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

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6 **Abstract**

Several muon telescopes have been developed in the last years at CEA-Saclay. Benefitting from a 15 year R&D on Micro-Pattern Gaseous Detectors (MPGDs) and on several recent innovations, these telescopes yield unprecedented resolution for real time instruments, and allow for high definition muography imaging. As a first application, 3 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 detection ever of internal structures of a pyramid from the outside, and participated to the discovery of a large void above the Grand Gallery.

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. 3 de ces instruments ont été déployés autour de la pyramide de Kheops 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.

7 *Key words:* Muography, Micro Pattern Gaseous Detectors, MPGD,
8 Micromegas, Pyramid, Khufu

9 1. Introduction

10 1.1. Cosmic rays and muons

11 Most of our Universe is a hostile place for life. In every galaxy, ionizing
12 particles are produced and accelerated during violent cosmic phenomena like
13 supernovae. The energy of these particles, essentially protons, can reach
14 the kinetic energy of a tennis ball hit at 150 km/h. In the Universe quasi-
15 perfect vacuum, they can travel during millions of year before being stopped
16 or absorbed. And every second, billions of such particles end their long
17 journey when approaching the Earth. The collisions with atoms of the upper
18 layers of our atmosphere create cascades, or showers of less energetic particles
19 like pions, kaons, neutrons and many more. At the sea level, the particle
20 flux is dominated by muons, with a rate of approximately 150 Hz/m². The
21 atmosphere thus acts as a giant, protecting umbrella converting hazardous
22 particles into a cosmic rain which actively participates to the evolution of
23 life. The production and propagation of muons derive from several complex
24 processes:

- 25 • their copious production from pions and kaons is a consequence of he-
26 licity conservation [1];
- 27 • though unstable with a life time of about 2 μ s, they can travel several
28 kilometers thanks to the time dilatation described by special relativity;
- 29 • 200 times more massive than electrons, they are much more penetrating
30 due to the (somehow counter-intuitive) phenomenon of Bremstrahlung
31 radiation.

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

37 1.2. Principles of muography

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

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

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

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

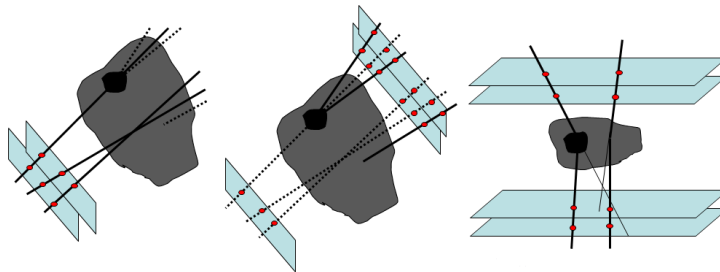


Figure 1: *Principle of muon imaging using transmission (left), absorption (middle) and deviation (right) modes with particle detectors (in blue). Muon trajectories are represented in bold and bold dotted, but only the former are actually used for a given mode.*

69 2. The CEA muon telescopes

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

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

84 Historically, 3 technologies have been mainly used in muography: nuclear
85 emulsions, scintillators and gaseous detectors. Nuclear emulsions have the
86 advantages to be completely passive and extremely precise, but quite sensi-
87 tive to the environment and with a very long and complex analysis procedure.
88 Scintillators are particularly robust and offer real time analysis, but with a
89 low resolution. Gaseous detectors somehow combine the advantages of the
90 first two, with a good resolution, robustness, and real time capabilities. Up
91 to recently, its use was however limited because of an expensive electronic
92 equipment and because its poor performance stability in outdoor conditions.

94 *2.1. Detectors*

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

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

113 Benefitting further from several technological improvements, in particular
114 the bulk technology [8] and the resistive film [9], robust 50x50 cm² detec-
115 tors were first manufactured in the CERN and Saclay MPGD workshops in
116 2014 [10], and assembled in a telescope.

