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The flavor of neutrinos in muon decays at a neutrino factory and the LSND puzzle

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Abstract: The accurate prediction of the neutrino beam produced in muon decays and the absence of opposite helicity contamination for a particular neutrino flavor make a future neutrino factory the ideal place to look for the lepton flavor violating (LFV) decays of the kind $\mu^+ \to e^+\bar{\nu}_e\nu_\mu$ and lepton number violating (LNV) processes like $\mu^- \to e^-\nu_e\nu_\mu$. Excellent sensitivities can be achieved using a detector capable of muon and/or electron identification with charge discrimination. This would allow to set experimental limits that improve current ones by more than two orders of magnitude and test the hypothesis that the LSND excess is due to such anomalous decays, rather than neutrino flavor oscillations in vacuum.

Keywords: Beyond Standard Model, Neutrino Physics, Rare Decays.

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Contents

1. Introduction

The Standard electroweak Model (SM) is built on an absolute conservation of three separate lepton flavors (LF): the electron flavor L_e, the muon flavor L_μ, and the tau flavor L_τ. The total lepton number is defined as $L_{\rm tot} = L_e + L_\mu + L_\tau$.

In a model independent way, the main decay mode of the positive muon[1] into a positron and two neutrinos can be written as [1, 2]:

$$\mu^+ \longrightarrow e^+ + n + n' \,, \tag{1.1}$$

where n and n' denote neutrinos, which can be either neutrinos or antineutrinos and of any flavor e, μ or τ. In the SM, individual LF conservation implies that $n \equiv \nu_e$ and $n' \equiv \bar{\nu}_\mu$.

The evidence from neutrino oscillation searches that the neutrinos are in fact massive and mixed, implies that the LF conservation is not exact. However, LF conservation is constrained by stringent experimental limits obtained in processes involving charged leptons. For example, the present experimental 90%C.L. upper

[1] Similar arguments hold for negative muons.

limits on the most interesting of these decays are:

$$\begin{aligned} BR(\mu \longrightarrow e\gamma) &< 1.2\times 10^{-11} \ : \ [3] \\ BR(\mu^+ \longrightarrow e^+e^+e^-) &< 1.0\times 10^{-12} \ : \ [4] \\ R(\mu^- Ti \longrightarrow e^- Ti) &< 6.1\times 10^{-13} \ : \ [5] \\ BR(\tau \longrightarrow \mu\gamma) &< 1.1\times\ 10^{-6} \ : \ [6] \end{aligned} \tag{1.2}$$

These stringent limits are not inconsistent with the neutrino oscillation results since given reasonable upper bounds on the neutrino masses, the effect induced within the SM would be too small to be seen [7]. However, within extensions of the SM, neutrino oscillations raised the possible prospect that there might exist observable processes that violate the charged-lepton number [8]. Projects are currently underway to improve several of these upper limits significantly.

In contrast to this, direct experimental limits on LF conservation in decays involving neutrinos are much less stringent. For example, the limit

$$BR(\mu^- \longrightarrow e^-\nu_e\bar{\nu}_\mu) < 1.2\times 10^{-2} \ : \ [9] \tag{1.3}$$

is orders of magnitude worse than limits involving charged leptons. In extensions of the SM, the existence of LF violation could open new modes of decay where n and n' in eq. (1.1) are indeed any given neutrinos or antineutrinos.

One would clearly like to experimentally test these limits by a sensitive study of the neutrinos produced in such decays. Such studies could directly be relevant to a further understanding of the neutrino sector, as described in the following sections and would represent complementary investigations to those for neutrino flavor oscillations.

If the excess of events found in the Los Alamos LSND experiment [10, 11] is interpreted as due to $\mu^+ \to e^+ + \bar{\nu}_e + n$ (with a branching ratio equal to the measured probability of $\bar{\nu}_e$ appearance in case of flavor neutrino oscillations), this anomalous decay could be easily tested at a future neutrino factory with a detector capable of charge discrimination, looking at the more convenient decay $\mu^- \to e^-\nu_e\nu_\mu$ as described in section 7.

Good sensitivities could also be reached at a neutrino factory for the search $\mu^+ \to e^+\bar{\nu}_\ell\nu_\mu$ described in section 6 in which one look for interactions of ν_μ giving μ^- in a pure beam that produces μ^+.

2. The neutrino oscillation sector

Hints that neutrinos are massive particles come from the observation of three anomalous effects — the LSND excess [10, 11, 12], the atmospheric anomaly [13]–[17] and the solar neutrino deficit [18]–[22]. In particular, the atmospheric results are the most convincing ones. All three effects can be naturally explained in terms of neutrino flavor oscillations, which will occur when neutrinos propagate through space, if their masses are non-degenerate and the weak and mass eigenstates are mixed [23].

However, in order to explain *all* three experimentally observed effects in terms of neutrino flavor oscillations, one is forced to invoke additional sterile neutrino states [24] to accommodate the very different frequencies of oscillations — given by the mass differences squared Δm^2's — indicated by the three different effects. The existence of such neutrinos is a currently unresolved problem and clearly demonstrates that the neutrino sector is not fully understood. Several attempts were made to explain all data in terms of only three massive neutrinos [25]. But they are all excluded by the latest data.

