Long Baseline Neutrino Experiments

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Abstract. Following the discovery of neutrino oscillations by the Super-Kamiokande collaboration, recently awarded with the Nobel Prize, two generations of long baseline experiments had been setup to further study neutrino oscillations. The first generation experiments, K2K in Japan, Minos in the States and Opera in Europe, focused in confirming the Super-Kamiokande result, improving the precision with which oscillation parameters had been measured and demonstrating the $\nu_\tau$ appearance process.

Second generation experiments, T2K in Japan and very recently NO$\nu$A in the States, went further, being optimized to look for genuine three neutrino phenomena like non-zero values of $\theta_{13}$ and first glimpses to leptonic CP violation (LCPV) and neutrino mass ordering (NMO).

The discovery of leptonic CP violation will require third generation setups, at the moment two strong proposals are ongoing, Dune in the States and Hyper-Kamiokande in Japan. This review will focus a little more in these future initiatives.

1. Introduction

We are talking about long-baseline neutrino beams because the original discovery of neutrino oscillations [1], recently awarded with the Nobel Prize for Physics 2015, set the delta mass squared $\Delta m^2$ for atmospheric oscillations at about $3 \cdot 10^{-3}$ eV$^2$, corresponding to an oscillation length for 1 GeV neutrinos of about 500 km. This low value of $\Delta m^2$ set a severe challenge for neutrino oscillation experiments at accelerators, because the required long distance implied very low fluxes at the far detector. For this reason very large (and expensive) neutrino detectors became mandatory. It could be said that with neutrino oscillation discovery Super-Kamiokande defined itself as the ideal detector for future accelerator neutrino experiments. Already in the original talk at the Neutrino 1998 talk at Takayama, Takaaki Kajita set the goals for future long-baseline experiments: improve the precision with which the oscillation parameters had been measured by Super-Kamiokande and decide if the oscillation mechanism was $\nu_\mu$-$\nu_\tau$ or $\nu_\mu$-sterile transitions (being the $\nu_\mu$-$\nu_e$ hypothesis already disfavored by Super-Kamiokande and disproved by Chooz [2]).

2. First generation long-baseline experiments

Three long-baseline experiments in three different continents had been setup to this purpose: K2K in Japan [4] and Minos in the States [5] improved the precision of the atmospheric parameters, while Opera at the CNGS established the $\nu_\tau$ appearance process [6], improving the Super-Kamiokande indication [7]. In the meantime the improved analysis of Super-Kamiokande atmospheric neutrino events allowed to detect the oscillatory signature in atmospheric neutrino distributions excluding exotic mechanisms as an explanation of the neutrino atmospheric deficits [8].
3. Second generation long-baseline experiments

Second generation long-baseline facilities had been optimized to detect $\nu_\mu \rightarrow \nu_e$ transitions, allowing powerful searches of non-zero values of $\theta_{13}$ and measurements of the neutrino mass ordering. The T2K experiment in Japan, [9], started data taking in 2009. It provided the first indication of a non-zero $\theta_{13}$ value [10], detected for the first time the neutrino oscillation appearance process, publishing evidence of $\nu_\mu, \nu_e$ transitions [11] and improved the precision of the measurement of atmospheric parameters [12]. The value of $\theta_{13}$ had been subsequently precisely measured by reactor experiments Daya Bay [13], Double Chooz [14] and Reno [15]. The progress in the years of the precision of global fits in atmospheric parameters and $\theta_{13}$ is displayed in Fig. 1. The NO$\nu$A experiment in the States, [16], started data taking in 2015 and recently reported interesting results both in $\nu_\mu \rightarrow \nu_e$ appearance and in $\nu_\mu$ disappearance [17].

3.1. Near term opportunities

At present both T2K and NO$\nu$A roughly integrated 10% of the expected statistics. It’s interesting to note that already at today the combined fit of $\nu_e$ appearance at accelerators and $\nu_e$ disappearance at reactors favors maximal violation of CP, with a best fit at $\delta_{CP} \approx -\pi/2$ [18]. T2K collaboration recently published a study of the potential of the T2K and T2K+NO$\nu$A experiments for the measurement of $\delta_{CP}$ and neutrino mass ordering [19], computed assuming their full statistics. The outcome of this study is that the ultimate sensitivity of T2K+NO$\nu$A is about $2\sigma$ for $\delta_{CP} = -\pi/2$ and about $3.3\sigma$ in rejecting the wrong neutrino mass ordering value for the most favorable combination of neutrino mass ordering and $\delta_{CP}$ (1.7$\sigma$ in the worst case).

