A search for the analogue to Cherenkov radiation by high energy neutrinos at superluminal speeds in ICARUS

The ICARUS Collaboration

M. Antonello[a], P. Aprili[a], B. Baibussinov[b], M. Baldo Ceolin[b†], P. Benetti[c], E. Calligarich[c], N. Canci[a], F. Carbonara[d], S. Centro[b], A. Cesana[f], K. Cieslik[g], D. B. Cline[h], A. G. Cocco[d], A. Dabrowska[g], D. Dequal[b], A. Dermenev[i], R. Dolfini[c], C. Farnese[b], A. Fava[b], A. Ferrari[j], G. Fiorillo[d], D. Gibin[b], A. Gigli Berzolari[c†], S. Gninenko[i], A. Guglielmi[b], M. Haranczyk[g], J. Holeczek[l], A. Ivashkin[i], J. Kisiel[l], I. Kochanek[l], J. Lagoda[m], S. Mania[l], G. Mannocchi[n], A. Menegolli[c], G. Meng[b], C. Montanari[c], S. Otwinowski[h], L. Periale[n], A. Piazzoli[c], P. Picchi[n], F. Pietropaolo[b], P. Plonski[o], A. Rappoldi[c], G. L. Raselli[c], M. Rossella[c], C. Rubbia[a,j], P. Sala[f], E. Scantamburlo[e], A. Scaramelli[f], E. Segreto[a], F. Sergiampietri[p], D. Stefan[a], J. Stepaniak[m], R. Sulej[m,a], M. Szarska[g], M. Terrani[f], F. Varanini[b], S. Ventura[b], C. Vignoli[a], H. Wang[h], X. Yang[h], A. Zalewska[g], K. Zaremba[o],

A. Cohen[q]

[a] *Laboratori Nazionali del Gran Sasso dell'INFN,*
Assergi (AQ), Italy

[b] *Dipartimento di Fisica e INFN,*
Università di Padova,
Via Marzolo 8, I-35131 Padova, Italy

[c] *Dipartimento di Fisica Nucleare e Teorica e INFN,*
Università di Pavia,
Via Bassi 6, I-27100 Pavia, Italy

[d] *Dipartimento di Scienze Fisiche,*
INFN e Università Federico II, Napoli, Italy

e Dipartimento di Fisica,
Università di L'Aquila,
via Vetoio Località Coppito,
I-67100 L'Aquila, Italy

[f] *INFN, Sezione di Milano e Politecnico,*

Via Celoria 16, I-20133 Milano, Italy

[g] *The Henryk Niewodniczanski,*

Institute of Nuclear Physics,

Polish Academy of Science, Krakow, Poland

[h] *Department of Physics and Astronomy,*

University of California, Los Angeles, USA

[i] *INR RAS, prospekt 60-letiya Oktyabrya 7a,*

Moscow 117312, Russia

[j] *CERN, CH-1211 Geneve 23, Switzerland*

[l] *Institute of Physics,*

University of Silesia,

4 Uniwersytecka st.,

40-007 Katowice, Poland

[m] *National Centre for Nuclear Research,*

A. Soltana 7, 05-400 Otwock/Swierk, Poland

[n] *Laboratori Nazionali di Frascati (INFN),*

Via Fermi 40, I-00044 Frascati, Italy

[o] *Institute of Radioelectronics,*

Warsaw University of Technology,

Nowowiejska 15/19,

00-665 Warsaw, Poland

[p] *INFN, Sezione di Pisa. Largo B. Pontecorvo,*

3, I-56127 Pisa, Italy

[q] *Physics Department,*

Boston University, Boston,

Massachusetts 02215, USA

† *Deceased*

*

(Dated: February 25, 2012)

(Submitted to Physics Letter B)

Abstract

The OPERA collaboration [1] has reported evidence of superluminal ν_μ propagation between CERN and the LNGS. Cohen and Glashow [2] argued that such neutrinos should lose energy by producing photons and e^+e^- pairs, through Z^0 mediated processes analogous to Cherenkov radiation. In terms of the parameter $\delta \equiv (v_\nu^2 - v_c^2)/v_c^2$, the OPERA result corresponds to $\delta \approx 5 \cdot 10^{-5}$. For this value[a] of δ a very significant deformation of the neutrino energy spectrum and an abundant production of photons and e^+e^- pairs should be observed at LNGS. We present an analysis based on the 2010 and part of the 2011 data sets from the ICARUS experiment, located at Gran Sasso National Laboratory and using the same neutrino beam from CERN. We find that the rates and deposited energy distributions of neutrino events in ICARUS agree with the expectations for an unperturbed spectrum of the CERN neutrino beam. Our results therefore refute a superluminal interpretation of the OPERA result according to the Cohen and Glashow prediction [2] for a weak current analog to Cherenkov radiation. In particular no superluminal Cherenkov like e^+e^-pair or γ emission event has been directly observed inside the fiducial volume of the bubble chamber like ICARUS TPC-LAr detector, setting the much stricter limit of $\delta < 2.5 \cdot 10^{-8}$ at the 90% confidence level, comparable with the one due to the observations from the SN1987a [4].

[a] Note that $(v_\nu - v_c)/v_c \approx \frac{\delta}{2} \approx 2.5 \cdot 10^{-5}$

* alfredo.ferrari@cern.ch

I. INTRODUCTION

The OPERA collaboration has presented evidence of superluminal neutrino propagation [1], reporting a travel time between CERN and the LNGS laboratory some 60 ns shorter than expected for travel at light speed. The OPERA result corresponds to $\delta \equiv (v_\nu^2 - v_c^2)/v_c^2 \approx 5 \cdot 10^{-5}$ with only small variations over the energy domain of the detected neutrinos. Observations of neutrinos from Supernova SN1987a at much lower energies around 10 MeV yield a strong constraint [4] $\delta < 4 \cdot 10^{-9}$ implying a rapid increase with energy of the hereby alleged anomaly.

