1-1-2003

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UCLA/02/TEP/23, CWRU-P13-02, NSF-ITP-02-97

Measuring the prompt atmospheric neutrino flux with down-going muons in neutrino telescopes

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(September, 2002)

In the TeV energy region and above, the uncertainty in the level of prompt atmospheric neutrinos would limit the search for diffuse astrophysical neutrinos. We suggest that neutrino telescopes may provide an empirical determination of the flux of prompt atmospheric electron and muon neutrinos by measuring the flux of prompt down-going muons. Our suggestion is based on the consideration that prompt neutrino and prompt muon fluxes at sea level are almost identical.

Atmospheric neutrinos and muons, i.e. neutrinos and muons produced in the atmosphere by cosmic ray interactions, are the most important source of background for present and future high-energy neutrino telescopes, which are expected to open a new window in astronomy by detecting neutrinos from astrophysical sources [1]. (In this Letter, 'muons' includes 'antimuons' and 'neutrinos' includes 'antineutrinos'.)

In their current design, neutrino telescopes consist of large arrays of phototubes located under water or ice. They detect high-energy neutrinos through the charged particles these produce in the water or ice inside or around the instrumented array.

Atmospheric muons can reach the detector only from above, because the range of muons in Earth is only a few kilometers. Atmospheric muons are therefore only down-going. Their flux is typically so high that the region of sky accessible to even very deep neutrino telescopes is only the hemisphere below the horizon.

Atmospheric neutrinos can instead reach the detector from all directions. Hence they are an irreducible background for diffuse astrophysical neutrino fluxes. It is therefore very important to evaluate their intensity with reasonable accuracy.

At GeV energies the atmospheric muon and neutrino fluxes are dominated by 'conventional' sources, i.e. decays of relatively long-lived particles such π and K mesons. With increasing energy, the probability increases that such particles interact in the atmosphere before decaying. This implies that even a small fraction of short-lived particles can give the dominant contribution to high energy muon and neutrino fluxes. These 'prompt' muons and neutrinos arise through semi-leptonic decays of hadrons containing heavy quarks, most notably charm.

Estimates of the magnitude of the prompt atmospheric fluxes differ by almost 2 orders of magnitude. Fig. 1 shows a compilation of prompt muon fluxes at sea level. Prompt neutrino fluxes are essentially identical, while

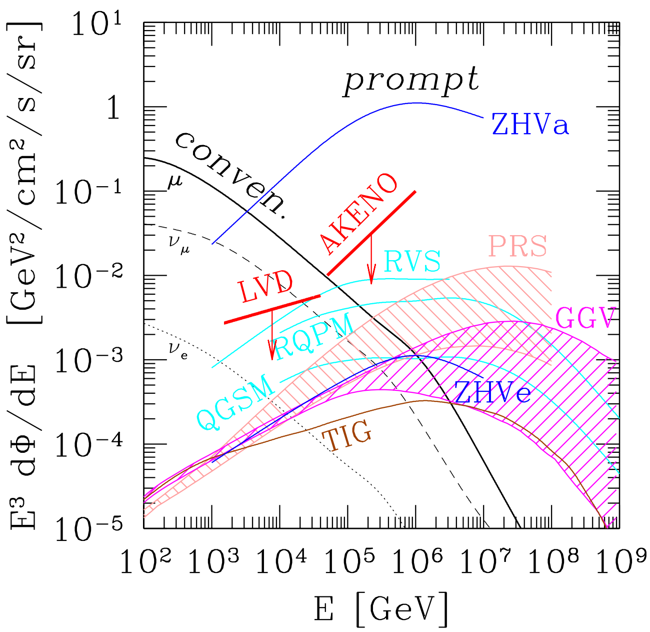

FIG. 1. Vertical atmospheric muon (and neutrino) fluxes. Muon and neutrino conventional fluxes from [2] (below 10^6 GeV) and [3] (above) (line marked conven. and dashed lines). Muon prompt fluxes from: two charm production models in [4] (ZHVa, ZHVe); empirical model in [5] (RVS); quark-gluon string model and recombination quark-parton model in [6] (QGSM, RQPM); perturbative QCD in [7] (PRS band), [8,9] (GGV band), and [3] (TIG). Also indicated are the experimental bounds on prompt muons from LVD [10] and AKENO [11].

conventional neutrino fluxes are lower by one (ν_μ) or two (ν_e) orders of magnitude. The crossing from conventional to prompt muon fluxes happens between 40 TeV and 3 PeV, while the analogous crossing for muon-neutrinos happens at lower energies, between 20 TeV and 800 TeV.

