Expected Muon Energy Spectra and Zenithal Distributions Deep Underwater

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Abstract

Energy spectra and zenith-angle distributions of atmospheric muons are calculated for the depths of operation of large underwater neutrino telescopes. The estimation of the prompt muon contribution is performed with three approaches to charm hadroproduction: recombination quark-parton model, quark-gluon string model, and a perturbative QCD based model. Calculations show that the larger are zenith angles and water thickness above the detector, the lower is the energy E_μ^c ("crossing energy") at which the prompt muon flux becomes equal to conventional one. For instance, for the depth of the Baikal Neutrino Telescope and for zenith angle of 78° the crossing energy is about 300 TeV, whereas it is only 8 TeV for the NESTOR depth. Nevertheless, the muon flux for $E = E_\mu^c$ at NESTOR depth is in order of magnitude lower in comparison with the Baikal depth.

1 Introduction:

The prompt muon (PM) contribution to the atmospheric muon flux originates from decay of charmed hadrons ($D^\pm$, D^0, $\overline{D}^0$, $\Lambda_c^+, \ldots$) that are produced in collisions of cosmic rays with air nuclei. The problem of charm hadroproduction, being very important both for particle physics and high-energy neutrino astronomy, is still remains unsolved. Modern-day data on high-energy atmospheric muon flux obtained with many ground-level and underground detectors are too conflicting to be applicable for a discrimination of charm production models (for a recent review see Bugaev et al., 1998). Accuracy of underground measurements is limited due to several reasons, mainly due to restricted effective volume and uncertainties in density and chemical composition of the matter overburden. Therefore, it seems to be interesting to discuss the potentiality for detecting the PM flux and testing validity of the accepted models for charm hadroproduction in future high-energy muon experiments with large underwater neutrino detectors (AMANDA, ANTARES, Baikal NT, NESTOR). Notice that the atmospheric neutrino induced muon "background" becomes negligible for high enough energy threshold.

Current studies of the PM problem apply phenomenological nonperturbative approaches (see Bugaev et al., 1998) and perturbative QCD based models (Thunman, Ingelman, & Gondolo, 1996; Pasquali, Reno, & Sarcevic, 1999; Gelmini, Gondolo, & Varieschi, 1999). The most recent pQCD calculations include the next-to-leading order corrections to the charm production cross sections. Vertical atmospheric PM flux predicted with pQCD becomes dominant over the conventional one in the energy range 200 to 1000 TeV; the specific value of E_μ^c depends on the QCD model parameters and on the choice of parton density function set. In present calculations, we use the quark-gluon string model (QGSM) and recombination quark-parton model (RQPM) (see Bugaev et al., 1998 and references therein). We compare our results with ones that follow from the pQCD based model by Pasquali et al. Notice that the PM flux predicted in (Gelmini, Gondolo, & Varieschi, 1999) is essentially larger than the earlier pQCD prediction (Thunman, Ingelman, & Gondolo, 1996) and very close to the results of (Pasquali, Reno, & Sarcevic, 1999).

2 Sea-level Muon Fluxes:

To calculate the muon spectra and angular distributions at sea level we apply the atmospheric nuclear cascade model that was described in detail in (Vall, Naumov, & Sinegovsky, 1986; Bugaev et al., 1998) (see also Naumov, Sinegovskaya, & Sinegovsky, 1998).

Differential energy spectra (scaled by factor E^3) at sea level are shown in Fig. 1 for conventional (π, K) muons and for the PM contributions estimated with the RQPM and QGSM for three directions corresponding to $\sec(\theta) = 1$, 3, and 5, where θ is the zenith angle.

