NEUTRINO CAPABILITIES OF THE AUGER DETECTOR

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ABSTRACT

The Pierre Auger Observatory is a hybrid detector (a combination of atmospheric fluorescence telescopes and a ground array of Čerenkov water tanks, over an area of 3000 km^2) designed to measure both the longitudinal profile and the lateral extension of giant air showers produced by cosmic rays of energy above 10^{19} eV. Additionally, it could be sensitive to quasi-horizontal showers induced deeply in the atmosphere by neutrinos, above 10^{17} eV. The acceptance of the Auger Observatory is evaluated and compared to the fluxes predicted by different models, describing neutrinos either as interaction products of accelerated particles, or as the result of top-down mechanisms from topological defects. A 10-year collection of data could give a significant signal, or exclude some speculative predictions, mainly in the range $10^{18} - 10^{20}$ eV.

1. Introduction: the neutrino fluxes

Neutrinos of very high energy (above 10^{17} eV) are expected from the decay of charged mesons produced in interactions of accelerated protons or nuclei, either with the ambient medium of the accelerating site, or with the cosmological microwave or infrared background (photoproduction of mesons: this is the GZK effect [1)]). The corresponding fluxes are in principle related to the observed fluxes of UHECR (ultra high energy cosmic rays); however they depend on unknown features of the astrophysical objects supposed to be their source (mainly AGNs, Active Galactic Nuclei), and the predictions of models may differ by one or two orders of magnitude. An upper limit has been proposed [2)], within some general assumptions, but exceptions cannot be excluded. If such neutrinos come directly from the primary source (i.e., excluding GZK neutrinos), their direction points exactly to this source and they arrive at the same time as photons (even with a mass of a few MeV).

On the other hand, a more speculative explanation of UHECR is based on the scenario of topological defects(TD), produced in a phase transition related to a symmetry breaking in the early Universe (monopoles, strings). For example, strings may evolute into loops which collapse and eventually decay into supermassive particles (at the GUT scale, typically 10^{25} eV); finally a cascade of standard objects (quarks and leptons) is produced, giving mainly neutral and charged mesons. In principle the sources are diffuse, unless the TDs are long lived and trapped in specific regions. The main feature of these models is a harder spectrum, extending up to the supermassive scale, and the predominance of photons and neutrinos in the incident fluxes; they

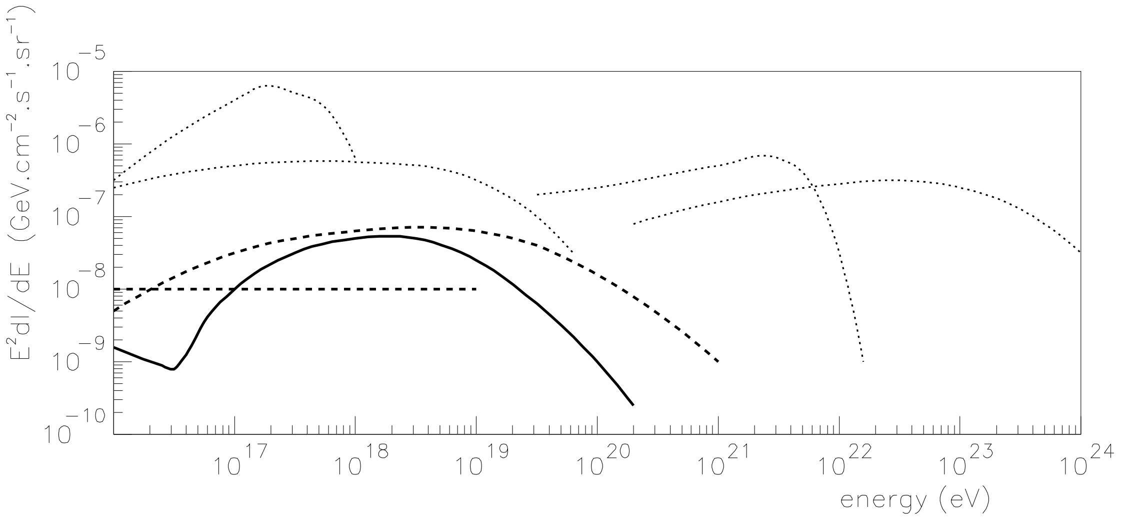

Fig. 1. Predictions of neutrino spectrum ($\nu_\mu + \bar{\nu}_\mu$), following Protheroe's classification. Solid line: almost sure; dashed lines: likely; dotted lines: speculative

have to cope with an experimental limitation of γ ray fluxes in the GeV region (see for example [3]).

