ELECTRON–MUON IDENTIFICATION BY ATMOSPHERIC SHOWER AND ELECTRON BEAM IN A NEW EAS DETECTOR CONCEPT

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ABSTRACT

We present results demonstrating the time resolution and $\mu e$ separation capabilities of a new concept for an EAS detector capable of measuring cosmic rays arriving with large zenith angles. This kind of detector has been designed to be part of a large area (several square kilometer) surface array designed to measure ultra high energy ($10–200$ PeV) $\tau$ neutrinos using the Earth-skimming technique. A criterion to identify electron-gammas is also shown and the particle identification capability is tested by measurements in coincidence with the KASCADE-GRANDE experiment in Karlsruhe, Germany.

Key words: astroparticle physics – cosmic rays – line: identification – neutrinos

1. INTRODUCTION

A large variety of 2D (surface) or 3D (volumetric) detector arrays with different detection techniques—Cherenkov (Antokhonov et al. 2011; Aharonian et al. 2002), air fluorescence (Abassi et al. 2010), and radio waves (Apel et al. 2010)—for ultra high energy cosmic rays have been constructed. These experiments mostly concentrate on detecting cosmic ray shower particles moving downward and the timing information is used to obtain shower angular information; none of the present detectors uses precision time measurements to discriminate upward or downward moving particles by Time Of Flight (TOF) and $\mu e$ separation. TOF discrimination is useful for experiments that seek to detect cosmic rays or cosmic neutrino interactions at zenith angles greater than 90°; $\mu e$ separation is useful to improve the signature. In this paper we show the results of a test on $\mu e$ separation, made in correlation with the KASCADE-GRANDE Experiment (KGE; Antoni 2003), with a prototype module planned for deployment in an array capable of measuring large zenith angle cosmic rays as well as detecting the signature of ultra high energy $\tau$ neutrino interactions using the “Earth-skimming strategy” (Beacom et al. 2003; Fargion et al. 1999, 2004; Fargion 2002; Feng et al. 2002; Zas 2005). Preliminary analysis of part of the data shown in this paper was presented in several conferences (Iori et al. 2012, 2013). The strategy described for $\mu e$ separation can also be used for future large arrays like the LHAASO project if TOF measurement is not implemented.

1.1. Description of the Module

To detect a single particle from a shower and determine its direction we have designed a detector using two pairs of 20 $\times$ 20 cm$^2$ and 1.4 cm thick scintillator plates separated by 160 cm and called a tower. A single tower has a geometrical acceptance of 25.0 cm$^2$ sr and its zenith angle range is $\pm 7.5$. In order to augment the acceptance of the detector, important for detecting low intensity fluxes like UHE neutrino flux, we put two towers with their axes parallel and separated 60 cm. This layout improves the acceptance of $\pm 20^°$ along the azimuthal angle. Each tile is read by one low voltage, high time resolution R5783 Hamamatsu photomultiplier (PMT), extensively used in the CDF muon detector (Artikov 2005). The PMT is connected to the scintillating tile and embedded in a PVC box. The module is composed of four boxes attached to a metallic frame. The excellent PMT time resolution ($\approx 400$ ps) provides good TOF measurements. The Cockroft–Walton generator used in PMT to generate high voltage 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.

With a TOF resolution of the order of 1 ns, it is possible, when we measure large zenith angle shower, to reject vertical air showers without need for any shielding. Hence we can select upward and downward particles passing through the detector with negligible intrinsic contamination. The module was set up vertically in the area of the KASCADE-GRANDE array to measure the parameters discussed in this paper.

At present the DAQ is based on waveform sampling, using a MATACQ system. This digitizes the scintillator waveform at 2 GS/s, covering a 2.5 $\mu$s window (Delagnes & Breton 2001). The MATACQ is triggered by an external signal that defines the direction of the track. The TOF for determining whether the track is moving up or down is refined offline and is obtained using an algorithm based on the linear fit of the front of the photomultiplier signal.

1.2. The Performance of the Working Prototype

The performance of this module was initially tested at the High Altitude Research Station Jungfraujoch, located in Switzerland at $\approx 3600$ m. Details of the first prototype are given in Iori & Sergi (2008). A second prototype was installed there in the summer of 2009 to test the latest electronics board (Iori et al. 2012). The module has shown a good upward/downward discrimination capability in all our tests. To reach the necessary upward–downward TOF discrimination 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 calibrating on vertical downward cosmic rays to set proper charge cuts to obtain a good time resolution. Because of the position variation of the light
collection efficiency, this slightly reduces the effective area per tower, but the effect is small. The time resolution we measure ($\approx 1.2$ ns), as shown in Figure 2, is comparable to the PMT transit time spread. This is achieved by avoiding any reflections in the light collection process. To improve the time resolution we have connected the $1 \text{ cm}^2$ PMT window directly to the scintillator plate by a silicone rubber pad. With this configuration the first light arriving at the PMT window dominates the leading edge of the signal.

