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Prompt atmospheric neutrino flux in perturbative QCD and its theoretical uncertainties

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Abstract. Using the most recent PDFs and the cosmic ray spectrum, we evaluate the charm/bottom induced prompt atmospheric muon neutrino fluxes including nuclear corrections. We investigate their impact in perturbative QCD and estimate the comprehensive uncertainties from other various factors. The prompt atmospheric tau neutrino fluxes are also presented.

1. Introduction

Atmospheric neutrinos produced from cosmic ray interactions with nuclei in the atmosphere are the main background to the astrophysical neutrinos. Atmospheric neutrinos can be classified into two types of components according to the hadrons produced in the cosmic ray and air nuclei collisions and decay to neutrinos: conventional neutrinos from the pion and kaon decay and prompt neutrinos from the heavy quark contained hadrons. While the conventional neutrinos dominate at relatively low energies, at high energies the prompt neutrino flux dominates. Therefore it is important to evaluate the flux of prompt neutrinos precisely for the accurate analysis of the experimentally measured high energy events, especially those observed at the IceCube Observatory [1].

This contribution is focused on the nuclear corrected fluxes evaluated in perturbative QCD at next-to-leading order (NLO), part of our more extended work in Ref. [2]. Nuclear corrections are incorporated by the recent nuclear parton distribution function (PDF), nCTEQ15 [3]. In this proceeding paper, we present our new prompt muon neutrino and tau neutrino fluxes evaluated using the nCTEQ15-nitrogen PDF set and the recent cosmic ray spectra parameterized in [6], and compare with the earlier calculation of BERSS [4] that used NLO QCD with free nucleon PDFs.

2. Cascade equation and Z-moment method

The propagation of the particles in the atmosphere can be described by the cascade equation. The atmospheric neutrino flux can be evaluated by solving a set of coupled cascade equations for cosmic ray protons, secondary hadrons and neutrinos. The general form of the cascade equation for particle type j is given by

$$\frac{d\phi_j}{dX} = -\frac{\phi_j}{\lambda_j} - \frac{\phi_j}{\lambda_j^{dec}} + \sum S(k \to j) \tag{1}$$

with the column depth X and the interaction (decay) length $\lambda^{(dec)}$. Here, $S(k \to j)$ is the (re)generation function for production and decay, expressed as

$$\begin{aligned} S(k \to j) &= \int_E^\infty dE' \frac{\phi_k(E',X)}{\lambda_k(E')} \frac{1}{\sigma_{kA}(E')} \frac{d\sigma(kA \to jY; E', E)}{dE} \quad \text{(production)}\,, \qquad (2)\\ S(k \to j) &= \int_E^\infty dE' \frac{\phi_k(E',X)}{\lambda_k(E')} \frac{1}{\Gamma_k(E')} \frac{d\Gamma(k \to jY; E', E)}{dE} \quad \text{(decay)}\,. \qquad (3) \end{aligned}$$

The coupled cascade equations can be solved using the so-called Z-moment method. The Z-moment can be expressed with the generation function as

$$Z_{kj}(E) \simeq S(k \to j) \frac{\lambda_k(E)}{\phi_k(E,X)}\ . \tag{4}$$

The solutions are given by approximate expressions in the low energy and high energy limit separately,

$$\phi_{h\to\nu}^{\text{low}} = \sum_h \frac{Z_{Nh} Z_{h\nu}}{1 - Z_{NN}} \phi_N^0\,, \qquad \phi_{h\to\nu}^{\text{high}} = \sum_h \frac{Z_{Nh} Z_{h\nu}}{1 - Z_{NN}} \frac{\ln(\Lambda_h/\Lambda_N)}{1 - \Lambda_N/\Lambda_h} \frac{\epsilon_h}{E} \phi_N^0 \tag{5}$$

with the cosmic ray flux ϕ_N^0, the Z-moments and the effective interaction lengths $\Lambda_k = \lambda_k/(1 - Z_{kk})$. The neutrino flux can be obtained by interpolating these approximate solutions. For the evaluation in this work, the fluxes are summed over $h = D^0,\ D^+,\ D_s,\ \Lambda_c$ for the charmed hadrons, and $h = B^0,\ B^+,\ (\ B_s,\ \Lambda_b)$ for the bottom hadrons for tau neutrinos (muon neutrinos) plus antineutrinos.

3. Essential Inputs

3.1. Heavy quark production

One of the essential inputs in evaluating the prompt flux is the production cross sections of the heavy quarks, which can be fragmented into the charm/bottom hadrons. The standard method to evaluate it is to use perturbative QCD, where the differential cross section for $q\bar{q}$ production can be used to calculate the Z production moments with fragmentation functions.

