A limit on the diffuse gamma-rays measured with KASCADE-Grande

D Kang[1], W D Apel[2], J C Arteaga-Velázquez[3], K Bekk[2], M Bertaina[4], J Blümer[1,2], H Bozdog[2], I M Brancus[5], E Cantoni[4,6,a], A Chiavassa[4], F Cossavella[1,b], K Daumiller[2], V de Souza[7], F Di Pierro[4], P Doll[2], R Engel[2], Z Feng[8], D Fuhrmann[9,c], A Gherghel-Lascu[5], H J Gils[2], R Glasstetter[9], C Grupen[10], A Haungs[2], D Heck[2], J R Hörandel[11], D Huber[1], T Huege[2], K H Kampert[9], H O Klages[2], K Link[1], P Łuczak[12], H J Mathes[2], H J Mayer[2], J Milke[2], B Mitrica[5], C Morello[6], J Oehlschläger[2], S Ostapchenko[13], N Palmieri[1], M Petcu[5], T Pierog[2], H Rebel[2], M Roth[2], H Schieler[2], S Schoo[2], F Schröder[2], O Sima[14], G Toma[5], G C Trinchero[6], H Ulrich[2], A Weindl[2], J Wochele[2], J Zabierowski[12]

[1] Institut für Experimentelle Kernphysik, KIT - Karlsruher Institut für Technologie, Germany
[2] Institut für Kernphysik, KIT - Karlsruher Institut für Technologie, Germany
[3] Universidad Michoacana, Instituto de Fisica y Matemáticas, Mexico
[4] Dipartimento di Fisica, Università degli Studi di Torino, Italy
[5] National Institute of Physics and Nuclear Engineering, Bucharest, Romania
[6] Istituto di Fisica dello Spazio Interplanetario, INAF Torino, Italy
[7] Universidade São Paulo, Instituto de Física de São Carlos, Brasil
[8] Institute of High Energy Physics, Beijing, China
[9] Fachbereich Physik, Universität Wuppertal, Germany
[10] Fachbereich Physik, Universität Siegen, Germany
[11] Dept. of Astrophysics, Radboud University Nijmegen, The Netherlands
[12] National Centre for Nuclear Research, Department of Astrophysics, Lodz, Poland
[13] Frankfurt Institute for Advanced Studies (FIAS), Frankfurt am Main, Germany
[14] Department of Physics, University of Bucharest, Bucharest, Romania
[a] now at: Istituto Nazionale di Ricerca Metrologia, INRIM, Torino;
[b] now at: DLR Oberpfaffenhofen, Germany;
[c] now at: University of Duisburg-Essen, Duisburg, Germany;

E-mail: donghwa.kang@kit.edu

Abstract. Using data measured by the KASCADE-Grande air shower array, an upper limit to the flux of ultra-high energy gamma-rays in the primary cosmic-ray flux is determined. KASCADE-Grande measures the electromagnetic and muonic components for individual air showers in the energy range from 10 PeV up to 1 EeV. The analysis is performed by selecting air showers with low muon contents. A preliminary result on the 90% C.L. upper limit to the relative intensity of gamma-ray with respect to cosmic ray primaries is presented and compared with limits reported by other measurements.

1. Introduction

The flux of diffuse gamma rays and its spectrum is a very interesting topic in astrophysics. This study gives information about processes and developments at extragalactic distances. Therefore, we can understand the origin and the propagation of galactic cosmic rays from investigations of the galactic diffuse emission. Since direct measurements of ultra-high energy photons by satellite or balloon-borne experiments are difficult due to the low fluxes. This detection can, however, be accomplished by large area ground-based detectors using the air shower array technique.

Extensive air showers are mainly characterized by the total electron number and the total muon number. In general, muons are produced by the decay of charged kaons or pions, which in hadronic showers are produced in nucleus-nucleus interactions, whereas in photon showers only in photoproduction processes. The ratio between the cross sections of photoproduction and nucleus-nucleus interaction processes is very small, in the order of $\sim 10^{-3}$. Therefore, the usual strategy for searches for primary gamma-rays in extensive air showers is to discriminate gamma-ray primaries from the hadronic background by identifying muon-poor extensive air showers.

There are two main plausible sources of diffuse flux of ultra-high energy gamma radiation: The first source is due to decays of neutral pions produced by the collision of cosmic-rays with interstellar gas and dust in the disk of the Galaxy. In this case, the predicted integral intensity is concentrated in the galactic plane. The second one is due to electromagnetic cascades resulting from the interactions of extremely high-energy cosmic-rays with the 2.7 K cosmological microwave background radiation or topological defects in early Universe. In this case, this results in an isotropic flux of secondary photons uniformly are distributed over cosmological distances. Therefore, the measurements of the diffuse isotropic gamma-ray flux might provide information on the ultra-high energy cosmic-ray components. In addition, this flux would represent a background for experiments searching for the gamma-ray enhancement from the direction of the galactic disk.

