HIGH ENERGY NEUTRINOS

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Abstract

In this paper we compare the results of the MACRO detector at Gran Sasso, that is the largest neutrino telescope operated before the year 2k, with theoretical predictions of the neutrino emission from some promising targets, such as blazars and GRB’s. In particular we propose a new statistical method, justified by the maximum entropy principle, for assessing a model independent upper limit to the differential flux of neutrinos inferred from the measured up-ward going muon flux. This comparison confirms that the acceptance of a detector of up-ward going muons should be of the order of 1 km$^2$, in order to challenge the present theoretical estimates of possible neutrino production in both galactic and extra-galactic objects.

1 Introduction

Large detectors of high energy (> 1 GeV) neutrinos, like MACRO in the Gran Sasso Laboratory[1] or SuperKamiokande[2] have been operated in the
last decade of the past century, but no extrasolar astrophysical source has been detected. The occasion of this paper is related to the decommissioning of the MACRO detector at Gran Sasso, that is the largest neutrino telescope operated before the year 2k. The proposal for the detector was accepted in November 1984 [3]. Physics runs started in March 1989, as soon as the first supermodule of the detector has been built [4, 5]. The full detector has been run from April, 1994 to December 31, 2000 when it has been decommissioned. A sample of a 1000 up-ward going muons has allowed the measurement of the flux of geophysical neutrinos collected up to September, 1999 [6], producing also interesting result [7]. The purpose of this paper is to compare the upper limits obtained by MACRO with current models of neutrino emission from astrophysical objects. First in the following §2 we will discuss the physics of neutrino detection in detectors of up-ward going muons. In particular in §2.1 we discuss the extrapolation of the differential neutrino cross section to the range of energies of interest for astrophysical neutrino detection, in §2.2 the conversion of neutrinos into muons in the rock and finally in §2.3 we give the rationale for a new statistical method for assessing a model independent upper limit to the differential flux of neutrinos inferred from the measured up-ward going muon flux. In §3 we present some results obtained from the MACRO survey of neutrino induced up-ward going muons. In §3.1 we present the constraint to the neutrino emission from the Crab nebula, in §3.2 that for a possible neutralino decay in the Galactic center, in §3.3 the constraint to diffuse neutrino background which can be inferred from the cumulative search of coincidences with blazars and in §3.4 we discuss the same topic for the GRB deriving an upper limit to the diffuse flux of neutrinos correlated with GRB. Finally in §4 we discuss the prospect for detection of neutrinos in the next future by the planned detectors.

2 Neutrino detection

2.1 Extrapolation of neutrino cross section

The detection process for muon neutrinos and anti neutrinos is the Charged Current (CC) scattering illustrated in Fig. 1 with double differential cross section

\[
\frac{d^2\sigma_{\nu(\bar{\nu})}}{dx\,dy} = \frac{G_F^2}{2\pi} \frac{m_N^2}{(Q^2 + M_W^2)^2} \times \left\{ \frac{y^2}{2} \right. \\
\left. \times \left[ 2x F_1^{\nu(\bar{\nu})}(x, Q^2) + (1 - y) F_2^{\nu(\bar{\nu})}(x, Q^2) + \pm \left(y - \frac{y^2}{2}\right) x F_3^{\nu(\bar{\nu})}(x, Q^2) \right] \right\} \tag{1}
\]

where \(y = 1 - E_\mu/E_\nu\) is the fraction of neutrino energy lost in the Lab system, \(x = Q^2/2m_N(E_\nu - E_\mu)\) the fraction of parton momentum carried by the struck parton, and \(Q^2 = xy(s - m_N^2)\) the square of the transferred
four momentum. The last term is positive for $\nu$'s and negative for $\bar{\nu}$'s. The three functions $F_1$, $F_2$ and $F_3$ are the structure functions (SF’s) of the nucleon. In the framework of the quark parton model (QPM) the parton are identified with quarks, and the SF’s can be expressed in terms of the probability density functions (PDF) of each quark types. The PDF’s are the functions $q(x, Q^2)$ where $q = u, d, s, c, b, t$ and the relative anti-quarks, which assign the probability that a quark carries a momentum fraction $x$.

