Gamma-Ray Source Studies using a Muon Tracking Detector (MTD)


1 Institut für Kernphysik, KIT - Karlsruher Institut für Technologie, Germany
2 Universidad Michoacana, Instituto de Física y Matemáticas, Morelia, Mexico
3 Dipartimento di Fisica Generale dell’ Università di Torino, Italy
4 Institut für Experimentelle Kernphysik, KIT - Karlsruher Institut für Technologie, Germany
5 National Institute of Physics and Nuclear Engineering, Bucharest, Romania
6 Fachbereich Physik, Universität Siegen, Germany
7 Istituto di Fisica dello Spazio Interplanetario, INAF Torino, Italy
8 Universidade São Paulo, Instituto de Física de São Carlos, Brasil
9 Fachbereich Physik, Universität Wuppertal, Germany
10 Dept. of Astrophysics, Radboud University Nijmegen, The Netherlands
11 Soltan Institute for Nuclear Studies, Lodz, Poland
12 Department of Physics, University of Bucharest, Bucharest, Romania
13 now at: Max-Planck-Institut Physik, München, Germany; 14 now at: Institute Space Sciences, Bucharest, Romania; 15 deceased; 16 now at: Univ Trondheim, Norway

Abstract: A large area (128m²) streamer tube detector, located within the KASCADE-Grande experiment, has been built with the aim to identify muons and their directions from extensive air showers by track measurements. We discuss the possibility of observation of Gamma-Ray sources by means of single isolated muons above the background of cosmic-ray muons using a muon tracking detector (MTD) exhibiting good angular resolution. Properties of the pion photo-production process and of the MTD which support the identification of Gammas are discussed. Preliminary Gamma-ray spectrum accumulated from Crab and the Mkn421 flux correlation with X-ray (RXTE/PCA) are presented.

Keywords: gamma ray sources, muon tracking

1 Introduction

A reliable understanding of the muon production by primary gamma-rays is mandatory to gauge the sensitivity of the experiment to gamma primaries. The Vector Meson Dominance Model is usually employed for photo-nuclear interactions at gamma energies above a few GeV. To illustrate the critical role played by the event generators in predicting the muon content of showers, the Feynman-x distribution of charged pions (in the laboratory frame) as calculated by the FLUKA code demonstrates [1] a basic difference between gamma and proton-induced collisions: The gamma primaries lead to a much larger fraction of high-x secondaries than the proton primaries, therefore, focussing the pions to very forward direction, and, therefore, compensating for the much smaller pion photo-production cross section.

High energy gamma rays produce muons in the Earth’s atmosphere that can be detected and reconstructed in relative shallow underground muon detectors. Such detectors are sensitive to muon energies of a few GeV. Although muons of such low energy compete with a large background of cosmic ray muons, they can be identified provided the detector has sufficient effective area and resolution. Unlike air-Cherenkov telescopes [2, 3, 4] muon detectors cover a large fraction of the sky with a large duty cycle. The advan-
tage is considerable in studying the emission from highly variable sources. Moreover, background multi-muon bundles can be conveniently rejected without suppression of the predominantly single-muon gamma signal.

Detected muons originate in gamma induced pion production with some 20 times higher gamma energies [5]. A low energy threshold for muon detection provides for the correspondingly low energy gammas a deep view into the Universe. Muons of $E_{\mu} > 1 \text{ GeV}$ associated with primary photons of several GeV provide an almost attenuation-free window into the depth of the universe suffering little from flux losses due to collisions with IR and CMB radiation via pair production.

2 Muons from Gammas

Gamma rays initiate atmospheric cascades of mostly electrons and photons, but also some muons. Muons originate from the decay of charged pions which are also photo-produced by high energy shower photons [6] albeit with much smaller cross section.

The signal-to-noise ratio, defined as the number of events divided by the square root of the number of background events in a resolution pixel of $\sigma^2 \times \sigma^2$, depends on the detector area $A$ and the zenith angle $\Theta$ as [6]: $S/N^{1/2} = A^{1/2}/\cos\Theta^{0.9} \sigma$. The formula simply expresses that the signal-to-noise ratio is improved for increased area $A$, better resolution $\sigma$ and sources observed at larger zenith angle $\Theta$, where the cosmic ray background muon rate is reduced.

The MTD [7] is sensitive to the gamma energy region above $\sim 10 \text{ GeV}$ while the muon energy cut equals to $0.8 \text{ GeV}$.

