Future Long-baseline Neutrino Oscillations ~ View from Asia ~

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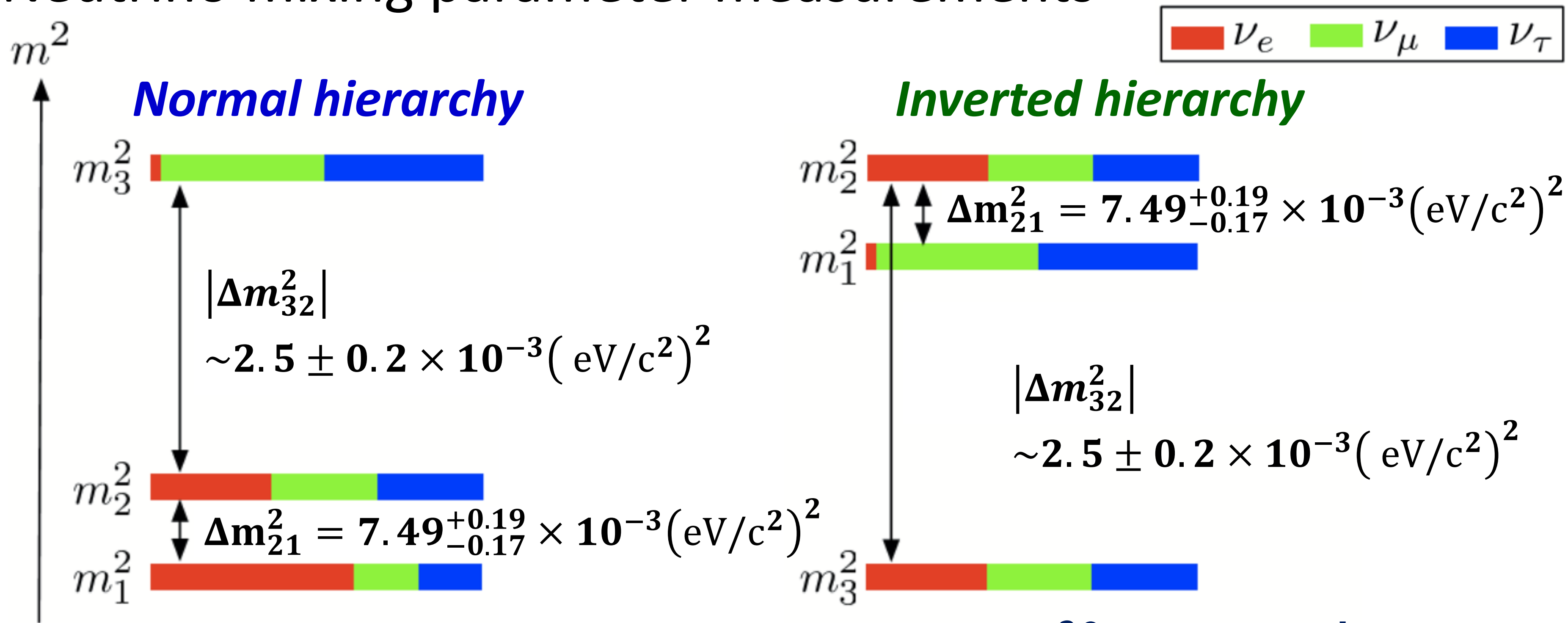
(Kamioka, ICRR, UTokyo)

Used material in this presentation Kindly Provided by

J-PARC accelerator group,
KEK neutrino group,
Hyper-Kamiokande working group, and
MOMENT group.

Neutrino mixing parameter measurements



$\sin^2\theta_{12} \sim 0.305 \pm 0.013$

$\sin^2 2\theta_{13} = 0.098 \pm 0.013$

Remaining questions

1) θ_{23} is really 45° or < 45° or >45° ?

Current uncertainty of $\sin^2\theta_{23}$ is still large ~ 10% level

$\sin^2\theta_{23} = 0.514 \pm 0.055$ **(T2K 2014)**

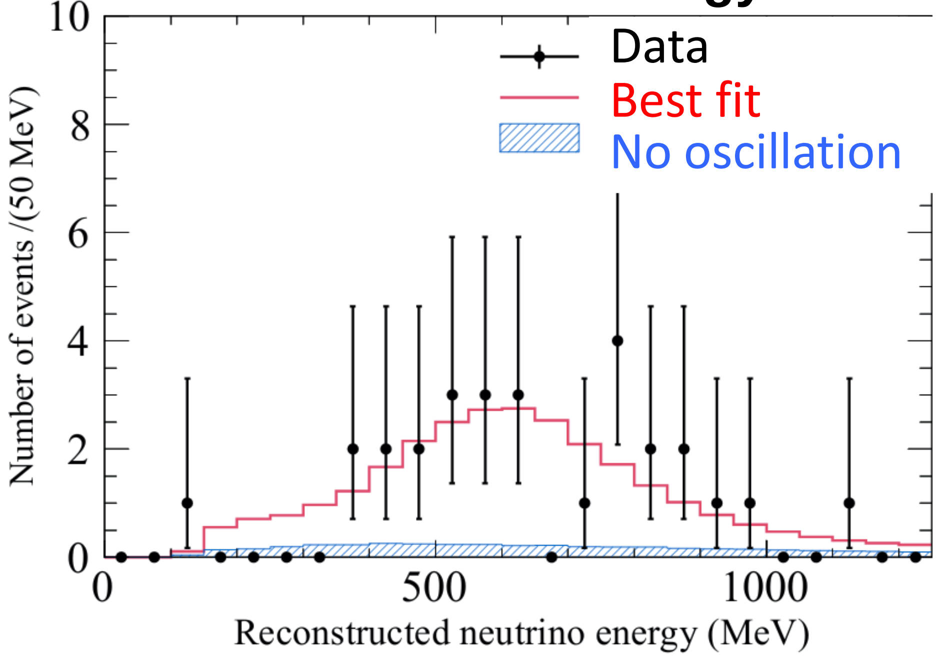
2) CP is violated or not (δ = 0 or not) ?

3) Mass hierarchy ~ which is heavier ? ($\Delta m^2_{32} > 0$ or < 0 ?)

