Towards a better measurement of the CP violation phase with Hyper-Kamiokande

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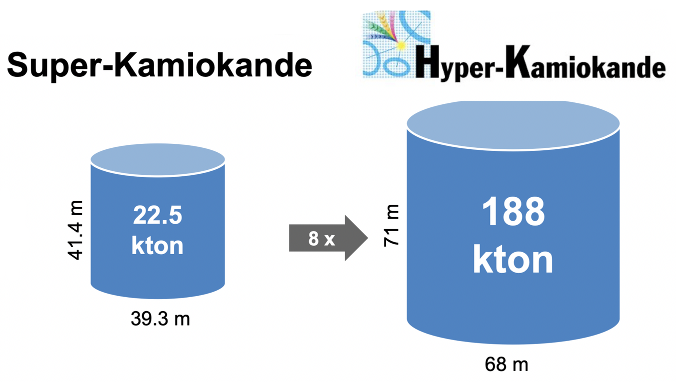
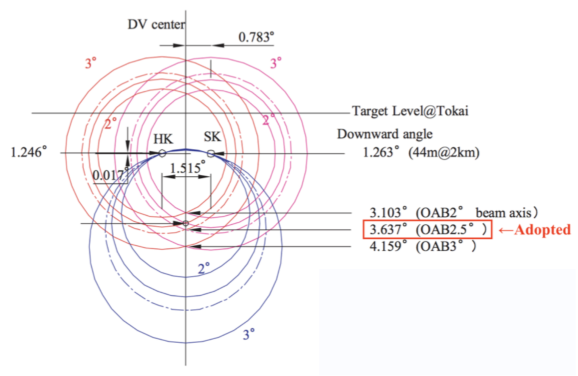
LPNHE

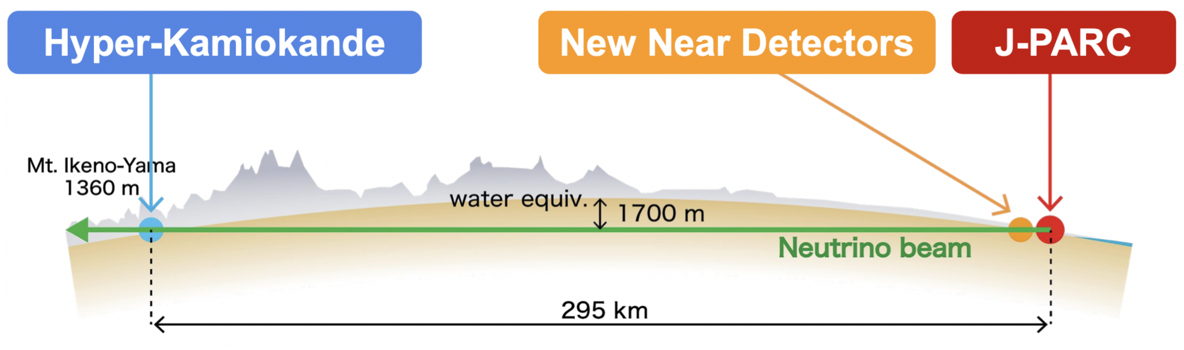
From T2K to Hyper-Kamiokande



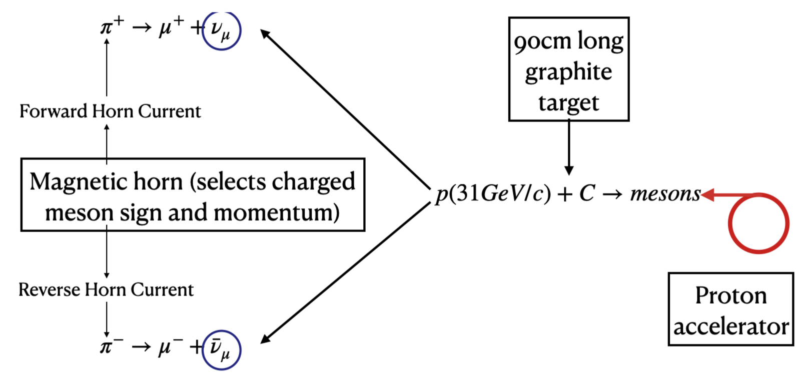
(a) Far detectors dimensions



(b) Off-axis angles



(c) J-PARC-HK beamline



(d) Beam production at J-PARC

Figure 1. The HK long baseline program will use the same neutrino beam as T2K but a bigger far detector. The beam will still be off axis by 2.5°.

The neutrino flux and interaction cross-sections are characterized at the near detectors including the upgraded ND280 and the future Intermediate Water Cherenkov Detector (IWCD). The appearance (and disappearance) of electron (and muon) neutrinos or antineutrinos will be measured at the far detector HK (currently SK). The comparison of the measured spectra with MC predictions allows to **measure** some **parameters of the neutrino mixing matrix (PMNS)**. The bigger volume of the far detector and the more intense (500kW → 1.3MW) and frequent (1.36s→ 1.16s per spill) proton beam will allow **HK to accumulate statistics much faster than T2K**.

