Atmospheric Neutrino Studies at Hyper-K

Advanced Workshop on Physics of Atmospheric Neutrinos - PANE 2018

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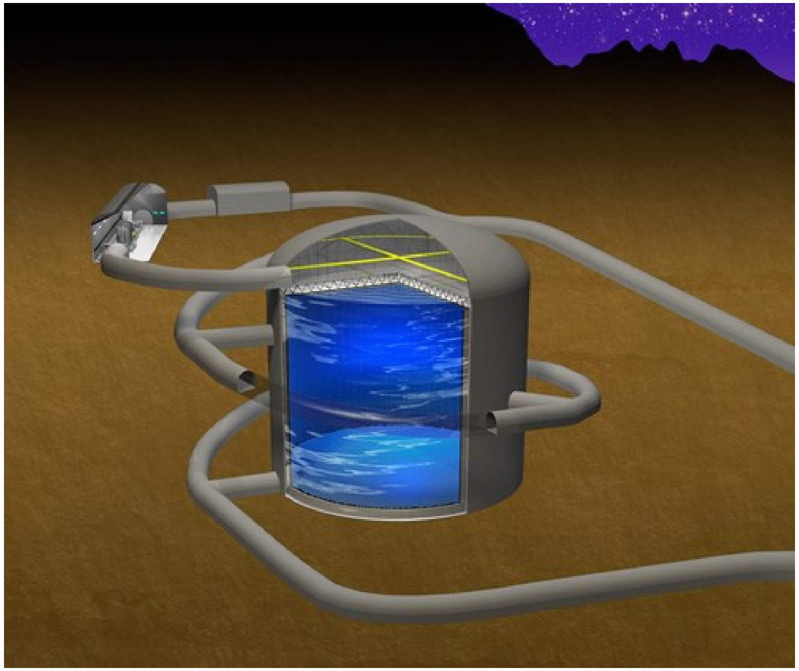
Outline

- Hyper-Kamiokande
- Atmospheric neutrino studies
- Tokai-to-Hyper-Kamiokande (T2HK)
- Atmospheric neutrinos and combination with beam neutrinos
- Second tank: staging and Korean detector options
- Summary

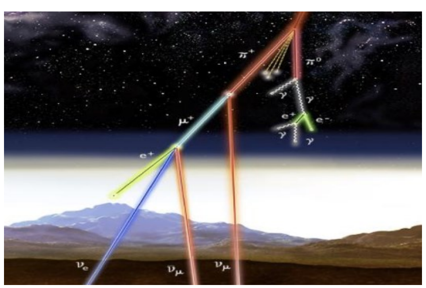
Hyper-Kamiokande: overview

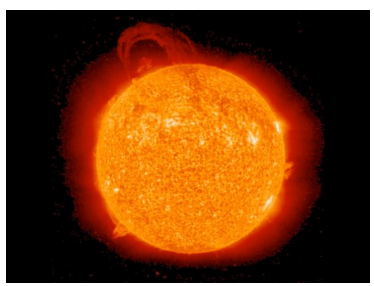


Hyper-Kamiokande is a multi-purpose **Water-Cherenkov detector** with a variety of scientific goals:

✧ Neutrino oscillations (atmospheric, accelerator and solar);
✧ Neutrino astrophysics;
✧ Proton decay;
✧ Non-standard physics.

Atmospheric ν



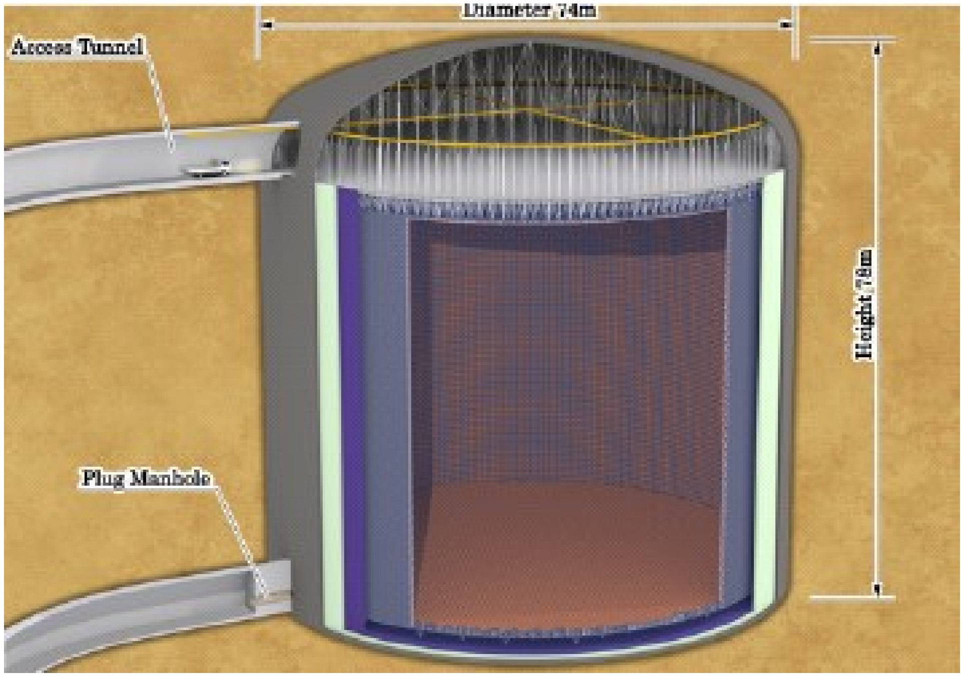


Solar ν

Supernova ν

Accelerator ν

Hyper-Kamiokande design



HK builds on the successful strategies used to study neutrino oscillations in Super-Kamiokande, K2K and T2K with:

- Larger detector for increased statistics
- Improved photo-sensors for better efficiency
- Higher intensity beam and updated/new near detector for accelerator neutrino part

2 tanks with staging construction.

- Cylindrical tank: Φ 74 m and H 60 m
- Total and fiducial volumes (for one tank): 0.26 and 0.19Mtons, resp.
- Photo-cathode coverage: 40%. 40,000 ID PMTs and 6700 OD PMTs per tank.

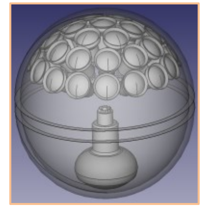
Planned time line:
Project approval 2019
Experiment 2026 (1st tank)
Proposals for a second tank

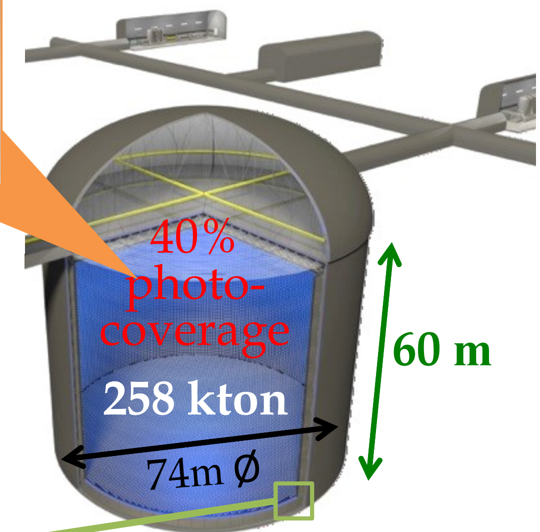
Recent R&D results on PMTs

Requirements

Wide dynamic range, High time&charge resolutions, high detection efficiency…

~nsec time resolution
low background
Clear photon counting,
High rate tolerance





187 kton Fiducial Mass

×2 tanks

About 7,000 PMTs for Outer Veto Detector

New high-QE 50 cm Box&Line PMT
×2 high pressure bearing for 60 m depth
×2 high detection efficiency
and half time&charge resolutions

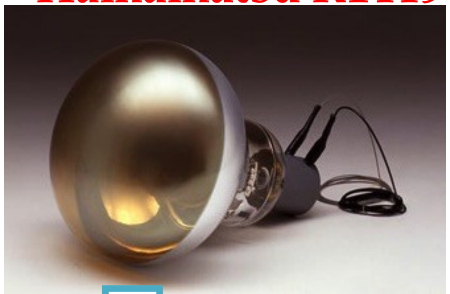
compared to Super-K PMT (up to ~40m depth)

ID: Planned 40,000 photosensors
Baseline option: 20'' PMTs
Alternative option:
50% 20'' PMTs and 50% mPMTs

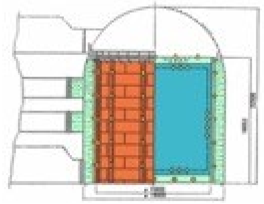
50 cm Photo-Detectors

First 20-inch (50 cm) Photomultiplier Tube (PMT)

Hamamatsu R1449 (Venetian blind dynode)



For Kamiokande



(1983-1996)

1k PMTs
/ 3 kton water

Supernova ν observation!

