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Neutrinos in the time of Higgs

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Abstract. In this paper, the recent progress in the determination of neutrino oscillation parameters and future prospects have been discussed. The tiny neutrino masses as inferred from oscillation data and cosmology cannot be explained naturally by the Higgs mechanism and warrant some new physics. The latter can be connected to the Majorana nature of the neutrinos which can be probed by neutrinoless double beta decay ($0\nu\beta\beta$). The paper also summarizes the latest experimental results in $0\nu\beta\beta$ and discusses some implications for the left–right symmetric model which could be a plausible new physics scenario for the generation of neutrino masses.

Keywords. Neutrino mass; oscillation; neutrinoless double beta decay.

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1. Introduction

Three fundamental questions about neutrinos puzzled physicists in the last century: (i) Do neutrinos have mass? If so then how small? (Pauli, Fermi, 1930s), (ii) are neutrinos Majorana particles i.e., can they be their own antiparticles (Majorana, 1930s) and (iii) do neutrinos of different flavour oscillate amongst each other? (Pontecorvo, 1960s). These questions have been answered partially in the last two decades. Neutrino oscillations have been observed from solar, atmospheric, reactor and accelerator neutrinos, establishing that neutrinos have mass and there is mixing between different flavours. Latest Planck results give a bound on the sum of the masses of the light neutrinos as $\sum m_i \leq 0.23$ eV [1].

The Majorana nature of the neutrinos can be probed by $0\nu\beta\beta$ process. However, there had been no definitive evidence yet for this. The tiny neutrino masses as deduced from oscillation data and cosmology cannot be incorporated naturally in the Standard Model (SM). Thus non-zero neutrino masses imply new physics beyond the SM. This can be connected to the Majorana nature of neutrinos and may throw light on the mechanism of mass generation, unification scenarios and the baryon asymmetry of the Universe.

2. Three-flavour neutrino oscillation

Neutrino oscillation is a quantum mechanical interference phenomenon in which neutrinos change flavour after passing through a long distance. This is possible if neutrinos have mass and mixing. In this case, the eigenstates of the propagation Hamiltonian are linear superposition of flavour or gauge eigenstates: $\nu_\alpha = U_{\alpha i}\nu_i$; here U is the mixing matrix. For three neutrino flavours, the mixing matrix known as the PMNS matrix is given as

$$U = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,\mathrm{e}^{-i\delta} \\ -c_{23}\,s_{12} - s_{23}\,s_{13}\,c_{12}\,\mathrm{e}^{i\delta} & c_{23}\,c_{12} - s_{23}\,s_{13}\,s_{12}\,\mathrm{e}^{i\delta} & s_{23}\,c_{13} \\ s_{23}\,s_{12} - c_{23}\,s_{13}\,c_{12}\,\mathrm{e}^{i\delta} & -s_{23}\,c_{12} - c_{23}\,s_{13}\,s_{12}\,\mathrm{e}^{i\delta} & c_{23}\,c_{13} \end{pmatrix} P, \tag{1}$$

where $c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$ and δ is the Dirac CP phase. The phase matrix $P = \mathrm{diag}(1, \mathrm{e}^{i\alpha_2}, \mathrm{e}^{i\alpha_3})$ contains the Majorana phases α_2 and α_3. In neutrino oscillation probabilities these phases do not appear. For a neutrino of flavour ν_α and energy E travelling through a distance L, the probability of oscillation in vacuum from one flavour to another is given by

$$\begin{aligned} P_{\alpha\beta} &= \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}(U_{\alpha i}U^{\star}_{\beta i}U^{\star}_{\alpha j}U_{\beta j})\ \sin^2(\Delta_{ij}) \\ &\quad +2\sum_{i>j}\mathrm{Im}(U_{\alpha i}U^{\star}_{\beta i}U^{\star}_{\alpha j}U_{\beta j})\ \sin(2\Delta_{ij}). \end{aligned} \tag{2}$$

In the above $\Delta_{ij} = \Delta m^2_{ij}L/4E$ and $\Delta m^2_{ij} = m^2_i - m^2_j$. For three neutrino flavours, the oscillation probabilities are governed by two independent mass squared differences. When neutrinos pass through matter then the interaction of the neutrinos with the electrons changes the mass, mixing and probability.

