Long-Baseline Neutrino Oscillation Physics Sensitivities of the Hyper-Kamiokande Experiment

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Outline

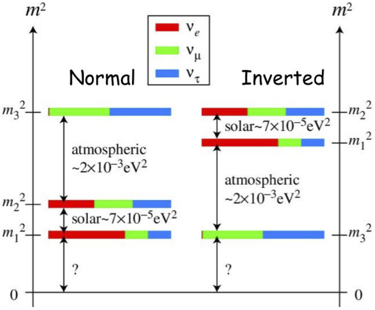
- Hyper-Kamiokande overview and status
- Hyper-Kamiokande long-baseline physics sensitivities
  - δ_{CP}
  - Mass Hierarchy
  - θ_{23}
  - Non-oscillation physics

Neutrino Oscillation

Neutrino oscillation can be described by the PMNS mixing matrix:

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +C_{23} & +S_{23} \\ 0 & -S_{23} & +C_{23} \end{pmatrix} \begin{pmatrix} +C_{13} & 0 & +S_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta_{CP}} & 0 & +C_{13} \end{pmatrix} \begin{pmatrix} +C_{12} & +S_{12} & 0 \\ -S_{12} & +C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$(C_{ij} = \cos\theta_{ij},\ S_{ij} = \sin\theta_{ij})$



- Mass Ordering unknown

Precisely measure all parameters to fully understand neutrino oscillation

- $\theta_{12} = 33.6^\circ \pm 0.8^\circ$ – solar ν's
- $\theta_{23} = 45.6^\circ \pm 2.3^\circ$
  – is θ_{23} maximal?
- $\theta_{13} = 8.3^\circ \pm 0.2^\circ$ – recent reactor $\bar{\nu}_e$ disappearance measurements

δ_{CP} unknown $\rightarrow$ possibility of CP violation in the lepton sector

$\rightarrow$ May be able to help explain the dominance of matter over anti-matter in the Universe

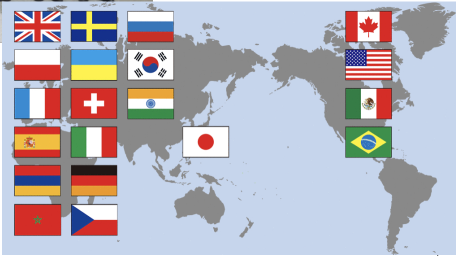
Hyper-Kamiokande Long-Baseline Program

- MW-class neutrino beam from upgraded J-PARC MR accelerator
  - Produce primarily ν_μ or $\bar{\nu}_\mu$ beam, 2.5° off-axis
- Neutrino flux and systematic errors constrained by upgraded ND280 detector and new Intermediate Water Cherenkov Detector
- Gigantic Hyper-Kamiokande water Cherenkov detector
  - Measure $\nu_\mu \to \nu_e$ appearance and $\nu_\mu \to \nu_\mu$ disappearance oscillations

The Hyper-Kamiokande Collaboration

HK collaborators (February 2020)

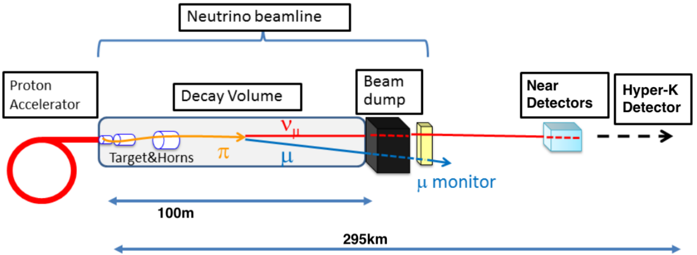
The Hyper-Kamiokande collaboration consists of >400 researchers from 20 countries



Hyper-Kamiokande Status

- Access/approach tunnel excavation reached the center of the future HK main cavern's dome June 2022
- Excavation of the circular tunnel around the dome has started

