NEUTRINO INDUCED EVENTS
IN THE PIERRE AUGER DETECTOR

GONZALO PARENTE and ENRIQUE ZAS
Departamento de Partículas, Universidad de Santiago
15706 Santiago de Compostela, Spain
E-mail: zas@gaes.usc.es

ABSTRACT

We study the potential of the Pierre Auger detector for horizontal air showers initiated by ultra high energy neutrino. Assuming some simple trigger requirements we obtain measurable event rates for neutrino fluxes from AGN, from topological defects and from the interactions of cosmic rays with the microwave background.

1. Introduction

It has been known for a long time that deeply penetrating high energy particles such as muons and neutrinos initiate horizontal air showers that can be detected at ground level [1)]. Since the interaction length for muons and neutrinos in the atmosphere is larger than the whole atmospheric depth, they have roughly equal probability to interact at any point in the atmosphere. On the other hand, the rate of air showers due to the hadronic particles, that constitute the bulk of the cosmic rays, decreases very rapidly with zenith angle as the atmospheric depth rises from about 1000 $g\,cm^{-2}$ in the vertical direction to close to 36000 $g\,cm^{-2}$ horizontally. The electromagnetic component of air showers started by electrons, photons and hadrons gets absorbed well before reaching the Earth's surface and only the muon component of the shower survives for sufficiently large zenith angles. A detector that is able to identify the electromagnetic component of air showers is then capable of identifying horizontal showers induced by such penetrating particles. Such an array will mainly trigger on horizontal showers that initiate at the appropriate depth so that the shower is close to shower maximum when it reaches the array.

The recent agreement between calculations of diffuse neutrino fluxes from Active Galactic Nuclei (AGN) has raised a lot of expectations for neutrino telescopes that are currently under development and construction. Although horizontal showers have ruled out an early prediction of neutrino fluxes from AGN [2)], these fluxes extend to the PeV region where the corresponding horizontal shower rate is very close to that expected from hard bremsstrahlung of the conventional atmospheric muon flux (produced in π and κ decays). Horizontal showers are currently being studied by several ground arrays because they should provide complementary information on prompt muon and neutrino production in the atmosphere which can be related to production of charm [3)] and of cosmic ray composition around the knee [5)]. It is accepted that the most appropriate technique for neutrino detection consists on detecting the Čerenkov light from muons or showers produced by the neutrino interactions in water or ice[4)].

The situation is however different for still higher energy neutrinos where the project to build two 3000 km^2 particle arrays one in each hemisphere (Pierre Auger Detector) may play an interesting role. The project is discussed in a separate article in these proceedings[6)]. The reference design combines an array of particle detectors and an air fluorescence device similar to Fly's Eye to detect cosmic ray air showers of energies above 10^{19} eV. The proposed particle detectors are water Čerenkov tanks, very appropriate for detecting particles arriving horizontally. The detector will be most efficient for high zenith angle showers of energy above 10^{19} eV when a large number of detectors of the array register significant signals. The electromagnetic component is separated from the muon component on the basis of the individual muon pulses that stand out of the average signal produced by the electromagnetic component of the shower. Neutrino predictions of such energies include those from interactions of the cosmic rays with the cosmic microwave background which have a solid foundation and would be of enormous value to establish the Greisen-Zatsepin-Kuz'min cutoff, as well as more speculative sources such as topological defects[7,8)] and primordial black holes[9)].

