Search for large-scale anisotropies in the distribution of cosmic rays with the Pierre Auger Observatory

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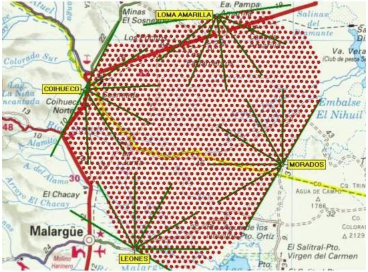
Overview

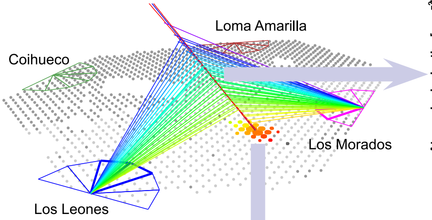
- The Pierre Auger Observatory
- 1-dimensional large-scale anisotropy search
- The geomagnetic effect
- Large-scale anisotropy search with the Infill array
- Outlook

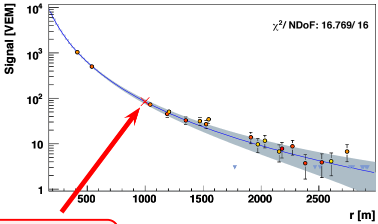
The Pierre Auger Observatory



- 3000 km^2 in the Argentinian Pampa (large, flat, empty, high altitude, clean atmosphere).
- 18 countries, 476 scientists
- data taking since 2004, installation completed in 2008
- hybrid detection technology (surface detectors and fluorescence telescopes)

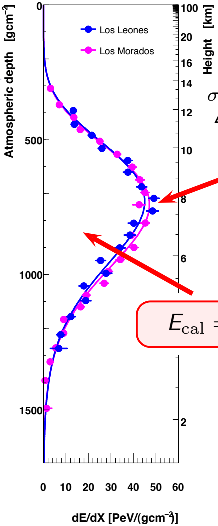
Overview of the reconstruction process





S_{1000}

$E_{\mathrm{surface}} = f(S_{1000}, \theta)$



$\sigma_{X_{\max}} < 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \approx 15\,\mathrm{g/cm^2}$

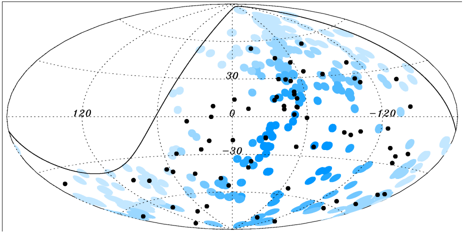
$X_{\max}$

$E_{\mathrm{cal}} = \int \mathrm{d}X \, \frac{\mathrm{d}E}{\mathrm{d}X}$

$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 22\,\%$

The search for anisotropies

- Motivation.
  - Identification of sources
  - Study of the magnetic field
- Two general strategies:
  - Point sources (highest energies, ca. 100 events above 50EeV)
  - Large-scale anisotropies (comparison of flux).
- No astronomy (except maybe for highest energies). Galactic and intergalactic magnetic fields deviate CRs.



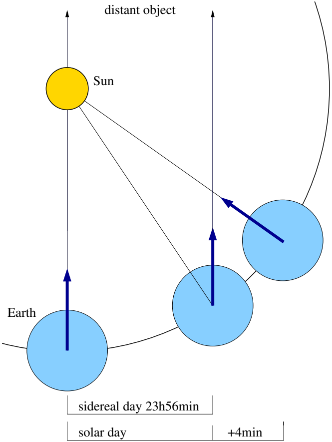
My thesis

- **1-dimensional large-scale anisotropy search**. Simplest technique, avoids systematics depending on declination.
- **2-dimensional large-scale anisotropy search**. Adds strong systematics. In particular: the influence of the **geomagnetic field** and 2d sky coverage.
- **Low energy large-scale anisotropy search** with an Auger extension, the **Infill Array**. Complete reconstruction has to be developed.

1-dimensional large-scale anisotropy search

The Rayleigh method (1-dimensional)

Fourier Transformation to extract the frequency patterns of the measured event times, corrected for their right ascension phase. Do we see a peak of the power distribution at the frequency of a **sidereal day**?



