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Summary report of MINSIS workshop in Madrid

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Recent developments on tau detection technologies and the construction of high intensity neutrino beams open the possibility of a high precision search for non-standard μ - τ flavour transition with neutrinos at short distances. The MINSIS — Main Injector Non-Standard Interaction Search– is a proposal under discussion to realize such precision measurement. This document contains the proceedings of the workshop which took place on 10-11 December 2009 in Madrid to discuss both the physics reach as well as the experimental requirements for this proposal[1].

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[1] The original slides can be found at the workshop web-site [1]

Contents

I. OVERVIEW OF TALKS

A. MINSIS — Main Injector Non-Standard Interaction Search — *A. Para*

Neutrino oscillations are the only known, so far, examples of the lepton flavor violating processes. The interactions responsible for the oscillations-induced lepton flavor violation are the same as the ones responsible for the neutrino masses and they are likely to operate at very high energies, similar to the GUT scale. On the other hand it is quite possible that there are other processes, beyond the minimal standard model, which operate at much lower energies and which induce lepton flavor violations. The examples of mechanisms include:

- Non-unitarity of the neutrino mixing matrix: TeV scale see-saw, inverse see-saw could be a typical example
- Leptoquarks mediated interactions
- R-parity SUSY particles violating interactions
- Charged Higgs mediated interactions

Neutrino oscillations constitute an irreducible background for such possible rare processes, hence the search for the non-standard interactions ought to be conducted at the short baseline, where oscillations probability is known to be very small. Muon neutrino to tau neutrino appears to be particularly promising proposition. The existing limit provided by the short-baseline neutrino oscillations experiments NOMAD and CHORUS is of the order of 10^{-4}.

The next generation of the short-baseline tau appearance experiments with the sensitivity improved by up to two orders of magnitude was well developed, but abandoned shortly after the discovery of the neutrino oscillations by the SuperK experiment and a determination that the atmospheric neutrino oscillations are induced by the mass difference of the order of 3×10^{-3} eV^2. This discovery has demonstrated that the oscillation probability is extremely low at the short-baseline oscillations.

What was a fatal blow for the neutrino oscillations search is a great advantage for the search for non-standard neutrino oscillations: signatures for potential new physics may appear on top the extremely low or no background. The proposals for the next generation short baseline oscillation search offered a major improvement of the sensitivity event with the detector technology of the late 90's. Such a search is complementary to the direct searches conducted at the LHC and it has somewhat different sensitivities. Advances in the experimental techniques in conjunction with modern high intensity neutrino beams offer an attractive prospect of discovery of the non-standard neutrino interactions or a significant improvement of the limits on the strength of such interactions:

- high intensity neutrino beam with flexible energy has been constructed at Fermilab
- a near detector hall, housing the near MINOS detector and the MINERvA experiment, has been constructed and it offers sufficient floor space for new additional experiment
- τ neutrino interactions have been observed using a new concept of the Emulsion Cloud Chamber (ECC)
- OPERA, a very large τ appearance experiment using the ECC technology has been constructed and it is currently operating in Gran Sasso
- automatic scanning and measurement of the emulsion films have been developed for the OPERA experiment, making it feasible to analyze vary large detector volumes

These initial studies indicate that the beam related backgrounds (primarily a τ neutrino component of the beam) as well as the instrumental background (primarily induced by mis-identified charm events) can be controlled at the levels allowing the tau appearance experiment at the short distance in the NUMI beam with a sensitivity better than 10^{-6}. Detailed optimization of the beam and detector configuration is necessary to establish a credible case, though. A significant body of experience developed by the OPERA experiment is of the key importance for such an effort.

B. ν_τ detection: the CHORUS and OPERA experiences — *P. Migliozzi*

The critical points in designing an experiment that aims at improving the sensitivity on $\theta_{\mu\tau}$ of the CHORUS and NOMAD experiments are the understanding of the background and its suppression. Here in the following we briefly summarize the experience gathered from the emulsion based experiments CHORUS and OPERA and possible improvements.

	$\tau \to e$	$\tau \to \mu$	$\tau \to h$
Charm background	7×10^{-6}	3×10^{-7}	5×10^{-6}
Large angle μ scattering		4×10^{-6}	
Hadronic background		3×10^{-6}	4×10^{-6}
Total=2×10^{-5}	7×10^{-6}	7×10^{-6}	9×10^{-6}

TABLE I: Background estimation of Emulsion Cloud Chamber by the OPERA collaboration.

The CHORUS experiment was designed to search for $\nu_\mu \to \nu_\tau$ oscillations through the observation of charged-current interactions $\tau \to \nu_\tau + X$ followed by the decay of the τ lepton, directly observed in a nuclear emulsion target. As discussed in detail in Ref. [2], the main source of background in the CHORUS experiment originates from the poor efficiency in measuring the momentum and the charge of the decay products. Indeed, the excellent sensitivity of the nuclear emulsions in detecting also nuclear recoils (which is extremely important in rejecting hadron reinteractions mimicking a decay topology) is spoiled by the low efficiency in performing a kinematical analysis of the events. The achieved background level (normalized to charged-current interactions) by the CHORUS Collaboration is $\approx 10^{-3}$.

An evolution of the "pure" nuclear emulsion target concept is the so called Emulsion Cloud Chamber (ECC). It consists of photographic emulsion films interleaved with lead (or iron) plates, where the emulsion films act as micrometric tracking device and the lead plates as passive material (target). The main advantages of this approach, on top of a micrometric decay topology reconstruction, are: momentum measurement (with an accuracy of about 20%) of charged particles by exploiting their Multiple Coulomb Scattering on lead; electron/pion separation and gamma identification through the electromagnetic shower reconstruction.

The ECC technique has been adopted by the OPERA Collaboration to search for $\nu_\mu \to \nu_\tau$ oscillations on the CNGS beam [3]. The synergy among the micrometric decay topology reconstruction and an efficient kinematical analysis allowed the OPERA Collaboration to estimate a background level of $\approx 10^{-5}$. The breakdown of the background, normalized to the charged-current events, for each decay channel is shown in Tab. I.

From Tab. I, it is evident that even if an OPERA-like experiment restricts the search to the muonic channel the background is still well above the $\sim 10^{-6}$ level. Indeed there are two sources of background that dominate: the large angle muon scattering and the hadron reinteractions. The knowledge of the former background is limited by the absence of data and by the fact that GEANT simulation does not take into account nuclear form factors. The present estimate is based on upper limits from measurements performed in the past, while a calculation that accounts for nuclear form factors gives a background five times smaller. On the other hand, the hadron reinteraction background in an ECC is amplified with respect to a detector that exploits a pure emulsion target since it is not possible to detect nuclear fragments produced in the interaction. Indeed, in OPERA this background is suppressed by applying strong kinematical cuts.

