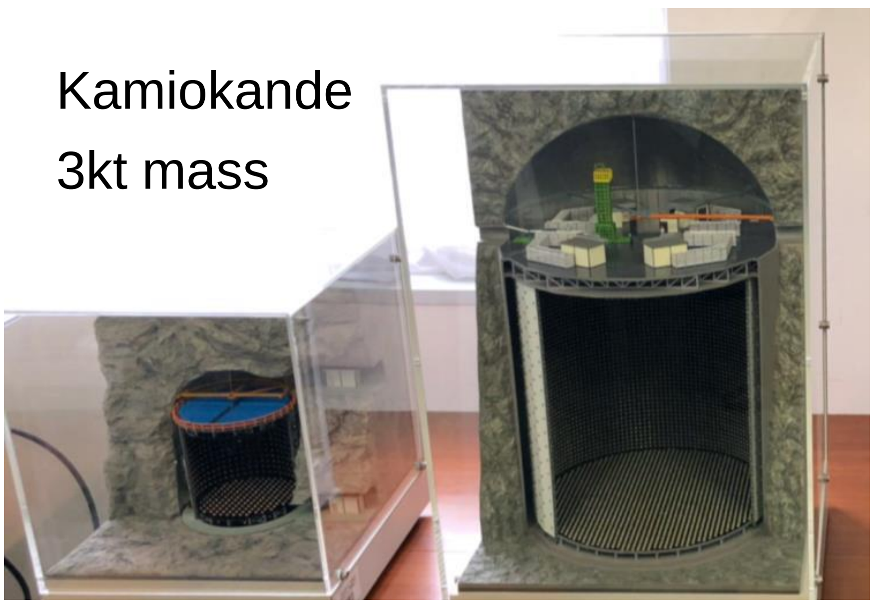
Long-baseline neutrino oscillation program at Hyper-Kamiokande

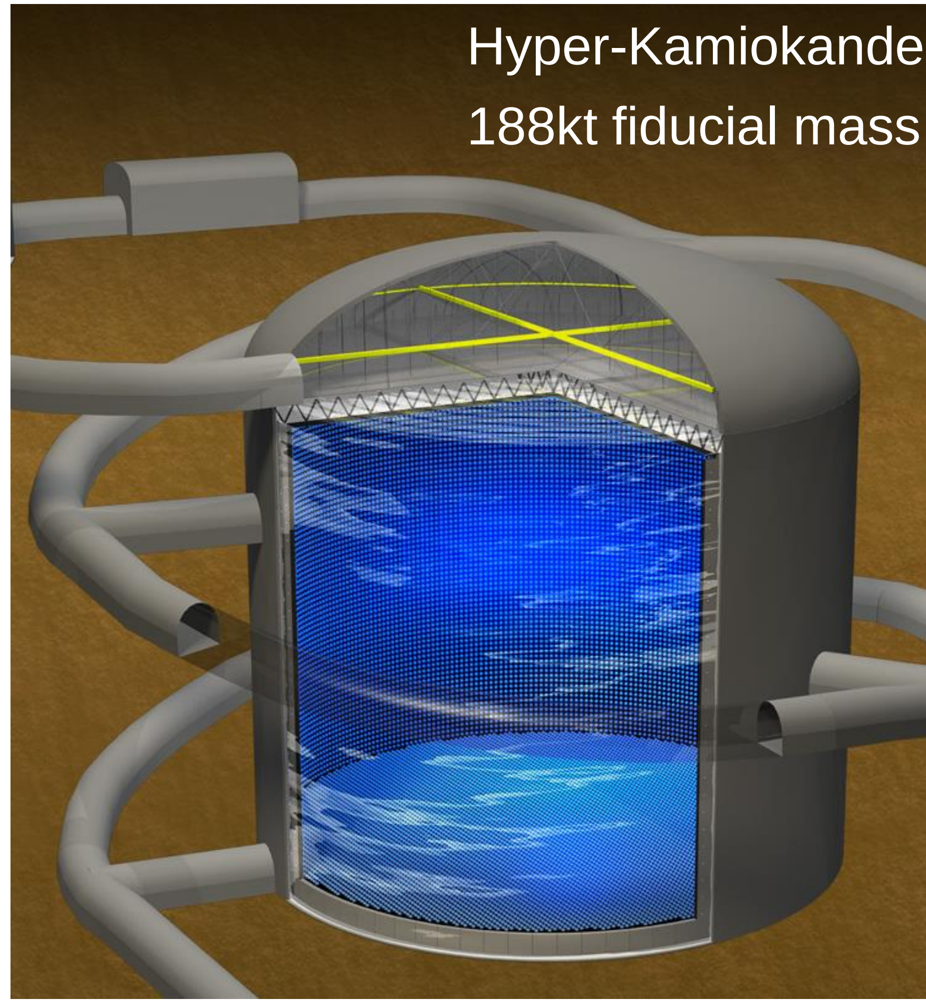
Mark Scott

Water Cherenkov detectors in Kamioka

Super-Kamiokande
22.5kt fiducial mass

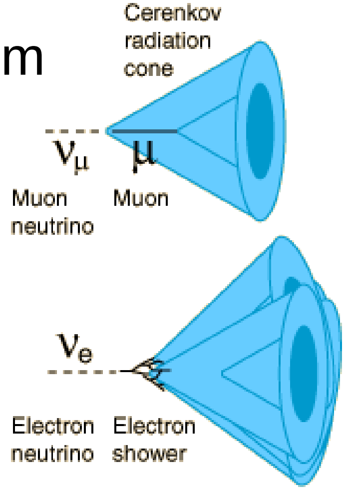
Kamiokande
3kt mass

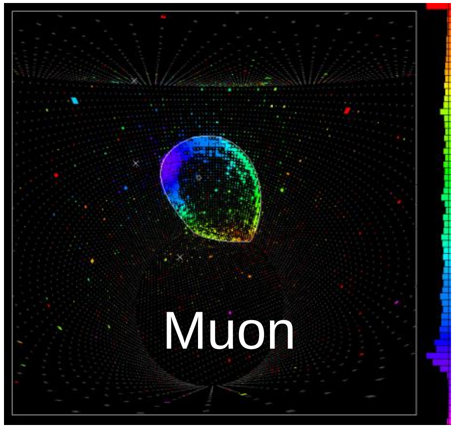


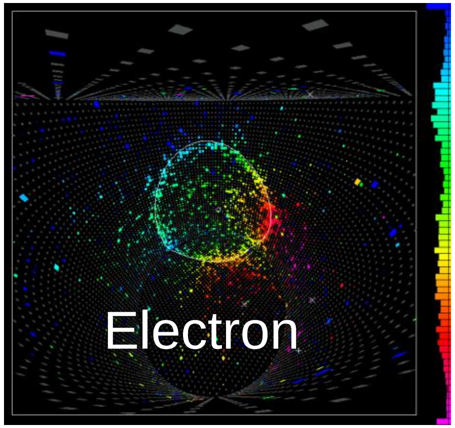


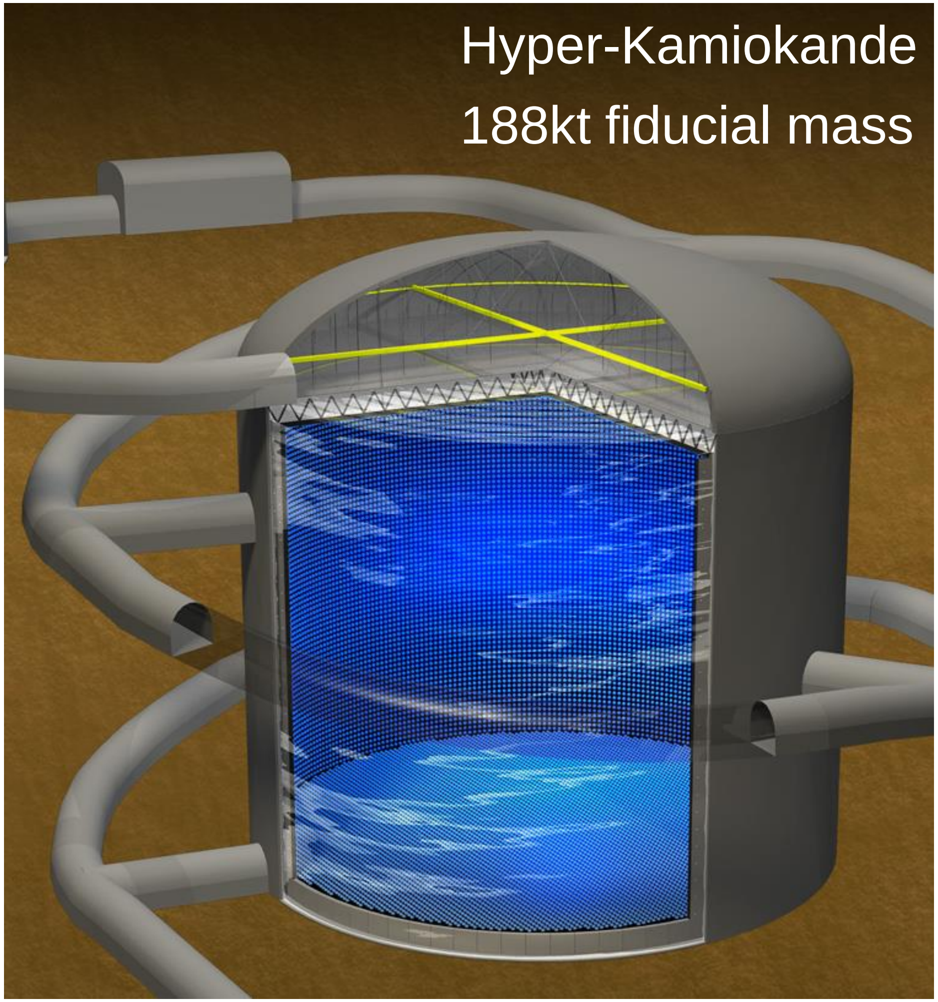
Water Cherenkov detectors in Kamioka

- Cherenkov ring from charged particles
- >99% μ/e separation
- Momentum and direction reconstruction



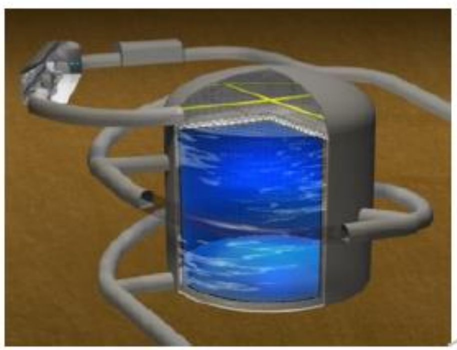




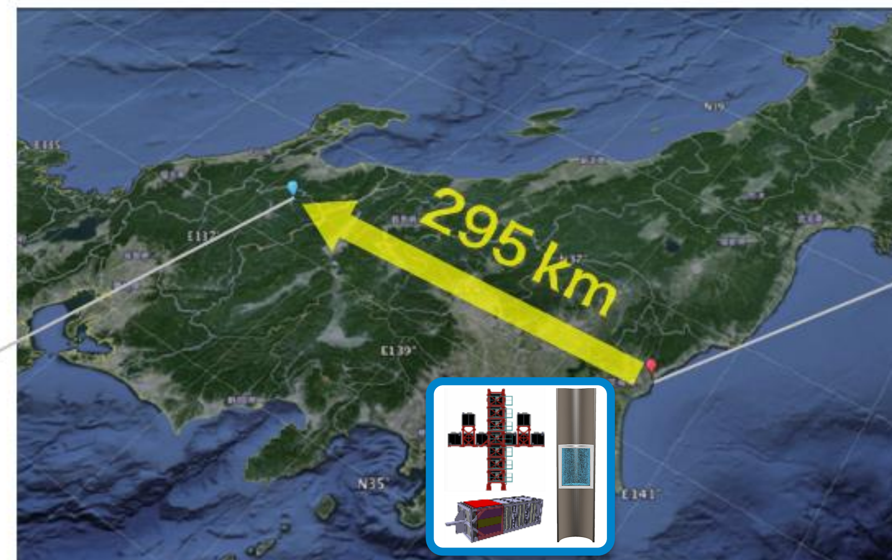


Hyper-Kamiokande experiment

- **Factor 20 increase in statistics compared to T2K**:
  - Upgrade of the J-PARC neutrino beam to 1.3 MW
  - New far detector with 188kt fiducial volume
- New intermediate detector and inherited upgraded near detectors
- Improved photosensors with twice the quantum efficiency



Hyper-K



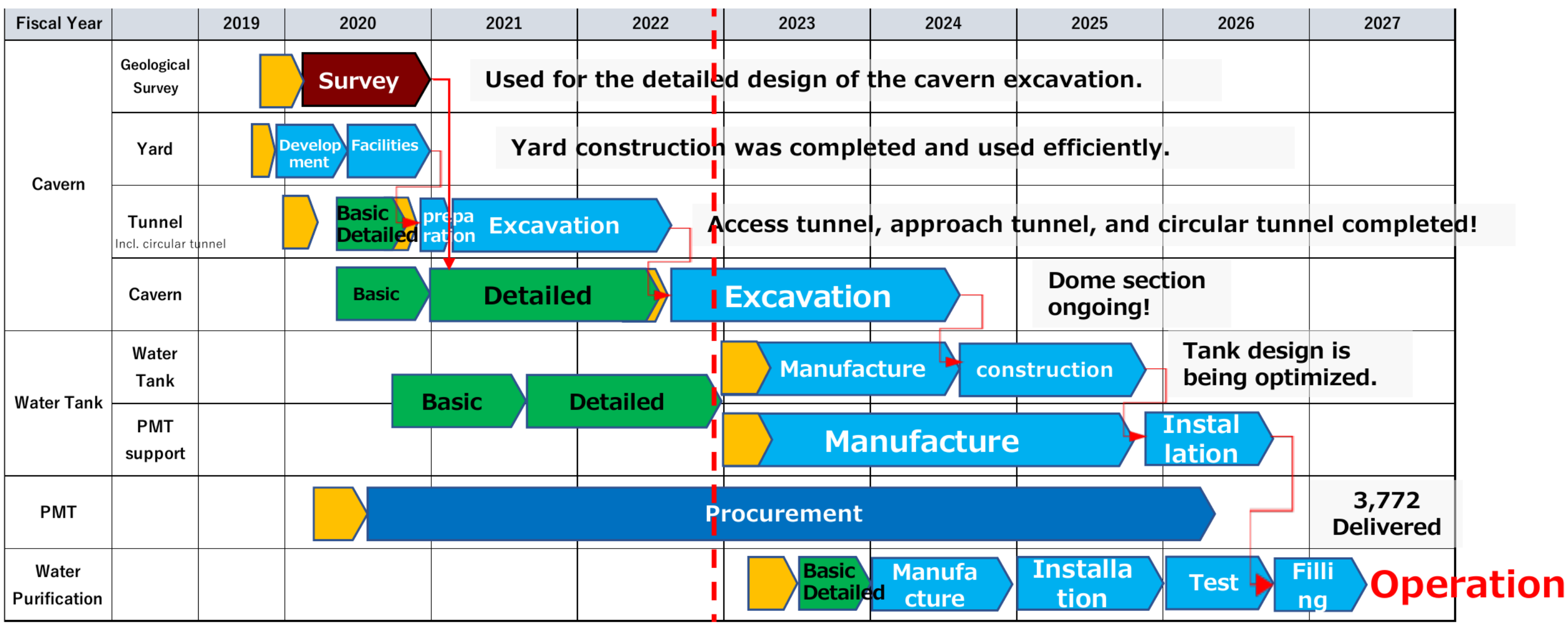
J-PARC
Accelerator Complex

Imperial College London

Hyper-Kamiokande construction status

Hyper-Kamiokande schedule

- Excavation of access tunnels complete
- Excavation of cavern well on the way
- Optimising design of tank and PMT support structure
- Expect operation in 2027



