Hyper-Kamiokande & the CP-asymmetry of neutrinos

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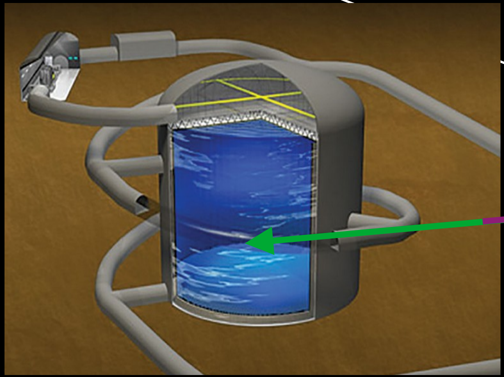
École de Physique des Houches – 17/02/2023

The Hyper-Kamiokande project

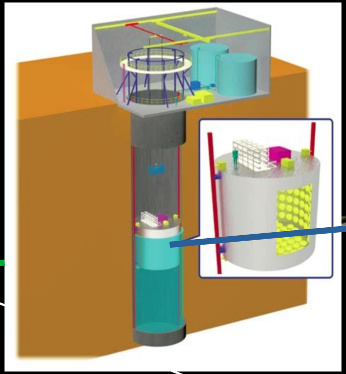
Next-generation observatory for neutrino physics and proton decay searches

The project hosts several experimental facilities from the east to the west coast of Japan

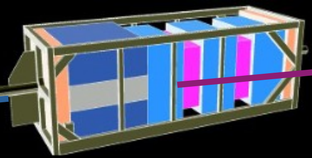
west ⟷ *east*



HK far detector @295 km



Intermediate water-Cherenkov detector @ ~1 km



Near detector complex @280 m

J-PARC neutrino beam

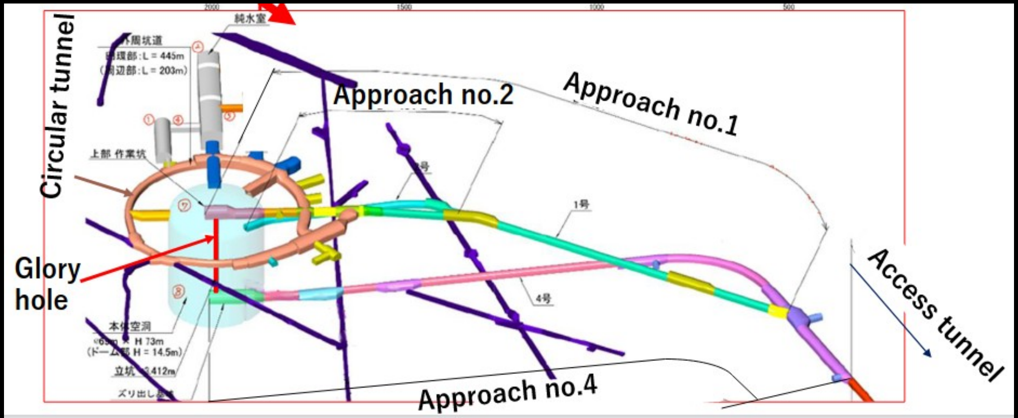
The HyperK Collaboration

Around 500 collaborators from all around the world working together, sharing expertise and building a milestone in particle physics

Next month: First in-person meeting since Feb. 2020

Status of HyperK

- Construction of far detector started in **April 2020**

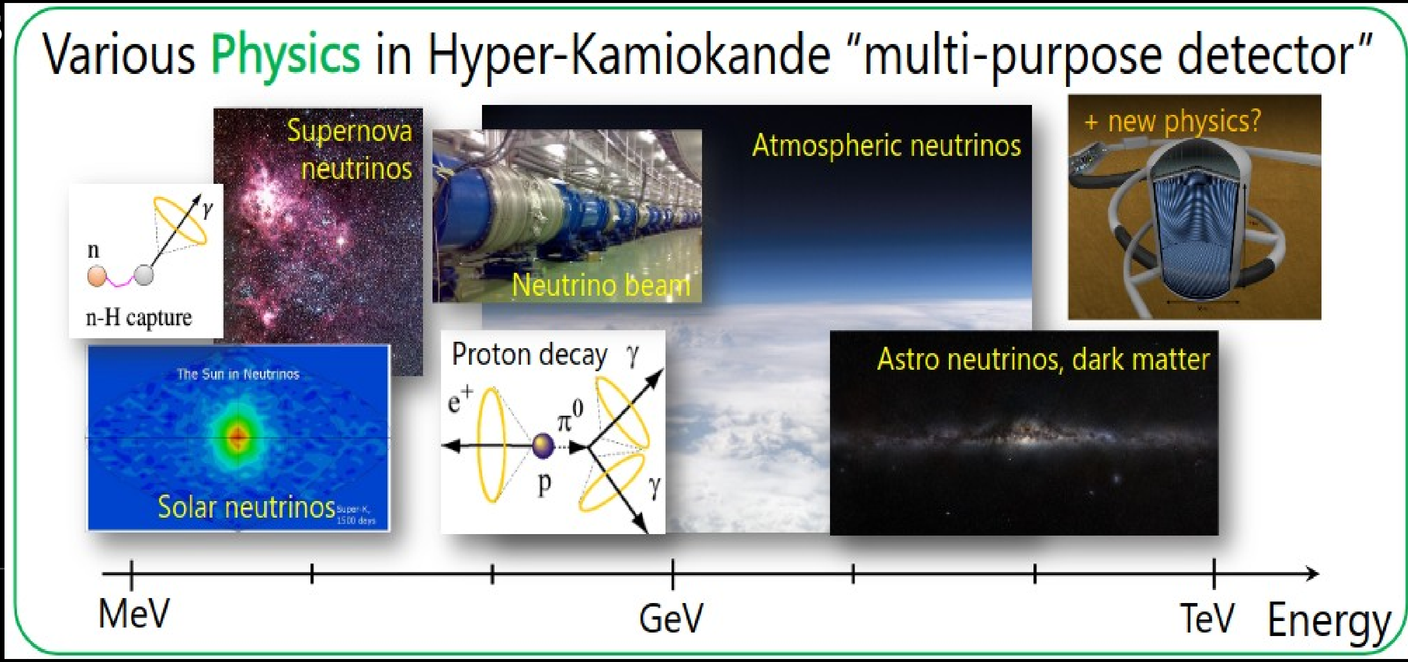


- Currently, working hard in the final design and production of all hardware components for all detectors and facilities
- J-PARC neutrino beam is being upgraded
- Installation works (incl. all facilities) will cover **2025** to the end of **2026**
- The experiment is expected to start operations in the 2nd half of **2027**

HyperK neutrino physics

Comprises a wide and ambitious experimental program in neutrino physics:

- Solar neutrinos
- Supernova burst neutrinos
- Diffuse supernova neutrino background
- Atmospheric neutrinos
- Accelerator neutrinos



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~~*CP-violating world*~~

Produced through the collision of **cosmic-rays** with atmosphere atoms, they hold the key to measure the **neutrino mass ordering** and provide constraints on the rest of mixing parameters, including δ_{CP}

Produced in the **J-PARC** accelerator complex **295 km** away from HyperK's far detector, they will provide the precise measurement of δ_{CP}

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Synergies and comprehensive approach for the study of δ_{CP} within the same experiment

CP-violating world

CP-violating world

CP-violating world

Neutrino oscillations & *CP phase*

In the 3ν scenario, neutrino evolution is described by six parameters:

- two mass-squared differences
- three mixing angles
- a complex phase parameterizing the violation of the CP-symmetry

$$P_{\nu_l \to \nu_{l'}}\left(L/E\right) \approx \sum_{i,j} U^{l'i}_{PMNS} (U^{li}_{PMNS})^* (U^{l'j}_{PMNS})^* U^{lj}_{PMNS} e^{-i\frac{\Delta m^2_{ij} L}{2E}}$$

$$U_{PMNS} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Neutrino oscillations & *CP phase*

In terms of the Jarlskog invariant J with the dependency on δ_{CP} factorized, the amount of CP-violation can be expressed as:

$$J = \Im[U^{l'i}_{PMNS}(U^{li}_{PMNS})^*(U^{l'j}_{PMNS})^*(U^{lj}_{PMNS})] = J_r \cdot \sin\delta_{CP}$$

$$P_{CP} = -8 J_r \sin\delta_{CP} \sin\Delta_{21} \sin\Delta_{31} \sin\Delta_{32}, \text{ where } \Delta_{ij} = \delta m^2_{ij} L/4E$$

The term is suppressed by the mass-splittings and modified by the rest of the mixing parameters

This makes crucial the L/E_ν ratio and the precise knowledge of the rest of the oscillation parameters*