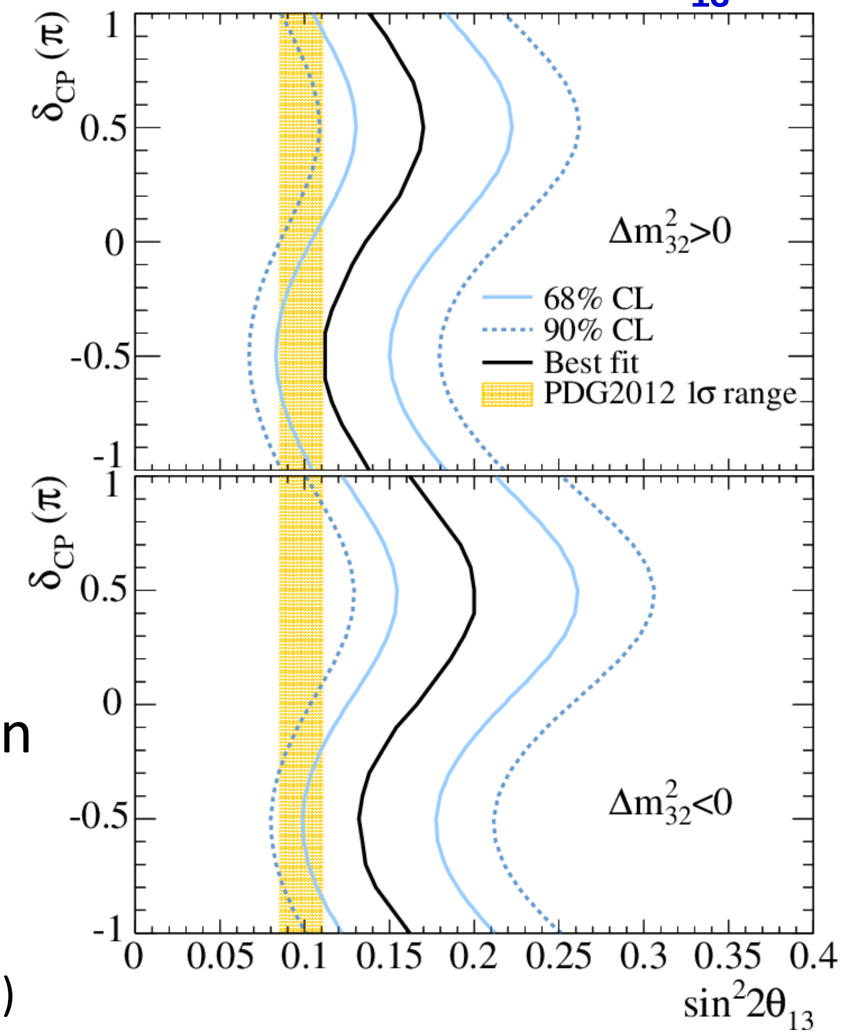
Recent results from Reactor & T2K

ν_e appearance clearly observed in T2K

Reconstructed ν energy



Allowed region of δ_{CP} for each $\sin^2 2\theta_{13}$

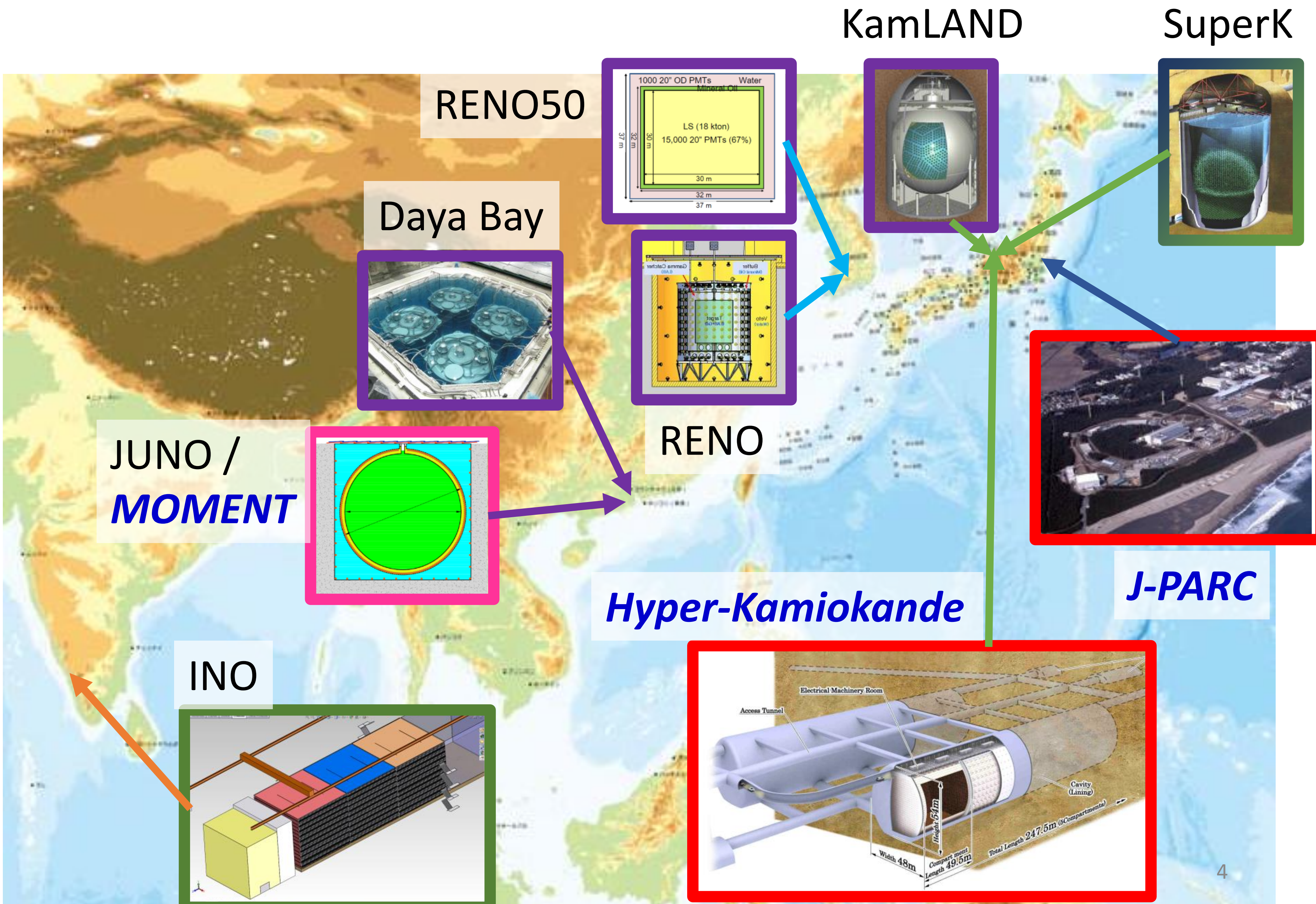


Extracted $\sin^2 2\theta_{31}$ is slightly larger than the ones from reactor experiments

$$\sin^2 2\theta_{13} = \begin{cases} 0.140^{+0.038}_{-0.032} & \text{(normal hierarchy)} \\ 0.170^{+0.044}_{-0.037} & \text{(inverted hierarchy)} \end{cases}$$

Indication of non-zero δ_{CP}?

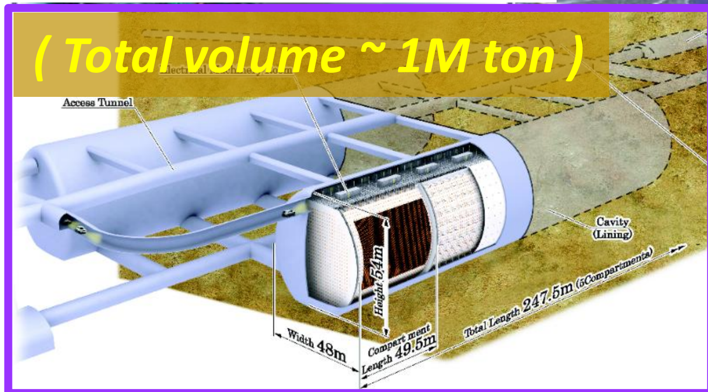
Neutrino experiments & related facilities in Asia



J-PARC neutrino beam
& Hyper-Kamiokande

Hyper-Kamiokande with J-PARC neutrino beam

Hyper-Kamiokande



J-PARC Main Ring
Neutrino beamline
(KEK – JAEA)

J-PARC neutrino beam line

One of the most powerful beamlines in operation
and further intensity upgrade (>750kW) is undergoing.

Hyper-Kamiokande

World largest water Cherenkov detector (fid. vol. 560 kt.)

Powerful combination
to search for the lepton sector CP violation!

Hyper-Kamiokande with J-PARC neutrino beam

J-PARC Accelerator & neutrino beamline

Proton intensity up to ***750 kW*** has been planned from the beginning.

Expected to achieve in 3 years.

Further upgrade (> 1MW) is under study.

All the beamline components are designed to accept full 750 kW beam.

Some unreplaceable components are designed to accept > MW beam.

