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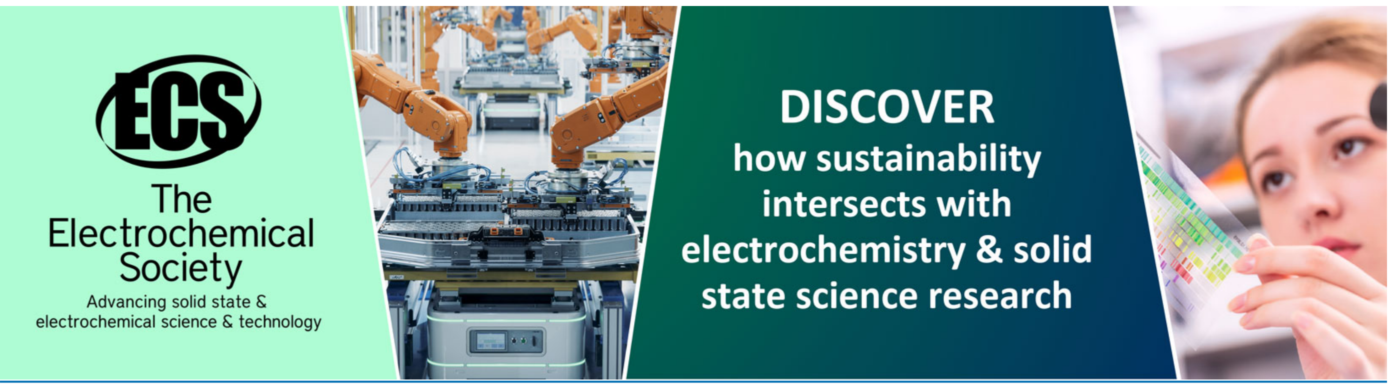

Inclined showers at the Pierre Auger Observatory

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Abstract. The cosmic ray showers detected at the Pierre Auger Observatory with zenith angles greater than 60° are the subject of a dedicated analysis. The spectrum of cosmic ray events above 10^{19} eV and zenith angles between 60° and 80° is presented. The potential of the surface detector of the Pierre Auger Observatory for detecting neutrinos through deeply penetrating inclined showers having a significant electromagnetic component has been studied, and an upper limit to the diffuse neutrino flux at EeV energies is presented.

1. Introduction

The Pierre Auger Observatory combines the surface and fluorescence techniques to study high-energy cosmic ray showers. The surface detector (SD) [1], uses 1.2 m deep water-Cherenkov tanks that provide enhanced sensitivity to muons and make the Auger Observatory suitable for studying inclined showers induced by hadronic nuclei. These constitute also the main background for the identification of neutrino induced showers.

2. Spectrum using showers with zenith angle greater than 60°

The analysis of inclined showers detected with the Pierre Auger Observatory allows to enhance both the exposure of the detector and its sky coverage. Showers induced by hadronic nuclei with zenith angles greater than 60° are mainly composed of muons at ground level and their detection provides complementary information, relevant for composition and studies of hadronic models.

Inclined events are reconstructed using a different analysis procedure to account for the muons deviating in the geomagnetic field [2]. Once the arrival direction of the shower is reconstructed using the timing of the signal, the core and the size of the shower are determined using the relative distributions of the muon number densities at ground level, "muon maps" , which are obtained from simulation. The shape of the muon maps is relatively independent of the details of the simulation or primary composition used to obtain them. The normalization factor of the muon map N_{19}, obtained using a maximum likelihood method can be used as an energy estimator. Its relation to shower energy is determined experimentally using inclined hybrid events. These events are recorded simultaneously by the Fluorescence Detector (FD) so a direct measurement of the energy released in the atmosphere by the electromagnetic component of the shower is available. The correlation between FD energies and N_{19} values is shown in figure 1. The calibration curve is obtained by a linear fit to the data points in this plot, in the form $N_{19} = 10^{\alpha} E_{FD}^{\beta}$, that yields best fit values of $\alpha = 0.77 \pm 0.06$ and $\beta = 0.96 \pm 0.05$ [3].

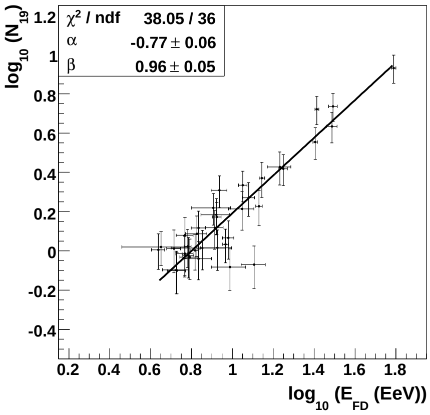

Figure 1. Correlation between FD energies and N_{19} in double logarithmic scale.

The SD high-level trigger definition requires that the tank closest to the reconstructed core is surrounded by an hexagonal ring of working stations. With this definition, the aperture is calculated, for a given array configuration, by counting the number of active hexagons and integrating in solid angle. The detection efficiency has been calculated using the muon maps and it exceeds 98% for the energy range $E > 6.3$ EeV considered in this analysis .