As is well known, charged particles travelling at speeds exceeding that of light emit characteristic electromagnetic radiation known as Cherenkov radiation. Because neutrinos are electrically neutral, conventional Cherenkov radiation of superluminal neutrinos does not arise or is otherwise weakened. However neutrinos do carry electroweak charge and, as pointed out by Cohen and Glashow [2], may emit Cherenkov-like radiation via weak interactions when traveling at superluminal speeds. Cohen and Glashow argue that, under the assumptions of the usual linear conservation of energy and momentum and only slow variation of δ over the OPERA-relevant energy domain, superluminal neutrinos would radiate and lose energy via the three following processes

$$\nu_x \to \nu_x + \gamma \tag{1}$$

$$\nu_x \to \nu_x + \nu_y + \bar{\nu}_y \tag{2}$$

$$\nu_x \to \nu_x + e^+ + e^- \tag{3}$$

The emission rate and energy loss is dominated by the third process, which is kinematically allowed under the stated assumptions. The process 3, from now on referred to as pair bremsstrahlung [2], proceeds through the neutral current weak interaction and has a threshold energy $E_{thr} \approx 2m_e/\sqrt{\delta}$ corresponding to about 140 MeV for the OPERA value of δ. In the high energy limit the electron and neutrino masses may be neglected, and Cohen and Glashow [2] compute[1] the rate of pair emission Γ, and the associated neutrino energy loss rate dE/dx to leading order in δ:

$$\Gamma = \frac{2}{35}\frac{G_F^2}{192\pi^3}E_\nu^5\delta^3 \tag{4}$$

$$\frac{\mathrm{d}E}{\mathrm{d}x} = -\frac{5}{112}\frac{G_F^2}{192\pi^3}E_\nu^6\delta^3 \tag{5}$$

[1] These expressions have corrected a numerical factor error in [2] of 4/5.

Note that the average fractional energy loss per pair emission event is $\frac{dE/dx}{\Gamma E} \approx 0.78$; that is, about $\frac{3}{4}$ of the neutrino energy is lost on average with each emission. Furthermore, under the approximation of a continuous energy loss, the integration of dE/dx over a distance L provides the following result for the final neutrino energy, $E_{\nu f}$, as a function of the initial energy, $E_{\nu i}$:

$$\frac{1}{E_{\nu f}^5} - \frac{1}{E_{\nu i}^5} = \frac{5}{112}\frac{G_F^2}{192\pi^3}\delta^3 L \tag{6}$$

Folding the initial neutrino spectrum of the CERN to Gran Sasso neutrino beam with the energy at Gran Sasso predicted with the above formula, the expected neutrino interaction rates and pair bremsstrahlung rates as a function of δ may be estimated. In particular, for $\delta = 5 \cdot 10^{-5}$ and $L = 732$ km, equation 6 would predict that few neutrinos with energy larger than $\approx$13 GeV would reach Gran Sasso.

However, since neutrinos lose a large fraction of their energy at each pair creation event, and the resulting deflection angles are not negligible with respect to the angular width of the CNGS neutrino beam, a continuous energy loss approximation is suitable only for a qualitative estimate of the spectral distortion.

A full three-dimensional Monte Carlo calculation of the propagation of neutrinos from CERN to Gran Sasso has therefore been performed for several values of δ (see section II). As a result, the expected rates of neutrino charged current interactions and of e^+e^- pair events have been obtained as a function of δ and are presented in the next section.

The rates obtained in this way have been compared with the results of year 2010 and part of the year 2011 exposures of the reconstructed neutrino charged current events in the ICARUS/CNGS2 experiment located in Hall B of the Gran Sasso Laboratory.

II. SIMULATION RESULTS

A full 3-dimensional simulation of the generation and transport of CNGS neutrinos from CERN to Gran Sasso while undergoing pair bremsstrahlung has been performed using the official CNGS simulation setup [9, 10], based on the FLUKA [11, 12] Monte Carlo transport code.

Accounting for the threshold, and under the hypothesis that δ does not vary significantly in the range of energies of interest, the pair bremsstrahlung interaction rate differential in

TABLE I. Expected neutrino and e$^+$e$^-$ rates at Gran Sasso. All rates are given for a 1 kt detector and 10^{19} pot.

δ	CC (all flavours)	NC (all flavours)	CC>60 GeV ($\nu_\mu + \bar{\nu}_\mu$)	e$^+$e$^-$
0	644	203	57	0
$5 \cdot 10^{-8}$	644	203	57	27
$5 \cdot 10^{-7}$	643	203	56	$2.1 \cdot 10^4$
$5 \cdot 10^{-6}$	594	188	8.5	$7.2 \cdot 10^5$
$5 \cdot 10^{-5}$	203	85	$< 10^{-6}$	$1.1 \cdot 10^7$

the neutrino energy loss, w, and in the pair invariant mass $s_{e^+e^-} \equiv s\delta$, can be expressed as:

$$\frac{\mathrm{d}^2\Gamma}{\mathrm{d}w\mathrm{d}s} = \frac{G_F^2\delta^3}{192\pi^3}\frac{s}{E_\nu^2}\left(1 - \frac{s_0}{s}\right)^{\frac{3}{2}}\left[2E_\nu(E_\nu - w) + w^2 - s\right] \tag{7}$$

$$s_0 \equiv \frac{4m_e^2}{\delta} \tag{8}$$

The kinematical limits are given by:

$$E_\nu^2 > w^2 > s > s_0 \tag{9}$$

The neutrino deflection angle Ψ with respect to the incident neutrino direction can be expressed as:

$$\cos\Psi = 1 - \delta\frac{w^2 - s(1+\delta)}{2E_\nu(E_\nu - w)} \tag{10}$$

and the e$^+$e$^-$ pair angle as:

$$\cos\theta = 1 - \frac{\delta}{2}\left(1 - \frac{w}{E_\nu}\right)\left(1 - \frac{s}{w^2}\right) \tag{11}$$

The resulting mean free path for a 19 GeV neutrino (the fluence-averaged energy of CNGS neutrinos) is ≈ 490 km for $\delta = 5 \cdot 10^{-5}$, and the deflection angle is of the order of $\sqrt{\delta}$, comparable with the angular width of the neutrino beam. Hence the need for a full Monte Carlo simulation of the neutrino propagation to Gran Sasso.

