A Monte Carlo Calculation of Muon Flux at Ground Level from Primary Cosmic Gamma Rays

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Abstract

The Monte Carlo program FLUKA was used to calculate the number of muons reaching detection level in events initiated by primary cosmic gamma ray interactions in the atmosphere. The calculation was motivated by the desire to gauge the sensitivity of arrays like that of Project GRAND to primary gamma cosmic rays while measuring single muons at detection level. Because direct gamma pair production is not a significant source of muons, normally the presence of muons is not considered as a signal for gamma rays. However, due to their non-negligible cross section for hadron production, high-energy gamma rays can initiate hadronic showers containing a large number of pions. These can decay producing secondary muons which then have a good chance of reaching detection level. The complete kinetic energy and space distribution of such muons can be predicted by simulating in detail the whole process by means of Monte Carlo techniques. However, the code used must be capable of handling both hadron-nucleus and photon-nucleus interactions. Unlike most available Monte Carlo particle transport programs, such interactions are implemented in FLUKA, up to several tens of TeV, based on Dual Parton and Vector Meson Dominance models. The FLUKA capability to describe hadronic cascades generated in the atmosphere by primary cosmic hadrons has already been shown in several studies. In the present paper, the investigation has been extended to primary gamma rays. The number of muons per photon is presented as a function of the primary energy in the region between 3 GeV and 10 TeV. As the energy of primary photons rises, their flux falls, whereas the number of muons per gamma rises. Combining these two effects, it can be predicted that gamma ray energies in the 30 GeV region produce the most muons at detection level. The radial and kinetic energy distributions of the muons are also presented.

1 Introduction:

Muons at detection level of Project GRAND (Poirier et al., 1999) have their origin mainly as decay products of pions generated in interactions of hadrons with nuclei of the atmosphere. However, a small but finite contribution is expected from hadronic interactions of high energy photons. The muon component originated by primary gamma rays presents a special interest because the photon direction cannot be deflected by magnetic fields and can be traced back to their source in space (Carpenter et al., 1999).

The number, kinetic energy spectrum, and radial distribution of gamma-generated muons can be estimated as a function of primary photon energy and altitude by means of Monte Carlo simulations. However, high energy photonuclear interactions are not implemented in most existing Monte Carlo particle transport codes. An exception is FLUKA (Fassò et al., 1993), a program originally developed for accelerator shielding calculations, but which is now being used in an increasing number of research fields, including cosmic rays (Schraube et al., 1997; Roesler, Heinrich & Schraube, 1998; Battistoni et al., 1998, 1999; Battistoni, Ferrari & Scapparone, 1999). Hadronic photon reactions are implemented in FLUKA according to the Vector Meson Dominance model (Bauer et al., 1978), taking into account shadowing and delta resonance (Fassò, Ferrari & Sala, 1994). The interaction initiated by vector mesons is described in the frame of the Dual Parton Model (Capella et al., 1991; Ferrari & Sala, 1996) in the same way as that of any other hadron.

2 Calculations:

The 1998 version of FLUKA was used to calculate the muon flux and kinetic energy spectrum at both sea level and 200 m (approximately the GRAND altitude), in 10 concentric rings of radii ranging from 10 m to 10 km. Photons of energy between 3 GeV and 10 TeV were assumed to enter the atmosphere vertically at 80 km and the full generated electromagnetic and hadronic showers were followed down to pion production threshold energy. The mean free path for photonuclear interaction was artificially biased in order to enhance the interaction probability by a factor 10 to 50. The statistical weight of each particle was adjusted accordingly, so that all distributions were preserved *exactly* (multiplicities, energy spectra, height of first interaction etc.).

The atmosphere was subdivided into 25 layers of different density, with thickness ranging from 0.2 to 100 g/cm^2. The effects of magnetic fields and of direct muon pair production by gamma rays were assumed to be negligible and were not considered.

For comparison purposes, a similar set of calculations was made to estimate the electron flux at the same positions. All conditions were identical except the shower energy cutoff which was lowered to 3 MeV. A run was also made with 10 TeV protons as primary particles.

3 Results:

Fig. 1 shows how the total number of muons and electrons grows with increasing photon energy. A summary of calculated data is reported in Table 1.

