Oscillation physics with Hyper-Kamiokande

Zhenxiong Xie

On behalf of Hyper-Kamiokande collaboration

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KING'S College LONDON

Hyper-Kamiokande

NOW 2022

Neutrino Oscillation Workshop

Rosa Marina (Ostuni, Italy)

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Outline

- Hyper-Kamiokande (HK)
  - HK Detector
  - Collaboration
  - Upgrade
  - Physics
- HK Long-Baseline Program
  - Sensitivity to CP Violation
  - Precision Measurements
- Proton Decay, Supernova Neutrinos

Akimoto, Yuki @ higgstan

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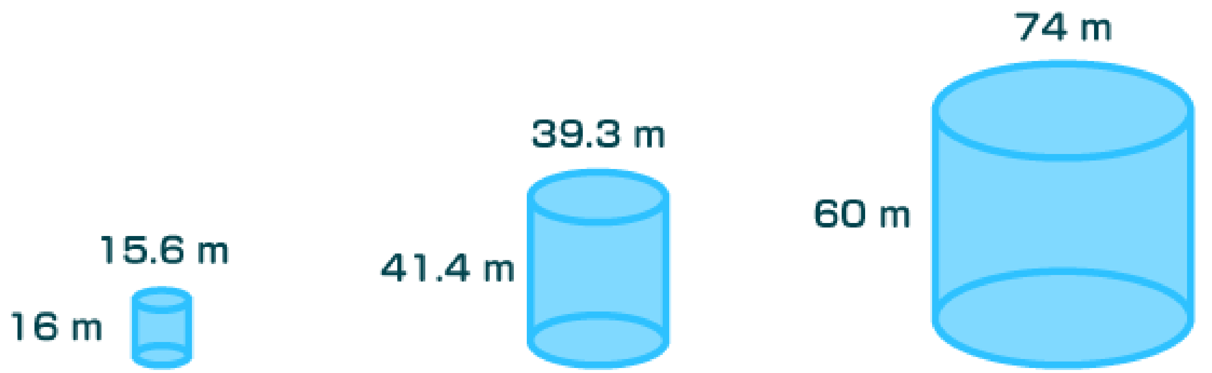
Hyper-Kamiokande

Kamiokande	Super-Kamiokande (SK)*	Hyper-Kamiokande (HK)
1983 - 1996	1996 -	2027 -



3,000 ton	50,000 ton	260,000 ton

- Next-generation neutrino experiment
- **8 times** fiducial volume of Super-Kamiokande (SK) water Cherenkov detector
- Aim to start taking data from 2027

* SK talk at 10:50 on 5th Sept - Yasuo Takeuchi
T2K talk at 9:50 on 5th Sept - Lukas Berns

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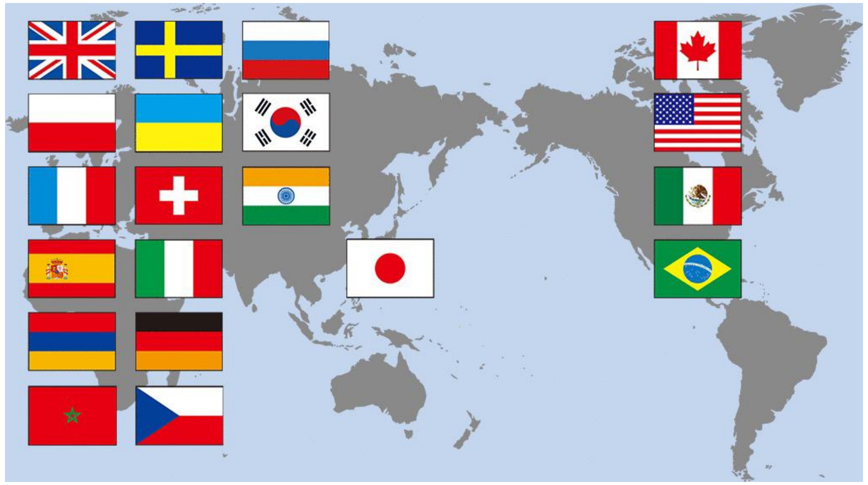
HK Collaboration



~520 members from 20 countries and ~100 institutes

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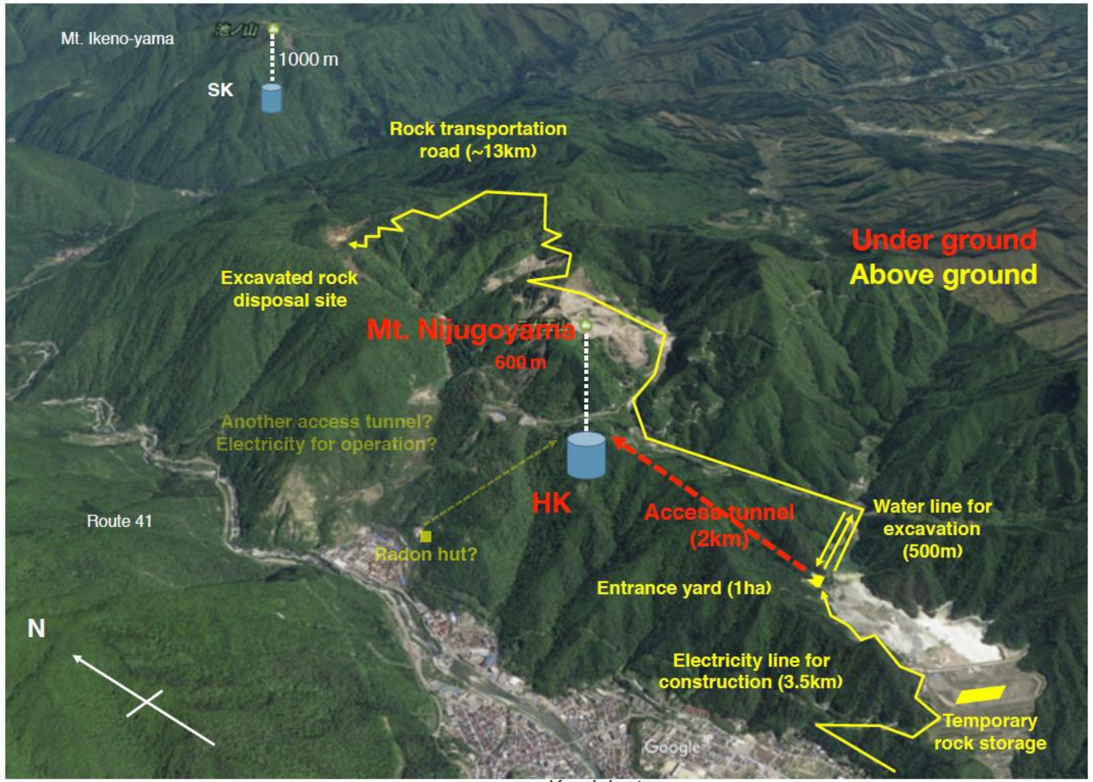
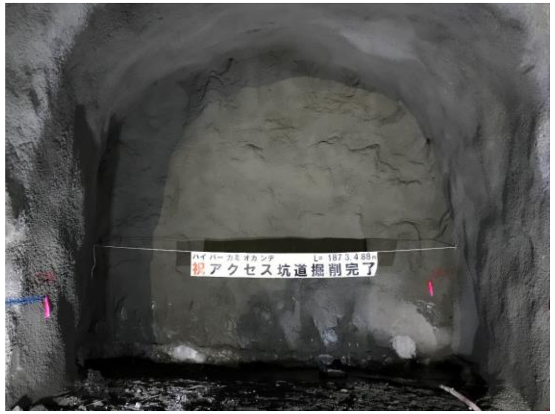
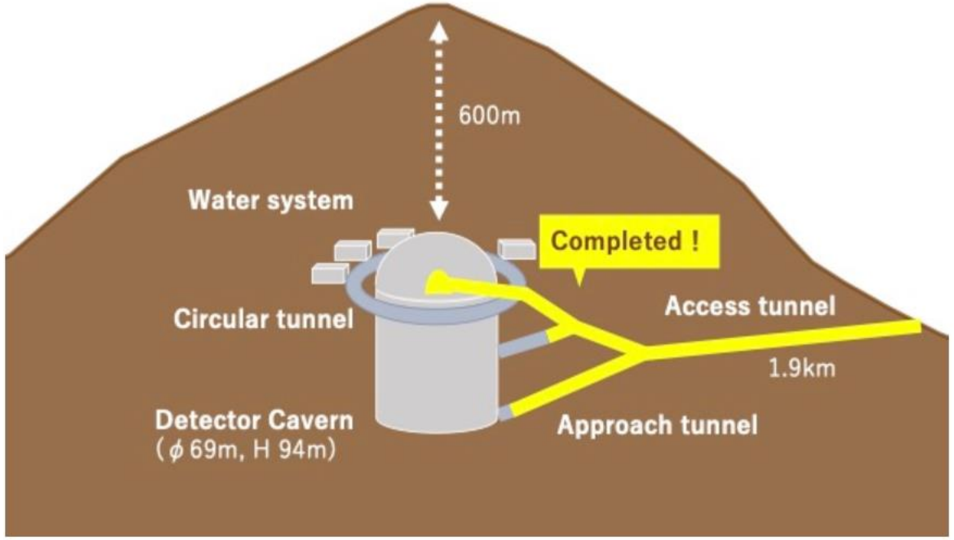
Cavern Excavation

Overview of the HK construction



Kamioka town





Access tunnel excavation has been finished as scheduled
Approach tunnel and circular tunnel excavation is ongoing

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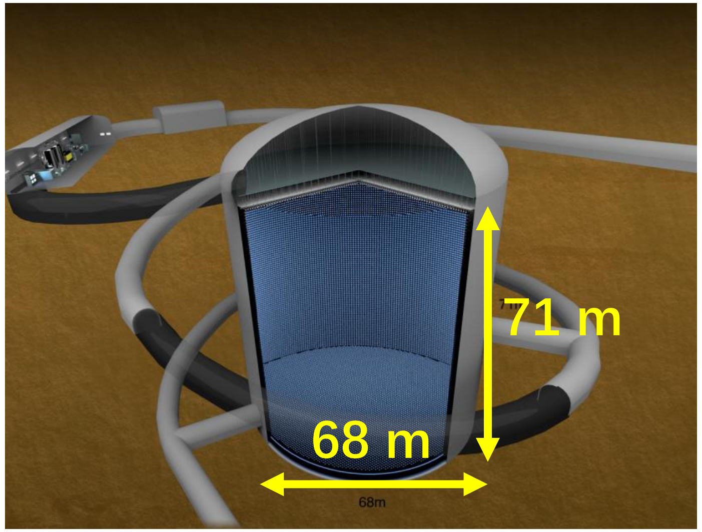
HK Experiment

Far detector



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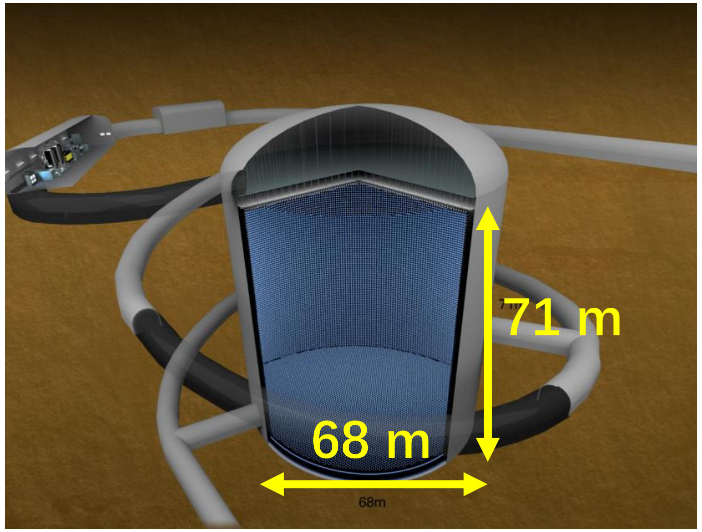
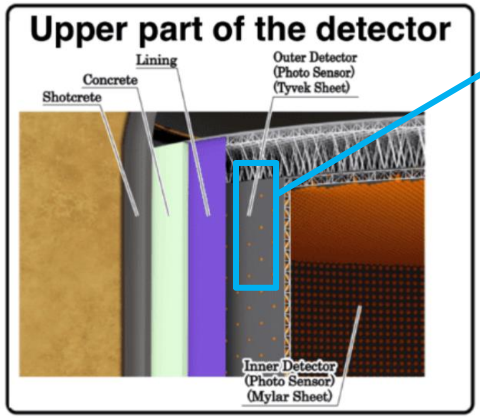
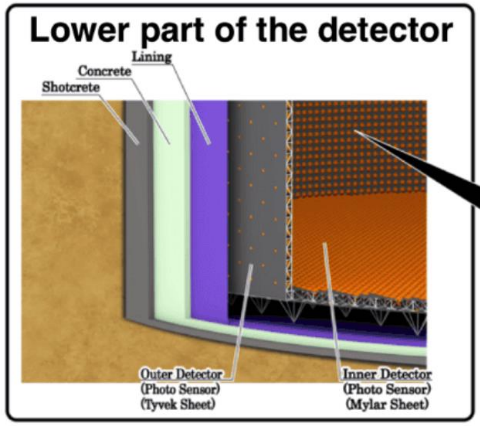


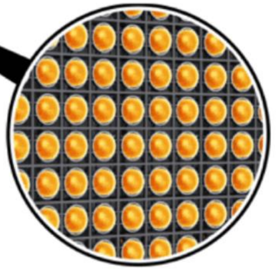




Outer Detector (OD)

Reject cosmic ray muons to constrain the external background (3-inch PMTs + WLS plates)

Photo-sensors



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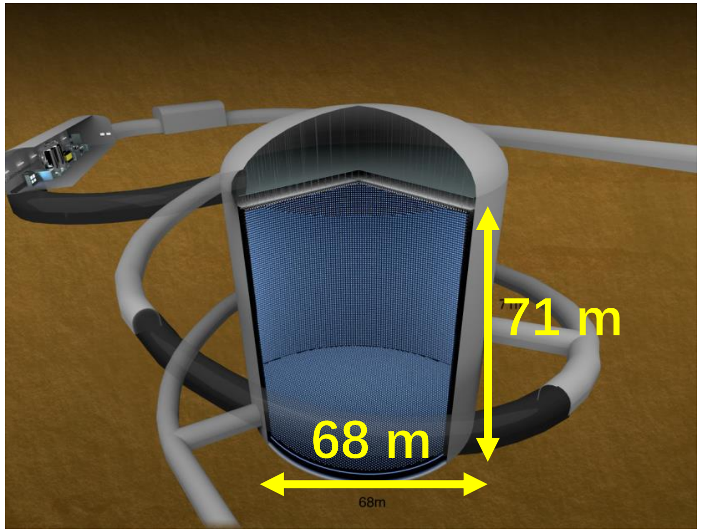

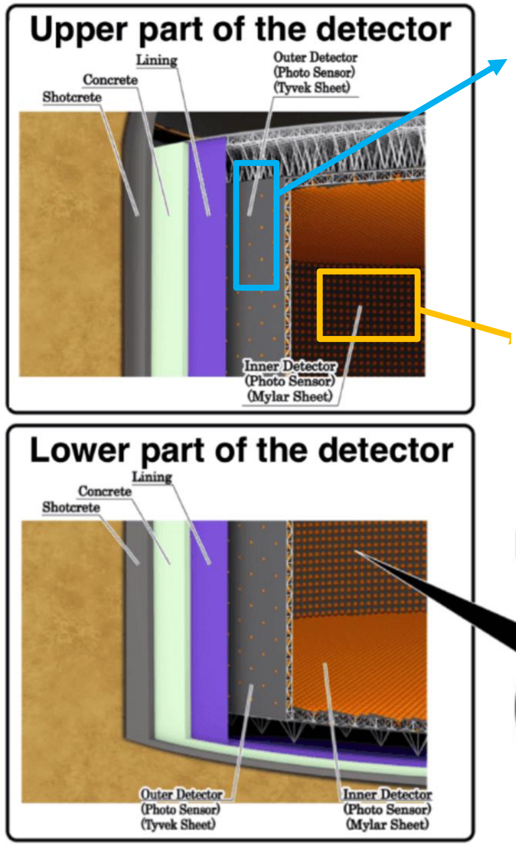

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Inner Detector (ID)

Cherenkov light from neutrino interaction (20-inch PMTs + mPMTs)

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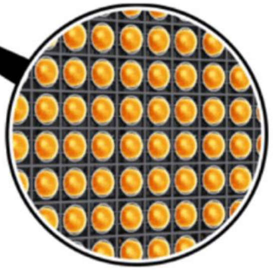