In order to efficiently exploit also the electronic and hadronic channels it is of the outmost importance to measure the charge of the daughter particles. This would allow a reduction of the background to a level comparable to the one of the muonic channel.

What can be the ultimate background level? — It is difficult to say without a better understanding of the large angle muon scattering background and of an optimization of the kinematical analysis. The latter strongly depends on the availability of a magnetic field. Indeed, if an ECC is immersed into a magnetic field, only the muonic channel is studied and the large angle muon scattering is confirmed to be smaller as expected from numerical calculations, then a background level of $\sim 10^{-6}$ can be achieved.

The feasibility of a background level $\sim 10^{-7}$ is a real challenge and deserves dedicated studies both on the detector and analysis optimization. Such a studies are more challenging and mandatory if one wants to search for decay by exploiting all τ decay channels.

C. NSI for Fermilab to DUSEL — *S. Parke*

Fermilab is planning a new neutrino beamline to send a conventional neutrino superbeam to DUSEL, the new underground laboratory at Homestake, South Daykota. Initially the beamline will be powered by the 700 kW of protons from the Fermilab Main Injector but will be upgraded to more than 2 MW once the new proton source, Project X, is completed. The detector complex at DUSEL will consists of up to 300 ktons of water Cerenkov (WC) detectors and up to 50 ktons of Liquid Argon TPCs (LAr) in some mix, e.g. 2 × 100 kton modules of WC and a 17 kton module of LAr. The combination of Project X and the detectors at DUSEL will have a sensitivity to $\sin^2 2\theta_{13} \approx 0.001$ and be able to determine the hierarchy and measure the CP violating phase with reasonable accuracy down to $\sin^2 2\theta_{13} \approx 0.01$. Preliminary studies indicate that with this facility one could new sets limits on Non-Standard Neutrino Interactions especially for $\epsilon_{e\mu}$, $\epsilon_{e\tau}$ and $\epsilon_{\mu\tau}$ at better than 0.1 level.

D. Non-unitarity PMNS matrix (Theory) — *S. Antusch*

Non-unitarity of the leptonic mixing matrix is a typical signal of new physics. Intuitively, non-unitarity results when the light neutrinos of the Standard Model (SM) mix with heavier states, for instance with heavy fermionic singlet states with masses above the energies of a given experiment. While the full mixing matrix is unitary, the effective mixing matrix relevant for the low energy experiment is just a submatrix and it is in general non-unitary [4].

Non-unitarity and neutrino masses can be introduced in an effective theory approach by adding only two gauge invariant operators to the SM. A minimal possibility, referred to as Minimal Unitarity Violation (MUV) [5] consists in adding the lepton number violating dimension 5 (Weinberg) operator for neutrino masses and the lepton number conserving dimension 6 operator which contributes to the kinetic energy term of the neutrinos (but not of the charged leptons). *The bounds on non-unitarity and the relevance for Minsis are summarized by M. Blennow.*

The non-unitarity effects can be sizable, for instance, when neutrino masses are generated in a SM extension by fermionic singlets at comparably low energies, i.e. close to the electroweak scale. The smallness of neutrino masses can be accommodated in this scheme by an approximately conserved lepton number symmetry. As a consequence, the dimension 6 operator effects generically dominate over the effects from the lepton number violating dimension 5 operator.

This can also have interesting consequences for the thermal leptogenesis mechanism, and the relation between non-unitarity and leptogenesis has briefly been discussed [6]: On the one hand, the flavoured decay asymmetries for leptogenesis can be strongly enhanced, and on the other hand additional flavour-equilibrating interactions in the thermal bath can become important. Both effects are due to the dimension 6 operator which induces non-unitarity.

E. Non-unitarity PMNS matrix (Bound) — *M. Blennow*

The current non-oscillation bounds on non-unitarity *(see text by Stefan Antusch)* are derived from the measurements of W and Z decay widths, rare lepton decays such as $\mu \to e\gamma$, and universality tests of weak interactions (see [5, 7]). The bound put on the $\varepsilon_{\mu\tau}$ parameter, which is the most relevant for the MINSIS experiment, is $|\varepsilon_{\mu\tau}| < 5 \cdot 10^{-3}$ at 90 % CL. However, if it is assumed that the non-unitarity is due to mixing with some heavy states, then it is required that ε is a negative semi-definite matrix and the relation $|\varepsilon_{\mu\tau}|^2 < |\varepsilon_{\mu\mu}\varepsilon_{\tau\tau}|$ then imposes the stronger bound of $|\varepsilon_{\mu\tau}| < 1.1 \cdot 10^{-3}$.

To leading order in $\varepsilon_{\mu\tau}$ and L, the oscillation probability at the MINSIS near detector is given by

$$P_{\mu\tau} \simeq |2\varepsilon_{\mu\tau} - iH_{\mu\tau}L|^2 = 4|\varepsilon_{\mu\tau}|^2 + |H_{\mu\tau}L|^2 + 4\ \mathrm{Im}(\varepsilon^*_{\mu\tau}H_{\mu\tau})L, \tag{1}$$

where $H_{\mu\tau} \simeq \Delta m^2_{31}\sin(2\theta_{23})/(4E)$. If we just regard the non-unitiarity term, then MINSIS sensitivity to $|\varepsilon_{\mu\tau}|$ would be $0.5\sqrt{P_{\mu\tau}\ \text{sensitivity}}$. This would mean that the bound could be strengthened by an order of magnitude if a $P_{\mu\tau}$ sensitivity of 10^{-7} could be achieved. Although the standard oscillation term is most likely just beyond the reach of the MINSIS sensitivity, the interference term (see, *e.g.*, [8]) could be sizable if $\varepsilon_{\mu\tau}$ is large, see Fig. 1. This effect would in principle allow for the detection of CP-violation in the non-standard sector if enough precision could be obtained. It should also be noted that this effect is not unique to non-unitarity, but would also be present in more general scenarios of non-standard neutrino interactions.

F. Non-standard neutrino Interactions (Theory) — *E. Fernández-Martínez*

Neutrino non-standard interactions (NSI) are a very widespread and convenient way of parametrizing the effects of new physics in neutrino oscillations experiments. NSI can affect the neutrino production and propagation processes, as well as the neutrino propagation through matter. For the MINSIS experiment the relevant NSI are those contributing to neutrino production and detection via hadronic interactions, these NSI can be described by effective four-fermion operators of the form:

$$\mathcal{L}^{\mathrm{NSI}} = -2\sqrt{2}G_F\varepsilon^{ud}_{\alpha\beta}[\bar{u}\gamma^\mu Pd][\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta] + \mathrm{h.c.}. \tag{2}$$

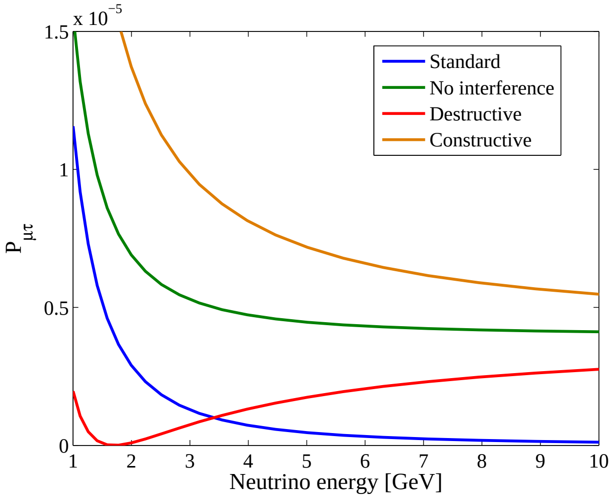

FIG. 1: Oscillation probabilities for $|\varepsilon_{\mu\tau}| = 10^{-3}$ at $L = 1$ km depending on whether interference is constructive, destructive, or absent. The standard oscillation probability is shown for comparison.