20-inch PMT production

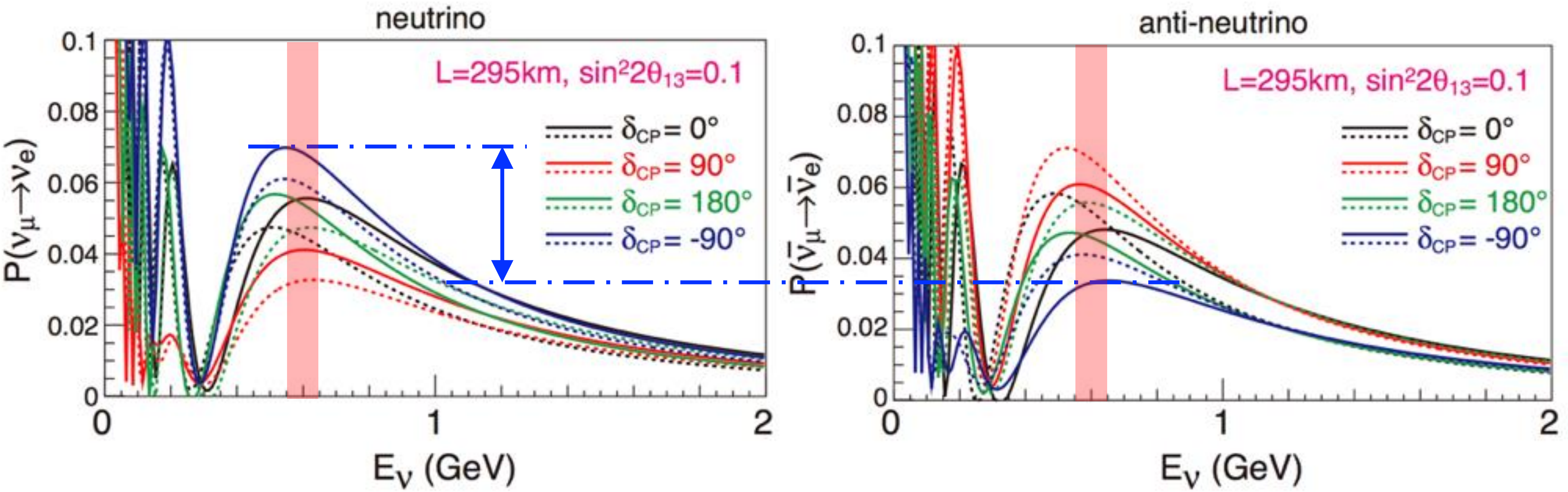
- > 3700 PMTs / 20,000 delievered as of May 2022.
- <u>Constant quality inspection :</u> visual, measurements …
- No delay so-far.

Neutrino oscillations

- Measure flavour composition of beam as function of L / E

$$P_{\alpha\to\beta} = \left|\sum_i U^*_{\alpha i} U_{\beta i} e^{-im_i^2 L/2E}\right|^2$$

- Compare neutrino beam and antineutrino beam to test CP symmetry

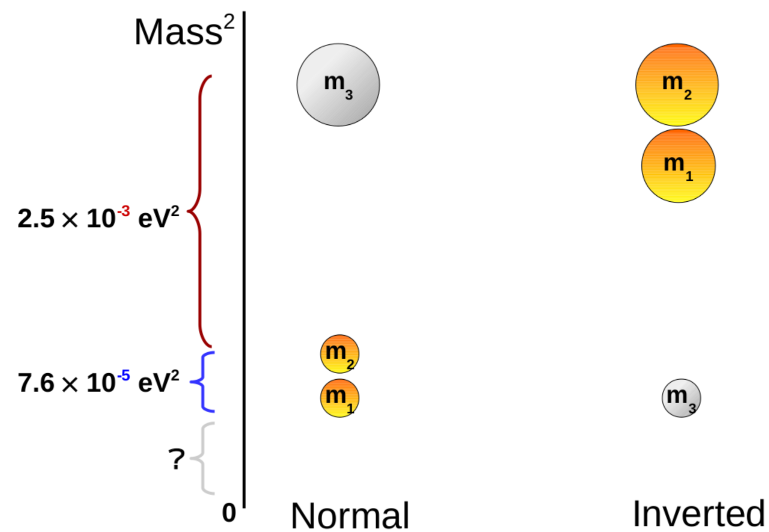


Neutrino oscillation formalism

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$

- Three mixing angles, θ_{12}, θ_{23} and θ_{13}
- Two mass splittings, $\Delta m^2{}_{12}$ and $\Delta m^2{}_{23}$
- One CP-violating phase, δ_{CP}



Neutrino oscillation formalism

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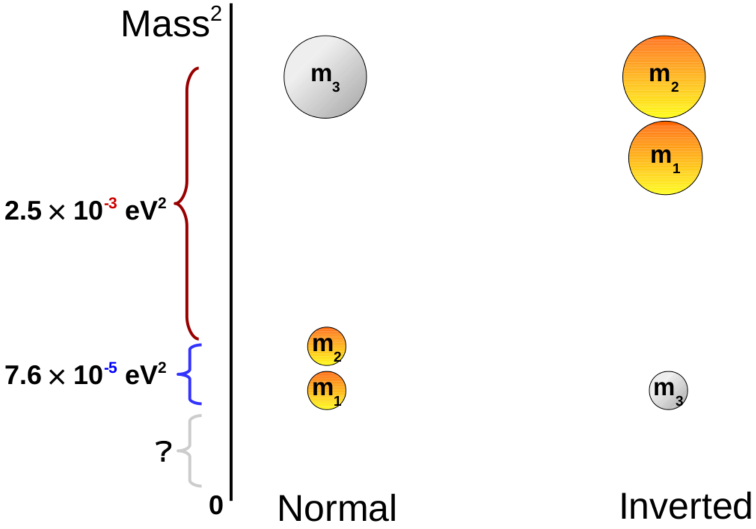
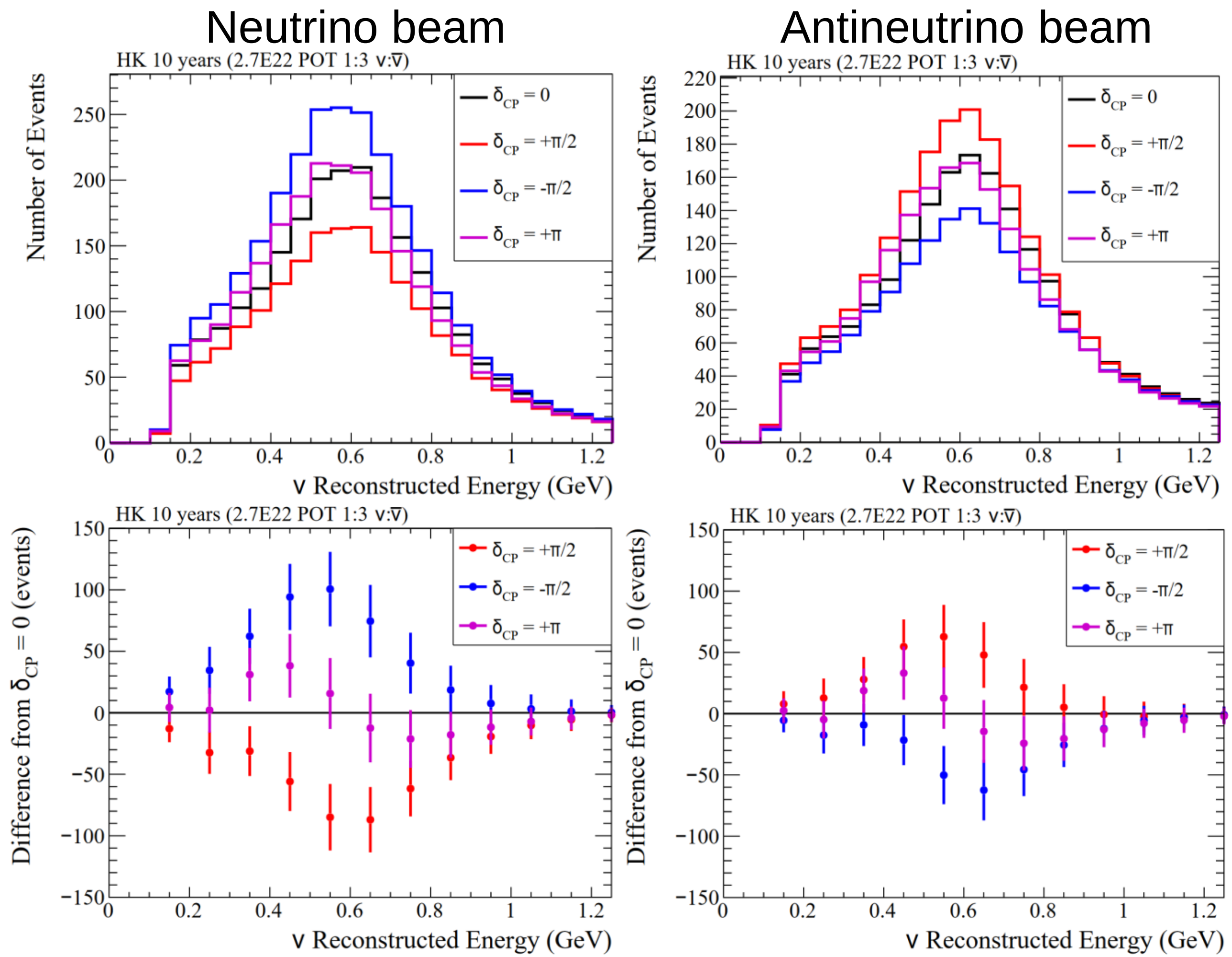
$$\boxed{\begin{array}{l} c_{ij} = \cos\theta_{ij} \\ s_{ij} = \sin\theta_{ij} \end{array}}$$

- **Is $\boldsymbol{\theta_{23}}$ above or below 45° (octant)?**
- **What is the neutrino mass ordering?**
- **Do neutrinos violate CP symmetry**?



Hyper-Kamiokande electron-like event samples

- Use Super-K MC, scaled to HK volume and exposure
- Expect approx:
  - 2300 ν_e events
  - 1900 $\bar{\nu}_e$ events
  - Assuming $\sin(\delta_{CP}) = 0$
- Difference between neutrino and antineutrino rates gives δ_{CP}

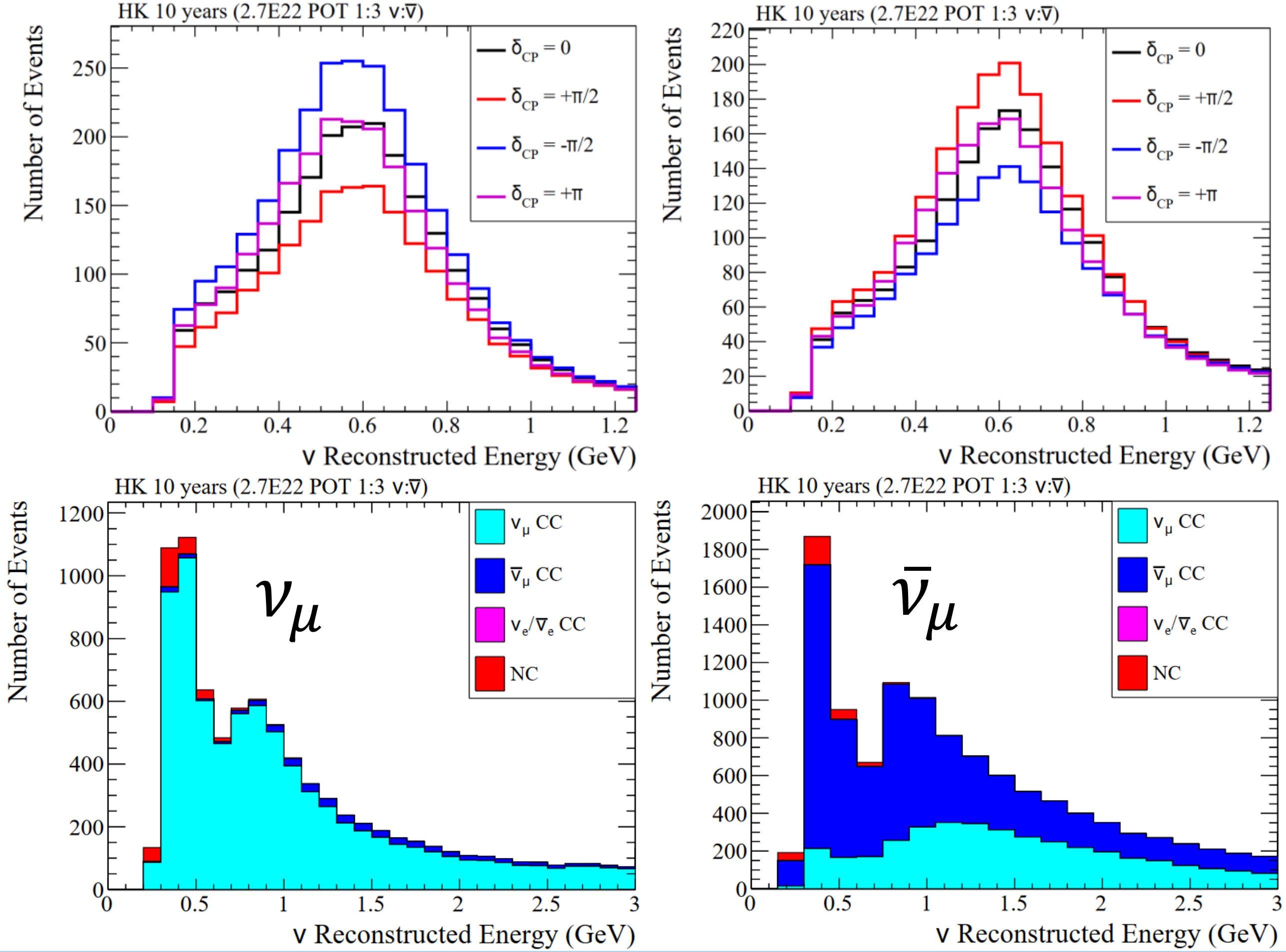


Hyper-Kamiokande electron-like event samples

- Use Super-K MC, scaled to HK volume and exposure
- Expect approx:
  - 2300 ν_e events
  - 1700 $\bar{\nu}_e$ events
  - Assuming $\sin(\delta_{CP}) = 0$
- Expect approx:
  - 9300 ν_μ events
  - 12300 $\bar{\nu}_\mu$ events

