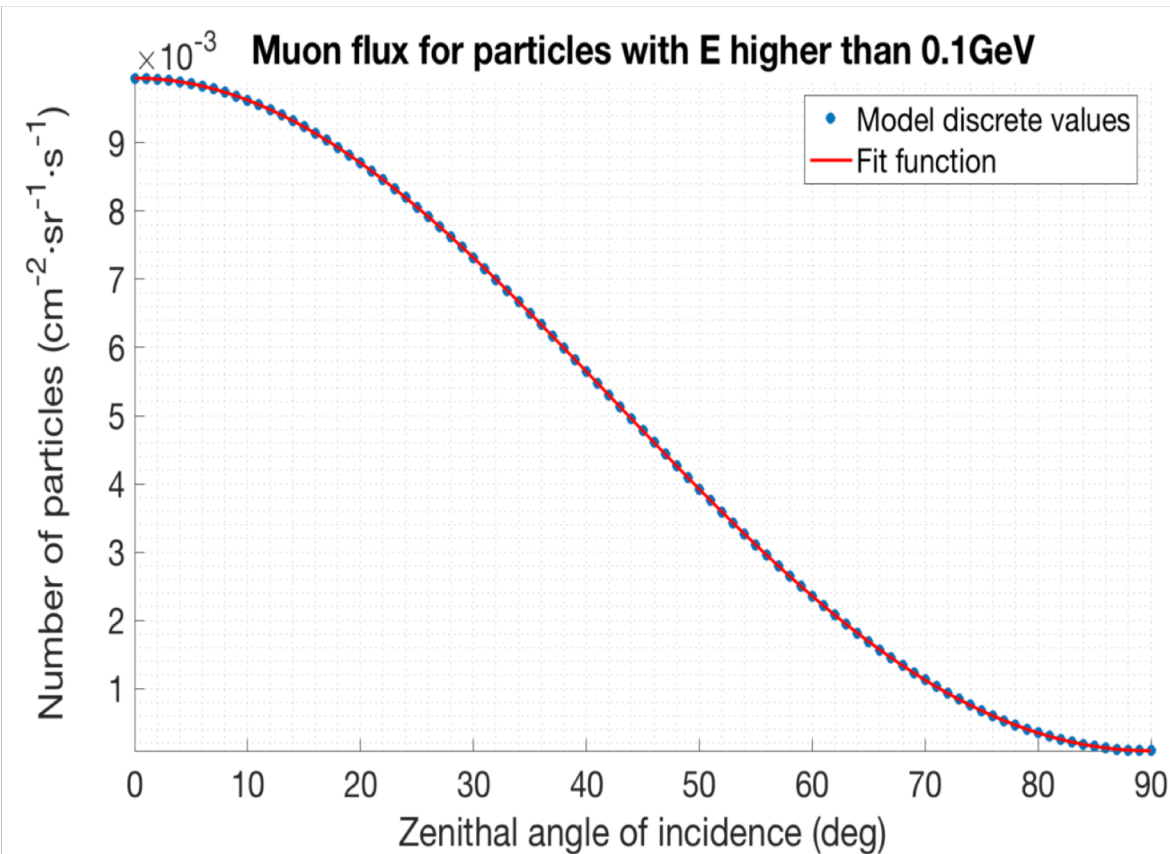
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Underground muon flux

Muon survival probabilities for a standard rock density (2.65 g/cm³)
Figure from Hivert (2015)



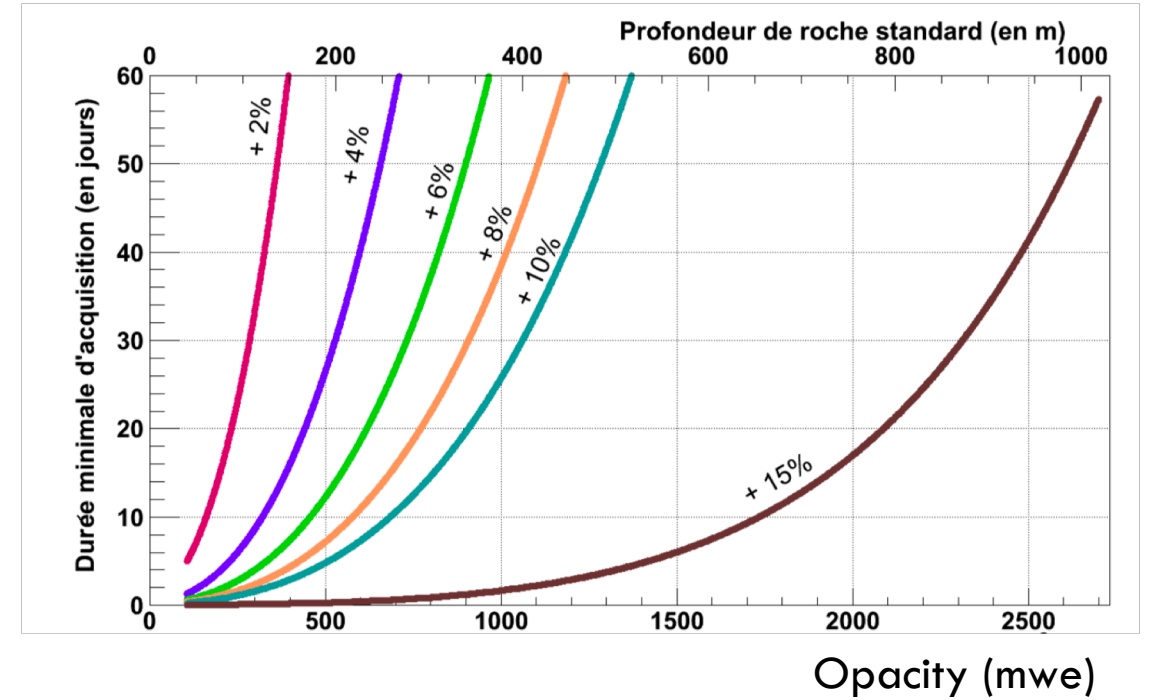
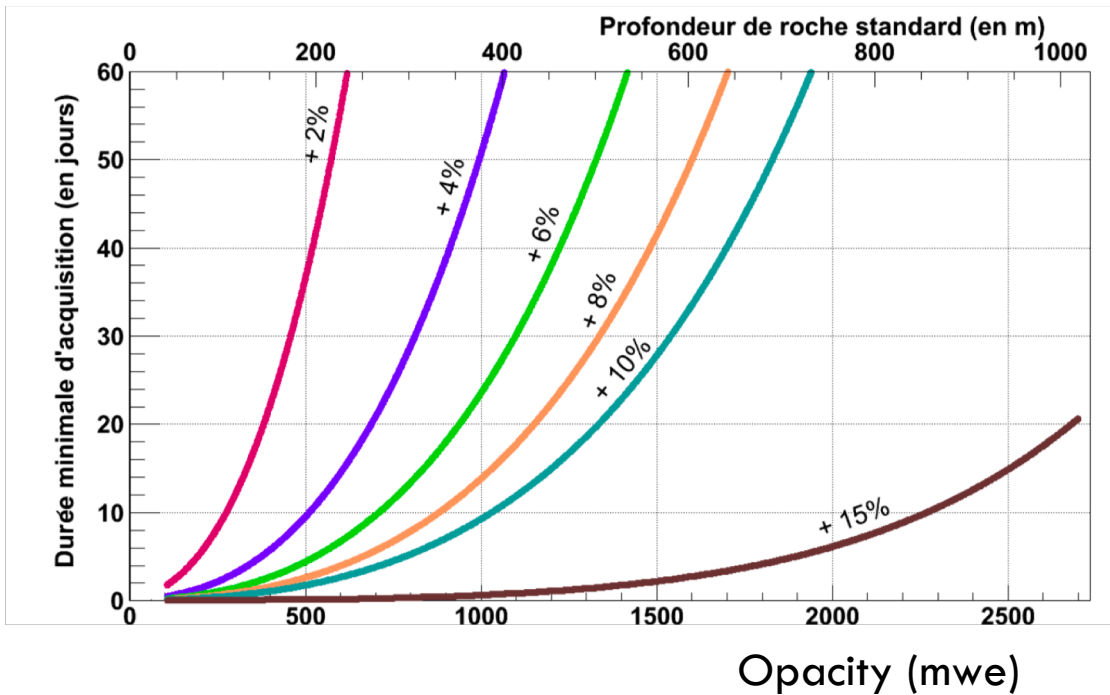
Muon flux integrated over energy at sea level as a function of the zenith angle.

