Experimental status of neutrino physics

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Abstract. After a fascinating phase of discoveries, neutrino physics still has a few mysteries such as the absolute mass scale, the mass hierarchy, the existence of CP violation in the lepton sector and the existence of right-handed neutrinos. It is also entering a phase of precision measurements. This is what motivates the NUFACT 11 conference which prepares the future of long baseline neutrino experiments. In this paper, we report the status of experimental neutrino physics. We focus mainly on absolute mass measurements, oscillation parameters and future plans for oscillation experiments [1].

1. Introduction

Over the last 15 years experiments have demonstrated that neutrinos oscillate and therefore mix and have masses, however few oscillation parameters are well measured. In addition, their absolute mass scale is still only described by upper limits. Finally, we do not know the nature of neutrino masses. Therefore despite the tremendous results of the last decade, there is still a vast open field with many discoveries in the making. In this paper we present the status of the absolute mass scale measurements and oscillation parameters measurements, and describe several possible new experiments for improving these measurements. This paper has been updated to take into account the results presented at the Neutrino 2012 conference in June 2012 in Kyoto [2].

2. Measurements of the absolute neutrino mass

Absolute neutrino masses can be measured in several ways. Astrophysical neutrinos, kinematic limits and neutrinoless double beta decay are all used to measure the absolute neutrino mass scale or set a limit on it.

2.1. Supernovae and cosmological constraints

Supernovae are copious sources of neutrinos: by measuring time shifts, it is in principle possible to measure neutrino masses down to 30 eV as in the case of SN1987a [3]. Since neutrinos are so numerous in the universe, even a tiny neutrino mass can have cosmological implications. Current cosmological bounds are down around $M_\nu < 0.17 - 0.33$ eV [4, 5] and new data from the Planck observatory should be available soon [6]. These results are quite model dependent and mostly illustrate the sensitivity of structure formation to neutrinos masses. They cannot replace direct laboratory experiments.

2.2. Tritium beta decay and KATRIN

Double beta decay experiments study the end of the beta decay spectrum in order to measure $m^2_{\nu_e} = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$. The current upper electron-neutrino mass limit from beta decay experiments is $m_{\nu_e} < 2.3$ eV [7]. The next generation experiment is KATRIN at Karlsruhe. It is sensitive down to 0.2 eV [8, 9].

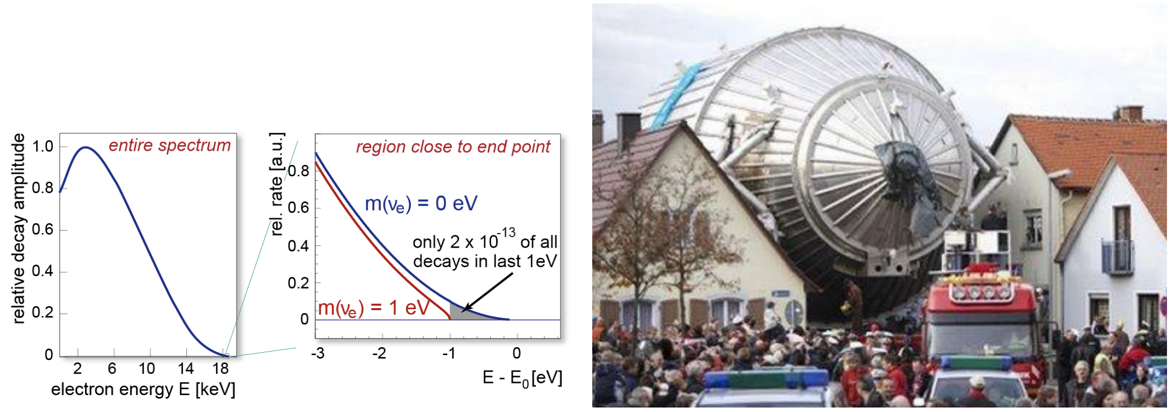

Figure 1. Left: Beta decay spectrum. **Right**: KATRIN detector [8].

