Summary of the Oscillation Physics Working Group

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Abstract. This is a summary of the Oscillation Physics Working Group (WG1) activity at the NuFact10 Conference.

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1. WG1 STATISTICS

At the conference we had 8 WG1 sessions plus 2 sessions joint with the Neutrino Scattering Physics working group (WG2). There have been 28 WG1 talks plus 8 talks in the WG1/WG2 joint sessions, delivered by 29 speakers in total. Among the talks there have been 15 theory/phenomenology talks and 21 experimental talks. Furthermore, 7 posters have been accepted. In the following we give a brief summary of some topics discussed in the WG1 and WG1/WG2 sessions.

2. MINOS RESULTS

Recent results from the MINOS experiment were presented [1], based on 7.24×10^{20} pot in the neutrino mode and 1.71×10^{20} pot in the anti-neutrino mode. Data on ν_μ disappearance provide clear evidence for oscillations, leading to the best determination of the "atmospheric" mass-squared difference with an accuracy at about 4% at 1σ. While the data on $\bar{\nu}_\mu$ disappearance confirm the presence of oscillations they seem to indicate a slightly different value for the oscillation parameters. As visible in fig. 1 there is some tension between the regions for neutrinos and anti-neutrinos, since there is only marginal overlap of the regions at 90% CL. While this effect is currently not significant, if real, would be very difficult to explain. In the standard neutrino oscillation picture CPT invariance ensures that neutrino and anti-neutrino disappearance probabilities are identical. Beyond the standard picture fundamental or environmental CP violation could explain such a feature. MINOS is currently taking more anti-neutrino data which should help resolve this tension.

Non-standard neutrino interactions (NSI) could in principle induce a different behavior for neutrino and anti-neutrino disappearance. Neutral current (NC) like NSI would induce a non-standard matter effect, whereas charged current (CC) like NSI in neutrino source or detector could induce CP violation due to an NSI/oscillation interference. Such NSI in the $\mu\tau$ sector have been discussed in [2], where it was shown that NC like NSI needed to explain the MINOS effect are excluded by atmospheric neutrino data by one order of magnitude, whereas CC like NSI can in principle explain the effect, see fig. 2. However, it was stressed that it is difficult to imagine the origin of NSI of the required size in a gauge invariant theory.

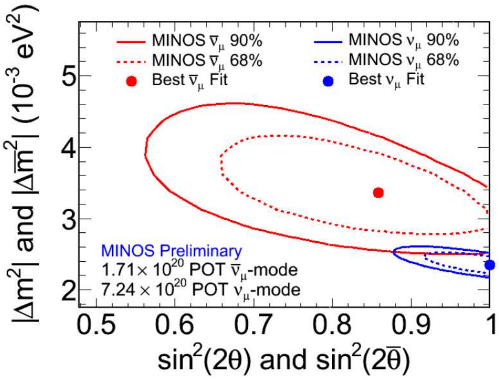

FIGURE 1. MINOS results from ν_μ and $\bar{\nu}_\mu$ disappearance searches [1].

Other explanations have been discussed, including NSI in the $e\tau/\tau\tau$ sector [3], sterile neutrinos at the Δm^2_{31} scale [3, 4], or a long-range leptonic force [5]. The speakers concluded that all these proposals either do not provide a significant improvement of the fit to MINOS data and/or are in conflict with some other data.

In a discussion session we have considered implications and prospects to resolve this possible anomaly. Unfortunately SuperKamiokande data on atmospheric neutrinos cannot contribute at the required level of precision to this question [6]. MINOS will be more powerful in constraining Δm^2_{31} for anti-neutrinos than NOνA on a short time scale, thanks to the magnetic field

