Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008

Vol. 5 (HE part 2), pages 1369–1372

30TH INTERNATIONAL COSMIC RAY CONFERENCE

Limits to the diffuse flux of UHE tau neutrinos at EeV energies from the Pierre Auger Observatory

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Abstract: With the Pierre Auger Observatory we have the capability of detecting ultra-high energy neutrinos by searching for very inclined showers with a significant electromagnetic component. In this work we discuss the discrimination power of the instrument for earth skimming tau neutrinos with ultra-high energies. Based on the data collected since January 2004 an upper limit to the diffuse flux of neutrinos at EeVenergies is presented and systematic uncertainties are discussed.

Introduction

The nature and the production mechanism of the cosmic rays of ultra-high energy (UHE), above 10^{19} eV, is still unknown. All proposed mechanisms are expected to produce neutrinos. Classical acceleration process of charged particles in astrophysical objects create neutrinos through interactions with the radiation within the source region or with the Cosmic Microwave Background (GZK neutrinos) [1]. In other type scenarios they arise as direct or indirect products of supermassive particles. The τ neutrinos are heavily suppressed at production. In the scenario of neutrino flavor oscillation and a maximal Θ_{23} mixing, the flavor balance changes when neutrinos reach the earth. After travelling cosmological distances, approximately equal fluxes for each flavor are obtained [2]. Tau neutrinos that enter the earth just below the horizon, the so-called skimming neutrinos, may undergo a charged-current interaction to produce a τ. When the interaction happens close to the surface a τ can exit the earth and its decay in the atmosphere can produce an Extended Air Shower (EAS) detectable with the Pierre Auger Observatory [3]. In the EeVrange, this channel has been shown to increase the prospect of detecting UHE neutrinos [4].

Search for neutrinos

UHE particles interacting in the atmosphere give rise to EAS with the electromagnetic component reaching its maximal development after a depth of the order of 1000 $\mathrm{g\,cm^{-2}}$ and extinguishing gradually within the next 1000 $\mathrm{g\,cm^{-2}}$. After a couple of vertical atmospheric depths only the muons survive. As a consequence very inclined showers induced by nuclei (or possibly photons) in the upper atmosphere reach the ground as a thin and flat front of hard muons. On the contrary, if a shower begins development deep in the atmosphere (a tau decay) its electromagnetic component can reach the ground and give a distinct broad signal. Therefore, the detection of very inclined showers with a significant electromagnetic component are a clear indication for UHE neutrinos.

The signal in each station of the surface detector is digitised using FADCs, allowing us to unambiguously distinguish the narrow signals from the broad ones and thus to discriminate stations with and without electromagnetic component (figure 1). We tag the stations for which the main segment of its FADC trace has 13 or more neighbour bins over the threshold of 0.2 VEM [5] and the area over peak ratio [6] is larger than 1.4. The event is selected if the tagged stations fulfil the trigger condition and they contain most of the signal. After this

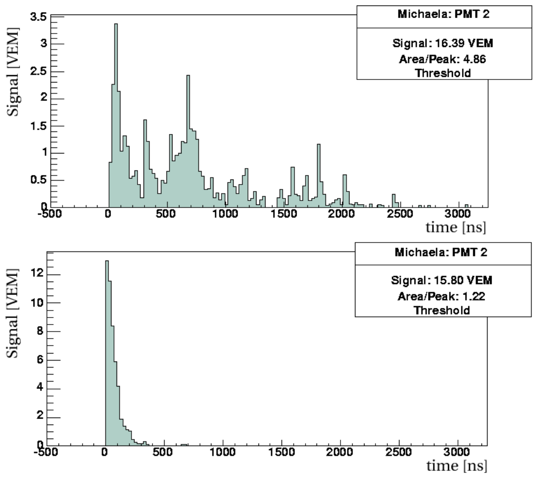

Figure 1: FADC traces from a station of two different real showers after subtraction of baseline and calibration. Top: moderately inclined (40°); bottom: quasi-horizontal (80°).

selection, an almost pure sample of young showers is isolated.