- Fourier coefficients:

$$a(\omega) = \frac{2}{W} \sum_i w_i \cos \omega t_i$$

$$b(\omega) = \frac{2}{W} \sum_i w_i \sin \omega t_i$$

- Amplitude:

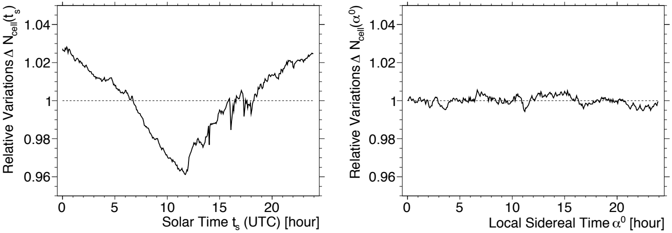
$$r = \sqrt{a^2 + b^2}$$

- Phase:

$$\phi = \arctan \frac{b}{a}$$

Systematics of 1-dim LSA search

1. The non-uniform exposure.



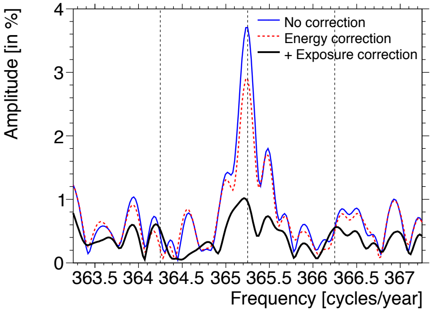
Correction: weighting events with the inverse of the corresponding exposure OR keeping constant exposure by rejecting "bad" periods.

2. The non-uniform atmosphere.

- Properties of the atmosphere, i.e. temperature, pressure and density, have a strong diurnal modulation ⇒ influence on the energy measurement, on which we cut the data.
- Model to account for theses effects:

$$E_{\text{measured}} = E_{\text{true}}/[1 - \alpha_P(P - P_0) - \alpha_\rho(\rho_d - \rho_0) - \beta_\rho(\rho - \rho_d)]^B$$

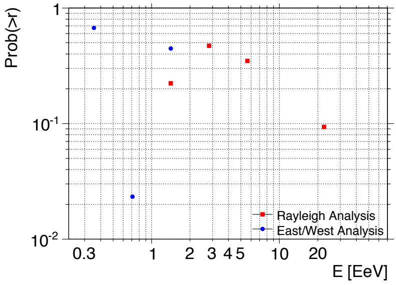
Result for $E > 1$ EeV



	$r_{\text{solar}}[\%]$	$P(> r_{\text{solar}})[\%]$	$r_{\text{anti-sid}}[\%]$	$P(> r_{\text{anti-sid}})[\%]$
no correction	3.7	$\simeq 2\,10^{-37}$	0.36	43
energy corrections	2.9	$\simeq 4\,10^{-23}$	0.15	85
+exposure correction	0.96	0.2	0.49	19

We show anti-sidereal, diurnal and sidereal frequency. The result at the sidereal frequency is compatible with **isotropy**.

Recent results of the 1-dimensional method



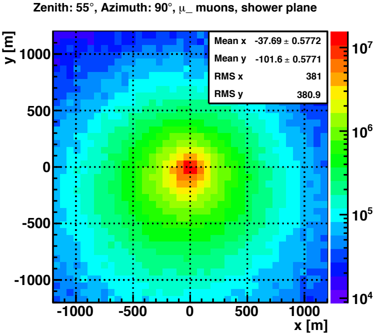
Phase Plot erased, see upcoming publication

- Probabilities for amplitudes r are compatible with isotropy.
- The phase is more sensitive to a real anisotropy.
- We see a correlation of the phases. Isotropy would give random phases.
- At lower energies, the phase points towards the galactic center.

The geomagnetic effect

The geomagnetic effect

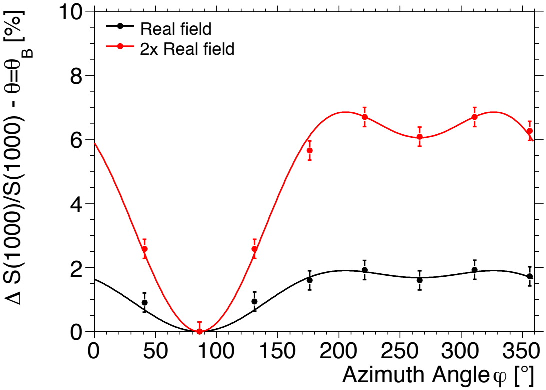
Motivation for LSA search: study the systematic due to the geomagnetic effect for 2-dimensional LSA.



- The charged shower particles will be deviated by the Lorentz force $\Rightarrow$ charge separation and deviation of the circular symmetry.
- **Effect on the energy determination (estimator S1000).**
- Muons have a much longer average travel distance than electrons, thus the magnetic deviation will be stronger for them.

Monte Carlo shower simulations

Monte Carlo shower simulations to compare the values obtained for S1000 with and without geomagnetic field. Fixed zenith angle $\theta = 55^\circ$ and different azimuth angles. Red: $30\mu T$; Green: $60\mu T$.



We obtain a $\sin^2(\angle(\vec{S}, \vec{B}))$ **dependency** of the S1000 (energy) shift. The shift is quadratic in field strength B.