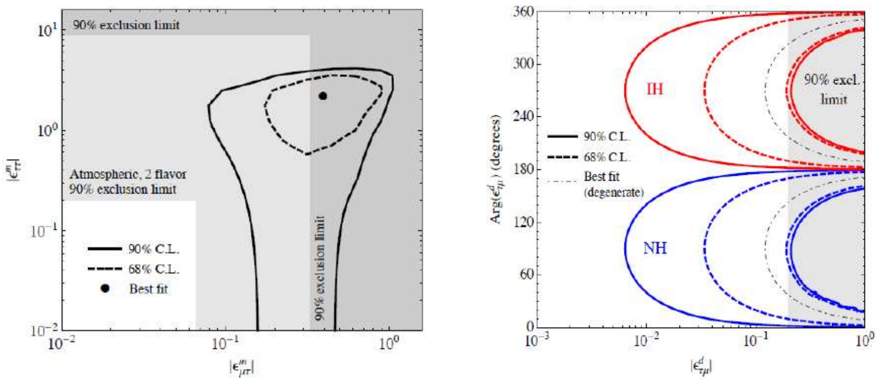

FIGURE 2. Fit to MINOS neutrino and anti-neutrino data including NC (left panel) or CC (right panel) type NSI, compared to the bounds from atmospheric neutrino data (shaded regions) [2].

which allows the separation of the neutrino contamination in the anti-neutrino beam. However after the ultimate NOνA exposure the final sensitivity will be better from NOνA [7]. Competing needs of neutrino/anti-neutrino beam power of various experiments at FNAL (MINOS, NOνA, MINERνA) have been discussed. The question was raised, whether it is good policy to base the experimental strategy on 2σ anomalies.

3. MINIBOONE RESULTS AND STERILE NEUTRINOS

Resent results from the MiniBooNE experiment were presented [8]. Data on the $\nu_\mu \to \nu_e$ appearance search from 6.5×10^{20} pot are consistent with the background expectation above 475 MeV but show an event excess at about 3σ below 475 MeV. Anti-neutrino data for $\bar{\nu}_\mu \to \bar{\nu}_e$ from 5.66×10^{20} pot show an event excess at about 2σ which is consistent with the parameter region indicated by LSND, if interpreted in terms of two-flavor neutrino oscillations. The data are shown in fig. 3. MiniBooNE wants to double the anti-neutrino data set for a total of about 10×10^{20} pot by spring 2011. If the signal continues at the current rate the significance will be at about 3σ with that exposure. A request for 15×10^{20} pot has been made in order to achieve a 4σ evidence.

It is well known that the LSND hint is very difficult to explain once global data from short-baseline experiments (including MiniBooNE) are taken into account. Adding one or more sterile neutrinos at the eV scale does not lead to a satisfactory description of the global data because of sever constraints from ν_e and ν_μ disappearance experiments, see [9].

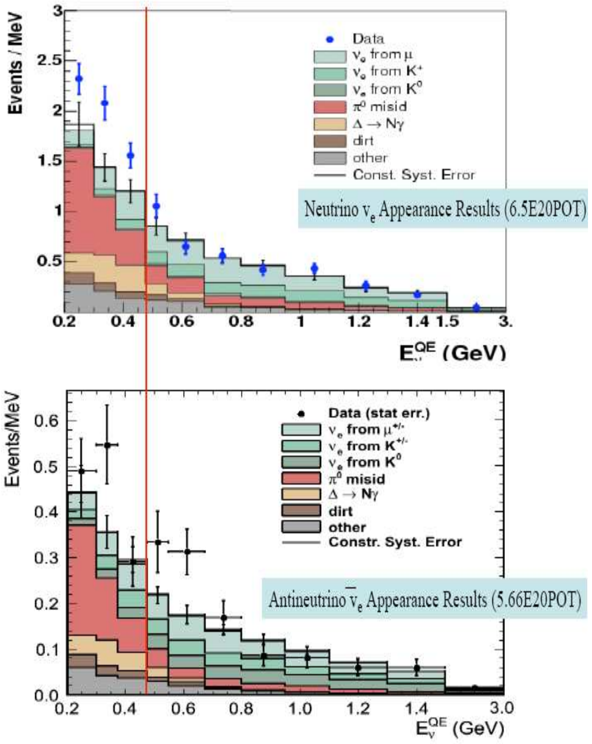

FIGURE 3. Comparison of MiniBooNE ν_e and $\bar{\nu}_e$ appearance results [8].

