Neutrino Flux Upper Limit from the Pierre Auger Observatory

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Abstract. Neutrino astronomy is an interesting and developing tool for understanding the Universe. Both surface detectors and fluorescence detectors of the Pierre Auger Observatory are sensitive to neutrino induced extensive air showers. Such events may be distinguished from hadronic showers by searching for inclined showers originating close to the detector – these events would have significant electromagnetic component leading to a broad signals in surface detector stations in contrast to short pulses caused nucleonic showers. In the present data from the surface detectors no such shower has been observed so upper limits to the neutrino flux have been calculated and presented.

Introduction

Neutrinos are a promising source of information about processes in the Universe. They interact only through the weak interactions, so they are not significantly affected by electromagnetic fields nor matter along the path of propagation inside and outside the source. Neutrinos are tightly connected to the process of acceleration of cosmic particles via photo-meson production or via proton-proton interaction. Direction of the incoming neutrino therefore points back to its source. Measuring or putting limits on neutrino flux it is possible to constrain the models of cosmic ray (CR) generation and propagation.

There has been many works predicting neutrino fluxes from various sources using various models (for overview of neutrino astronomy see work [Geisser et al., 1995]). Apart from astrophysical sources of neutrinos, Greisse-Zatsepin-Kuzmin (GZK) cutoff (Greissen (1966), Zatsepin, Kuzmin (1966)) would be one of important sources for the possible detection of neutrinos at the Pierre Auger Observatory. It is a process when ultra-high energy (UHE) particles interact with cosmic microwave background producing unstable pions that decay into muons and neutrinos. Analogous effect occurs of course even for optical and infrared photons as well. This effect should significantly reduce the energy of CR travelling cosmological distances and produce flux of neutrinos at energies $10^{17} – 10^{20}$ eV (see figure 2).

Neutrino’s low interaction probability is, however, not only virtue but also vice. Small cross section causes difficulties for detection of the cosmic neutrinos on the Earth. Experiments focused on neutrino detection at highest energies $> 10^{17}$ eV must be in kilometre scales in order to get reasonable event rates.

The Pierre Auger Observatory, among other important results, has published also the upper limits for neutrino fluxes. Mass composition estimation of the CR is not possible event by event so identification of neutrinos must be done by a special approach. The identification of neutrino induced showers is based on study of deeply penetrating down-going inclined showers and up-going showers. The two methods are different: while down-going showers may be induced by neutrinos of all flavours and have hadronic background, up-going showers may be generated only by tauon neutrinos with almost no background. So far only data from surface detectors have been used although fluorescence detectors allow neutrino detection as well, however, with shorter measurement time.

Pierre Auger Observatory

The Pierre Auger Observatory is a hybrid detector of the UHE CR. It observes extensive air showers (EAS) induced by a collision of a cosmic particle with an air nucleus of the Earth atmosphere. The hybrid design of the Observatory combines detection of the showers using two physical principles: observing fluorescence photons emitted by excited nitrogen molecules and direct detection of secondary particles of EAS at the Earth surface. The fluorescence detector (FD) consists of 24 telescopes placed in 4 sites. Each telescope has the field of view 2° to 30° in elevation above the horizon and 30° in azimuth. The surface detectors are water Cherenkov counters and they are placed in triangular grid with 1.5 km spacing. In total the surface detector array (SD) covers 3,000 km² using 1,600 water tanks. The Observatory is designed to be sensitive at the CR energies above approximately $E > 10^{17.5}$ eV.

The advantage of using SD is that it may operate 24 hours of a day, while FD data are taken in about 13% of the total year time. Combination of these two approaches allows the Pierre Auger Observatory to
take advantages of both by calibrating SD by FD data (using hybrid events – showers that were detected simultaneously by SD and FD). As a result, reconstruction of SD data is more precise and less model dependent.

