To be submitted to
Phys. Rev. D

ISTITUTO NAZIONALE DI FISICA NUCLEARE
Laboratori Nazionali di Frascati

LNF-86/7(P)
10 Luglio 1986

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EVOLUTION OF STRUCTURE FUNCTIONS AND UPWARD NEUTRINO INDUCED MUON SIGNAL IN UNDERGROUND EXPERIMENTS

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Servizio Documentazione

LNF-86/27(P)
10 Luglio 1986

Evolution of structure functions and upward neutrino induced muon signal in underground experiments.

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Abstract

The inclusion of QCD evolution in the neutrino structure functions considerably increases the charged current neutrino cross sections at extremely high energies. We show that this increase is however unimportant for the neutrino induced muon signal in underground experiments, even for the expected flat spectra from point sources like Cygnus X3. We also derive the muon energy spectra at the detector expected for point sources.

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The possibility of measuring fluxes of high energy cosmic neutrinos with underground experiments depends on detection of muons produced by charged current interactions of the neutrinos. The interaction can take place either inside a large detector or in the material surrounding the detector. In either case, one depends on the long range of the muons to extend the sensitive area of the detector and so overcome the low flux times interaction rate of the (anti)neutrinos.

Upward going fluxes of neutrino-induced muons have been measured and are in agreement with what is expected from ν_μ and $\bar{\nu}_\mu$ produced by cosmic ray interactions in the atmosphere on the other side of the Earth. (Downward going ν-induced muons are of course produced, in the atmosphere, but they are overwhelmed by muons produced in the atmosphere that penetrate down to the detector).

The rate of neutrino induced muons depends on the differential charged-current neutrino cross-sections as well as on the neutrino flux and muon range. For atmospheric neutrinos, the flux is so steep ($dN_\nu/dE_\nu \sim E_\nu^{-3.7}$) that the rate of muons above several hundred GeV essentially depends only on the neutrino cross section below several hundred GeV where it has been directly measured.

Possible extra-terrestrial sources of neutrinos may, however, have much flatter energy spectra, in which case the behavior of the neutrino cross-section at very high energy becomes more important. The same is also true if the detection threshold energy is very high, as in the case of the search for upward $\nu_e \to e \to$ Extensive Air Showers with Fly's Eye.[1]

Recently Mc Kay and Ralston [2] have pointed out that QCD effects in the nucleon structure functions will lead to much higher neutrino cross-sections than that obtained in some previous calculations [3] -- by more than an order of magnitude above 10^9 GeV. They raise the possibility that this will have a significant effect on extimated signal rates for various potential sources.

The purpose of this paper is to investigate the effect of using evolved QCD structure functions on expected rates in underground detectors. We show that the effect is not important for estimates of signal in deep detectors from such possible sources as Cygnus X3, Vela X1,LMC. We also give some details of the energy distribution of the neutrino-induced muons and of the parent neutrinos that are relevant for understanding possible signals.

The full expression for the ν - induced signal is [3]

$$S(>E_\mu) = \int_{E_\mu}^{\infty} dE_\nu \frac{dN_\nu}{dE_\nu} P(E_\nu > E_\mu) \quad , \tag{1}$$

where

$$P(E_\nu > E_\mu) = \int_{E_\mu}^{E_\nu} \left\{ \int_{E'_\mu}^{E_\nu} dE''_\mu \, N_A \frac{d\sigma}{dE''_\mu} \int_0^{\infty} g(X, E'_\mu, E''_\mu)\, dX \right\} dE'_\mu \tag{2}$$

Avogadro's number is N_A and $g(X,E'_\mu,E''_\mu)$ is the differential probability that a muon produced with energy E''_μ travels a distance X and ends up with energy E'_μ.

If the average energy loss rate for muons is given by

$$\frac{dE}{dX} = -\alpha - \beta E \qquad (3)$$

then in the approximation in which straggling is neglected, the range to go from E_μ'' to E_μ' is

$$X_0 = \frac{1}{\beta} \ln \left(\frac{E''_\mu + \varepsilon}{E'_\mu + \varepsilon} \right) \qquad (4) \qquad (4)$$

where $\alpha \sim 0.02$ GeV cm^2/g and $\beta = 3.9\ 10^{-6}$ cm^2 /g.