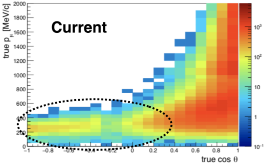
J-PARC Neutrino Beam

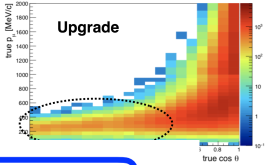


- Slam high-intensity 30GeV proton beam into 90-cm carbon target
- Focus outgoing hadrons in 3 electro-magnetic focusing horns
  - Switch between ν- or $\bar{\nu}$-mode by changing the horn polarity
- Pions decay to muons and ν_μ's in 100-m-long decay volume
- Stop interacting particles in beam dump; neutrinos continue on to near and far detectors
  - Monitor >5GeV muon beam by Muon Monitor in beam dump
- Constrain proton interactions by external hadon production measurements (NA61, EMPHATIC) to precisely simulate the flux
- Upgrades to J-PARC accelerator underway now towards 1.3+MW proton beam power for HK

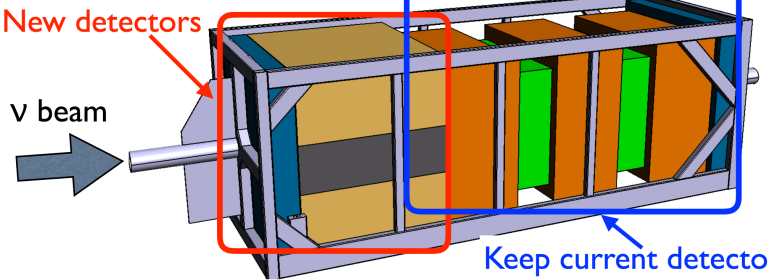
ND280 Near Detector Complex

- Suite of Near Detectors 280 m from the neutrino source
  - Monitor the neutrino beam stability and direction
  - Constrain the neutrino flux
  - Precisely measure neutrino cross sections
- Upgrades to ND280 underway now
  - Improve acceptance for high-angle and backwards tracks to improve systematic error constraint

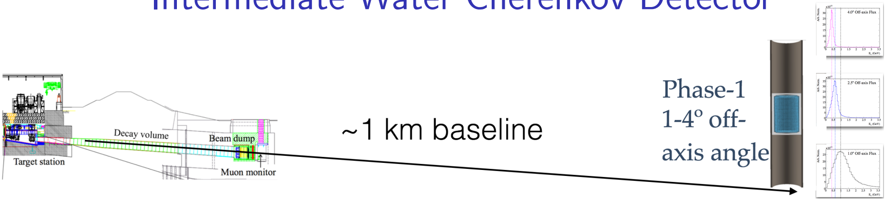




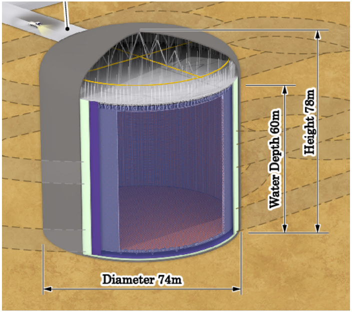
Detectors inside a magnet



Intermediate Water Cherenkov Detector



- 1 kilo-ton scale water Cherenkov detector located $\sim$1 km from the neutrino source
- Position of instrumented part of the detector can be moved in $\sim$50 m shaft to make measurements at different off-axis angles
  - Take advantage of pion decay kinematics to probe neutrino interactions as a function of neutrino energy
- Measurements to address uncertainties on neutrino-nucleus scattering modeling for Hyper-K
  - Measure relationship between neutrino energy and final state particles
  - Precisely measure the $\nu_e/\bar{\nu}_e$ cross section
  - Measure neutron production in neutrino-nucleus scattering
- Now finalizing site selection + optimizing detector design