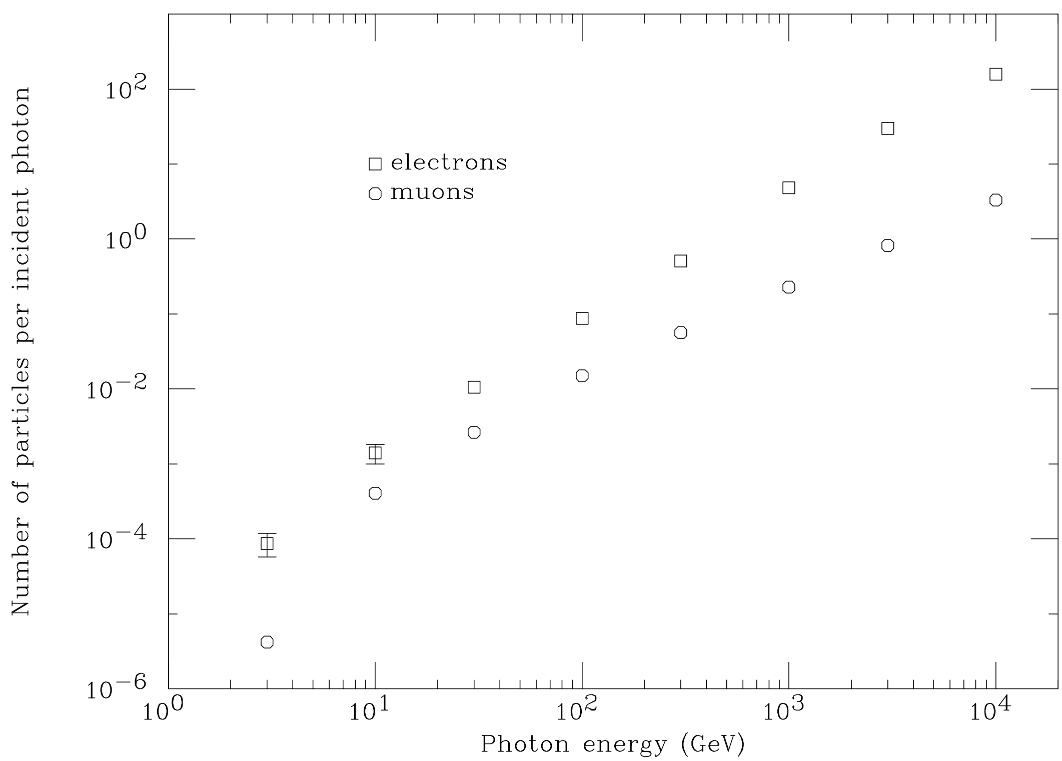

Figure 1: Number of muons and electrons at 200 m a.s.l. as a function of photon energy

The dependence on radial distance is shown in Fig. 2. The total number of muons within a given radius is plotted as a function of radius. In general, the circle containing one half of all the muons reaching ground has a radius of little more than 500 m. At the lowest photon energies, however, this circle radius is of the order of 2000 m.

The calculated spectra are too numerous to be reported here: a representative example, referring to 4 different primary photon energies at distances <500 m, is shown in Fig. 3.

Primary particle	Kinetic energy (GeV)	electrons (both charges) 200 m a.s.l.	electrons (both charges) sea level	muons (both charges) 200 m a.s.l.	muons (both charges) sea level
p	10^4	44.9 ± 2.1	39.3 ± 1.8	75.4 ± 0.9	74.6 ± 0.8
γ	10^4	158 ± 7	121 ± 6	3.31 ± 0.07	3.18 ± 0.07
γ	3000	30 ± 3	23 ± 3	0.82 ± 0.03	0.79 ± 0.03
γ	1000	4.8 ± 0.7	3.7 ± 0.6	0.227 ± 0.011	0.220 ± 0.010
γ	300	0.51 ± 0.06	0.41 ± 0.05	0.0561 ± 0.0008	0.0545 ± 0.0009
γ	100	0.0879 ± 0.0006	0.0584 ± 0.0004	0.0150 ± 0.0007	0.0147 ± 0.0007
γ	30	0.0106 ± 0.0016	0.0088 ± 0.0014	0.00264 ± 0.00018	0.00255 ± 0.00017
γ	10	0.0014 ± 0.0003	0.0010 ± 0.0005	$(4.06 \pm 0.15) \times 10^{-4}$	$(3.95 \pm 0.15) \times 10^{-4}$
γ	3	$(8.7 \pm 3.0) \times 10^{-5}$	$(3.8 \pm 1.6) \times 10^{-5}$	$(4.2 \pm 0.6) \times 10^{-6}$	$(3.6 \pm 0.5) \times 10^{-6}$

Table 1: Number of secondaries per primary particle within a 10 km radius at 200 and 0 m above sea level