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Estimating the integration time

3 sigma

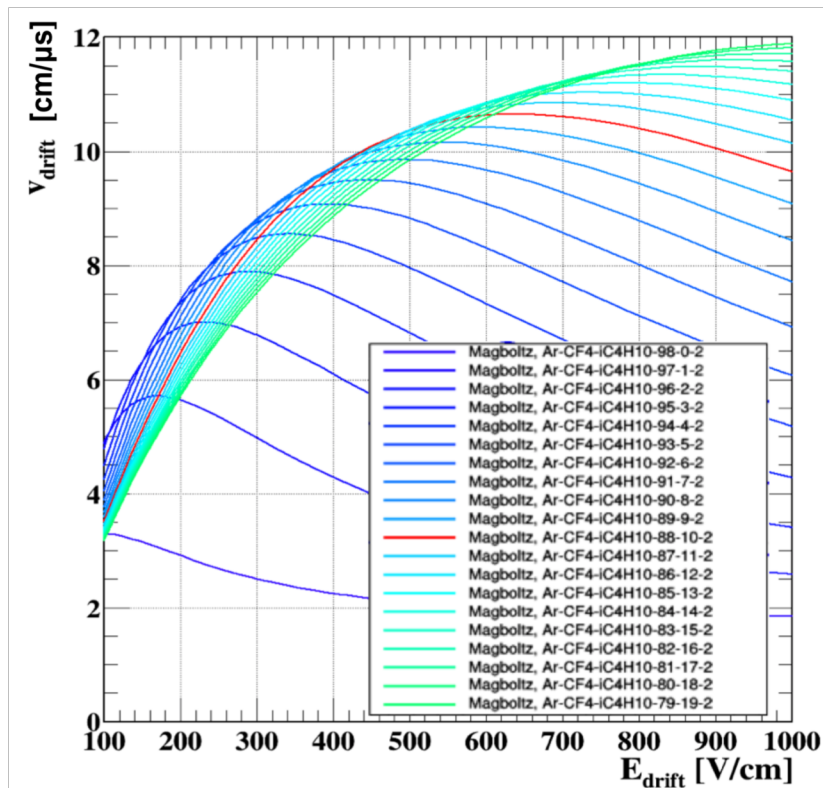
5 sigma



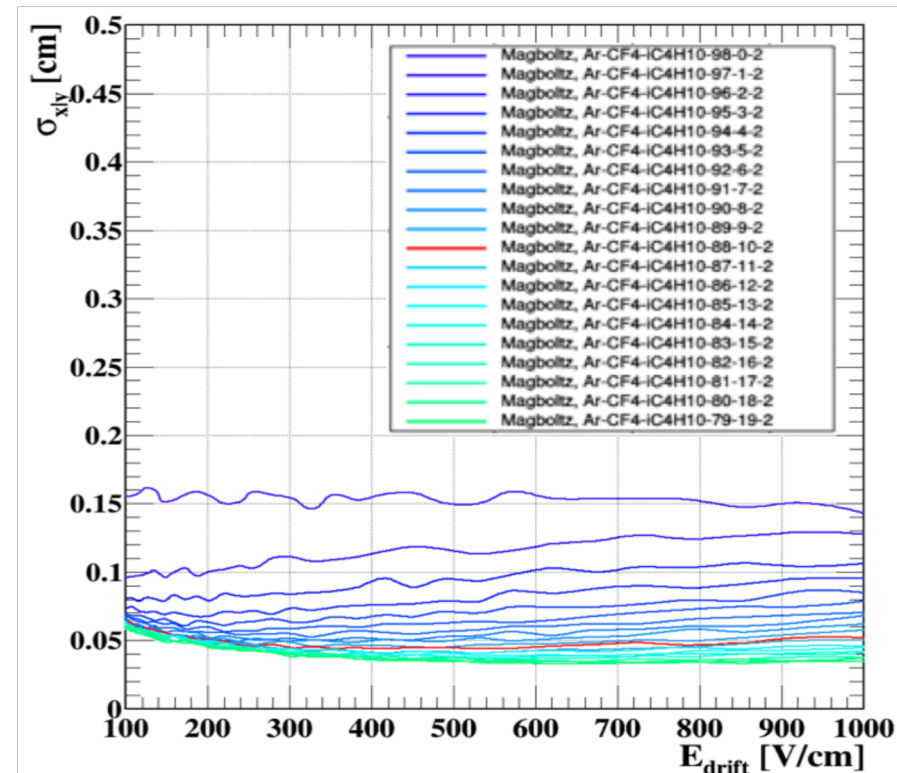
Active surface of 1m², angular acceptance 10°
 Figures from Hivert (2015)

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Simulation results for electron mean drift velocity as a function of the drift electric field.

