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# The secret chambers in the Chephren pyramid

Bartosz Gutowski<sup>1</sup>, Witold Józwiak<sup>1</sup>, Markus Joos<sup>2,4</sup>,  
Janusz Kempa<sup>3</sup>, Kamila Komorowska<sup>1</sup>, Kamil Krakowski<sup>1</sup>,  
Ewa Pijus<sup>1</sup>, Kamil Szymczak<sup>1</sup> and Małgorzata Trojanowska<sup>1</sup>

<sup>1</sup> L.O. im. Marsz. Małachowskiego, Płock, Poland

<sup>2</sup> CERN, Geneva, Switzerland

<sup>3</sup> Faculty of Civil Engineering, Mechanics and Petrochemistry, The Institute of Civil Engineering, Warsaw University of Technology, Warsaw, Poland



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E-mail: [markus.joos@cern.ch](mailto:markus.joos@cern.ch)

## Abstract

In 2016, we (seven high school students from a school in Płock, Poland) participated in the CERN Beamline for Schools competition. Together with our team coach, Mr. Janusz Kempa, we submitted a proposal to CERN that was selected as one of two winning proposals that year. This paper describes our experiment from the early days of brainstorming to the trip to Geneva.

## Introduction: the mystery of the pyramids

Pyramids are the greatest architectural achievement of ancient civilization, so people all over the world are curious as to the purpose of such huge constructions. No other structure has been studied as thoroughly, nor have so many books and articles been written about it. However, the pyramids are still the most mysterious pieces of architecture on Earth and it seems that they still hide numerous mysteries. One of the biggest and the most intriguing to us is the internal structure of the pyramid of Chephren (Khafre). The Chephren Pyramid does not seem to hide any more than a modest chamber (known as the ‘Belzoni Chamber’), unlike his fathers, Cheops’, Great Pyramid, which has many sophisticated

internal structures (see figure 1): the King’s Chamber, the Queen’s Chamber and the Great Gallery. The fact that the Egyptians set up 2.5 million stone blocks without any purpose seems to be unimaginable. Therefore, we attempt to examine the internal structure of the pyramid using muon tomography [1].

In the 1930s, the attenuation of muons under the ground was used to measure the depth of the London subway [2]. In recent years, Japanese teams have used muon tomography to estimate the level of lava in volcanoes [3] and to check the damages of the nuclear reactor in Fukushima after the 2011 tsunami [4].

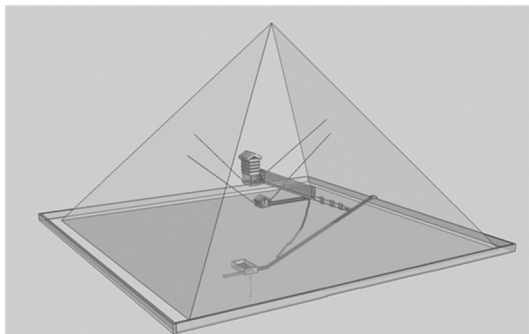
## The making of our proposal

In 2009 our school started a cooperation with the Warsaw University of Technology in the field of mathematics and physics. The result of this partnership was the creation of a special class where emphasis was placed on these areas of science. All members of our team, the ‘Pyramid Hunters’, chose this class because of the opportunity to learn physics in a more interesting

<sup>4</sup> Author to whom any correspondence should be addressed.



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**Figure 1.** 3D representation of Cheops' pyramid.

way. We were not disappointed. During one of the physics lesson Professor J Kempa started a discussion about research that has taken place on the Great Pyramids of Giza, Egypt. These studies were based on muon tomography. When the BL4S competition was announced, we remembered that topic. Janusz Kempa has been helping us from the beginning. He is the one who told us about the competition and encouraged us to take part. During our work on the computer model and later on the proposal, we received many very useful books from him. Some of them were written in Russian which none of our team knew, so J Kempa's help was invaluable. Moreover, he devoted a lot of time to us and we always could count on his help. He is very modest, and about our project and victory in BL4S, he said: 'The success of my students at BL4S2016 is their success. My role as their teacher was mainly to take care of what they were doing. A good teacher lives by the successes of his pupils. They must feel his devotion to them. They must feel that the teacher cares about their success that he is with them. Anyone can give it to their students'.

