ICRC 2001

Neutrino Sensitivity and Background Rejection of the Auger Observatory

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Abstract. The Auger Observatory will be the largest air shower array ever built. This array of water Cherenkov pools offers the unique advantage of a large acceptance at very low zenith angle. Auger is therefore very well suited for studying horizontal air showers and in particular neutrino induced showers. In this short lecture the main characteristics of the acceptance will be given as well as the means by which neutrino induced showers can be disantangled from the large hadronic horizontal shower background. We will also present recent results on the possible detection of tau lepton induced shower from charge current ν_τ interaction in the gound surrounding the Auger array.

1 Introduction

The origin of Ultra High Energy Cosmic Rays observed on Earth is a long lasting mystery (Yoshida and Dai, 1998; Bhattacharjee and Sigl, 2000; Bertou et al., 2000; Nagano and Watson, 2000). While the cosmic ray spectrum is now shown (Matthews and Jui, 2000; Takeda et al., 1999) to extend beyond 10^{20}eV, mechanisms producing or accelerating particles with energies near or above 10^{21}eV are still uncertain.

Only very powerful astrophysical objects can, in principle, produce these energies through conventional acceleration. However the environment of the source itself generally prevents the accelerated particle to escape the site without severe energy losses, making such scenarios unlikely to explain the origin of UHECR.

Alternative hypotheses involving new physics such as collapse of Topological Defects (TD) or decay of Super Massive Relic Particles (SMRP) are well suited to produce particles above 10^{20}eV but they still lack a proof of existence. Moreover such models may reproduce the power law spectrum observed for the cosmic rays only at the condition that the decaying particle is much heavier than 10^{20}eV.

Transport from the source to Earth is also an issue. At those extreme energies the Cosmic Microwave Background Radiation makes the Universe essentially opaque to protons, nuclei and photons which suffer energy losses from pion photo-production, photo-disintegration or pair production. These processes led Greisen (1966), Zatsepin and Kuzmin (1966) to predict a spectral cutoff around 5×10^{19}eV, the GZK cutoff. The available data, although still very scarce, do not support the existence of such a cutoff. Therefore the sources are either close by and locally more dense for the cutoff not to show, or new physics modifies the expected energy losses of UHECR against the CMB photons.

In this framework neutrino are an invaluable probe of the nature and the distribution of the potential sources. Essentially unaffected on their journey to Earth they may allow us to disentangle the source characteristics from the propagation distortions. In the following we will briefly describe the Auger observatory and show how ν_τ are expected to interact and propagate in the Earth crust and be detected in Auger as low altitude and almost perfectly horizontal showers. In the framework of full $\nu_\mu \leftrightarrow \nu_\tau$ mixing we will then evaluate our sensitivity to potential neutrinos sources and in particular to the low but almost certain flux of GZK neutrinos.
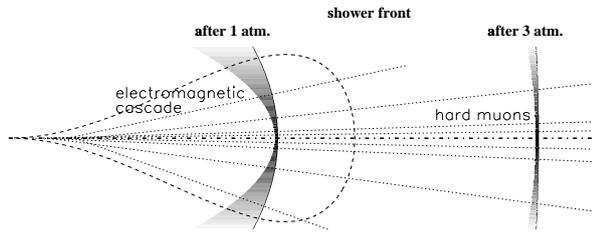
2 Detection of neutrino interacting in the atmosphere

Large area ground based detectors do not observe the incident cosmic rays directly but the Extensive Air Showers (EAS), a very large cascade of particles, that they generate in the atmosphere. All experiments aim to measure, as accurately as possible, the direction of the primary cosmic ray, its energy and its nature. There are two major techniques used. One is to build a ground array of sensors spread over a large area, to sample the EAS particle densities on the ground. The other consists in studying the longitudinal development of the EAS by detecting the fluorescence light emitted by the nitrogen molecules which are excited by the EAS secondaries.

The Auger Observatories[1] (Auger Collaboration, 1995) com-

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[1]Named after the French physicist Pierre Auger.

Fig. 1. Horizontal shower development.

