Outlook: Theory

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Abstract. I select and discuss a few recent theoretical developments in neutrino physics

1. Beyond the Standard Model and ν masses

The existence of tiny neutrino masses is probably the first signal of physics beyond the Standard Model (SM). One can envision various possibilities for such new physics, and the simplest is to assume that it's associated energy scale is above the electroweak scale. It is well-known, since the pioneering work of Weinberg [1], that the appropriate language to describe the low-energy effects of such new physics, no matter what it is, is that of *effective field theory*. The effects of *any* beyond-the-standard-model dynamics with a characteristic energy scale, $\Lambda \gg v$, can be described at low-energies, ie. $E < \Lambda$, by the SM Lagrangian plus a tower of operators with mass dimension, $d > 4$, constructed out of the SM fields and satisfying all the gauge symmetries. Even though the number of such operators is infinite, they can be classified according to their dimension, d, since an operator of dimension d must be suppressed by the scale Λ^{d-4}, and therefore higher dimensionality means stronger suppression in the high-energy scale:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{\alpha_i}{\Lambda} \mathcal{O}_i^{d=5} + \sum_i \frac{\beta_i}{\Lambda^2} \mathcal{O}_i^{d=6} + ... \tag{1}$$

Different fundamental theories correspond to different values for the *low-energy couplings* $\alpha_i, \beta_i, ...$, but the structure of the effective interactions is the same.

It turns out that the first operator in the list is the famous Weinberg's operator:

$$\mathcal{O}^{d=5} = \bar{L}^c \Phi \Phi L, \tag{2}$$

where Φ, L are the SM Higgs and lepton doublets respectively. This operator is the only one with $d = 5$ in the SM, and brings in three essential new features to the minimal SM:

- neutrino masses,
- lepton mixing,
- lepton number violation.

Upon spontaneous symmetry breaking, such operator induces a neutrino mass matrix of the form:

$$m_\nu = \alpha \frac{v^2}{\Lambda}, \tag{3}$$

where α is generically a matrix in flavour space. Neutrino masses are therefore expected to be naturally small if $\Lambda \gg v$.

If we assume that the neutrino masses we have measured are the result of this leading operator, one could ask the question, what type of new physics would induce such an interaction. In the same way that one can conjecture the presence of a massive gauge boson from the Fermi four-fermion interaction, one can classify the extra degrees of freedom that can induce at tree-level Weinberg's interaction. It turns out there are the three well-known possibilities as depicted in Fig. 1:

- type I seesaw: SM+ heavy singlet fermions [2]
- type II seesaw: SM + heavy triplet scalar [3]
- type III seesaw: SM + heavy triple fermions [4]

or combinations. The masses of the extra states define the scale Λ.

It is also possible that Weinberg's interaction is generated by new physics at higher orders, such as in the famous Zee model [6] and related ones [7]. In this case, the coupling α in eq. (1) will be suppressed by loop factors $1/(16\pi^2)$.

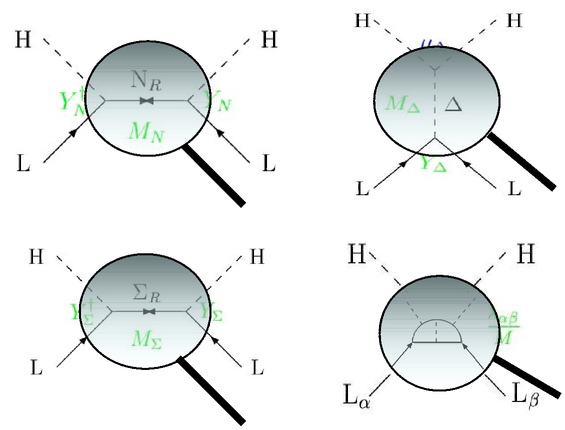

Figure 1. Magnifying-glass view of Weinberg's operator in seesaws Type I (up-left), Type II (up-right), Type III (down-left) and Zee-Bau model (down-right).

Unfortunately the measurement of neutrino masses alone will not tell us which of these possibilities is the one chosen by Nature. In particular, the measurement of Weinberg's interaction, leaves behind an unresolved $\alpha \leftrightarrow \Lambda$ *degeneracy* that makes it impossible to know what the scale of the new physics is, even if we knew the absolute value of neutrino masses.