Notice that different chirallity structures other than the example of Eq. (2) can be considered. While vector or axial couplings have the same chirallity structure than the Standard Model (SM) contribution and can therefore interfere with them, for the neutrino production via pion decay NSI involving scalar or pseudoscalar couplings are enhanced with respect to the SM model contribution since a chirallity flip of the charged lepton is not required for spin conservation.

The model independent bound on the NSI relevant for MINSIS that can be set by the phenomenological implications of the operator of Eq. (2) is $\varepsilon^{ud}_{\mu\tau} < 1.8 \cdot 10^{-2}$ at the 90% CL [9]. However, saturating the bound in particular extensions of the SM is rather challenging, since NSI are expected to be produced together with charged fermion non-standard interactions due to SU(2) gauge invariance [7, 10]. The implications of the gauge invariant counterpart of the operators relevant for MINSIS involving charged fermions are discussed in the talk by T. Ota and [11], here we will instead explore the possibility of extensions of the SM that induce neutrino NSI but do not generate the related charged fermion interactions.

At $d = 6$ this can be realized in two ways. The first realization involves the addition of fermion singlets (right-handed neutrinos) to the SM particle content. The light active neutrinos mix with the extra singlets inducing a non-unitary mixing matrix that modifies the neutrino couplings to the W and Z and that generates NSI upon integrating out the gauge bosons. However, as was described in the talk by M. Blennow, the bounds on non-unitarity are stronger, in particular, for the MINSIS experiment $\varepsilon_{\mu\tau} < 1.1 \cdot 10^{-3}$ [5, 7]. The second possibility involves the addition of singly charged scalar SU(2) singlets that couple to a pair of lepton doublets. Upon integrating out the singlets the following operator is induced:

$$(\overline{L^c}_\alpha i\sigma_2 L_\beta)(\bar{L}_\gamma i\sigma_2 L^c_\delta) \ . \tag{3}$$

This operator can contribute to matter NSI of ν_μ and ν_τ with electrons, but these NSI are not relevant for the MINSIS experiment, as matter effects are too weak for the short baseline considered.

At the level of $d = 8$ operators the only extensions of the SM inducing NSI but avoiding their charged fermion counterparts involve either one of the two realizations at $d = 6$ (and the consequent strong bounds), or rather unnatural fine-tunings between different mediators to cancel the undesired charged fermion contribution, both at the tree and the loop level [7, 10, 12].

The most promising NSI realization avoiding the bounds set by gauge invariance thus seems non-unitarity. However, a sensitivity to the oscillation probability of 10^{-7} at the 90% CL would be necessary to improve the present bounds.

G. Non-standard neutrino Interactions (Bound) — *T. Ota*

After integrating out the heavy degrees of freedom, a model would be described by the Standard Model (SM) interactions and non-renormalizable interactions of the SM fields, which respect the SM gauge symmetries. Non-Standard neutrino Interactions (NSI) may emerge as such effective interactions at the electroweak scale. On theoretical aspects of NSIs, see the talk presented by E. Fernandez-Martinez. In general, NSIs are constrained by the corresponding charged Lepton Flavour Violating (LFV) processes through the SM gauge symmetries. An important exception is the Minimal Unitarity Violation (MUV) in which NSIs are induced with the (spontaneous) violation of the SM gauge symmetries, and therefore, the NSIs are not directly constrained by the charged LFV (for a theoretical motivation of MUV and constraints, see the talks given by S. Antusch and M. Blennow). In this talk, we investigated the bounds to the coefficients of the four-Fermi NSIs which were relevant to MINSIS from the various LFV rare tau decay processes. We found that the coefficients were constrained at $\mathcal{O}(10^{-4}) \times G_F$ where G_F was Fermi constant. With this value, the ratio of the signal and the standard model process is naively expected to be $\mathcal{O}(10^{-7}\text{-}10^{-8})$ which is far below the scope of the expected MINSIS sensitivity. However, a scalar-mediated NSI which is described with the effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \varepsilon [\bar{\nu}_\tau (1+\gamma^5)\mu][\bar{d}\gamma^5 u] \tag{4}$$

can make an enhanced effect in a pion decay (see e.g., Ref. [13]). The decay rate calculated from the Lagrangian Eq. (4) is

$$\Gamma(\pi^+ \to \mu^+ \nu_\tau) = |\varepsilon \omega_\mu|^2 \cdot \Gamma(\pi^+ \to \mu^+ \nu_\mu), \tag{5}$$

where ω_μ is the chiral enhancement factor which is about a factor of ten. With this enhancement factor, the ratio can be expected to become $7.9 \cdot 10^{-5}$ which is expected to be achieved in MINSIS experiment [11]. The bounds are summarized in Tab. II.

Beam (channel)	$2L2Q$	$4L$	NU
$\pi(\mu \to \tau)$	$7.9 \cdot 10^{-5}$	n/a	$4.4 \cdot 10^{-6}$
$\beta(e \to \tau)$	$< 10^{-6}$	n/a	$1.0 \cdot 10^{-5}$
$\mu(\mu \to \tau)$	$< 10^{-6}$	$1.0 \cdot 10^{-3}$ $(3.2 \cdot 10^{-5})$	$4.4 \cdot 10^{-6}$
$\mu(e \to \tau)$	$< 10^{-6}$	$1.0 \cdot 10^{-3}$ $(3.2 \cdot 10^{-5})$	$1.0 \cdot 10^{-5}$

TABLE II: Bounds at the 90 % CL on the probability of tau appearance at a near detector in a neutrino beam from π decay, β decay or μ decays for the three types of new physics, NSI with two leptons and two quarks ($2L2Q$), NSI with four lepton doublets ($4L$), and the non-standard effect induced from non-unitarity of the PMNS matirx (NU). Two different values, the bound to the effective four-Fermi interactions and that under the assumption of the singlet scalar mediation (in parenthesis), are shown in the column of leptonic NSI. Table taken from Ref. [11].

