Current theoretical status of neutrino masses and mixing

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Abstract. Neutrino oscillation results and their robustnes are briefly reviewed, along with neutrino mass generation schemes, from high to low-scale seesaw, with and without supersymmetry, as well as phenomenological implications.

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OSCILLATION PARAMETERS

Reactor and accelerator results imply that oscillations provide the only viable explanation for the observed flavor conversion of solar and atmospheric neutrinos first seen at underground experiments [1, 2, 3]. The discovery of neutrino oscillations provides the first evidence of physics beyond the Standard Model (SM), namely the existence of neutrino mass and mixing, as generally expected in gauge theories [4, 5]. The lepton mixing matrix constitutes the basic tool to describe oscillations. Its existence follows from the fact that in gauge theories the charged lepton and neutrino mass matrices that follow from symmetry breaking are not simultaneously diagonal. The full study of its structure in general gauge theories, including all types of seesaw schemes, was given in Ref. [5]. Within the unitary approximation the lepton mixing matrix is expressed as a product of three complex rotations

$$K = \omega_{23}\omega_{13}\omega_{12}.$$

It differs [5] from the quark mixing matrix in that each factor has a physical phase attached. Indeed, thanks to the Majorana nature of neutrinos, CP violation (CPV) starts with 2 generations, through the 12-phase. Going to 3 generations brings in a similar 23-phase. Moreover, with 3 generations one can form the rephasing invariant combination

$$\phi_D \equiv \phi_{12} - \phi_{13} + \phi_{23}$$

which is the Dirac phase, the leptonic analogue of the Kobayashi-Maskawa phase. Only this phase enters in conventional neutrino oscillations [6, 7]. However, Majorana phases affect lepton number (L)-violating processes, such as neutrinoless double beta decays.

Current experiments are mainly insensitive to CP violation, and are well described by just the three mixing angles $\theta_{12}, \theta_{23}, \theta_{13}$ and the two squared-mass splittings $\Delta m^2_{21} \equiv m^2_2 - m^2_1$ and $\Delta m^2_{31} \equiv m^2_3 - m^2_1$ characterizing solar and atmospheric transitions. Setting $\Delta m^2_{21} = 0$ in the analysis of atmospheric (but not accelerator) data, and Δm^2_{31} to infinity in the solar and reactor data analysis one obtains the neutrino oscillation parameters given in Figs. 1 and 2. The left panel in Fig. 1 gives the allowed values of "solar" oscillation parameters θ_{12} & Δm^2_{21}, while the middle and right panels show those of "atmospheric" parameters θ_{23} & Δm^2_{31}, for normal (NH) and inverted hierarchy (IH), respectively. The dot, star and diamond indicate the best fit points of solar (atmospheric), KamLAND (MINOS) and global data, respectively. Notice that in both cases we marginalize with respect to the undisplayed parameters.

Note the synergy between "artificial" and "natural" neutrino data: reactor and accelerators give the best determination of squared-mass-splittings, while data from underground experiments mainly determine the mixings.

Fig. 2 shows how data slightly favor a nonzero θ_{13} value, at 1.6 and 1.7 σ for normal and inverted hierarchy, respectively, see details and tables in the addendum of Ref. [3]. Prospects for probing θ_{13} are illustrated in Fig. 3 (left), taken from [8]. The expected CPV effect in oscillations is so small that models predicting maximum leptonic CP violation become especially attractive [9, 10], as illustrated by the right panel in Fig. 3. Prospects for searching for CP violation in upcoming long-baseline neutrino oscillation experiments are reviewd in [11, 12].