A very recent study has elaborated the sensitivity of T2K in case of upgraded power of the J-Parc proton driver (3 times the nominal statistics), upgraded beam optics, better event reconstruction and reduced systematic errors (the latter three performances are considered realistic based on the experience accumulated within T2K). Under these hypothesis (T2K-II), the experiment could reach the $\delta_{CP}$ $3\sigma$ sensitivity with a coverage of about 30%.

4. The hunt for leptonic CP violation

4.1. General considerations

The smallness of the atmospheric $\Delta m^2$ is probably the only bad news about the values of neutrino oscillation parameters. In order to have a detectable CP phase $\delta_{CP}$ it is necessary that all the oscillation amplitudes $\theta_{12}, \theta_{23}, \theta_{13}$ are big, and that the solar $\Delta m^2$ is not too small (a
solar $\Delta m^2$ as small as $\Delta m^2 \leq 4 \cdot 10^{-3} \text{eV}^2$ had prevented any possibility of measuring $\delta_{\text{CP}}$, see for instance [20]), and actually this is the case.

The large value of $\theta_{13}$ furthermore allows for large oscillated event rates in the far detector. This feature favors the approach of conventional neutrino beams guaranteeing sufficient signal statistics and sufficient control of background events. On the other hand the asymmetry of oscillation rates between neutrino and antineutrino is reduced, such that systematic errors become an issue (for a more detailed discussion about different strategies for the different possible values of $\theta_{13}$ see [21]). Under these circumstances the "quick and dirty" approach of conventional neutrino beams may provide setups capable of reaching interesting sensitivities in leptonic CP violations while innovative concepts like Neutrino Factories [22] or Beta Beams [23] have been for the moment abandoned.

In [24] have been discussed the general properties of an experiment willing to search for LCPV. It turn out that to achieve a $3\sigma$ sensitivity with a coverage of 70% (roughly corresponding to a $5\sigma$ sensitivity with a coverage of 50%) it is necessary to integrate about 1 Megaton $\times$ MWatt $\times$ years (where Megaton refers to the mass of the far detector and MWatt to the power of the proton driver). Different baselines as well different detector technologies (water or liquid argon) or different beam configuration (on-axis or off-axis) don’t seem to change too much this requirement.

The parameter that can play an important role in LCPV sensitivity is the amount of systematic errors. While the exposure of 1 Megaton $\times$ MWatt $\times$ years value had been computed or systematic errors at 3%, a value of 5% would require an exposure of 2.5 in the same units for the same coverage and a 10% systematic errors would prevent to reach this coverage regardless to the exposure. It is interesting to signal that the T2K experiment made significant progress in reducing systematic errors along the years, achieving a value of about 7% for neutrinos [11] and about 11% for antineutrinos [25].

### 4.2. Third generation long-baseline experiments

While Europe, following the decisions of CERN and the outcome of the Laguna design study [26], abandoned any plan of building an intense neutrino source and a gigantic underground neutrino detector (but some activity still remains, see [27]), very ambitious plans exist in the States, Dune [28], and in Japan, Hyper-Kamiokande [29]. The two proposal follow very different experimental strategies.

The Dune experiment uses a very long baseline of 1300 km and a wide band on-axis neutrino beam. In this configuration it has good sensitivity to neutrino mass ordering and it could detect neutrino events ranging from the second oscillation maximum to the energy region above the tau lepton mass threshold. The liquid argon technology looks appropriate to detect neutrino events ranging from the quasi-elastic to the deep inelastic cross section regions, producing events with very different topologies. The wide band beam anyway suffers from larger background rates from the intrinsic beam $\nu_e$ contamination and the larger rates of non-oscillated events challenge the energy reconstruction performances of a liquid argon detector.

The Hyper-Kamiokande configuration is identical to T2K: a “short”, off-axis, long baseline with reduced sensitivity to neutrino mass ordering and an off axis setup. It is clearly a configuration optimized for leptonic CP violation (keeping as low as possible the intrinsic $\nu_e$ configuration) and for a water Čerenkov detector (being the majority of neutrino interaction quasi elastics, very well reconstructed in water).