As mentioned above the background includes some fraction of multi-muon events. Rejecting multi-muon events not only improves the signal-to-noise ratio, it also improves the angular resolution which may be degraded by less reliable reconstruction of complex muon bundles initiated by high energy cosmic ray particles which are accompanied by other shower particles. MTD with its detection area of $A_{MTD} = 128 m^2$ has below the shielding an average rate of $2.5 kHz$ which results above an energy of $0.8 \text{ GeV}$ in $\sim 10^7$ tracks from background muons per year in a $1^\circ \times 1^\circ$ pixel. Assuming a further reduction because of the strong focusing of the gamma induced muons by about 10, this rate may lead for Crab [6] to $S/N^{1/2} = 40$ for one year of running.

3 Muon Tracking Detector (MTD)

The MTD [7] is built out of Streamer Tube (ST) chambers of $4 \text{ m}$ length and located in the KASCADE-Grande experiment [9]. The ST chambers are grouped in, so called, modules. Four modules, three positioned on horizontal planes (top, middle, bottom) and one arranged vertically (wall), form a muon telescope. The whole detector comprises 16 telescopes arranged in two rows. The low mass structure of the detector design reduces secondary interactions in the sensitive detector part.

To deal with clean muon tracks an efficient filter absorbing a large fraction of the low energy electromagnetic component of proton induced showers is mandatory. The larger Bethe-Heitler cross-section induced showers for gammas leading to pair production and subsequent electromagnetic cascade are readily absorbed by the filter. The energy threshold ($0.8 \text{ GeV}$) is suitable for background reduction. Following the characteristic energy $\epsilon_\mu = m_\mu c^2/\tau_{\mu} c \sim 0.8 \text{ GeV}$ muons from proton induced showers do not survive over the path length of 6.4 km and with energies close to the MTD threshold but decay to electrons which are readily absorbed. Photo-nuclear produced muons survive more easily because of comparatively lower production height. This situation improves the S/N ratio for photon detection. The stability of the MTD [7] is very good. The detector gas system follows precisely the atmospheric gas pressure.

The first-level $\gamma$/proton discrimination is mostly achieved by the characteristics of the MTD. The ratio of the number of hits in the top module to the track number $N_{\text{hit}}^\text{top}/N_{\text{track}}$ in each tower is a powerful tool in discriminating against hadron induced air showers. Only tracks with one hit in each module are accepted. Only hits with small cluster size ‘cls’ (clusters of readout wires or readout strips) are accepted. The background of high energy electrons or hadrons is further reduced by cuts in the track quality $Q^2$ (see [7]). Showering electrons or hadrons lead to larger ‘cls’ and, therefore, smaller $Q^2$.

For the subsequent analysis the following cuts in the data have to be employed: 1) Only data over one full sidereal day (86163 solar seconds) are considered. 2) Only sidereal days where all 16 telescopes are functioning are used. 3) The daily rate should follow a Gaussian distribution, and only days with rate within $\pm 4\sigma$ are accepted. 4) Only data corrected for pressure and temperature in the atmosphere and in the detector are included.

4 Gamma-Source Search

To identify sources which emit high energy gammas and which are with small probability converted to single muons deep in the atmosphere, we have the possibility to restrict the arrival direction and arrival time. The restriction in time and direction has the task to reduce other disturbing sources like the Sun. We have to cope with about 3 orders of magnitude larger background from cosmic ray muons in a canonical $1^\circ \times 1^\circ$ window in the sky.

The optimal square bin size for the search of a point gamma-ray source with the MTD is $1^\circ$ on a side, corresponding to a Gaussian angular resolution of about $0.3^\circ$.

For the search of point sources, the fluctuation of events in a fixed direction of the sky is investigated. When examining the fluctuation of the number of muon events bin by bin and
searching for possible sources with a muon event excess, we employ the numbers $N_{on}, T_{on}, N_{off}, T_{off}$. We use Li-Ma [10] formula to examine the fluctuation of the number of muon events bin by bin and to search for possible muon event excess. In the current analysis this procedure is used with bin size $\Delta \delta = 0.25^\circ$ and $\Delta \alpha = \Delta \delta / \cos \delta$, confined to specific regions on the sky to investigate the MTD sensitivity to specific gamma-ray sources. Only specific track directions in $\Theta$ and $\Phi$ and only specific arrival time intervals, where the corresponding source is high (winter months for Crab) ($\Theta_{source} < 35^\circ$) are chosen to accumulate clean single muon events in the $\delta$ versus $\alpha$ (declination versus right ascension) plane.

The analysis shows that the strong requirements of only 1 hit in each detector module and all $cls < 3$ give good profiles for Crab and Mkn421.

