Searching for cavities in the Teotihuacan Pyramid of the Sun using cosmic muons

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Abstract: The Pyramid of the Sun, at Teotihuacan, Mexico, is being searched for possible hidden chambers, by means of muon attenuation measurements inside the pyramids volume. The muon tracker is located in a tunnel, running below the base and ending close to the symmetry axis of the monument. This study presents a brief description of the experimental technique and data analysis, as well as a comparison of the first year preliminary experimental results with physics simulations using GEANT4.

Keywords: Cosmic muons, muon radiographi

1 Introduction

The use of cosmic muons to measure inhomogeneities in large volumes is a rapidly growing field. A classical example of this was the experiment carried out by Luis Alvarez et al. [1] who measured the attenuation of cosmic muons in the mass of the Keops Pyramid, in Giza, Egypt, while searching for hidden empty chambers. Although this technique has been applied to other practical problems, few archeological monuments present the necessary conditions to carry out a muon attenuation inspection of its volume. Among those exceptions is in the Mexican Pyramid of the Sun at Teotihuacan, hereafter referred to as Pyramid of the Sun. In a previous presentation [2] in this conference series, we described a project aimed at solving important archeological questions concerning the Sun at Teotihuacan, using muon attenuation. Here we present an update on this project, which began its data-taking few months ago, including important experimental aspects, and details of the corresponding GEANT 4 Monte Carlo [3] simulations which are compared with our first experimental image.

2 Experimental setup

The instrumental array (Fig. 1) consists of four 1m x 1m scintillator planes (SC1, SC2, SC3 & SC4), for muon identification and background-rejection rejection, and six MWPCs (also having a 1m x 1m sensitive area) for muon-tracking purposes. The plastic scintillators used were 1.5 cm-thick BC404 read on two opposite its extremes using 1 m x 1 cm x 1 cm BC484 wavelength-shifting bars (WLSB), each coupled to photo-multiplier PMT XP2802 tubes on one of its extremes. The other WLSB-extreme was covered with a thin aluminum sheet for light-reflection. Two of the scintillator planes (SC1 & SC2), contained in light-tight aluminum boxes, were placed at the bottom of the detection system, while the other two were placed just below the upper-most MWPC, for solid-angle maximization purposes. The registration efficiency is fairly independent on the position of the surface of each plane and is larger than 95%. The usage of 4 scintillator planes allows the estimation of absolute trigger efficiency. The 200-wire MWPC anode was read using the delay-line method with a 4ns pitch, using standard copper-layered circuit-board sheets.

Figure 1: Detector schematic view.
as cathodes, mounted on CNC-machined aluminum frame and Lucite spacers, to guarantee a $5\pm 0.5$ mm anode-cathode separation. A fast, low-noise and very high gain $A = 2500$ voltage preamplifier was developed [4] by us for this system. The gas used is a 90% Ar + 10% CO$_2$ mixture, handled through using manual gas flow regulators and exhaust oil bubblers.

3 Signal processing and DAQ

Standard NIM electronics modules are used to process the scintillator and MWPC signals according to the circuit schematically described in Fig. 2. The data acquisition DAQ trigger was obtained by connecting the fast-logic signals from the two upper scintillators to a fast coincidence unit in OR mode, and similarly for the two bottom ones (SC3 & SC4), then requiring a coincidental AND signal between the upper and lower scintillator pairs. The preamplified analogic signals from the two extremes of each MWPC were digitized using CAEN v1729-VME 4-channel 12 bit sampling-flash ADC (FADC) similar to one described in [5].

For rapid off-line efficiency-monitoring, all 12 MWPC signals are also processed using commercial constant-fraction discrimination modules, the corresponding logic signals are connected to a (VME) 16 channel fast input-output register and a (VME) 16 channel scalar. Both, the DAQ and the PMT & MWPC HV supplies are remotely monitored and controlled using an internet data-line. Gas pressure and flow is also monitored remotely.

The digitized data processing has been carried out using a single board CPU Concurrent Technology. The read out is synchronized with the trigger interruption. For each trigger 12-bit 12 time spectra from FADC, counters bit (with an input output register) and scalar information is reading through VME bus. The trigger time is fixed using CPU Unix time, which is saved for each trigger. The busy signal is organized from the hardware and software buses are unified as OR and have been used to veto the coincidence module performing the trigger. The dead time of read-out is of order of $10\text{ms}$. For the few Hz trigger rate will not introduce significant trigger lost. The volume of a week information is about $100\text{Gb}$.