2.3. Neutrinoless double beta decay

Neutrinoless double beta decay ($0\nu\beta\beta$) experiments are the main method to investigate whether neutrinos have a Majorana mass term which couples left-handed neutrinos to right-handed anti-neutrinos. It is also an excellent tool to probe the absolute mass scale and, in combination with oscillation experiments, gives a hint on the mass hierarchy (Fig. 2).

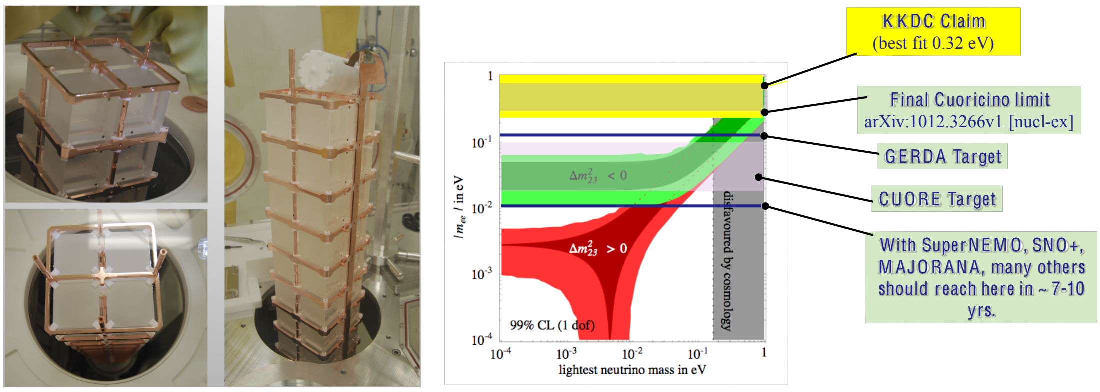

Figure 2. Left: CUORE-0 detector [10]. **Right**: Neutrinoless double beta decay. Target sensitivity of several experiments [1].

A whole set of $0\nu\beta\beta$-decay experiments are currently running or are about to start taking data: GERDA, CUORE-0, EXO and KamLAND-Zen began in 2011. SNO+, Majorana and NEXT should start in 2013, and SuperNEMO, Lucifer, EXO-gas, XMASS and CUORE are scheduled to start later. While we cannot report every result here, we report that KamLAND-Zen found that $\langle m_{\beta\beta}\rangle < 0.26 - 0.54$ eV at 90% C.L. [11] and that EXO-200 found $\langle m_{\beta\beta}\rangle < 0.14 - 0.38$ eV at the same significance [12].

3. Oscillation parameters measurements

Since solar neutrino experiments revealed the famous solar neutrino problem, we have known that neutrinos behave atypically. Since then the fact neutrinos transmute and thus have mass has been established by the Super-Kamiokande measurement of atmospheric neutrinos [13] and by solar data from SNO [14]. Neutrino oscillations is governed by a 3×3 unitary mixing matrix and by mass differences. The mixing angles (Fig. 3, left) have all been measured but even though the two mass splittings have also been measured (Fig. 3, right), the mass hierarchy and the CP violating phase are still unknown. In this section, we will present the current status of the measurement of each oscillation parameter.