JFY	2011	2012	2013	2014	2015	2016	2017
			Li. upgrade				
FX power [kW]	150	200	300	400			750
Cycle time of main magnet PS New magnet PS for high rep.	3.04 s	2.56 s R&D →	2.4 s →	→	Manufacture installation/test →		1.3 s
Present RF system New high gradient rf system	Install. #7,8	Install. #9 R&D →	→	→	Manufacture installation/test →		
Ring collimators	Additional shields	Add.collimators and shields (2kW)	Add.collimators (3.5kW)				
Injection system FX system	New injection kicker	Kicker PS improvement、Septum 2 manufacture /test → LF septum, PS for HF septa manufacture /test →					

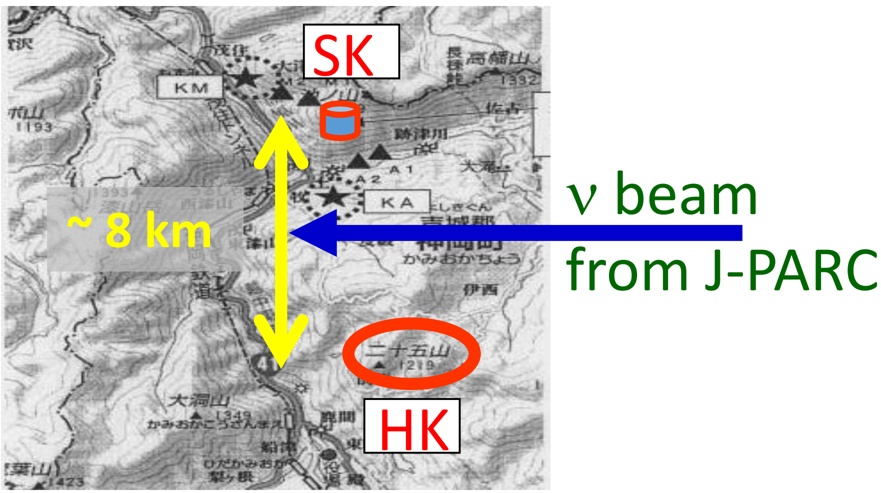
T. Koseki@1st Hyper-K meeting

Hyper-Kamiokande with J-PARC neutrino beam

Off-axis narrow band ν / $\bar{\nu}$ beam

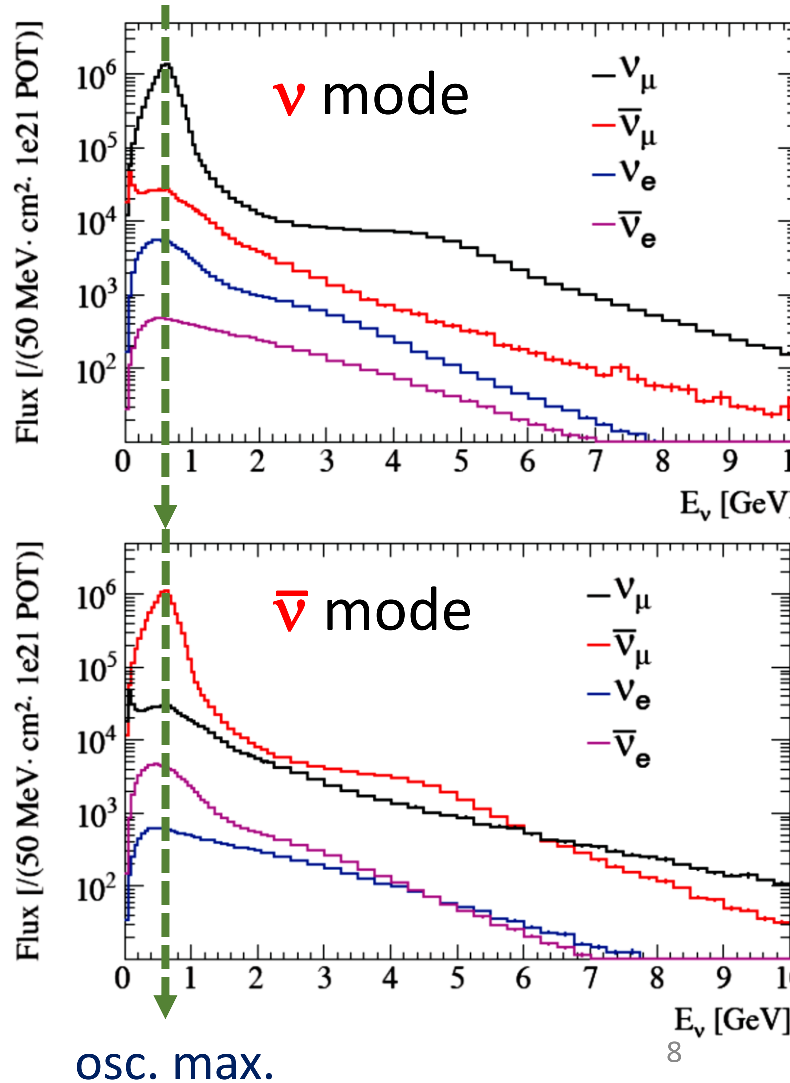
Optimized for the neutrino oscillation experiments in Kamioka.

(Both for SK and Hyper-K.)



Designed to have same off axis angle at both sites.

Small ν_e / $\bar{\nu}_e$ background around the flux peak

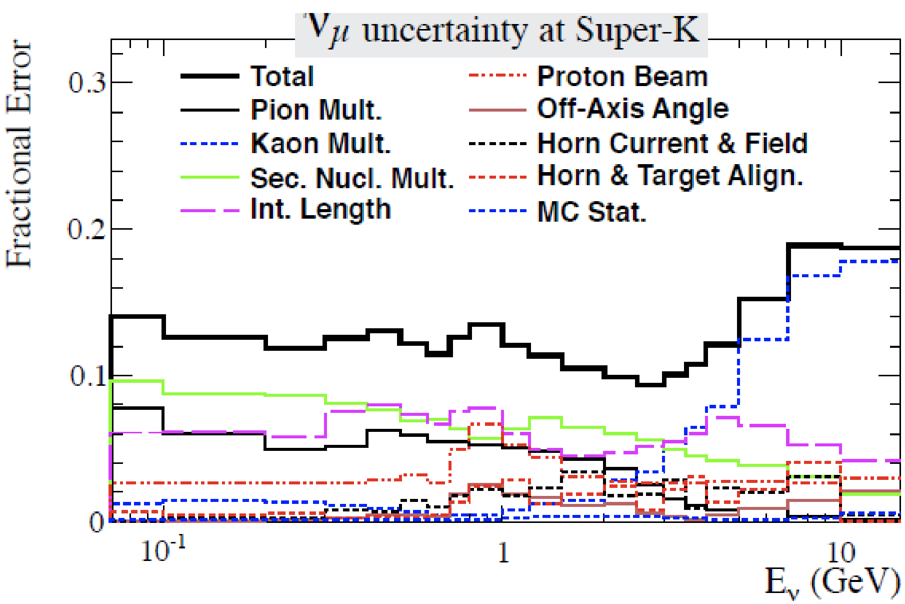


Hyper-Kamiokande with J-PARC neutrino beam

Off-axis narrow band beam

Extensive studies have been performed to understand the characteristics of the neutrino beam.

1) Dedicated hadron production experiments (as a part of NA61-Shine)



2) With ND280 measurements, uncertainties on the ratio (near/far ratio) is ***less than 2%*** near the flux peak.

& Further reduction is expected.

2) Established beam monitoring scheme.
Primary, secondary (μ) and ν themselves.

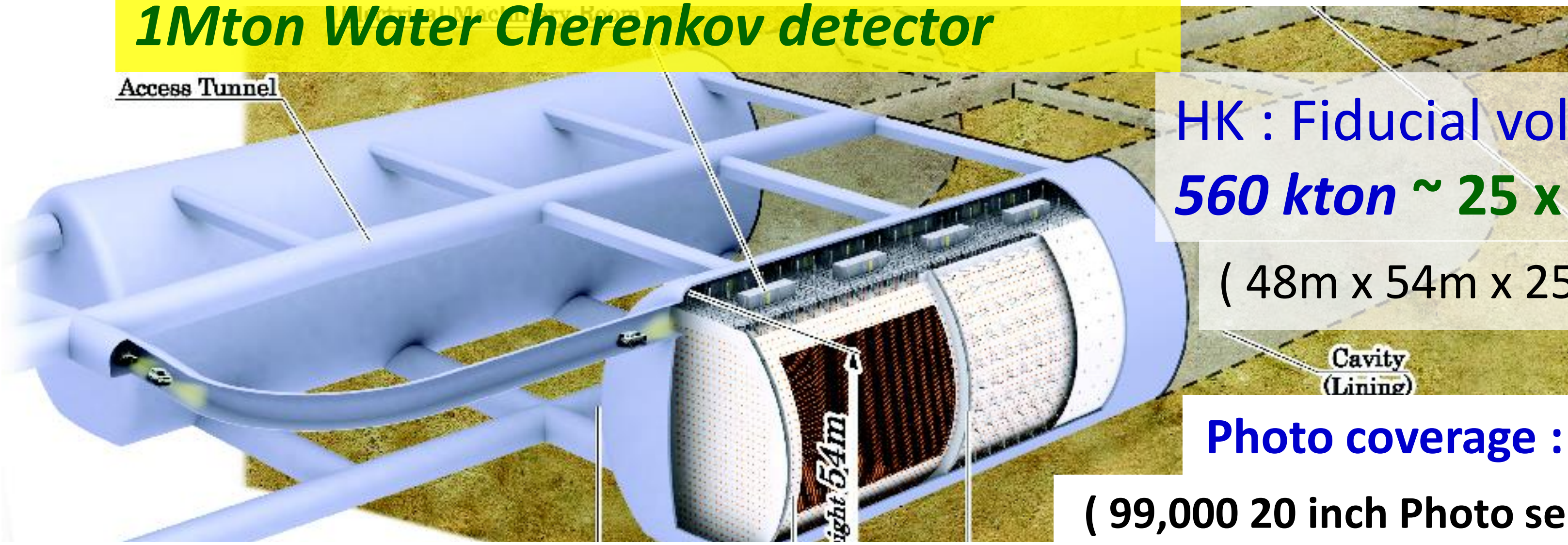
→ ***Properties of the neutrino beam is well understood.***