Generically however, the new physics will give other signals beyond Weinberg's operator. The next in importance are the $d = 6$ operators of eq. (1)[5]. Recently the $d = 6$ operators induced at tree level in see-saw models of Types I-III have been worked out [8]. They give rise to a rich phenomenology, that could discriminate between the models. In particular, they could induce beyond the standard model signals in Z and W decays, deviations in the ρ parameter or the W mass, and mediate rare lepton decays, as well as violations of universality and unitarity of the neutrino mass matrix. It would therefore be extremely important to search for these effects. Whether they are large enough to be observed or not depends strongly on how high the scale Λ is, since all these effects are suppressed by two powers of Λ.

As mentioned before, neutrino masses alone do not tell us what Λ is, but there are several theoretical prejudices of what this scale should be. The most popular one is to relate Λ to a grand-unification scale, given the intriguing fact that the seesaw-type ratio $\frac{v^2}{M_{GUT}} \sim 0.01-0.1eV$, in the right ballpark of a neutrino mass scale. Recently however it has been pointed out [9] that within see-saw models, and without supersymmetry, this choice would destabilize the electroweak scale, since the Higgs mass would receive quadratic loop corrections in Λ. A naturalness argument would then imply that $\Lambda < 10^7$ GeV, at least if there is no supersymmetry.

Another possibility is to consider Λ to be related to the electroweak scale, i.e. not far from it. After all, the electroweak scale is the only scale we are sure exits. The question is then if such a choice would be testable via the measurement of the $d = 6$ operators. The answer to this question is no in the simplest type I seesaw model, because in order to get neutrino masses in the right ballpark when $\Lambda \sim$ TeV, it is necessary to have extremely small Yukawa couplings, which suppress also the $d = 6$ operators to an unobservable level. Several recent works have discussed the possibility to have larger effects of the $d = 6$ operators [11, 10, 8]. One possibility is that realized in Zee-type models where $d = 5$ operators are forbidden at tree level and are therefore suppressed by loop factors, while $d = 6$ operators are allowed at tree level and therefore unsuppressed. A more radical possibility is the existence of two independent scales in eq. (1), one that suppresses $d = 6$ operators, Λ_6, and another one, $\Lambda_5 \gg \Lambda_6$, that suppresses the $d = 5$ one. This possibility is not unnatural, because the $d = 5$ and $d = 6$ operators can be classified according to a a global symmetry: total lepton number. If we therefore assume that the scale at which lepton number is broken, Λ_{LN} is much higher than the scale at which lepton flavour violation, Λ_{LFV} is relevant, we can ensure that $d = 5$ operator, that breaks lepton number, is suppressed by the former scale, $\Lambda_5 \sim \Lambda_{LN}$, while the lepton-flavor effects induced by operators of $d = 6$ would be only suppressed by a lower scale $\Lambda_6 \sim \Lambda_{LFV} << \Lambda_{LN}$. The effective field theory describing such possibility would look therefore as:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{\alpha_i}{\Lambda_{LN}} \mathcal{O}_i^{d=5} + \sum_i \frac{\beta_i}{\Lambda_{LFV}^2} \mathcal{O}_i^{d=6} + ..., \tag{4}$$

where the operators that break lepton number and those that preserve this symmetry are generically suppressed by different scales. Such possibility has been recently considered in the context of the popular Minimal Flavour Violation hypothesis[11]. The underlying rationale for such an assumption is not completely ad hoc, since in this context one could hope to explain two apparently contradicting facts:

- common origin of lepton and quark family mixing at a scale Λ_{LFV},
- large gap between neutrinos masses and remaining fermions since neutrino masses would be suppressed by Λ_{LN} .

In fact this separation of scales is built-in in several of the models mentioned before. The simplest example being the type II see-saw model, where the scalar-triplet mass, M_Δ is directly connected with the Λ_{LFV}, while the scale of lepton number violation is M_Δ^2/μ, where μ is a dimensionfull coupling in the scalar potential of the triplet. In fact, it is the separation of scales that makes the phenomenology of this model much richer at low energies than that of type I see-saw models in their simplest version.

If this possibility is realized, there would be many interesting consequences:

- lepton flavour violation could be measurable beyond neutrino oscillations
- the scale of lepton flavour violation, Λ_{LFV} could be reached at LHC.

