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Flavour physics and CP violation / Physique de la saveur et violation de CP

CP violation in the neutrino sector: The new frontier

Violation de la symétrie CP dans le secteur leptonique : Une nouvelle frontière

Pilar Hernández

Dpto. Física Teórica-UV and IFIC-CSIC, Edificio Institutos Investigación, Apt. 22085, 46071 Valencia, Spain

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ABSTRACT

The discovery of neutrino masses has revealed a new flavour sector in the Standard Model. Just like the quark flavour sector, it contains a seed of CP violation, resulting in an asymmetric behaviour of matter and antimatter. It is argued that this new source of leptonic CP violation may be discovered in more precise neutrino oscillation experiments involving neutrino beams with energies in the GeV range that will be sent to distances of a few thousand kilometres.

RÉSUMÉ

La découverte du caractère massif des neutrinos a révélé un nouveau secteur de « saveur », le secteur leptonique. Tout comme dans le secteur des quarks, il offre la possibilité d'une brisure de la symétrie CP, conduisant à une asymétrie entre matière et antimatière. Nous montrons que cette violation de CP dans le secteur leptonique pourrait être mise en évidence en utilisant des faisceaux de neutrinos d'énergie de l'ordre du GeV, se propageant à des distances de quelques milliers de kilomètres.

1. Introduction

Neutrinos are the most elusive particles in the Standard Model. W. Pauli conjectured their existence much before they were observed, in order to ensure energy conservation in nuclear β decay. A nuclear β^- decay occurs when a neutron in the nucleus transmutes into a proton emitting an electron, that can be measured, and a neutrino that goes undetected, but takes away part of the energy.

Fermi predicted the structure of the interaction responsible for β decay as a four-fermion interaction (see the left diagram in Fig. 1). The Standard Model (SM) provided a magnified view, showing that it was due to the exchange of a gauge boson, the $W^\pm$, later discovered at CERN. Similar processes, mediated by the weak interactions, established the existence of the μ- and τ-type neutrinos. Three neutrino species are known to exist in the SM, the partners of the electron, muon and τ leptons. They were initially assumed massless, because β-decay experiments established very stringent bounds on the neutrino mass by accurately measuring the electron end-point spectrum. The present direct bound from tritium β-decay experiments [1] is

$$m_{\nu_e} \leqslant 2.3 \text{ eV } (95\% CL) \tag{1}$$

E-mail address: m.pilar.hernandez@uv.es.

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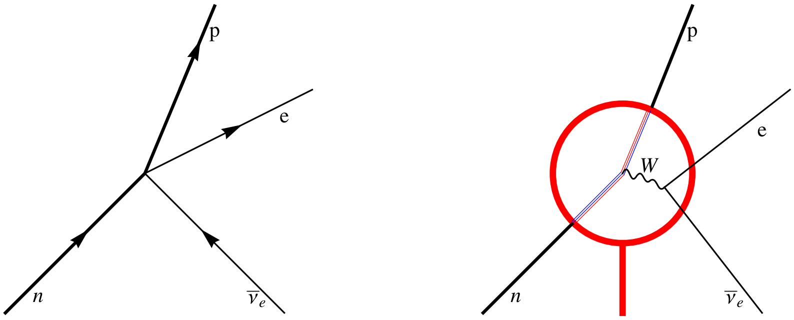

Fig. 1. β decay in Fermi approximation (left) and in the SM (right).

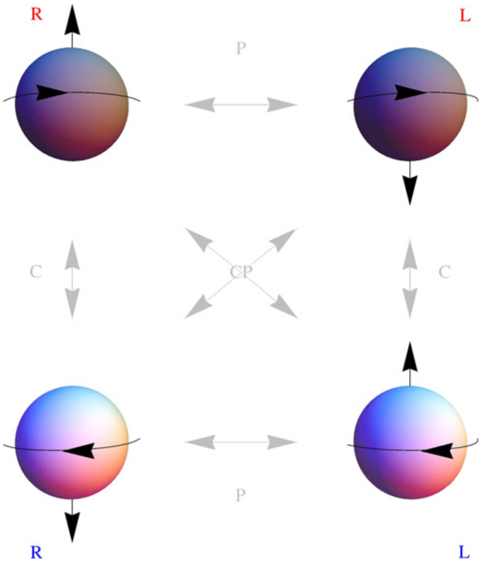

Fig. 2. Left: Degrees of freedom in a Dirac fermion. Left and right helicity particles (up) and left and right helicity antiparticles (down). A massless fermion decomposes into two Weyl fermions, the two diagonal pairs.