A possible explanation has been discussed in [10], introducing a sterile neutrino at the eV scale plus CC-like NSI (similar to the ones considered in [2] in the MINOS context). In this scenario LSND and KARMEN can be decoupled from the other data due to the different neutrino production process, and CP violation can be obtained by NSI–oscillation interference in order to reconcile MiniBooNE neutrino and anti-neutrino data. The tension between appearance and disappearance experiments is resolved, however the MiniBooNE low-energy excess cannot be explained. This model requires NSI at the level of few % compared to G_F, consistent with present bounds. Again the question arises whether it is possible to write down a gauge invariant model in order to generate sufficiently large NSI parameters.

The need to sort out the LSND/MiniBooNE anomaly was stressed, in view of envisaged future high precision oscillation experiments. Various possibilities have been mentioned, such as MicroBooNE, BooNE, a new beamline at CERN, liquid argon projects, or some of the NOνA or LBNE near detectors. Various other ideas to search for sterile neutrinos have been presented. The possibility to use a stopped pion source close to the SuperKamiokande detector doped with gadolinium was discussed in [11]. This would allow to observe the oscillation pattern due to a $\Delta m^2 \sim 1$ eV^2 as a function of the distance within the detector. In [12] it was proposed to use an in-line production of radio active isotopes injected in to a LENS-like detector. Again this would give a distance dependent effect of ν_e disappearance due to $\Delta m^2 \sim 1$ eV^2. The sensitivity of a future neutrino factory to sterile neutrinos (at the eV scale as well as within a much wider range of masses) has been discussed in [13].

4. A (BI) MAGIC BASELINE AT 2540 KM

The talks [14, 15] discussed special properties of the oscillation probability at a baseline of 2540 km, in analogy to the well known "magic" baseline at about 7500 km [16]. At leading order in the small parameters $s_{13} \equiv \sin\theta_{13}$ and $\tilde\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31} \sin 2\theta_{12}$ one has for the $\nu_\mu \to \nu_e$ appearance probability:

$$P_{\mu e} \approx 4 s_{13}^2 s_{23}^2 \frac{\sin^2 \Delta(1-A)}{(1-A)^2} + \tilde\alpha^2 c_{23}^2 \frac{\sin^2 A\Delta}{A^2} + 2\tilde\alpha s_{13} \sin 2\theta_{23} \cos(\Delta + \delta_{\rm CP}) \frac{\sin \Delta A}{A} \frac{\sin \Delta(1-A)}{1-A}\,, \qquad (1)$$

with the definitions

$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E}\,, \quad A \equiv \frac{2EV}{\Delta m^2_{31}}\,, \qquad (2)$$

where L is the baseline, E is the neutrino energy, and V is the effective matter potential. Note that the neutrino mass hierarchy, i.e., the sign of Δm^2_{31}, determines the signs of $\tilde\alpha$, Δ, and A. For anti-neutrinos V and $\delta_{\rm CP}$ change sign. The magic baseline [16] is based on the observation that the combination $A\Delta \equiv LV/2$ is independent of neutrino parameters and energy. By choosing a baseline such that $LV/2 \approx \pi$ only the first term in eq. 1 remains nonzero, and hence, the $\delta_{\rm CP}$ dependence of the probability disappears and a clean measurement of θ_{13} is possible.

In [14, 15], in contrast, the combination $\Delta(1-A)$ appearing in the last term of eq. 1 is considered, which now depends on oscillation parameters, and in particular on whether the neutrino mass hierarchy is normal (NH) or inverted (IH). Demanding $\sin[\Delta(1-A)] = 0(1)$ for IH (NH) gives two equations which can be solved for L and E yielding $L \approx 2540$ km and $E_{\rm IH} \approx 3.3$ GeV [14]. Another possibility is to demand $\sin[\Delta(1-A)] = 0(1)$ for NH (IH), which has a solution for $L \approx 2540$ km and $E_{\rm NH} \approx 1.9$ GeV [15]. By choosing these baselines and energies one can enhance or suppress the effect of $\delta_{\rm CP}$ for a given mass hierarchy, see fig. 4. This baseline was discussed in the context of a NOνA-like superbeam experiment [14] and a low-energy neutrino factory [15]. It has to be demonstrated, though, that there is really some "magic" property of this baseline, since in previous optimization studies no particular sensitivity increase has been found at $L \approx 2540$ km (see, e.g. [17]), apart from the well known fact that increasing the baseline (and hence the matter effect) in general improves the sensitivity.

