Sensitivity studies for the HK long baseline (LBL) program

IRN Neutrino meeting

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Hyper-Kamiokande

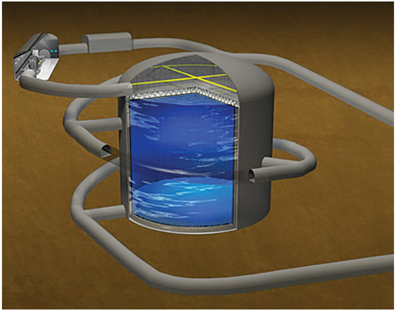
Content

1. The HK-LBL program
2. Sensitivity studies
3. Ongoing activities
   - New Inputs
   - Impact of $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$
4. Conclusion
5. Back-up

Hyper-Kamiokande

The Hyper-Kamiokande project

The new water Cherenkov neutrino detector under construction in Japan,
~ 8 times bigger fiducial volume than Super-Kamiokande.



Physics program

- Nucleon decay searches
- Neutrino astronomy
- Neutrino oscillation

The construction started in 2020 and the physics data-taking should begin by 2027.

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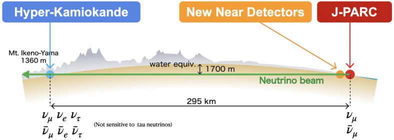
The HK-LBL program

The long baseline program is the natural evolution of the T2K experiment to measure $\nu_\mu \to \nu_e$ oscillation using HK as the far detector (FD) which will be placed with the same off-axis angle (2.5°).



Beam production at J-PARC:
More intense beam
(750kW $\to$ 1.3MW)
2.7×10^{21} POT per year

New near detectors (ND) to constrain systematics:

- Upgraded ND280 at 280m (inherited from T2K) [1]
- Water Cherenkov detector (IWCD) at 1km

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The HK-LBL program

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Parameters constrained by T2K and HK LBL program: δ_{CP}, $\sin^2\theta_{13}$, $\sin^2 2\theta_{23}$ and Δm^2_{32}

Figure 1: PMNS neutrino mixing matrix

Various neutrino experiments already provided significant constraints on the oscillation parameters but some questions remain unanswered :

- What is the mass ordering? (Δm^2_{32} positive or negative)
- Is $\sin^2\theta_{23}$ superior or inferior to 0.5 (octant degeneracy)?
- Does neutrino oscillation violate CP?[1]

[1] sensitivity to δ_{CP} by comparing ν_e and $\bar{\nu}_e$ appearance rates.

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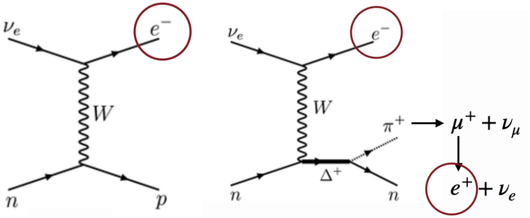
Sensitivity studies

HK sensitivity to oscillation parameters is estimated by fitting generated MC SuperK events but scaled to HK statistics, considering 5 event samples:

- $\nu(\bar{\nu})$**-mode 1R**μ binned in neutrino reconstructed energy Erec: one ring μ-like
- $\nu(\bar{\nu})$**-mode 1Re** binned in Erec-θ (lepton scattering angle): one ring e-like
- ν**-mode 1Re1D** binned in Erec-θ: one ring e-like + 1 decay e-like (due to a pion production)



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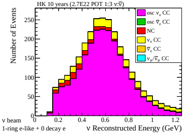
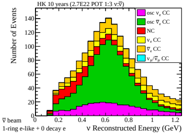
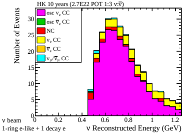
Sensitivity studies



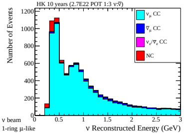
(a) ν-mode 1Re



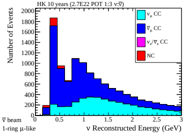
(b) $\bar{\nu}$-mode 1Re



(c) ν-mode 1Re1D



(d) ν-mode 1Rμ



(e) $\bar{\nu}$-mode 1Rμ

Figure 3: Expected neutrino reconstructed energy spectra at HK for each sample for 6.75×10^{21} POT in ν-mode and 20.25×10^{21} POT in $\bar{\nu}$-mode (10 years). $\delta_{CP} = -\pi/2$, $\sin^2\theta_{23} = 0.528$, $\Delta m^2_{32} = 2.509\text{E-3 eV}^2/\text{c}^4$, $\sin^2\theta_{13} = 0.0218$, $\Delta m^2_{21} = 7.53\text{E-5 eV}^2/\text{c}^4$ and $\sin^2\theta_{12} = 0.307$.