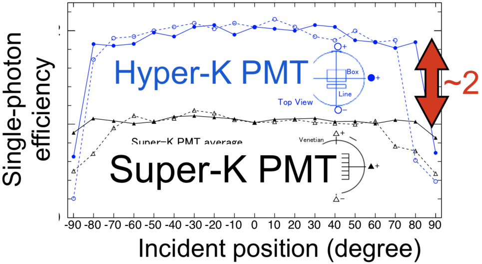


Hyper-Kamiokande Detector

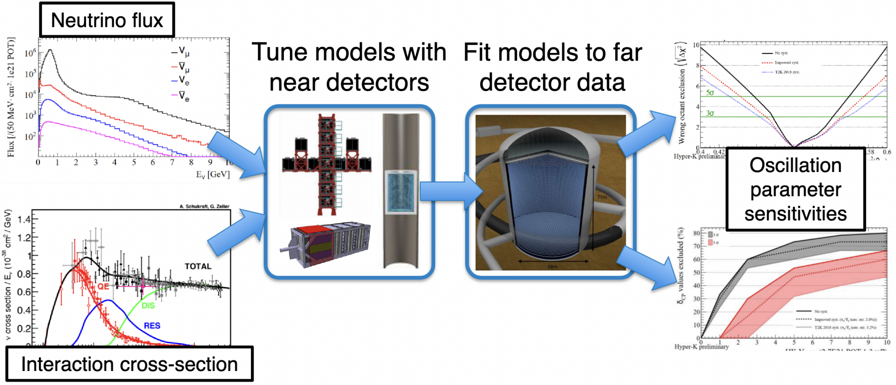
- 188kton fiducial mass water Cherenkov detector (∼8x larger than SK)
- Sub-GeV ring-imaging capability
- Excellent ν_e/ν_μ particle ID capability
- 20k 50cm Box and Line Dynode ID PMTs
- Multi-PMTs for directional information, improved spacial and timing resolution
- Scheduled to turn on in 2027

50cm Hyper-K PMT

- sensitivity: 2 x SK
- Time resolution: 1/2 x SK
- Pressure: 2 x SK

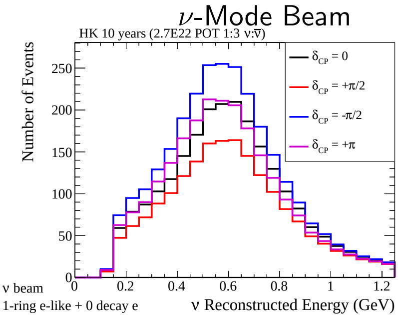


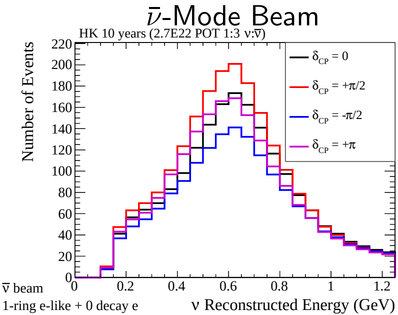
Hyper-Kamiokande Oscillation Analysis Method



- Based on T2K oscillation analysis method
- Simultaneous fit of HK far detector ν_e reconstructed energy vs angle + ν_μ reconstructed energy spectra

Hyper-K Long-Baseline ν_e Spectra

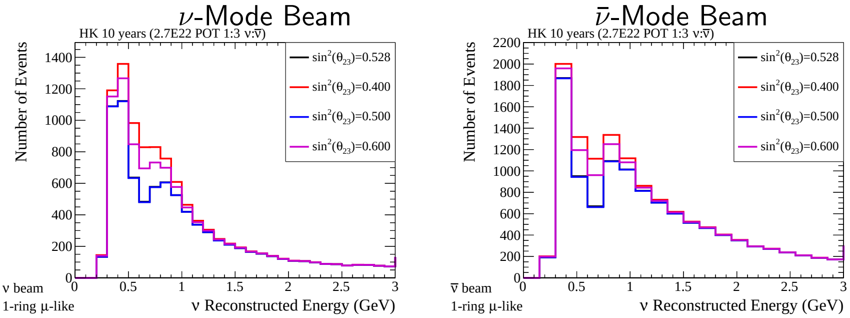




- Sensitivity to δ_{CP} comes mainly from $\nu_\mu \rightarrow \nu_e$ appearance – number of events in neutrino- vs antineutrino-modes
- Number of expected ν_e-like events (assuming 10 years at 1.3MW$\times 10^7$seconds, 1:3 ν:$\bar{\nu}$, NH, $\sin^2\theta_{13} = 0.0218$, $\delta_{CP} = 0$) :

	$\nu_\mu \rightarrow \nu_e$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Beam ν_μ	Beam $\bar{\nu}_\mu$	Beam ν_e	Beam $\bar{\nu}_e$	NC	Total
ν-Mode, ν_e CCQE-like	2252.51	11.70	6.53	0.23	326.15	12.34	130.30	2739.76
$\bar{\nu}$-Mode, ν_e CCQE-like	257.26	796.55	3.24	4.99	147.70	236.90	177.33	1623.97
ν-Mode, ν_e CC1π-like	207.36	0.23	4.49	0.14	34.46	0.29	10.65	257.63

