1.2 Testing the Standard Oscillation Paradigm

Neutrino oscillations are irrefutable evidence for physics beyond the Standard Model of particle physics. The observed properties of the neutrino – the large flavor mixing and the tiny mass – could be consequences of phenomena which occur at energies never seen since the Big Bang, they also could be triggered at energy scales as low as a few keV. Determining the energy scale of the physics responsible for neutrino mass is one of the primary tasks at the Intensity Frontier, which will require, ultimately high precision measurements. High precision is required since the telltale effects from either a low or high energy scale responsible for neutrino masses and mixing will be very small, either because couplings are very small, as in low-energy models, or the energy scales are very high and thus its effects are strongly suppressed.

The three flavor oscillation framework is quite successful in accounting for a large number of results obtained in very different contexts: the transformation of ν_e into $\nu_{\mu,\tau}$ from the Sun [42]; the disappearance of ν_μ and $\bar{\nu}_\mu$ from neutrinos produced by cosmic ray interactions in the atmosphere; the disappearance of ν_μ and $\bar{\nu}_\mu$ [43, 44] from neutrino beams over distances from 200-740 km [45, 46, 47]; the disappearance of $\bar{\nu}_e$ from nuclear reactors over a distance of about 160 km [48]; the disappearance of $\bar{\nu}_e$ from nuclear reactors over a distance of about 2 km [49, 50, 18]; and at somewhat lower significance also the appearance of ν_e [20, 19] and, at even lower significance, the appearance of ν_τ [51] has been observed in experiments using man-made neutrino beams over 200-740 km distance. All these experimental results can be succinctly and accurately described by the oscillation of three active neutrinos governed by the following parameters, including their $1\,\sigma$ ranges [52]

$$\delta m^2 = 7.54^{+0.26}_{-0.22} \times 10^{-5}\,\mathrm{eV}^2\,, (3.2\%) \qquad \Delta m^2 = 2.43^{-0.06}_{+0.1} \times 10^{-3}\,\mathrm{eV}^2\,, (3.3\%) \tag{1.8}$$

$$\sin^2\theta_{12} = 3.07^{+0.18}_{-0.16} \times 10^{-1}\,, (16\%) \qquad \sin^2\theta_{23} = 3.86^{+0.24}_{-0.21} \times 10^{-1}\,, (21\%) \tag{1.9}$$

$$\sin^2\theta_{13} = 2.41 \pm 0.25 \times 10^{-1}\,, (10\%) \qquad \delta = 1.08^{+0.28}_{-0.31}\,\mathrm{rad}\,, (27\%)\,, \tag{1.10}$$

where for all parameters whose value depends on the mass hierarchy, we have chosen the values for the normal mass ordering. The choice of parametrization is guided by the observation that for those parameters the χ^2 in the global fit is approximately Gaußian. The percentages given in parenthesis indicate the relative error on each parameter. For the mass splitting we reach errors of a few percent, however, for all of the mixing angles and the CP phase the errors are in the 10-30% range. Therefore, while three flavor oscillation is able to describe a wide variety of experiments, it would seem premature to claim that we have entered the era of precision neutrino physics or that we have established the three flavor paradigm at a high level of accuracy. This is also borne out by the fact that there are significant hints at short baselines for a forth neutrino [53]. Also, more general, so-called non-standard interactions are not well constrained by neutrino data, for a recent review on the topic see Ref. [54]. The issue of what may exist beyond three flavor oscillations will be discussed in detail in Sec. 1.6 of this report.

Once one realizes, that the current error bars are uncomfortably large, the next question is: how well do we want to determine they various mixing parameters? The answer can be given on two, distinct levels, one is a purely technical one – if I want know X to a precision of x, I need to know Y with a precision of y; an example is, where Y is given by θ_{13} and X could be the mass hierarchy. The answer, at another level, is driven by theory expectations of how large possible phenomenological deviations from the three flavor framework could be. In order to address the technical part of the question, one first has to define the target precision from a physics point of view. Looking at other fields of high-energy physics it is clear that the target precision is evolving over time, for instance, predictions for the top quark mass, in hindsight, seem to have been always ahead by only a few GeV of the experimental capabilities, while at the time, there always was a valid physics argument for why the top quark is just around the corner. A similar evolution can be observed in B physics. Thus, any argument based on model-building inspired target precisions is always of a preliminary nature, as our understanding of models evolves over time. With this caveat in mind, one argument for a target precision can be based on a comparison to the quark sector. Based on a theoretical preference for Grand Unification, one would expect that the answer to the flavor question should find an answer for leptons and quarks at same time (or energy scale) and therefore, a test of such a models should be most sensitive if the precision in the lepton and quark sector is comparable. For instance, the CKM angle γ, which is the exact analog of δ in the neutrino sector, is determined to $(70.4^{+4.3}_{-4.4})^\circ$ [55] and thus, a precision target for δ of roughly 5° would follow.