The neutrino revolution of the past decade has established nevertheless that at least two neutrinos are indeed massive, albeit much lighter than the remaining fermions in the SM.

2. Massive versus massless fermions: Dirac versus Weyl

All the electrically-charged spin 1/2 particles in the SM are massive Dirac fermions. A Dirac field contains the degrees of freedom corresponding to spin or helicity,[1] and charge conjugation (particle/antiparticle). See Fig. 2. In the limit of zero mass, the left and right helicity states decouple, while the mass of a particle can be seen as the coupling strength between the two helicity states.

One of the most striking features of the SM is that only the left-handed fermions, or their right-handed antiparticles, are charged under the weak interactions, implying a maximal breaking of the left–right or *parity* symmetry of the fundamental interactions. If neutrinos were massless, the right-handed neutrinos would be strictly undetectable, being neutral with respect to all the electromagnetic, strong and weak interactions. For this reason, in the original SM, where neutrinos were assumed massless, they were represented as Weyl fields instead, i.e. with half of the degrees of freedom: only left-handed helicity particle states, and the opposite helicity antiparticles. The breaking of parity is therefore nowhere more obvious than in the neutrino sector of the SM, where the parity conjugate of the neutrino state does not exist. Similarly, the left-handed antineutrino does not exist, so the symmetry under charge conjugation, C, is also maximally violated. However CP which rotates a left-handed neutrino field to a right-handed antineutrino field is exact in the lepton sector of the SM.

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[1] The spin can be projected on the momentum to give the helicity of the state. Spin degrees of freedom can be written in terms of the two possible helicity states, positive: when the spin points in the direction of the momentum; and negative, when it points in the opposite direction.

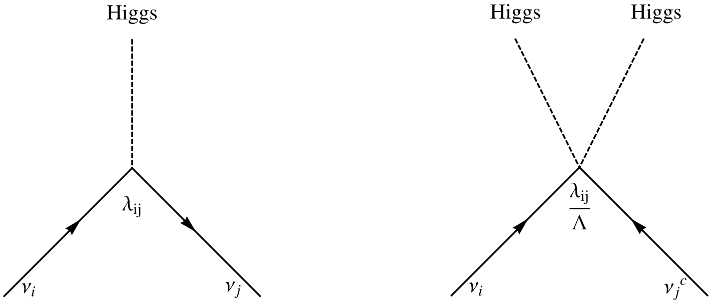

Fig. 3. Interaction of the neutrinos with the Higgs field that induce neutrino masses, Dirac type (left) and Majorana type (right). The different values of the λ_{ij} break the family symmetries and CP.

The recent experimental confirmation of neutrino masses implies that the *other* neutrino helicity states are needed, or maybe not…

3. Neutrino masses

The electron neutrino was detected by Cowan and Reines 30 years after Pauli's conjecture. It was in an ingenious experiment that was sensitive to the inverse β-decay reaction induced by an incoming neutrino (from a nearby nuclear power plant) that transmuted a proton into a neutron inside a purpose-made detector.

Since then, large amounts of ingenuity have triggered the spectacular progress in experimental neutrino physics in the last decades. Davies in the 1960s detected solar neutrinos for the first time, and counted too few of them [2]. This deficit remained a puzzle for a long time, until SNO [3] established in a definite way that solar neutrinos come in the right numbers, but there are as many muon- and tau-type neutrinos in the flux as there are electron neutrinos (the latter being the only ones Davies's experiment could detect). In the range of energies of solar nuclear reactions only electron neutrinos can be produced, therefore flavour conversions must take place when neutrinos travel to Earth.