Neutrino beam

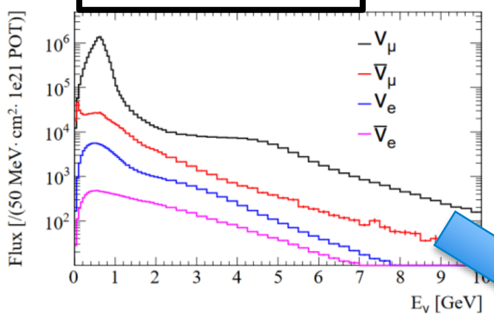
Antineutrino beam

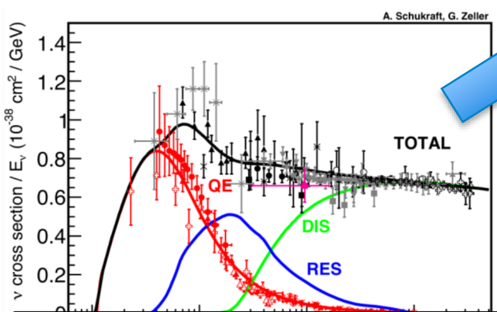


HK Oscillation Analysis

- Based on T2K analysis method

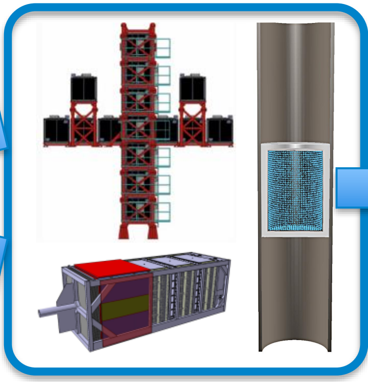
Neutrino flux



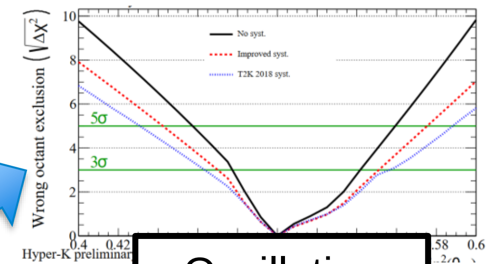


Interaction cross-section

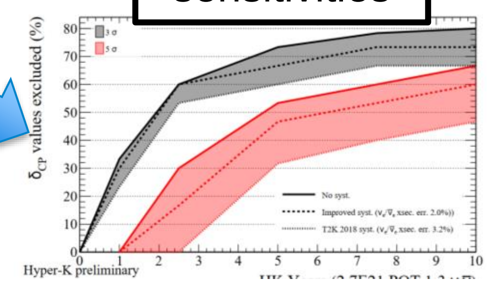
Tune models with near detectors



Fit models to far detector data

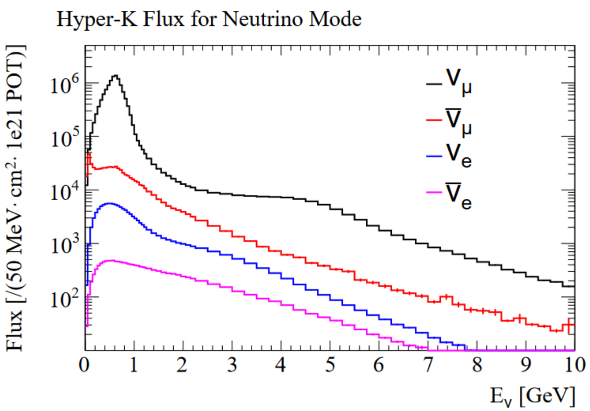


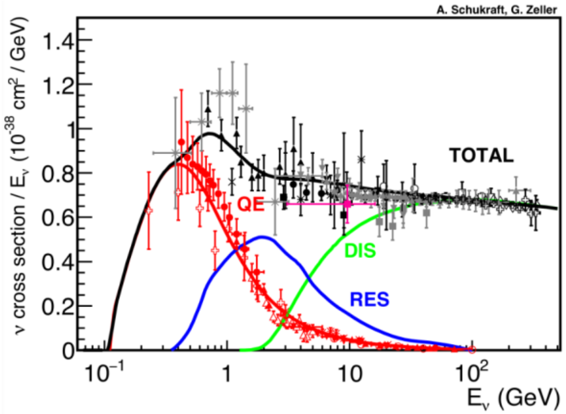
Oscillation parameter sensitivities



Systematic uncertainties

- High statistics experiment, limited by systematics





- NA61/SHINE thin-target hadron-production data
- J-PARC neutrino beamline uncertainties

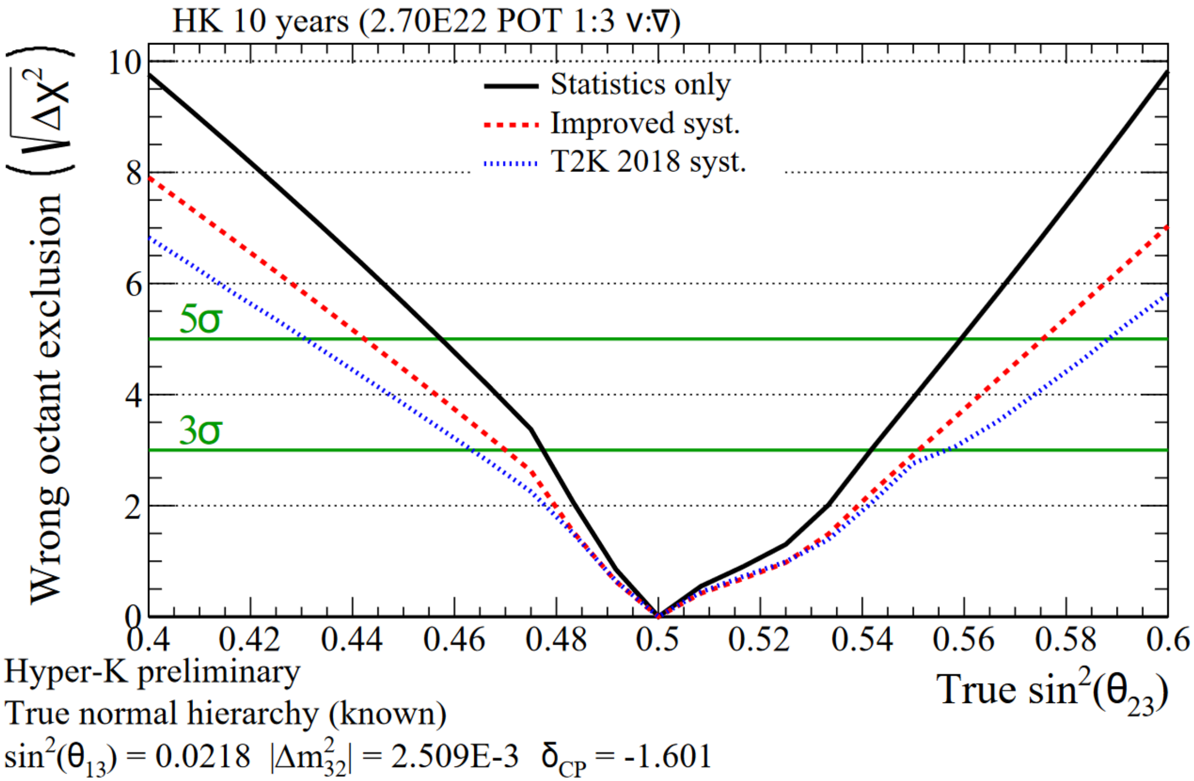
- NEUT 5.4 and T2K 2018 uncertainty model as baseline
  (*Nature* **volume 580**, pages339–344(2020))
- Nucleon removal energy uncertainty included directly

- Use T2K near detector fit to provide initial constraint on model uncertainties
- Scale uncertainties to expected Hyper-K near detector performance

Lifting the $\sin^2\theta_{23}$ degeneracy

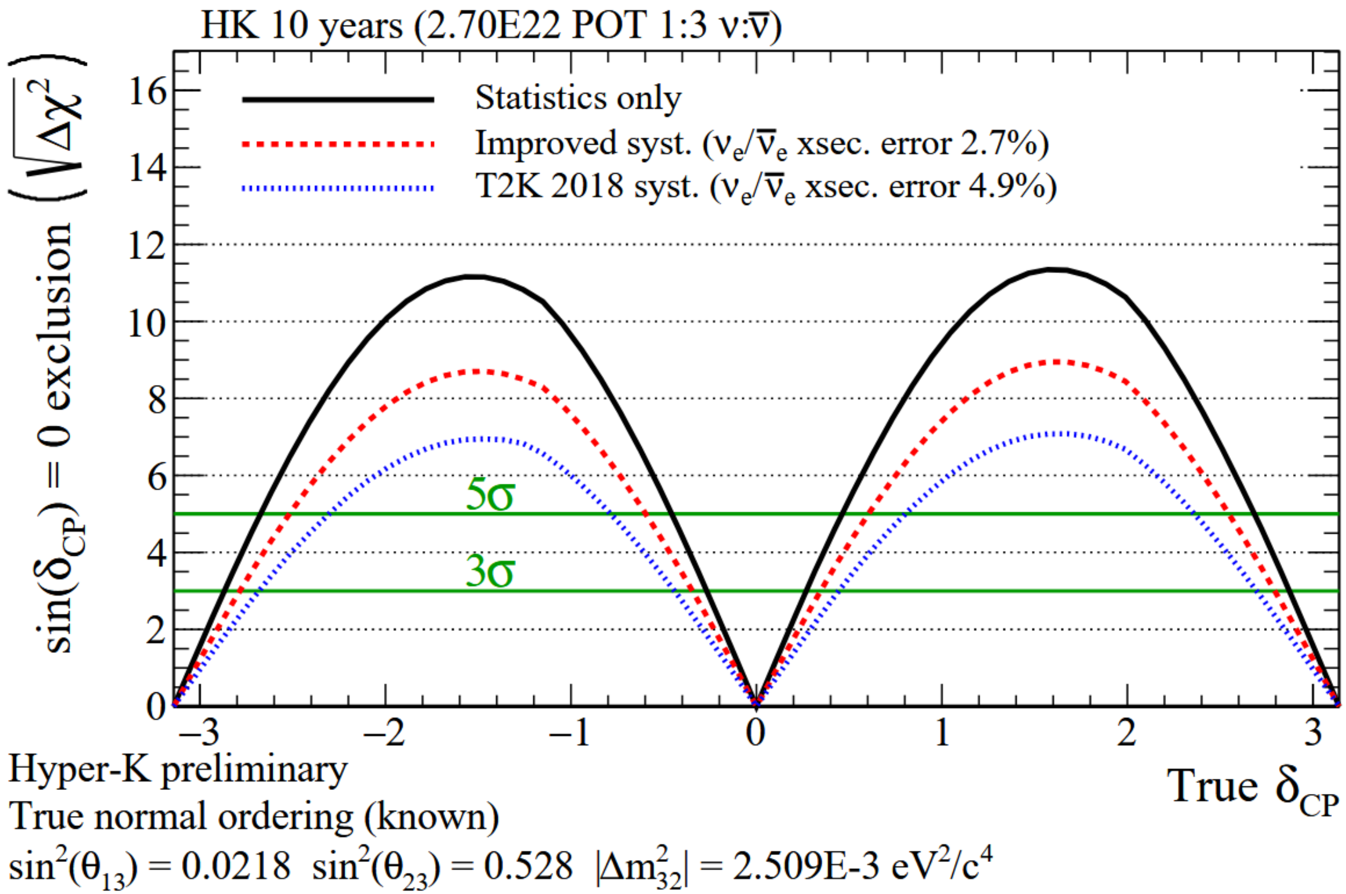
- All analyses assume 10 years of HK data
  - 1:3 ratio of neutrino beam to antineutrino beam
  - **Not** including atmospheric neutrino sample

- Wrong octant exclusion versus true value of $\sin^2\theta_{23}$
- Estimated systematic uncertainty on muon sample reduced from 4.6% to 1.9% with improved near detectors
- Achieve 3σ exclusion for:
  - $\sin^2\theta_{23} < 0.47$
  - $\sin^2\theta_{23} > 0.55$