Hyper-Kamiokande

Far detector " Hyper-Kamiokande"

What is not sufficient in SK? => ~ Statistics = target mass ~

1Mton Water Cherenkov detector



HK : Fiducial volume
***560 kton* ~ 25 x SK**

(48m x 54m x 250m)

Photo coverage : 20%

(99,000 20 inch Photo sensors)

Maximum utilization of resources and experiences in SK
~ Use established technology for the long term operation
to achieve physics goal in timely manner.

Broad science programs

1) **Accelerator neutrinos from J-PARC**
2) Atmospheric, Solar, Super Nova and cosmic neutrinos
3) Nucleon decay searches etc....

Physics in Hyper-Kamiokande

Neutrino oscillation

- Accelerator neutrinos
- Atmospheric neutrinos
- Solar neutrinos

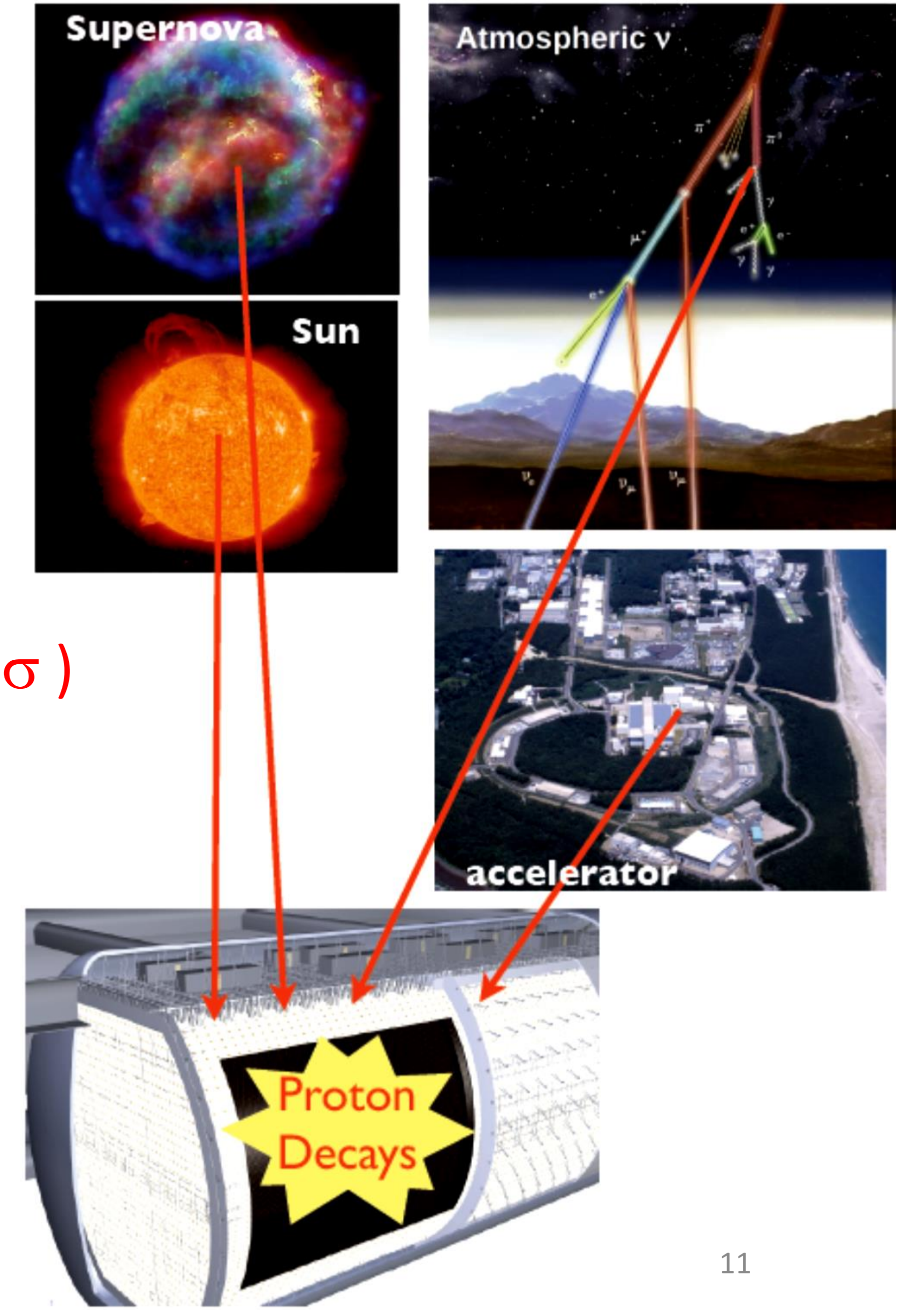
Proton decay search ~ GUT

Possible discovery with ~10 times better sensitivities than SK

$p \rightarrow e^{+} + \pi^{0}$: ~ 5.7 x 10^{34} years
$p \rightarrow K^{+} + \bar{\nu}$: ~ 1.2 x 10^{34} years
(3σ)

Neutrino astrophysics

- Super nova burst neutrino
  Expected ~200,000 ν events from SN @ 10kpc
- Relic SN neutrinos
  Expected several hundreds of events



Hyper-Kamiokande with J-PARC neutrino beam

Water Cherenkov detector

- Well established technology

  Past experiences in the long term operation

  ~ Need O(10) years of operation ~

- Continuous improvements in the data analysis

  (Event reconstruction & background rejections)

  One particular example ***~ New π^0 rejection method ~***

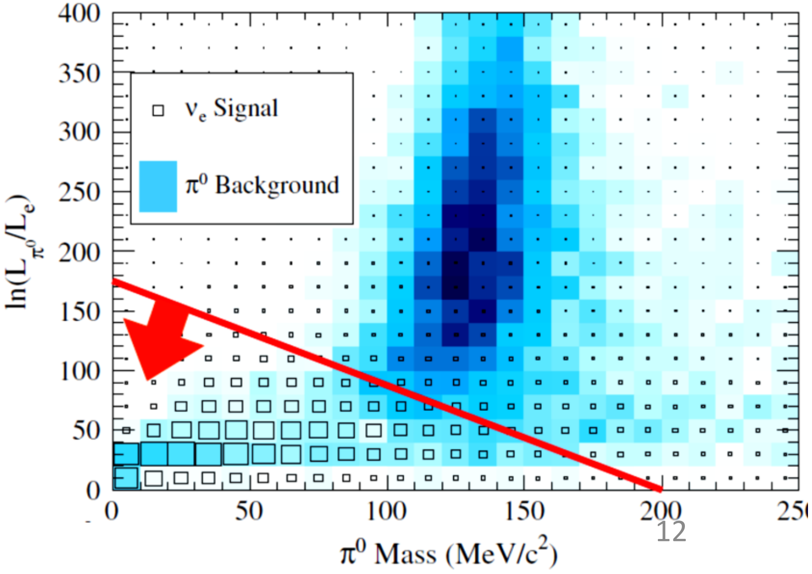
  π^0 used to be one of the dominant background sources in ν_e appearance search.

