C. R. Physique 20 (2019) 521–528

Contents lists available at ScienceDirect

Comptes Rendus Physique

www.sciencedirect.com

Prix Ivan-Peychès 2018 de l'Académie des sciences

Development of high-definition muon telescopes and muography of the Great Pyramid

Développement de télescopes à muons à haute définition et muographie de la Grande Pyramide

Sébastien Procureur [a,*], David Attié [b]

[a] *CEA, Centre de Saclay, Irfu/DPhP, 91191 Gif-sur-Yvette, France*
[b] *CEA, Centre de Saclay, Irfu/Dedip, 91191 Gif-sur-Yvette, France*

A R T I C L E I N F O

Article history:
Available online 3 October 2019

Keywords:
Muography
Micro Pattern Gaseous Detectors
MPGD
Micromegas
Pyramid
Khufu

Mots-clés :
Muographie
Détecteurs de gaz à micro-motifs
MPGD
Micromégas
Pyramide
Khéops

A B S T R A C T

Several muon telescopes have been developed in the last years at CEA-Saclay. Benefitting from 15 years of R&D on Micro-Pattern Gaseous Detectors (MPGDs) and from several recent innovations, these telescopes yield unprecedented resolution for real-time instruments, and allow for high-definition muography imaging. As a first application, three of them were deployed around Khufu's Pyramid from 2015 to 2017, showing very good performance and stability in harsh conditions. They also provided the first-ever detection of internal structures of a pyramid from the outside, and participated in the discovery of a large void above the Grand Gallery.

R É S U M É

Plusieurs télescopes à muons ont été mis au point ces dernières années au CEA-Saclay. Bénéficiant de 15 années de R&D sur les détecteurs gazeux à micro-pistes (MPGDs) et de plusieurs innovations récentes, ces télescopes offrent une résolution inégalée pour des instruments temps réel, et ouvrent la voie à la muographie haute définition. Trois de ces instruments ont été déployés autour de la pyramide de Khéops entre 2015 et 2017, démontrant de très bonnes performances et une grande stabilité dans des conditions particulièrement difficiles. Ils ont également fourni la toute première détection de structures internes d'une pyramide depuis l'extérieur et participé à la découverte d'un grand vide situé au-dessus de la Grande Galerie.

* Corresponding author.
E-mail address: sebastien.procureur@cea.fr (S. Procureur).

https://doi.org/10.1016/j.crhy.2019.09.003

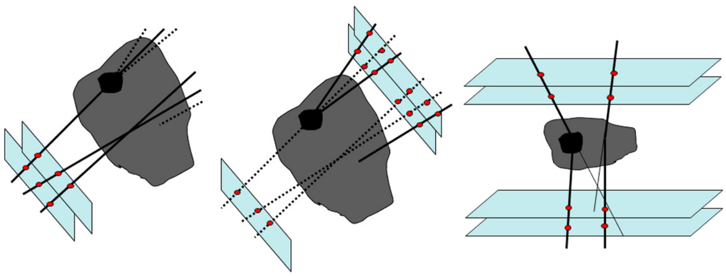

Fig. 1. Principle of muon imaging using transmission (left), absorption (middle) and deviation (right) modes with particle detectors (in blue). Muon trajectories are represented in bold and bold dotted, but only the former are actually used for a given mode.

1. Introduction

1.1. Cosmic rays and muons

Most of our Universe is a hostile place for life. In every galaxy, ionizing particles are produced and accelerated during violent cosmic phenomena like supernovae. The energy of these particles, essentially protons, can reach the kinetic energy of a tennis ball hit at 150 km/h. In the Universe quasi-perfect vacuum, they can travel during millions of year before being stopped or absorbed. And every second, billions of such particles end their long journey when approaching the Earth. The collisions with atoms of the upper layers of our atmosphere create cascades, or showers of less energetic particles like pions, kaons, neutrons and many more. At the sea level, the particle flux is dominated by muons, with a rate of approximately 150 $\mathrm{Hz/m^2}$. The atmosphere thus acts as a giant, the protecting umbrella converting hazardous particles into a cosmic rain that actively participates in the evolution of life. The production and propagation of muons derive from several complex processes:

- their copious production from pions and kaons is a consequence of helicity conservation [1];
- though unstable with a life time of about 2 μs, they can travel several kilometers thanks to the time dilatation described by special relativity;
- 200 times more massive than electrons, they are much more penetrating due to the (somehow counterintuitive) phenomenon of bremstrahlung radiation.