Another puzzle showed up in the number of neutrinos produced in the atmosphere, as secondary products of primary cosmic ray collisions. The expected ratio of muon to electron type neutrinos in these processes is predicted to be close to 2. The observation by SuperKamiokande [4] showed that the number was much smaller in the flux of neutrinos coming from below and was roughly right for those coming from above. This could be understood also in terms of flavour transitions that vary with the distance travelled by the neutrinos from the production point to the detector (the distance is much longer for those coming from below, since they have to cross the Earth).

In the last ten years, these effects have been confirmed, and measured more precisely, in experiments with man-made neutrino sources. The solar flavour transitions have been confirmed by measuring the flux of reactor neutrinos at distances of the order of hundreds of kilometres [5], while those relevant for atmospheric neutrinos have been measured with neutrino beams produced at accelerators, at KEK [6] and Fermilab [7] laboratories, and detected with kton-size detectors located at distances from the source of 300–700 km.

An accurate explanation of both effects can be achieved assuming that at least two neutrinos are in fact massive.

4. Flavour transitions and neutrino masses

As happens in the quark sector, if neutrinos are massive, they must get their mass from their interaction with the Higgs field that can mediate the interaction between the two helicity states that carry different weak charges. These are the so-called Yukawa couplings. This interaction generically breaks the family or flavour symmetries completely, since it couples any two flavours with different strengths (see Fig. 3). The neutrino mass is therefore an arbitrary matrix in flavour space:

$$m_{ij} \sim \lambda_{ij} v \tag{2}$$

where v is vacuum expectation value of the Higgs field. As a result the basis in flavour space where the mass is diagonal does not coincide generically with the flavour basis (where the charged weak interactions are diagonal). The two are related by a general unitary rotation. This rotation is the famous Pontecorvo–Maki–Nakagawa–Sakata (PMNS) mixing matrix [8], which is the equivalent to the Cabbibo–Kobayashi–Maskawa (CKM) matrix in the quark sector. Such matrices depend generically on three Euler angles and one CP violating phase, called the Dirac phase.[2]

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \tag{3}$$

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[2] If neutrinos are Majorana particles, the PMNS matrix depends on two more CP violating phases.

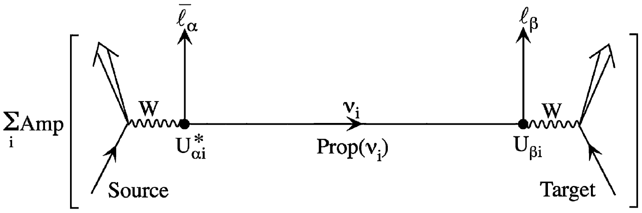

Fig. 4. Neutrino interferometer.

Right-handed neutrino states must be introduced to have the Yukawa couplings of the left diagram of Fig. 3. However, another possibility does exist to make neutrinos massive. Being neutral under the electromagnetic and strong interactions, a coupling to two Higgses is also possible [9] if the right-handed neutrino is substituted by the right-handed antineutrino state, as in the right diagram of Fig. 3. In this case we say the neutrino is a Majorana fermion, and the mass would be given by

$$m_{ij} \sim \lambda_{ij} \frac{v^2}{\Lambda} \tag{4}$$

where Λ has dimensions of mass as required by dimensional analysis. The relevance of this unknown scale will be discussed later. Concerning the mixing, however, Dirac or Majorana masses are almost indistinguishable.

A spectacular implication of neutrino mixing is that an experiment that produces and detects a neutrino is an interferometer in flavour or family space.

4.1. Neutrino interferometry

Neutrinos are produced and detected via weak processes, therefore by definition they are produced or detected as flavour states (see Fig. 4). However, a neutrino state of a definite flavour is a superposition of neutrino mass eigenstates, which propagate at different speeds in vacuum, since they have different masses. Therefore, when a neutrino is detected some distance away, the different quantum states get different phases creating an interference pattern that depends on the neutrino mass differences. This phenomenon, first conjectured by Pontecorvo [10], is called *neutrino oscillations*. The probability to detect a different flavour down the beam line oscillates as a function of the distance with a wavelength that depends on the neutrino mass differences and the neutrino energy, E, as

$$\lambda_{\rm osc} \sim \frac{E}{m_i^2 - m_j^2} \equiv \frac{E}{\Delta m_{ji}^2} \tag{5}$$