Properties of Neutrino Induced Showers

When a cosmic ray particle (proton or a nucleus) enters the atmosphere, it interacts within few tens of g/cm$^2$ and the shower development to the depth with maximum number of particles $X_{\text{max}}$ is not more than a few thousand g/cm$^2$. The extremely small cross section of neutrino interaction however causes that neutrino may interact deep in the atmosphere or under the Earth surface. A flux of neutrinos would cause existence of showers originating also in points close to the detector from the directions where no hadronic shower should be observable. In the horizontal direction the track trough the atmosphere is about 36 times longer than in the vertical direction so there is very unlikely that proton or nucleus penetrates that deep. In the case of the up-going showers, once again, no proton or nucleus would be able to traverse the Earth crust and cause such a shower. The fact that the interaction occurs close to the detector means that the showers are young – they are in early stage of their development: they have strong electromagnetic component creating broad signal in the detector, and their shower front is curved. Very inclined and young showers are therefore direct signatures of neutrino (or other exotic) interactions.

The neutrino interaction has more channels and each of them must be treated separately. In the Standard Model, it may interact through the weak interactions: either via charged current – the exchange of the $W$ boson – or via neutral current – exchange of the $Z$ boson. In the case of the neutral currents, $\nu + N \rightarrow \nu + \text{hadrons}$, the neutrino interaction is a deep inelastic scattering. This process is the same for all flavours. However, when a neutrino interacts through the charged current, $\nu_l + N \rightarrow l + \text{hadrons}$, different leptons in the final state are created leading to different properties of the shower. These generated leptons carry about 75% of neutrino’s energy [Anchordoqui et al., 2006]. In the vertex there is always a shower started for all the flavours.

For the charged currents, if the neutrino is of the electron flavour, the generated electron interacts immediately and starts a shower, which is mixed with the shower from the neutrino interaction with a nucleus. When a tauon is created, it does not induce electromagnetic shower because it is too heavy to radiate bremsstrahlung. However, its lifetime is short so after propagating certain distance it decays and creates a new shower – a double-bang event. Then two spatially separated showers may be distinguished: one from the neutrino interaction and the other from tau decay. In this case it may also happen that the neutrino interaction occurs in the Earth crust and the tauon penetrates all the way to the atmosphere and generates an up-going EAS. When a muon is generated, only the shower from vertex is present. It is because muon is too heavy to radiate strong enough bremsstrahlung to start a shower and it is also stable so it is very likely that it escapes detector volume before its decay. An illustration of interactions of neutrino in different channels is in the figure 1.

The $N\nu$ cross section increases with increasing neutrino energy. This means that at high energies the Earth becomes opaque for neutrinos. Up-going showers however still may appear for Earth skimming tau neutrinos due to the fact that generated tauon may penetrate to the atmosphere and decay in the active detector volume. In the case of tau neutrino regeneration effect may also occur: when tau neutrino interacts in the Earth crust it produces tauon that decays or interacts and produces another tau neutrino with smaller energy. Down going inclined showers may be induced by any neutrino.

![Figure 1. Illustration of neutrino interactions with air in different channels and for different flavours. The picture is taken from [Tiffenberg for the Pierre Auger Collaboration, 2009].](image-url)
Results of the Pierre Auger Observatory

The neutrino identification based on data from SD is based on several parameters, as described in detail elsewhere [Pierre Auger Collaboration 2009, Tiffenberg for the Pierre Auger Collaboration, 2009]. Two kinds of the parameters are used: first type selects horizontal showers are chosen and the other type is used to find young showers. While parameters to find horizontal showers are the same for up and down going showers, the youth of the showers must be recognized differently for the two opposite directions.

If we denote $L$ the length and $W$ the width of the footprint of a shower in the SD array (i.e. shape of the area in which the individual detectors were triggered), than the parameter $L/W$ should distinguish the horizontal shower. In order to lower the number of background events, two more parameters are calculated: apparent velocity $<v>$ and its dispersion $\sigma_v$. Apparent velocity is the velocity with which the signal was detected on the ground along the longest axis of the shower footprint. It is defined as the mean value of the fraction $d_{ij}/t_{ij}$ where $d_{ij}$ is the distance between the tanks $i$ and $j$ and $t_{ij}$ the time difference of the first signals in the tanks. If the shower front was planar, this apparent velocity should be $<v>=c/\sin \theta$ where $c$ is the speed of light (approximately equal to the speed of the shower) and $\theta$ the azimuth angle. However, the shower front is in fact curved so the formula is only approximate.

For horizontal showers apparent velocity should be close to the speed of light but for vertical shower it should be much greater. Dispersion of apparent velocity eliminates accidental coincidence.