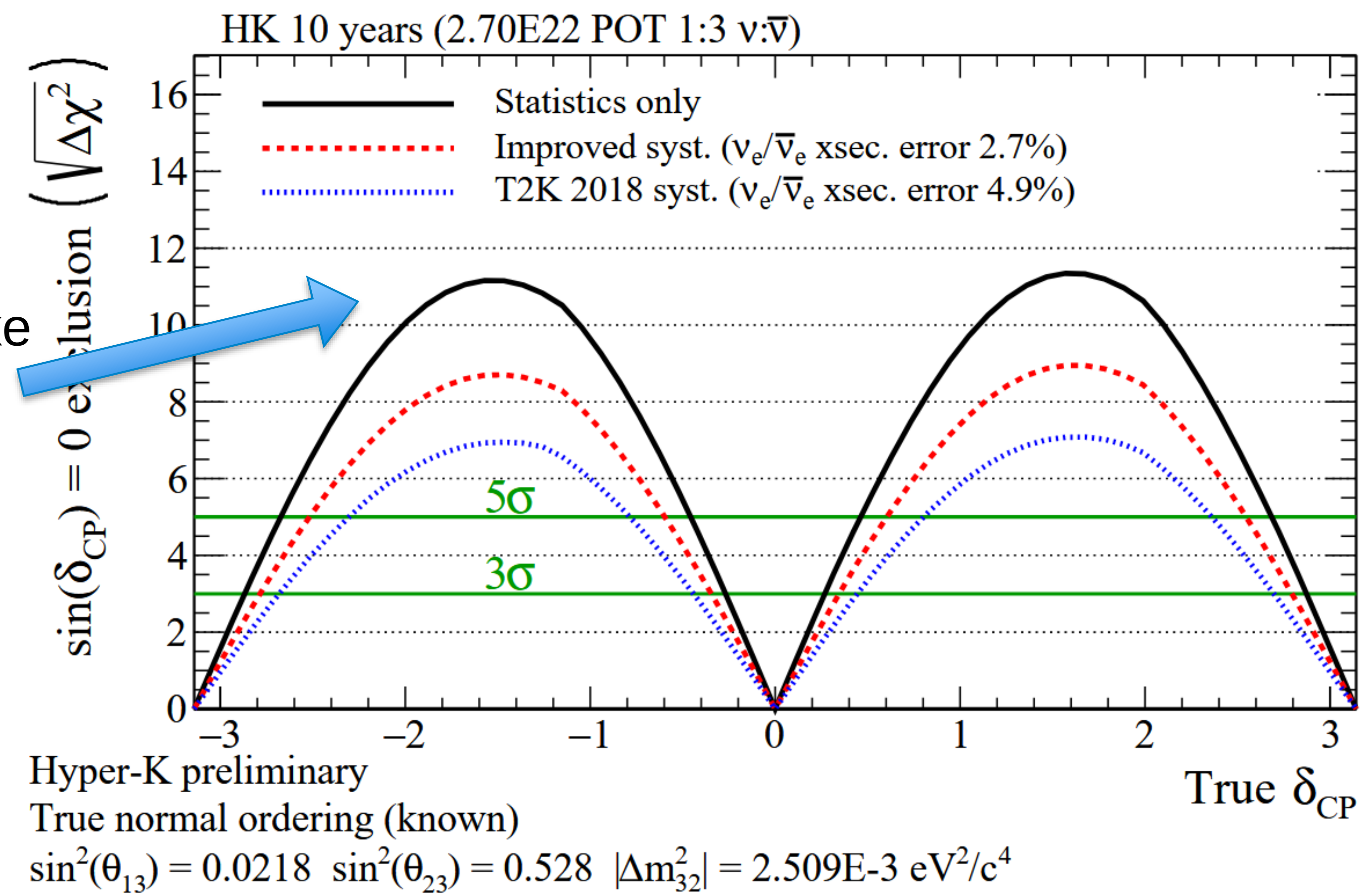
CP violation sensitivity

- Ability to exclude CP conservation versus true value of δ_{CP}



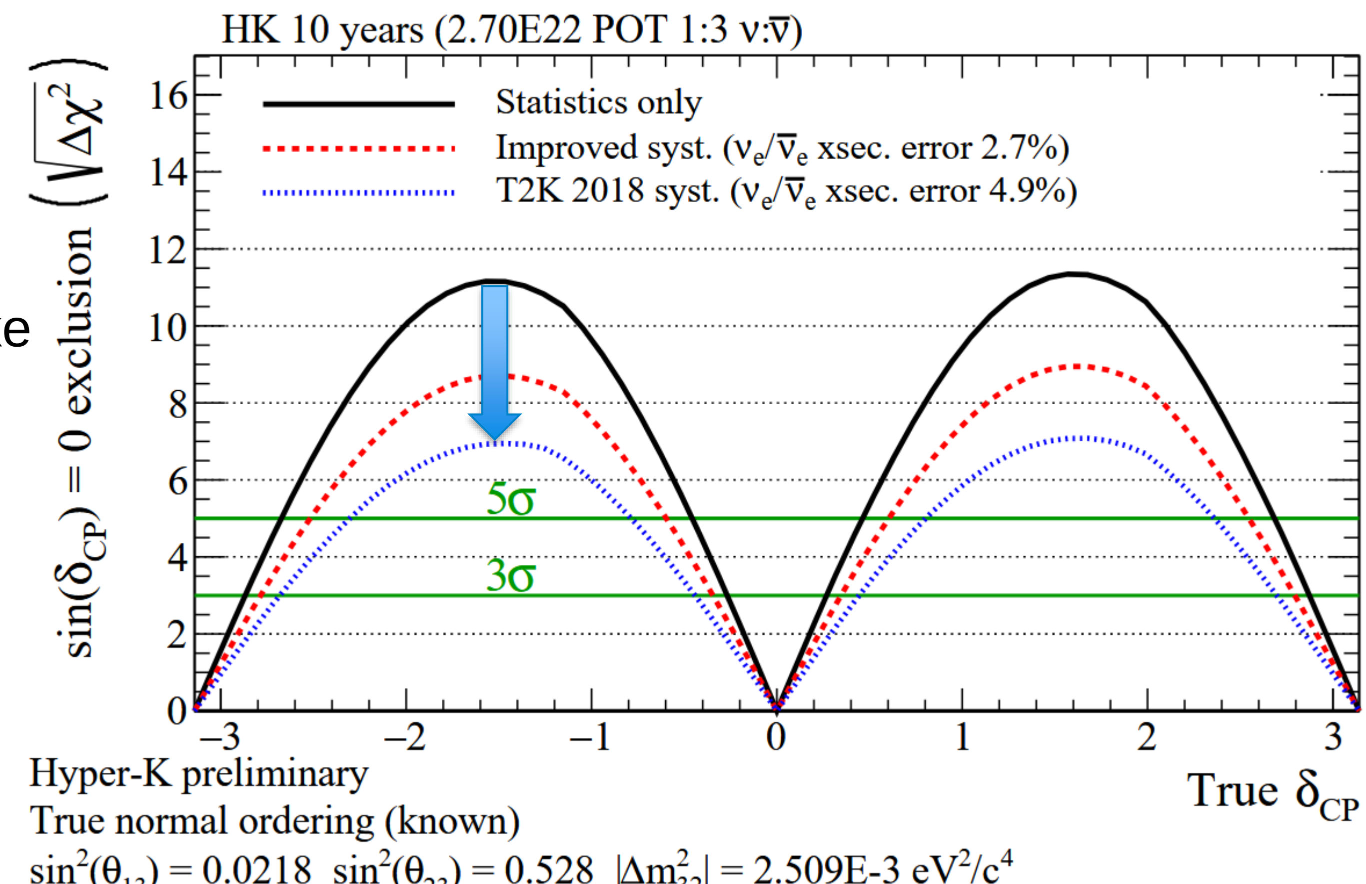
CP violation sensitivity

- Ability to exclude CP conservation versus true value of δ_{CP}
- Large electron-like samples provide high statistics



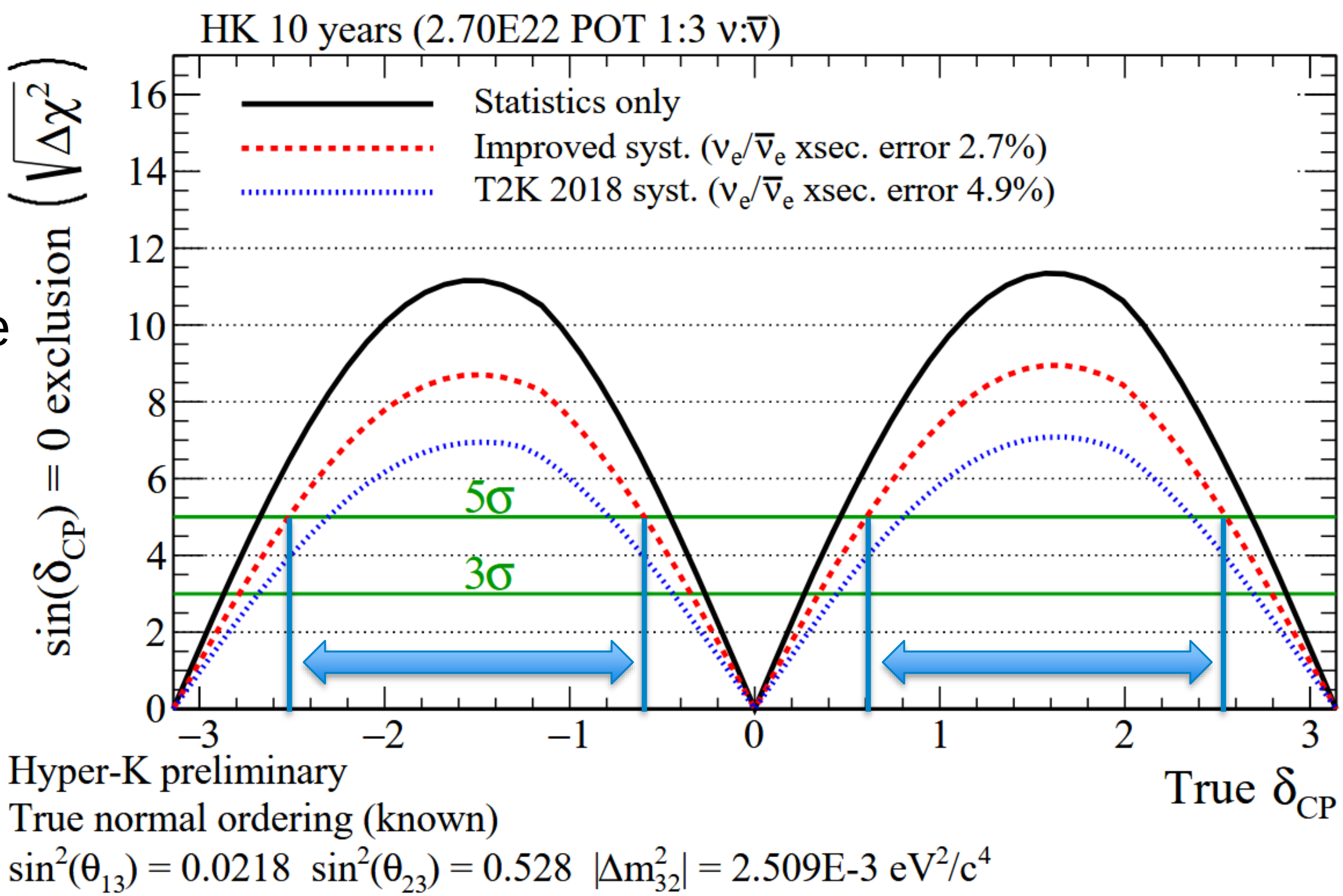
CP violation sensitivity

- Ability to exclude CP conservation versus true value of δ_{CP}
- Large electron-like samples provide high statistics
- Limited by systematics



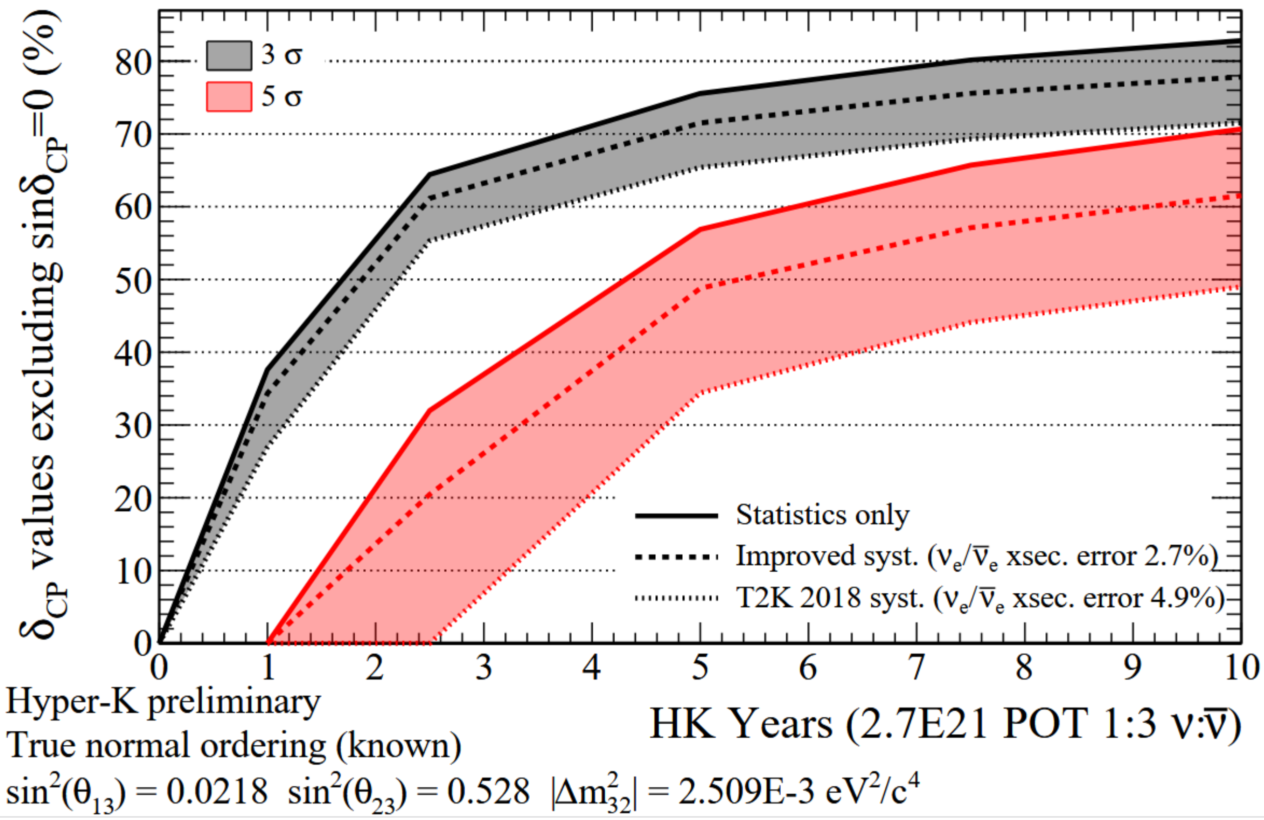
CP violation sensitivity

- Ability to exclude CP conservation versus true value of δ_{CP}
- Large electron-like samples provide high statistics
- Limited by systematics
- **Can exclude ~60% of true δ_{CP} values at 5σ**