All results presented in this section are for 10^{19} protons on target (pot) and, for rates, for a detector (Argon) mass of 1 kt. In this way they can be easily rescaled to whichever Gran Sasso detector mass and exposure, neglecting the minor differences in neutrino cross sections

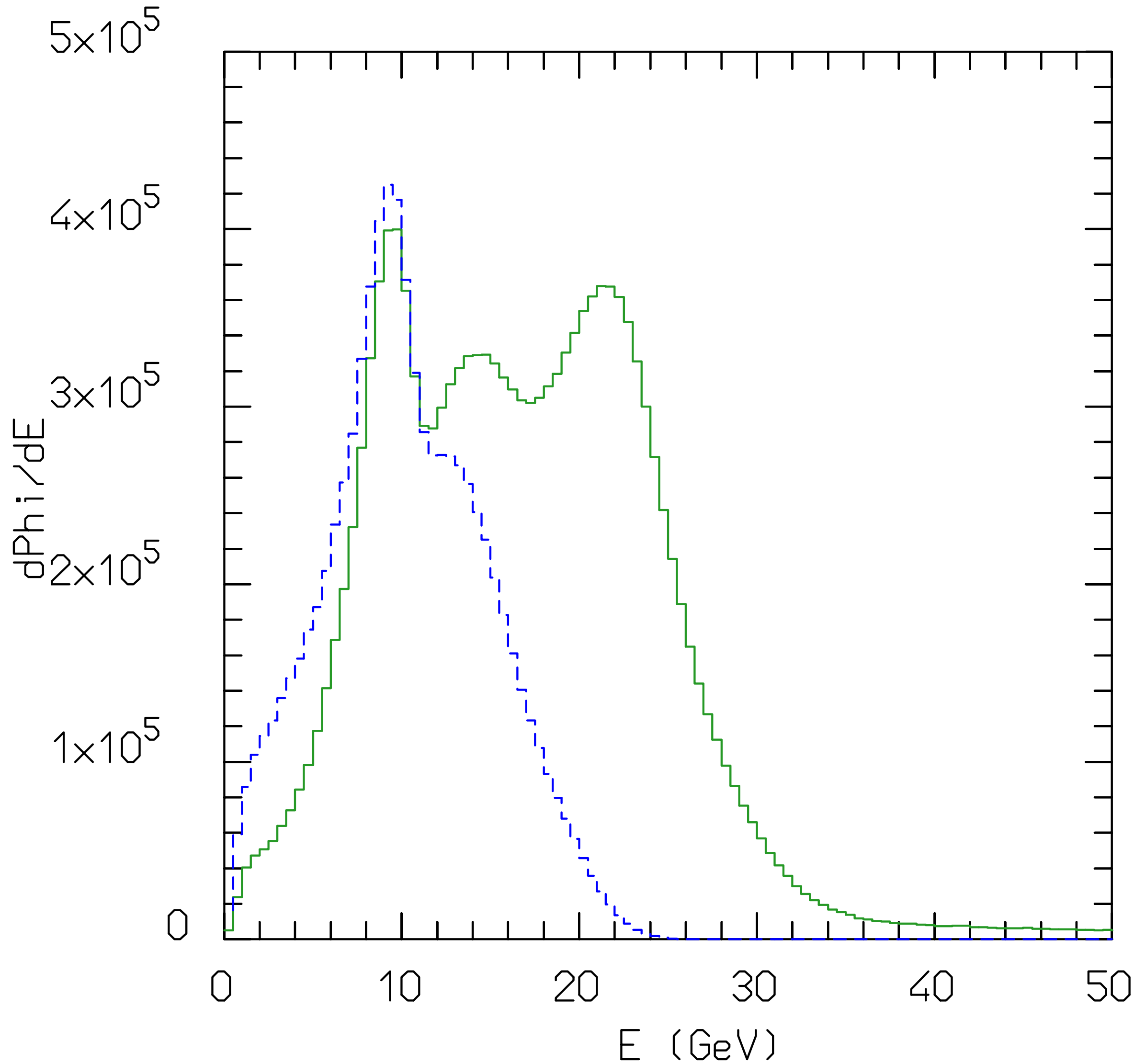

FIG. 1. Computed ν_μ spectra at Gran Sasso for $\delta = 0$ (solid line, green), and for $\delta = 5 \cdot 10^{-5}$ (dashed line, blue). The units are $\nu\ cm^{-2}\ GeV^{-1}\ 10^{-19} pot^{-1}$, where pot=protons on target.

in an energy range dominated by DIS among Argon and other materials. The nominal yearly number of protons for CNGS is $4.5 \cdot 10^{19}$ pot. The statistical error on integrated values (e.g. total rates, total fluence, etc) is less than one percent in all cases. The systematic error on the computed neutrino (and hence e^+e^- pairs) rates is mostly due to the uncertainties in the hadron production model of FLUKA, and can be conservatively estimated to be lower than 10% (see for example [11, 13]).

The unperturbed ($\delta = 0$) fluence spectra of CNGS ν_μ at Gran Sasso, and the one com-