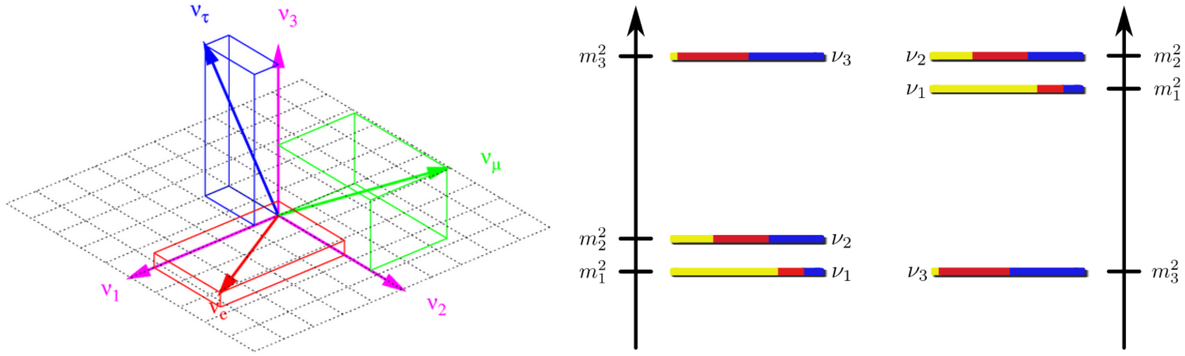

Figure 3. Left: Neutrino mixing angles. **Right**: Neutrino mass hierarchy (normal, inverted).

3.1. Measurement of θ_{13}

Until last year, θ_{13} was the sole remaining unknown mixing angle, the only knowledge of this parameter came from the Chooz experiment and was an upper limit of 0.15 at 90% C.L. [15]. A hint that θ_{13} was non-zero did however come from global fit of available oscillation data [16]. In June of 2011, T2K presented their first electron neutrino appearance measurement, six events on a predicted background of $1.5 \pm 0.3(syst.)$ indicating a non-zero value of θ_{13} at 2.5σ [17]. The analysis was not strictly speaking blind but all the cuts for the electron neutrino event selection in the Super-Kamiokande detector were decided well before T2K even started taking data. At Neutrino 2012, all the data up to May 15th 2012 were analyzed and presented [18]. Ten events are observed in the far detector and θ_{13} is excluded at 3.2σ. At 90% C.L., the T2K results is $\sin^2 2\theta_{13} = 0.104^{+0.60}_{-0.45}$ for $\delta_{CP} = 0$ and normal hierarchy. The T2K selected ν_e candidates are shown in Fig. 4. Two weeks after T2K released their results, the MINOS collaboration presented results which disfavour $\theta_{13} = 0$ at 89% C.L. with 62 events on a background of $49.6 \pm 7.0(stat) \pm 2.7(syst.)$ [19]. At Neutrino 2012, MINOS disfavors $\theta_{13} = 0$ at 96% C.L. [20].

Finally in March 2012, outstanding results came from the reactor experiments Daya Bay [21, 22] and Reno [23]. The Daya Bay collaboration excluded $\theta_{13} = 0$ at 5.2σ [21, 22], while RENO excluded it at 4.9σ [23]. Their best fit values are respectively $\sin^2 2\theta_{13} = 0.089 \pm 0.010(stat.) \pm 0.005(syst.)$ and $\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat.) \pm 0.019(syst.)$ and their data is also shown in Fig. 6. Double Chooz excluded $\theta_{13} = 0$ at 3.1σ and their best fit is $\sin^2 2\theta_{13} = 0.109 \pm 0.030(stat.) \pm 0.025(syst.)$ [24]. All experiments are still statistically dominated and the clearly demonstrate that θ_{13} is greater than zero.

Reactor experiments measure the disappearance of electron anti-neutrinos to measure θ_{13} as shown in Fig. 5 and Eq. 1. Current accelerator experiments measure the appearance of electron neutrinos in a muon-neutrino beam (Eq. 3). In addition the accelerator measurement depends on