This contribution presents limits on the relative intensity of the gamma-ray component of the cosmic rays measured by the KASCADE-Grande experiment.

2. The KASCADE-Grande experiment

KASCADE-Grande was an extensive air shower experiment located at Karlsruhe Institute of Technology (49.1° north, 8.4° east, 110 m above sea level). It operated until the end of 2012 and all components were by now dismantled.

The KASCADE-Grande [1] array covering an area of 700×700 m^2 was optimized to measure extensive air showers up to primary energies of 1 EeV. It comprised 37 scintillation detector stations located on a hexagonal grid with an average spacing of 137 m for the measurements of the electromagnetic and muonic shower components. Each of the detector stations was equipped with plastic scintillators covering a total area of 10 m^2. The angular resolution of KASCADE-Grande is better than 0.5 ° over the whole energy range, so that it will allow us to perform also gamma-ray searches.

2.1. Selection of data

For this analysis full data sets taken from 2003 to 2012 were used, where only successfully reconstructed and precisely measured events were selected. The core positions of the showers are inside a circular area of 152,214 m^2 around the center of the array to avoid large reconstruction errors at the edges of the detector field. The zenith angle is smaller than 40° to ensure full efficiency. After applying all quality cuts, we obtained in total ca. 1.7×10^7 events for a measurement time of ca. 1865 days.

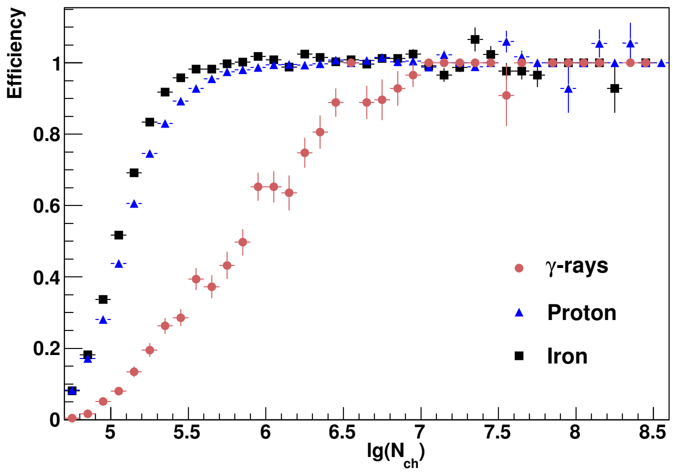

Figure 1. Trigger and reconstruction efficiency as a function of the number of charged particles for air showers induced by photons, protons and iron primaries.

3. Gamma and cosmic ray simulations

An essentail part of the present analysis is the Monte Carlo simulation of the experiment.

For the simulation of the physical processes in the air shower development the CORSIKA [2] program has been used, applying hadronic interaction models. To determine the signals in the individual detectors, all secondary particles at the ground level are passed through a complete detector simulation program using the GEANT package. The predicted observables at ground level, such as e.g. the number of electrons, muons and photons are then compared to the measurements.

The FLUKA [3] ($E < 200$ GeV) model has been used for hadronic interactions at low energies. High-energy interactions were treated with different models QGSJETII-2 [4]. Showers initiated by primary photons, protons, He, CNO, Si and iron nuclei have been simulated. The simulations covered the energy range of 10^{14} - 10^{18} eV with zenith angles in the interval 0° - 60°. The spectral index in the simulations was -2 and for the analysis it is weighted to a slope of -3. For each particle type the same number of showers was generated.

3.1. Efficiency

The trigger and reconstruction efficiency of KASCADE-Grande as a function of the shower size, i.e. the number of charged particles, is demonstrated in Fig. 1. The efficiency is defined by the ratio of the number of events in the reconstructed area to the number of events in the true area, in which the binomial statistical errors are used. Efficiencies above one are due to cuts on the reconstructed core positions, i.e. events falling outside the selected area can be reconstructed inside. Full efficiency is reached at the number of charged particles of around 10^6 for air showers induced by protons and iron primary particles, which approximately corresponds to a primary energy of 10^{16} eV. However, for showers induced by photon primaries the full efficiency is higher due to the missing muon trigger at large distances. The limit at high energies is due to the restricted area of the Grande array.