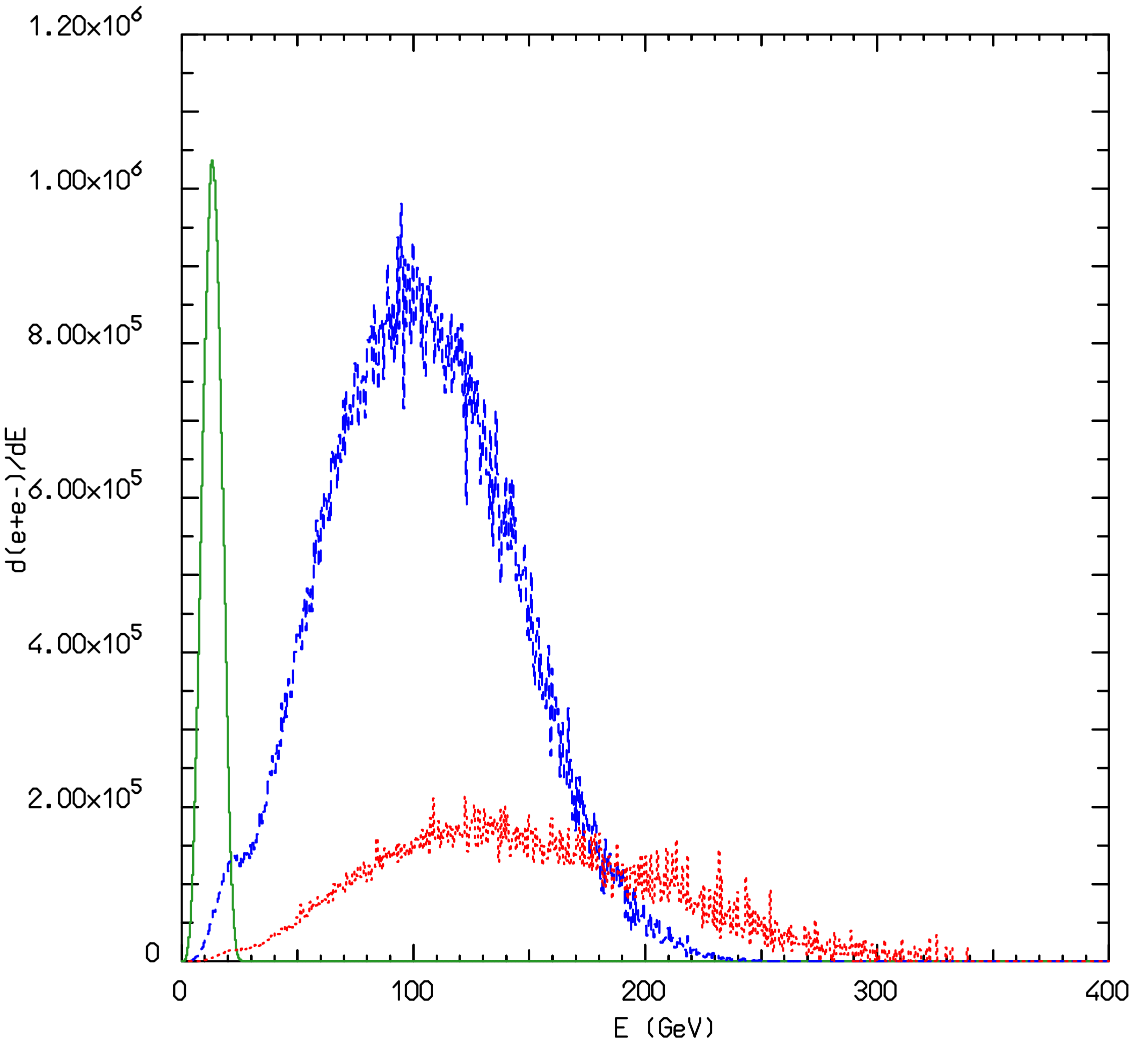

FIG. 2. Computed e^+e^- pair spectra at Gran Sasso for $\delta = 5 \cdot 10^{-5}$ (solid line, green), $\delta = 1 \cdot 10^{-6}$ (dashed line, blue, multiplied by 1000), and $\delta = 5 \cdot 10^{-8}$ (dotted line, red, multiplied by 10^6). The event rate units are GeV^{-1} for a 1 kt detector and 10^{19} protons on target (pot).

puted corresponding to $\delta = 5 \cdot 10^{-5}$ are shown in Fig. 1: the lack in the latter spectrum of the sharp 12.5 GeV ridge predicted by formula 6 can be easily appreciated.

The computed spectra of the expected events due to e^+e^- pairs at Gran Sasso are shown in Fig. 2, for $\delta = 5 \cdot 10^{-5}$, $1 \cdot 10^{-6}$, $5 \cdot 10^{-8}$ respectively.

The computed (anti)neutrino charged and neutral current rates (all flavours included), the charged current rates for ν_μ and $\bar{\nu}_\mu$ with energy above 60 GeV, and the pair bremsstrahlung