In the past years a lot of activity has been devoted to studying possible signals of neutrino masses at the LHC. There was a nice review talk on this topic by G. Senjanovic at this conference [12]. Lepton number violation could give rise to spectacular signals at LHC, like same-charge lepton pairs [13]. This signal has been studied in detail recently in various see-saw models. In one-scale models of type I, neutrino masses restrict these processes to be highly suppressed beyond detectable levels [14]. However, the separation of scales mentioned before, allows to have light enough triplets in the type II see-saw to be pair-produced at LHC:

$$pp \to H^{++}H^{--} \to l^+l^+l^-l^-, \tag{5}$$

leading to the powerfull signal of same-charge lepton pairs. Not only the invariant mass can be reconstructed from the two leptons pairs, but the flavour structure of the branching rations to different leptons is in one-to-one correspondance with the flavour structure of the neutrino mass matrix. Therefore the putative measurement of these processes would provide direct information on the neutrino mass matrix [15].

Solving the flavour problem of the Standard Model is surely a quixotesque enterprise and we will need to explore as many avenues as we can. In recent years it has become increasingly clear that besides quark flavour factories, we can get very valuable information on different aspects of this puzzle also from LHC and lepton flavour factories.

1.1. Leptogenesis

One of the most interesting implications of neutrino masses is the possibility to explain the baryon asymmetry observed in the Universe through leptogenesis [16]. It has been shown to work in most models of neutrino masses, in particular in the type I [16], II [17] and III[18] see-saw models, from the out-of-equilibrium decay of the various heavier states involved. Recently there has been an important step forward in these analyses: lepton flavour has been properly taken into account, what has been refered to as *flavoured leptogenesis* [19]. It has been shown that following the dynamics of the independent lepton numbers L_e, L_μ, L_τ can lead to significant differences with respect to the old analyses where flavour effects were neglected, such as relaxing the tight bound on the lightest neutrino mass.

There was a very nice review on this topic by Y. Nir at this conference [20] and I refer to his contributions for details. A brief summary of the present situation is that the leptogenesis requires as ingredients: 1) rather heavy extra states with masses above 10^9 GeV (e.g. the singlets or triplets in the see-saw models), 2) not too light lightest neutrino mass (the bound has been relaxed to a confortable $m_\nu <$ few eV, 3) CP and lepton number violation in the lepton flavour sector, that have not been confirmed yet. With these ingredients, a Universe like ours could have developed from a matter-antimatter symmetric initial condition. Unfortunately the neutrino mass matrix does not contain sufficient information to provide us with the exact recipe to our Universe, or in other words, we cannot predict quantitatively the baryon asymmetry of the Universe from the precise measurement of the neutrino mass matrix.

1.2. Neutrino masses and hidden sectors

Beyond the flavour puzzle there are various other unsolved puzzles in the Standard Model such as dark matter, dark energy, the LSND anomaly, etc. Several possibilities to solve these problems have been discussed in the literature, that involve *hidden* sectors: new particles/interactions relevant at low-scales (below the electroweak scale), but too weakly interacting with ordinary matter to be observed. Examples of this type are: keV sterile neutrinos that have been proposed as candidates for dark matter[21], mass-varying neutrinos that could be responsible for dark-energy [22], and a long etcetera.

These *hidden* sectors do not offer an explanation of the small ν masses, but neutrinos can play a leading role as messengers with the hidden sector, since they are the only particles in the Standard Model that carry no conserved charge.

I will briefly mention a couple of examples that were introduced last year in an attempt to reconcile the LSND result. The simplest old explanation of the LSND anomaly is the existence of light sterile neutrino species, which could be classified as a *hidden* sector, according to the above definition. A recent analysis [23] shows that both possibilities $3+1$ and $3+2$[24] (ie. one or two extra sterile species) are in very bad shape after the first MiniBoone results. This has given way to the exploration of new, more exotic avenues. In particular, the observation that the neutrino energy and baseline for LSND are one order of magnitude smaller than for MiniBoone suggests that they might be reconciled with an energy-dependent effect. Two intriguing possibilities have been considered:

- Light sterile neutrinos and a very light $B-L$ gauge boson[25]: the effective $B-L$ potential for neutrinos propagating in matter could induce a MSW effect strongly affecting the MiniBoone oscillation probabilities, and to a lesser extent those measured by LSND. For values of the parameters consistent with other neutrino oscillation data and with constraints on massive gauge bosons, the neutrino appearance oscillation probability at MiniBoone is highly suppressed, and that in antineutrinos will be strongly enhanced, while reproducing the LSND result.
- Soft quantum-decoherence with a peculiar energy dependence of the decoherence parameter of the form

$$\gamma \sim \frac{1}{E_\nu^4} \tag{6}$$

is consistent with all available neutrino oscillation data including MiniBoone and LSND [26]. The model is however very constrained to the extent that it even predicts a non-zero value of θ_{13}, that could be within reach in future reactor experiments and in T2K.