The penetration capability of cosmic muons is remarkable: about 50% of them can cross 10 m of water, and 1% survive beyond 100 m of rocks, making them much more penetrating than artificial sources like X-rays or neutrons. Still, as charged particles, muons interact with matter, and these interactions give hints on the amount of material they crossed.

1.2. Principles of muography

The electromagnetic interactions between muons and matter result in an energy loss described by the Bethe–Bloch [2] equation, and in a deviation of their trajectory by collisions with nuclei forming the material (multiple scattering) [3].

In the first case, the Bethe–Bloch equation shows that the fraction of cosmic muons that is absorbed in a certain length of material of local density $\rho(x)$ is determined by the integral $\int \rho(x)\,\mathrm{d}x$, called the opacity. Measuring the muon absorption (or transmission) factor in a given direction thus provides the average density in this direction, as the length is usually known. With a set of muon detectors pointing to the structure to study, one obtains a 2D map of its density, called *muography*. A muography can be formed either using transmitted or absorbed muons, the former being the most common mode for large objects. Because of the modest flux and the small amount of information available in this mode, a transmission or absorption muography usually takes from a few hours to a few months, depending on the configuration and on the size of the object.

In the deviation mode, a set of detectors placed on both sides of the object measures the upstream and downstream muon trajectory [4]. According to Moliere theory, the typical scattering angle is also determined by the opacity of the material, and to some extent by its atomic weight Z. The advantage of this method is that it uses much more information from every muon, and gives access to the scattering point in 3D. A deviation muography, also called muon tomography because of its 3D nature, can be obtained in a few minutes only. However, it is restricted to relatively small objects in practice (typically a few cubic meters) because of the surface to cover and also because of the blurring of the image for thick materials.

The three muon imaging modes are schematically represented in Fig. 1, and more details about the muography principles and applications can be found in [5].

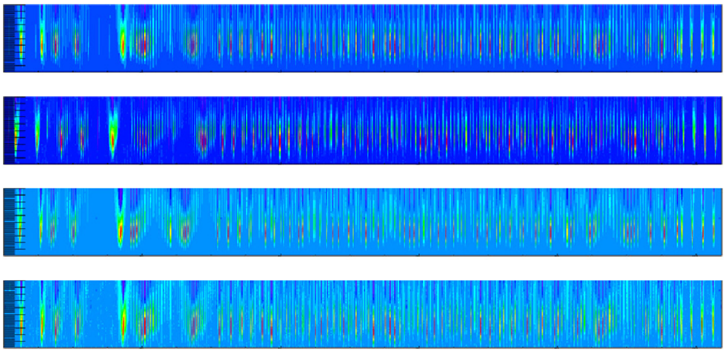

Fig. 2. Typical muon event in a four-detector telescope. Each histogram represents the signal amplitude (color scale) as a function of the detector position (horizontal axis) and time (vertical axis). The complex pattern results from the multiplexing scheme, but the muon position can be easily identified as the biggest colored structures in each detector, resulting in a nearly vertical track.

2. The CEA muon telescopes

Charged particles like muons have been routinely detected by particle physicists for about a century. The specificities of muography however impose a number of requirements which are difficult to satisfy simultaneously:

- a large detection area to compensate for the modest muon flux, as for any optical telescope
- a good angular resolution to obtain precise images
- robustness, in the (likely) case of transportation and *in situ* measurements
- compactness, for the same reason as well as for an easy manipulation or insertion in confined areas
- real time capabilities, in the case of dynamical studies
- minimal consumption (electric, gas, etc.) in the case of operation in the wild
- a reasonable price.

Historically, three technologies have been mainly used in muography: nuclear emulsions, scintillators, and gaseous detectors. Nuclear emulsions have the advantage to be completely passive and extremely precise, but quite sensitive to the environment and with a very long and complex analysis procedure. Scintillators are particularly robust and offer real-time analysis, but with a low resolution. Gaseous detectors somehow combine the advantages of the first two, with a good resolution, robustness, and real-time capabilities. Until recently, its use was however limited because of an expensive electronic equipment and because of its poor performance stability in outdoor conditions.

