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**Citation:** Conrad, J M. "Neutrino Experiments and the Large Hadron Collider: Friends Across 14 Orders of Magnitude." Phys. Scr. T158 (December 1, 2013): 014012.

**As Published:** <http://dx.doi.org/10.1088/0031-8949/2013/T158/014012>

**Publisher:** IOP Publishing

**Persistent URL:** <http://hdl.handle.net/1721.1/88406>

**Version:** Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

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# Neutrino Experiments and the LHC: Friends Across 14 Orders of Magnitude

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**Abstract.** This proceeding explores some of the questions that connect the LHC and neutrino experiments: What is the origin of mass? What is the meaning of flavor? Is there direct evidence of new forces or particles? The neutrino program investigating these questions is large and diverse. The strategy here, to narrow the discussion, is to focus on relatively new ideas for experiments that may be less known within the LHC community.

## 1. Introduction

Despite the wide difference in energy scales, the LHC and neutrino experiments have a great deal of intellectual overlap. This talk explored three high-level questions as examples:

- What is the origin of mass?
- What is the meaning of flavor?
- Is there direct evidence of new forces or particles?

These are questions that resonate with the LHC community. In this proceeding, I explore information and ideas that the neutrino community adds to the debate.

This discussion of the neutrino program has two biases used to narrow the scope to a manageable scale for a 20 minute talk and 15 page proceeding. First, the approach is data-driven. A separate talk at the symposium, by Stephen Parke, was given on neutrino theory, and the reader is referred to this for a more top-down approach to the questions. Second, the emphasis is on highlighting recent experimental ideas which may be new to the LHC community. This necessarily leaves out a large number of exciting, but better-known experiments, however some very good reviews of these are available in Refs. [1, 2, 3, 4, 5].

## 2. The $\nu$ SM

The discussions below assume a “neutrino Standard Model” ( $\nu$ SM). This is a minimal increment to the Standard Model driven by the present  $> 5\sigma$  results. This phenomenology has been developed with an agnostic approach to the underlying theory. It simply describes the data.

At this point, as demonstrated by LEP, we know that there are only three active flavors,  $\nu_e$ ,  $\nu_\mu$  and  $\nu_\tau$ , with masses less than  $M_Z/2$  [6]. We know that these are related to at least three mass states,  $\nu_1$ ,  $\nu_2$  and  $\nu_3$ , although there is not a one-to-one correspondence. In fact, the data are consistent with very large mixings with the mass states [7]:

$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} 0.795 - 0.846 & 0.513 - 0.585 & 0.126 - 0.178 \\ 0.205 - 0.543 & 0.416 - 0.730 & 0.579 - 0.808 \\ 0.215 - 0.548 & 0.409 - 0.725 & 0.567 - 0.800 \end{pmatrix}, \quad (1)$$

Reaching this level of accuracy, with every element of this Pontocorvo–Maki–Nakagawa–Sakata (PMNS) matrix measured at some level, represents a highlight of the work of the last decade in neutrino physics.

The limits on neutrino mass from kinematic studies of tritium beta decay indicate that the neutrino mass states are less than  $\sim 1$  eV [8]. We know that at least two of the three mass states must have non-zero mass, because we have measured two distinct mass splittings in oscillation experiments to high accuracy in atmospheric [9] and solar

neutrino experiments [10]. Three neutrino mass states can be mapped onto two distinct splittings, and, when combined with reactor [1] and accelerator neutrino experiments [2], yield  $\Delta m_{31}^2 = (2.473 \pm 0.069) \times 10^{-3} \text{ eV}^2$  and  $\Delta m_{21}^2 = (7.50 \pm 0.19) \times 10^{-5} \text{ eV}^2$  [7].

These additions to the Standard Model (SM)– that neutrinos mix as per  $U_{PMNS}$ , and that at least two mass states are nonzero with mass less than 1 eV–are assumed throughout the discussion below.

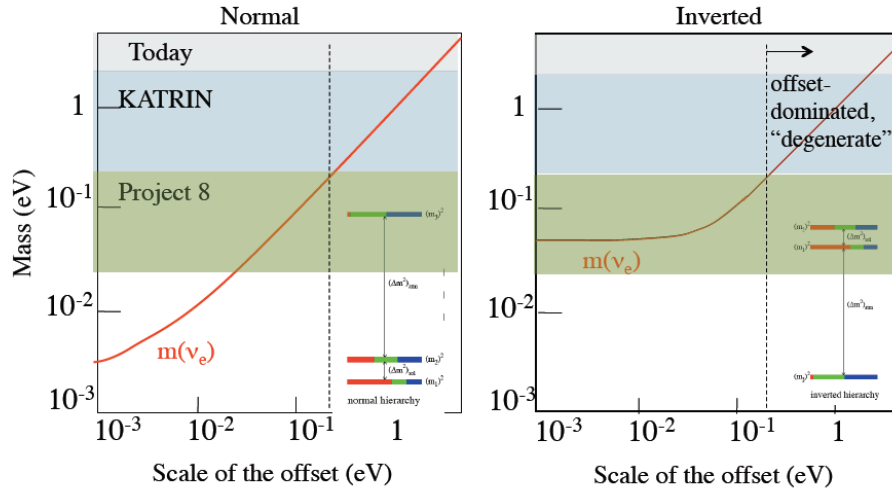
### 3. What Can Neutrinos Say About the Origin of Mass?

With the discovery of the Higgs, we have made a major step forward in understanding how mass terms should appear in the SM Lagrangian. However, as highlighted at the conference, the underlying meaning of the fermion mass spectrum we observe is unclear. Moreover, we have yet to find any indication for a mechanism which prevents the masses of all fermions from being at the Planck scale. So, obviously, something is seriously wrong. We need more clues.