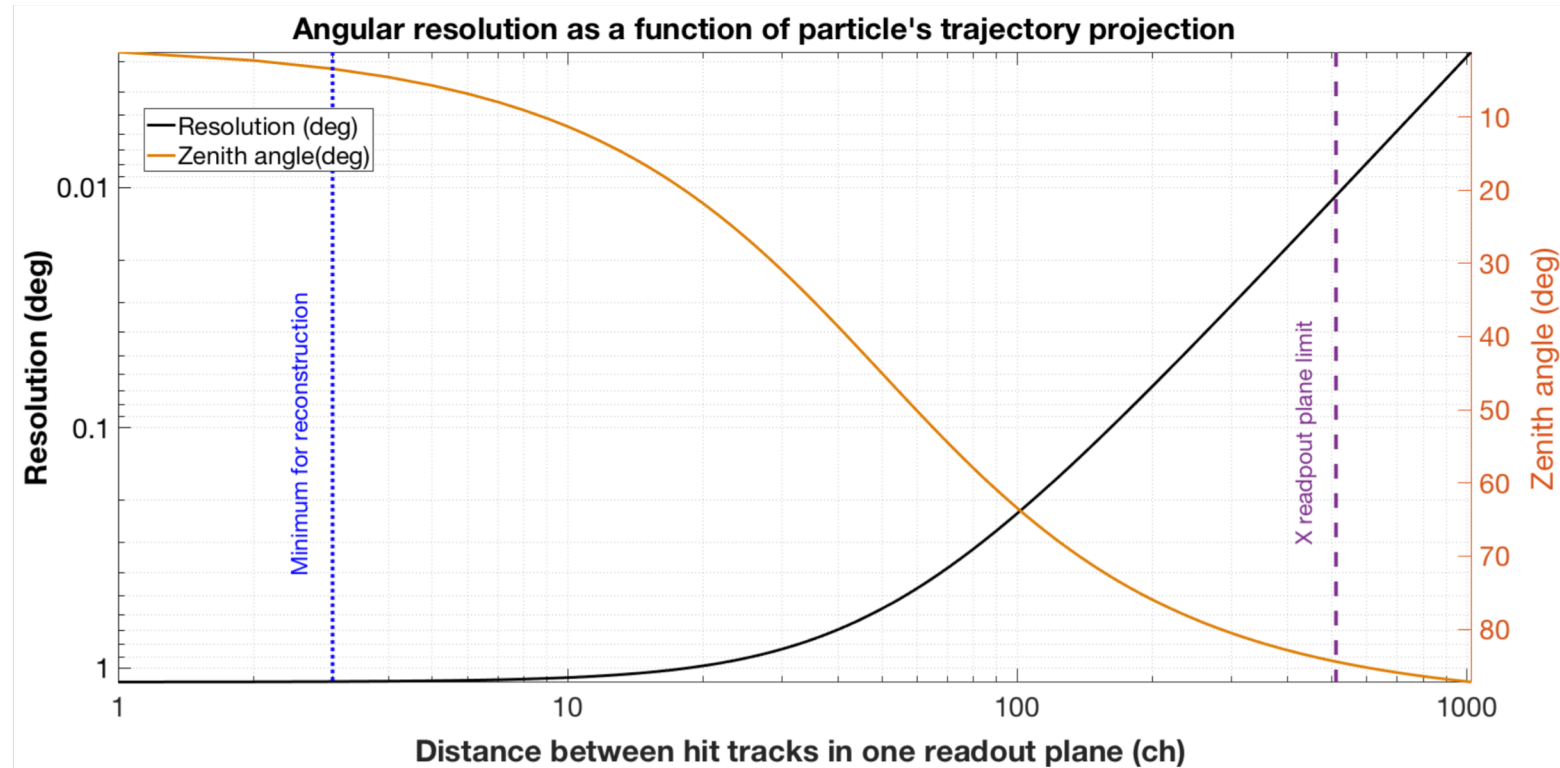


Simulation results for transverse diffusion as a function of the drift electric field.



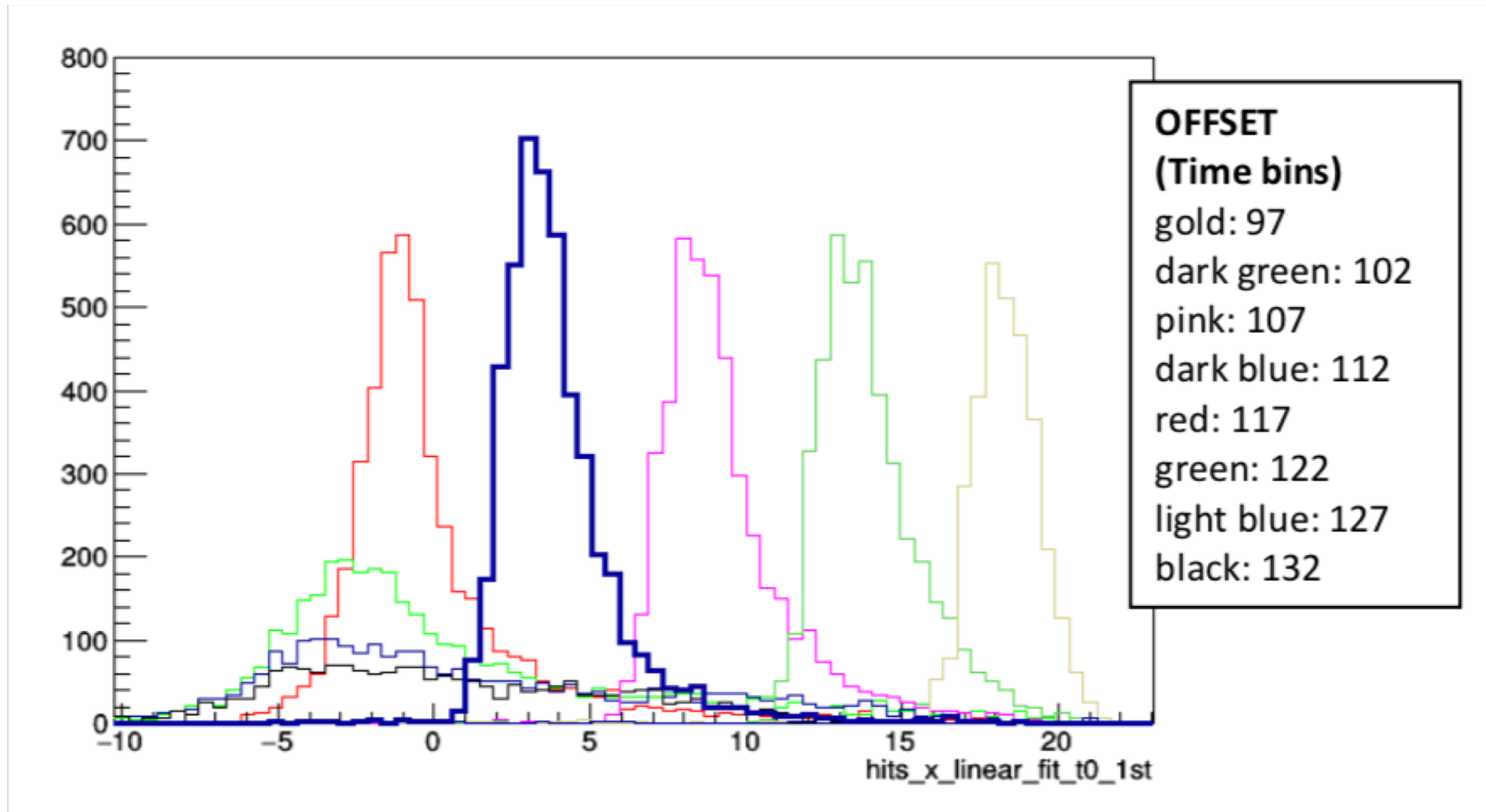
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Angular resolution of the MUST² camera as a function of the muon's trajectory projection over the readout plane.