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HK Experiment

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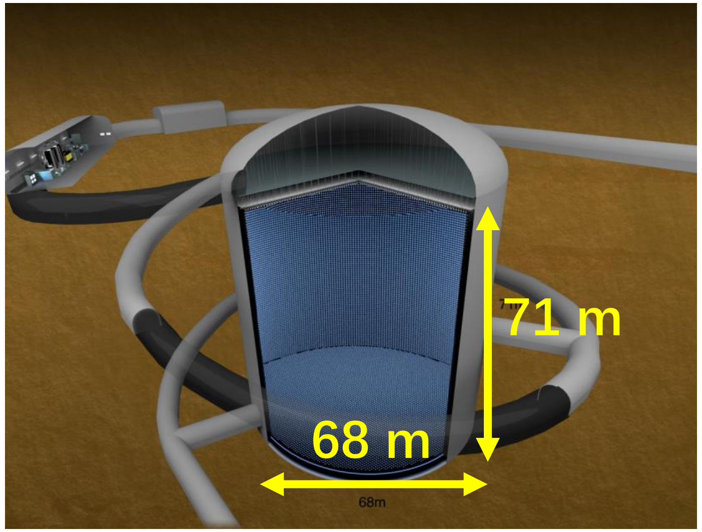

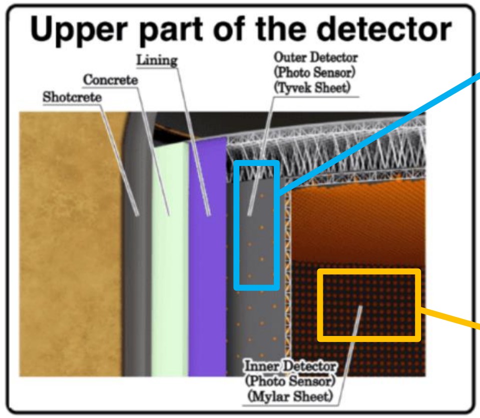

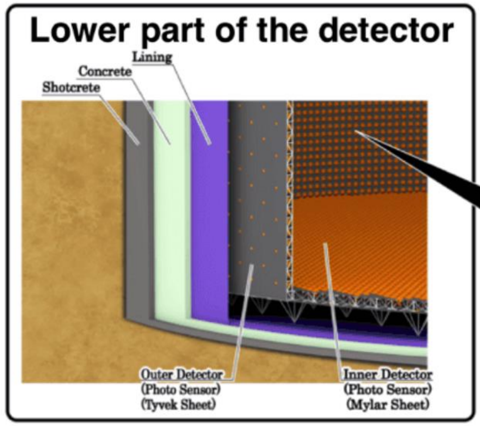

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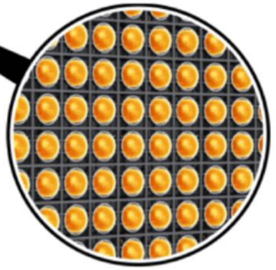
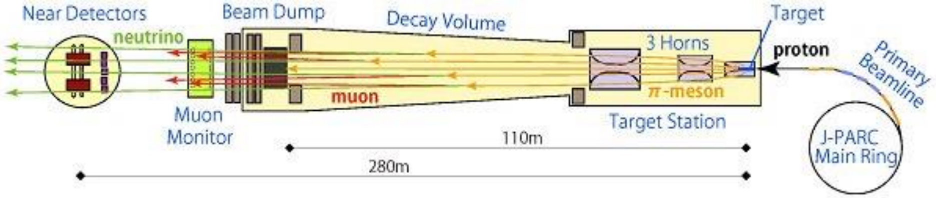


Beam neutrinos

J-PARC



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HK Experiment

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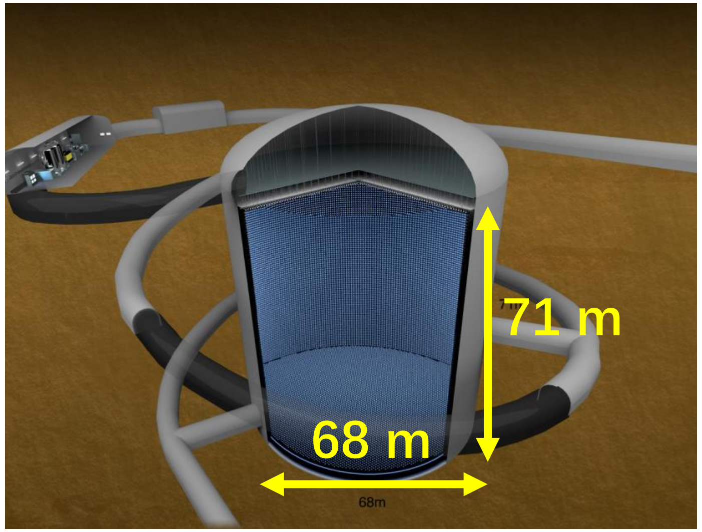

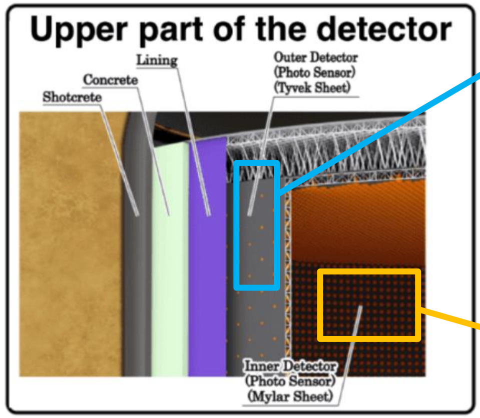

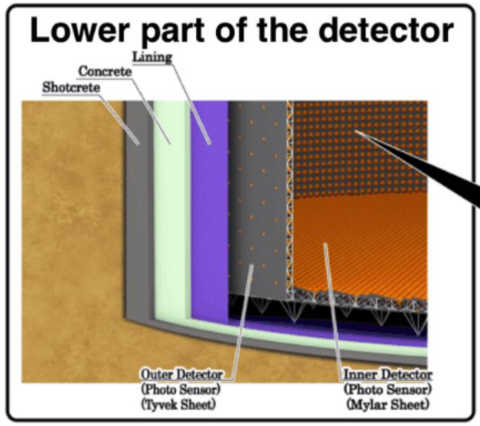

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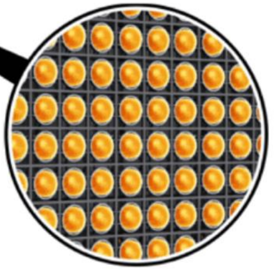
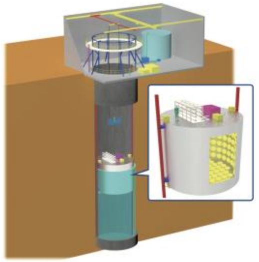
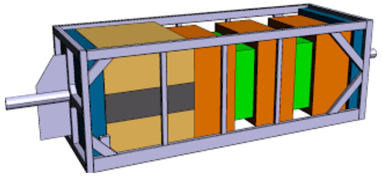


Near detectors

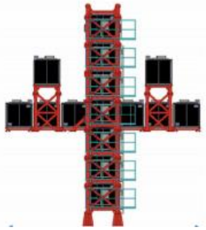
IWCD



ND280

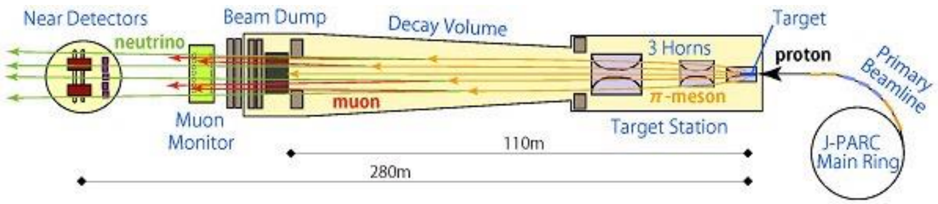


INGRID



Beam neutrinos

J-PARC



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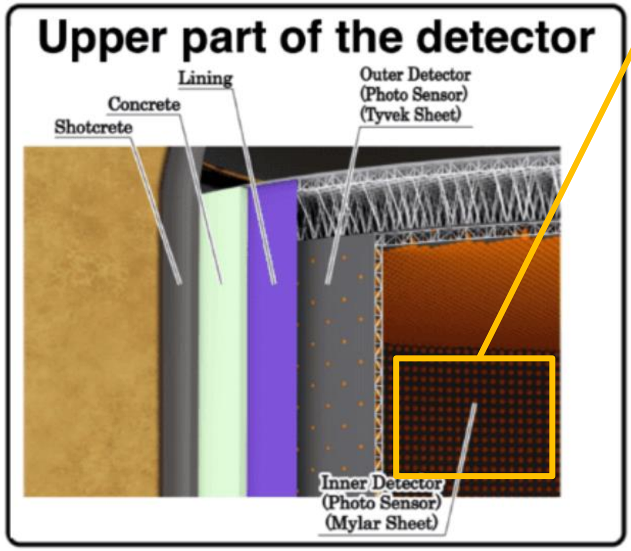
Far Detector



Inner Detector (ID)

20,000 50 cm Box and Line Dynode **ID PMTs**

- 2.6 ns timing resolution
- 2 times SK PMT efficiency

Additional mPMTs:
19 8 cm PMTs + electronics inside single pressure vessel

- Directional information of arrival photons
- Accurate photon counting
- Excellent timing resolution

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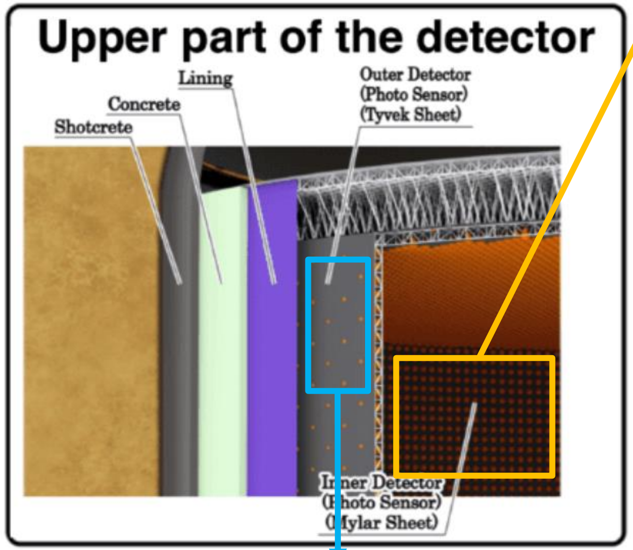

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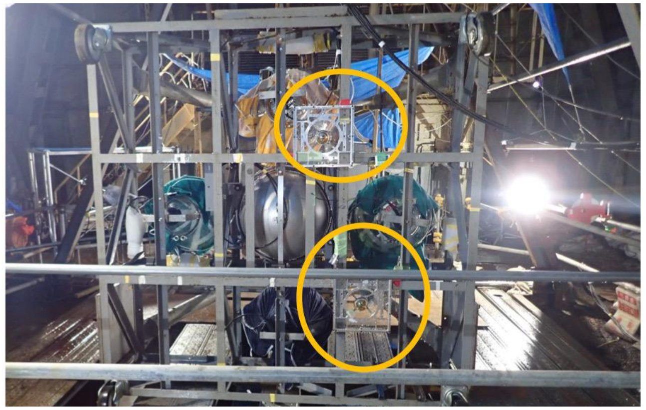

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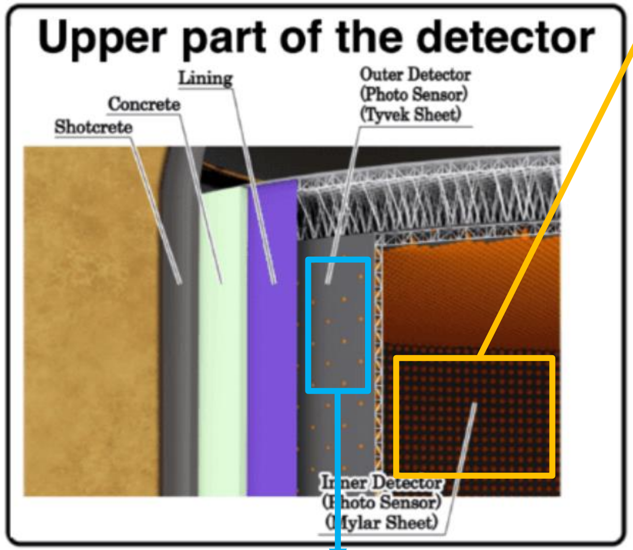

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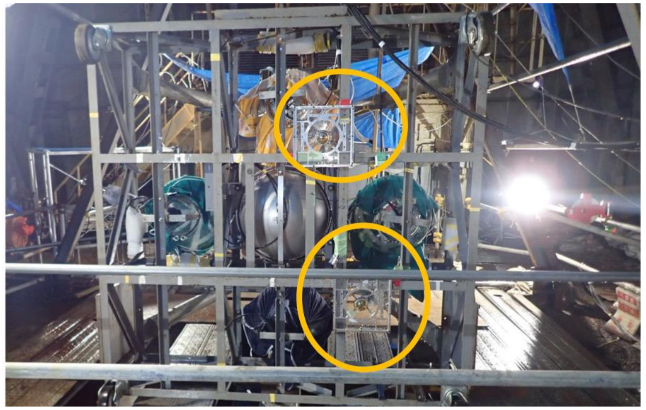

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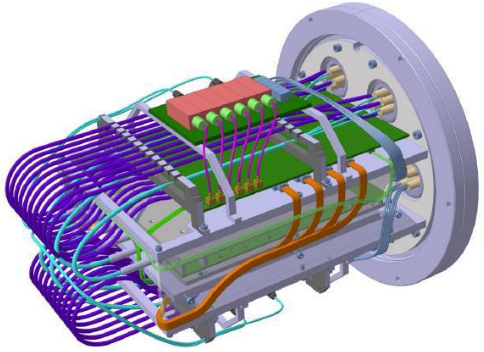
ID+OD Electronics



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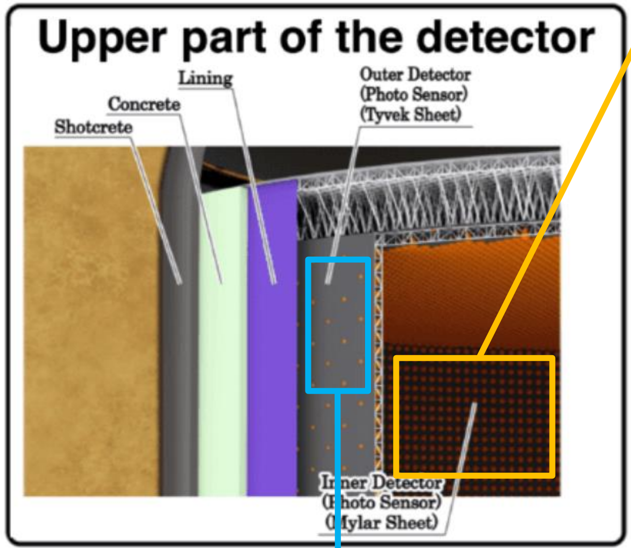

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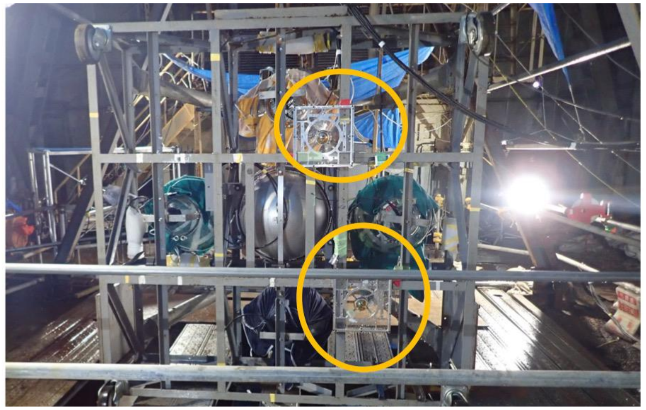
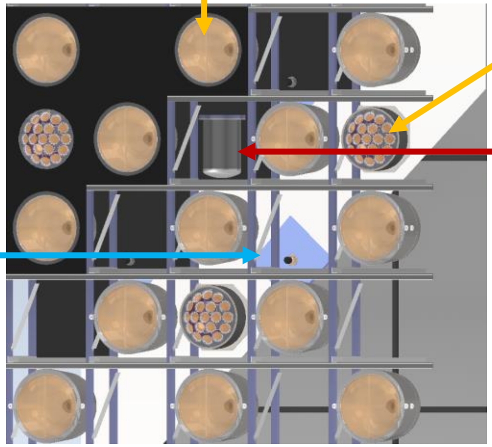
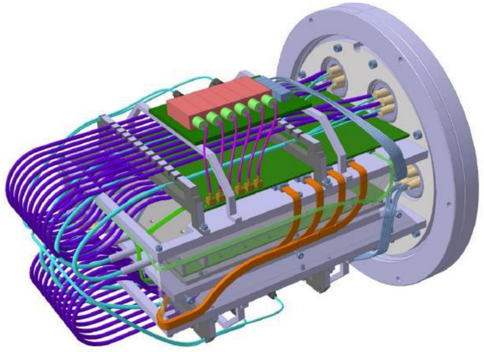