Therefore the measurement of the oscillation length gives a direct measurement of the neutrino mass differences. Such measurement has been possible both for the solar neutrino oscillation and that in atmospheric neutrinos and the result is that [11]

$$\Delta m_{12}^2 = \Delta m_{\rm solar}^2 \simeq 7.6 \times 10^{-5} \, \frac{{\rm eV}^2}{c^4}, \qquad \left|\Delta m_{23}^2\right| = \Delta m_{\rm atm}^2 \simeq 2.5 \times 10^{-3} \, \frac{{\rm eV}^2}{c^4} \tag{6}$$

The sensitivity is spectacular, as is usually the case in interferometry. Neutrino oscillations allow one to detect tiny neutrino mass differences that could be impossible to detect kinematically.

The amplitudes of the oscillations in turn measure the size of the mixing angles in the PMNS matrix. In the case of three neutrinos, the number of physical angles are the three Euler angles. Two of them are known from studying the solar and atmospheric oscillations and surprisingly are rather large:

$$\theta_{12} \simeq \theta_{\rm solar} \simeq 34^\circ, \qquad \theta_{23} \simeq \theta_{\rm atm} \simeq 45^\circ \tag{7}$$

This is very different to the quark sector where all the mixing angles are small. The third angle, denoted as θ_{13}, has been recently found to be different from zero at a level of 3σ by the T2K experiment [12].

5. Leptonic CP: matter–antimatter asymmetry in neutrino oscillations

In an extension of the SM to include three massive neutrinos, a new seed of CP violation appears that will induce a matter–antimatter asymmetry in leptonic processes. The origin of this asymmetry lies in the complex nature of the coupling constants in Fig. 3. Many of the phases in these couplings are unphysical, but in the case of three flavours at least one phase remains physical generically. One can in principle detect such a phase via interferometry: observing a difference between the oscillation probability for neutrinos and antineutrinos: $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$.

Assuming that CPT is a good symmetry,[3] it is easy to show that the probabilities for neutrinos and antineutrinos must be the same if the initial and final flavour is the same:

$$P(\nu_\alpha \to \nu_\alpha) = P(\bar{\nu}_\alpha \to \bar{\nu}_\alpha) \tag{8}$$

Therefore, in order to detect an asymmetry we need to have different initial and final flavours, this is what is called an *appearance neutrino oscillation experiment*.

Furthermore by unitarity we must have

$$\sum_\beta P(\nu_\alpha \to \nu_\beta) = 1, \qquad \sum_\beta P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = 1 \tag{9}$$

The combination of Eqs. (9) and (8) implies that no asymmetry exists if there were two neutrino families only (effectively this is also the situation if we neglect one neutrino mass difference). In the case of three families, all the transitions $\alpha \to \beta$, with $\alpha \neq \beta$ must be non-vanishing for the same reason. This is equivalent to saying that all the mixing angles of the PMNS matrix must be non-vanishing.

We can define CP asymmetries by

$$A^{\mathrm{CP}}_{\alpha\beta} \equiv \frac{P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}{P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)} \tag{10}$$

In the case of three neutrinos, the CP-odd terms in the numerator are the same for all initial and final flavours $\alpha \neq \beta$:

$$A^{\mathrm{CP}}_{\alpha\beta} = \frac{\overbrace{\sin\delta}^{\text{CP phase}}\ \overbrace{\cos\theta_{13}\sin 2\theta_{13}}^{\text{unknown}}\ \overbrace{\sin 2\theta_{12}\frac{\Delta m^2_{12}L}{4E_\nu}}^{\text{solar}}\ \overbrace{\sin 2\theta_{23}\sin^2\frac{\Delta m^2_{13}L}{4E_\nu}}^{\text{atmos}}}{P^{\text{CP-even}}_{\nu_\alpha\nu_\beta}} \tag{11}$$

As expected, the numerator is GIM suppressed in all the Δm^2_{ij} and all the angles, because if any of them is zero, the CP-odd phase becomes unphysical.