**No surprise δ_{CP} is the least-known parameter and needs a dedicated experimental program*

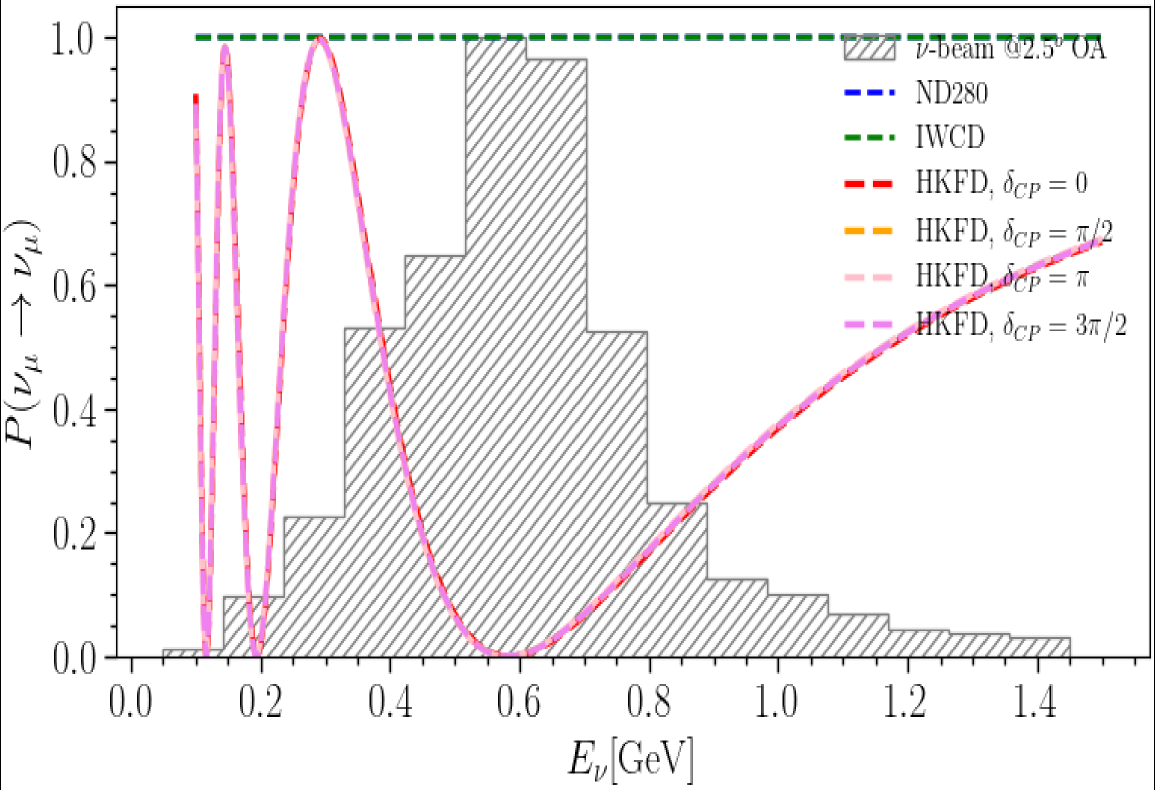
HyperK strategy – *beam*

Beam made mostly of ν_μ

L/E_ν choice:

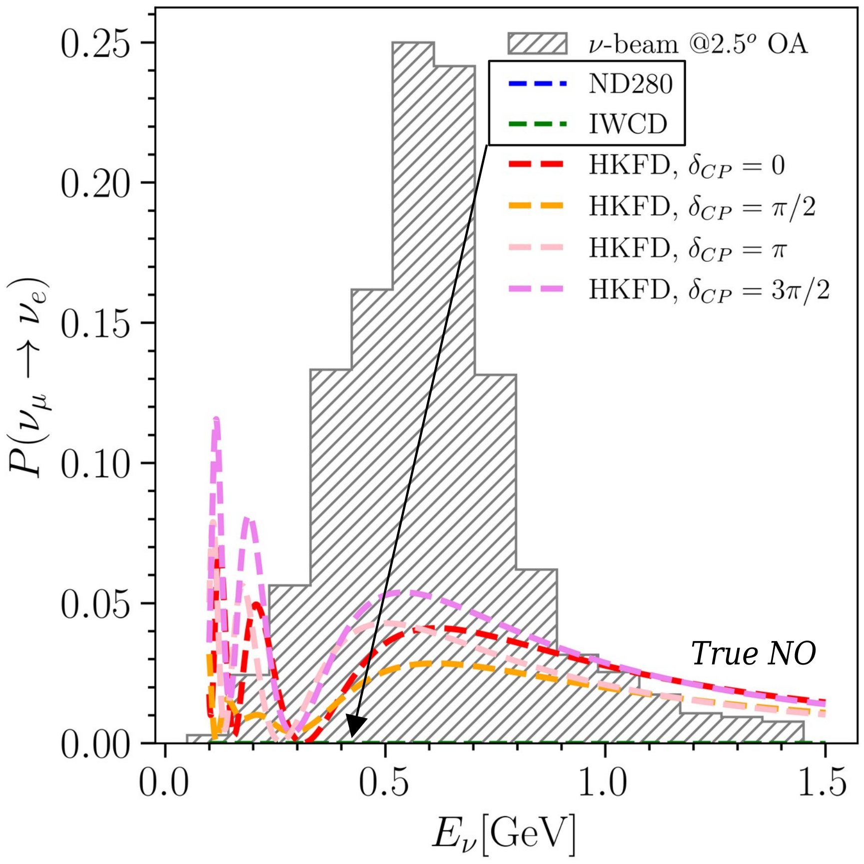
- at the minimum oscillation probability in the disappearance channel (ν_μ to ν_μ)

- at the maximum oscillation probability in the appearance channel (ν_μ to ν_e)

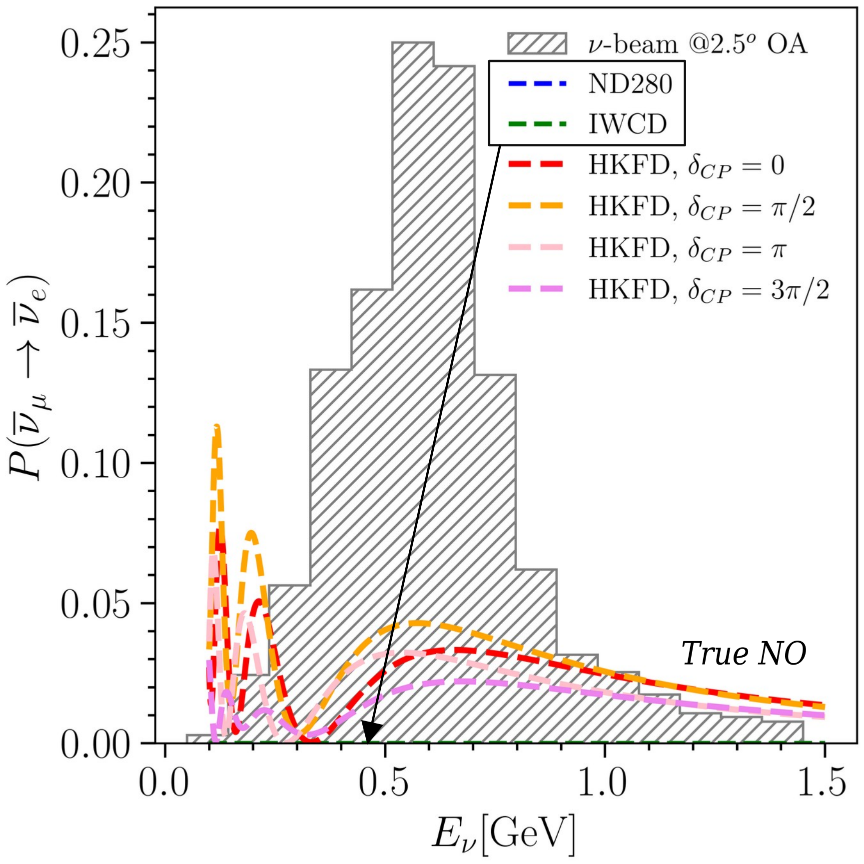


HyperK strategy – *beam*

neutrino mode



antineutrino mode



HyperK strategy – *beam*

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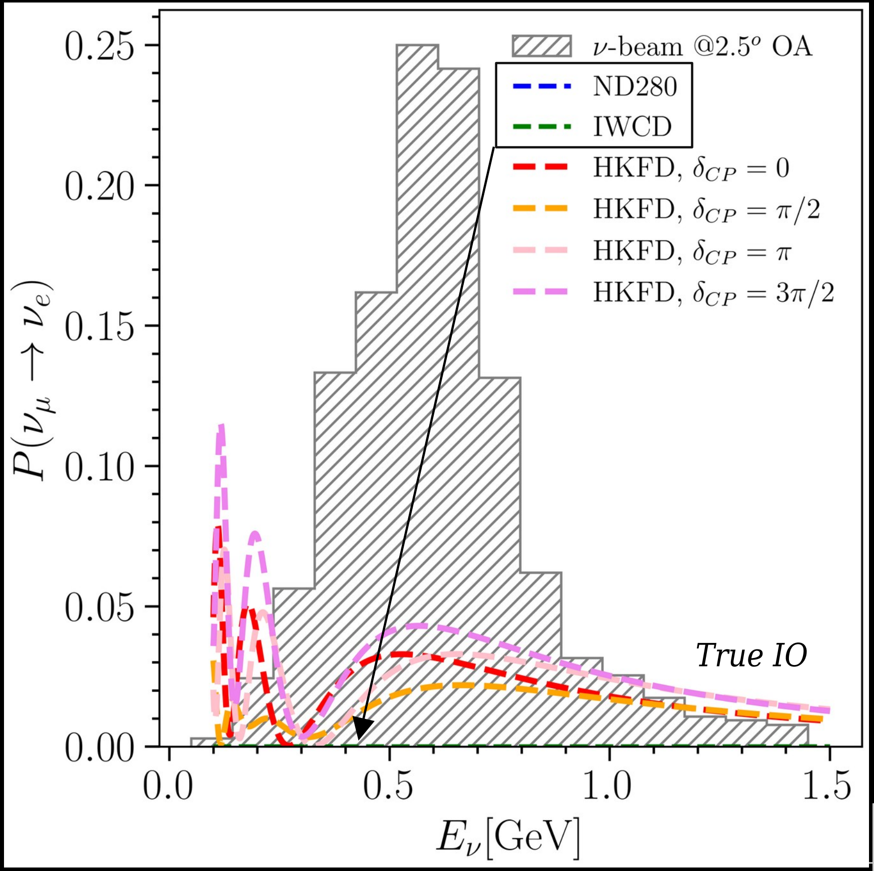
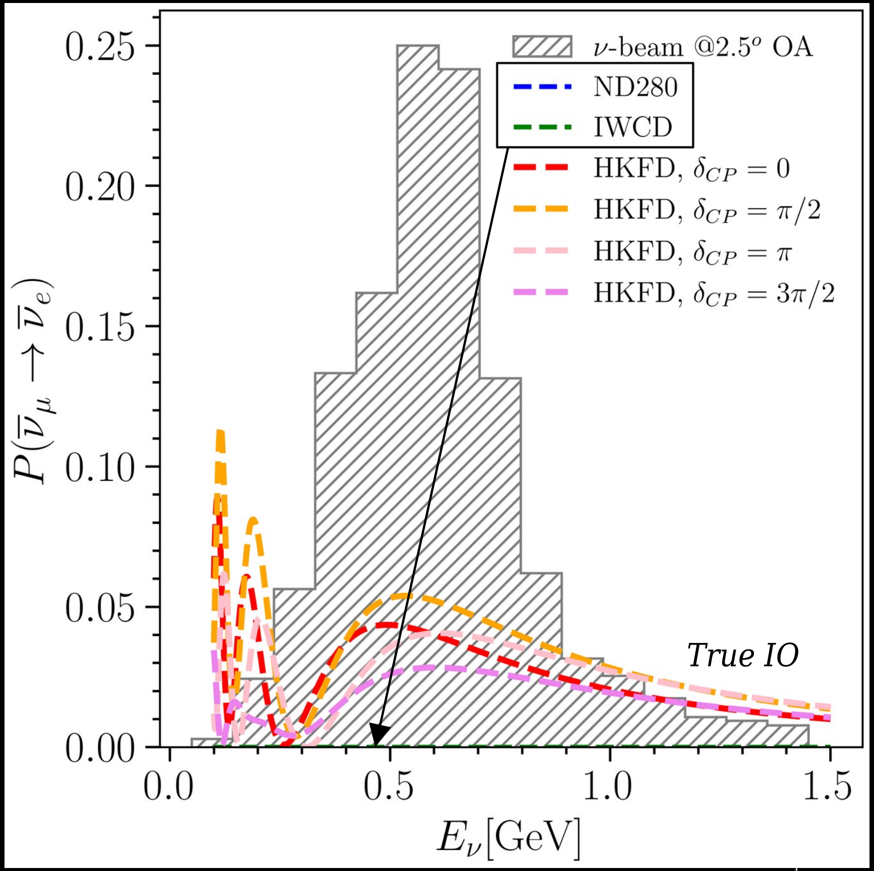