As a matter of facts the two approaches are truly complementary (for a more detailed discussion see [30]), also considering the astroparticle physics potential of the two experiments; in the following the two experimental setups will be discussed in greater detail.
Figure 2. The significance with which the CP violation can be determined by DUNE as a function of the value of CP for an exposure of 300 kt × MW × year assuming normal NMO (left) or inverted NMO (right). The shaded region represents the range in sensitivity due to potential variations in the beam design. The sensitivity is computed assuming systematic errors at 3.5%. From [31].

4.3. Dune

The “Deep Underground Neutrino Experiment”, DUNE, [31, 32] is designed to be built in the Sanford Underground Research Facility, South Dakota, at a depth of about 1500 m, and at a baseline of 1300 km from Fermilab, where the neutrino beam will be produced. So far Dune is a collaboration of 776 physicists from 144 Institutions. The proton driver of the neutrino beamline will be PIP-II: with a power of about 1.2 MW by 2025, while it is expected to reach a power beyond 2 MW with PIP-III after a phase of R&D. The near detector baseline design is a Fine Grained Tracker (i.e. straw tubes) in magnetic field, complemented by calorimetry and muon range. It will be located at a distance of 574 m from the target, at a depth of 65 m. The far detector id designed to be a set of four liquid argon detectors of 10 kton fiducial volume (total volume of each detector: 17.1 kton), each module being installed in a dedicated cavern. Excavation should start in 2017. The first liquid argon module will be based on the single-phase technology (the same of the Icarus detector, [33]) and its construction should commence in 2019. It has to be decided if the following modules will be single-phase or double-phase, it will strongly depend on the ongoing R&D, supported by CERN via the WA105 initiative [34]. The present timescale foresees the start of data taking with the first 10 kton module in 2025 and the full configuration ready by 2029. Dune performances are summarized in Fig.2: it is expected a $3\sigma$ CP coverage of 75% and a $5\sigma$ coverage of 50% for an exposure of about 1 Mton × MWatt × year (20 years run with 40 kton LAr and 1.2 MW). These sensitivities still depend on the allowed range of values of other neutrino oscillation parameters. Regarding neutrino mass ordering sensitivity, Dune will separate the two possibilities (normal or inverted hierarchy) with a $\Delta \chi^2 \geq 25$ with a 10 years run, for the worst case of oscillation parameters.
4.4. Hyper-Kamiokande

Hyper-Kamiokande [35, 36, 29] is designed to be a 0.99 Mton Water Čerenkov detector (inner volume 0.74 Mton, fiducial volume 0.56 Mton: 25 times Super-Kamiokande) composed by two horizontal cylinders of 48 m diameter and 53 m length. The baseline option for the phototubes is the so called Box&Line PMT, which have, compared to the Super-Kamiokande phototubes, 2 times the single photon efficiency, twice better time resolution (1 ns against 2 ns) and better single electron charge resolution (35% against 53%). The inner detector will require 99000 PMT’s to achieve a photocatode coverage of 20%, while the outer detector should be equipped with 25000 8” PMT’s. The detector will be placed at the same distance and the same off-axis angle of Super-Kamiokande, but not necessarily at the same location. The beamline will be the same used by T2K, the assumed beam power is 0.75 MW. The proto collaboration so far counts 13 countries and about 240 members. The collaboration plans to submit a formal proposal within 2016, in case of approval construction could start in 2018 and operations could start around 2025. Hyper-Kamiokande could still use the same T2K near detectors (INGRID [37] and ND280 [9]), but several concepts had been already proposed as Water Čerenkov detectors at intermediate distance: the off-axis angle spanning orientation mPRISM [38] and the Gd loading, magnetized muon range detector TITUS [39].

Assuming systematic errors at 3.5% Hyper-Kamiokande is expected to achieve in a 10 years run at 0.75 MW power a coverage of 78% of the possible values of $\delta_{CP}$ for a $3\sigma$ sensitivity and a coverage of 56% at $5\sigma$, see figure 3.

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1 Hyper-Kamiokande design configuration changed very recently and it isn’t yet documented in published papers. As far as concerns CP and NMO sensitivities the new performances are not very different from those illustrated in these proceedings.
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