  In the latest T2K analyses,

  only 23% is coming from π^0s!

  *) 74% of background events are beam intrinsic ν_e.

Reconstructed π^0 mass vs likelihood



Hyper-Kamiokande project

Selected one of the ***27 'top projects'***

in 'Japanese master plan for large scale research projects'

by Science Council of Japan

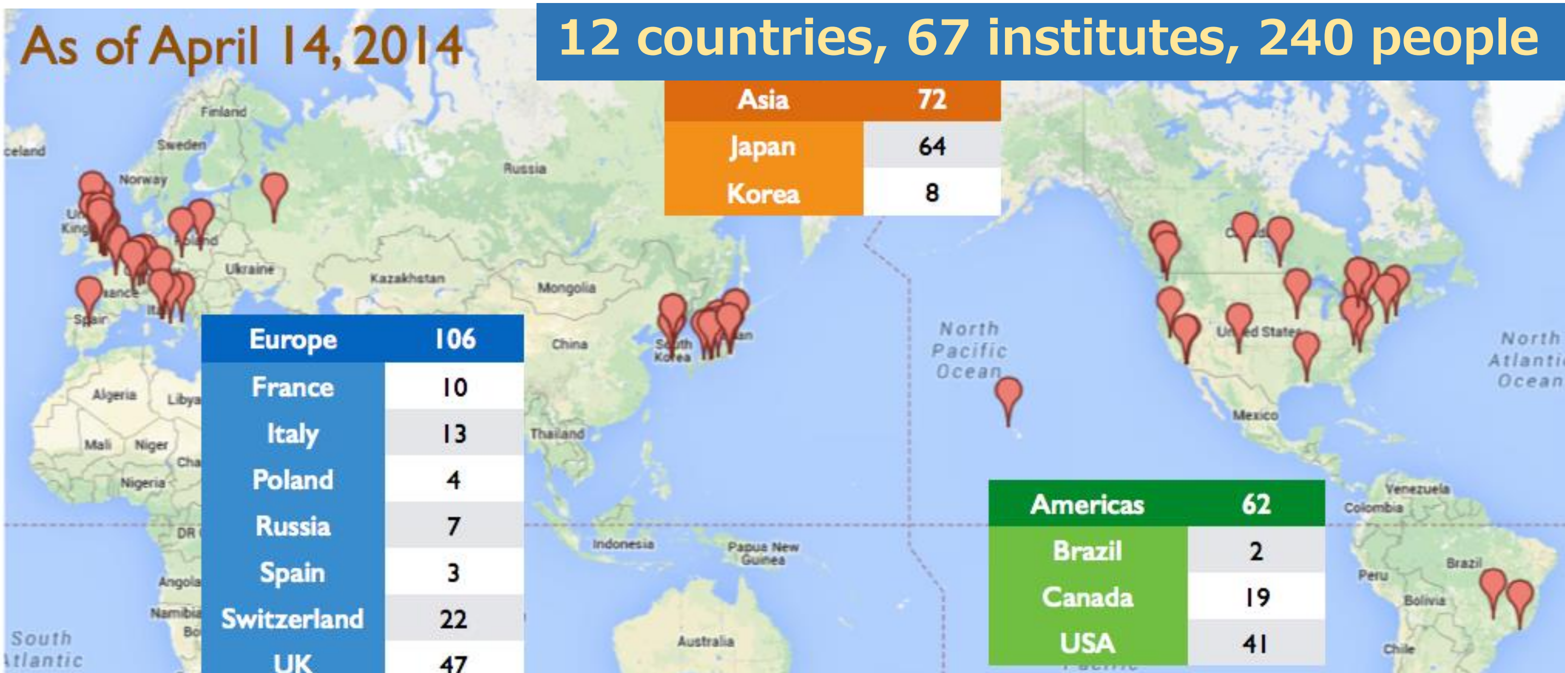
International working group was formed (http://www.hyperk.org)

~ Wide variety of physics attracts many people from the world ~

Next open meeting : July 19-22, 2014 in Vancouver

http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=34

12 countries, 67 institutes, 240 people



Asia	72
Japan	64
Korea	8

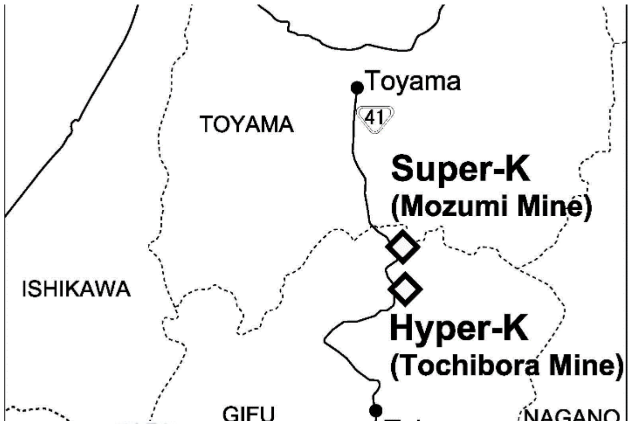
Europe	106
France	10
Italy	13
Poland	4
Russia	7
Spain	3
Switzerland	22
UK	47

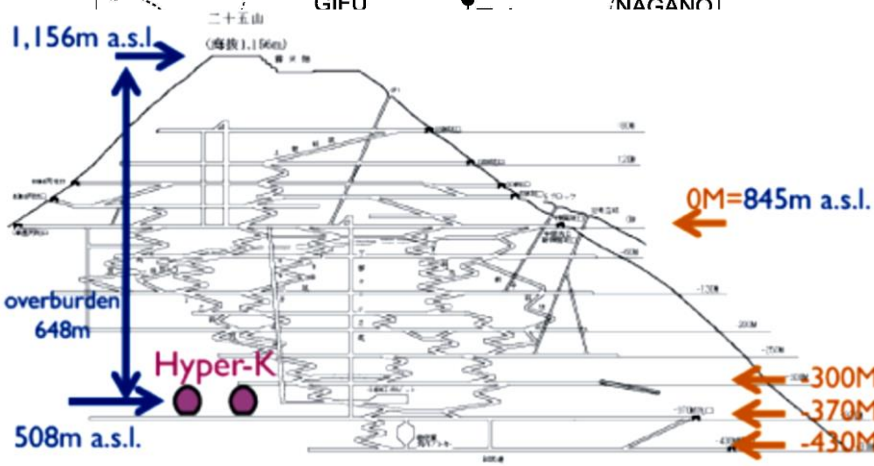
Americas	62
Brazil	2
Canada	19
USA	41

Hyper-Kamiokande detector

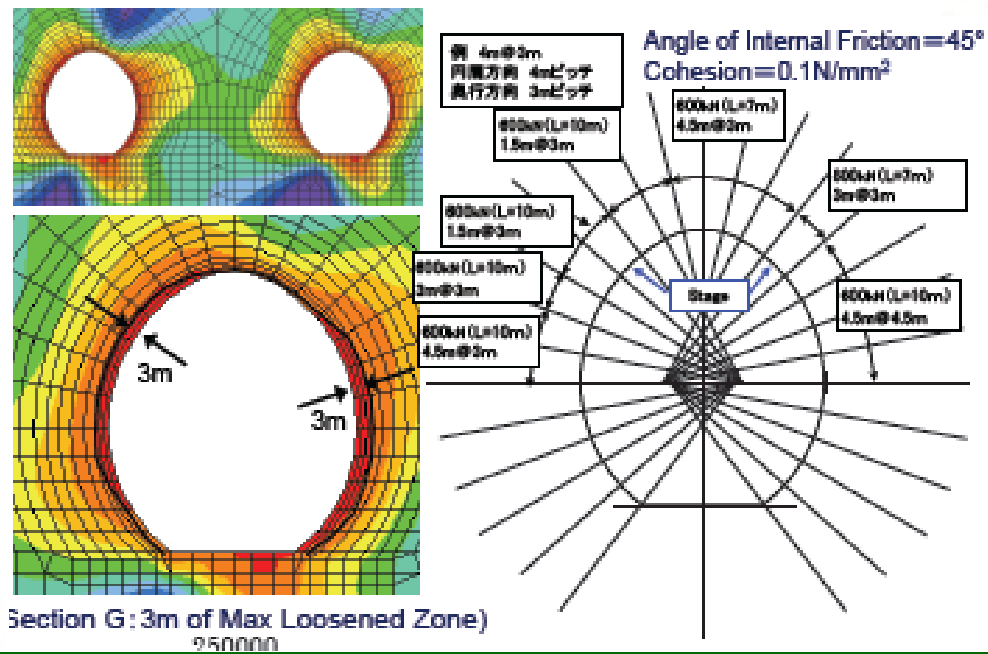
Is it possible to construct such gigantic detectors?