2. ELECTRON-GAMMA AND MUON IDENTIFICATION

2.1. Electron-gamma

Electron identification is obtained using a layer of lead with optimized thickness able to produce an electromagnetic shower in front of a tile. The module in the test made at KGE was set up vertically and a layer of 1.5 cm lead, corresponding to $3X_0$, covered the bottom tile (B). By using TOF we select tracks that are vertically crossing downwards or diagonally crossing the top (T) and B tiles of either the same tower or different towers, respectively.

An algorithm that extrapolates the front of the signal to zero voltage after applying a 6 mV threshold cut (the mean amplitude of the signal is 60 mV after cable attenuation) is used to find the time of arrival, $t_0$, of the track. Then TOF was evaluated simply by taking the difference between $t_0$ of the bottom and top tiles. Figure 1 shows the TOF distributions for vertical and diagonal tracks.

For the analysis we used two data sets, one with the lead layer inserted at the top of the bottom tile with 5792 good tracks reconstructed, the other with no lead layer with 2520 good tracks. The term good means the TOF of the track was in the interval $5 \pm 3 \text{ ns}$, which corresponds to $2\sigma$. The reason why we used a lead layer in front of the bottom tile is to produce more light at the B tile due to electromagnetic processes such as pair production or Compton effect for electrons or gammas, $\gamma$. The lead layer will show no differences in the T and B tiles for muons ($\mu$). A good variable to separate the electromagnetic component from $\mu$ is the ratio ($R$) of the charge in the B tile ($q_B$) to the charge deposited in the T tile ($q_T$).

By GEANT4 we have simulated a normal-incident uniform flux of $\gamma$, electrons, and $\mu$'s with different momentum (50, 100, 150, 200, and 500 MeV) passing through the scintillating T tile and with and without lead layer in front of the B tile. Then we have evaluated the ratio $R$, obtained as the energy deposited in the scintillator in the B tile divided by the energy deposited in the T tile. Evaluating the ratio $R$ we applied a 1 MeV energy cut to the T and B tiles, which corresponds to the energy loss in the scintillating tiles. The ratio $R$ of $\gamma$'s, electrons, and $\mu$'s at different energies without lead (upper row) and with lead (lower row) is shown in Iori et al. (2013). The $\gamma$ and electron $R$ distributions indicate an evident difference of the slope at $R > 2$ in the run with lead because more energy is deposited in the B tile in this run. In the case without lead the electron $R$ distribution is clustered near unity, close to 1, quite similar to the $\mu$'s. The muon $R$ value is always close to 1 except for the 50 MeV $\mu$'s where the Coulomb effect in the lead layer produces electrons that spread out the $R$ distribution. The 500 MeV $\gamma$'s and electrons have a broad $R$ distribution because of the relativistic rise in energy loss. Different gains and light collection might influence the measurement of the $R$ distribution. To correct this effect we have selected a sample of tracks with a single peak signal in both tiles. We expect that this sample, which contains mostly $\mu$ tracks, will deposit the same energy in both tiles with Landau fluctuation. Therefore this sample should produce a narrow charge distribution close to the mean value of the total charge collected by the photomultiplier.

Comparing the mean values of charge distribution between the T and B tiles we calculate the ratio correction factor, $k$. The correction factor was calculated by comparing the mean value of the charge distribution of the T tile and the B tile. This results in each tower's $k$ being $0.89 \pm 0.09$ and $0.82 \pm 0.08$, respectively. To verify the presence of lead we have compared the $R$ and the inverse ratio $R^*$ distribution because $R^* = \frac{q_T}{q_B}$ distributions. We know that the $R$ and $R^*$ distributions when the lead is absent should be almost equal; the symmetry can be broken by downward moving tracks that interact in the T tile.

Figure 2 shows the corrected ratio $R^*$ (solid) and $R$ (dotted) of the good tracks in the run without (left) and with (right) lead. The slope is the same and the loss of events in the $R^*$ distribution (solid) below $R = 1$ is due to the interactions in the T tile $q_T < q_B$ as verified by GEANT4. Figure 2 (right) indicates an obvious increase in the number of events at $R > 2$. This increment is related to the production of an electromagnetic component in the lead layer and detected by the B tile.