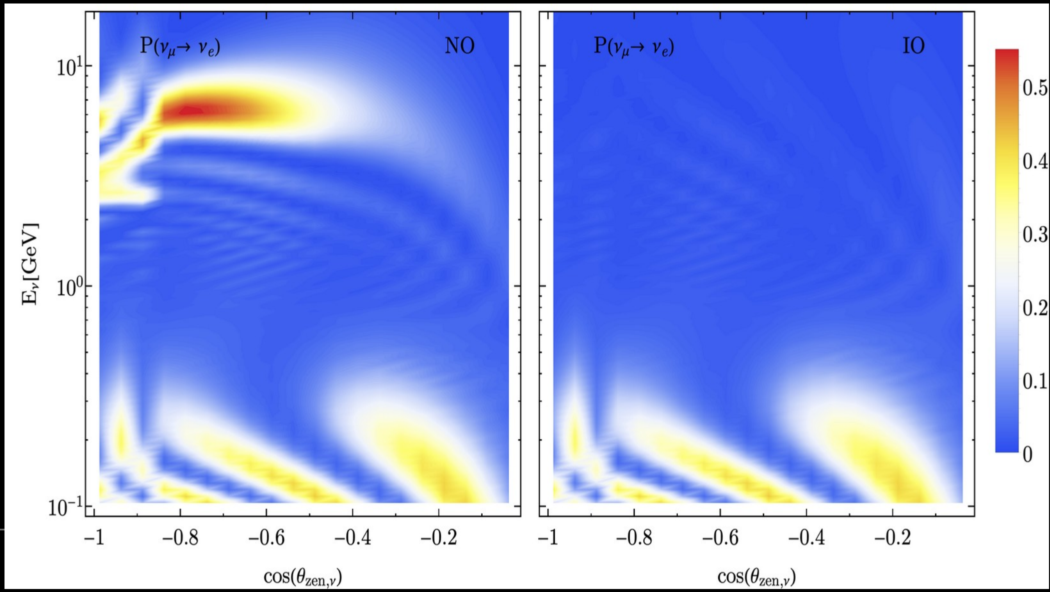
antineutrino mode



HyperK strategy – *atmospherics*

Electron and muon (anti)neutrinos covering several orders of magnitude in the ratio L/E_ν and going through large amounts of matter
→ Larger statistics but larger systematics

- They provide very important input in resolving uncertainties from $\boldsymbol{\theta_{23}}$ **and** $\boldsymbol{\Delta m^2_{31}}$
- **Mass Ordering** measurement through MSW, reducing the degeneracy between δ_{CP} *values* in LBL



HyperK strategy – *atmospherics*

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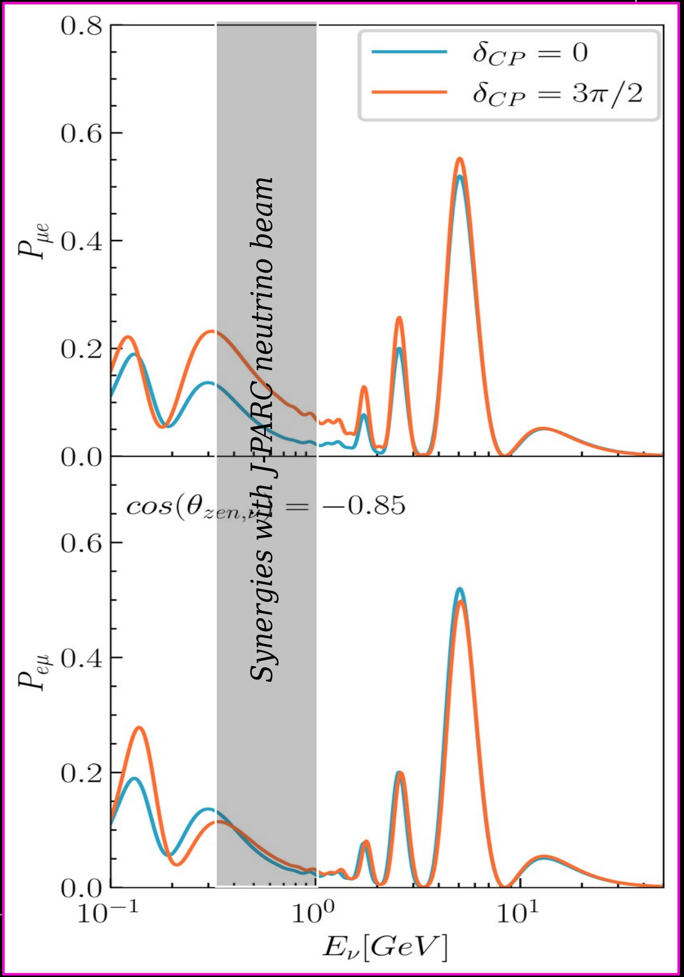
- Standalone ***CP phase*** measurement – δ_{CP} results in a different normalization of the probability and a shift in the oscillation phase at sub-GeV energies



Building HyperK for measuring δ_{CP}

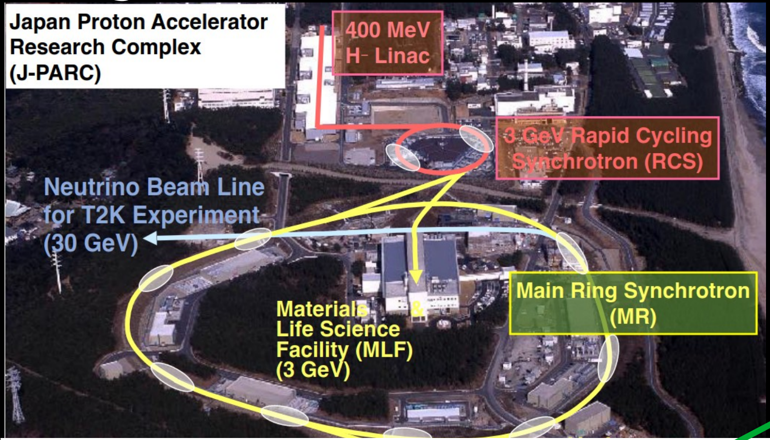
The HyperK project addresses the main two obstacles for measuring the neutrino CP phase in current experiments (NOvA and T2K)

- Larger neutrino event statistics:
  - Power upgrade of the J-PARC (anti)neutrino beam; 0.5 MW to 1.3 MW (x2.6)
  - New and larger far detector;
    fiducial mass from 22.5 kilotonne (Super) to 186 kilotonne (Hyper) (x8.3)

- Reduced systematic uncertainties:
  - Upgrade and extension of T2K's near-detector, ND280++
  - New intermediate water-Cherenkov detector, IWCD