Youth of a shower may be recognized by examining signal in the first triggered tanks. Typically, a signal from a young horizontal shower should last for about 1 $\mu$s around the maximum of the shower and 150 ns at the tail. For up-going showers good parameters are the ratio of the number of detectors passing strengthened trigger requirements (condition for broad enough signal) over the total number of triggered detectors, rise time and fall time of first triggered detectors. Rise time and fall time are defined as the time interval during which $10-50\%$ and $50-90\%$ respectively, of the signal is collected.

For down-going showers $\text{AoP}$ (area over peak – the area under the curve of signal as a function of time over its peak) however proved to be a strong and simple parameter for identification neutrinos. For the 4 first triggered stations the $(\text{AoP})^2$ and $(\text{AoP}_1 \ast \text{AoP}_2 \ast \text{AoP}_3 \ast \text{AoP}_4)$ and also a global early-late asymmetry $(\text{AoP}_{\text{early}} \ast \text{AoP}_{\text{late}})$ are calculated. Because background is expected, the proper identification values must be found using Fisher’s method combining all the sensitive parameters into one Fisher variable [R. Fisher (1936)].

Running simulations one may calculate trigger efficiency as the fraction of the number of the showers passing the triggers and the total number of simulated neutrino events. Efficiency of identification of neutrino showers may be calculated analogously using beside the triggers also the identification conditions.

When a diffuse flux of neutrinos $\Phi(E_\nu)$ at neutrino energy $E_\nu$ is assumed and acceptance $A(E_\nu)$ is known including effects of topography, geometry as well as identification efficiency, the number of observed events $N$ in time $\Delta T$ is

$$N = \Delta T \int_{E_{\nu\text{min}}}^{E_{\nu\text{max}}} A(E_\nu) \Phi(E_\nu) dE_\nu. \quad (1)$$

Acceptance is in fact a function of time as the SD area was constantly growing. It is also subject to systematic uncertainties given e.g. by the uncertainty of neutrino cross-section at ultra-high energies.

With a positive signal, the differential flux may be calculated as

$$\Phi(E) = \frac{N(E_\nu)}{E_\nu \Delta \ln(E_\nu) \Delta T A(E_\nu)} \quad (2)$$

and assuming $\Phi = k E^{-2}$ the integrated flux yields

$$k = \frac{N}{\Delta T \int A(E_\nu) E_\nu^2 dE_\nu}. \quad (3)$$

When no events are observed then within 90\% confidence level and with no background, value $N=2.44$ should be used [Feldman, Cousins, 1998].

So far, the Pierre Auger Observatory detected no events so only upper limits are given [Tiffenberg for the Pierre Auger Collaboration, 2009]:

$$k < 3.2 \times 10^{-7} \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \quad \text{for all down going } \nu \quad (4)$$

$$k < 4.7^{+2.5}_{-2.2} \times 10^{-8} \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \quad \text{for up going } \nu_\tau. \quad (5)$$
Figure 2. Calculated upper limits of neutrino fluxes compared to limits of the other experiments and theoretical flux of GZK neutrinos. Picture is taken from [Tiffenberg for the Pierre Auger Collaboration, 2009].

The integrated and differential upper limits for up-going tau neutrinos and down-going neutrinos of all flavours compared to the limits from other experiments are drawn in the figure 2.

For the fluorescence telescopes no systematic study has been done so far. Due to only 13% duty cycle there is much less data. On the other hand, the effective volume of the detector is greater, especially for higher neutrino energy. This growth of the effective volume for high energies should partially compensate the lack of data resulting in the similar sensitivity as for the SD and the resulting upper flux limits should be comparable.

Summary

Surface detector array of the Pierre Auger Observatory is sensitive to neutrino induced air showers and allows identification of them among the background of hadronic showers for nearly horizontal and up-going showers. Since no such event has been observed, upper limits may be calculated. In the case of up-going showers, the surface detectors are mostly sensitive to tau neutrinos. No systematic study of identification of neutrinos using the fluorescence detectors has been performed but this work is in progress and results should be expected soon. This method will be independent and will complement the results from the SD. If no neutrino will be observed, the Observatory will lower the upper limit by more than one order in magnitude during 20 years of planned operation.

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