ID+OD Electronics



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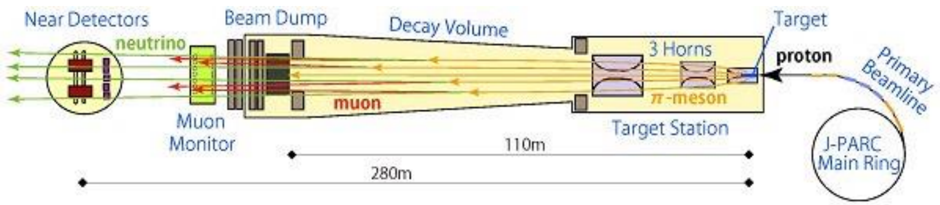
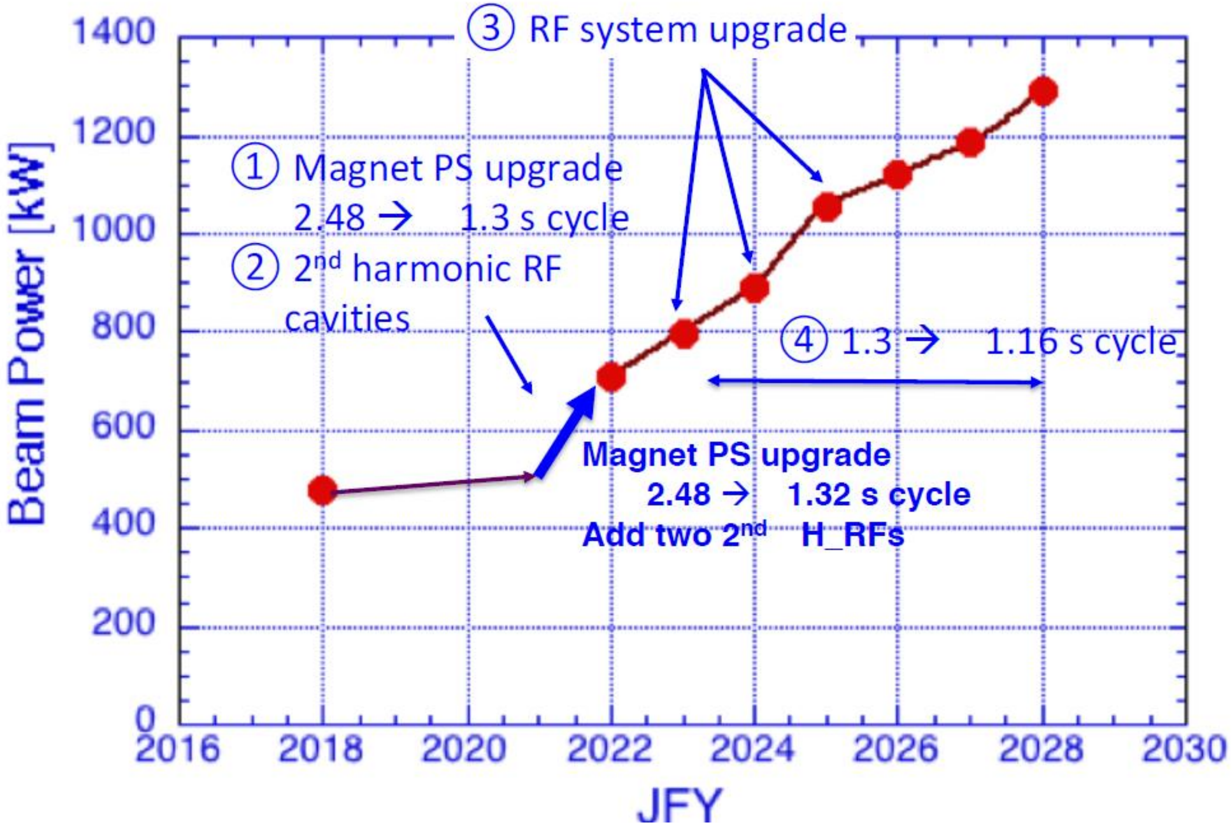
J-PARC Upgrade

T2K talk at 9:50 on 5th Sept - Lukas Berns



- 295 km baseline
- 2.5° off-axis, where $\nu_\mu/\bar{\nu}_\mu$ peak at 0.6 GeV
- neutrino beam is expected to reach 1.3 MW by 2028



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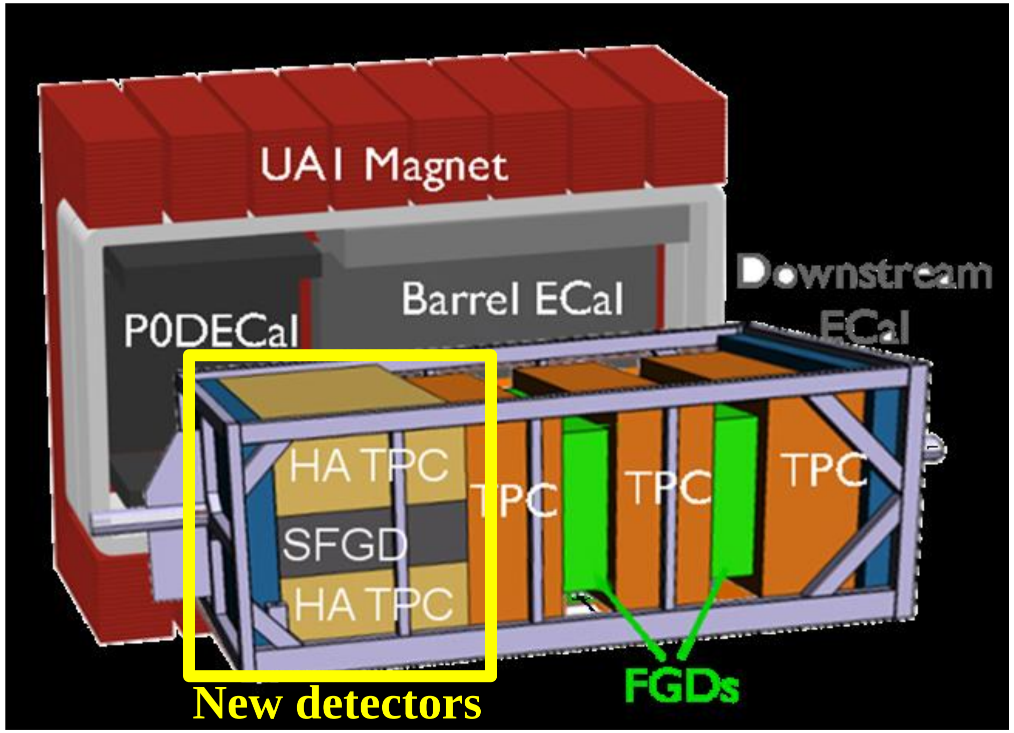
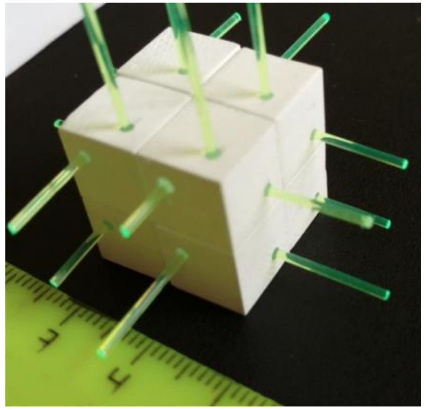
ND280 Upgrade

- ND280 is 280 m from the beam source
  - Currently is T2K and will be part of HK
  - Constrain the neutrino flux
  - Precisely measure neutrino cross sections
- ND280 upgrade
  - High angle events
  - Low particle detection thresholds
  - Improved to measure hadronic final states
- Improve acceptance for high-angle and backwards tracks to improve systematic error constraint





Details see Jaafar Chakrani's talk at 16:00 on 6th Sept

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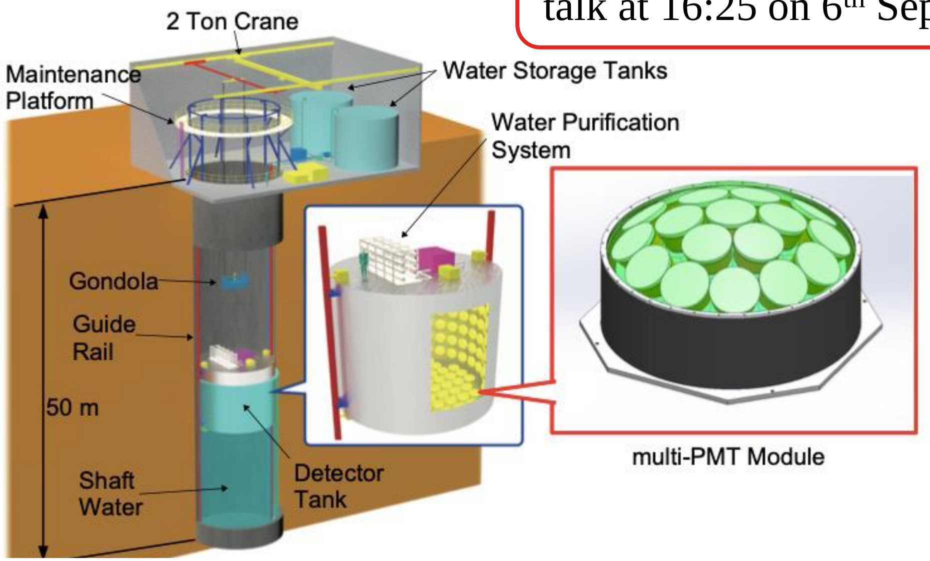
IWCD (Intermediate Water Cherenkov Detector)

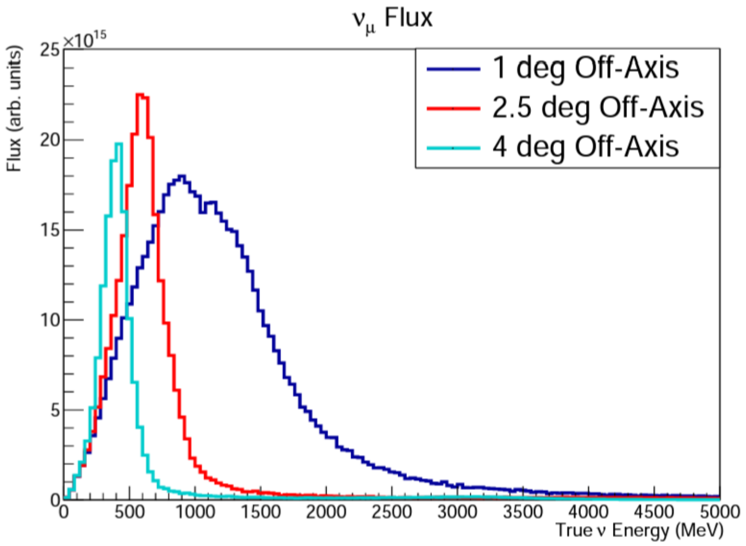
Details see Tailin Zhu's talk at 16:25 on 6th Sept

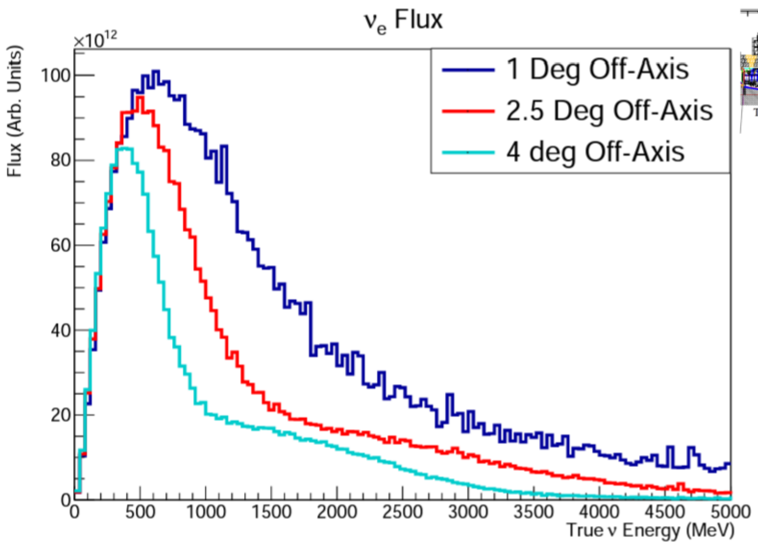
- Water Cherenkov detector
- Tall vertical shaft located ~1km from beam source
- ~1% residual $\nu_e/\bar{\nu}_e$ beam components

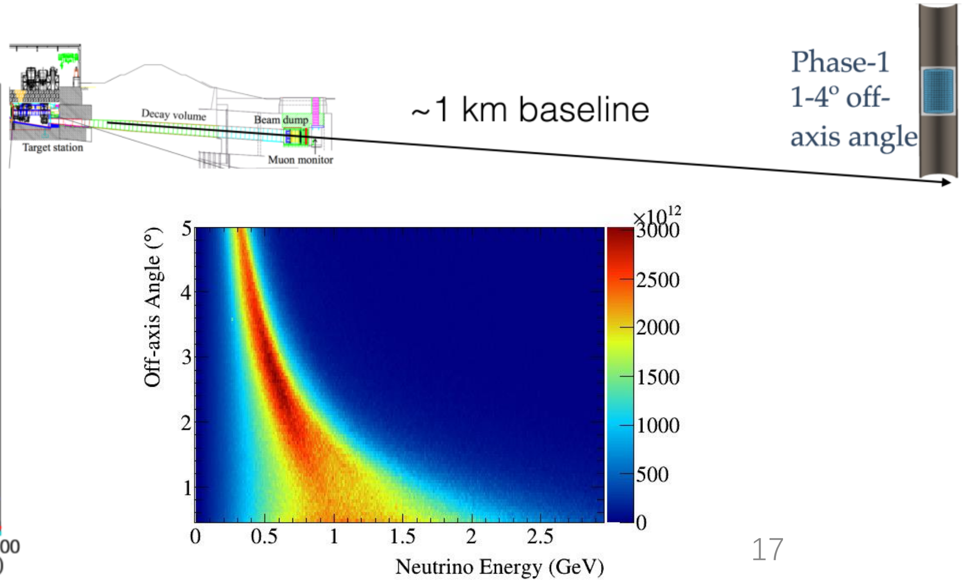
  Large fraction at far-OA angle

  Constrain $\boldsymbol{\nu_e/\bar{\nu}_e}$ cross sections in water
- Approved HK project includes IWCD









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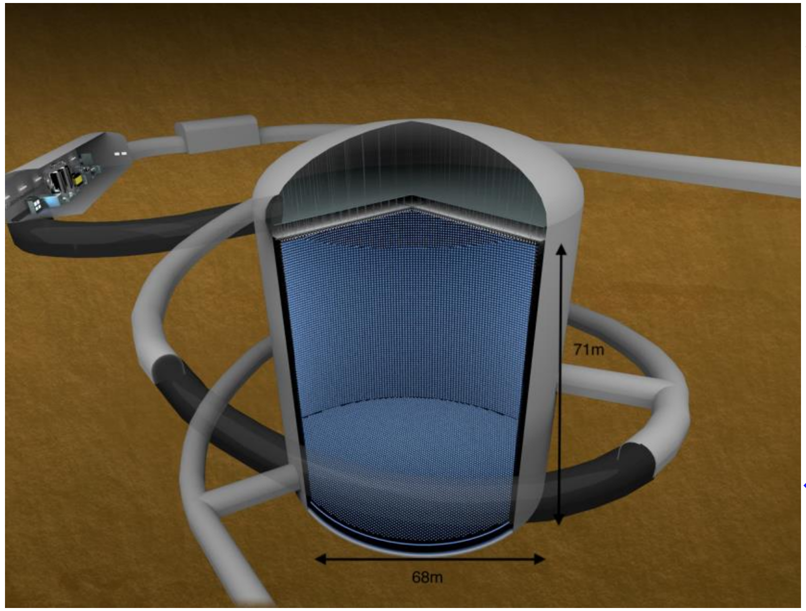
HK Experiment

Far detector



- 8 times fiducial volume of SK
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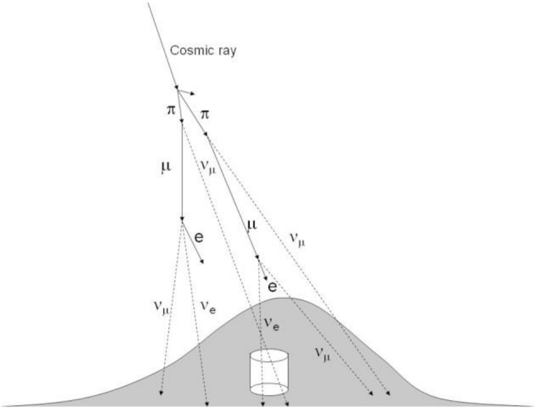
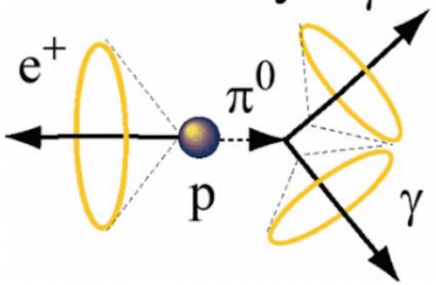
- 3-inch OD PMTs + WLS plates

