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HiRes Limits on the Tau Neutrino Flux at the Highest Energies

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Abstract: Data from the High Resolution Fly's Eye detector that measures cosmic rays with the fluorescence technique is used to set limits on the flux of tau neutrinos in the energy range from 10^{17} to 10^{21} eV. This energy range is particularly interesting as we expect a guaranteed flux of cosmogenic neutrinos from the GZK mechanism.

Introduction

Cosmogenic neutrinos are neutrinos generated by cosmic rays (CRs) as they propagate over cosmological distances and lose energy in interactions on various photon backgrounds. Excitations of the Δ^+ resonance in protons moving through the Cosmic Microwave Background (CMB) are predicted for proton energies above $\sim 6 \times 10^{19}$ eV [1]. With the GZK feature evident in the HiRes monocular spectra, and with the early Auger spectrum in good agreement with HiRes at the relevant energies, there is a strong case for the existence of cosmogenic neutrinos. In 2003 Semikoz and Sigl explored the constraints on cosmogenic neutrino fluxes imposed by the measured CR and gamma ray fluxes [2]. In a separate paper submitted to this conference we calculate the neutrino fluxes expected from our fits of power law sources with redshift evolution to the HiRes monocular spectra.

The HiRes Detector

The HiRes experiment consists of two detector sites located 12.6 km apart that each monitor the surrounding sky for fluorescence emission from extensive air showers. On clear, moonless nights individual telescopes continuously survey a patch of the sky that measures roughly 16 degree along the horizon and 14 degree in elevation. 256 photomultiplier tubes (PMTs) per telescope allow a pixelisation with a pixel size of 1 degree in the sky. If all telescopes are online, both detectors achieve nearly full coverage in azimuth. HiRes 1 (HR1) has 22 telescopes viewing the elevation band from 3 degree above the horizon to 17 degree above the horizon. It is equipped with sample-and-hold electronics that record the threshold crossing time for each pixel and a charge integral over 3.6 μs. HiRes 2 (HR2) has 42 mirrors that cover elevations from 3 to 33 degree. It is equipped with flash-ADC electronics that trace the signal evolution for every pixel with 100 ns resolution over 10 μs.

Monte Carlo Simulation

Our Monte Carlo (MC) simulation of neutrino interactions and tau propagation and decay is based on the All Neutrino Interaction Generator (ANIS) [3]. ANIS incorporates a model of the earth interior with the appropriate density changes between inner and outer core and mantle. It offers two alternatives for the extrapolation of neutrino cross sections: A smooth power-law extrapolation of pQCD CTEQ5 structure functions, and a hard pomeron enhanced extrapolation. The two differ by about a factor of three at 10^{20} eV. Our calculations were done with the lower cross section extrapolation that did not have the pomeron enhancement. As far as the cross sections are concerned our limit should therefore be conservative, but neutrino cross section extrapolation is the major systematic uncertainty in this analysis.

ANIS also incorporates code for the propagation and decay of the tau leptons. The intrinsically stochastic energy losses at high energy are approximated by a smooth energy loss function. For HiRes the ensuing suppression of potential subshowers resulting from catastrophic energy loss events along the path of the tau lepton is not much of a concern, as the trigger threshold of the detector even for very close events if of order 10^{16} eV. Tau decays in ANIS are modeled with the TAUOLA package.

As ANIS was designed for underground detectors, it has neither an atmosphere nor any topographic structure on the earth surface built into it. We integrated both a US standard desert atmosphere [4] and the detailed surface topography of the surroundings of the HiRes detectors. The elevation model we incorporated is based on a 30 arcsec grid [5].

Figure 1 is a scatter plot of the ν_τ interaction points for ν_τ where the ensuing tau lepton decays above ground. The figure clearly highlights the role of the surrounding mountains as target mass. It can also be seen that HR1 has greater proximity to the bulk of that target mass. While ν_τ interactions in the atmosphere are not suppressed in this simulation, they do not play a role due to the limited target mass available.

A prominent feature of the tau leptons that emerge into the atmosphere is that their zenith angles are concentrated within a few degrees from horizontal. Figure 2 shows the distribution of zenith angles of the tau leptons that decay in the atmosphere. Zenith angles larger than 90 degree are upward going. We exploit this feature to constrain the neutrino injection directions to ± 10 degree above and below the local horizon at HiRes, thus saving significant computing time in our simulations. We also limit the impact parameter of neutrino trajectories to within 75 km of the geometrical center between HR1 and HR2.