Here $\varepsilon = \alpha/\beta = 510$ GeV is the characteristic energy above which catastrophic losses (bremsstrahlung, direct pair production and hadroproduction) dominate muon energy loss.Thus the effective range of a muon of energy E_0 is

$$R = (\ 2.6 \text{ Km.w.e.}\ ) \ln (\ 1 + E_0/510 \text{ GeV}\ ).$$

Muon energy at detection (as function of initial energy E''_μ and distance X) is

$$E'_\mu = \varepsilon (\ 1 + E''_\mu /\varepsilon)^{1-X/R} - \varepsilon$$

Thus the median muon energy at the detection, for a given production energy is

$$E_\mu = [\ \varepsilon (\varepsilon + E''_\mu)\ ]^{1/2} - \varepsilon$$

Numerically this gives $E_\mu = 1.8$ TeV for $E''_\mu = 10$ TeV.

The advantage of expressing the result in the form of Eq (1) is that it divides the signal into two factors, one of which is the neutrino flux and the other is a function indepent of the flux that depends only on the neutrino cross section and on neutrino propagation. The physical interpretation of P is the probability that a neutrino aimed at the detector gives a muon above threshold in it.

With the neglect of range-straggling $g(X, E'_\mu, E''_\mu) \sim \delta(X-X_0)$, so the integral over range can be done trivially.

The cross section is

$$\frac{d\sigma}{dE''_\mu} = \frac{1}{E_\nu}\frac{d\sigma}{dy} = \frac{1}{E_\nu}\int_0^1 \frac{d\sigma}{dx\,dy}\,dx \qquad (5)$$

where $y = 1 - E_\mu''/E_\nu$ and $x = Q^2/(2m(E_\nu - E_\mu''))$ are the usual scaling variables.

Thus to evaluate $P(E_\nu, >E_\mu)$ requires a triple integration, over x , y and E''_μ. The outermost integration can be done by parts, leaving a double numerical integration.

In the process, however, information on the muon energy spectrum at the detector is lost. Since this may be of value in distinguishing, for example, a flat astrophysical spectrum from a steep atmospheric one, we have done the integration both ways, with results displayed in figs (1 - 5).

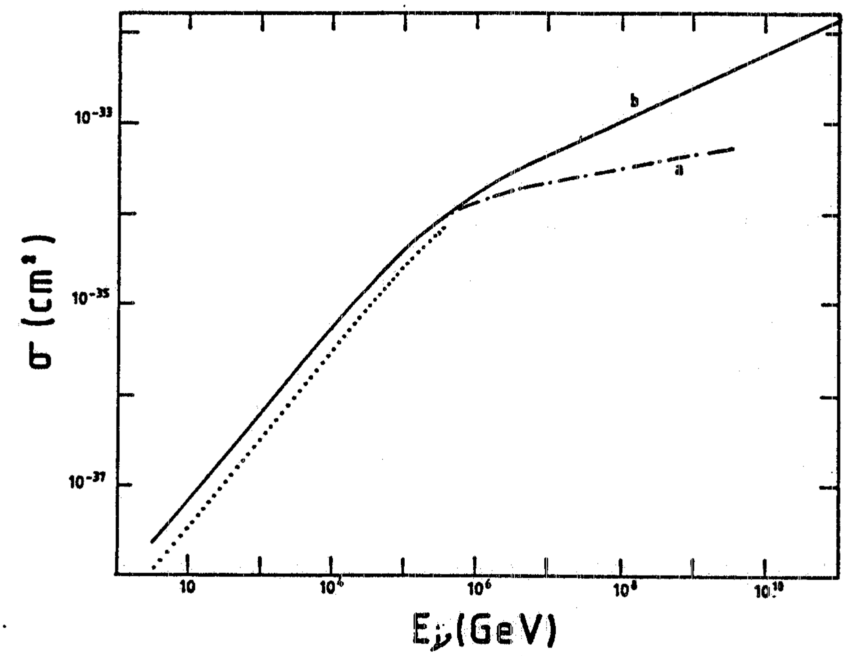

Fig. 1 - Total neutrino and anti-neutrino cross sections. Dotted curve refers to anti-neutrinos. Note that above 10^6 GeV neutrino and anti-neutrino cross sections are equal. Curve (a) is obtained through the use of scaling structure functions, (b) with evolved ones.