Hyper-K Long-Baseline ν_μ Spectra



- Sensitivity to $\sin^2\theta_{23}$ and Δm^2_{32} comes mainly from ν_μ disappearance – depth and energy of oscillation dip
- Number of expected ν_μ-like events (assuming 10 years at 1.3MW$\times 10^7$seconds, 1:3 ν:$\bar{\nu}$, NH, $\sin^2\theta_{23} = 0.528$, $\Delta m^2_{32} = 2.509 \times 10^{-3}$ eV^2) :

	ν_μ	$\bar{\nu}_\mu$	ν_e	$\nu_\mu \to \nu_e$	$\bar{\nu}_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	NC	Total
ν-Mode, ν_μ CCQE-like	8583.80	479.91	0.24	2.32	0.01	0.01	282.99	9349.30
$\bar{\nu}$-Mode, ν_μ CCQE-like	4399.40	7688.44	0.28	0.33	0.24	0.42	285.92	12375.02

HK Long-Baseline Systematic Error Model

Three systematic error models shown here:

- T2K 2018 (after the near detector fit)
- Improved systematics, calculated by scaling the T2K-2018 error model assuming increased run time + sensitivities from ND280-upgrade and IWCD
  - Scaling uncertainty on flux, cross-section and SK detector systematics by $1/\sqrt{N}$, where N = 8.7 is the relative increase in neutrino beam exposure from T2K to Hyper-K
  - Studies from ND groups used to apply a further constraint to the cross-section model uncertainties:
    - A factor of 3 reduction on all non-quasi-elastic uncertainties
    - A factor of 2.5 reduction on all quasi-elastic uncertainties
    - A factor 2 reduction on all anti-neutrino uncertainties
    - A reduction in neutral current uncertainties to the $\sim$10% level
    - The $\nu_e/\bar{\nu}_e$ cross-section ratio error was varied from $\sim$3.6% to 1% to assess its impact
    - No parameter was allowed to have an uncertainty of less than 1%
- Statistics only (no systematics)

HK Long-Baseline Systematic Errors

- For current sensitivity studies - base HK long-baseline systematics on T2K errors
  - More robust HK systematic error model under development now

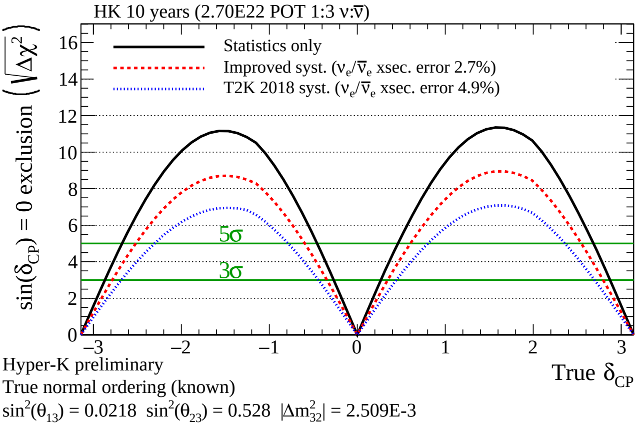
T2K 2018 errors:

	1-Ring ν_μ-Like		1-Ring ν_e-Like			
Error source	ν-Mode	$\bar{\nu}$-Mode	ν-Mode CCQE-like	$\bar{\nu}$-Mode CCQE-like	ν-Mode CC1π-like	ν-Mode/$\bar{\nu}$-Mode CCQE-like
Flux + xsec	3.27%	2.95%	4.33%	4.37%	4.99%	4.52%
Detector+FSI	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%

Improved HK errors:

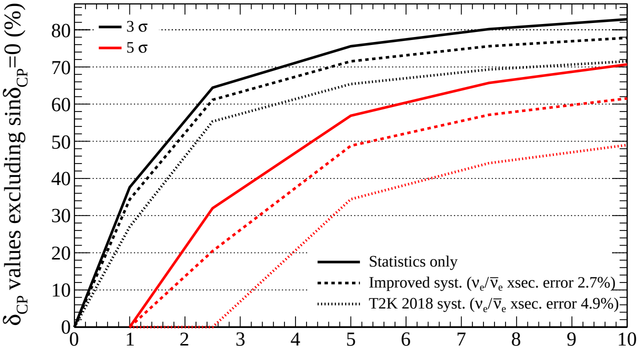
	1-Ring ν_μ-Like		1-Ring ν_e-Like			
Error source	ν-Mode	$\bar{\nu}$-Mode	ν-Mode CCQE-like	$\bar{\nu}$-Mode CCQE-like	ν-Mode CC1π-like	ν-Mode/$\bar{\nu}$-Mode CCQE-like
Flux + xsec	0.81%	0.72%	2.07%	1.88%	2.21%	2.28%
Detector+FSI	1.68%	1.58%	1.54%	1.72%	5.21%	0.97%
All syst	1.89%	1.74%	2.56%	2.53%	5.63%	2.45%

Impact of Systematics on the δ_{CP} Measurement



- Sensitivity to exclude $\sin\delta_{CP} \neq 0$ for different true values of δ_{CP} assuming the MO is known
- Significant change in sensitivity to δ_{CP} depending on the systematic error model – particularly sensitive to the error on the $\nu_e/\bar{\nu}_e$ ratio

Fraction of δ_{CP} Resolved

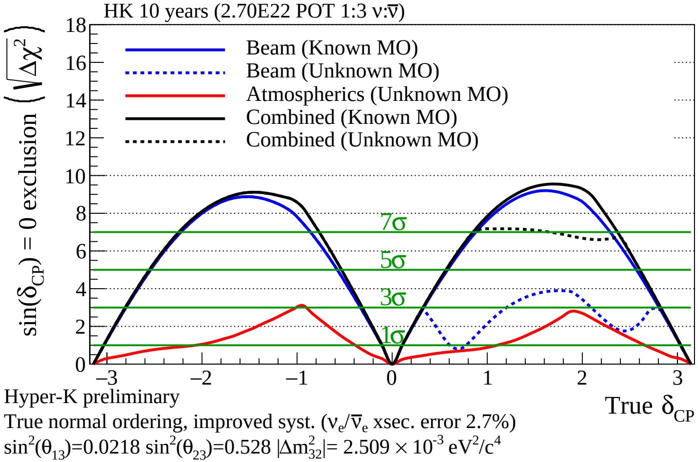


Hyper-K preliminary
True normal ordering (known)
$\sin^2(\theta_{13}) = 0.0218$ $\sin^2(\theta_{23}) = 0.528$ $|\Delta m^2_{32}| = 2.509\text{E-}3$

- Can resolve non-zero δ_{CP} for ∼60% of possible true values of δ_{CP} at 5σ and ∼80% at 3σ assuming the optimistic error model if the MO is known
- Significant change in sensitivity to δ_{CP} depending on the systematic error model – particularly sensitive to the error on the $\nu_e/\bar{\nu}_e$ ratio

Resolving the Mass Ordering with HK Atmospheric Neutrinos

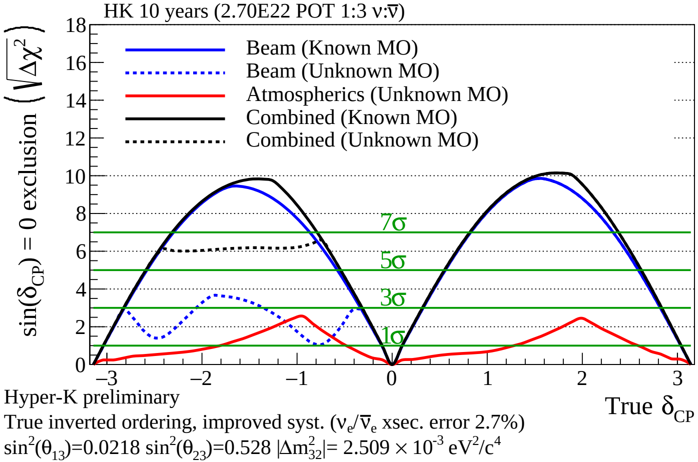
True Normal Ordering



- Combined fit of Hyper-K long-baseline and atmospheric neutrinos
- Atmospheric neutrinos can help to resolve the MO

