Anisotropy studies around the galactic center
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We present the first results for anisotropy searches around the galactic center at EeV energies using data from the Pierre Auger Observatory. Our analysis, based on a substantially larger data set, do not support previous claim of anisotropy found in this region by the AGASA and Sugar experiment. Furthermore we place un upper limit on a possible point like source located at the galactic center which exclude several scenarios predicting neutron sources in this location.

1. Introduction

The Galactic Centre (GC) is an attractive target for the studies of cosmic ray (CR) anisotropy at EeV energies. The GC contains objects that might be candidates for powerful CR accelerators, and the recent high significance observation by H.E.S.S. of a TeV \( \gamma \) ray source near the location of Sagittarius A* [1], together with the discovery of extended emission from giant molecular clouds in the central 200 pc of the Milky Way [2], motivates the search for excesses in this direction. The GC passes only 6° from the zenith at the site of the Pierre Auger Observatory in the southern hemisphere and makes it particularly suitable for anisotropy studies in this region. The number of CRs of EeV energies accumulated so far at the Pierre Auger Observatory from this part of the sky greatly exceeds that from previous observations. We adopt hereafter for the GC co-ordinates the Sagittarius A* J2000.0 coordinates, \((\alpha, \delta) = (266.3^\circ, -29.0^\circ)\).

There have also been reports by the AGASA experiment [3,4] indicating a 4.5\( \sigma \) excess of cosmic rays in the energy range \(10^{18} - 10^{18.4} \) eV and by the Sugar experiment [5]. Note that the GC itself lies outside the AGASA field of view (\(\delta > -24.2^\circ\)).

We also searched for a point-like excess from the GC, as EeV neutrons emitted by one of the possible energetic sources in the centre of the Galaxy may reach the Earth before decaying.

After a brief description of the Auger detector we discuss the angular resolution of our surface array and the sky coverage estimation. We follow with a presentation of the data set used in this analysis and with the results concerning the AGASA and SUGAR claims as well as an upper limit on a neutron source located at the centre of our galaxy.

2. The Auger detector. The hybrid design

A fundamental characteristics of the Pierre Auger Observatory [6] is its capability of hybrid reconstruction of cosmic ray showers [7]. Two independent detectors, the Surface Detector (SD), which samples the shower particles at ground, and the Fluorescence Detector (FD), which collects the fluorescence light emitted by the shower particles along their path in the atmosphere, are able to measure the energy and direction of the same cosmic ray shower. The enhanced capabilities of the Auger hybrid detector are examined in this paper.

The Pierre Auger Observatory was designed to observe, in coincidence, the shower particles at ground and the associated fluorescence light generated in the atmosphere. This is achieved with a large array of water Cherenkov detectors coupled with air-fluorescence detectors that overlook the surface array. It is not simply a dual experiment. Apart from important cross-checks and

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measurement redundancy, the two techniques see air showers in complementary ways. A single air shower is detected 3-dimensionally. The ground array measures the 2-dimensional lateral structure of the shower at ground level, with some ability to separate the electromagnetic and muon components. The fluorescence detector records the longitudinal profile of the shower during its development through the atmosphere.

A hybrid event is an air shower that is simultaneously detected by the fluorescence detector and the ground array. The Observatory was originally designed and is currently being built with a cross-triggering capability. Data are recovered from both detectors whenever either system is triggered. If an air shower independently triggers both detectors the event is tagged accordingly. There are also cases where the fluorescence detector, having a lower energy threshold, promotes a sub-threshold array trigger. Surface stations are then matched by timing and location. This is an important capability because these sub-threshold hybrid events would not have triggered the array otherwise. The geometrical reconstruction of the air shower’s axis is accomplished by minimizing a \( \chi^2 \) function involving data from all triggered elements in the eye and on the ground. The reconstruction accuracy is far better than the ground array counters and the single eye could achieve independently [9].

The combination of the air fluorescence measurement and the particle detection on the ground provides an absolute energy calibration.