Neutrinos coming from interactions of cosmic rays with interstellar matter, or with the atmosphere, are negligible in our energy range.

It is convenient to draw the various expected neutrino spectra in terms of E^2dI/dE: following Protheroe's classification [4], solid predictions in the range $10^{17} - 10^{21}$ eV are at the level of 10^{-9} to 10^{-7} GeV.cm^{-2}.s^{-1}.sr^{-1}, while speculative models rise up to 10^{-6} or even more (see Fig. 1, which is a simplified version of a plot given in [4]); the upper limit claimed in [2] is between 10^{-8} and 5.10^{-8}. In this study we want to compare the acceptance of the Pierre Auger Observatory to these levels: by convention, the threshold of sensitivity corresponds to a rate of 0.3 events per decade of energy per year.

In sect. 2, we explain how neutrinos interacting in the atmosphere may be distinguished from other types of cosmic rays. In sect. 3, the features of the Auger Observatory which are relevant to neutrino detection are described. In sect. 4, the method to define criteria and evaluate the acceptance is described, and the acceptance is computed from a Monte-Carlo method.

2. Characterization of neutrino induced showers

Let us first consider "normal" showers, developing from a primary hadronic interaction of a proton or a nucleus, which occurs after a few tens of g.cm^{-2}, that is always in the highest part of the atmosphere. In their development we can distinguish two main phases (which actually overlap):

- the *hadronic* cascade, producing mainly mesons, and ending when their decay length becomes shorter than their interaction length (altitude between 10 and 20 km); charged mesons decay into muons of relatively large energy (essentially above 1 GeV), which generally reach the ground before decaying or losing their energy.

- the *electromagnetic* cascade, initiated from the decay of π^0, containing mainly photons, and also electrons and positrons; with a very high primary energy, its longitudinal extension is larger than the vertical depth of the atmosphere; outside the core, the ground particles are mainly photons and electrons of low energy (typically 1 to 100 MeV).

If the primary particle is a photon, the shower starts early as well; it is mainly electromagnetic, but a reduced hadronic cascade is created through photohadronic reactions. Otherwise the development is quite similar.

In the atmosphere, the probability of interaction of very high energy neutrinos with nuclei is not completely negligible ($\simeq 10^{-5}$ for 1000 g.cm^{-2} in the range 10^{17} to 10^{19} eV). At these energies, charged current interactions are favoured, for both neutrinos and antineutrinos. In any case, the interaction produces a set of hadrons carrying a fraction of the initial energy (20 to 25 % in average, depending on the initial energy); according to the simulations, they give something quite similar to a shower produced by a unique proton having the total hadronic energy. If the final lepton is an electron, it produces a shower with the same characteristics as a photon; else (muon or neutrino), it escapes detection. Hence we can distinguish two types of neutrino showers: "mixed" (with full energy) or "pure hadronic" (with reduced energy). If the primaries are mainly electronic and muonic neutrinos, with ratios (1:2), as expected from pion decays without further mixing, the fraction of "mixed" showers is about 40 %. If τ neutrinos are to be considered, the situation is more complicated, because of a possible decay of the $\tau^{\pm}$ (the mean flight distance, in km, is $50(E/10^{18}$ eV)): the result is in between a "mixed" and a "pure hadronic" shower, depending on the decay mode.