In particular we have for an isoscalar target

$$F_2^{\nu N} = x \{ u + \bar{u} + d + \bar{d} + 2s + 2c + 2b + 2t \}$$

$$xF_3^{\nu N} = x \{ u - \bar{u} + d - \bar{d} \pm 2s \pm 2c \pm 2b \pm 2t \}$$

At very high energies the SF’s $F_2$ and $2xF_1$, are equal, but if the transverse momentum of the $W$ is not negligible, they are related by the equation

$$2xF_1(x, Q^2) = F_2(x, Q^2) \frac{1 + 4m_N^2x^2/Q^2}{1 + R(x, Q^2)} \quad (2)$$

where $R(x, Q^2) = \sigma_L/\sigma_T$ is the ratio of the longitudinal to transversal cross section of the $W$.

The structure functions $F_2$ and $xF_3$ and the function $R$ have been measured experimentally up to $E_\nu \approx 500$ GeV by the CCFR/NuTeV collaboration [9, 10, 11, 12]. To calculate the neutrino cross sections at higher energies, as we are interested in this paper, the SF’s should be extrapolated. The propagator term in Eq. (1) $M_W^4/(Q^2 + M_W^2)^2 \to 0$ for $Q^2 \gg M_W^2$, therefore the cross section at any energy will vanish for $Q^2 \gtrsim \max[xys - m_N^2, M_W^2]$. However the double differential cross section of Eq (1) must be integrated to obtain the differential cross section $d\sigma/dy$ for a given $y$ in the interval $Q^2/y(s - m_N^2) \leq x \leq 1$. If the minimum detectable energy for the muon in the detector is $E_{th}$ the lower integration limit is $x_{min} \approx Q^2/2m_NE_\nu$. In Fig. 2 we have reported the area of the plane $\log_{10}(1/x), Q^2$ corresponding to $E_\nu = 10^6$ GeV where Eq. (1) must be integrated, compared with the area where the SF’s have been measured.
Figure 2: Physical integration domain over which Eq. (1) must be integrated for a given energy of the neutrino.

Figure 3: Differential neutrino cross section at $E_\nu = 425$ GeV measured by CCFR experiment. The fit is the differential cross section obtained in this paper applying CTEQ5 PDF's.

In the same plot of Fig. 2, we have reported the lines $W^2 = Q^2(1/x - 1) = 4m_h^2$ where $m_h$ are the masses of the heavy quarks $c, b$ and $t$. Above these...
lines the production of the heavy quarks will give an important contribution to the cross section. In fact it is well established that above \( \approx 100 \text{ GeV} \) the contribution of the quark production to the total cross section is of the order of 20\% \[13\]. From the plot of Fig. 2 we are forced to conclude that the experimental knowledge of the physics underlying the extrapolation of the cross section is, up to now, rather incomplete. In the framework of quantum chromodynamics (QCD), the gauge field theory which describes the strong interactions of colored quarks and gluons, the cross sections can be calculated perturbatively in ascending order of the strong coupling constant \( \alpha_s \). In practice this corresponds to the solution of a set of partial differential equations \( \partial F_i(x,Q^2)/\partial \ln(Q^2) \) (the DGLAP equations) at fixed \( x \), starting from the knowledge of the SF’s \( F_i(x,Q^2) \) with \( i = 1, 2, 3 \) at a given lower value \( Q_0^2 \) (see e.g. Sterman G. et al. 1999 and references therein). This method has been checked, using the measured differential cross sections. For example we report in Fig. 3 the fit to the measured differential cross section obtained using PDF’s calculated by the CTEQ5 collaboration \[14\], with evolution equations resulting from NLO analysis from a starting scale \( Q_0^2 = 1 \text{ GeV}^2 \). It is evident from this figure that the agreement is reasonable but not perfect \[15\].