2. Large Showers from Neutrinos

Neutrinos produce showers in most interactions with the atmosphere but the showers are of different nature depending on the process in consideration. In the interactions the target nucleons break up and the debris behaves as a group of hadrons that results in a shower similar to those induced by regular hadronic cosmic rays. Such shower is produced in both neutral and charged current interactions. If the neutrino is of electron flavor there will be an additional shower produced by the electron at the leptonic vertex of charged current interactions. This shower is of electromagnetic type, somewhat narrower and with a smaller muon content than the hadronic showers. The resulting shower for the charged current interactions of electron neutrinos is thus a superposition of two parallel showers one of hadronic type and the other electromagnetic. For high energy neutrino interactions the average fractional energy transfer to the nucleon in the lab frame (y) is $< y > \simeq 0.2$ so the electromagnetic shower carries on average 80% of the neutrino energy and is therefore most important. The interactions of the neutrinos with the electrons have in general much smaller cross sections and can be disregarded except for the resonant electron-antineutrino electron interaction which dominates just for neutrino energies around the resonant value of 6.4 PeV. In that case the character of the shower depends on the disintegration channel of the produced W boson in the s-channel.

The showers regardless of their character can be detected by a particle array if they are initiated at an appropriate distance by a neutrino with sufficient energy.

They will resemble ordinary air showers the main difference being that horizontal showers develop in a more uniform atmosphere. Electromagnetic showers should have lateral and depth distributions according to standard parametrizations when the corresponding lengths are measured in depth (g cm^{-2}). Similarly we assume that hadronic showers will be not too different to ordinary cosmic ray showers. Large zenith angle showers of energies above the array threshold can be detected if a suitable trigger is selected, provided the plane of the array intersects the shower at a location where the number of particles is close to its maximum. This is a conservative statement since the particle detectors of the array are more closely distributed in the transverse plane to a near horizontal shower. The triggering to be developed will be however very different from the standard trigger for vertical showers, in particular the relative timing of the signals in adjacent detectors will reflect the shower propagation across the array.

3. Event Rates

For a neutrino flux $d\Phi_\nu/dE_\nu$ interacting through a process with differential cross section $d\sigma/dy$, where y is the fraction of the incident particle energy transferred to the target, the event rate for horizontal showers can be obtained by a simple convolution:

$$\Phi_{sh}[E_{sh} > E_{th}] = N_a \rho_{air} \int_{E_{th}}^{\infty} dE_{sh} \int_0^1 dy \, \frac{d\Phi_\nu}{dE_\nu}(E_\nu) \, \frac{d\sigma}{dy}(E_\nu, y) \, \mathcal{A}(y, E_\nu) \tag{1}$$

where N_a is Avogadro's number and ρ_{air} is the air density. The energy integral corresponds to the shower energy E_{sh} which is related to the primary neutrino energy E_ν in a different way depending on the interaction being considered. $\mathcal{A}$ is a geometric acceptance which contains the volume and solid angle integrals for different shower positions and orientations with respect to the array.

3.1. Acceptance

We define the effective acceptance $\mathcal{A}$ as the integral over volume and solid angle in $d\Omega = d\phi d(\sin\bar{\theta})$ where ϕ is the azimuthal angle in the array plane. It depends on the energy transfer to the shower and on the type of shower produced in the interaction. We take the shower axis to go through the array and assume showers are large enough to trigger when they start at an adequate point. The effective area is then simply given by $S \sin\bar{\theta}$ where S is the area covered by the array and $\bar{\theta} = 90^o - \theta_z$ is the angle between the neutrino arrival direction and the array plane, (complementary to the zenith angle). To obtain the effective volume it must be multiplied by a "depth interval". For a given neutrino direction and impact parameter the depth interval is basically the range of positions of the interaction point that will trigger the array. As a given shower is moved through all possible first interactions points it spans an infinite cylinder which we refer as a shower-tube. Such tube intersects the array plane in an ellipse with a major axis given by $q = 2r/sin\bar{\theta}$ where r is the radius of the shower-tube. We can take the projection of this length onto the shower axis as the depth interval, which is equivalent to demanding that the shower maximum intercepts the array. This is conservative because it ignores the shower length which increases the range of allowed positions for the first interaction point. Since the depth interval cannot exceed the length of the array, W, we take the minimum of q and the average length of the array $\widehat{W}$.

