Neutrino Oscillations with a Next Generation Liquid Argon TPC Detector in Kamioka or Korea Along the J-PARC Neutrino Beam

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Abstract

The "baseline setup" for a possible, beyond T2K, next generation long baseline experiment along the J-PARC neutrino beam produced at Tokai, assumes two very large deep-underground Water Cerenkov imaging detectors of about 300 kton fiducial each, located one in Korea and the other in Kamioka but at the same off-axis angle. In this paper, we consider the physics performance of a similar setup but with a single and smaller, far detector, possibly at shallow depth, composed of a 100 kton next generation liquid Argon Time Projection Chamber. The potential location of the detector could be in the Kamioka area ($L \sim 295$ km) or on the Eastern Korean coast ($L \sim 1025$ km), depending on the results of the T2K experiment. In Korea the off-axis angle could be either $2.5^o \sim 3^o$ as in SuperKamiokande, or $\sim 1^o$ as to offer pseudo-wide-band beam conditions.

1. Introduction

The well-established observations of solar and atmospheric neutrinos, in particular from Superkamiokande (SK) [1], SNO [2] and KamLAND [3] and the recent negative result from MiniBOONE[4], are very strong indicators of the validity of the 3×3 PMNS [5] mixing matrix U ($\nu_\alpha = U_{\alpha i}\nu_i$) to describe all the observed neutrino flavor conversion phenomena. In order to complete this picture, all the elements (magnitude and phase) of the mixing matrix must be determined. That includes the U_{e3} element ($|U_{e3}|^2 = \sin^2\theta_{13}$ in the standard parameterization), for which today there is only an upper bound. The best constraint comes from the CHOOZ [2] reactor experiment, corresponding to $\sin^2 2\theta_{13} \lesssim 0.14$ (90%C.L.) at the mass squared difference $|\Delta m^2_{atm}| \simeq 2.5 \times 10^{-3}$ eV^2.

Long baseline neutrino experiments have the task to complete the present knowledge on the mixing parameters, possibly including the complex phase. A non vanishing $|U_{e3}|$ would open the possibility of CP/T violation in the leptonic sector, as a direct consequence of non-trivial complex phases in the 3×3 mixing matrix. The determination of the missing elements is possible via the study of $\nu_\mu \rightarrow \nu_e$ transitions at a baseline L and energy E with the choice $E/L \sim \Delta m^2_{atm}$. At the same time, the sign of the parameter Δm^2_{atm} is unknown and this affects, in some region of the parameter space which depends on the value of $\sin^2 2\theta_{13}$, our ability to unambiguously detect CP-violation, as we will illustrate it for our setup later on. On the other hand, the sign of Δm^2_{atm} could be determined by (1) precision measurement of the $\nu_\mu \rightarrow \nu_e$ oscillation probability as a function of energy at sufficiently long baselines (i.e. $L \gtrsim 300$ km), (2) by a comparison of oscillations involving neutrinos and antineutrinos at sufficiently long baselines, (3) by a comparison of probabilities at similar energies with two detectors, one located at a shorter and one at a longer baseline, or (4) by some combination of all the above methods (1)-(3). Hence, for some region of the $\sin^2 2\theta_{13}$ angle, the determination of CP-violation and the neutrino mass hierarchy must be addressed simultaneously

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in order to avoid the mass hierarchy degeneracy problem.

The purpose of this workshop was to investigate the possible options with an upgraded J-PARC neutrino beam after the present T2K experiment [7], in particular by placing a second detector in Korea. The center of the T2K neutrino beam will go through underground beneath SK, and will automatically reach the sea level east of the Korean shore. Therefore, placing a detector in an appropriate location in Korea will probe neutrino oscillations at a baseline of 1000 to 1200 km away from the source.

The neutrino beam spectrum in Korea will depend on the off-axis angle and on the exact geographical location chosen, because of the non-cylindrical shape of the decay tunnel in the neutrino beam line. When the upper side of the beam at $2°$ to $3°$ off-axis angle is observed at SK, the lower side of the same beam at $0.5°$ to $3.0°$ off-axis angle can be observed in Korea. See Ref. [8] for beam spectra computed in some reference locations and for details.

The measurements in T2K might indicate that the θ_{13} angle is in a region where the simultaneous determination of neutrino mass hierarchy and the CP violating phase becomes possible. In Ref. [8], the possibility of using two next generation ~ 300 kton fiducial identical Water Cerenkov detectors placed at different baseline distances but at the same off-axis angle was explored. The authors concluded that this setup would have the ability to resolve the mass hierarchy by comparing the event yields at the two baselines, one being more sensitive to matter effects than the other.

In the present paper, we consider an alternative setup composed of a single 100 kton liquid Argon TPC located somewhere on the eastern coast of Korea with off-axis angles ranging from $\sim 1^o$ to 2.5^o. We explore the physics reach of this experiment in terms of sensitivity to discover θ_{13}, to determine the CP-violation phase δ and to resolve the mass hierarchy.

