ULB-TH/01-08
MADPH-01-1221
April 2001

The prompt TeV-PeV atmospheric neutrino window

C.G.S. Costa[(1)], F. Halzen[(2)] and C. Salles[(1)]

[(1)] *Service de Physique Théorique, CP 225, Université Libre de Bruxelles, Blvd du Triomphe, 1050 Brussels, Belgium*

[(2)] *Department of Physics, University of Wisconsin, Madison, WI 53706, USA*

Abstract

We discuss the possible existence of an observational window, in the TeV-PeV energy range, for the detection of prompt neutrinos from the decay of charmed particles produced in cosmic ray interactions with the atmosphere. We calculate the event rates for muon and tau neutrinos of heavy quark, mostly charm, origin. We argue that their prompt fluxes are observable in a kilometer-scale neutrino telescope, even though the calculations are subjected to large uncertainties, which we quantify. We raise the possibility that a small component of prompt neutrinos may already be present in the observed samples of current experiments. We also discuss the interplay of the predicted fluxes with those produced by the flavor oscillation of conventional atmospheric neutrinos, and by anticipated cosmic sources.

Typeset using REVTEX

The quest to search for sources of cosmic neutrinos beyond the sun, to search for the particles that constitute the cold dark matter, and to exploit other science opportunities ranging from astronomy to particle physics, led to the commissioning of large volume high-energy neutrino telescopes. While AMANDA and Baikal are taking data [1,2], similar and much larger instruments are contemplated [3–6]. These detectors collect the Cherenkov radiation emitted by charged secondaries (electrons, muons and taus) produced in neutrino charged current interactions in the ice or water surrounding the optical sensors. In order to filter the background of atmospheric muons created by cosmic-ray interactions, only upward-going neutrinos which traverse the Earth are monitored. The first mission of a new neutrino telescope is to calibrate the detector on the known flux of atmospheric neutrinos [7]. Up to about 10 TeV, the main source of atmospheric neutrinos is the decay of pions and kaons in the atmosphere produced in the interactions of cosmic rays with the Earth's atmosphere; we will refer to them as constituting the "conventional" atmospheric neutrino flux. At higher energies, these mesons interact rather than decaying into a neutrino because of the increasing lifetime of the parent mesons. Therefore the semileptonic decay of very-short lived charmed particles becomes the dominant atmospheric source, giving rise to the "prompt" neutrino flux. The energy dependence of prompt neutrinos follows the cosmic ray spectrum whereas the spectrum of conventional neutrinos is steeper by one power in energy because of the competition of decay with interaction of the parent particles. The prompt neutrino flux is independent of zenith angle whereas conventional neutrinos are preferentially produced in the rarified atmosphere at large zenith.

In this letter we discuss the possible existence of an observational window for prompt neutrinos in the TeV-PeV energy range. We calculate neutrino induced muon and tau event rates, recognizing that the fluxes are subject to large uncertainties arising from the combination of extreme atmospheric cascade parameters with different charm production models. We will argue that the prompt fluxes are observable in high-energy neutrino telescopes and analyse the interplay of the predicted fluxes with those produced by the flavor oscillation of conventional atmospheric neutrinos, and by anticipated cosmic sources.

Prompt neutrinos are produced by production and semileptonic decay of heavy quarks produced in cascades initiated by cosmic rays in the atmosphere. In order to appreciate the main ingredients in calculating the production of prompt leptons in the atmosphere, we write an approximate solution to the cascade equations [8], valid for energies below the charm critical energy ($\approx 10^8$ GeV):

$$\Phi_l(E) = Z_{pi}(E)\; Z_{il}(E)\; \frac{\Lambda_p(E)}{\lambda_p(E)}\; \Phi_p(E,0), \tag{1}$$