Typically these type of models are strongly constrained by neutrino physics and cosmology which implies that they can be tested in the near future, however sometimes in unexpected ways. For example the light $B-L$ gauge-boson model predicts an observable possitive signal in the MiniBoone antineutrino run. The decoherence model predicts that the reactor experiment Double-Chooz would observe a large disappearance signal, but it will be the same in both near and far detector, making it challenging to control systematic errors to the required level.

The moral of all this is that neutrino physics can constrain significantly unconventional types of new physics (for a recent review of the neutrino constraints on some of these models see [27]) that in many cases will be hard to test otherwise. This underlines the importance of exploring unexplored neutrino oscillation parameter space, beyond that indicated by the standard three-family mixing scenario. It is good news that future experiments will do precisely this, such as the Osc-SNS experiment [28], Minerva, or even LHC [29].

2. News in Standard Model massive neutrinos

Recent years have brought interesting news concerning massive neutrinos doing standard things.

2.1. Foundations of neutrino oscillations

In the past year, there was a heated discussion, once more, about the foundations of neutrino oscillations, in the context of two new types of experiments: one proposed, Mössbauer neutrinos [30], and one at GSI that has found an anomaly, which has been suggested to be a neutrino oscillation phenomena[35]. A typical neutrino oscillation experiment is depicted in Fig. 2, where *localized* initial states at source and target interchange a neutrino, that being so weakly interacting can propagate over macroscopically large distances. The fact that the initial states are localized implies that they are not mometum eigenstates, and this is essential because oscillations in space require an uncertainty in momentum. On the other hand the uncertainty in energy of those states might or might not be related to the uncertainty in momentum. For relativistic states they are of course related since the external states are on shell and we necessarily have $\Delta E/E \sim \Delta p/p$. However if the initial state is a bound state then the energy

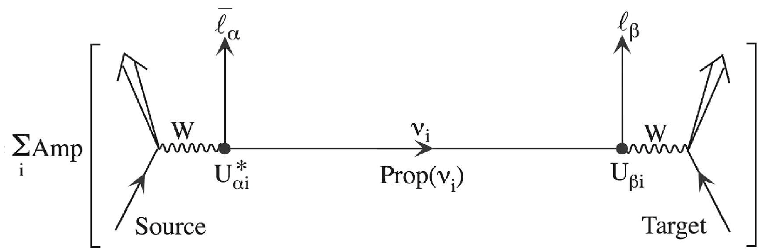

Figure 2. Amplitude in a typical neutrino oscillation experiment.

could be much better defined than the momentum (e.g. a state of the harmonic oscillator is an eigenstate of energy but not of momentum). Mössbauer neutrino oscillation experiment can be modelled precisely in this way. In this type of experiment neutrinos are produced by e-capture in tritium atoms that are bound in a cristal. The energy of the neutrino is as well-defined as the energy of the initial tritium atom, because the recoil is strongly suppressed, as in the standard Mössbauer experiments with light. The neutrino is then absorbed by the inverse process in a similar *detector* cristal located some distance away. It has been argued that neutrino oscillations cannot occur in this setup since the uncertainty in energy of the neutrinos is as small as $\Delta E/E \sim 10^{-15}$. Akhmedov and collaborators [31] have argued otherwise by modelling this setup like a typical neutrino oscillation experiment in which the external states that produce and absorbe the neutrino are states of an harmonic oscillator. They have explicitely computed the oscillation probability and found that neutrinos can oscillate as a function of the distance between the source and detector cristals, provided the uncertainty in momentum of the ion states is large enough. They have also shown how this result is compatible with the uncertainty relation of time and energy, contradicting the results of [32].

I believe that the possibility to observe neutrino oscillations in Mössbauer neutrino experiments is sound from a theoretical point of view. Whether these experiments can be done in practice is a different story (the technical challenges have been described in Potzel's talk [33]). If feasible they would be extremely interesting. Recent works have shown that they could even be sensitive to the hierarchy of neutrino masses from a very precise measurement of the two mass splittings $|\Delta m^2_{13}|$ and $|\Delta m^2_{23}|$ [34].