Atmospheric neutrinos

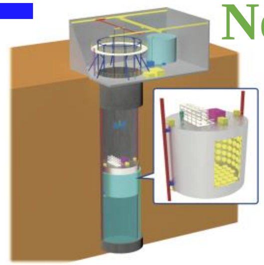


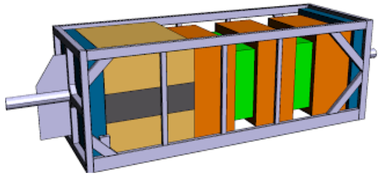
Astrophysical Neutrinos

Proton decay



Near detectors





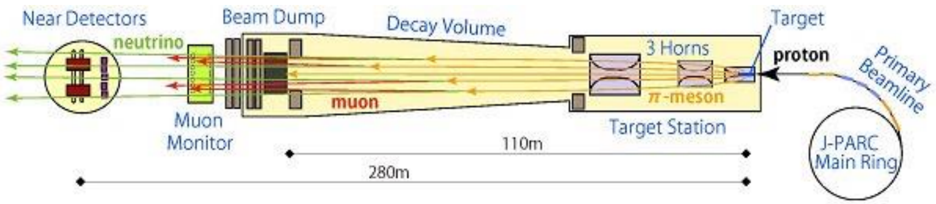
IWCD

Constrain $\nu_e/\bar{\nu}_e$ cross sections in water

ND280

Measure hadronic final states

Beam neutrinos



J-PARC

- Will upgrade to 1.3 MW
- **2.7×10^{22} POT (protons on target) for 10 HK years**

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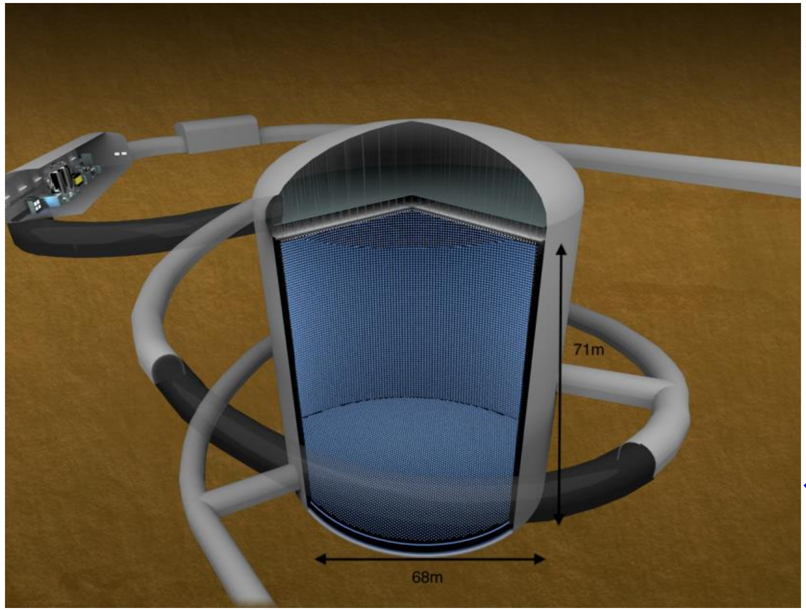
HK Experiment

Far detector



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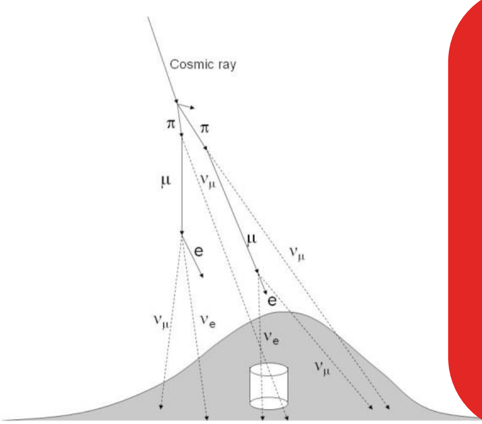
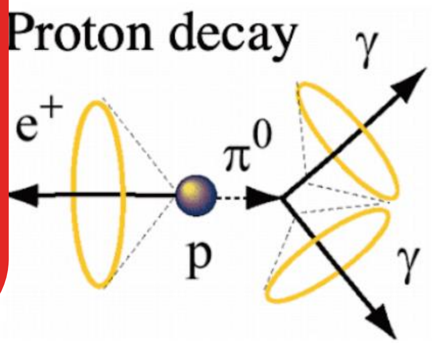


Diverse physics program!

- Neutrino oscillation
- Proton decay
- Supernova neutrino
- Dark matter

Astrophysical Neutrinos



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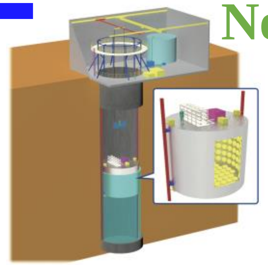

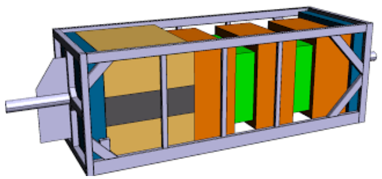

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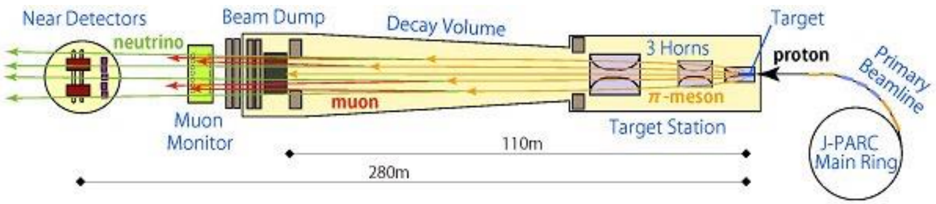

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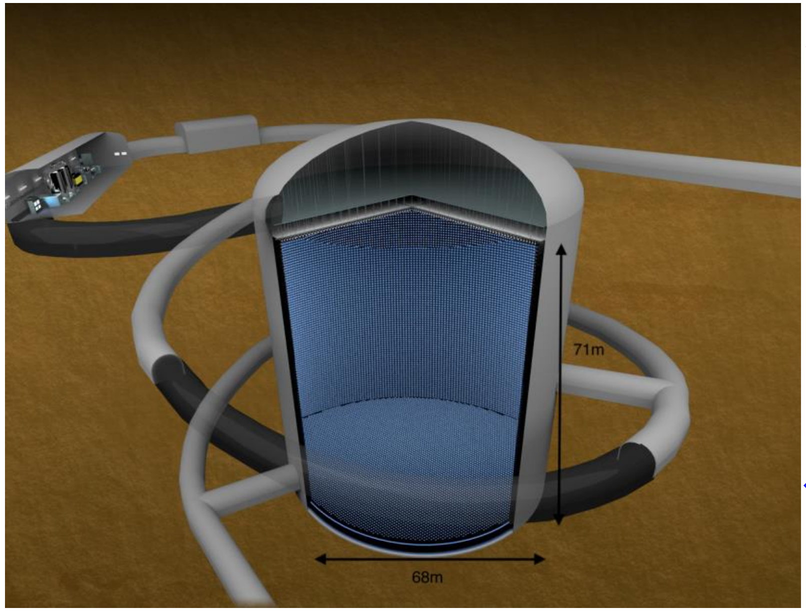
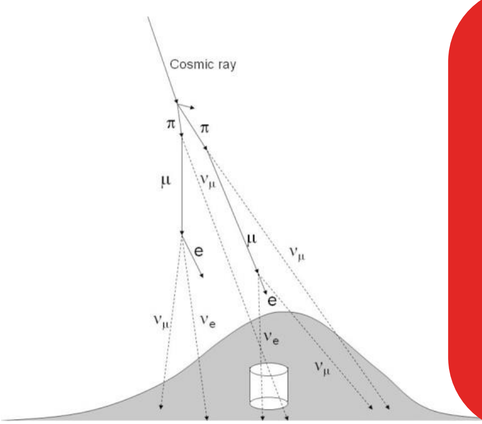
HK Experiment

Far detector



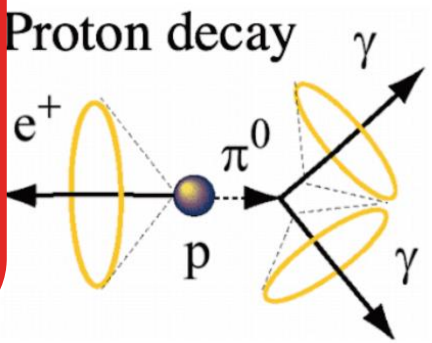
- 8 times fiducial volume of SK
- 20-inch ID PMTs + mPMTs
- 3-inch OD PMTs + WLS plates

Atmospheric neutrinos

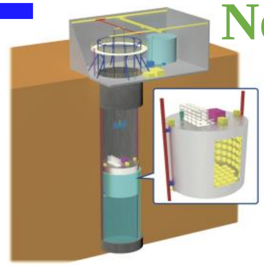


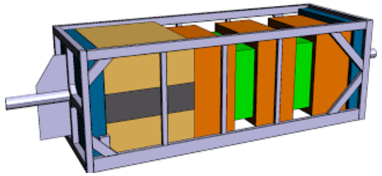
Astrophysical Neutrinos

Diverse physics program!
- **Neutrino oscillation**
- Proton decay
- Supernova neutrino
- Dark matter



Near detectors

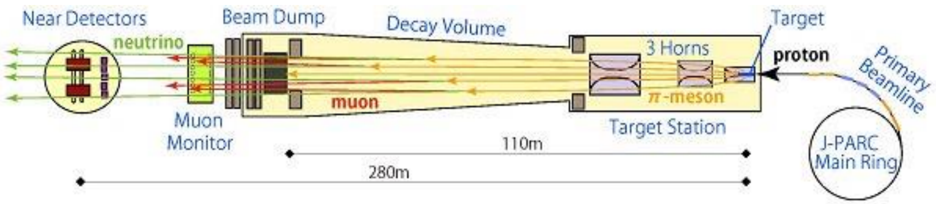




IWCD
Constrain $\nu_e/\bar{\nu}_e$ cross sections in water

ND280
measure hadronic final states

Beam neutrinos



J-PARC
- will upgrade to 1.3 MW
- $\mathbf{2.7 \times 10^{22}}$ **POT (protons on target) for 10 HK years**

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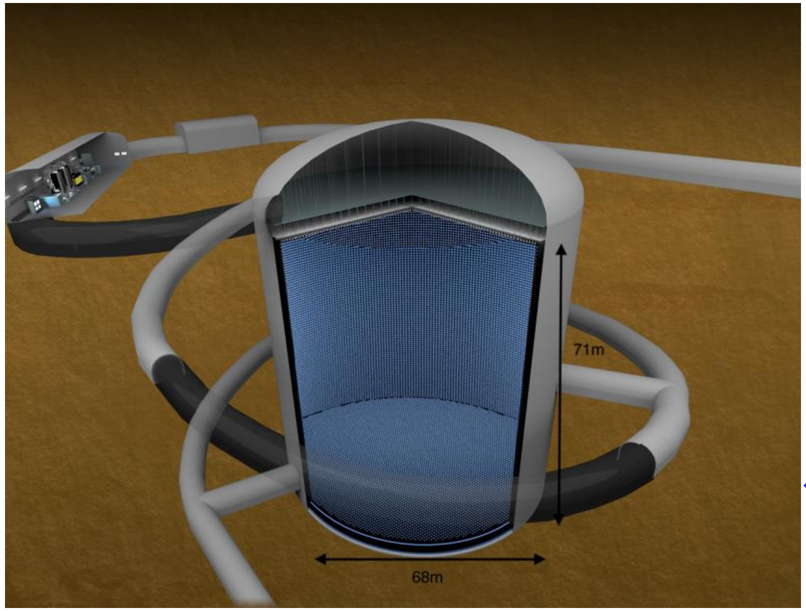
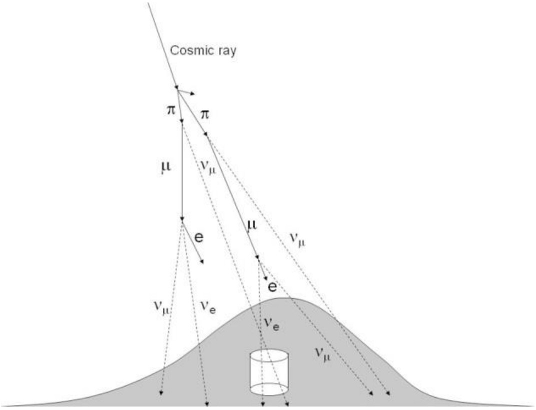
HK Long-Baseline Program

Far detector



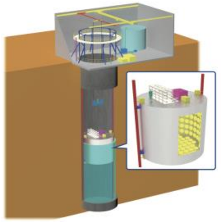
- 10 years data taking
- 1:3 $\nu:\bar{\nu}$ run plan

Atmospheric neutrinos

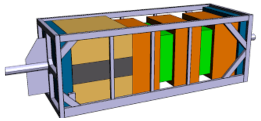


T2K long-baseline program talks
9:50 on 5th Sept - Lukas Berns
16:50 on 5th Sept - Junjie Xia

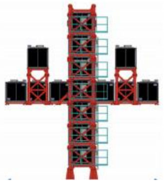
Near detectors



IWCD

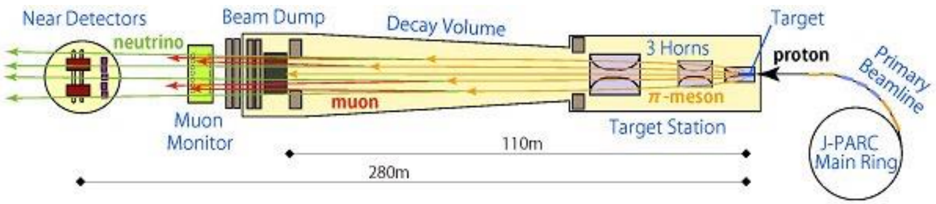


ND280



INGRID

Beam neutrinos



J-PARC

Near Detector constraints
- Flux model
- Neutrino cross-section model

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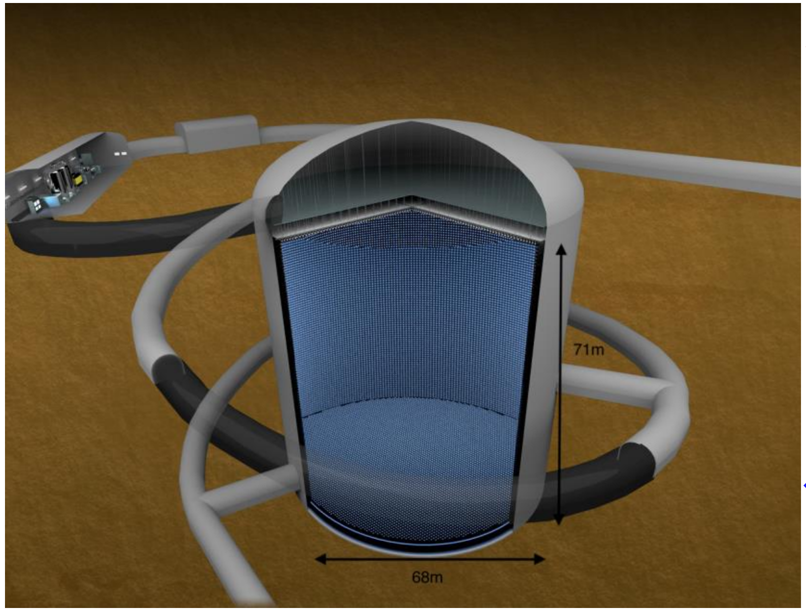
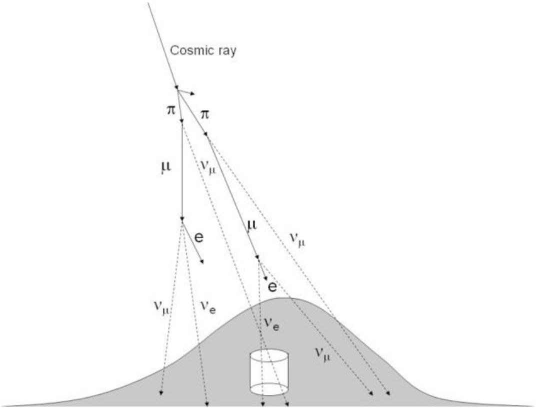
Analysis Strategy

Far detector



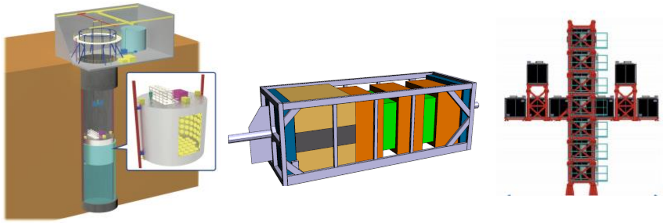
- Using SK information scaled for HK POT exposure
- 10 years data taking
- 1:3 $\nu : \bar{\nu}$ run plan