From a phenomenological point of view, we recall that the neutrino flavor oscillation hypothesis predicts a well defined dependence of the phenomenon as a function of the neutrino energy, characterized by the so-called L/E behavior, where L is the distance between the source and detector and E the neutrino energy. So far, no experiment has conclusively demonstrated such a L/E dependence of the anomalous effect, with maybe the exception of the SuperKamiokande data which favors [26] a dependence $\propto LE^n$ where $n \approx -1$.

In such an unclear situation, is it possible to envisage "non-flavor-oscillation" mechanisms to explain part of the neutrino data?

Aside from theoretical arguments against sterile neutrinos, we argue that, from a phenomenological point of view, the LSND effect is particular: it has a small probability, measured to be $(2.5 \pm 0.6 \pm 0.4) \times 10^{-3}$ [11], in contrast to the solar and atmospheric neutrino anomalies, which are large. Hence, LSND is a natural candidate for an interpretation involving a different physics than in atmospheric and solar neutrino flavor oscillations.

3. Relevance to the LSND puzzle

We recall that the LSND effect was first reported as an excess of $\bar{\nu}_e$'s in the $\bar{\nu}_\mu$'s flux from the μ^+ Decay-At-Rest (DAR) process [10]. The neutrino beam is obtained with 800 MeV kinetic energy protons hitting a series of targets, producing secondary pions. Most of the π^+ come to rest and decay through the sequence $\pi^+ \to \mu^+\nu_\mu$, followed by $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$, supplying the experiment with the $\bar{\nu}_\mu$'s with a maximum energy of 52.8 MeV. The intrinsic contamination of $\bar{\nu}_e$'s coming from the symmetrical decay chain starting with π^- is estimated to be small since most negatively charged mesons are captured before they decay.

The excess of $\bar{\nu}_e$'s, explained in terms of neutrino flavor transitions of the type $\bar{\nu}_\mu \to \bar{\nu}_e$, occurs via the reactions:

$$\mu^+ \longrightarrow e^+\nu_e\bar{\nu}_\mu\,; \qquad \bar{\nu}_\mu \xrightarrow{\text{vacuum}} \bar{\nu}_e\,; \qquad \bar{\nu}_e p \longrightarrow e^+ n\,. \tag{3.1}$$

Additional evidence in favor of neutrino oscillation was reported in the Decay-In-Flight (DIF) sample, though with a low statistical significance [12]. In a recent re-analysis of the complete data sample collected [11], the significance of the DIF data seems to be even lower. Hence, we concentrate on the hint from stopped muons, and ignore the DIF result.

The latest KARMEN2 results [27] come very close to contradicting the LSND claim, however the experimental sensitivity is marginal to conclusively exclude or confirm completely the LSND excess. A new experiment, MiniBOONE [28], will confront the flavor oscillation hypothesis with a very high statistical accuracy.

In case of a negative result, one will only be able to conclude that the LSND excess was not due to neutrino flavor oscillations in vacuum.

The implications of exotic muon decays on the LSND excess has been studied [29] showing that two explicit models predicted interactions of about one order of magnitude smaller than what would be relevant for LSND. In a model independent proof in which any contributions from neutrino mixing is neglected, the authors of ref. [30] prove that new lepton flavor violating interactions, under the constraint of LF data involving charged leptons, fail short to explain the LSND effect by a rate factor of almost three. However in ref. [31], it is reported that exotic decays that produce two antineutrinos

$$\mu^+ \longrightarrow e^+ + \bar{\nu}_e + \bar{\nu}_\ell\,, \qquad (\ell = e, \mu, \tau) \tag{3.2}$$

cannot be ruled out as the cause of the LSND excess in a model independent way.

Regardless of any theoretical prejudice, the excess of electrons found by the LSND experiment stands today as a still unresolved puzzle of neutrino physics. The study of many thousands of neutrino interactions from muon decays will certainly help to understand this unresolved problem.

4. Searches at a neutrino factory

A neutrino factory [32, 33] is understood as a machine where low energy muons of a given charge are accelerated in a storage ring. The two neutrinos n, n' produced in the decay eq. (1.1) will be boosted in the forward direction of the muon flight path. Hence, the muon storage ring is composed of long straight-lines in order to produce directional neutrino beams.

In such machines, muons are produced in decays of secondary pions produced by few GeV protons incident on a target. In current designs, muons are captured with high efficiency and very high integrated protons-on-target intensities are envisaged in order to produce very intense neutrino sources.

The neutrino physics potentialities of such machines has been largely discussed in the literature [34, 35]. In particular, we mention our study in the context of a short-baseline experiment to search for neutrino flavor oscillation in a background free environment in the Δm^2 region indicated by LSND [36].

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A neutrino factory is also an ideal place to study neutrinos from exotic muon decays. The envisaged flux of neutrinos is sufficiently high to obtain large statistics of neutrino interaction events. More importantly, we can take advantage from the fact that the neutrino beam is produced from muons of a definite sign and therefore the decay processes can be studied with *a pure initial state*. This is not the case for traditional pion decay neutrino beams, in which contaminations are always present at some level.