R3600 (Venetian blind dynode, improved)

For Super-Kamiokande

(1996-)

11k PMTs
/ 50 kton water

ν oscillation discovery!

For Hyper-Kamiokande

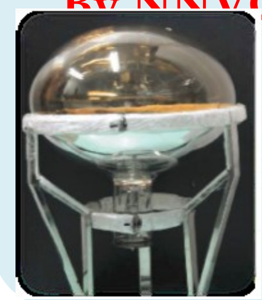
For other experiments

42 cm (17”) Box&Line PMT

R7250
(Box&Line dynode)
with 50 cm bulb
of R3600

For KamLAND

50 cm MCP PMT
By NNVC, IHEP



For JUNO
Recently
developed
in **China**

50 cm Box&Line PMT
R12860-HQE (Box&Line dynode)

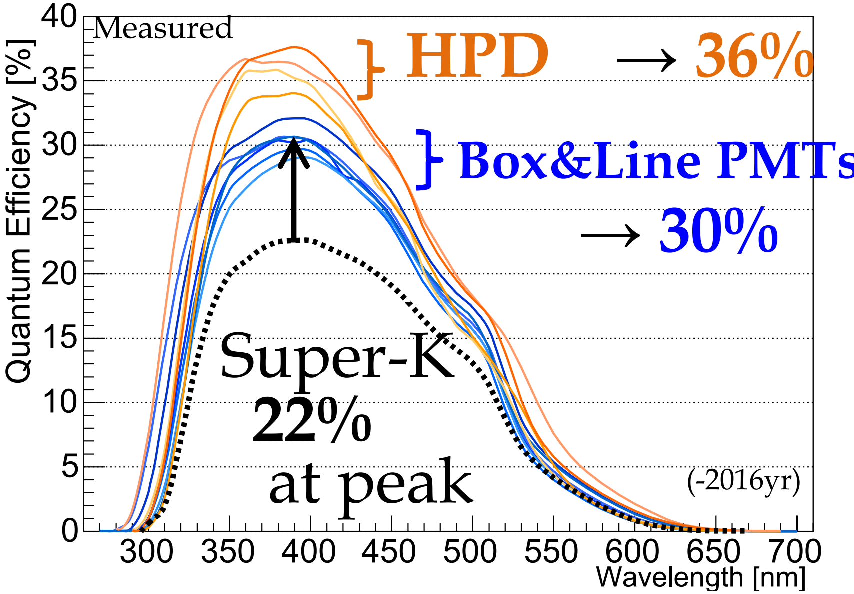
Developed
→ Photo-detector
in Hyper-K
baseline design

50 cm Hybrid Photo-Detector (HPD)
R12850-HQE (Avalanche diode)

Under development
→ Possible further
improvement of
Hyper-K

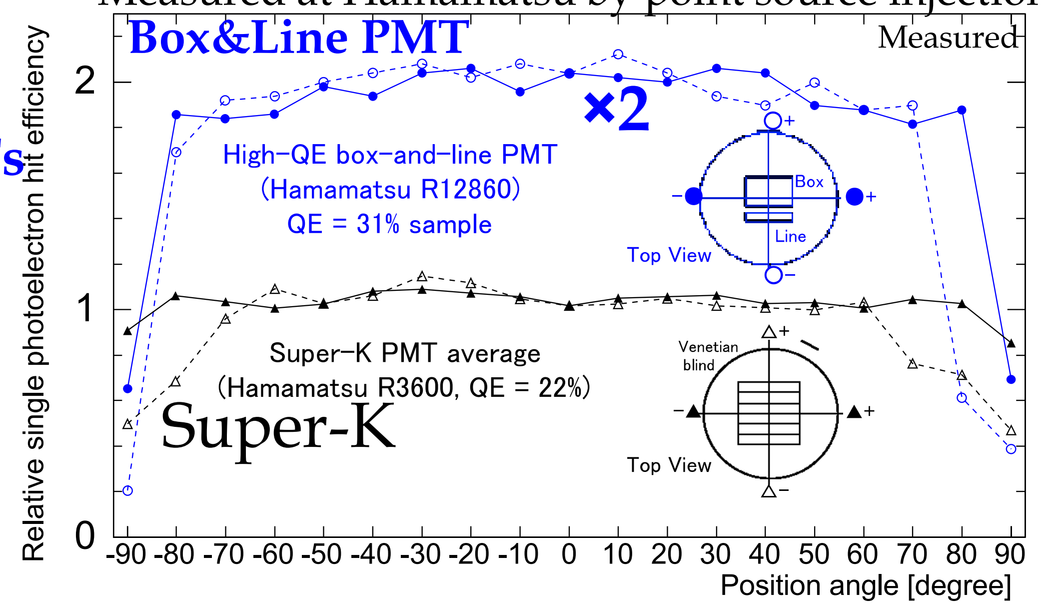
50 cm Photo-Detectors

High Quantum Efficiency (QE)



Total Detection Efficiency of 1 PE

Measured at Hamamatsu by point source injection



Collection Efficiency (CE)

By simulation In 46cmΦ (50cmΦ)

- Super-K 67% (61%)
- Box&Line PMT 95% (85%)
- HPD (1ch 20mmΦAD) 97% (80%)

Relative comparison of single PE counting compared with SK PMT by a uniform light injection

Box&Line PMT : 1.91 of SK PMT

HPD (2ch 20mmΦAD) **: 1.76** of SK PMT

(Low due to higher threshold for 1 PE)

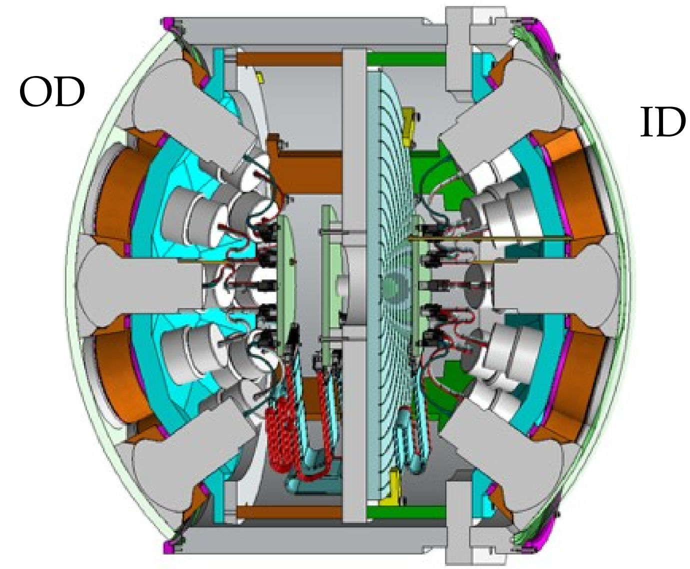
Detection efficiency was doubled in both new photo-detectors