Nevertheless the extrapolation at higher energies of the neutrino cross section is still subjected to a non negligible uncertainty because, as is shown in Fig. 3, the domain of integration at higher energies extends to smaller and smaller values of \( x \). Therefore, even if the evolution of SF’s at fixed \( x \) to higher \( Q^2 \) can be calculated with the DGLAP equations, still we lack of information about the SF’s at low \( x \) values. Various estimates, based on different physical assumption \[16, 17, 18, 19, 20\], as shown in Fig. 4 disagree by factors up to 2-4 for \( E_\nu \gtrsim 10,000 \text{ GeV} \). The experimental point has been obtained by the H1 Collaboration \[21\]. The higher values of the cross section is given by extrapolation of the SF’s for \( x < 10^{-5} \) based on the Regge theory \[22, 23\].

In the same Fig. 4 we have reported the cross section of the reaction \( e^- p \rightarrow \nu X \) by the H1 experiment at HERA (Ahmed et al. 1994) which seems to be in better agreement with the lower cross section estimate. In the rest of this paper we will take as a baseline extrapolation of the cross section the more conservative one, shown as a solid line in Fig. 4, based on the CTEQ5 PDF’s.

### 2.2 Evaluation of conversion probability

The probability \( P_{\mu\nu}(E_\nu) \) of detecting a muon with energy \( \geq E_{\text{th}} \) in the detector, originated by a neutrino with energy \( E_\nu \), is given, in the continuous
Figure 4: Various extrapolations of the total cross section for isoscalar target and equal mixture of $\nu_\mu$ and $\bar{\nu}_\mu$. Solid line is the baseline estimate adopted in the following of this paper (see text.). Finely dotted line is based on the small $x$ structure functions measured at HERA, dash-dotted on the dynamical parton model, which is practically coincident with coarsely dotted line, dashed on the Regge theory for $x < 10^{-5}$ (see text).

slowing down approximation, by the integral [24]

$$ P_{\mu\nu}(E_\nu) = \frac{1}{m_N} \int_0^{1-E_{th}/E_\nu} \left[ a + b (1-y) E_\nu \right]^{-1} \int_0^1 \frac{d^2\sigma_{\mu\nu}}{dy \ dx} \ dy \ dx $$ \hspace{1cm} (3)

where $m_N$ is the mass of the nucleon, $a$ and $b$ are the coefficient of the muon energy loss $-dE_\mu/dz = a(E_\mu) + b(E_\mu) E_\mu$ [25].

Figure 5: Conversion probability for various $E_{th}$ values.

2.3 Model independent upper limits

The differential up-ward going muon flux in the detector will be $d\Phi_\mu/dE_\nu = P_{\mu\nu} d\Phi_{\nu}/dE_\nu$ where $d\Phi_{\nu}/dE_\nu$ is the spectral distribution of the neutrino flux.
However what is measured in an up-ward going muons neutrino telescope, like MACRO, is only the integrated muon flux

$$\Phi^{\text{obs}}_\mu(> E_{\text{th}}) = \int_{E_{\text{th}}}^{\infty} P_{\mu\nu} \frac{d\Phi_\nu}{dE_\nu} dE_\nu$$

(4)

The conversion of the muon flux into a neutrino flux is subject to the ambiguities arising from the lack of knowledge of the shape of the neutrino spectrum itself. The usual approach followed in the literature [1, 26] is to give the upper limit to the neutrino fluxes assuming a spectrum $d\Phi_\nu/dE_\nu \propto E^{-2}_\nu$. In this case the integrated neutrino flux can be estimated using an average conversion probability

$$\Phi_\nu(> E_{\text{th}}) = \frac{\Phi^{\text{obs}}_\mu(> E_{\text{th}})}{\int_{E_{\text{th}}}^{\infty} E^{-2}_\nu P_{\mu\nu} dE_\nu}$$

(5)

We propose here to apply the maximum entropy principle [27, 28] to infer the unknown neutrino differential flux, with the less prior assumption on the spectral shape. In fact, even if the maximum entropy principle has been questioned for the lack of solid theoretical foundations, it gives very significant results in several fields of applications of spectral deconvolution [29]. According to this principle we assume that the probability distribution function of the energy of the neutrino that could have produced a muon in the MACRO detector will be uniform. In this case we have the ansatz $P_{\mu\nu} d\Phi^{\text{ME}}_\nu/dE_\nu = \text{const}$. Therefore, normalizing to the integrated neutrino flux of Eq. (5), we have derived the estimate of the upper limit to the neutrino flux which will be shown in the following.

