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A MC simulation of neutrino showers and their detection with the Pierre Auger Observatory

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Abstract: In this paper we present a study about the possibility to detect neutrino induced extensive air showers at the Pierre Auger Observatory. The Monte Carlo simulations performed take into account the details of the neutrino propagation inside the Earth, the air as well as the surrounding mountains, which are modelled by a digital elevation map. Details on the sensitivity with respect to the incoming direction as well as the aperture, the acceptance and the total observable event rates, on the basis of various assumptions of the incoming neutrino flux, and an upper limit for ultra high energy neutrinos, above 0.1 EeV, are given.

Introduction and method

The Pierre Auger Observatory has the capability to detect neutrino induced showers. Especially, if a ν_τ interacts close to the Earth's surface, the so–called Earth skimming neutrinos, it can produce a tau lepton which can emerge from the Earth, decay and produce extended air showers. If the decay vertex of a tau lepton is close enough to the surface array, it can be detected and distinguished from very inclined showers induced by a proton or nuclei due to the presence of the electromagnetic component. As shown in Fig. 1A, the Southern site (SO) is surrounded by a large amount of rock (the Andes mountains). This is the natural target for Earth skimming neutrinos which leads to a significant enhancement of the tau lepton flux with respect to calculations done with the simple spherical model of the Earth. In case of the Northern site (NO) the mountains which might enhance the tau lepton flux are far away, Fig. 1B, so that the influence of the mountains is not very pronounced. However due to a larger area of the detector (the planned area is about 3.5 times larger than SO) the rate is supposed to be about three times larger than the one for the Southern site. In order to simulate the neutrino propagation through the Earth and the τ lepton decay, an extended version of the ANIS code was used [2]. First, for a fixed energy of the tau neutrinos, 200.000 events were generated with a zenith angle in the range between $90^\circ - 95^\circ$ and azimuth between $0^\circ - 360^\circ$ at the top of the atmosphere. Then tau neutrinos are propagated to the detector in small steps. At each step of propagation the probability of a ν_τ nucleon interaction is calculated according to the parameterization of the cross section based on the CTEQ5 [3] parton distribution function. The propagation of tau leptons through the Earth was simulated with the energy loss model (continuous energy loss approach) given by Dutta et al. in Ref. [4]: $\beta(E_\tau) \equiv 1.2 \times 10^{-6} + 0.16 \times 10^{-6} ln(E_\tau/10^{10})$ cm^{2}g^{-1}. The factor β parameterizes the τ lepton energy loss through bremsstrahlung, pair production, and photonuclear interactions. The computations were done by using digital elevation maps (DEM) [1] and then they were repeated by using the spherical model of the Earth (SP), with its radius set to 6371 km (sea level). As a result, the flux of the emerging τ leptons, i.e. the energy and the decay vertex position, was calculated inside a given detector volume. For the Southern site the geometrical size of the detector was set to $50 \times 60 \times 10\,\mathrm{km}^3$ and the detector was positioned at 1430 m above

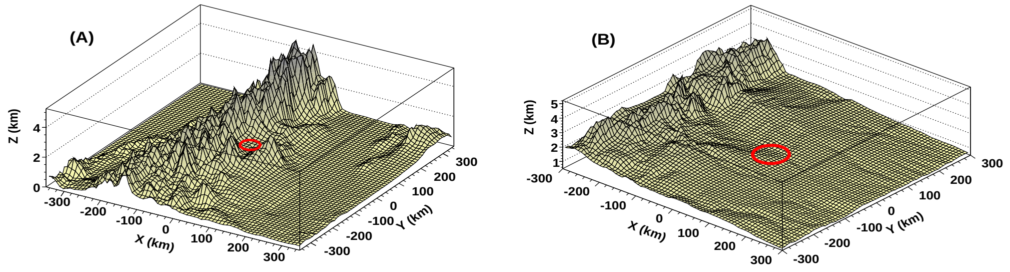

Figure 1: (A) Topography of the Southern site according to CGIAR-CSI data [1]. The center of the map corresponds to the center of the Auger array (latitude $\phi_{SO} = 35.25°$ S, longitude $\lambda_{NO} = 69.25°$ W); (B) Topography of the Northern site where the center of the map corresponds to $\phi_{NO} = 37.75°$ N, $\lambda_{NO} = 102.75°$ W. The Southern and Northern site positions are marked by a circle.