In the same figure, we also present the pQCD based results by Pasquali et al. obtained with three sets of QCD parameters (the factorization scale M, the renormalization scale μ, and the mass of c quark m_c) and with the two sets of parton density functions (STEQ3 and MSRD-). Comparisons with other models one can find in (Bugaev et al., 1987; Thunman, Ingelman, & Gondolo, 1996). The difference among the presented results is caused mainly by differences between the charm production cross sections. However, many assumptions and input parameters (primary cosmic-ray spectrum and composition, nucleon and light meson production cross sections, etc.) used in the nuclear-cascade calculations also play a part. Notice that Pasquali et al. implicitly consider the PM flux to be isotropic. This is a good approximation for $E_\mu \lesssim 10^3$ TeV and for $\theta \lesssim 70°$. But for muon energies and zenith angles under discussion, the PM flux anisotropy becomes significant and should be properly taken into account.

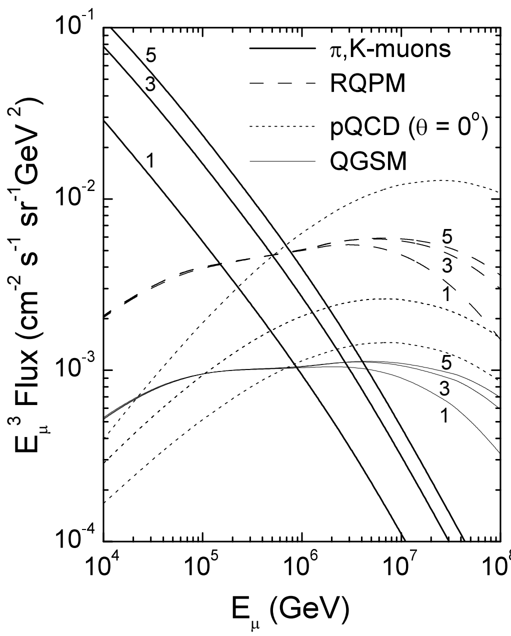

Figure 1: Sea-level muon fluxes for three zenith angles. The curves are for the π, K-muons (solid) and for the PM contributions estimated with the RQPM (dashed), pQCD (dotted), and QGSM (thin solid). The numbers shown nearby the curves are for values of $\sec(\theta)$.

As is seen from the figure, the crossing energies $E_\mu^c(\theta)$ for the RQPM case are roughly 140, 480, and 750 TeV for $\sec(\theta) = 1$, 3, and 5, respectively, that is close to the highest pQCD prediction. In the QGSM case, the values of $E_\mu^c(\theta)$ (≈ 860, 2700, and 4000 TeV for the same zenith angles) are fairly close to the lowest pQCD predictions.

3 Muon Spectra and Angular Distribution Underwater:

The muon energy spectra and zenith-angle distributions deep underwater are calculated with a semianalytical method (Naumov, Sinegovsky, & Bugaev, 1994). By this method one can solve the problem of muon transport through dense matter for an arbitrary sea-level muon spectrum and real energy dependence of differential cross sections for muon-matter interactions. The method is checked with full Monte Carlo. The calculations of conventional and prompt muon fluxes underwater at different zenith angles and depths are performed with all above mentioned charm production models.

Fig. 2 shows zenith-angle distributions for the π, K and prompt muons underwater at $E_\mu > 1$ TeV and $E_\mu > 10$ TeV for depths $h = 1.15$, 2, 3, and 4 km. Here we present the results obtained with two charm production models, the RQPM and pQCD. The version of pQCD we use is based on the CTEQ3 parton distributions with $M = 2\mu = 2m_c$ and $m_c = 1.3$ GeV/c^2 (this version corresponds to the middle dotted curve in Fig. 1; from here on, we shall call pQCD just this specific model).