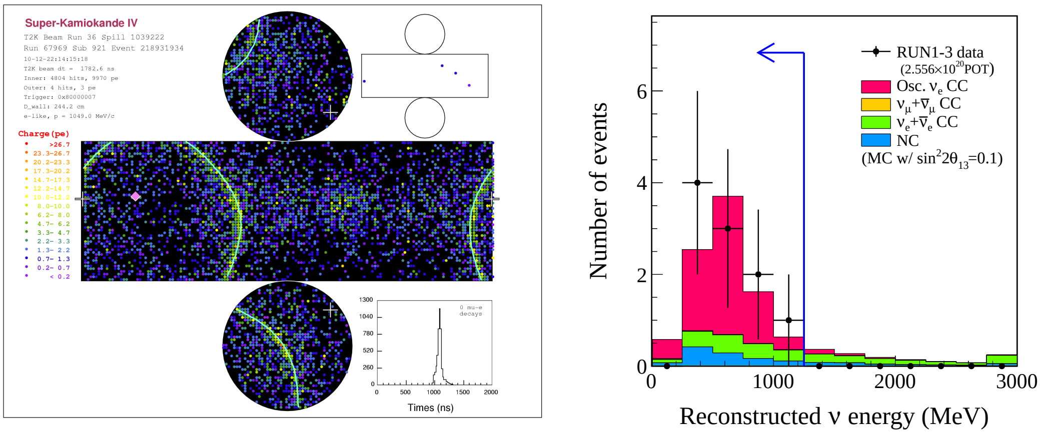

Figure 4. Left: An electron neutrino event in SK. **Right**: Reconstructed neutrino energy distribution for fully-contained, fiducial volume, single-ring e-like events with Evis $>$ 100 MeV, no decay-e and POLfit mass less than 105 MeV/c^2 in RUN1+2+3 [18].

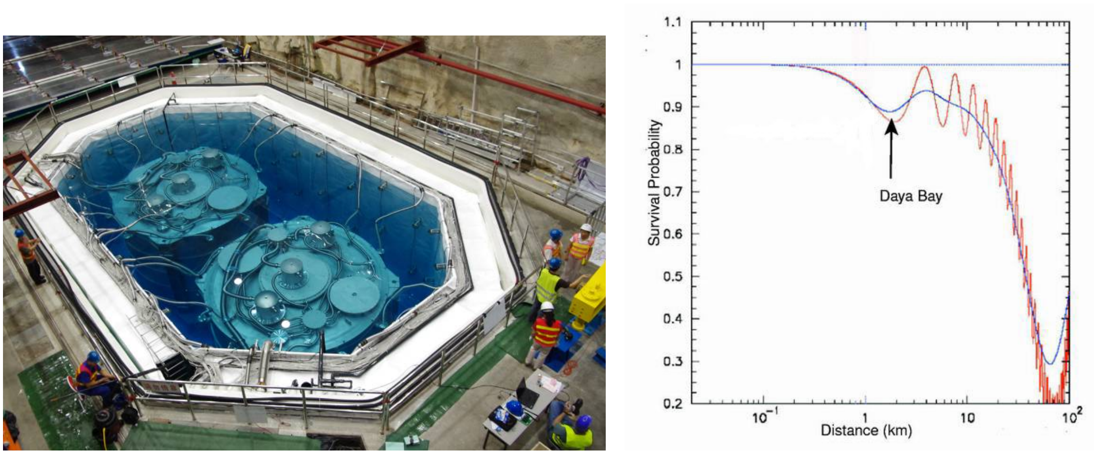

Figure 5. Left: Picture of Daya Bay detectors [22]. **Right**: Survival probability of electron neutrino as a function of the distance.

the value of the CP phase δ while the reactor measurement does not. Because these experiments are fundamentally different it is very interesting to continue both in parallel.

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2(1.267 \Delta m^2_{13} L/E) \quad (1)$$

$$\begin{aligned} P[\nu_\mu \ \rightarrow \ \nu_e] &= \sin^2 2\theta_{13} s^2_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \frac{1}{2} s^2_{12} \sin^2 2\theta_{13} s^2_{23} \left(\frac{\Delta m^2_{21} L}{2E}\right) \sin\left(\frac{\Delta m^2_{31} L}{2E}\right) \\ &+ \ 2J_r \cos\delta \left(\frac{\Delta m^2_{21} L}{2E}\right) \sin\left(\frac{\Delta m^2_{31} L}{2E}\right) - 4J_r \sin\delta \left(\frac{\Delta m^2_{21} L}{2E}\right) \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \\ &+ \ \cos 2\theta_{13} sin^2 2\theta_{13} s^2_{23} \left(\frac{4Ea(x)}{\Delta m^2_{31}}\right) \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \\ &- \ \frac{a(x)L}{2} \sin^2 2\theta_{13} \cos 2\theta_{13} s^2_{23} \sin\left(\frac{\Delta m^2_{31} L}{2E}\right) + c^2_{23} \sin^2 2\theta_{12} \left(\frac{\Delta m^2_{21} L}{4E}\right)^2, \end{aligned} \quad (2)$$