117
118

119 *2.2. Validation of the first telescope prototype: the WatTo experiment*

120 The first telescope consisted in 4 detectors with a 2D readout. It was
121 controlled with a Hummingboard nano-PC interfaced with all the electronic
122 equipments:

- 123 • a dedicated High Voltage Power Supply card equipped with miniatur-
124 ized CAEN A750x modules to set and monitor the high voltages on
125 each detector

- 126 • a Front End Unit card based on the DREAM Asic [11] ensuring the
127 readout, triggering, collection and digitization of the signals generated
128 by incoming muons

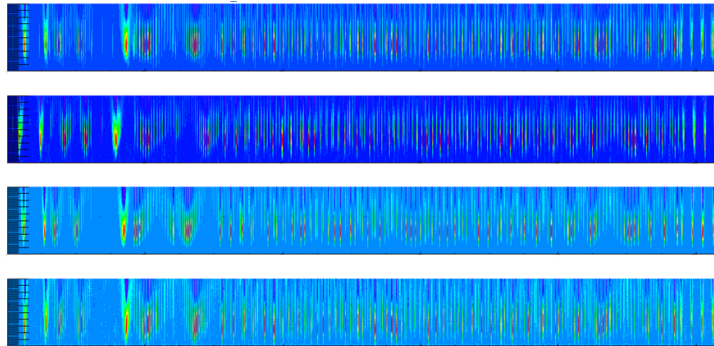


Figure 2: *Typical muon event in a 4 detector telescope. Each histogram represents the signal amplitude (color scale) as a function of the detector position (horizontal axis) and time (vertical axis). The complex pattern results from the multiplexing scheme, but the muon position can be easily identified as the biggest colored structures in each detector, resulting in a nearly vertical track.*

- 129 • environmental probes measuring the outside temperature, pressure and
130 humidity
- 131 • a disk for data storage

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

135 The 4 detectors were attached to an inclinable, mechanical frame allowing
136 to point in different directions. A non flammable gas bottle (Ar-iC₄H₁₀-CF₄,
137 95-2-3, called T2K gas) with a manual flowmeter ensured the serial gas cir-
138 culation in the detectors, with a typical flow of 1.5 L/h.

139 In May 2015 this telescope was assembled and tested in outdoor conditions
140 in front of the CEA-Saclay water tower. During 3.5 months, different im-
141 ages were obtained validating the performance level of the instrument (see
142 Fig. 3, the first muography of a structure that can be recognized by eye).
143 The dynamical sensitivity was also established by detecting variations of the
144 water level in the tank [12]. During the last month, the telescope was also
145 operated successfully with 2 solar boards, resulting in a slight increase of the
146 electronics noise.

147
148 This experiment also revealed a certain number of problems, and in partic-
149 ular very large fluctuations of the signal amplitude in the detectors related

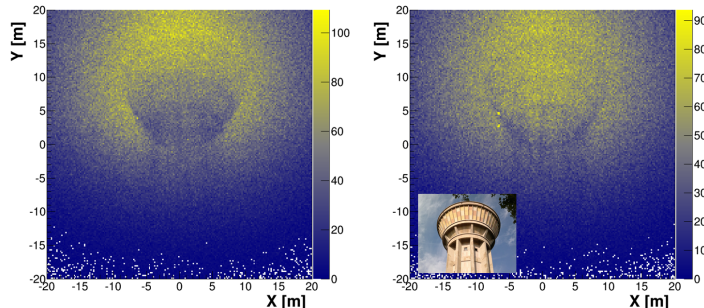


Figure 3: *Muographies of the CEA-Saclay water tower, obtained during the WatTo experiment with a $50 \times 50 \text{ cm}^2$ telescope. Data were accumulated during 4 days each, with a full (left) then empty (right) tank.*

150 essentially to the temperature. These fluctuations translate into a signal sat-
 151 uration during the nights, and an efficiency drop during the days. A first HV,
 152 online feedback was empirically implemented based on the measurement of
 153 the outside temperature and pressure, and partially corrected for these fluc-
 154 tuations.

155 3. Muography of Khufu’s pyramid

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

160 3.1. The Scanpyramids mission

161 Scanpyramids is an internal mission gathering scientists of different disci-
 162 plines, with the aim to study the 4 largest pyramids of the IVth dynasty with
 163 modern, non destructive techniques. Coordinated by Prof. H. Helal from
 164 Cairo University and M. Tayoubi from HIP Institute, under the authority of
 165 the Egyptian Ministry of Antiquities, ScanPyramids is the latest generation
 166 of a long series of scientific explorations of the Egyptian pyramids. The
 167 proposed techniques include thermal measurements and muography for pen-
 168 etrating imaging, as well as photogrammetry, simulation and 3D modeling.
 169 The muography programme was initially ensured by two Japanese teams from
 170 Nagoya University and KEK. They respectively developed nuclear emulsions

171 and scintillator instruments to be installed inside the pyramids. In 2015 a
172 first test was conducted with the emulsions on the Bent pyramid in Dahshour,
173 allowing to detect the Upper Chamber from the Lower one.