Given the low cross sections, the neutrino interactions are expected to be much less abundant than the "normal" cosmic rays, unless the fluxes are assumed to be unreasonably large. Then the only hope to distinguish them is to search at large zenith angles (in practice greater than 70 degrees). In these conditions the slant depth at ground level is more than 2500 g.cm^{-2} and the electromagnetic part of "normal" showers is extinguished; the only surviving particles are high energy muons, coming

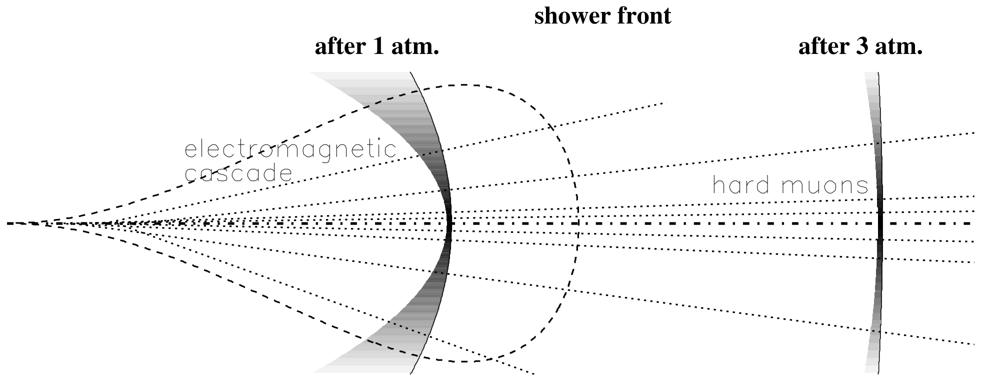

Fig. 2. Schematic view of the development of an quai-horizontal shower. The dashed line is the contour of the electromagnetic zone (density above the detection sensitivity).The grey areas represent two successive states of the development; they contains 90 % of the active particles at a given time, starting from the front (solid line). The scales are somewhat arbitrary: the curvature and the thickness are exaggerated for clarity

directly from the hadronic cascade, over a distance of 100 km or more, with the velocity of light; the shower front is like a flat and thin pancake (the radius of curvature is of the order of the flight distance of the muons). Geomagnetic deflections over such distances give important, but predictable distorsions of the lateral distribution at ground; the shower front remains a thin plane.

On the contrary, a "deep" shower induced by a neutrino in the lower atmosphere may reach the ground with a large electromagnetic content, hence a thick and curved front, giving a signal spread in time. In the region where the electromagnetic cascade is well developed, this can be described with a few approximate values: the spread (expressed as the time between the first particles and 90 % of the integrated signal) increases roughly as the square of the distance to the core: it is typically 1 μs at 1000 m. The radius of curvature of the front (first particles) is typically 10 km. This corresponds to a delay of 150 ns with respect to a plane front, at 1 km from the core. Fig.2 illustrates the differences.

Some additional features may help to characterize deep interactions: when hitting the ground, the core of the shower is absorbed and does not feed the electromagnetic cascade anymore; as a result, the ground signals exhibit a characteristic assymmetry: at a given distance from the core, the density and the spread are smaller in the region downstream the impact on the ground.