We now turn to the issue of the robustness of the oscillation interpretation against astro and particle physics uncertainties. For example, there may exist magnetic fields in the solar convective [13, 14, 15] or radiative-zones [16, 17]. These would induce spin-flavor precession [18, 19, 20] or density fluctuations in the Sun's deep interior [21, 22, 23], with a potentially large effect on the solar neutrino fluxes that reach our underground detectors. However, KamLAND reactor neutrino data imply that these effects, if present, must be only at the sub-leading level with respect to oscillations. As a result the determination of solar neutrino oscillation parameters remains prettly robust against

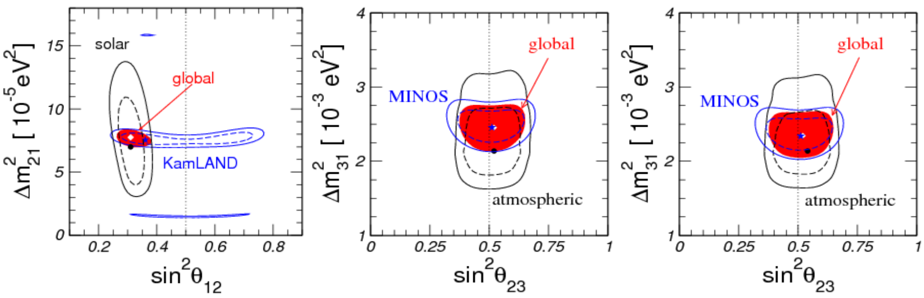

FIGURE 1. Current solar (left) and atmospheric (mid/right panels for NH/IH) neutrino oscillation parameters, from [3].

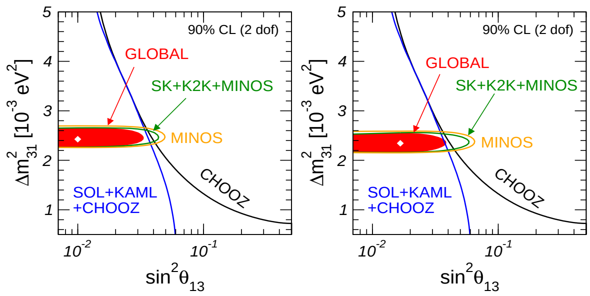

FIGURE 2. Constraints on $\sin^2\theta_{13}$ from different neutrino oscillation data sets [3]: NH (left) and IH (right).

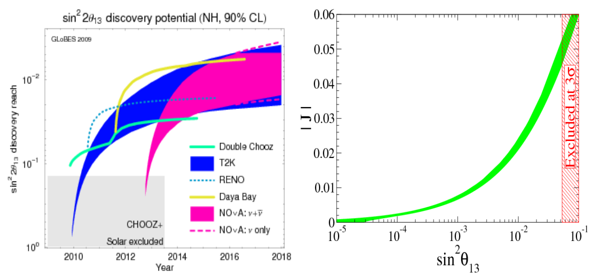

FIGURE 3. θ_{13} sensitivities at long-baseline experiments (left) [8], maximum leptonic CPV invariant [10] (right).

astrophysical uncertainties. However, the situation is not yet fully robust against the presence of nonstandard neutrino interactions (NSI) which might affect neutrino propagation, as well as fluxes and detection cross sections. This allows for a new "dark side" solution that survives the inclusion of reactor data [24]. By contrast, thanks to the large statistics of atmospheric data over a wide energy range, the determination of atmospheric oscillation parameters Δm^2_{31} and $\sin^2\theta_{23}$ is fairly robust in the presence of NSI, at least within the 2–neutrino approximation [25], a situation which would further improve with future neutrino factories [26]. However, the presence of NSI may have dramatic consequences for the sensitivity to θ_{13} at a neutrino factory [27] and may affect the interpretation of future supernova neutrino data in as well [28, 29, 30, 31].

LEPTON-NUMBER VIOLATION

The observation of neutrino oscillations and the expectation that neutrinos are Majorana particles suggest that light neutrino exchange will induce nuclear $0\nu\beta\beta$ (neutrinoless double beta decay) as illustrated in the left panel of Fig. 4. Searching for $0\nu\beta\beta$ complements high sensitivity single beta decay studies [32], cosmic microwave background and large scale structure observations in probing absolute neutrino masses, which oscillations do not.