The tau leptons decay to 70% into hadronic decay channels. Charged pion initiated showers are used in the subsequent shower simulation. In case a leptonic decay channel is entered, the ensuing lower energy tau is followed on, a muon is given up as unobservable, and an electron fed into the appropriate electromagnetic shower simulation.

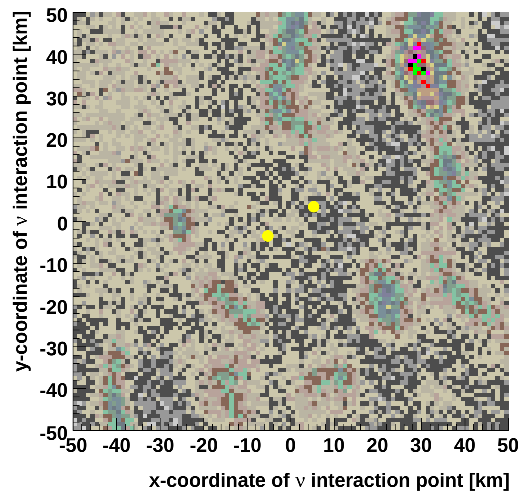

Figure 1: A map of the surroundings of the HiRes detectors made from the interaction points of tau neutrinos for which the tau leptons decay in the atmosphere. The mountains are visible in green, and two yellow dots mark the positions of the HiRes detectors.

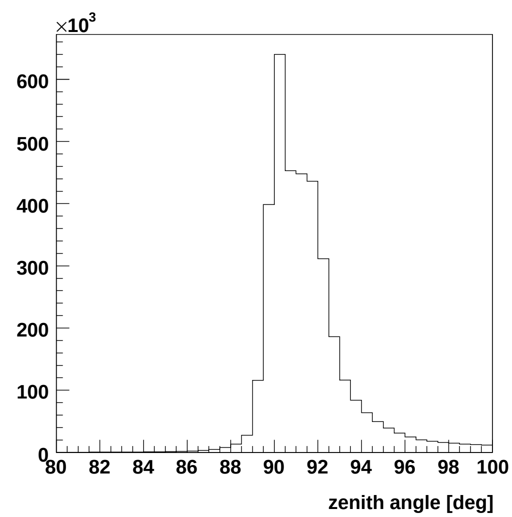

Figure 2: Zenith angles of tau lepton directions for tau leptons that decay in the atmosphere.

For the hadronic decays air shower simulation is carried out with the help of CORSIKA [6] version 6.200. Shower libraries are generated using QGSJET [7] that contain 400 quasi-horizontal hadronic showers each in a matrix of thirteen evenly spaced energies from 10^{15} eV to 10^{21} eV and nine evenly spaced heights between 1 km and 5 km above ground. After a suitable tau decay is identified in the ANIS output, a set of shower parameters is chosen randomly from the appropriate library, and scaled from the nearest energy found in the library to the energy extracted from the ANIS simulation. These shower parameters and the ANIS generated event location and direction are then handed over to the standard version of the HiRes stereo Detector Monte Carlo (DMC) program. If the tau lepton decays to an electron, the DMC itself generates the appropriate profile for an electromagnetic shower.

The DMC generates fluorescence (and Cherenkov) light according to the geometry and energy of the shower, propagates both through the atmosphere towards the detector, and performs a detailed simulation of the detector response.

494 M tau neutrinos with impact parameters up to 75 km were injected into ANIS. Their input energies were distributed between 10^{18} and 10^{21} eV according to an E^{-2} differential spectrum. While there was no constraint on the azimuth angle of the neutrino injection, the zenith angle was constrained to within ± 10 degree of the horizon. From this input we got a total of 5829 events that triggered the detector: 4243 triggers in HR1, and 2456 in HR2. 870 events were seen in stereo.