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Sensitivity studies

For each sample s, the following likelihood is maximised by the Migrad algorithm of Minuit

$$\ln \mathcal{L}_s(N_s^{\text{obs}}, \mathbf{x}_s^{\text{obs}}, \mathbf{o}, \mathbf{f}) = \sum_{i \in \text{bins}} [(N_{s,i}^{\text{exp}} - N_{s,i}^{\text{obs}}) + N_{s,i}^{\text{obs}} \times \ln \left(N_{s,i}^{\text{obs}} / N_{s,i}^{\text{exp}} \right)]$$

where i runs through each bin, and $N_{s,i}^{\text{exp}} = N_{s,i}^{\text{exp}}(\mathbf{o}, \mathbf{f})$ is the number of expected events in HK for the given values **o** and **f** of the oscillation and systematic parameters.
We use **flat priors for the oscillation parameters** of interest (δ_{CP}, $\sin^2\theta_{23}$, Δm^2_{32}) and **Gaussian priors for the systematic parameters**. The prior constraints on systematic parameters are given by the ND fit and studies on atmospheric samples.

Systematic error model

A prediction of the covariance matrix for HK era was built from the T2K ND fit results:

1. The errors are multiplied by $1/\sqrt{N}$ where N is the relative POT increase between HK and T2K ($N \approx 8$ after 10 years).
2. Studies of the ND280 upgrade and IWCD sensitivity lead to a further reduction of the errors on neutrino interaction cross-section by a factor 2 to 3
3. The error on the ratio $\frac{\sigma(\nu_e)/\sigma(\nu_\mu)}{\sigma(\bar{\nu}_e)/\sigma(\nu_\mu)}$ was scaled down from 4.9% to 2.7% assuming a better understanding of nuclear theory combined with direct measurements

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Ongoing activities

A lot of ongoing activities with three new PHD students in France:

- Denis Carabadjac, CEA/LLR (Palaiseau): new T2K oscillation analysis, HK sensitivity studies, HKROC
- Ulysse Virginet, LPNHE (Paris): ND280 upgrade, measurement of ν_e and $\bar{\nu}_e$ interaction cross-section in ND280
- Claire Dalmazzone, LPNHE (Paris): HK sensitivity studies, hadron production measurement in NA61/SHINE

Inputs updates

The T2K collaboration recently published new results [2] with:

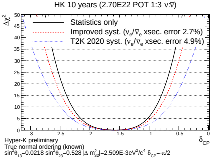
- $3.13 \times 10^{21} \rightarrow 3.6 \times 10^{21}$ POT
- updated neutrino interaction model (Relativistic Fermi Gas $\rightarrow$ Spectral Function)
- updated constraints on detector parameters
- New external measurements to tune neutrino flux simulation using a replica of T2K target [2]

New sensitivity studies are being produced using these new inputs and another framework. In the new analysis, the data are binned in scattered lepton momentum p and scattering angle θ for 1Re(1D) samples or Erec-θ for 1Rμ samples.

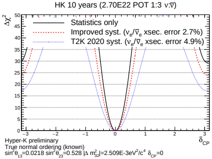
[2] See backup on NA61/SHINE experiment

New sensitivity results

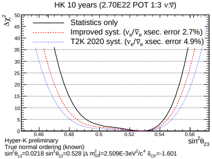
The new results show good consistency with previous ones.



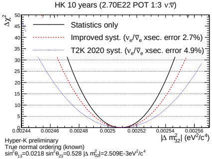
(a) true $\delta_{CP} = -90°$



(b) true $\delta_{CP} = 0°$



(c) true $\sin^2\theta_{23} = 0.528$

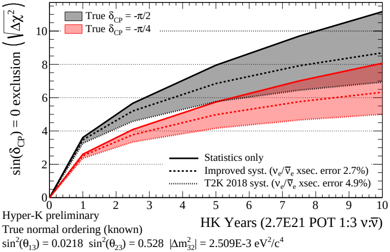


(d) true $\Delta m^2_{32} = 2.509 \times 10^{-3}$ eV^2/c^4

Figure 4: 1D χ^2 curves for the oscillation parameters of interest. The mass ordering is considered known and normal.

Impact of $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$

The main goal of the HK-LBL program is to measure δ_{CP} with a better precision and to exclude the CP-conserving values of δ_{CP} (if CP is violated).