sea level. For the Northern site the geometrical size of the detector was set to $100 \times 100 \times 10$ km^3 at 1300 m above sea level. A DEM with resolution of 500(5000) m was used for the NO(SO). In case of the computations with the simple spherical model of the Earth, the same size of the detector was assumed, but with the position of the detector set to 10 m above sea level. In order to calculate the acceptance, the trigger efficiency $T_{eff}(E_\tau, h_{10})$ shown in Fig. 2B according to the results obtained in Ref. [5], was used. The parameter, h_{10}, corresponds to the height of the shower at 10 km from the tau decay point. In this work the acceptance for a given initial neutrino energy E_ν is given by

$$A(E_\nu) = N_{gen}^{-1} \times \sum_{i=1}^{N_\tau} \sum_{j=1}^{N_{\theta,\phi}} P_{i,j}(E_\nu, E_\tau, \theta) \times T_{eff}(E_\tau, h_{10}) \times A_j(\theta) \times \Delta\Omega, \quad (1)$$

where N_{gen} is the number of generated neutrino events, N_τ is the number of emerging τ leptons from the Earth with energy E_τ^f larger than threshold energy of the detector (E_{th}) for which the decay vertex position is above ground and inside the detector volume, $N_{\theta,\phi}$ is the number of tau leptons coming from a given direction inside the detector volume, $P(E_\nu, E_\tau, \theta)$ is the probability that a neutrino with energy E_ν crossing the distance ΔL would produce a τ lepton with an energy E_τ^i (this probability was used as ”weight” of the event), $\Delta\Omega$ is the space angle. In case of aperture calculations the Eq. (1) was used, but the $T_{eff}(E_\tau, h_{10})$ was set to 1. Finally the total observable rates (number of expected events) on basis of three neutrino fluxes, shown in Fig. 2D, are calculated according to $N = \Delta T \times \int_{E_{th}}^{E_{max}} A(E_\nu) \times \Phi(E_\nu) \times dE$ where $\Phi(E_\nu)$ is the isotropic neutrino flux and ΔT the observation time.

Results

In Fig. 2A the calculated aperture and acceptance are shown for a threshold energy of the detector of $E_\tau > 0.1$ EeV. In case of the Southern site the two computations with the DEM and SP show clear differences: for example, at the energy of 0.3 EeV, the DEM calculations lead to an aperture of about 10% larger than the one obtained with the SP calculation, and to an aperture about 2 times larger at the energy of 10 EeV. In other words the effect on the aperture is energy dependent and it increases by increasing the energy of the initial neutrino. The observed differences are due to the increase of the neutrino cross section with energy. The initial neutrino interacts with the mountains surrounding the Auger site and produces a τ lepton. For higher energies of the initial neutrino, the produced lepton in the mountains can reach the detector from larger distances. In case of the Northern site the calculated aperture with the DEM is almost the same as the aperture with the SP computations. Only for initial neutrino energies larger than a few EeV we can observe that the DEM computations give larger values for the aperture, within 10%, than the SP computations. In case of the acceptance calculations, Fig. 2C, the observed differences between