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

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

Figure 2. Parametrization of the PMNS matrix

The oscillation analysis

Near Detectors (ND) fit: constrains the **neutrino flux and interactions**. The results can be used as input for the far detector (FD) fit.

Far Detector fit: Binned likelihood fit of the neutrino spectra at the far detector. χ^2 is minimized with $\mathcal{L}$ a Poissonian likelihood

$$\chi^2(\Theta) = \frac{-2}{N_{\text{throws}}}\sum_{i=1}^{N_{\text{throws}}}\log(\mathcal{L}(\Theta,\eta_i))$$

- Θ: the constrained oscillation parameters of interest (e.g.: δ_{CP})
- η_i: the other free parameters (nuisance) parameters. Their values are randomly thrown N_{throws} times according to the distributions provided by prior knowledge (e.g.: ND fit) and the contribution is **marginalized over**.

The systematic parameters

There are three types of systematic parameters:

1. The flux parameters characterize the ratio of the expected number of neutrinos per energy bin in the simulation and in the data
2. The cross-section parameters characterize the interactions model
3. The detectors parameters characterize the response of the detectors

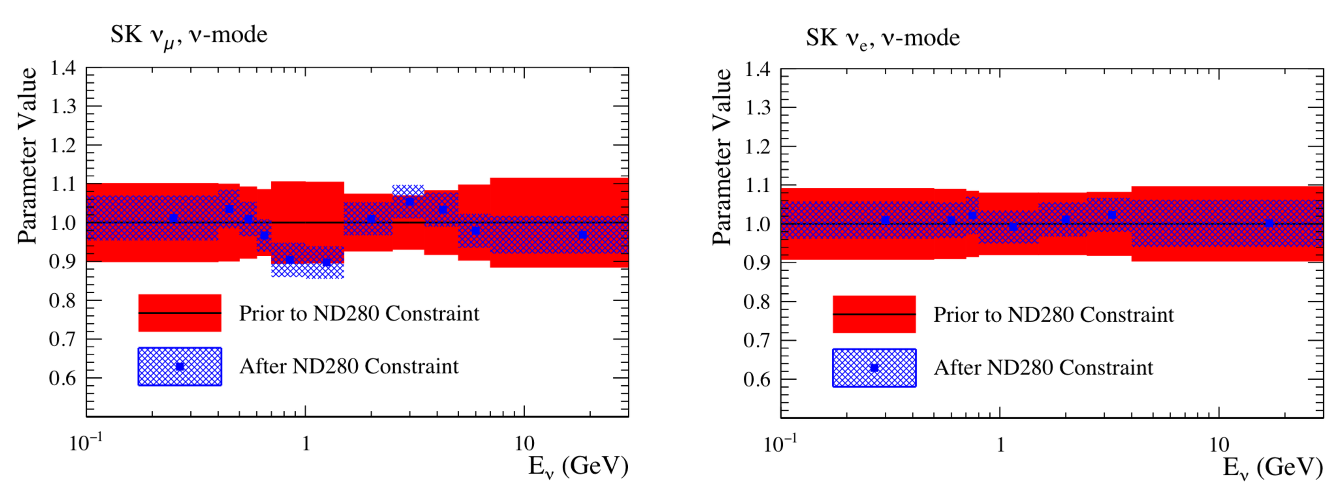
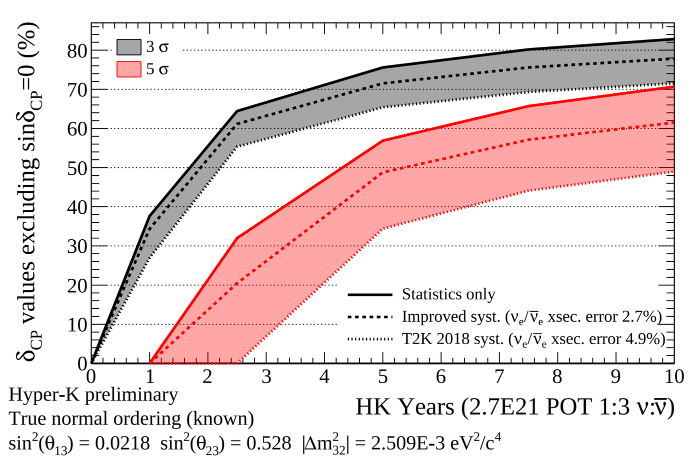