3 Results of the MACRO survey

3.1 Neutrino emission from the Crab nebula

Gamma ray spectrum of the Crab Nebula extends up to 25 TeV. Above $\approx 500$ GeV the spectrum is a simple power law with $\alpha \simeq 2.5$. The total $\gamma$-ray luminosity is above $500$ GeV $L_\gamma \simeq 1.5 \times 10^{26}$ erg cm$^{-2}$ s$^{-1}$. The detection of neutrino emission from the Crab could support the possibility that this high energy emission is due to hadronic interactions. Bednarek & Protheroe (1997) have analyzed the consequences of acceleration of heavy nuclei in the pulsar magnetosphere as a possible mechanism of energetic radiation from the Crab Nebula. The MACRO limit for the Crab Nebula is

$$\Phi^{\text{Crab}}_\mu(> 1.2 \text{ GeV}) \leq 2.5 \times 10^{-14} \text{ cm}^{-2} \text{ s}^{-1} \ (90\% \ C.L.)$$

(6)

In Fig. 3 we compare the limit on the neutrino flux, with two extreme
Figure 6: Neutrino sky after MACRO (lower panel). In the upper panel is shown the complementary result of the AMANDA survey.

Figure 7: MACRO Upper Limit (90% C.L.) for neutrino emission from the Crab Nebula

models. The present emission is determined by the trapped high energy proton’s density in the nebula. Therefore the present emission is mainly due to acceleration in the early times after supernova explosion. Magnetic dipole losses determine the pulsar period at present, but the initial period is determined largely by gravitational losses and it has been probably shorter than 10 ms. Hence the two models consider two initial periods: 5 ms, and 10 ms.\textsuperscript{30}
3.2 Neutralino annihilation in the Galactic Center

Intense emission from the Galactic center is predicted if cold dark matter is present there, as in current models of the dark galactic halo \[31, 32, 33\]. In particular it could be expected, according to Gondolo & Silk (1999) that a massive black hole at the galactic center could redistribute the WIMP’s into a cusp. The effect of this redistribution would be a strong enhancements of the self-annihilation rate of neutralinos. In Fig. 8 we report the predicted upward going muon flux in the two cases. After the complete run MACRO [1]

![Figure 8: Predicted up-ward going muon flux from Galactic Center. The possible enhancement due to the redistribution of neutralinos is shown in the upper panel.](image)

the 90% C.L. upper limits on up-ward going muons from the Galactic Center is \(\Phi_\mu \leq 0.34 \times 10^{-14} \text{ cm}^{-2} \text{s}^{-1}\). This new limit is reported in Fig. 8. It is clear from this figure that the predicted enhancement has not been observed. One possible explanation of this negative result has been given from a subsequent more careful evaluation, in a recent paper, of the dynamics of the cusp formation [34]. The MACRO negative observation supports the possibility that the accreting matter could not spiral fast enough by dynamical friction only. Thus within a Hubble time only a mild enhancement could have taken place.

3.3 Diffuse emission from Blazars

The second EGRET catalog of high-energy \(\gamma\)-ray sources [35] contains 40 high confidence identification of AGN and all appear to be blazars. This is the main reason for which several authors [36, 37] have proposed this type of object as potential powerful sources of high energy neutrinos. The proton
The blazar model [38] both protons and electrons are accelerated and protons interact with synchrotron radiation produced by electrons photoproducing pions that decay into γ-rays and neutrinos.