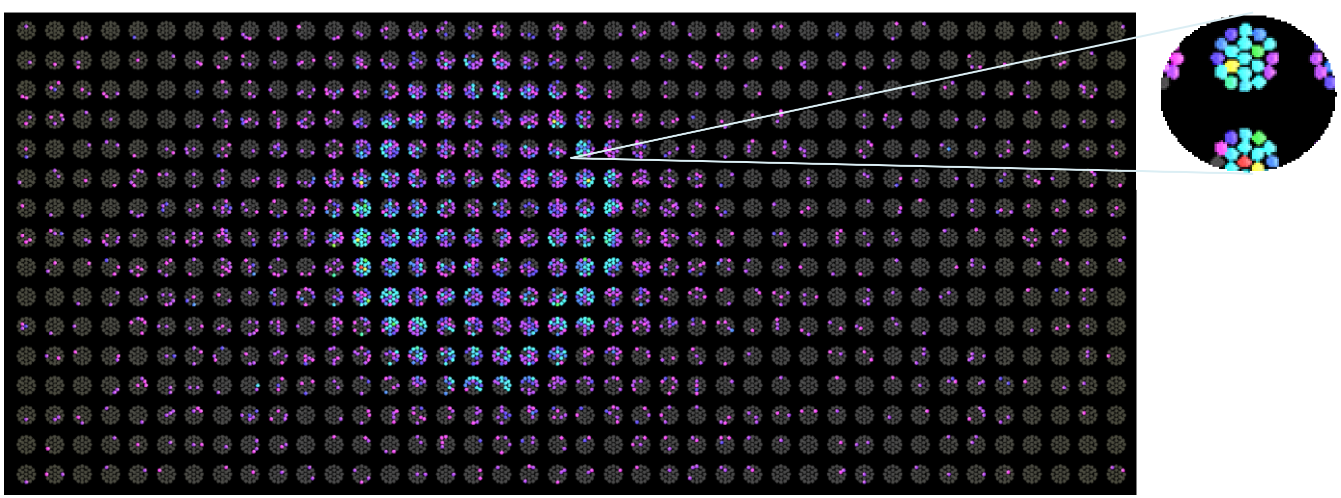
Multi-PMT Option for Hyper-K

Based on KM3NeT optical module

Photodetectors and electronics arranged inside a pressure resistent vessel

- (Almost) uniform coverage by PMTs
- Directionality
- Several manifacturers





<u>Increased granularity</u> enhanced event reconstruction, in particular for multi-ring events

Atmospheric neutrinos

Now that θ_{13} is known to be quite large, there are several open questions remaining, including

- ordering of the neutrino masses
- octant of the atmospheric mixing angle
- whether or not neutrino oscillations violate CP

Atmospheric neutrinos are a good tool for studying L/E-style oscillations in a broad sense

- ❑ With larger statistics, they can also provide information on sub-leading effects

Matter effect gives improved sensitivity

- ❖ Mass hierarchy → Asymmetry between neutrinos and antineutrinos
- ❖ size of θ_{13} and δ_{CP} → Magnitude of resonance effect
- ❖ Octant of θ_{23} → Appearance and disappearance interplay

Atmospheric neutrinos

- Matter-induced parametric oscillations in the energy range 2-10 GeV lead to significant enhancement of either the $\nu_\mu \rightarrow \nu_e$ or the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance probability for upward-going neutrinos depending upon the mass hierarchy.

  For the normal (inverted) hierarchy neutrino (antinuetrino) oscillations are enhanced

- The separation of atmospheric neutrino data into neutrino-like and antineutrino like subsets with neutron tagging can be used to extract the hierarchy signal

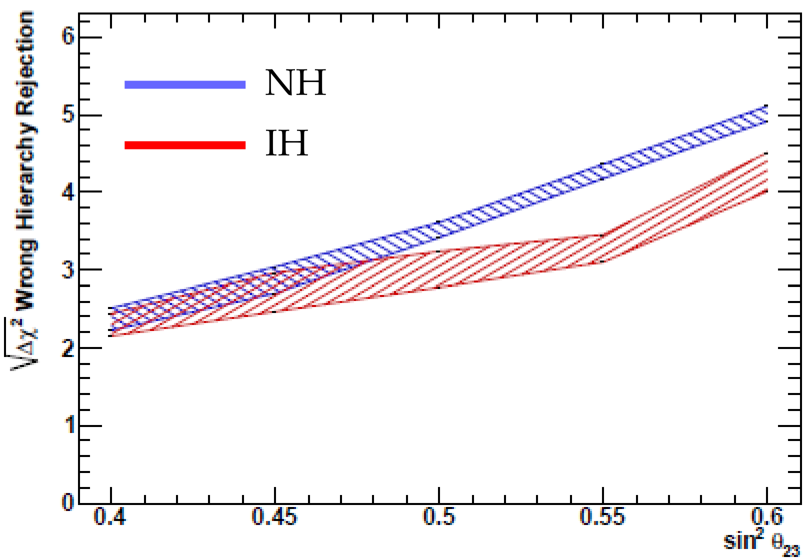
- Improved photon collection and increased statistic is expected to improve the sensitivity of atmospheric neutrinos

Atmospheric neutrinos

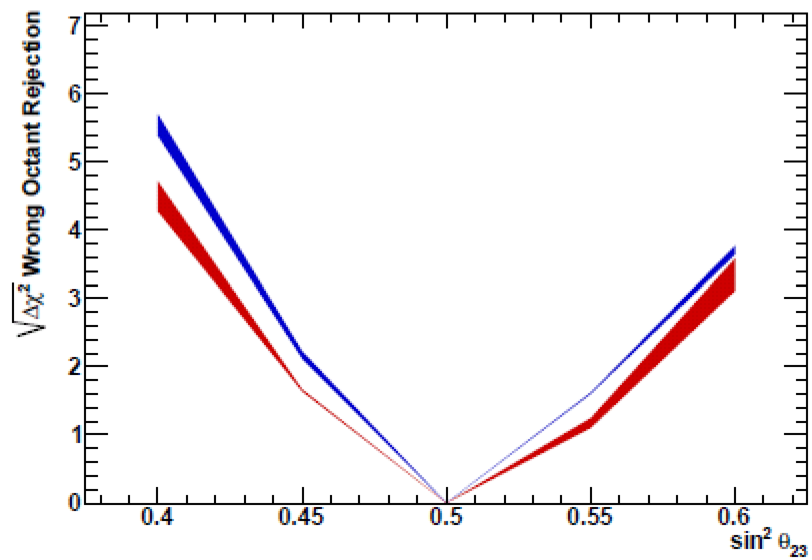
Using atmospheric neutrinos alone:

- ❖ Determine mass hierarchy at 3σ when $\sin^2\theta_{23} > 0.53$
- ❖ Some sensitivity to θ_{23} octant
- ❖ Sensitivities depend on true θ_{23} value

Mass hierarchy determination



Octant determination



Sensitivity studies based on SK analysis

- Scaled SK MC
- 10 years running with one 187 kt fv detector
- No improvement of Super-K systematics assumed
- True mass hierarchy not assumed to be known

(see talk by C. Bronner)

Width of the bands shows the uncertainty from δ_{CP}

Tokai-to-Hyper-Kamiokande (T2HK)