3. Surface Array Angular Resolution

The angular resolution for the SD is determined, on an event by event basis, from the zenith (\( \theta \)) and azimuth (\( \phi \)) uncertainties obtained from the geometrical reconstruction, using the relation:

\[
F(\eta) = 1/2 \left( V[\theta] + \sin^2(\theta) \right) V[\phi]
\]

where \( \eta \) is the space-angle, and \( V[\theta] \) and \( V[\phi] \) are the variance of \( \theta \) and \( \phi \) respectively. If \( \theta \) and \( \phi/\sin(\theta) \) have Gaussian distribution with variance \( \sigma^2 \), then \( F(\eta) = \sigma^2 \) and \( \eta \) has a distribution proportional to \( e^{-\eta^2/2\sigma^2} \) \( d(\cos(\eta))d\phi \). Then, if we define the angular resolution \( (AR) \) as the angular radius that would contain 68\% of showers coming from a point source, \( AR = 1.5 \sqrt{F(\eta)} \).

The angular resolution depends strongly on the timing resolution of the water Cherenkov detectors (WCDs) and weakly on the shower front model and the core position uncertainty. The WCDs timing uncertainty is directly modeled from the data (section 3.1). This model is based on the physics of the shower and the measurement process. It can be adjusted using two pairs of adjacent stations located in the surface array (section 3.2). The model is validated by studying the \( \chi^2 \) probability distribution for the geometrical reconstruction (section 3.3). The angular resolution is estimated for the SD-only reconstruction and by comparison with the hybrid data (section 3.4).

3.1. The Time Variance Model

The angular accuracy of the SD events is driven by the accuracy with which one can measure the arrival time \( (T_0) \) of the shower front in each station. The particle arrival time in the shower front can be described as a Poisson process over some interval time \( T \). The first particle arrival time is used as the estimator for the shower front arrival.

It is given by \( T_0 = T_s + t_1 \), where \( T_s \) is the shower front time and \( t_1 \) is taken to follow an exponential distribution function with decay parameter \( \tau \).

Since we estimate the parameter \( T \) from the data itself, the variance of \( T_1 \) (given by the variance of \( t_1 \)) is:

\[
V[T_1] = \left( \frac{T}{n} \right)^2 \frac{n - 1}{n + 1}
\]

The variance of the arrival of the first particle in the SD stations, taking into consideration the GPS uncertainty and the resolution of the flash analog-to-digital converters (FADC), can then be written as:

\[
V[T_1] = a^2 \left( \frac{2 T_{50}}{n} \right)^2 \frac{n - 1}{n + 1} + b^2
\]

where \( T_{50} \) is the time interval that contains the first 50\% of the total signal as measured by the

\(^2\)In fact, an unbiased estimator should be \( T_0 = T_1 - E[t_1] \), where \( E[t_1] \) is the expectation value.
photomultiplier FADC traces. The two free parameters $a$ and $b$ can be determined with the adjacent station data. We expect that the parameter $a$ should be close to 1, while $b$ should be given by the GPS clock accuracy (about 10 ns) and the FADC trace resolution $25/\sqrt{12}$ ns, that is $b \approx 12$ ns.

To calculate the number of particles ($n$) we assume that all particles hit the detector with the same direction than the shower axis, and that the muons are mostly the ones that contribute to the time measurements. Then, we obtain $n$ as the ratio between the total signal ($S$) in the WCD and the average track length, $TL(\theta)$, of the particles.

The average track length can be computed as the ratio of the detector volume ($V$) and the area ($A$) subtended by the arriving particles, and is:

$$TL(\theta) = \frac{V}{A} = \frac{\pi r^2 h}{\pi r^2 \cos(\theta) + 2rh \sin(\theta)}$$

where $\theta$ is the zenith angle, $r = 1.8$ m is the detector radius, and $h = 1.2$ m is the detector height.