We calculate $\mathcal{A}$ integrating this volume over the possible solid angle orientations of the shower, $d\Omega = 2\pi d sin\bar{\theta}$, and restrict the integration to horizontal showers i.e. $0^o < \bar{\theta} < \bar{\theta}_{max} \simeq 20^o$.

$$\mathcal{A} = S \times 2\pi \left(\int_{\sin\bar{\theta}_1}^{\sin\bar{\theta}_{max}} d(\sin\bar{\theta}) \sin\bar{\theta} \frac{2r}{\sin\bar{\theta}} + \int_0^{\sin\bar{\theta}_1} d(\sin\bar{\theta}) \sin\bar{\theta}\; W \right)$$
$$= S \times 2\pi\, r (2\sin\bar{\theta}_{max} - \sin\bar{\theta}_1) \tag{2}$$

For $\bar{\theta} < \bar{\theta}_1 = \sin^{-1}(2r/\widehat{W})$, the intersection of the tube reaches $\widehat{W}$, its maximum value.

3.2. Sensitivity to Neutrino Fluxes

It is now a matter of substituting reasonable values for the parameters to get an estimate for the acceptance. For $S = 3000\ km^2$ the "diameter" of the array is approximately $D = 65\ km$. For $\widehat{W}$ we should take the average length across the array for all possible impact parameters, we obtain $\widehat{W} \simeq 0.70D \sim 45\ km$. The acceptance scales with the tube radius which we take as $r = 1.5\ km$, the separation between the individual detectors of the array. Ordinary cosmic ray showers are expected to give measurable signals in detectors that are this distance away from the shower axis. The showers we consider here have shower maximum intercepting the array plane so they should have similar particle densities. We can now obtain $\bar{\theta}_1 = 0.07$ rad and an acceptance of $\mathcal{A} = 17000\ km^3\ sr$ which when multiplied by an air density $\rho_{air} \simeq 1.1\ 10^{-3}\ g\ cm^{-3}$ gives $2\ 10^7\ kT\ sr$. Neutrino detectors in planning aim towards an active volume in the range of 1 km^3 [10]. Their effective volume is enhanced because of the long range of the energetic muon produced, but for electron and tau neutrinos they have to collect the the Čerenkov light from the showers they produce. If their energy is well above the PeV region the Earth will be opaque to these neutrinos and the corresponding acceptance of a 1 km^3 detector for contained events is at most $6\ 10^6\ kT\ sr$, illustrating how the Pierre Auger project may come into play.

In order to obtain a rough estimate of the rate of horizontal showers above $10^{19}\ eV$ produced by a given neutrino flux we can simply take the product of the neutrino flux above 10^{19} eV, the total cross section σ and the acceptance $\mathcal{A}$. For charged current neutrino electron interactions all the neutrino energy is transferred to the shower. The cross section corresponding to charged current neutrino interactions at this energy is uncertain because of the unknown behavior of the structure functions at low x and high Q^2 which take part in the calculation. Extrapolations of the structure functions lead to cross sections in the $\sigma = 1.3 - 4\ 10^{-32}\ cm^2$ range[11]. If we take the extreme neutrino fluxes from topological defect models [7] divided by a factor of 2 to account for electron neutrinos, the integral neutrino flux ranges from $\Phi = 10^{-16}\ [cm^2\ s\ sr]^{-1}$ for the model with $p = 1.5$ to $\Phi = 4\ 10^{-14}\ [cm^2\ s\ sr]^{-1}$ for the model with $p = 0$. We obtain $2 - 5\ 10^{-8}\ s^{-1}$, in the range of one event per year for the lowest flux and about 400 times that for the highest. The result is extremely encouraging because the calculation is very conservative. There are several issues that will rise the event rate: we have ignored the neutral current interactions and muon neutrinos all together, the cross section and the acceptance integral should both increase with energy, large showers which are very horizontal may trigger the array even if their axis falls outside the array area and it is also possible that the particle arrays have a lower threshold for horizontal showers.

