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# Uncertainties in prompt atmospheric neutrino flux calculations

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## Abstract

Possibilities to put upper and lower limits on prompt atmospheric neutrino fluxes up to some hundreds of TeV are discussed. The conclusions are made based on charm production mechanism data being obtained from experiments on accelerators, modern theoretical considerations and on data on cosmic ray muons. Discrepancies which exist among the results set out in different works can be restricted. © 1999 Published by Elsevier Science B.V. All rights reserved.

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## 1. Introduction

It is very important to know atmospheric neutrino fluxes well since they represent the main background for experiments with cosmic neutrinos: namely atmospheric neutrinos define how large the size and exposition of installations should be for the lucky search for diffuse cosmic neutrinos and what the angular resolution of these installations should be for the lucky search for point sources of neutrinos in the sky. These experiments are planned to be realized in the nearest future with the new generation of giant neutrino telescopes built and planned to be built all over the world (for example, AMANDA, ANTARES, AUGER, BAIKAL, NESTOR, SuperKAMIOKANDE, etc.).

Attempts have been made to calculate atmospheric neutrino fluxes taking the charm particle production mechanism as it is described at high energies within the frames of this or that theoretical model in a number of works (for example [1–4]).

A very detailed consideration of the charm production mechanism at high center-of-mass energies up to  $\sqrt{S} = 40$  TeV is made in [5] using a non-perturbative QCD approach, the Quark Gluon String model. There the production cross-sections and produced charmed particle spectra are calculated.

All these models endow the charm particle production mechanism with the features that are in good agreement with the data obtained with accelerators but their results differ from each other very much at higher energies unattainable today with accelerators. As a result calculated in different works prompt atmospheric neutrino fluxes can differ from each other two orders in magnitudes at energies of some tens of TeV.

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The main reason for the considerable discrepancy described earlier is the difference in the spectra of charmed particles produced in nuclear interactions of nucleons that were used in different works. A reasonable assumption, that breaking down of Feynman's scaling in the fragmentation region for charm production is not larger than that occurs in the process of pion production, allows to constrain the mentioned above divergence among the results described in different works<sup>1</sup>. This assumption is supported with the NLO model. Thus the main uncertainties in calculated prompt particle fluxes in the atmosphere seem to be related to uncertainties in the values of cross-sections for charm particle production. This leads to the conclusion that uncertainties in the prompt neutrino fluxes could be less than one order in magnitude.

## 2. Prompt atmospheric neutrino fluxes

We shall mainly deal with particles at energies of  $\geq 1$  TeV below. The equations for cosmic ray particle propagation through the earth's atmosphere can be solved analytically in this case.

The differential energy spectrum of primary nucleons can be written as:

$$P_N(E_N) dE_N = C \cdot E_N^{-(\gamma+1)} dE_N \quad (\text{nucleons cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1}), \quad (1)$$

where  $C = 2.6$  and  $\gamma = 1.7$  for nucleon energy  $E_N \leq 3 \cdot 10^6$  GeV, and  $C = 228$ , and  $\gamma = 2$  for  $E_N \geq 3 \cdot 10^6$  GeV.

If we assume the spectra of charmed particles produced in nuclear interactions of nucleons with air nuclei to be proportional to  $(1-u)^\delta$ , where  $u = E_\eta/E_N$ <sup>2</sup> then the number of muon or electron neutrinos  $\alpha_\nu^{\text{charm}}$  from decays of charmed particles produced in the atmosphere at an angle  $\theta$  to the

vertical per one nuclear interaction of a nucleon can be written as:

$$\alpha_\nu^{\text{charm}}(E_\nu, \theta) = \sum_i W_{sl}^\eta \cdot \int_{w_{\min}}^{w_{\max}} \int_0^1 b \cdot \varphi^\eta(u) \cdot (1-u)^\delta \cdot \sigma_{NA}^{D\bar{D}, \Lambda_c \bar{D}}(E_\nu/u/w) / \sigma_{in}^{NA}(E_\nu/u/w) \cdot w^\gamma \cdot f(w) / (1 + E_\nu/w/E_\eta^{cr}(\theta)) du dw, \quad (2)$$