  → Both providing powerful constraints on flux and cross-section systematics

HyperK neutrino beam @ J-PARC

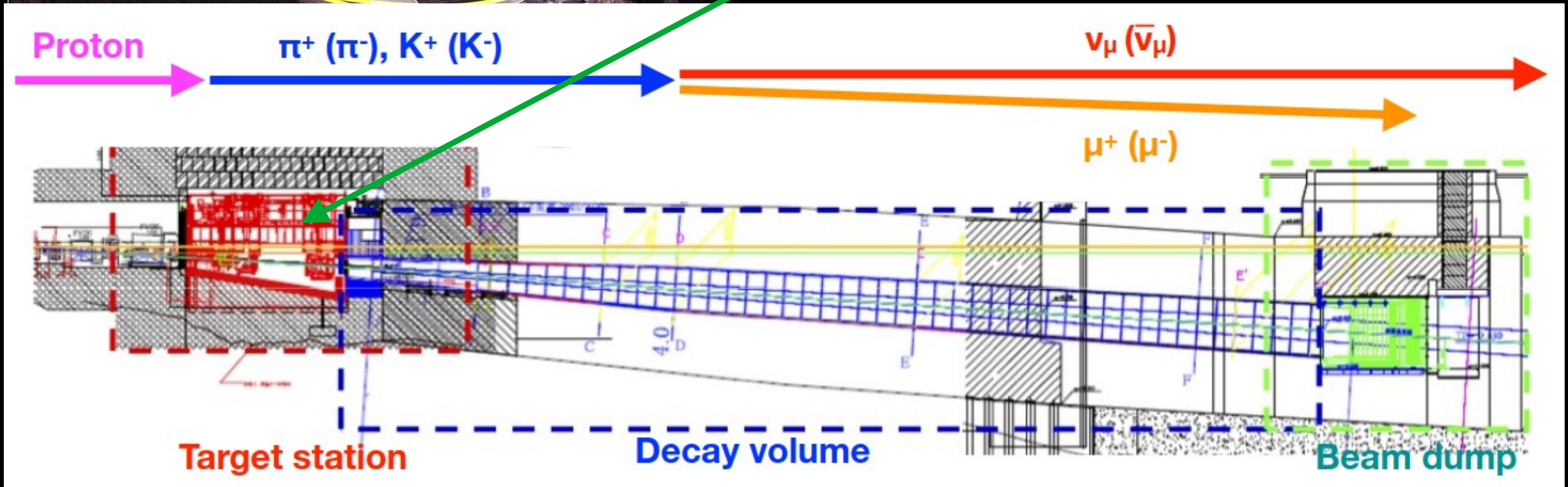


Located in Tokai, currently serves as the T2K beam

2.5° off-axis: neutrino spectrum peaked at 0.6 GeV

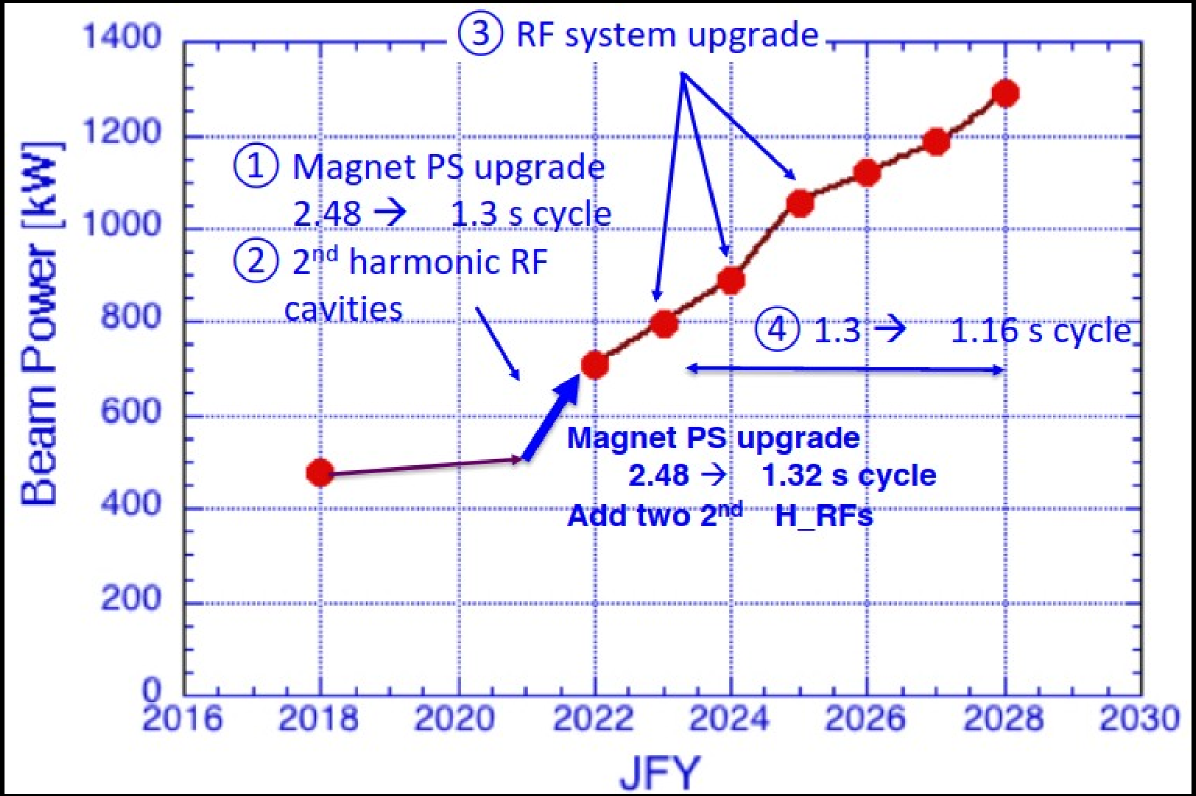
295 km baseline to HyperK's far detector

ν_μ or $\bar{\nu}_\mu$ selected by horn current
small intrinsic ν_e (<1% at peak)



HyperK neutrino beam @ J-PARC

Undergoing various upgrades to achieve 1.3 MW by 2027 for HyperK

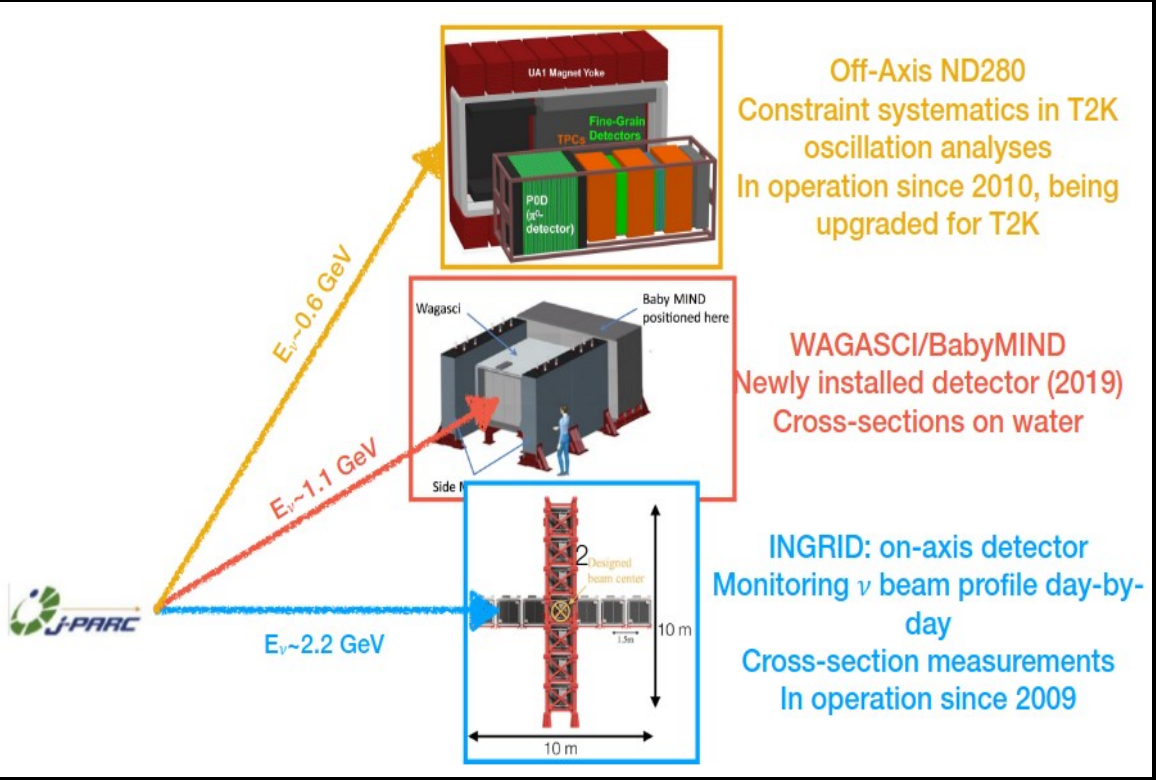


HyperK near detectors

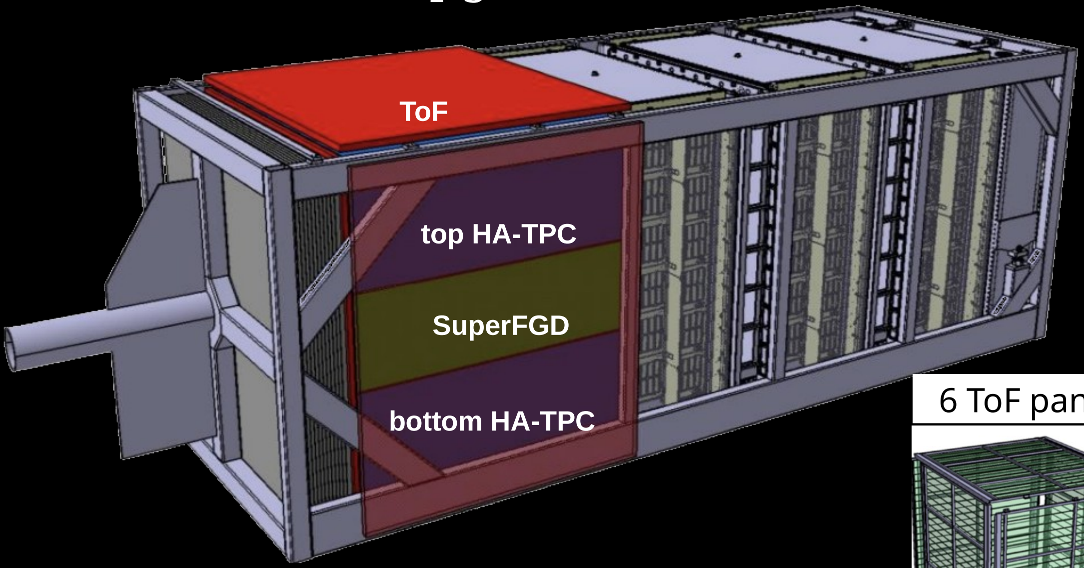
The T2K near-detector complex is being upgraded
→ additional upgrade for HK is under study