Concerning the GSI anomaly, this refers to the observation of a beating pattern in the decay probability as a function of time of highly-ionized hydrogen-like ions (e.g. $^{140}Pr^{58+}$) that decay inside a storage ring via electron capture. The synchroton frequency of the circulating ions is monitored in real time in such a way that the decay time can be identified by a jump in the synchroton frenquency resulting from the change in the charge-to-mass ratio. Neutrinos are produced in each of these decays and it has been suggested in [35] that the beating pattern could be associated to the oscillation of neutrinos between the different mass eigenstates, the oscillation frenquency being related to the solar mass splitting. A number of papers have appeared in the archives arguing in favor [36] or against [37] this mechanism.

For this mechanism to work, the amplitudes for decay into the different neutrino mass eigenstates must be added coherently, which is in blunt contradiction to the rules of quantum mechanics, where we are told that the amplitudes corresponding to different final states should be added incoherently in order to compute a decay probability. This incoherent sum actually results from a basic principle such as unitarity. Indeed the survival probability of a state $|i\rangle$ is given by

$$|\langle i|S|i\rangle|^2 = 1 - \sum_{f\neq i} |\langle i|S|f\rangle|^2 \tag{7}$$

where S is the S-matrix and the sum over final states $|f\rangle$ is incoherent. It is trivial to arrive at the right-hand side by a simple manipulation of the left-hand side:

$$\langle i|S|i\rangle\langle i|S^\dagger|i\rangle = \langle i|S\sum_f |f\rangle\langle f|S^\dagger|i\rangle - |\langle i|S\sum_{f\neq i}|f\rangle\langle f|S^\dagger|i\rangle, \tag{8}$$

where using only the unitarity $SS^\dagger = Iden$ and the completeness of the basis of states $\sum_f |f\rangle\langle f| = Iden$, one gets eq. (7).

A completely different story is if there is coherence in the initial state, instead of looking at the survival probability of a state $|i\rangle$ we look at that of a mixed state $\alpha_i|i_1\rangle + \alpha_2|i_2\rangle$. In fact such beating pattern has been observed before in systems where the initial state is a mixture of levels. In this case, the phenomenon of beating generically takes place and the beating frecuency is related to the splitting of those levels. Would this be the explanation of the GSI anomaly, the challenge is to understand the origin of the tiny mass splitting that is required: $\Delta E \sim 10^{-15} eV$.

In this conference, M. Lindner [38] presented another account of why the GSI anomaly cannot be abscribed to neutrino oscillations and I refer to this reference for further details. The good news is that the anomaly will be further scrutinized at GSI, by for example changing the parent ion.

2.2. Anomaly mediated $\nu\gamma$ interactions

It has been recently pointed out [39] that anomalous processes could give rise to standard, but previously overlooked, $\nu\gamma$ interactions. The same mechanism that allows us to describe the decay $\pi^0 \to \gamma\gamma$, via the axial anomaly, would predict the presence of the vertex $Z\gamma\omega$ via the $B+L$ anomaly. At sufficiently low energies both processes can be described by the Wess-Zumino-Witten chiral Lagrangian [40], where the structure of this vertex is fixed [39] by the anomaly matching.

Such processes could provide a new source of irreducible neutral current background to the appearance channel $\nu_\mu \to \nu_e$ as shown in Fig. 3, since the photon at low energies cannot be distinguished from an electron. Even though there is a significant uncertainty in the normalization of the vertex of Fig. 3, an order-of-magnitud estimate indicates that it could be significant in MiniBoone and actually could be even related to the low-energy excess observed at low-energies below 500 MeV (see MiniBoone contribution to this conference [41]). If this mechanism is confirmed to play a role in the MiniBoone excess it would be fair to call this excess the MiniBoone anomaly !

There are other potentially relevant applications of this mechanism in the cooling of neutron start and the supernova energy transfer that are starting to be studied.

This mechanism underlines the importance of measuring and understanding neutrino cross-sections at low-energies, as many running and future experiments will be doing in the near future such as MiniBoone, SciBoone, Minerva, T2K, etc (see talk by S. Zeller on this topic [42]). After all, these anomalous interactions are a direct consequence of the presence of $B+L$ violation in the SM and might be the only direct way to test this essential ingredient of baryogenesis: all mechanisms that can explain the matter/antimatter asymmetry of the universe rely on the anomalous breaking of this global symmetry.