H. Minimal Flavour violation at MINSIS — *R. Alonso*

The aim of our work was to confront the parameters in our simplest minimal feour violation (MFV) model with the bounds on non-unitarity and determine if the sensitivity expected for MINSIS would give us further information.

Our model is the simplest MFV type I seesaw[1]. Simplest, as there is only one fermionic singlet N and the Dirac-Mass connected $\overline{N}'$ added to the Standard Model that possess a global U(1) symmetry. Discussion of such models was carried by Wyler, Wolfenstein, Mohapatra, Valle . . . It also occurs that the number of parameters in our model almost equals the low energy range ones, so we are able to express the formers in terms of mixing angles and phases.

The result of the comparison was that a **sensitivity of** 10^{-7} **would improve the restrictions** coming from current non-unitarity data. It would even **improve the results of experiments such as MEG** (with it's huge expected sensitivity) **for a certain region in our parameter space**. That is so because there our model predicts a cancellation of the ν_e coupling in the yukawas and therefore the interesting place to look is a ν_τ-ν_μ transition experiment such as MINSIS.

Here we plot the allowed values for a quotient of parameters in our model as a function of the Majorana phase α (Fig. 2). We can see how MINSIS improves the MEG bound for an interval in α when $\theta_{13} = 0.19$.

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[1] Minimal Flavour Seesaw Models [14].

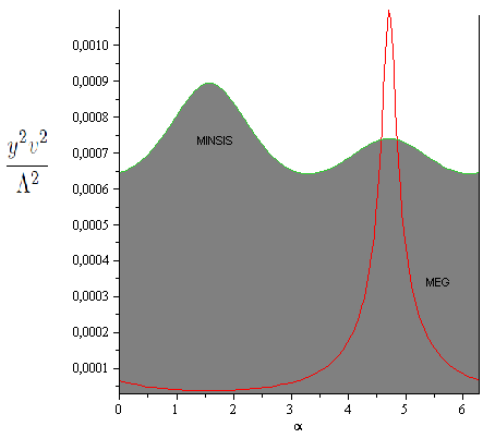

FIG. 2: Allowed parameter region in the scenario of Minimal Flavour Violation.

I. NSI bounds from ICECUBE — *O. Mena*

We focus here on nonstandard interactions which may affect the neutrino propagation in matter. Constraining the new parameters of the effective low energy theory which parametrizes the new physics responsible for the nonstandard neutrino interactions might need (a) very intense and (b) high energy ($\mathcal{O}$ 10 GeV) neutrino beams. Far future neutrino facilities, as neutrino factories and/or superbeams provide an ideal setup to test neutrino-matter nonstandard interactions, see for instance Ref. [15] and references therein.

Cosmic ray interactions in the atmosphere give a natural beam of neutrinos, with a steeply falling spectrum which covers several orders of magnitude in energy (from hundreds of MeV to hundreds of TeV), with a peak around 1 GeV. Atmospheric neutrinos in the GeV range have been used by the Super-Kamiokande detector (SK) to provide evidence for neutrino oscillations. Straight up atmospheric neutrinos traverse the Earth's core and are extremely sensitive to neutrino matter interactions. Consequently, atmospheric neutrinos at GeV energies may also constitute an ideal tool to test neutrino nonstandard interactions [16–19], see Ref. [20] for an analysis using the SK phase I data set.

The Icecube Deep Core Subarray (ICDC) [21, 22], a low energy extension of the IceCube detector, will accumulate an enormous number of muon events from atmospheric muon neutrino charged current interactions, down to muon energies as low as 5 GeV. These muon events are usually considered as a background astrophysical neutrino searches. In this talk we will show that these " muon neutrino background events" provide a great opportunity for measuring neutrino-matter nonstandard interactions. We concentrate on $\epsilon_{e\tau}$, $\epsilon_{\mu\tau}$ and $\epsilon_{\tau\tau}$, setting the remaining nonstandard interaction parameters to zero. Furthermore, we will assume that $\epsilon_{e\tau}$ and $\epsilon_{\mu\tau}$ are real. Our results are similar to those obtained in Ref. [20] using the SK phase I data set [23]. However, further improvements in the sensitivity to the neutrino-matter NSI parameters can be done if the ν_τ identification in the Deep Core detector becomes feasible.

J. Probing the Seesaw Scale — from nano to mega electron-volts — *A. de Gouvêa*

Sterile neutrinos are among the simplest and most benign extensions of the standard model of particle physics. They are gauge singlet fermions and can only couple to the standard model at a renormalizable level through a Yukawa interaction ($\mathcal{L}_{\rm int} = -y(LH)N$, where L are the lepton doublets, H is the Higgs scalar doublet and N are the gauge singlet fermion fields, aka right-handed neutrinos, aka sterile neutrinos. y are the Yukawa couplings). The most general Lagrangian consistent with the standard model augmented by n gauge singlet fermions N contains the Yukawa couplings above and Majorana masses for the N fields: $\mathcal{L}_{\rm mass} = -(M/2)NN$. After electroweak symmetry breaking, this Lagrangian describes $3+n$ electrically neutral, generically massive fermions and can fit all experimental data if one judiciously chooses the values of y and M (and n).

For any value of M, there is an associated value of y that allows one to fit all the neutrino oscillation data, at least superficially. For example, in the case $M \equiv 0$, the neutrinos are massive Dirac fermions and their mass matrix is given by $m_D = yv$, where v is the Higgs boson vacuum expectation value. In this case, the data require $y \sim 10^{-11}$ and the Lagrangian has an exact global, nonanomalous $U(1)_{B-L}$ symmetry. This symmetry is broken when both y and M are nonvanishing, a fact that teaches us that any value of M is technically natural (as defined by 'tHooft).

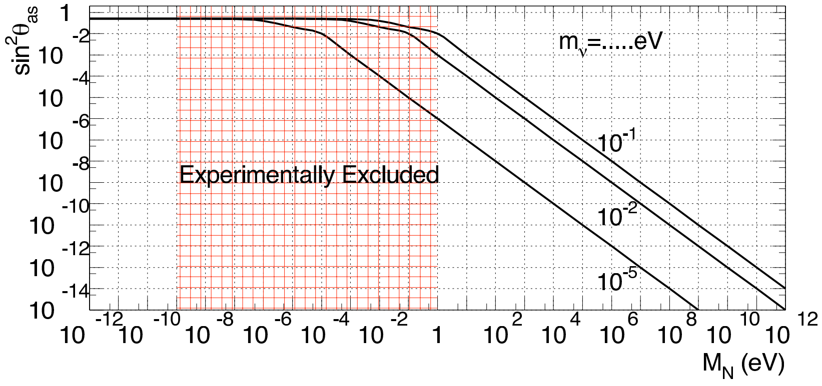

FIG. 3: The mixing angle θ_{as} between active and sterile neutrinos as a function of the right-handed neutrino mass M_N for different values of the mostly active neutrino masses m_ν [24].