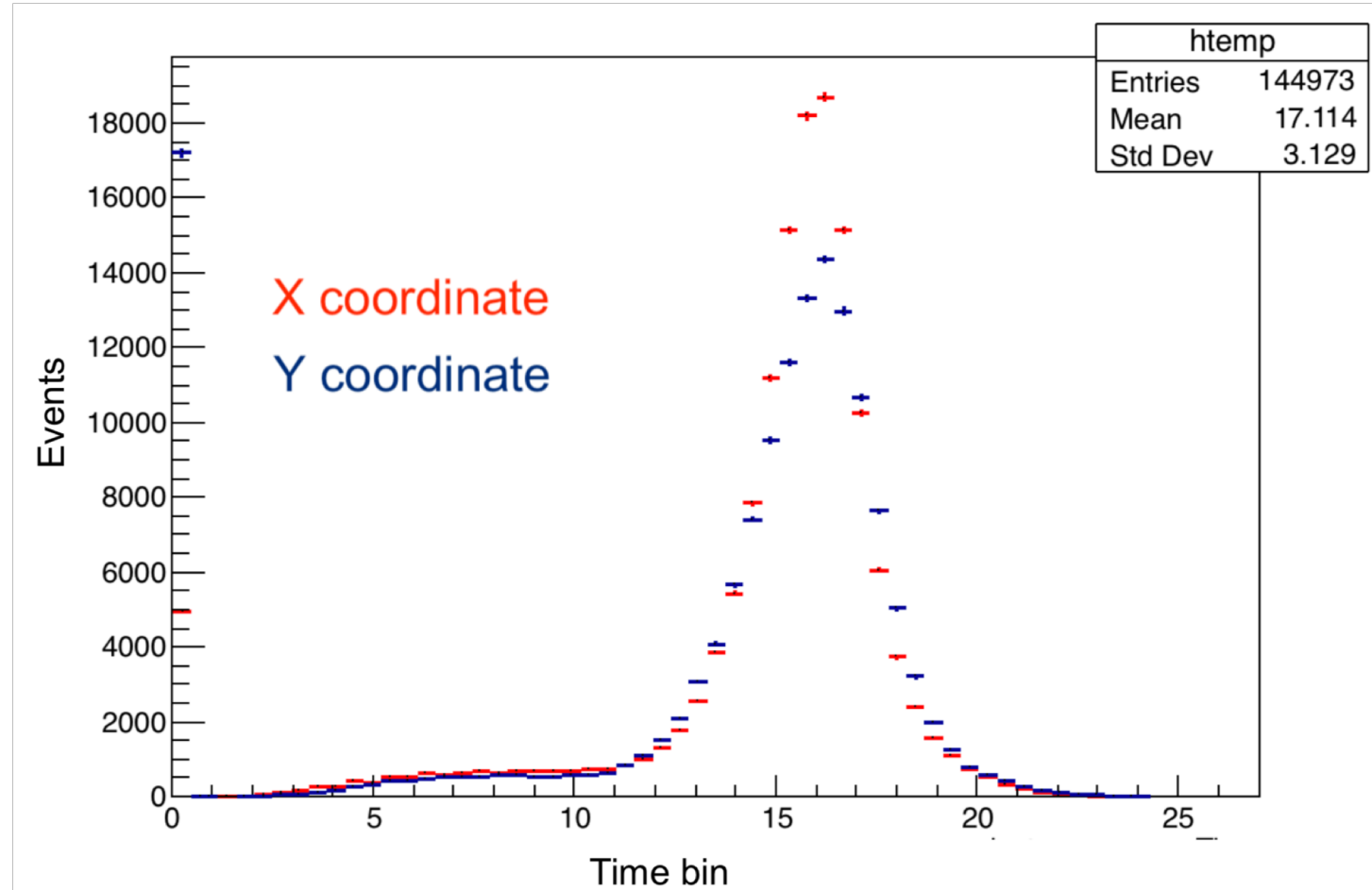


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Electronics latency



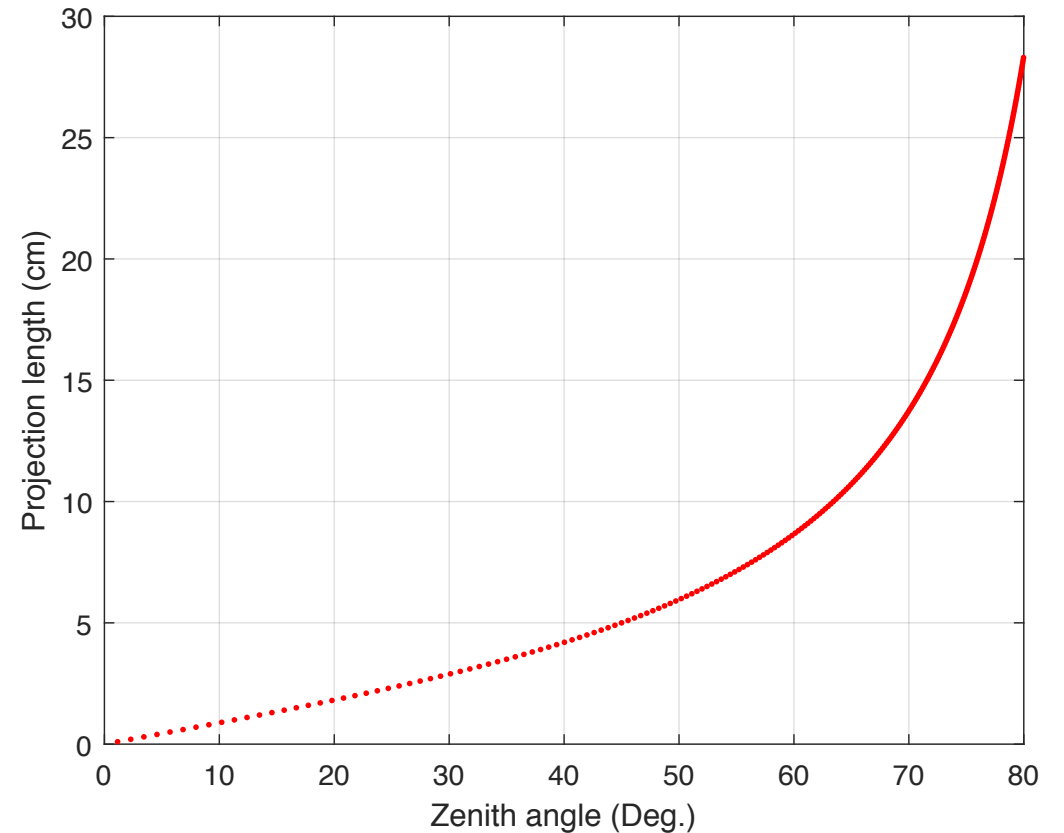
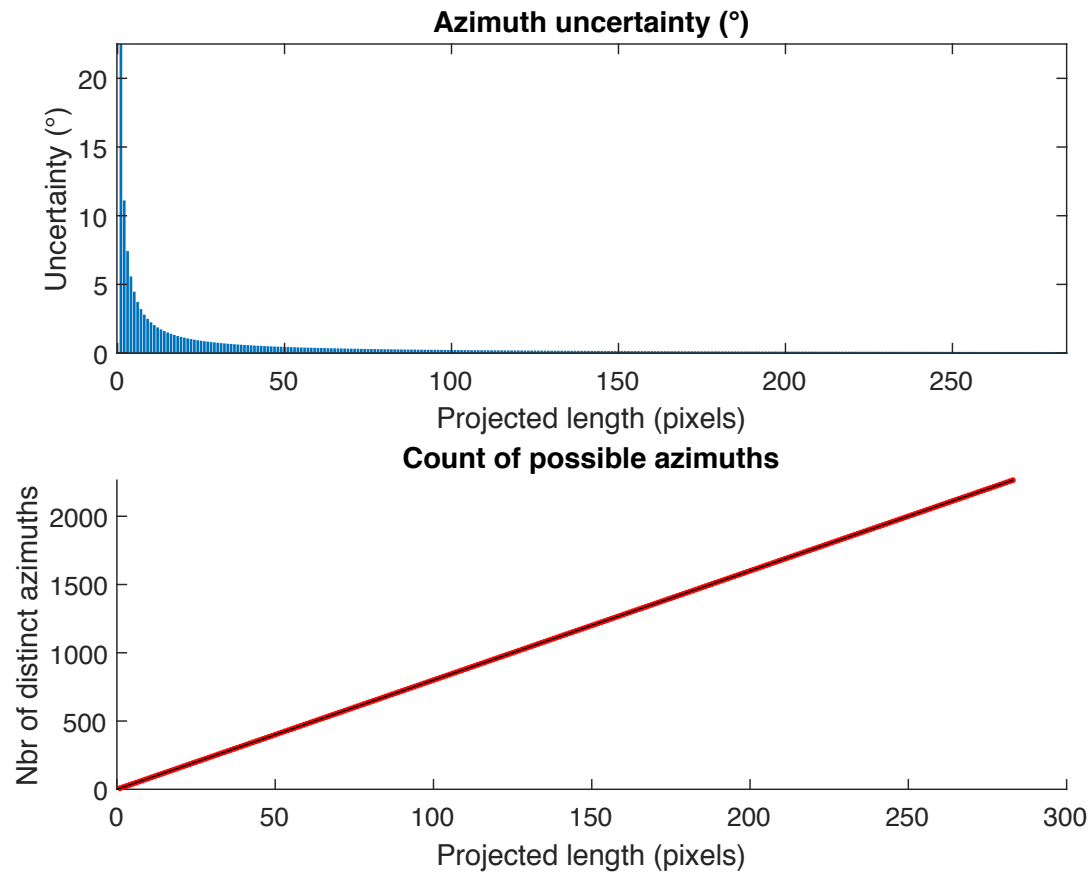
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Time over threshold