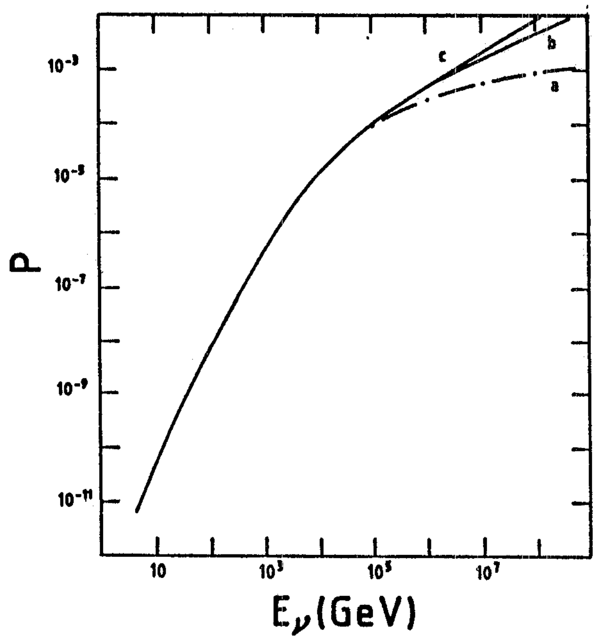

Fig. 2 - Plot of $P(E_\nu)$. (a) and (b) as above, (c) is derived from fit 2 of Ref. [5].

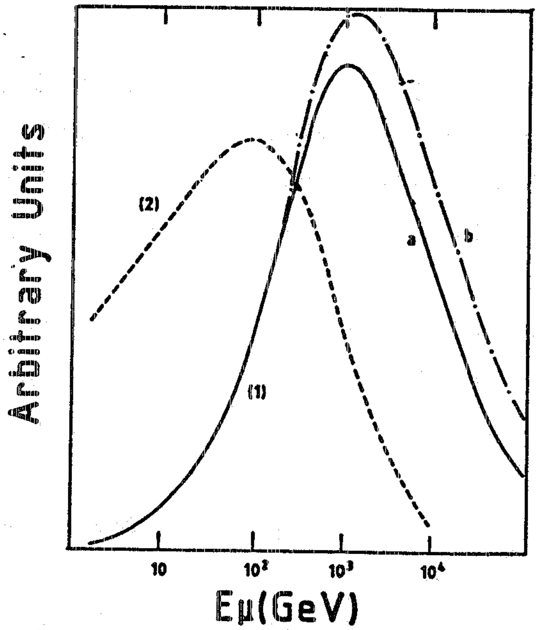

Fig. 3 - Muon distribution ($dN_\mu/d\ln E_\mu$) at the detector for neutrino spectrum $dN/dE_\nu \sim E^{-\gamma}$. (a) and (b) as above. (1) $\gamma = 2.$, (2) $\gamma = 2.8$. Note that below $\gamma = 2.6$ (a) and (b) are practically the same.

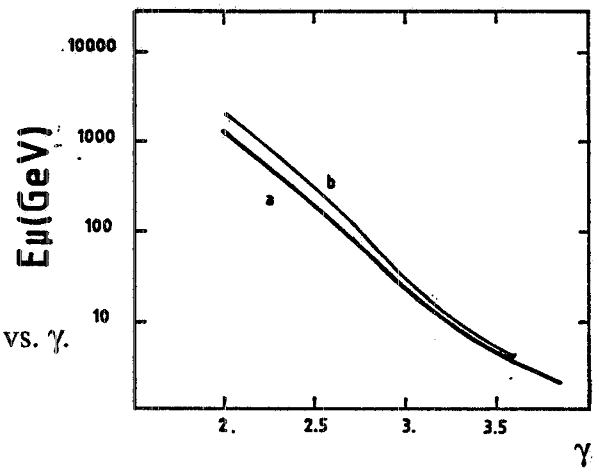

Fig. 4 - Median muon energy at the detector vs. γ.