For non-zero values of M, this so-called "Seesaw Lagrangian" predicts that the neutrinos are Majorana fermions, and that there exists more neutrinos than the three active ones that have already been accounted for. If $M \lesssim 1$ MeV, these extra neutrinos are light sterile neutrinos that can only be directly probed by neutrino-related experiments, including searches for neutrino oscillations at short baselines (most relevant for MINSIS), searches for kinematical effects of neutrino masses, especially studies of the end-point of the spectrum of beta-rays, and searches for neutrinoless double-beta decay. In the case of neutrinoless double-beta decay, the prediction is that, in spite of the fact that there are more neutrinos and that all are Majorana fermions, the expected rate vanishes with very good precision as long as all M values are smaller than about an MeV.

In the case of searches for neutrino oscillations, one can relate values of M and the "active" neutrino oscillation parameters to the sterile–active mixing angles to which the different oscillation probabilities are sensitive. This means that once new, heavier neutrino mass eigenstates are discovered, along with their flavor composition, it will be possible, in principle, to test whether the seesaw Lagrangian describes the new degrees of freedom and to measure the Lagrangian parameters. Conversely, if no new neutrino mass eigenstates are discovered, one might be able to rule a range of potential values of the seesaw energy scale (i.e., values of M will be ruled out). A summary of what one can already say about M, and what the expected values of the active–sterile mixing angles are is depicted Fig. 3. Searches for $\nu_\mu \to \nu_\tau$ at short baselines are sensitive to $\theta^2_{\mu s}\theta^2_{\tau s}$. The figure 3 hints that an experiment sensitive to $P_{\mu\tau} \gtrsim 10^{-6}$ should be sensitive to $M \lesssim 100$ eV. The exact capability of MINSIS and other short-baseline neutrino oscillation experiments to detect seesaw neutrinos is still to be ascertained.

K. Sterile neutrino mixings and near detectors — *O. Yasuda*

Sensitivity of a neutrino factory, with a near detector or with far detectors, to sterile neutrino mixings was reviewed, based on the two works [25, 26]. In the case of a neutrino factory with a near detector at the oscillation maximum $\Delta m^2_{41}L/4E \simeq \pi/2$ (with far detectors for $\Delta m^2_{41} \gtrsim 0.1\text{eV}^2$), we can improve the sensitivity to $4|U_{e4}U_{\mu 4}|^2$, $4|U_{e4}U_{\tau 4}|^2$ and $4|U_{\mu 4}U_{\tau 4}|^2$ by 2, 4, 1 orders (by 1.5, 2.5, -1 orders) of magnitude compared to the present bound, respectively (See Figs. 2, 4 and 5 in Ref. [27]). Near τ detectors are useful not only to improve sensitivity to sterile neutrino mixings by themselves, but also to reduce the systematic errors of the far τ detectors.

L. Sterile neutrinos in the MINSIS experiment — *T. Li and J. López-Pavón*

We have performed a preliminary analysis of the sensitivity of the MINSIS experiment to sterile neutrinos, using the 3+1 model as an initial study. We have assumed a NOνA beam (peaking at ~ 2 GeV) and use a flux and detector mass of 4 kton; the total number of charged-current ν_μ events at 1 km is then $\sim 10^9$. The number of events above the τ threshold is $\sim 10^8$.

At a baseline of 1 km, the ν_μ disappearance and ν_τ appearance probabilities can be approximated as follows:

$$\begin{aligned}
P_{\nu_\mu\to\nu_\mu} &= 1 - 4c^2_{14}s^2_{24}(1 - c^2_{14}s^2_{24})\sin^2\Delta_s = 1 - \sin^2 2\theta^{\mu\mu}_s \sin^2\Delta_s \\
P_{\nu_\mu\to\nu_\tau} &= 4c^4_{14}s^2_{24}c^2_{24}s^2_{34}\sin^2\Delta_s = \sin^2 2\theta^{\mu\tau}_s \sin^2\Delta_s
\end{aligned}$$

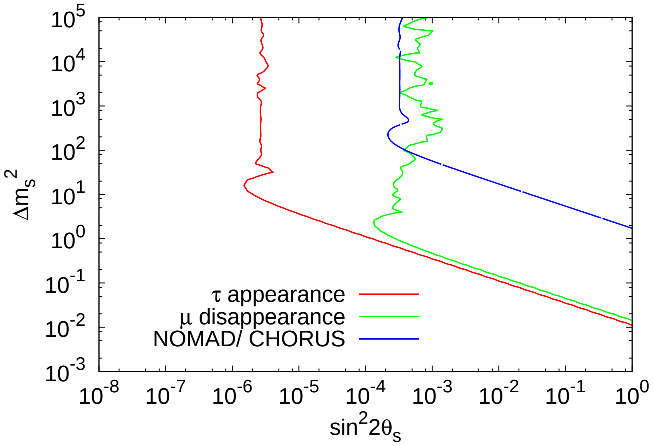

FIG. 4: Comparison between the sensitivity reach with the discovery channel and that with the disappearance channel.

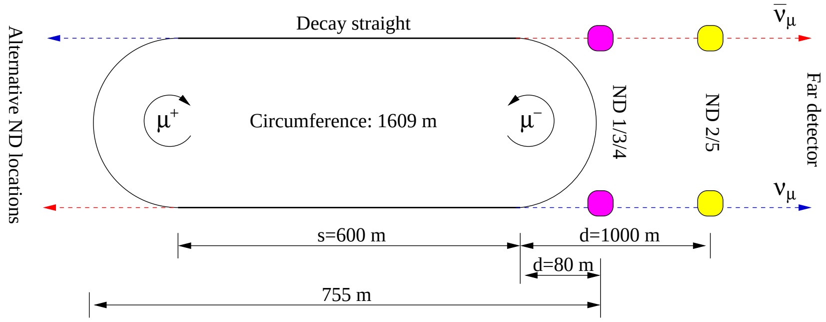

FIG. 5: Geometry of the muon storage ring and possible near detector (ND) locations (not to scale). The baseline L is the distance between production point and near detector, *i.e.*, $d \leq L \leq d + s$. Figure taken from Ref. [28].

where $\mathrm{c}_{ij} = \cos\theta_{ij}$, $\mathrm{s}_{ij} = \sin\theta_{ij}$ and $\Delta_s = \Delta m_s^2 L/4E$.