Evidences for three-flavour neutrino oscillation have come from solar, atmospheric, accelerator and reactor experiments. Below we summarize the main results obtained so far: (i) Results from SuperKamiokande experiment have confirmed oscillation of atmospheric neutrinos with $\Delta m^2_{31} \sim 10^{-3}$ eV^2. The dominant mode is $\nu_\mu \to \nu_\tau$ vacuum oscillation. Result from K2K, MINOS and T2K confirmed atmospheric neutrino oscillations using accelerator neutrinos. (ii) Results from the SNO solar neutrino experiment established the presence of ν_μ/ν_τ in the solar ν_e flux, thus confirming the indications of disappearance of solar neutrinos observed in the Homestake, Gallex, SAGE, GNO and the Kamiokande and Superkamiokande experiments. The data can be explained by the so-called large mixing angle (LMA) MSW effect with $\Delta m^2_{21} \sim 10^{-4}$ eV^2. Results from the KamLAND experiment confirmed the LMA solar neutrino oscillations using reactor neutrinos. Recently, a non-zero value for the mixing angle θ_{13} is reported by T2K as well as reactor experiments Daya-bay, RENO and Double-CHOOZ [2,3]. For small values of θ_{13} and $\Delta m^2_{21} \ll \Delta m^2_{31}$, the two sectors are almost decoupled and approximate two-generation scenario works well. For relatively larger values of θ_{13} there can be subleading effects in solar and KamLAND as well as in atmospheric neutrinos. For the latter, enhanced matter effects can increase the ν_e events. Long baseline accelerator data (K2K, MINOS, T2K) are sensitive mainly to Δm^2_{31}, θ_{23}, θ_{13}. Interplay between all these sectors are incorporated in the global analysis of world neutrino data [4–6]. The best-fit points and 3σ ranges of oscillation parameters from [4] are given in table 1.

Table 1. The best-fit values along with 1σ errors of neutrino oscillation parameters from global analysis of world neutrino data (from [4]).

$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$\frac{\lvert\Delta m^2_{31}\rvert}{[10^{-3}\ \mathrm{eV}^2}$	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	$\delta_{\mathrm{CP}}/°$
$7.50^{+0.19}_{-0.17}$	$0.304^{+0.012}_{-0.012}$(NH)	$2.458^{+0.002}_{-0.002}$	$0.451^{+0.001}_{-0.001}$(NH)	$0.0219^{+0.0010}_{-0.0011}$	251^{+67}_{-59}
	$-2.448^{+0.047}_{-0.047}$(IH)		$0.577^{+0.027}_{-0.035}$(IH)		

The important unknowns that remain to be determined are: (i) the neutrino mass hierarchy or sgn(Δm^2_{31}) ($\Delta m^2_{31} > 0$ corresponds to normal hierarchy (NH) and $\Delta m^2_{31} < 0$ corresponds to inverted hierarchy (IH), (ii) the octant of θ_{23}. Lower octant (LO) denotes $\theta_{23} < 45°$, while higher octant (HO) denotes $\theta_{23} > 45°$, (iii) the value of the leptonic CP phases – δ_{CP}, α_2, α_3, (iv) the absolute neutrino mass scale and (v) the nature of neutrinos: Dirac or Majorana.

3. Future prospects

The current-generation Superbeam experiments are: (i) T2K: with a baseline of 295 km from Tokai to Kamioka. The detector is the SuperKamiokande detector. Neutrino beam power is 0.75 MW with peak energy – $E \sim 0.76$ GeV. It is already taking data [7] and has published the results in the neutrino mode. It has recently started its run in the antineutrino mode. (ii) NOνA: which has a baseline of 810 km from FNAL to Minnesota [8]. It uses the NuMI beam with a beam power of 0.7 MW and energy $E \sim 1$–3 GeV. NOνA has started taking neutrino data and the first neutrino events have been observed in the far detector. Both these experiments use the off-axis technique to reduce the beam background.