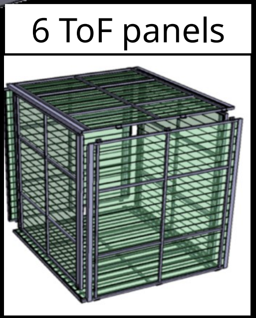
Located 280 m from the neutrino beam target

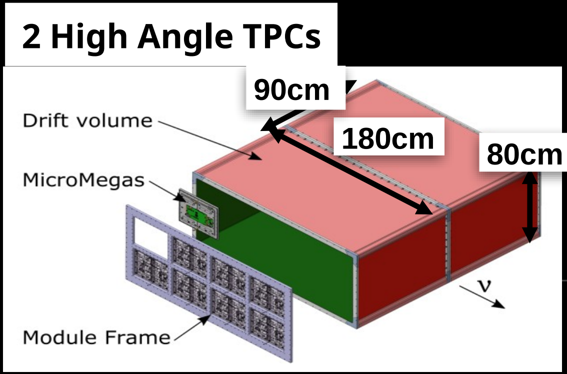
The near detector suite will provide much information for the composition and spectrum of the **beam flux** and for the **cross section** of the relevant (CCQE, CC2p2h, CC1π) interactions

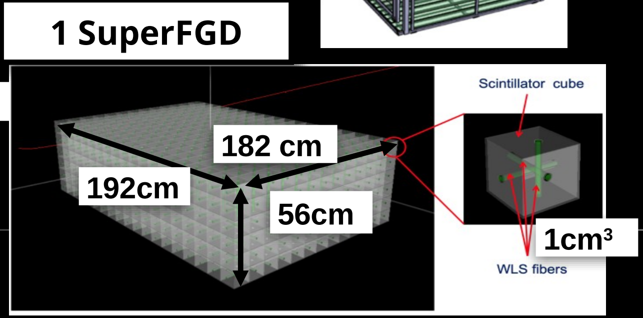


T2K - ND280 upgrade







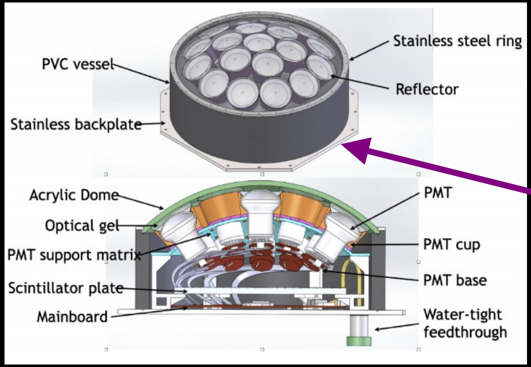


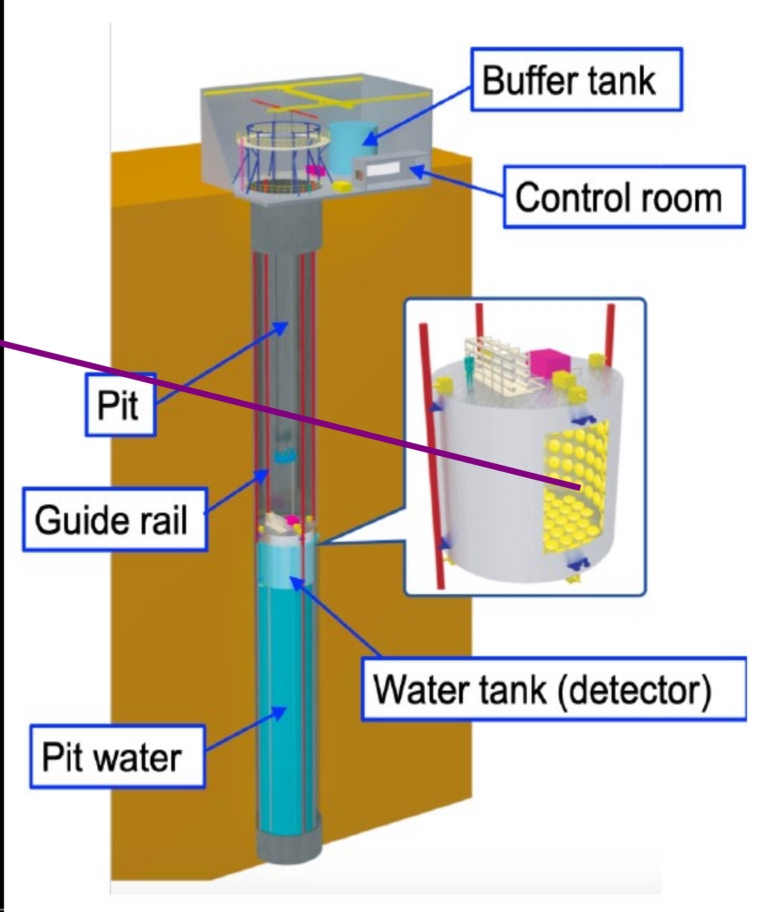
- Novel scintillator tracker (SuperFGD): lower particle detection thresholds, neutron detection, 3D event reconstruction
- High Angle-TPCs for particle identification and precise momentum measurement
- Time-of-Flight (TOF) system with 150 ps time resolution to suppress environmental background

HyperK intermediate detector (IWCD)

New water-Cherenkov detector at intermediate baseline, ~ 1 km from the target

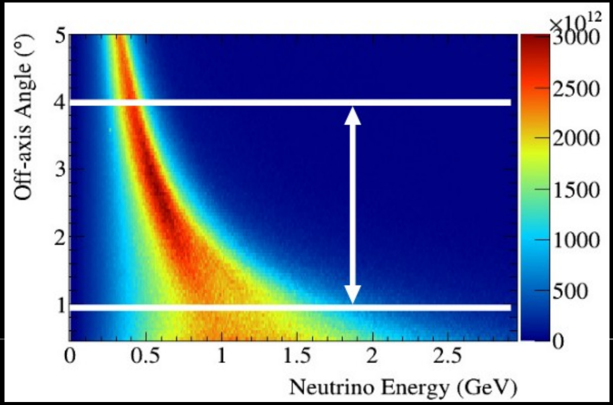
650 tonne detector instrumented with ~500 multi-PMT modules (19 3”-PMTs each)





Moving capabilities to access 1º to 4º off-axis (diff. spectra)

Measure the intrinsic electron (anti)neutrino component of the beam



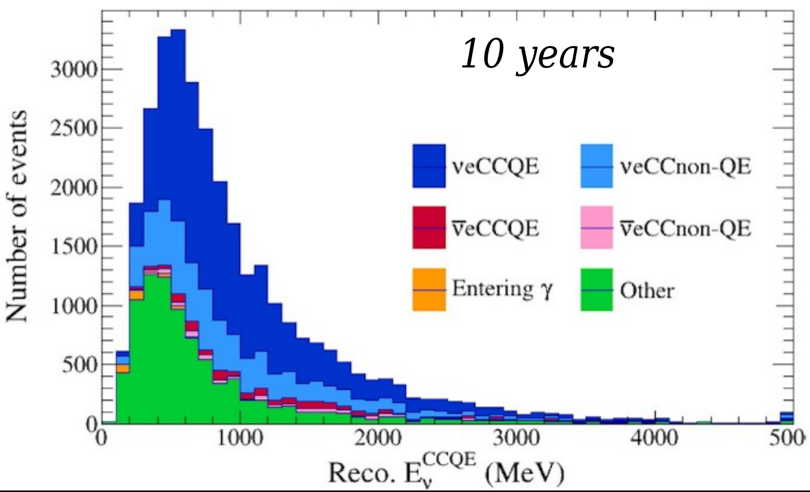
HyperK intermediate detector (IWCD)

Allows for a precise characterization of the flux at different off-axis angles

- Intrinsic ν_e , $\bar{\nu}_e$ and NC background measurements

Allows for a precise cross section measurements of ν_μ and ν_e, and $\bar{\nu}_\mu$ and $\bar{\nu}_e$ in water covering the full sub-GeV region

- Precisely measure the cross section ratio $\sigma_{\nu e} / \sigma_{\nu\mu}$
- Measure $CC\sigma_{\nu e}$ / $CC\sigma_{\bar{\nu} e}$ ratio with <4% precision



Key to reduce the systematic uncertainties in the LBL CP analysis needed for HyperK

→ *Joint R&D for IWCD and Hyper-K far detector with the Water Cherenkov Test Experiment (WCTE) at CERN in 2024*