### 3.2. Testing the model with doublets

Two pairs of adjacent surface detector stations separated by 11 m (“doublets”) have been installed in the field of the Auger Observatory. These pairs enable comparison of timing and signal accuracy measurements. We used the data of the doublets to verify the time variance model and also to adjust the constants $a$ and $b$ from it. For each event we computed the time difference as $\Delta T = dT^{(1)} - dT^{(2)}$ where $dT^{(1)}$ ($dT^{(2)}$) is the time difference from the first (second) detector of the doublet to the fitted shower front. Doing that, $\Delta T$ does not depend on the shower front shape, since the twin detectors are very close to each other. We used 1693 events (from April/2004 to June/2006) to fit for the two parameters $a$ and $b$, and we obtained:

$$a^2 = 0.98 \pm 0.05$$
$$b^2 = 150 \text{ ns}^2 \pm 18 \text{ ns}^2$$

which is in good agreement with our expectations ($a^2 = 1$, $b^2 = 144 \text{ ns}^2$).

### 3.3. Validation of the Time Variance Model

If the time variance model describes correctly the measurement uncertainties, the distribution of $\Delta T/\sqrt{V[\Delta T]}$, as a function of the shower zenith angle (top), the average signal in the doublet detectors (middle), and the distance to the shower core (bottom).

In figure 1 we plot the $\chi^2$ probability distribution from our geometrical reconstruction procedure using as timing errors the model above. We only plot probabilities larger than 1% to avoid the large peak at zero corresponding to badly reconstructed events ($\sim 9\%$). These distribution are almost flat indicating that our error model is correct.

### 3.4. Surface Detector Only

Given the correctness of our error model, we can extract the angular resolution on an event
by event basis directly out of the minimization procedure.

The angular resolution is about $2.7^\circ$ in the worst case of vertical showers with only 3 stations hit. This value improves significantly for 4 and 5 stations\textsuperscript{3}. For 6 or more stations, which corresponds to events with energies above 10 EeV, the angular resolution is in all cases better than $1^\circ$.

All quoted errors are statistical only. We did not, at this stage, investigate possible biases or systematics in the determination of the arrival direction angles.

3.5. Comparison with Hybrid events

Finally, in figure 3 we show the space angle between the SD-only and hybrid geometrical reconstructions for showers with different number of stations and different zenith angle ranges. The distributions plotted were fitted with a Gaussian resolution function $dp \propto e^{-\eta^2/2\sigma^2} d(cos(\eta))d\phi$, where $\eta$ is the space-angle. The $\sigma$ obtained in the fit is related to the angular resolution by $RA = 1.5 \sigma$.

The parameter $\eta$ given by the fit is in good agreement with the value from figure 3 using an hybrid resolution parameter $\eta$ of $0.5 - 0.6^\circ$.

The angular resolution of the surface detector is then found to be better than $2.7^\circ$ for 3-fold events, better than $1.7^\circ$ for 4-fold and 5-fold events and better than $1.0^\circ$ for higher multiplicity (which corresponds to energies larger than 10 EeV).

4. Coverage

To study anisotropy, one needs the background expectations for the different sky directions under the assumption of an isotropic CR distribution. Modulations of the exposure in right ascension are induced by the dead time of the detectors and by the constantly growing array size. So those experimental issues (that are carefully recorded by

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\textsuperscript{3}4 and 5 stations events have the same number of degrees of freedom in the geometrical fit, hence similar resolution.
Figure 4. Comparison between hybrid and SD-only geometrical reconstructions. Top, for 3 stations with two zenith angle ranges ($0^\circ < \theta < 30^\circ$ and $30^\circ < \theta < 50^\circ$). Middle 4 stations (left) and 5 stations (right) with $30^\circ < \theta < 50^\circ$. Bottom, for 6 stations or more with two zenith angle ranges ($30^\circ < \theta < 50^\circ$ and $50^\circ < \theta < 50^\circ$).

The Auger data acquisition system (which gives a measure of the aperture for events satisfying the quality trigger criterion) as a function of time, assuming a uniform response in azimuth. Through this procedure one obtains an exposure which accounts for the non-saturated acceptance effects and for the non-uniform running times and array growth.