The uncertainty in the intensity of conventional atmospheric neutrinos and muons is thought to be approximately 30% at present, but could decrease to about 10% with coming improvements [12]. At about 1 TeV, the contribution of prompt neutrinos taking into account the LVD bound could be as high as 10% of the conventional neutrino flux.

Between 1 TeV and 100 TeV, prompt neutrinos become the biggest source of uncertainty in the atmospheric neutrino flux. So the level of prompt neutrinos is a potential problem which would limit the search for diffuse astrophysical neutrinos at energies of about 1 TeV, much smaller than the energies where they become dominant (see for example [12]).

Here we suggest a way to overcome the theoretical uncertainty in the magnitude of the prompt electron and muon neutrino fluxes by deriving their intensity from a measurement of the *down-going prompt muon* flux. Our suggestion is based on the observation that, due to the charmed particle decay kinematics and the same branching ratios for the semi-leptonic decays into $e\nu_e$ and $\mu\nu_\mu$, the prompt electron and muon neutrino fluxes and the prompt muon flux are essentially the same at sea level [3,7–9,13]. This result is independent of the charm production model.

We want to stress that we are suggesting to use down-going prompt muons and not up-going neutrino-induced muons whose flux is orders of magnitude smaller. While an important contribution to up-going muons is expected from astrophysical neutrinos, no astrophysical signal is expected in down-going atmospheric muons.

Moreover, prompt muons are much easier to detect than prompt neutrinos, since the latter have to convert to a charged particle within the effective volume of the detector. In fact, the flux of upcoming muons induced by muon neutrinos at 1 TeV is about 10^{-7} of the neutrino flux at sea level (using charge-current cross sections in [14] and muon ranges in [15]). On the other hand, the flux of down-going muons at a slant depth of about 3 km w.e. is only a fraction 0.4–0.6 of the muon flux at sea level (the exact suppression factor depending on depth, energy spectra and zenith angle [15]). Thus close to 1 TeV, taking into account that the conventional neutrino fluxes at sea level are about 10% of the muon fluxes (see Fig. 4 below), for each up-going neutrino-induced muon there are 4–6 10^7 down-going muons. Of these, as much as a few percent may be prompt.

From Fig. 1, the vertical conventional muon flux above 1 TeV is approximately 10^{10} muons/km^2/yr/sr at sea level. This implies roughly 10^9 down-going events per year in a kilometer-size detector at a depth of about 3 km. Thus, to extract a 1% fraction of prompt muons at 1 TeV, it would suffice to record 1 out of 10^5 down-going events per bin in the sky for a year (fewer events would need to be recorded at higher energies).

For what we suggest, it is important to separate the prompt muons from the conventional ones for two reasons: (1) the conventional neutrino fluxes are small fractions, less than 10%, of the conventional muon flux, and our method of using the ratio of neutrino to muon fluxes would become less straightforward; and (2), as a consequence of the previous reason, the ratio of neutrino to muon fluxes depends on the crossing energy between conventional and prompt fluxes, and so on the large uncertainty on the absolute value of the prompt fluxes, making our method inapplicable.

There are ways of separating the prompt muons from the conventional ones in underwater or under-ice detectors, such as the different zenith angle dependence of the prompt and conventional fluxes; the different depth dependence at a given zenith angle; and the different spectral shape at a given depth and zenith angle (see e.g. Ref. [16,17])

In a series of papers [8,9,13] (called GGV1, GGV2 and GGV3 from now on), we studied the prompt lepton fluxes using a model for charm production in the atmosphere based on Quantum Chromo-Dynamics (QCD), the theoretically preferred model. We used a next-to-leading order perturbative QCD (NLO pQCD) calculation of charm production, as implemented in the Mangano-Nason-Ridolfi program [18] calibrated at low energies, followed by a full simulation of particle cascades in the atmosphere generated with PYTHIA routines [19].

In our first paper (GGV1), we tried different modes of cascade generation, different options allowed by PYTHIA in the various stages of parton showering, hadronization, interactions and decays, etc., noticing changes of at most 10% in the final results. We decided to use what we called our 'single' mode simulation, with showering, independent fragmentation, interactions and semileptonic decays according to Ref. [3]. In our 'single' mode we enter only one c quark in the particle list of PYTHIA, and we multiply the result by a factor of 2 to account for the initial $\bar{c}$ quark. PYTHIA performs the showering, standard independent fragmentation, and follows all the interactions and decays using default parameters and options.