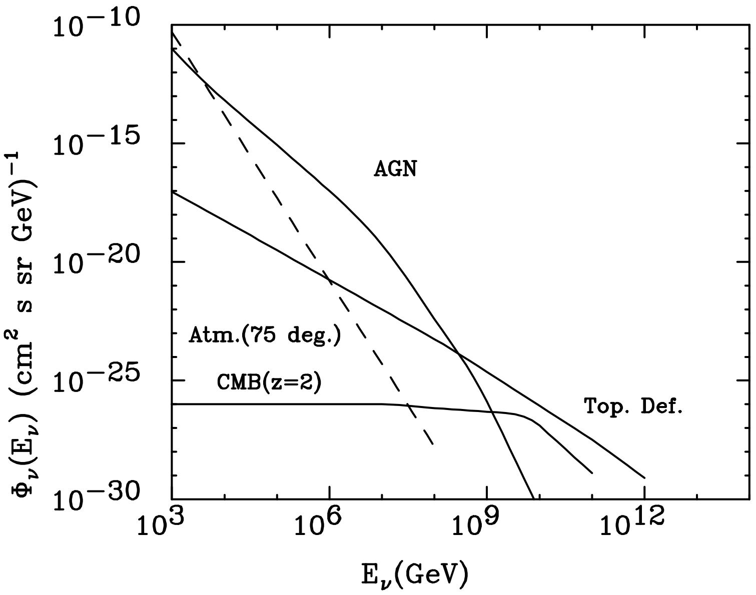

Fig. 1. Neutrino flux predictions in the EeV range.

The neutrino flux predictions for topological defects have been normalized in a maximal way, assuming the observed highest energy cosmic ray spectrum is due to the topological defects themselves but it may be that such fluxes are close to ten orders of magnitude below [12]. It should be stressed that there are solid predictions for neutrinos produced in the cosmic ray interactions with the cosmic microwave background responsible for the GZK cutoff. In the range $10^{19} - 10^{20}$ eV they only differ from topological defects by less than one order of magnitude (see Fig. 1). It is well possible that such interesting events become accessible to the two detector arrays planned.

3.3. Full Event Rate Calculation

For more realistic calculations, which are in progress, triggering details become important. We estimate such effects demanding that a number of consecutive particle detectors in a row have an electron density above a fixed value. The integral for the effective acceptance can be calculated numerically using parametrizations of the lateral distribution functions for both electromagnetic and hadronic showers. The results obtained in both cases are quite similar. As the threshold electron density is decreased the detector increases its acceptance for showers of lower energy because these showers are small and have to be extremely well aligned with the detector rows in order to trigger. However for the larger energy showers the acceptance does not change much as the threshold is lowered. Preliminary results for three triggering requirements are illustrated in Fig. (2) reflecting the stability of the results for shower energies above 10^{19} eV.