where summing up over  $i$  is summing up over all kinds of charmed particles;  $W_{sl}^\eta$  is the probability that a charmed particle decays with neutrino production;  $b = 1.08$  and  $\delta = 5$  for D-mesons,  $b = 1.4$  and  $\delta = 0.4$  for  $\Lambda_c$ -baryons;  $w = E_\nu/E_\eta$ ;  $w_{\max}$ ,  $w_{\min}$  and  $f(w)$  are connected with the kinematics of a three-body decay of a charmed particle; ( $\varphi^\eta(u) = u^{\gamma-1}$  for D-mesons and ( $\varphi^\eta(u) = u^\gamma$  for  $\Lambda_c$ -baryons

$$E_\eta^{cr}(\theta) = m_\eta / (c \cdot \tau_{0\eta} \cdot \zeta(\theta))$$

is a charmed particle critical energy ( $m_\eta$  is the rest mass of the  $\eta$ -particle,  $\tau_{0\eta}$  is its rest life-time,  $c$  is the light velocity,  $\theta$  is an angle to the vertical and  $\zeta(\theta) = \rho(h, \theta)/h$ , where  $\rho(h, \theta)$  is the air density in the atmosphere at a depth  $h$ ;  $\sigma_{NA}^{D\bar{D}, \Lambda_c \bar{D}}$  and  $\sigma_{in}^{NA}$  are cross-sections for charmed particle pairs<sup>3</sup> production in nucleon–air nuclei interactions and for inelastic interactions of nucleons with air nuclei in the atmosphere correspondingly.

We consider possible reasons for the dramatic divergence among the results set out in different works on prompt atmospheric neutrino flux calculations<sup>4</sup>.

From Eq. (2) it is easy to see which parameters and expressions are responsible for the fluxes under discussion. First of all the values  $W_{sl}^\eta$  taken from accelerator data [6] are the same in all the works discussed. The parameters that are connected with three-body decays of charmed particles are calculated very well. Variation in  $\gamma$  within the reasonable interval ( $\pm 0.1$ ) exerts slight influence on the value  $\alpha_\nu^{\text{charm}}$  ( $\sim 10\%$ ). Thus, only adopted values for

<sup>1</sup> The fragmentation region is responsible for the production of secondary particles in cosmic rays because of very rapid decreasing primary nucleon flux with an energy increase.

<sup>2</sup>  $E_\eta$  is an energy of a produced charmed particle.

<sup>3</sup>  $D\bar{D}$ -pair and  $\Lambda_c \bar{D}$ -pair.

<sup>4</sup> Neutrino produced in charmed particle decays.

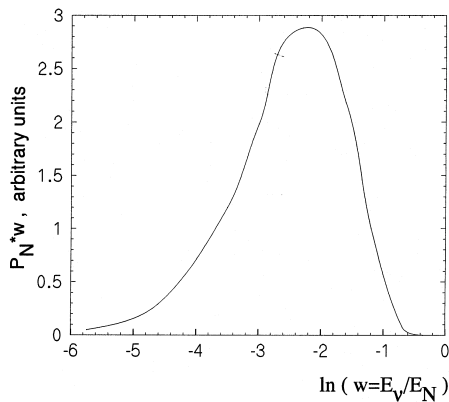


Fig. 1. Differential energy spectrum of nucleons  $P_N$  responsible for production of neutrinos capturing  $w = E_\nu/E_N$  portion of nucleon energy (neutrinos from D-meson decays) multiplied by  $w$ .

cross-sections mentioned earlier and the spectra of charmed particles produced in nucleon–air nuclei interactions should be responsible for considerable differences that take place in the works in question.

For example, prompt atmospheric muon fluxes calculated in [2] and [4] differ from each other  $\sim 40$  times in their magnitudes at  $\sim 100$  TeV. This takes place in spite of the fact that cross-sections for charmed particle production at  $10^3$  TeV are used almost the same in both works ( $10^3$  TeV are effective energies of nucleons responsible for production in the atmosphere of particles considered: see Fig. 1). Thus, as to the difference shown in those two works it can be accounted for by the difference in the charmed particle production spectra used in those works.