Atmospheric neutrinos



Atmospheric samples are based on SK information and HK size and exposure for 10 years of HK running

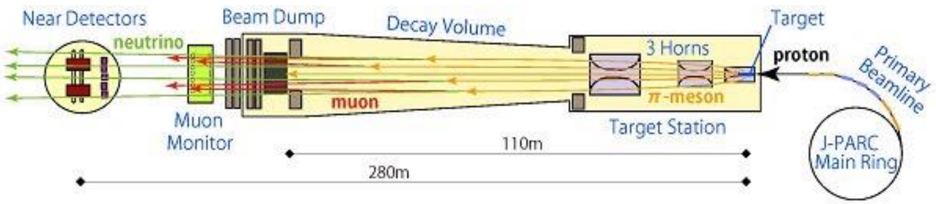
Near detectors



IWCD ND280 INGRID

Estimate size of flux and cross-section uncertainties using upgraded ND280 & IWCD

Beam neutrinos



J-PARC

2.7×10^{22} POT for 10 HK years

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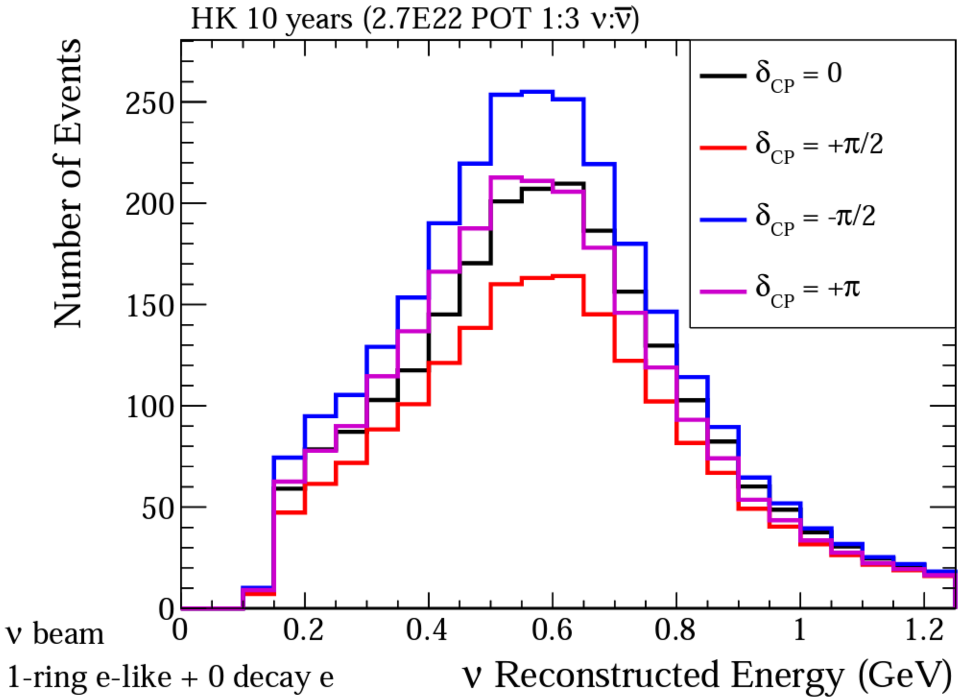
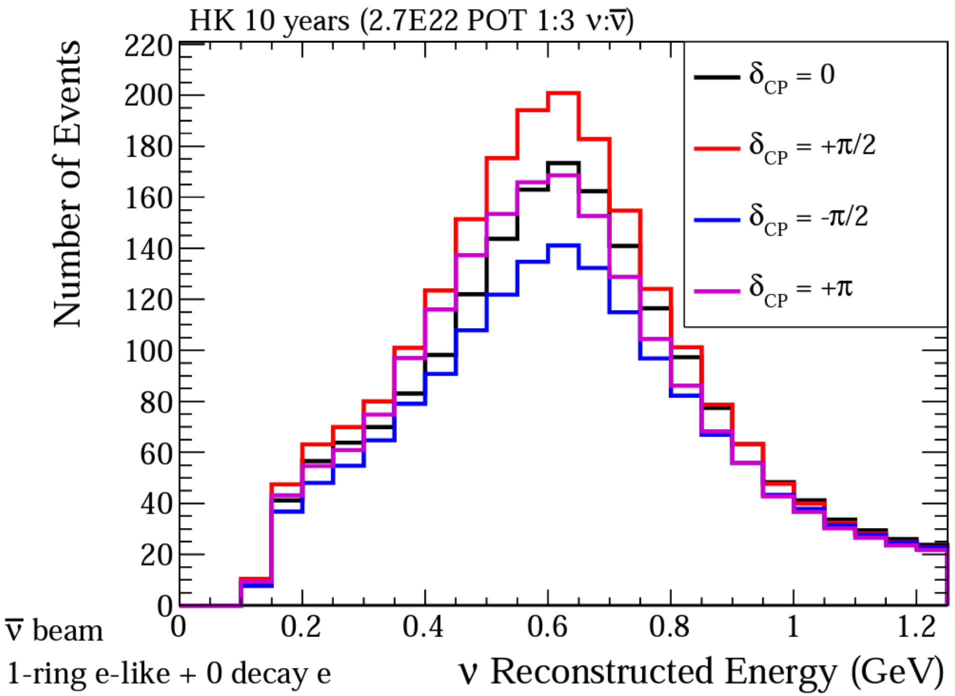
HK Long-Baseline ν_e Spectra





- Sensitivity to δ_{CP} mainly comes from $\nu_\mu \rightarrow \nu_e$ appearance
- The amount of ν_e-like events signals assuming 10 HK years (2.7×10^{22}POT), 1:3 $\nu:\bar{\nu}$, NO, $\sin^2\theta_{13} = 0.0218$, $\delta_{CP} = 0$.

	$\nu_\mu \rightarrow \nu_e$	$\nu_\mu$bar $\rightarrow \nu_e$bar	Beam ν_μ	Beam $\nu_\mu$bar	Beam ν_e	Beam $\nu_e$bar	NC	Total
ν-mode ν_e CCQE-like	2252.51	11.70	6.53	0.23	326.15	12.34	130.30	**2739.76**
νbar-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**

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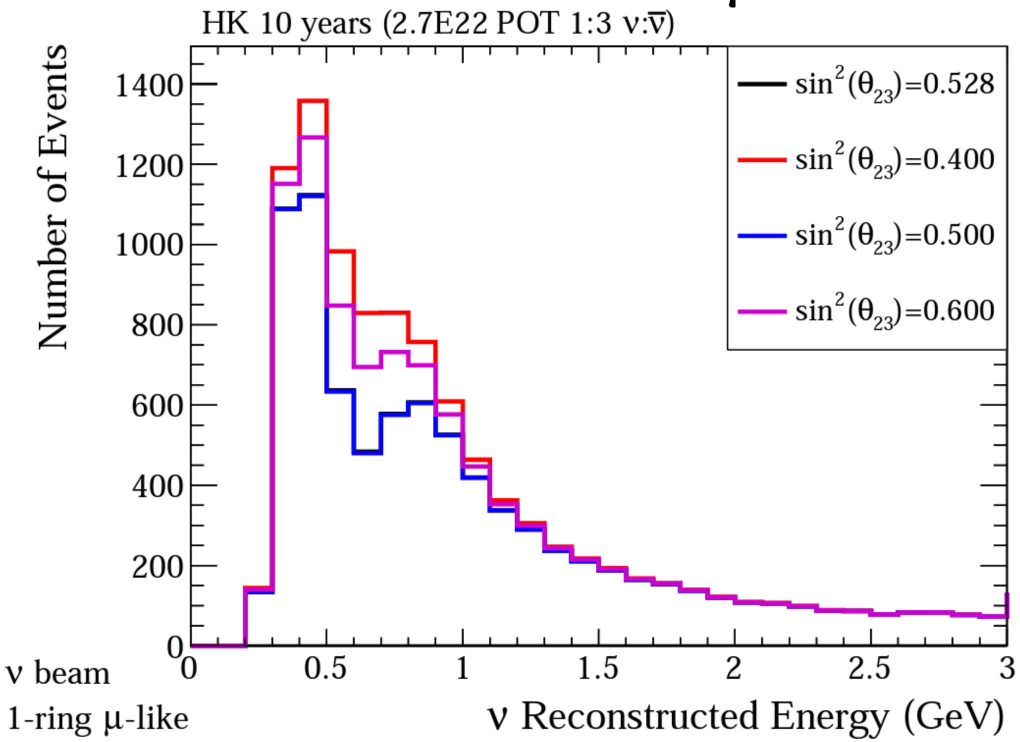
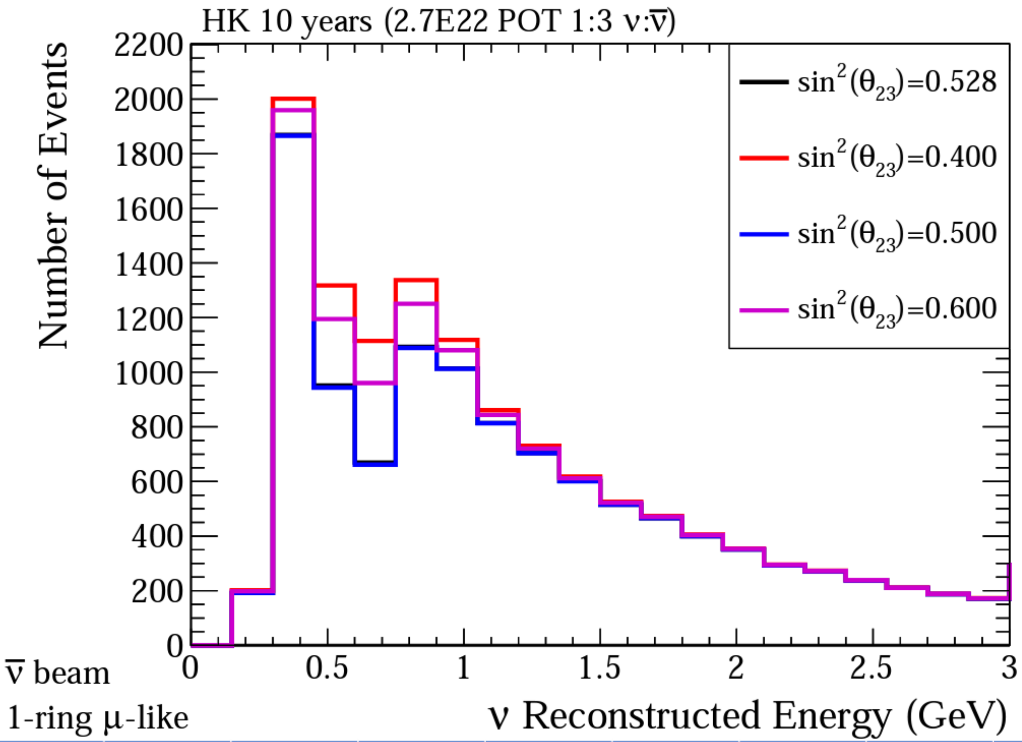
HK Long-Baseline ν_μ Spectra





- Sensitivity to $\sin^2\theta_{23}$ and Δm^2_{32} mainly comes from ν_μ disappearance
- The amount of ν_μ-like events signals assuming 10 HK years (2.7×10^{22}POT), 1:3 $\nu:\bar{\nu}$, NO, $\sin^2\theta_{13}=0.0218$, $\delta_{CP}=0$.

	ν_μ	$\nu_\mu$bar	ν_e	$\nu_\mu\rightarrow\nu_e$	$\nu_e$bar	$\nu_\mu$bar $\rightarrow\nu_e$bar	NC	Total
ν-mode ν_μ CCQE-like	8583.80	479.91	0.24	2.32	0.01	0.01	282.99	9349.30
νbar-mode ν_μ CCQE-like	4399.40	7688.44	0.28	0.33	0.24	0.42	285.92	12375.02

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HK Long-Baseline Systematic Uncertainties Model

T2K 2018 Syst. uncertainties (Phys. Rev. D 103, 112008 (2021))

Increased run time
+
Sensitivities from ND280-upgrade and IWCD

	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-/$\bar{\nu}$-Mode CCQE-like
Flux + Cross section	3.27%	2.95%	4.33%	4.37%	4.99%	4.52%
Detector + FSI +SI	3.22%	2.76%	4.14%	4.39%	17.77%	2.06%
All systematics	4.63%	4.10%	5.97%	6.25%	18.49%	4.95%

HK Improved Syst. uncertainties

	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-/$\bar{\nu}$-Mode CCQE-like
Flux + Cross section	0.81%	0.72%	2.07%	1.88%	2.21%	2.28%
Detector + FSI +SI	1.68%	1.58%	1.54%	1.72%	5.21%	0.97%
All systematics	1.89%	1.74%	2.56%	2.53%	5.63%	2.45%

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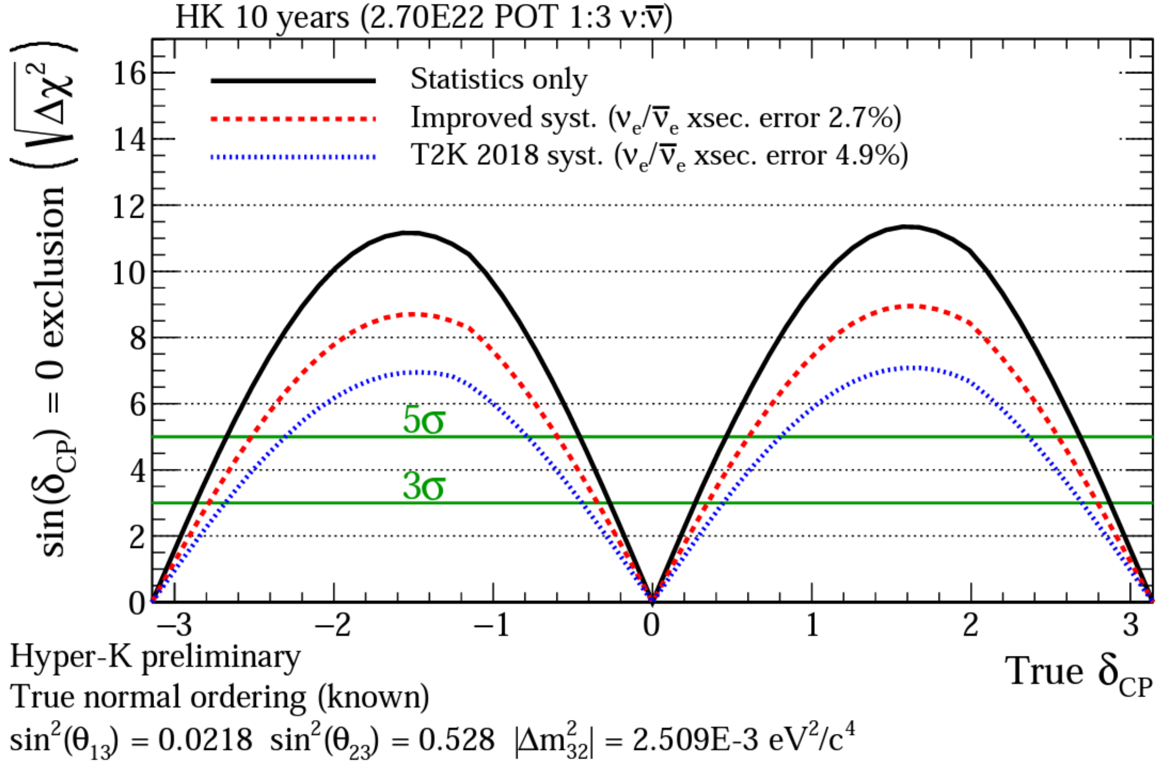
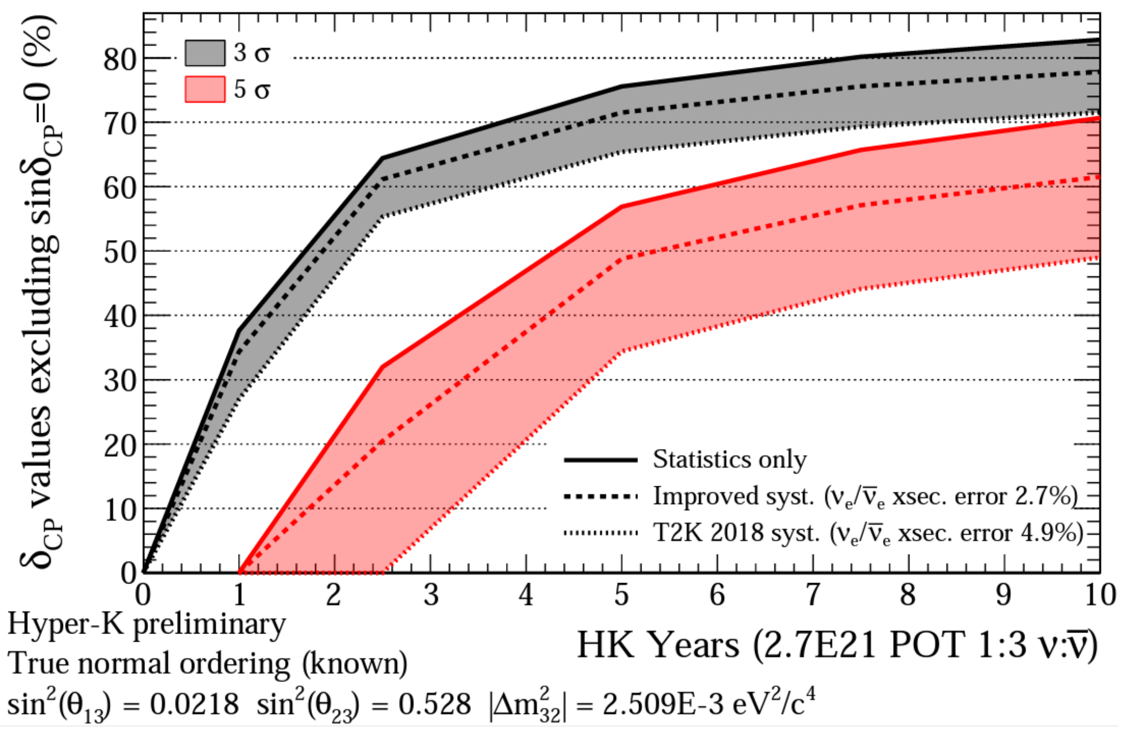
Impact of systematic uncertainties





- Assume normal mass ordering is true, **improved HK systematic uncertainties** can improve the sensitivity to CP violation.
- After 10 HK-years, **61%** of true δ_{CP} values can be excluded at **5-σ** with the improved syst. error model.