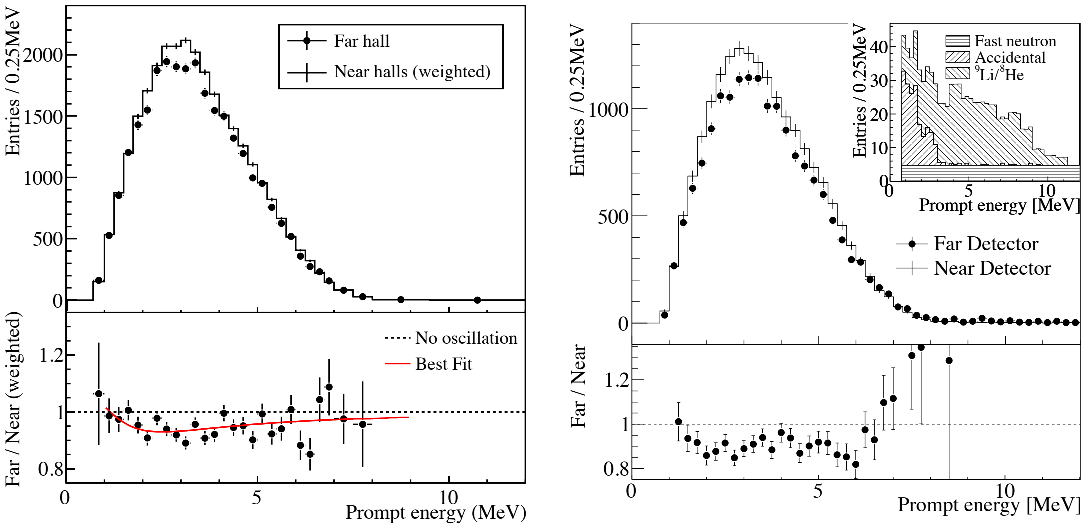

Figure 6. Left, Daya Bay data: Top: Measured prompt energy spectrum of the far hall (sum of three ADs) compared with the no-oscillation prediction from the measurements of the two near halls. Spectra were background subtracted. Uncertainties are statistical only. Bottom: The ratio of measured and predicted no-oscillation spectra. The red curve is the best- fit solution with $\sin^2 2\theta_{13} = 0.089$ obtained from the rate-only analysis. The dashed line is the no-oscillation prediction [21, 22]. **Right, RENO data:** Observed spectrum of the prompt signals in the far detector compared with the non-oscillation predictions from the measurements in the near detector. The backgrounds shown in the inset are subtracted for the far spectrum. The background fraction is 5.5% (2.7%) for far (near) detector. Errors are statistical uncertainties only. Bottom: The ratio of the measured spectrum of far detector to the non-oscillation prediction [23].

(3)

where $a(x) = \sqrt{2} G_F N_e(x)$, G_F is the Fermi constant, $N_e(x)$ is the electron number density at x in the earth, $J_r = c_{12} s_{12} c_{12}^2 s_{13} c_{23} s_{23}$ is the Jarlslog determinant.

3.2. Measurement of the solar parameters: Δm^2_{21} and θ_{12}

The solar parameters are now well constrained by both solar and reactor data, and the newly measured value of θ_{13} further reduces the uncertainty of this measurement. A very good summary of current data is presented by T. Schwetz [25] and the current values of these parameters are given below.

$$\Delta m^2_{21} = 7.59^{+0.20}_{-0.18} \times 10^{-5}\ \mathrm{eV}^2 \quad \text{and} \quad \sin^2\theta_{12} = 0.312^{+0.017}_{-0.015}$$

The values of Δm^2_{21} and $\sin^2\theta_{12}$ have been obtained using the KamLAND neutrino data and the Super-Kamiokande and SNO solar data.