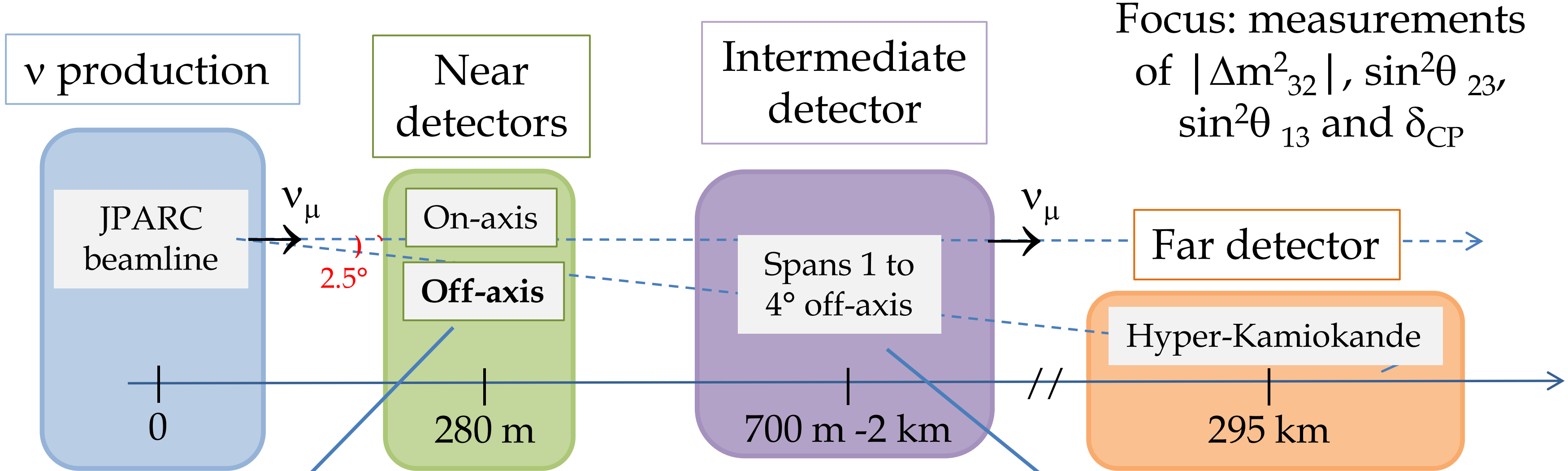
long baseline neutrino oscillation experiment

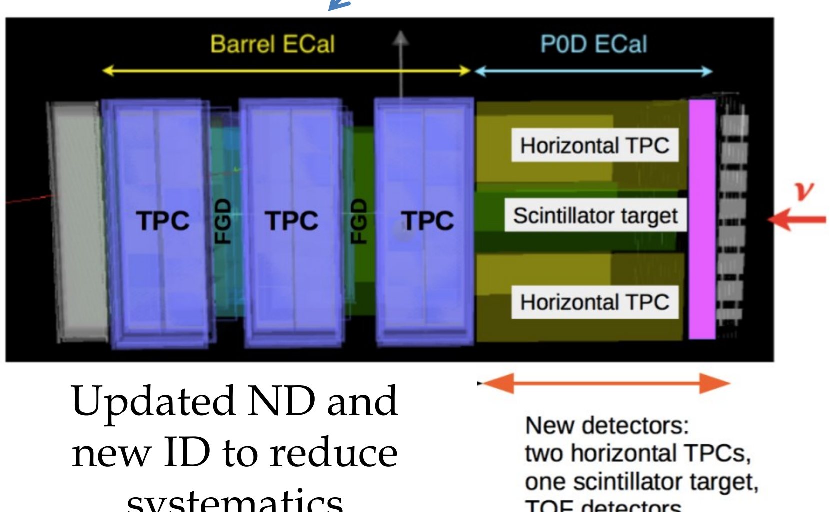
- ✧ Upgraded facility at J-PARC will deliver a muon (anti-)neutrino beam towards Hyper-K (≈ 0.75MW, 1.56×10^{22} protons on target with 30 GeV proton beam);
- ✧ 2.5° off-axis narrow-band beam:
  - ❑ Suppresses high energy background;
  - ❑ $E_\nu \approx 0.6$ GeV peak at oscillation maximum;
- ✧ Pure ν_μ beam with < 1% ν_e contamination.

new power upgrade plan of J-PARC → we expect ~>900kW by 2020, and ~1.3MW as early as 2026

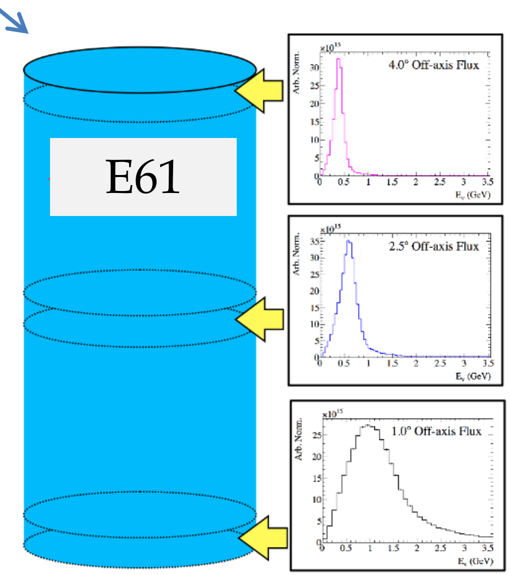
Tokai-to-Hyper-Kamiokande (T2HK)

Focus: measurements of $|\Delta m^2_{32}|$, $\sin^2\theta_{23}$, $\sin^2\theta_{13}$ and δ_{CP}





Updated ND and new ID to reduce systematics

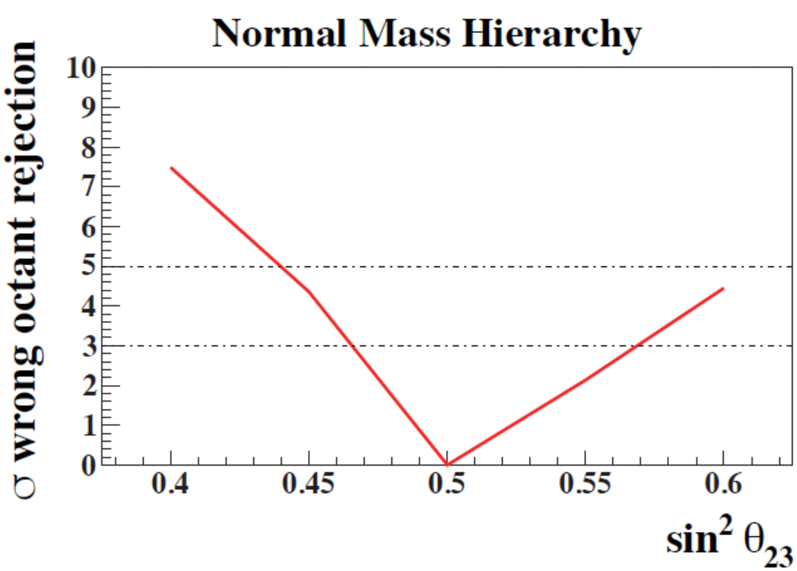


T2HK: Sensitivity to atmospheric parameters

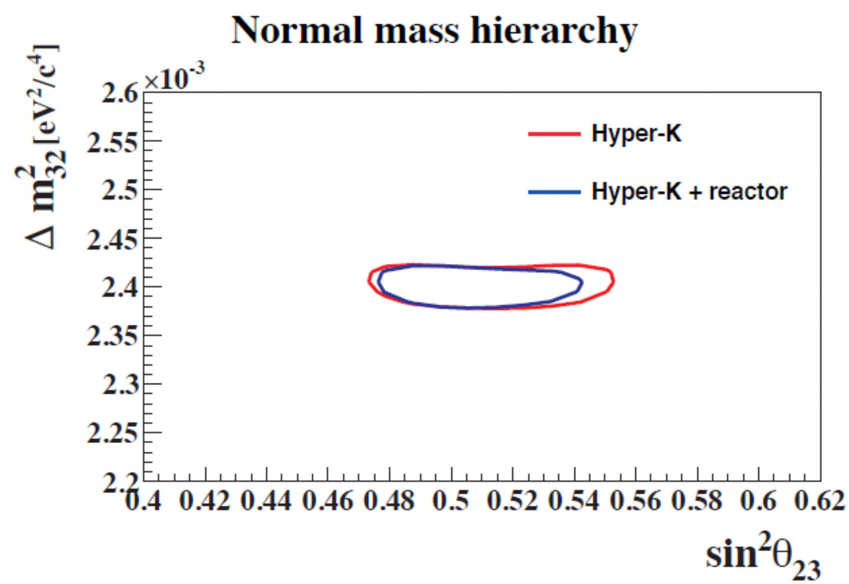
After 10 years:

- Measure Δm^2_{32} with 1.4×10^{-5}ev^2 precision
- Measure $\sin^2\theta_{23}$ with precision 0.006 to 0.017
- Some ability to determine octant of θ_{23}

A joint fit of ν_μ and ν_e samples to precisely measure $\sin^2\theta_{23}$ and Δm^2_{32}



Expected significance for wrong octant rejection, with reactor constraint,vs true $\sin^2\theta_{23}$



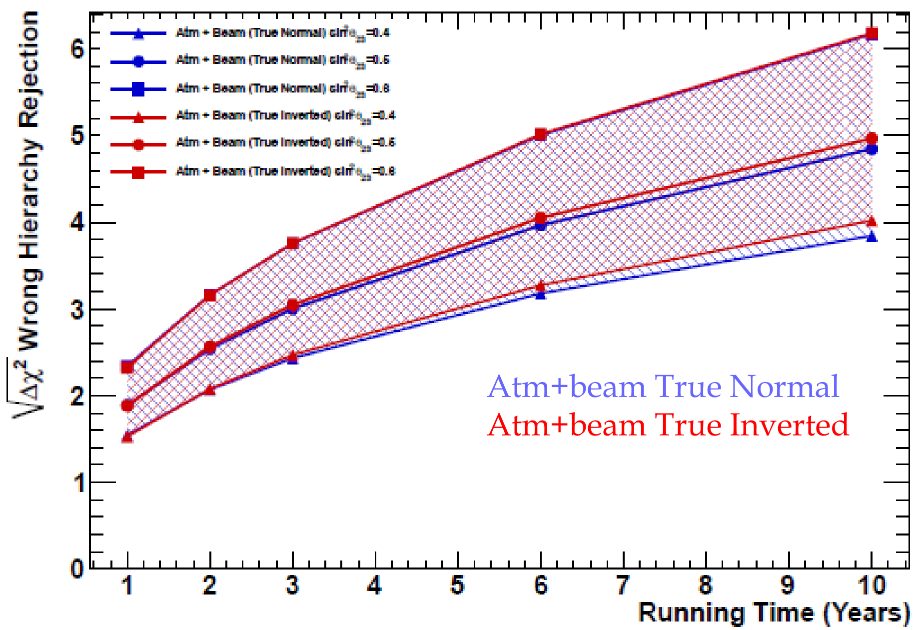
90% CL allowed regions for the true values of $\sin^2\theta_{23} = 0.5$ and $\Delta m^2_{32}= 2.4 \times 10^{-3}$ eV^2
Reactor constraint on $\sin^2 2\theta_{13} = 0.1 \pm 0.005$

T2HK: Sensitivity to mass hierarchy

Atmospheric+beam neutrinos

<u>Atmospheric neutrinos</u>

- ❖ Sensitive to mass hierarchy through matter induced resonance
- ❖ Size of the effect depends of θ_{23}
- ❖ Limited precision for θ_{23} and $|\Delta m^2_{32}|$



<u>Beam neutrinos</u>

- ❖ Very limited sensitivity to MH
- ❖ Good precision for θ_{23} and $|\Delta m^2_{32}|$ measurements

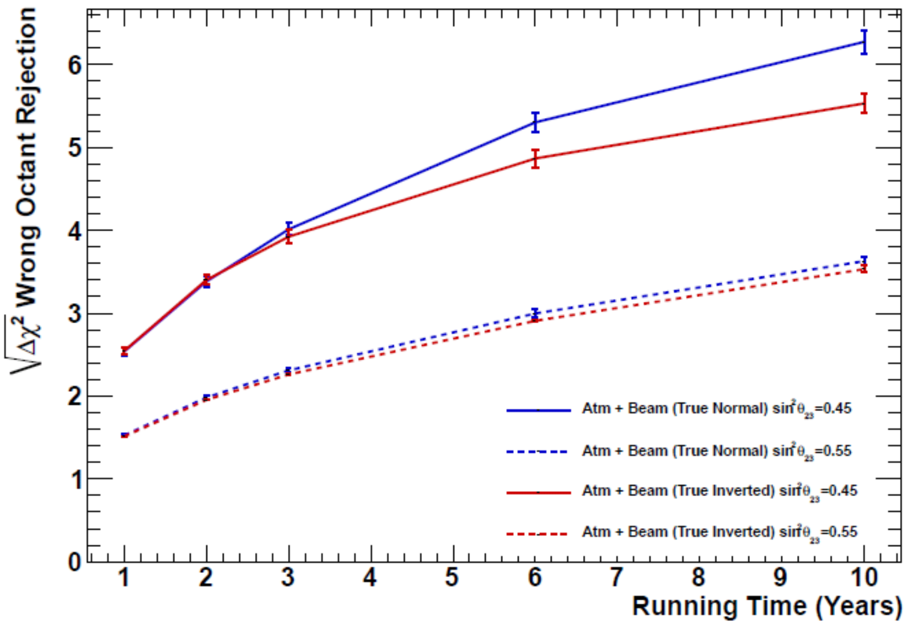
<u>Combining the two:</u>

- ✓ >3σ ability to reject wrong MH
- ✓ 5σ for larger values of $\sin^2\theta_{23}$

True $\sin^2\theta_{23}$	Atmospheric only	Atmospheric +beam
0.4	2.2 σ	3.8 σ
0.6	4.9 σ	6.2 σ

T2HK: octant resolution sensitivity

Atmospheric+beam neutrinos



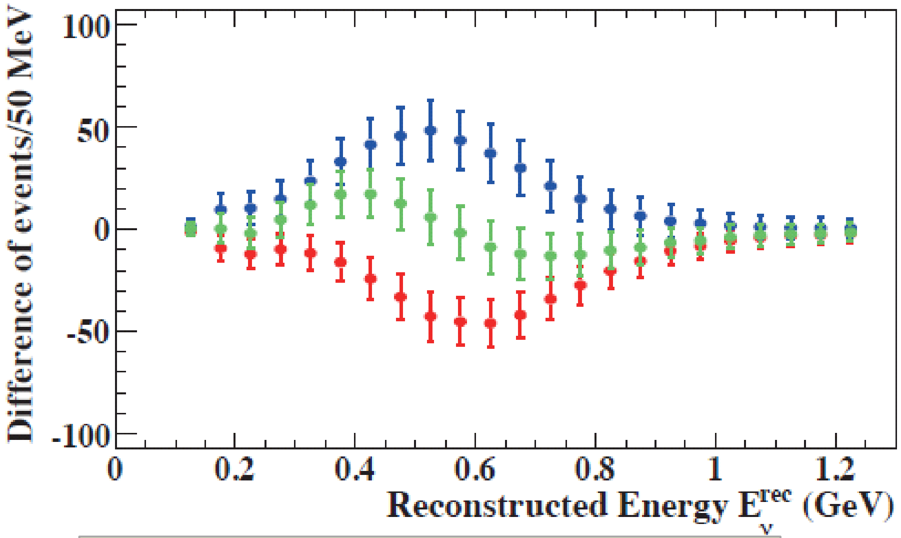
assuming a normal hierarchy, $\Delta m^2_{32} = 2.5 \times 10{-}3eV^2$, $\sin^2\theta_{23} = 0.0219$, and the value of CP that minimizes the sensitivity