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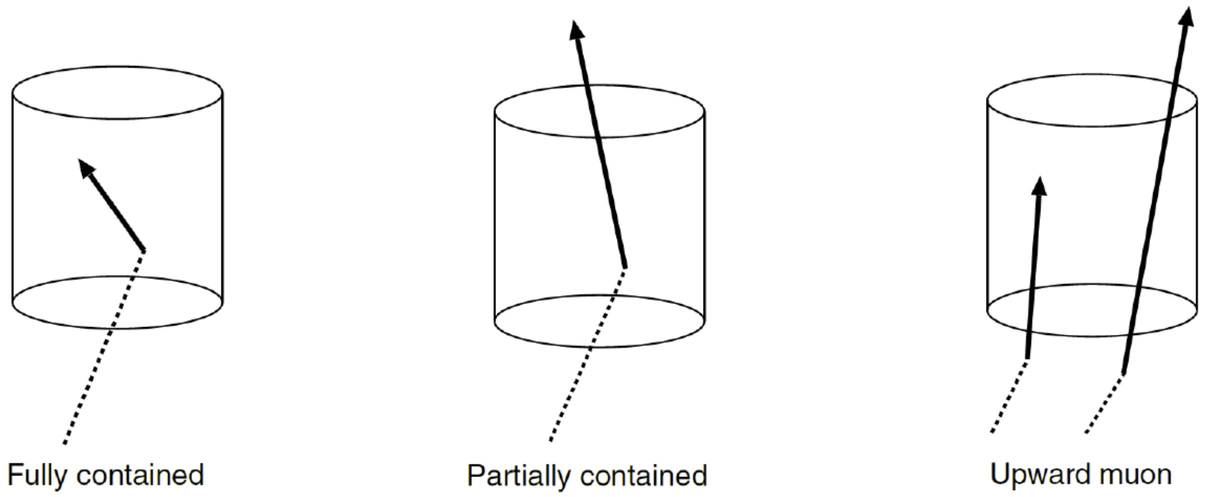
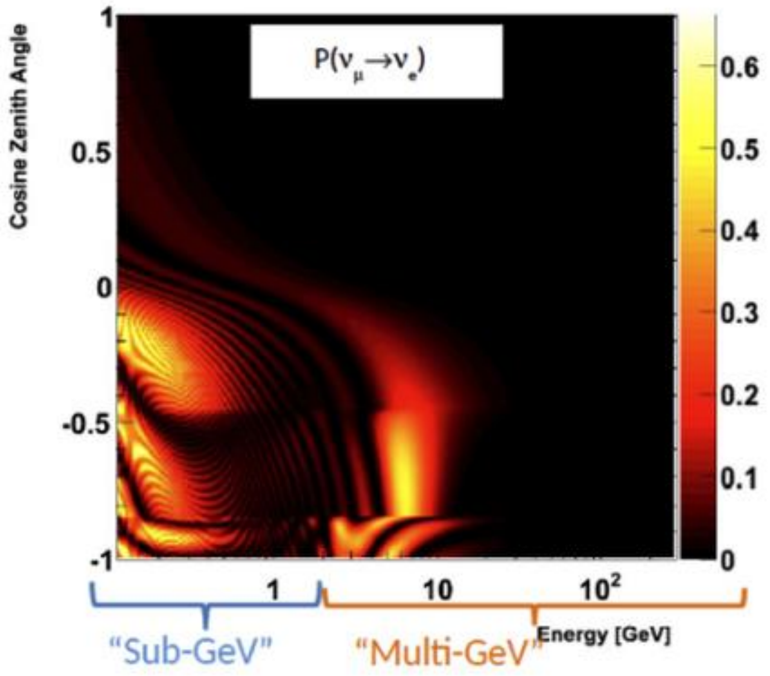
Atmospheric neutrinos

- Traveling through a substantial matter density modifies the vacuum oscillation probability
- Mass Ordering sensitivity predominantly comes from the "MultiGeV" upward-going electron neutrinos
- HK has the potential to determine the neutrino mass ordering from atmospheric neutrinos alone.





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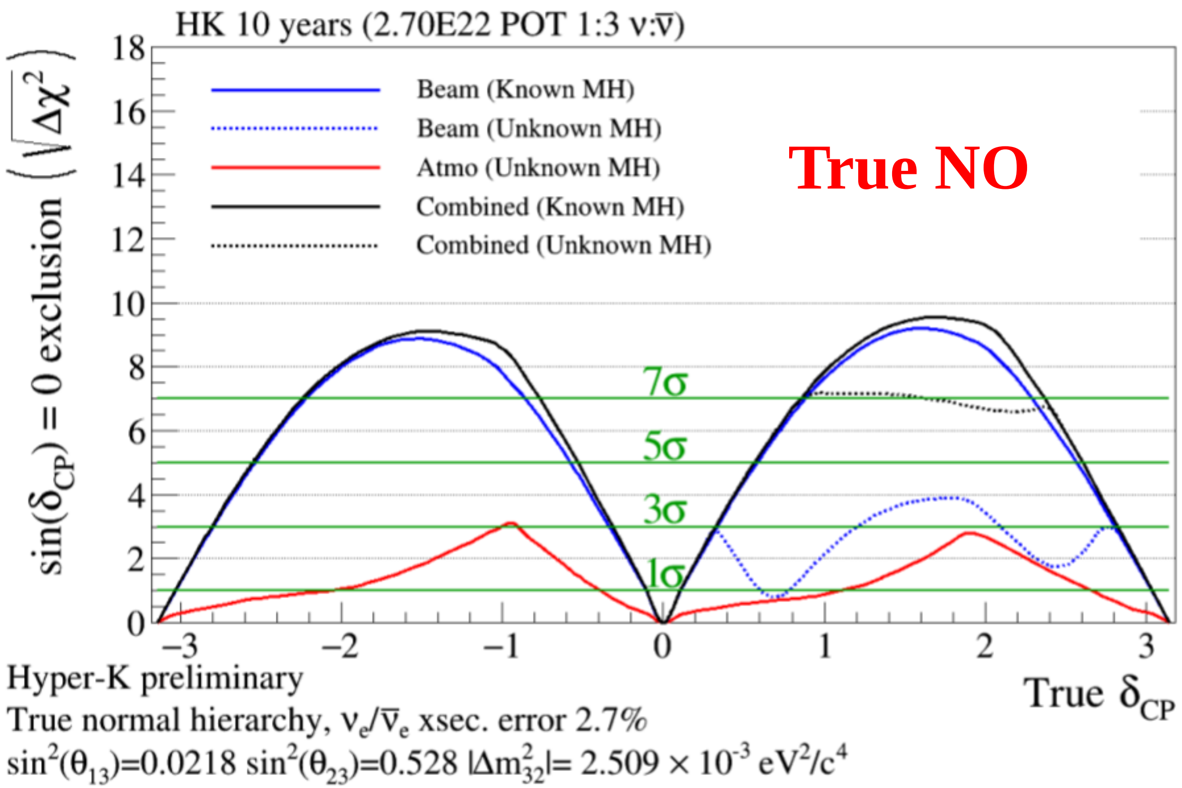
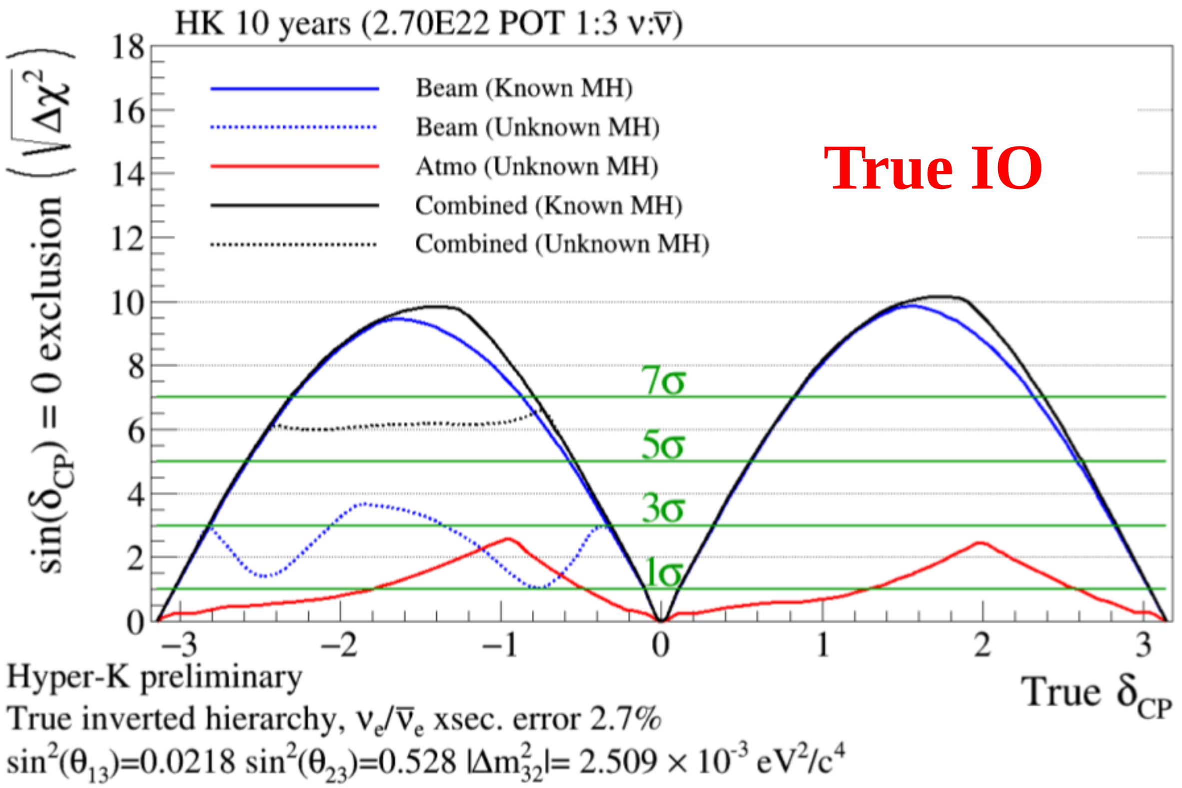
HK Sensitivity Study





- Using only beam neutrinos, HK has very good sensitivity to CPV but this depends on whether the mass ordering is known.
- By combining **beam** and **atmospheric** neutrinos can achieve 5-σ sensitivity to CPV regardless the true mass ordering

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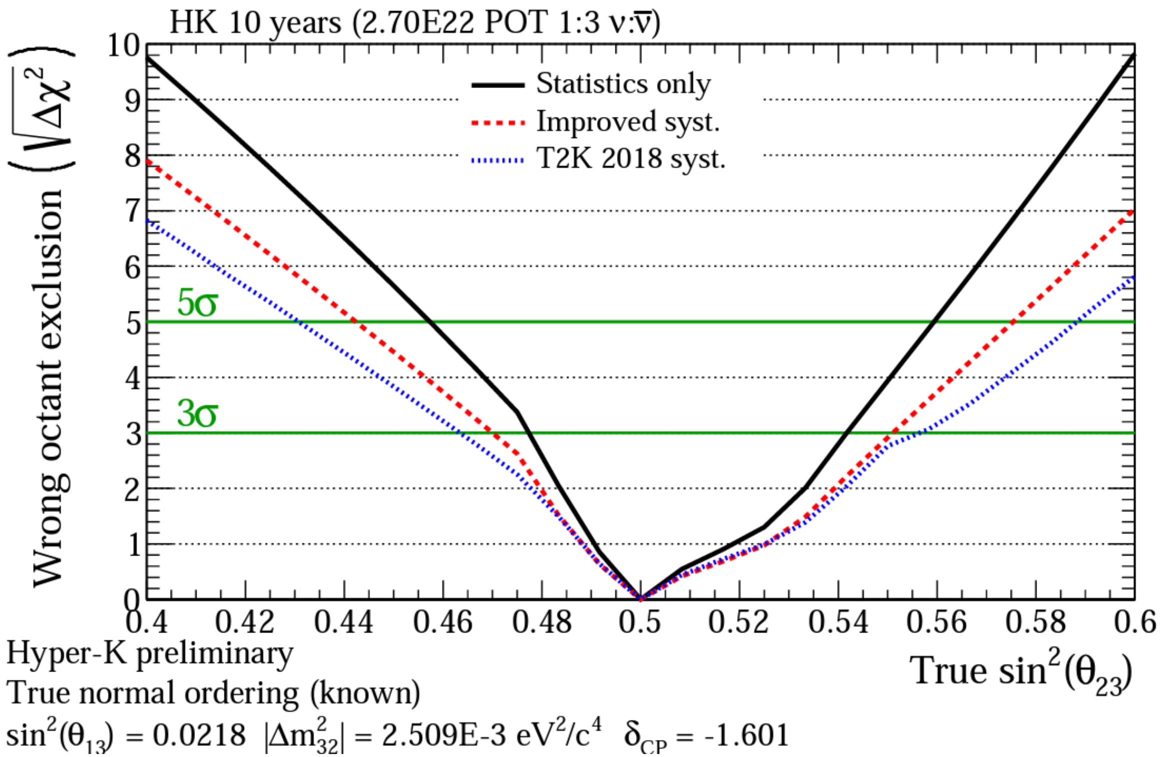
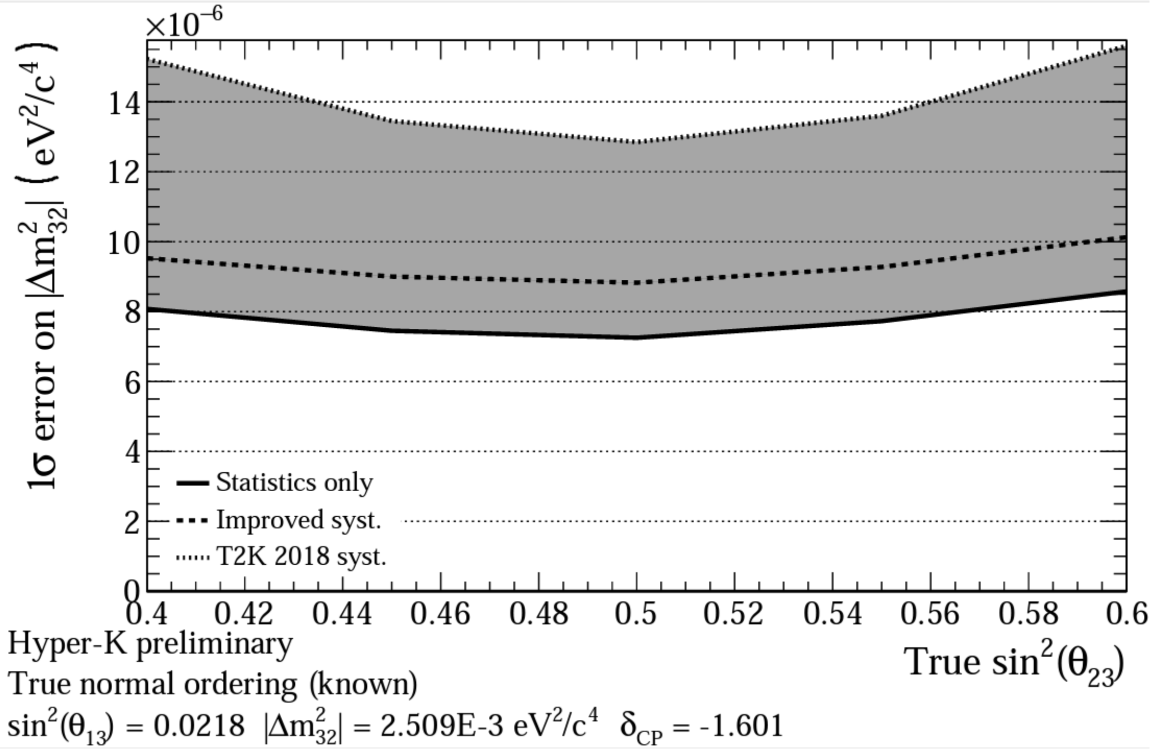
$\sin^2\theta_{23}$ and Δm^2_{32}