2.1. Detectors

The telescopes developed at Irfu are based on the Micromegas [6], one of the main Micro-Pattern Gaseous Detectors (MPGDs). Its active volume is separated into a conversion gap where the charged incident particle ionizes the gas, and an amplification gap where the charges from primary ionizations are multiplied through an avalanche process. The generated electrons and ions then induce a charge on copper strips etched on a Printed Circuit Board, which allows for the localization of the incident particle. The accuracy of this localization is determined by the pitch of the copper strips, and typically yields 100–500 microns. However, such a high density of strips results in a large number of electronic channels leading to an expensive equipment and a large electric consumption.

This difficulty was solved during R&D for another project, where a specific multiplexing scheme was introduced [7]. In this scheme, two given channels are connected to *neighbouring* strips at most once in the detector, thus allowing for non-ambiguous demultiplexing, as illustrated in Fig. 2. Thanks to the modest muon flux, a large multiplexing factor can be used, and a single channel could be connected to 17 strips while keeping the detection efficiency above 95% for a single detector.

Benefitting further from several technological improvements, in particular the bulk technology [8] and the resistive film [9], robust $50 \times 50\text{-cm}^2$ detectors were first manufactured in the CERN and Saclay MPGD workshops in 2014 [10], and assembled in a telescope.

2.2. Validation of the first telescope prototype: the WatTo experiment

The first telescope consisted of four detectors with a 2D readout. It was controlled with a Hummingboard nano-PC interfaced with all the electronic equipments:

- a dedicated High Voltage Power Supply card equipped with miniaturized CAEN A750x modules to set and monitor the high voltages on each detector;

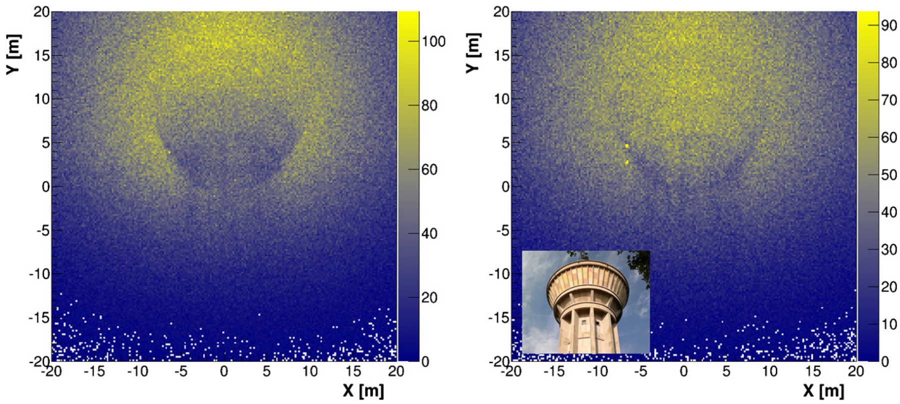

Fig. 3. Muographies of the CEA-Saclay water tower, obtained during the WatTo experiment with a 50×50-cm^2 telescope. Data were accumulated during four days each, with a full (left) then empty (right) tank.

- a Front End Unit card based on the DREAM Asic [11] ensuring the readout, triggering, collection and digitization of the signals generated by incoming muons;
- environmental probes measuring the outside temperature, pressure and humidity;
- a disk for data storage.

Thanks to the reduction of the channel number and the miniaturization of the different modules, all the electronic equipment fitted in a 20-cm side box, with an overall consumption of only 30 W.

The four detectors were attached to an inclinable, mechanical frame allowing them to point in different directions. A non-flammable gas bottle (Ar/iC$_4$H$_{10}$/CF$_4$, 95:2:3, called T2K gas) with a manual flowmeter ensured the circulation of the serial gas in the detectors, with a typical flow of 1.5 L/h.

In May 2015, this telescope was assembled and tested in outdoor conditions in front of the CEA-Saclay water tower. During 3.5 months, different images were obtained, validating the performance level of the instrument (see Fig. 3, the first muography of a structure that can be recognized by eye). The dynamical sensitivity was also established by detecting variations of the water level in the tank [12]. During the last month, the telescope was also operated successfully with two solar boards, resulting in a slight increase of the electronics noise.

This experiment also revealed a certain number of problems, and in particular very large fluctuations of the signal amplitude in the detectors related essentially to the temperature. These fluctuations translate into a signal saturation during the nights, and an efficiency drop during the days. A first HV, online feedback was empirically implemented based on the measurement of the outside temperature and pressure, and partially corrected for these fluctuations.