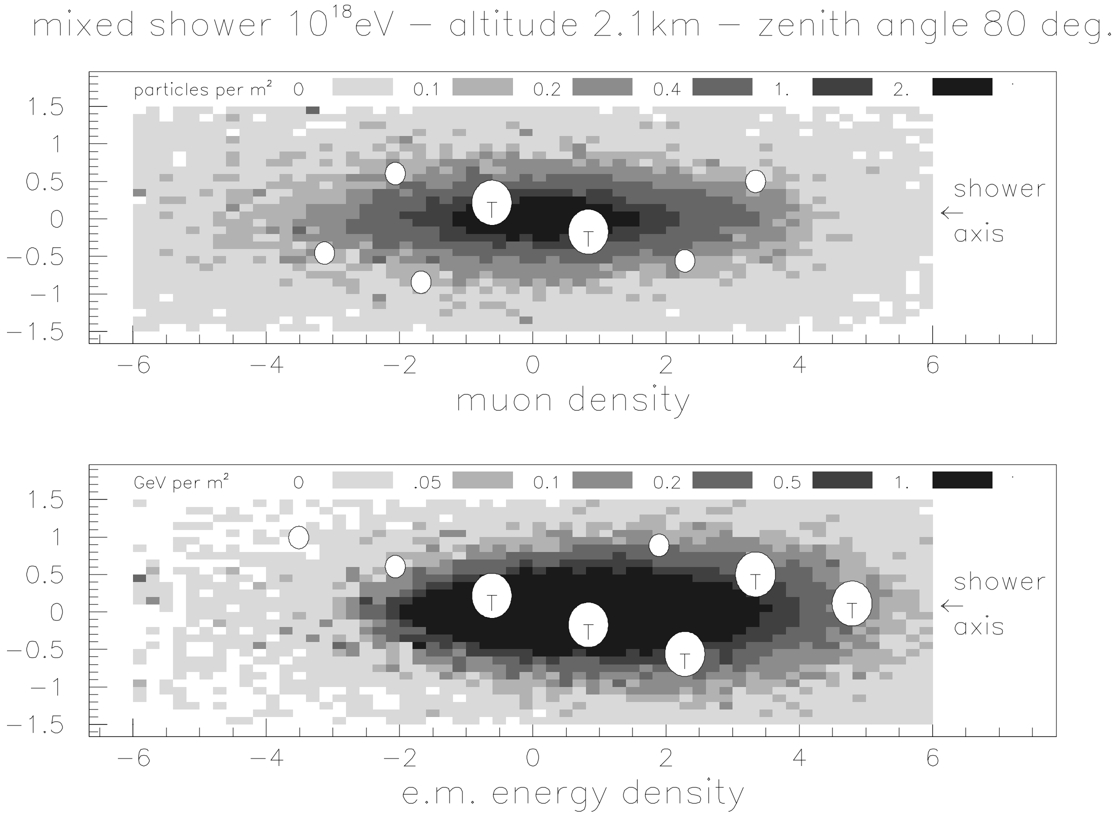

Fig. 3. Muonic and electromagnetic densities at ground level, obtained from a mixed shower (neutral current interation of $\nu_e/\bar{\nu}_e$), compared to the Auger ground array sensitivity. Circles indicate the positions of water tanks with a significant signal. Large circles with a T are above local trigger when only accounting for the electromagnetic or muonic contribution (of course the actual trigger is sensitive to the total).

Moreover a large zenith angle θ offers geometrical advantages: the interaction probability is enhanced; the size of the "ground spot" (the ground area where the density, measured normally to the axis, is above a given value) is increased by a factor $1/\cos\theta$: if the ground detectors have a large acceptance to horizontal particles (this is true in Auger ground array, see next section), inclined showers may be detected at an energy below the threshold of "normal" cosmic rays, seen at lower zenith angles.

Fig.3 gives an example of "ground spot" and shows the assymmetry of the electromagnetic component.

3. The Pierre Auger Observatory

This Observatory is designed to observe with a full efficiency atmospheric showers induced by early interacting primaries (nuclei, protons or photons) above 10^{19} eV, at zenith angles from 0 to 60 degrees. Two sites are planned to provide a full sky coverage: the first one in southern hemisphere (Mendoza, Argentina, to be built from this year); the second one in northern hemisphere (Utah). Both sites are between 35 and 40 degrees of latitude, at an altitude between 1200 and 1400 m a.s.l. Each one consists in:

- An hexagonal ground array (covering 3000 km^2 with a spacing of 1.5 km) of water tanks (radius 1.8 m, height 1.2 m), equipped with PMTs to collect the Čerenkov light emitted by relativistic charged particles. They provide a sampling of the lateral distribution of particles at ground level.

- Sets of telescopes with mirrors oriented in all directions (the "fly's eye" technique), sensitive to the nitrogen fluorescence, which is proportional to the number of charged particles (mostly $e^{\pm}$), and concentrated in the shower core: this gives the longitudinal profile of the shower development. If the telescopes are in duty (in clear moonless nights, that is about 10 % of the time), a shower at 10^{19} eV is generally seen by at least one of them and four ground stations, allowing a complete 3D reconstruction.

The signals are digitized in FADCs at a frequency of 40 MHz. The time for collecting the light emitted by one particle in a tank (after one or several diffusions on the internal lining of the walls) is a few tens of nanoseconds: this is much less than the typical duration of the global signal; this also allows a measurement of the curvature.

Horizontal showers are detected with a good efficiency, because of the large intercepting surface from side; moreover high energy particles (especially the muons) have a longer range, in average, than in the vertical direction, hence they give more light.