In the figure below (Fig. 4) we demonstrate how the ν_τ *appearance* channel (red line) has a more powerful reach than the ν_μ *disappearance* channel (green line), qualitatively comparing the sensitivities of the two channels to $\sin^2 2\theta$ and Δm^2 (where $\sin^2 2\theta = \sin^2 2\theta_s^{\mu\mu}$ or $\sin^2 2\theta_s^{\mu\tau}$). We use hypothetically 'perfect' ν_μ detection (100% efficiency, zero background, negligible systematic errors) corresponding to $\sim 10^9$ charged-current ν_μ events, comparing it with that of realistic ν_τ detection (10% efficiency, 2 background events, 10% systematic errors) corresponding to $\sim 10^7$ events above the τ threshold. Also shown are the current bounds on $\sin^2 2\theta^{\mu\tau}$ and Δm^2, as obtained by the NOMAD and CHORUS experiments (blue line).

The MINSIS combination of high statistics and good background rejection produces an impressive physics reach, improving on current bounds by a factor of ~ 100 for both $\sin^2 2\theta^{\mu\tau}$ and Δm^2 using the flux described above. We find that using a beam with a peak energy above ~ 12 GeV would produce the best results, together with maximizing the detector efficiency and background rejection. Systematic errors and energy resolution have negligible effects on the experimental sensitivity.

M. New physics searches with near detectors at a neutrino factory — *W. Winter*

Near detectors at a neutrino factory are required for standard oscillation physics to measure the ν_μ and $\bar{\nu}_\mu$ cross sections, to monitor the beam (such as by elastic scattering or inverse muon decay interactions), and to control the backgrounds (such as the ones from charm production). If the μ^+ and μ^- circulate in different directions (*cf.*, Fig. 5), two near detectors are required. In this case, flavor identification is sufficient to measure the inclusive ν_μ and $\bar{\nu}_\mu$ cross sections. Charge identification is needed for the background measurements. As it is demonstrated in Ref. [28], the size, location, and geometry of the near detectors hardly matter for standard oscillation physics even in extreme cases of possible near detectors. Because of the high statistics in all energy bins of the near detectors, the physics potential

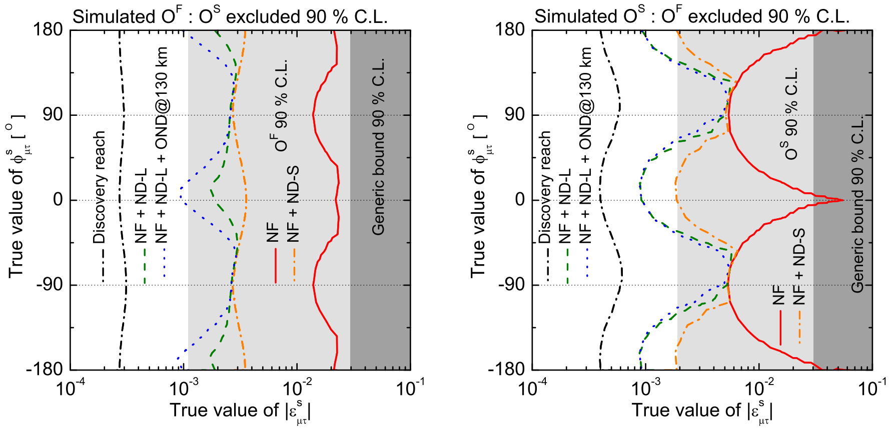

FIG. 6: Regions in the ($|\varepsilon^s_{\mu\tau}|$-$\phi^s_{\mu\tau}$)-plane where the simulated $\epsilon^s_{\mu\tau}$ induced by one type of operator can be uniquely established, *i.e.*, the other type of operator is excluded at the 90% C.L. (regions on the right-hand side of the curves). Left panel: the simulated $\varepsilon^s_{\mu\tau}$ is induced by $\mathcal{O}^{\mathcal{F}}$ (non-unitarity) and fitted with $\mathcal{O}^{\mathcal{S}}$ (NSI from $d = 6$ operator). Right panel: the simulated $\varepsilon^s_{\mu\tau}$ is induced by $\mathcal{O}^{\mathcal{S}}$ and fitted with $\mathcal{O}^{\mathcal{F}}$. The different curves corresponds to the IDS-NF baseline setup (NF), an additional (small) silicon vertex-sized near detector (ND-S), an additional OPERA-like near detector at 1 km (ND-L), and an additional OPERA-like near detector at 130 km (OND@130 km). In both panel, the discovery reach is also displayed. Figure taken from Ref. [30].

is generally limited by the statistics in the far detector(s). Therefore, some characteristics of the near detectors, such as the location, may be driven by new physics searches. However, note that rare interactions used for flux monitoring, such as inverse muon decays or elastic scattering, may require large enough detectors. A possible near detector design for a neutrino factory is, for instance, discussed in Ref. [29].

Comparing potential new physics searches at a neutrino factory and the MINSIS superbeam based detector, the two beams have different characteristics. At the neutrino factory, neutrinos are produced from muon decays, implying that both ν_μ ($\bar{\nu}_\mu$) and $\bar{\nu}_e$ (ν_e) are in the beam for μ^- (μ^+) stored, 50% each. The origin of the neutrinos is typically determined by charge identification of the secondary particle in the detector. For tau neutrino detection, the origin can be $\bar{\nu}_e \to \bar{\nu}_\tau$ ($\nu_e \to \nu_\tau$) or $\nu_\mu \to \nu_\tau$ ($\bar{\nu}_\mu \to \bar{\nu}_\tau$) transitions. At the superbeam, the neutrinos are mainly produced through pion decays. Only ν_μ ($\bar{\nu}_\mu$) are in the beam for π^+ (π^-) decays, with some contamination from other flavors and polarities. For tau neutrino detection, only $\nu_\mu \to \nu_\tau$ ($\bar{\nu}_\mu \to \bar{\nu}_\tau$) transitions are accessible with reasonable sensitivities. However, the absence of a significant amount of $\bar{\nu}_e$ (ν_e) in the beam may, depending on the detector technology, also be an advantage with respect to the suppression of $\bar{\nu}_e$ (ν_e) charm induced backgrounds. In summary, the new physics searches at a neutrino factory and superbeam may be very complementary if the new physics effect

- is only present in either muon decays or pion decays (such as leptonic versus hadronic source NSI)
- requires either low backgrounds (superbeam) or the $\bar{\nu}_e \to \bar{\nu}_\tau$ ($\nu_e \to \nu_\tau$) channel (neutrino factory).