2.3. New standards in nuclear matrix elements of neutrinoless double beta decay

The pesimistic view presented in [43] concerning the huge uncertaintities in the computation of nuclear matrix elements for neutrinoless double beta decay, steered a lot of activity in the nuclear theory community to try and improve those estimates.

In the past years we have seen a significant improvement in the understanding of the systematics of the different approaches. The result is a much better agreement between the

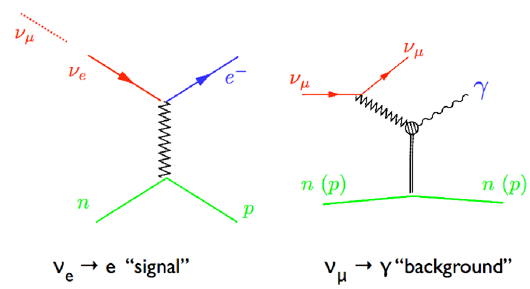

Figure 3. Left: neutral current process via $B + L$ anomaly that could mimick an electron charged-current (right).

two main approaches: the quasi-particle random phase approximation (QRPA) and the Shell model (ShM). An updated comparison of the two (see for example the recent review [44]) shows that for some elements like Xenon they agree very well, while for others they disagree within a factor 2 or so. Detailed recent studies in the context of the ShM [46] and the QRPA [45] have shown that differences between the two could be abscribed to the different treatment of the contribution of broken-pair states (higher seniorities), and of the short-range correlations. Both effects have been shown to be much more relevant that previously thought. This also shows how the different approaches must be improved. Although uncertainties are still high, the possibility that eventually it will be possible to predict robustly those matrix elements looks much more promising that a few years back.

2.4. Supernovae neutrinos fluxes

In the past two years the field of supernova neutrinos has moved *back-to-basics*, after the realization [47] that non-linear effects due to coherent $\nu - \nu$ interactions inside a supernova give rise to new and interesting collective effects that can significantly modify previous predictions for supernova ν fluxes. There seems to be a robust prediction, the famous *spectral split* [48] if the hierarchy is inverse and θ_{13} is not zero, which gives rises to a peculiar spectral shape of the ν_e fluxes as compared to the ν_μ and ν_τ fluxes. Whether such effect can be measured in practice is still unclear.

There was a detailed review talk on supernova neutrinos at this conference [49] and I refer to the writeup of this talk for details and the extensive recent literature on the subject.

3. Future

There are a number of smoking-guns for new physics associated to neutrino masses, and future neutrino experiments will follow those leads:

- the Majorana nature of neutrinos implies a new physics scale,
- the presence of other light (and sterile) neutrino species implies that there is at least another mechanism for mass generation, since a Higgs Yukawa cannot work for these extra states
- violations of unitarity in mixing are quite generic in models of neutrino masses

- flavour symmetries in lepton Yukawa matrices could be responsible for the large mixing angles [1]
- other non-standard neutrino interactions
- violations of funamental symmetries: CPT, Lorentz, etc
- subleading effects in oscillations: decay, decoherence, etc

In spite of whether we find any of the above, we should at least aim at measuring as precisely as possible the neutrino mass matrix, which involves generically nine physical parameters: three masses, three mixing angles and three CP violating phases (one if there is no violation of lepton number).

We have seen in this conference how we have already entered an era of precision for several of these quantities. R. Zukanovitch-Funchal reported the following results of global analyses of neutrino data (see [51] for details) at 2σ CL:

$$\theta_{23} = [36.9^\circ, 51.3^\circ] \quad \theta_{23} = [32.3^\circ, 37.8^\circ] \quad \theta_{13} < 10.3^\circ \tag{9}$$

$$\Delta m^2_{21} = 7.66(35) \times 10^{-5} eV^2 \quad |\Delta m^2_{23}| = 2.38(27) \times 10^{-3} eV^2. \tag{10}$$