These general arguments imply that the observability of the CP phase requires an interferometry experiment that has sensitivity to both the neutrino mass differences, but also to all the mixing angles. In this sense it is fortunate that the mass differences of solar and atmospheric neutrinos are not widely different, and that the mixing angles that have been measured so far are large. Obviously the final key to Alicia's mirror world is the angle θ_{13}, that should be large enough, as recent data seem to indicate.

5.1. Golden channels for leptonic CP violation

Given that the numerator in Eq. (11) is the same for any flavour transition, the asymmetry will be more significant the smaller the denominator is. The golden channel is $\nu_e \leftrightarrow \nu_\mu$ at energies and baselines optimised to detect the atmospheric oscillation length, i.e. $\langle E_\nu \rangle / L \sim \Delta m^2_{\mathrm{atmos}}$ [13]. One important challenge to measure CP violation, however, is the fact that neutrinos must cross the Earth and the oscillations in matter are modified by coherent neutrino scattering on Earth matter [14] that induce a fake CP asymmetry, which depends very sensitively on the value of some parameters that are still not known, such as θ_{13}. Disentangling the two effects, or the simultaneous measurement of the CP phase and other unknowns, is non-trivial and requires measuring the oscillation probabilities at different neutrino energies or/and baselines.

From the experimental point of view, even if CP asymmetries in this golden channel are large, the oscillation probabilities themselves are small as shown in Fig. 5. Measuring oscillations with small amplitude is a new challenge in neutrino physics that will require not only more intense neutrino fluxes and bigger detectors, but also a significant improvement in the control of systematic errors.

The latter is difficult with conventional neutrino beams that are produced at accelerators from secondaries when protons hit a fixed target. These beams are mostly ν_μ beams with a few per cent contamination of ν_e. This component becomes an irreducible background in the search for the golden $\nu_\mu \to \nu_e$ transitions.

A number of good ideas have been put forward to improve this situation. The so-called neutrino factory would produce a neutrino beam from a muon storage ring, where muons of a fixed and well known energy are left to decay pointing to some far away detector. If negative muons are stored, the resulting beam contains ν_μ and $\bar{\nu}_e$ only. The golden transition $\bar{\nu}_e \to \bar{\nu}_\mu$ can be searched for by looking for positive muons or *wrong-sign muons* in the detector [15]. Charge identification would be mandatory to reduce the enormous background of negative muons induced by the ν_μ in the beam. The CP conjugated channel can be measured by storing positive muons instead.

Another alternative would be the so-called β-beams [16], where the parent particles are not muons but radioactive ions that decay via β processes. The beam contains in this case only ν_e or $\bar{\nu}_e$, depending on whether the decay is β^+ or β^-,

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[3] CPT is the combination of charge conjugation, parity and time reversal.

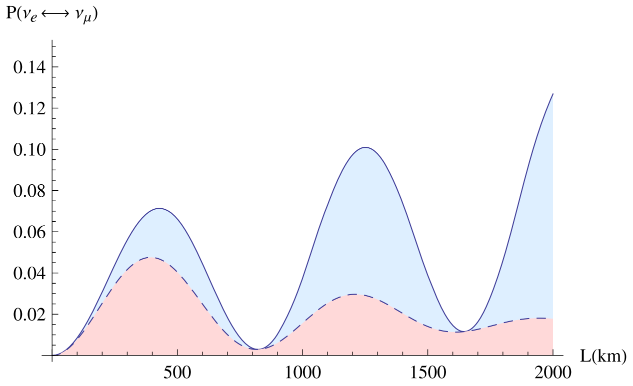

Fig. 5. Oscillation probability in vacuum for neutrinos (solid) and antineutrinos (dashed) for the $\theta_{13} = 10°$ and $\delta = 90°$ as a function of the distance for a neutrino beam of energy $E_\nu = 1$ GeV.