3. Muography of Khufu's pyramid

The WatTo experiment ended in September 2015, and the telescope was brought back to the lab for various muon scattering measurements. By a nice coincidence, the Scanpyramids mission [13] was announced a month later in the media.

3.1. The Scanpyramids mission

Scanpyramids is an internal mission gathering scientists of different disciplines, with the aim to study the four largest pyramids of the IV$^{\text{th}}$ dynasty with modern, non-destructive techniques. Coordinated by Prof. H. Helal from Cairo University and M. Tayoubi from HIP Institute, under the autority of the Egyptian Ministry of Antiquities, ScanPyramids is the latest generation of a long series of scientific explorations of the Egyptian pyramids. The proposed techniques include thermal measurements and muography for penetrating imaging, as well as photogrammetry, simulation, and 3D modeling. The muography programme was initially ensured by two Japanese teams from Nagoya University and KEK. They respectively developed nuclear emulsions and scintillator instruments to be installed inside the pyramids. In 2015, a first test was conducted with the emulsions on the Bent pyramid in Dahshour, allowing one to detect the Upper Chamber from the Lower one.

From a historical point of view, it is worth mentioning here that the muography imaging of a pyramid was actually first proposed by the Nobel Prize physicist L. Alvarez in the late 1960s and applied to the Khafre pyramid [14]. More recently, a team led by A. Menchaca Rocha also conducted extensive measurements on the Sun Pyramid in Teotihuacan (Mexico) [15].

3.2. Telescope improvements

The quality of the muographies obtained with the first prototype convinced the coordinators of the interest of the telescope and it was decided that the CEA will deploy instruments outside the pyramid to complement the Japanese inside

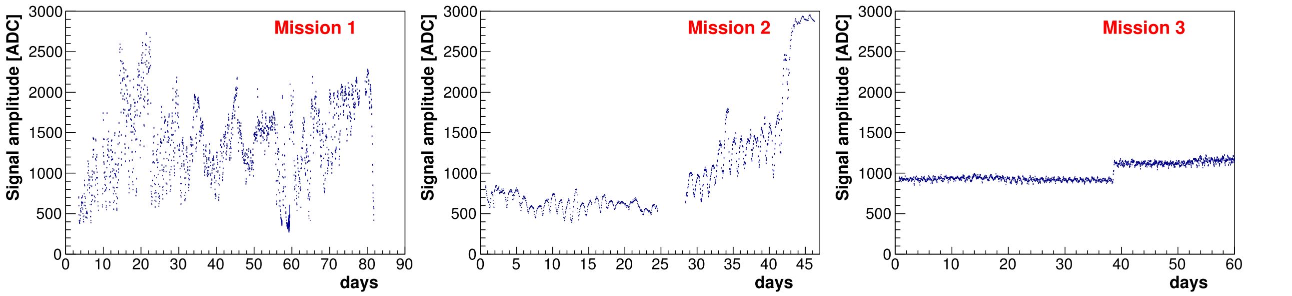

Fig. 4. Time evolution of the mean amplitude in the detectors for the three outdoor missions. The vertical scale is identical on the three plots. High voltages were adjusted every 15 minutes using the outside temperature and pressure (left), the gas temperature and pressure (middle), and the mean signal amplitude from the online reconstruction (right).

measurements. Neither the emulsions nor the scintillators could indeed be operated outdoors, the former suffering from high temperatures and the latter from low spatial resolution.

Three new Micromegas-based telescopes[1] were therefore built from January to April 2016 with several improvements to cope with the expected environment:

- a fly-case box embedding each telescope for an easy and safe transportation;
- a thermal protection tapped on the fly-case walls to limit the temperature variations;
- a 3G/4G key for remote access and control;
- an online track reconstruction and analysis in order to reduce the data transfer to Saclay (one telescope produced in average 20 GB of raw data per day but only 20 MB of processed data);
- temperature probes inserted within the gas circuit for a more precise high-voltage feedback.

This feedback was replaced in the last outdoor mission by an amplitude one, updating the high voltages from the measurements of the mean signal amplitude in each detector [16]. This feedback provided a nearly constant amplitude with time, as illustrated in Fig. 4.