(a) $\sin\delta_{CP} = 0$ exclusion limit

(b) 1σ error on δ_{CP}

Figure 5: Evolution of the sensitivity to δ_{CP} with accumulated statistics

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Experimental measurement of $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$

The systematic uncertainty on the measurement of δ_{CP} is dominated by the ratio $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$ whose current measurement by ND280 in T2K is limited by statistics (the main constraint comes from theory).

One goal in HK era is to measure experimentally this parameter. Studies are ongoing to estimate how well this ratio could be constrained by ND280 upgrade and IWCD. The combination of the two measurements could lead to a constraint below 3% level (compared to the current 4.9%).

Experimental measurement of $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$ with ND280

ND280 is being upgraded and will likely undergo further upgrade during HK data-taking. Ulysse is working on estimating the constraints that these upgraded versions could put on $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$.

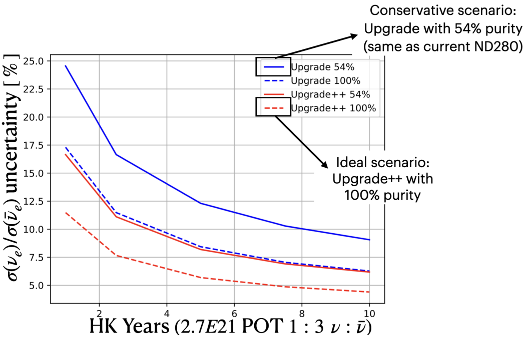
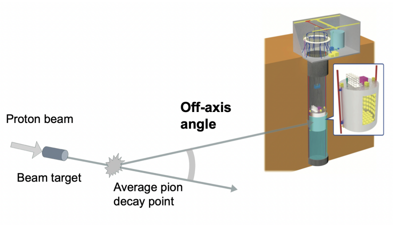


Figure 6: First estimations of the expected uncertainty on the measurement of $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$ using ND280 upgrade or ND280 upgrade++ detector mass

Experimental measurement of $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$

Vertically movable water Cherenkov detector at 1km from J-PARC [3]



Allows to measure neutrino interaction for different flux configurations using off-axis angles (θ_{OA}) from 1° to 4°

Larger θ_{OA} coverage
$\rightarrow$ more neutrinos with $E_\nu > 1$GeV
$\rightarrow$ better constraints on CC non-QE interactions.

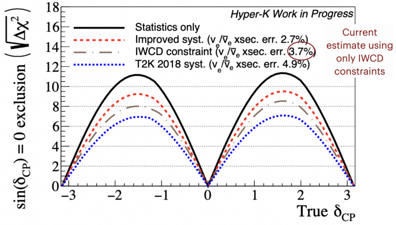


Figure 7: Significance level to exclude CP conservation after 10 HK Years

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Conclusion

Lot of ongoing activities:

- Implementing T2K most up to date models
- New analysis framework is validated! Considerably reduced CPU time allows for more refined studies of systematic error impact on HK long-term sensitivity
- ND280 upgrade and IWCD sensitivity to $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$: a 2.7% constraint at 10 years would allow to measure δ_{CP} with a resolution better than 20°
- Lot of near future plans: joint ND280 and IWCD studies, refined studies of systematic effects, joint studies with atmospheric samples etc. Stay tuned!

Thank you!

Hyper-Kamiokande

References for further information

Thorsten Lux.
The upgrade of the t2k nd280 detector.
Journal of Physics: Conference Series, 2374(1):012036, nov 2022.

The T2K Collaboration.
Measurements of neutrino oscillation parameters from the t2k experiment using 3.6×10^{21} protons on target, 2023.

Tailin Zhu.
Long-baseline neutrino oscillation sensitivities with Hyper-Kamiokande and impact of Intermediate Water Cherenkov Detector.
In *Proceedings of Neutrino Oscillation Workshop — PoS(NOW2022)*, volume 421, page 028, 2023.

Impact of the off-axis angle

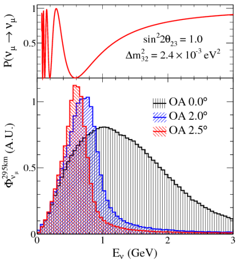

Figure 8: Muon neutrino survival probability at 295 km and neutrino fluxes for different off-axis angles. An OA of 2.5° was chosen.

A **narrow** energy band peaking at 0.6GeV is obtained.

This corresponds to a **minimum in ν_μ survival probability**.