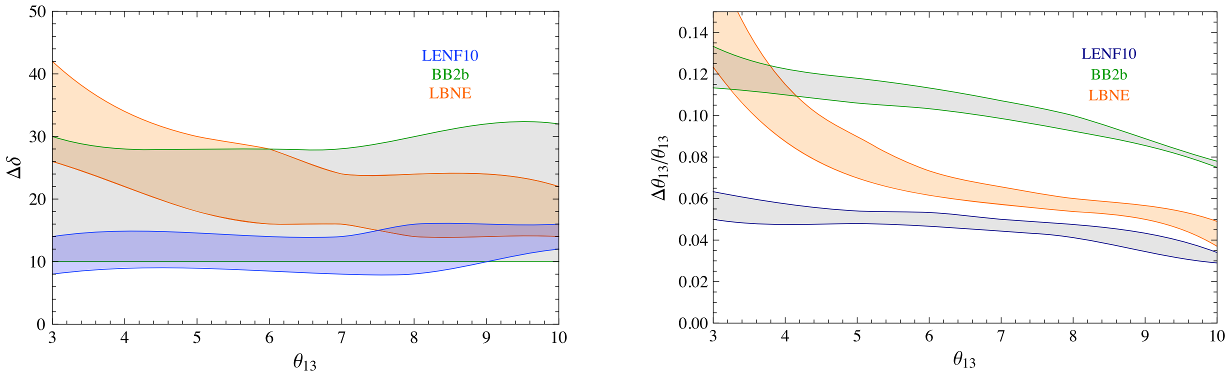

Fig. 6. Expected error band on the CP phase in degrees (left) and the relative error on θ_{13} (right) as a function of $\theta_{13} = 3$–$10°$ (present favoured range) achievable in three future neutrino oscillation experiments: one using a more intense conventional beam (LBNE) [18], a neutrino factory (LENF10) [19] and a β-beam (BB2b) [20].

which depends on the ion used. The detection of the signal requires the search for muons in the detector signalling the $\nu_e \to \nu_\mu$ transition.

In both cases, the neutrino beam properties are extremely well known, because the spectrum can be accurately predicted from the muon or β-decay kinematics. In order to resolve parameter degeneracies, either detectors with extremely good energy resolution or a combination of baselines are usually considered. A number of sophisticated studies have been performed in recent years to show the potential of such new facilities to detect leptonic CP violation [17]. Fig. 6 shows[4] the expected error band on the CP phase (in degrees) as well as the relative error on θ_{13} as a function of the true unknown angle θ_{13}, on three proposed future experiments. Unless θ_{13} is extremely small, there is a very good opportunity to discover a new source of asymmetry between matter and antimatter in the fundamental laws of physics. In fact, if the recent indication of θ_{13} is confirmed, then even the less sophisticated experiments, such as the conventional superbeams, could have a good chance of discovering leptonic CP violation.

6. Beyond the Standard Model and ν masses

If discovering new asymmetries between matter and antimatter is of fundamental importance to understand questions such as the presence of baryons in the universe [21], there are no less important questions in neutrino physics that could shed light into other open problems in particle physics and in cosmology. Are neutrinos Dirac or Majorana particles? In the latter case, what is the unknown scale Λ? Is it related to the electroweak scale or is it a truly new scale of physics, such as a Grand Unification scale? Why are neutrinos so much lighter than the remaining fermions in the SM? What is the absolute scale of neutrino masses?

The answer to these questions will be searched for from different angles in a plethora of planned experiments: more precise neutrino oscillation and β-decay experiments, as the ones mentioned above, but also searching for rare processes such as neutrinoless double-beta decay, stretching the high energy frontier at LHC or looking for the imprint of neutrinos in the cosmic microwave background, and in the large scale structure of the universe.

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[4] I thank P. Coloma and A. Donini for kindly preparing these plots.

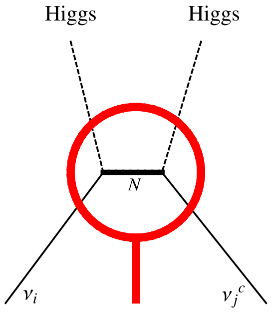

Fig. 7. Neutrino masses from a seesaw model.

We can expect that all these future experiments will provide a magnifying glass to reveal some underlying dynamics (like the SM did with the Fermi interaction) that could look like the seesaw model [22] depicted in Fig. 7, in which the Λ scale is related to the mass of new heavy Majorana fermions, explaining the smallness of the neutrino masses by the large mass of these mediators.

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