The flavor of the interacting neutrinos can be tested via their charged current processes. In case of purely lepton flavor conserving decays $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$, we expect to detect only

$$\begin{aligned} \nu_e + N &\longrightarrow e^- + X\,, \\ \bar{\nu}_\mu + N &\longrightarrow \mu^+ + X \end{aligned} \tag{4.1}$$

while exotic decays can be immediately identified by various processes

$$\begin{aligned} \mu^+ \to e^+ + n + \nu_\mu &\longrightarrow & \nu_\mu + N \to \mu^- + X\,, \\ \mu^+ \to e^+ + \bar{\nu}_e + n &\longrightarrow & \bar{\nu}_e + N \to e^+ + X\,, \\ \mu^+ \to e^+ + n + \nu_\tau &\longrightarrow & \nu_\tau + N \to \tau^- + X\,, \\ \mu^+ \to e^+ + n + \bar{\nu}_\tau &\longrightarrow & \bar{\nu}_\tau + N \to \tau^+ + X\,, \end{aligned} \tag{4.2}$$

where n stands for neutrinos or anti-neutrinos.

Charge discrimination of electrons and muons can trivially separate the two types of decays. The presence of taus is more difficult to identify but can be achieved using topological or kinematical signatures. It requires neutrino beams of high energy in order to exceed the tau lepton production threshold. We do not consider tau identification any further in this paper, and concentrate on the identification of electrons and muons in a low energy setup.

In order to predict the energy distribution of the (anti)neutrinos in the detector we assume for definiteness two types of generic decays:

$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\ell + \nu_\mu\,, \tag{4.3}$$

$$\mu^- \longrightarrow e^- + \nu_e + \nu_\ell\,. \tag{4.4}$$

We address the search for LFV, eq. (4.3), using wrong sign muons, which are experimentally simpler to detect. In order to profit from the enhanced cross-section of neutrinos versus antineutrinos, it is better to select positive muons in the storage ring, since in this case, the LFV decays produce ν_μ's.

In case we consider the LNV decay of eq. (4.4), for which $\Delta L = 2$, we should look for wrong sign electrons. We select μ^- in the ring since the signal searched for in this case has two neutrinos in the final state, therefore we profit from the enhanced neutrino cross sections. Naturally, both signs of muons could be studied in a real experiment, in order to provide possible checks for different behaviors in μ^+ or μ^- decays.

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Following the discussion in [31], LNV interactions can naturally arise via mixing of heavy bosons that transform differently under the Standard Model group but identically under the unbroken $U(1)_{EM}$. In particular, the effective four-fermion operator relevant for the reaction:

$$\mu_L^- \longrightarrow e_R^- + \nu_e + \nu_\ell \tag{4.5}$$

which violates lepton number conservation by two units, has the form $(\mu_L \bar{\nu}_e)$ $(\bar{\nu}_\ell \bar{e}_R)$. It couples ν_e to μ^- and e^- to ν_ℓ. This operator can be induced, for example in supersymmetric models without R-parity, through the mixing of sfermions that are $\mathrm{SU}(2)_L$ singlets with sfermions that are $\mathrm{SU}(2)_L$ doublets.

After explicit calculation, we obtain that the square of the scattering amplitude for the decay (4.5) is $\langle|\mathcal{M}|^2\rangle \propto (p_\mu \cdot p_{\nu_e})(p_e \cdot p_{\nu_\mu})$ (where p_i is the four-momentum of particle i). This expression is similar to the one obtained for the standard decay $\mu^- \to e^- \bar{\nu}_e \nu_\mu$; therefore the flux of ν_e's coming from (4.5) is equal to the one of $\bar{\nu}_e$'s produced in the standard μ^- decay as shown in figure 1.

5. Experimental considerations

We address a few experimental considerations in the context of an optimization of searches for LFV and LNV decays of the muon.

5.1 Beam setup

Unlike for neutrino flavor oscillations in vacuum, the distance L between source and detector is in this case an irrelevant physical parameter. It is hence advantageous to place the experiment close to the source in order to gain flux like $1/L^2$ due to the beam divergence.

We think that a neutrino beam energy of a few GeV would be optimal in order to facilitate the discrimination of the muon and electron charges, and in order to reduce misidentified electrons or muons background coming mostly from neutral current interactions. We therefore consider a low-energy muon storage ring[2] with three possible muon energies $E_\mu = 1$, 2 or 5 GeV.

In table 1, we list the expected event rates from standard muon decays per ton of target and 10^{19} standard muon decays. The detector is located at a distance $L = 100$ m from a 100 m long straight section of the storage ring. The expected event energy spectra are shown in figure 2.

[2]We also note that studies indicate that the cost of a neutrino factory is driven by the muon energy E_μ and rises very rapidly with E_μ, hence a low energy muon beam is also financially favored.

