PROCEEDINGS OF SCIENCE

Search for gamma-ray point sources with KASCADE

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Extensive air showers with primary energies around 300 TeV were measured with a large detector array of KASCADE. Using all events in the full KASCADE data set, a search of a pointlike sources of high-energy cosmic rays for the northern hemisphere are performed. In addition, a subset of muonless events, i.e., extensive air showers which are more similar to gamma-ray induced showers, are analyzed. The equi-zenith method has been used for the background estimation. No significant excess for pointlike sources has been observed in a region around the Galactic plane. However, an interesting hot point at right ascension 77.75° and declination 70.85° has been observed. In this contribution, the preliminary results including an upper limit for a steady point source are presented.

The 34th International Cosmic Ray Conference,
30 July- 6 August, 2015
The Hague, The Netherlands

PoS(ICRC2015)812

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1. Introduction

Besides the investigation of the all-particle energy spectrum of cosmic rays, in general, measurements of the anisotropy of the primary cosmic rays can yield valuable results for the discussion of models of the origin, acceleration and propagation of cosmic rays.

Since charged cosmic rays are deflected by the galactic magnetic field and photons are absorbed by cosmic microwave background radiation, an almost isotropic distribution of the arrival directions of cosmic rays is expected in the energy region of about 4 PeV. Low energy charged cosmic rays from distant sources cannot be traced back to their origin, whereas at large energies the deflection of the charged particles in galactic magnetic fields decreases substantially, so that particles from sources farther away can keep their directional information. Therefore, small scale anisotropies, i.e. clustering of the arrival directions, could result in the identification of point sources. Several sky surveys for steady gamma-ray sources have been performed by air shower experiments at energies from 100 TeV to 1 PeV. None of the experiments has found any point source. Only the Tibet air shower array [1] and Milagro experiments reported the observation of the known point source Crab Nebula at lower energies.

First sky studies for the gamma-ray sources with about one-third of full KASCADE data have been reported in Ref. [2], generating the expected background by the time-shuffling technique. Therefore, in this contribution, using the full statistics of the KASCADE experiment, the small scale anisotropy, i.e. point source search, is presented. The investigated energy covers from a few 10^{14} eV to nearly 10^{16} eV. For this analysis, the background estimation is based on the equi-zenith angle method. The analysis result agrees inside the statistical limits with an iostropic distribution of the arrival directions of cosmic rays.

2. The KASCADE experiment

The KASCADE experiment [3], located at Karlsruhe Institute of Technology (49.1° north, 8.4° east, 110 m above sea level), was successfully operated for more than 25 years and dismantled by now. It was designed to measure primary cosmic rays in the energy range of about 0.5 to 100 PeV. The KASCADE array consists of 252 scintillator detector stations with unshielded and shielded detectors located on a grid of 200×200 m^2 for the measurement of the electromagnetic and muonic shower ($E_\mu > 230$ MeV) components independently.

The excellent time resolution of these detectors allows reconstructions of the arrival directions of the showers for searching of large scale anisotropies as well as of cosmic ray point sources.

3. Analysis

3.1 Data set

The full data taken by KASCADE were carefully checked by a comprehensive moon shadow analysis. Selected data sets from 1998 May to 2010 May are used for the present analysis. The zenith angle is shown to be smaller than 40° for full efficiency. The angular resolution of KASCADE is better than 0.8°, so that it allows us to search for gamma-ray point sources with KASCADE data. The core position of showers has to lay inside a circular area of 91 m radius around the center of the array to omit large reconstruction uncertainties at the edges of the detector field. After the selection, in total, ca. 3×10^8 events were obtained for a data-taking of 3817.7 days.

3.2 Gamma discrimination

Since the deflection of the charged particles of cosmic rays is expected due to galactic magnetic fields, point sources can be seen only by neutral particles, i.e. high-energy photons or neutrons. The sensitivity to γ-ray induced showers can be enhanced by the suppression of hadron-induced showers. This suppression is done by using the ratio of the number of muons to the number of electrons in a shower.

Figure 1 shows the distribution of electron ($\lg N_e$) and the truncated muon number ($\lg N_{\mu,tr}$) for measured showers, where $N_{\mu,tr}$ is the number of muons in the distance range of 40 to 200 m from the shower core. The electron number is corrected for a zenith angle of 18° by using an attenuation length of Λ_{N_e} = 175 g/cm^2. The shower size distribution for simulations of gamma-ray induced showers is also superimposed. The showers are simulated in the energy range of 3×10^{13} to 5×10^{15} eV with a power law with a spectral index of -2.