It took us three months to write the proposal and produce a short clip. Our project was very extensive and we had to analyze much data, create a mathematical model and create muon absorption charts. Our team was divided into two parts. One focused on the mathematical model and calculations and the other concentrated on Alvarez's data and charts. We met many times and shared our progress. The last thing we had to do before the competition was write the proposal to BL4S, which we did together as one team. All the members participated in writing the paper and made suggestions for corrections for each chapter.

Finally, we had to shoot a short clip in our school and town. All of us were involved and enjoyed promoting our school. During this time, we had support from our teachers: J Kempa, C Obczyński and the school management. Thanks to the headmistress of our school, we could stay after the end of the lessons and access the necessary equipment such as computers. Cezary Obczyński helped us with some mathematical issues which are not taught in school. After CERN announced the results of the competition, the headmistress organized a course for us, which took place in the Physics Institute of Polish Academy of Sciences in Kraków, Poland. This would not have been possible without the involvement of Krzysztof Woźniak, a professor working for the Polish Academy of Science. Thanks to him we learned some useful information about data analysis as well as detectors and other devices like those used at CERN.

### A mathematical model and calculations

We created a computer model of the pyramid. To validate the model, we compare our calculations with the experimental data of Luis W Alvarez [5]. L Alvarez installed his detectors (spark chambers) inside the Belzoni Chamber. This chamber is displaced from the centre of the base by  $y_0 = 13.5$  m to the east and  $x_0 = 4$  m to the north (figure 2).

Considering this displacement, we calculate the distance covered by muons, which reach the chamber, passing through the walls of the pyramid. As an assumption, we consider only muons that enter the pyramid from the top. We used the equation of the plane surface N, W, S and E of the pyramid, equation (1), to calculate the flux of the muons.

$$A = a\sqrt{\left(\frac{b}{2}\right)^2 + h^2} + b\sqrt{\left(\frac{a}{2}\right)^2 + h^2}. \quad (1)$$

With  $a$  the base length,  $b$  the base width and  $h$  the pyramid's height.

We introduced the scale factor ' $k$ ' due to the symmetry:

$$k = \frac{143.5}{4}. \quad (2)$$

In the mathematical model of the Chephren pyramid we developed, we assumed that the pyramid

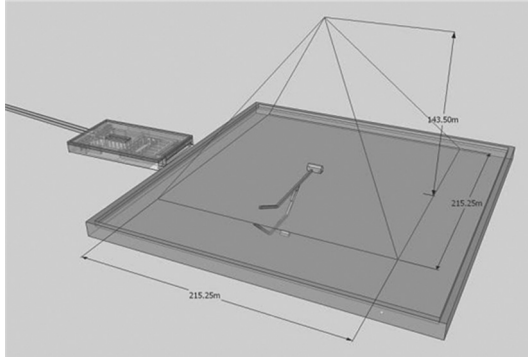


Figure 2. 3D model of Chephren's pyramid.

is a regular pyramid with a quadratic base. The height of the pyramid:  $h = 4k$ , the side of the base:  $a = 6k$ . Height of the sidewall of the pyramid:  $l = 5k$  (Egyptian triangle).

From equations (1) and (2) we derive the formulas for the distances from any point on the side wall to the Belzoni Chamber.

The distance  $t$  to the Belzoni Chamber from the east lateral face (figures 3 and 4) is:

$$t = \frac{8y_0 + 24}{3\sqrt{3} - 4\sin\alpha} \text{ (m)}, \quad (3)$$

where  $x_0, y_0$  are the parameters that introduce the shift of the centre of the chamber with respect to the centre of the pyramid, and  $\alpha$  is the azimuthal angle.

### Cosmic muons

The integral sea-level muon spectra can be approximated by a power law [6]:

$$N(E_\mu, R) = AE_\mu^{-\gamma}, \quad (4)$$

where  $N$  is the integral energy spectrum of muons,  $E_\mu$  is the energy of muons in GeV,  $\gamma$  is the exponent of the energy spectrum of muons,  $R$  is the range of the muons inside the limestone rock (that the pyramid is made of) and  $A$  is a normalisation factor.