- **The shuffling technique:** Here the expected number of events in any direction is obtained by averaging many data sets obtained by shuffling the observed events in the energy range of interest so that the arrival times are exchanged among them and the azimuths are drawn uniformly. The shuffling can be performed in separate zenith angle bins or by just mixing them all, and we found no significant difference between these two possibilities. By construction, this exposure preserves exactly the $\theta$ distribution of the events and accounts for the detector dead times, array growth and even for weather-induced modulations. It might however partially absorb modulations induced by large scale intrinsic anisotropy present in the CR flux, such as those due to a global dipole.

The background estimate obtained with the two technique differ by less than 1% in the GC region. It is 0.5% larger with shuffling than the semi-analytic method. This difference is much smaller than the size of the excesses we are testing and also below the Poisson fluctuations. In the following we mainly quote the values obtained using the semi-analytic technique.

### 5. Data set

The Auger surface detector [6], has been growing in size during the data taking period considered in this work. 154 detectors deployed in January 2004 and 930 in March 30th 2006.

The basic cell of surface detectors is triangular, with separations of 1.5 km between detector units, and hence the complete array with 1600 detectors will cover an area of 3000 km$^2$.

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4 A detailed account of weather effects is certainly necessary to test large scale patterns at the few percent level. Relevant studies are in progress.
We consider the events from the surface detector (SD) array with three or more tanks triggered in a compact configuration. The events have to satisfy the level 5 quality trigger condition, which requires that the detector with the highest signal be surrounded by a hexagon of working detectors, since this ensures that the event is well reconstructed. We also restrict the events to zenith angles $\theta < 60^\circ$.

The energies are obtained using the inferred signal size at 1000 m from the reconstructed shower core, $S(1000)$, adopting a conversion that leads to a constant flux in different sky directions above 3 EeV, where the acceptance is saturated. This is the so-called Constant Intensity Cut criterion implemented in [12]. A calibration of the energies is performed using clean fluorescence data. The estimated systematic uncertainty in the reconstructed shower energy with the fluorescence technique is currently 25% [13].

From the uncertainty in the measurements of the signals from the Cherenkov tanks [15] the statistical uncertainty in the energy determination which results from the fitting procedure is about 20% for the energy range considered in this work, i.e. $10^{17.9} \, \mathrm{eV} < E < 10^{18.5} \, \mathrm{eV}$. Notice that in this energy range 48% of the events involve just three tanks, 34% involve 4 tanks and only 18% more than 4 tanks. For three tank events the 68% quantile angular resolution is about $2.2^\circ$ and the resolution improves for events with 4 tanks or more [9].

Regarding the hybrid events, i.e. those with signal from both the fluorescence detectors (FD) and surface array, the angular resolution achieved is much smaller, typically below 1 degree [9]. Also, given that hybrid events may trigger with just one surface detector, the associated energy threshold ($\sim 10^{17} \, \mathrm{eV}$) is lower, and events up to zenith angles of $75^\circ$ are included in the data set. However, the statistics accumulated are significantly less, in part due to the $\sim 15\%$ duty cycle of the fluorescence telescopes and also because at EeV energies the FD is not fully efficient at detecting showers over the full SD array.

There are for instance 79265 SD events in the data set considered with energies $10^{17.9} \, \mathrm{eV} < E < 10^{18.5} \, \mathrm{eV}$, while the corresponding number of well reconstructed hybrid events in the same energy range is just 3439. Note that $\sim 25\%$ of the hybrid events in this energy range involve less than three surface detectors, and are hence not included in the SD only data set.

6. Results

All results presented in this section are part of a dedicated publication [17].