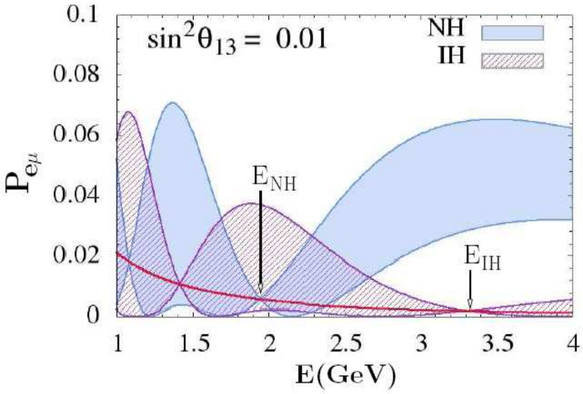

FIGURE 4. Appearance probability at $L = 2540$ km for NH and IH. The bands indicate the dependence on $\delta_{\rm CP}$ [15].

5. MUONS FROM TAU DECAYS AT A NEUTRINO FACTORY

In a neutrino factory the primary signal are muons, induced from $\nu_e \to \nu_\mu$ oscillations ("wrong sign" muons) or from the disappearance channel $\nu_\mu \to \nu_\mu$ ("right sign" muons). In both cases, $\nu_e \to \nu_\tau$ or $\nu_\mu \to \nu_\tau$ oscillations occur with a probability comparable to the respective main channels. Hence, τ leptons are produced in CC interactions, which will decay with a branching fraction of about 17% into a muon plus two neutrinos, and hence contributing to the muon signal. The importance to take this effect into account at a neutrino factory has been stressed in [18, 19]. Tau-induced muons will appear at lower energy, since some energy is carried away by the neutrinos. Therefore, the proper way to include this effect in an analysis is via a migration matrix, which is going to be implemented for future sensitivity studies. As

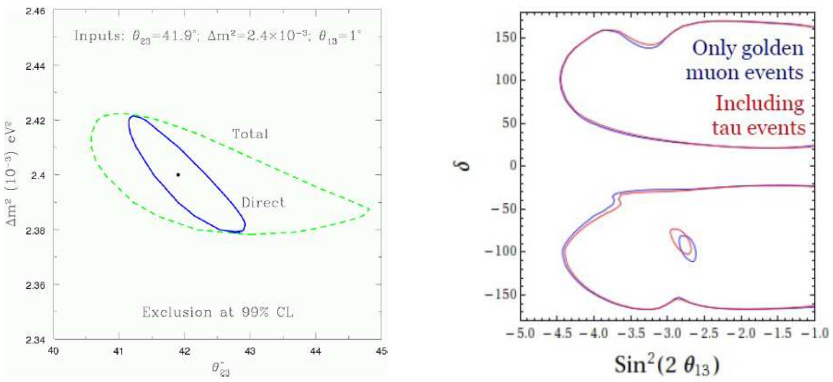

FIGURE 5. Impact of τ-induced muons on the determination of Δm^2_{31} and θ_{23} from the disappearance channel (left panel) [18] and on the sensitivity to CP violation from the appearance channel (right panel) [19].

shown in fig. 5, τ-induced muons have a sizable impact on the determination of Δm^2_{31} and θ_{23} from the disappearance channel [18], while the impact on the sensitivity to CP violation is small [19].

6. NON-STANDARD NEUTRINO INTERACTIONS

Several aspects of NSI have been discussed, including the talks related to MINOS [2, 3, 5] and MiniBooNE [10] mentioned above. CC-like NSI have been considered in [20]. From a general dimension-6 operator analysis, bounds on charged lepton-flavor violation bounds on NSI parameters at the level of 10^{-4} have been derived. This requires sensitivities in probability of of order 10^{-6} to 10^{-8}, rendering such searches rather challenging. The sensitivity of IDS-inspired neutrino factory setups to NSI have been re-considered [21]. In that talk NC-like NSI have been considered, taking into account various parameter correlations. Sensitivity reaches of order 10^{-3} have been obtained. Furthermore, the possibility of CP violation from NSI has been considered, which might be observable even for $\theta_{13} = 0$.