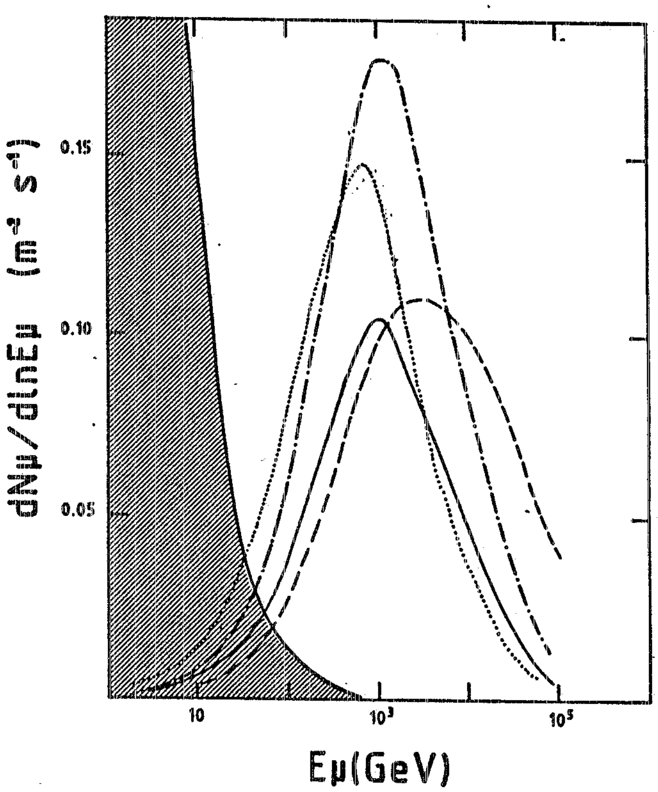

Fig. 5 - Muon signal from Cygnus X3 in different hypotheses [6]:
(1) ······ Proton spectrum $dN_p/dE_p \sim E_p^{-2}$ 2.8 $M_\odot$ companion
(2) ___ Monoenergetic spectrum, $E_p = 10^8$ GeV, 2.8 $M_\odot$ companion
(3) - - -1000 g/cm^2 slab, $\rho = 10^{-7}$ g/cm^3
(4) --- 1000 g/cm^2 slab, $\rho = 10^{-9}$ g/cm^3.
Shaded area is the contribution of atmospheric neutrinos within the angular resolution for a point source.

We have evaluated the cross section Eq.5 both with the use of standard, scaling structure functions [4] and evolved ones [5].

In Fig. 1 we report the cross section computed both ways: as reported also in ref.[2] the cross section using evolved structure functions is larger than the scaling one, by an order of magnitude at 10^9 GeV. The effect on the muon spectrum at the detector is, however, not very important (Fig. 2, 3, 4) even with the hardest neutrino spectrum expected from point sources. For steeper spectra the difference is totally unimportant.

We have also computed the number of muons detectable in a 1000 m^2 detector (Fig. 5) from a source like Cygnus X3 in different hypotheses on the structure of the binary system. The use of evolved structure functions increases the sygnal by less than 50 % even for the hardest spectrum in Fig. 5.

Comparison of figures 3 and 5 shows that the most probable energy at the detector for a point source with a flat spectrum is no more than 1 -2 TeV.

After this calculation was completed we received a paper by Quigg, Reno and Walker [7] which independently obtain the same results as we find in Figs. 1 and 2 . Their paper also contains a full discussion of structure functions.

We thank Dr. V. Valente for his collaboration during an earlier part of this work, and Dr. G. Auriemma for useful discussions. T.K.G. has been supported in part by the U.S. Department of Energy.

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