Distance to shower axis (m)

Fig. 2. Particle time spread with respect to a planar shower front versus distance to the shower axis for 10^{19}eV protons at 80 deg zenith angle. The primary altitude is given at the interaction point, early interactions (bottom) correspond to high altitude and produce old shower at the ground level, late interactions (top) correspond to penetrating particle and young shower.

bine both techniques. The detector is designed to be fully efficient for showers above 10 EeV (1 EeV$\equiv 10^{18}eV$), with a duty-cycle of 100% for the ground array, and 10 to 15% for the fluorescence telescope. The 1600 stations of the ground array are cylindrical Čerenkov tanks of 10 m^2 surface and 1.2 m height filled with filtered water; they are spaced by 1.5 km into a triangular grid. The construction started in the fall of 2000 in Argentina. Once completed in 2006, the observatories will be covering one site in each hemisphere. Their surface, 3000 km^2 each, will provide high statistics. With a total aperture of more than 14000 km^{2}sr, the Auger Observatories should detect every year of the order of 10000 events above 10 EeV and 100 above 100 EeV.

Previous studies on UHE neutrino interaction in the atmosphere and observation with Auger were reported in (Capelle et al., 1998; Billoir et al., 1999). The UHE neutrinos may be detected and distinguished from ordinary hadrons by the shape of the horizontal EAS they produce. Ordinary hadrons interact at the top of the atmosphere. At large zenith angles (above 80 deg.) the distance from the shower maximum to the ground becomes larger than 100 km. At ground level the electromagnetic part of the shower is totally extinguished (more than 6 equivalent vertical atmosphere were gone through) and only high energy muon survive. In addition, the shower front is very flat (radius larger than 100 km) and the particles time spread is very narrow (less than 50 ns) [see Figure 1].

Unlike hadrons, neutrinos may interact deeply in the atmosphere and can initiate a shower in the volume of air immediately above the detector. This shower will appear as a "normal" one - although horizontal -, with a curved front (radius of curvature of a few km), a large electromagnetic component, and with particles well spread over time (over hundreds of nanoseconds). These differences are striking when one looks at the ground particles time distribution versus the shower axis as shown by figure 2. Therefore, if the fluxes are high enough. neutrinos will be detected and identified in Auger.

3 Interaction in the Earth : Tau neutrino detection

Standard acceleration processes in astrophysical objects hardly produce any ν_τ. In top-down models there is a full equivalence between all flavors at the beginning of the decay chain but this symmetry breaks down at the end of the fragmentation process where the pions which yield most of the expected neutrino flux are produced.

This situation changes radically in the case of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with full mixing, a hypothesis that seems to be supported by the atmospheric neutrino data and the K2K experiment (Fukuda et al., 1998). In such a case the $\nu_e : \nu_\mu : \nu_\tau$ flux ratios originally of $1 : 2 : 0$ evolves towards $1 : 1 : 1$ for a very wide range in δm^2 (given the very large distance between the source and the Earth). Half of the ν_μ gets converted into ν_τ and all flavors are equally represented in the cosmic ray fluxes.

Unlike electrons which do not escape from the rocks[2] or muons that do not produce any visible signal in the atmosphere[3], taus, produced in the mountains or in the ground around the Auger array, can escape even from deep inside the rock and produce a clear signal if they decay above the detector.

The geometrical configuration that must be met to produce

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[2]If one does not take into account the LPM effect which significantly increases the electron path length above 10^{18} eV.

[3]The electro-magnetic halo that surrounds very high energy muons does not spread enough in space to produce a detectable signal in an array of detectors separated by 1.5 km.
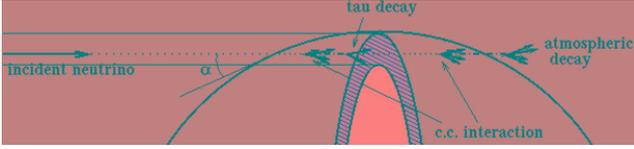
Fig. 3. Chain of interactions producing an observable shower.

a visible signal is rather severe. Neutrinos must be almost perfectly horizontal (within 5 deg.). Therefore less than 10% of the solid angle is available while the neutrino energy and the distance between the interaction and the detector must match to have a good chance of observing the tau decay. Indeed these criteria can be met, and we observed that most of the detectable signal (90%) comes from upward going ν_τ where the interactions occur in the ground all around the array and only 10% from downward going ν_τ coming from interactions in the mountains surrounding the array.