The value of $17,114 \pm 3,129$ time slots corresponds to $427,85 \pm 78,22$ ns, in good agreement with the value estimated with the theoretical drift speed.

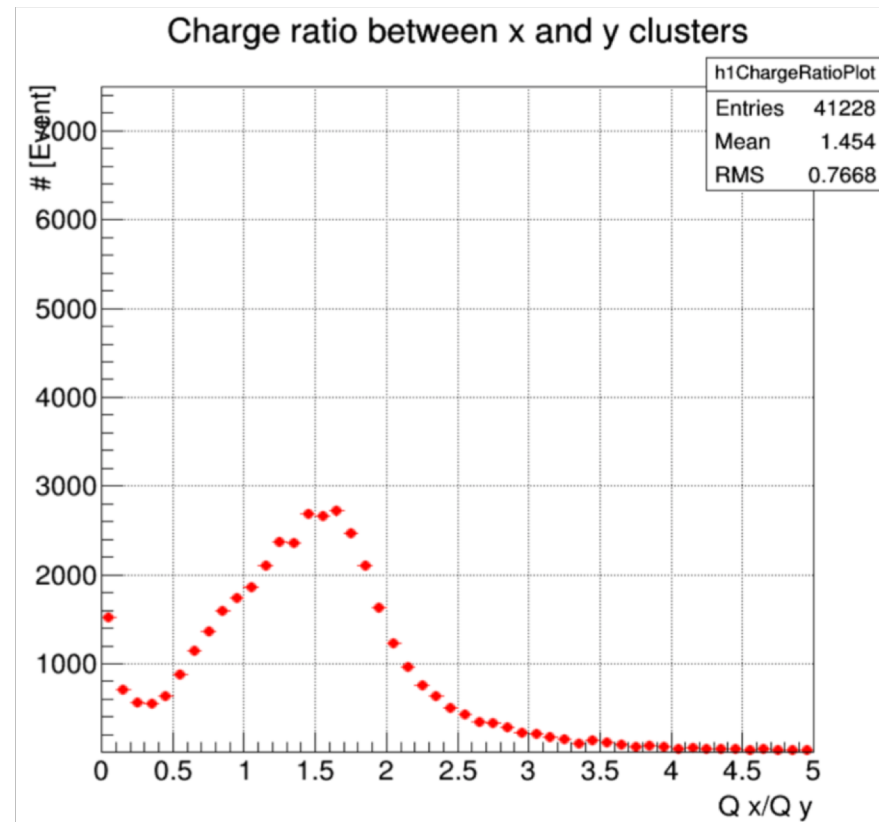
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Angular resolution of the MUST² camera as a function of the muon's trajectory projection over the readout plane.



