Test results of a new concept of an EAS detector for UHE neutrinos

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Abstract. **We present results demonstrating the time resolution and μ/e separation capabilities with a new concept of an EAS detector capable for measurements of cosmic rays arriving with large zenith angles. This kind of detector will be part of a large area (several square kilometer) surface array designed to measure Ultra High Energy (0.01-100 EeV) neutrinos using the Earth-skimming technique. Because of the very good time resolution and adjustable orientation of the detector elements, we can separate upward-moving tracks from downward tracks at any orientation with high efficiency. The detectors have been tested by measurements in coincidence with the KASCADE-Grande cosmic ray facility located at Forschungszentrum Karlsruhe/Karlsruhe Institute of Technology (KIT), Germany. First results on the capability of muon-electron separation by these detectors are reported.**

Keywords**: UHECR, neutrino, τ, scintillator**

I. Introduction

The interest in Ultra High Energy Cosmic Rays (UHECR) has spawned a large variety of 2d(surface) or 3d(volumetric) detector arrays using different detection techniques (Cherenkov, air fluorescence and radio waves). Almost all applications concentrate on cosmic ray shower particles moving downward or possible sideways toward the detection elements. While timing information is often used to obtain shower angular information, none of the present detectors uses precision time measurements to separate upward- or downward-moving particles by time of flight(tof). Such discrimination is essential to experiments that seek to identify cosmic ray or cosmic neutrino interactions at zenith angles greater than 90^o, so-called *earth-skimming* events.

In this paper we show the test results for tof resolution and μ/e separation capabilities of a prototype element intended for deployment in an array capable of measuring large zenith angle cosmic rays as well detecting the signature of Ultra High Energy τ neutrino interactions using the Earth skimming strategy [1], [2], [3], [4].

A. Description of the module

For the experimental application the module was designed to recognize single particles and determine the direction of motion (up/down) and measure the trajectory angles. It uses two pairs of scintillator counters, named *towers*, each composed by two tiles ($20 \times 20\ cm^2$, 1.4 cm thick), separated by $160\ cm$. Each tile is read by one low voltage R5783 Hamamatsu photomultiplier (PMT), extensively used in the CDF muon detector [5] as shown in Fig. 1. Each tile is embedded in a PVC box which also contains the PMT. This PMT has excellent time resolution ($\approx 400\ ps$) for good tof precision. It contains its own Cockroft-Walton high voltage generator and consumes very little power. This opens the possibility to power the system using a renewable energy power source like a solar panel or a wind turbine - an important feature for an elementary module in a large area array. The solid angle of a single *tower* is about 1.4 $\times 10^{-2}$ sr and its zenith angle range is $\pm\ 7.5^o$ around the axis. The geometrical acceptance is $5.1\ cm^2 sr$. With a tof resolution of the order of $1\ ns$, it is possible to reject vertical air showers without need of any shielding. We can select upward and downward particles passing through the detector with negligible intrinsic contamination. To increase the solid angle coverage we mount two *towers* with their axes parallel, separated by $\sim$ 60 cm. This increases the acceptance to $\pm\ 20^o$ along the azimuthal angle; the covered solid angle increases almost by a factor 3. This is particularly important in situations like a large array whose target are rare events (i.e. UHE neutrino flux).

At present the DAQ is based on waveform sampling, using a MATACQ system. This digitizes the scintillator waveform at $1GS/s$, covering a $2.5\ \mu s$ window [6]. The MATACQ is triggered by an external signal that defines the direction of the track. The time of flight for determining whether the track is moving up or down is refined offline, using an algorithm based on the photomoltiplier signal shape. In the future we are working on next-generation waveform sampling chips to reduce the cost of electronics for the full system.

We also simulated an ideal surface kilometer detector based on $\sim$500 *modules* arranged on a 22 x 22 square grid with elements separated by about 70 m. The array is located on a steep mountain slope to be efficient for upward-moving shower tracks. The efficiency of the array to detect tau decays is evaluated using the Corsika MonteCarlo 6900v [8]. The expected sensitivity is of order of $10^{-7} GeV cm^{-2} s^{-1} sr^{-1}$ in the energy interval $10^{17} - 10^{19} eV$. In the text the module will be called *Tauwer*.