In principle, deep quasi-horizontal showers could be seen by a fluorescence telescope, even if their electromagnetic cascade disappears before reaching the ground; however, a good geometrical reconstruction requires a stereoscopic observation by at least two telescopes: this is very unlikely at energies below 10^{19} eV. In this study we neglect this contribution to the acceptance, and we require a signature of the electromagnetic component at the ground level through time spread criteria. The fluorescence profile could give an interesting confirmation of an ambiguous ground signal, but the rate of such events is expected to be low.

The acquisition system needs no modification to accept inclined showers. A "local trigger" occurs in a tank if a signal is found above a given threshold (of the order of 4 times the signal of a vertical muon, or equivalently 1 GeV of electromagnetic energy); if needed, the rate of triggers due to mini-showers will be reduced with an additional condition on the time spread. An event is accepted if a minimum number of neighbour (or almost neighbour) tanks are triggered; this multiplicity will be 3 or 4 depending on the rate of random coincidences in the operating conditions on the site.

4. Evaluation of the acceptance

4.1. Aim and limitations

In this section we want to evaluate the number of events that can be identified as neutrino interactions, after cuts to reduce the background (random coincidences or tails of "normal" cosmic rays) to a rate well below one per year. Some ingredients rely on observations on prototypes and need to be measured on the site; the discrimination criteria are in a preliminary status, and the possibility of triggering the acquisition with only 3 tanks is questionable. The uncertainties mainly affect the lower energies (10^{17} to 10^{18} eV); the results given here will probably hold within ± 50 %.

On the other hand, we do not care yet for reconstruction (direction and primary energy). To precisely estimate the energy, one needs to know the altitude of the interaction, which is *a priori* undefined; moreover a large part of the energy is invisible in the case of a pure hadronic shower, which may be difficult to recognize. The direction may be estimated from the time measurements, with a precision depending on the number of tanks (a few degrees with three of them, if they are not aligned).

4.2. Shower and detector simulations

Atmospheric showers are simulated with the AIRES program[6)], allowing various primary particles and injection altitudes; because of the huge number of particles (up to 10^{11}), the cascade cannot be fully simulated; the output of the program consists in a list of weighted particles at ground level, following a "thinning" algorithm that gives unbiased estimators of densities. A "pure hadronic" neutrino shower is represented by a single proton, with 20 % of the primary energy; to describe a "mixed" shower, an electron with the rest of the energy is added.

At seven energies between 10^{17} and 10^{20} eV, 100 to 150 showers have been simulated at zenith angles bewteen 72 and 90 degrees,and different injection altitudes. Each sample of ground particles is moved and rotated in 50 random positions with respect to the array.

The detector response is evaluated with a semi-detailed simulation, which reproduces the main sources of statistical fluctuations. The set of particles entering a tank is obtained through a weighted sampling in a zone around its actual position; for each one, the arrival time and the expected Čerenkov-emitting range in water are evaluated and transformed into a contribution to the FADC output. The integrated amplitude A, the starting time t_0 of the signal and an indicator of the spread (time t_{90} when the integrated signal is 90 % of A) are extracted from the full FADC trace.

4.3. Selection criteria for background suppression

- A local condition is first applied (assuming that the local trigger condition is weaker) to suppress the contribution of isolated particles or mini-showers: either $A > 8$ v.e.m. (vertical equivalent muons), or $A > 4$ v.e.m. and $t_{90} - t_0 > 200$ ns. With these conditions the rate is expected to be less than 0.5 Hz.
- Then the electromagnetic character is requested through the condition that more than one third of the local signals (at least two in any case) fulfill $t_{90} - t_0 > 150$ ns; this eliminates drastically the muonic tails of "normal" showers at zenith angles above 75 degrees. Between 70 and 75 degrees, the simulation studies are less conclusive and they will need to be checked against real data; it is important to notice that this angular region only contributes to the acceptance above 10^{19} eV, with very large trigger multiplicities: this could allow more refined criteria.
- To reduce the rate of random coincidences, we exploit geometrical constraints: at low energy, the triple triggers correspond to tanks close to the shower core (less than 500 m at 10^{17} eV), then the spread is reduced and the effects of the curvature are negligible: as a consequence, the time differences may be approximately predicted from the configuration. For example, requesting a "time alignment" within 500 ns, the rate of random coincidences would be less than 3.10^{-9} Hz (0.1 per year) in the whole array. If needed, the time window could be reduced to 250 ns without changing strongly the acceptance. Configurations with four tanks or more (which are predominant at high energy) allow internal constraints on times and need no specific cuts.