It was found in accelerator experiments at proton energy  $S^{0.5} \sim 62$  GeV that charmed particle production spectra for D-mesons were characteristic of “central” character while they showed the “leading” character for  $\Lambda_c$ -baryons:

$$df_D(E_N, E_D)/dE_D \sim \left(1 - \frac{E_D}{E_N}\right)^\delta / E_D, \quad \delta = 5$$

$$df_{\Lambda_c}(E_N, E_{\Lambda_c})/dE_{\Lambda_c} \sim \left(1 - \frac{E_{\Lambda_c}}{E_N}\right)^\delta / E_D, \quad \delta = 0.4$$
(3)

D-mesons make the main contribution to prompt atmospheric neutrino flux (see, for example, [4]). That is why neutrino fluxes are more sensitive to a change in D-mesons spectra. If we substitute  $\delta = 3$  for  $\delta = 5$  the value  $\alpha_\nu^{\text{charm}}$  is increased two times in magnitude<sup>5</sup>.

We should put  $\delta = 50$  to receive cosmic ray prompt muon flux  $\sim 30$  times lower than in calculations with D-meson spectra (Eq. (3)) with  $\delta = 5$ . Thus we are to have a very large change in the  $\delta$  value (from 3–5 up to 50) at an energy change from  $\sim 2$  up to 1000 TeV.

Spectra of charmed particles at high energies are usually calculated in different models based on QCD. These spectra depend heavily on the quark and gluon structure functions. Indeed two calculations of prompt cosmic ray muon fluxes made in [1] within the framework of the PQCD model but with different assumptions concerning behavior of gluon structure functions<sup>6</sup> gave the difference in the results  $\sim 20$ –40 times the magnitude at 100–1000 TeV. It is needed to know these functions at very small values of Bjorken variable  $x < 10^{-4}$  at the energies considered here. Indeed the charm quark ( $C\bar{C}$ ) production in pp-interaction through gluon–gluon ( $gg$ ) fusion<sup>7</sup> in the parton model is schematically represented in Fig. 2, where  $x_1$  and  $x_2$  are Bjorken’s variables for gluons.

The values of variables  $x_F = x_1 - x_2$  in the interval  $\sim 0.1$ –0.2 give the main contribution into charmed particle fluxes produced in the atmosphere because of the nature of primary radiation spectra in cosmic rays.

$x_1 \cdot x_2 = M^2/S$ , where  $M^2$  is the square of produced charm quarks pair mass,  $S$  is the square of energy in the rest system of interacting protons.

Then for the projectile proton energy in the laboratory system  $\sim 50$ –500 TeV the value  $x_2$  is  $\sim 10^{-4}$ – $10^{-5}$ .

<sup>5</sup> Accelerators data do not exclude  $\delta$  to be equal to 3.

<sup>6</sup> For their soft and hard behavior but within the ambiguity in the existing data from modern experiments on accelerators.

<sup>7</sup> This process is predominantly responsible for the charm production at the high energies considered.

Cross-section for charm pair production in pp-interaction in the conventional NLO parton model (for example [7–10]) can be written as:

$$\sigma(pp \rightarrow C\bar{C}) \sim \int dx_1 dx_2 \sigma_{gg}(M^2) f_g(x_1) f_g(x_2), \tag{4}$$

where  $f_g$  are structure functions of gluons which are known from experiments on accelerators with accuracy near 30% for values of  $x$  discussed here.

The calculations of these cross-sections made in the NLO model have big uncertainties due to bad knowledge of heavy quark masses and the default choice for the factorization and renormalization scale [11]. The consideration of the behavior of charmed particle production spectra with projectile proton energy increase leads to the conclusion that  $xd\sigma/dx$  can change its absolute value but does not change its shape. The analysis of experimental data on cosmic ray muons shows [12] that the scaling is broken very weakly in the fragmentation region from energies of accelerators' experiments up to energies in the range of some hundreds of TeV in spectra of pions produced in nucleon–air nuclei interactions. Considerations in the framework of the NLO model show that

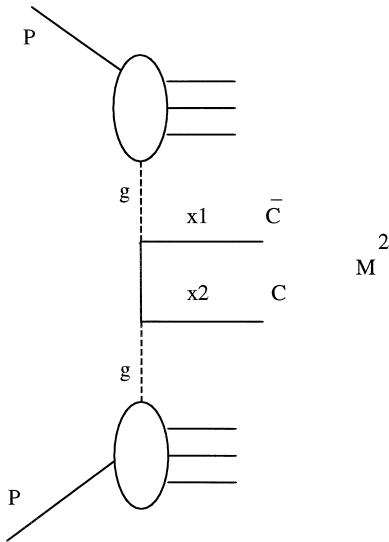


Fig. 2. Charm quark ( $C\bar{C}$ ) production in pp-interaction through gluons (gg) in parton model.

