PROCEEDINGS OF SCIENCE

Neutrino oscillation physics potential of Hyper-Kamiokande

Linda Cremonesi *[†]
on behalf of the Hyper-Kamiokande Collaboration
Queen Mary University of London
E-mail: `l.cremonesi@qmul.ac.uk`

Hyper-Kamiokande (Hyper-K) is a megaton scale water Cherenkov detector proposed to be built in Japan. Hyper-K is the logical continuation of the highly successful program of neutrino physics and proton decay searches using a water Cherenkov technique. Hyper-K will study the CP asymmetry in neutrino oscillations using the neutrino and anti-neutrino beams produced at J-PARC. With an exposure of 7.5 MW $\times 10^7$ seconds, δ_{CP} can be measured to better than 19°at all values, and CP violation can be detected with more than 3 sigma (5 sigma) significance for 76% (58%) of values of δ_{CP}.

The European Physical Society Conference on High Energy Physics
22–29 July 2015
Vienna, Austria

PoS(EPS-HEP2015)054

---

[*] Speaker.

[†] currently at University College London

1. Hyper-Kamiokande

Hyper-Kamiokande (Hyper-K) is a proposed next generation underground water Cherenkov detector [1, 2] that has a variety of physics goals; these include the study of neutrino oscillation (atmospheric, solar or from accelerator), neutrino astrophysics, proton decay and non-standard physics.

The baseline design consists of 2 separate tanks lying along side (as shown in Figure 1), each having an egg-shape cross section and dimensions 48 m × 54 m × 250 m. The total (fiducial) mass is 0.99 (0.56) million metric tons, about 20 (25) times larger than that of the current running detector, Super-Kamiokande. The large mass will provide Hyper-K with a lot of statistics which is crucial in neutrino oscillation experiments.

The two water tanks are divided into 10 optically separated compartments. The inner detector (ID) is covered by 99,000 Hamamatsu R3600 20-inch diameter photomultiplier tubes (PMTs), giving a photocatode coverage of 20%. The outer detector (OD) is equipped with 25,000 8-inch diameter PMTs. These PMTs are the same used in the Super-K experiment and provide excellent particle identification (PID) in the sub-GeV region (better than 99%).

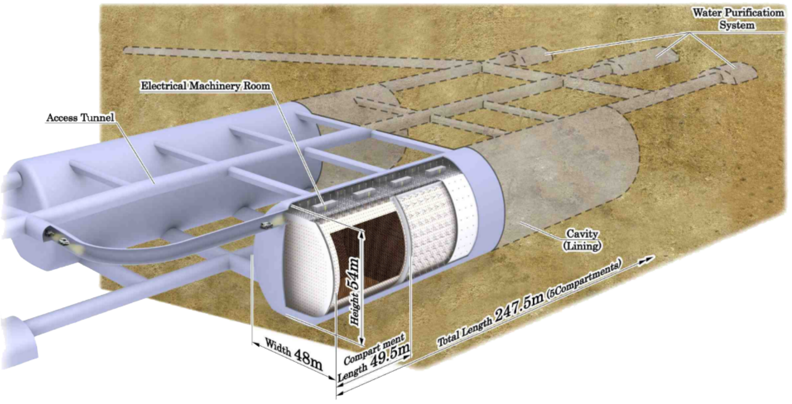


Figure 1: Schematic view of the Hyper-Kamiokande detector.

2. Tokai to Hyper-Kamiokande

The candidate site for Hyper-K is the Tochibora mine (Kamioka town, Gifu, Japan), at 295 km from J-PARC, the ideal position for a future long-baseline neutrino experiment. This site has 648 m overburden rock (1,750 m water equivalent) and a cosmic ray muon flux of 8×10^{-7} sec^{-1} cm^{-2}.

Following the experience of the T2K experiment, the J-PARC facilities will deliver a narrow band (≈0.6 GeV) muon (anti-)neutrino beam directed 2.5°off-axis to Hyper-K. The expected beam power is about 1 MW or more.

Figure 2 shows the oscillation probability as a function of energy (ν-mode on left and $\overline{\nu}$-mode on right) for a baseline of 295 km, evaluated with θ_{23} maximal and normal mass hierarchy. At nominal $\delta_{CP} = 0$, the difference between neutrino and anti-neutrino appearance probability is as large as 25%.