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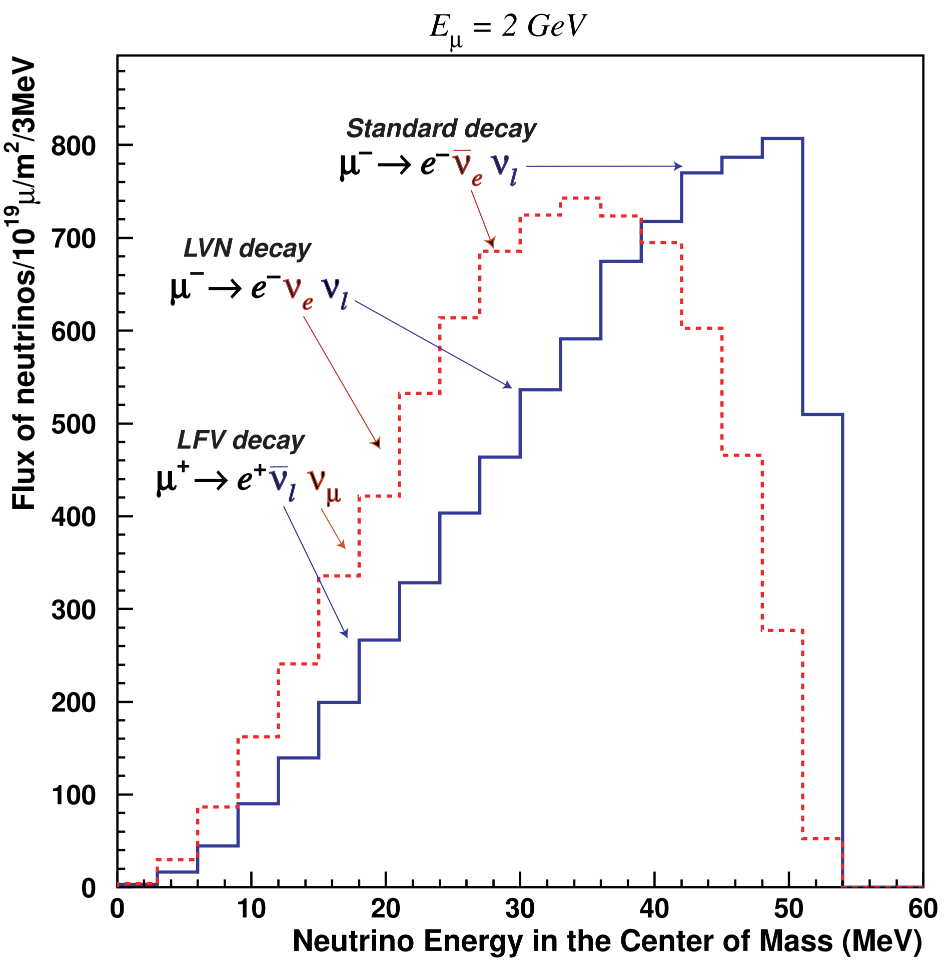

Figure 1: Expected neutrino fluxes for the standard, lepton flavor and lepton number violating μ^- decays as a function of the neutrino energy in the center of mass reference frame.

5.2 Detector parameters

Experimentally, the presence of LFV decays will characterize themselves by the observation of events with "wrong sign leptons". It is therefore mandatory to ensure a very good and efficient determination of the lepton charge.

The muon charge is most easily determined with the help of bending in a magnetic field. The radius of curvature in meters in a 1 T field is approximately $10p(\mathrm{GeV})/3$, or 3 meters for $p = 1\,\mathrm{GeV}$. In the case of electrons, the capability to measure the charge is limited by the radiation length of the target which determines the distance after which the electromagnetic shower develops at a level where the primary electron is not distinguishable any longer.

At low energies, we expect events to exhibit simple topologies and many of them will be quasi-elastic-like. Hence, the events will be dominated by a leading hard lepton accompanied by few soft hadrons. Such events were traditionally best

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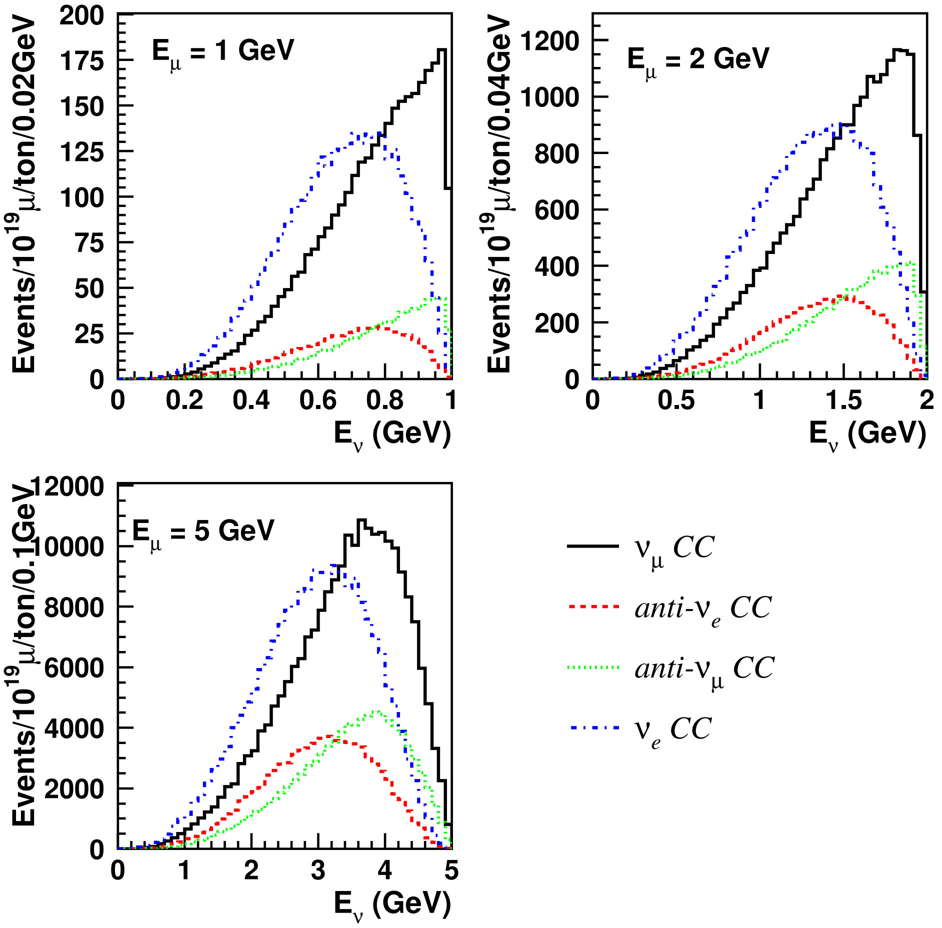