HyperK far detector

Being excavated in the Tochibora mine (near Kamioka) since 2020

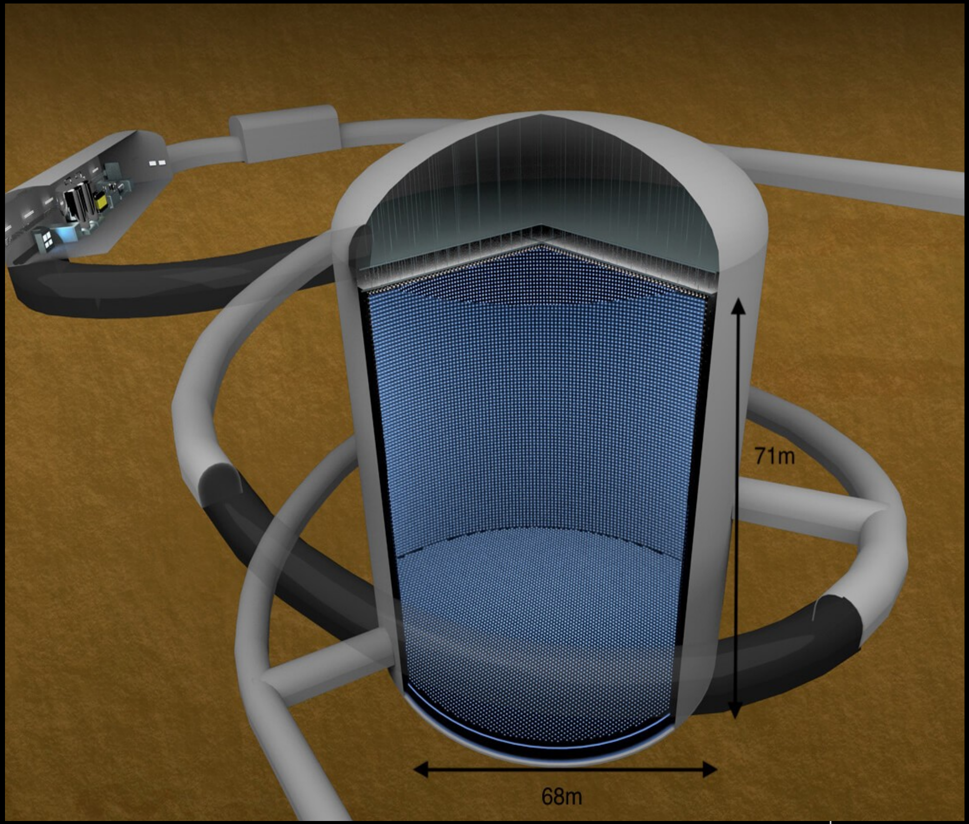
Overburden of 650 m of rock (1700 m.w.e.)

68m diameter x 71m height

258 kilotonne of ultra-pure water
186 kilotonne of fiducial mass

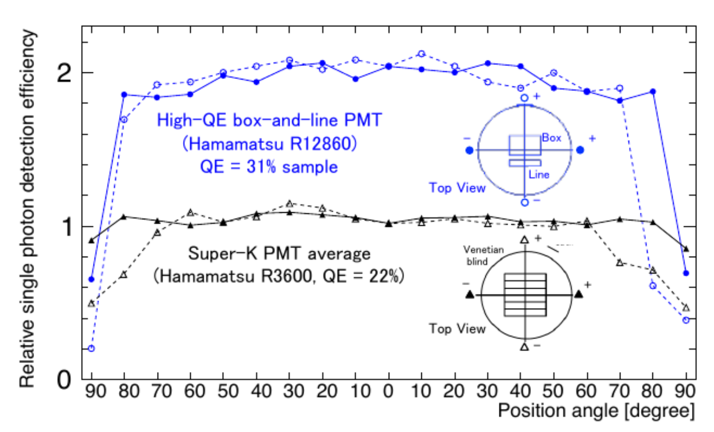
Outer detector acting as veto for cosmic rays

Inner detector instrumented with ~20,000 50 cm-PMTs and multi-PMTs



HyperK far detector

20% photocoverage (half of SuperK) with improved PMT technology – x2 photon detection efficiency and 2.6 ns timing resoluton



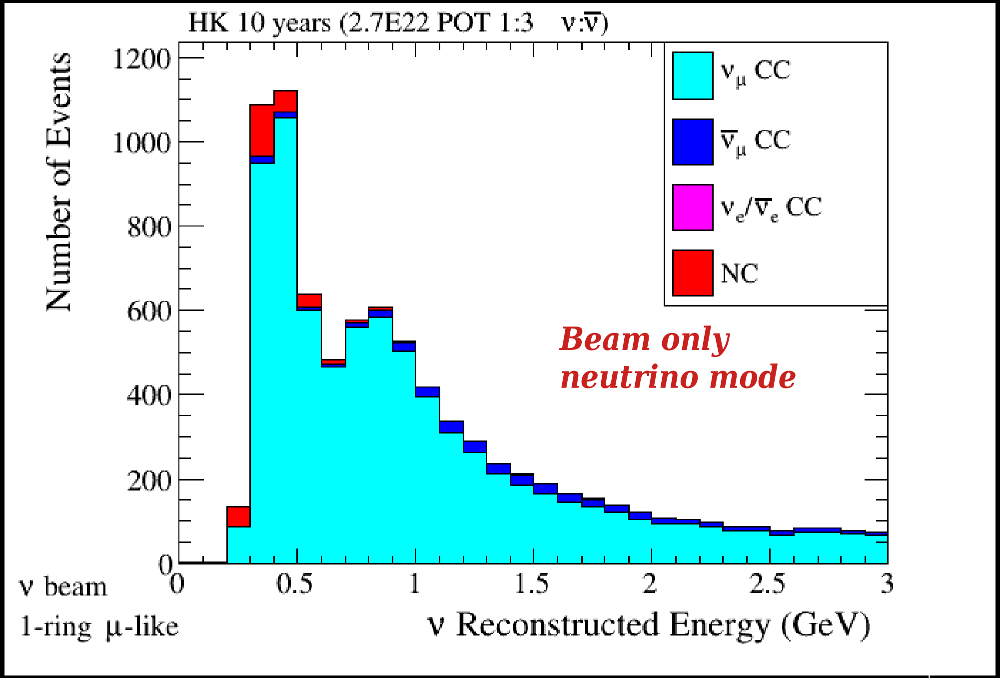
PMT production started in 2021 and will extend until 2026

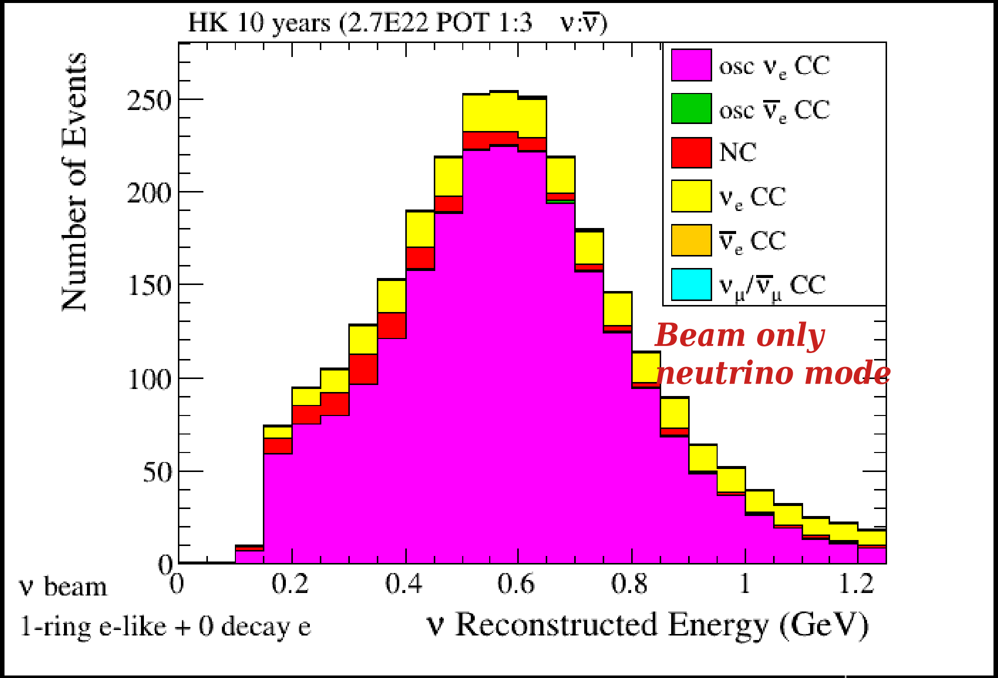
Additional mPMT modules (same as for IWCD) for improved time and spatial resolution

Taking advantage of all the knowledge from SuperK and expanding it with new calibration sources and techniques

HyperK prospects for the CP phase

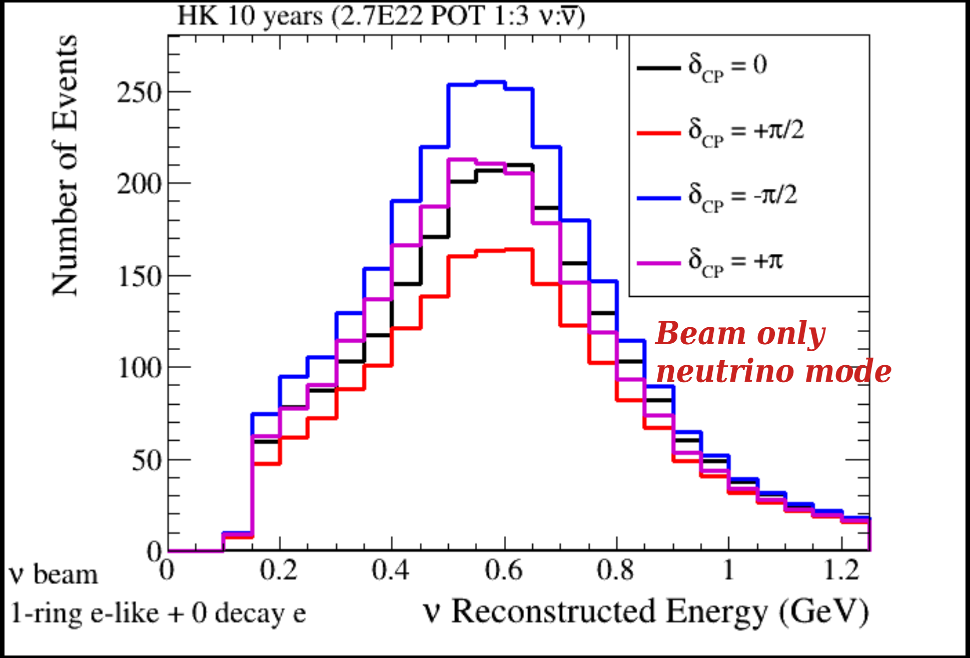
Reconstructed neutrino beam event samples disappearance (left) and appearance (right) channels