This size distribution of γ-ray induced showers is a motivation for the following cuts to suppress hadron-induced showers: $\lg N_{\mu,tr} < 2.4$ for $\lg N_e < 4.5$ and $\lg N_{\mu,tr} < \lg N_e - 2.1$ for $\lg N_e > 4.5$. The selection of muon-poor showers is indicated by the green line in Fig. 1. In addition, showers with no registered muons are plotted as $\lg N_{\mu,tr}$ = 1.5, thus the selection of muonless showers is indicated by straight line as $\lg N_{\mu,tr} < 2$ in Fig. 1.

The number of events in each energy bin for the whole data and for a subset of the muonless events are shown in Fig. 2. The number of the whole data set is shown as a blue histogram and the number of muonless events, i.e. extensive air showers with no detected muons, is shown as a red histogram. These muonless events are assumed to stem from gamma-ray induced showers only, and used for the further analysis of point source. All results will be presented here for the whole data set, as well as for the data set consisting of muonless showers only.

3.3 Background estimation

The search for pointlike sources is performed by comparing the measured distributions of the arrival direction in equatorial coordinates with an isotropic background distribution. The short distance equi-zenith angle method [1] has been used for the background estimation in this analysis.

Since we are not able to distinguish the gamma-ray induced shower events from the cosmic-ray background shower events, we count the number of events in an “on-source window” centered at a candidate point source direction with a size of angular resolution. The number of background events must be estimated from the observational data recorded in side bands, which is usually referred as “off-source window”.

If the off-source window are chosen to be close enough in distance to the on-source window, the large-scale anisotropy of the cosmic-ray intensity can be approximated to be neglected, since the cosmic-ray intensity changes only slowly in the sky. Thus the sky is divided into 0.1° by 0.1° cells, from 0 to 360° in right ascension and from 20 to 80° in declination. We denote the number of events in on-source window as N_{on}, and the number of events in the ith off-source window as N_{off_i}, Assuming the uniform azimuth angle distribution, the number of background events can be

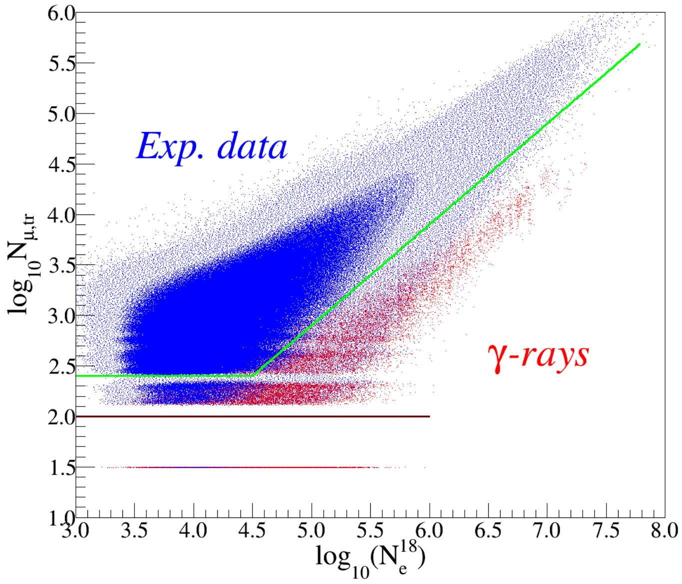

Figure 1: Scatter histogram of the measured number of muons $\lg(N_\mu)$ and number of electrons $\lg(N_e)$ (blue) superimposed with simulated gamma-ray showers (red). The green line indicates the choice of the cut for the selection of the muon-poor showers.