At energies below 10^{17} eV the first two conditions suppress drastically the acceptance: even if the fluxes are very large, neutrino interactions cannot be distinguished.

4.4. Results

The acceptance is expressed as the product of a effective mass (conveniently given in equivalent km^3 of water) and a solid angle. It is computed as a function of the primary energy with the following formula:

$$\mathcal{A}(E) = S \int_{\theta_{min}}^{\pi/2} 2\pi \sin\theta \; d\theta \int_0^{h_{max}} \rho_0 \; \exp(-h/H) \; \mathcal{P}(E,\theta,h) \; dh$$

where $S = 3000$ km^2 is the area, $\rho_0 \simeq 1.15$ kg.m^{-3}, $H \simeq 8$ km; $\mathcal{P}(E,\theta,h)$ is the probability of detection at given energy E, altitude h and zenith angle θ. This acceptance is computed for both pure hadronic ($\mathcal{A}_h$) and mixed showers ($\mathcal{A}_m$), from a summation on (h,θ) boxes, with $\theta_{min} = 72$ deg, $h_{max} = 15$ km, with the samples and the selection criteria described above (requesting the trigger multiplicity to be at least 3, or 4). Fig.4 illustrates the "phase space" of showers detected at $E = 10^{18}$ eV.

The nuclear cross sections of (anti)neutrinos at our energies need to be extrapolated from measured data at collider energies, in a model-dependent way [7]. Here we use the following approximation:

$$\sigma_{c.c.}(E) = 10^{-32}(E/10^{18}\ eV)^{0.4}\ cm^2$$

hence the event rate (assuming a ratio (2:1) between ν_μ and ν_e, and $\sigma_{n.c.} = \sigma_{c.c.}/4$):

$$n \int dE \; dI/dE \; [\; 1.1 \; \mathcal{A}_h(E) + 0.4 \; \mathcal{A}_m(E) \;] \; \sigma_{c.c.}(E)$$

where dI/dE is the total differential flux of muonic neutrinos and antineutrinos.

Finally we determine the limit of sensitivity on $E^2 dI/dE$, defined as the level giving 0.3 event per year (10^{-8} per second), per decade of energy: the lowest value is 10^{-7} GeV.cm^{-2}.s^{-1}.sr^{-1}, in the range 10^{18} to 10^{19} eV. The acceptances for pure hadronic and mixed showers, and the sensitivity are summarized on Fig.5.

Within the uncertainties our results at $10^{18} - 10^{19}$ GeV are comparable to a previous evaluation[8], based on simple geometric arguments; our estimation is lower at both low energy (selection cuts) and high energy (decrease of air density with altitude)

5. Conclusion

The Pierre Auger Observatory offers a window for neutrino astronomy above 10^{17} eV, with the observation of very inclined showers deeply induced in the atmosphere. The crucial criterion to distinguish them from the background is the characterization of an electromagnetic component at ground level, through the time spread of the signals. With some reasonable assumptions of the selection cuts, the expected acceptance is about 15 to 20 km^3 of equivalent water at 10^{19} eV, and slightly increasing above; at these energies most events (neutral or charged current interactions) are detected in a large number of local stations. In the lower range (10^{17} to 10^{18} eV), there are still uncertainties on the practical trigger limitations and the efficiency of the background rejection; the reconstruction of individual interactions, especially the estimation of the primary energy, will be poor.