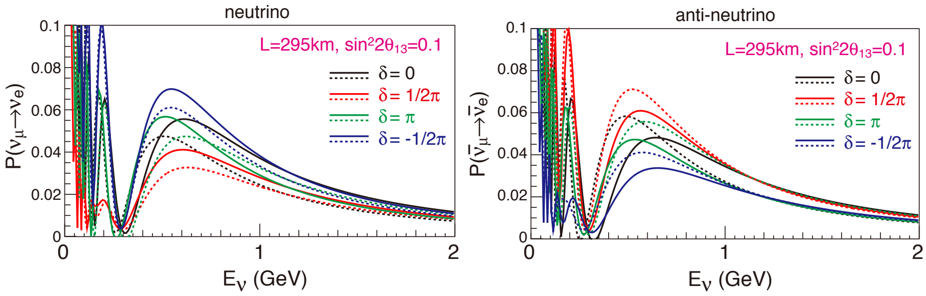


Figure 2: Oscillation probability as a function of the energy for $\nu_\mu \to \nu_e$ (left) and $\overline{\nu}_\mu \to \overline{\nu}_e$ (right). Different values of δ_{CP} (0, $1/2\pi$, π, $-1/2\pi$) are overlaid.

Table 1: Expected number of events after the ν_e ($\overline{\nu}_e$) appearance selection during ν ($\overline{\nu}$) running mode.

	Signal		Background					Total
	$\nu_\mu \to \nu_e$	$\overline{\nu}_\mu \to \overline{\nu}_e$	ν_μ CC	$\overline{\nu}_\mu$ CC	ν_e CC	$\overline{\nu}_e$ CC	NC	
ν mode	3016	28	11	0	503	20	172	3750
$\overline{\nu}$ mode	396	2110	4	5	222	396	265	3397

2.1 Near detectors

The near detector complex at 280 m will include upgrades of the current existing detectors, INGRID (on axis detector used to monitor the beam position and for beam mean energy measurements) and ND280 (off axis detector used for neutrino flux measurement and constraint of systematic uncertainties). The addition of new detectors, like a 3D grid-like neutrino near detector with a water target (WAGASCI), a high pressure TPC [3] or a water-based liquid scintillation detector [4] are also being investigated.

The addition of a new water-based intermediate (1-2 km) detector is planned to better constrain uncertainties on flux and cross-section. Currently there are two proposals, the nuPRISM [5] (a water column detector to minimise dependence on ν interaction sampling the beam at several off-axis angles) and the TITUS [6] (a water Cherekov detector gadolinium doped, surrounded by a muon range detector), detectors.

The upgraded near detectors and the addition of the intermediate water Cherenkov detector will reduce the systematic uncertainties on the neutrino flux and cross-sections.

2.2 Expected observables at Hyper-K

Table 1 and Figure 3 show the expected number of events after the $\nu_e/\overline{\nu}_e$ appearance selection. In ν running mode the main background is composed of beam ν_e CC and all NC interactions. In $\overline{\nu}$ running mode, the wrong sign appearance is also non-negligible.

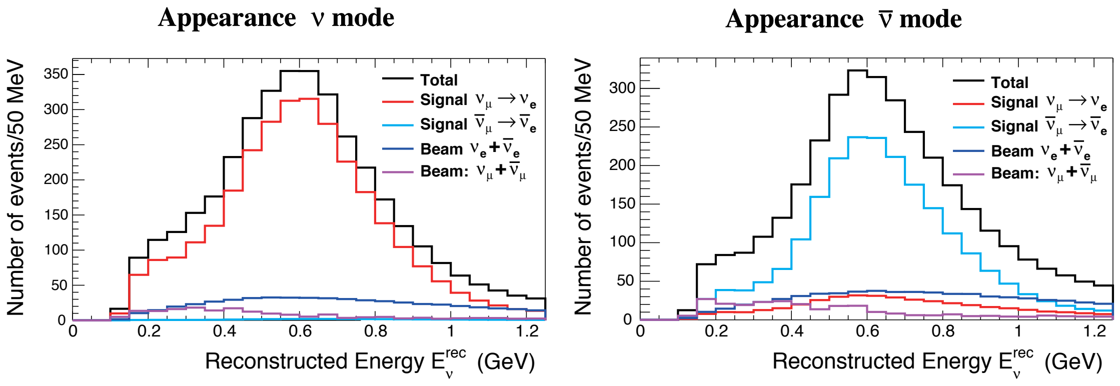
Table 2 shows the expected number of events after the $\nu_\mu/\overline{\nu_\mu}$ disappearance selection. In both running modes the main background comes from NC interactions.