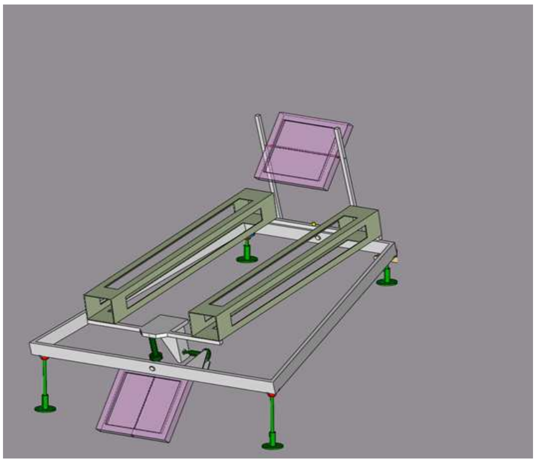

Fig. 1. Schematic view of the module. The tiles and electronic box and the wireless connection are not shown.

B. The performances of the working prototype

The performance of this module was initially tested at the High Altitude Research Station Jungfraujoch (HF-SJG), located in Switzerland at $\approx 3600\ m$. A second prototype will be installed there in the summer of 2009 to test the latest electronics board. Details with the first prototype are given in [7]. The module has shown a good upward/downward discrimination capability in all our tests. In order to reach the necessary upward-downward tof separation the light collection technique has been optimized, focusing on the time resolution at the expense of energy resolution. The definition of a vertical MIP is made by calibration on vertical downward cosmic rays, to set proper charge cuts to obtain a good time resolution. Because of the position variation of light collection efficiency, this slightly reduces the effective area per *tower*, but the effect is small and stable.

The time resolution we measure ($\approx 1.2\ ns$) is comparable to the PMT transit time spread. This is achieved by avoiding any reflections in the light collection process. The $1\ cm^2$ PMT window is directly coupled by a silicone rubber pad to the scintillator. The scintillator is wrapped with Tyvek for diffuse reflection. This configuration lets the first light arriving at the PMT window dominate for the leading edge of the phototube signal, optimizing time resolution.

II. μ-ELECTRON SEPARATION TEST

To identify upward-moving τ decay showers from Earth-skimming neutrinos and to reject deep cosmic ray

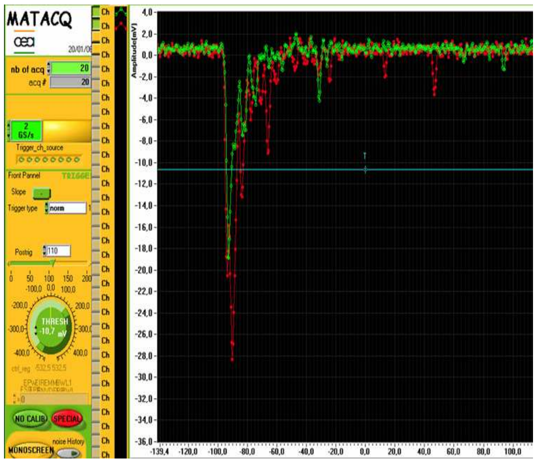

Fig. 2. Two photomultiplier signals of same tower displayed by Matacq board. The units are mV (vertical axis) and ns (horizontal axis). A sdquare is 2mV times 20 ns

interactions we need to measure the muon and electron densities transverse to the tau shower axis. Electron- μ separation is obtained by installing a layer of lead in front of the downstream tile in a *tower*. This information helps both to reconstruct the τ direction and to reject horizontal atmospheric EAS. In high altitude interactions the EAS electromagnetic component is totally absorbed, while deep interactions are not fully developed and have very few particles. Both of these features are quite different from the showers generated by hadronic τ decays, which typically have a showering length of 5 interactions lengths of air before they reach the detector array.

For a given track, the pulse height ratio of the two tiles in a *tower* gives along with the e/μ particle identification likelihood as a function of the pulse height ratio to separate electrons and muons. We use Geant4 to simulate the energy deposition of electron and muon tracks in the *tower* geometry. We simulate particles at different energies and determine the weighted average probability using the electron and muon energy profile from Corsika for sea-level EAS events.