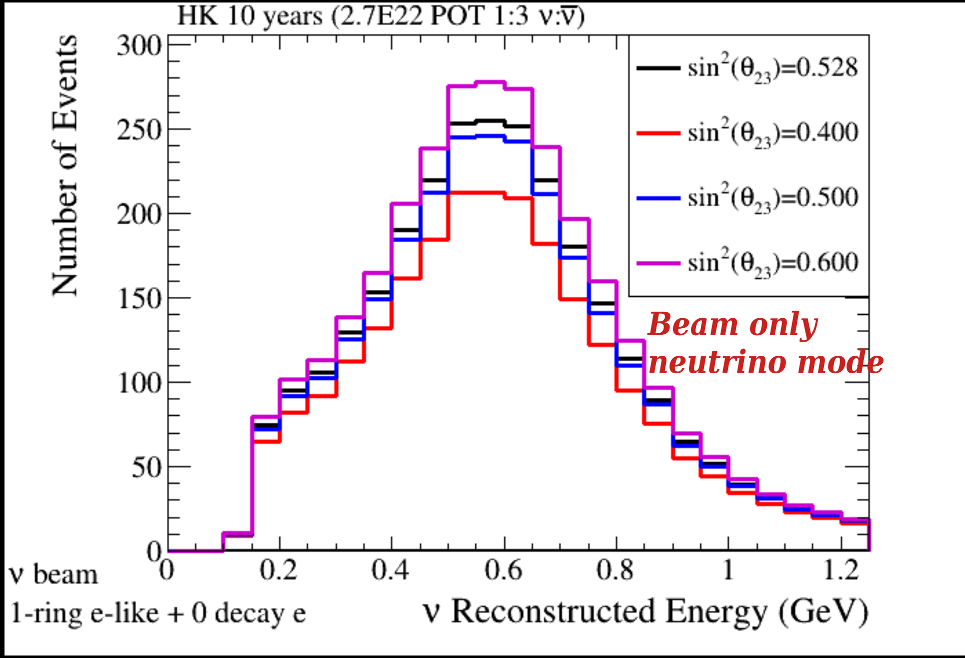


HyperK prospects for the CP phase

Appearance channel is sensitive to the values of CP

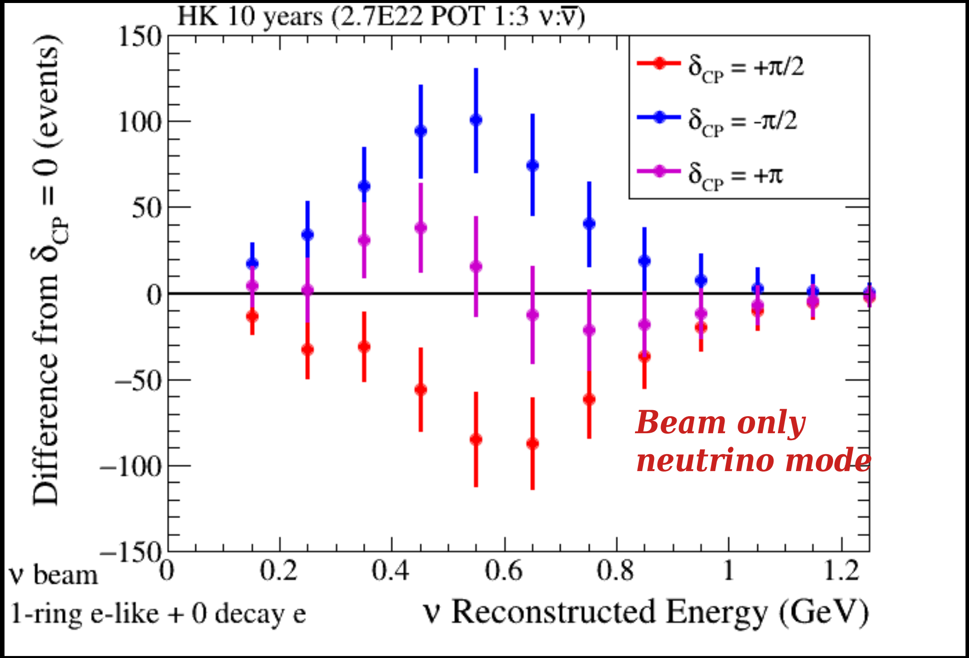


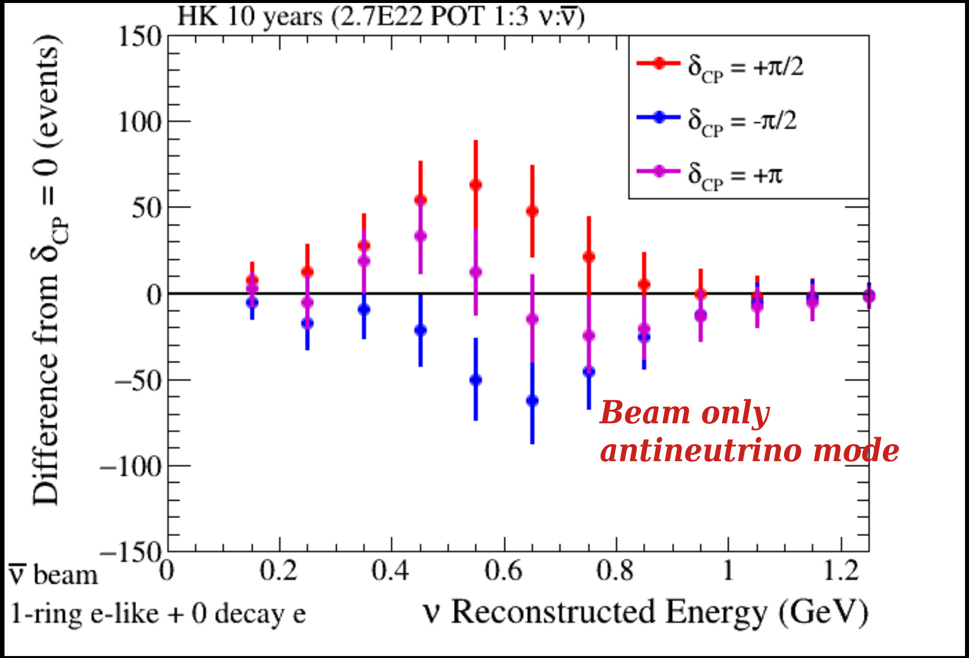
But needs the precise measurement of the rest of parameters, e.g. θ_{23}



HyperK prospects for the CP phase

Operating the **beam** in neutrino and antineutrino modes and the various muon and electron-like samples help solving degeneracies