The up-ward going muons distribution, shown in Fig. 6 has been searched for angular coincidences in a 3° cone with each of the 181 blazars, listed in a recent catalogue [39], with a declination δ ≤ 40°. No significant excess has been found for any individual source, with a cumulative average upper limit to the muon flux Φ(µ) ≥ 1.2 GeV) ≤ 5.44 × 10^{-16} cm^{-2} s^{-1}. A bias in favour of northern declinations is clearly present in the sample. In fact 178 out of the 233 objects listed in the catalog, have δ > 0° and there are no known BL Lacs with δ < −57°. We can estimate, very roughly, that the MACRO survey has covered the declination band −57° ≤ δ ≤ 40°, corresponding to ≈ 3.2π sr of sky. From this figure we can estimate the U.L. to the diffuse up-ward going muons from blazars

\[
\frac{dΦ^{BLac}}{dΩ} ≤ 0.98 × 10^{-14} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad (90\% \text{ C.L.})
\]

Applying the maximum entropy method we obtain the upper limit to the diffuse neutrino flux reported in Fig. 9. In the same plot we have reported the model independent upper bound that can be derived if the UHE cosmic rays are also accelerated in the same source [40]. The higher prediction is obtained, presuming a blazar’s luminosity cosmological evolution following that of QSO’s, which may be described as \( f_{QSO} = (1+z)^3 \) at redshift \( z < 1.9 \) and constant above. The lower prediction is for no evolution of the blazar’s density.

### 3.4 Search for neutrinos from GRB’s

Several mechanisms for production of intense HE and UHE neutrino and γ burst associated with the main pulse, in the 0.1 MeV have been proposed
in the literature [41, 42, 43, 44]. It is somewhat surprising however that a phenomenon that was discovered in the keV-MeV region could be the herald of big activity in the multi-TeraVolt region.

We have searched the catalogues BATSE 3B & 4B [45] containing 2527 gamma ray bursts from 21 Apr. 1991 to 5 Oct. 1999 [1]. They overlap in time with 1085 upward-going muons collected by MACRO during this period. In Fig. 10 it is shown a plot of angular distance among the GRB and upward going muons in MACRO as a function of arrival time difference. We observe that if neutrino are massive, as suggested by observation of neutrino oscillations, the neutrino burst from cosmological GRB will be delayed respect to the observation of the γ rays observed by the GRB itself. The time delay will be

\[ \delta t = \frac{1 - \beta}{\beta} (t_z - t_0) \]  

where \( \beta = \sqrt{E_{\nu}^2 - m_{\nu}^2c^4}/E_{\nu} \). For \( E_{\nu} \gg m_{\nu}c^2 \) we can put \( (1 - \beta)/\beta = 1/2(E_{\nu}/m_{\nu}c^2)^{-2} + \mathcal{O}(E_{\nu}/m_{\nu}c^2)^{-4} \). In Fig. 11 we show the expected delay of the massive neutrino signal, for GRB in the range \( z = 0.5 - 2 \) as a function of the Lorentz factor of the neutrino. In the same figure we have reported the normalized Lorentz factor distribution (for a source spectrum \( dN_{\nu}/dE_{\nu} \propto E_{\nu}^{-2} \)) of neutrinos that produce upward going muons in the MACRO detector. From this figure we see that a maximum delay of \( \approx 1000 \) s could be expected for very massive neutrinos (\( m_{\nu} = 10 \) eV).

Therefore the time window to be searched for should to be expanded up to \( \approx 1000 \) s after the detection of the GRB for the muon to be detected in

Figure 10: Coincidences of up-ward going muons in MACRO with the 2527 gamma ray bursts from 21 Apr. 1991 to 5 Oct. 1999 (see text).
Figure 11: Time delay of the neutrino burst from the main pulse as a function of energies for different neutrino masses.

Figure 12: MACRO Upper Limit (90% C.L.) for the diffuse neutrino emission from GRB’s.