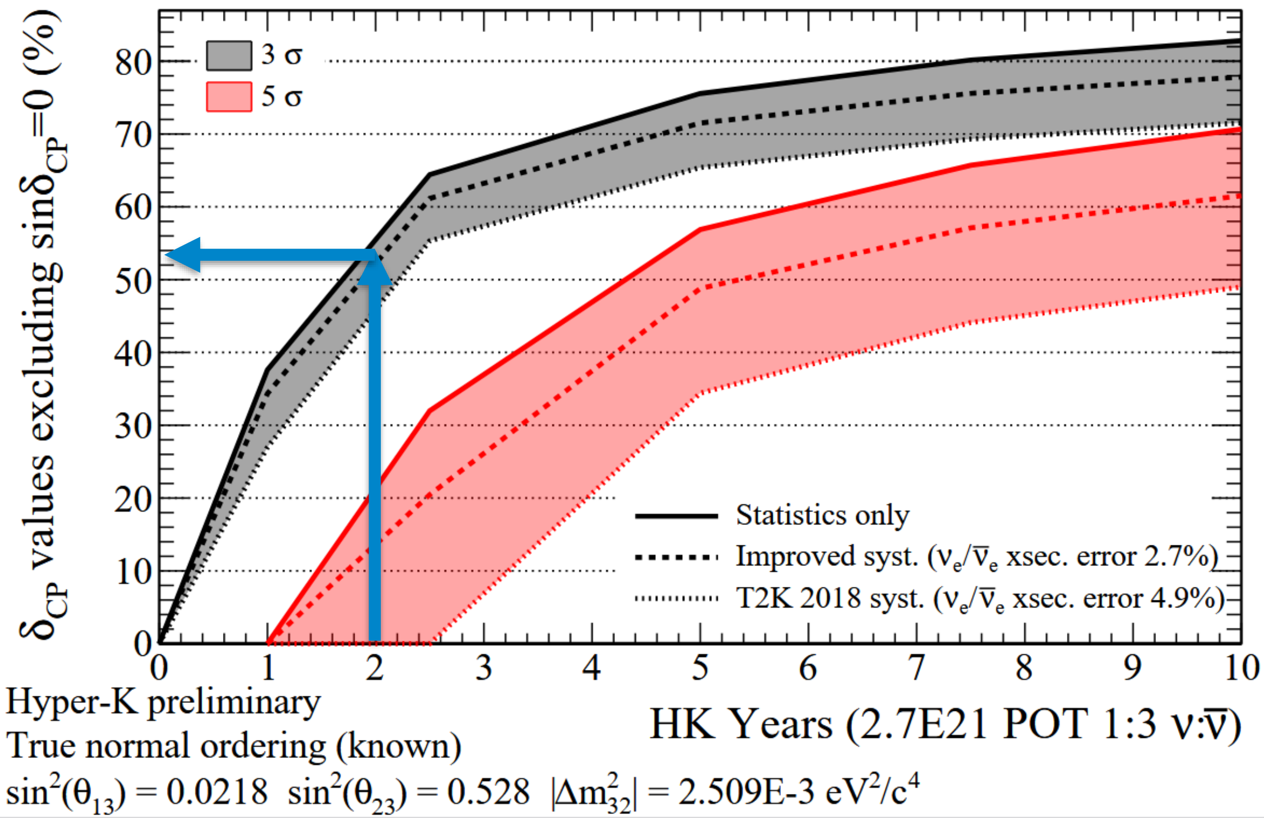
CP violation sensitivity over time

- Percentage of true δ_{CP} values where CP conservation can be excluded as a function of running year



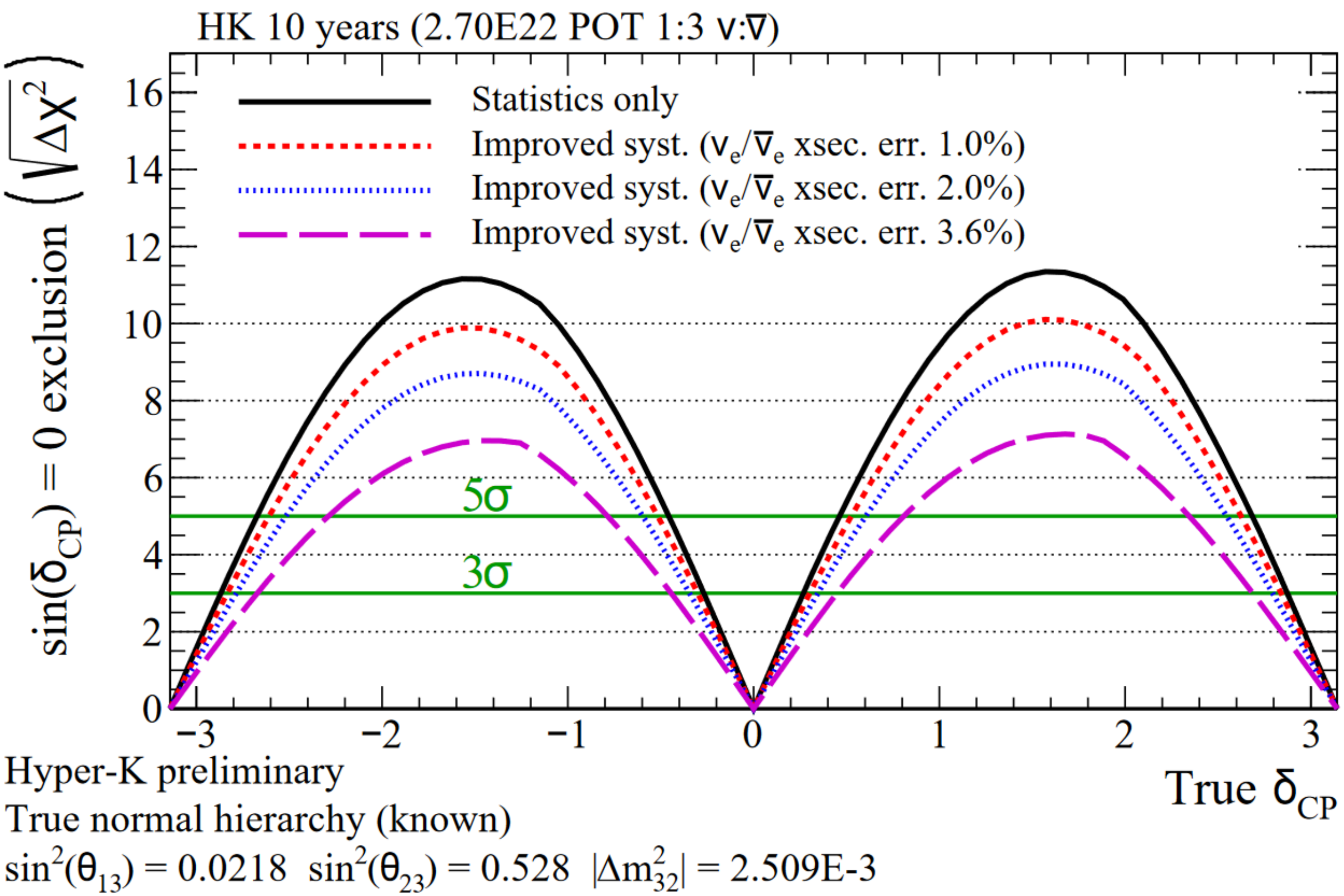
CP violation sensitivity over time

- Percentage of true δ_{CP} values where CP conservation can be excluded as a function of running year
- Can achieve 3σ CP violation result over significant regions of δ_{CP} after 2 years operation



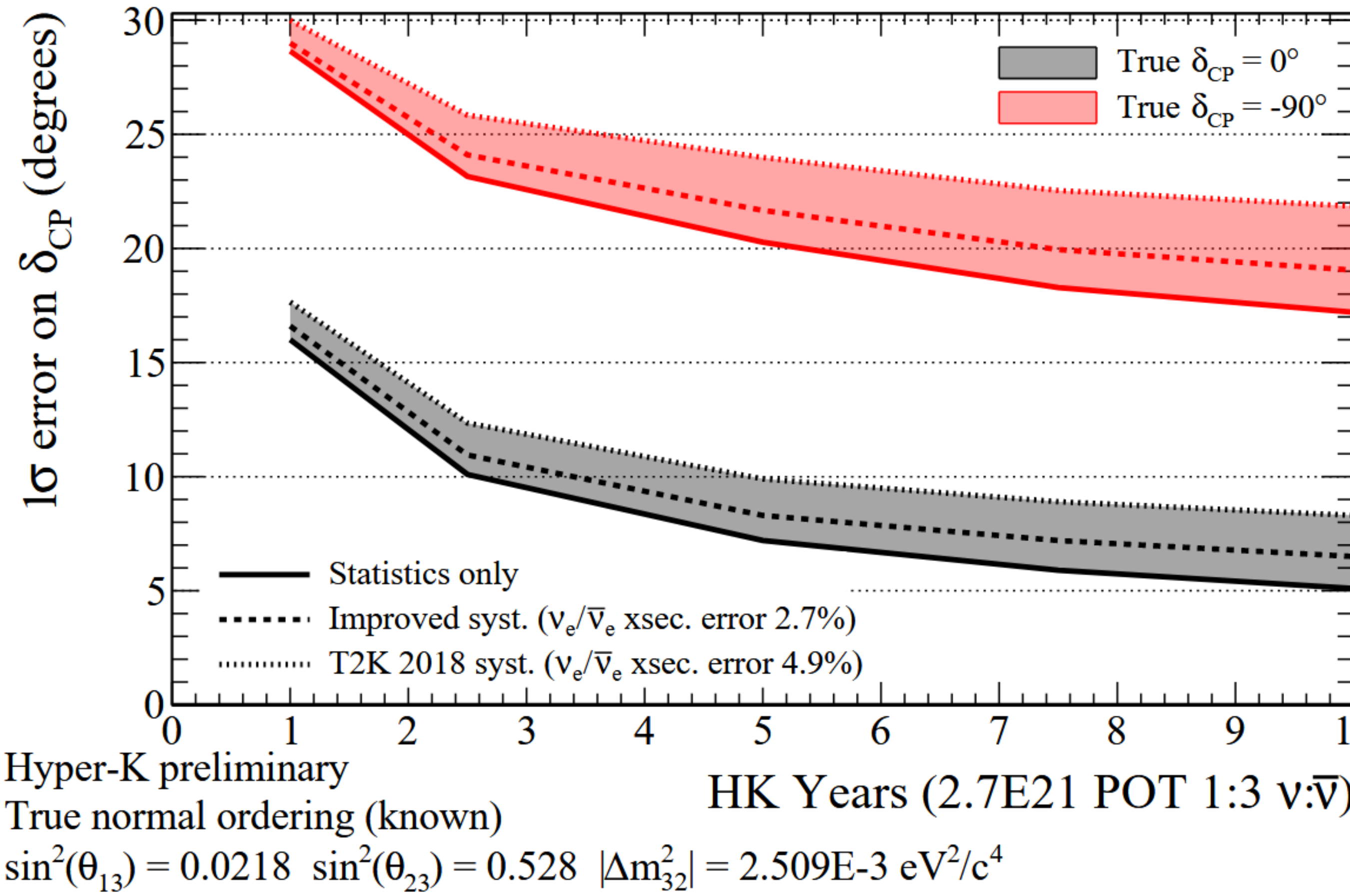
CPV and systematic uncertainties

- $(\nu_e)/(\bar{\nu}_e)$ cross-section uncertainty dominates
- Current theory uncertainty ~4.9%



Precision measurement of δ_{CP}

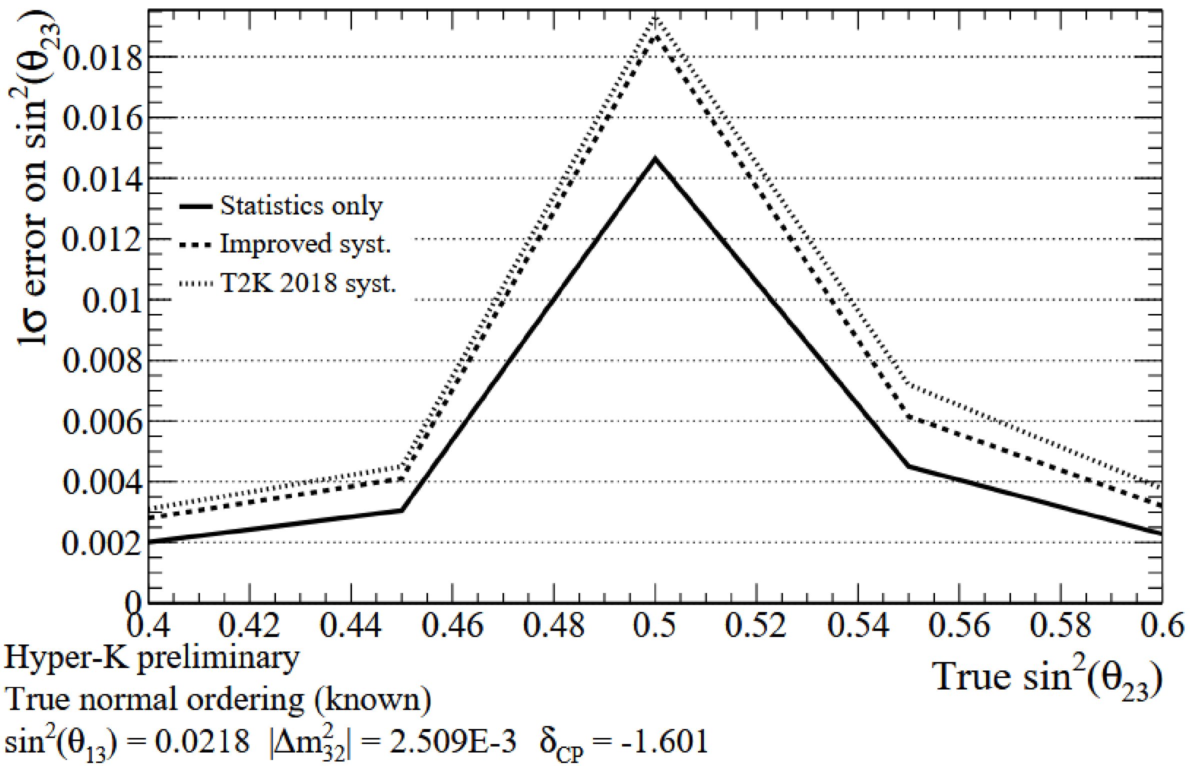
- Precision on δ_{CP} depends on true value
- Limited by ν_e spectrum shape uncertainty if **maximal CPV**
- $(\nu_e)/(\bar{\nu}_e)$ cross-section uncertainty limiting factor for **CP conservation**