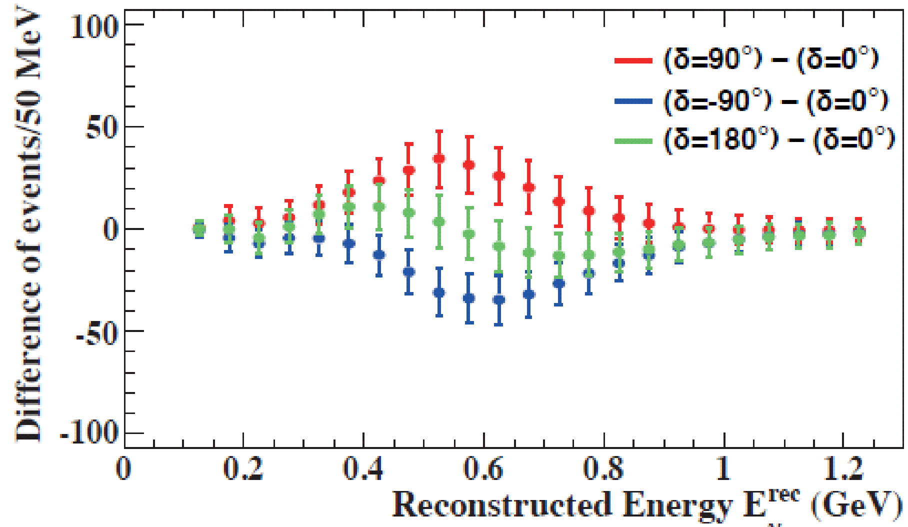
The ability to resolve the θ_{23} octant improves with the combination

Atmospheric neutrinos alone can resolve the octant at 3σ if $|\theta_{23} - 45| > 4°$
With combined analysis it can be resolved when this difference is only 2.3°

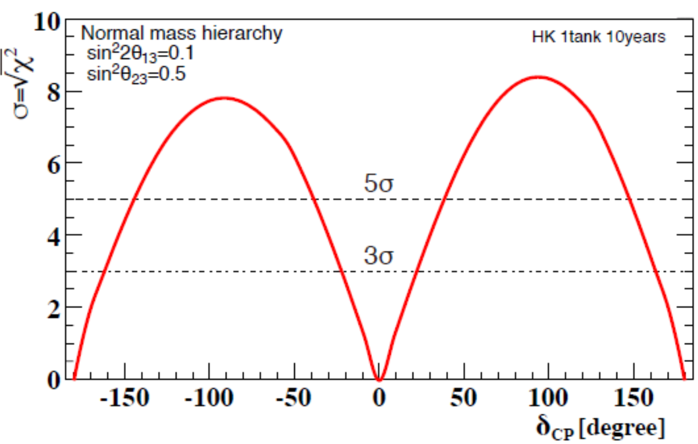
True $\sin^2\theta_{23}$	Atmospheric only	Atmospheric +beam
0.45	2.2 σ	6.2 σ
0.55	1.6 σ	3.6 σ

T2HK: Sensitivity to CP-violation



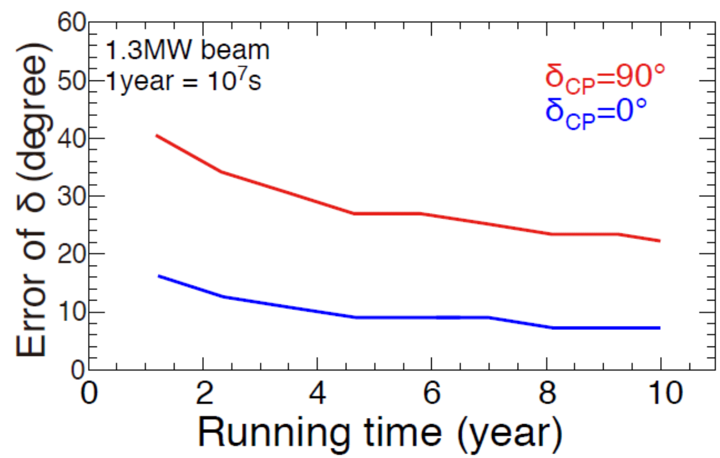


Ability to exclude CP conservation



Exclude CP conservation at 5σ (3σ) for 57% (76%) of possible true values of δ

Precision of δ measurement



Measure δ: 7° (true δ=0) to 23° (true δ=90°) precision

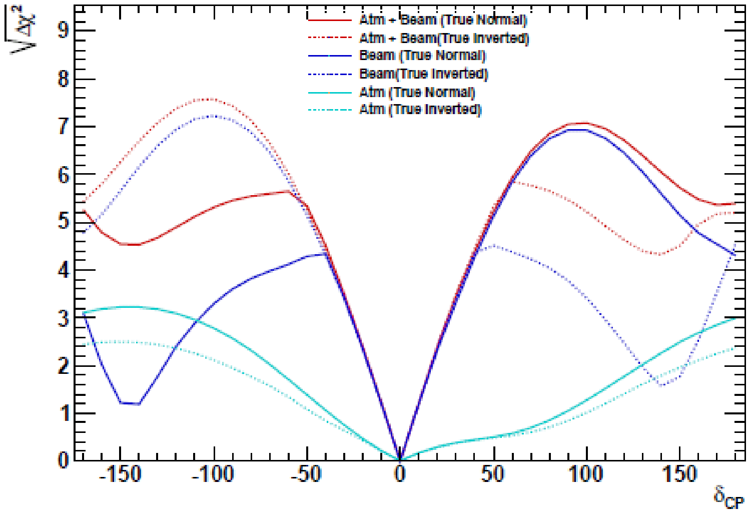
T2HK: Sensitivity to CP-violation

Atmospheric+beam neutrinos

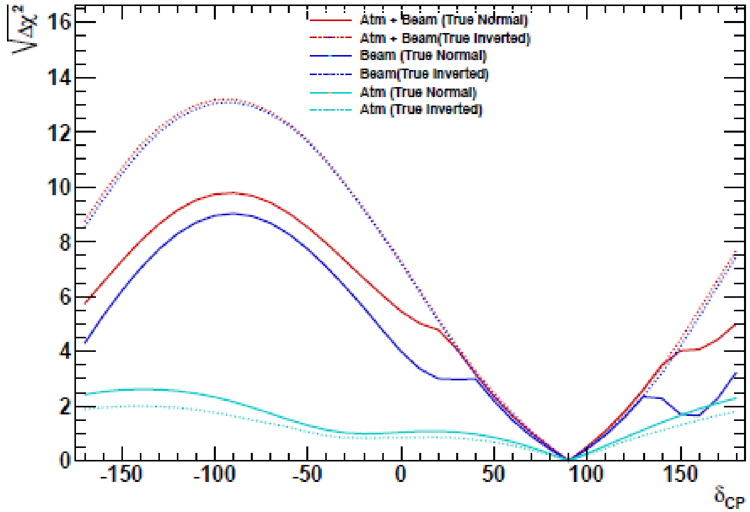
Sensitivity to CP violation mainly coming from beam neutrinos

Atmospheric neutrinos allow to break possible degeneracies between MH and δ when MH is unknown

