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Investigation of backgrounds for horizontal neutrino showers at ultra-high energy

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Abstract: A possible signature of a neutrino-induced air shower is a near-horizontal event developing very deeply in the atmosphere at depths exceeding a few thousand g/cm^2. Making use of high-statistics shower libraries we study the background to such events from high-energy muons produced in primary proton events, which may propagate deeply into the atmosphere before initiating a subcascade. The rates of background events are compared with various flux models of ultra-high energy neutrino production.

Introduction

The Pierre Auger Observatory is one of the detectors able to detect neutrino showers and, in the relevant energy range, Auger is equivalent to tens of km^3 of water. The detection of neutrinos is not the main aim of the Auger Observatory, but it can be considered as a very rich by-product for many reasons. We are investigating if we can extract a ν signal above the hadronic background. If no signal is observed, this will put severe constraints on models which predict high-energy neutrino production.

Why are we interested in neutrinos? Mainly because: 1) Neither the GZK cutoff nor magnetic fields operate on ν. Therefore the reconstructed directions should point directly to the source, with the intrinsic angular precision of the detector. 2) The existence of detectable fluxes of neutrinos with energies in excess of 10^{18} eV is in principle one of the signatures of Topological Defect theories. 3) At around 10^{17} eV we are close to the highest energies accessible to the large future neutrino telescope projects and give some indications, several years before such detectors become operational, on the validity of the models used in the design of such projects (detecting mainly predicted neutrinos produced in AGNs).

Above 10^{15} eV the Earth becomes opaque to ν and only down-going or Earth-skimming EeV neutrinos can be detected. The challenge lies in the identification of these showers in the background of down-going cosmic rays and atmospheric muons. Inclined showers in the atmosphere are expected to play a crucial role for the detection of EeV neutrinos. The background for the detection of inclined showers produced by neutrinos is mainly due to showers induced by protons and nuclei. The first ones are expected to develop high in the atmosphere so that when the shower front reaches ground level it has very different properties from ‘ordinary’ showers that are observed in the vertical direction. They are called “old showers“. Deep-inclined showers induced by neutrinos can develop close to ground level so that their shower front looks like a typical vertical proton cosmic ray shower. Another type of background to inclined showers induced by ν is given by deep showers induced otherwise.

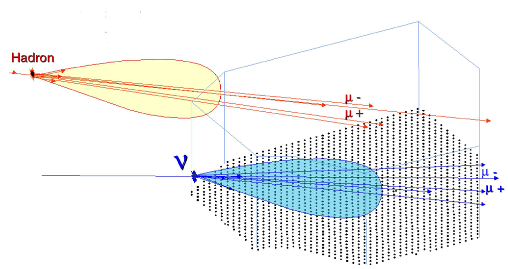

Figure 1: ”Old“ and ”young“ cosmic rays showers.

The electromagnetic part of cosmic ray showers gets practically absorbed in the first 2000 g/cm^2

and, to a very good approximation, only muons generated in highly inclined showers reach the ground. The lower energy muons actually decay in flight and can contribute a small electromagnetic component that follows closely that of the muons. As a result, the average energy of the muons reaching ground increases rapidly as the zenith angle increases. The shower front that reaches ground level for inclined showers is very different from vertical showers. Most of the inclined shower fronts practically only contain energetic muons and their density patterns have lost the cylindrical symmetry because of the Earth's magnetic field which is separating the negative muons from the positive ones, in inverse proportion to their energy.

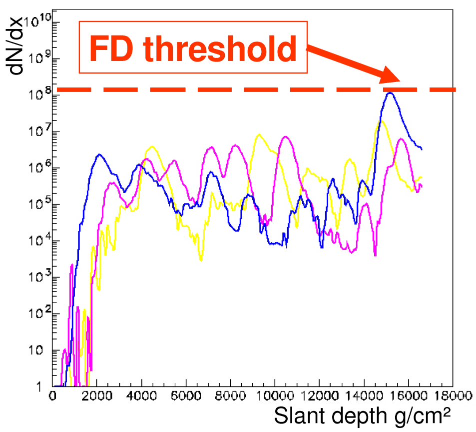

Figure 2: Example of light curves for individual muons which maybe produced in a proton induced shower at 10^{19} eV and $\theta = 87^o$.

Different muon's behavior in a shower

For a better understanding of the muon behavior, individual muon induced showers were generated with the CORSIKA code and made available in a library in Wuppertal University. The shower particle profiles and the energy deposits were investigated in order to check if there are events which exceed the threshold given by the fluorescence detector (FD). Such cases would be considered background events.