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

179

180 *3.2. Telescope improvements*

181 The quality of the muographies obtained with the first prototype con-
182 vinced the coordinators of the telescope interest and it was decided that the
183 CEA will deploy instruments outside the pyramid to complement Japanese
184 inside measurements. Neither the emulsions nor the scintillators could in-
185 deed be operated outdoors, the former suffering from high temperatures and
186 the latter from low spatial resolution.

187 Three new Micromegas-based telescopes¹ were therefore built from January
188 to April 2016 with several improvements to cope with the expected environ-
189 ment:

- 190 • a fly-case box embedding each telescope for an easy and safe trans-
191 portation
- 192 • a thermal protection tapped on the fly-case walls to limit the temper-
193 ature variations
- 194 • a 3G/4G key for remote access and control
- 195 • an online track reconstruction and analysis in order to reduce the data
196 transfer to Saclay (one telescope produced in average 20 Gb of raw data
197 per day but only 20 Mb of processed data)
- 198 • temperature probes inserted within the gas circuit for a more precise
199 high voltage feedback.

¹named after the three famous scientists Alhazen, Alvarez and Brahic who sadly passed away during the preparation of the telescopes

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

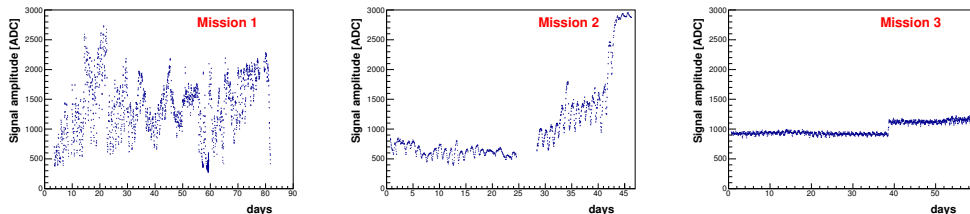


Figure 4: *Time evolution of the mean amplitude in the detectors for the 3 outdoor missions. The vertical scale is identical on the 3 plots. High voltages were adjusted every 15 minutes using the outside temperature and pressure (left), the gas temperature and pressure (middle), and the mean signal amplitude from the online reconstruction (right).*

203

204 The 3 telescopes were transported by plane to Cairo in April (Alhazen) and
 205 May (Alvarez and Brahic) 2016, reassembled and connected in Cairo Univer-
 206 sity, and finally brought to the Giza plateau by car in end of May. Even if a
 207 solar board power supply was prepared, a 220 V cable was finally provided.
 208 The necessity to guard the telescopes 24/7 on the plateau offered some unex-
 209 pected comfort, in particular protection tents and air-conditioning. Because
 210 of the latter, temperatures did not exceed 45 degrees during the hottest days,
 211 *i.e.* safely below the 55 degrees tested at Saclay in an oven.

212 3.3. Data taking and analysis

213 As a first goal to validate their capability, the CEA telescopes were as-
 214 signed the detection of a known cavity along the North-East edge, already
 215 described from XIXth century explorations. Accessible via the largest notch
 216 of the pyramid, its volume yields about 15 m^3 and is invisible from the ground.
 217 Simulations were first performed to identify the telescope positions with the
 218 optimal sensitivity, taking into account the observation zenith angle, the dis-
 219 tance to the cavity and the relative opacity variation. The two best positions
 220 were localized 37 m away from the basis, and 25 m from the pyramid central
 221 axes², see Fig. 5. Alhazen was therefore positioned on the North side, while

²by an unfortunate coincidence which was not predicted by our simulation, the East position turned out to be the exact place of the camel WC.

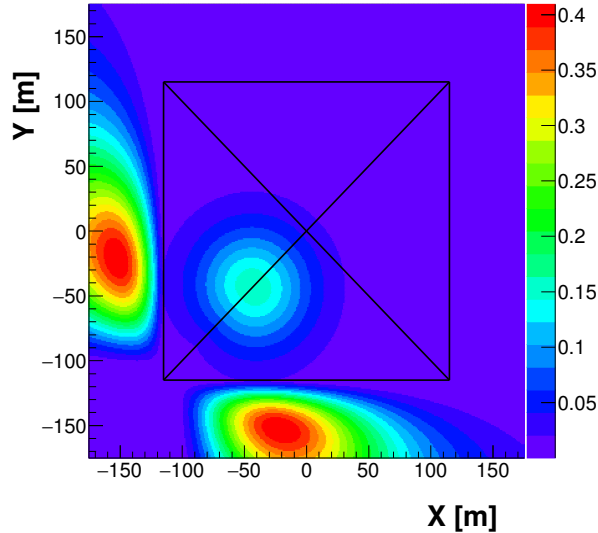


Figure 5: *Simulation showing the sensitivity (in arbitrary units) to detect the known cavity along the North-East edge, as a function of the telescope position. The time needed for an unambiguous detection at 5 sigma level is inversely proportional to the sensitivity. Because of the pyramid symmetry,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