where $\Phi_l(E)$ is the flux of secondary leptons ($l = \mu, \nu_e$ and ν_μ) from the decay of charmed hadrons ($i = D, D_s$ or Λ_c) produced by cosmic ray hadrons. The charm production spectrum-weighted moment $Z_{pi}(E)$ describes the inclusive charm production cross section; $Z_{il}(E)$ is the charm decay spectrum-weighted moment which represents the semileptonic three-body decay kinematics; $\Lambda_p(E)$ and $\lambda_p(E)$ are, respectively, the proton attenuation and interaction lengths in air [9]. The primary cosmic ray flux at the top of the atmosphere $\Phi_p(E,0)$ is assumed to be composed of protons although the validity of the superposition approximation guarantees that the calculation extends to heavier nuclei. Above the charm critical energy (the energy where interaction and decay of the charm particle compete in the evolution of the cascade), the charm interaction length $\lambda_i(E)$ must also be taken into account and the complete solution has to be considered. What the prompt tau-neutrino flux ($l = \nu_\tau$) is concerned, it suffices to calculate a generalized decay Z-moment $Z_{il}(E)$, in Eq. (1) which accounts for the decay chain: $D_s \rightarrow \tau\nu_\tau$ followed by $\tau \rightarrow \nu_\tau X$ (where X is either a $\mu\nu_\mu$ pair or a meson) [10].

Detailed investigation of the charm induced muon-neutrino flux [11] reveals the large uncertainties in the prompt component resulting from the imprecise knowledge of atmospheric particle showering parameters: primary cosmic ray spectrum Φ_p, spectrum-weighted moments $Z_{i\nu}$, attenuation and interaction lengths, Λ_p, λ_p and λ_i. Further uncertainty is associated with the extrapolation to high energy of a variety of models describing the accelerator data on charm production such as the Quark Gluon String Model (QGSM) [12], Recombination Quark Parton Model (RQPM) [13] and perturbative QCD (pQCD) [14]. In the end, we conclude that the calculated fluxes, for both ν_μ and ν_τ, are subjected to uncertainties of up to one order of magnitude for a given charm model. When comparison is made of alternative charm production models, the spread reaches two orders of magnitude. We will therefore define an allowed range between the maximum and minimum prompt neutrino fluxes.

There are two contrasting approaches in calculating charm production cross sections. The first is to blindly apply perturbative QCD. This is a questionable procedure because, at the extreme energies considered here, large logarithms connected with the small ratio of the charm quark mass and the square root of the center of mass energy, $x = m_c/\sqrt{s}$, are likely to modify the calculation. For instance, this procedure, even though subject to large ambiguities, routinely underestimates the production of strange particles at accelerator energies. It may therefore be more appropriate to calculate charm production in the context of QCD-inspired models that have been patterned to accommodate accelerator data on strange particle production. QGSM and RQPM fall into this category and predict similar and larger extrapolations for the charm production cross section at higher energies.

The detection rates of upward-going prompt neutrinos, i.e. the rates of neutrino induced muons and taus, per year per effective detection area (in 2π sr), can be estimated from our flux calculations following the prescription of Gandhi *et al.* [15]. We first concentrate on the operating neutrino telescopes, BAIKAL NT-200 [2] and AMANDA-II [1], and subsequently consider the proposed km^3 experiment, ICECUBE [5]; see Table I. Calculations use the maximum and minimum allowed prompt fluxes. We show for comparison the expected rates for muon-neutrinos from conventional atmospheric decays. Absorption in the Earth of the highest energy neutrinos is taken into account. From Table I we anticipate a situation where more then a thousand prompt muon-neutrinos above 1 TeV may be extracted from ICECUBE data using their flat zenith angle distribution as a signature. Furthermore, we predict about 200 prompt tau-neutrino candidates which also produce characteristic showers in the detector [16]. Above 10 TeV, the 20 remaining tau-neutrinos will have no counterpart from the tau-neutrinos resulting from the oscillation of conventional atmospheric neutrinos, a source of which we consider further on.

Our calculations raise the possibility that prompt neutrinos may be observed by high-energy neutrino telescopes, especially because models extrapolating to the larger fluxes are, at least in our opinion, more robust. We next discuss the interplay of the predicted fluxes with those produced by the flavor oscillation of conventional atmospheric neutrinos, and by anticipated sources of cosmic neutrinos.

In Figure 1 we present prompt ν_μ fluxes corresponding to the allowed range between maximum and minimum predictions [11], along with the conventional atmospheric flux [14]. Among the potential candidates of other high-energy neutrino sources [17], we will concentrate on cosmic accelerators such as active galactic nuclei and gamma ray bursts which produce the highest energy photons observed, and are theorized to produce the highest energy cosmic rays. Their anticipated diffuse neutrino flux is bounded by experimental information on measured high-energy fluxes of cosmic rays, specifically neutrons, and gamma rays. The two upper curves in Figure 1 labeled MPR (solid and dotted lines), represent the allowed range of neutrino fluxes from sources that are optically thick or thin to the emission of neutrons [18], respectively. The two intermediate straight lines labeled WB (dashed and long–dashed), represent bounds imposed on sources which produce the highest energy cosmic rays [19]. The higher flux allows for cosmological evolution of the sources.