A place to look for more clues is the neutrino sector. Other than the facts that at least two neutrino states must have non-zero mass and that the mass spectrum corresponding to the active flavors must be less than  $\sim 1 \text{ eV}$ , we know very little about neutrino masses. Our limited knowledge raises a host of other questions: How far below the upper limits do the neutrino masses lie? Why would the coupling of the Higgs to the neutrinos be more than five orders of magnitude less than the couplings to the charged fermions? Can there be other mass-producing mechanisms at play that lead to this effect? And will neutrinos have the same mass hierarchy as the quark sector, with the small splitting seen at the lowest masses and the large splitting associated with the highest mass? These are all questions we can investigate in the next decade to shine more light on the continuing question of the origin of mass.

At present, we know that the gap between the neutrino mass states of the  $\nu\text{SM}$  and the electron mass is five orders of magnitude, This is as large as the span of masses of the charged fermions, from electron to top quark. However, this is just a limit in the neutrino sector, and the lightest mass state might be as low as  $\sqrt{(\Delta m_{31}^2)} \sim 50 \text{ meV}$ , leading to a “desert” between the fermions of  $10^7 \text{ eV}$ . As we think about the problem of mass, we must consider what produces such a gap. There are two opposing approaches. One introduces new physics into the  $\nu\text{SM}$ , such as the See-saw Model [11] to motivate the gap. The other argues that the masses are just an accident of nature, like the orbits of the planets, and, as in the case of orbits of planets, gaps happen. However, to push the analogy further, the study of the Mars-Jupiter gap has given interesting insights into the formation of the solar system and potential exo-solar-systems; similarly, even if the specific values of our fermion mass spectrum turn out to be accidents of nature, the origin of this “gap-feature” may lead to interesting insights in particle physics.

The first question, then, is: How big is the gap? The most precise method of attack comes from the study of the kinematics of tritium  $\beta$  decay [8]. Neutrino mass will lead to a lower endpoint of the  $\beta$ -decay spectrum. These experiments measure  $m_{\nu_e}$ , which is



**Figure 1.** Cartoon of the possible values of  $m_{\nu_e}$  as a function of absolute offset. Left and right apply to the two hierarchies, shown in inset. The KATRIN and Project 8 sensitivities are shown.

a flavor weighted average of the neutrino masses:

$$m_{\nu_e}^2 = \sum |U_{ei}|^2 m_{\nu_i}^2, \quad (2)$$

where the sum,  $i = 1..3$ , is over the three mass states. The allowed values of  $m_{\nu_e}$  in nature depend upon 1) the absolute offset of the neutrino mass states, which is the equivalent of the mass of the lowest state, and 2) the mass hierarchy.

To illustrate the point, consider Fig. 1, which is a cartoon of possible values of  $m_{\nu_e}$  as a function of absolute offset, where left and right apply to the two hierarchies, shown in inset. If the absolute offset is large with respect to the mass splittings, then there is little difference between the potential  $m_{\nu_e}$  values for the two hierarchies—this is called the “degenerate range.” However, for smaller values of offset, there is a substantial difference in the range of possible values which must be probed. To see this, consider the inset diagrams, where each bar represents a mass state and the colors indicate the flavor mixings. The mass state  $\nu_3$  is defined to have the smallest electron flavor content. The normal hierarchy (left) places  $\nu_3$  at the top of the mass spectrum, thus the highest mass state contributes a small weight in Eq. 2. On the other hand, the inverted hierarchy places  $\nu_3$  at the bottom, resulting in large electron-flavor content in two high mass states. This inverted arrangement allows an experiment with sensitivity below  $m_{\nu_e} \sim 0.05$  eV to cover the entire range of potential values.

KATRIN, which will run in 2015, will be the first experiment to weigh in, and will have a sensitivity of  $\sim 0.2$  eV at 90% CL[12]. This will cover the degenerate range of potential solutions. KATRIN is a classic electromagnetic spectrometer. To reach high resolution at the  $\beta$ -decay endpoint, the central region of the spectrometer must be 10 m in diameter, which is enormous and is likely to make the KATRIN experiment the last

of its kind.

To move to the next order of magnitude in sensitivity a new technology is required, and an interesting possibility has been put forward by the Project 8 collaboration [13]. This technique traps the  $\beta$ 's from tritium decay in a magnetic bottle. As the electrons traverse the bottle, they will radiate in the RF, at the fW level. In principle, the radiation can be observed with MHz antennae now under development as listening devices for cell phones. The combination of time-of-flight and the frequency of the radiation allows the electrons with energies at the very endpoint of the decay to be isolated and counted. This has the potential to push the sensitivity to  $m_{\nu_e}$  down to  $\sim 0.02$  eV, covering the entire range of potential values in the case of the inverted hierarchy.

A related question to the absolute mass offset is whether neutrinos acquire mass in the same way as the other fermions. Because neutrinos are neutral with respect to the electromagnetic and strong forces, they can, potentially, be their own antiparticle—where neutrino and antineutrino are distinguished by the spin state. This allows introduction of an additional “Majorana” mass term, beyond the Higgs mechanism, into the Lagrangian. Through the See-saw model, this mass term can be connected to physics at higher energy scales, leading to an explanation of the large mass gap we observe.

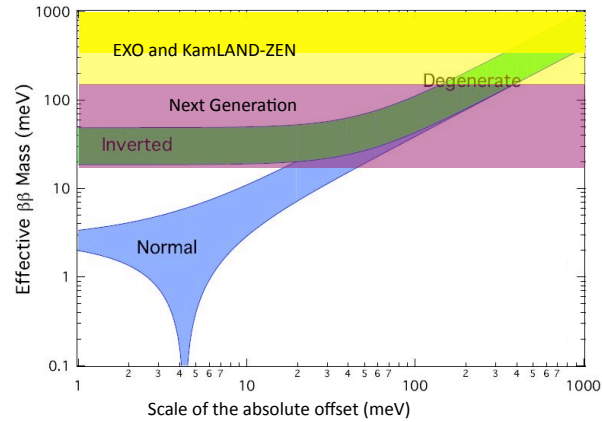
The most precise way to test for the Majorana nature of neutrinos is through neutrinoless double beta decay ( $0\nu\beta\beta$ ). This is the neutrinoless analogue to the observed process of double beta decay to  $\beta\beta\bar{\nu}_e\bar{\nu}_e$ , which has been observed to occur in the handful of elements where single beta decay is energetically forbidden. In the case of  $0\nu\beta\beta$ , the two antineutrinos annihilate—allowed by their Majorana nature. While it might be surprising to think that total lepton number can be violated in this way, in fact nothing in the SM prevents this. So under the argument that, “if is it not forbidden, it is compelled,”  $0\nu\beta\beta$  is natural.

