Search for point sources at energy $E > 5 \times 10^{18}$ eV with the Pierre Auger Observatory

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Introduction

Cosmic rays above few 10^{18} eV are believed to be of extragalactic origin and pose some of the most intriguing questions of the contemporaneous research in astrophysics; their composition, acceleration and production mechanisms are still unclear [1].
One of the crucial points in the search for the origin of cosmic rays is to identify and locate their sources. At the highest energies, above the threshold corresponding to the observed flux suppression [2], due to the rigidity of these particles, one expects anisotropy in the arrival directions of cosmic rays for nearby sources. At lower energies, around 1 EeV (1 EeV = 10^{18} eV), the cosmic ray trajectories are bent and isotropized by the galactic magnetic field and the flux is expected to become more isotropic; anyway we can still expect some intermediate scale clustering and correlation with the sources distribution.
At energies above 10^{18} eV, a point-like signal should appear if there is a neutral component of cosmic rays. If the observed TeV gamma radiation is produced through the photo-meson interaction with ambient photon fields, a flux of 10^{18} eV neutrons is expected because they are produced more efficiently than gamma rays by energetic protons. The decay length of neutrons of energy 10^{18} eV is roughly 8.5 kpc approximately equal to the distance between us and the Galactic Center. On the other hand, neutrons below 10^{18} eV decay before reaching the Earth.
A search for point source has been conducted with the data of the Pierre Auger Observatory. The search of excesses of events from point-like regions is common to both the Cosmic Ray and Gamma Ray astronomy fields so many technique used in the γ-astronomy are used in the cosmic rays field.

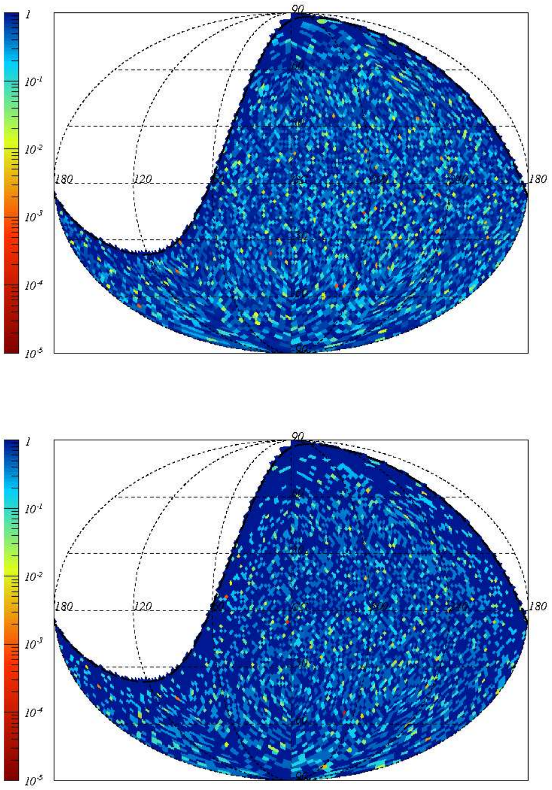

Figure 1. Poisson probability maps in galactic coordinates selecting events with $E > 5$ EeV (on the top) and with $E > 10$ EeV (on the bottom). In each direction of the sky there is the probability (scale on the left) to obtain an equal or larger number of events from the expected background.

Point Source Search

Two maps of the sky are constructed: a signal map (which comprises the actual numbers of events N_{on} coming from each bin of the sky) and a background map (which estimated the expected number of events from each direction of the sky). Usually the background is estimated with the shuffling technique [6] using the arrival times and the local coordinates of the data. An anisotropy on the sky modifies the arrival times distribution so that part of this actual anisotropy will be absorbed because included in the coverage map. This problem ca be solved with the following method: an isotropic distribution of events can be constructed in the sky considering the effective operation time (on-time) and the full efficiency of the detector above about 3 EeV. This distribution is used to calculate the probability $f(l, b)$ that an event comes from different angular element of the sky corresponding to the galactic coordinates (l, b). Then the background is given by $N_{off}\ (l, b)\ = f(l, b) \times N$, where N is the total number of real events for the considered energy threshold.

The significance of the excess is calculated using two specific techniques dealing with low statistic data: the first method is based on the Poisson probability while the second one on the Feldman-Cousins approach.

Poisson Method

The measured and the expected number of events in each region of the sky are assumed to follow a Poisson distribution. Then the significance can be calculated using simple Poisson probabilities that k or more events in one region are due to a fluctuation of the expected background is given by, $P = \sum_{k=N_{on}}^{\infty} e^{-b} b^k/k!$, where $b = N_{off}$. In Figure 1 there are the poisson maps for the events with $E > 5$ EeV (on the top) and for events with $E > 10$ EeV (on the bottom), there are no bins with a particular lower poisson probabilities.

Feldman-Cousins Method

The second proposed method uses the Feldman Cousins limits [3] to check the presence of a source. This approach has been developed in the framework of experiments that deal with notoriously weak or non-existing signals. Given the expected number of events in each direction of the sky an interval in the space of the measured value is constructed and then a confidence interval which contains the observed number of events with a probability α, the confidence interval is obtained using the Feldman-Cousin approach. If there is a region of the sky with a positive value of the lower limit one can claim an expected signal in that direction of sky at a given confidence level α. In Figure 2 there are the lower limit maps at 99% of confidence level. The colored filled bins in Figure 2 are the only bin in the sky where there are the lower limits at 99% of confidence level, on the z-axis there is the value of the lower limit. Increasing the confidence level at 4σ we do not find any lower limit and so any evidence of expected signal for events with $E > 5$ EeV and for $E > 10$ EeV.