We note that the energy where the prompt neutrino flux exceeds the conventional one is roughly 10 TeV. Separation of the two components can be made, taking advantage of the fact that the conventional atmospheric flux has a characteristic and calculable zenith angle distribution, while the prompt component is isotropic.

If cosmic sources exist near the MPR bounds, the prompt muon-neutrino window is definitely closed. Neutrino telescopes will detect cosmic neutrinos at very high rates and the prompt component is a background to be dealt with. The AMANDA experiment is already exploring this range of fluxes [7]. Between 10^5 GeV and 10^6 GeV the MPR bound for thin sources has essentially the same slope as the prompt flux. Since the bound is an upper limit, it may happen that the cosmic sources actually produce as many detectable neutrinos as atmospheric interactions do, and it will be difficult to disentangle both components. The situation is quite different when considering the extragalactic flux subjected to the WB-bounds. For evolving sources, there is room for an excess of prompt neutrinos in the range 20-300 TeV. For non-evolving sources scenario, then the prompt window may be open up to about 2 PeV.

The allowed band for atmospheric charm-induced tau-neutrinos is presented in Figure 2. In the absence of neutrino flavor oscillations, atmospheric ν_τ's from charm are the only source of tau-neutrinos and the prompt window is completely open. We remind the reader that cosmic beam dumps produce negligible fluxes of tau-neutrinos. Recent measurements of the Super-Kamiokande experiment [20] do however favor non-vanishing neutrino masses and produce compelling evidence for $\nu_\mu \to \nu_\tau$ flavor transitions, with maximum mixing angle ($\sin^2 2\theta = 1$) and a square mass difference of $\Delta m^2 = 3.2 \times 10^{-3}$ eV^2. We therefore consider a scenario where the conventional atmospheric ν_μ flux in Figure 1 is modified by this oscillation mechanism. In the calculation we consider the range $\log_{10}(\Delta m^2/\mathrm{eV}^2) = 2.5 \pm 0.5$. Similarly, the bounds bracketing the extragalactic diffuse muon-neutrino flux can be translated into estimates of bounds on a cosmic tau-neutrino flux by adopting a typical value for the ratio of ν_τ to ν_μ vacuum flavor conversion, over astronomical baselines, of $F_{\nu_\tau/\nu_\mu} = 0.5$ [21]. The resulting fluxes are also shown in Figure 2. The appearance of a tau-neutrino below 1 TeV is a clear indication of atmospheric neutrino oscillations from a conventional ν_μ flux. Above ≈ 2 TeV, we face again the interplay between extragalactic bounds and the atmospheric prompt component. For MPR scenarios, the prompt window may be closed; for WB-bounds the prompt tau-neutrino appearance may dominate extragalactic oscillation fluxes up to 50 TeV (for evolving sources), or even 500 TeV (for non-evolving sources).

In conclusion, we observe that the calculations of prompt neutrino fluxes are subjected to large uncertainties, arising from possible extreme cascade parameters combined with different charm production models. We identified the possibility that prompt fluxes are observable in a kilometer-scale neutrino telescope, particularly in the region from 2 TeV to 2 PeV. At the upper range of the predictions, a small component of prompt neutrinos may already be present in the observed sample of high-energy atmospheric neutrinos of the AMANDA experiment [7].

Detection of the atmospheric prompt-ν_μ will provide unique information on heavy quark interactions at energies not accessible to particle accelerators. The better characterization of the charm induced neutrino component will increase the discrimination power of neutrino detectors at higher energies. Knowledge of atmospheric charm production is essential in identifying the origin of a detected ν_τ above a few TeV, whose appearance may also result from neutrino flavor oscillations.

ACKNOWLEDGMENTS

We would like to thank Jean-Marie Frère for valuable discussions and suggestions. This work was partially supported by the I.I.S.N. (Belgium), by The Communauté Française de Belgique - Direction de la Recherche Scientifique, programme ARC, by the U.S. Department of Energy under Grant No. DE-FG02-95ER40896 and by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation.