7. AGASA and SUGAR excesses

The map of overdensities around the GC region is shown on Figure 5. Significances in this map are calculated in circular windows of $5.5^\circ$ using a Gaussian approximation to the Poisson law (counts in the $5.5^\circ$ windows are well above 100) The angular scale chosen and the energy range shown ($10^{17.9} – 10^{18.5} \, \mathrm{eV}$) mimics the Sugar search window and is also convenient to visualize the distribution of overdensities in the window explored by AGASA. The galactic plane is shown as a solid line (a cross for the GC) The big circle region in which AGASA reported an excess (in a slightly narrower energy range). The dashed line indicates the lower boundary of their observations.

Overdensities present in this map are consistent with the expectation from statistical fluctuations of an isotropic sky. On Figure 6 we show the distribution of these overdensities together with the expectations from an isotropic flux and no significant departure from isotropy is observed.

In the 20$^\circ$ circle centered at the AGASA location and for energies between $10^{18} \, \mathrm{eV} < E < 10^{18.4} \, \mathrm{eV}$, we counted 2116 events while while 2169.7 are expected using the shuffling technique ( 2159.6 using the semi-analytic) No significant excess is observed.

There may be systematic differences in the energy calibration of the two experiments. To test if these differences could possibly mask the AGASA excess, we calculated the observed and expected rates for different energy ranges in offsets of 0.1 decade keeping $E_{\text{max}}/E_{\text{min}}$ fixed. We have also added a systematic error of 1% to the expected rates to account for possible weather induced modulations. We found no significant excesses...
in the AGASA region for any of these cases. In particular, at the $2\sigma$ level (95% CL) the excess in this region is always less than 6%, well below the 22% excess reported by AGASA.

The acceptance of Auger in this energy range is not yet saturated. It is larger for heavy nuclei than for protons because showers initiated by heavier primaries develop earlier and are hence more spread out at ground level. Using ref. [19] for the acceptance of p and Fe primaries, we find that the sensitivity to protons is about $\sim 30\%$ smaller than to Fe in the energy range studied (assuming an $E^{-3}$ spectrum). If the 22% excess reported by AGASA (which had full efficiency at EeV energies) was due to nucleons while the background was due to heavy nuclei, at least a 15% excess should have been expected in Auger data. This is much larger than the upper limit we are obtaining.

For the excess reported by the SUGAR experiment, we find in the same angular window and energy range that $n_{\text{obs}}/n_{\text{exp}} = 286/289.7 = 0.98 \pm 0.06$, and hence with 10 times the statistics we found no significant excess in this window.

8. Neutron source at the GC

8.1. Surface detector

The energy range for this search is between $E_{\text{min}} = 10^{17.9}$ eV and $E_{\text{max}} = 10^{18.5}$ eV. Below $E_{\text{min}}$ the Auger SD acceptance is suppressed
Figure 6. Histogram of overdensities on 5.5° radius windows and for $10^{17.9}$ eV $< E < 10^{18.5}$ eV, together with the average isotropic expectations (gaussian of unit width and zero mean). The histogram is built over the same sky patch as figure 6 ($-65° < dec < 5°$ and $160° < RA < 360°$).

and most neutrons from a source at the GC would have decayed before reaching the Earth. Energies above $E_{\text{max}}$ are assumed to be hard to achieve for galactic sources.

The optimal search window for a point-like source is obtained using a Gaussian filter matching the angular resolution of the experiment [20]. Following section 3 we used a 68% quantile $\sigma$ of 2.25° for the average resolution of the events in this energy range (in fact more than 80% of the events have a better resolution than this).

In the direction of Sagittarius A* we get $n_{\text{obs}}/n_{\text{exp}} = 53.8/45.8$ (a ratio of 1.17 ± 0.10). Applying the results of [20], we get a 95% CL upper bound on the number of events from the source of $n^s = 18.5$.