The three telescopes were transported by plane to Cairo in April (Alhazen) and May (Alvarez and Brahic) 2016, reassembled and connected in Cairo University, and finally brought to the Giza plateau by car at the end of May. Even if a solar board power supply was prepared, a 220-V cable was finally provided. The necessity to guard the telescopes 24/7 on the plateau offered some unexpected comfort, in particular protection tents and air-conditioning. Because of the latter, temperatures did not exceed 45 °C during the hottest days, *i.e.* safely below the 55 °C tested at Saclay in an oven.

3.3. Data taking and analysis

As a first goal to validate their capability, the CEA telescopes were assigned the detection of a known cavity along the north-east edge, already described by 19th-century explorations. Accessible via the largest notch of the pyramid, its volume yields about 15 m^3 and is invisible from the ground. Simulations were first performed to identify the telescope positions with the optimal sensitivity, taking into account the observation zenith angle, the distance to the cavity and the relative opacity variation. The two best positions were localized 37 m away from the basis, and 25 m from the pyramid central axes,[2] see Fig. 5. Alhazen was therefore positioned on the north side, while Brahic and Alvarez were installed on the east side, see Fig. 6.

The simulation further indicated that two months of data taking would be - containing high-pressure T2K gas were thus procured to provide enough gas for a three-month campaign. In total, around 75 millions of triggers were accumulated by the three telescopes. Though the Alvarez telescope collected less data because of some gas issues, Alhazen and Brahic were able to detect a significant muon excess (above 5σ) at the position of the known cavity. Surprisingly, data analysis further revealed a very similar excess, about 30 m higher than the first one, interpreted as another cavity, see Fig. 7.

After this first campaign, the telescopes were redeployed in January 2017 around the other edges of the pyramid[3] to check for the presence of more cavities, as shown in Fig. 8. More than 88 millions of triggers were accumulated in the second campaign, but split on the different edges. This campaign was interrupted in May 2017 after the Nagoya team reported on a large muon excess close to the Grand Gallery, as it was decided to point the telescopes on this zone to confirm the excess. This decision was further motivated by the necessity to get another observation point for a precise triangulation, as all Japanese instruments were located in the Queen's Chamber. After two months of data taking, Alhazen and Brahic confirmed at a (combined) 8.4-σ level the presence of the Grand Gallery, and observed a second excess above

[1] Named after the three famous scientists Alhazen, Alvarez, and Brahic, who sadly passed away during the preparation of the telescopes.
[2] By an unfortunate coincidence that was not predicted by our simulation, the east position turned out to be the exact place of the camel WC.
[3] Alhazen looking at the north-west edge, Brahic at the south-east one, and Alvarez at the south-west one.

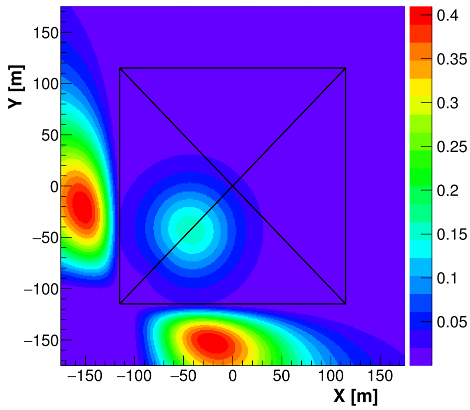

Fig. 5. Simulation showing the sensitivity (in arbitrary units) to detect the known cavity along the north-east edge, as a function of the telescope position. The time needed for an unambiguous detection at 5-σ level is inversely proportional to the sensitivity. Because of the pyramid symmetry, two best positions are identified, on the north and east sides.

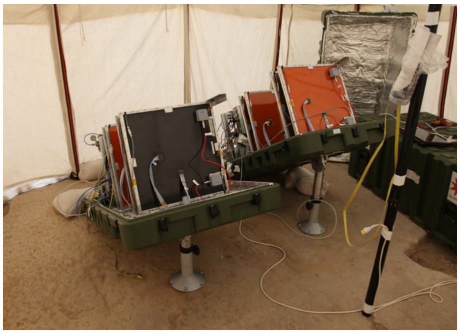

Fig. 6. Photography of Alvarez and Brahic telescopes during their installation in the East tent.