We had a discussion session on the topic whether one can expect NSI at a measurable level within a realistic theoretical framework. Since neutrinos and leptons are grouped in SU(2) doublets, in a gauge invariant theory in general NSI come together with effects in charged lepton flavor violation, where bounds are strong. Typically the sensitivity to NSI of long-baseline experiments is at the level of 10^{-3}. It turns out that in "typical" gauge invariant theories it is difficult to obtain NSI parameters at that level due to charged lepton flavor violation constraints. The important question arises, which ingredients for a theory are required to obtain NSI at the 10^{-3} level.

7. ALSO DISCUSSED

Let us briefly mention other topics discussed at the working group. We had status reports from the experiments OPERA [22], T2K [23], NOνA [7], as well as the three upcoming reactor experiments Double Chooz, RENO, and Daya Bay [24]. Latest results from SuperKamiokande data on atmospheric neutrinos have been presented [6], including a preliminary full three-flavor analysis taking into account sub-leading oscillation modes due to θ_{13}, Δm^2_{21}, and $\delta_{\rm CP}$.

The status of the LBNE program in US has been presented [25], and in the WG1/WG2 joint session various detector developments have been discussed in the LBNE context, including near detector plans [26] and R&D for large liquid argon (LAr) and water Cerenkov (WC) detectors [27]. The current plan is to have a 200 kt WC or a 34 kt LAr detector, or a combination thereof, located at the DUSEL mine, about 1300 km from Fermilab. Detector construction should start 2014/15, delivering physics by the end of the decade. Another topic in the WG1/WG2 joint session has been the extrapolation from near to far detectors, which has been discussed in the context of an on-axis beam (MINOS), off-axis beams (NOνA and T2K), and reactor experiments [28].

Investigations to use a large liquid scintillator detector (LENA) for long-baseline neutrinos in the GeV range have been presented [29]. Promising track reconstruction and energy reconstruction abilities have been obtained, while the background from NC events needs to be investigated. The Daedalus project proposes to use several high-power (MW) cyclotrons, placed close to a 100 kt scale WC detector doped with gadolinimum for oscillation studies [30]. Sensitivity to θ_{13} and $\delta_{\rm CP}$ are obtained from a spectral fit, and the synergy with the LBNE beam has been emphasized [30, 11].

More theoretical aspects of neutrino physics have been discussed in a session on neutrino mass models. The possibility to generate neutrino masses by operators at dimensions $d \geq 7$ has been discussed in [31], to distinguish from the usual $d = 5$ Weinberg operator. Such scenarios lead to a scale of new physics much lower than the conventional seesaw scale of $\sim 10^{14}$ GeV. Hence, neutrino mass generation by $d \geq 7$ operators may be testable at collider experiments. Four-zero neutrino Yukawa Textures, $\mu - \tau$ symmetry and baryogenesis has been discussed in [32], and [33] considered quasi-degenerate neutrinos in SO(10) grand-unified theories.

8. QUESTIONS FOR NUFACT11

We formulate here tasks and questions to be addressed by the neutrino oscillation working group for NuFact11.

1. Perform sensitivity and optimization studies for future oscillation facilities. This includes studies in the standard oscillation framework as well as searches for exotic neutrino physics.
2. Write down a specific and consistent model which provides non-standard neutrino interactions at an observable level while satisfying all present constraints. In the past most emphasis has been on model-independent sensitivity studies, and good progress has been made in this respect. Now it is important to understand how theoretically motivated the search for NSI actually is.
3. Provide physics motivation of long-baseline oscillation searches within the wider context of particle physics, beyond the relatively small circle of neutrino aficionados. This is of high importance, given the expected cost of the facilities under discussion, which has to be supported by a large part of the particle physics community.

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