4 Simulation

The muon transport through the body of pyramid is simulated using the GEANT4 Monte Carlo package [3]. The pyramid shape is constructed using an aerial gray-scale photo taken. The contours of equal gray palette in the photo have been digitized and used as the contours of the pyramid shape at a given altitude (see Fig 3). There is also GPS leveling measurements of the gross pyramid structures. Although these measurements are less detailed, so that they and cant be used as a base for the construction of the pyramid shape, nevertheless, they are used to estimate the systematic uncertainties of the used shape. The comparison of these two alternative methodologies shows that for the pyramid gross structures lie within $2\text{m}$ of each other. Approximately the same level of error is observed in the estimation of the height of the pyramid. The photographic measurements relative errors depend on the thickness of the lines and are of the order of $1\text{m}$. The detector position inside the tunnel is also estimated to be better than $1\text{m}$. The orientation of the detector main axis is measured relative to magnetic north pole, and is about 1 degree. Initial muon energy spectrum and angular distribution simulations are performed as in study [6], where the pyramid geometry and other details of the simulations can also be found. The simulation results of the projection angles distribution is presented in Fig 4. This distribution shape is easily correlated to the pyramid gross features. For exam-
Example, since the detector location on the $z$-axes lies close to the pyramids symmetry center, the $\theta_z$-profiles should also show a near-symmetric distribution, reflecting the approximately symmetric shape of the pyramid. The $\theta_x$ profile is not symmetric relative to the vertical direction, because the detector is located further away from the symmetry center in that direction. Another observable which can be used to calibrate the experimental conditions in general is the total trigger rate, which depends on many parameters, such as the pyramid shape and density profile, the detector position, and the muon detection efficiency.

5 Results

The trigger rate was sufficiently stable during the 6-month measurement, being $2.7(\pm0.05)\ Hz$, which is close to the Monte-Carlo simulation predictions of 2.62, reflecting that the detector position, pyramid average-thickness and average density, used in the simulations are consistent with the observation. The muon-track coordinate corresponding to each chamber has been estimated by means of the FADC signal shape analysis [4]. For each FADC signal up to 3 timing candidates are considered, and the best pair for each chamber is chosen previously by the total time ($200\times4\ ns = 800\ ns$) sum-rule. The tracks have been reconstructed using 2-, and 3-fired chambers conditions for each coordinate. In case of 3-fired chambers, the track is estimated by the linear fit. The shift of the position from the fit for each chamber, have been used to estimate the coordinate resolution as well as the angular resolution. The coordinate resolution is almost the same for all chambers, about $1.0\ cm$, corresponding to an angular resolution for each projection angle of about 1.1 degree. To be able to compare experimental data with the simulation one should also correct the coordinate dependence of the efficiency of each chamber. The coordinate distributions obtained by the Monte-Carlo simulation have been used for that purpose.

Efficiency-dependent on the zenith angle location corrections need also be included, since the chamber detection process is not included the simulations. This is possible due to the low efficiency of reconstructed tracks ($20 - 30\%$). Once all those corrections are taken into account for each chamber, the results of two-dimensional plot on projection angles is presented in Fig 5, which is seemingly similar to what is shown in Fig 4, though one can notice a slight difference in the $\theta_x$ dependence. Other observables, such as the mean values and the standard deviations are also close to the values in Fig 4. One also can notice a slight difference on the maximum position on the $\theta_x$ axes. To make this difference more visible the bin by bin difference of these to distributions is presented in Fig 6, in significance units (defined as bin difference divided on the error of that difference). Probably this large area mass difference on $\theta_x$ direction ($\theta_x < -20$ and $\theta_x > 20$) is due to the difference between the assumed pyramid geometry in the simulation and the real one.
6 Conclusions

Progress in the muon attenuation experiment carried out at the Pyramid of the Sun, at Teotihuacan, Mexico, is reported, including experimental and simulation details. After 6 months of data taking, experiment-simulation comparisons show qualitative and quantitative resemblances. Given the limited statistics accumulated so far, it is still early to confirm, or discard, the possibility of a human-size hidden empty cavity within the pyramids volume.

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References