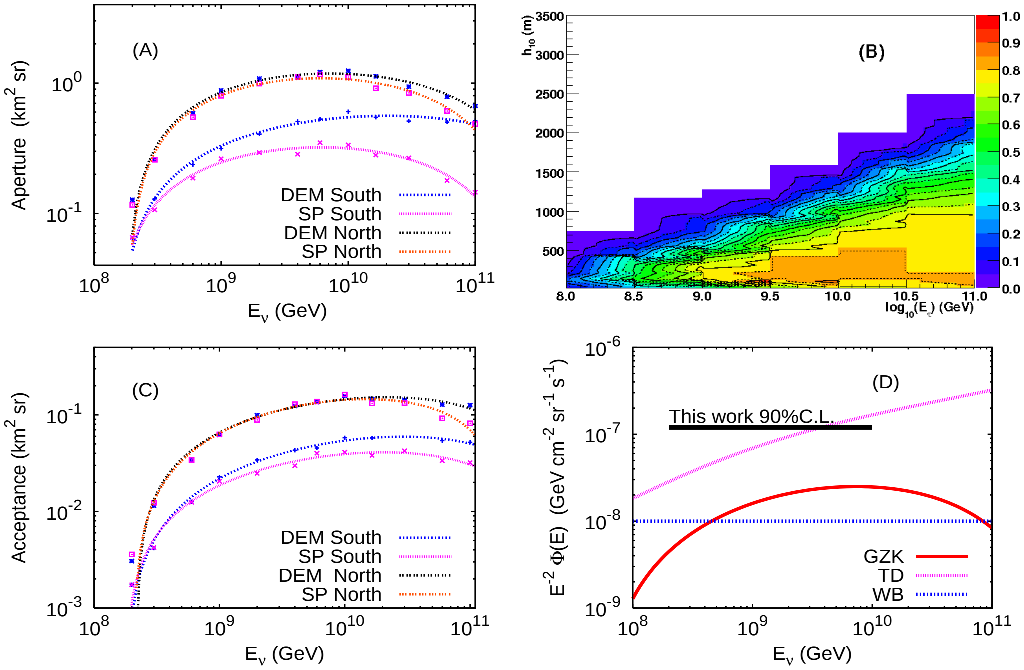

Figure 2: (A) The effective aperture for the Pierre Auger Observatory. Here the computations including the topography of the Auger site (DEM) and with the simple spherical model of the Earth (SP), are shown; (B) The trigger efficiency (including the muon decay channel) as a function of the height h_{10}, see Ref. [5] for more details; (C) The effective acceptance for the Pierre Auger Observatory; (D) Tau neutrino and anti-neutrino fluxes from different theoretical models. In addition the flux limit at 90% C.L. (thick black line) for E^{-2} flux of tau neutrino is shown for one year of operation.

DEM and SP computation are smaller. This is due to the fact that the energy and the zenith angle distribution of the emerging τ leptons are different in case of the DEM and SP calculations. Thus, even if we use the same trigger probability presented in Fig. 2B, the capability to detect neutrino induced showers is not the same in the case of DEM and SP calculations and this effect levels out the differences seen in the aperture. Indeed we have to notice that the acceptance for the Northern site is biased by the assumption of the same trigger efficiency as the one for the Southern site. In case of the Northern site the larger spacing of surfaces detectors as compared to the Southern site is planned. Since the area of the Northern site is not flat, there are many small hills, which can ”shadow” tanks, so that the expected efficiency will be rather smaller than the one for the Southern site.

In Tab. 1 the rate (number of events per year) for the different injected neutrino fluxes, and based on our acceptance and aperture calculation, are listed. The WB rate is obtained for the Waxman-Bahcall bound [6], $\Phi(E_{\nu_\tau+\bar{\nu}_\tau}) = 1 \times 10^{-8} E^{-2}$ (GeV s^{-1} cm^{-2} sr^{-1}). Other rates are calculated for the GZK [7] flux and Topological Defects (TD) [8]. The GZK flux refers to the possible scenario of cosmogenic neutrinos, which are those produced from an initial flux of UHE protons. The TD case is an example of exotic model. To quantify the influence of the topography of the Auger Observatory on the calculated rate, we define the factor $k = (N_{DEM} - N_{SP})/N_{SP}$, where N_{DEM} is the rate calculated with the DEM and N_{SP} the one calculated with the spherical model of the Earth. As one can see from Tab. 1 the rates for the Southern site are about 50% larger, in case of our aperture calculations, and about 20% larger, in case of our acceptance calculations, than the rate calculated with the simple spherical model of the Earth. For the Northern site the calculated rates

		WB			GZK			TD		
		N_{DEM} (yr^{-1})	N_{SP} (yr^{-1})	k (%)	N_{DEM} (yr^{-1})	N_{SP} (yr^{-1})	k (%)	N_{DEM} (yr^{-1})	N_{SP} (yr^{-1})	k (%)
N_{Aper}	SO	3.39	2.27	56	4.85	3.27	43	24.8	16.20	53
	NO	8.22	7.72	6	11.80	11.10	7	58.94	54.95	7
N_{Acc}	SO	0.21	0.18	17	0.33	0.28	18	1.80	1.46	23
	NO	0.59	0.58	2	0.97	0.95	2	5.05	4.93	2

Table 1: Expected event rate in (yr^{-1}) for the Southern (SO) and the Northern (NO) site based on aperture (N_{Aper}) and acceptance calculations (N_{Acc}). The precision on the listed values is about 4%.

are about 7% and 2% larger than the rate for the SP computations, in case of our aperture and the acceptance calculations, respectively.

Finally as an exercise the limit for an injected spectrum $K * \Phi(E)$ with a known shape $\Phi(E) \propto E^{-2}$ is calculated using the same method as the one applied to the Auger data [9]. The 90% C.L. on the value of K according to Ref. [10] is $K_{90\%} = 2.44/N_{WB}$. Assuming a negligible background, zero neutrino events have been observed by the Auger Observatory. In such a case the upper limit for tau neutrinos is $1.2 \pm 0.6 \times 10^{-7}$ GeV km^{-2}yr^{-1}sr^{-1}, where the uncertainty is coming from the poor knowledge of the ν cross-section, the tau lepton energy loss and the tau lepton polarization. This limit is valid in the energy range from 0.1 EeV up to about 10 EeV, where the 90% of the expected events are located.

To conclude, in this work we show a study about the possibility to detect neutrino induced extensive air showers at the Pierre Auger Observatory taking into account the actual topography of the Auger Observatory. We find an enhancement (about 20% wrt a spherical Earth) on the neutrino rate for skimming tau neutrinos for the Southern site. In addition our calculated limit, proves the sensitivity of the Auger Observatory to GZK neutrinos.

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