Figure 2: Neutrino events energy spectrum for muon ring energy of 1, 2 and 5 GeV. The ν_μ (line) and $\bar{\nu}_e$ (dashed) events come from standard μ^- decays, while $\bar{\nu}_\mu$ (dotted) and ν_e (dash-dotted) events come from standard μ^+ decays.

studied in bubble chambers, due to the required low density, high granularity and homogeneity to capture soft escaping tracks at all angles. In addition, a low density, high granularity instrumented target is mandatory to efficiently recognize electrons and to discriminate muons from pions. Different detector configurations meeting the previously mentioned specifications can be clearly envisaged.

6. Results for $\mu^+ \to e^+ + \bar{\nu}_\ell + \nu_\mu$

We consider a 10 ton fiducial mass detector located at a distance of 100 m from the muon storage ring.

For a 2 GeV muon ring energy, the expected event samples for a total of 10^{19} standard μ^+ decays are 72'000 $\bar{\nu}_\mu$ CC and 215'000 ν_e CC events, and 18'300 $\bar{\nu}_\mu$ NC and 36'600 ν_e NC.

		$E_\mu = 1\,\mathrm{GeV}$	$E_\mu = 2\,\mathrm{GeV}$	$E_\mu = 5\,\mathrm{GeV}$
	ν_μ CC	3300	23200	233400
μ^-	ν_μ NC	410	4470	58600
10^{19} decays	$\bar{\nu}_e$ CC	630	6250	80200
	$\bar{\nu}_e$ NC	100	1450	23100
	$\bar{\nu}_\mu$ CC	730	7200	91200
μ^+	$\bar{\nu}_\mu$ NC	140	1830	27600
10^{19} decays	ν_e CC	3060	21500	211700
	ν_e NC	310	3660	50100

Table 1: Expected event rates (CC=charged current, NC=neutral currents) per ton of target per 10^{19} standard muon decays in a storage ring with a straight line of 100 m and located 100 m away from the neutrino detector. Only 50% of the muons are assumed to decay in the direction of the detector, the other 50% are lost.

To estimate the signal efficiency, we assume that the LFV decay proceeds through a similar diagram as the standard muon decay as given by the $V - A$ theory, however, with interchanged neutrino flavors. We can then essentially assume that *at the detector location* the flux of ν_μ's from LFV decays is similar to the one of ν_e's in the standard muon decay. It is clear that other type of interactions could be envisaged and could lead to different energy spectra which can be experimentally tested by studying the visible energy distribution of wrong sign muon events.

If LFV decay occur with a branching Br(LFV), we expect to observe the number of negative muon events

$$
\begin{aligned}
N_{\mu^-,\mathrm{CC}} &= \int \Phi_{\mathrm{LFV}}(\nu_\mu, E_\nu)\sigma^{\mathrm{CC}}(\nu_\mu, E_\nu)dE_\nu \\
&\approx \mathrm{Br(LFV)} \times \int \Phi(\nu_e, E_\nu)\sigma^{\mathrm{CC}}(\nu_\mu, E_\nu)dE_\nu\,, \qquad (6.1)
\end{aligned}
$$

where Φ_{LFV} is the flux of ν_μ neutrinos from LFV decays, $\Phi(\nu_e)$ is the flux of electron neutrinos in standard μ^+ decays and σ^{CC} the charged current cross-sections.

For the branching indicated by LSND and 10^{19} μ^+ decays, we obtain

$$
\begin{aligned}
N_{\mu^-,\mathrm{CC}} &\approx 215'000 \times \mathrm{Br(LFV)} \\
&= 540 \qquad (6.2)
\end{aligned}
$$

for the fiducial detector mass of 10 ton.

For muon tracks of a few GeV momentum bent in the magnetic field, we expect wrong charge confusion at the level of $\approx 10^{-3}\%$. We therefore think that the background produced by $\bar{\nu}_\mu$ CC events with mismeasured charge of the muon to be less than one event.