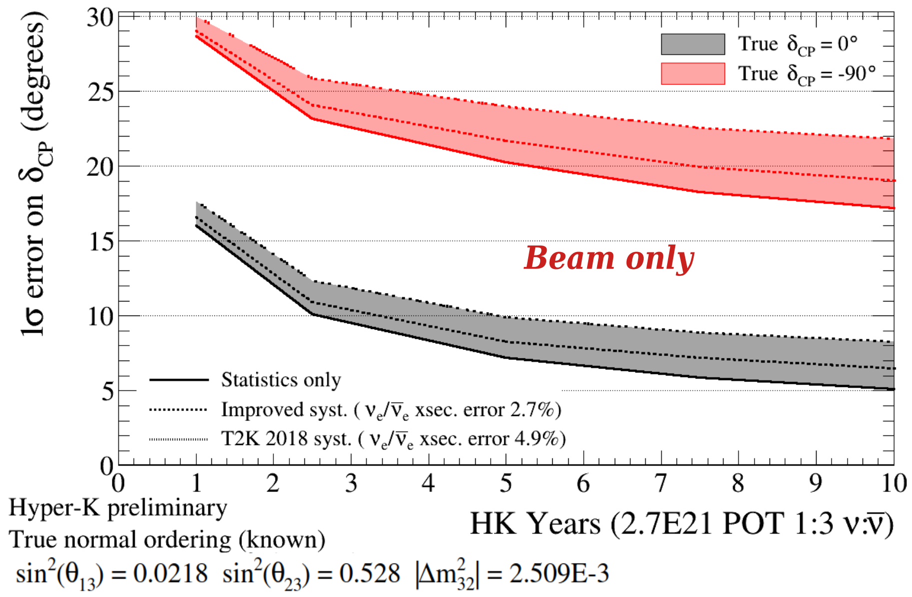


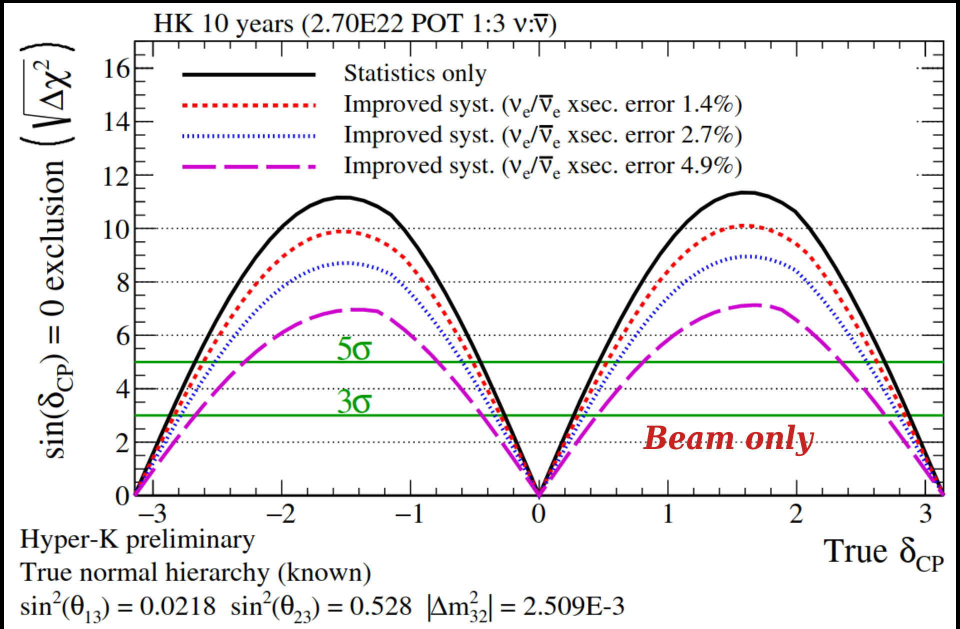


As so does the input from atmospheric neutrinos

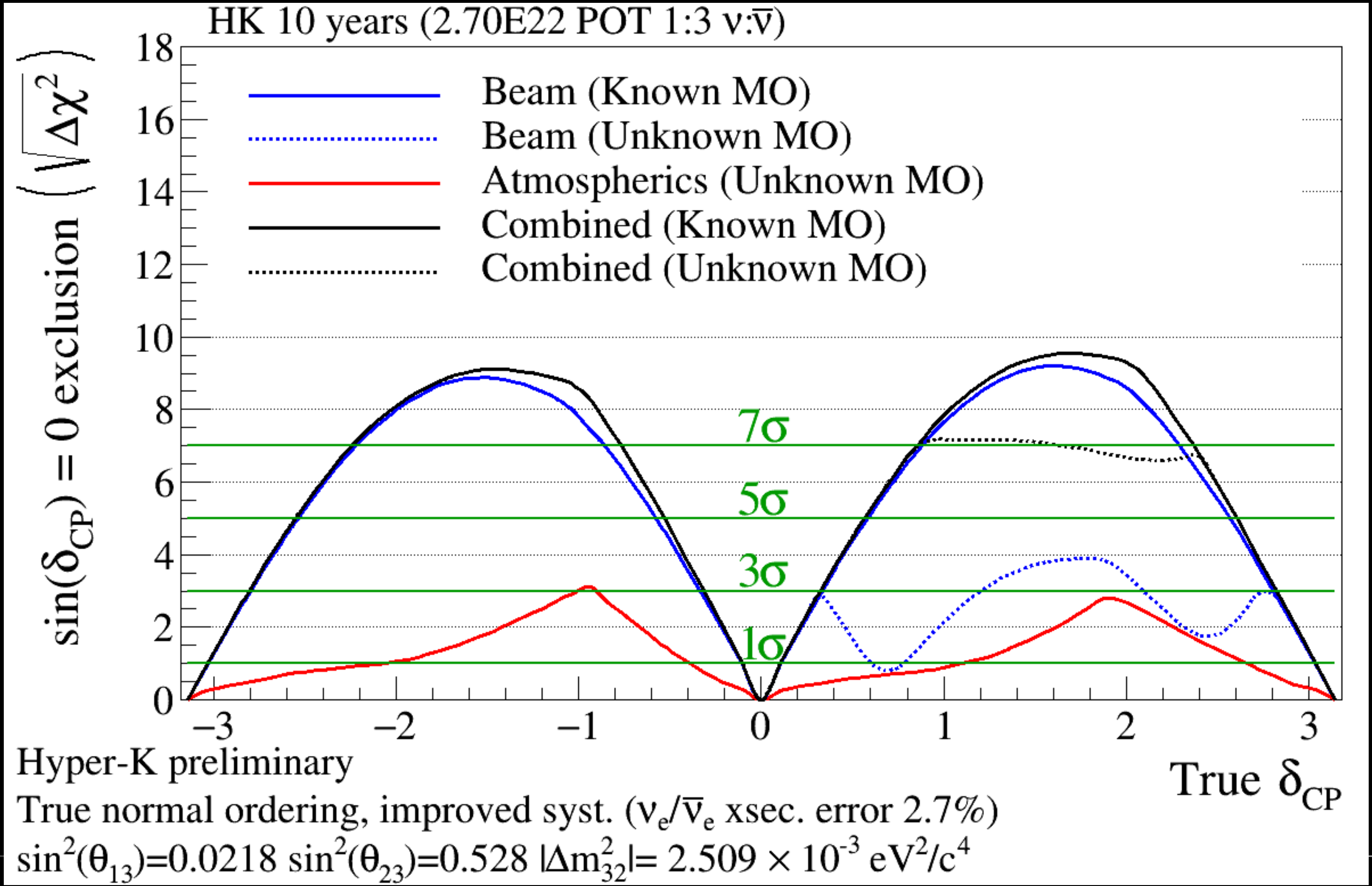
HyperK prospects for the CP phase

The biggest impact from systematics comes from the uncertainty in the ratio of the ν_e and $\bar{\nu}_e$ cross sections

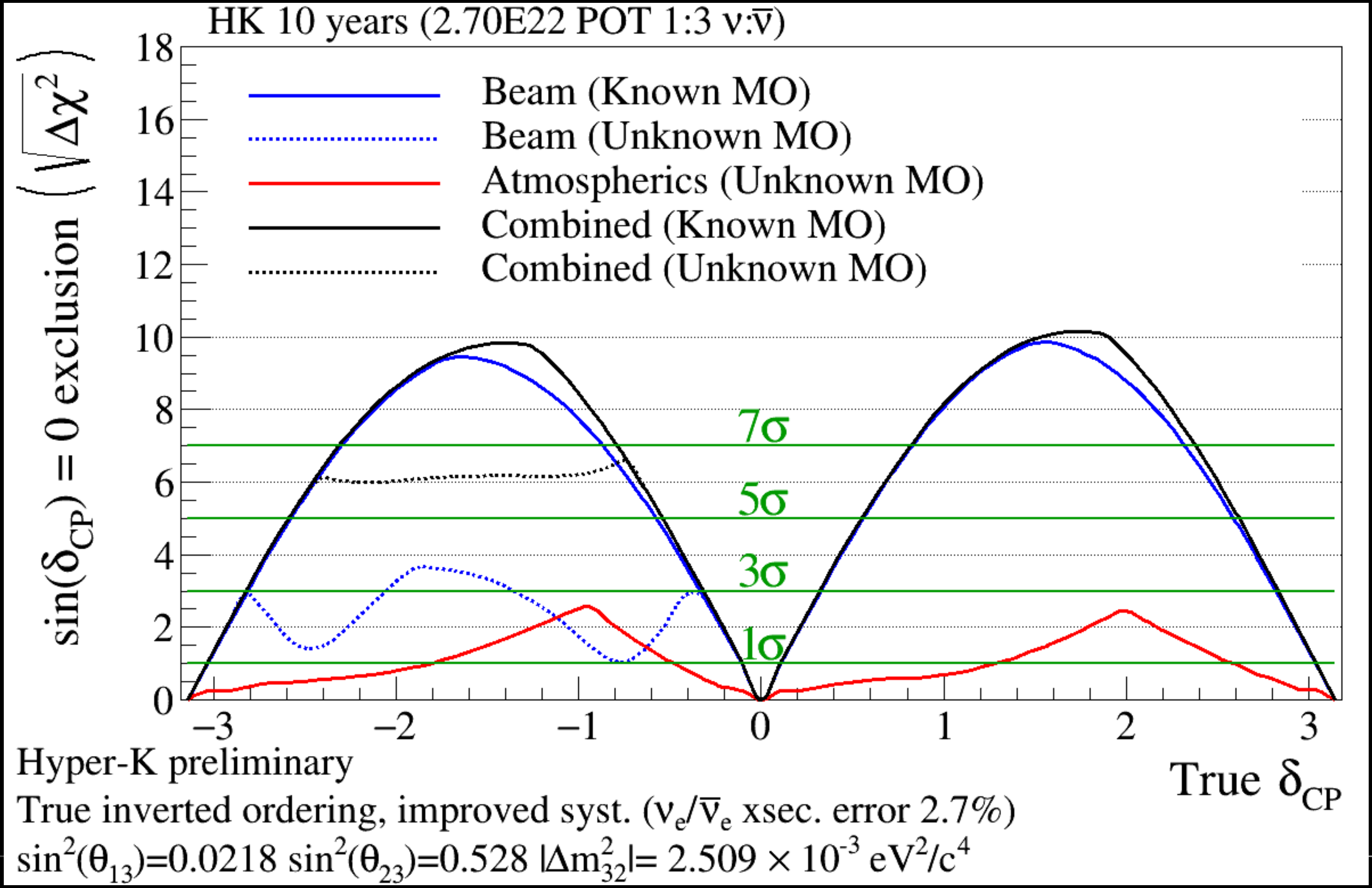




HyperK prospects for the CP phase



HyperK prospects for the CP phase



Conclusions

The HyperK project will start taking data in 2027 with the measurement of the CP phase in the neutrino sector as one of the top goals

Huge and complex experimental program has to be carried out to achieve large statistics and low systematic errors

- Improved neutrino beam and near detectors
- New intermediate and far detectors with improved technologies

Long-baseline analysis complemented with atmospheric neutrinos

Precise measurement of neutrino oscillations and the CP phase is getting closer

HyperK intermediate detector (IWCD)

Moving capabilities to access 1^{o} to 4^{o} off-axis allows to measure the neutrino beam at different energy spectra