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Search for Extremely High Energy Gamma Rays with the KASCADE Eperiment

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Abstract.
Data observed with the KASCADE extensive air shower experiment have been analyzed with respect to a possible contribution by primary gamma rays in the energy range of 0.3 to 10 PeV. The study makes use of the good definition of electron and muon numbers by the experiment. Possible gamma induced events are mainly identified by their low muon to electron ratios but, in addition, the steepness and smoothness of the electron lateral distributions are exploited. No positive identifications can be claimed but our results confirm and, in the lower part of the energy range, improve upper limits of a possible gamma contribution made by previous experiments. The distribution on the sky of the 53 most 'gamma-like' events out of a sample of 13.6 million events is indistinguishable from that of all the events registered. The results are based on a measurement time of approximately half a year.

1 Introduction

Gamma rays represent a small but important fraction of primary cosmic rays. Their importance derives mainly from the fact that gamma rays, being electrically neutral, are not deflected by interstellar or intergalactic magnetic fields and therefore their direction of incidence points back to their point of origin. In the TeV range the imaging atmospheric Cherenkov technique has thus been able to identify a (still small) number of galactic and extragalactic point sources. The highest gamma ray energies measured by this technique are close to 50 TeV (Tanimori et al., 1998). But the gamma ray spectrum is expected to extend to even higher energies: The interstellar matter in our galaxy is permanently bombarded by the charged component of cosmic rays. Their interactions will lead to the production of neutral pions whose decay then results in gamma rays of energies up to roughly a tenth of that of the charged particles and the spectrum of the latter is known to extend beyond 10^{20} eV. It therefore appeared worthwhile to search the data registered by the KASCADE experiment for evidence which might be attributed to primary gamma rays.

Previous experiments (Aglietta et al., 1996; Chantell et al., 1997) have set upper limits of the order of 10^{-5} to 10^{-4} for the gamma ray fraction among primary cosmic rays in the energy range above a few hundred TeV. Identifying such a small fraction is not trivial, especially in view of the large fluctuations inherent in extensive air showers (EASs) which are the only means at present to register high energy cosmic rays. The main feature which can be exploited for discriminating primary gamma rays from charged cosmic ray particles is the ratio of electrons to muons on observation level. Gamma rays interact in the atmosphere predominantly by producing electron-positron pairs. The corresponding production of pairs of muons is suppressed by more than four orders of magnitude due to the larger muon mass. It is only via the photoproduction of hadrons that muons occur to an appreciable extent in EASs induced by gamma rays.

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The KASCADE experiment is well suited for such an investigation due to its large detector area for muons. In addition, the large dynamic range of the KASCADE array scintillators allows a good definition of the lateral electron distribution which can be used to further discriminate gamma induced EASs. Our basic procedure is to compare the measured data to simulated gamma induced events. This implies that assumptions about high energy strong interactions enter into our results only to the extent that they influence hadron photoproduction and the subsequent interactions of the secondary hadrons. The cross section for photoproduction has been measured at the HERA collider at DESY up to equivalent laboratory energies of 20 TeV (Derrick et al., 1992; Ahmed et al., 1993) and it is well described by theory. Hence the extrapolation to the higher energies required here appears justified. These data have been incorporated in the CORSIKA EAS simulation program (Heck et al., 1998) which was used for the simulations. Inaccuracies in the treatment of secondary hadron interactions are not supposed to be of prime importance in our situation because the error of the determined muon number is governed by statistics for the events with a small muon number which are of interest for the present investigation. The Monte Carlo program which describes the detector response to the CORSIKA output is based on the GEANT program (GEANT 1994).

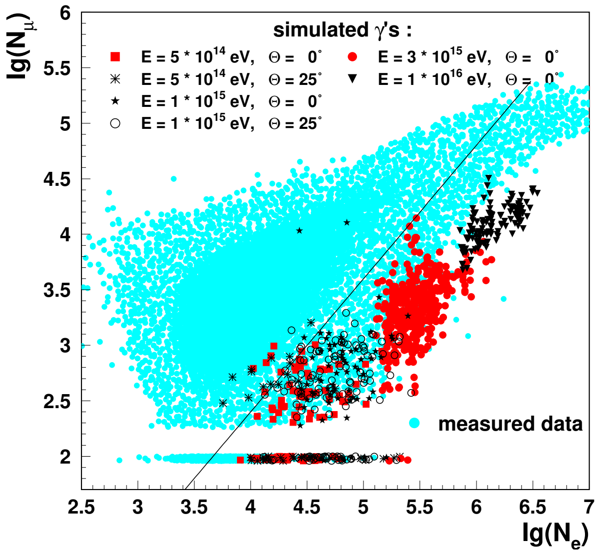

Fig. 1. Distribution of the observed events in the $lg(N_e) - lg(N_\mu)$ plane (light blue) with simulated gamma showers superimposed. The horizontal band at $lg(N_\mu) = 2$ represents EAS with no registered muon (and hence an estimated muon number 0).