The next-generation experiments include: (i) T2HK from J-PARC to Kamioka with a baseline of 295 km with a higher beam power of 1.6 MW as compared to T2K and using HyperKamiokande, which is the proposed successor of SuperKamiokande, as the detector [9]; (ii) LBNO for which one of the proposed configurations uses the CERN–Phyasalami baseline ($\sim$2300 km) with a beam power of 0.77 MW and liquid argon time projection chamber detector [10]; (iii) LBNE which proposes to send neutrinos from FNAL to Homestake ($\sim$1300 km) with a beam power of 0.7 MW [11]. Recently, there have been discussions to combine the expertize of the LBNE and LBNO Collaborations in one single long baseline neutrino facility which is named DUNE [12].

4. The hierarchy degeneracy and bimagic baseline

The most useful channel to determine hierarchy, octant and δ_{CP} in the LBL experiments is the conversion probability from ν_μ to $\nu_e(P_{\mu e})$. However, the survival channel, $P_{\mu\mu}$ also plays a role by improving the precision of θ_{23} and $|\Delta m^2_{31}|$. For these experiments, neutrinos pass through the Earth's mantle and the constant density approximation holds good. In this approximation, the survival probability $P_{\mu\mu}$ goes as $\sim 1 - \sin^2 2\theta_{23} \sin^2 \Delta m^2_{31} L/4E$

to leading order. Hence this channel lacks sensitivity to sgn(Δm^2_{31}) and octant of θ_{23}. To leading order there is no dependence on the CP phase $\delta_{\rm CP}$ as well.

The conversion probability in constant density matter can be expressed in terms of small parameters $\alpha = \Delta m^2_{31}/\Delta m^2_{31} \approx 0.04$ and $\sin^2\theta_{13} \sim 0.01$ as

$$P_{\mu e} = 4 s^2_{13} s^2_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2} + \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2 A\Delta}{A^2}$$
$$+ \alpha s_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta + \delta_{\rm CP}) \frac{\sin(A-1)\Delta}{(A-1)} \frac{\sin A\Delta}{A}. \quad (3)$$

The notations used are as follows: $s_{ij}(c_{ij}) = \sin\theta_{ij}(\cos\theta_{ij})$; $\Delta = \Delta m^2_{31} L/4E$, $A = VL/2\Delta$, $V = \pm\sqrt{2} G_{\rm F} n_e$ is the Wolfenstein matter term. The '$+(-)$' sign is for neutrino(antineutrino). $n_e(x)$ denotes the ambient electron density. The antineutrino oscillation probability can be obtained by replacing $\delta_{\rm CP} \to -\delta_{\rm CP}$ and $V \to -V$. Note that $\Delta > (<) 0$ for NH(IH) for both neutrinos and antineutrinos. However, the matter term A is positive for NH and negative for IH for neutrinos while for antineutrinos, the sign of A gets reversed. Thus, matter effect induces hierarchy sensitivity in $P_{\mu e}$. However, the ignorance of the CP phase $\delta_{\rm CP}$ can lead to the hierarchy-$\delta_{\rm CP}$ degeneracy [13].

Figure 1 shows the hierarchy sensitivity of the T2K and NOνA experiments as well as T2K+NOνA following [14]. For T2K, we consider only neutrino run with total protons on target (pot) as 8×10^{21}, whereas for NOνA we consider three years of neutrino and three years of antineutrino run.

The figures show that if true hierarchy is NH then the lower half plane (LHP, $-180° < \delta_{\rm CP} < 0$) is favourable for determining hierarchy, whereas if true hierarchy is IH, the upper half plane (UHP, $0 < \delta_{\rm CP} < 180°$) has better hierarchy sensitivity. Thus, the lack of knowledge of $\delta_{\rm CP}$ reduces the hierarchy sensitivity. Hierarchy sensitivity of NOνA is better than T2K because matter effects can develop as the baseline is longer. However, adding T2K and NOνA improves the hierarchy sensitivity showing the synergistic aspect between these experiments [14]. This is because, due to different baselines the wrong hierarchy regions occur for different values of $\delta_{\rm CP}$. Even then, 3σ hierarchy sensitivity