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Cuts	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	ν_e NC	LFV ν_μ CC
$E_{\mu^+} = 2\,\mathrm{GeV}$				
Initial	72000	18300	36600	540
μ^- candidate	9890	660	1197	540
$E_{\mu^-} > 1.1\,\mathrm{GeV}$	< 0.1	0.6	2	130
$E_{\mu^+} = 5\,\mathrm{GeV}$				
Initial	912000	276000	501000	5290
μ^- candidate	133500	10500	17900	5290
$E_{\mu^-} > 3\,\mathrm{GeV}$	3	0.3	0.6	645
$E_{\mu^+} = 1\,\mathrm{GeV}$				
Initial	7300	1400	3100	76
μ^- candidate	873	46	99	76
$E_{\mu^-} > 0.6\,\mathrm{GeV}$	< 0.1	0.1	0.6	16

Table 2: Effect of cuts on background and signal. We assumed a positive muon ring energy E_{μ^+} of 1, 2 and 5 GeV and a total of 10^{19} standard decays. The LFV decay has the branching probability of 2.5×10^{-3}. Backgrounds come from hadrons escaping the detector without interacting or muons from meson decays. For the charged current background, no veto on the positive muon has been included. E_{μ^-} is the energy of the identified negative muon in the event.

One crucial experimental aspect is the discrimination of muons versus pions. In addition, secondary muons from meson decays produce background, especially at low energies. In order to assess realistic efficiencies and experimental backgrounds, we illustrate results with a detector with the characteristics of the ICARUS liquid Argon imaging TPC [37]. The detector would be on a medium-sized LAr vessel surrounded by a dipole magnet. The size of such detector would be in the range of $2 \times 2 \times 6\,\mathrm{m}^3$ for a total mass of about 30 tons. The magnetic field would be oriented perpendicular to the drift E-field and the incoming neutrino direction, in order to bend the charged particles in the direction of the drift field, where a resolution in the range of $200\,\mu\mathrm{m}$ is expected from the LAr TPC. Given the hadronic interaction length of LAr of $\lambda_I = 84\,\mathrm{cm}$, muons which loose about 240 MeV/m are distinguished from pions which interact hadronically.

The effect of simple cuts on background and signal are illustrated in table 2. We assumed in this case a positive muon ring energy and a total of 10^{19} standard decays. The LFV decay has the branching probability of 2.5×10^{-3}, compatible with the LSND excess.

We considered all sources of backgrounds by means of fully generated neutrino events. Large event samples were produced for all neutrino species with the proper

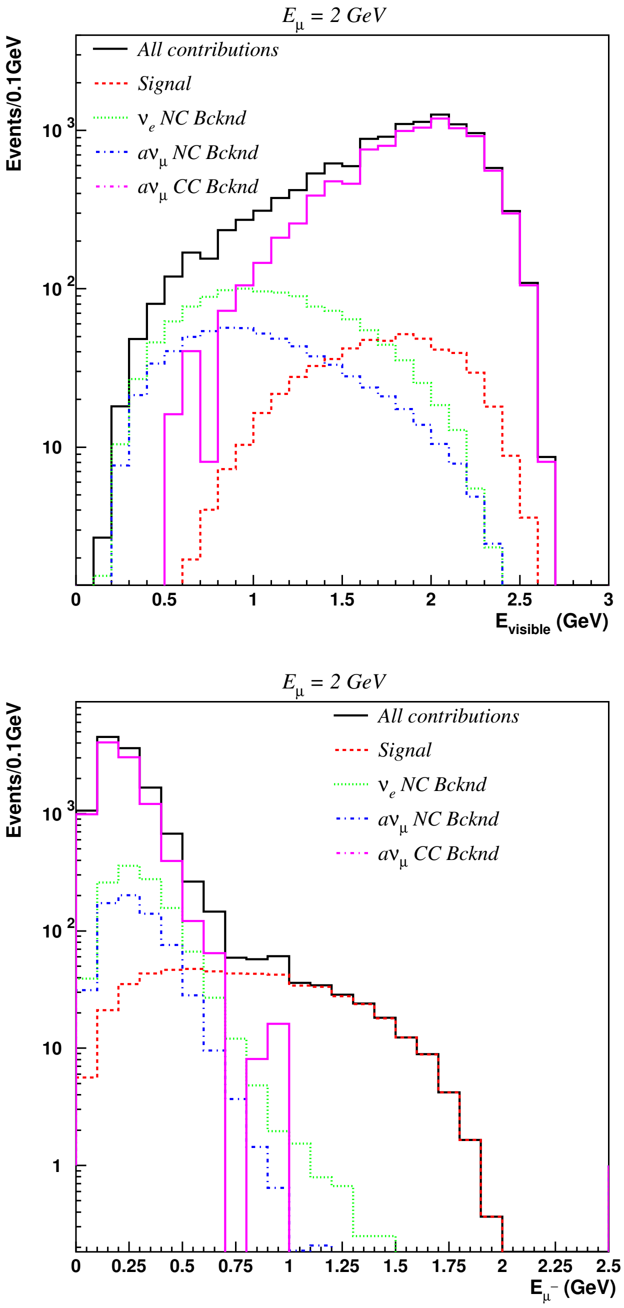

Figure 3: Visible energy (upper) and candidate muon (lower) distribution for LFV decays (see text) normalized to LSND excess and 10^{19} positive muon decays for 10 ton detector. The background from neutral current using the characteristics of an ICARUS *LAr* TPC is also shown.

energy distribution with the help of an event generator [38] which includes all exclusive final states and a realistic treatment of the low energy region.