True δ =0



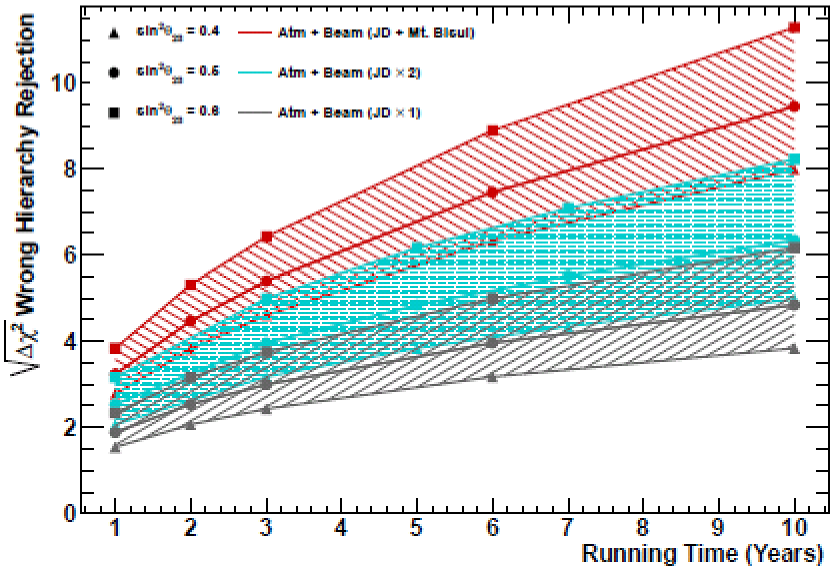
True δ =90°

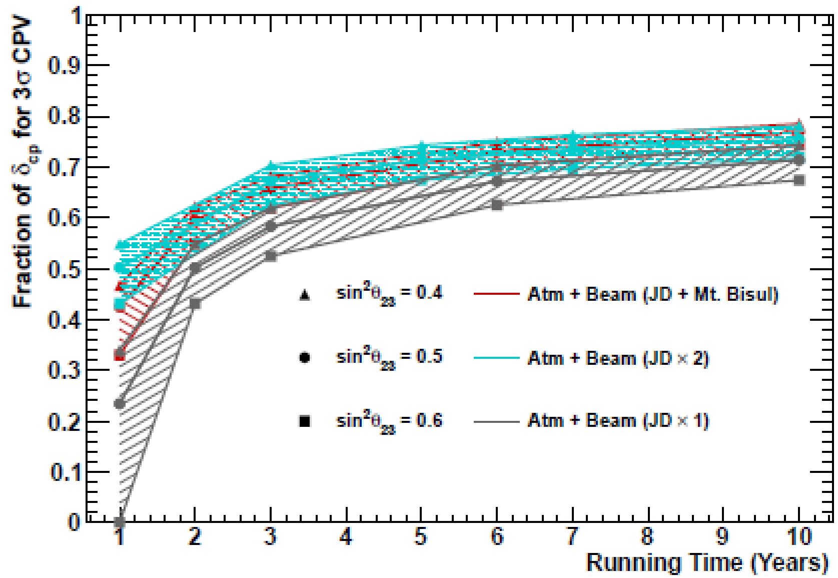


Second detector

Staging approach

second water Cherenkov detector in a later stage:
- possibly in Korea: baselines of 1,000-1,300 km and OAAs of 1°-3°
- possibly in Japan

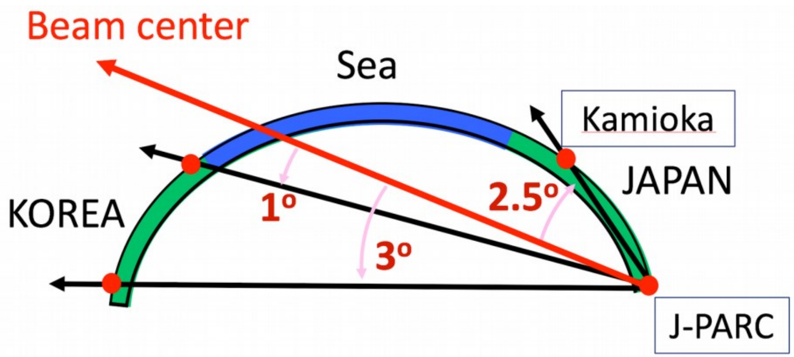




Second detector

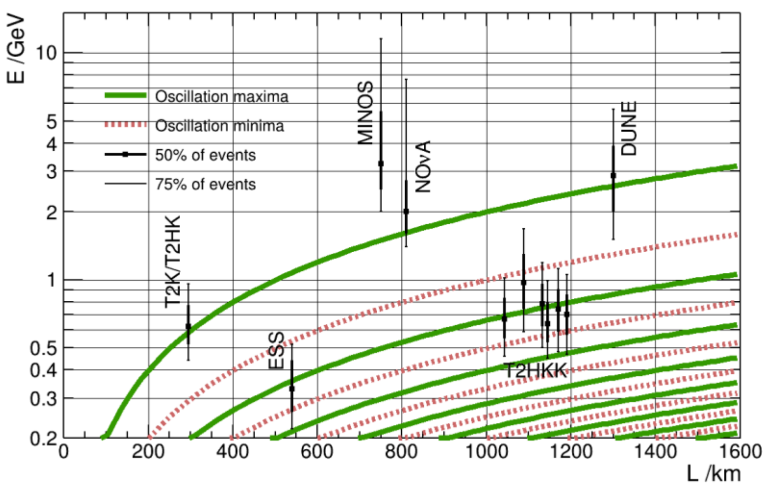
Second detector in Korea

- 2 identical detectors with different baseline
- Longer baseline to Korea: study mass hierarchy with beam neutrinos
- Different L/E regions



Candidate sites at different OAA and L

	Off-axis angle	Baseline
Mt. Bisul	1.3°	1088 km
Mt. Bohyun	2.2°	1040 km



Korean detector depth ~1000 m → reduce the flux of cosmic ray muons

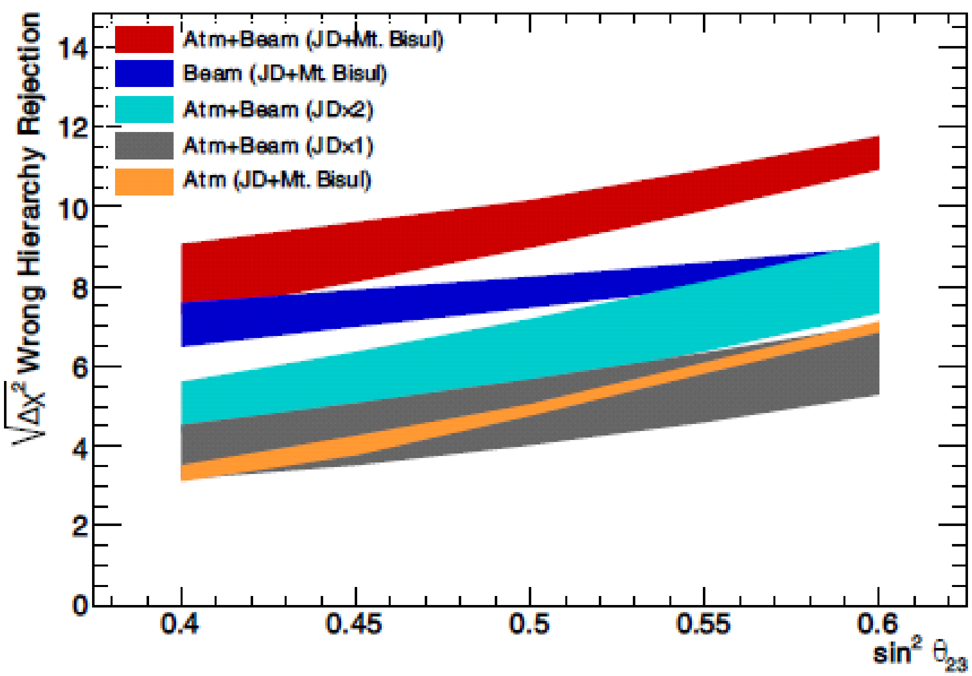
Look at oscillations at the 2nd oscillation maximum

Second detector in Korea

Mass hierarchy determination

Longer baseline to Korea: sensitivity to mass hierarchy with beam neutrinos

- ➢ Can determine mass hierarchy at 5σ after 10 years
- ➢ Combining with atmospheric neutrinos increases sensitivity