2.3 Assumptions on systematic uncertainties

The experience of the T2K experiment offers a realistic estimation of the systematic uncer-

Table 2: Expected number of events after the ν_μ ($\overline{\nu}_\mu$) disappearance selection during ν ($\overline{\nu}$) running mode.

	ν_μ CC	$\overline{\nu_\mu}$ CC	ν_e CC	$\overline{\nu}_e$ CC	NC	$\nu_\mu \to \nu_e$	total
ν mode	17225	1088	11	1	999	49	19372
$\bar{\nu}$ mode	10066	15597	7	7	1281	6	26964



Appearance ν mode

Appearance ν̄ mode

Figure 3: Reconstructed neutrino energy distribution of the ν_e candidate events.

tainties. These are evaluated assuming the T2K neutrino beam line and the current near detectors, but also taking into account possible improvements in the detectors and analyses.

The largest uncertainties are coming from the flux and cross-section parameters constrained by the fit to the current near detector data, which are assumed to stay at the same level as those of the T2K experiment. The cross-section uncertainties that are not constrained by the fit to the near detector data and the far detector uncertainties will be reduced by the presence of upgraded and new near detectors and by the availability of a larger atmospheric neutrino sample.

Table 3 gives a summary of the assumptions on the systematic uncertainties for the appearance and disappearance analyses in neutrino and anti-neutrino running modes.

Table 3: Uncertainties (in %) for the expected number of events at Hyper-K from the systematic uncertainties assumed in this study.

Source	ν mode		$\overline{\nu}$ mode	
	Appearance	Disappearance	Appearance	Disappearance
Flux & ND-constrained cross section	3.0	2.8	5.6	4.2
ND-independent cross section	1.2	1.5	2.0	1.4
Far detector	0.7	1.0	1.7	1.1
Total	3.3	3.3	6.2	4.5

3. Neutrino oscillation physics potentials

Sensitivity studies have been performed taking into account an integrated beam power of 7.5 MW $\times 10^7$ sec (corresponding to 1.56×10^{22} protons on target with 30 GeV J-PARC beam) and a 1:3 ratio of neutrino to anti-neutrino running. In the framework used, the appearance and disappearance spectra are fitted simultaneously and δ_{CP}, θ_{13}, θ_{23} and Δm^2_{32} are considered free parameters.

3.1 Sensitivity to CP violation

Figure 4 shows the expected significance to exclude $\sin\delta_{CP} = 0$ (CP conserved case) when the true mass hierarchy is normal and known. The significance is calculated as $\sigma = \sqrt{\Delta\chi^2}$, where $\Delta\chi^2$ is the difference of the trial value of δ_{CP} and $\delta_{CP} = 0$ or 180°(the smaller value of the difference is taken).

Figure 5 (left) shows the fraction of δ_{CP} for which $\sin\delta_{CP} = 0$ can be excluded at 3σ or 5σ: CP violation in the lepton sector can be observed with 3σ (5σ)for 76% (58%) of the δ_{CP} parameter space.

Figure 5 (right) shows the 1σ uncertainty for δ_{CP} as a function of the integrated beam power: considering full Hyper-K statistics the δ_{CP} phase could be determined to better than 19 degrees for all possible values of δ_{CP}.

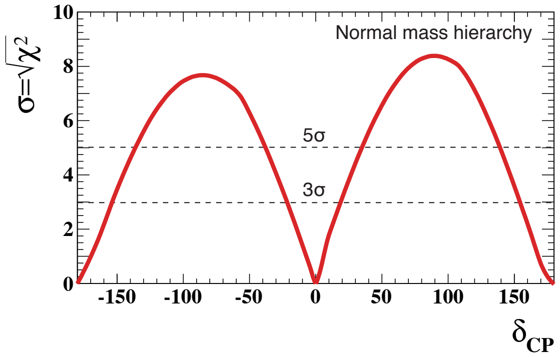


Figure 4: Expected significance to exclude $\sin\delta_{CP} = 0$.