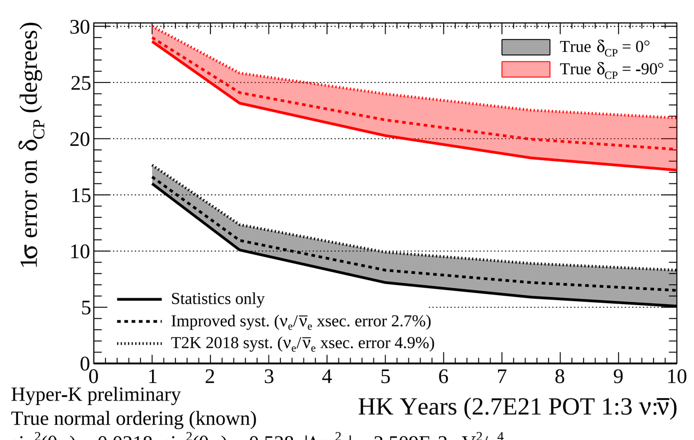
Figure 3. Flux parameters errors before and after the ND fit (Fig 34 in [3]).

Predictions for Hyper-Kamiokande

The Improved syst. are a modified version of the T2K 2018 systematic errors and $\nu_e/\bar{\nu}_e$ xsec error refers to the ratio of cross-section of ν_e and $\bar{\nu}_e$.



(a) Percentage of true values of δ_{CP} for which $\sin(\delta_{CP}) = 0$ can be excluded at 3 or 5σ as a function of HK-years.



(b) 1σ error on δ_{CP} for true $\delta_{CP} = -\pi/2$ or true $\delta_{CP} = 0$ as a function of HK-years

Figure 4. Prediction of HK sensitivity to the neutrino CP violation phase [4]

After 10 years, δ_{CP} could be measured with a less than 20° precision. Systematic uncertainties can be improved with:

- the upgrade of ND280
- the addition of the IWCD
- better constraints on the flux with **new NA61/SHINE [1] data**

NA61/SHINE experimental setup

The NA61/SHINE spectrometer is presented in Fig.5.