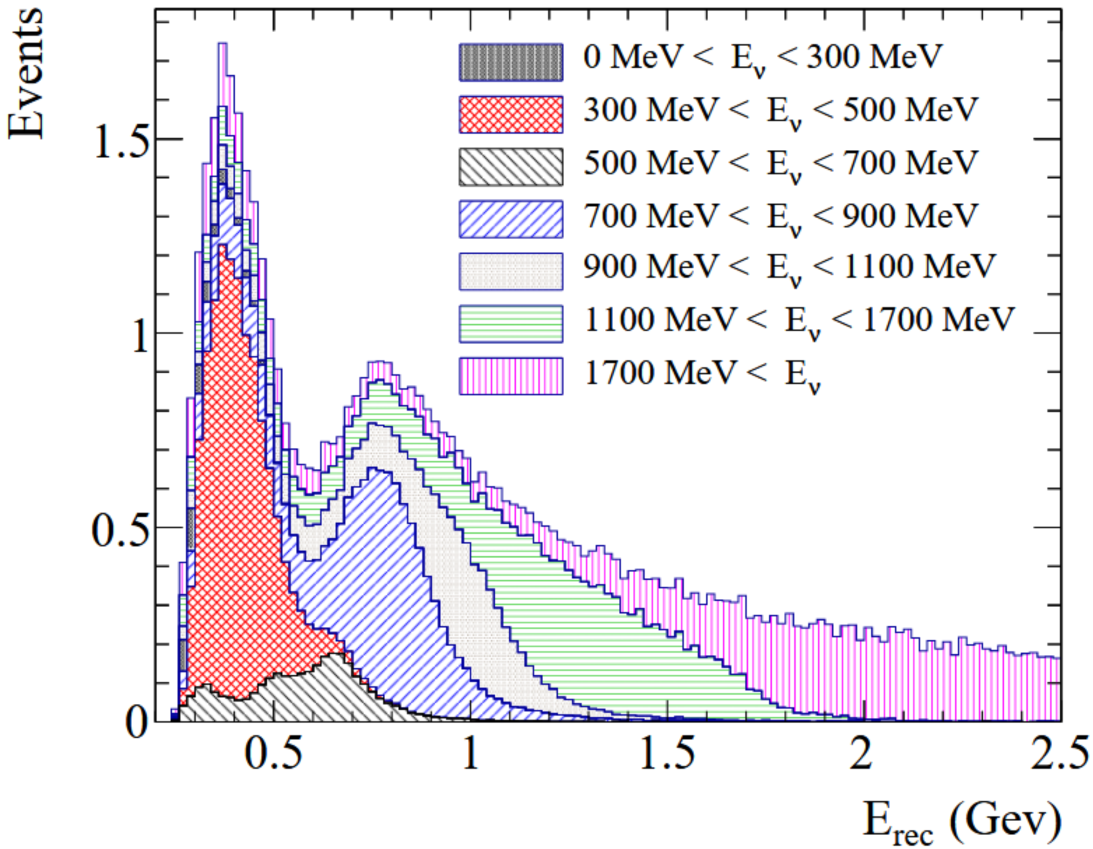
Precision for $sin^2\theta_{23}$

- Precision depends on true value
- Systematics limited result

- Can achieve 3.6% uncertainty at $\sin^2\theta_{23} = 0.5$
- Better than 1% uncertainty for $\sin^2\theta_{23} < 0.45$ and $\sin^2\theta_{23} > 0.55$



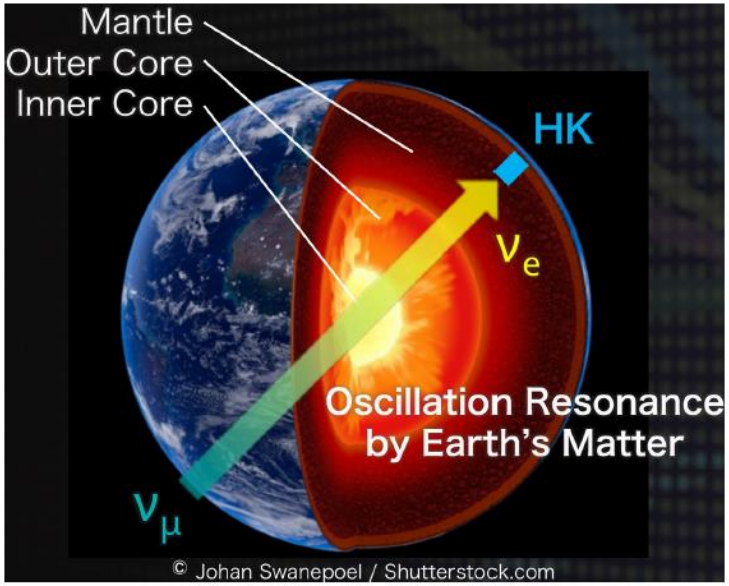
Event “feed-down”

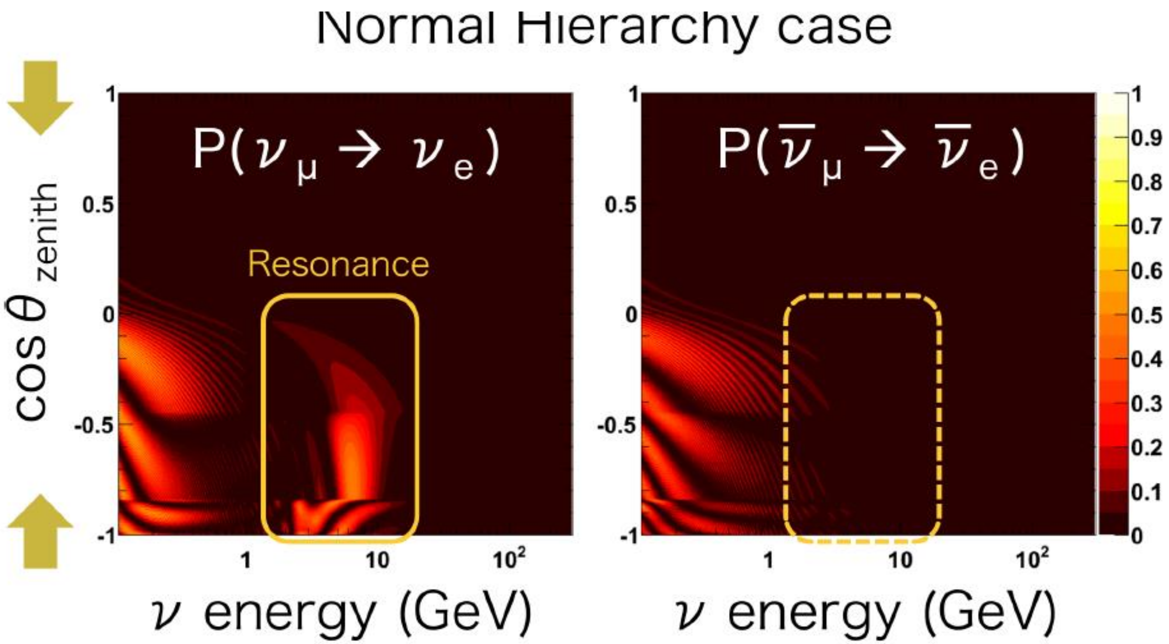


- Reconstructed neutrino energy under-estimates true neutrino energy
  - WC threshold
  - Neutrons in LAr
- Events at higher true energies appear as lower energy (blue – purple histograms on left)
- Can bias or introduce error to oscillation measurements

Atmospheric neutrinos

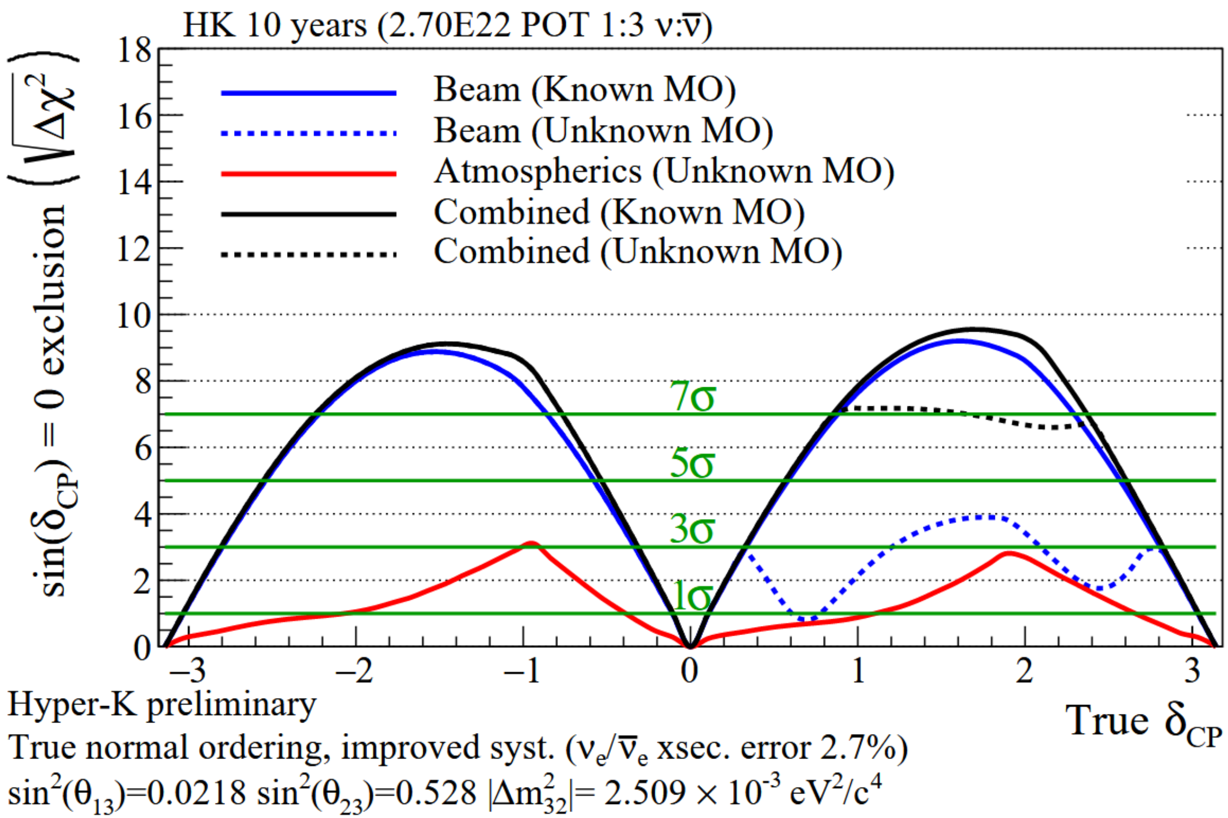
- Atmospheric neutrinos have longer baseline and higher energies – gives sensitivity to neutrino mass ordering
- Mass hierarchy determined with upward-going multi-GeV ν_e sample: atm. baseline ≤ 13000 km ≫ 295 km accelerator baseline





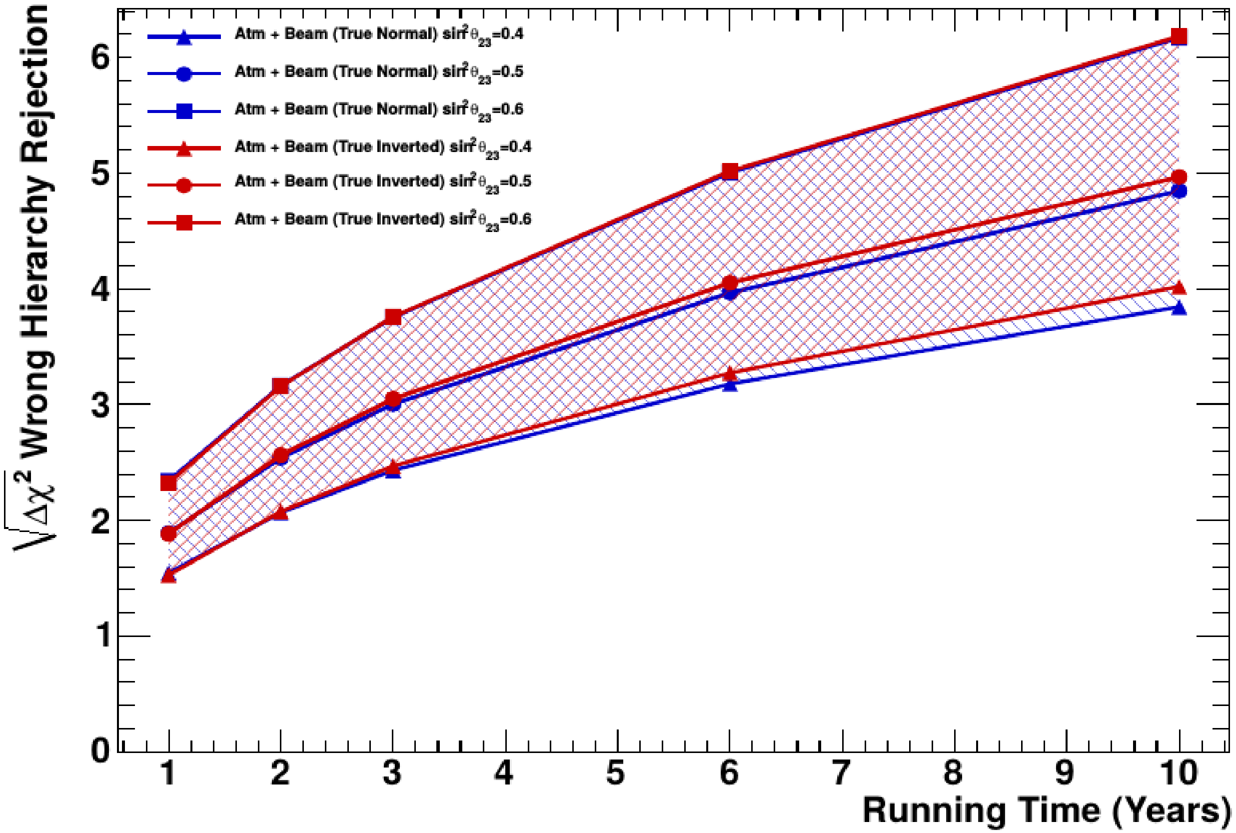
Atmospheric neutrinos and CPV

- If MO unknown, beam analysis less sensitive for some values of δ_{CP}
- Joint **atmospheric and beam analysis** restores sensitivity above 5σ
- Slight improvement in region of δ_{CP} space that can be excluded at 5σ



