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

ICARUS Collaboration

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ABSTRACT

The OPERA Collaboration (2011) [1] has reported evidence of superluminal ν_μ propagation between CERN and the LNGS. Cohen and Glashow (2011) [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 (note that $(v_\nu - v_c)/v_c \approx \frac{\delta}{2} \approx 2.5 \cdot 10^{-5}$) 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, as also reported by OPERA. Our results therefore refute a superluminal interpretation of the OPERA result according to the Cohen and Glashow (2011) prediction [2] for a weak current analog to Cherenkov radiation. In a dedicated search, 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,

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comparable with the one due to the observations from the SN1987a (M.J. Longo, 1987 [4]). The observations of high energy neutrino events by Super-Kamiokande and IceCube are also pointing to a much stricter limit on δ.

1. 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 travelling 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 $E_{\rm thr} \approx 2m_e/\sqrt{\delta}$ 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[2] the rate of pair emission Γ, and the associated neutrino energy loss rate dE/dx to leading order in δ:

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

$$\frac{dE}{dx} = -\frac{5}{112}\frac{G_F^2}{192\pi^3}E_\nu^6\delta^3 \tag{5}$$

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, Eq. (6) would predict that few neutrinos with energy larger than ≈ 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 2). 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.

According to the formulae above, the δ value claimed by OPERA would have resulted in a huge number of e^+e^- pair in ICARUS and in similar experiments, like MINOS, T2K, NOMAD, and OPERA itself. Also, high energy upward going neutrino events detected by Super-Kamiokande and IceCube [5] would be impossible in this scenario.

2. Simulation results

A full three-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 [11,12], based on the FLUKA [13,14] 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 the neutrino energy loss, w, and in the pair invariant mass $s_{e^+e^-} \equiv s\delta$, can be expressed as:

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

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

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:

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

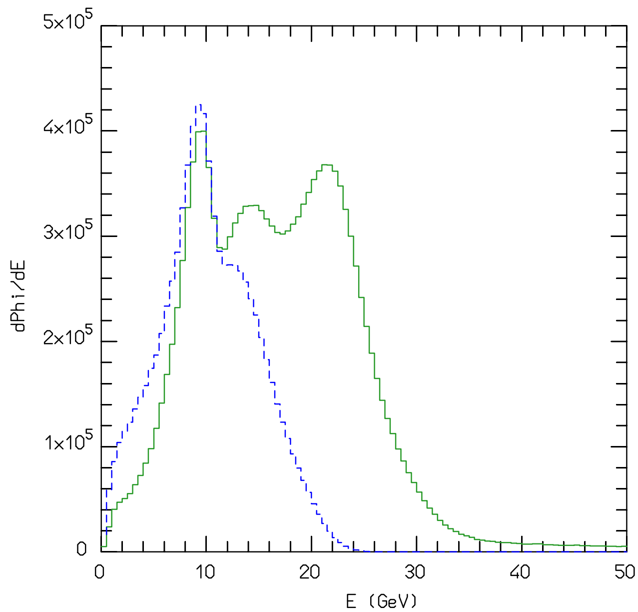

Fig. 1. Computed ν_μ spectra at Gran Sasso for $\delta = 0$ (solid line, green), and for $\delta = 5 \cdot 10^{-5}$ (dashed line, blue). The units are ν cm^{-2} GeV$^{-1} \cdot 10^{-19}$ pot^{-1}, where pot = protons on target. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

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

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.

It should be noted that the pair emission angle with respect to the incoming neutrino direction is also of the order of $\sqrt{\delta}$.

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 re-scaled to whichever Gran Sasso detector mass and exposure, neglecting the minor differences in neutrino cross sections 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 computed neutrino rates presented in this Letter take always into account the dominant two flavour $\nu_\mu \to \nu_\tau$ oscillation, with $\Delta m^2_{23} \approx 2.4 \cdot 10^{-3}$ eV^2, $\sin^2(2\theta_{23}) \approx 1$. Oscillations are irrelevant for the pair bremsstrahlung rates, since δ, if any, must be the same for all flavours to the $\Delta\delta \approx 10^{-20}$ level. 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 [15,13]). The agreement between the reconstructed neutrino spectrum and expectations published by OPERA [6][3] is a further confirmation of the accuracy of the CNGS beam predictions and of the absence of any major systematics in the predicted spectrum.