The signal for  $0\nu\beta\beta$  is the production of two monoenergetic electrons at the endpoint of the  $\beta$  spectrum. Thus these experiments have a great advantage in knowing exactly where to look for a new physics signal. The expected rate is related to a flavor-weighted neutrino mass:

$$|\langle m_{\beta\beta} \rangle| = \left| \sum m_i U_{ei}^2 \right|. \quad (3)$$

The allowed values of  $m_{\beta\beta}$  as a function of absolute mass offset are shown in Fig. 2 for the inverted and normal mass hierarchies, overlaid. The basic form is similar to that of  $m_{\nu_e}$  from the direct mass searches, with a degenerate region for large absolute offsets and larger average mass expected for inverted rather than normal hierarchy. But the differences in flavor-weighting (compare Eqs. 2 and 3) lead to a spread of potential allowed values in the  $0\nu\beta\beta$  case arising because the elements of  $U$  can have arbitrary phases. As a result, the allowed regions are wide bands on Fig. 2. An accurate measurement of  $m_{\nu_e}$  can allow us to hone in on these  $CP$ -violating phases if  $0\nu\beta\beta$  is observed, providing valuable input to Leptogenesis models [14].

The progress in the search for  $0\nu\beta\beta$  is indicated by the yellow shaded region, which



**Figure 2.** The allowed values of  $m_{\beta\beta}$  as a function of absolute mass offset for the inverted and normal mass hierarchies, overlaid. The uncertainty from the matrix element is indicated by the pale yellow region. Next generation experiments are described in the text.

are the limits from EXO and KamLAND-Zen [3]. The excluded region becomes pale in the lower regions, indicating the theory error from the calculation of the nuclear matrix element of Xenon. The theory error for all of the potential  $0\nu\beta\beta$  elements is large. This has led to a set of next generation  $0\nu\beta\beta$  experiments that employ a range of different elements, so that cross comparison of signals and limits can allow a precise interpretation of the results with less sensitivity to the underlying nuclear theory. The elements include Neodymium (SNO+), Tellurium (CUORE, potentially SNO+), Germanium (GERDA and Majorana) and Xenon (NEXT, as well as continuations of EXO and KamLAND-Zen) [3].

As with the direct mass measurements, the ambition of the next generation is to entirely cover the potential values of  $m_{\beta\beta}$  for the inverted mass hierarchy. Each of the above experiments is pressing for improvements to reach this level, and it is unclear, which, if any, will succeed. However, an interesting new step is being pursued by SNO+, to switch from Nd to Te, which may make this experiment the first to pass below the inverted hierarchy in sensitive. This step can be taken because of a very nice synergy among neutrino experiments. A set of recent reactor-based experiments has solved the problem of doping scintillator oil with a high fraction (a few percent) of metal isotopes [15]—research pursued to improve the neutron capture cross section in those experiments. This same technology appears to allow SNO+ to dope with 3% Te. Since the natural abundance of the double beta decaying isotope of Te is 34%, this results in sensitivity across the full range of potential mass values for SNO+, assuming they can achieve the necessary resolution at the endpoint [16].

From the above discussion, it is clear that the hierarchy is playing a crucial role in accessing the physics. Beyond this, the hierarchy itself is an interesting question, if one

is seeking to make a model of fermion masses. Thus, it would be best if the question of the hierarchy could be addressed separately from the quantitative mass measurements. Luckily, this can be done in certain neutrino oscillation experiments.

To understand the sensitivity of oscillations to the hierarchy, consider the three neutrino mass states propagating through the earth. Because the earth is filled with electrons, the neutrinos feel a weak potential. The effect of this potential on the propagation will be different for each mass state, because of the varying electron-flavor content, leading to a change in the oscillation probability. This “matter effect” is enhanced with energy and distance. The sign of the matter effect is opposite for neutrinos and antineutrinos, and thus can be regarded as faux- $CP$ -violation. But unlike true  $CP$  violation, the effect will appear in both appearance and disappearance oscillation experiments.

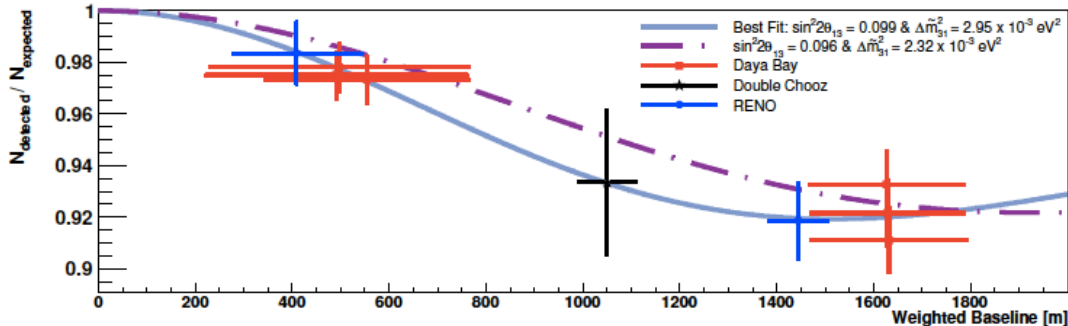
From the above description, one can see that an ideal setting to search for matter effects, and thus determine the mass hierarchy, is long baseline oscillations. While the traditional approach has been to look to accelerator-based sources, if what one wants is extremely long baseline, with a high-rate of events in the 1 to 20 GeV range, then nothing beats a cross-earth atmospheric neutrino experiment. To this end, the IceCube Experiment is upgrading their Deep Core central region with additional strings of PMTs in order to explore this physics. This upgrade, called PINGU, can be completed on a relatively short timescale, and will have 3 to  $5\sigma$  capability within a few years of running [17]. As a result, one can imagine the mass hierarchy question—normal or inverted—being answered on the same timescale as the direct and  $0\nu\beta\beta$  mass measurements.