REFERENCES

[1] The AMANDA Collaboration, Astropart. Phys. **13,** 1 (2000); Nucl. Phys. B (Proc. Suppl.) **91,** 423 (2001).

[2] The BAIKAL Collaboration, Astropart. Phys. **14,** 61 (2000); Nucl. Phys. B (Proc. Suppl.) **91,** 438 (2001).

[3] The ANTARES Collaboration, Nucl. Phys. B (Proc. Suppl.) **81,** 174 (2000); Nucl. Phys. B (Proc. Suppl.) **91,** 431 (2001).

[4] The NESTOR Collaboration, Nucl. Phys. B (Proc. Suppl.) **87,** 448 (2000).

[5] F. Halzen *et al.*, in *Proceedings of the 26th International Cosmic Ray Conference,* South Lake City (USA), edited by D. Kieda, M. Salamon and B. Dingus, Vol. 2, 428-431 (1999); C. Spiering, Nucl. Phys. (Proc. Suppl.) **91,** 445 (2001).

[6] The NEMO Collaboration, Nucl. Phys. B (Proc. Suppl.) **87,** 433 (2000).

[7] E. Andres *et al.*, Nature **410,** 441 (March 22, 2001).

[8] L. Pasquali, M.H. Reno and I. Sarcevic, Phys. Rev. D **59**, 034020 (1999).

[9] Cascade parameters are well defined by T.K. Gaisser, in *Cosmic Rays and Particle Physics*, (Cambridge University, Cambridge, 1992).

[10] L. Pasquali and M.H. Reno, Phys. Rev. D **59,** 093003 (1999).

[11] C.G.S. Costa, Astropart. Phys. (to be published, 2001), hep-ph/0010306.

[12] A.B. Kaidalov and O.I. Piskunova, Z. Phys. C **30,** 145 (1986); L.V. Volkova *et al.*, Nuovo Cimento C **10,** 465 (1987).

[13] E.V. Bugaev *et al.*, Phys. Rev. D **58,** 054001 (1998).

[14] M. Thunman, G. Ingelman and P. Gondolo, Astropart. Phys. **5**, 309 (1996); G. Gelmini, P. Gondolo and G. Varieschi, Phys. Rev. D **61**, 036005 (2000).

[15] R. Gandhi, C. Quigg, M.H. Reno and I. Sarcevic, Phys. Rev. D **58**, 093009 (1998).

[16] T. Stanev, Phys. Rev. Lett. **83**, 5427 (1999).

[17] T.K. Gaisser, F. Halzen and T. Stanev, Phys. Rep. **258,** 173 (1995); F. Halzen, Phys. Rep. **333-334,** 349 (2000).

[18] K. Mannheim, R.J. Protheroe and J.P. Rachen, astro-ph/9908031 (1999); Phys. Rev. D **63**, 023003 (2000).

[19] E. Waxman and J. Bahcall, Phys. Rev. D **59**, 023002 (1999); hep-ph/9902383 (2000).

[20] The Super-Kamiokande Collaboration, Phys. Rev. Lett. **85,** 3999 (2000).

[21] J. Alvarez-Muniz, F. Halzen and D.W Hooper, Phys. Rev. D **62**, 093015 (2000).

TABLES

TABLE I. Upward-going muon and tau event rates per year arising from charged current interactions of atmospheric neutrinos in ice or water, for different neutrino telescopes' effective areas and thresholds. Prompt flux calculation based on maximum (MAX) and minimum (MIN) range limits described in the text.

			$\mu^+ + \mu^-$			$\tau^+ + \tau^-$	
Experiment	Threshold	A_{eff}	Conventional	Prompt MAX	Prompt MIN	Prompt MAX	Prompt MIN
BAIKAL NT-200	1 TeV	2×10^3 m^2	22	3	0	0	0
AMANDA-II	1 TeV	3×10^4 m^2	330	44	2	7	0
ICECUBE	1 TeV	1 km^2	11000	1470	53	216	11
ICECUBE	10 TeV	1 km^2	170	157	3	22	1