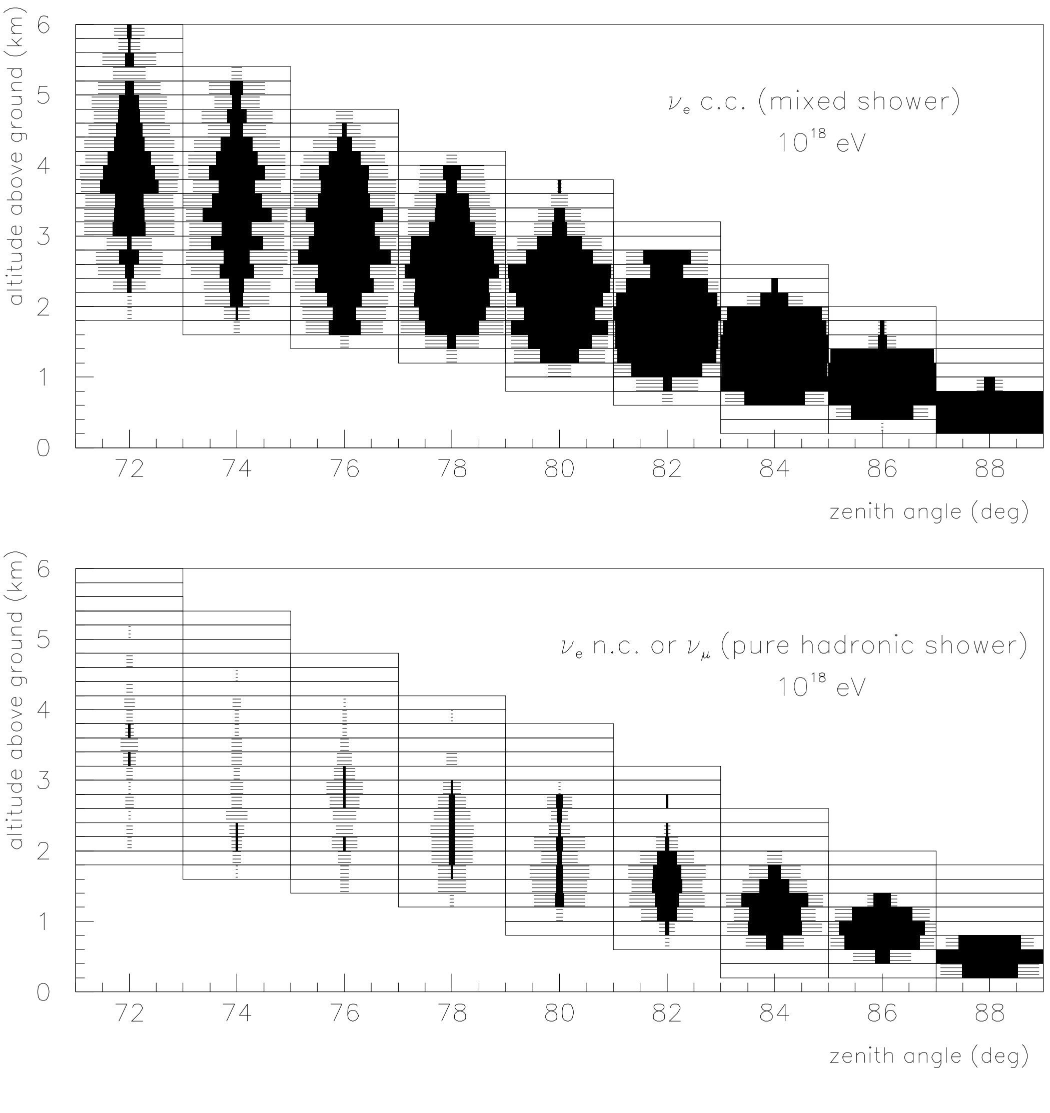

Fig. 4. Domain of detection of neutrino showers at 10^{18} eV. In each cell the black area represents the fraction of showers triggered in at least 4 tanks, the shaded area corresponds to triple triggers