The combination of the three approaches to questions of mass is powerful. In the cases where both the direct and  $0\nu\beta\beta$  experiments see signals, very valuable information can be added to the models for new physics at high mass scales, including Leptogenesis. With or without a signal observed in direct and  $0\nu\beta\beta$  experiments, the result can constrain cosmology. It should be noted that cosmology gets a good fit assuming no neutrinos [18], and mechanisms have been put forward that reduce or eliminate the cosmic neutrino background [4], and so constraints from earth-based experiments are quite important. Lastly, there is the potential for experimental discrepancies that force us to entirely rethink our nascent understanding of neutrino mass.

#### 4. What Can We Learn From Neutrino Flavor Studies?

If one is looking for patterns in the SM, then the neutrino flavor mixings expressed by Eq. 1 are as strange as the neutrino masses. Completely opposite to the quark sector, all of the off-diagonal entries in the mixing matrix are large. Even the smallest entry,  $|U_{e3}|$  is an order of magnitude larger than its quark-sector equivalent. As with the case of the masses, it may be that this is just a random occurrence in nature—this model is called “Anarchy” in the neutrino community. But we are, at this point, far from the level of precision where it is time to just give up on searching for a pattern. Indeed,





**Figure 3.** Measurements from the reactor experiments at various baselines, overlaid with a fit to  $\Delta m^2$  [23]. Improved measurements of  $\theta_{13}$  at multiple baselines will allow tests of deviations from the oscillation expectation due to non-standard interactions.

neutrino physics is, now, at the level of precision of the quark sector in 1995 [19]:

$$U_{CKM}^{1995} = \begin{pmatrix} 0.9745 \text{ to } 0.9757 & 0.219 \text{ to } 0.224 & 0.002 \text{ to } 0.005 \\ 0.218 \text{ to } 0.224 & 0.9736 \text{ to } 0.9750 & 0.036 \text{ to } 0.046 \\ 0.004 \text{ to } 0.014 & 0.034 \text{ to } 0.046 & 0.9989 \text{ to } 0.9993 \end{pmatrix} \quad (4)$$

So a whole world of precision flavor measurement is only now opening up to the neutrino community.

The ultimate goal will be to develop unitarity tests that are as precise as those in the quark sector. However, this will require precision measurement in muon-to-tau and electron-to-tau appearance experiments. Because of the tau mass suppression in charged current interactions, this requires high energy neutrino beams. Since the oscillation length of these studies is fixed in the  $\nu$ SM by  $\Delta m_{21}^2$  and  $\Delta m_{31}^2$ , high energy inevitably means ultra-long baselines, which require ultra-high intensity. Thus the only practical solution is a  $> 20$  GeV neutrino factory, which will not be realized until far in the future.

Nevertheless, improving the precision measurements we can do today can potentially produce indications of new physics. The neutrino community is very interested in models with non-standard interactions that produce instantaneous transmutation of neutrino flavor at production and interaction, as well as modify the oscillation probability. Cross comparing results of matrix element measurements from different experiments may provide sensitivity to such effects. But before looking for something completely different than in the quark sector, one can also look closely at the  $\nu$ SM to ask if it is complete. We know that the quark mixing matrix has an arbitrary phase which leads to  $CP$ -violation. It is important to ask if such a phase is appearing in the lepton sector also. It would be quite striking if it did not, since this would speak against the dictum of “that which is not forbidden is compelled.” It would also be

striking if the value were large, the opposite to the quark sector, as that would make the apparent dichotomy between the quarks and leptons even more sharp. Thus, even if unitarity tests are far away, there are a great deal of important checks we can pursue in neutrino flavor physics in the near future.

As an example of a precision  $\nu$ SM search that we can do within the next decade, consider  $\theta_{13}$ . Since the PMNS matrix simply produces a rotation between flavor and mass states, the flavor mixing is most commonly parametrized as through three Euler angles,  $\theta_{12}$ ,  $\theta_{23}$  and  $\theta_{13}$ . The relationship between the matrix elements and the angles is complicated except for one entry,  $U_{e3}$ , which depends purely on  $\sin(\theta_{13})$ . This turns out to be the smallest mixing angle, and was only recently observed to be non-zero [7]. This was an exciting result both for theories describing the PMNS matrix and also because non-zero  $\theta_{13}$  is crucial for the potential to observe  $CP$ -violation. Neutrino physicists consider 2011-12 “The Year of  $\theta_{13}$ ” for the neutrino sector, in the same way it was “The Year of the Higgs” for the LHC. And, now, like the Higgs, the next thing to do is explore this new measurement for hints of the unexpected.