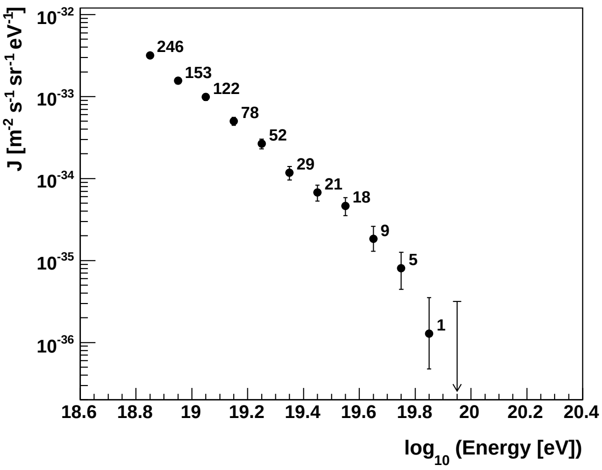

Figure 2. Cosmic ray energy spectrum obtained from events between 60° and 80° (statistical errors or 95% CL). The number of events in each energy bin is indicated.

The cosmic ray energy spectrum as measured by the Pierre Auger observatory between 1 January 2004 and 28 February 2007 between 60° and 80° is shown in figure 2. There are 734 events above 10 EeV. The integrated exposure in this period amounts to 1510 km^2 sr year, i.e. 29 % of the exposure for events below 60° [4]. The spectrum observed is in good agreement with the SD spectrum for events below 60° [5] and its implications for composition and/or hadronic models are presently under study [6].

3. Neutrinos

Neutrinos are expected to be produced in sources where UHECRs are thought to be accelerated, as well as during the propagation of UHECRs through the cosmic microwave background radiation. In the Pierre Auger Observatory neutrinos have to be identified in the background of showers initiated by nucleonic cosmic rays. They can penetrate large amounts of matter and generate showers close to the SD array ("young showers"), while hadrons and photons interact soon after entering the atmosphere. Young showers are expected to exhibit a significant electromagnetic component at ground [7].

The SD of the Pierre Auger Observatory is sensitive to upwards going and downwards going neutrinos in the EeV range and above. Downwards going neutrinos of any flavor may interact through both charged and neutral current interactions producing different combinations of hadronic and/or electromagnetic showers. To identify downwards going neutrino showers, very inclined shower are inspected for broad signals in time in those tanks triggered before the shower core hits the ground. Simulations suggest that a good identification criterium is to require that there are broad signals in the first two triggered tanks of the event [8].

Fluxes of τ neutrinos, heavily suppressed at production, are expected to reach the earth due to flavor oscillation and mixing at cosmological distances [9]. Skimming τ neutrinos that enter the earth just below the horizon may undergo a charged-current interaction to produce a τ near the surface. This τ can exit the earth and its decay in the atmosphere can produce a shower detectable with the Pierre Auger Observatory.

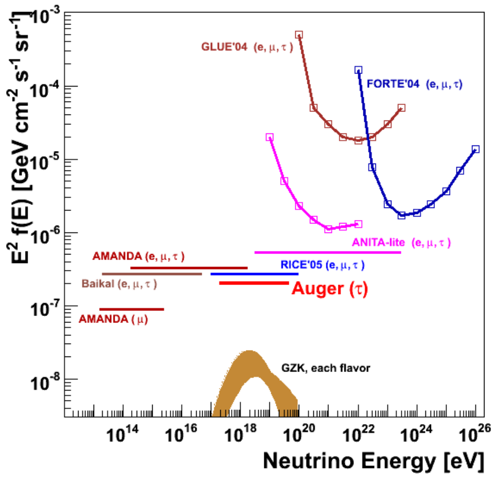

Figure 3. Limit to an E^{-2} diffuse flux of ν_τ at EeV energies. The limit is at 90% CL in the most pessimistic scenario for the systematic uncertainties. Other experiments are shown for comparison, assuming flavor equipartition.

The acceptance of the Pierre Auger Observatory to earth skimming tau neutrinos and the identification criteria have been evaluated using Monte Carlo techniques. The data of the surface detector from January 2004 until December 2006 have been analyzed and no event has fulfilled the selection criteria. Based on this, a limit in the incident spectrum of diffuse τ neutrinos can be placed at 90% CL with value $E_\mu^2 \cdot \mathrm{d}N_\nu/\mathrm{d}E_\nu < 1.5^{+0.5}_{-0.8}\ 10^{-7}$ GeV cm^{-2}sr^{-1} s^{-1} [10]. Systematic uncertainties are evaluated in the acceptance calculation and include those arising from the neutrino cross-section, the τ energy losses and the τ polarisation. The limit is presented in figure 3. It is still considerably higher than the GZK neutrino prediction, but it will improve by over an order of magnitude during the lifespan of the Observatory.

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