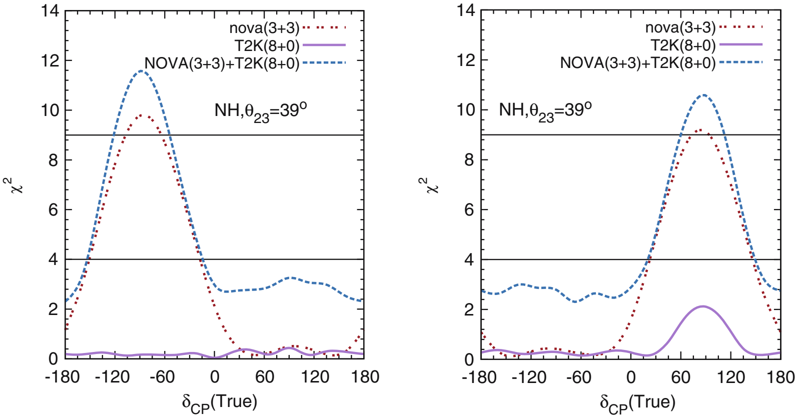

Figure 1. Hierarchy sensitivity of T2K, NOνA and their combination as a function of $\delta_{\rm CP}$ [14]. The left(right) panel is for NH(IH).

is reached only for limited values of δ_{CP}. These plots are generated using the Globes software [15].

An elegant way to overcome this problem was provided by noting that if the condition $\sin(A\Delta) \simeq 0$ is satisfied, then the CP-dependent term in $P_{\mu e}$ vanishes. Consequently, the hierarchy-δ_{CP} degeneracy is also absent. The above condition implies $\frac{1}{\sqrt{2}} G_{\mathrm{F}} n_e L = \pi$ giving $L \simeq 7690$ km. Note that this condition is independent of neutrino parameters and energy and is valid if either NH or IH is the true hierarchy. This was termed as the magic baseline [16]. An experiment performed with neutrinos traversing this baseline can provide a clean measurement of hierarchy. Experiments like neutrino factories and β-beams capable of producing beams which can traverse such long distances were studied extensively for this purpose. However, one of the problems with this baseline is that it has no CP sensitivity. International Design Study of Neutrino Factory Group recommended another experiment at 4000 km for δ_{CP} with $E_\mu = 25$ GeV. For such very long baselines one requires high acceleration of the muons. Also one needs to take into consideration the $1/r^2$ fall in flux. This led to the question: can there be a single experiment at a shorter baseline and lower muon energy which can determine both hierarchy and δ_{CP}.

It was pointed out in [17] that the CP-dependent term in $P_{\mu e}$ also goes to zero if the condition $\sin[(1 - A)\Delta] = 0$ is satisfied. In that case $P_{\mu e} \approx \mathcal{O}(\alpha^2)$ i.e., very small. Note that unlike the magic baseline this condition depends on the choice of true hierarchy through the term Δ. Thus, one can demand that for one of the hierarchies there is no δ_{CP} dependence in the probability, whereas for the other, the probability is maximum [17]. This generates two sets of conditions:

(i) No δ_{CP} dependence in $P_{\mu e}$ for IH and maxima for NH, i.e.,

$$(1 + A)\Delta = n\pi (n > 0); \quad (1 - A)\Delta = (m - 1/2)\pi.$$

Simultaneous solution to both is obtained for $L = 2540$ km and $E = 3.34$ GeV for $n = m = 1$.

(ii) No δ_{CP} dependence in $P_{\mu e}$ for NH and maxima for IH, i.e.,

$$(1 - A)\Delta = n\pi (n > 0); \quad (1 + A)\Delta = (m - 1/2)\pi.$$

The solution to the above set of equations is also obtained for $L = 2540$ km, but $E = 1.9$ GeV for $n = 1$, $m = 2$ [18]. Thus, the 2540 km baseline has the magical property of having hierarchy sensitivity without CP dependence for both NH and IH though at different energies. The probability $P_{\mu e}$ is shown in figure 2 [18] for 2540 km. It is seen that for $E = 1.9$ GeV, the NH probability is independent of δ_{CP} but IH probability is δ_{CP}-dependent. Thus, there is δ_{CP} sensitivity for IH near this energy. On the other hand, for $E_{\mathrm{IH}} = 3.3$ GeV, IH probability is independent of δ_{CP} and non-overlapping with NH indicating strong hierarchy sensitivity. There is also CP sensitivity for NH. For antineutrinos, NH and IH will be interchanged. This baseline was termed as the bimagic baseline [18]. Lowest bimagic baseline is at ~2540 km. Higher values of *n, m* imply lower *E* to satisfy the condition of no CP dependence, which implies a lower flux and lower efficiency.