We studied the properties of e/μ separation in vertical air shower events by measurements for two *towers*, operated in coincidence with the KASCADE-Grande experiment (KGE) at Karlsruhe Istitute of Technology, Germany [9], using their trigger. The KASKADE-Grande array has large shower reconstruction efficiency for incoming cosmic rays having zenith angles from vertical to 40 degrees. Given the small acceptance of a single pair of *towers* we set up our modules vertically as shown in Fig.3. A layer of lead covers the bottom tile. We select events from the KGE data with zenith angles in the range 0-10 degrees. For each event the KGE data predict the lateral distribution the muon and electron density as distance from the core. In the KGE data identified electrons and muons have mimimum energy of 5 MeV and 230 MeV respectively. Fig. 4 shows the

EAS shower distribution on the KGE array plane.

Fig. 3. Setup of the module. The layers of lead are on the bottom tile. The DAQ is located in the cluster room n.12.

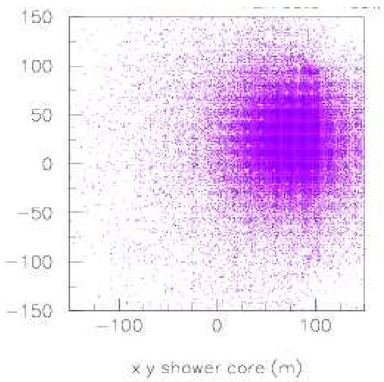

Fig. 4. Shower core on the array plane, y vs x. The module is located at x=75 m and y=19 m.

Each *tower* has an angular acceptance of 15^0 and an equivalent area of 35 $\times$ 35 cm^2. Monte Carlo studies show us that for the energy profile of EAS particles at sea level the optimum thickness of lead to have the maximum of electromagnetic shower near the lead/scintillator interface is 1.5-2.0 cm (3-4 X_o).

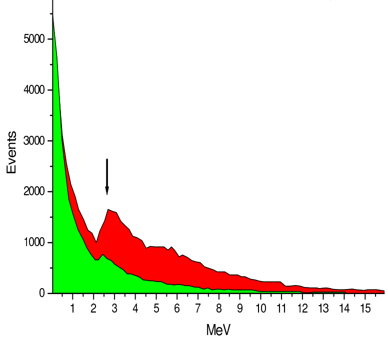

Fig. 5. Energy deposited by 200 MeV electron on the bottom tile covered by a layer of lead of 5 cm (gray) and 2.5 cm (black) .The arrow shows the average of energy deposited on top tile.

Fig. 5 shows simulation results for the energy deposited by a 200 MeV electron on the bottom tile covered by a layer of lead of 5 cm or 2.5 cm. The large difference in the distributions above 3 MeV reflects the high probability for total absorption in the 5 cm Pb. The arrow indicates the average energy deposited in the top tile. To evaluate the tof by using the shape of the signal we applied a threshold cut of 6mV (the average amplitude of signal is 60 mV after cable attenuation). Using the time-amplitude profile from the waveform digitizer, we apply the following particle *selection criteria*: a muon has only a sharp, singly-peaked signal in both tiles while an electron (or gamma) has multiple signal peaks in the bottom tile within a 50 ns time interval. It also has a larger pulse height in the bottom tile, but no specific pulse height ratio requirement has yet been applied. The resultant muon sample is contaminated by a small percentage of electrons. As described above, the best variable to discriminate μ and electrons is the ratio of charge deposited in the bottom tile to the top tile. This ratio is one for muons and it reaches 10 for electron/gammas.

A. *Comparing KGE and Tauwer Data*

The KASCADE-Grande trigger rate for all 16 sectors is about 3.0 Hz. Tauwer events are recorded only for the KASCADE-Grande events with a shower core in sector 14, where our modules are installed, with a rate of 0.18 Hz. 56$\%$ of triggers have a reconstructed shower close to the KASCADE-Grande detector. In the triggered data the rate at which Tauwer modules show at least one hit tile is 0.015 Hz, or 1 hit in Tauwer for each 12 KGE triggers. Of these single-hit events 3$\%$ have a reconstructed track in the tower despite the small sampling area. Thus, the Tauwer tracks come from shower electrons or muons moving nearly vertical, as one would expect for sea-level EAS tracks. Fig. 6 shows the time of flight for vertical and diagonal tracks.

B. *KASCADE-Grande validation*

KASCADE-Grande provides the density of muon or electrons per square meter. Fig.7 shows the density of electron and muons as a function of radial distance from the shower axis.