What has been reported by the Double Chooz [20], Daya Bay [21] and RENO [22] reactor experiments, was a deficit in anti-electron neutrinos at  $L/E \sim 1/\Delta m_{atm}^2$ . This would be consistent with the expectation of disappearance in the  $\nu$ SM model, and the mixing angle can be extracted from this equation:

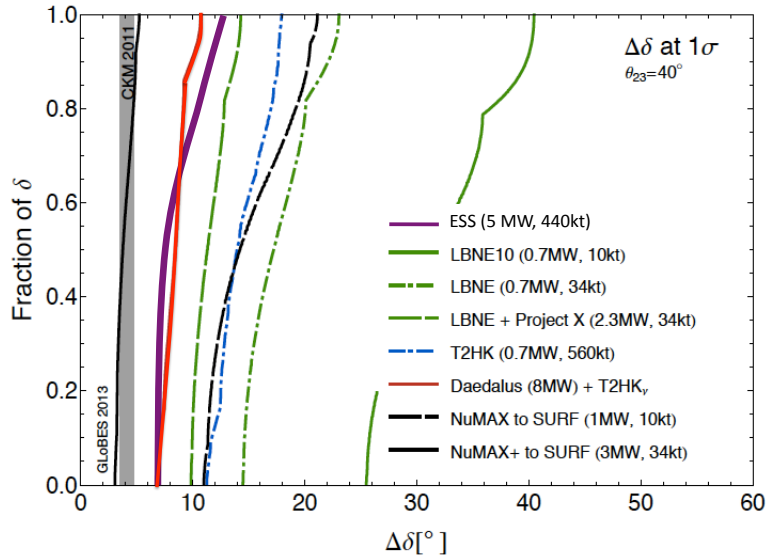
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2(1.27\Delta m_{atm}^2 L/E). \quad (5)$$

The approximation arises from dropping subleading-terms from  $\Delta m_{12}^2$  which are very small and by employing the assumption that  $\Delta m_{13}^2 = \Delta m_{23}^2 = \Delta m_{atm}^2$ .

One sees immediately that the  $\nu$ SM makes very specific predictions as a function of  $L/E$ . These are modified in the presence of non-standard interactions. And so an important next step is to test for this  $L/E$  dependence. We can already begin to test the  $L$  dependence of the  $\theta_{13}$  measurements, because the three reactor experiments are at different baselines [23]. Fig. 3 shows the data associated with the various baselines. Daya Bay has a particularly complicated reactor-core to detector arrangement, and that is why they report results from many baselines. The dot-dashed line shows the expectation from the  $\nu$ SM, allowing  $\sin^2 2\theta_{13}$  to float and fixing  $\Delta m_{atm}^2$  to the measurement from MINOS [24]. The solid blue line allows both  $\sin^2 2\theta_{13}$  and  $\Delta m_{atm}^2$  to float. The result is a rather high value for  $\Delta m_{atm}^2$ , but allowable within errors. However, there is clearly room for models beyond the  $\nu$ SM, introduced as sub-leading additions, to fit the data.

Understanding  $\theta_{13}$  is also key to the search for  $CP$  violation in the neutrino sector.  $CP$  violation will modify the oscillation probability of appearance experiments. For muon-to-electron appearance, which is a channel we can test in the near future, the oscillation probability is given by:

$$P = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \Delta_{13} \\ \mp \sin \delta_{cp} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin^2 \Delta_{13} \sin \Delta_{12}$$



**Figure 4.** Fraction of  $\delta$  parameter space covered at  $1\sigma$  given the measurement precision of  $\delta$ . The plot is from P. Huber’s review at Snowmass 2013 [25], with the ESS expectation for the 360 km site added. Conventional designs are in green, blue and purple. DAE $\delta$ ALUS, in red, uses three sites at 1 MW, 2 MW and 5 MW to produce DAR beams to trace the oscillation wave. The black line indicates the capability of a neutrino factory.

$$\begin{aligned}
& + \cos \delta_{cp} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta \sin \Delta_{13} \cos \Delta_{13} \sin \Delta_{12} \\
& + \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta_{12},
\end{aligned} \tag{6}$$

where  $\Delta_{ij} = 1.27\Delta m_{ij}^2 L/E$ , and  $-(+)$  refers to neutrinos (antineutrinos).

For the large values of  $\theta_{13}$  which have been observed, measurement of a non-zero  $CP$ -violating phase in the PMNS matrix (eq. 1) ensures non-vanishing baryon asymmetry [14]. The theoretical problem is how to quantify the effect so as to understand whether this is the sole source of baryon asymmetry. Thus,  $CP$  violation is a place where experiment is pushing theory as hard as theory often pushes experiment. Two outcomes are particularly interesting: if experimentalists provide a measurement of  $CP$  in the neutrino sector that is large, a major contribution to the baryon asymmetry is necessary[14]; and if the  $CP$  violation parameter is limited to less than  $5^\circ$ , theorists must begin seriously considering how to explain zero  $CP$  violation in the lepton sector, when it is observed in the quark sector.

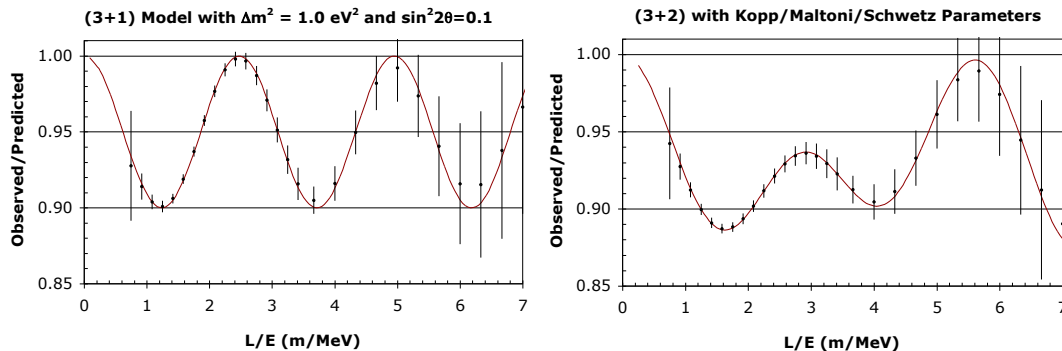
$CP$  violation necessarily requires an appearance experiment, and the most feasible channel is muon to electron flavor oscillations. The classic, or “conventional,” approach to studying  $CP$  violation is to exploit the change of sign in the oscillation probability by running with neutrinos versus antineutrinos (see Eq. 6). However, an alternative method is to run strictly in either neutrino or antineutrino mode, and instead trace out the oscillation wave, which is modified by a nonzero value of  $\delta$ . Because non-standard interactions may also be occurring in the neutrino sector, measurements using both approaches is warranted. In either case, a precise measurement of  $CP$  violation is best

done at low energies and relatively short baselines, where matter effects do not add ambiguity to the result.