2. The Liquid Argon Time Projection Chamber

The liquid Argon Time Projection Chamber (LAr TPC) (See Ref. [31] and references therein) is a powerful detector for uniform and high accuracy imaging of massive active volumes. It is based on the fact that in highly pure Argon, ionization tracks can be drifted over distances of the order of meters. Imaging is provided by position-segmented electrodes at the end of the drift path, continuously recording the signals induced. T_0 is provided by the prompt scintillation light.

In this paper, we assume a detector following the GLACIER concept [32] with mass order of 100 kton. The pros and cons of the LAr TPC, in particular in comparison to the Water Cerenkov Imaging technique, can be summarized as follow:

- **Pros**: The liquid Argon TPC imaging should offer optimal conditions to reconstruct with very high efficiency the electron appearance signal in the energy region of interest in the GeV range, while considerably suppressing the NC background consisting of misidentified π^0's. MC studies show that an efficiency above 90% for signal can be achieved while suppressing NC background to the permil level [12]. This MC result was shown to be true over a wide range of neutrino energy, typ. between 0 and 5 GeV. If verified experimentally, this implies that the intrinsic ν_e flux will be the dominant background in a liquid Argon TPC coupled to a superbeam [13]. The systematic error on this flux ($\lesssim 5\%$) will be determining the final sensitivity of the experiment.

- **Pros**: the physics performance per unit mass of the LAr TPC is expected to be superior to that of the WC detector; hence, the LAr TPC detector could be smaller than the WC detector to achieve the same physics performance; the 100 kton detector considered here is approximately twice the size of the

Superkamiokande detector. In addition, a LAr TPC should allow operation at shallow depth. The constraints on the excavation and the related siting issues of the detector should hence be reduced in the case of a LAr TPC. For a quantitative discussion on the possible operation at shallow depth, see Ref. [14].

- **Pros**: the imaging properties and the good energy resolution of the LAr TPC would allow to consider all events around the GeV region and above, while the WC technology is essentially limited to quasi-elastic (QE) events and background considerations limit the beam energy to lie below the GeV range. Hence, broader band beams, as for example obtained at J-PARC with smaller off-axis angles than SK, e.g. 1^o off-axis, covering more features of the oscillation probability (e.g. first maxima, first minima, second maxima, etc.) can be contemplated.

- **Cons**: the community has less experience with the LAr TPC technology than the WC; the largest detector ever operated, the ICARUS T300, has a modular design which is not easily extrapolated to the relevant masses. Significant R&D and improvements in the design are therefore required in order to reach a scalable design which could offer a path for a 100 kton mass facility in a cost effective way. For an overview and results of one such R&D program, see Refs. [15, 16, 17, 18].

- **Cons**: the procurement and underground handling of large amounts of liquid Argon is more difficult than that for water, however, safe, surface or near-surface, storage of very large amounts of cryogen (with volumes larger than the ones considered here) has been achieved by the petrochemical industry; liquid Argon is a natural by-product of air liquefaction which has large industrial and commercial applications and can be in principle produced nearby any chosen location.

3. The J-PARC Neutrino Beam

The measurements considered by future long baseline experiments will require to accumulate sufficiently large statistics in the far detectors to study with high precision the neutrino oscillation phenomena. The physics performance of these facilities will therefore depend on the ability of the involved accelerator complexes and of the neutrino beam infrastructures to offer stable and long-term fault-less operations. In Table 1 we summarize the design parameters for the J-PARC beam under the three conditions "baseline", "upgraded" and "ultimate":

- **The "baseline" 0.6 MW T2K beam [7]:** The J-PARC neutrino beam is under construction for the T2K experiment and is planned to begin operation in 2009 at low intensity. The final goal for the T2K experiment is to reach an integrated intensity of 5×10^{21} pots, or equivalently a beam power of ~ 0.6 MW during 5 years.

- **The "upgraded" 1.66 MW beam [6]:** there is a plan to further upgrade the accelerator complex to potentially provide an increased beam power of 1.66 MW to the neutrino target. This upgrade should in principle not require major modifications in the beamline infrastructure which has been designed up to 2 MW.

- **An "ultimate" 4 MW beam [7]:** The physics reach of a megaton (Mton)-class water Cerenkov detectors coupled to a beam power of 4MW was originally considered in Ref. [7]. Although such a power might require significant upgrades of the J-PARC facility, it was chosen as default value in the "baseline setup" for the two Water Cerenkov detectors configuration in Korea

Table 1 Design parameters for the various beams at J-PARC. Comparison with the dedicated CNGS intensity and assumed upgrades of the CERN SpS complex (see text). The beam power corresponds to the instantaneous power on the neutrino target while the product $E_p \times N_{pot}$ corresponds to the total amount of energy deposited on the target per year, which is more relevant to calculate neutrino event rates.