The $0\nu\beta\beta$ detection prospects were discussed in [33] and are summarized in the middle panel in Fig. 4. One sees also how the $0\nu\beta\beta$ amplitude discriminates between IH and NH schemes, since in the latter case the amplitude can vanish as a result of destructive interference between individual neutrinos. These bands are computed for the current allowed values of oscillation parameters discussed above, taking into account the full range of variation of the relevant Majorana CP phase.

Note that, although $0\nu\beta\beta$ is a flavor-blind process, its amplitude is flavor-dependent, as illustrated by the two sub-branches in the lower band in the middle panel, which correspond to two tri-bi-maximal (TBM) mixing schemes based on inverse and linear seesaw [34]. Notice how one can have a lower bound on the $0\nu\beta\beta$ decay rate even for normal hierarchy [35, 36]. On the other hand, models leading to quasi-degenerate neutrinos [37, 38] give the largest possible $0\nu\beta\beta$ signal. Taking into account state-of-the-art nuclear matrix elements [39] one can determine experimental sensitivities [33], also displayed in summarized form in the mid-panel in Fig. 4. The importance of $0\nu\beta\beta$ lies in the fact that this process probes the basic nature (Dirac versus Majorana) of neutrinos through the "black-box theorem" [40], as illustrated in the right panel of Fig. 4. Though its quantitative implications are very model-dependent [41], this argument holds in any "natural" gauge theory. It may be stated as saying that the observation of $0\nu\beta\beta$ implies a Majorana mass for at least one neutrino.

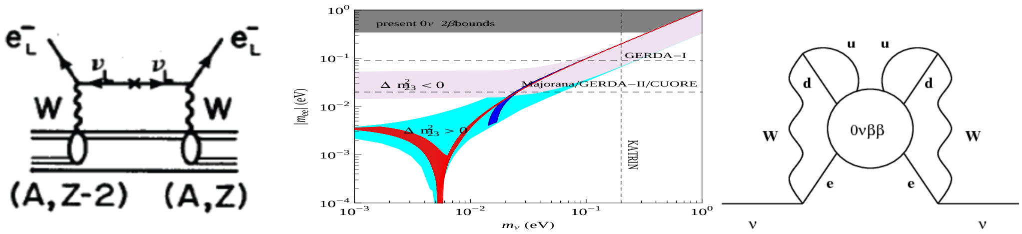

FIGURE 4. Left: Neutrino mass mechanism. Middle: $0\nu\beta\beta$ decay amplitude parameter versus lightest neutrino mass for IH (upper branch) and NH (lower branch). NH sub-branches correspond to two seesaw schemes in [34]. Right: black box theorem [40].

ORIGIN OF NEUTRINO MASSES

The origin of neutrino mass remains as elusive as ever. In contrast to charged fermions in the Standard Model (SM), which get mass directly by coupling the two chiral species to the SM Higgs scalar doublet, neutrinos are expected to get Majorana-type mass [5]. The simplest lepton number violating (LNV) operator is $\mathcal{O} \equiv \lambda L\Phi L\Phi$ [4], where $L \equiv (\nu_L, e_L)$ is a lepton doublet, see Fig. 5 (left) (for higher-dimension operators see [42].).

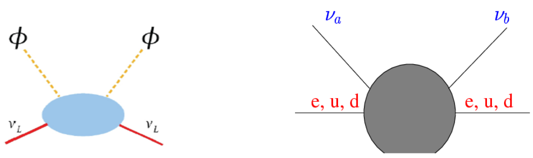

FIGURE 5. Neutrino mass operator [4] (left) and the resulting non-standard neutrino interactions (NSI) [5] (right).

The smallness of neutrino mass would follow from the suppression of the $\Delta L = 2$ LNV dimension-five operator $\mathcal{O}$, which can arise in many ways [43]. Depending on the nature of the spontaneous LNV mechanism there may be new dynamics associated to neutrino mass generation: either an extra neutral gauge boson coupling to B-L [44, 45, 46] or the corresponding Goldstone boson. The latter, called majoron [47], would couple to neutrinos [48] and to the Higgs boson [49].