Figure 3 shows the hierarchy sensitivity of the proposed experiments LBNE (~1300 km) and LBNO (~2290 km) as a function of δ_{CP} by assuming IH as the true hierarchy.

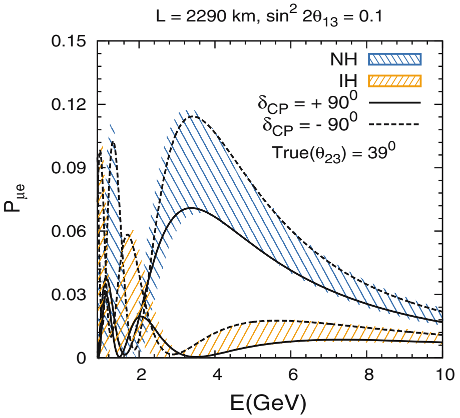

Figure 2. $P_{\mu e}$ vs. energy for 2290 km baseline length. The hatched region denotes variation over $\delta_{\rm CP}$ [18].

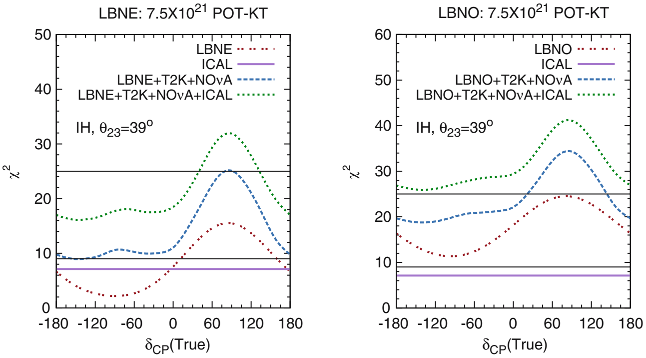

Figure 3. Hierarchy sensitivity of LBNE and LBNO as a function of $\delta_{\rm CP}$ for IH. Also shown are the hierarchy sensitivity of ICAL as well as combined hierarchy sensitivity.

We assume an exposure of 7.5×10^{21} pot-kt and use the latest fluxes. The figure shows that LBNE can achieve more than 3σ sensitivity for favourable values of $\delta_{\rm CP}$. However, LBNO can reach 5σ level for favourable $\delta_{\rm CP}$ values, while 3σ is reached even for unfavourable $\delta_{\rm CP}$ values. LBNE(LBNO) + T2K + NOνA reach $>3(4)\sigma$ hierarchy sensitivity for $\delta_{\rm CP}$ in LHP, while for upper half plane it can reach upto $5(6)\sigma$. Exceptional hierarchy sensitivity of LBNO is due to its proximity to bimagic baseline.

5. Can atmospheric neutrinos help?

Atmospheric neutrinos are produced by the interaction of cosmic rays with the air molecules. They provide a broad range of L/E band ($\sim$1 to 10^5 km/GeV). The longer baseline allows matter effects to develop. Atmospheric neutrino flux consists of both neutrinos and antineutrinos.

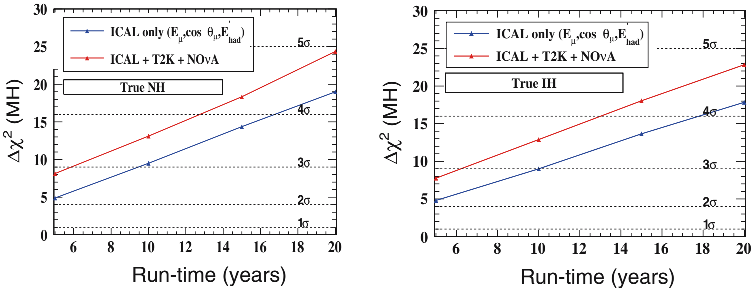

Figure 4. Hierarchy sensitivity of INO as a function of run-time. Also shown are the combined sensitivity with T2K and NOνA [23].