The unperturbed ($\delta = 0$) fluence spectra of CNGS ν_μ at Gran Sasso, and the one computed 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 rates at Gran Sasso are presented in Fig. 3. The expected rates are summarised in Table 1 for a few representative values of δ.

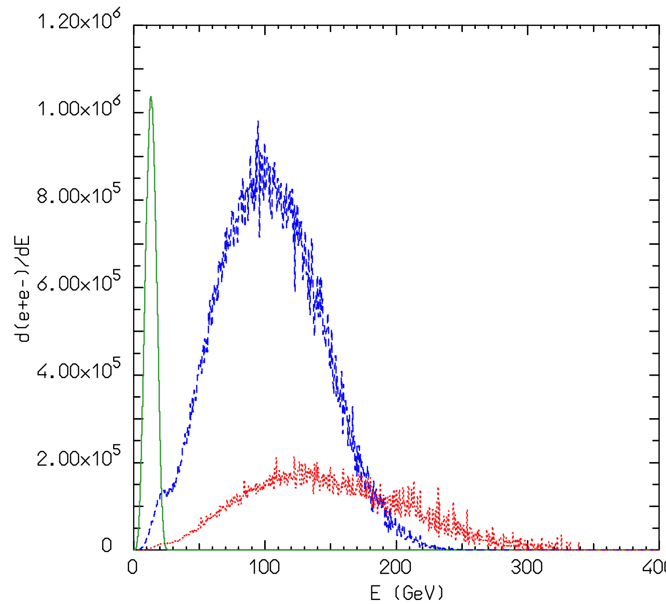

Fig. 2. Computed e^+e^- pair spectra at Gran Sasso for $\delta = 5 \cdot 10^{-5}$ (solid line, green), $\delta = 1 \cdot 10^{-6}$ (dashed line, blue, multiplied by 1000), and $\delta = 5 \cdot 10^{-8}$ (dotted line, red, multiplied by 10^6). The event rate units are GeV^{-1} for a 1 kt detector and 10^{19} protons on target (pot). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

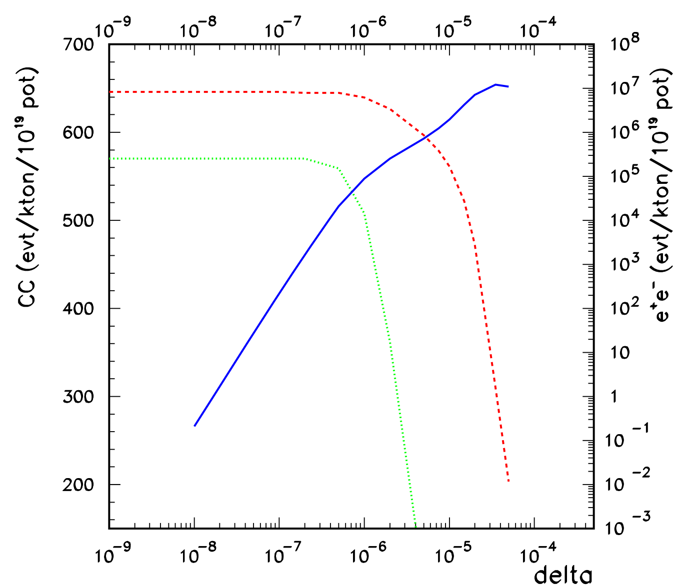

Fig. 3. Computed neutrino charged current rates (dashed line, red, left vertical scale), ν_μ and $\bar{\nu}_\mu$ charged current rates ($\times 100$), $E_\nu > 60$ GeV (dotted line, green, left vertical scale), e^+e^- rates (solid line, blue, right vertical scale) at Gran Sasso, for 10^{19} protons on target (pot) and 1 kt detector. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

[3] OPERA is using the CNGS flux computed by the ICARUS group, see Ref. [14] of [1].