	J-PARC			CERN SpS			
	design [7]	upgrade [6]	ultimate [7]	CNGS	+ [13]	1 [20]	2 [20]
Proton energy E_p	30 GeV		40 GeV	400 GeV			
$ppp(\times 10^{13})$	33	67	> 67	4.8	14	4.8	15
T_c (s)	3.64	2	< 2	6	6	6	6
Efficiency	1.0	1.0	1.0	0.55	0.83	0.8	0.8
Running (d/y)	130	130	130	220	220	240	280
N_{pot} / yr ($\times 10^{19}$)	100	380	$\simeq 700$	7.6	33	12	43.3
Beam power (MW)	0.6	1.6	4	0.5	1.5	0.5	1.6
$E_p \times N_{pot}$ ($\times 10^{22}$ GeV·pot/yr)	4	11.5	28	3	13.2	4.7	17.3
Relative increase		$\times 3$	$\times 7$		$\times 4$	$\times 1.5$	$\times 6$
Timescale	> 2009	2014?	$>$2014?	> 2008	$>$2016 ?		

and Kamioka [8]. For ease of comparison, we also assume this value, unless otherwise stated.

Finally for reference, Table 1 includes the intensity expected at the CERN NGS as well as figures corresponding to assumed upgrades of the CERN accelerator complex [13, 20]. The upgraded CNGS performance will be discussed in Section 8..

4. Expected Event Rates in Korea and Physics Analysis

We carry out an analysis following our previous work outlined in Ref. [13]. For the fit procedure, we assume at this stage identical running periods for each horn polarity, i.e. assume equal neutrino and antineutrinos runs. In an actual experiment, the plain exploration of $\sin^2 2\theta_{13}$ would suggest more neutrinos, while the CP-violation search requires a comparison between neutrinos and antineutrino runs. Assuming that the neutrino flux at the far location will be precisely known by extrapolation of the near data measured by detectors located at 280 m [7] and possibly at 2 km [12], we assumed a systematic error on the $\nu_e + \bar{\nu}_e$ flux at the far location of 5%. The simulated data and background is fitted in energy bins of 100 MeV each. More refined treatments of the systematic errors, including also instrumental effects, will be included at a later stage.

Assuming an integrated intensity of 35×10^{21} pots (or 5 years of running at 4 MW) for each horn polarity mode (labelled neutrino and antineutrino runs for a total of 10 years), the number of events expected neglecting flavor oscillations are reported in Table 2 for three locations: (1) 295 km, OA 2.5^o corresponding to the Kamioka region; (2) 1025 km, OA 1.0^o corresponding to most east region of Korea; (3) 1025 km, OA 2.5^o. In the Table, the interactions of neutrinos and antineutrinos are separated, however, for the analysis we sum them, as we do not consider the possibility to discriminate between the two on an event-by-event basis. The higher rates are clearly expected at 295 km, while the $1/L^2$ dependence reduces the flux in Korea by an order of magnitude. A significant fraction of the loss compared to Kamioka (OA 2.5^o) can indeed be recovered by locating the

Table 2 Number of events calculated for 35×10^{21} p.o.t. (7×10^{21} pot per year $\times$ 5 years) for each polarity mode and a detector of 100 kton. A cut of 5 GeV has been set on neutrino energy.

	neutrino run			antineutrino run		
Location	ν_μCC ($\overline{\nu}_\mu$CC)	ν_eCC ($\overline{\nu}_e$CC)	$(\nu_e + \overline{\nu}_e)$ / $(\nu_\mu + \overline{\nu}_\mu)$	ν_μCC ($\overline{\nu}_\mu$CC)	ν_eCC ($\overline{\nu}_e$CC)	$(\nu_e + \overline{\nu}_e)$ / $(\nu_\mu + \overline{\nu}_\mu)$
J-PARC - 40 GeV/c protons - T2K optics - 4MW						
295 km 2.5 deg (0-5 GeV)	205000 (5970)	3619 (416)	1.9 %	27562 (60404)	1225 (1136)	2.7 %
1025 km $\sim$ 1 deg (0-5 GeV)	81650 (3249)	716 (60)	0.9 %	9737 (24415)	176 (212)	1.1 %
1025 km 2.5 deg (0-5 GeV)	16980 (495)	300 (34)	1.9 %	2283 (5003)	101 (94)	2.7 %

Table 3 Number of oscillated events calculated for a detector of 100 kton and 35×10^{21} pots with horns on neutrino polarity. The parameters used for the oscillation are the following: $\Delta m^2_{32} = 2.5\times10^{-3}$ eV^2, $\Delta m^2_{12} = 7 \times 10^{-5}$ eV^2, tg^2 (θ_{12})= 0.45, sin^2 (θ_{23})= 0.5, sin^2 $(2\theta_{13})$= 0.002, $\rho = 2.8$ g/cm^3.