4 Detector response, reconstruction, acceptance

4.1 Detector response

Horizontal showers produced from a τ decay have the same characteristics as neutrino ones. We simulated both of them with the AIRES program (Sciutto, 2000). The set of weighted ground particles in a "sampling region" around each station is used to regenerate a set of particles entering the tank, statistically reproducing all significant characteristics of the incident flux : global normalization of the different particles, distribution in energy and direction.

Then a simplified simulation is performed for interactions (cascade of Compton scattering and pair production for photons, energy loss for charged particles) and Čerenkov emission in the water. The production of Čerenkov photons and their propagation in the tank is performed until they hit a PMT or are absorbed in the water or in the tank walls. The PMT response is assumed to be proportional to the amount of light emitted. This is a good approximation in most cases, in particular for the sum over the three PMTs collecting the light from the tank.

The level of the local trigger (one tank) is set to 4 *vem* (vertical equivalent muons), and a global trigger is built if at least 4 stations are locally triggered within 20 μs with a relatively compact topology. For exemple at least two stations must be within 3 km from a "central" one, and an additional one within 6 km.

The probability to detect a shower with a given visible energy depends essentially on the altitude of the core at the maximal lateral development. It is not very sensitive to the exact definition of the local trigger threshold nor to the global configuration.

4.2 Reconstruction

The direction of origin may be estimated from the times of arrival of the shower front on the stations, which is, as a first approximation, a plane moving at speed c. The precision on the azimuthal angle φ is of the order of 1 deg, and could be improved by taking into account the front curvature and by weighting each station contribution according to its integrated amplitude.

As a horizontal array is only sensitive to $\sin\theta$ the zenith angle θ is quite difficult to obtain precisely when theta approches 90 deg but a precision of better than 1 deg can be acheive up to 85 deg. The reconstruction of the energy E_i of the incident neutrino is much more delicate as estimation of the shower energy depends strongly on the altitude of the shower core which is *a priori* unknown. However, if many stations are hit, there is a hope to evaluate it from the transverse distribution.

A careful statistical analysis of all observable characteristics such as tank multiplicity, longitudinal and transverse profile of the ground spot and time structure will certainly give additional information on the original spectrum. We also beleive that for events where a arge number of tanks are struck we can obtain an estimate of the neutrino energy but those studies need to be done. Of course, the hybrid reconstruction (involving both the ground array and the fluorescence detector of Auger) will be extremely valuable to remove some ambiguities (zenith angle, visible energy), but such "golden" events are expected to be less than 10% of the total event rate.

4.3 Acceptance

The rate of observable events on a given surface A (surface covered by the Ground Array) is simply the rate over the whole earth, multiplied by $A/(4\pi R_T^2)$, where R_T is the radius of the earth. This rate may be evaluated from a parallel flux crossing the earth section (πR_T^2) as the integration over the solid angle just gives an additional factor of 4π.

A tau emerging with an angle α over the horizon greater than $\alpha_m = 0.3$ rad has no chance of producing an observable shower at ground level while interaction in the atmosphere are considered as neutrino candidates only if this angle is below 30 deg ($\alpha_m = 0.5$). For various incident energies, neutrinos were simulated and the complete history up to the trigger was followed, giving the total number N_{acc} of accepted events. The apperture at a given energy may then be defined as:

$$A_{\text{eff}} \;=\; \pi A \sin^2 \alpha_m \, \frac{N_{\text{acc}}}{N_{\text{sim}}}$$

and the rate of events (integrated over the solid angle) coming from neutrinos of energy between E_1 and E_2 as :

$$\frac{dN_{\text{acc}}}{dt} = \int_{E_1}^{E_2} f(E)\, A_{\text{eff}}(E)\, dE$$

where $f(E)$ is the incident flux.

Table 1. Number of events from ν_τ interaction in the full mixing hypothesis, for five years of data taking as expected from the various models presented in (Protheroe, 1998) (See Fig. 4).