If we compare the situation of the lepton and quark mixing matrices however the situation is rather unsatisfactory. From the PDG:

$$V_{CKM} = \begin{pmatrix} 0.97383(24) & 0.2272(10) & 3.96(9) \times 10^{-3} \\ 0.2271(10) & 0.97296(24) & 42.21^{+0.10}_{-0.80} \times 10^{-3} \\ 8.14^{+0.32}_{-0.64} \times 10^{-3} & 41.61^{+0.12}_{-0.78} \times 10^{-3} & 0.9991^{+0.000034}_{-0.000004} \end{pmatrix}, \tag{11}$$

while from [27]:

$$|U|_{3\sigma} = \begin{pmatrix} 0.77 \to 0.86 & 0.50 \to 0.63 & 0. \to 0.22 \\ 0.22 \to 0.56 & 0.44 \to 0.73 & 0.57 \to 0.8 \\ 0.21 \to 0.55 & 0.40 \to 0.71 & 0.59 \to 0.82 \end{pmatrix}. \tag{12}$$

There is clearly some homework to do since a similar precision will be essential to test GUT inspired models and lepton flavour symmetries [50]. In recent years a lot of effort has been devoted to figuring out how to do this in future neutrino experiments. It turns out that the measurement of the two unknown parameters: θ_{13}, δ, as well as the determination of the neutrino hierarchy and the octant of θ_{23} can be all determined in neutrino oscillations in the atmospheric range, involving the ν_e. In particular the channel $\nu_e \leftrightarrow \nu_\mu$ has been identified as the *golden* one. The challenge will be to measure for the first time tiny amplitudes, and to resolve all the parameters, since there are various parameter degeneracies [53].

Several strategies have been proposed and studied in detail in the context of neutrino factories, superbeams and beta-beams or combinations of them. Figure 4 shows the range of neutrino energies of the proposed future facilies. The measurement of thea ppearance golden channel in the atmospheric range requires to be close to the thick line labelled "atm" and above muon threshold. The experiments will need therefore baselines in the range of $\mathcal{O}$(few 100) or $\mathcal{O}$(few 1000) km, implying that these projects will necessarily transpasse national frontiers. Reactor experiments measuring the disappearance channel will provide very valuable information on θ_{13} that can help in resolving parameter degeneracies [54, 55].

A recent review of the studies of the physics reach of various future facilities is the ISS report from which we took Figure 5 [56]. See also the topical talks in this conference[57, 59, 58, 60] for further details. The summary of the present situation is that it looks feasible to measure leptonic CP violation and the neutrino mass hierarchy down to $\sin^2 2\theta_{13} \sim 10^{-4}$.

[1] S. King reviewed models of neutrino masses and I refer to his contribution for an update on this subject [50].

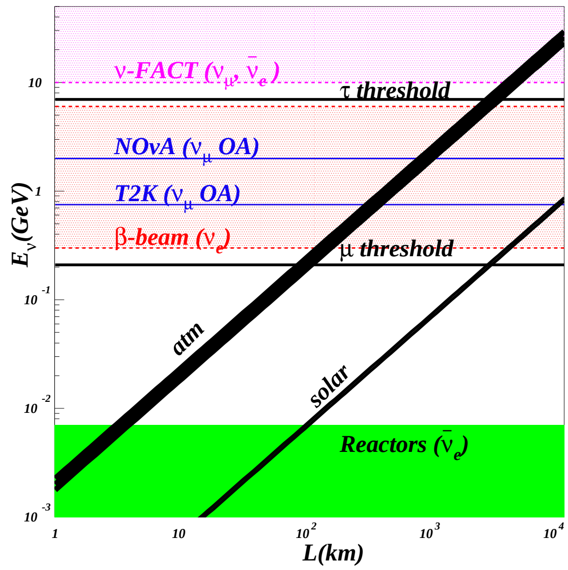

Figure 4. Energy of the proposed future neutrino oscillation experiments: Nufact, β-beam, superbeams (T2K and NOvA) and reactors. The *atm* and *solar* black bands correspond to the first atmospheric and solar oscillation peaks respectively.