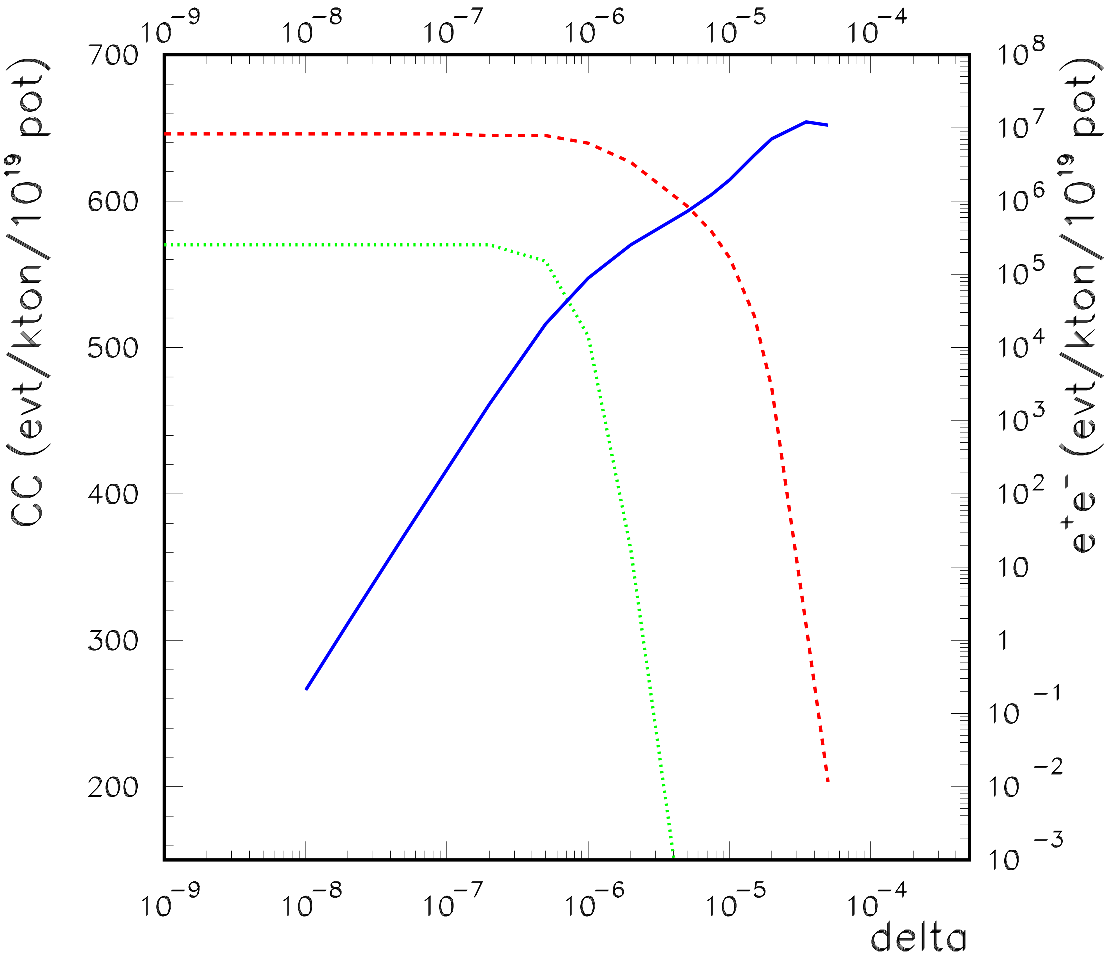

FIG. 3. Computed neutrino charged current rates (dashed line, red, left vertical scale), ν_μ and $\bar{\nu}_\mu$ charged current rates (x 100), $E_\nu > 60$ GeV (dotted line, green, left vertical scale), e^+e^- rates (solid line, blue, right vertical scale) at Gran Sasso, for 10^{19} protons on target (pot) and 1 kt detector.

rates at Gran Sasso are presented in Fig. 3. The expected rates are summarized in Table I for a few representative values of δ.

III. EXPERIMENTAL RESULTS AND RELATED CONSTRAINTS

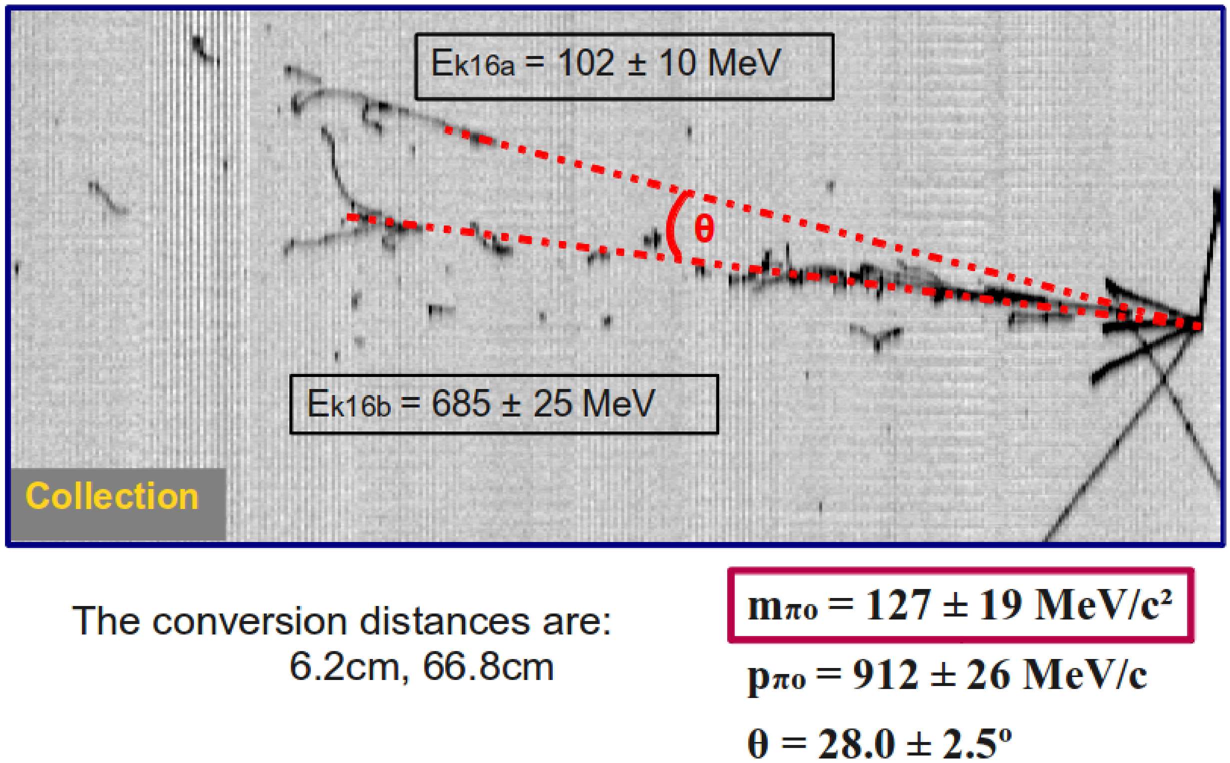

FIG. 4. Typical event recorded in ICARUS. Evidence for a pair of γ's from a π^0 (tracks 16a and 16b) with a momentum of 912 MeV/c pointing at the primary vertex, showing the typical behavior of γ conversions in the TPC-LAr Imaging chamber.

The ICARUS experiment [5–8] consists of 760 t of super-pure Liquid Argon operated as a very high resolution Time Projection Chamber, namely a Bubble Chamber–like detector recording all events with an energy deposition in excess of a few hundred MeV within a window of 60 μs centered around the neutrino pulse from the CERN-SPS. The hadronic and electromagnetic energy depositions of each event are accurately measured by calorimetric determination while the muon momenta are measured with the help of the multiple scattering along the very many points of the long muon tracks. An example of an event with a pair of γ's produced by a secondary π^0 is shown in Fig. 4.