AGN-1	TD	GRB	GZK	AGN-2
190	11	4	12	20
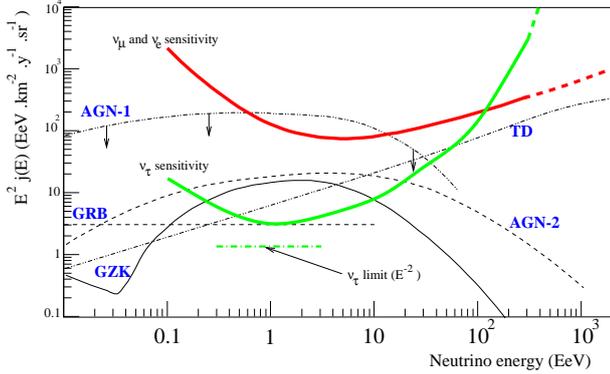
Fig. 4. Muon neutrino and anti neutrino fluxes ranking from various sources taken from (Protheroe, 1998), dotted lines are speculative fluxes, dashed probable and solid certain. The thick solid lines represent the Auger sensitivity defined by $f(E) * I_{10}(E) = 1$, i.e. one event per year and per decade. Top for horizontal shower from ν_e and ν_μ interactions in the atmosphere bottom for tau induced showers. Any flux lying above those curves for at least one decade will give more than one events per year in Auger. We also plotted the 90% C.L. limit (background free detection) for an E^{-2} flux between 0.3 and 3 EeV that Auger could acheive in five years. Note that ν_τ fluxes are at most half of the ν_μ fluxes as is indicated by the arrows on the AGN-1 flux.

With this definition we calculated (Bertou at al., 2001) an apperture for tau neutrino events of 0.13 km^{2}sr at 1 EeV reaching a maximum of 0.45 km^{2}sr at 300 EeV. Above this energy the apperture slowly decreases as the probablility for a tau to decay above the detector becomes smaller and smaller. For neutrino interaction in the atmosphere the apperture is about 0.005 km^{2}sr at 1 EeV and saturate at 0.45 km^{2}sr above 100 EeV (Billoir et al., 1999).

Introducing the event rate per decade (Bertou at al., 2001):

$$I_{10}(E) = \ln 10\, E\, f(E)\, A_{eff}(E)$$

one can define the Auger flux sensitivity as the neutrino flux giving at least one observed event per decade of energy every year i.e. for which the product $f(E) * I_{10}(E) = 1$. This flux is shown on Fig. 4 for both atmospheric and ground interactions together with the expected fluxes from a model calculation by Protheroe (Protheroe, 1998). All predicted fluxes are ν_μ fluxes. In the full mixing hypothesis ν_τ fluxes are half of those.

For standard neutrino interactions in the atmosphere, each site of the Auger observatory reaches 10 km^3 water equiva-

lent (w.e.) of target mass at 1 EeV, and only the models classified as speculative by Protheroe (Protheroe, 1998) are expected to yield a detectable signal. However, for tau induced showers the target mass is increased by a factor of about 30 at 1 EeV, allowing for a detectable signal even for the lowest expected fluxes. The expected number of events, after five years of data taking, from the various UHECR production models and from the GZK neutrinos (a very low but almost certain flux) are presented in Table 1.

The data in the table demonstrate the capability of the Auger detector to probe the GZK neutrino flux. This is a crucial test as most acceleration mechanisms of protons in cosmologically distributed sources as well as top-down models will produce a neutrino flux at least equal to this one.

5   Conclusions

With the very large area and the non zero acceptance to horizontal showers of the Auger ground array we have shown that the observation of ultra high energy neutrino interaction in the atmosphere, or , in the case of oscillation, of tau neutrino interaction in the Earth is very likely. In the later case almost all models produce a detectable signal of a few events per year. If, however, no signal was found, we could, in five years of data taking, set a 90% confidence limit on the neutrino flux as low as $1.2 \times E_{18}^{-2}$ EeV^{-1}km^{-2}y^{-1}sr^{-1} (equivalent to $4 \times 10^{-9} E_{18}^{-2}$ Gev^{-1}cm^{-2}s^{-1}sr^{-1}).

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