Another argument for a similar level of precision can be made, based on the concept of so-call neutrino sum-rules [56]. Neutrino sum-rules arise in models where the neutrino mixing matrix has a certain simple form or texture at a high energy scale and the actual low-energy mixing parameters are modified by a non-diagonal charged lepton mass matrix. The simplicity of the neutrino mixing matrix is typically a result of a flavor symmetry, where the overall Lagrangian possesses an overall flavor symmetry G, which can be separated into two sub-groups G_ν and G_l for the neutrinos and charged leptons; it is the mismatch between G_ν and G_l which will yield the observed mixing pattern, see *e.g.* [57]. Typical candidates for G are given by discrete subgroups of SU(3) which have a three dimensional representation, *e.g.* A_4. In a model-building sense these symmetries can be implemented using so-called flavon fields which undergo spontaneous symmetry breaking and it is this symmetry breaking which picks the specific realization of G, for a recent review see [58]. The idea of flavor symmetries is in stark contrast to the idea that neutrino mixing parameters are anarchic, *i.e.* random numbers with no underlying dynamics, for the most recent version of this argument, see Ref. [59]. To find out whether neutrino mixing corresponds to a symmetry or not should be one of the prime tasks of neutrino physics and furthermore, finding out which symmetry, should be attempted, as well.

In practice, flavor symmetries will lead to relations between measurable parameters, whereas anarchy will not. For example, if the neutrino mixing matrix if of tri-bi-maximal form it predicts $|U_{e3}| = 0$, which is clearly in contradiction to observations. In this case, a non-diagonal charged lepton mass matrix can be used to generate the right value of $|U_{e3}|$ and the following sum-rule arises

$$\theta_{12} - \theta_{13}\cos\delta = \arcsin\frac{1}{\sqrt{3}}\,, \tag{1.11}$$

which can be tested if sufficiently precise measured values for the three parameters $\theta_{12}, \theta_{13}, \delta$ are available. Depending on the underlying symmetry of the neutrino mixing matrix different sum-rules are found. In Fig. 1-3 several examples are shown and for each case the values of θ_{13} and θ_{12} or θ_{23} are drawn many times from a Gaußian distribution where the mean values and ranges are taken from Eq. 1.8. The resulting predictions of the value of the CP phase δ are histogramed and shown as colored lines. The width of the distribution for each sum-rule arises from the finite experimental errors on θ_{12} or θ_{23} and θ_{13}. Two observations arise from this simple comparison, first the distance of the means of the distributions is as small as 15° and secondly the width of the distributions is significant compared to their separation and a reduction of input errors is mandated. The thin lines show the results if the errors are reduced to the value given in the plot which would be achieved by Daya Bay for $\sin^2 2\theta_{13}$, by Daya Bay II for $\sin^2\theta_{12}$ and by NOvA for $\sin^2\theta_{23}$. Assuming that the errors on θ_{12}, θ_{23} and θ_{13} are reduced to this level, the limiting factor is natural spread between models, which is about 15°, which for a $3\,\sigma$ distinction between models translates into a target precision for δ of 5°. A measurement at this precision would allow to obtain valuable information on whether indeed there is an underlying symmetry behind neutrino mixing. Moreover, it is likely that is also allows to provide hints which specific class of symmetries is realized. This would constitute a major breakthrough in our understanding of flavor.

For the parameter $\sin^2 2\theta_{13}$ the *status quo* is determined by the results from the reactor experiments Double Chooz [49], Daya Bay [60] and RENO [50] and their results agree well. It is expected that Double Chooz will improve its systematical error by a significant amount with the planned addition of a near detector by the end of 2013. Daya Bay started running in its full eight detector configuration only in the summer of 2012 and it is expected that a 3 year run with all detectors will eventually reach a 3% error on $\sin^2 2\theta_{13}$, compared