Table 1
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	$< 10^{-6}$	$1.1 \cdot 10^7$

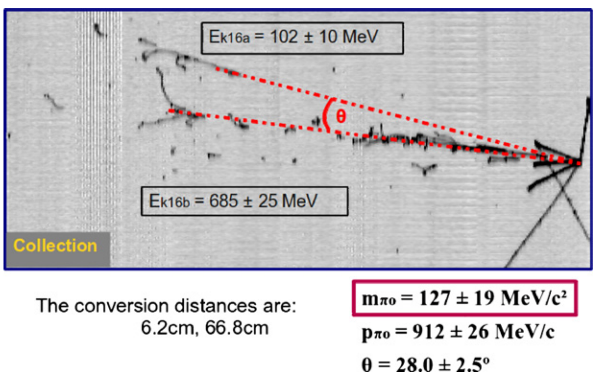

Fig. 4. Typical event recorded in ICARUS. Evidence for a pair of γ's from a π^0 (tracks 16a and 16b) with a momentum of 912 MeV/c pointing at the primary vertex, showing the typical behaviour of γ conversions in the TPC-LAr imaging chamber.

3. Experimental results and related constraints

The ICARUS experiment [7–10] 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 centred 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 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: only the correction for the signal quenching in LAr has been applied to both the experimental and Monte Carlo results. The statistical errors on the expected neutrino rates and energy deposition spectra presented in the following are dominated by the number of fully simulated events, which are ≈ ten times more than the experimental ones.

A dedicated search for e^+e^- events has been also carried out using the same exposure. This analysis constrains δ to values a few orders 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

Table 2
Observed and expected neutrino and e^+e^- rates at Gran Sasso for the ICARUS experiment. Both the experimental and computed rates are normalised to the exposure used for the analysis of the corresponding experimental channel (see text for details). The indicated errors are statistical only.

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	$7.4 \cdot 10^6$

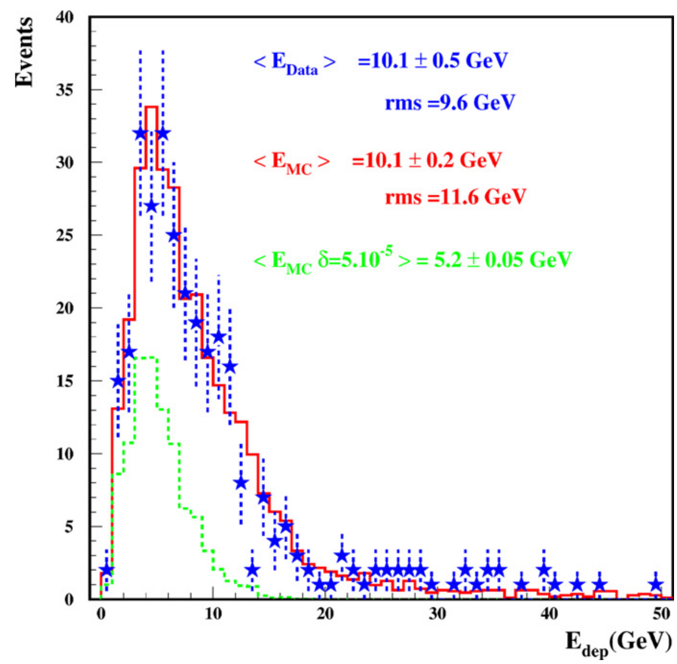

Fig. 5. Experimental raw energy E_{dep} distribution for ν_μ and $\bar{\nu}_\mu$ CC interactions in ICARUS (blue symbols) compared with the Monte Carlo expectations for an unperturbed spectrum (red solid histogram), and for $\delta = 5 \cdot 10^{-5}$ (green dashed histogram). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

dead-time. 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 analysed 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 current (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 2: 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 experi-