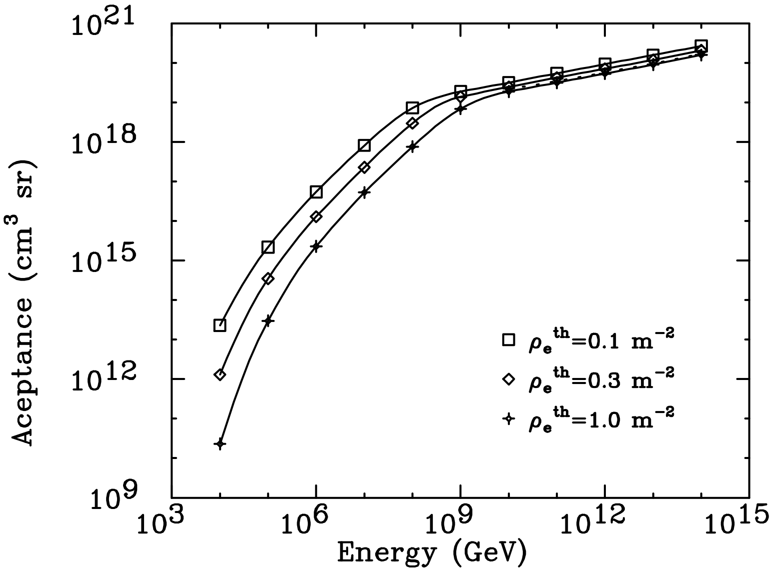

Fig. 2. Acceptance calculation for three trigger models

To calculate event rates we use two sets of structure functions MRS(G) [13] and GRV [14]. For the first we extrapolate to low x beyond validity of the parametrization using the slope of $xq(x)$, where $q(x)$ is the standard parton distribution. The second set, GRV, can be cautiously used on its own for low x. Fig. (3) shows both predictions in comparison with a data point obtained from H1 collaboration in HERA [15]. We take three neutrino fluxes for reference calculation. We use the lowest prediction of ref. [7,8] for neutrinos produced in the decay of topological defects with $p = 1.5$. This flux is very flat and would dominate the neutrino sky for energies above $E_\nu = 10^{17}\ eV$. We take the upper limit of the band calculated in ref. [16] and the prediction of the neutrino fluxes from cosmic ray interactions with the cosmic microwave background calculated in ref. [17] integrated up to redshift $z = 2$. Fig. (1) illustrates these fluxes compared to other predictions setting the scale of the sensitivity of the Pierre Auger project to high energy neutrino fluxes. We approximate the electron neutrino flux to be a factor of two below the muon neutrino for all three cases. This ratio can be naively expected from the number of channels in the decays of pions. The results are shown in table 1.

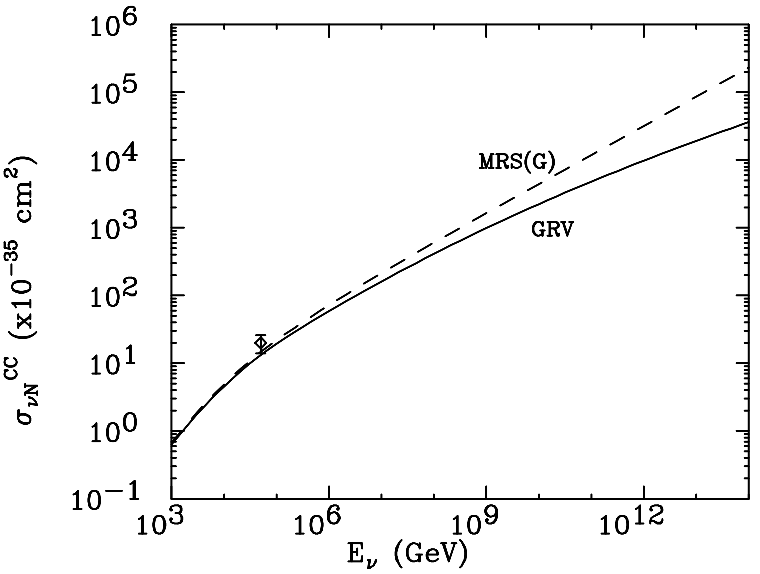

Fig. 3. Comparison of two neutrino cross section predictions in the EeV range

The acceptance curve shown in Fig. (2) is a continuous function of shower energy and when it is combined with the AGN flux prediction it can give measurable rates. Because these fluxes are typically of PeV energies they will produce small showers

ρ_e^{th} (m^{-2})	$MRS(G)$	GRV
	AGN	
1	2	2
0.1	40	30
	CMB	
1	0.9	0.5
0.1	2.9	0.9
	TD $p = 1.5$	
1	26	9
0.1	51	17

Table 1: Yearly neutrino event rates for diffuse fluxes from AGN, for neutrinos from the interactions with the cosmic microwave background (CMB) and for topological defects in the model described in the text (TD).