Observation of Mkn421 with the ARGO-YBJ experiment is reported by S.Vernetto et al. [11]. The FERMI view of the TeV blazar Mkn421 is given in [12] and the MAGIC observations of Mkn421 and related optical/X-ray/TeV multiwavelength studies are reported in [13]. Mkn421 is a very active Galaxy nucleus showing strong variation in the X-ray and TeV Gamma-ray fluxes and appears at 38.3°, 11.08 h which is 0.1° closer to the zenith and 0.15° later in time than the nominal position. The muon intensity is sampled and weighted with the actual MTD efficiency and smoothed afterwards. Again, only data epochs are considered when Mkn421 is high. Interestingly, the source profile is improved when employing days (properly matched in time) for which appreciable X-ray flux (> 2.5 photons/day) is reported [15]. For the Mkn421 source a correlation analysis with the X-ray flux measurements by the All-Sky-Monitor (ASM) onboard the RXTE-satellite [15] was performed providing the correlation as shown in Fig. 1. The picture exhibits a clear correlation between the time averaged (1 day) high energy muon flux and the time averaged X-ray flux above 2 keV. A narrow window around the nominal Mkn421 position improves the correlation in Fig. 1. Also a correlation between the muon flux from the MTD in the region of Mkn421 and the gamma flux in the GeV range recorded by FERMI satellite [16] is observed. The dashed line in Fig. 1 represents a fit to the correlation and deserves further studies. Employing days with almost constant X-ray activity from Mkn421, the conversion of GeV gammas into muons in the atmosphere above the MTD can be investigated. Fig. 2 shows the correlation of the muon rate with the atmospheric pressure overburden. It shows the strong gain of photo-produced pions with pressure especially after correction (solid points in Fig. 2) for the pressure dependent track detection efficiency of the MTD [7]. The strong dependence of the muon rate on the atmospheric pressure suggests the pion photoproduction to occur in the lower atmosphere.

Fig. 3 shows for Crab a two-dimensional multi-quadratic interpolation [8] of the data points in the $\delta$ versus $\alpha$ (declination versus right ascension) plane (in the boundaries of a MAGIC presentation). The contour scale is in units of excess counts per smoothing radius. The position of the source as quoted by the MAGIC group [14] is given by the cross. The displacement of the source to larger zenith $\Theta$, and smaller azimuth $\Phi$, and possible deformation is due to the geomagnetic field $B_{geo}$ and is expected to depend on the momentum of the muons and their orientation with respect to the geomagnetic field components.

Gamma-ray induced muons in the deep atmosphere we expect to be almost charge symmetric. Therefore, the spread of the source profile is reproducing the muon momentum distribution. Muons are considered to exhibit negative charge if they are deflected towards the East from the line connecting the actual Crab position with the geomagnetic field direction. Mean deflection of about 0.6° is expected for 1 GeV muons created 1 km above ground. Only negatively charged muons to the East side of the source are considered for accumulating an angle-distance spectrum. The frequency of muon tracks as function of $1/distance$ to the nominal Crab source position is plotted in the Fig. 4, resulting in steep falling spectrum. The inverse angle-distance is expressed in muon momentum, assuming a $\sim p_{\mu} \times B_{geo}$ dependence. Assuming further that muons at threshold ($0.8 GeV$) stem from gammas about 10 times higher in momentum would provide a preliminary gamma energy scale. The preliminary flux normalization considers the gamma flux attenuation in the air, the small $\sigma_{\gamma\pi}$ cross section on air, the mass density of the atmosphere and the momentum dependence of the $\pi \rightarrow \mu$ conversion rate and the exposure of the MTD. The dashed line represents a $flux_\mu \sim p_{\mu}^2$ flux dependence. A more detailed unfolding of the gamma source spectrum has still to be carried out.
5 Outlook

The high resolution muon tracking detector MTD in the KASCADE-Grande experiment demonstrates to be capable to identify gamma point sources in the sensitivity range of Crab fluxes. The highly variable gamma source Mkn421 provides in its 'high' state a test beam to study the efficiency of $\gamma \Rightarrow \mu$ conversion in the atmosphere depending on the atmospheric parameters, and further tuning of the MTD response to gammas. Future analysis of a larger data sample will provide more detailed information on the nature of high energy gamma source muons. There is a common understanding that the high energy gamma source muons serve as sensitive probes to investigate the high energy photon interactions in the atmosphere, providing a gamma detector in the multi-GeV range.

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References

[17] http://www.swift.psu.edu/monitoring