Resolving the Mass Ordering with HK Atmospheric Neutrinos

True Inverted Ordering



- Combined fit of Hyper-K long-baseline and atmospheric neutrinos
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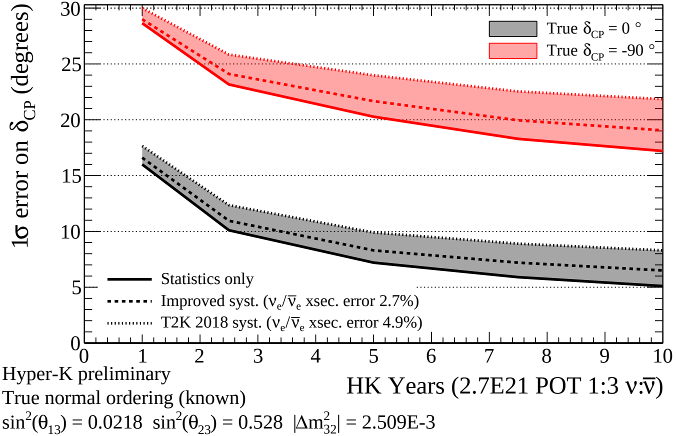
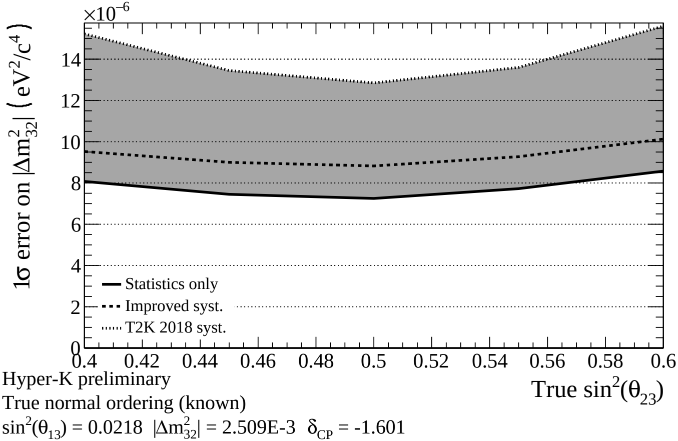
Error on δ_{CP} Measurement



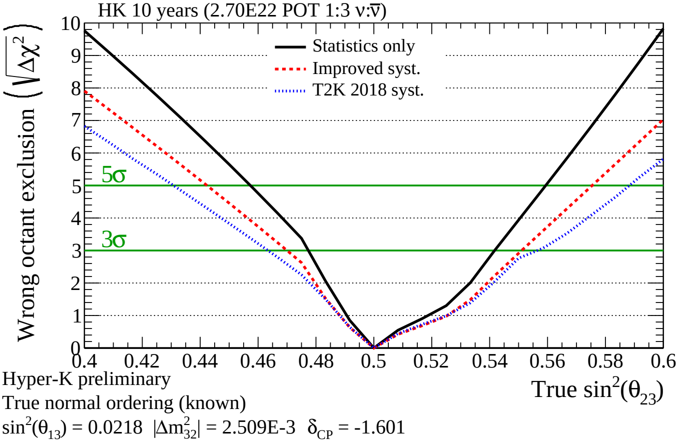
- Can make a precise measurement of δ_{CP} – $\delta_{CP} = -90^\circ \pm 19^\circ$, $\delta_{CP} = 0^\circ \pm 6.5^\circ$ assuming optimistic error model
- Significant change in sensitivity to δ_{CP} depending on the systematic error model – particularly sensitive to the error on the $\nu_e/\bar{\nu}_e$ ratio

Measurement of Δm^2_{32}



- 1σ resolution of Δm^2_{32} as a function of true $\sin^2\theta_{23}$ – $\sim 9 \times 10^{-6}$ eV^2 1σ error on Δm^2_{32}
- Systematics-limited measurement
- (Long-baseline fit only shown here – further sensitivity improvement when including atmospheric neutrinos)

Measurement of θ_{23} Octant



- Wrong θ_{23} octant can be excluded at 3σ for true $\sin^2\theta_{23} < 0.47$ and true $\sin^2\theta_{23} > 0.55$
- Systematics-limited measurement
- (Long-baseline fit only shown here – further sensitivity improvement when including atmospheric neutrinos)

Hyper-Kamiokande Beam Non-Oscillation Physics Sensitivity

- Precision measurements of various important neutrino cross sections at the HK near detectors
  - Upgraded ND280 has unique capabilities to make precise measurements
  - Intermediate Water Cherenkov Detector allows for precision interaction measurements at different off-axis angles $\rightarrow$ different beam energies
- Also aim for a search of non-standard/new physics in the HK near detectors :
  - Sterile neutrinos, heavy neutrinos (heavy neutral leptons), Lorentz violation, etc...