3.2 Sensitivity to θ_{23} and Δm^2_{32}

Hyper-K will be able to look at the appearance and disappearance spectra simultaneously and hence also measure $\sin^2\theta_{23}$ and Δm^2_{32}. The 90% CL allowed regions in the $\sin^2\theta_{23}$–Δm^2_{32} plane are shown in Figure 6 for two different values of $\sin^2\theta_{23}$ (left 0.5, right 0.45). If θ_{23} is non-maximal, with a constraint on $\sin^2 2\theta_{13}$ from the reactor experiments Hyper-K will be able to resolve the octant degeneracy and precisely measure θ_{23}.

3.3 Sensitivity to mass hierarchy

The CP sensitivity results shown in Subsection 3.1 assume that the mass hierarchy is known. In case the mass hierarchy is not discovered before Hyper-K starts taking data, the atmospheric

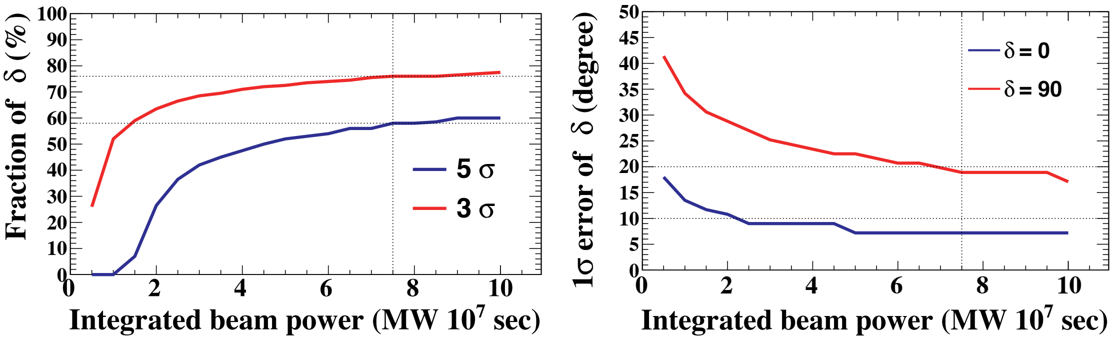


Figure 5: Fraction of δ_{CP} for which $\sin\delta_{CP} = 0$ can be excluded at 3σ (left). 1σ uncertainty for δ_{CP} as a function of the integrated beam power (right).

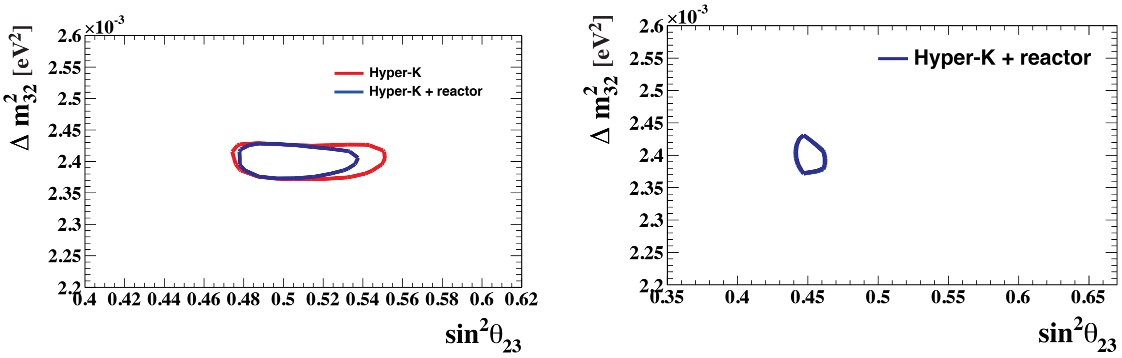


Figure 6: The 90% CL allowed regions in the $\sin^2\theta_{23}$–Δm^2_{32} plane. The true values are $\sin^2\theta_{23} = 0.5$ (left), $\sin^2\theta_{23} = 0.45$ (right) and $\Delta m^2_{32} = 2.4\times10^{-3}$ eV^2. Effect of systematic uncertainties is included. The red (blue) line corresponds to the result with Hyper-K alone (with reactor constraints on $\sin^2 2\theta_{13}$).

neutrino sample through the matter effect inside the Earth, can provide a good sensitivity to the mass hierarchy.