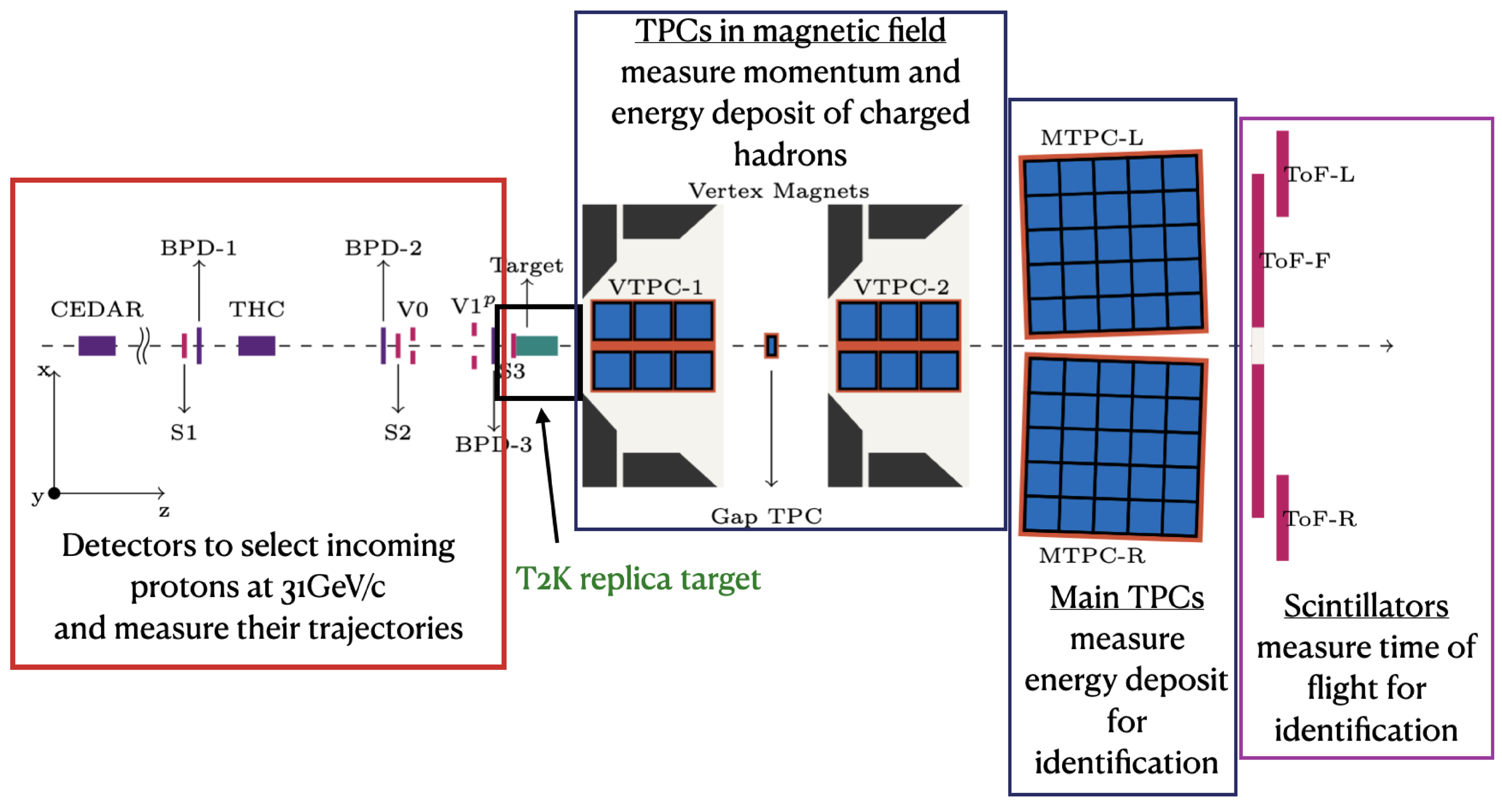


Figure 5. NA61/SHINE experimental setup

New T2K replica target data have been taken in summer 2022 with a freshly upgraded detector (higher trigger rate, new TPC readout electronics): ~ 160 million events recorded!

Replica target tuning

NA61/SHINE results are used to tune the hadron production part of the T2K neutrino flux simulation which is a major source of uncertainty. **In 2020, the replica target tuning allowed to divide by 2 the uncertainty on the flux at peak energy.**

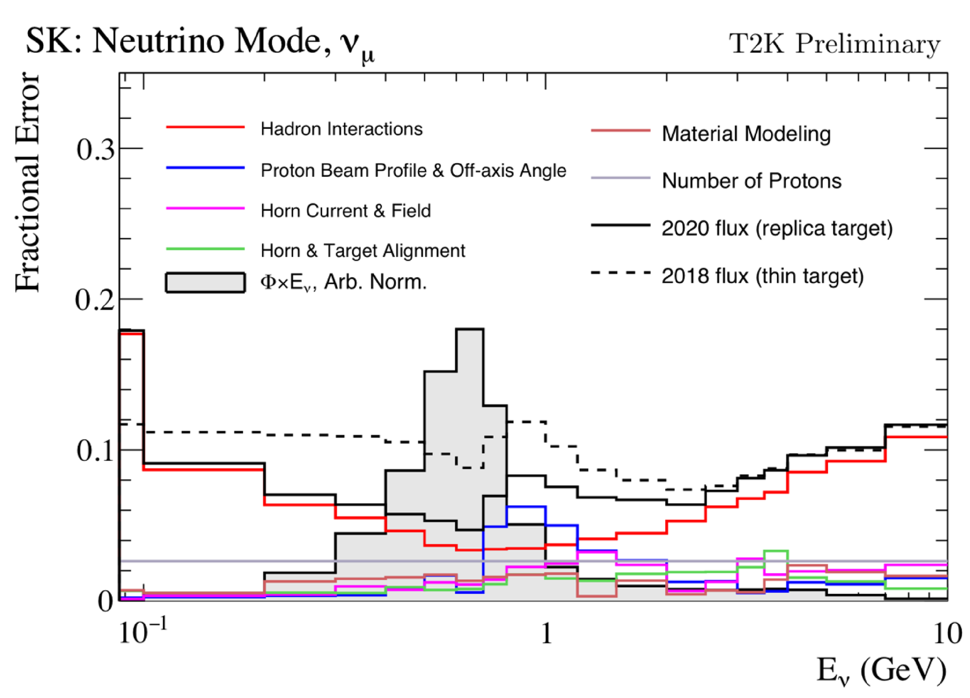


Figure 6. Sources of uncertainty on the neutrino flux prediction in T2K and impact of the last replica target tuning. The tuning was done with NA61/SHINE measurements presented in [2].

With a better coverage of the produced kaons responsible for the highest energy neutrinos in T2K, **the new NA61/SHINE dataset will help reducing the uncertainty on the flux parameters.**

References

[1] N. Abgrall et al. NA61/SHINE facility at the CERN SPS: beams and detector system. *JINST*, 9, 2014.

[2] N. Abgrall et al. Measurements of $\pi^\pm$ differential yields from the surface of the T2K replica target for incoming 31 GeV/c protons with the NA61/SHINE spectrometer at the CERN SPS. *Eur. Phys. J. C*, 76(11):617, 2016.

[3] K. Abe et al. Improved constraints on neutrino mixing from the T2K experiment with 3.13×10^{21} protons on target. *Physical Review D*, 103(11), jun 2021.

[4] Laura-Iuliana Munteanu. Long-baseline neutrino oscillation sensitivities with Hyper-Kamiokande. In *22nd International Workshop on Neutrinos from Accelerators*, volume NuFact2021, page 056, Cagliari, Italy, September 2021.