A muon candidate is identified as a track which stops without interacting in the Argon or leaves the detector vessel before interacting or stopping. Hence, charged

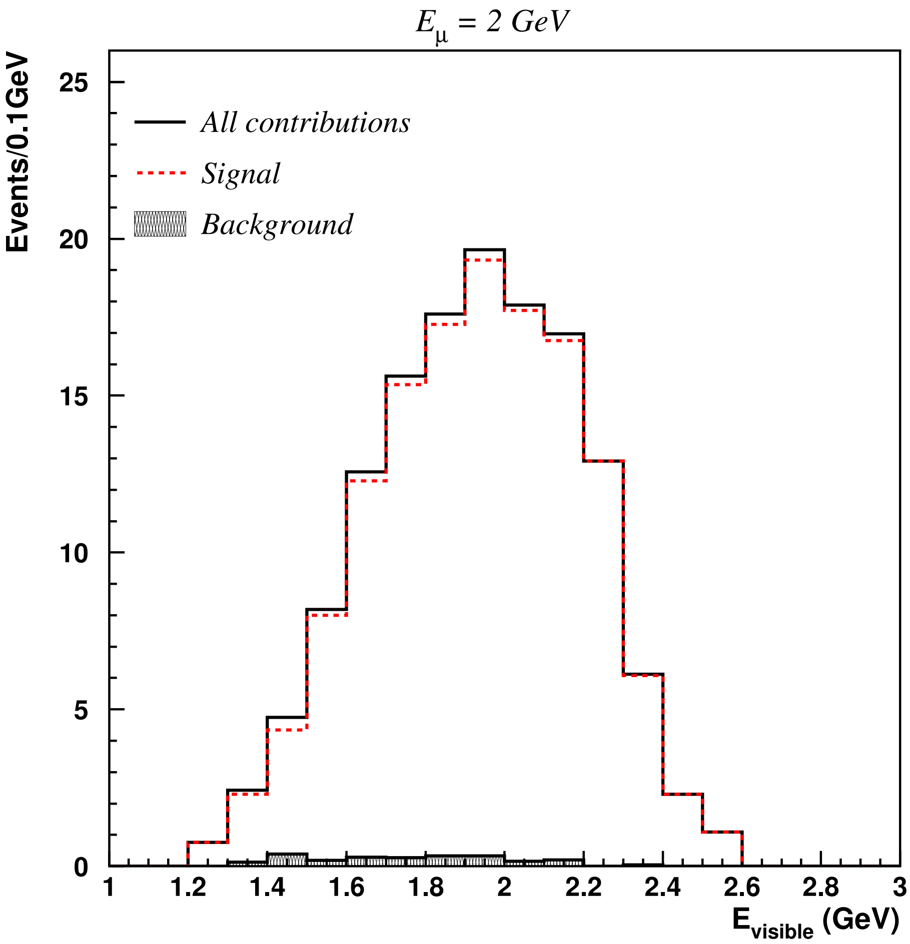

Figure 4: Visible energy distribution (see figure 3) after a cut on the candidate muon momentum for LFV signal (see text) and backgrounds expected in a detector with the characteristics of an ICARUS *LAr* TPC.

and neutral current backgrounds come from hadrons escaping the detector without interacting or or from actual muons from meson decays. For the charged current background, no veto on the positive muon has been included.

In table 2, we observe that the presence of LFV decays will produce an excess of events with μ^- candidates. The visible energy and the candidate muon energy spectra are shown in figure 3. As expected, the excess is most visible at the highest end of the muon energy distribution, since background comes from misidentified soft hadrons. A simple cut on the muon candidate energy can be used to largely suppress background to negligible level, while keeping a large fraction of the LFV signal events, as shown in the table 2. The visible energy distribution of events for $E_{\mu^+} = 2\,\mathrm{GeV}$ with a cut on the muon candidate momentum of 1.1 GeV (efficiency for LFV of 25%) is shown in figure 4. The statistics is clearly sufficient to constrain any theoretical prediction of the energy distribution of the LFV neutrinos.

7. Results for $\mu^- \to e^- + \nu_e + \nu_\ell$

The experimental signal consists in the appearance of final state electrons, while standard events have positrons in the final state. Therefore, to experimentally detect reaction (4.4), it is mandatory to envisage an experiment endowed with charge discrimination capabilities for electrons. This is a true experimental challenge given the short radiation lengths in dense targets.

In order to evaluate realistic efficiencies and backgrounds, we consider an experimental setup similar to the one discussed in the previous section, namely, an ICARUS liquid Argon imaging TPC with a magnetic field provided by an external dipole magnet.