In the following an analysis of neutrino interactions from the 2010 and part of the 2011 CNGS runs is compared with the expectations for different values of δ. While the fine details of the analysis could still somewhat evolve, it will be shown that δ values of the order of the

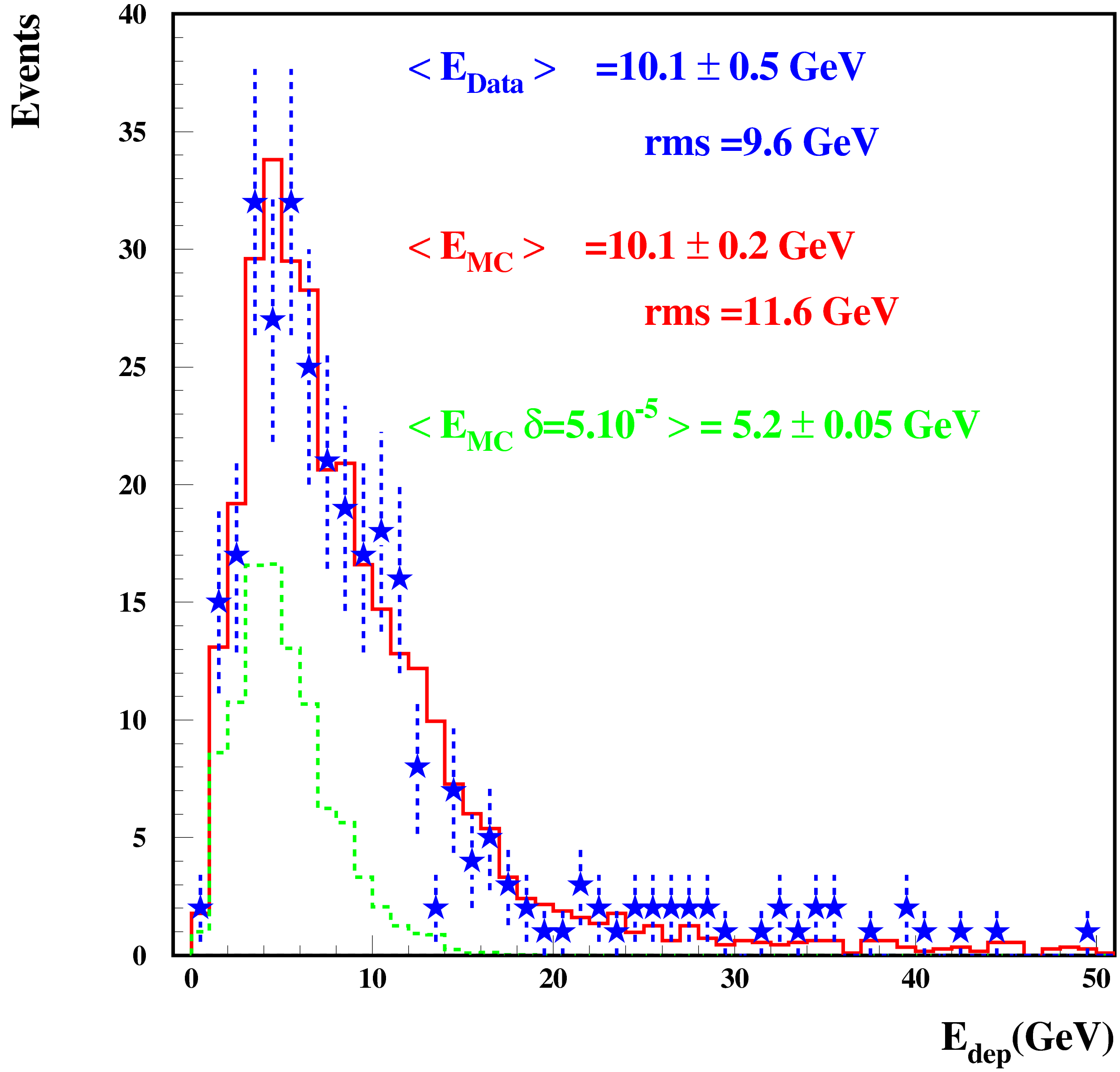

FIG. 5. Experimental raw energy E_{dep} distribution for ν_μ and $\bar{\nu}_\mu$ CC interactions in ICARUS (blue symbols) compared with the Monte Carlo expectations for an unperturbed spectrum (red solid histogram), and for $\delta = 5 \cdot 10^{-5}$ (green dashed histogram).

one claimed by OPERA can be readily excluded on the basis of the observed rates and raw energy deposition spectra. In order to carry out as much as possible a bias-free analysis, the raw energy deposition distributions as recorded in ICARUS with the calorimetric methods have been compared with the expectations of a full Monte Carlo simulations of the detector:

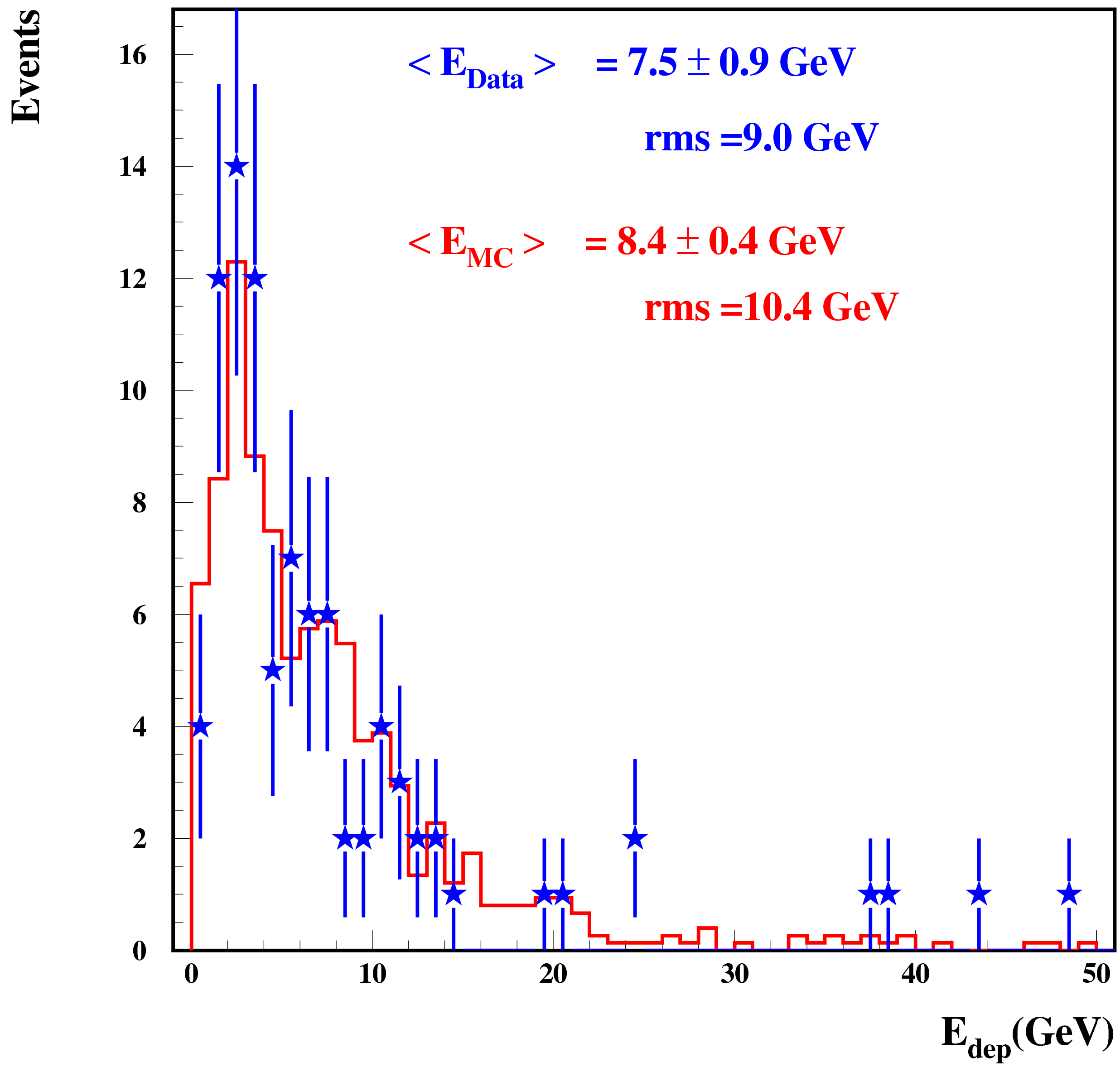

FIG. 6. Experimental (blue symbols) raw energy deposition distribution for neutral current events compared with the Monte Carlo expectations (red histogram) for the unperturbed CNGS spectrum. Only experimental and Monte Carlo events with energy deposition greater than 500 MeV have been considered.

only the correction for the signal quenching in LAr has been applied to both the experimental and Monte Carlo results.

A dedicated search for e^+e^- events has been also carried out using the same exposure.

TABLE II. Observed and expected neutrino and e^+e^- rates at Gran Sasso for the ICARUS experiment. Both the experimental and computed rates are normalized to the exposure used for the analysis of the corresponding experimental channel (see text for details).

Rates	Observed	Expected $\delta = 0$	Expected $\delta = 5 \cdot 10^{-5}$
CC	308	315±5	98.1±2
NC	89	93.1±3	33.0±1
ν_μ CC, $E_{dep} > 25$ GeV	25	18 ±1.3	$< 10^{-6}$
e^+e^-	0	0	$7.4 \cdot 10^6$

This analysis constrains δ to values a few order of magnitude smaller than the one claimed by OPERA.

The number of collected neutrino interactions has been compared with the predictions for the CERN SPS neutrino beam in the whole energy range, corrected for the fiducial volume and DAQ deadtime. The experimental analysis corresponds to an integrated exposure of $6.70 \cdot 10^{21}$ t·pot. This exposure is the combination of a fiducial volume of 447 t of Liquid Argon and a total number of protons on target (pot) at CERN of $4.9 \cdot 10^{18}$ for the year 2010, and 434 t and $1.04 \cdot 10^{19}$ pot for the fraction of the year 2011 analyzed up to now. This exposure applies fully to the search for pair bremsstrahlung events which do not require any further cut on the fiducial volume because of their expected clean signature.

In order to identify ν_μ and $\bar{\nu}_\mu$ charged current (CC) as well as neutral curent (NC) events, further cuts have been applied to the fiducial volume: in particular events with the vertex in the last 2.5 metres of the detector have not been considered for this analysis in order to identify cleanly possible muon tracks. The total number of identified ν_μ and $\bar{\nu}_\mu$ CC events, and of neutral current events, are compared in Table II: 21 events cannot be safely assigned despite the reduced fiducial volume. The resulting reference exposure for NC and CC events is $5.05 \cdot 10^{21}$ t·pot.

The measured raw energy deposition E_{dep} for ν_μ and $\bar{\nu}_\mu$ CC events as obtained from a calorimetric measurements corrected only for signal quenching is presented in Fig. 5. The experimental distribution is compared with a full Monte Carlo simulation of the experimental apparatus for $\delta = 0$ and $\delta = 5 \cdot 10^{-5}$. The experimental finding matches well the Monte Carlo expectations for the unaffected CERN neutrino beam.

The analysis of neutral current events gives similar results. The experimental and expected spectra of the deposited energy for NC events are presented in Fig. 6: only events with experimental or Monte Carlo energy deposition in excess of 500 MeV have been considered, in order to avoid possible misidentifications or inefficiencies.

The strong constraints of Cohen and Glashow [2] predict that a superluminal high energy neutrino spectrum will be heavily depleted and distorted after $L = 732$ km from CERN to LNGS: in particular for δ in the range indicated by OPERA the charged current rate would be reduced to roughly 32% of the expected one, the average ν_μ energy would be 12.1 GeV (against 19 GeV), the average energy of ν_μ undergoing charged current interactions would be 12.5 GeV (against 28.7 GeV), and no neutrino interactions should be observed above 30 GeV. Indeed at $\delta = 5 \cdot 10^5$ essentially no $E_\nu > 30$ GeV should arrive from CERN to LNGS, while our results are indicating no visible deviation of the incoming neutrino beam with respect to the expected rate and energy distribution. This result confirms the inconsistence between the OPERA δ value and the observed neutrino rate and spectrum already reported in ref. [2].