Candidate site : Tochibora mine in Kamioka





Design of the cavern and its supporting structures



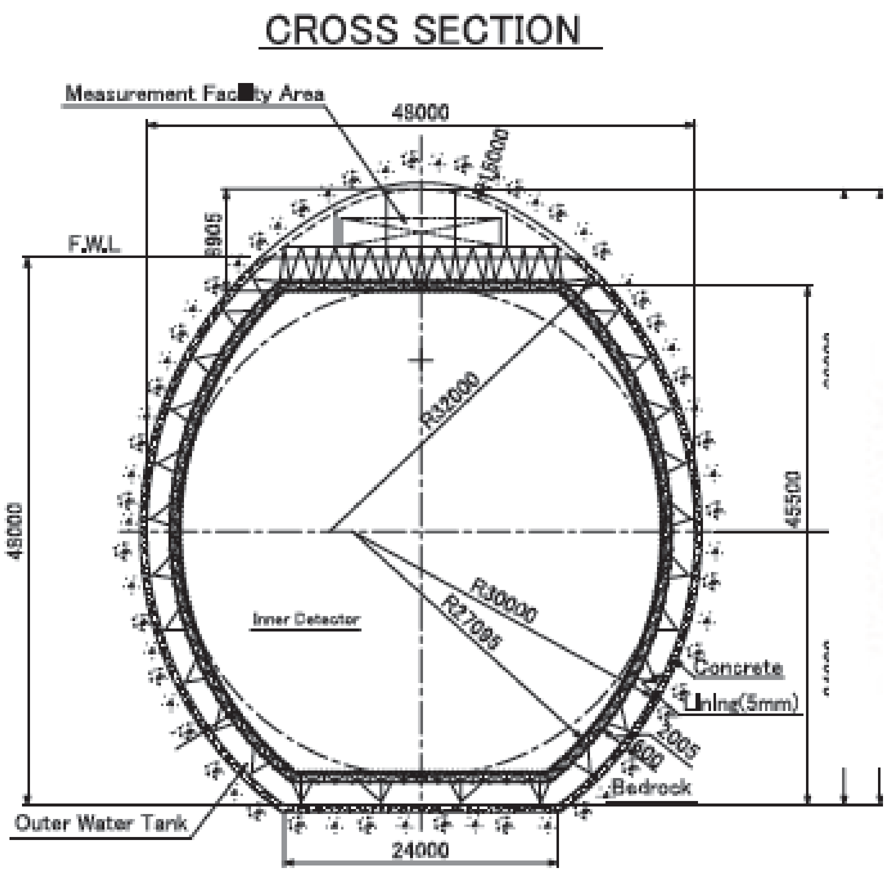
➡ Based on the geological survey and analyses, the cavern and the supporting structures were designed.

Possible to construct HK Caverns with existing technology.

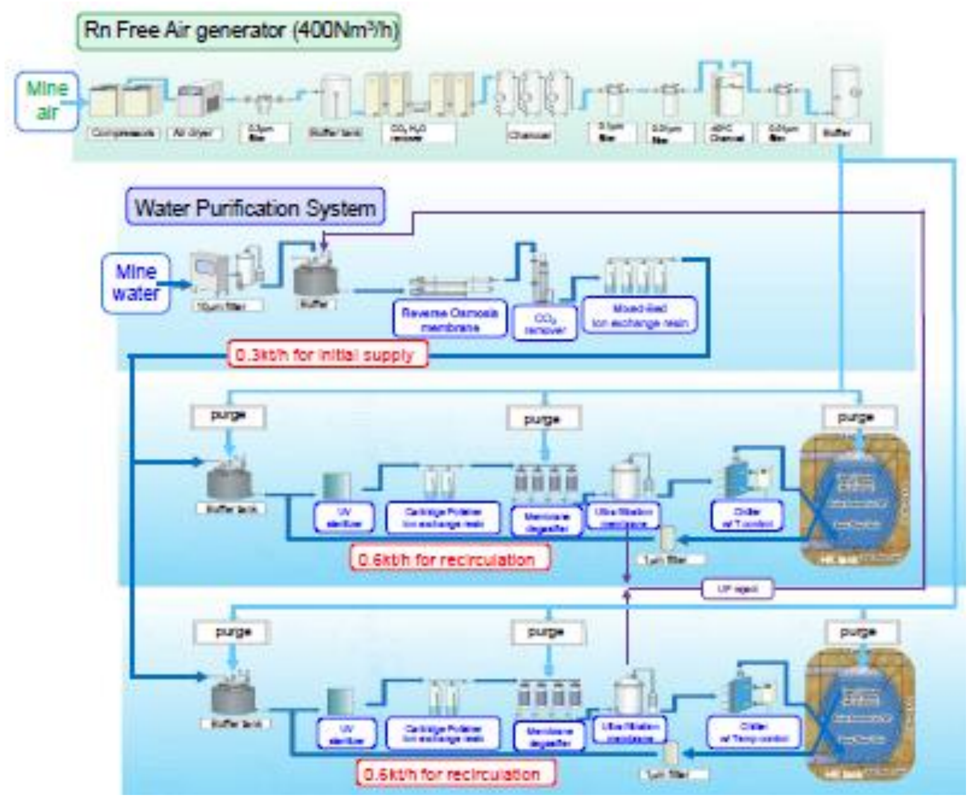
Hyper-Kamiokande detector

Design of the detector structure

Incl. PMT supports



Schematic diagram of water purification system for HK detector



➡ ***Baseline design of the detector is finished based on the past experiences in SK.***

Hyper-Kamiokande detector ~ Further improvements ~

Photo sensors ~ ***R&D to improve the detector performance***

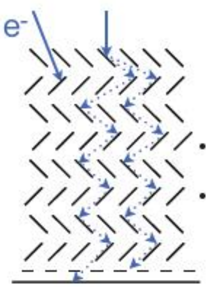
Better timing resolution ~ better vertex resolution

Higher quantum efficiency

Baseline (reference)

20" Super-K PMT

Venetian blind dynode



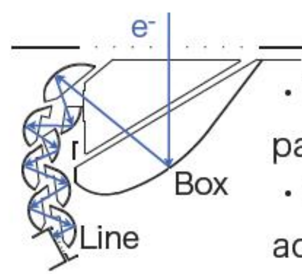
- Various drift path
- Might miss dynode

Candidates (R&D phase)

20" Box&line PMT

R12860

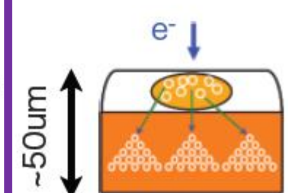
Box&line dynode



- Unique drift path
- Large acceptance

20" HPD

Avalanche diode (AD)



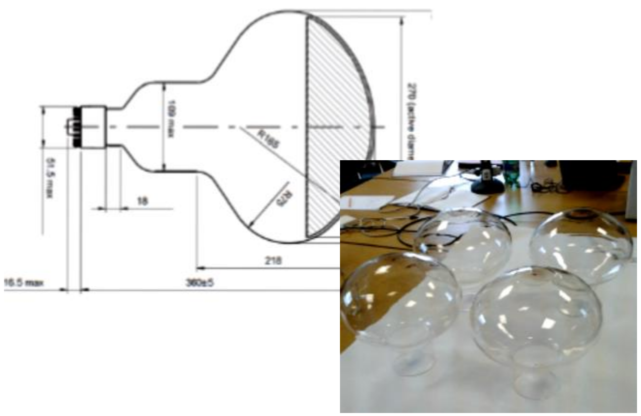
- Short drift path
- High first step gain (×1600)