compared to the typical showers detected in the Auger detector and the showers will have to run well aligned with a row of particle detectors to trigger. These showers will undoubtedly produce signals that are very different from those of typical showers. The low energy part of these curves is very sensitive to the triggering conditions and there are large differences between event rates for different trigger models. This is not the case for the topological defect fluxes and for the flux from interactions of cosmic rays with the cosmic microwave background. These fluxes are much flatter and hence the horizontal shower rate peaks for neutrino energies in the region where the acceptance integral is fairly stable strengthening the results obtained.

4. Conclusions

The Pierre Auger project can be made sensitive to ultra high energy neutrino fluxes through horizontal showers if an appropriate trigger is implemented. Its acceptance for detecting contained neutrinos events of energy above $E_\nu \sim 10^{19}$ eV will be of the order of other neutrino telescopes in planning. The peak of horizontal shower acceptance for the Pierre Auger Project is at energies about 10^{19} eV, a lot higher than the optimal region for AGN neutrino detection, for which the conventional approach to detect neutrinos is best suited. The Pierre Auger Project is best suited for detection of neutrinos from interactions of cosmic rays with the cosmic microwave background and from the decay of topological defects. The event rates expected under some simplifying models for the trigger are high enough to be observed.

Acknowledgments

We thank James W. Cronin for a large number of stimulating discussions and support to pursue this idea, Jaime Alvarez Muñiz, Jose Juan Blanco Pillado, Francis Halzen, Antoine Letessier-Selvon and R. Vázquez for discussions and suggestions. This work was supported in part by the Xunta de Galicia under contract XUGA-20604A93 and in part by and the CICYT under contract AEN93-0729.

References

1) V.S. Berezinsky and A.Yu. Smirnov, *Astrophys. Space Science* ***32*** *(1975) 461.*
2) F. Halzen and E. Zas, Phys. Lett. B289 (1992) 184.
3) M.C. González-García, F. Halzen, R.A. Vázquez and E. Zas, Phys. Rev. D49 (1994) 2310.
4) T.K. Gaisser, F. Halzen and T. Stanev, Phys. Rep. 238 (1995) 173.
5) G. Parente, A. Shoup and G.B. Yodh, Astropart. Phys. 3 (1995) 17.
6) M. Boratav these proceedings.
7) P. Battacharjee, C.T. Hill, D.N. Schramm, Phys. Rev. Lett. **69** (1992) 567.
8) S. Yoshida et al., Proc. 24th ICRC, Rome, vol. 1, p. 793 (1995).
9) J.H. MacGibbon and B.J. Carr, Astrophys. J. **371** (1991), 447; F. Halzen, B. Keszthelyi and E. Zas, Phys. Rev. **D52** (1995) 2310.
10) F. Halzen these proceedings.
11) G. Parente and E. Zas, Proc.of Int. Europhys. Conf. Brussels, (1995); R. Ghandi *et al*, Preprint FERMILAB-PUB-95/221-T (1995).
12) A.J. Gill and T.W.B. Kibble, Phys. Rev. **D50** (1994) 3660.
13) A.D. Martin, W.J. Stirling and R.G. Roberts, *Phys. Lett.* ***B354*** *(1995) 155.*
14) M. Glück, E. Reya and A. Vogt, *Z Phys. C Particles and Fields* ***67*** *(1995) 433.*
15) T. Ahmed et. al, H1 Collaboration, **B324**1994241
16) A.P.Szabo, and R.J. Protheroe, in Proc. High Energy Neutrino Astrophysics Workshop (U. Hawaii, March 1992), ed. V.J. Stenger, J.L. Learned, S.Pakvasa and X. Tata, World Scientific, 1993, p. 24.
17) F.W. Stecker, C. Done, M.H. Salomon and P. Sommers, Phys. Rev. Lett. **66** (1991) 2697.