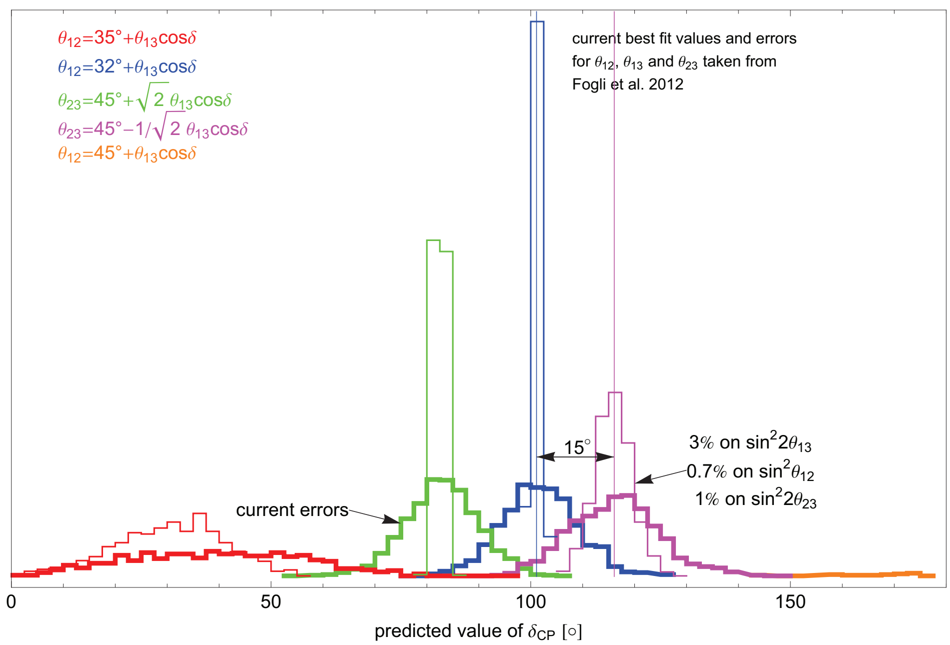

Figure 1-3. *Shown are the distributions of predicted values from δ from various sum-rule as denoted in the legend and explained in the text.*

to currently about 12.5% on this parameter. Of all beam experiments only a neutrino factory will be able to match this precision [61]. A comparison of the values of θ_{13} obtained in $\bar{\nu}_e$ disappearance at reactors with the result of ν_e and $\bar{\nu}_e$ appearance in beams will be a sensitive test of the three flavor framework, which is particularly sensitive to non-standard matter effects.

For the atmospheric Δm^2 currently the most precise measurement comes from MINOS [46] with an error of 3.2% and MINOS+ [**?**] will slightly improve on this result. It is expected that both NOνA and T2K will contribute measurements with errors of $\sim 3\%$ and $\sim 4\%$, respectively. Daya Bay will provide a measurement of this parameter in $\bar{\nu}_e$ disappearance of about 4%. By increasing the size of the event sample and going to an off-axis location, CHIPS [**?**] has the potential to reduce the current error maybe be as much as a factor 2-3, which is of course subject to sufficient control of systematical errors and needs further study. Daya Bay II [**?**] ultimately may have the potential to bring the error down to below one percent. For θ_{23} two related but distinct question arise: what is the precise value of $\sin^2 2\theta_{23}$ or how close it is to unity; and secondly, if $\sin^2 2\theta_{23} \neq 1$, is θ_{23} smaller or larger than $\pi/4$, the so-called octant of θ_{23}. An experiment can be very good at determining the value of $\sin^2 2\theta_{23}$ without obtaining any information on the octant question. The resolution of the octant question can be either achieved by comparing long-baseline data obtained at different baselines, like NOνA and T2K or by comparing a precise $\nu_\mu \to \nu_e$ long-baseline measurement with a precise determination of $\bar{\nu}_e \to \bar{\nu}_e$ oscillations from a reactor experiment like Daya Bay. Within the U.S. program the long-baseline pieces of data can come from the NuMI beam and NOνA is well positioned, as would be potential extensions of the NuMI program in the form of extended NOνA running, GLADE and CHIPS. Eventually, LBNE with its very long baseline and wide beam spectrum will provide good sensitivity to the octant on its own. NOνA and T2K have the potential to reduce the error on $\sin^2 2\theta_{23}$ to 1-2% and most likely further improvements in beam experiments beyond that will require an improved understanding of systematics.

For the solar δm^2 the current errors are determined by KamLAND and a future improvement is necessary to measure the mass hierarchy without using matter effects as proposed by Daya Bay II. Daya Bay II is able to reduce the error to below 1%. The solar mixing parameter $\sin^2\theta_{12}$ is most accurately measured by SNO and there are basically two independent ways to further improved this measurement: One is to do a precision measurement of the solar pp-neutrino flux, since this flux can be predicted quite precisely from the solar luminosity and the $\nu - e$ scattering cross section is determined by the Standard Model, an error of 1% maybe achievable. The experimental challenge is the required very low threshold and associated low backgrounds in a large detector. The other method relies on the observation of $\bar{\nu}_e$ disappearance at a distance of about 60 km as proposed in Daya Bay II, with the potential to bring this error to below 1%. The value of θ_{12} and its associated error play an important role for sum-rules, as explained previously, but also for neutrinoless double β-decay.