Location	$\sin^2(2\theta_{13})$ = 0.002	neutrino run ν_μCC + $\bar{\nu}_\mu$CC no osc.	ν_eCC + $\bar{\nu}_e$CC δ=0	90^o	270^o	180^o	beam
J-PARC - 40 GeV/c protons - T2K optics - 4MW							
295 km 2.5 deg (0-5 GeV)	Matter (n.h.)	210970	274	39	393	158	4035 $\sqrt{B} = 64$
1025 km $\sim$ 1 deg (0-5 GeV)	Matter (n.h.)	85900	226	138	389	300	776 $\sqrt{B} = 28$
1025 km 2.5 deg (0-5 GeV)	Matter (n.h.)	17475	94	60	126	92	334 $\sqrt{B} = 18$

Korean detector at OA 1.0^o. In this case, the rate in Korea is approximately half that at Kamioka. In addition, given the different kinematics in 3-body kaon decays, the beam background ratio ν_e/ν_μ is more favorable at smaller OA angles.

Based on these arguments, one would conclude that an OA 1.0^o in Korea is favored compared to the OA 2.5^o. However, it was pointed out by the authors of Ref. [8] that the same OA angle at Kamioka and Korea would allow to cancel certain systematic errors associated to the beam. At this stage we have not attempted to quantify this further.

5. Sensitivity on θ_{13}

We report in Table 3 the expected number of oscillated events including matter effects for a normal neutrino hierarchy ($\rho = 2.8$ g/cm^3) for different values of the

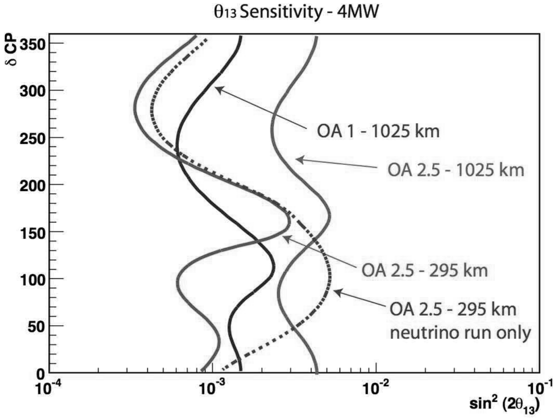

Fig. 1 θ_{13} sensitivity at 3σ C.L. for our three locations. The dashed line corresponds to a neutrino run only for the 295 km, OA 2.5^o configuration.

CP-violation phase δ and $\sin^2(2\theta_{13}) = 0.002$ for the three same detector locations of Table 2. The parameters used for the oscillation are the following: $\Delta m^2_{32} = 2.5\times10^{-3}$ eV^2, $\Delta m^2_{12} = 7 \times 10^{-5}$ eV^2, tg^2 $(\theta_{12})= 0.45$, $\sin^2$ $(\theta_{23})= 0.5$, and $\sin^2(2\theta_{13}) = 0.002$.

The number of oscillated events depends as expected on the chosen value of the δ-phase. For the normal hierarchy and neutrinos, the smallest number of events is observed for δ around 90^o. Relative to the intrinsic beam ν_e background, the number of oscillated events is significant (see table for the $\sqrt{B}$), even for the small value of $\sin^2(2\theta_{13}) = 0.002$.

These results translate in the θ_{13} 3σ C.L. sensitivity shown in Figure 1. The configurations 295 km, OA 2.5^o and 1025 km, OA 1.0^o yield similar sensitivities, while 1025 km, OA 2.5^o is slightly worse. The role of the antineutrino run for the region $0 < \delta < 150^o$ is also illustrated with the dashed curve which corresponds to a neutrino run only.

6. CP-Violation Discovery

For our definition of CP-violation sensitivity and the sensitivity fitting procedure please refer to Ref. [13]. In short, the CP-violation can be said to be discovered if the CP-conserving values, $\delta = 0$ and $\delta = 180^o$, can be excluded at a given C.L. The reach for discovering CP-violation is computed choosing a "true" value for δ $(\neq 0)$ as input at different true values of $\sin^2 2\theta_{13}$ in the $(\sin^2 2\theta_{13}, \delta)$-plane, and for each point of the plane calculating the corresponding event rates expected in the experiment. This data is then fitted with the two CP-conserving values $\delta = 0$ and $\delta = 180^o$, leaving all other parameters free (including $\sin^2 2\theta_{13}$!). The opposite mass hierarchy is also fitted and the minimum of all cases is taken as final χ^2.