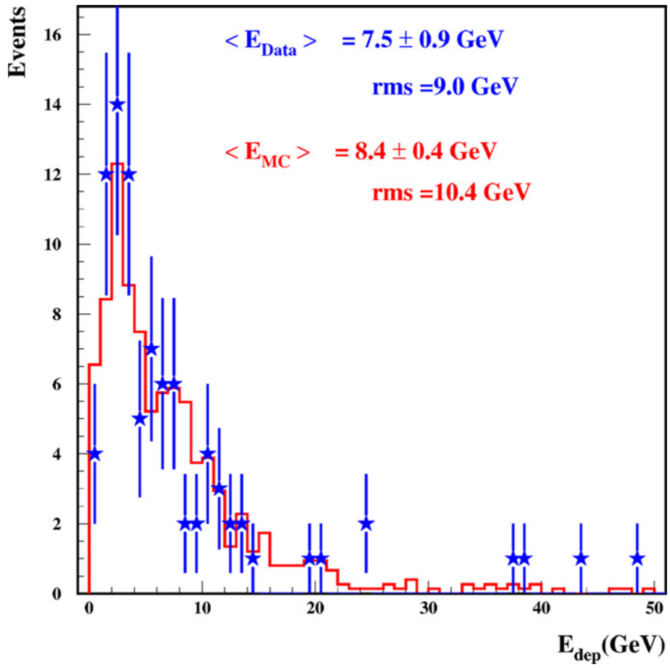

Fig. 6. Experimental (blue symbols) raw energy deposition distribution for neutral current events compared with the Monte Carlo expectations (red histogram) for the unperturbed CNGS spectrum. Only experimental and Monte Carlo events with energy deposition greater than 500 MeV have been considered. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

mental 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 flux-averaged 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 interaction caused by neutrinos above 30 GeV should be observed. 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 inconsistency between the OPERA δ value and the observed neutrino rate and spectrum already reported in Ref. [2]. It is consistent with published results [6] about the fully reconstructed energy of interacting neutrinos in OPERA which also show no significant deviations from expectations.

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 (Eqs. (1), (3)) generated by the passing superluminal neutrinos. These events would be characterised 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 $2.1 \cdot 10^{12}$ neutrinos passing through the detector.

Candidate pair bremsstrahlung events have been searched for requiring the absence of any hadronic activity, the presence of a single electromagnetic shower with vertex internal to the fiducial volume, energy deposition of at least 200 MeV, and direction pointing towards the beam axis within 150 mrad (a loose cut compared with the pair emission angle). No event survived all these cuts. A further selection, the request for a double ionisation initial track, has never been used, since no candidate survived the other cuts. Only two events were considered as candidates after a first screening. The former was discarded since the shower is directed at 60 degrees with respect to the beam, and is starting from one corner of the fiducial volume. In the latter case, a careful investigation of the shower revealed the existence of two distinct photons.

Hypothetical background sources have been investigated through Monte Carlo simulations of both neutral current events occurring inside the fiducial volume of detector, and NC or CC events in the surrounding passive layers and rock. Coherent π^0 production has been evaluated according to Ref. [16], and added to the internal NC sample. The simulated exposures were much larger than the experimental one. The same cuts have been applied as in the experimental search. The possibility that two almost superimposed photons can be misidentified as a single one has also been included with a conservative assumption. Under these conditions, the expected number of internal background events, for the same exposure and fiducial volume as in the real data, is 0.13 ± 0.03. Concerning external events, only one NC simulated event survived the cuts, corresponding to an expectation of 0.01 ± 0.01 background events for the real data exposure. The absence of background candidates in the CC simulated sample allows to set a limit to the expected background for the present search to less than 0.06 events. As a summary, 0.14 ± 0.03 background events are expected under very conservative assumptions. The background due to ν_e and $\bar{\nu}_e$ CC interactions is negligible. Only about 4 events are expected, resulting in less than 0.002 background events when the requirements on the absence of hadronic activity and on the single versus double ionization are taken into account.

The expected number of neutrino–electron elastic events for the experimental exposure is 0.04, which would be further reduced by the double ionisation requirement.

As a control sample, the total number of expected internal events with a single isolated π^0 has been evaluated to be 1.4 ± 0.05. As described above, one such event has been detected in the real data, in agreement with expectation. For external events, the expectation for an isolated photon without any angular cut is 2 ± 0.4 events. One event is observed in the real data, in agreement with expectations, with an angle of 60 degrees with respect to the beam direction. In summary, no Cherenkov-like event has been detected in ICARUS.

The experimental event rates are compared in Table 2 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 events with deposited energy in excess of 25 GeV are present in Fig. 5 in agreement within 1.6σ with the expectation of 18 ± 1.3).

The lack of pair bremsstrahlung events allows to set the limit $\delta < 2.5 \cdot 10^{-8}$ at 90% CL for CNGS neutrinos,[4] comparable to the limit $\delta < 1.4 \cdot 10^{-8}$ established by Super-Kamiokande [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 of 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.

The detection of upward going neutrinos in experiments like IceCube [5] or Super-Kamiokande can potentially be used to set stringent limits on δ in their respective energy ranges.

4. 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 [2,17]. 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 translates into a 90% CL limit of $\delta < 2.5 \cdot 10^{-8}$ for multi-GeV neutrinos.

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

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