3.3. Measurement of atmospheric parameters: $|\Delta m^2_{31}|$ and θ_{23}

The atmospheric parameters have also been well measured by the Super-Kamiokande atmospheric data and by the MINOS experiment. Their results have also been summarized by T.Schwetz [25] and are given below.

$$|\Delta m^2_{31}| = \begin{cases} 2.45 \pm 0.09 & \times 10^{-3}\ \mathrm{eV}^2 \quad (\mathrm{NH}) \\ 2.34^{+0.10}_{-0.09} & \times 10^{-3}\ \mathrm{eV}^2 \quad (\mathrm{IH}) \end{cases} \quad \text{and} \quad \sin^2\theta_{23} = 0.51 \pm 0.06$$

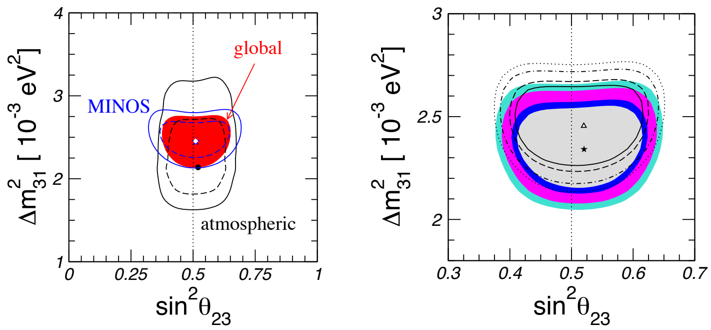

Figure 7. Determination of the atmospheric oscillation parameters. **Left**: interplay of atmospheric (black) and MINOS disappearance (blue) data and the combination (red/shaded region) for normal hierarchy at 90% C.L. (dashed) and 3σ (solid). **Right**: combined allowed regions for normal (black curves) and inverted hierarchy (colored regions) at 90%, 95%, 99%, 99.73% C.L. [25].

The $|\Delta m^2_{31}|$ value is obtained from doing a combined fit of MINOS and Super-Kamiokande atmospheric results. In addition the first measurements of $\sin^2 2\theta_{23}$ using an off-axis neutrino beam has been presented by the T2K collaboration [26]. The value of the mass splittings are well known but the ordering of the masses, (the mass hierarchy), is still unknown. Discovering the mass hierarchy is one of the goals of future experiments not only because it obscures the CP violation measurement, but if neutrino masses were inverted it would be the first time that fermions do not have increasing masses with increasing generation number.

4. Future plans

With the discovery that θ_{13} is large, the gateway for studying CP violation in the lepton sector and the mass hierarchy has been opened. Future experiments plan to do just that. Three types of proposals have emerged: high power conventional super beams, beta-beams and neutrino factories. In addition given the large value of θ_{13} Daya Bay could be able to study the mass hierarchy by placing a 20 kton detector at 60 km [27, 28].

4.1. Super beams

A super beam is a conventional beam, based on pion decays but reaching powers of the order of the mega-watt. Three such beams have been proposed. In Japan, the current T2K beam will be a super beam once it reaches its design luminosity of 750kW. This beam in combination with the proposed Hyper-Kamiokande detector [29] would be a very powerful tool to measure δ_{CP} assuming that the mass hierarchy is known. In the US the LBNE project plans to direct a neutrino beam from FermiLab to the Homestake mine where a large LAr detector would be built. And in Europe the LAGUNA-LBNO project presents three possible setups where the preferred option is a super-beam from CERN-SPS to Pyhäsalmi in Finland (baseline = 2300 km).

Today's large value of θ_{13} implies that any future experiment will quickly be systematic-limited. Therefore an effort needs to be made to reduce systematic errors. Experiments like NA61 [30], SciBoone [31], MINERνA [32] and nuSTORM [33] are extremely important to constrain hadron production cross-sections and neutrino cross-sections.