The source of this potential neutrino background changes with the energy, in function of the critical energy ϵ_c of the parent particle. The critical energy delimits the competition between decay and interaction length of the particle and is calculated in terms of the particle rest energy mc^2, the mean life τ and, by adopting the isothermal atmosphere

Table 1: The "prompt" and "conventional" muon flux generated in air showers.

The charm contribution gives the "prompt" flux				
Particle	Struct.	$c\tau$	ε_c (GeV)$^{(1)}$	%$^{(2)}$
D^+, D^-	$c\bar{d}, \bar{c}d$	317 μm	$3.8 \cdot 10^7$	17.2
$D^o, \bar{D}^o$	$c\bar{u}, \bar{c}u$	124 μm	$9.6 \cdot 10^7$	6.8
D_s^+, D_s^-	$c\bar{s}, \bar{c}s$	149 μm	$8.5 \cdot 10^7$	5.2
Λ_c^+	udc	62 μm	$2.4 \cdot 10^8$	4.5
π and K contribution gives the "conventional" flux				
π^+, π^-	$u\bar{d}, \bar{u}d$	7.8 m	115	100
K^+, K^-	$u\bar{s}, \bar{u}s$	3.7 m	855	63.5
Λ^o	uds	7.9 cm	$9.0 \cdot 10^4$	0.1
μ^+, μ^-	lepton	659 m	1.0	100

(1) According to ε_c, with $h_o = 6.4$ km.

(2) For inclusive decays yielding leptons.

approximation, a scale constant h_o, so we obtain: $\varepsilon_c = \frac{mc^2}{c\tau} h_o$.

Comparing the critical energies we find that above 1-10 TeV, the semileptonic decay of very short lived charmed particles (mainly D-mesons and Λ_c^+-hyperons) is the dominant source. These constitute the so called "prompt" flux, while the low energy products (from pions and kaons) are giving the "conventional" flux. The main contribution for the prompt flux comes from $D->K+\mu+\nu$ and $\Lambda_c->\Lambda_0+\mu+\nu$.

Estimation of event rates

Several groups were investigating the prompt flux, and the debate over the years provided us several models. We are taking into account three of these, including the extremes. The flux estimations vary by several orders of magnitude due to different models used to calculate the charm cross section and energy spectra. This huge model dependence is due to the need to extrapolate charm production data obtained at accelerator energies, which are several orders of magnitude below the relevant cosmic rays collisions. The most conservative model was studied in several papers based on Thunman et al. [7](TIG), using state-of-the-art models to simulate charm particle production through perturbative QCD processes in high energy hadron-hadron interactions, and investigations of a possible non-perturbative mechanism for the case of an intrinsic charm quark component in the nucleon. The next model considered is Gondolo et al. [2](GGV) and it is considered an improvement of the TIG values, being compatible with the results from Pasquali et al. [6] which used a complementary analysis. They used higher K factors for the parton distribution functions (PDF's) as function of energy, making a full simulation of the cascades, while PRS used approximative analytic solution to the cascade equations in the air. The most exotic model we took into account is the one presented by Zas et al. [8] (ZHV), which pushes the charm production to 10%, thus obtaining a very high charm flux. Each paper cited here used several parameters and methods, obtaining results which may differ by 2 orders of magnitude. However, in our interval of interest, we chose, for a simple estimate, the following values of the E^3-weighted-flux of the muons F_μ: for TIG, 10^{-5}, for GGV, 10^{-3} and for ZHV, 10^{-1} $GeV^3/cm^2\ sr\ s$.

All the prompt fluxes presented here are vertical fluxes. At the energies $< 10^{16}$ eV, the horizontal flux has a slower cutoff than the vertical one, and, in our interval, we assume that the horizontal flux is 10 times higher than the vertical one, using the estimations given by Martin et al in [4].

The estimate of the rate of the potential backgrounds for the neutrino showers detected by Auger is given by dN_μ/dt in the following form:

$$D \int d\Omega \int d\epsilon_\mu \frac{dN_\mu}{dt d\Omega d\epsilon_\mu} \int dV * P_{non-int} * P_{int} \quad (1)$$

The background light introduces a duty cycle which limits its acceptance both for cosmic ray and neutrino detection. In this equation we take into account the duty cycle D for the fluorescence detector in Auger which is considered 10%. The solid angle in which the considered showers may arrive is $\int_{80^\circ}^{90^\circ} \int_0^{360^\circ} \sin(\theta) d\theta d\phi$

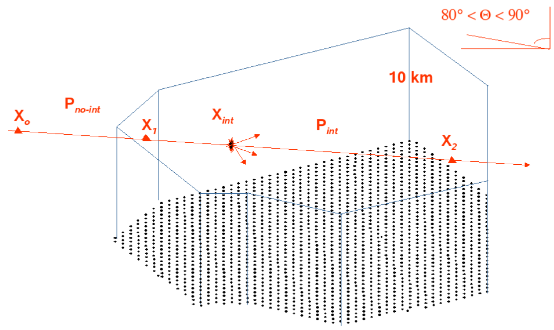

Figure 3: The interaction should take place in the sensitive area of Auger.