222 Brahic and Alvarez were installed on the East, see Fig. 6.

223

224 The simulation further indicated that 2 months of data taking would be re-
 225 quired for each telescope to be able to detect this cavity. Six 5L bottles
 226 containing high pressure T2K gas were thus procured to provide enough gas
 227 for a 3 month campaign. In total, around 75 millions of triggers were accu-
 228 mulated by the three telescopes. Though the Alvarez telescope collected less
 229 data because of some gas issues, Alhazen and Brahic were able to detect a
 230 significant muon excess (above 5 sigma) at the position of the known cavity.
 231 Surprisingly, the data analysis further revealed a very similar excess, about
 232 30 m higher than the first one, interpreted as another cavity, see Fig. 7.

233

234 After this first campaign, the telescopes were redeployed in January 2017

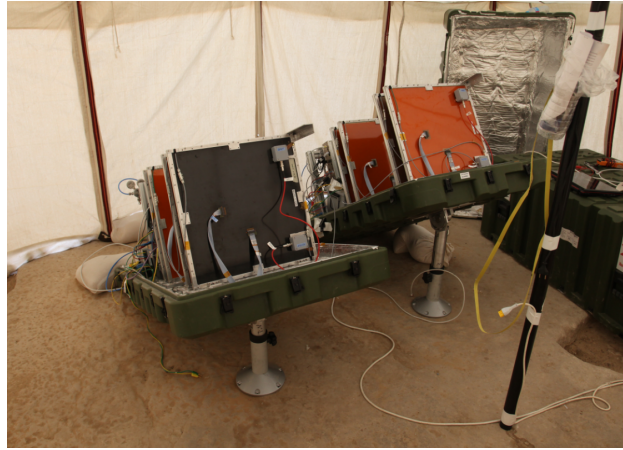


Figure 6: *Photography of Alvarez and Brahic telescopes during their installation in the East tent.*

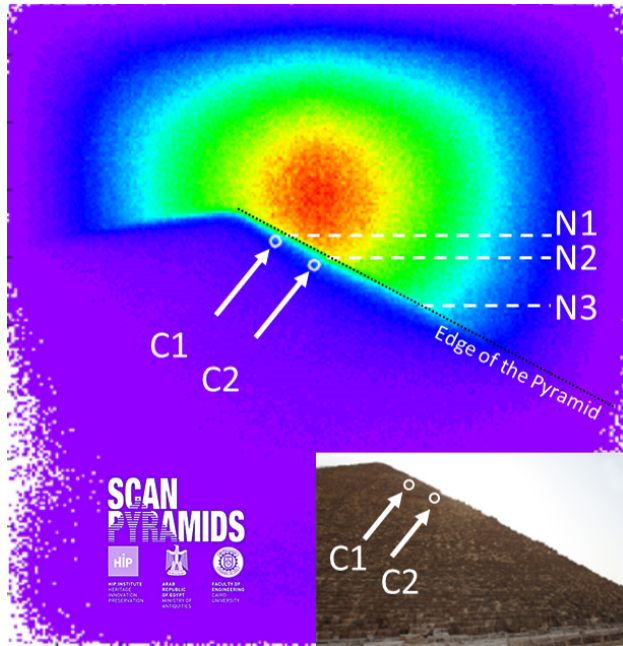


Figure 7: *Result of the first CEA campaign in 2016, showing the positions of the known (C2) and new (C1) cavities on the North-East edge.*

235 around the other edges of the pyramid³ to check for the presence of more cav-

³Alhazen looking at the North-West edge, Brahic at the South-East and Alvarez at the South-West