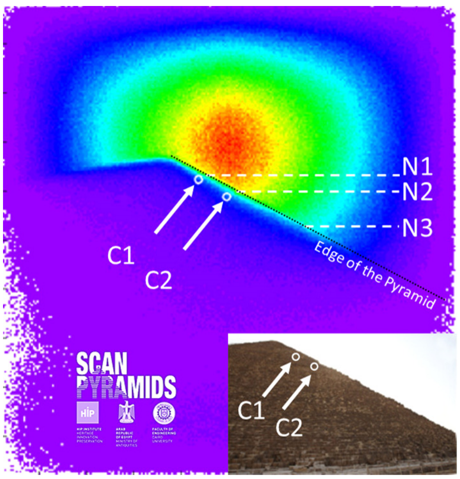

Fig. 7. Result of the first CEA campaign in 2016, showing the positions of the known (C2) and new (C1) cavities on the north-east edge.

it, at a (combined) 5.8-σ level, see Fig. 9. The 3D model confirmed that this excess nicely overlapped with the excess observed by the Nagoya team. To our knowledge, the observations of the Grand Gallery and of the cavity above[4] are the first detections of inner structures of a pyramid ever obtained from the outside.

[4] Called the *ScanPyramids Big Void*.

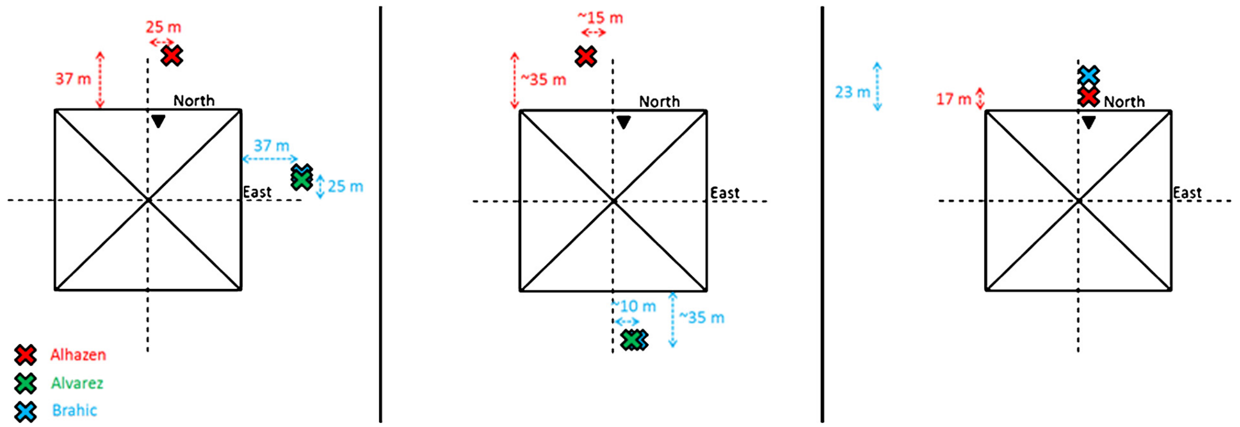

Fig. 8. Positions of the CEA telescopes during the three measurement campaigns.