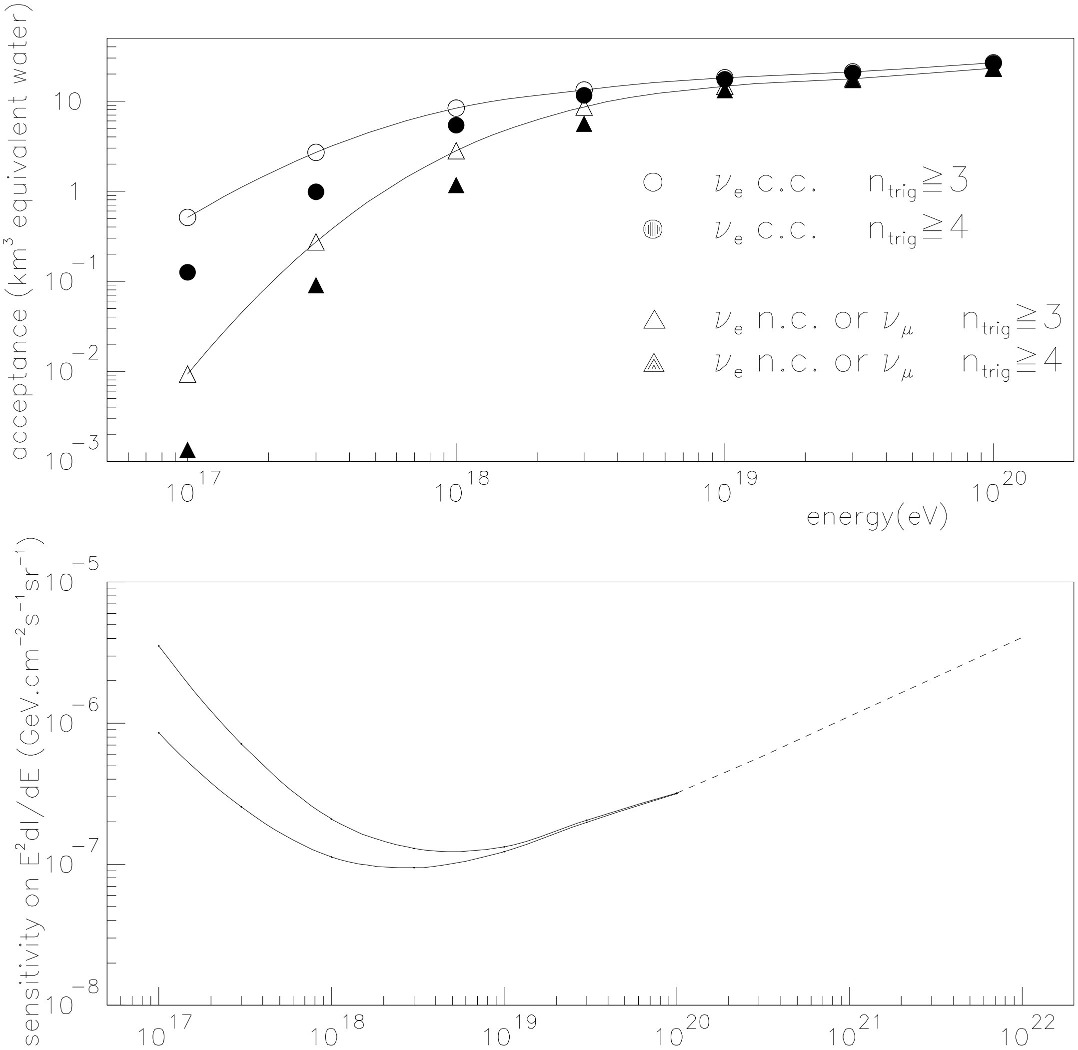

Fig. 5. Top: Acceptance to neutrinos as a function of the energy, for both mixed and pure hadronic showers. Down: sensitivity to $E^2 dI/dE$: the upper curve corresponds to $n_{trig} \geq 4$, the lower curve to $n_{trig} \geq 3$; the dashed extrapolation assumes the acceptance to be saturated beyond 10^{20} eV

The solid predictions on neutrino fluxes (essentially from interactions of cosmic rays with interstellar medium) are just below the sensitivity of Auger. Some reasonable models of AGN would produce a few inambiguous events over 10 years of observation. The most speculative scenarii (proton blazars, topological defects) are expected to give several tens of events; a negative result would be a severe constraint on such models.

Finally the neutrino capability of Auger is not sufficient to measure detailed spectra; however, combined with its ability to recognize photons, it will provide either a confirmation of the *top-down* mechanism as an explanation for the highest energetic cosmic rays, or very significative constraints.

6. Acknowledgements

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More details and references may be found in Auger Web sites:
http://www.auger.org
http://www-lpnhep.in2p3.fr/auger