	20" Super-K PMT	20" Box&line PMT	20" HPD
Quantum eff.	**22%**	**30%**	**30%**
Collection eff.	**80%**	**93%**	**95%**
Timing res. (FWHM)	**5.5 nsec**	**2.7 nsec**	**1 nsec**

Hyper-Kamiokande detector ~ Activities in the world ~

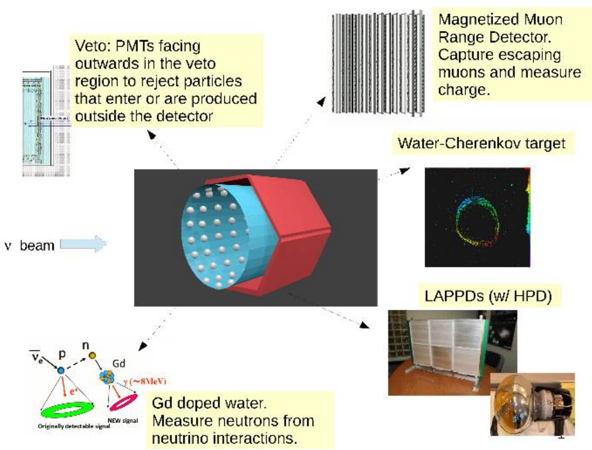
USA ~ New PMT R&D

First WATCHMAN/Hyper-K
11" ETEL/ADIT PMT envelopes
prior to glass finishing

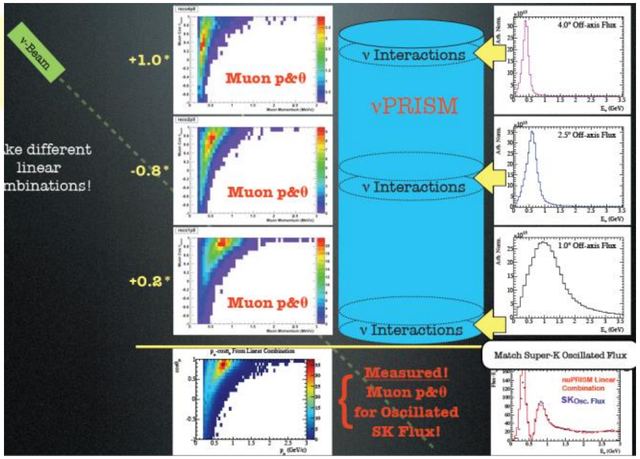


Europe & Canada
~ Near detector designs

TITUS



νPRISM

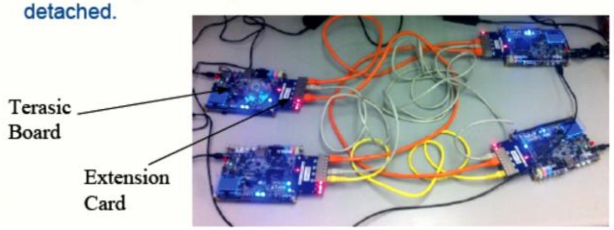


Canada

Photo sensor test facility

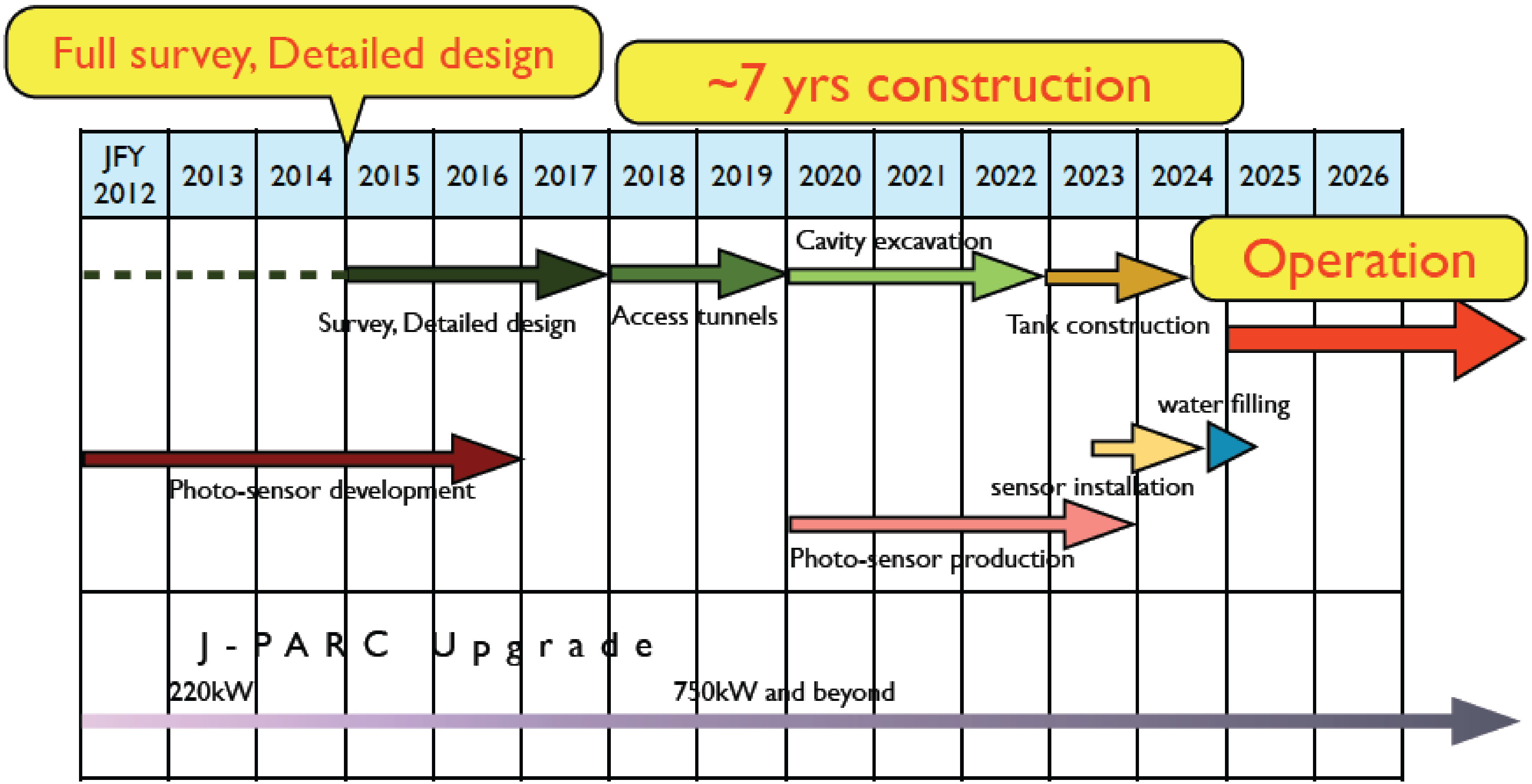
Network I/O module study

- Implemented 4 RapidIO cores in FPGA on each board; each RapidIO core has associated DMA engine.
- Managed to get each of 4 links running at 135MB/s; can also run faster, near 250MB/s, but needs to tweak DMA.
- Starting to work on the routing functionality; did some tests already, checking fail-over when cables are detached.