Let us illustrate this complementarity with one example from Ref. [30]. If new physics comes from heavy mediators, which are integrated out above the electroweak symmetry breaking scale, the lowest order contributions (apart from neutrino mass) to the Standard Model come from effective $d = 6$ operators. Heavy neutral fermions lead to an addition to the kinetic energy of the neutrinos, also known as minimal flavor violation, which implies a non-unitary (NU) mixing matrix after the re-diagonalizing and re-normalization of the kinetic terms of the neutrinos. Heavy bosons, such as singly charged scalar SU(2) singlets, on the other hand, lead to non-standard interactions (NSI) at tree level. Therefore, distinguishing between NU and NSI may be interpreted as distinguishing between fermions and bosons as heavy mediators, at least to leading order at $d = 6$ and tree level. We therefore refer to these effects at $d = 6$ as $\mathcal{O}^{\mathcal{F}}$ and $\mathcal{O}^{\mathcal{S}}$, respectively. At a neutrino factory, the phenomenology of $\mathcal{O}^{\mathcal{F}}$ and $\mathcal{O}^{\mathcal{S}}$ is, however, very similar. Both effects can be parametrized in form of NSI. For $\mathcal{O}^{\mathcal{F}}$, particular correlations among source, propagation, and detection effects are present [7, 8]. For leptonic $\mathcal{O}^{\mathcal{S}}$, similar correlations are obtained for operators without charged lepton flavor violation [10]. Consider, for instance,

$$\varepsilon^m_{\mu\tau} = -(\varepsilon^s_{\mu\tau})^* \qquad (\text{NSI}) , \tag{6}$$
$$\varepsilon^m_{\mu\tau} = -\varepsilon^s_{\mu\tau} \qquad (\text{NU}) . \tag{7}$$

In this case, the two effects can be mostly distinguished by the absence of detection effects in the case of $\mathcal{O}^{\mathcal{S}}$. Alternatively, one could use a superbeam-based source, where Eq. (6) does not hold because of the neutrino production by pion decays. We illustrate the identification of the class of effect in Fig. 6. Obviously, the effects can be hardly distinguished with a neutrino factory alone beyond the current bounds. However, the discovery reach for the non-standard effects clearly exceeds the current bounds. The MINSIS detector could disentangle the two effects in the region between the bounds and the discovery reach if it had a sensitivity significantly exceeding 10^{-3} in $|\epsilon^s_{\mu\tau}|$.

N. Very short baseline electron neutrino disappearance — *M. Laveder*

In Ref.[31] possible indications of Very-Short-BaseLine (VSBL) electron neutrino disappearance into sterile neutrinos in MiniBooNE neutrino data and Gallium radioactive source experiments have been considered. The compatibility of such a disappearance with reactor and MiniBooNE antineutrino data has been discussed. A tension between neutrino and antineutrino data has been found, which could be due to: 1) statistical fluctuations; 2) underestimate of systematic uncertainties; 3) exclusion of our hypothesis of VSBL ν_e disappearance; 4) a violation of CPT symmetry. Considering the first possibility, the results of a combined fit of all data have been presented, which indicate that $P_{ee} < 1$ with 97.04% CL. The possibility of CPT violation has been considered, which leads to the best-fit value $A^{CPT,bf}_{ee} = -0.17 \pm 0.05$ for the asymmetry of the ν_e and $\bar{\nu_e}$ survival probabilities and $A^{CPT}_{ee} < 0$ at 99.7% CL. This result translates in an oscillation amplitude $\sin^2 2\theta_{es} = 0.34 \pm 0.10$ for the active-sterile electron neutrino oscillation to be searched for in coming SBL experiments like the MINSIS proposal. In Ref. [32] short-baseline and very-short-baseline ν_e disappearance at a neutrino factory have been studied. Geometric effects, such as from averaging over the decay straights, and the uncertainties of the cross sections were taken into account. An approach similar to reactor experiments with two detectors were followed: two sets of near detectors at different distances were used to cancel systematics. It was demonstrated that such a setup is very robust with respect to systematics, and can have excellent sensitivities to the effective mixing angle and squared-mass splitting. In addition, the possibility of CPT violation can be tested (depending on the parameters) up to a 0.1% level.

O. Tau detection using the kinematic and impact parameter techniques — *F. J. P. Soler*

Tau detection techniques

Currently there are three possible techniques for detecting taus:

- Direct observation of the decay kink of the tau with the use of emulsion technology, like in OPERA [3] or CHORUS [2];
- The identification of taus through the kinematic analysis of the tau decay, like that used by NOMAD [33];
- The reconstruction of taus from an impact parameter signature with a dedicated silicon vertex detector, as in the NAUSICAA proposal [34], prototyped by NOMAD-STAR [35].

NOMAD

NOMAD was a $\nu_\mu \to \nu_\tau$ neutrino oscillation experiment at the CERN SPS between 1994-1998 [33]. The main aim was to search for the appearance of ν_τ in a predominantly ν_μ beam. A total of 1.35×10^6 ν_μ charged current (CC) events were recorded in NOMAD for 5×10^{19} protons on target (pot). NOMAD used the kinematic technique, where the visible products from the tau decay are measured, and kinematically separated from background by exploiting that taus decay emitting one or two neutrinos (which are not observed) thereby producing events with larger missing transverse momentum (p_t) than normal ν_μ CC events. NOMAD was sensitive to 82.4% of the branching fraction of the taus. The analysis exploited a set of likelihood functions that parametrized the missing p_t and isolation of the tau candidates. The final sensitivity achieved was $P(\nu_\mu \to \nu_\tau) < 1.63 \times 10^{-4}$ at 90% confidence level. In the NOMAD analysis, a number of kinematic regions of the tau decay phase space were exploited to optimize the sensitivity. However, about half the sensitivity came from low background bins, which could in principle be exploited further, in a higher statistics experiment. Therefore, there is room for improvement of the kinematic technique in a higher statistics experiment, like the MINSIS experiment being proposed at Fermilab. A liquid argon experiment could, in principle, carry out a similar analysis and further exploit this analysis technique at MINSIS. One would need to take into account the intrinsic tau contamination of the neutrino beam from D_s decay, which was estimated to be 3.5×10^{-6} in the CHORUS-NOMAD beam (450 GeV), going down to 9.6×10^{-8} at the Main Injector at Fermilab (120 GeV) [36, 37].

Impact parameter detection of taus

The impact parameter technique for detection of taus was first proposed by Gomez Cadenas et al. in a proposal called NAUSICAA [34]. A silicon vertex detector with a B_4C target was proposed as an ideal medium to identify taus. Standard ν_μ CC interactions have an impact parameter resolution of 28 μm, while tau decays have an impact parameter resolution of 62 μm. By performing a cut on the impact parameter significance (σ_{IP}/IP) one can separate one prong decays of the tau from the background. For three prong decays of the tau, a double vertex signature is used to separate signal from background. The total net efficiency of the tau signal in NAUSICAA was found to be 12%. With this efficiency, one could have a sensitivity of $P_{\mu\tau} < 3 \times 10^{-6}$ at 90% C.L. on the $\mu - \tau$ conversion probability.