The newest and most powerful proposal for a conventional  $CP$  violation experiment using neutrino and antineutrino muon-to-electron flavor oscillations is to be built in Sweden. This experiment [28] would make use of the European Spallation Source (ESS), now under construction at Lund, to produce a conventional decay-in-flight, wide-band neutrino beam peaking at about 200 to 300 MeV. Operation of the ESS linac proton beam will start at reduced power in 2019, increasing to the full design power of 5 MW in 2022. To produce the neutrino beam, the 2.5 GeV linear accelerator would be upgraded by another 5 MW, allowing  $\sim 10^{23}$  protons per year for neutrino production, concurrent with the neutron spallation running. A large water tank Cherenkov detector can be located underground in a mine at a depth of  $\sim 3000$  mwe at two potential locations: Zinkgruvan, which is 365 km from Lund, and Garpenberg, which is 540 km from Lund. These locations offer very similar rock and depths to the Pyhäsalmi mine in Finland that is under consideration for a CERN long baseline program [26]. Data would be taken with 2 years of neutrino running and 8 years of antineutrino running. The design of the water Cherenkov detector is that of MEMPHYS [27], which is 440 kt of water.

The resulting capability compared to other conventional beam experiments is shown in Fig. 4, which shows the fraction of  $\delta$ -space covered at  $1\sigma$  for a given precision in  $\delta$ . The ESS experiment (purple) substantially outperforms the other proposed conventional designs (LBNE (green)[29] and T2HK (blue) [30]) due to several factors. First, the low energy of the ESS beam highly suppresses neutral current events in the detector that produce  $\pi^0$ 's, the principle and pernicious background to  $\nu_\mu \rightarrow \nu_e$  measurements. At this energy, the electron-like charged current quasielastic events are straightforwardly separated from the muon-like events in an ultra-large Cherenkov detector, as has been well-established by past experiments [38, 32]. Second, while most low energy conventional beams are produced via targeting off axis, which yields a narrow band beam which limits reach in  $\delta$ , the low energy of the ESS beam provides low proton energy and produces a wide-band beam. Third, if the 540 km ESS baseline is used, then the resulting energy distribution of the flux allows for the study of the second oscillation maximum. The  $CP$  violating asymmetry is significantly larger at the second maximum than at the first maximum, enhanced by the large value of  $\theta_{13}$ . In contrast, the LBNE and T2HK designs, which were set before  $\theta_{13}$  was measured, were chosen to be most sensitive to the first oscillation maximum.

The alternative approach to measuring  $\delta$  is to measure the change induced in the oscillation wave as a function of  $L/E$ . The first proposal to pursue this method has been developed by the DAE $\delta$ ALUS collaboration [35]. This experiment uses cyclotrons at three sites to produce identical neutrino fluxes from the decay-at-rest of pions and muons. Events from the near cyclotron site allows constraint of the initial flux. The middle and far sites then allow the shape of the oscillation wave to be accurately measured. The useful flux from decay at rest beams range from 20 to 50 MeV, and thus this is a very short baseline experiment, with the sites located at  $< 1.5, 8$  and



**Figure 5.** Example data sets for 5 years of running for 3+1 (left) and 3+2 (right) oscillation scenarios for IsoDAR running at KamLAND.

20 km. A  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  signal can be detected in a large detector with free proton targets (water or scintillation) via inverse  $\beta$  decay (IBD),  $\nu_e + p \rightarrow e^+ n$ . In the case of a water detector, in order to observe the neutron capture, Gd-doping, as is presently done in the EGADS experiment [33] is required. Thus, this experiment could use the same detector as is planned for ESS. Other detectors under consideration are HyperK (water) [30] and LENA (scintillator)[34].

Fig. 4, red, shows the DAE $\delta$ ALUS capability for a 10 year run [35]. While this sensitivity was calculated for running DAE $\delta$ ALUS with the Hyper-K design, the result when paired with ESS will be very similar. This capability is similar to that of the ESS proposal, and both approach the measurement of  $\delta$  in the quark sector (gray band). The combination can take the measurement of  $\delta$  beyond a simple measurement, to a strong test of the potential presence of non-standard interactions.

## 5. Is There Direct Evidence of New Forces or Particles?

This is the question that unites physicists across many subfields. In the discussion, we have already highlighted several neutrino experiments where new, non-standard forces may be observed. So here, we consider the potential to directly produce and observe new particles. Direct production of new particles has been widely regarded as the preserve of the highest energy scale experiments. However, new developments in dark matter [36, 37] and sterile neutrino studies have recently sparked interest at high-intensity, low energy experiments.

As an example, consider light (0.1 to 10 eV) sterile neutrinos. Several anomalies have motivated the search for light sterile neutrinos with mass  $\sim 1$  eV. The results arise from short baseline accelerator, reactor and source experiments [38, 39, 40, 41], and include both neutrinos and anti-neutrino scattering, electron and muon flavors, and more than two orders of magnitude in energy range. Models which introduce one, two or three sterile neutrinos, referred to as “3+1”, “3+2”, or “3+3,” respectively, have been introduced to explain the data [42]. Global fits have identified ranges in this extended parameter space where the anomalies can be reconciled in the 3+2 and 3+3 cases [43].

Until now, all of these measurements have been made at specific  $L$  values and with rather limited ranges in  $E$ . An important goal of the next generation of these searches must be “oscillimetry,” where the oscillation curve is traced in  $L/E$  space in a single experiment. This is the only way to clearly establish that these anomalies arise from oscillations rather than from some other non-standard, or indeed some unexpected standard, effect. Sufficient sensitivity to make a definitive  $> 5\sigma$  statement is required.