The sample of Tauwer events for a 5 cm Pb absorber which were selected with the previous criteria are validated by the KASCADE-Grande data to be a muon or electron by selecting KGE events in which there is only one shower track, either electron or muon, in the Tauwer module's sensitive area. Only 25 $\%$ of the Tauwer tracks have the KASCADE-Grande validation because of the strict selection on KGE track density. The other 75% typically have two or more KGE tracks within the Tauwer area and the event is rejected. Fig. 8 shows the charge ratio bottom tile to top tile for the tracks selected by tof and the signal criteria described in sec. 2 (right), the same sample with the KASCADE-Grande validation is also shown (left) . The loss of events below the ratio of 0.5 reflects the large absorption in the 5 cm Pb, as noted previously in the Monte Carlo discussion.

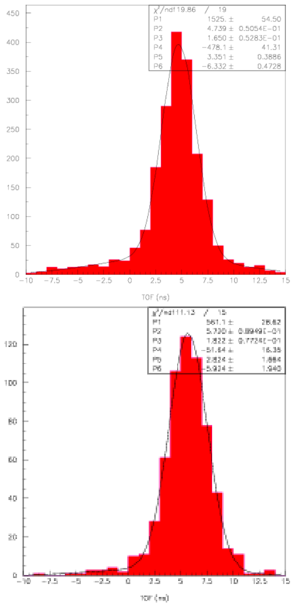

Fig. 6. The distribution of time of flight between the two $20 \times 20\ cm^2$ tiles 160 cm apart, for downward vertical cosmic ray events (top) and digonal (bottom). The towers are apart 60 cm.

The Montecarlo shows the purity of the identification should be higher for data with the thinner absorber, as indicated in Fig. 5.

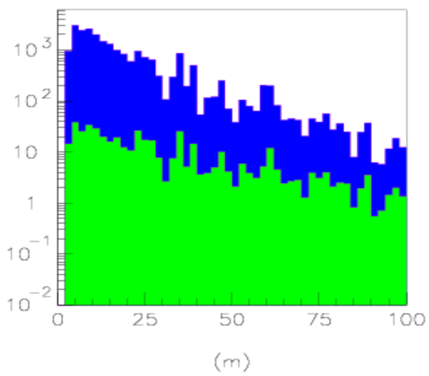

Fig. 7. Electron (black) and muon (gray) density per m^2 versus distance from the core for recontructed tracks by tof in the interval 2-8 ns.

III. Conclusions

By using the KASCADE-Grande trigger we have tested a method to select low momentum electrom-muon on a prototype designed to measure horizontal cosmic ray flux as well as be a EAS produced by skimmed tau neutrinos. By the digitization of the PM signal and optimizing the thickness of a lead layer located on the surface of the bottom scintillating tile we find that when the deposited energy is more of 50% of energy on top tile, the track, defined by tof, can be assumed to be an electron or gamma . Otherwise if the ratio of energy deposited on top and bottom tile is about one we have a

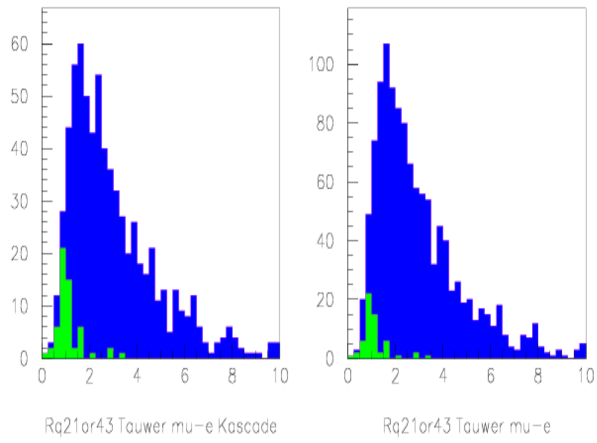

Fig. 8. Ratio of deposited energy on bottom tile to top tile for tracks having a tof between 2-8 ns. Right: Electron (black) and muon (gray) are separated by criteria shown in sec. 2.0. Left: The same sample with KASCADE-Grande validation.

probable muon. Detailed Monte Carlo studies of Particle Identication Confidence Levels are in progress.

IV. Acknowledgements:

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