A model for the shower muons 1

Transverse magnetic deviation of **a single muon in the shower**:

$$\delta_{\pm} = \frac{\pm qcB_T}{2} \frac{z^2}{E}$$

q: charge, z: distance traveled, E: muon energy.

$$B_T = ||\vec{B} \times \vec{S}|| = B_{\text{Earth}} \sin(\angle(\vec{B}, \vec{S}))$$

Shift in the shower density due to geomag. field:

$$\rho_{\text{deviated}} = \frac{1}{2}(\rho_+(x + \delta_+) + \rho_-(x + \delta_-))$$

$\rho_+ = \rho_-$ is the undeviated density of positive (negative) muons.
Developing in first approximation

$$\rho_{\text{deviated}} \simeq \rho(x, y) + \frac{\delta^2}{2} \frac{\partial^2 \rho}{\partial x^2}(x, y)$$

Thus the effect is **proportional to** $||\vec{B}||^2 \propto \sin^2(\vec{B}, \vec{S})$ as found in Monte Carlo.

A model for the shower muons 2

Assume an exponential muon density function on the ground

$$\rho(x, y) = e^{(-r/a)}$$

where a is given by $a = \frac{zp_0c}{E}$ and r is the radial distance from the shower axis.
Integration over θ and averaging yields

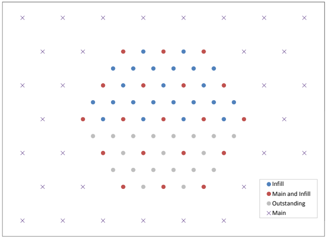
$$\frac{\rho_{\text{deviated}}(r)}{\rho(r)} = 1 + \frac{\delta^2}{2}(\frac{1}{2a^2} - \frac{1}{2ar})$$

For $r > a$, the average density will be increased by the magnetic field, for $r < a$ it will be decreased.
For a typical muon (z=5 km, E=2 GeV), we obtain a=0.425 km
$\Rightarrow$ In Auger ($d_{tanks} = 1.5$ km) for most events **increase of the reconstructed energy**.

Low energy LSA search with the Infill Array

The Auger Infill Array

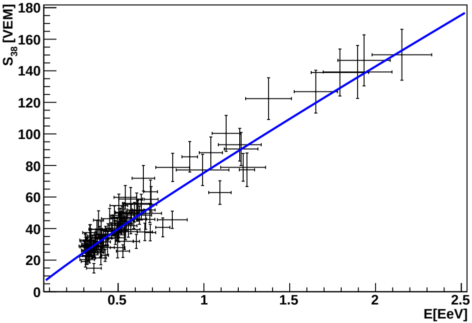
Low energy extension of Auger since 2008.



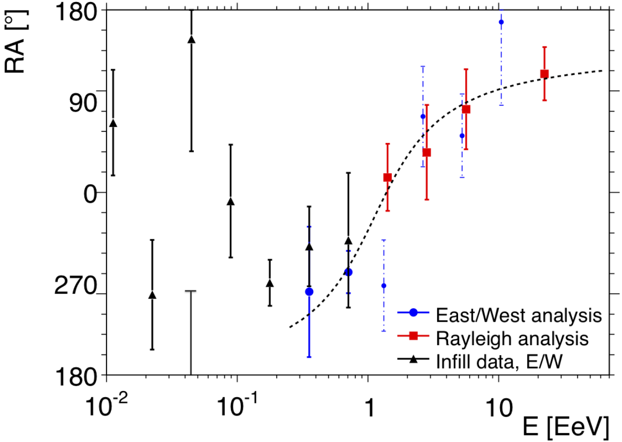
- Better understanding of the **regular array behavior at low energies**.
  - Study the evolution of the detection probability of the regular array with energy and angle.
  - Check the energy determination of the regular array.
- Direct **large-scale anisotropy search** with the Infill Array.
  - Extend the Rayleigh & East-West analysis to lower energies.

Energy calibration with the FD

- Use hybrid (Infill and FD) events for the energy calibration.
- FD gives a **calorimetric energy measurement**.
- We use a new energy estimator S450 instead of S1000.
- We obtain $E = (9.19 \pm 1.21)\ S_{38}^{(1.08 \pm 0.034)}\ 10^{-3} EeV$.



Preliminary results on 1-dim E-W method with the Infill



Phase of the first harmonic in right ascension, as shown before, with Infill data added (black points).

Outlook

- 1-dimensional large-scale anisotropy search
  - Repeat Rayleigh analysis and East-West method with the Infill data.
  - Use the Infill to study the low energy behavior of the main array.
- 2-dimensional large-scale anisotropy search
  - Analyzing higher order multipoles.
  - Applying the geomagnetic field correction.
- Compare results to theoretical predictions and give limits on anisotropy.