Several atmospheric neutrino detectors are planned/proposed. This includes: (i) A 50–100 kt magnetized iron calorimeter (ICAL) detector pursued by the India-based neutrino observatory (INO) [19]. The hallmarks are excellent muon energy measurement, direction reconstruction and charge discrimination capability. It can also determine the neutrino energy through hadron shower reconstruction. (ii) Megaton water Cerenkov detectors like HyperKamiokande (HK) [9] which is a successor or SK and MEMPHYS [20]. These do not have charge identification capability. However, the large volume and ability to detect both electron and muon events are the advantages. (iii) Multimegaton ice detectors, which also use the Čerenkov technology. Examples are PINGU pursued by the IceCube Collaboration [21]. (iv) There are also studies of detectors using liquid argon time projection chamber for detecting atmospheric neutrinos [22].

In this paper, we concentrate on the ICAL detector of the INO Collaboration. In figure 4 we show the hierarchy sensitivity of ICAL experiment using 50 kt detector volume. The analysis is done using information on muon energy and zenith angle and hadron energy [23]. The figure also shows the combined sensitivity of T2K+NOνA and INO. It is seen that the combined hierarchy sensitivity is much better. This plot is for $\delta_{\rm CP} = 0$.

In figure 3, we also show the hierarchy sensitivity of ICAL as a function of $\delta_{\rm CP}$. It is seen that there is no $\delta_{\rm CP}$ dependence. This is expected as the dominant channel is $P_{\mu\mu}$. Also, as neutrinos come from all directions, the angular resolutions smear out the $\delta_{\rm CP}$ dependence [26]. However, the figure shows that when the information from ICAL is added to that of T2K, NOνA and LBNE/LBNO then the combined hierarchy sensitivity improves [24,25].

This synergy can also play a role in CP discovery χ^2 which is defined as $\Delta\chi^2 = \chi^2(\delta_{\rm CP}^{\rm true}) - \chi^2(\delta_{\rm CP}^{\rm test})$. In figure 5a, we show the CP discovery potential of the T2K+NOνA for true hierarchy as NH and for different values of true θ_{23}. It is seen that in the unfavourable region, the CP discovery potential is much worse for lower values of θ_{23}. This is due to hierarchy-$\delta_{\rm CP}$ degeneracy. In figure 5b, we show the effect of the addition of the ICAL data to T2K+NOνA. It is seen that after adding this, 3σ sensitivity is possible in the wrong hierarchy region for $\theta_{23} = 39^\circ$ also. For $\theta_{23} = 51^\circ$, because of higher hierarchy sensitivity, the wrong hierarchy solution does not come with T2K+NOνA. Therefore, ICAL does not help in this. Thus, for unfavourable parameter values, the first hint of CP violation can come after adding ICAL data to T2K+NOνA [26].

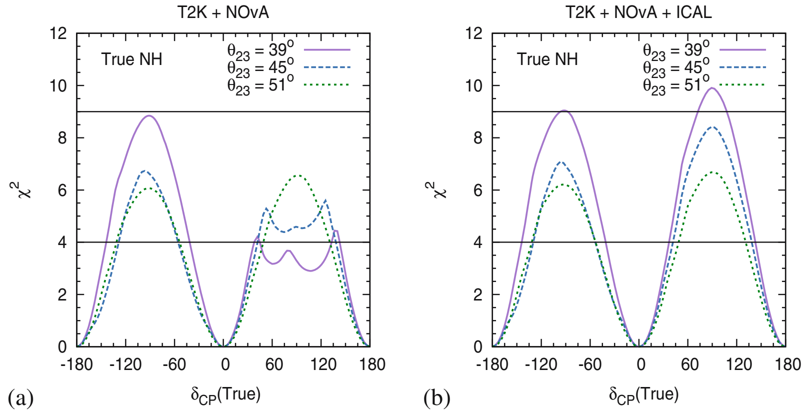

Figure 5. CP sensitivity of (**a**) T2K+NOνA and (**b**) T2K+NOνA+ICAL [26].