The big challenge is to identify the underlying *mechanism* generating $\mathcal{O}$, the *scale* characterizing the mass of the messenger whose exchange induces $\mathcal{O}$, and its *flavor structure*. Gravity, which is often argued to break global symmetries [50, 51], would generate $\mathcal{O}$ with magnitude suppressed by the Planck scale, hence too small to generate the neutrino masses required by current data [52]. As a result new physics is needed, characterized by a sub-Planck scale, possibly associated to unification. The required suppression of $\mathcal{O}$ may also come from loop factors and/or from naturalness realized in the sense of t'Hooft, at a much lower scale for L-violation, suggesting that the origin of neutrino mass may be probed at accelerator experiments like the LHC. There are three classes of mechanisms: (i) tree level, such as the seesaw [43], (ii) radiative [53, 54], and (iii) hybrid [55], all of which may have high- and low-scale realizations. Understanding the flavor structure suggests extra symmetries.

Notice that the generation of neutrino mass in gauge theories is typically accompanied by non-standard neutrino interactions (NSI), e. g. effective sub-weak strength flavour-changing (FC) or non-universal (NU) dimension-6 operators, see right panel in Fig. 5. In seesaw schemes such NSI arise from the rectangular structure of the lepton mixing matrix, that leads to effectively non-unitary lepton mixing matrix describing neutrino propagation [5]. By contrast, in radiative schemes NSI arise from the exchange of scalars. The expected NSI magnitude is very model-dependent, but may be relatively large in low-scale seesaw schemes, such as the inverse [56, 57] or linear [46] seesaw. Improved NSI tests will shed light upon the origin of neutrino mass, helping to discriminate between high and low-scale schemes.

How to understand flavor? As we saw above, current oscillation experiments indicate that two of the lepton mixing angles are large. Their pattern is well reproduced by the tri-bi-maximal mixing ansatz [58],

$$\tan^2\theta_{23} = 1, \quad \sin^2\theta_{13} = 0, \quad \tan^2\theta_{12} = 0.5.$$

Such a pattern is hardly accidental, rather it suggests further underlying symmetries in nature, associated to flavor. Implementing it in unified theories where quarks and leptons are related poses a big challenge, though many attempts have been made. Leaving quarks aside, various discrete flavor-symmetry groups have been used that lead at least to partial predictions, e. g. [37, 38, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68]. In any case one expects to have deviations from tri-bi-maximality [69, 70]. When the flavor symmetry is imposed at high energies [71, 72] these may be renormalization-group-calculable.

A simple possibility is that neutrino masses unify at high energies, the same way as gauge couplings do, due to supersymmetry. This can happen as a result of an A4 flavor symmetry [37, 38]. Such quasi-degenerate neutrino picture predicts $\theta_{23} = \pi/4$ and $\theta_{13} = 0$, leaving the solar angle θ_{12} undetermined, though large. In the presence of CP violation θ_{13} becomes arbitrary, with maximal Dirac phase [61]. There is a lower bound on the absolute Majorana neutrino mass scale $m_0 \gtrsim 0.3$ eV

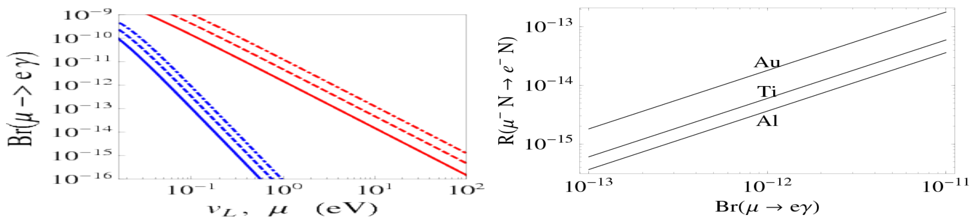

FIGURE 6. Left: $Br(\mu \to e\gamma)$ versus the LNV scale for inverse seesaw (top: red color) and linear seesaw (bottom, blue color) for a messenger mass fixed at $M = 100\,GeV$ (continuous line), $M = 200\,GeV$ (dashed line) and $M = 1000\,GeV$ (dot-dashed line), from [34]. Right: typical correlation between mu-e conversion and $Br(\mu \to e\gamma)$, from [73].

ensuring that the model will be probed by future $0\nu\beta\beta$ searches and by cosmology.