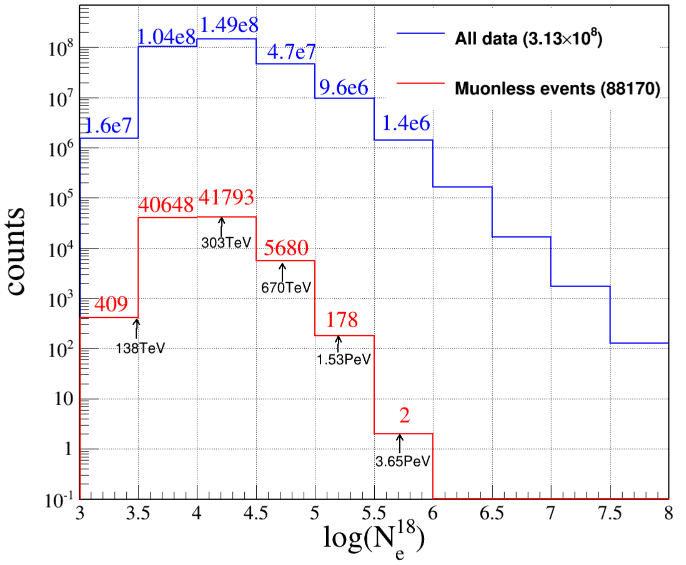

Figure 2: Number of events in each energy bin for the whole data (blue) and for the data sample of the muonless events (red), respectively. The energies of gamma-ray induced showers are denoted as well.

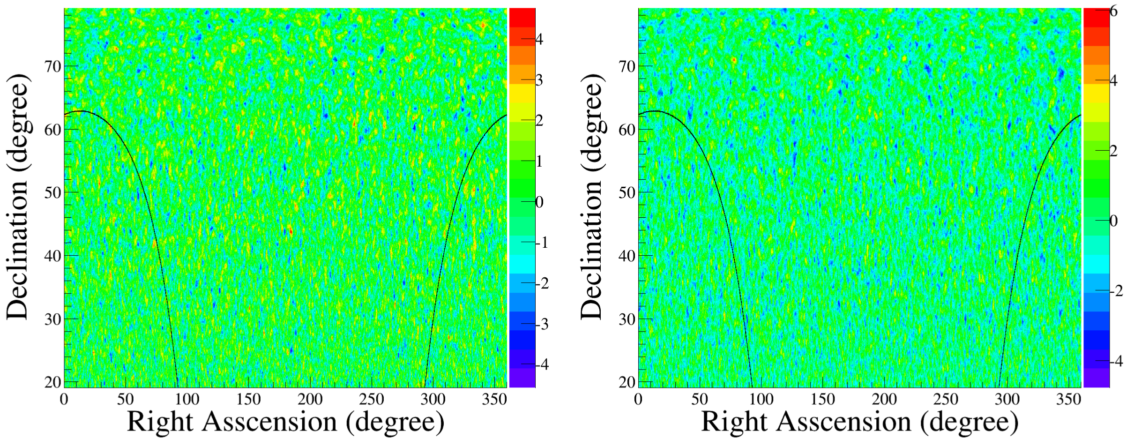

Figure 3: Significance distributions in equatorial coordinates for the whole data (left) and for the data sample of muonless showers (right). The Galactic plane is indicated by the lines.

estimated as:

$$N_{BG} = \frac{\Sigma_{i=1}^{10} N_{off_i}}{10}. \tag{3.1}$$

The data with a zenith angle less than 4.2° were not used, since the 10 off-source windows as defined in Eq. (3.1) become to be overlapped, if the zenith angle is smaller than 4.2°.

However, the distribution of the azimuth angle is not completely uniform, i.e. the calculated number of events from off-source window, N_{BG}, from Eq. (3.1) cannot describe the background number in the on-source window exactly. Thus we corrected N_{BG} with a correction factor, taking into account the non-uniform azimuth angle distribution.

4. Results

The significance for the deviation from the expected background is calculated by the widely used Li-Ma method [5], where the expected background is estimated by the equi-zenith angle method.

The sky map of significance distributions in equatorial coordinates for the all data and for the data sample of muonless showers, respectively, are shown in Fig. 3. The significance values are mostly between -1 and 1, and the largest values are around $|\sigma|$ = 5. The distributions of the significance values derived from the sky maps are shown in Fig. 4 for the whole data set and for the subset of muonless showers. For no pointlike sources, the distribution of significance values shows a consistency of a Gaussian distribution with a mean value $\mu = 0$ and width $\sigma = 1$. On the other hand, in case of the possible candidates for pointlike sources, the occurrence of large significance values or some deviations from isotropy would be expected in the significance distributions.