In GGV1 we found that the NLO pQCD approach produces fluxes in the bulk of older predictions (not based on pQCD) as well as of a pQCD semianalytical analysis [7]. We also explained the reason of the low fluxes of the model of Ref. [3], which were due to the chosen extrapolation of the gluon partonic distribution function (PDF) at small momentum fractions x.

In GGV2, we considered four sets of PDF's: MRS R1-R2 [20], CTEQ 4M [21] and MRST [22]. Besides the choice of the PDF set, our procedure has the freedom to choose reasonable values of the charm mass m_c, the factorization scale μ_F, and the renormalization scale μ_R, so as to fit the experimental data. In GGV1 and GGV2 we made the standard choice [18,23] of $\mu_F = 2m_T$, $\mu_R = m_T$, where $m_T = \sqrt{p_T^2 + m_c^2}$ is the transverse mass. The

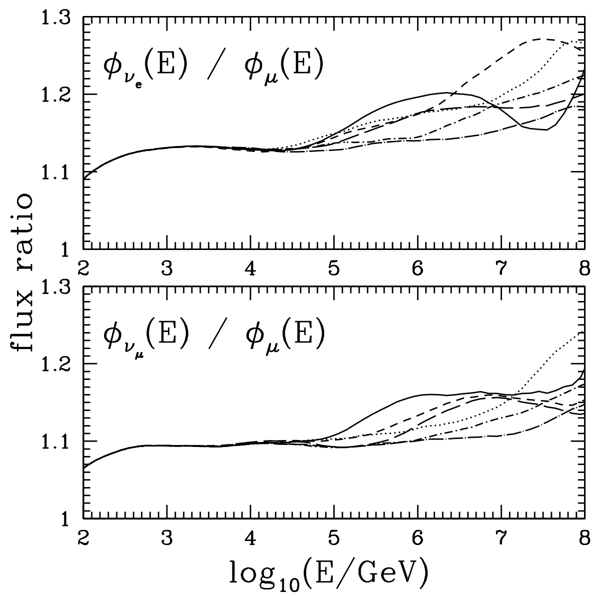

FIG. 2. Ratio of prompt neutrino to prompt muon fluxes as a function of lepton energy using the MRST PDF with $\lambda = 0$ (solid line), 0.1 (dotted), 0.2 (short-dashed), 0.3 (long-dashed), 0.4 (short-dashed dotted), and 0.5 (long-dashed dotted).

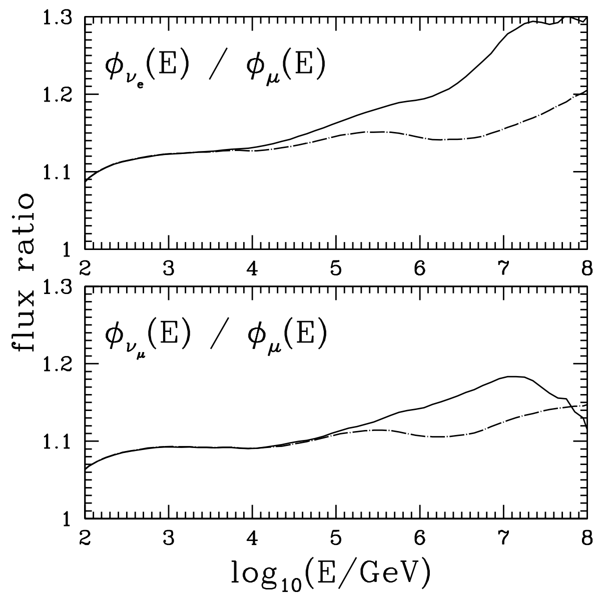

FIG. 3. As Fig. 2, but for CTEQ 4M and $\lambda = 0$ and 0.5.

values of the charm mass were taken slightly different for each PDF set, namely: $m_c = 1.185$ GeV for MRS R1, $m_c = 1.310$ GeV for MRS R2, $m_c = 1.270$ GeV for CTEQ 4M, and $m_c = 1.250$ GeV for MRST.