Assuming the muon energy losses increase linearly with their energy  $E_\mu$ , we derived the formula for the range  $R$  of the muons:

$$R = \frac{1}{b} \ln \left( 1 + \frac{b}{a} E_\mu \right), \quad (5)$$

where  $a$  describes the average ionization energy loss in the energy range relevant to the

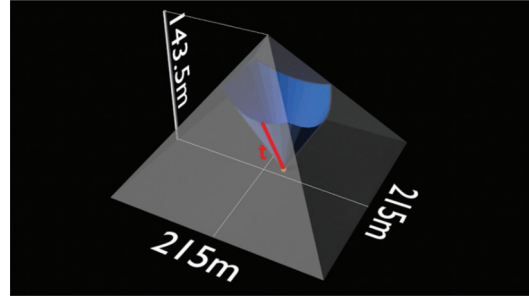


Figure 3. Graphic representation of our mathematical model.

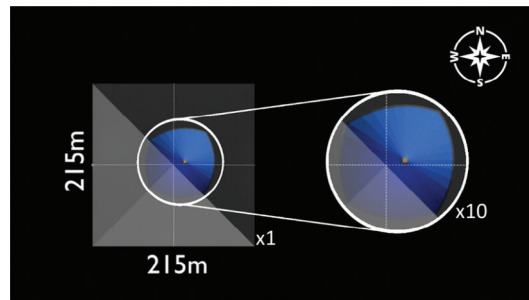


Figure 4. Graphic representation of our mathematical model (vertical projection). The yellow spot represents the location of the Belzoni Chamber.

problem and  $b$  summarizes processes of muon Bremsstrahlung, direct electron pair creation and nuclear interaction.

From equation (5) we have obtained the formula for the energy of muons as a function of the constants  $a, b$  and the range of muons  $R$ :

$$E_\mu = \frac{a}{b} (e^{Rb} - 1). \quad (6)$$

From Taylor's theorem we know that:

$$e^{Rb} \approx 1 + Rb. \quad (7)$$

By substituting (6) into (7) we get:

$$E_\mu = \frac{a}{b} (e^{Rb} - 1) \approx \frac{a}{b} (1 + Rb - 1). \quad (8)$$

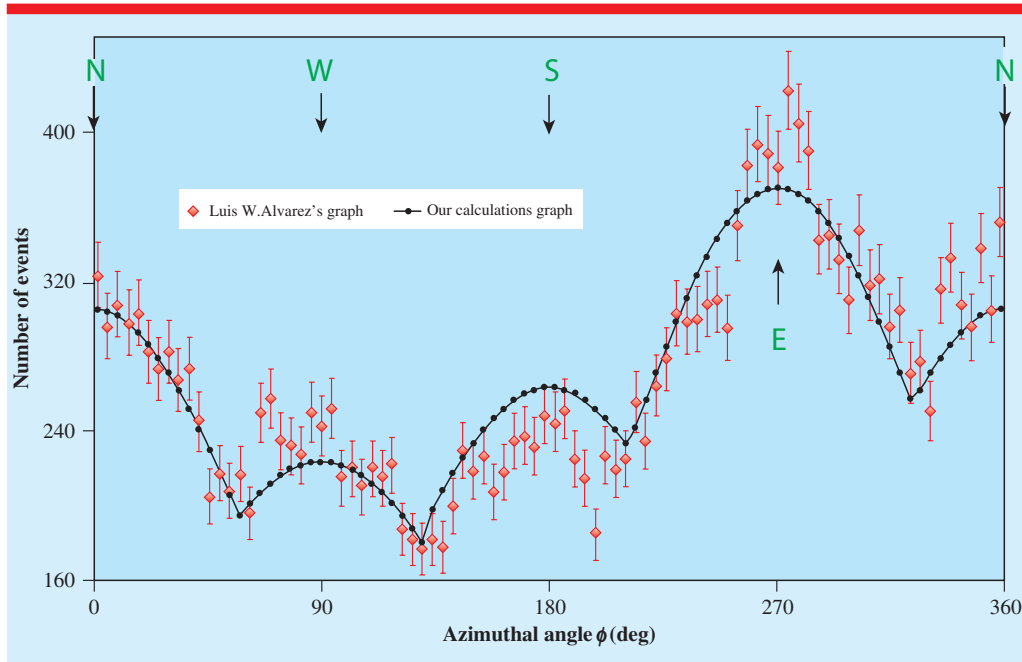
Hence:

$$E_\mu \approx aR. \quad (9)$$

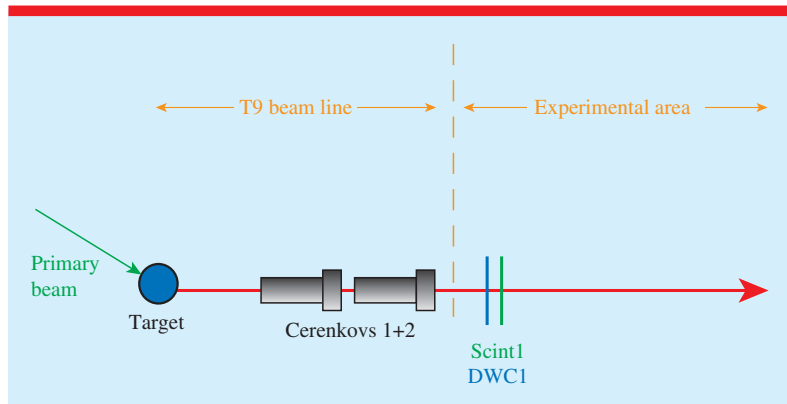
The range of muons inside the rock can be written as:

$$R = \rho t, \quad (10)$$

where  $\rho$  is the rock density in  $\text{g cm}^{-3}$ , and  $t$  is the distance in cm.



**Figure 5.** Results for 650.000 insident muons from zenith angles between 20° and 40°. Our calculations are normalized to the number of muons (180) registered for the 130-degree angle.



**Figure 6.** Sketch of the beamline in the T9 experimental area.

By substituting equations (9) and (10) into equation (4) we get the number of muons that reach the detectors inside the Belzoni chamber:

$$N(E_\mu, R) = A(apt)^{-\gamma}. \quad (11)$$

By using equation (11) for two different distances  $t_1$  and  $t_2$ , we can determine the ratio of the number of muons registered for the two considered distances:

$$\frac{N(t_1)}{N(t_2)} = \frac{A(apt_1)^{-\gamma}}{A(apt_2)^{-\gamma}} = \left(\frac{t_1}{t_2}\right)^{-\gamma}. \quad (12)$$

Using the above equations, we estimate the number of muons that reach the chamber, from  $\theta = 30^\circ$  zenith angle and different azimuth angles. Our results, together with the data from [5], can be seen in figure 5. We observe an unexpectedly high peak for  $\theta = 270^\circ$  (perhaps there is a corridor or irregularities in the construction). Between angles  $\theta = 62^\circ$  and  $\theta = 72^\circ$  we see a possibly higher number of events in comparison to the model. A possible explanation could be that a chamber is located there, which is similar in size to the King's

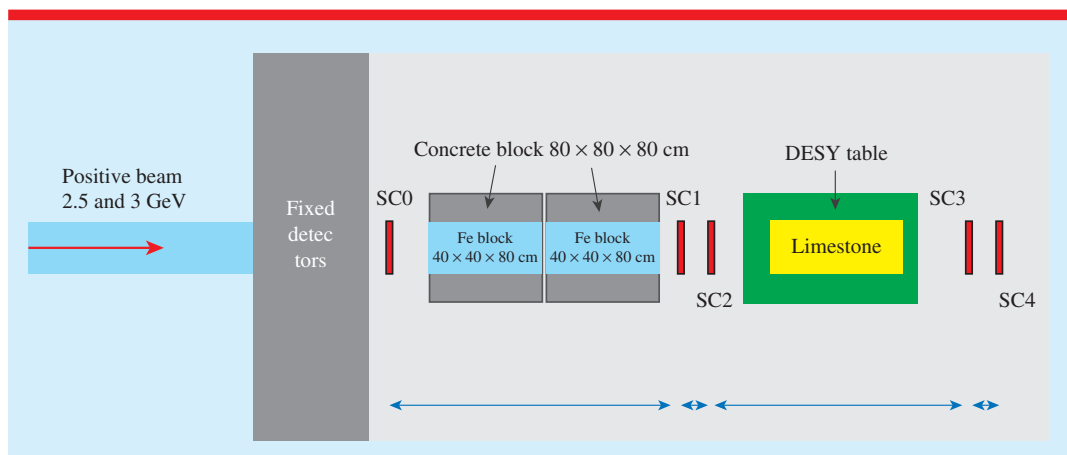


Figure 7. Schematic drawing of the experimental setup.



Figure 8. Panoramic photo of the experiment in the T9 hall.

Chamber in the Great Pyramid. Another area of interest is between  $\theta = 192^\circ$  and  $\theta = 203^\circ$ . An object of much higher density (e.g. pharaoh gold) could explain this reduced number of muons.