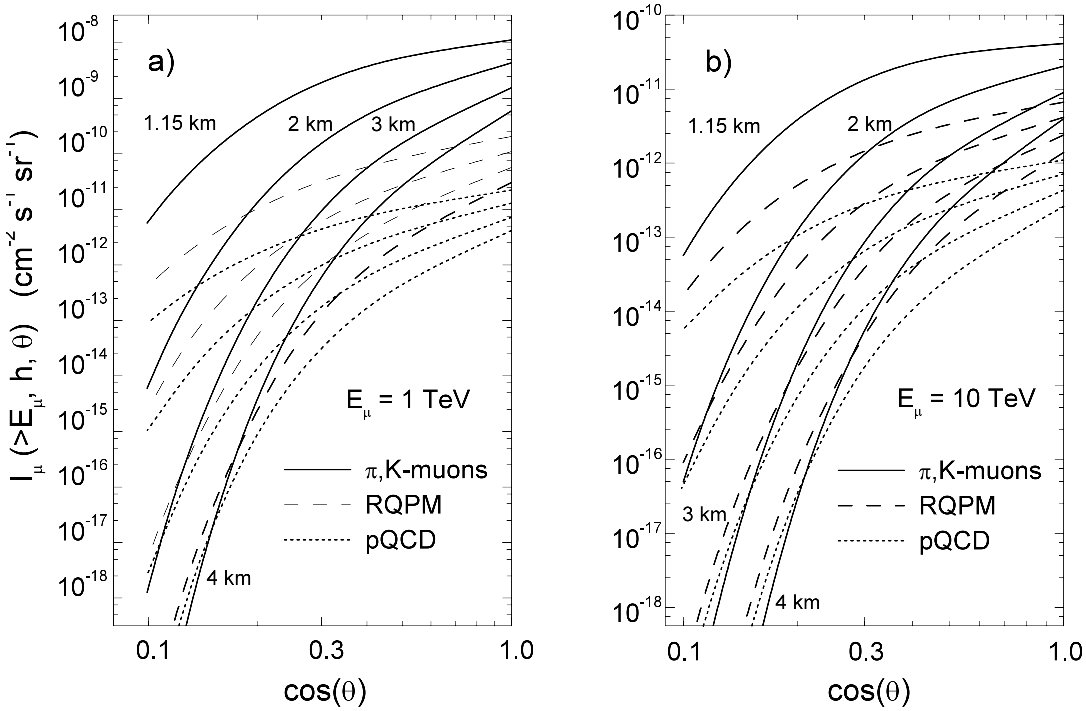

Figure 2: Muon fluxes underwater as a function of the zenith angle at $E_\mu > 1$ TeV (a) and $E_\mu > 10$ TeV (b) for depths $h = 1.15$, 2, 3, and 4 km (from top to bottom).