Leaving all unknown parameters free and letting vary the known ones within their experimental errors in the fit, the CP-violation 3σ C.L. discovery sensitivity is shown in Figure 2 for the three geographical configurations 295 km OA 2.5^o, 1025 km OA 1^o and OA 2.5^o, assuming an integrated intensity of 35×10^{21} pots for each horn polarity mode (5 yrs neutrino and 5 yrs antineutrino runs for a total of 10 years). For the shortest baseline (295 km), the mass hierarchy degeneracy

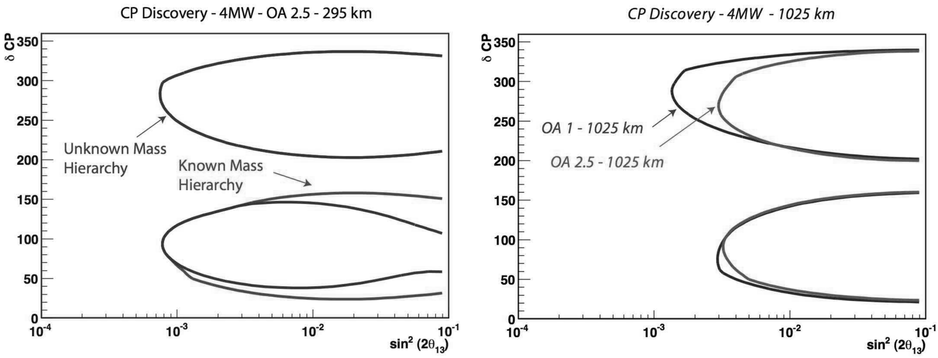

Fig. 2 CP-violation discovery at 3σ C.L. assuming an integrated intensity of 35×10^{21} pots for each horn polarity mode (5 yrs neutrino and 5 yrs antineutrino runs for a total of 10 years), for the (left) 295 km with (blue line) and without (red line) a priori knowledge of the mass hierarchy and (right) 1025 km OA 1^o (blue line) and OA 2.5^o (red line).

affects the sensitivity at large $\sin^2 2\theta_{13} \gtrsim 10^{-2}$. Given the limited sensitivity to matter effects at this baseline, the data could be fitted with a conserving value of δ and the wrong (opposite to true) sign of Δm^2_{32}.

This effect can be qualitatively understood by noting that the neutrino beam is optimised to cover the first maximum of oscillation which corresponds, at the selected baseline, to about 600 MeV neutrinos. At this energy the oscillation bi-probabilities for neutrinos and antineutrinos with $\delta = 90^o$ and $\Delta m^2 > 0$, essentially coincide with that with $\delta = 0$ and $\delta = 180^o$ for $\Delta m^2 < 0$, therefore the data can be very well fitted with a conserving value of δ and the opposite mass hierarchy.

The mass hierarchy degeneracy problem can be resolved by choosing a longer baseline and/or by extending the energy range of the beam spectrum, like for example is the case when we reduce the OA angle. In the Korean configuration, the situation is resolved as can be seen from Figure 2 (right): the CP-violation discovery region for the OA 1 and OA 2.5 configurations are therefore favored for large values of $\sin^2 2\theta_{13}$, but it also emerges that the small off-axis angle configuration is favoured by the higher statistics, and for small values of θ_{13} the sensitivity is better than that obtained in Korea.

To summarize, the results are plotted in terms of δ coverage in Figure 3. If the Korean scenario is chosen, the OA 1^o angle guarantees a better sensitivity. In the Kamioka scenario, the CP-coverage decreases for values of $\sin^2 2\theta_{13} \gtrsim 0.01$. It is a striking coincidence that this value approximately corresponds to the expected sensitivity of the T2K experiment! Hence, in case a signal is observed with $\sin^2 2\theta_{13} \gtrsim 0.01$ one should aim at the largest possible δ coverage, and a longer baseline should be chosen to avoid neutrino mass hierarchy degeneracy. In this case, the authors of Ref. [21] claim that one should pay attention to other systematic errors.

On the contrary, if no signal is measured and $\sin^2(2\theta_{13}) \lesssim 0.01$, the priority is to reach the best CP-sensitivity for the smallest possible value of the mixing parameter θ_{13} and the shortest baseline could be favored.

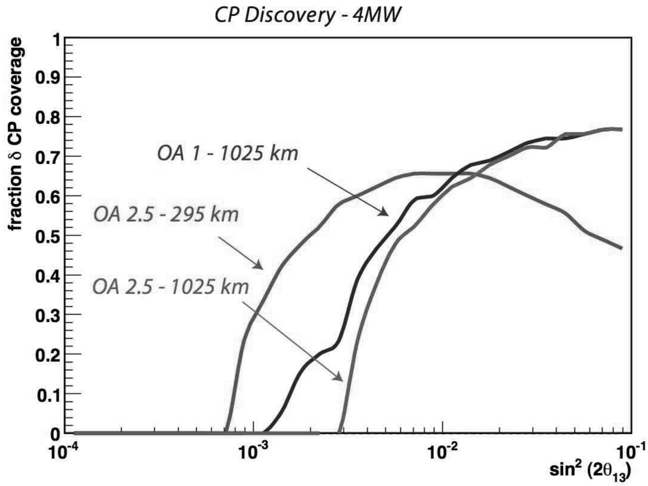

Fig. 3 Fraction of δ coverage for CP-violation sensitivity at 3σ C.L. for our three configurations, corresponding to Figure 2.