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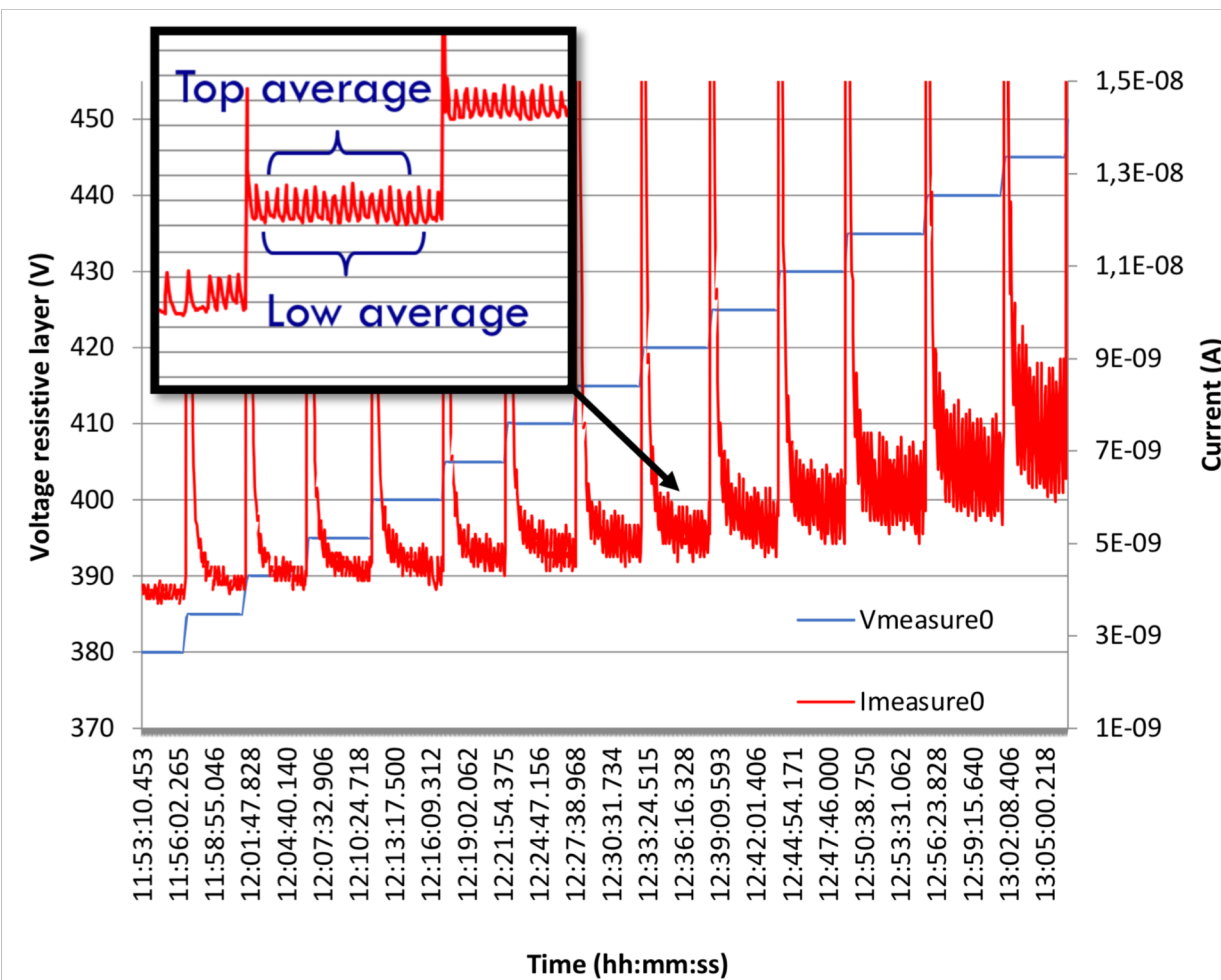
Charge ratio between readout layers



Charge is computed as the total sum of all ADC counts during 675 ns.

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Current and voltage of the resistive layer during the test beam

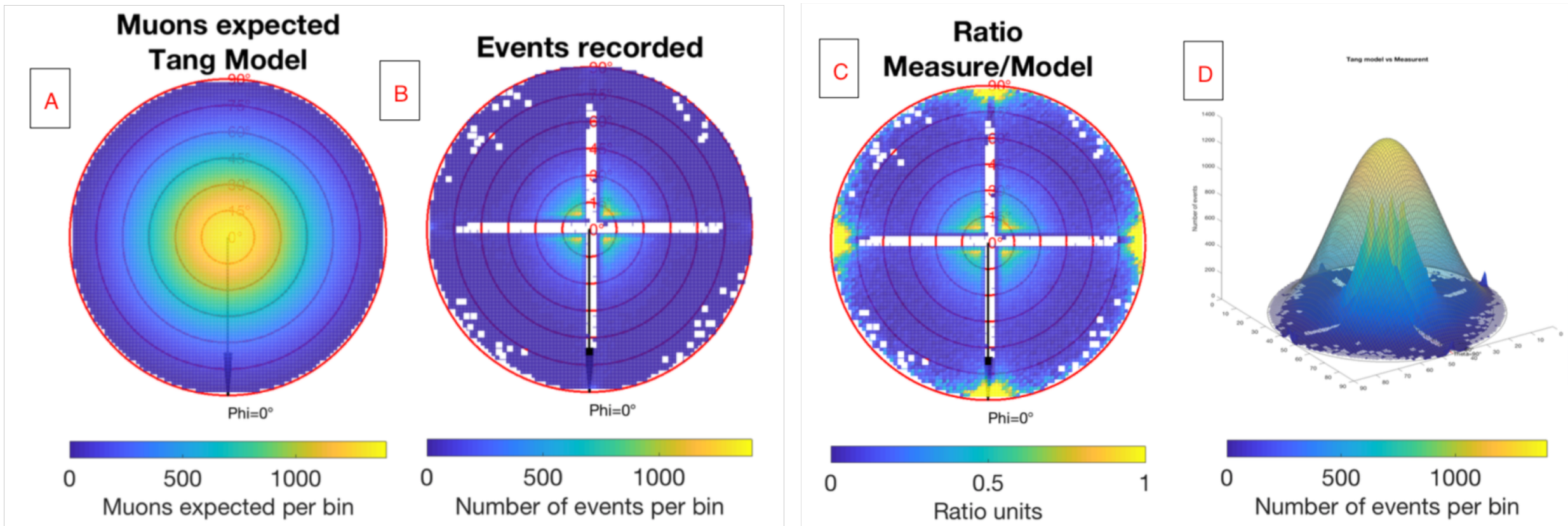


$$Gain = \frac{\Delta I}{N_T \cdot d \cdot \mu / s \cdot \text{charge of } e^-}$$