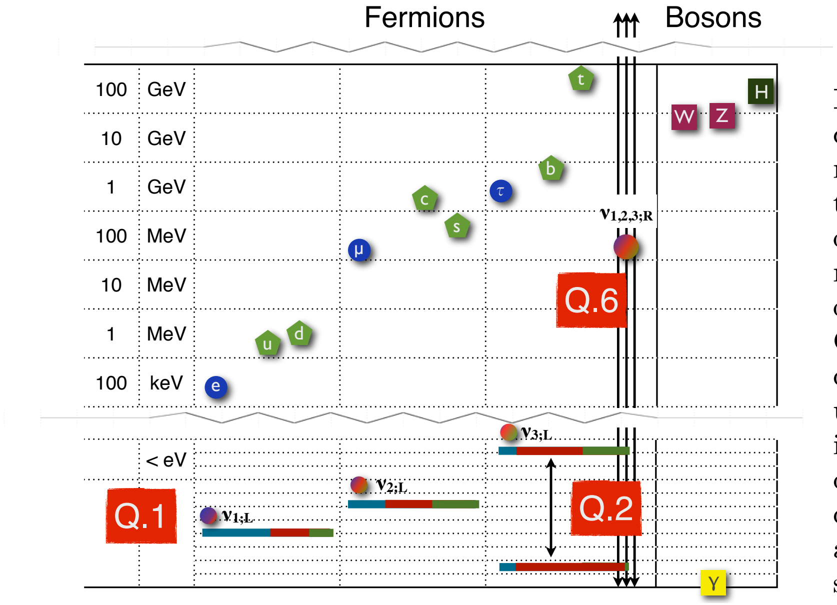

Figure 8. The remaining questions of the Standard model are: **Q.1** Determination of the absolute mass scale of neutrinos. **Q.2** Determination of the mass hierarchy of the active neutrinos. **Q.3** CP violation in neutrino oscillations. **Q.4** Violation of unitarity of the neutrino mixing matrix. **Q.5** Neutrinoless double beta decay. **Q.6** Discovery of effects implying unambiguously the existence of sterile neutrino(s).

4.2. Beta-beams and neutrino factories

The super beams can probably give us the value of δ_{CP} and the mass hierarchy. But precision similar to the precision of the CKM matrix will only be achieved with more powerful facilities. These facilities will also be needed to test the unitarity of the PMNS matrix and test whether neutrinos oscillate to become sterile neutrinos. Beta-beams [34, 35], where a radioactive ion is accelerated and then beta decays creating $\bar{\nu}_e$ beam, could be an option.

Another option is the neutrino factory. Here, μ^- and μ^+ trains simultaneously circulate in opposite direction in the storage ring and are separated in time. They are subsequently allowed to decay in flight to create pure $(\nu_\mu, \bar{\nu}_e)$ and $(\bar{\nu}_\mu, \nu_e)$ beams respectively. The golden channel of the neutrino factory is $\nu_e \to \nu_\mu$, but since ν_μ are also present in the beam, measurements similar to today's (electron neutrino appearance and muon neutrino disappearance) are also possible. The presence of ν_μ, $\bar{\nu}_e$, and $\bar{\nu}_\mu$, ν_e in different trains is perfect to study CP violation since we can directly compare the oscillation of a neutrino to the oscillation of the anti-neutrino. Furthermore, because ν_μ, $\bar{\nu}_e$, $\bar{\nu}_\mu$ and ν_e are present in the beam, the near detector of a neutrino factory would be able to measure all four types of neutrinos cross-sections and reduce systematics considerably. In order to see oscillations, the far detector needs to be magnetized to differentiate $\nu_e \to \nu_\mu$ from an interacting $\bar{\nu}_\mu$. A magnetized iron detector is envisaged as far detector. It was found that an optimal neutrino factory given the current value of θ_{13} uses 10 GeV muons and a baseline of 2200 km [36, 37].

5. Conclusions

The years 2011 and 2012 have without any doubt seen tremendous progress in neutrino physics. Only a year ago, nobody knew if θ_{13} was even large enough to be measured, yet today the precision on θ_{13} is already better than the precision on θ_{23}. With this measurement the prospect of measuring the mass hierarchy and especially the CP phase δ is better than ever and the years to come will be fascinating. With the announcement on July 4th 2012 that the Higgs was probably found, the remaining questions in the Standard Model (Fig. 8) are in neutrinos physics.

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