2 Measurements and data analysis

The experiment has been described in detail before (Klages et al., 1997). Therefore we only give here a brief account of the main features relevant for the present analysis. The KASCADE array consists of 252 detector stations set up as a square grid of 13 m spacing on a total area of $200 \times 200\,\mathrm{m}^2$. All stations contain scintillation detectors for registering electrons with a total detector area of $490\,\mathrm{m}^2$. The dynamic range of these detectors is at least 5000. 192 of the detector stations also contain scintillation counters for the measurement of muons with a total area of $620\ \mathrm{m}^2$. Of the KASCADE central detector, only the 456 scintillation detectors of the trigger plane were used to register muons. Their total area is $205\ \mathrm{m}^2$. Their threshold is slightly higher than that of the array muon detectors (400 MeV versus 230 MeV). This difference could have been accounted for in the analysis but was instead ignored because the corrections would have been much smaller than the statistical accuracy.

The signals from the electron detectors were analysed by the usual KASCADE procedures to yield electron number N_e, steepness of the lateral electron distribution ('age'), core position and, from timing, the direction of incidence of the shower. For more details of the analysis cf. Weber (1999). The electron counters were also used to trigger data acquisition. The muon number N_μ was determined by a maximum likelihood method assuming a fixed lateral distribution. The latter assumption is of course an approximation but unavoidable because the number of registered muons was always small for the showers of interest. The trigger threshold was set so low that electron and muon numbers could only be determined for about a quarter of all triggered events. As the result of the analysis we obtain a two-dimensional spectrum on the $lg(N_e) - lg(N_\mu)$ plane.

3 Gamma hadron discrimination

Fig. 1 shows the distribution of the reconstructed events as the light blue data points. Superimposed are simulated gamma events of fixed energy and zenith angle. They concentrate along the lower edge of the observed showers, as expected.

For further analysis we concentrate on the events below the straight line in fig. 1. They amount to 34534 out of a total of 13.6 millions. In the region above this line the density of observed events is so large that identification of the few possible gamma induced events appears hopeless. EASs induced by heavy nuclei exhibit a large muon to electron ratio and are therefore expected to be located at the upper edge of the observational range in fig. 1. The events near to and to some extent overlapping the simulated gamma events, on the other hand, are expected to be mainly due to primary protons. A further reduction of the hadron background therefore depends on a suppression of proton induced showers which, according to simulations, exhibit much steeper lateral distributions (small 'age') than those initiated by gamma rays. We therefore compare in fig. 2 the ages of observed and simulated events and remove all data outside the band

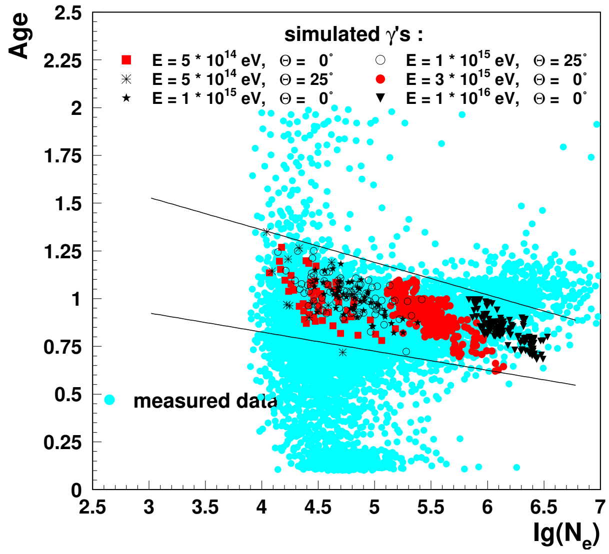

Fig. 2. Age distribution of observed events below the straight line in fig. 1 versus $lg(N_e)$ with simulated gamma showers superimposed. Only events in between the two straight lines are retained for further analysis.