The next step uses the footprint of local stations included in the global trigger to select very inclined showers. First a tensor is built using the station signals and the ground positions (in analogy to the inertia tensor) and the corresponding major and minor axes are used to define a "length" and a "width". Then, for each pair (i,j) of tanks, a "ground speed" is defined as $d_{i,j}/|\Delta t_{i,j}|$, where $d_{i,j}$ is the distance between them (projected onto the major axis) and $|\Delta t_{i,j}|$ is the difference between the start times of their signals. Horizontal showers have an elongated shaped (large value of length/width) and they have ground speeds tightly concentrated around the speed of light. In figure 2, we show the distributions of these discriminating variables for real events and simulated tau showers. The following cuts are applied: length/width > 5, average speed $\in$ (0.29,0.31) m ns^{-1} and r.m.s.(speed) $<$ 0.08 m ns^{-1}. We keep about 80 $\%$ of the τ showers that trigger the surface detector. The final sample is expected to be free of background.

Acceptance and neutrino limit

Both the criteria to identify neutrino induced showers and the calculation of the ν_τ acceptance are based on Monte Carlo techniques. The former uses the simulation of the shower development in the atmosphere as well as the detector response. The latter needs the simulation of the interactions that happen while the neutrino crosses the earth [7].

The total acceptance collected from January 2004 until December 2006 with the Pierre Auger Observatory is the time integration of the instantaneous aperture.

$$Acc(E_\nu) = \int_0^{E_\nu} dE_\tau \int_0^\infty dh_c \left(\frac{d^2 N_\tau}{dE_\tau dh_c} Acc_\tau \right)$$

$$Acc_\tau(E_\tau, h_c) =$$

$$= \int_T dt \int_A dxdy\, I_{eff}(E_\tau, h_c, x, y, A_{Conf}(t))$$

where $dN_\tau/dE_\tau dh_c$ is the flux of emerging τs and I_{eff} the probability to identify a τ. It depends on the energy of the τ (E_τ), the altitude of the shower center defined 10 km after the decay point (h_c) [4], the instantaneous configuration of the detector ($A_{Conf}(t)$), and the relative position of the shower footprint in the array (x, y).

The $Acc(E_\nu)$ is computed by Monte Carlo in two independent steps. First, the integral on time and area are performed using the simulations of the EAS and the detector, allowing us to account for the time evolution of the detector. The second step computes the integral on h_c and E_τ by adding $Acc_\tau(E_\tau, h_c)$ for all emerging τ, given by the simulation of the earth interactions. The statistical precision due to the statistic of the Monte Carlo simulation is at a few percent level.

The Monte Carlo simulations use several physical magnitudes that have not been experimentally measured at the relevant energy range, namely the ν cross-section, the τ energy losses and the τ polarisation. We estimate the uncertainty in the acceptance due to the first two to be 15$\%$ and 40$\%$ respectively, based on Particle Distribution Function (PDF) uncertianties. The two polarizations give 30$\%$ difference in acceptance. We take it as the corresponding uncertainty. The relevant range for

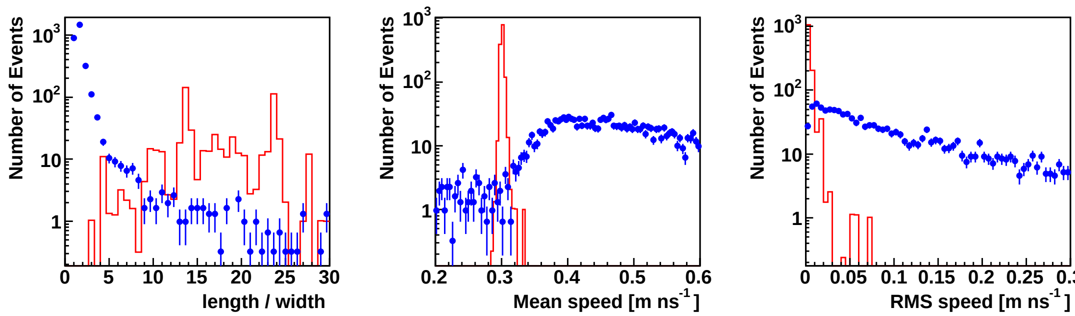

Figure 2: Distribution of discriminating variables for neutrinos with an E^{-2} flux (histogram) and real events passing the "young shower" selection (points). Left: length/width ratio; middle: average of the speed between pairs of stations; right: r.m.s. of the speeds.

PDFs includes combinations of x and Q^2 where no experimental data exist. Different extrapolations to low x and high Q^2 would lead to a wide range of values for the ν cross-section as well as the τ energy losses. The uncertainties on the low x regime as well as possible large ν cross-sections have not been added on the quoted systematics.