MACRO. However according to the current ideas on the production of the GRB explosion, it should not be possible to have the neutrino emission long before the GRB. Therefore we can assume that the coincidences between muons detected in the time window preceding the GRB should be very likely accidental. From the lower panel of Fig. 12 we estimate that the accidental coincidences among up-going muons and GRB with $\Delta \theta \leq 20^\circ$ will be 0.4 in the overlap period. From the upper panel of the same figure we could candidate two events as possible true coincidences, one event after 39.4 s from 4B950922 at an angular distance of 17.6$^\circ$ and another very horizontal event in coincidence with the 4B940527 inside 280 s at 14.9$^\circ$. However the cumulative Poissonian probability that those two events are accidental is $7.9 \times 10^{-3}$. We assume then that those events are expected accidental, and calculate that the 90% confidence interval for the unobserved true coincident upward-going muons will be $\leq 5.41$. The corresponding upper limit to the muon fluence from the average GRB is $\Phi_{\mu}(\geq 1.2 \text{ GeV}) \leq 0.79 \times 10^{-9} \text{ cm}^{-2} \text{ (90\%C.L.)}$ for neutrino masses $m_\nu \leq 10 \text{ eV}$. From this cumulative limit we can derive
an upper limit to the diffuse neutrino background from GRB’s, taking into account the fact that the MACRO live time in the period from 21 Apr. 1991 to 5 Oct. 1999 has been 4.62 y, that neutrinos could have been detected for GRB’s with declination $\delta \leq 40^\circ$ (corresponding to 3.53 $\pi$ sr of sky) and that the exposure factor for BATSE in this declination range is 55% we can convert the upper limit for the average burst to a diffuse background

$$\frac{d\Phi^{GRB}_\mu}{d\Omega} \leq 2.25 \times 10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad (90\% \text{ C.L.}) \quad (9)$$

We obtain also in this case the upper limit to the diffuse neutrino emission from GRB’s reported in Fig. 12. In the same figure we have reported the prediction of diffuse neutrino background produced by a cosmological distribution of GRB’s. Also we have reported the flux expected from the intriguing possibility that before the jet could emerge from the dense stellar progenitor of the GRB, the accelerated protons could interact with the thermal X-ray photon leading to neutrinos with energy $\gtrsim 5$ TeV. In this model the intensity of diffuse neutrino background depends from the amount of collimation of the jet $\Omega_{jet}/4\pi$, because the $\simeq 1000$ GRB’s observed per year, are only a small fraction of the actual explosions.

4 Conclusions

![Figure 13: A gallery of past, present and future HE neutrino telescopes.](image)

In Fig. 13 we show a gallery of past, present and future HE neutrino telescopes, compared with a massive detector with 1 km$^3$ of volume. From this figure we have a direct impression of the smallness of the detectors which were operated in the past century, compared with the ones under
construction. It is also worth noticing that the preliminary results obtained by Amanda, from April to October, 1997 which are reported in the upper panel of Fig. 3 include 1097 up-ward going muons. A number comparable to the number of events detected by MACRO in \( \approx 4.6 \) live years. This shows directly that the acceptance of the AMANDA-II detector is already more then a factor 10 greater then the acceptance of MACRO.

In the previous §§ we have practically shown how far was MACRO from effectively testing theoretical production models. From Fig 7 it can be crudely estimated that an acceptance \( \approx 10^4 \) MACRO \( \approx 1 \) km\(^2\) will be needed to challenge possibly the predictions for galactic neutrino sources. The situation could be slightly better for the statistical detection of emission from selected classes of objects, like for example the association of up-ward going muons with blazars, where a possible detection seems to be attainable with an acceptance \( \approx 0.1 \) km\(^2\).

References

[1] MACRO Collaboration, M. Ambrosio et al., “Neutrino astronomy with the macro detector,” Astrophys. J. 546 (2001) 1038–1054, astro-ph/0002492.

[2] SuperKamiokande Collaboration, Y. Fukuda et al., “Neutrino-induced upward stopping muons in super-kamiokande,” Phys. Lett. B467 (1999) 185–193, hep-ex/9908049.

[3] C. De Marzo et al., “Proposal for a large area detector dedicated to monopole search, astrophysics, and cosmic ray physics at the gran sasso lab,”. CALT-68-1237.

[4] MACRO Collaboration, M. Calicchio et al., “Status report of the macro experiment at gran sasso,” Nucl. Instr. Meth. A264 (1988) 18.