Table 3 shows the effect of the cuts applied for a normalization of 10^{19} muon decays. To compute the expected number of signal events we have taken a branching probability of 2.5×10^{-3}. Given the low muon energies considered, most of the events will be quasielastic. We thus require a final state configuration containing an electron and a reconstructed proton[3] and no additional hadronic particles. These criteria reduce the quasielastic background (where we expect a neutron rather than a proton in the final state) by almost three orders of magnitude, while keeping more than 50% of the signal. The NC background, where electron candidates come from π^0 conversion, is in general soft. After a cut on the electron candidate momentum, this kind of background becomes negligible.

As mentioned before, charge discrimination between electrons and positrons is a must for this kind of search. Preliminary studies show [39] that for a LAr detector immerse in a 1 T magnetic field, a fit to the direction of the electromagnetic shower could provide a good determination of the charge of leading electrons. When loose criteria are applied, the expected charge contamination from $\bar{\nu}_e$ CC amounts to 2% for an electron efficiency of 25%. Tighter requirements reduce the charge confusion to the per mil level for an electron identification efficiency close to 10%. Table 3 shows that applying loose criteria in the determination of the lepton charge is enough to eliminate $\bar{\nu}_e$ CC background.

8. Experimental sensitivities

Table 4 shows the expected sensitivities in case a negative result is found as a function of the muon energy circulating in the accumulation ring. Three different normalizations have been considered: 10^{18},10^{19} and 10^{20} muons. For comparison we also show the current best limit on the LFV decay $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ [9]. We note that the indirect limit obtained in ref. [30] using processes involving charged leptons is 5.8×10^{-4}.

[3] We assume a kinetic threshold of $T > 50\,\mathrm{MeV}$ in order to detect a proton.

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Cuts	ν_e CC	$\bar{\nu}_e$ CC
$E_{\mu^-} = 2\,\mathrm{GeV}$		
Initial	540	62500
One proton	367	11000
No pions	323	100
$E_e > 1\,\mathrm{GeV}$	103	17
Candidate charge	21	0.4
$E_{\mu^-} = 5\,\mathrm{GeV}$		
Initial	5290	802000
One proton	3390	212160
No pions	2112	495
$E_e > 3\,\mathrm{GeV}$	351	163
Candidate charge	71	4
$E_{\mu^-} = 1\,\mathrm{GeV}$		
Initial	76	6300
One proton	53	529
No pions	48	8
$E_e > 0.2\,\mathrm{GeV}$	43	4
Candidate charge	10	0.1

Table 3: Effect of cuts on background and signal. We assumed a negative muon ring energy E_{μ^-} of 1, 2 and 5 GeV and a total of 10^{19} standard decays. The lepton number violating decay has the branching probability of 2.5×10^{-3}. E_e is the energy of the identified electron in the event.

For a statistics corresponding to 10^{19} muon decays we could improve the present sensitivity by more than two orders of magnitude. Three orders of magnitude can be reached for 10^{20} muons. Therefore the interpretation of the LSND excess in terms of anomalous muon decay that violates lepton flavor and/or total lepton number could be thoroughly experimentally tested. In addition, the limit from ref. [30] could also be tested.

9. Conclusion

A negative result from the MiniBOONE experiment would indicate that the neutrino flavor oscillation is not the correct hypothesis to explain the excess seen in LSND. It would however not contradict other possible non-flavor-oscillation interpretations of the effect.

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μ Decays	Decay mode	Current direct Limit	$E_\mu = 1\,\mathrm{GeV}$	$E_\mu = 2\,\mathrm{GeV}$	$E_\mu = 5\,\mathrm{GeV}$
10^{18}			4×10^{-3}	5×10^{-4}	1×10^{-4}
10^{19}	$P(\mu^+ \to e^+ \bar{\nu}_\ell \nu_\mu) <$	1.2×10^{-2}	5×10^{-4}	1×10^{-4}	3×10^{-5}
10^{20}			2×10^{-4}	6×10^{-5}	2×10^{-5}
10^{18}			6×10^{-3}	3×10^{-3}	9×10^{-4}
10^{19}	$P(\mu^- \to e^- \nu_e \nu_\ell) <$	–	6×10^{-4}	3×10^{-4}	3×10^{-4}
10^{20}			1×10^{-4}	1×10^{-4}	2×10^{-4}

Table 4: Achievable limits in case of negative result at the 90%$C.L.$ for $\mu^+ \to e^+ \bar{\nu}_\ell \nu_\mu$ and $\mu^- \to e^- \nu_e \nu_\ell$ decays with a 10 ton detector for three different number of muon decays. For comparison, the indirect limit obtained in ref. [30] using processes involving charged leptons is 5.8×10^{-4}.

In particular, LFV and LVN decays could play a role in the interpretation of the LSND excess. Theoretical arguments based on experimental limits obtained on exotic charged lepton decays, indicate that most probably the LSND excess cannot be explained by these processes. However, if the LSND puzzle remains unsolved after the MiniBOONE [28] results, a better understanding of these processes would then be particularly relevant, if not mandatory.

A neutrino factory is an ideal machine to probe such anomalous decays of the muon. The pure initial state beam allows to look for these decays without intrinsic beam contamination.

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