We also took into account uncertainties coming from neglecting the actual topography around the site of the Pierre Auger Observatory (18%). We are confident on the simulations of the interactions undergoing in the earth at 5 % level. And we quote a 25 % systematic uncertainty due to Monte Carlo simulations of the EAS and the detector.

Data from January 2004 until December 2006, which equate to about 1 year from the completed surface detector, have been analysed. In figure 3, we show the collected acceptance on the analysed period, for the most and least favourable scenarios of the systematics. Over that period, there is not a single event that fulfils the selection criteria. Based on that, the Pierre Auger Observatory data can be used to put a limit for an injected spectrum $K \cdot \Phi(E)$ with a known shape. For an E^{-2} incident spectrum of diffuse ν_τ, the 90% CL limit is $E_\nu^2 \cdot dN_{\nu\tau}/dE_\nu < 1.5^{+0.5}_{-0.8}\ 10^{-7}$ GeV cm^{-2} sr^{-1} s^{-1}, where the uncertainties come from the systematics. The central value is computed using the ν cross-section from [8], the energy losses from [9] and an uniform random distribution for the tau polarisation. The bound is drawn for the energy range 2 10^{17}-5 10^{19} eV over which 90% of the events are expected. In figure 4, we show the limit from the Pierre Auger Observatory in the most pessimistic scenario of systematic uncertainties. It improves by a factor ~3 in the most optimistic one. Limits from other experiments are also shown assuming a $1:1:1$ balance among flavors due to the oscillations.

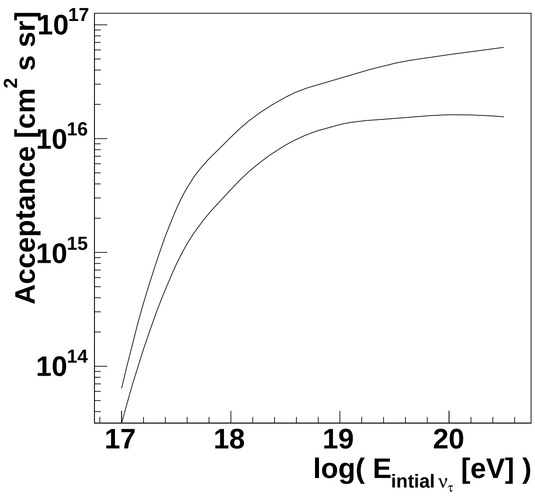

Figure 3: The Pierre Auger Observatory acceptance from January 2004 until December 2006 for the most and least favourable scenarios of the systematics.

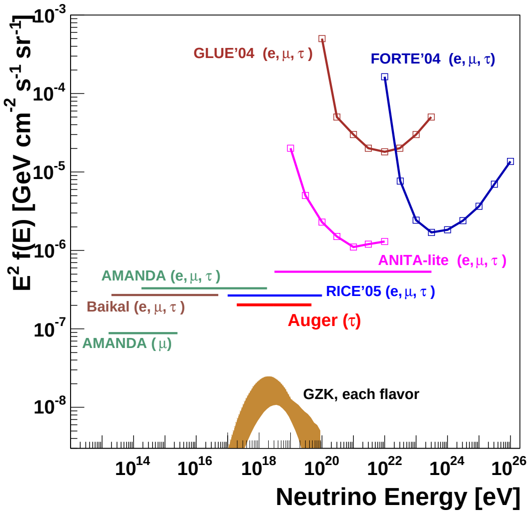

Figure 4: Limit at 90% C.L. to an E^{-2} diffuse flux of ν_τ at EeV energies from the Pierre Auger Observatory. Limits from other experiments [10, 11, 12, 13, 14, 15, 16] as well as fluxes for GZK ν [17, 18] are also shown. For each experiment, the flavors to which is sensitive are stated.

Summary and Prospects

The dataset from January 2004 until December 2006, collected by the Pierre Auger Observatory, is used to present upper limits on the diffuse incident ν_τ flux. The skimming technique is flavor sensitive and together with the configuration of the surface detector gives the best sensitivity around few EeV, which is the most relevant energy to explore GZK neutrinos. The limit is still considerably higher than GZK neutrino predictions. Neutrinos that interact in the atmosphere can also be distinguished from nucleon showers [7]. Hence, the Pierre Auger Observatory can explore UHE νs with two techniques that depend differently on ν properties like flavour or cross-section. The Pierre Auger Observatory will keep taking data for about 20 years over which the bound will improve by over an order of magnitude if no neutrino candidate is found.

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