[5] MACRO Collaboration, S. P. Ahlen et al., “First supermodule of the macro detector at gran sasso,” Nucl. Instrum. Meth. A324 (1993) 337–362.

[6] MACRO Collaboration, S. P. Ahlen et al., “Muon astronomy with the macro detector,” Astrophys. J. 412 (1993) 301–311.

[7] MACRO Collaboration, M. Ambrosio et al., “Measurement of the atmospheric neutrino-induced upgoing muon flux using macro,” Phys. Lett. B434 (1998) 451–457, hep-ex/9807005.

[8] MACRO Collaboration, M. Ambrosio et al., “Matter effects in upward-going muons and sterile neutrino oscillations,” Phys. Lett. B517 (2001) 59–66, hep-ex/0106049.
[9] CCFR/NuTeV Collaboration, U. K. Yang et al., “Extraction of $r = \sigma(l)/\sigma(t)$ from ccf ru/mu fe and anti-ru/mu fe differential cross sections,” hep-ex/0104040.

[10] CCFR/NuTeV Collaboration, U. K. Yang et al., “Measurements of $f_2$ and $x_f^3(nu) - x_f^3(anti-nu)$ from ccf ru/mu fe and anti-ru/mu fe data in a physics model independent way,” Phys. Rev. Lett. 86 (2001) 2742–2745, hep-ex/0009041.

[11] CCFR/NuTeV Collaboration, A. Bodek et al., “Extraction of $r = \sigma(l)/\sigma(t)$ from ccf ru/mu fe and anti-ru/mu fe differential cross sections,” hep-ex/0105067.

[12] NuTeV Collaboration, J. McDonald et al., “Preliminary measurement of the differential cross section from neutrino nucleon deeply inelastic scattering at nutev,” hep-ex/0107082.

[13] CCFR Collaboration, A. O. Bazarko et al., “Determination of the strange quark content of the nucleon from a next-to-leading order qcd analysis of neutrino charm production,” Z. Phys. C65 (1995) 189–198, hep-ex/9406007.

[14] CTEQ Collaboration, H. L. Lai et al., “Global QCD analysis of parton structure of the nucleon: Cteq5 parton distributions,” Eur. Phys. J. C12 (2000) 375–392, hep-ph/9903282.

[15] S. Kretzer, F. I. Olness, R. J. Scalise, R. S. Thorne, and U.-K. Yang, “Predictions for neutrino structure functions,” Phys. Rev. D64 (2001) 033003, hep-ph/0101088.

[16] G. M. Frichter, D. W. McKay, and J. P. Ralston, “Prediction on the ultrahigh energy neutrino nucleon cross section from new structure function data at small $x$,” Phys. Rev. Lett. 74 (1995) 1508–1511, hep-ph/9409433.

[17] J. P. Ralston, D. W. McKay, and G. M. Frichter, “The ultra high energy neutrino nucleon cross section,” astro-ph/9606007.

[18] G. C. Hill, “Detecting neutrinos from agn: New fluxes and cross sections,” Astropart. Phys. 6 (1997) 215–228, astro-ph/9607140.

[19] M. Gluck, S. Kretzer, and E. Reya, “Dynamical qcd predictions for ultrahigh energy neutrino cross sections,” Astropart. Phys. 11 (1999) 327–334, astro-ph/9809273.

[20] J. Kwiecinski, A. D. Martin, and A. M. Stasto, “Penetration of the earth by ultrahigh energy neutrinos and the parton distributions inside the nucleon,” hep-ph/9905307.
[21] H1 Collaboration, T. Ahmed et al., “First measurement of the charged current cross-section at hera,” Phys. Lett. B324 (1994) 241–248.

[22] A. Donnachie and P. V. Landshoff, “Small x: Two pomerons!,” Phys. Lett. B437 (1998) 408–416, hep-ph/9806344.

[23] V. S. Berezinsky, A. Z. Gazizov, and S. I. Yanush, “On hard pomeron enhancement of ultrahigh-energy neutrino nucleon cross-sections,” astro-ph/0105368.