In order to quantify the contributions coming from electromagnetic components in the $R$ distributions, we performed a MINUIT fit to experimental data using $R$ distributions obtained from the GEANT4 simulations performed for electrons, $\gamma$'s, and $\mu$'s with energies starting from 50 up to 500 MeV. The density of particles in a shower are generated in the detector acceptance as a function of momentum and used to weight the $R$ distribution. Density strongly depends on the distance from the shower center. At 25 m from the center of the
core, the density drops to approximately 10 particles m$^{-2}$ for both electrons and $\gamma$s, reducing the probability of detecting vertical tracks.

Using the proton as the primary particle, 100 vertical showers are created. Results show that 57% of $\gamma$'s with momentum less than 150 MeV, and 16% with momentum between 150 and 250 MeV, are inside a distance of 25 m from the core of the detector acceptance. The rest (27%) have higher momentum. 61% of electrons have momentum less than 250 MeV. 74% of $\mu$'s have momentum greater than 500 MeV (Knapp & Heck 1993).

The predicted number of events for electrons, $\gamma$'s, and $\mu$'s in bin $i$ used to fit the experimental distribution is

$$F(p_j, R_i)_{e,\gamma,\mu} = N_D(w(p_j)f_{p_j}(R_i))_{e,\gamma,\mu},$$

where $N_D$ is the total number in the data sample; $w(p_j)$ is the normalized density of tracks around the detector for three different average momentums 100, 200, and 500 MeV for electrons, 100, 200, and 500 MeV for $\gamma$'s and 200 and 500 MeV for muons in the interval of $\pm$50 MeV inside a radius of 25 m; and $f_{p_j}(R_i)$ is the fraction of simulated tracks by GEANT4 in each bin as a function of the momentum.

The best result corresponds to a detected track sample of 86.7 $\pm$ 1.6% electrons, 5.4 $\pm$ 0.4% $\gamma$'s, and 7.9 $\pm$ 0.8% of $\mu$'s.

We also generated showers at $5 \times 10^7$ GeV using carbon and iron as the primary particles. Assuming about 20% of iron in the cosmic ray flux (Apel et al. 2011), we found the fit results within 2$\sigma$. The fit results are also within 2$\sigma$ when changing the the range of momentum distribution used in the fit and the size of the core from 25 to 100 m.

At the Fermilab Meson Test Beam Facility we obtained data using a 500 MeV electron beam. Electrons were identified by a gas Cherenkov counter. They traversed two scintillator tiles spaced 6 cm apart, with 1.5 cm of lead covering the downstream tile. We obtained data by sampling over the entire tile area. The left 10% of the downstream scintillator was not covered by the lead. We used events in this region to normalize the pulse height distributions between the two scintillator tiles. The measured pulse height ratio for the counter after the lead to that before the lead was 3.56 $\pm$ 0.14, in good agreement with the GEANT4 prediction. A simple ray-tracing program predicts the variation of the ratio across the face of the scintillator and the comparison of the test beam to the data agrees within 10%.

2.2. KASCADE-GRANDE Validation

After we have performed a fit to evaluate the percentage of electrons and muons in the sample of tracks selected by TOF, we considered the particle identification provided by KGE operating in coincidence with our detector in a gate of 600 ms to validate a criterion to separate electrons and muons. The KASCADE array has large shower reconstruction efficiency for incoming cosmic rays having zenith angles from vertical to 40°.

For each event KGE predicts via lateral shower distribution the $\mu$ and electron density per square meter as the distance from the core. The electrons and $\mu$'s identified by KGE have minimum energies of 5 MeV and 230 MeV, respectively, and no direction information. Our module selects tracks from KGE data with zenith angles in the range $\pm$7.5. The KGE trigger rate for all 16 sectors is about 3.0 Hz. Only KGE events with a shower core in sector 14, where our module has been installed, with a rate of 0.18 Hz, are recorded. 56% of the triggers have a reconstructed shower in the KGE sector. In the triggered data, the rate at which our module shows at least one hit tile is 0.015 Hz, or 1 hit for every 12 KGE triggers. Of these single-hit events 3% have a reconstructed track in the tower despite the small sampling area. By using a CORSIKA simulation of vertical showers as reconstructed by KGE we found good agreement with the percentage of the reconstructed tracks. The sample of the good tracks for a 1.5 cm lead absorber that were selected by TOF are verified with the KGE data to be either $\mu$. 

Figure 2. Corrected ratio $R'$ (solid) and $R$ (dot) of the good tracks from the run without (left) and with (right) lead. The small excess of events in the $R$ distributions above $R = 2$ comes from more interactions in the B tiles that lead to an increase in the released charge in the B tile.
or electron; this was done by selecting KGE events in the sensitive area where there is one or more shower tracks, either electron or $\mu$. To validate the $R$ distribution in our module we normalized the particle density provided by KGE to the acceptance of our module.