LFV PHENOMENOLOGY

Neutrino oscillation data imply that flavor is violated in nature. It is natural to expect that, at some level, lepton flavor violation (LFV) will also show up as transitions involving the charged leptons, since these belong to the same electroweak doublets as neutrinos. LFV may take place either through: (i) neutral heavy lepton exchange [74, 75, 76, 77] or (ii) slepton exchange [78, 79], where sleptons are supersymmetric partners of leptons.

Typically high-scale seesaw models lead to sizeable LFV rates only in the presence of supersymmetry. A remarkable feature of these models is that they bring in the possibility of direct LFV in the production of supersymmetric particles, possibly testable at the LHC [80]. For the $\tau\mu$ sector one finds that, indeed, the production cross section times branching ratio for LFV decays of the next-to-lightest neutralino $\sigma \times B(\chi_2^0 \to \mu\tau\chi_1^0)$ can achieve reasonable values in minimal supergravity seesaw models [81]. In contrast, LFV in the $e\mu$ sector is typically small, as a result of the non-observation of $\mu \to e\gamma$. However, in the presence of left-right symmetry one can reconcile a large LFV effect at LHC with acceptable $\mu \to e\gamma$ rates [82].

Low-scale seesaw schemes can lead to sizeable admixture of heavy "right-handed" neutrinos in the charged current [5]. This implies that heavy $SU(3) \otimes SU(2) \otimes U(1)$ singlet exchange can induce potentially large LFV rates even in the absence of supersymmetry [74]. An important point to stress is that LFV [75, 76] and CP violation [83, 84] can occur in the massless neutrino limit. As a result the rates for these processes are unconstrained by the smallness of neutrino masses. In Fig. 6 we give $Br(\mu \to e\gamma)$ as a function of the small LNV parameters μ and v_L that characterize two variant low-scale seesaw schemes, the inverse and the linear seesaw, respectively. One notes that the LFV rates can be quite sizeable in both cases (the different slopes with respect to the LNV parameters follow from the fact that $\Delta L = 2$ in the first case while $\Delta L = 1$, in the second). Similarly in these models the nuclear $\mu - e$ conversion rates [73] lie within the sensitivities planned for future experiments with intense muon sources [85]. Note that models with tri-bi-maximal mixing relate the expected rates for the different LFV processes [34, 86].

PROBING NEUTRINOS AT THE LHC

The scale characterizing the messengers responsible for generating neutrino masses can be related to the unification or, alternatively, can be as low as the electroweak scale, in which case it be probed directly by producing the new states at accelerators like the LHC [87]. An example of the latter is provided by the inverse type-III seesaw scheme [86].

A remarkable example of accessing neutrino properties at high energy accelerators is provided by supersymmetry. The requirement is the spontaneous violation of R parity [88, 89, 90, 91], driven by a nonzero vev of an $SU(3) \otimes SU(2) \otimes U(1)$ singlet sneutrino [88, 89, 90]. What one gets is an effective version of the MSSM model in which bilinear violation of parity is included [92, 55]. This provides the minimal way to provide neutrino masses [55] in an intrinsically supersymmetric way [93, 94, 95].

One typically finds that the atmospheric scale is generated *a la seesaw* through neutralino-exchange, while the scale characterizing solar neutrino transitions is radiatively induced [96]. Since there is no symmetry to provide the stability of the lightest supersymmetric particle (LSP), it will decay. Taking into account the masses indicated by neutrino oscillation experiments one finds that the decay path is typically large enough to be experimentally resolved, leading to a displaced vertex inside the LHC detectors [96, 97, 98]. The most striking feature is that LSP decays correlate with the neutrino mixing angles. For example in minimal supergravity one finds a strong correlation of LSP decay branchings with the atmospheric angle θ_{23} [99, 100, 101]. Simulations indicate that, indeed, LHC will have the potential to re-determine θ_{23} with sensitivity competitive with that of Super-K.

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