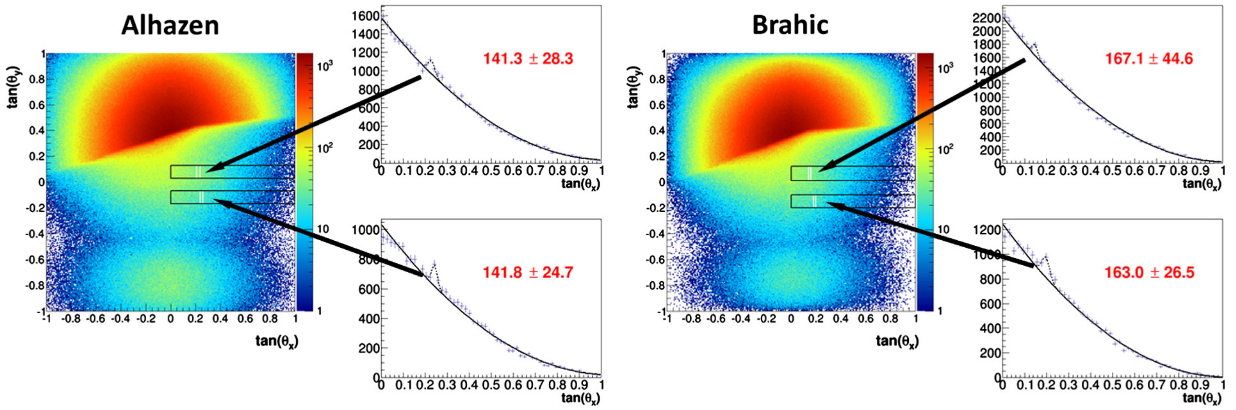

Fig. 9. Result of the third CEA campaign in 2017, showing the muon excesses (see red numbers, obtained from a fit) measured in both telescopes and corresponding to the Grand Gallery (bottom) and to the ScanPyramids Big Void (top). θ_x and θ_y represent the angles of the muon tracks in the x–z and y–z planes, z being the axis perpendicular to the telescope and x,y the horizontal and vertical axes.

4. Conclusion and perspectives

Initiated by a R&D lab for the characterization of nuclear physics detectors, the muography activity has turned into a fantastic scientific and human adventure. The telescopes deployed by the CEA team has shown a remarkable robustness in harsh conditions, and opened the way to real-time, high-definition muography. In order to study in more details the Pyramid and its Big Void, the team has then built in 2018 two new telescopes, which have been installed inside the Grand Gallery of the pyramid, where they faced additional challenges: transportation within the small corridors, extreme humidity brought by the tourist attendance, presence of cable-eating mice, etc. To cope with this new environment, additional improvements have been implemented, in particular on the gas circuit, with the goal to build completely sealed instruments in the next years.

Beyond the ScanPyramids mission, the possibility to explore unaccessible worlds in a non-destructive way evidently elicited a large interest. Several *Proofs of Concepts* are in progress, both experimentally and with simulations, and a collaboration has been recently initiated with Iris Instruments to commercialize these telescopes in a near future.

Interestingly, the required R&D to improve the telescopes has in turn benefitted to high energy physics, via a better understanding and control of the gas quality of particle detectors. These telescopes are also now adapted, with very little changes, to build a precise tracker for an anti-matter experiment at CERN.

Acknowledgements

This work could not have been done without the unvaluable help of the muography team at IRFU, and to all the people who helped in the preparation of the instruments. The ELVIA group and the CERN MPGD workshop also had a decisive contribution by manufacturing a large part of the Micromegas detectors. We are particularly grateful to P. Chomaz, A-I. Etienvre, E. Delagnes, and H. Goutte, who have strongly supported this activity. Part of these instruments have been built with the financial support of the 'Région Île-de-France' (within the SESAME call) and the P2IO LabEx. More importantly, we are indebted to Khufu's architects, who have managed to hide these cavities to all the explorators during 4500 years. We wish that this small work will contribute to the recognition of their phenomenal genius.

References

[1] D. Griffiths, Introduction to Elementary Particles, second edition, Wiley-VCH, 2008 [section 9.4].
[2] H.A. Bethe, Phys. Rev. 89 (1953) 256.
[3] C. Patrignani, et al., Particle Data Group, Chin. Phys. C 40 (2016) 100001.
[4] K.N. Borozdin, et al., Nature 422 (2003) 277.
[5] S. Procureur, Nucl. Instrum. Methods A 878 (2018) 169.
[6] I. Giomataris, et al., Nucl. Instrum. Methods A 376 (1996) 29.
[7] S. Procureur, R. Dupré, S. Aune, Nucl. Instrum. Methods A 729 (2014) 888.
[8] Y. Giomataris, et al., Nucl. Instrum. Methods A 560 (2006) 405.
[9] T. Alexopoulos, et al., Nucl. Instrum. Methods A 640 (2011) 110.
[10] S. Bouteille, et al., Nucl. Instrum. Methods A 834 (2016) 187.
[11] C. Flouzat, et al., Dream: a 64-channel Front-end Chip with Analogue Trigger Latency Buffer for the Micromegas Tracker of the Clas12 Experiment, 2014, TWEPP conference.
[12] S. Bouteille, et al., Nucl. Instrum. Methods A 834 (2016) 223.
[13] http://www.scanpyramids.org/.
[14] L.W. Alvarez, et al., Science 167 (1970) 832.
[15] S. Aguilar, et al., Proceedings of the 33rd International Cosmic Ray Conference, Rio de Janeiro, 2013.
[16] S. Bouteille, S. Procureur, Procédé et dispositif de rétroaction sur la haute tension d'un détecteur gazeux, French patent No. 17 57755, 2017.