At this energy, the main neutrino interaction is the **CCQE**:

$$\overset{(-)}{\nu}_l + N \to l^\pm + N'$$

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Particle identification

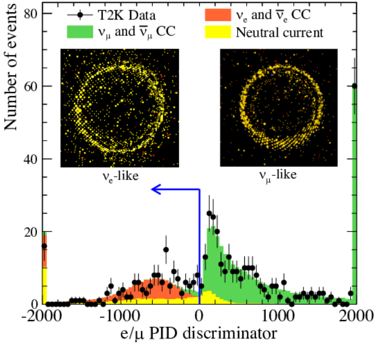

Figure 9: Distribution of the particle identification (PID) parameter used to classify Cherenkov rings as electron-like (left) and muon-like (right). The filled histograms show the expected number of single ring events after neutrino oscillations. The vertical error bars on the data points are the standard deviation due to statistical uncertainty. The PID algorithm uses properties of the light distribution such as the blurriness of the Cherenkov ring to classify events.

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Systematic error model

Three types of systematic parameters:

1. **Flux** parameters: 50 normalization factors to rescale the predicted neutrino flux per energy bin
2. **Cross-section** parameters: related to the modelling of the neutrino interactions
3. **Detectors** parameters

The near detectors provide a constraint on $F \times \sigma$.

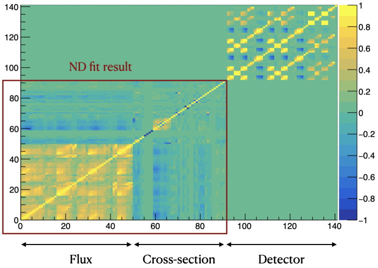

Figure 10: Correlation matrix used as input for the FD fit in T2K 2020 OA

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Systematic error model

	ν_μ-Like		ν_e-Like			
Source	ν	$\bar{\nu}$	ν1Re	$\bar{\nu}$ 1Re	ν 1Re1D	$\nu/\bar{\nu}$ 1Re
Flux+xsec	3.27%	2.95%	4.33%	4.37%	4.99%	4.52%
Detector	3.22%	2.76%	4.14%	4.39%	17.77%	2.06%
All syst	4.63%	4.10%	5.97%	6.25%	18.49%	4.95%

Table 1: Uncertainty on the expected number of events in HK with the T2K 2018 error model

Systematic error model

	ν_μ-Like		ν_e-Like			
Source	ν 1Rμ	$\bar{\nu}$ 1Rμ	ν 1Re	$\bar{\nu}$ 1Re	ν 1Re1D	$\nu/\bar{\nu}$ 1Re
Flux+xsec	0.81%	0.72%	2.07%	1.88%	2.21%	2.28%
Detector	1.68%	1.58%	1.54%	1.72%	5.21%	0.97%
All syst	1.89%	1.74%	2.56%	2.53%	5.63%	2.45%

Table 2: Uncertainty on the expected number of events with the Improved error model. See back-up for the uncertainties using T2K 2018 error model.

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Sensitivity to δ_{CP}

Systematic model	$\delta_{CP} = 0°$	$\delta_{CP} = -90°$
Statistics only	5.1°	17.2°
Improved syst.	6.5°	19.1°
T2K 2018 syst.	8.3°	21.8°

Table 3: Table showing the 1 sigma resolution of δ_{CP} at $\delta_{CP} = -90°$ and $\delta_{CP} = 0°$ after 10 HK-years.

Sensitivity to δ_{CP}

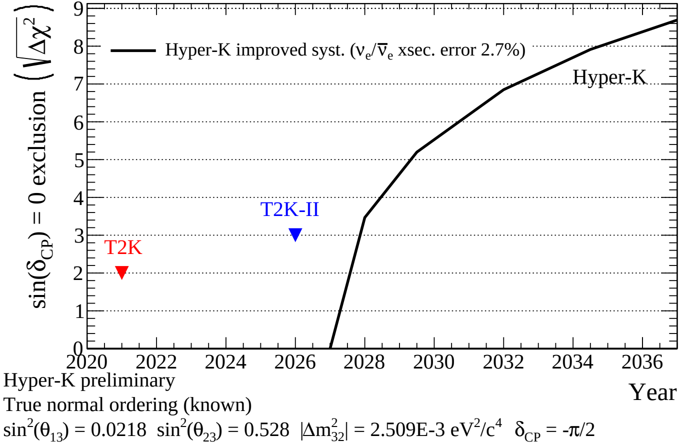


Figure 11: Sensitivity to exclude $\sin(\delta_{CP}) = 0$ for true $\delta_{CP} = -90°$, as a function of calendar years.