- The number of produced electrons depends on the muon incident angle.
- Two independent gain scans with different angles

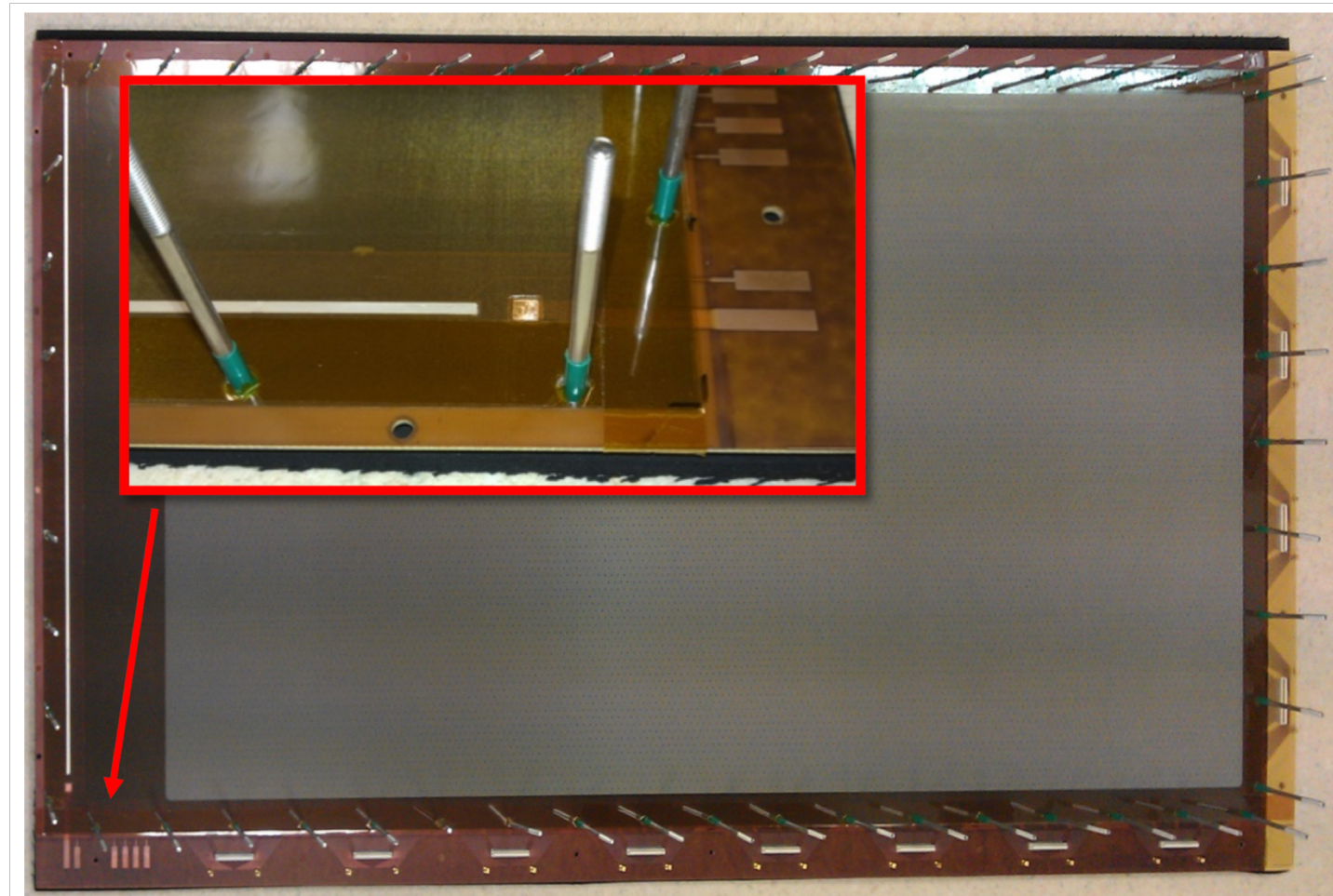
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Polar chart of the muon arrival distribution for the Tang model and experimental measurements.



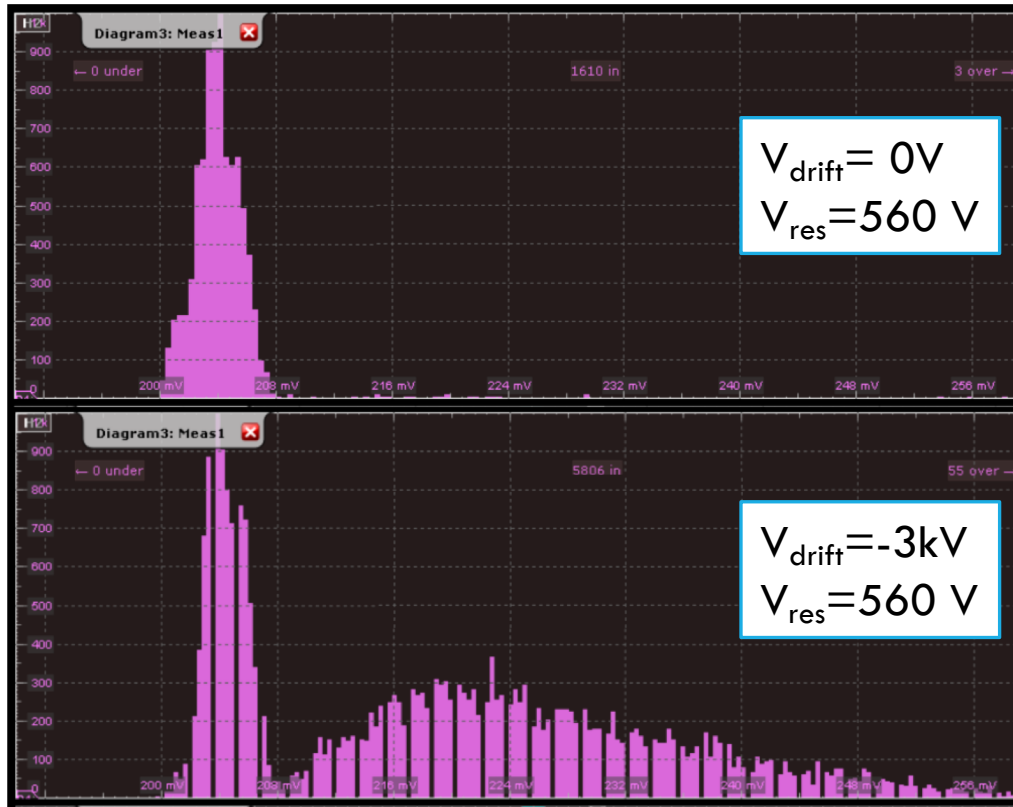
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Isolated micromesh