[24] G. Auriemma, M. Falcini, P. Lipari, and J. L. Stone, “Resonant oscillations of atmospheric neutrinos with an underground muon detector,” Phys. Rev. D37 (1988) 665.

[25] Particle Data Group Collaboration, D. E. Groom et al., “Review of particle physics,” Eur. Phys. J. C15 (2000) 1–878.

[26] E. Andres et al., “Observation of high-energy neutrinos using cerenkov detectors embedded deep in antarctic ice,” Nature 410 (2001) 441–443.

[27] E. T. Jaynes, “Information theory and statistical mechanics i.,” Phys. Rev. 106 (1957) 620–630.

[28] E. T. Jaynes, “Information theory and statistical mechanics ii.,” Phys. Rev. 108 (1957) 171–190.

[29] C. Smith and G. Erickson, Maximum-Entropy and Bayesian Spectral analysis and Estimation problems. D. Reidel Publishing Co., 1983.

[30] W. Bednarek and R. J. Protheroe, “Gamma rays and neutrinos from the crab nebula produced by pulsar accelerated nuclei,” Phys. Rev. Lett. 79 (1997) 2616–2619, astro-ph/9704186.

[31] V. Berezinsky, A. Bottino, and G. Mignola, “High-energy gamma radiation from the galactic center due to neutralino annihilation,” Phys. Lett. B325 (1994) 136–142, hep-ph/9402215.

[32] D. Tsiklauri and R. D. Viollier, “Dark matter concentration in the galactic center,” Astrophys. J. 500 (1998) 591, astro-ph/9805273.

[33] P. Gondolo and J. Silk, “Dark matter annihilation at the galactic center,” Phys. Rev. Lett. 83 (1999) 1719–1722, astro-ph/9906391.

[34] P. Ullio, H. Zhao, and M. Kamionkowski, “A dark-matter spike at the galactic center?,” Phys. Rev. D64 (2001) 043504, astro-ph/0101481.
[35] D. e. a. Thompson, “The second egret catalog of high-energy gamma-ray sources,” *Astroph. J. Suppl.* **101** (1995) 259–286.

[36] F. W. Stecker and M. H. Salamon, “High energy neutrinos from quasars,” *Space Sci. Rev.* **75** (1996) 341–355, astro-ph/9501064.

[37] R. J. Protheroe, “High energy neutrinos from blazars,” astro-ph/9607168.

[38] L. Nellen, K. Mannheim, and P. L. Biermann, “Neutrino production through hadronic cascades in agn accretion disks,” *Phys. Rev.* **D47** (1993) 5270–5274, hep-ph/9211257.

[39] P. Padovani and P. Giommi, “Sample oriented catalog of blazars,” *Mon. Not. R. Astron. Soc.* **277** (1995) 1477, astro-ph/9511065.

[40] E. Waxman and J. N. Bahcall, “High energy neutrinos from astrophysical sources: An upper bound,” *Phys. Rev.* **D59** (1999) 023002, hep-ph/9807282.

[41] M. Vietri, “Ultra high energy neutrinos from gamma ray bursts,” *Phys. Rev. Lett.* **80** (1998) 3690–3693, astro-ph/9802241.

[42] E. Waxman, “High energy cosmic-rays and neutrinos from cosmological gamma-ray burst fireballs,” *Phys. Scripta T85* (2000) 117–126, astro-ph/9911395.

[43] D. Guetta, M. Spada, and E. Waxman, “On the neutrino flux from gamma-ray bursts,” astro-ph/0102487.

[44] P. Meszaros and E. Waxman, “Tev neutrinos from bursting and choked fireballs,” astro-ph/0103275.

[45] W. S. Paciesas *et al.*, “The fourth batse gamma-ray burst catalog (revised),” *Astroph. J. Supp.* **122** (1999) 465–495, astro-ph/9903203.

[46] G. J. Feldman and R. D. Cousins, “A unified approach to the classical statistical analysis of small signals,” *Phys. Rev.* **D57** (1998) 3873–3889, physics/9711021.