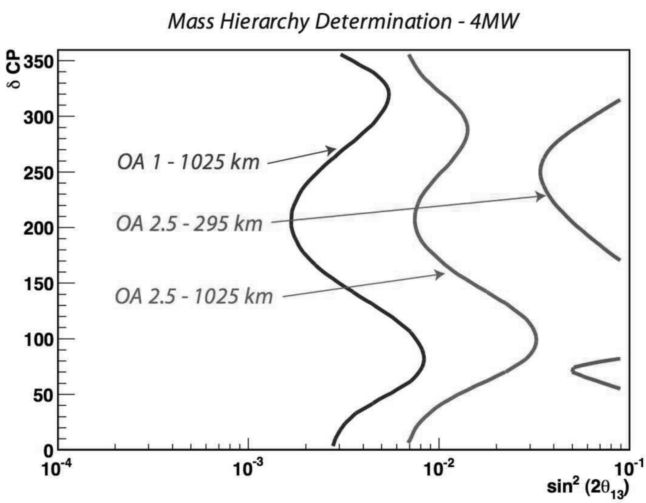

Fig. 4 Mass hierarchy determination at 3σ C.L. for several detector configurations.

7. Mass Hierarchy Determination

For CP-violation discovery, the best setup depends on the value of $\sin^2 2\theta_{13}$. The situation for mass hierarchy determination is completely different: the longer baseline represents the best solution. At the same OA 2.5^o, the Korean baseline gives an improvement in the sensitivity of a factor 5 with respect to the Kamioka baseline (See Figure 4). The higher rate, i.e. the smaller OA angle, improves the mass hierarchy determination: going from OA 2.5^o to OA 1^o improves the sensitivity by a factor of 2.

8. Other Options at J-PARC and Comparison to the CERN Case

The main focus of the CERN program is the Large Hadron Collider (LHC) however CERN is engaged in long baseline neutrino physics with the CNGS project [22] and supports T2K as a "recognized" experiment. The CNGS beam has recently begun operation and first events have been collected in the OPERA detector [23]. The current optimization provides limited sensitivity to the $\nu_\mu \to \nu_e$ reaction and OPERA should ultimately reach a sensitivity $\sin^2 2\theta_{13} \lesssim 0.06$ (90%C.L.) in 5 years of running with the nominal 4.5×10^{19} pot/yr [24]. The ICARUS T600 [31], still to be commissioned, will detect too few contained CNGS events to competitively study electron appearance.

Ideas to improve the $\nu_\mu \to \nu_e$ sensitivity at the CNGS have been discussed in the past [25, 26]. Recently, in Ref. [13] we discussed the physics potential of an intensity upgraded and energy re-optimized CNGS neutrino beam coupled to a 100 kton liquid Argon TPC located at an appropriately chosen off-axis position, and showed that improvements in θ_{13} sensitivity, search for CP-violation and mass hierarchy determination were potentially possible. The discussion relied on the observation that whereas J-PARC provides a rapid cycle with high intensity proton bunches at ~ 40 GeV, the CERN proton complex has fewer protons and a slower cycle but can accelerate up to 400 GeV. Hence, the resulting target beam powers are – on paper – comparable (See Table 1). In particular, it was noted that future upgrades of the CERN LHC injection chain (to be envisaged in the context of the luminosity upgrades) could provide increased proton intensities in the SPS. This option labelled "CNGS+" in Table 1 accordingly envisioned 3.3×10^{20} pots/yr.

The same idea was subsequently and independently re-analyzed assuming a smaller detector of 20 kton located at an angle OA 0.8^o at a baseline of 730 km (MODULAr [20]). In this case, two possible upgrades for CNGS beam labelled as "CNGS1" and "CNGS2" yielding 1.2×10^{20} pot/yr and 4.33×10^{20} pot/yr were considered.

A CERN accelerator division report [27] subsequently indicated that with an upgrade of the SPS RF and new injectors, it would indeed potentially be possible to accelerate 2.4×10^{20} pot/yr. This means that the CNGS+ exposure would correspond to a run of 7 years instead of 5 years and the CNGS2 beam to 9 years instead of the assumed 5 years. Yet intensity limitations will be coming from the design of the equipment in the current CNGS facility and from radiation and waste issues. The desired intensities would therefore require a major re-assessment or a complete reconstruction of the CERN neutrino beam infrastructure (we however point out that the low energy beams considered here would accommodate a significantly reduced decay tunnel compared to the one of the CNGS).