236 ities, as shown in Fig. 8. More than 88 millions of triggers were accumulated
 237 in the second campaign, but splitted on the different edges. This campaign
 238 was interrupted in May 2017 after the Nagoya team reported on a large muon
 239 excess close to the Grand Gallery, as it was decided to point the telescopes on
 240 this zone to confirm the excess. This decision was further motivated by the
 241 necessity to get another observation point for a precise triangulation, as all
 242 Japanese instruments were located in the Queen’s Chamber. After 2 months
 243 of data taking, Alhazen and Brahic confirmed at a (combined) 8.4 sigma level
 244 the presence of the Grand Gallery, and observed a second excess above it,
 245 at a (combined) 5.8 sigma level, see Fig. 9. The 3D model confirmed that
 246 this excess nicely overlapped with the excess observed by the Nagoya team.
 247 To our knowledge, the observations of the Grand Gallery and of the cavity
 248 above⁴ are the first detections of inner structures of a pyramid ever obtained
 from outside.

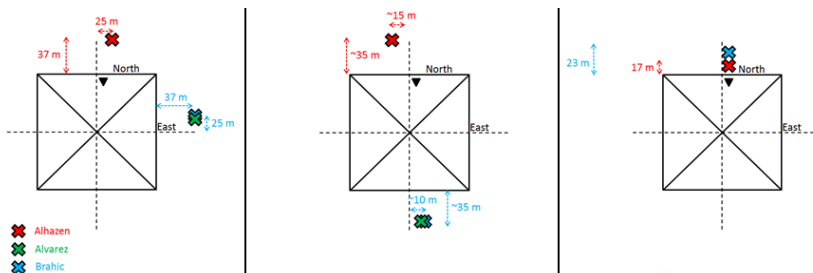


Figure 8: *Positions of the CEA telescopes during the 3 measurements campaigns.*

249
 250
 251

252 4. Conclusion and perspectives

253 Initiated by a lab R&D for the characterization of nuclear physics detectors,
 254 the muography activity has turned into a fantastic scientific and human
 255 adventure. The telescopes deployed by the CEA team has shown a remarkable
 256 robustness in harsh conditions, and opened the way to real time, high
 257 definition muography. In order to study in more details the Pyramid and
 258 its Big Void, the team has then built in 2018 two new telescopes which have

⁴called the *ScanPyramids Big Void*

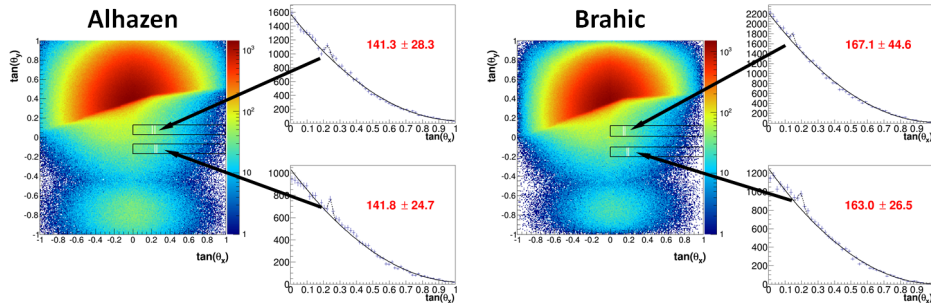


Figure 9: *Result of the third CEA campaign in 2017, showing the muon excesses (see red numbers, obtained from a fit) measured in both telescopes and corresponding to the Grand Gallery (bottom) and to the ScanPyramids Big Void (top). θ_x and θ_y represent the angles of the muon tracks in the $x - z$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

259 been installed inside the Grand Gallery of the pyramid, where they faced
 260 additional challenges: transportation within the small corridors, extreme hu-
 261 midity brought by the touristic activity, presence of cable-eating mice, etc.
 262 To cope with this new environment, additional improvements have been im-
 263 plemented, in particular on the gas circuit, with the goal to build completely
 264 sealed instruments in the next years.

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

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

275 5. Acknowledgments

276 This work could not have been done without the invaluable help of the
 277 muography team at IRFU, and to all the people who helped in the prepara-
 278 tion of the instruments. The ELVIA group and the CERN MPGD workshop
 279 also had a decisive contribution by manufacturing a large part of the Mi-
 280 cromegas detectors. We are particularly grateful to P. Chomaz, A-I. Etien-

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283 Région Ile-de-France (within the SESAME call) and the P2IO LabEx. More
284 importantly, we are indebted to Khufu's architects, who have managed to
285 hide these cavities to all the explorators during 4,500 years. We wish that
286 this small work will contribute to the recognition of their phenomenal genius.

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