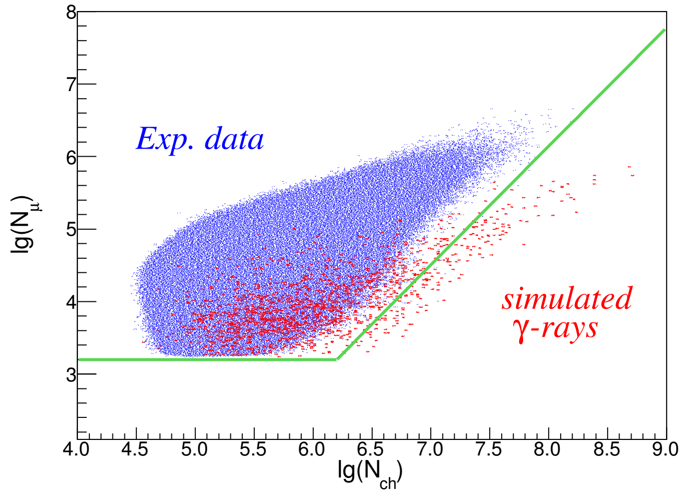

Figure 2. Scattered distribution of the measured number of muons $\lg(N_\mu)$ and number of charged particles $\lg(N_{ch})$ superimposed with simulated gamma-ray showers. The green line indicates the choice of the cut for the selection of the muon-poor showers.

4. Gamma hadron discrimination

Figure 2 shows a scatter diagram of the observed number of muons $\lg(N_\mu)$ and charged particles $\lg(N_{ch})$. The simulated gamma-ray showers are superimposed as well. The blue data points indicate the whole experimental data set, whereas the red one illustrate the simulated gamma-ray events. The shower size is corrected to a zenith angle of 20 ° using the method of constant intensity [5].

Since gamma-ray induced air showers are notable for their lack of muons, compared to hadronic showers, we select a data sample enriched in photon showers by rejecting showers containing muons, i.e., we therefore take a more conservative way in which the expected background is not subtracted from the event number below the cut line.

The selection of muon-poor showers is indicated by the straight line in Fig. 2. The events below the straight line were taken into consideration for further analysis. They amount to 1060 out of a total of 17 millions events. In the region below this line the events are expected to be mainly due to primary photons because air showers induced by heavy nuclei show a larger muon to electron ratio.

5. The analysis and results

There is no possible excess of events consistent with a gamma-ray signal seen in the data. Hence, we assume that all events below the selection line are background and set upper limits on the gamma-ray fraction of the cosmic rays. We estimate the 90% C.L. upper limit on the number of observed events, applying standard statistical methods [6] and the efficiency for gamma-ray detection.

Assuming that all events passing the gamma-ray selections are indeed gamma-rays, the 90% upper limit on the fraction of the gamma-ray integral flux relative to the cosmic-ray integral flux, I_γ/I_{CR}, is estimated by [6]

$$\frac{I_\gamma}{I_{CR}} < \frac{N_{90}}{N_{tot}\varepsilon_\gamma}\left(\frac{E_{CR}}{E_\gamma}\right)^{-\beta+1}, \tag{1}$$

Table 1. Results of the search for diffuse ultra-high energy gamma-rays at different threshold values of N_{ch}. The mean cosmic-ray energy, E_{CR}, and the mean gamma-ray energy, E_γ, are given in the unit of TeV. I_γ/I_{CR} is the 90% C.L. upper limit on the integral gamma-ray fraction, and I_γ is the 90% C.L. upper limit on the integral gamma-ray flux in the unit of photons cm^{-2}s^{-1}sr^{-1}.

$\lg(N_{ch})$	N_{tot}	N_{90}	ε_γ	E_{CR}	E_γ	I_γ/I_{CR}	I_γ ($\times 10^{-17}$)
>6.5	6.19×10^6	358	0.61	3.21×10^4	1.64×10^4	$<2.98\times10^{-5}$	<1.88
>7	85537	351	0.88	8.72×10^4	6.29×10^4	$<2.37\times10^{-3}$	<9.83
>7.5	9640	214	∼1.0	2.21×10^5	1.32×10^5	$<7.29\times10^{-3}$	<5.89
>8	1239	122	∼1.0	5.31×10^5	2.75×10^5	$<2.11\times10^{-2}$	<3.30

where N_{90} is the 90% C.L. upper limit on the number of detected events, ε_γ is the efficiency for gamma-ray detection, and β is the integral cosmic-ray spectral index ($\beta = 3.0$, $E_\gamma > 4$ PeV). E_{CR} and E_γ are the mean energies of cosmic-ray and gamma-ray, respectively, which produce the same shower size (N_{ch}). Therefore, they are calculated for a fixed N_{ch} bin using the resulting Gaussian function.

Table 1 shows the results of the search for diffuse ultra-high energy gamma-rays for different threshold values of N_{ch}. To determine upper limits to the integral flux of gamma-rays at fixed gamma-ray energies, we use measurements of the all-particle primary energy spectrum of Ref. [7]. The flux limits are also given in Table 1.

Figure 3 displays the measurements on the gamma-ray fraction as a function of energy, including this work, for the energy range of 200 TeV up to 300 PeV. The limits presented here represent the first results in the energy range above 5×10^{16} eV.