6. Neutrinoless double beta decay

The key issues to be addressed in connection with neutrino masses and mixing are: (i) why are these much smaller than the quark and charged lepton masses and (ii) why are there two large and one small mixing angles unlike in the quark sector where all mixing angles are small. The most natural explanation for smallness of neutrino masses come from see-saw mechanism which relates this to some new physics at a high scale. This new physics may be due to some heavy field present at a high scale Λ. Tree-level exchange of this heavy particle can give rise to an effective dimension 5 operator at low scale $\mathcal{L} = \kappa_5 l_L l_L \phi\phi, \kappa_5 = y_\kappa/\Lambda$. This operator violates lepton number by two units signifying that neutrinos are Majorana particles. The mass of this new particle is $\sim 10^{15}$ GeV to generate neutrino masses $\sim\sqrt{10^{-3}}$ eV. This scale is close to the grand unification scale leading to a natural generation of neutrino masses in GUT models. In the context of LHC, the question has also been raised as to whether the scale of the new physics can be TeV. This can give rise to like-sign dilepton which can also probe the Majorana nature of neutrinos [27].

Majorana nature of neutrinos can be tested by $0\nu\beta\beta$ process: $(A, Z) \rightarrow (A, Z+2) + 2e^-$. In the standard picture $0\nu\beta\beta$ is mediated by the light neutrinos with half-life,

$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}|\mathcal{M}_\nu|^2 \left|\frac{m^\nu_{ee}}{m_e}\right|^2 , \tag{4}$$

$G_{0\nu}$ contains the phase-space factors; $\mathcal{M}_\nu$ is the nuclear matrix element. $|m^{ee}_\nu| = |U^2_{ei}\, m_i|$ is the effective mass that governs neutrinoless double beta decay via exchange of light neutrinos. This depends on seven out of nine parameters of neutrino mass matrix and allows to probe the neutrino mass matrix. Positive claim of $0\nu\beta\beta$ was made in [28] with $T^{0\nu}_{1/2} = 2.23^{+0.44}_{-0.31} \times 10^{25}$ yr at 68% CL using ^{76}Ge. Recently, there have been new results from experiments using ^{136}Xe from the KamLAND-ZEN and EXO Collaborations giving a combined bound on the half-life as, $T^{0\nu}_{1/2} > 3.4 \times 10^{25}$ yr at 90% CL [29,30], To test the compatibility between the claim in ^{76}Ge and the null results in ^{136}Xe, it is useful to study the correlation between their half-lives. Eliminating m^{ν}_{ee}, one gets the equation

$$T^{0\nu}_{1/2}(^{136}\text{Xe}) = \left(3.61^{+1.18}_{-0.83} \times 10^{24}\ \text{yr}\right) \left| \frac{\mathcal{M}_{0\nu}(^{76}\text{Ge})}{\mathcal{M}_{0\nu}(^{136}\text{Xe})} \right|^2 . \tag{5}$$

Experimental bound on $T^{0\nu}_{1/2}(^{136}\text{Xe})$ greater than the predicted value from the above equation would imply inconsistency with the positive claim. This was examined in [31] for nuclear matrix elements (NME) obtained by different groups. It was found that the claim in [28] is compatible with the combined limit in [29] for all the NME values, except the one given in [32]. The reason is the very small NME for ^{136}Xe in [32].