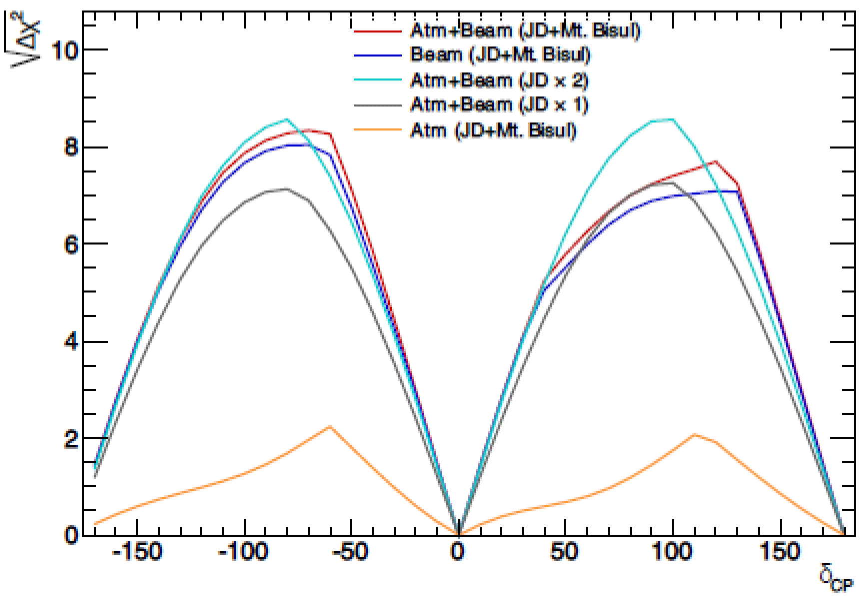


Error bands: uncertainty due to unknown δ value
JD: Japanese Detector, KD: Korean detector, JDx2 does not assume staging
True normal mass hierarchy

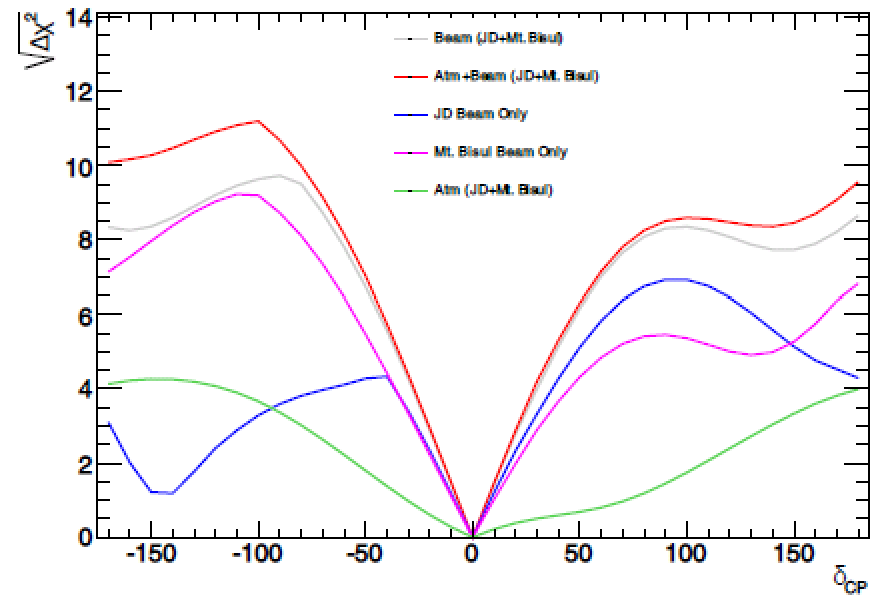
Second detector in Korea

Sensitivity to CP violation

Ability to exclude CP conservation



Sensitivity to $\delta_{CP} = 0$



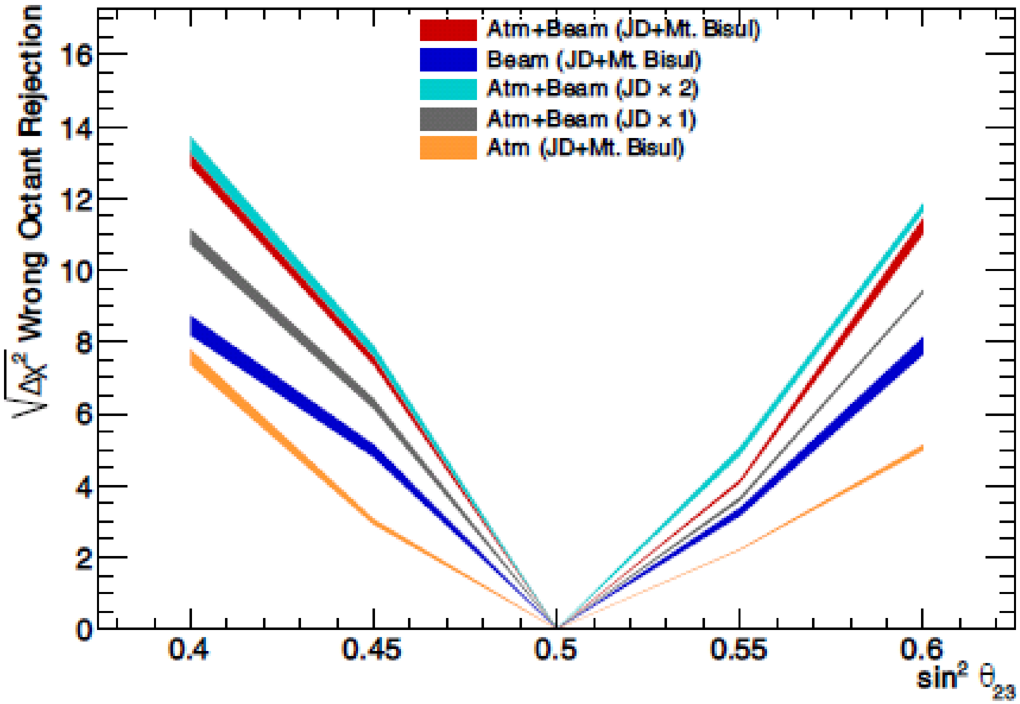
beam + atmospheric neutrinos
10 year exposure

Second detector in Korea

Octant of θ_{23}

With 10 years of beam and atmospheric data:

- Can determine octant at 5σ if $\sin^2(\theta_{23})<0.46$ or $\sin^2(\theta_{23})>0.56$ with one detector
- Increased sensitivity with a second detector



Summary

<u>Hyper-Kamiokande detector</u>

- ~x2 higher photon detection efficiency
- Larger detector

<u>Physics potential is expected to be very high</u>

- Atmospheric neutrino analyses benefit the most from increased statistics
- Improved photon collection is expected to improve the sensitivity of atmospheric neutrinos:
    - Neutrino and antineutrino separation with neutron tagging will benefit mass hierarchy and δ_{CP} sensitivity
- Expect better than ~3σ sensitivity to the mass hierarchy using atmospheric neutrinos alone (~5σ combining atm+beam ν)
- Many other interesting physics (proton decays, solar and supernova neutrinos, …)

Thank you!

Atmospheric Neutrino Fit

This study is an extrapolation of the standard three-flavor oscillation fit done at Super-K

- Approximately ~8 Fully Contained events per day
- Assumes no future enhancements, just project the SK exposure onto Hyper-K scales

Atmospheric neutrino sample

- 18 Event categories, binned by momenta and zenith angle, classified by
  - Number of rings
  - Sub-Gev / Multi-GeV
  - Whether or not all particles are contained in the inner volume

No event-by-event discrimination between neutrinos and anti-neutrinos…do this statistically

Primary three-flavor signal occurs in Multi-GeV electron-like samples

Zenith angledistributions