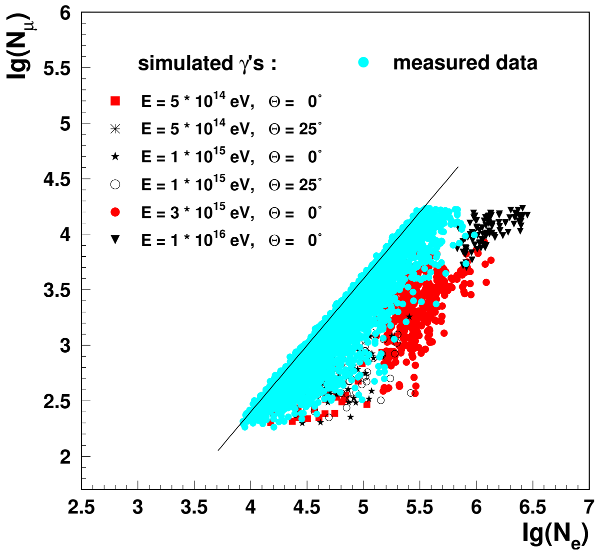

Fig. 3. Distribution of the observed events surviving the age and χ^2 cuts in the $lg(N_e) - lg(N_\mu)$ plane superimposed upon simulated gamma showers. Events above $lg(N_\mu) = 4.2$ have been omitted here because they have not yet been corrected for saturation in the muon detectors.

between the two straight lines. Proton induced EASs are furthermore characterized by their large fluctuations of all shower observables. This feature is exploited very advantageously for gamma/hadron separation by the imaging atmospheric Cherenkov technique to measure extraterrestrial gamma rays in the TeV range (for details cf. Fegan 1997). The parameters which characterize an EAS: shower size N_e, age and core position, are determined via minimizing the quantity

$$\chi^2 = \sum_1^D \frac{(n_i - m_i)^2}{m_i}$$

Here D is the number of detectors included in the analysis, n_i the number of electrons observed in detector i and m_i the corresponding theoretical value. Furthermore we have assumed that the fluctuations of the n_i are Poissonian. Since gamma induced showers are expected to show a more regular lateral distribution than proton induced ones the minimum value of χ^2 will be on average larger for the latter ones. The mean value of χ^2 is known to be equal to the number of degrees of freedom $F = D - 4$. Therefore the ratio χ^2/F is usually quoted but this does not take into account that the variance of χ^2 also depends on F which is not constant in our case. We therefore use the ratio of $\chi^2 - F$ to its standard deviation as a further discriminator. The latter is calculated accounting for the fact that the quantities n_i are not described by Gaussian but rather by Poissonian distributions. A more detailed description of this procedure is given elsewhere (Schatz 2001). Again we remove events for which this ratio is larger than that of the simulated gamma events. Fig. 3 displays the distribution of the 16712 events remaining after these cuts in the $lg(N_e) - lg(N_\mu)$ plane.

The (altogether 9300) events for which no muon was registered (displayed in the horizontal band near $lg(N_\mu) = 2$ in fig. 1) were analysed in a corresponding way and yield a statistically independent estimate of the number of gamma rays.

The usual method applied by previous experiments (Aglietta et al., 1996; Chantell et al., 1997; Karle et al., 1995) to set an upper limit to the number of gammas among the observations is to choose a separating line (in our case in the $lg(N_e) - lg(N_\mu)$ plane) and assume that all events on one side of the line represent gamma rays. In our opinion this procedure is unnecessarily conservative because the distribution of observed events in the region of simulated gamma ray showers does not bear any resemblance with the one expected for gamma rays. Their density decreases strongly from upper left to lower right. This implies that most of the events have to be attributed to the tail of hadron induced showers. The distribution of gamma induced events would form a ridge approximately parallel to the straight line in fig. 3. In our opinion, a more realistic way of estimating an upper limit of the number of gamma events can be obtained in the following way: The distribution of gamma induced events in the $lg(N_e) - lg(N_\mu)$ plane is known from simulations. It is then possible to determine the maximum number of events exhibiting the same distribution which may be contained in the observations without producing a marked excess anywhere. A simple statistical algorithm serving this purpose has been developed (Schatz 2001). This then gives us an upper limit to the gamma ray flux when the duration of