θ_{23} wrong octant exclusion

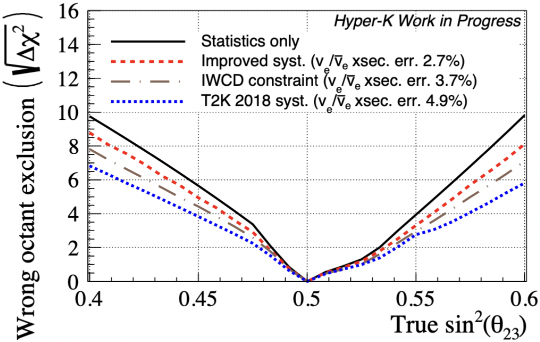
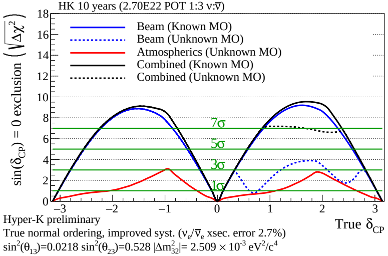


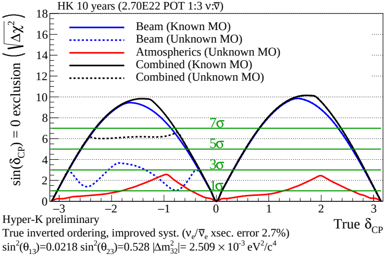
Figure 12: Significance level to exclude the wrong $\sin^2\theta_{23}$ octant

Sensitivity to mass hierarchy

The results shown were obtained considering that the neutrino mass hierarchy (MH) is known and normal ($m_3 > m_2$).
HK will also be sensitive to MH mostly from the atmospheric neutrinos sample: joint beam+atm oscillation analysis will allow to measure CPV and MH simultaneously.



(a) Normal hierarchy



(b) Inverted hierarchy

Figure 13: Sensitivity to exclude $\sin(\delta_{CP}) = 0$, as a function of true δ_{CP} value, for 10 HK-years

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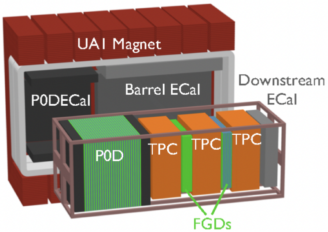
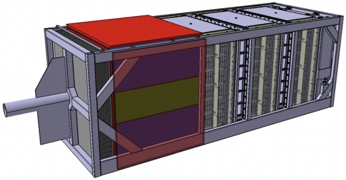
ND280 upgrade



(a) Current ND280



(b) Upgraded ND280

The P0D detector will be substituted by:

- A super fine grain detector (SuperFGD) consisting of scintillating cubes
- Two high angle TPCs below and above the SuperFGD
- 6 time of flight (ToF) panels

See [1] for more details

Neutrino beam production at J-PARC

The neutrino flux is a major source of systematic effects: the systematic parameters are constrained by the ND280 data fit using prior constraints set by models and external measurements.

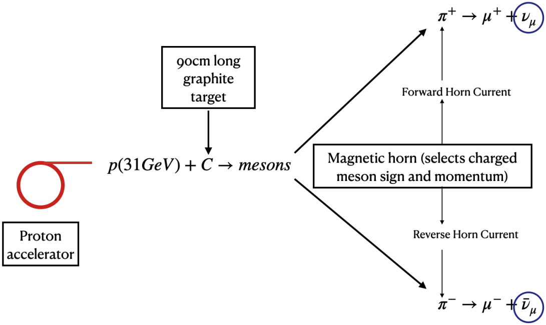
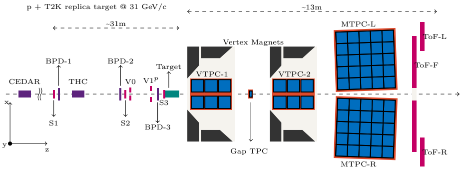


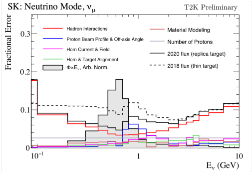
Figure 15: Neutrino beam production at J-PARC

NA61/SHINE hadron production measurements

NA61/SHINE spectrometer is used to measure the production of hadrons at the surface of the T2K replica target.



(a) Spectromètre NA61



(b) Impact of NA61/SHINE measurements on SK event rates uncertainties

New data has been taken in summer 2022 with the recently upgraded spectrometer.