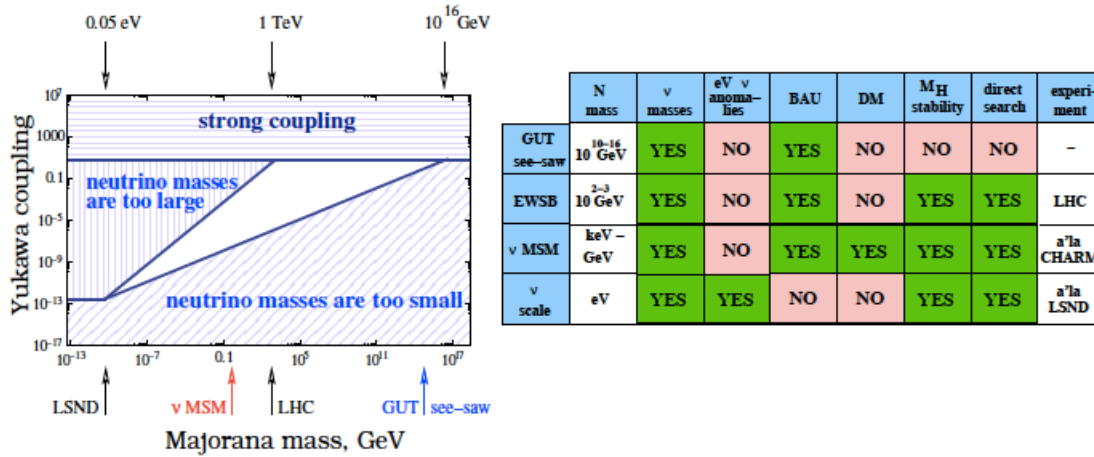
The experiments that can make decisive measurements are based on pion/muon or isotope decay-at-rest (DAR) sources. The DAE $\delta$ ALUS experiment described above could be used to generate a pion DAR beam for such a measurement. However, a proposal which uses the DAE $\delta$ ALUS injector cyclotron, called IsoDAR, can come on line much more quickly and produce a definitive result. This design uses protons from the injector cyclotron to produce neutrons, which then capture on  ${}^7\text{Li}$  to generate an isotope DAR source. Positioned next to a kiloton-scale scintillator detector such as KamLAND, one can search for sterile neutrinos by observing a deficit of antineutrinos as a function of the distance  $L$  and antineutrino energy  $E$  across the detector[44].

Specifically, the proposed IsoDAR target will be placed 16 m from the center of the KamLAND detector. The antineutrinos propagate a distance of 9.5 m, through a combination of rock, outer muon veto, and buffer liquid, to the active scintillator volume defined by a 6.5 m radius nylon balloon. The antineutrinos are then detected via the IBD interaction. The excellent energy and position resolution of KamLAND leads to a well-reconstructed  $L/E$  for the event. Example data sets for favored 3+1 and 3+2 sterile neutrino parameters are shown in Fig. 5.

The production of sterile neutrinos connects directly back to the LHC physics. The previous discussion has considered heavy neutrinos in the  $\sim$  eV range. However, much heavier neutrinos, in the 100s of GeV range, can arise from certain see-saw models and loop models [11]. Fig. 6, from Ref. [4], presents possible allowed masses and Yukawa couplings of sterile neutrinos within seesaw models. The right panel summarizes the role that these sterile neutrinos may play in solving Standard Model problems and Beyond Standard Model anomalies. The final column shows the preferred type of experiment to address the sterile neutrino, underlying the very strong connection between the experiments discussed in this paper and the LHC.

## 6. Conclusion

This review has highlighted the strong intellectual ties between LHC and neutrino experiments. We have explored the intellectual overlap through three example questions: What is the origin of mass? What is the meaning of flavor? Is there direct evidence of new forces or particles? However, these are only a few of the questions which bridge the two communities. The richness of particle physics as a field can be seen by the way these two very different approaches to experiments push the community toward new ideas and questions.



**Figure 6.** Allowed combinations of sterile neutrino masses and Yukawa couplings in see-saw models [4].

## References

- [1] C. Mariani, *Mod. Phys. Lett. A* **27**, 1230010 (2012) [arXiv:1201.6665 [hep-ex]].
- [2] G. J. Feldman, J. Hartnell and T. Kobayashi, *Adv. High Energy Phys.* **2013**, 475749 (2013) [arXiv:1210.1778 [hep-ex]].
- [3] B. Schwingerheuer, *Annalen Phys.* **525**, 269 (2013) [arXiv:1210.7432 [hep-ex]].
- [4] K. N. Abazajian, *et al.*, “Light Sterile Neutrinos: A White Paper,” arXiv:1204.5379 [hep-ph].
- [5] A. Karle, *Nucl. Phys. Proc. Suppl.* **235-236**, 364 (2013) [arXiv:1210.2058 [astro-ph.IM]].
- [6] S. Schael *et al.* [ALEPH and DELPHI and L3 and OPAL and SLD and LEP Electroweak Working Group and SLD Electroweak Group and SLD Heavy Flavour Group Collaborations], *Phys. Rept.* **427**, 257 (2006) [hep-ex/0509008].
- [7] M. C. Gonzalez-Garcia, M. Maltoni, J. Salvado and T. Schwetz, *JHEP* **1212**, 123 (2012) [arXiv:1209.3023 [hep-ph]].
- [8] C. Weinheimer and K. Zuber, *Annalen der Physik*, **525**, 565 (2013) [arXiv:1307.3518 [hep-ex]].
- [9] T. Kajita, *Adv. High Energy Phys.* **2012**, 504715 (2012).
- [10] M. Nakahata, *Lect. Notes Phys.* **367**, 49 (1990).
- [11] R. N. Mohapatra, *J. Phys. Conf. Ser.* **408**, 012005 (2013).
- [12] M. Sturm [KATRIN Collaboration], *PoS DSU* **2012**, 037 (2012).
- [13] J. A. Formaggio [Project 8 Collaboration], *Nucl. Phys. B, Proc. Suppl.* 229-232 **2012**, 371 (2012) [arXiv:1101.6077 [nucl-ex]].
- [14] S. Pascoli, S. T. Petcov and A. Riotto, *Phys. Rev. D* **75**, 083511 (2007) [hep-ph/0609125].
- [15] M. Yeh, A. Garnov and R. L. Hahn, *Nucl. Instrum. Meth. A* **578**, 329 (2007).
- [16] J. Klein, private communication.
- [17] T. IceCube [PINGU Collaboration], “PINGU Sensitivity to the Neutrino Mass Hierarchy,” arXiv:1306.5846 [astro-ph.IM].
- [18] P. A. R. Ade *et al.* [Planck Collaboration], “Planck 2013 results. XVI. Cosmological parameters,” arXiv:1303.5076 [astro-ph.CO].
- [19] L. Montanet, *et al.* [Particle Data Group], *The Review of Particle Physics*, *Phys. Rev. D* **50** (1995) 1173.