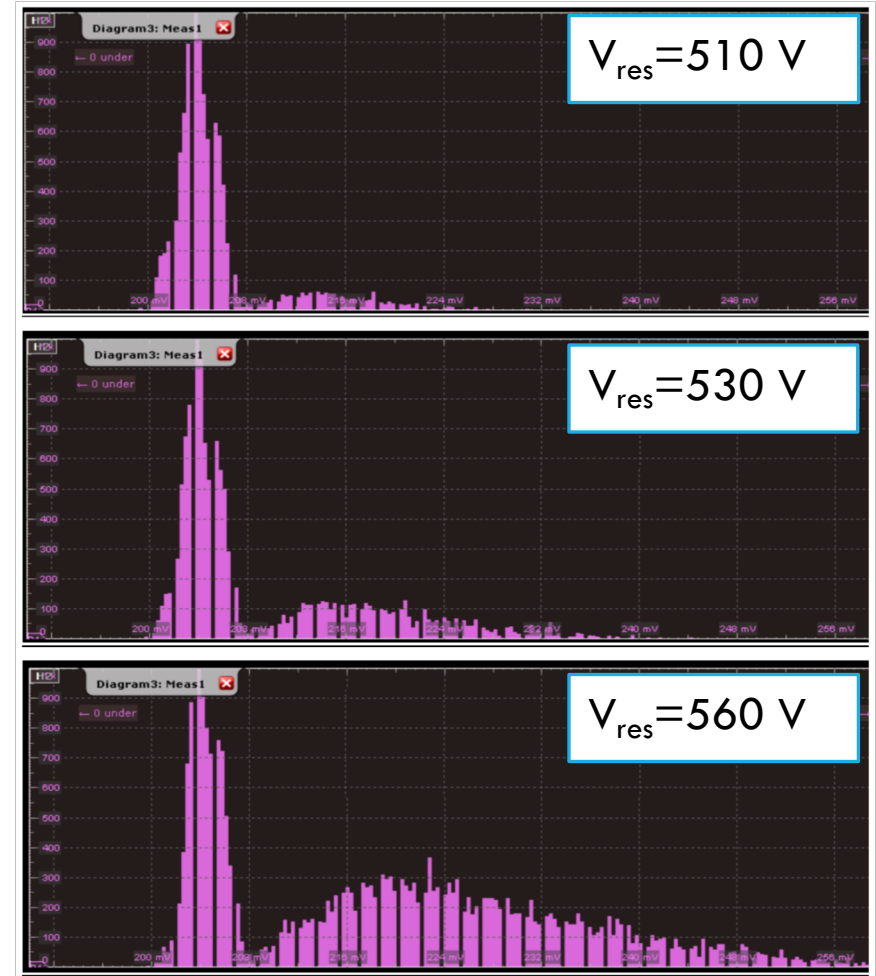


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Trigger from the mesh test



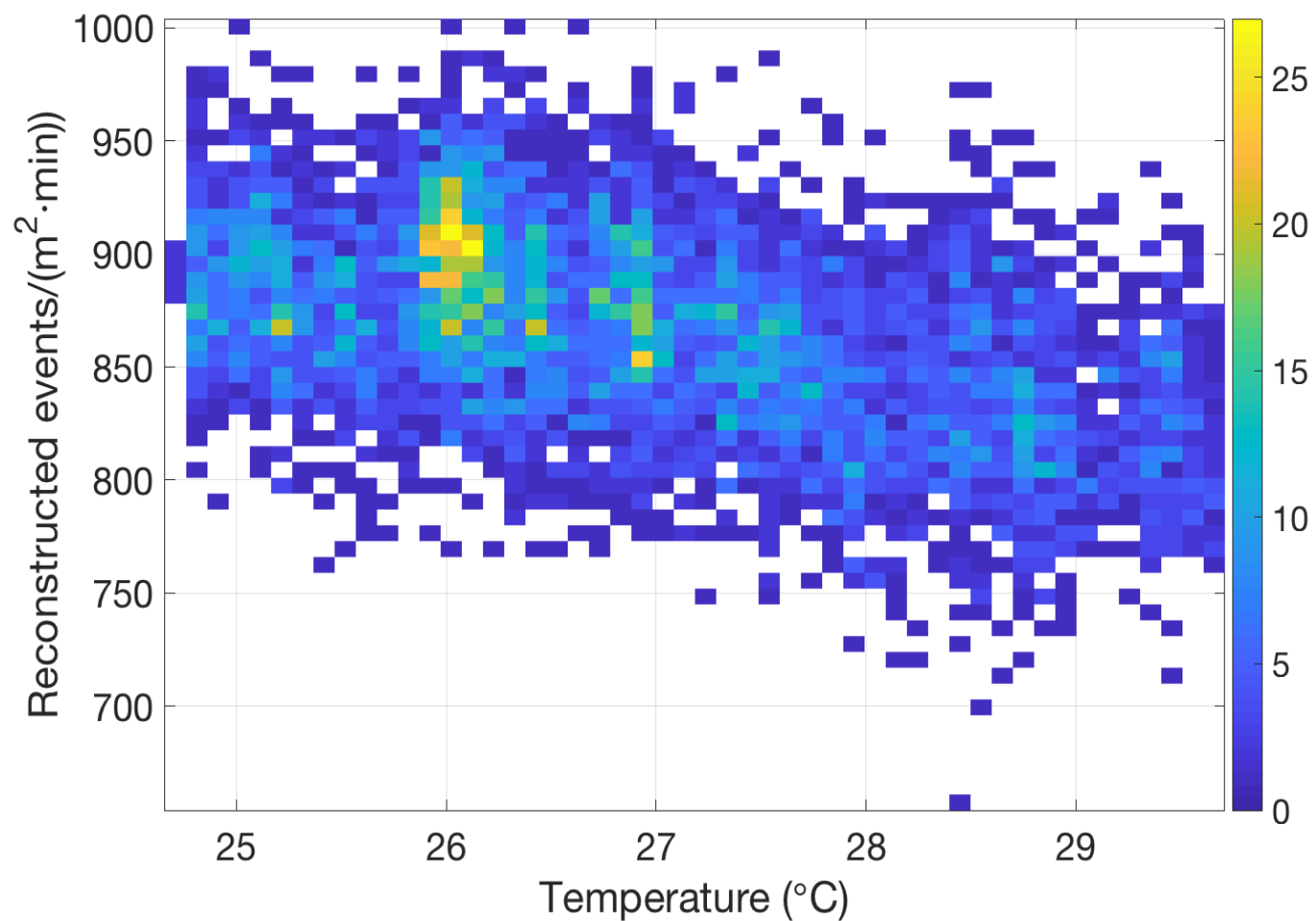
Signal apparition associated to the activation of the TPC



Signal amplitude modification as a function of the gain

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Influence of temperature in the reconstructed muon flux



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Environmental parameters during acquisition