We consider events only with the interaction is in the sensitive volume. The probability for this is given by $P_{int} = 1 - e^{-\frac{x_2 - x_1}{\lambda_{int}}}$ while the one to enter the volume without interaction is $P_{non-int} = e^{-\frac{x_1 - x_0}{\lambda_{int}}}$, with x_1, x_0 and x_2 as in the figure, where a symbolic Auger volume is shown, for a 10 km height.

The integral prompt muon flux in our energy range (in GeV) $\int d\epsilon_\mu$ is $\int_{10^8}^{10^{11}} \frac{F_\mu}{{E_\mu}^3} dE_\mu$. We denote

$$D \int d\Omega \int d\epsilon_\mu \frac{dN_\mu}{dt d\Omega d\epsilon_\mu} = C \quad (2)$$

and dN_μ/dt becomes:

$$C \int dA_\perp P_{non-int} \int_{l1}^{l2} \frac{dP_{int}(x_{int})}{dx_{int}} \rho(x_{int}) dl \quad (3)$$

where $\rho(x_{int})dl = dx_{int}$ and $A_\perp$ is the transversal area for the line elements of the trajectories inside the considered volume.

For the case $x_{int} - x_1 << \lambda_{int}$ we can approximate $e^{-\frac{x_{int} - x_1}{\lambda_{int}}} \approx 1$ and, for the moment, we do not include the energy loss. We consider $\rho = -\frac{dXv}{dh}; Xv = X_0 e^{-\frac{h}{h_0}}; \int \rho dl = x$ and we get

$$\frac{dN_\mu}{dt} = C \int dA \frac{1}{\lambda_{int}} \int_{X2}^{X1} dXv \quad (4)$$

with h_0=8.4 km and X_0=1030 g/cm^2 and A, the fiducial surface of Auger South.

$M_{Auger} = \int dA \int_{X2}^{X1} dXv = 1.64 \cdot 10^{10} tons$ is the mass of the air above the Auger South surface, in a layer of 10 km thickness. The interaction length $\lambda_{int} = \frac{m_{air}}{N_a \cdot \sigma_{\mu-air}}$ is calculated using m_{air}=14.54 g/mol, $N_a = 6.023 \cdot 10^{23}$ mol^{-1} and the cross section $\sigma_{\mu-air}$, taken from the CORSIKA simulations.

Results

Table 2 summarises the results of the calculated event rates according to previous section. The

Table 2: Possible FD background from HE muon-induced showers (events/year).

θ	TIG [7]	GGV [2]	ZHV [8]
$80° - 90°$	$1.4 \cdot 10^{-5}$	$1.4 \cdot 10^{-3}$	0 .14
$60° - 90°$	$4 \cdot 10^{-5}$	$4 \cdot 10^{-3}$	0.4

Table 3: FD hadronic background to ν FD signal

ν/year/model$^{(1)}$	TIG [7]	GGV [2]	ZHV [8]
0.043 / GZK-WB	0.1%	10 %	100%
0.67 / NH	0.006%	0.6%	60 %

(1) According to [5] for $60° - 90°$

background values are computed also for $\theta = 60^o - 90^o$ in order to compare them with the neutrino signal predicted by Miele et al. [5], including here the conservative value obtained assuming the GZK flux for Waxman-Bahcall scenario for cosmogenic neutrinos (GZK-WB) and the extreme one given by the exotic model for generating UHECR with large associated neutrino fluxes, named New Hadrons (NH).

Conclusions

High energy muons from heavy flavor decay can induce young horizontal showers similar to the ν signatures. The theoretical uncertainties are huge, so the predicted possible background values spread over several orders of magnitude. muon energy loss is neglected is rather important. This calculation neglected the energy loss, thefore, the estimated muon-induced event rates are upper limits. For the most exotic perspective, ZHV [8], the background rates almost rule out the ν detection, but, in turn, one could think about an interesting capability to detect charm, once the appropriate tools to recognize the charm signature are there. However, this is possible due to the assumption of a 10% charm production, which is not supported by the Akeno data [8]. For the other two considered models, the predicted background rates are sufficiently low, opening an interesting window to study high energy neutrinos with Auger.

While the present estimate was performed for the FD, further sensitivity to ν's is provided by the surface array of Auger Observatory.
Another possible background source would be photon induced showers which due to the LPM effect develop very deep in the atmosphere. Related investigations are ongoing.

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