Recently, new data from phase I of GERDA experiment was published. This puts new limits on $0\nu\beta\beta$ half-life of ^{76}Ge: $T^{0\nu}_{1/2}(^{76}\text{Ge}) > 2.1 \times 10^{25}$ yr at 90% CL [33]. The combined bound of this with other Ge experiments like HM [34] and IGEX [35] is $T^{0\nu}_{1/2}(^{76}\text{Ge}) > 3.0 \times 10^{25}$ yr at 90% CL. This bound disfavours the claim in [28] independent of NME uncertainties. Figure 6a shows the half-life of $0\nu\beta\beta$ process in Ge for the canonical light neutrino contribution. The shaded region denotes the NME uncertainties. It is seen that this contribution by itself cannot saturate the GERDA+HM+IGEX limit for values of lightest neutrino mass favoured by cosmology, even after including NME uncertainties. Figure 6b shows the half-life after including additional contributions from a type-II TeV-scale left–right symmetric model (LRSM) [31]. In this, apart from the usual diagram via the light neutrino exchange, an additional W_R mediated diagram with heavy neutrino exchange is included [36]. From the figure it is seen that the current experimental bound can be saturated by hierarchical neutrinos in type-II LRSM for lower values of lightest neutino masses as well. In fact, for smaller values of masses, the experimental limit is crossed by putting a lower bound on neutrino masses as (2–3) meV (NH) and (0.03–0.2) meV for IH [31].

Apart from neutrinoless double beta decay, Majorana nature of the neutrinos in LRSM can also be probed by the same-sign dilepton signal in colliders originating from resonance production of N and its subsequent decay [27]. In this case, constraints complimentary to that of NH are obtained from $0\nu\beta\beta$ which is shown in figure 7. However, for IH no such constraints are obtained because of cancellations.

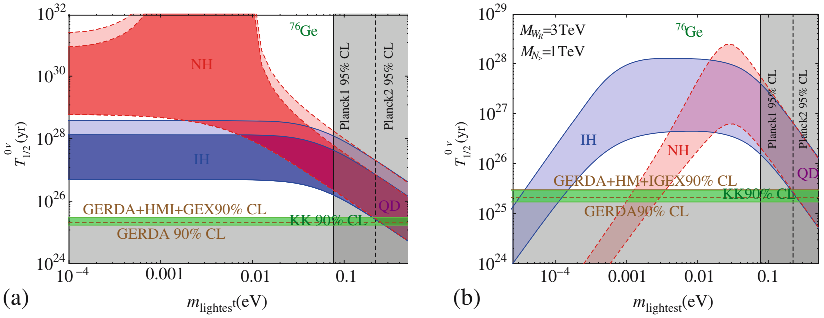

Figure 6. The half-life for ^{76}Ge with the standard contribution (**a**) and in type-II LRSM (**b**). The current experimental bounds on half-life are shown [31].

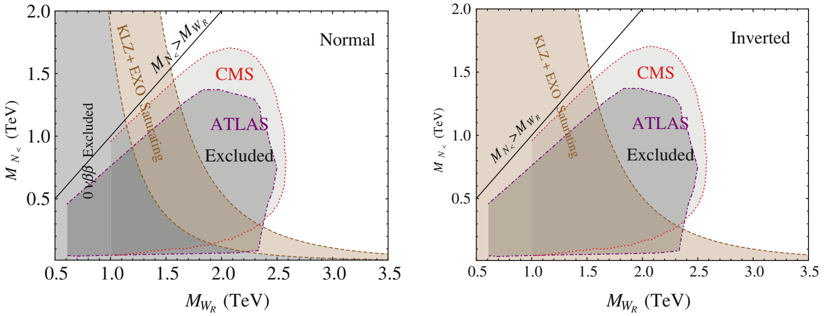

Figure 7. Complementarity between $0\nu\beta\beta$ and LHC in LRSM [31]. See also [37].

7. Conclusions

From neutrino oscillation experiments we have information on mass squared differences and mixing angles. Two major unknown parameters are the sign of $|\Delta m^2_{31}|$ and the leptonic CP phase $\delta_{\rm CP}$. Current-generation long baseline experiments T2K/NOνA and the future longer-baseline experiment LBNE/LBNO (or the unified initiative LBNF/ DUNE) are proposed to look for this. Synergy between various experiments, specially long-baseline and atmospheric experiments, could play an important role in planning future facilities. We demonstrate this by taking ICAL@INO as an example. Models of neutrino mass should explain the values of masses and mixing angles inferred from the data. Future high precision measurements on mixing angles, mass ordering and CP phase will help in restricting models. To conclude, neutrinos in the time of LHC provides a complimentary window to probe physics beyond the Standard Model.

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