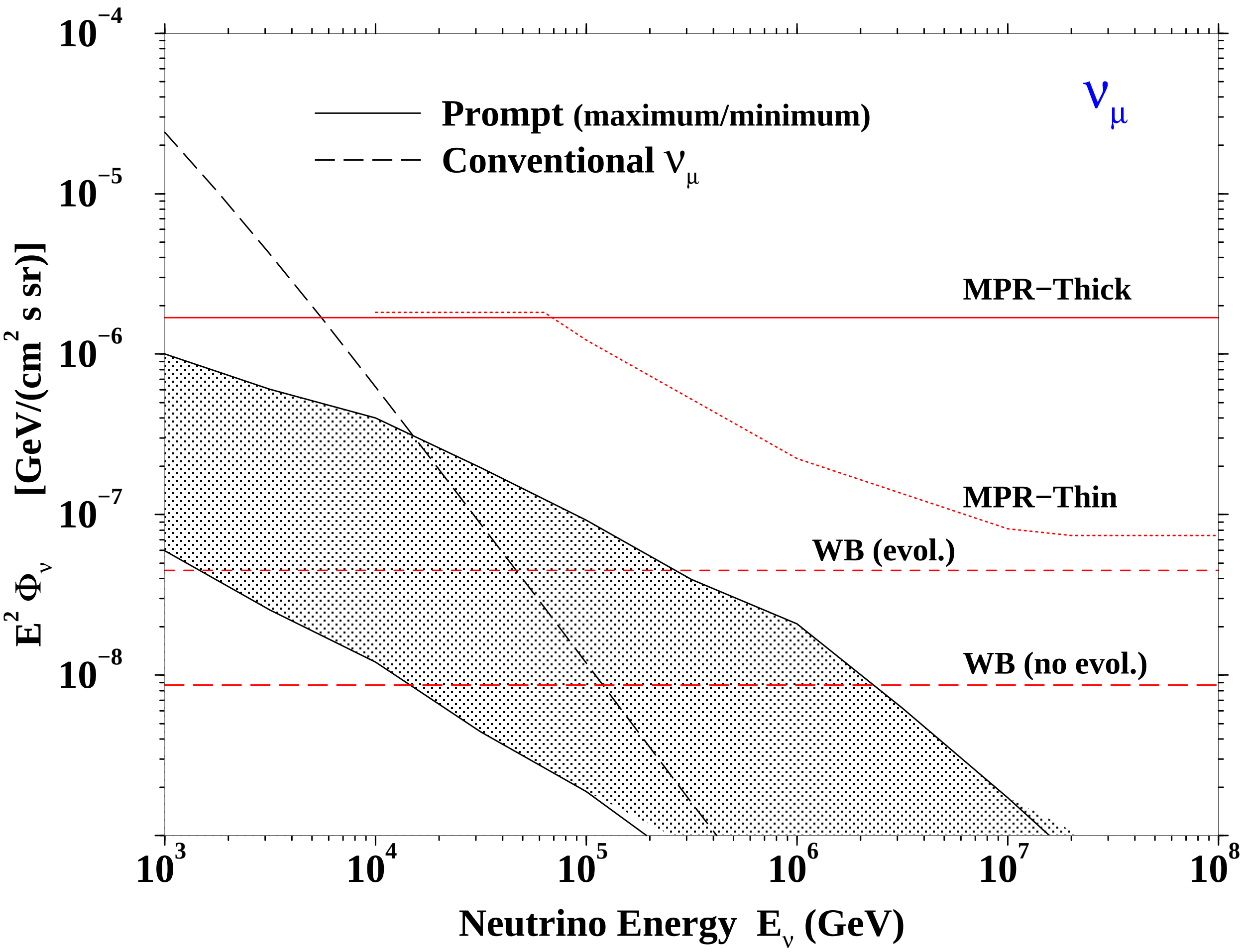

FIG. 1. Comparison of several contributions to the high-energy ν_μ flux. The band represents the allowed range between maximum and minimum atmospheric prompt neutrino fluxes. Thick dashed line is the conventional atmospheric flux. Solid, dotted, dashed and long-dashed lines correspond to upper bounds imposed to diffuse extragalactic neutrino flux by the observation of high-energy cosmic-ray and gamma-ray spectra, according to different scenarios explained in the text. Fluxes are multiplied by E^2.