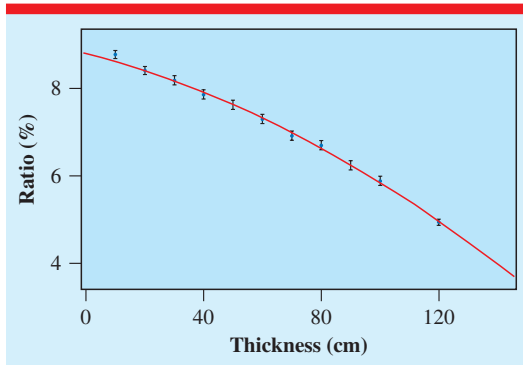
### The experiment at Beamline for Schools

To increase our understanding on the interactions of muons with matter we submitted our written proposal [7] to the Beamline for Schools competition 2016 [8] at CERN. More specifically our aim was to understand how the thickness of the limestone walls of the pyramids affects the number of muons that penetrate them, for a given energy.

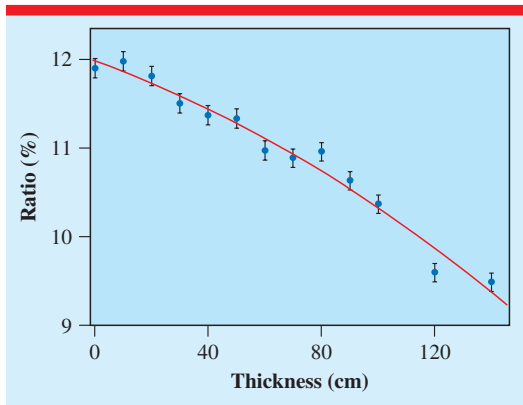
### Beam characteristics

The incoming proton beam from the Proton Synchrotron accelerator impinges on the primary target and produces secondary particles, which enter the T9 experimental area [9]. The collisions of the protons with the target provide a variety of particles, such as electrons, positrons, pions, kaons and (anti)protons. Muons are also present in the beam, from the decay of pions and kaons. The T9 beam line, used for the experiment, is therefore a mixed hadron and electron beam and can transport either positively or negatively charged particles with momenta between 0.5 GeV/c and 10 GeV/c. The beam arrives in





**Figure 9.** Ratio of muons that passed through the limestone over the initial number of muons, as a function of thickness of limestone for 2.5 GeV/c.

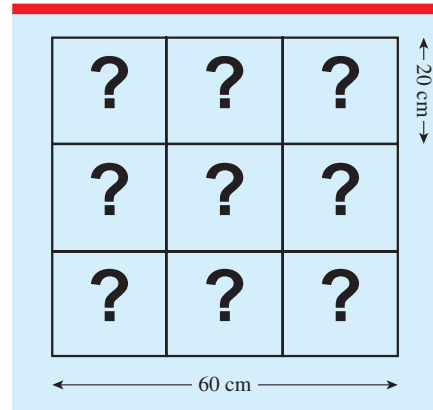


**Figure 10.** Ratio of muons that passed through the limestone over the initial number of muons, as a function of thickness of limestone for 3 GeV/c.

bursts of 0.4 s. Depending on the scheduling, such a burst is provided typically once or twice per minute. The maximum number of particles per burst of  $10^6$  is achieved for a 10 GeV/c positive beam, but drops for lower momenta. For a negative beam, the rates are typically lower. The beam travels approximately 55 m before it enters the experimental area. The fixed setup of detectors consists of two Cherenkov counters, one scintillator and one delay wire chamber (DWC) (figure 6).

### Experimental setup

A schematic drawing of our experimental setup is shown in figure 7 and a panoramic photo in figure 8. Two iron blocks of total length of 160 cm at the entrance of T9 to serve as muon filters.



**Figure 11.** A limestone structure of unknown inner shape was positioned on the motorized ‘DESY’ table. It was scanned with the muon beam both in X and Y direction.

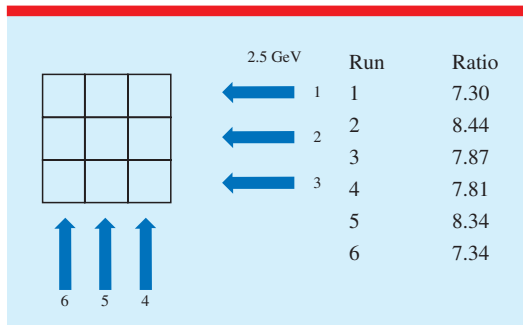
The muon beam exiting the iron block is defocused and has a wide momentum distribution. The muon momentum is reduced by an average of approximately 1 GeV/c for 80cm of iron. Two scintillators in coincidence, after the muon filter, with a distance of 2.7 m between them count the number of muons that will enter the limestone. The limestone was positioned on a movable table. After the limestone, another scintillator coincidence measures the muons that passed through the entire width of the limestone.