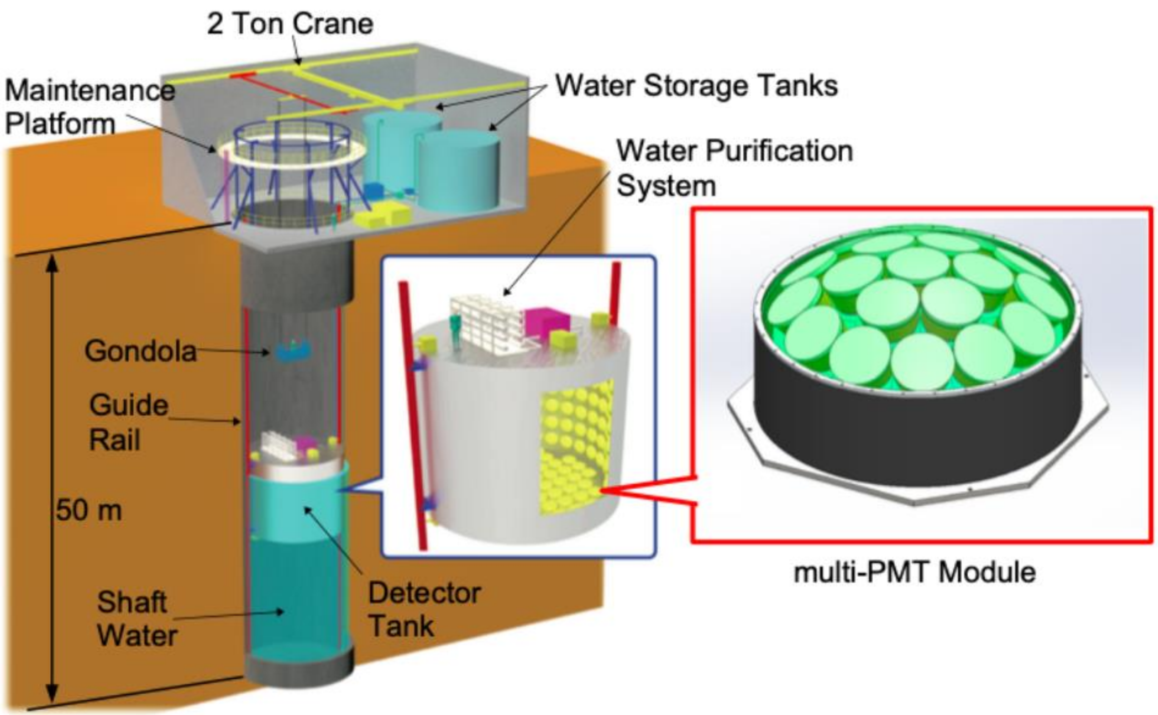
Mass hierarchy determination

- Can exclude incorrect mass ordering at $4 - 6\sigma$ significance (depending on value of $\sin^2\theta_{23}$)



Intermediate Water Cherenkov Detector (IWCD)

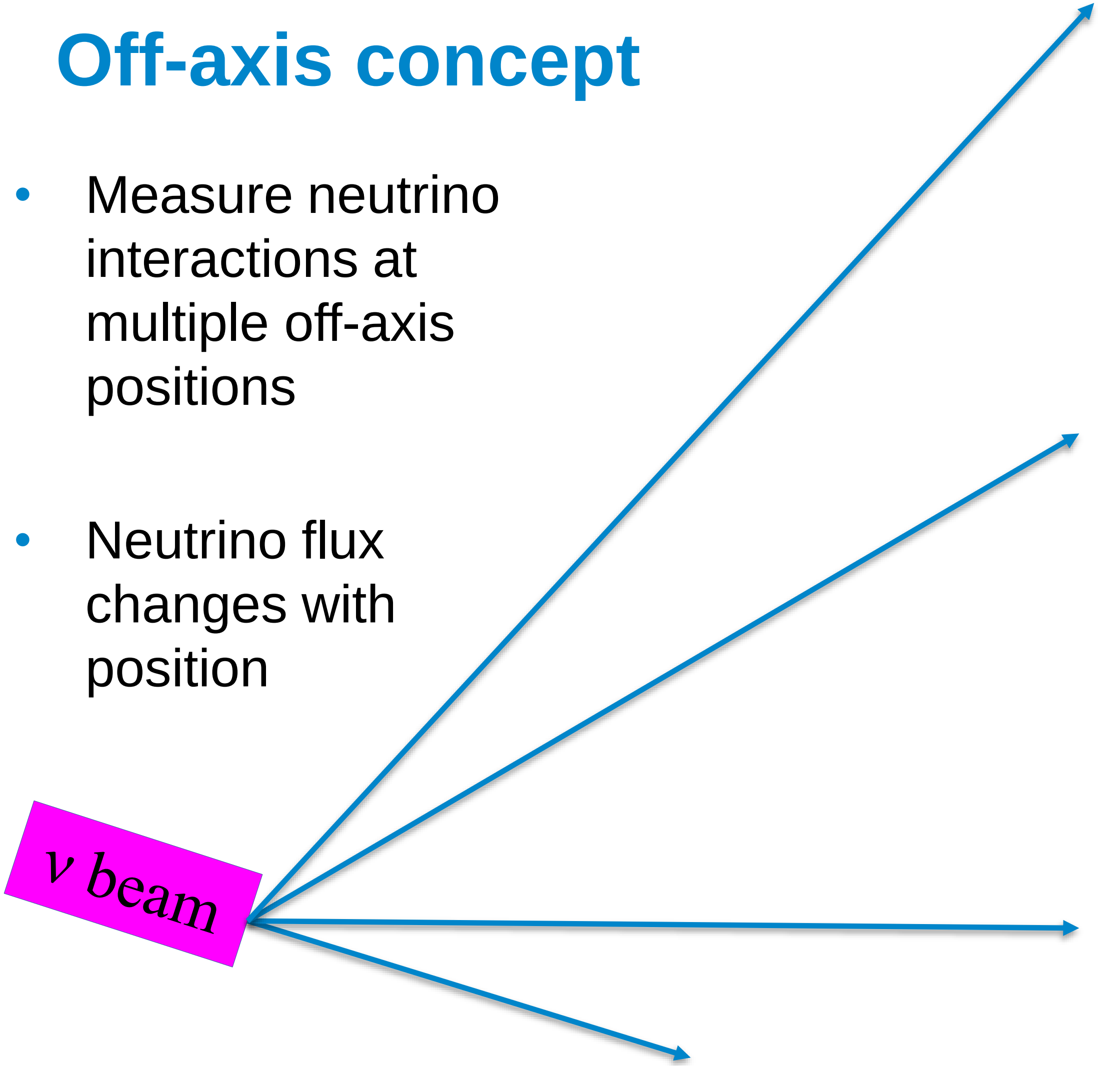
- Approx. 300-tonne water Cherenkov detector located ~1km from beam production point
- Movable to different off-axis angles

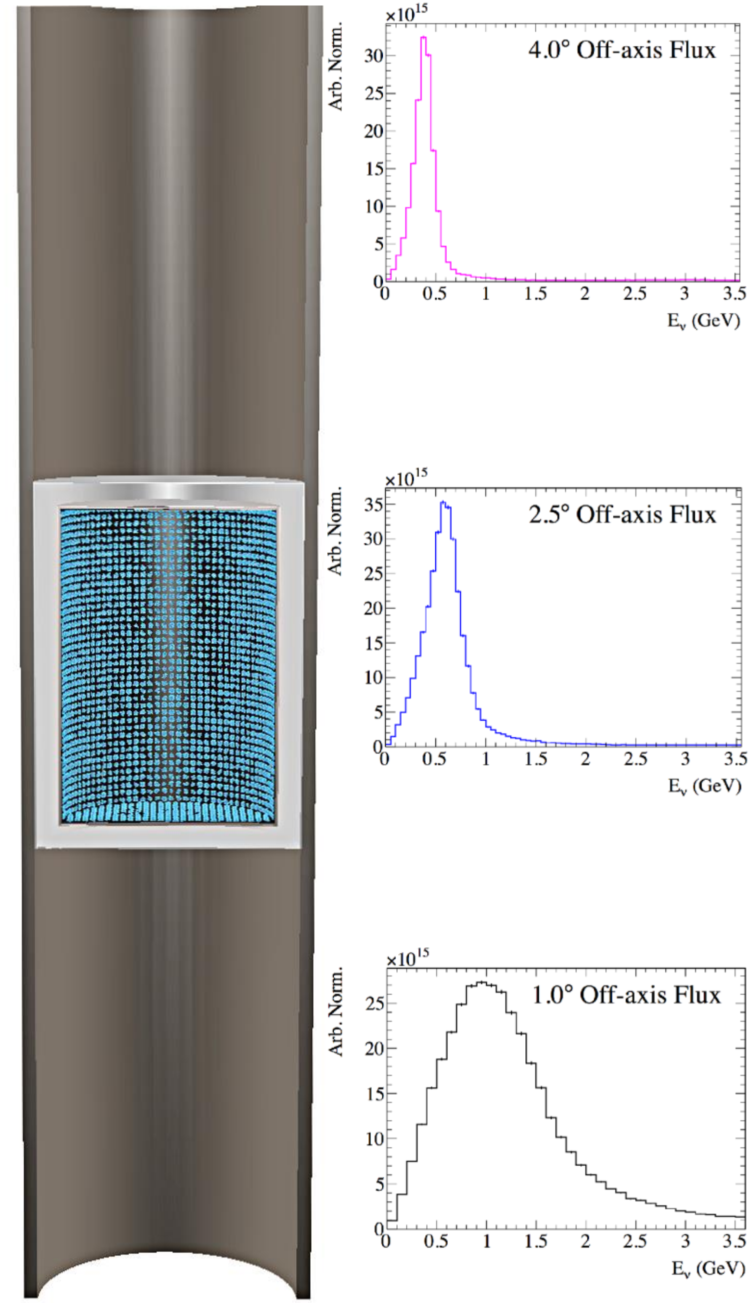


Imperial College London

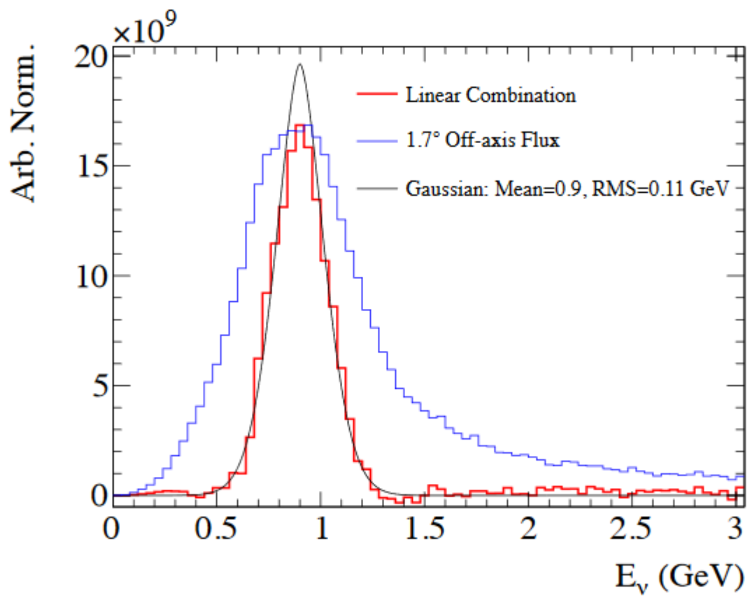
Off-axis concept

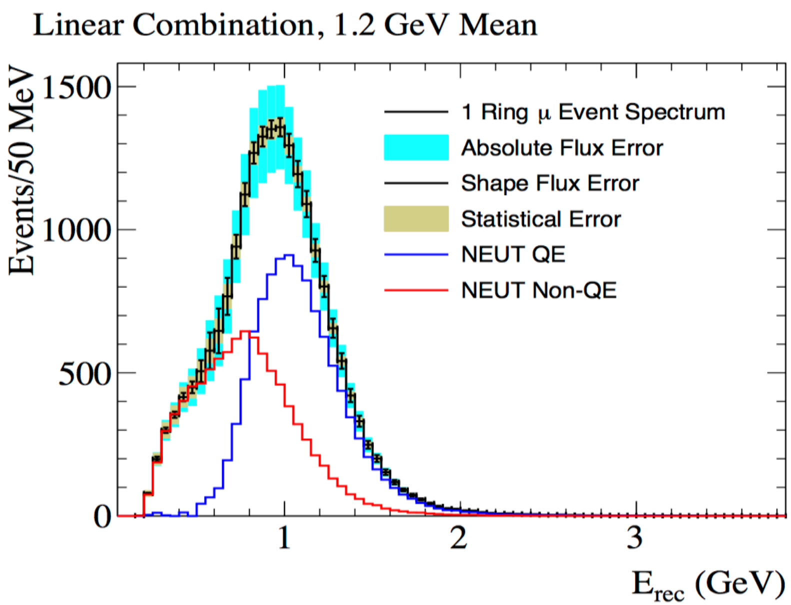
- Measure neutrino interactions at multiple off-axis positions
- Neutrino flux changes with position