- [20] Y. Abe *et al.* [DOUBLE-CHOOZ Collaboration], Phys. Rev. Lett. **108**, 131801 (2012) [arXiv:1112.6353 [hep-ex]].
- [21] F. P. An *et al.* [Daya Bay Collaboration], Chin. Phys. C **37**, 011001 (2013) [arXiv:1210.6327 [hep-ex]].
- [22] J. K. Ahn *et al.* [RENO Collaboration], Phys. Rev. Lett. **108**, 191802 (2012) [arXiv:1204.0626 [hep-ex]].
- [23] T. J. C. Bezerra, H. Furuta, F. Suekane and T. Matsubara, Phys. Lett. B **725**, 271 (2013) [arXiv:1304.6259 [hep-ex]].
- [24] P. Adamson *et al.* [MINOS Collaboration], Phys. Rev. Lett. **110**, 251801 (2013) [arXiv:1304.6335 [hep-ex]].
- [25] P. Huber, Talk presented on Friday, “CP violation reach in the next decade and beyond,” presented at Snowmass at the Mississippi July 26 August 6, 2013, Minneapolis.
- [26] T. Enqvist, A. Mattila, V. Fohr, T. Jamsen, M. Lehtola, J. Narkilahti, J. Joutsenvaara and S. Nurmeniemäki *et al.*, Nucl. Instrum. Meth. A **554**, 286 (2005) [hep-ex/0506032].
- [27] L. Agostino *et al.* [MEMPHYS Collaboration], JCAP **1301**, 024 (2013) [arXiv:1206.6665 [hep-ex]].
- [28] E. Baussan, M. Dracos, T. Ekelof, E. F. Martinez, H. Ohman and N. Vassilopoulos, arXiv:1212.5048 [hep-ex].
- [29] C. Adams *et al.* [LBNE Collaboration], arXiv:1307.7335 [hep-ex].
- [30] E. Kearns *et al.* [Hyper-Kamiokande Working Group Collaboration], “Hyper-Kamiokande Physics Opportunities,” arXiv:1309.0184 [hep-ex].
- [31] A. A. Aguilar-Arevalo *et al.* [MiniBooNE Collaboration], Nucl. Instrum. Meth. A **599**, 28 (2009) [arXiv:0806.4201 [hep-ex]].
- [32] M. Fechner *et al.* [Super-Kamiokande Collaboration], Phys. Rev. D **79**, 112010 (2009) [arXiv:0901.1645 [hep-ex]].
- [33] M. R. Vagins, Nucl. Phys. Proc. Suppl. **229-232**, 325 (2012).
- [34] M. Wurm *et al.* [LENA Collaboration], Astropart. Phys. **35**, 685 (2012) [arXiv:1104.5620 [astro-ph.IM]].
- [35] C. Aberle, A. Adelman, J. Alonso, W. A. Barletta, R. Barlow, L. Bartoszek, A. Bungau and A. Calanna *et al.*, arXiv:1307.2949 [physics.acc-ph].
- [36] C. Boehm, P. S. B. Dev, A. Mazumdar and E. Pukartas, JHEP **1306**, 113 (2013) [arXiv:1303.5386 [hep-ph]].
- [37] Y. Zhang, X. Ji and R. N. Mohapatra, “A Naturally Light Sterile neutrino in an Asymmetric Dark Matter Model,” arXiv:1307.6178 [hep-ph].
- [38] J. M. Conrad, W. C. Louis and M. H. Shaevitz, Ann. Rev. Nucl. Part. Sci. **63**, 45 (2013) [arXiv:1306.6494 [hep-ex]].
- [39] G. Mention, *et al.*, Phys. Rev. D **83**, 073006 (2011) [arXiv:1101.2755 [hep-ex]].
- [40] J. N. Abdurashitov *et al.* [SAGE Collaboration], Phys. Rev. C **80**, 015807 (2009) [arXiv:0901.2200 [nucl-ex]].
- [41] F. Kaether, W. Hampel, G. Heusser, J. Kiko and T. Kirsten, Phys. Lett. B **685**, 47 (2010) [arXiv:1001.2731 [hep-ex]].
- [42] M. Sorel, J. M. Conrad and M. Shaevitz, Phys. Rev. D **70**, 073004 (2004) [arXiv:hep-ph/0305255].
- [43] J. M. Conrad, C. M. Ignarra, G. Karagiorgi, M. H. Shaevitz and J. Spitz, Adv. High Energy Phys. **2013**, 163897 (2013) [arXiv:1207.4765 [hep-ex]].
- [44] A. Bungau, A. Adelman, J. R. Alonso, W. Barletta, R. Barlow, L. Bartoszek, L. Calabretta and A. Calanna *et al.*, Phys. Rev. Lett. **109**, 141802 (2012) [arXiv:1205.4419 [hep-ex]].