These results are compared with other previous experiments [10, 11] and with theoretical curves by a specific IceCube excess model [9] in Fig. 4. The lines are IceCube excess model coming from different distances of sources of neutrinos in the galaxy, where these ν's are also responsible for primary gamma-rays. The KASCADE results [8] are compatible with the theoretical prediction of the IceCube excess model coming from < 20 kpc in the galactic plane. It might hence set some constrains on the distance of sources for the IceCube Excess. The result of the KASCADE experiment will be updated with more data. Details will be described elsewhere in a forthcoming publication.

It should be noted that all values in Fig. 4 are limits, except that one from MSU [12]; This reported positive signal seems to be disproved by the presented results.

6. Conclusion

Using full data sets measured by the KASCADE-Grande experiment, the 90% C.L. upper limits to the diffuse flux of ultra-high energy gamma-rays for the energy range of 200 TeV to 300 PeV are determined by selecting showers with low muon contents.

The best upper limit to the fraction of the gamma-ray to the cosmic-ray flux is obtained: $I_\gamma/I_{CR} < 2.98 \times 10^{-5}$ for 16.4 PeV. These stringent limits are the first results in the energy range above 10 PeV, and might constrain a limit to the background rate of muon-poor showers in the search for the galactic disk enhancement of cosmic rays.

Comparison of these experimental upper limits with the theoretical predictions is still required, since no theoretical predictions exist so far at energies around 10 PeV. The statistics on the gamma-ray simulation is currently limited, so that these preliminary results will be improved by more gamma-ray simulations and also by a new muon reconstruction.

In addition, the results of the original KASCADE experiment will be updated by including

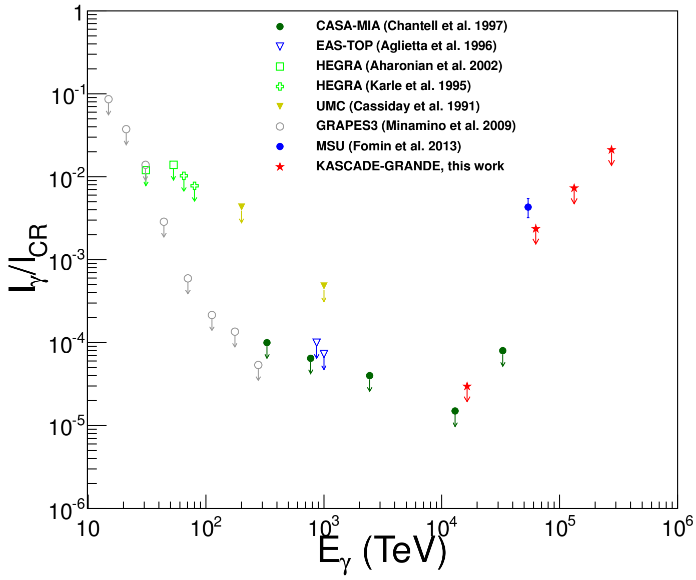

Figure 3. Fraction of gamma-rays relative to the cosmic rays. The red stars represent the results from KASCADE-Grande.

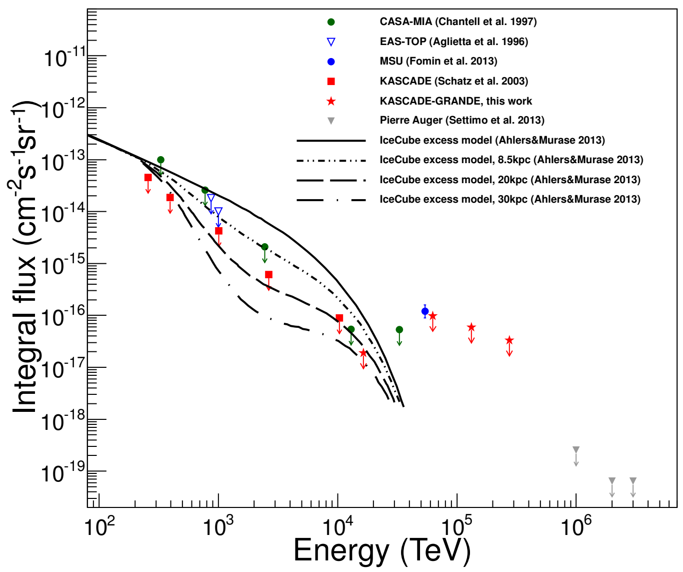

Figure 4. Comparison of integral flux of gamma-rays with previous results and with theoretical curves by an IceCube excess model [9].

eight years of more data since the publication in Ref. [8]. It should be mentioned that this might set some constraints on the distance of sources for the IceCube excess.

Acknowledgments

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