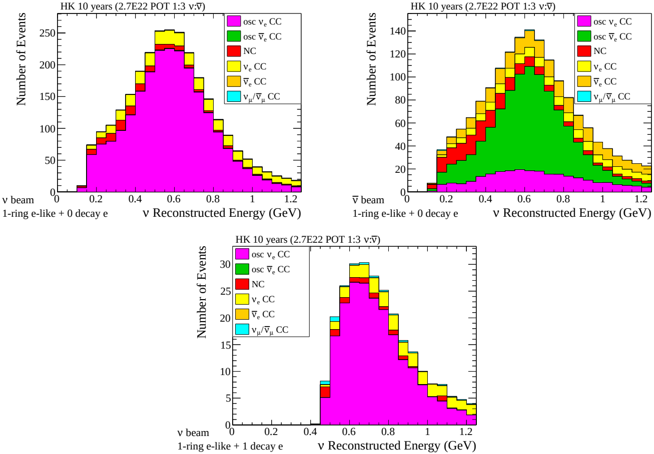
Conclusion

- Excavation for the Hyper-Kamiokande detector is ongoing – detector will turn on in 2027
- Essential to constrain systematic errors to achieve maximum sensitivity
- Hyper-Kamiokande long baseline neutrino oscillation measurements have sensitivity to:
  - Exclude CP conservation at 5σ for $\sim$60% of δ_{CP} parameter space
  - Measure δ_{CP} with precision of $< 20^\circ$ (better, depending on the true value of δ_{CP})
  - Determine the Mass Ordering to $>3\sigma$
  - Achieve 3σ exclusion of wrong θ_{23} octant for $\sin^2\theta_{23} < 0.47$ or $\sin^2\theta_{23} > 0.55$

- Sensitivities shown here based on T2K analysis tools
  - Various improvements to T2K analysis since 2018 not implemented yet
  - Now developing dedicated HK analysis tools
  - Development of robust systematics model based on HK detectors underway

Backup Slides

Hyper-K Long-Baseline ν_e Spectra



Number of expected ν_e-like events (assuming 10 years at $1.3\text{MW}\times10^7$seconds, 1:3 ν:$\bar{\nu}$, NH, $\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = 0$) :

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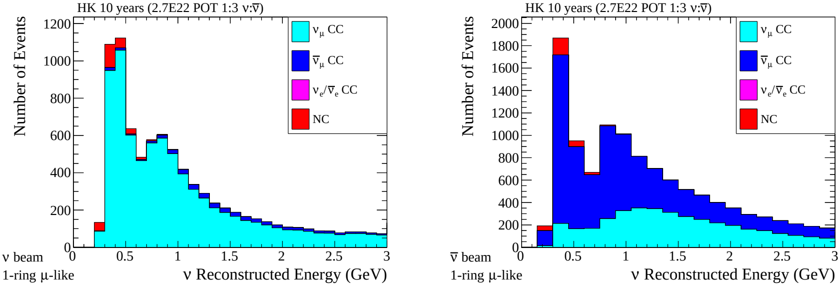

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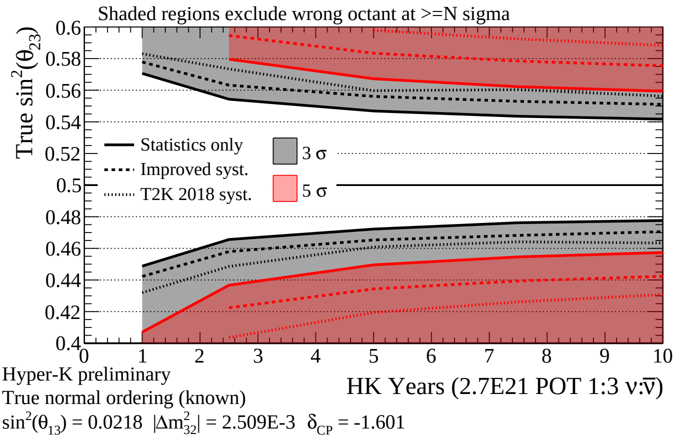

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