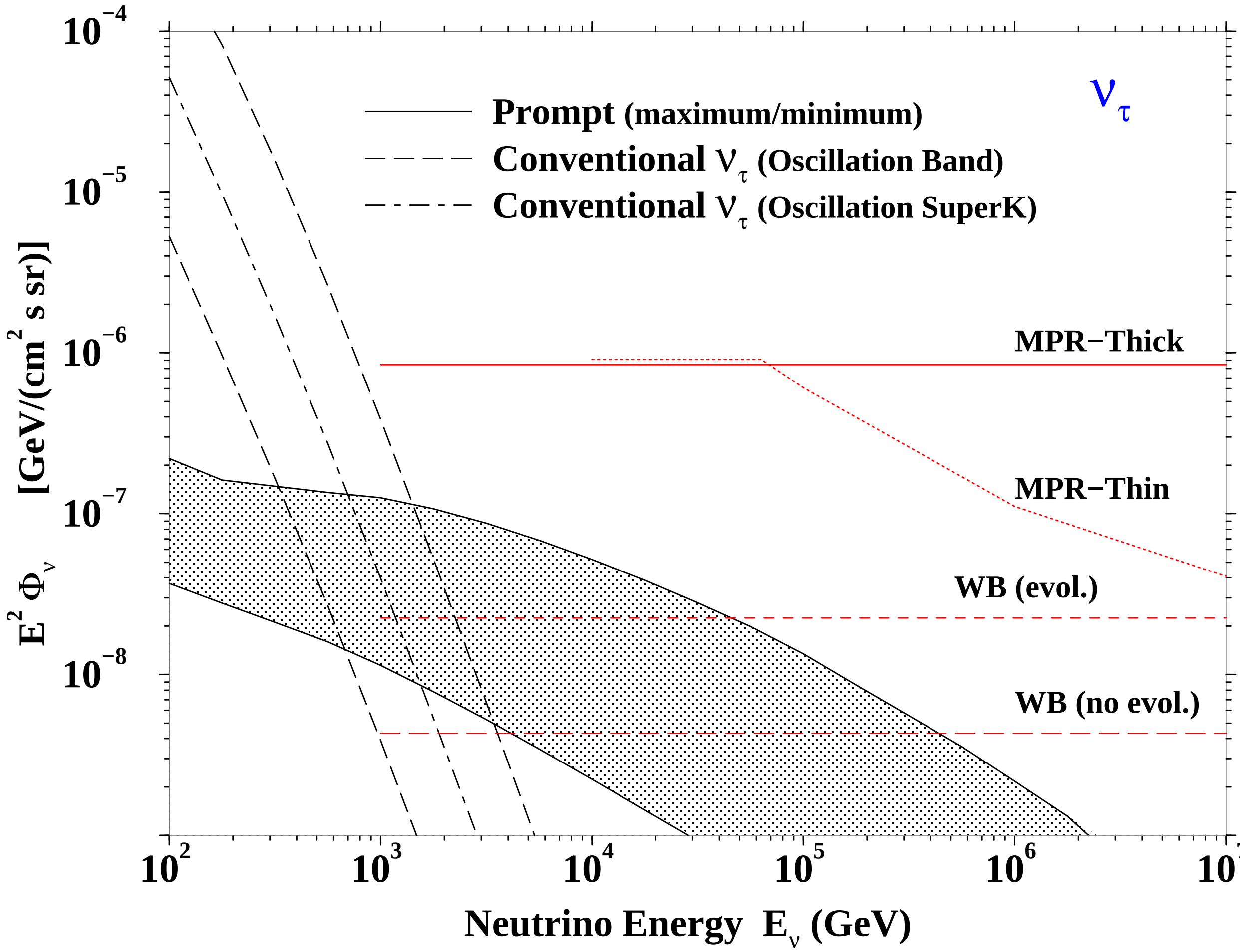

FIG. 2. Comparison of several possible contributions to the high-energy ν_τ flux. The band represents the allowed range between maximum and minimum atmospheric prompt neutrino fluxes. Thick dashed lines are the result of maximum mixing flavor oscillation of the conventional atmospheric ν_μ flux, for Δm^2 around the Super-Kamiokande value (thick dot-dashed line), as explained in the text. Solid, dotted, dashed and long-dashed lines correspond to the upper bounds in Figure 1, subjected to vacuum flavor oscillation, averaged in transit to Earth. Fluxes are multiplied by E^2.