Figure 3 shows the (a) electron and (b) $\mu$ density (particles m$^{-2}$) versus $R$ obtained by the interpolation of the electron/$\mu$ multiplicity from the KGE stations closer to our detector. The Figure 3(a) results require a $\mu$ density less than $10^{-3}$ particles m$^{-2}$. The Figure 3(b) results require at least a muon predicted by KGE in the detector area without any cut on electron density. The $\mu$’s are mainly concentrated at $R = 1$. The events with $R > 2$ can be interpreted as being due to the contribution of electrons with a large momentum (>500 MeV) or $\mu$’s with a low momentum (<50 MeV) as predicted by GEANT4 Monte Carlo studies (Iori et al. 2013). To evaluate this contamination we used the sample of 100 vertical showers generated by CORSIKA at $5 \times 10^7$ GeV ($p$, C, and Fe) and selected the muons with electrons in a m$^2$ within 25 m. We have found 36.3% of the electrons in the shower core have momentum higher than 500 MeV in the presence of a muon and 80% are within 25 m away from the center. This explains that the tail at $R > 2$ is due to hard electrons present in the detector acceptance when there is a $\mu$. The aim of this prototype is to measure tracks at large zenith angles so we performed a test where the detector was placed horizontally to evaluate the noise from two vertical tracks shifted in time and with a TOF of about 5 ns. The probability obtained counting this category of events with the TOF 3 ns and 7 ns (−7 ns and −3 ns for upwarding) over all events with signals on both tiles results in $10^{-2}$ for a single tower and a rate of $10^{-6}$ Hz.

3. CONCLUSIONS

Using the KASCADE-GRANDE trigger we have tested a method to select low momentum electron–$\mu$ on a prototype designed to measure horizontal cosmic ray flux. By optimizing the thickness of a lead layer located on the surface of the B scintillating tile we find that the tracks depositing more energy in the B tile are electrons with momentum of about 200 MeV. The analysis suggests that when we require $R$ to be bigger than two, we should select electrons with no contamination of $\mu$’s. If we discard the TOF measurement, a station made with a layer of lead between the large T and B tiles can be used in a new generation of experiments such as the LHAASO project.

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REFERENCES

Abbasi, R. U., Abu-Zayyad, T., Allen, M., et al. 2010, ApJ, 713, L64
Aharonian, F., Akhperjanian, A., Beilicke, M., et al. 2002, A&A, 398, 89
Antokhonov, B. V., Beregnev, S. F., Budnev, N. M., et al. 2011, NIMPA, 628, 124
Antoni, T., Apel, W. D., Badea, F., et al. 2003, NIMPA, 531, 490
Apel, W. D., Arteaga, J. C., Asch, T., et al. 2010, ApJ, 32, 294
Apel, W. D., Arteaga-Velázquez, J. C., Bekk, K., et al. 2011, PhRvL, 107, 171104
Artikov, A., Budagov, I., Chirikov-Zorin, I., et al. 2005, NIMPA, 538, 358

Figure 3. KGE track density in m$^2$ vs. $R$ distribution for electron (a) and muon tracks (b) reconstructed in the detector and validated by KGE.
Beacom, J. F., Bell, N. F., Hooper, D., et al. 2003, PhRvD, 68, 093005
Breton, D., Delagnes, E., & Houry, M. 2005, ITNS, 52, 2853
Delagnes, E., & Breton, D. Échantillonneur analogique rapide grande profondeur mémoire, French patent n01-05607 April 26th 2001. US patent 6,859,375 Feb 22nd 2005: fast analog sampler with great memory depth
Fargion, D. 2002, ApJ, 570, 909
Fargion, D., Aiello, A., Conversano, R., et al. 1999, in AIP Conf. Proc., 26th International Cosmic Ray Conference: ICRC XXVI, ed. B. L. Dingus, D. B. Kieda, & M. H. Salman (Melville, NY: AIP), 396
Fargion, D., Lucentini, De Sanctis, P. G., De Santis, M., Grossi, M., et al. 2004, ApJ, 613, 1285
Feng, J. L., Fisher, P., Wilczek, F., et al. 2002, PhRvL, 88, 161102
Iori, M., Arslan, E., Denizli, H., et al. 2012, NIMPA, 692, 285
Iori, M., Arslan, E., Denizli, H., et al. 2013, JPCS, 409, 012131
Iori, M., Atakisi, I. O., Chiodi, G., et al. 2014, NIMPA, 742, 265
Iori, M., & Sergi, A. 2008, NIMPA, 588, 151
Knapp, J., & Heck, D. 1993, Corsika Manual (available online at https://web.ikp.kit.edu/corsika/userguide/corsika_tech.html)
Zas, E. 2005, NJPh, 7, 130