IWCD Physics





- Can combine different off-axis positions to create new flux shapes – Gaussian on left
  - Look at reconstructed energy to directly measure feed-down
- Will also have large electron neutrino sample – constrain $(\nu_e)/(\bar{\nu}_e)$ to < 4%

Summary

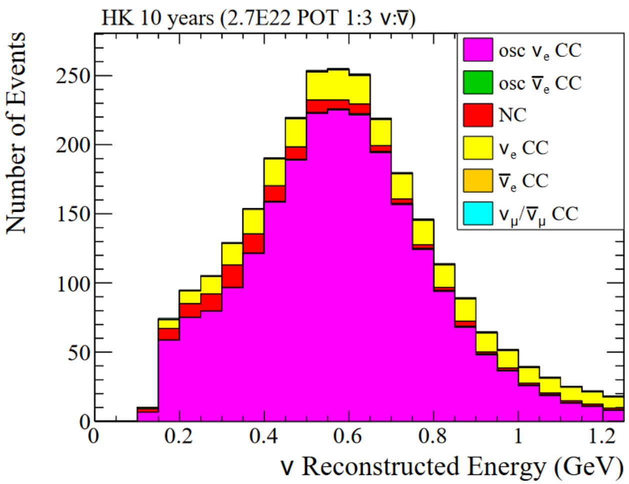
- After 10 years data taking Hyper-Kamiokande will:
  - Exclude CP conservation at 5σ for 60% of δ_{CP} parameter space
  - Reach $4 - 6\sigma$ exclusion of the wrong mass ordering
  - Achieve 3σ exclusion of wrong octant for $\sin^2\theta_{23} < 0.47$ and $\sin^2\theta_{23} > 0.55$
  - Achieve between 19° - 7° precision on δ_{CP}
  - Achieve 3.6% precision or better on $\sin^2\theta_{23}$

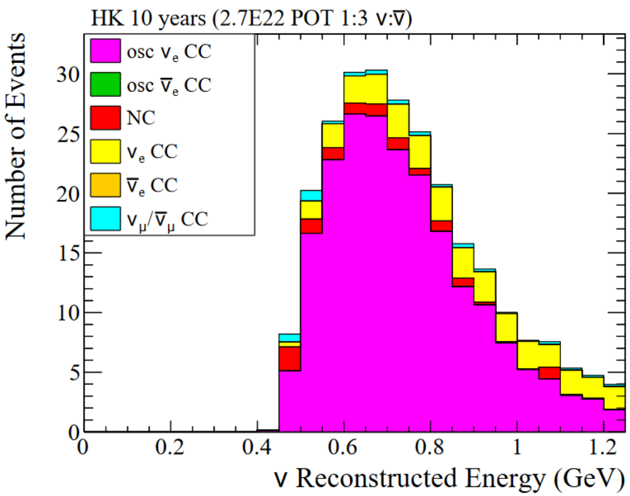
- Large statistics for long-baseline and atmospheric neutrinos
  - Understanding systematics and reducing them is key challenge
  - $(\nu_e)/(\bar{\nu}_e)$ uncertainty and "feed-down" of high energy events are significant challenges
  - Reducing uncertainties in neutrino flux prediction and detector performance also necessary

Supplementary slides

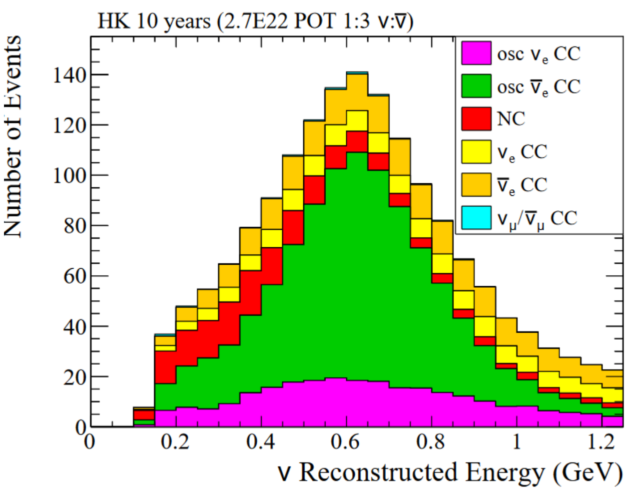
Hyper-Kamiokande electron-like sample breakdown

Neutrino beam





Antineutrino beam



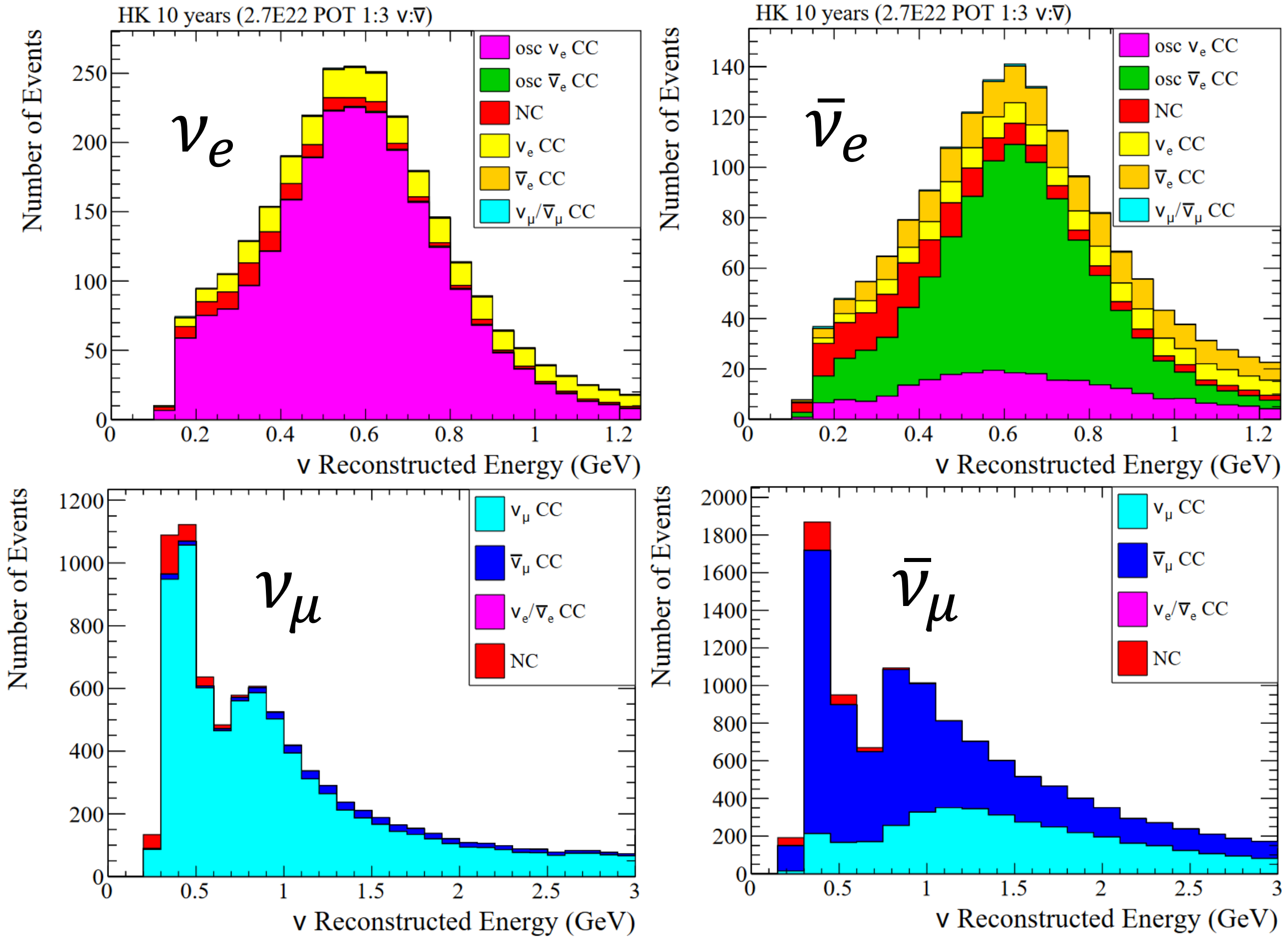
- A sample of CC-1π events is included from the neutrino beam data
- The sample selects single-ring, electron-like events with the presence of a Michel electron tagging a pion below Cherenkov threshold
- The energy of this sample is calculated assuming a Δ_{1232} resonance

Hyper-Kamiokande sample breakdown

- Antineutrino beam:
  - Larger “wrong-sign” component
  - Larger neutral current component due to increased exposure
- Expect approx:
  - 9300 ν_μ events
  - 12300 $\bar{\nu}_\mu$ events

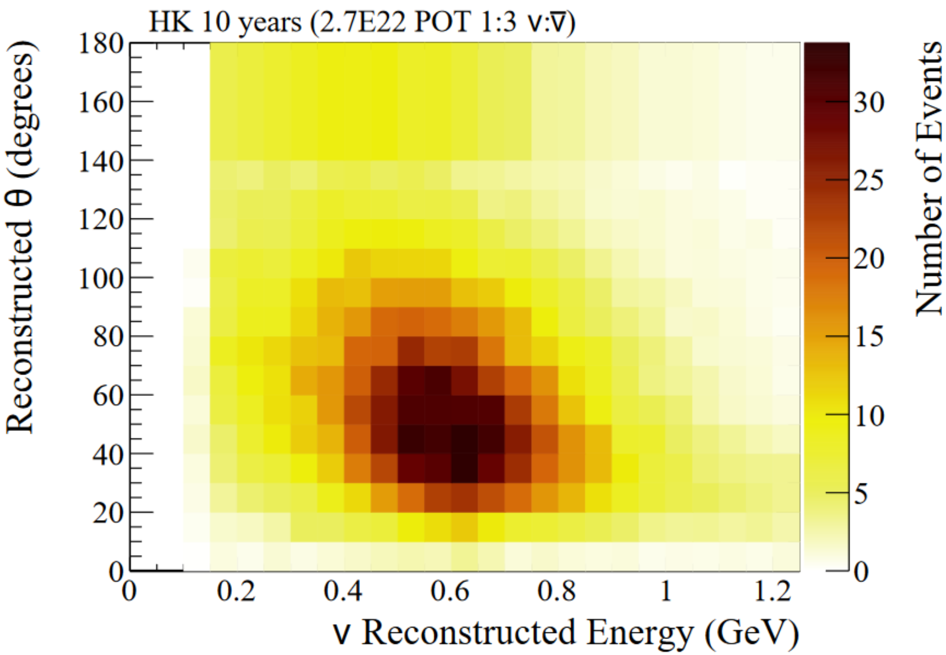
Neutrino beam

Antineutrino beam



Oscillation analysis fit

- Simultaneous likelihood fit of electron-like and muon-like samples at HK
- Profile systematics and oscillation parameters
- Fit electron-like samples in 2D (reconstructed energy vs lepton angle relative to the beam)
- Muon-like samples fit in 1D as function of reconstructed neutrino energy (assuming CCQE kinematics)
- Include flux and cross-section uncertainties using T2K 2018 near detector fit results
- Far detector uncertainties based on 2018 Super-K systematics



Scaled HK systematics

- Scale 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 the ND280 Upgrade group (see talk #392 by D. Sgalaberna) and the HK Intermediate Water Cherenkov Detector were 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 ~10% level
- The electron neutrino / electron antineutrino cross-section ratio error was varied from ~3.6% to 1% to assess its impact
- No parameter was allowed to have an uncertainty of less than 1%

Uncertainty on event samples

- T2K 2018 uncertainties on the HK event samples

	1-ring μ-like		1-ring e-like			
Error source	ν-mode	$\bar{\nu}$-mode	ν-mode 0 d.e.	$\bar{\nu}$-mode 0 d.e.	ν-mode 1 d.e.	ν-mode/$\bar{\nu}$-mode 0 d.e.
Cross section	4.77%	4.02%	5.61%	5.09%	5.05%	4.24%
Flux	4.28%	4.12%	4.38%	4.26%	4.46%	2.07%
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%

Table 6: Percentage error on event rate by error source and sample, for the T2K-2018 syst error model.

- Scaled HK uncertainties, with a 3.6% error on the electron neutrino/antineutrino cross-section

	1-ring μ-like		1-ring e-like			
Error source	ν-mode	$\bar{\nu}$-mode	ν-mode 0 d.e.	$\bar{\nu}$-mode 0 d.e.	ν-mode 1 d.e.	ν-mode/$\bar{\nu}$-mode 0 d.e.
Cross section	0.92%	0.77%	3.43%	2.62%	3.43%	3.72%
Flux	0.85%	0.80%	0.87%	0.83%	0.89%	0.51%
Flux + xsec	0.82%	0.72%	3.44%	2.62%	3.51%	3.76%
Detector+FSI	1.69%	1.59%	1.54%	1.72%	5.22%	0.95%
All syst	1.88%	1.74%	3.75%	3.12%	6.24%	3.88%

Table 8: Percentage error on event rate by error source and sample, for the HK 3.6% error model.

Event number variations with δ_{CP}

	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$
ν-mode beam 1-ring μ-like	9349.30	9335.51	9348.29	9365.49
$\bar{\nu}$-mode beam 1-ring μ-like	12375.02	12344.43	12375.21	12408.46
ν-mode beam 1-ring e-like + 0 decay e	2739.76	2285.17	1845.99	2300.57
$\bar{\nu}$-mode beam 1-ring e-like + 0 decay e	1623.97	1883.40	2117.98	1858.56
ν-mode beam 1-ring e-like + 1 decay e	257.63	223.18	179.45	213.91

Parameter(s)	AsimovA-2020
$\sin^2\theta_{23}$	0.528
$\sin^2\theta_{13}$	0.0218±0.0007
$\sin^2\theta_{12}$	0.307
$\lvert\Delta m^2_{32}\rvert$ (NH) / $\lvert\Delta m^2_{13}\rvert$ (IH)	2.509×10^{-3} eV^2/c^4
Δm^2_{21}	7.53×10^{-5} eV^2/c^4
δ_{CP}	-1.601
Mass Hierarchy	Normal

CPV sensitivity over time