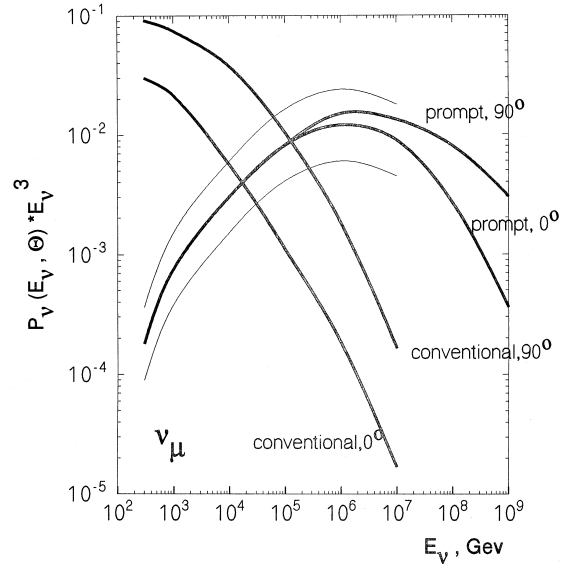


Fig. 3. Differential energy spectra  $P_\nu(E_\nu, \theta)$  of muon and electron neutrinos multiplied by neutrino energy cubed for neutrinos coming to the sea level in the vertical ( $0^\circ$ ) and horizontal ( $90^\circ$ ) directions (the upper and lower thin curves illustrate fluxes of prompt neutrinos calculated for charm production cross-sections two times as big and two times as low than in Eq. (5) correspondingly) in units of neutrinos  $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}$ .

this break should take place even in a lower measure for charmed particles.

Data from experiments on accelerators E653 and E743 on total charm production cross-sections in pp-interactions at a proton energy of  $\sim 1$  TeV have good statistics and do not contradict each other within their statistical uncertainties ([11], and references therein).

These data can be considered as a reasonable normalization for  $D\bar{D}$  production cross-section:

$$\sigma_{pN}^{D\bar{D}}(E_p) = 0.48 \cdot (\lg E_p - 3.075), \tag{5}$$

that was used in [4] for  $E_p \geq 2 \cdot 10^3$  GeV.

The differential energy spectra of atmospheric neutrinos<sup>8</sup> are given for conventional<sup>9</sup> and

<sup>8</sup> Multiplied by neutrino energy cubed.

<sup>9</sup> Neutrinos generated in pion, kaon and muon decays.

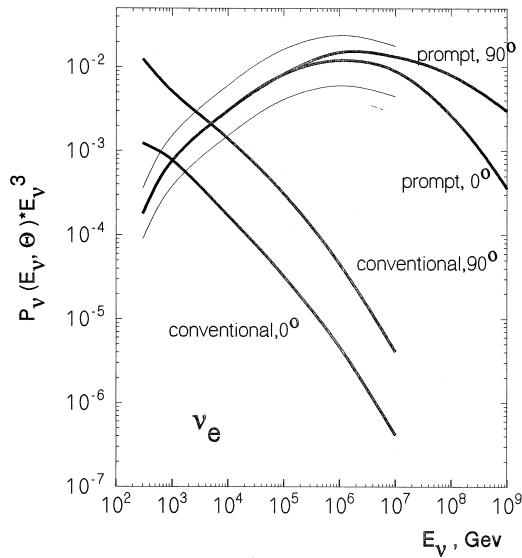


Fig. 4. See legend to Fig. 3.

prompt<sup>10</sup> mechanisms in Figs. 3 and 4. Conventional neutrino fluxes are taken from [13]<sup>11</sup> and prompt neutrino fluxes are taken from [4]. The fluxes are given for neutrinos coming to the sea level in the vertical and horizontal directions.

The spectra for conventional (conv) and prompt (pr) neutrinos can be approximated by using simple formulas that can be useful in different calculations with atmospheric neutrino fluxes:

$$P_{\nu}^{\text{conv}}(E_{\nu}, \theta) = A \cdot E_{\nu}^{-(\gamma+1)} \quad (6)$$

$$P_{\nu}^{\text{pr}}(E_{\nu}, 0^{\circ}) = \frac{A \cdot E_{\nu}^{-(\gamma+1)}}{1 + 3 \cdot 10^{-8} \cdot E_{\nu}} \quad (7)$$

$$P_{\nu}^{\text{pr}}(E_{\nu}, 90^{\circ}) = \frac{A \cdot E_{\nu}^{-(\gamma+1)}}{1 + 2.9 \cdot 10^{-6} \cdot E_{\nu}^{0.685}} \quad (8)$$

The  $A$  and  $\gamma$  values are given in Table 1.