Whereas the overall distribution is in a good agreement with isotropy in Fig. 3, points with unexpectedly large significance with 5.5 σ has been observed at an area around right ascension 77.75°, declination 70.85°. Nearly all cells with exceeding 5 σ in Fig. 4 (right) are coming from

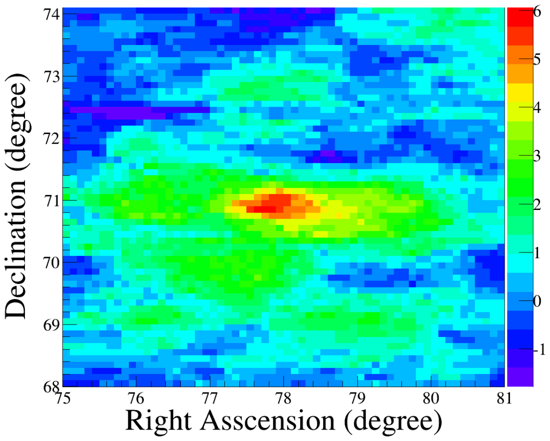

Figure 4: Zoom to the significant region above 5 σ in equatorial coordinates.

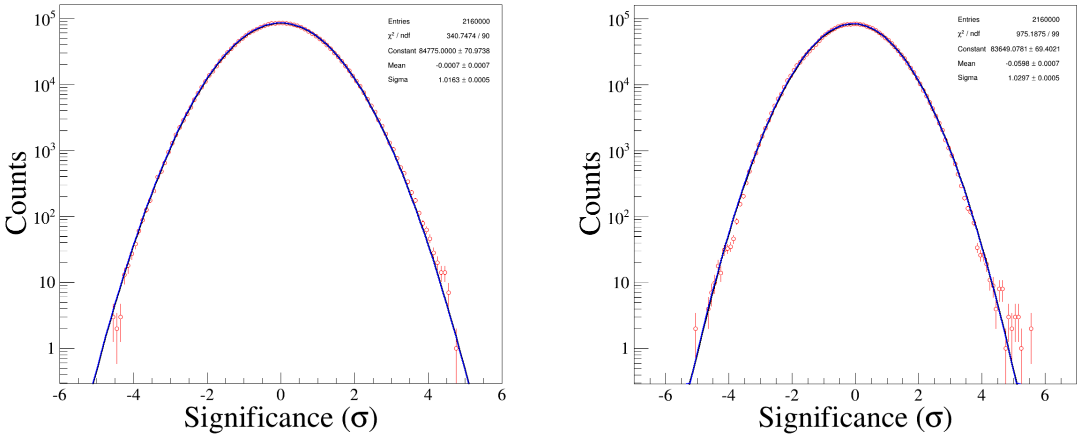

Figure 5: Distributions of the significance values from the sky maps for the whole data sets (left) and for the subset of muonless showers (right). The significance values for both cases are calculated by Li-Ma method. The lines show a Gaussian with mean value $\mu = 0$ and width $\sigma = 1$.

this region. Figure 5 shows a zoom of the large significant region. But, the most probable candidates for TeV gamma-ray point sources are expected to be of Galactic origin, which is shown as a line in Fig. 3. In the region of the observed source candidate, however, there is no indication for currently known TeV gamma-ray sources.

Except the significant point discussed above, no unexpectedly large significance values are visible in the subset of muonless showers, as well as in the whole data set. Therefore, the upper limit (90% confidence level) of events above background in the source regions is determined by the method of Helene [6]. With the measured primary energy spectrum of KASCADE [7], the 90% upper flux limit for pointlike sources is determined for the present data set to about 10^{-10} m^{-2} s^{-1} at an energy of about 300 TeV.

5. Conclusion

A search for TeV gamma-ray pointlike sources, i.e. small scale anisotropies, in a data set measured with the KASCADE experiment from 1998 to 2010 has been performed. The whole data set and a subset of muonless events, i.e. extensive air showers, which are mainly gamma-ray induced showers, are analyzed. The significance of the deviation from the expected background is calculated by the method of Li-Ma, where the expected background is estimated by the equi-zenith angle method. As a result, one significant candidate for gamma-ray signals above 5σ has been found at (77.75°, 70.85°). Assuming this hot spot to be a statistical fluctuation, an upper limit for the detection of pointlike sources are determined to be around 10^{-10} m^{-2} s^{-1} at the energy of about 300 TeV.

Acknowledgments

The authors would like to thank the members of the engineering and technical staff of the KASCADE-Grande collaboration, who contributed to the success of the experiment. The KASCADE-Grande experiment is supported in Germany by the BMBF and by the 'Helmholtz Alliance for Astroparticle Physics - HAP' funded by the Initiative and Networking Fund of the Helmholtz Association, by the MIUR and INAF of Italy, the Polish Ministry of Science and Higher Education, and the Romanian Authority for Scientific Research UEFISCDI (PNII-IDEI grants 271/2011 and 17/2011). J.C.A.V. acknowledges the partial support of CONACyT.

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