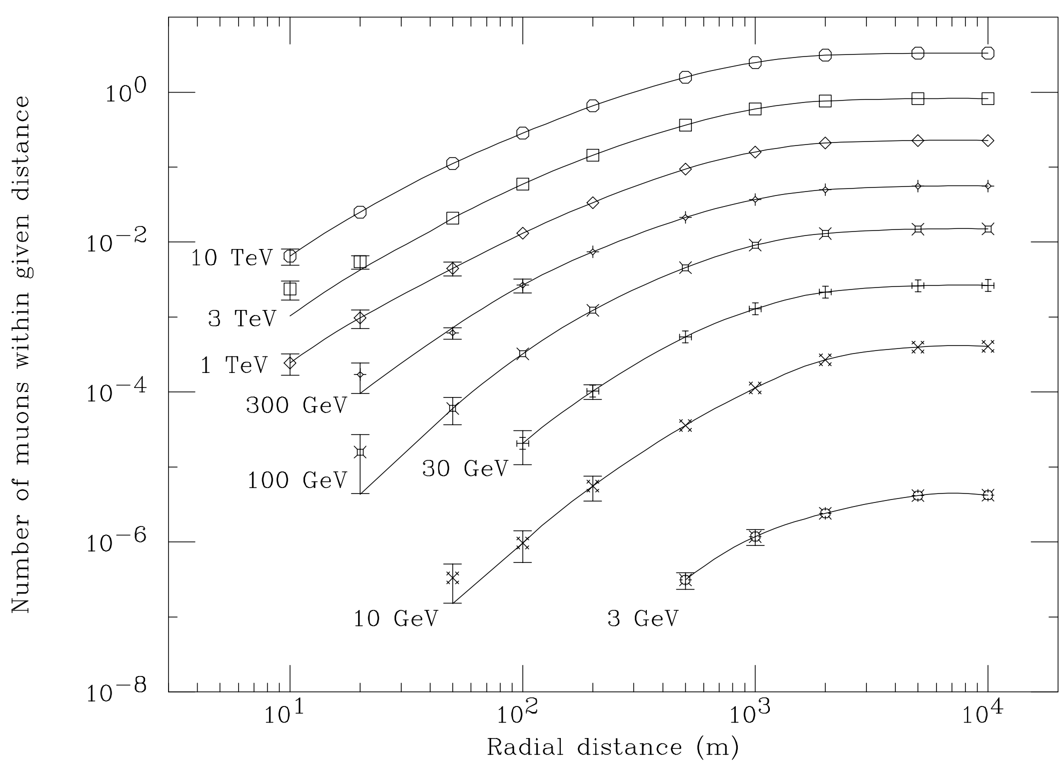

Figure 2: Number of muons per incident photon of different energy vs. radial distance

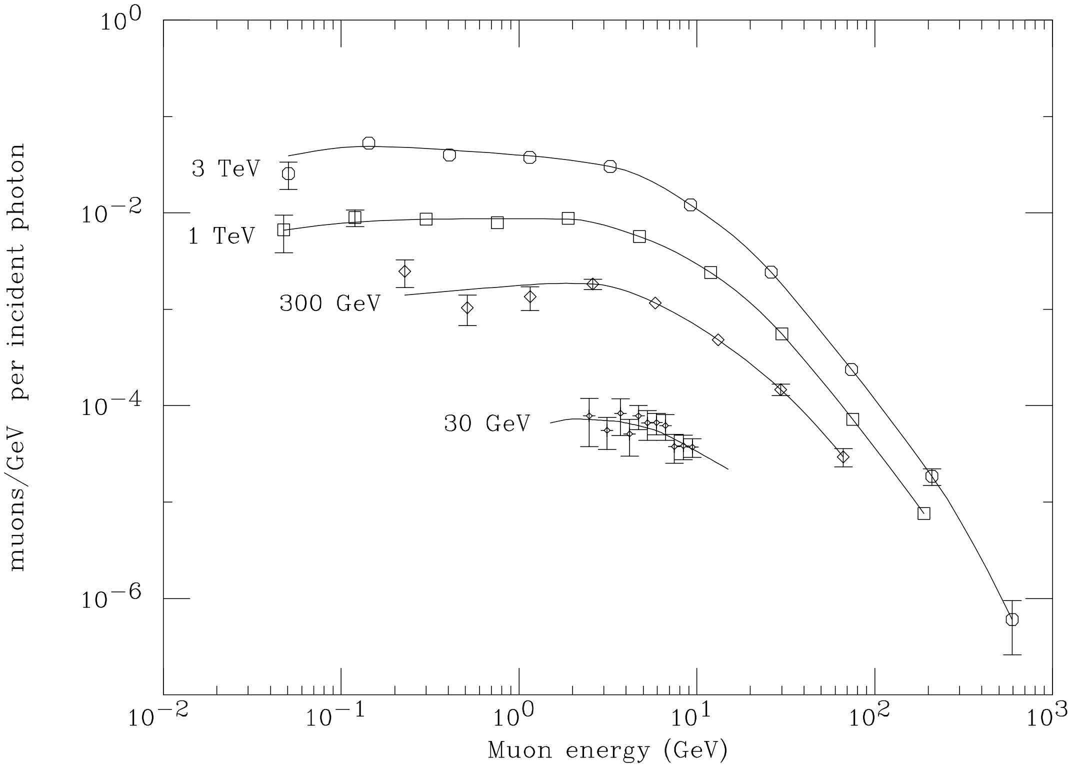

Figure 3: Muon kinetic energy spectra at radial distances < 500 m from the shower center, at 200 m a.s.l.

To estimate the actual number of muons reaching detection level, the calculated data should be folded with the incident primary photon spectrum, but the latter is not known. Assuming an energy dependence as $E^{-2.7}$, similar to hadronic cosmic rays, it is found that the largest contribution to muons is probably due to photons with energies of the order of 30 GeV.

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