HiRes Data and Analysis

The HR1 data used in this analysis stem from the equivalent of 20,132,360 seconds of operation with all HR1 mirrors and were taken between 05/1997 and 11/2005. The HR2 data were taken over the equivalent of 13,096,693 seconds of operation with all HR2 mirrors between 10/1999 and 11/2005. This data set includes 10,128,727 seconds of stereo operation. A total of 75 million data records were analyzed. In a first step noise events and artificial light sources are eliminated.

The relevant variables characterizing the EAS geometry are the zenith angle Θ, the azimuth angle Φ, and the impact parameter R_p of the shower axis with respect to the individual detector location:

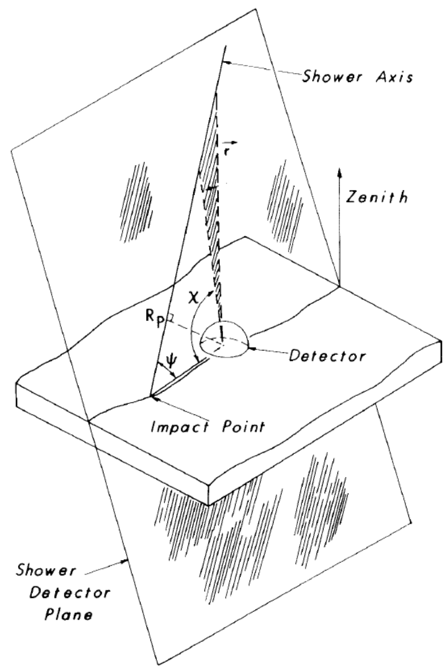

Figure 3: Basic geometry of air shower reconstruction: Detector location and EAS axis define the shower detector plane. The zenith angle of the shower is defined with respect to the vertical so that a vertically downward moving shower has a zenith angle of zero degree.

Two defining characteristics identify our ν_τ events:
- They are horizontal (zenith angle cut)
- They are low in the atmosphere (R_p cut)

The last criterion is not trivial as very high up in the atmosphere CR events can develop almost horizontally. In order to reliably extract ν_τ events we impose cuts on the quality of the event reconstruction. After these quality cuts and application of an $R_p < 20$ km cut events with reconstructed zenith angles between 88.8 and 95.1 degree (1.55 and 1.66 radians) are kept as neutrino candidates. With these cuts we keep 366 neutrino MC events in HR1 and 209 in HR2, out of which 21 are stereo events.

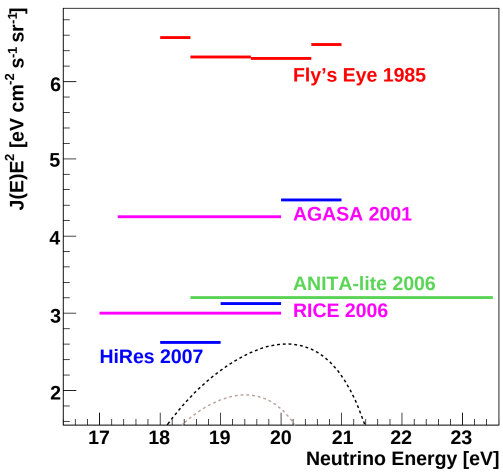

Figure 4: The HiRes ν_τ limits in context. The solid line outlines the maximal flux from [2] consistent with both CR and the EGRET diffuse γ limit. The dashed line exhausts only 20% of the EGRET limit.

Applying the same criteria to the data yields 75 events from HR1 and 59 events from HR2. All of these 134 neutrino candidate events are unfortunately laser events. The reason that these events pass all our laser cuts have to do with weather: Light scattered off haze near the ground lets these particular events reconstruct as horizontal. Unlike true neutrino events their individual geometries can all be shown to repeat that of another event inside or outside of the set of selected neutrino candidates. Our conclusion is that HiRes has zero neutrino candidates, and the resultant limits on the neutrino flux are based on Feldman/Cousins unified confidence intervals and shown in figure 4.

Conclusions

Searching for horizontal showers low in the atmosphere HiRes has set a new limit on tau neutrino fluxes. For neutrino energies from 10^{18} through 10^{19} eV these new limits are the best currently available. At 10^{19} eV the tau lepton decay length (not counting energy losses) reaches 500 km, so that despite the growing cross section for neutrino interaction the subsequent tau lepton decay at higher energies increasingly is pushed beyond the physical limits of the atmosphere.

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