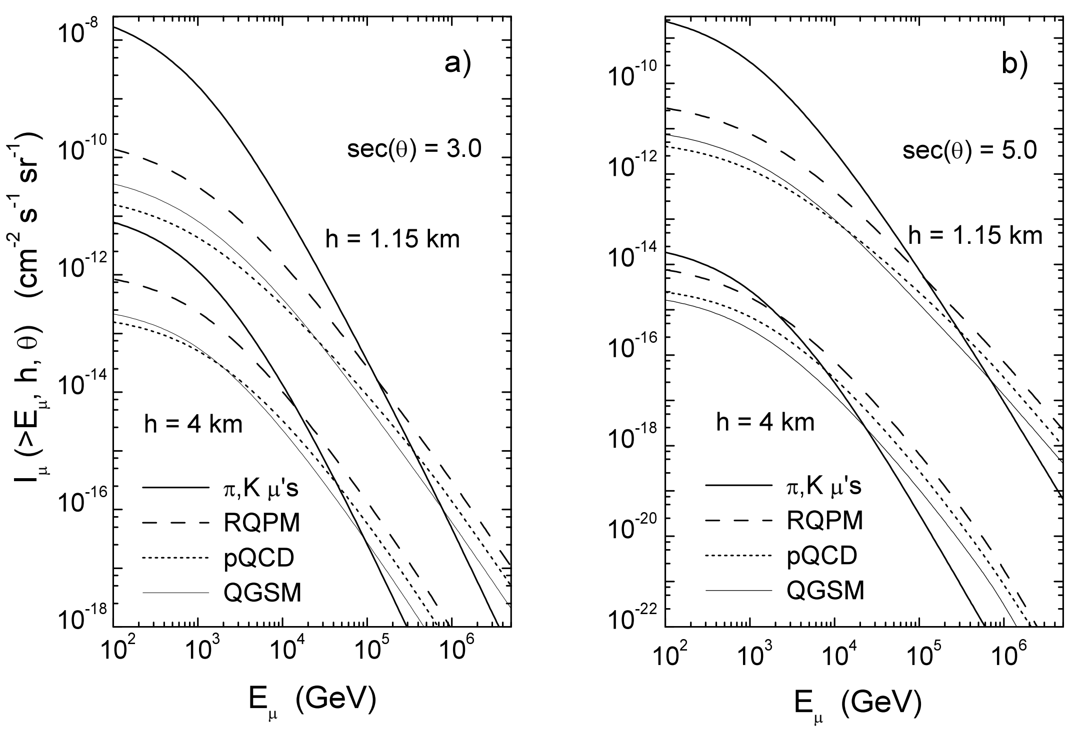

Figure 3: Integral energy spectra of conventional (π, K) and prompt muons underwater for two inclined directions: sec $(\theta) = 3$ (a) and sec $(\theta) = 5$ (b). Four upper curves are for $h = 1.15$ km and the rest curves are for $h = 4$ km.

As Fig. 2 suggests, for not-too-deep water ($h < 1.5 - 2$ km) there is no intersection between the curves which represent the conventional and prompt muon fluxes at $\theta \lesssim 85^\circ$ and $E_\mu \lesssim 10$ TeV. The intersection point shifts to smaller zenith angles with increasing depth.

The absolute value of the muon flux in this point drastically depends on the charm production model. This is a promising fact which is able to help in the establishment of experimental constraints to the charm hadroproduction models from the measuring the muon zenith-angle distribution for high enough detection threshold.

Fig. 3 shows integral energy spectra of muons for $h = 1.15$ km (the Baikal NT depth) and $h = 4$ km (the NESTOR depth) and for $\sec(\theta) = 3$ ($\theta \simeq 70.5^\circ$) and $\sec(\theta) = 5$ ($\theta \simeq 78.5^\circ$). The predictions of three charm production models are presented. The crossing energies for the NESTOR depth are essentially lower in comparison with ones for the Baikal depth (a factor of about 8 for $\sec(\theta) = 3$ and of 35 to 60 for $\sec(\theta) = 5$). In particular, for $\sec(\theta) = 5$, $E_\mu^{c\,(\rm pQCD)} \approx 8$ TeV for NESTOR while $E_\mu^{c\,(\rm pQCD)} \approx 300$ TeV for Baikal. Nevertheless, above the crossing energies, the muon flux is almost in order of magnitude higher for the Baikal depth.

4 Conclusions:

Energy spectra and zenith-angle distributions of atmospheric muons have been calculated for the depths 1 to 4 km that correspond the depths of operation of large underwater neutrino telescopes. The estimation of the sea-level prompt muon contribution performed with RQPM, QGSM and pQCD shows that the energy, at which the prompt muon flux becomes equal to conventional one ("crossing energy"), spreads within a wide energy range 140 to 4000 TeV.

For large zenith angles, the crossing energies (and hence the necessary detection thresholds) are in order of magnitude larger for the operation depth of the Baikal detector in comparison with ones for the NESTOR depth. Despite of this fact, the Baikal depth proves to be more suitable for the problem under discussion, compared to the NESTOR one (all other things being equal) considering that the absolute muon intensity for $E > E_\mu^c$ at the NESTOR depth is almost in order of magnitude lower. More generally, comparatively small depths ($1 - 2$ km) and not-too-large zenith angles ($\theta \lesssim 80^\circ$) have certain advantages for future underwater experiments with prompt muons.

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