Figure 7 shows the $\Delta\chi^2$ discrimination of the wrong hierarchy hypothesis as a function of the assumed true value of $\sin^2\theta_{23}$. The 90% CL region of $\sin^2\theta_{23}$ allowed by T2K is also shown. The sensitivity to distinguish the wrong mass hierarchy is strongly dependent on the true value of θ_{23}. Nonetheless, assuming 10 years statistics, Hyper-K will be able to reject the wrong hierarchy at more than 3σ level for all values of θ_{23} currently allowed.

4. Conclusion

The neutrino oscillation physics potential of the Hyper-K detector has been studied based on the experience of the T2K and Super-Kamiokande experiments.

If the mass hierarchy is known by the time Hyper-K starts taking data, with an integrated beam power of 7.5 MW×10^7 sec, the value of δ_{CP} can be determined to better than 19°for all values of

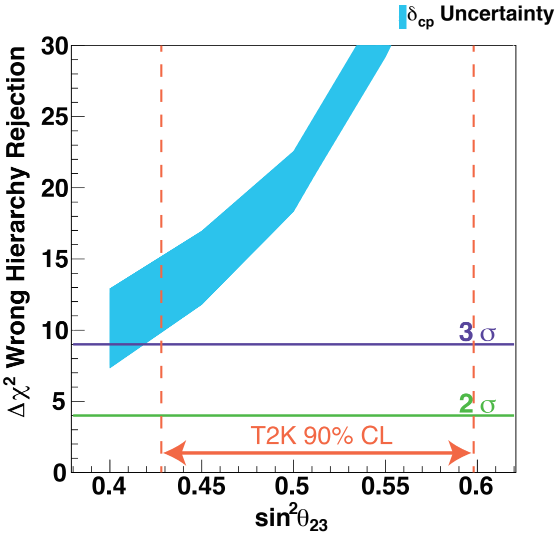


Figure 7: Atmospheric neutrino sensitivities for a ten year exposure of Hyper-K assuming the mass hierarchy is normal. The $\Delta\chi^2$ discrimination of the wrong hierarchy hypothesis as a function of the assumed true value of $\sin^2\theta_{23}$ [2].

δ_{CP}. *CP* violation in the lepton sector can be observed with more than 3 σ (5 σ) significance for 76% (58%) of the possible values of δ_{CP}.

If the mass hierarchy is not known, Hyper-K using atmospheric neutrinos will be able to reject the wrong mass hierarchy with more than 3σ for all the allowed values of θ_{23}.

Furthermore, using the constraint to θ_{13} coming from the reactor experiments, Hyper-K will be able to distinguish the θ_{23} octant and precisely measure both θ_{23} and Δm^2_{32}.

References

[1] Abe K *et al* 2011 Letter of Intent: The Hyper-Kamiokande Experiment—Detector Design and Physics Potential *arXiv preprint* hep-ex 1109.3262

[2] Hyper-Kamiokande Working Group, Abe K *et al* 2015 Physics Potential of a Long Baseline Neutrino Oscillation Experiment Using J-PARC Neutrino Beam and Hyper-Kamiokande *Prog. Theor. Exp. Phys.* (2015) 053C02.

[3] M. Ravonel, F. Sanchez, High Pressure Gas TPC, at Near detector workshop 19th January 2014, Tokai.

[4] M. Yeh, S. Hans, W. Beriguete, R. Rosero, L. Hu, *et al* 2011 *Nucl. Instrum. Meth.* **A660**, 51-56.

[5] Bhadra S *et al* Letter of Intent to Construct a nuPRISM Detector in the J-PARC Neutrino Beamline `arXiv:1412.3086 [physics.ins-det]`

[6] Lasorak P Prouse N TITUS: An Intermediate Distance Detector for the Hyper-Kamiokande Neutrino Beam `arXiv:1504.08272 [physics.ins-det]`