Assuming :

- that the source spectrum shape is similar to that of the bulk CRs, ($\propto E^{-3}$ in this energy range),

we have [20]:

$$4\pi\eta^2 \frac{\Phi_{CR}}{n_{\text{exp}}} = \frac{\Phi^s}{n^s}$$

(5)

Where $\Phi_{CR}$ and $\Phi^s$ are the bulk CR flux and the source 95% flux upper limit integrated in the energy range under study and where $n_{\text{exp}}$ and $n^s$ are as above. $\eta$ is the parameter of the optimal Gaussian window that corresponds to our angular resolution 5 (here $\eta = 2.25/1.5 = 1.5°$)

For the differential CR spectrum flux we take

$$\Phi_{CR}(E) \simeq \xi 30 \left(\frac{E}{\text{EeV}}\right)^{-3} \text{EeV}^{-1}\text{km}^{-2}\text{yr}^{-1}\text{sr}^{-1},$$

(6)

which has an $E^{-3}$ dependence. The factor $\xi$ is close to unity and parametrizes the uncertainties in the CR flux normalization, so that the flux bounds will be simply proportional to $\xi$.

From eq. 5 we get a 95% CL upper bound for the source flux integrated over the energy range considered of :

$$\Phi^s = \xi 0.08 \text{ km}^{-2} \text{ yr}^{-1}.$$  

(7)

If the bulk of the CRs were heavy nuclei the upper limit to the flux from the source need to be scaled by a factor $\sim 1.3$ under the assumption that the CRs are iron nuclei and that the source is of neutrons. We thus see that the bound on the neutron flux could be up to $\sim 30\%$ higher if the CR composition at EeV energies were heavy.

Theoretical predictions for neutron fluxes (only those associated with the AGASA claim) are based on the AGASA normalization. This normalization is about a factor of 3 larger than the Auger one so these predictions must be reduced by this factor to be compared with our flux bound. The predictions of refs. [21], [22] and [23], which exceed the upper-bound obtained by more than one order of magnitude, are already excluded, and that of [24] is at the level of the present Auger sensitivity.

\footnote{Remember that $\eta$ and the 68% resolution quantile $\sigma$ are related by $\sigma = 1.5\eta$ (cf section 3).}
8.2. Hybrids

As discussed earlier, hybrid events, detected by both the FD and SD have a better angular resolution, $0.7^\circ$ at 68% C.L. in the energy range studied.

For energy between $10^{17.9}$ eV < $E$ < $10^{18.5}$ eV, no significant excess is seen in the GC direction. Using, for instance an optimal top-hat window of 1.59$\sigma \simeq 0.75^\circ$ radius, 0.3 events are expected (shuffling technique estimate) while no event direction falls within that circle.

This gives to a source flux upper-bound at 95% CL of

$$\Phi_9^{95} = \xi \, 0.15 \text{ km}^{-2} \text{ yr}^{-1},$$

which is about a factor of two weaker than the SD flux bound.

Note that quality requirement for hybrid events is to have the maximum of the shower development inside the field of view of the telescopes, this affects the sensitivity to different primaries. The bound obtained here is a conservative one if the bulk of the CRs are heavy nuclei.

9. Conclusions

The Pierre Auger Observatory is a hybrid detector with excellent capabilities for studying the highest energy cosmic rays. Much of its capability stems from the accurate geometric reconstruction it achieves.

The construction of the Southern Observatory is well under way. Eighteen FD telescopes and more than 60% of the surface array are in operation taking data routinely. At the present rate of deployment, construction will be finish in mid 2007. Detectors are performing very well and the first results are very encouraging.

The angular resolution of the surface detector was found to be better than $2.7^\circ$ for 3-fold events, better than $1.7^\circ$ for 4-fold and 5-fold events and better than $1.0^\circ$ for higher multiplicity (which corresponds to energies larger than 10 EeV).

Using a bit more than the 2 first year of Auger data we have searched for localized anisotropy near the direction of the Galactic Centre. With statistics much greater than those of previous experiments, we have looked for a point-like source in the direction of Sagittarius A, without finding a significant excess.

We exclude several scenarios of neutron sources in the GC as suggested recently. Our searches do not support the large excesses reported in AGASA data (of 22% on 20$^\circ$ scales) and SUGAR data (of 85% on 5.5$^\circ$ scales).

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