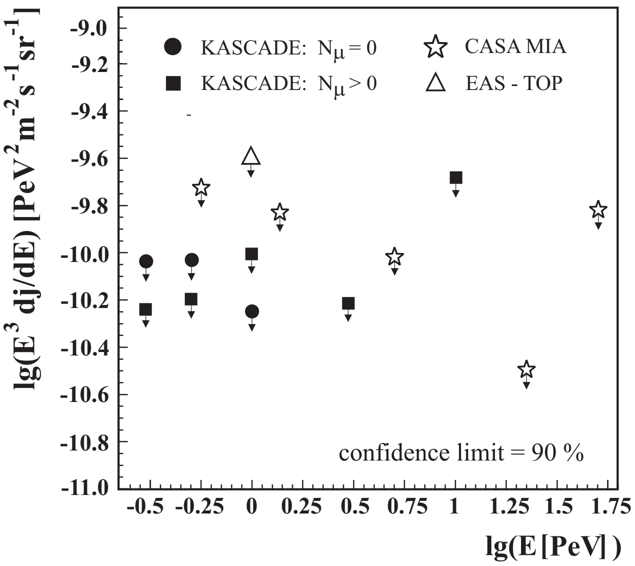

Fig. 4. Comparison of our derived upper limits with previous results by the CASA-MIA (Chantell et al., 1997) and EAS-TOP (Aglietta et al., 1996) experiments. Two limits are given for the KASCADE experiment derived from events with $N_\mu = 0$ and $N_\mu \neq 0$.

the measurements, detector area, solid angle, and detection efficiency are taken into account. The latter is obtained from the number of simulated events surviving all cuts.

Fig. 4 compares our result with those of the CASA-MIA (Chantell et al., 1997) and EAS-TOP (Aglietta et al., 1996) experiments. Since these authors have given their results as the maximum gamma ray fraction of their observed spectrum we have calculated a corresponding gamma flux by multiplying their ratios with the energy spectra reported by the same groups (Glasmacher et al., 1999 and Aglietta et al., 1999, respectively). We prefer this presentation of the results because the determination of the energy spectrum of primary cosmic rays may be subject to systematic uncertainties which stem from hadronic interaction models and whose size is difficult to estimate.

4 Distribution on the sky

As mentioned in the introduction high energy gamma rays are expected to be produced by interactions of charged cosmic ray particles with interstellar matter in the galaxy. (Extragalactic gamma rays are not expected in the energy range of this study due to their absorption by the cosmic microwave background.) Hence their origins should be concentrated near the galactic plane. We have therefore investigated the distribution on the sky of events which appear most 'gamma-like' (i.e. whose distance to the straight line in figs. 1 and 3 is the largest). Fig. 5 displays the distribution of 53 such events in equatorial and galactic coordinates. Obviously there is no enhancement of the intensity with respect to the galac-

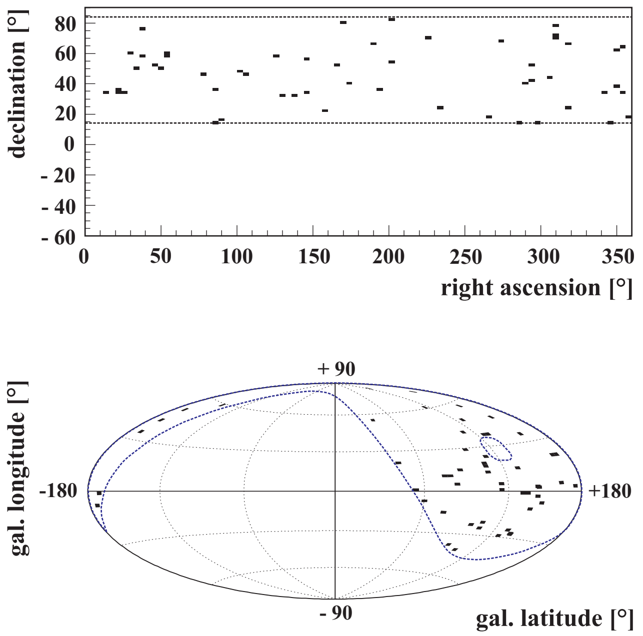

Fig. 5. Distribution of the 53 most 'gamma-like' events on the sky in equatorial and galactic coordinates. The dashed lines indicate the limits of the KASCADE acceptance.

tic plane. This is supported by a Kolmogorov-Smirnov test comparing their distribution to that of all data.

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