The expressions for prompt neutrino fluxes in the denominators are defined by the change occurring in the primary nucleon spectrum at the nucleon energy

Table 1

$A$  and  $\gamma$  values for approximations (6)–(8) of differential energy spectra of muon and electron neutrinos (in neutrinos  $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}$ ) from conventional and prompt production mechanisms.

		$E_{\nu}$ (GeV)			
		$10^3-10^4$	$10^4-10^5$	$10^5-10^6$	$\geq 10^6$
<i>(a) Conventional neutrinos</i>					
$\nu_{\mu}$	$A$	$0^{\circ}$ 0.1	0.1	0.58	7
		$90^{\circ}$ 0.32	0.32	5.8	70
	$\gamma$	$0^{\circ}$ 2.7	2.7	2.85	3.03
$\nu_e$	$A$	$0^{\circ}$ 2.05	2.05	11.5	278
		$90^{\circ}$ 0.6	6	110	2780
	$\gamma$	$0^{\circ}$ 2.65	2.65	2.8	3.03
		$90^{\circ}$ 2.3	2.55	2.8	3.03
<hr/>					
<i>(b) Prompt neutrinos (<math>\nu_{\mu,e}</math>)</i>					
$A$	$0^{\circ}$	$1.2 \cdot 10^{-5}$	$4.6 \cdot 10^{-5}$	$4.15 \cdot 10^{-2}$	$1.15 \cdot 10^{-2}$
		$1.2 \cdot 10^{-5}$	$4.6 \cdot 10^{-5}$	$4.1 \cdot 10^{-3}$	$1.65 \cdot 10^{-2}$
$\gamma$	$90^{\circ}$	1.4	1.55	2.09	2
		1.4	1.55	1.91	2

$\sim 3 \cdot 10^6$  GeV and by the influence exerted by charmed particle decays.

### 3. Accuracy of atmospheric neutrino fluxes

The main uncertainties in calculations of conventional atmospheric neutrino fluxes are accounted for by the uncertainties in our knowledge of the primary nucleon flux and the portion of kaons produced in nuclear interactions of nucleons with air nuclei<sup>12</sup>. The main uncertainties in calculations of prompt atmospheric neutrino fluxes seem to be due to uncertainties in charm particle production cross-sections. Numerical calculations of these cross-sections made in accordance with different theoretical models are ambiguous because of poor knowledge of heavy quark masses and other parameters that are needed in such calculations. If data on these cross-sections received in up-to-date experiments on accelerators at energies of  $\sim 1$  TeV are used as a normalization to

<sup>10</sup> Neutrinos from charmed particle decays.

<sup>11</sup> Spectra are recalculated for  $\gamma = 1.7$  since in [13] it is  $\gamma = 1.65$ .

<sup>12</sup> In our calculations kaons make 16% of the number of pions produced with the same energy.

estimate cross-sections at higher energies than differences among results of different works are not large (within approximately twice the magnitudes of estimated cross-sections in the energy interval from 1 up to  $10^6$  TeV [2]). The fluxes calculated with charm production cross-sections two times higher and lower than Eq. (5) are given in Figs. 3 and 4 (thin curves) to see the influence of these uncertainties on prompt atmospheric neutrinos.

#### 4. Conclusion

The analysis presented in this work showed that prompt neutrino fluxes become to be equal to conventional neutrino fluxes at  $\sim 1$  TeV for electron neutrinos and  $\sim 10$  TeV for muon neutrinos coming to the sea level in the vertical direction. For the horizontal direction this can take place at energies approximately one order of magnitude higher. For higher energies prompt fluxes begin to dominate over the conventional ones.

It is obvious that prompt neutrinos increase the background for experiments with cosmic neutrinos significantly. But an optimistic remark is that some features of these fluxes are to be different from those of cosmic neutrinos. For example, they should have angular distributions that differ from those of cosmic neutrinos as well as they should have different ratios of neutrinos of different flavors and conjugations.

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