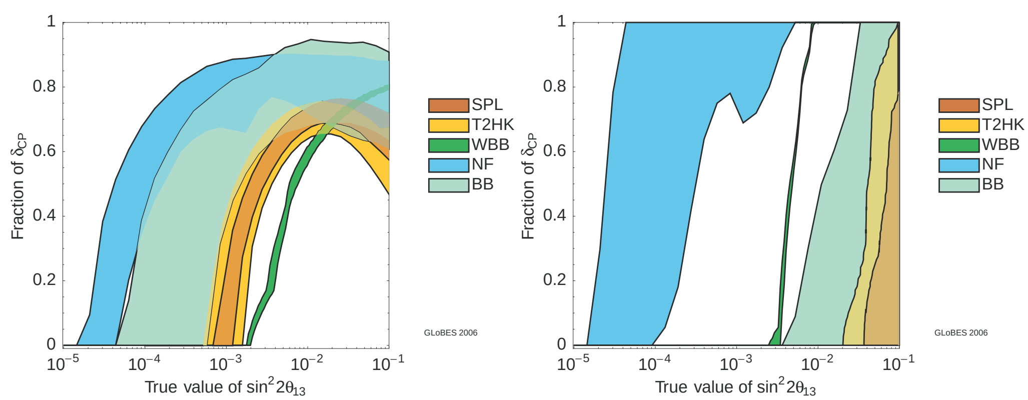

Figure 5. Left: sensitivity limit to leptonic CP violation in the plane $(\sin^2 2\theta_{13}, \delta)$ of superbeams (SPL, T2KHK), the wide band beam (WBB), Neutrino Factory (NF) and β-beams (BB). The bands correspond to most/less conservative assumptions concerning the facility/detectors. Right: sensitivity limits to the neutrino mass hierarchy in the same facilities.

Besides long-baseline experiments, it has become clear in recent years that there are very important synergies with neutrino experiments from natural sources. In particular it has been pointed out that atmospheric neutrino experiments with more massive/more performing detectors could give very valuable complentary information on θ_{23} or the neutrino hierarchy [61, 62, 63]. Also suprisingly, neutrino telescopes could provide information of θ_{13}, θ_{23} and δ in certain regions of parameter space (see [65]). Finally a supernova neutrino signal could be the only way to test extremely small values of θ_{13} and the neutrino hierarchy [49].

Beyond the standard 3ν scenario these future facilities could also improve significantly the sensitivity to new physics in the neutrino sector in the form of non-standard interactions, violation of CPT or unitarity. A lot has already been done in the past years and more is expected (see [23, 57] for details). It has been pointed out that if synergies are important to resolve parameter degeneracies in the standard scenario, they are even more crucial in the presence of non standard physics. In particular it will be very important to search for deviations from the standard scenario in all possible accelerator-based experiments: long baseline, short baseline, searches of rare processes, eletroweak precision tests and even LHC; but also in reactor experiments, as well as in astrophysical neutrino experiments.

Concerning the absolute scale of neutrino masses or the *Majorananess* of neutrinos, other non-oscillation experiments will be needed. The best hope is at present the detection of neutrinoless double-beta decay, and the input from cosmology that can constrain the neutrino component of matter in the Universe. In both areas important progress is to be expected in the near future. Figure 6 (taken from [64]) shows the summary of the present situation. The contours labelled IH (inverted hierarchy) and NH (normal hierarchy) indicate the present allowed regions in the plane of the two quantities measured by neutrinoless double-beta decay, $m_{\beta\beta}$, and cosmology, $\Sigma = \sum_\nu m_\nu$. These bounds are rather conservative as they only include cosmology information from CMB measurements. The next step in the neutrinoless double-beta decay experiments is to reach the 0.1 eV level, but there are already plans to improve even another order of magnitude, so that the full IH region can be explored (see [66, 67, 68, 70]). On the horizontal axis, cosmology is expected to improve the present limit by another order of magnitude in the next ten years [71].

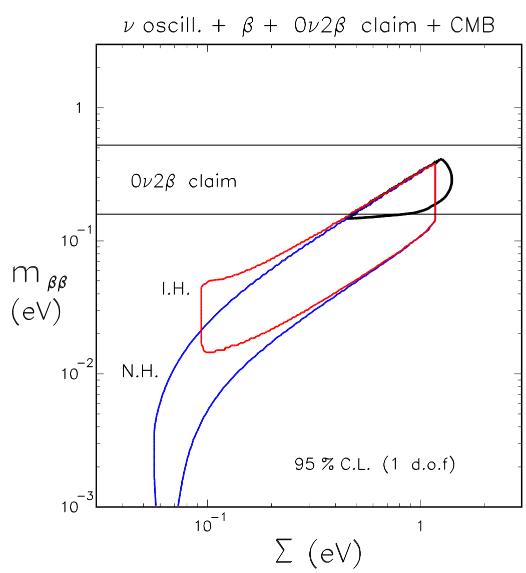

Figure 6. Present constraints on $m_{\beta\beta}$ and Σ from neutrino experiments and CMB data. Taken from [64].

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