In addition, with ICARUS a bubble chamber like detector a much more stringent limit to δ may be set from the direct observation inside the ICARUS detector volume of Cherenkov like events (eq. 1,3) generated by the passing superluminal neutrinos. These events would be characterized either by a single gamma ray converting into an e^+e^- pair (eq. 1) and/or two single electrons (eq. 3) both with no hadronic recoils in the incoming neutrino direction. The transverse momenta of the particles in the events (1) and (3), as determined by the centre of mass system, are however far too small to be experimentally observable. Therefore events of both types (1) and (3) would appear as narrow e^+ e^- pairs pointing directly to the beam direction, with no detectable hadronic activity. The rate of such events for the ICARUS detector exposure under consideration ($6.70 \cdot 10^{21}$ t·pot) can be derived from those presented in Fig. 3. With the OPERA result ($\delta \approx 5 \cdot 10^{-5}$) more than $7 \cdot 10^6$ electron positron pairs should have been observed for this exposure, each with an energy spectrum peaked around 10 GeV (see Fig. 2). This number should not be a surprise since the CC neutrino event rates of the 2010 and the 2011 ICARUS samples with average energy of ≈28 GeV represents a total of $2.1 \cdot 10^{12}$ incoming neutrinos. No Cherenkov like event has been detected in ICARUS. The experimental event rates are compared in table II with the expected ones, for $\delta = 0$ and $\delta = 5 \cdot 10^{-5}$. The results presented in the table clearly show that the latter value for δ can be excluded. Taking into account both the absence of narrow e^+e^- pairs pointing directly to the beam direction and the presence of several high energy charged current events (for instance, 25±5 events with deposited energy in excess of 25 GeV are present in Fig. 5 against 18±1.3 expected), we can set the limit $\delta < 2.5 \cdot 10^{-8}$ at 90% CL for CNGS neutrinos[2], comparable to the limit $\delta < 1.4 \cdot 10^{-8}$ established by SuperKamiokande [3] from the lack of depletion of atmospheric neutrinos, and somewhat larger than the lower energy velocity constraint $\delta < 4 \cdot 10^{-9}$ from SN1987a [4]. The ICARUS events already collected during 2011 represent conservatively a factor three higher statistics and should provide more accurate information on the indicated process. A similar increase in statistics is expected from the 2012 CNGS run. However, due to the δ^3 dependence of the pair bremsstrahlung cross section, no major change of the δ limit can be expected if no e^+e^- event will be found in the final data sample.

CONCLUSIONS

The spectra and rates at Gran Sasso of neutrino and e^+e^- for the CNGS beam have been computed in the theoretical framework presented in [2, 14]. In particular, pair bremsstrahlung events have been accounted for during the propagation of neutrinos from CERN to Gran Sasso National Laboratory. The resulting neutrino spectra and rates for $\delta \approx 5 \cdot 10^{-5}$ as suggested by OPERA are significantly different from the unaffected ones. Preliminary results from the ICARUS experiment do not support any statistically significant deviation from the unperturbed spectrum and therefore exclude δ values comparable to the one claimed by OPERA.

Furthermore ICARUS did not detect any e^+e^- event, despite a few millions were expected for $\delta = 5 \cdot 10^{-5}$. The lack of e^+e^--like event translate into a 90% CL limit of $\delta < 2.5 \cdot 10^{-8}$ for multi–GeV neutrinos.

ACKNOWLEDGMENTS

The ICARUS Collaboration acknowledges the fundamental contribution of INFN to the construction and operation of the experiment. The Polish groups acknowledge the support of the Ministry of Science and Higher Education in Poland, including project 637/MOB/2011/0

[2] $\delta = 2.5 \cdot 10^{-8}$ corresponds to a 10% probability of observing zero events for an exposure of $6.70 \cdot 10^{21}$ t·pot

and grant number N N202 064936. The work of A. Cohen was supported by the U.S. Department of Energy Office of Science. Finally we thank CERN, in particular the CNGS staff, for the successful operation of the neutrino beam facility

---

[1] T. Adam et al., (The OPERA Collaboration), arXiv:1109.4897v2, (2011)

[2] A.G. Cohen, and S.L. Glashow, Phys. Rev. Lett., **107**, 181803 (2011)

[3] SuperKamiokande Collaboration, Y. Ashie et al., A Measurement of atmospheric neutrino oscillation parameters by SUPER-KAMIOKANDE I, Phys.Rev. D71 (2005) 112005, arXiv:hep-ex/0501064 [hep-ex]. Super-Kamiokande Collaboration, S. Desai et al., Study of TeV neutrinos with upward showering muons in Super-Kamiokande, Astropart. Phys. 29 (2008) 4254, arXiv:0711.0053 [hep-ex]. Super-Kamiokande Collaboration, M. E. Swanson et al., Search for Diffuse Astrophysical Neutrino Flux Using Ultrahigh Energy Upward-Going Muons in Super-Kamiokande I, Astrophys. J. 652 (2006) 206215, arXiv:astro-ph/0606126 [astro-ph].

[4] M.J. Longo, "Tests of Relativity from SN1987a" Phys. Rev. **D36** 3276 (1987) and references therein.

[5] C. Rubbia, "The Liquid-Argon Time Projection Chamber: A New Concept For Neutrino Detector", CERN-EP/77-08 (1977).

[6] ICARUS Collaboration, F. Arneodo et al. "Observation of long ionizing tracks with the ICARUS T600 first half-module", NIMA **508**, 287 (2003)

[7] ICARUS Collaboration, S. Amerio et al., "Design, construction and tests of the ICARUS T600 detector", NIMA **526**, 329 (2004)

[8] ICARUS Collaboration, M. Antonello et al., "Underground operation of the ICARUS T600 LArTPC: first results", JINST **6**, P07011 (2011)

[9] A. Ferrari, A.M. Guglielmi, and P.R. Sala, Nuclear Physics B (Proceedings Supplements), **168**, 169-172 (2007)

[10] A. Ferrari, A.M. Guglielmi, M. Lorenzo-Sentis, S. Rösler, P.R. Sala, and L. Sarchiapone, "An updated Monte Carlo calculation of the CNGS neutrino beam", AB-Note-2006-038, CERN-AB-Note-2006-038 (31 pages), Geneva, CERN, 20 Aug 2007.

[11] G. Battistoni, S. Muraro, P.R. Sala, F. Cerutti, A. Ferrari, S. Rösler, A. Fassò, J. Ranft, "The FLUKA code: Description and benchmarking", Proceedings of the Hadronic Shower

Simulation Workshop 2006, Fermilab 6–8 September 2006, M.Albrow, R. Raja eds., AIP Conference Proceeding 896, 31-49, (2007)

[12] A. Ferrari, P.R. Sala, A. Fassò, and J. Ranft, “FLUKA: a multi-particle transport code”, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773

[13] G. Collazuol, A. Ferrari, A. Guglielmi, P.R. Sala, Nucl. Instr. Meth. **A449**, 609 (2000)

[14] S. Coleman, S.L. Glashow, Phys. Rev. **D59**, 116008 (1999)