- Wrong octant can be excluded at 3-σ for true $\sin^2\theta_{23} < 0.47$ and true $\sin^2\theta_{23} > 0.55$
- 1-σ resolution of Δm^2_{32} as a function of true $\sin^2\theta_{23}$, after 10 HK-years

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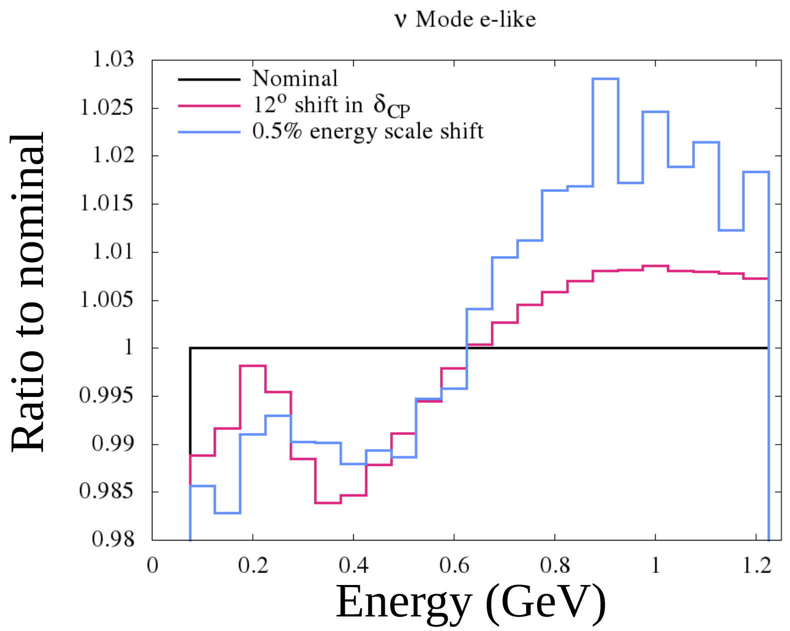
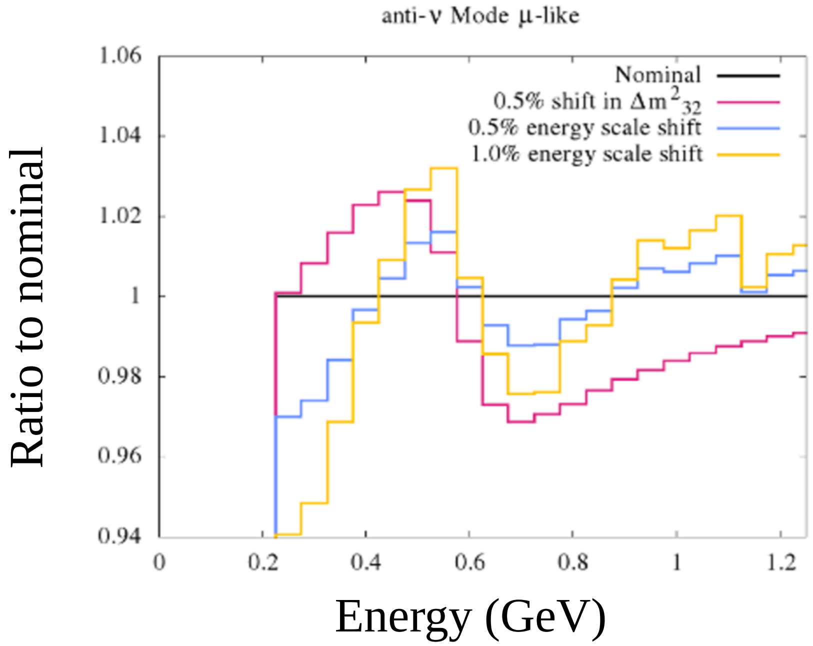
Precision measurements

Some Systematic errors present degeneracies with oscillation parameters, e.g. the detector energy scale uncertainty.





- Current T2K energy scale error is 2.4%, assuming fully correlated and linear at all energies.
- HK target energy scale error is 0.5% .
- Need the development of the proper calibration and analysis strategy!

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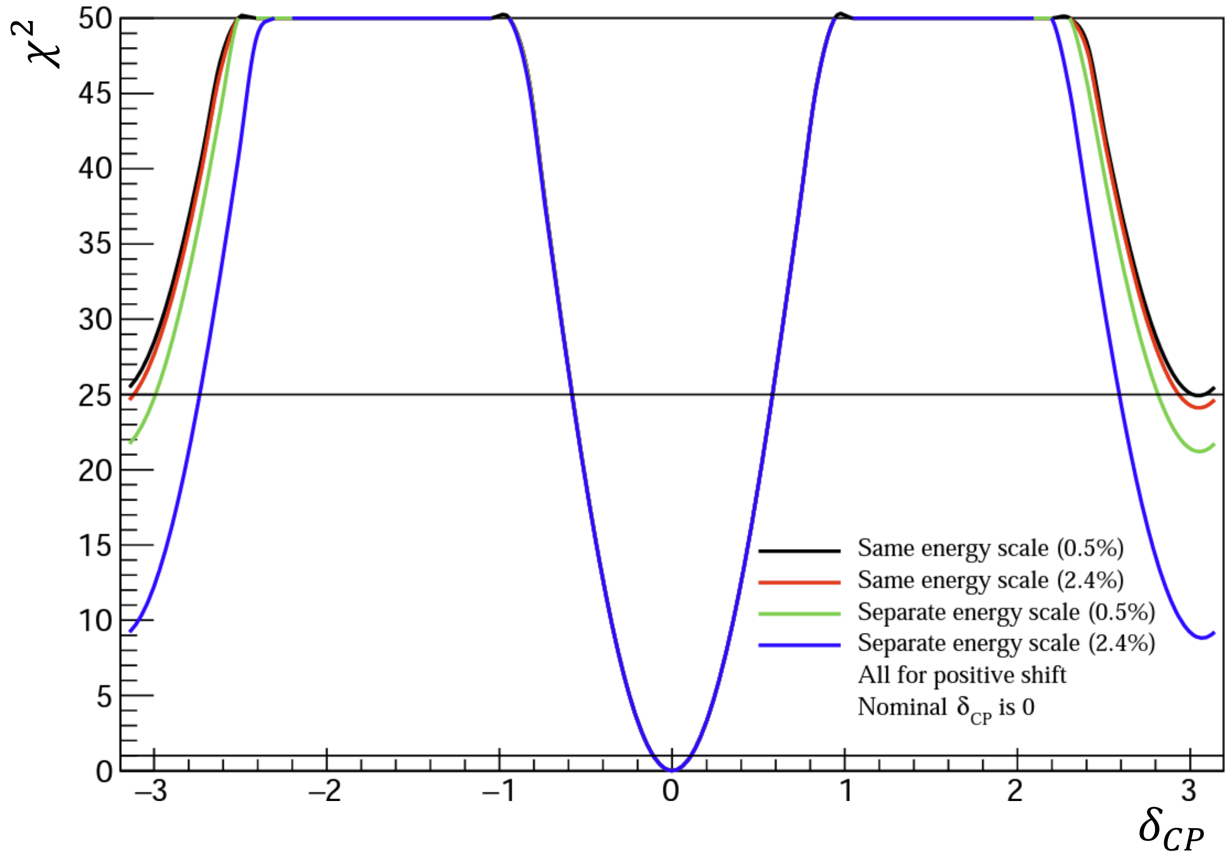
Detector Energy Scale Uncertainty

- HK target energy scale error 0.5%

- Different method to estimate energy scale uncertainties of $\nu_e(\bar{\nu}_e)$ and $\nu_\mu(\bar{\nu}_\mu) \rightarrow$ Separately

- Either increasing the error or separate energy scale uncertainties of $\nu_e(\bar{\nu}_e)$ and $\nu_\mu(\bar{\nu}_\mu)$ will lose sensitivity



- mPMTs with PMTs to do cross-calibration & Bottom-up approach

The calibration procedure should be able to disentangle and precisely model all fundamental causes of energy scale uncertainties as a function of energy and neutrino flavor.

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Physics program

Neutrino oscillation physics

Neutrino oscillation parameters, Charge Parity Violation

- Upgraded ND280 and IWCD will improve the sensitivity to CPV
- Combined beam and atmospheric neutrinos can achieve 5-σ sensitivity to CPV regardless the mass ordering
- Precision measurements require development of proper calibration and analysis strategies

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Search for proton decays

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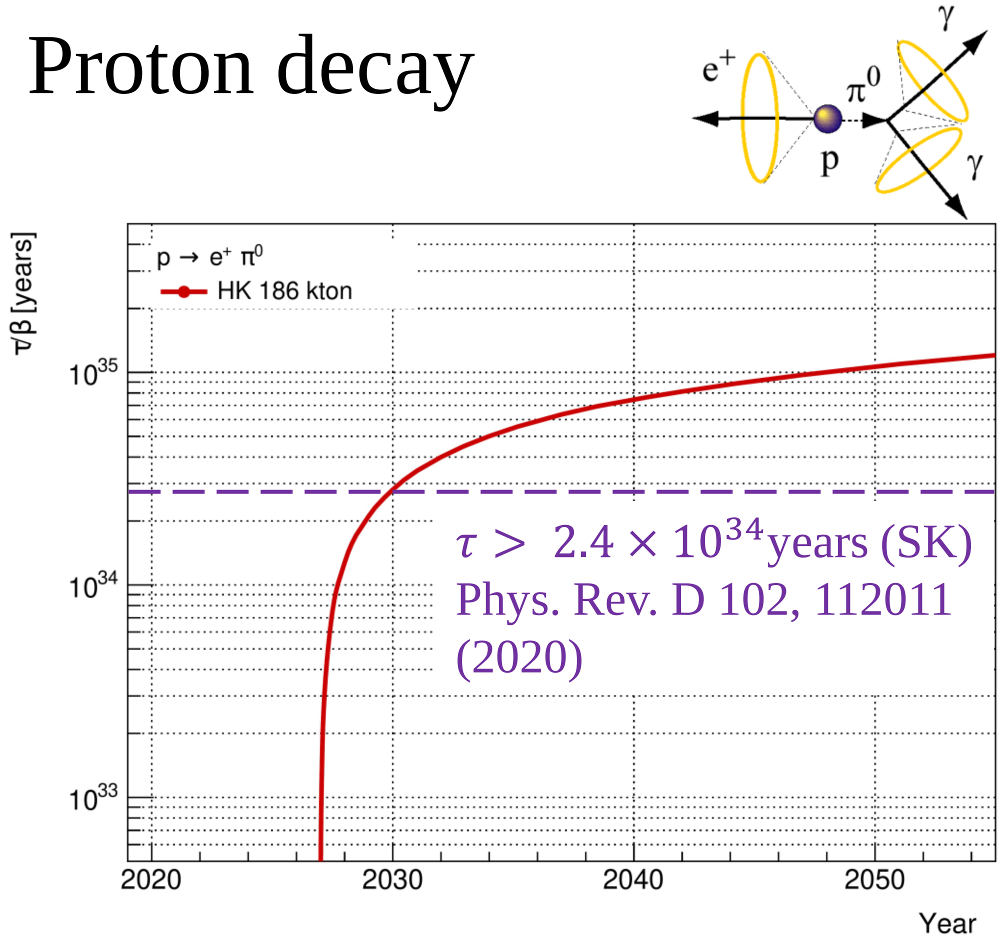
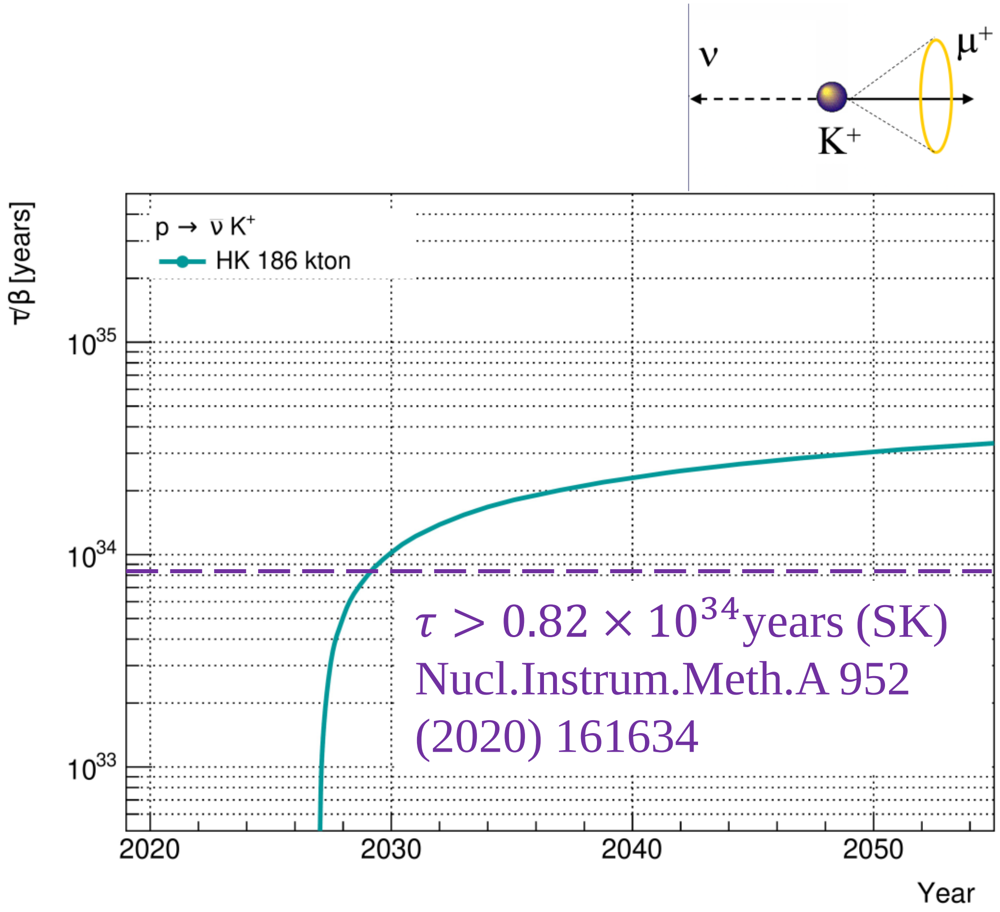
Proton decay





- Largest detector with sensitivity to multiple modes
  - Potential searching for more modes
  - GUT confirmation potential

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Search for proton decays

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- GUT confirmation potential