In order to compare these options with the possible upgrades at J-PARC, we focus on the $\sin^2 2\theta_{13}$ sensitivity. The obtained conclusions can be readily extrapolated to the CP-violation and mass hierarchy determination.

Figure 5 shows the expected θ_{13} sensitivity at the 3σ C.L. for a 20 kton LAr TPC detector located at Kamioka after 5 years of neutrino run with (a) the upgraded beam power of 1.6 MW (b) the ultimate beam power of 4 MW. The expected sensitivity with the existing SK detector and 1.6 MW is also shown. Finally, the sensitivity of a 100 kton detector at the CNGS+ computed assuming 5 yeas of neutrino run and 5 years of antineutrino run is plotted. A 20 kton LAr TPC at Kamioka is an effective way to improve the θ_{13}-sensitivity of the T2K experiment. Fig. 6 compares the sensitivity of a 20 kton LAr TPC at Kamioka to the ModuLAr expectation [20].

As argued above, assuming similar target masses, the upgraded T2K and upgraded CERN beams theoretically provide comparable sensitivities, however, we stress that the current CNGS beam line infrastructure has not been designed to

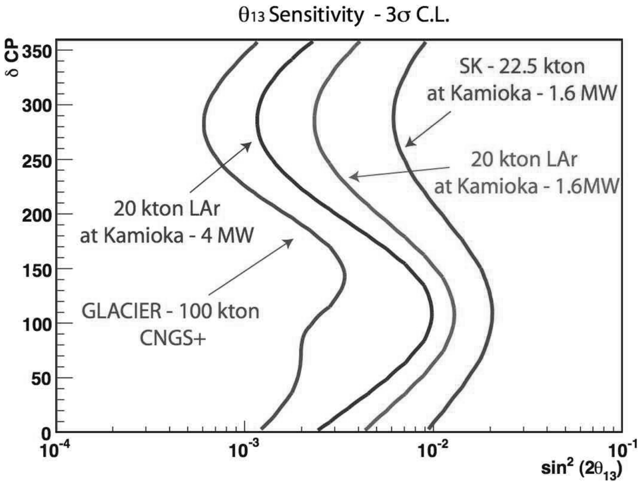

Fig. 5 θ_{13} sensitivity at 3σ C.L. for 20 kton LAr detector at 295 km, 2.5 degrees off-axis for 5 years of neutrino beam at 1.6 MW (green line) and 4 MW(blue line). For comparison the sensitivity of T2K (22.5 kton WC at Kamioka - 1.6 MW) and GLACIER-100 kton on upgraded CNGS [13] are given.

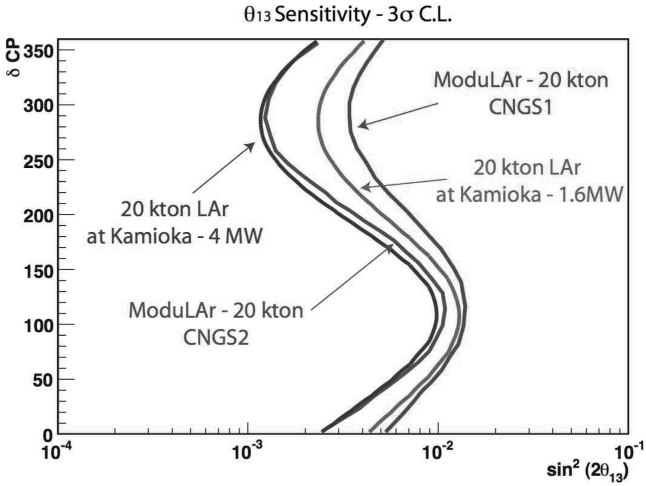

Fig. 6 θ_{13} sensitivity at 3σ C.L. for 20 kton LAr detector at 295 km, 2.5 degrees off-axis for 5 years of neutrino beam at 1.6 MW (green line) and 4 MW(blue line). For comparison the sensitivity of ModuLAr-20 kton experiment [20] for two different upgrades of CNGS beam are shown (see text for details).

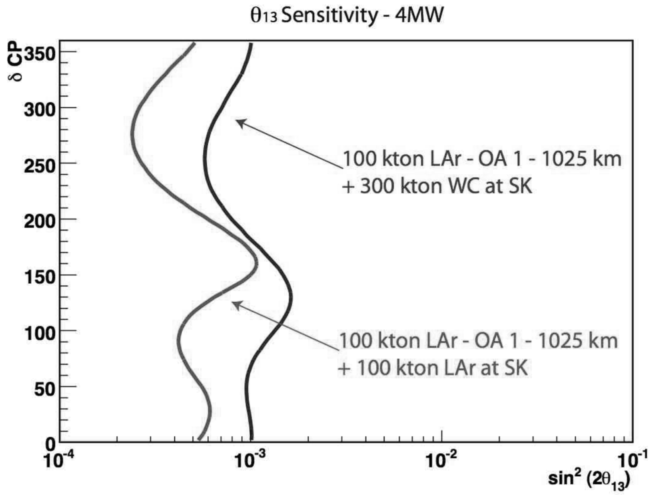

Fig. 7 θ_{13} sensitivity at 3σ C.L. for a two detector configuration. A 100 kton LAr detector is located at 1025 km, 1 degree off-axis and a second detector i.e 300 kton WC (blue line) or 100 kton LAr (red line) is located at SK.

exceed 7.8×10^{19} pot/yr, so further upgrades and/or reconstructions must be envisaged in order to cope with the potential increase of intensity from the SPS accelerator complex.