Here, we evaluated the heavy quark production cross section at NLO, using the factorization (M_F) and renormalization (M_R) scales constrained by experimental data from RHIC and LHC as discussed in [5]. One of the largest uncertainties is the scale dependence. We vary the scales $M_F = (1.25, 2.1, 4.65)m_T$ and $M_R = (1.48, 1.6, 1.71)m_T$ with $m_T = \sqrt{p_T^2 + m_c^2}$ as suggested by [5] and used in BERSS [4]. Here, we use $m_c = 1.27$ GeV. At very high energies, the small-x behavior of the PDFs is also relevant. For the results shown here, we have used a power law extrapolation for the low-x nCTEQ15-nitrogen PDFs, e.g. $xg(x,Q) \sim x^{-\lambda(Q)}$, where the extrapolation is used for $x < 3 \times 10^{-7}$.

3.2. Cosmic ray fluxes

For incident cosmic ray flux, the broken power law (BPL) is the traditional spectrum used in many evaluations of the neutrino flux and is still a useful flux for comparisons,

$$\begin{aligned} \phi_N^0(E)[\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}\,\text{GeV}^{-1}] &= 1.7\ (E/\text{GeV})^{-2.7} \quad \text{for} \quad E < 5 \cdot 10^6\ \text{GeV} \\ &= 174\ (E/\text{GeV})^{-3} \quad \text{for} \quad E > 5 \cdot 10^6\ \text{GeV}\ . \qquad (6) \end{aligned}$$

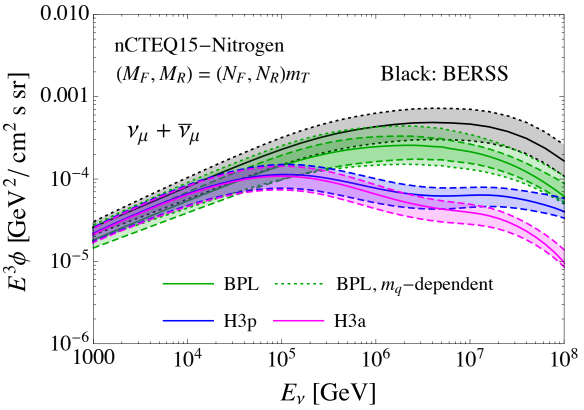

Figure 1. The prompt atmospheric muon neutrino fluxes from the charm and bottom hadrons with the nCTEQ15-nitrogen PDFs.

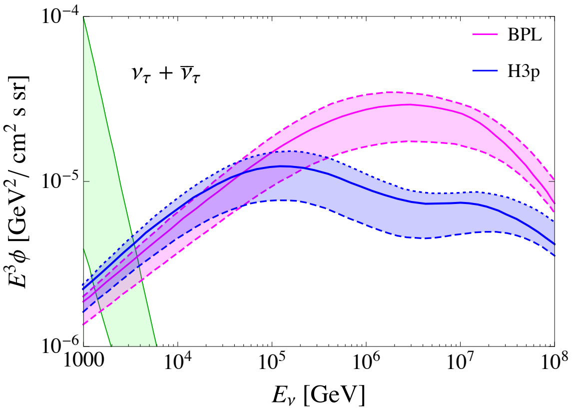

Figure 2. The prompt atmospheric tau neutrino flux.The green band shows the flux of ν_τ from the conventional ν_μ's oscillation.

For the BPL, all cosmic ray particles are assumed as protons. Nowadays, however, there are more elaborated spectra parameterized considering the cosmic ray's composition and its source populations. In our evaluation, we use three spectra: the BPL and the other two provided in [6] that are parameterized based on model for three populations (supernova remnants, other galactic sources and extragalactic sources) including 5 nucleus components (p, He, CNO, Mg-Si, Fe). The difference between the two [6] is the composition of cosmic rays from the extragalactic sources: one has a mixed composition (here called H3a), and the other has only protons (H3p).

4. Prompt neutrino fluxes

Our resulting fluxes for prompt muon neutrinos are shown in Fig. 1 for BPL, H3p and H3a, with bands to reflect the uncertainties from the scale variation. For comparison, we also include the BERSS results. Compared to BERSS, there are several updated factors: the PDF set, the bottom hadron contributions and the fragmentation for the charmed hadrons. First, the updated fragmentation fraction reduces the overall flux $\sim 20\%$. The B hadron contribution gives a $\sim 5-10\%$ increase at $E_\nu \sim 10^5 - 10^8$ GeV. With the nCTEQ15 PDF set, we can see the effect of the updated PDF is about $3-44\%$ at the same energy range by comparing the charm induced fluxes with nCTEQ15-proton PDFs and the BERSS results. We also found that the result with nCTEQ15-nitrogen is less than for proton targets by $\sim 20-35\%$ due to the nuclear effect. The combined effect of these factors listed above result in the muon neutrino fluxes that are $40-60\%$ lower than the BERSS results. In Fig. 2, for completeness, we presented the tau neutrino flux from the D_s, B^0 and B^+ hadrons, which is about 10 % of the muon neutrino flux.

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