Supernova neutrinos

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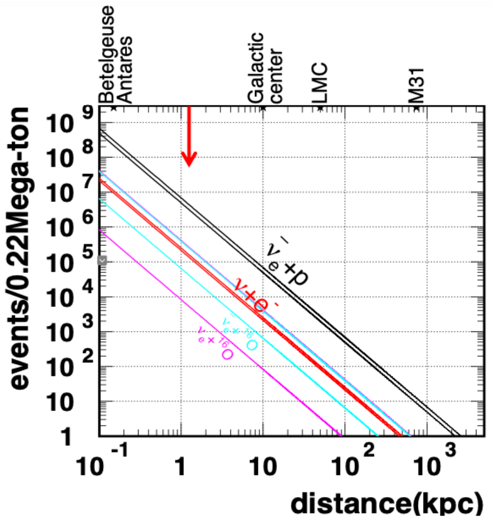
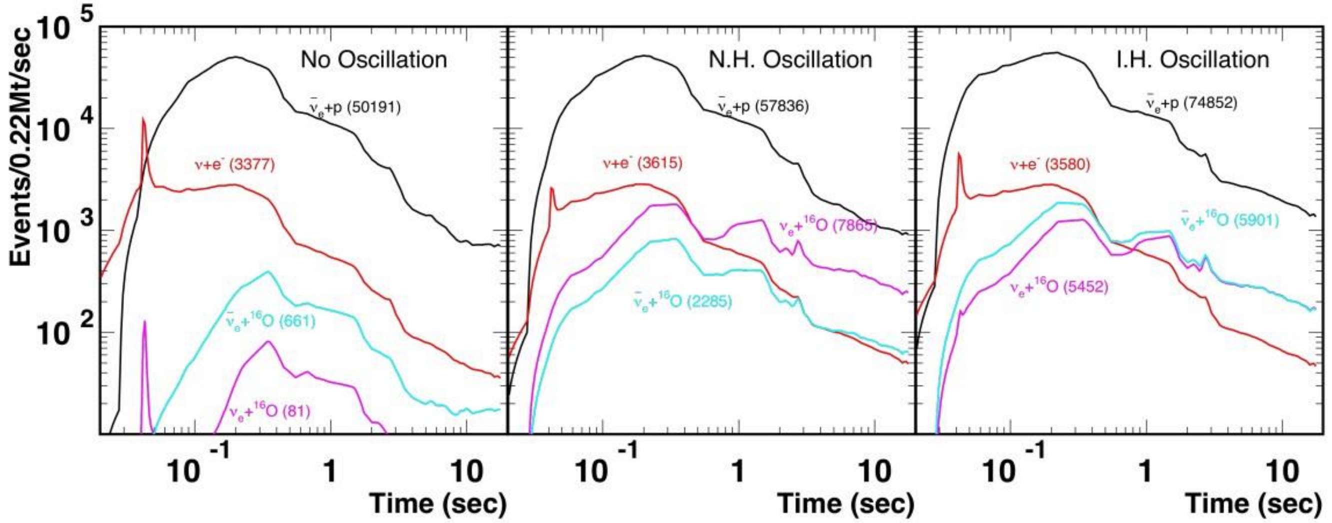
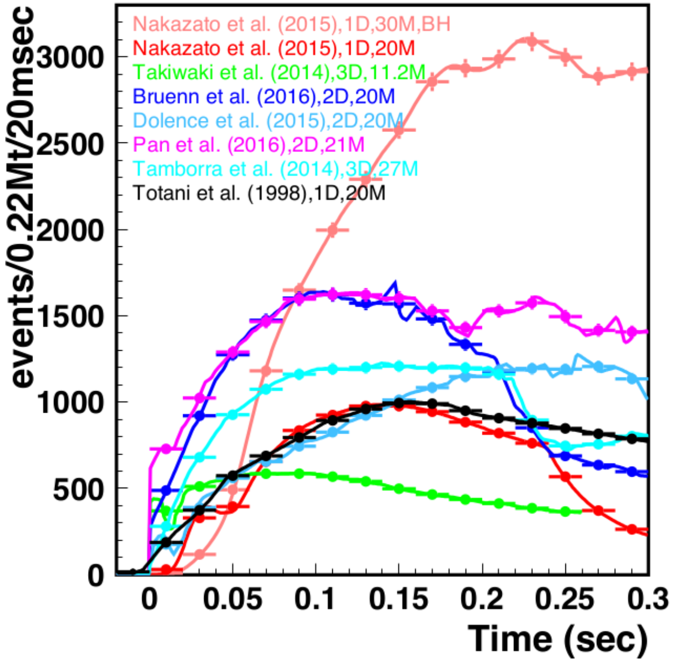
Supernova neutrinos

- Expected time profile and event numbers in HK for a supernova at 10 kpc (Livermore simulation)
- Numbers in brackets total interactions integrated over the 10 s burst
- Peak event rate of inverse beta decay events (black) reaches ~50 kHz
- Model discrimination (Astrophys.J. 916 (2021) 15)







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Physics program

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- Combined beam and atmospheric neutrinos can achieve 5-σ sensitivity to CPV regardless the mass ordering
- Precision measurements require development of proper calibration and analysis strategies

Search for proton decays

- Potential searching for more modes
- GUT confirmation potential

Supernova neutrinos

- Potential to have a large statistics if there is a supernova burst
- Distinguish between different explosion mechanism models

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Summary

- Hyper-Kamiokande is the next generation neutrino experiment located in Japan
  - 260 kton Underground water Cherenkov far detector
  - 1.3 MW upgraded neutrino beam from J-PARC
  - Upgraded ND280 and additional IWCD
  - Aim to start data taking from 2027

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- Hyper-K has various physics programs
  - CP violation, mass ordering……
  - Combined beam and atmospheric neutrinos can achieve 5-σ sensitivity to CPV regardless the mass ordering
  - Precision measurements require development of proper calibration and analysis strategies
  - Searching for proton decay, supernova neutrinos

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Summary

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  - CP violation, mass ordering……
  - Combined beam and atmospheric neutrinos can achieve 5-σ sensitivity to CPV regardless the mass ordering
  - Precision measurements require development of proper calibration and analysis strategies
  - Searching for proton decay, supernova neutrinos
- New collaborators welcome!

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Backup

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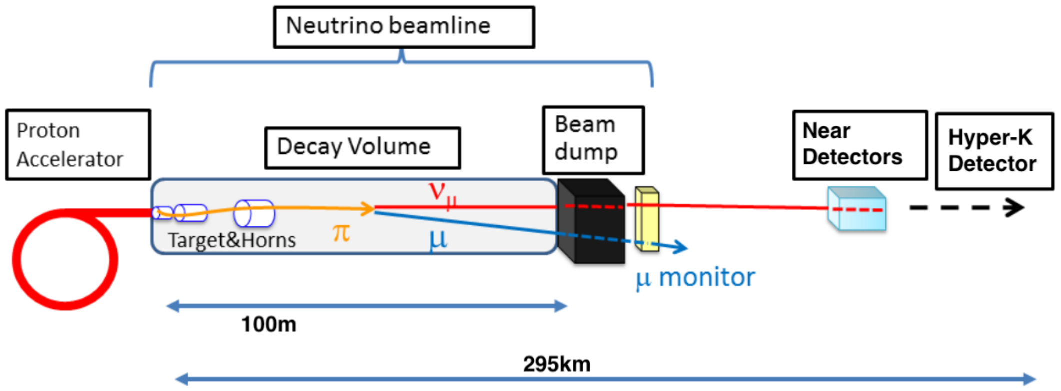
J-PARC Upgrade



- 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 $\nu\mu$'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

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Improved HK Syst. Model

- 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 ∼10% level
    - The $\nu_e/\bar{\nu}_e$ 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%
- Statistics only (no systematics)

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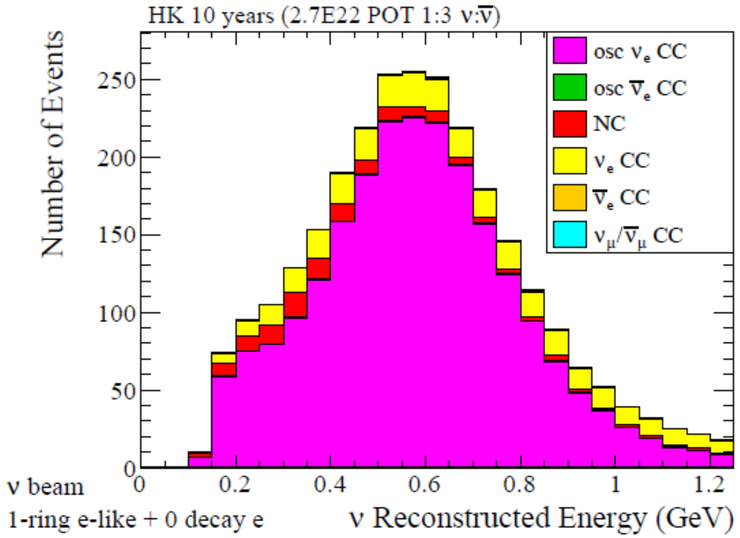
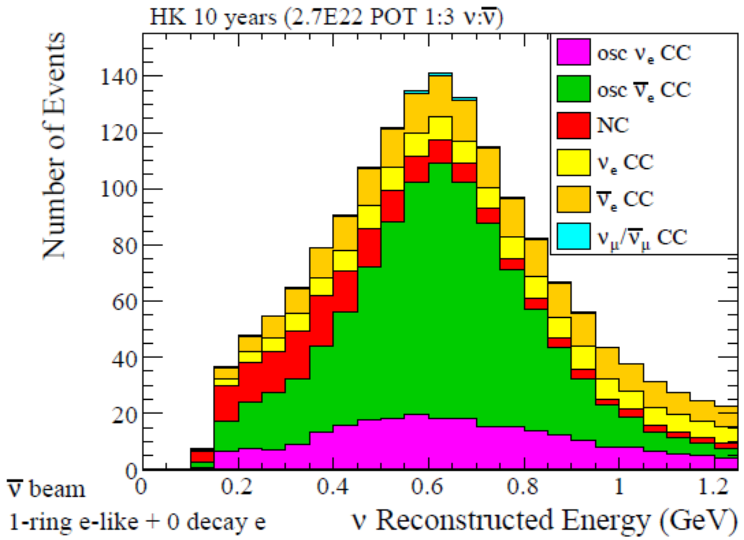
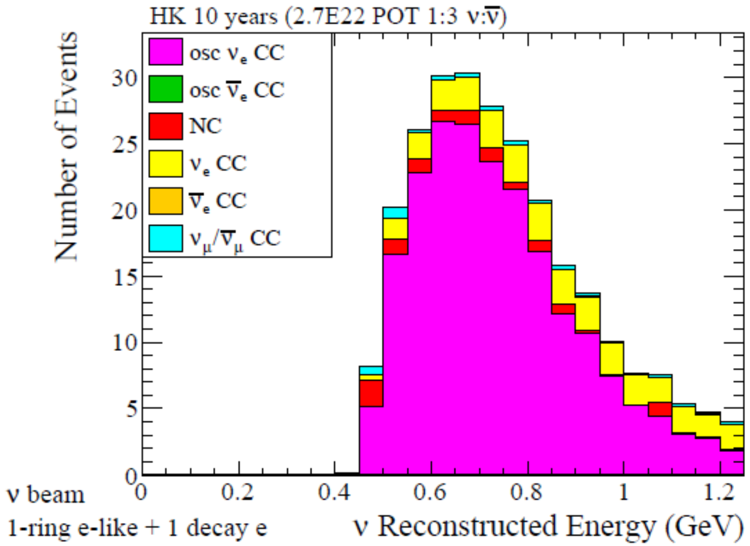
HK Long-Baseline ν_e Spectra







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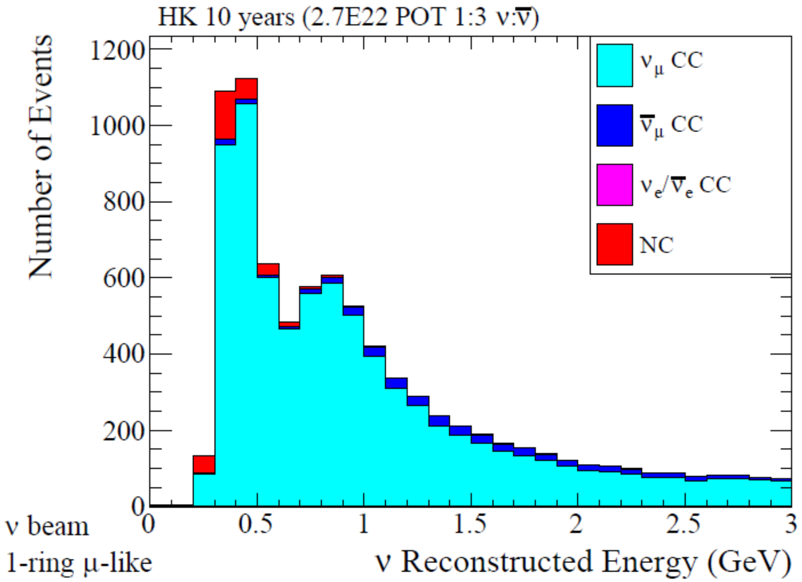
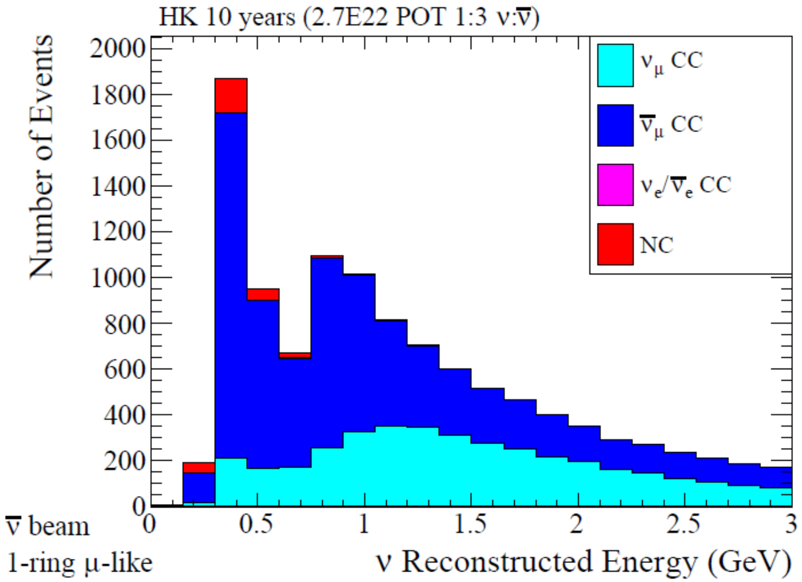
HK Long-Baseline ν_e Spectra





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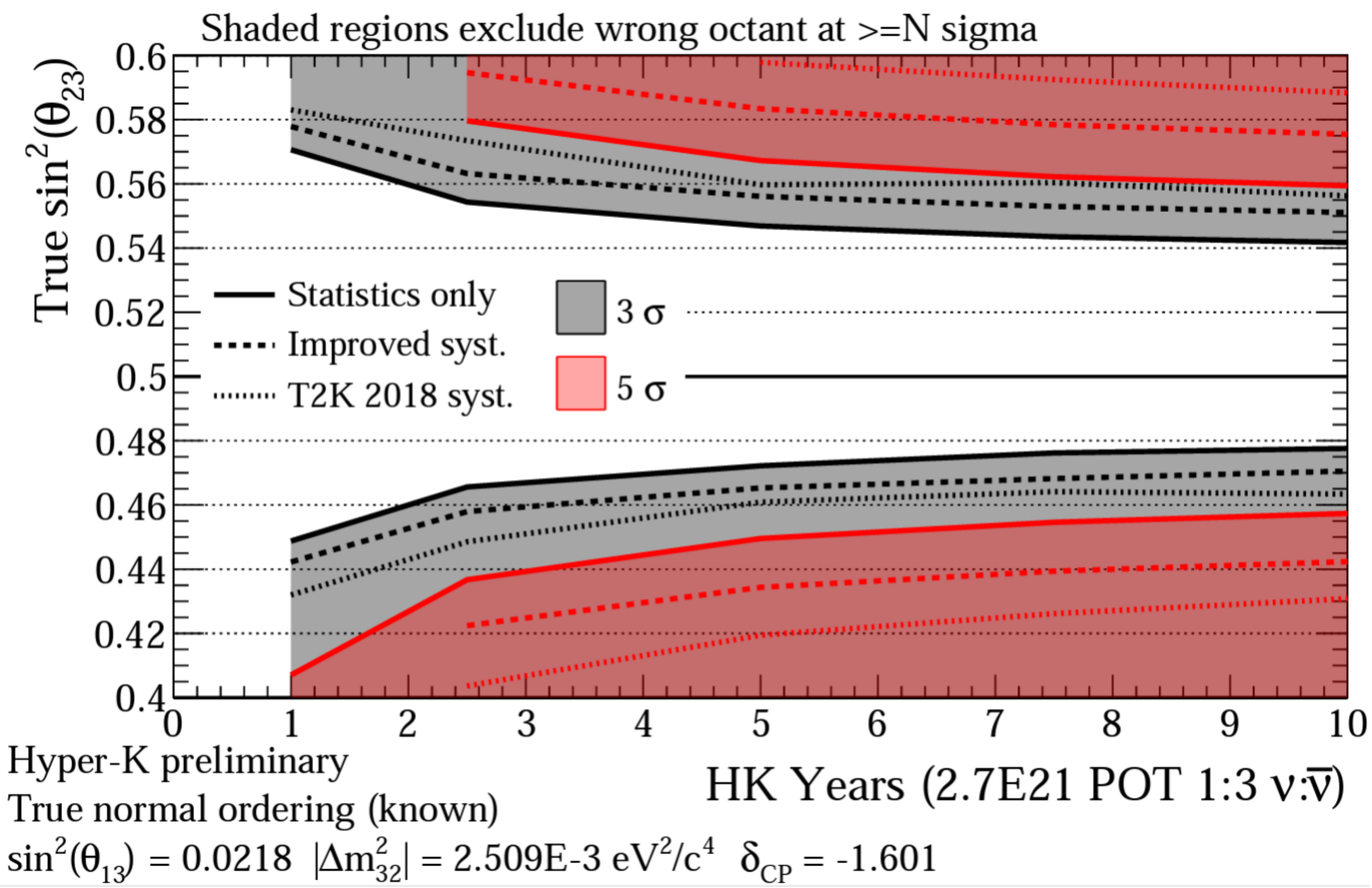
Measurement of θ_{23} Octant



Sensitivity to exclude the wrong $\sin^2\theta_{23}$ octant, as a function of true $\sin^2\theta_{23}$ and HK-years.

The shaded areas exclude $\sin^2\theta_{23}$=0.5 at greater than 3 σ and 5 σ.