Another idea proposed in 1996 was to use a hybrid detector emulsion- silicon tracking to improve the tau detection efficiency [38]. A Letter of Intent (called TOSCA) was submitted to the CERN SPSC in 1997 [39] with a detector based around this idea. Tau detection efficiencies of 42%, 10.6% and 27% were determined for the muon, electron and one charged hadron decays of the tau, yielding a net probability of $P_{\mu\tau} < 0.75 \times 10^{-5}$ for the CERN SPS beam at 350 GeV. A program of R&D, called NOMAD-STAR, including a 50 kg prototype silicon-B_4C target, operated between 1997-1998 in the NOMAD beam [35]. It was able to demonstrate an impact parameter resolution of 33 μm and a double vertex resolution of 18 μm, which were the expected parameters to achieve the $\nu_\mu - \nu_\tau$ sensitivity of NAUSICAA and TOSCA. About 45 charm events were detected with NOMAD-STAR over the duration of the run [40].

Tau detection at a near detector of a neutrino factory

A near detector at a neutrino factory needs to measure the charm cross-section to validate the size of the charm background in the far detector, since this is the main background to the wrong-sign muon signature. The charm cross-section and branching fractions are poorly known, especially close to threshold, so this detector would need to be able to detect charm particles. Since tau events have a similar signature to charm events, any detector that can measure charm should be able to measure taus as well. A semiconductor vertex detector is the only viable option in a high intensity environment ($\sim 10^9$ ν_μ CC events per year in a detector of mass 1 ton), for charm detection, since a liquid argon detector would not be fast enough to cope with the rate and emulsion would perish in this environment.

Assuming 12% efficiency from the NAUSICAA proposal, and assuming that charm production is about 4% of the ν_μ CC rate between 10 and 30 GeV (CHORUS measured $6.4 \pm 1.0\%$ at 27 GeV) [41], would imply a signal of 1.2×10^8 tau events (with $P_{\mu\tau} = 3D100\%$ conversion rate) and 4×10^7 charm events. Charm events from anti-neutrinos (for example $\overline{\nu}_e$) mimic the potential signal. The identification of the positron can reduce the background, but electron and positron identification normally has a lower efficiency than muon identification. It is very important to have a light detector (ie, a scintillating fibre tracker) behind the vertex detector inside a magnetic field to identify the positron with high efficiency (in the best scenarios $\sim$ 80% would be the maximum achievable). A further way to separate the charm background from signal is to use the kinematic techniques of NOMAD. Assuming the NOMAD net efficiency yields a $P_{\mu\tau} < 2 \times 10^{-6}$, which is not better than what the MINSIS detector could achieve at Fermilab.

Summary

So, in summary, a MINSIS detector based on the emulsion cloud chamber technique (like OPERA) could potentially achieve a $P_{\mu\tau}$ sensitivity of 10^{-6}. However, there is also the potential for a liquid argon detector to perform a tau search using the kinematic technique as in NOMAD. While it is likely that the sensitivity might not be as low as the OPERA like detector, it could serve as very useful R&D for liquid argon, and provide a useful physics outcome.

A TOSCA like detector, with silicon and emulsion, could also be done for MINSIS. However, adding silicon complicates things and the sensitivity gain is not obvious any more, since scanning technology has advanced so much that one could potentially scan all the emulsion obviating the need for the silicon detector.

A silicon target only (as in NAUSICAA) has less efficiency but does not rely on emulsion. The advantage of this approach would be that the analysis could be performed faster than with emulsion and, in principle could achieve a limit of about 3×10^{-6}. At a neutrino factory near detector one can also measure charm and taus using a silicon tracker. Neither emulsion nor liquid argon would be suitable at a neutrino factory near detector since the event rate is too high. However, the background at a neutrino factory is higher than at a conventional neutrino beam from pion decay, since there is a charm background from anti-neutrinos. This background could, in principle, be reduced with a combination of the impact parameter and kinematic approach for tau detection, but the sensitivity of 2×10^{-6} would not be any better than what could be achieved at MINSIS.

II. WORKSHOP SUMMARY

The MINSIS idea aims at a measurement of τ appearance events in a near position close to the NuMI beam target with a minimum senstivity of 10^{-6}. The talks Secs. I A, I B, and I O discussed the challenges and requirements for achieving such sensitivity with a "standard" emulsion detector as well as with possible variations using a detector with a pure silicon target or a silicon-emulsion combination.

The theoretical motivation was the core of the discussions in the workshop. On one hand it is clear that the discovery of τ appearance at short distances at rates above 10^6 would be an exciting evidence for non-standard physics. On the other hand resides the challenge of finding theoretically motivated forms of new physics which could give signals at this level.

The first consideration is the requirement on the sensitivity. For the MINSIS baseline and energy one obtains for standard $\nu_\mu \to \nu_\tau$ oscillations induced by the "atmospheric" mass difference

$$P^{\mathrm{atm}}(\nu_\mu \to \nu_\tau) = \sin^2 2\theta_{23} \sin^2(\Delta m^2_{31} L/4E) \approx 10^{-7} \left(\frac{L}{1\ \mathrm{km}} \cdot \frac{10\ \mathrm{GeV}}{E} \right)^2 .$$

Hence, the atmospheric oscillations represent an irreducible background, at the level of 10^{-7}, for the typical energy of the NUMI beam for τ appearance of 10 GeV or higher. This sets the natural limit for the sensitivity.

We discussed two possible forms of new physics which generically can induce τ appearance at short distance:

- **Sterile neutrinos with masses in the range $m_s \gtrsim 1$ eV**. Such states are a theoretical possibility. The open question is the theoretical motivations for sterile neutrinos in that mass range. From the purely phenomenological perspective current bounds in the relevant parameter range are of order 10^{-4} and hence, MINSIS could explore a new parameter space of about 2 to 3 orders of magnitude.

- **Non-standard neutrino interactions (NSI) and Non Unitarity (NU) in the leptonic mixing matrix**. Theoretically these two forms of new physics can be of very different origin but phenomenologically they are closely related to each other as stressed in several of the talks in this workshop. A discovery of NSI or NU would be an important step towards our understanding of the mechanism of neutrino mass generation. This would be exciting complementary information to data from oscillations, charged lepton flavour violation, neutrinoless double beta decay, and the LHC.

  The challenge is the level at which they can be expected. Theoretically one does not expect a signal above the 10^{-6} level as long as the low energy operators respect $SU(2)$. In brief, once an effective operator which induces NSI/NU is written down, the same operator (or operators derived from gauge invariance and similar arguments) will induce charged lepton flavour violation, which is severely bounded. Taking into account these bounds one arrives at the conclusion that, under rather generic assumptions, neutrino NSI/NU are not expected to be detectable above the level of $10^{-7} - 10^{-6}$ (and often are even much smaller than this). The caveat to this argument is that we have no proof that it cannot be avoided in specifically constructed models, although an explicit example for such a model is still missing.

In brief, the 10^{-6} sensitivity is the minimum requirement for an unambiguous identification of the new physics signal. To find "well motivated" theoretical frameworks that predict signals at this level while complying with all the existing bounds is possible but challenging. Conversely, if a signal was observed at this level, we would be confronted with the exciting news of an unexpected form of new physics.

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