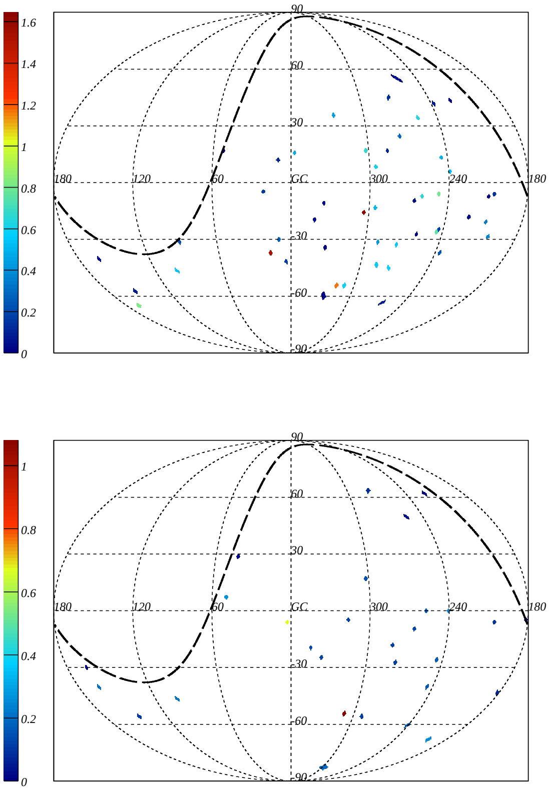

Figure 2. Lower Limit maps in galactic coordinates at 99% of confidence level for 5 EeV (on the top) and 10 EeV (on the bottom). Only the bins where there are the lower limits are shown. The lower limit gives the expected number of events at 99% of confidence level over the background.

Flux Upper Limit Maps

In the Auger sky any significant excess has been found respect to an isotropic distribution of cosmic rays then an upper limit map as a function of celestial coordinates is calculated. To estimate the flux upper limit map an accurated estimation of the detector acceptance is required.

Acceptance Map

To calculate the acceptance as a function of the celestial coordinates one can proceed in a similar way to the method used to calculate the background map. It is important to remark that from the beginning of the data taking the detector, due to the maintenance activity or partial malfunctioning, fraction of the apparatus can be switch off for short period of time.

To take into account the detector instability the period of data analyzed is divided in time slots of one minute, for each time slot the detector configuration of that minute and therefore the acceptance (AT) are considered. Than 100 events are simulated uniformly distributed in the sky assuming an isotropic distribution. Because for $E > 5$ EeV the detector is fully efficient we do not need to take into account this efficiency. This procedure is equivalent to simulated an isotropic flux I of cosmic rays equal to $I = 100/AT$ (particles / km^2 sr minute). The sky map obtained for this time slot with this method $\rho(l, b)$ represents a possible isotropic sky as could be seen by the Pierre Auger Observatory in that minute if the cosmic rays flux had been I. Dividing $\rho(l, b)$ by the simulated flux I the acceptance map $\mathrm{AT}(l, b)$ can be obtained as $AT(l, b) = \frac{\rho(l,b)}{I}$, where l and b are the galactic coordinates. Repeating the same operation for each minute time slot and sum all the acceptance sky maps the acceptance sky map is obtained for the whole period.

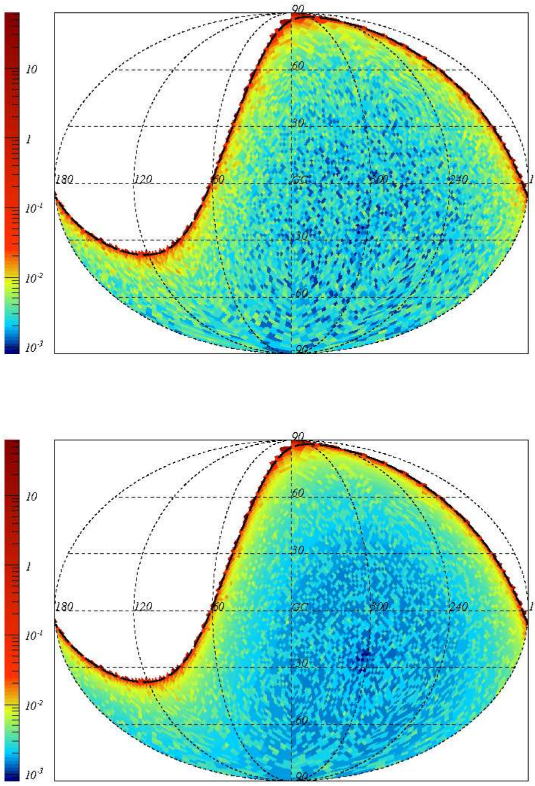

Figure 3. Upper Limit fluxes maps in particles/(km^2 yr) in galactic coordinates at 99% of confidence level for 5 EeV (on the top) and 10 EeV (on the bottom).

Upper Limit Flux calculation

Now the upper limits on cosmic ray fluxes in each direction of the sky can be calculated. The upper limit at the 99% of confidence level is given by $\Psi(99\mathrm{CL}\ \%) = UL(99\mathrm{CL}\ \%)/\mathrm{AT}$, where the numerator is the upper limit calculated from the number of measured events and the number of expected background events in the sky bin and the denominator is the acceptance of the detector, which is the area of the apparatus seen by the source during its running time. To evaluate the upper limits (UL) we use the Feldman and Cousin approach [3]. In Figure 3 there are the flux upper limit maps selecting events with $E > 5$ EeV (on the top) and with $E > 10$ EeV (on the bottom).

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