Due to the steep decrease with increasing energy of the incoming flux of cosmic rays, only the most energetic charm quarks produced count and those come from the interaction of projectile partons carrying a large fraction of the incoming nucleon momentum. Thus, the characteristic x of the projectile parton, x_1, is large, $x_1 \simeq O(10^{-1})$. We can then immediately understand that very small parton momentum fractions are involved in pQCD charm production as follows. Typical partonic center of mass energies $\sqrt{\hat{s}}$ are close to the $c\bar{c}$ threshold $2m_c \simeq 2$ GeV, (since the differential $c\bar{c}$ production cross section decreases with increasing $\hat{s}$) while the total center of mass energy squared is $s = 2m_N E$ (with $m_N \simeq 1$ GeV the nucleon mass, and E the energy per nucleon of the incoming cosmic ray). Calling x_2 the momentum fraction of the target parton in the nucleus of the atmosphere, we have $x_1 x_2 = \hat{s}/s = 4m_c^2/(2m_N E) \simeq \text{GeV}/E$. Hence $x_2 \simeq O(\text{GeV}/0.1\,E) \simeq O(\text{GeV}/E_l)$, where $E_l \simeq 0.1E$ is the dominant muon or neutrino energy.

In GGV2, we analyzed in detail the dependence of the fluxes on the extrapolation of the gluon PDF at small x, which, according to theoretical models, is assumed to be a power law with exponent λ, $xg(x) \sim x^{-\lambda}$, with λ in the range 0–0.5. Particle physics experiments are yet unable to determine the value of λ at $x < 10^{-5}$. We found that the choice of different values of λ at $x < 10^{-5}$ leads to a wide range of final prompt fluxes at energies above 10^5 GeV.

Due to this result, in GGV2 and GGV3 we suggested the possibility of measuring λ through the atmospheric muon fluxes at energies above 10^5 GeV, using not the absolute fluxes, because of their large theoretical error, but rather their spectral index (i.e. the "slope" of the flux). In particular, in GGV3 we proposed to use the slope of the flux of down-going prompt muons, and presented an overall error analysis of the model we used.

Here again we are suggesting to use down-going prompt muons, at energies $E_\mu \gtrsim 1$ TeV where prompt muons can be separated from conventional ones [17], this time to measure the flux of prompt electron and muon atmospheric neutrinos at sea level. We find that the ratio of prompt neutrino to prompt muon fluxes is about 1.1, constant with energy to within 10%, and almost independent of the choice of PDF and charm production parameters. This is shown in Figs. 2 and 3 for the MRST and CTEQ 4M PDF's with a range of λ values from 0 to 0.5. We do not show results obtained with the MRS R1 and R2 PDF's because they are similar. We expect that other models of charm production in the atmosphere, even not based on perturbative QCD, will lead to a similar ratio, because this ratio depends essentially only on the decay properties of the charmed hadrons.

To complete the discussion, in Fig. 4 we plot the neutrino-over-muon ratio of the sum of conventional plus prompt lepton fluxes as a function of lepton energy. In this figure, we use the conventional fluxes in Ref. [3] and the prompt fluxes of GGV2 with the MRST PDF and

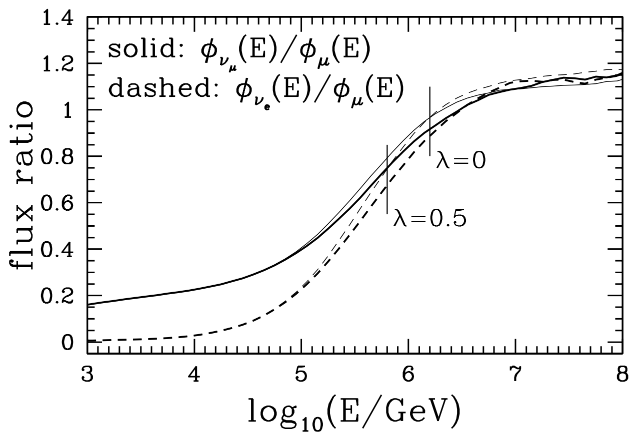

FIG. 4. Total neutrino-over-muon ratio as a function of lepton energy. Vertical marks denote the crossing energy from conventional to prompt muons.

$\lambda = 0$ (thick lines) and 0.5 (thin lines). For each λ, the crossing energy from conventional to prompt muons, from Fig. 2 in GGV2, is marked with a vertical stroke.

We have suggested a way to overcome a potential problem which would limit the search for diffuse astrophysical neutrinos in underwater or under-ice neutrino telescopes, namely the theoretical uncertainty of about two orders of magnitude in the intensity of the prompt atmospheric neutrino fluxes. Concretely, we have suggested to determine their intensity from a measurement of the downgoing prompt muon flux at sea level, whose intensity is the same to within 10% or better.

This work was supported in part by U.S. Department of Energy grant DE-FG03-91ER40662 TaskC at UCLA, and in part by National Science Foundation under Grant No. PHY99-07949 at the Kavli Institute for Theoretical Physics at UCSB. G.V. was supported by an award from Research Corporation.

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