9. An "ultimate" Two-Detectors Configuration at J-PARC and the Synergies with Proton Decay Searches

So far we have considered one far detector, either in the Kamioka region or in Korea. In this last section, we discuss as "ultimate" configuration the one which uses of two very large detectors, possibly of different technologies, located at different baselines.

In order to cope with the harder beam at the angle OA 1.0^o we consider a 100 kton LAr TPC at 1025 km in Korea. We have argued in the previous paragraphs that the smaller off-axis angles give best performance for the detector in Korea. For the closer detector at 295 km OA 2.5^o we consider either a 300 kton Water Cerenkov detector or a 100 kton LAr TPC. For the WC detector we used the "standard" analysis present in GLoBES as explained in appendix A of Ref. [28] which treats QE and non-QE events in a different way analysing only the region between 0.4 and 1.2 GeV. The results on the sensitivity for θ_{13} and CP-violation are shown respectively in Fig. 7 and Fig. 8.

On one hand, following the argument of the authors of Ref. [8], the use of the same technology for the detector at Kamioka and Korea would allow to cancel some instrumental systematic errors. The option with two 100 kton LAr detector yields also better overall results, allowing for CP-violation discovery already for $\sin^2(2\theta_{13}) \sim 5 \times 10^{-4}$.

On the other hand, if one considers the broader physics programme including also non-accelerator physics as astrophysical neutrino observation (supernovae type II, etc...) and the search for proton decay, studies show that the combination of water and Argon target would offer very attractive complementarities in their physics programs (see e.g. Ref.[29, 30]). As a concrete example, the combination

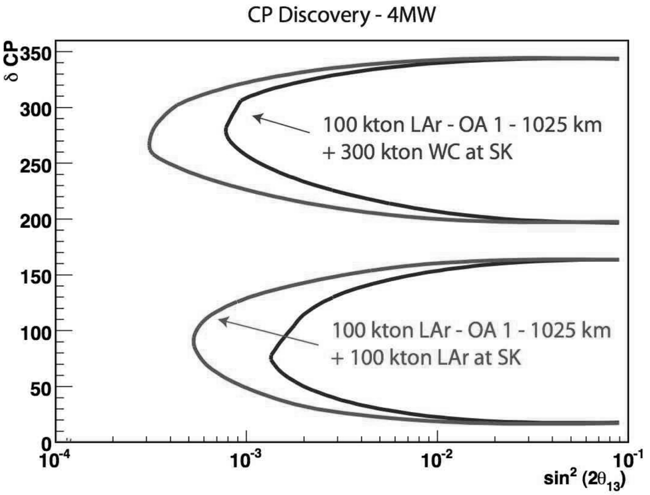

Fig. 8 CP-violation sensitivity at 3σ C.L. for a two detector configuration. A 100 kton LAr detector is located at 1025 km, 1 degree off-axis and a second detector i.e 300 kton WC (blue line) or 100 kton LAr (red line) is located at SK.

of the two technologies would allow to simultaneously address the $p \to e^+\pi^0$ and $p \to \bar{\nu}K^+$ channels with lifetime sensitivities above 10^{34} years.

10. Conclusions

Neutrino oscillations with one next generation liquid Argon TPC detector in Kamioka or in Korea at an upgraded J-PARC neutrino beam offers very interesting prospects. We concentrated on the physics reach of a 100 kton liquid Argon TPC. Several configurations were considered changing the baseline and the off-axis angle. If the detector is located at Kamioka (295 km and OA 2.5^o), a 3σ sensitivity for $\sin^2(2\theta_{13}) < 8 \times 10^{-4}$ could be achieved with an 4 MW upgraded neutrino beam and 5 years of running. Discovery of CP-violation at 3σ becomes possible down to $\sin^2(2\theta_{13}) \sim 2 \times 10^{-3}$ for 50% of δ coverage. If a signal will be observed in T2K, locating a detector in Korea is the best option to observe CP-violation, and the only option to discriminate between normal and inverted mass hierarchy. A two-detector configuration with one at Kamioka and the other in Korea, although very challenging, would offer an even improved sensitivity and very interesting complementarities, for example if two different detector technologies were chosen.

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