The area of coincidence of the detectors is  $20 \times 24$  cm for the detectors SC1, SC2 and SC3, SC4. The choice of the area of coincidence for both systems ensured the maximum acceptance of focused muons that pass through the entire width of limestone.

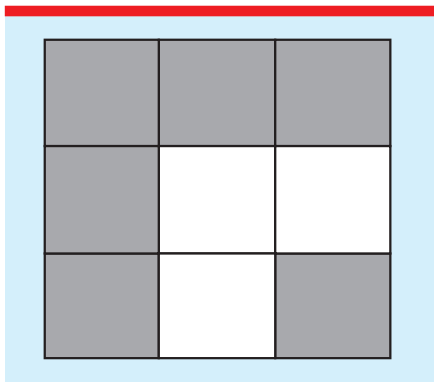
### Results

We first measured the number of muons that passed through the coincidences of the detectors SC1, SC2 and SC3, SC4 without limestone (reference measurement). Then we took measurements placing 10cm thick limestone blocks ( $10 \times 20 \times 40$  cm) between them. The total thickness of the limestone ranged from 10cm to 140cm. The measurement was repeated for beam momenta of 2.5 GeV/c and 3.0 GeV/c. The ratio of muons, which passed through the limestone over the number of muons recorded by both coincidences, without the limestone was calculated

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**Figure 12.** We performed a 2D scan of the unknown structure, which resulted in 6 measurements.



**Figure 13.** The reconstructed limestone structure. The grey squares correspond to limestone bricks and the white to empty space.

for the different lengths of blocks of limestone. A plot of this ratio with respect to the limestone thickness can be seen in figure 9 for 2.5 GeV/c and figure 10 for 3 GeV/c. The red curve corresponds to the best fit to the experimental data (equations (12) and (13), respectively).

$$y = (-1.386 \cdot 10^{-4} \pm 0.001 \cdot 10^{-4})x^2 - (1.772 \cdot 10^{-2} \pm 0.002 \cdot 10^{-2})x + 8.8507 \pm 6 \cdot 10^{-4}. \quad (13)$$

$$y = (-6.74 \cdot 10^{-5} \pm 0.01 \cdot 10^{-5})x^2 - (9.19 \cdot 10^{-3} \pm 0.02 \cdot 10^{-3})x + 11.909 \pm 6 \cdot 10^{-4}. \quad (14)$$

### Muon tomography

The above measurements served as a calibration to our muon tomography setup. To prove the validity of the fits of equations (12) and (13) the staff of

Beamline for Schools placed an unknown structure on the motorised table of known external dimensions (figure 11). Its external dimensions were 60 cm × 60 cm and consisted of 20 cm × 20 cm squares with or without limestone. We performed a 2D scan of the structure, using a primary beam of 2.5 GeV/c, by moving it by 20 cm at a time. In total six measurements were taken (see figure 12).

By using equation (12) we computed the thickness of the limestone structure for each direction and we reconstructed the structure. The uncertainty of our prediction of the was around 2 cm (see figure 13).

### Conclusions

With our measurements we performed and verified a calibration of the attenuation of muons for primary beam momenta of 2.5 GeV/c and 3 GeV/c at the T9 experimental area of CERN. The obtained results gave us an insight on how the thickness of a limestone block affects the flux of muons. Our goal is to use these results together with Geant 4 simulations to try to assess the role of fluctuations in the range of muons in the limestone rocks and to accurately calculate the intensity of cosmic ray muons in the Belzoni chamber of the Chephren pyramid.

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**Team Plock:** The seven students of the team as well as (on the left) the team coach Mr. Kempa. At the time of the trip to Geneva all members of the team were high school students at the L.O. im. Marsz. Małachowskiego, Płock, Poland. They have later graduated from their school and are now studying at different universities.



**Markus Joos** is an engineer working at CERN, Geneva and was in 2016 the project leader of the CERN Beamline for Schools competition.