UK **DAQ system, HPD/LAPPD, Calibration system R&D etc..**

Hyper-Kamiokande project ~ Notional Timeline ~



-2015 Full survey, Detailed design (3 years)
-2018 Excavation start (7 years)
-2025 Start operation

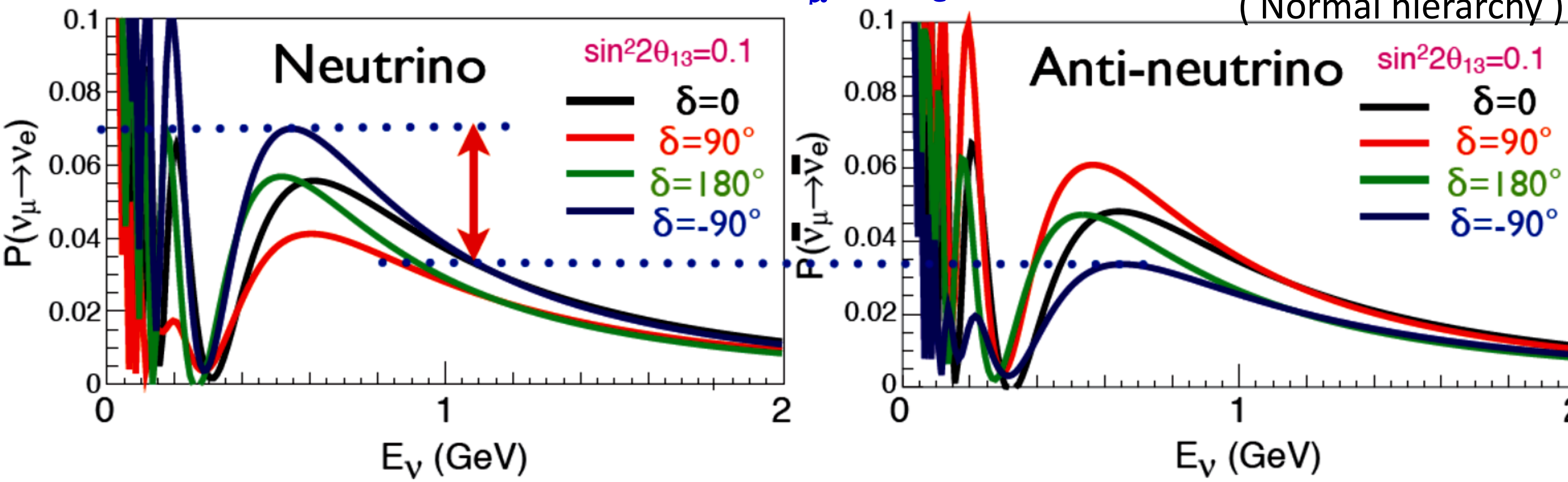
Neutrino physics of LBL J-PARC & HK ~ Determination of CP δ

CP-non conservation term in osc. prob. $\propto$ $\sin\theta_{13}\sin\delta$ **($\sin^2 2\theta_{13}$ ~ 0.1)**

(sign of δ for anti-neutrino is different from neutrino)

Oscillation prob. for $\nu_\mu \rightarrow \nu_e$ @ 295km

(Normal hierarchy)



→ Hyper-Kamiokande + J-PARC neutrino beam

~ 3000 ν_e & ~ 2000 $\bar{\nu}_e$ signal events are expected, when $\delta = 0$

(7.5 x 10^7 MW·sec)

Measurements of δ by comparing oscillations of ν and $\bar{\nu}$.

At maximum CP violation, ~25% difference from δ=0 case.

Neutrino physics of LBL J-PARC & HK ~ Determination of CP δ

- Expected # of events for $\sin^2 2\theta_{13} = 0.1$, $\delta = 0$ and NH

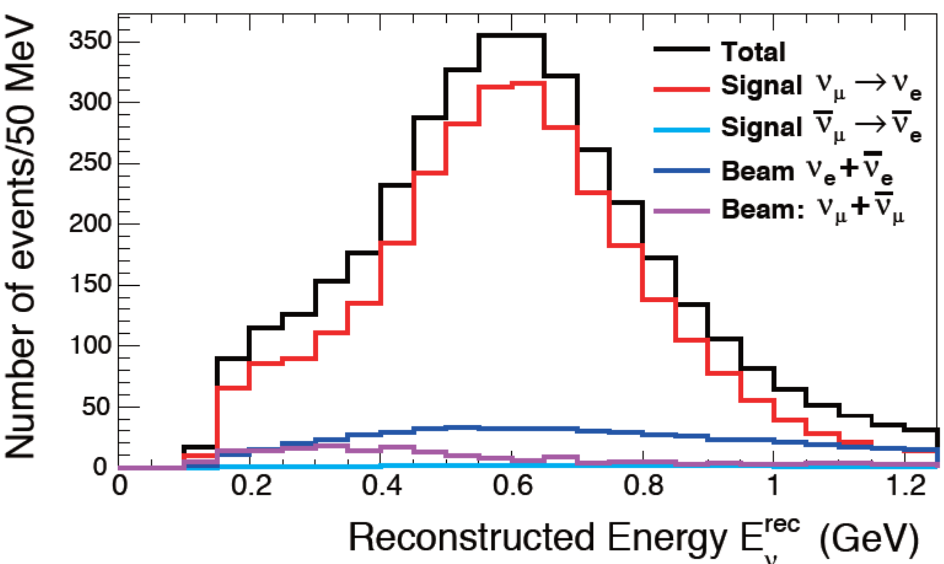
(7.5 x 10^7 MW·sec)

	Signal ($\nu\mu \rightarrow \nu e$ CC)	Wrong sign appearance	$\nu\mu/\bar{\nu}\mu$ CC	beam $\nu e/\bar{\nu}e$ contamination	NC
ν	3,016	28	11	523	172
$\bar{\nu}$	2,110	396	9	618	265

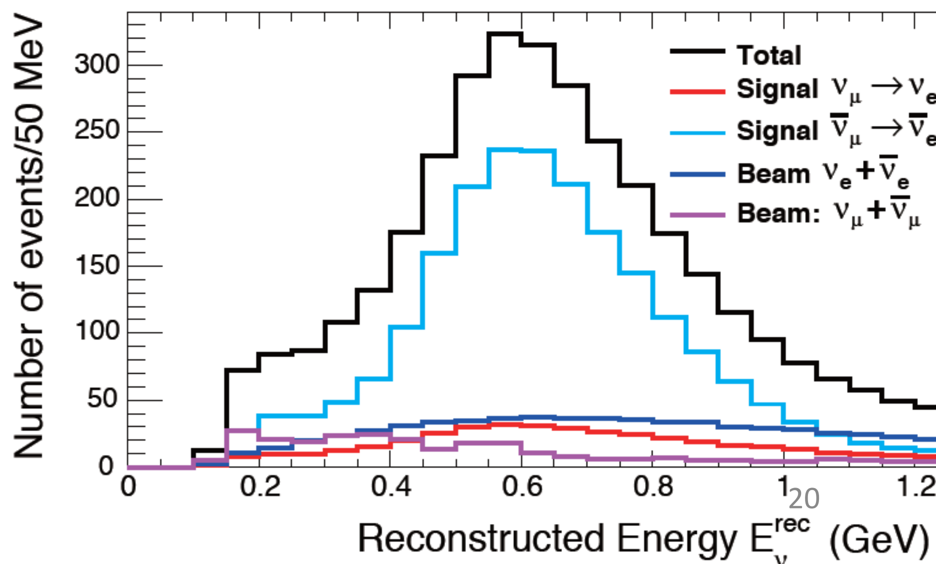
NC (π^0) is not the dominant background already.

- Reconstructed energy of neutrino for candidate events

Neutrino mode beam



Anti neutrino mode beam



Neutrino physics of LBL J-PARC & HK ~ Determination of CP δ

Systematic error Errors used in the sensitivity studies

~ Realistic estimation of the errors based on the experiences ~

	ν mode		anti-ν mode	
	νe	νμ	νe	νμ
Flux&ND	3.0	2.8	5.6	4.2
XSEC model	1.2	1.5	2.0	1.4
Far Det. +FSI	0.7	1.0	1.7	1.1
Total	3.3	3.3	6.2	4.5

(T2K 2014)	
νe	νμ
2.9	2.7
4.7	4.9
3.5	5.6
6.8	8.1

Reduction of errors in the XSEC models

New measurements of neutrino interactions

Improved theoretical modeling

Reduction of errors in the far detector + Final state interactions

Increased statistics of atmospheric ν control sample in HK

New near (intermediate) detectors with H_2O target

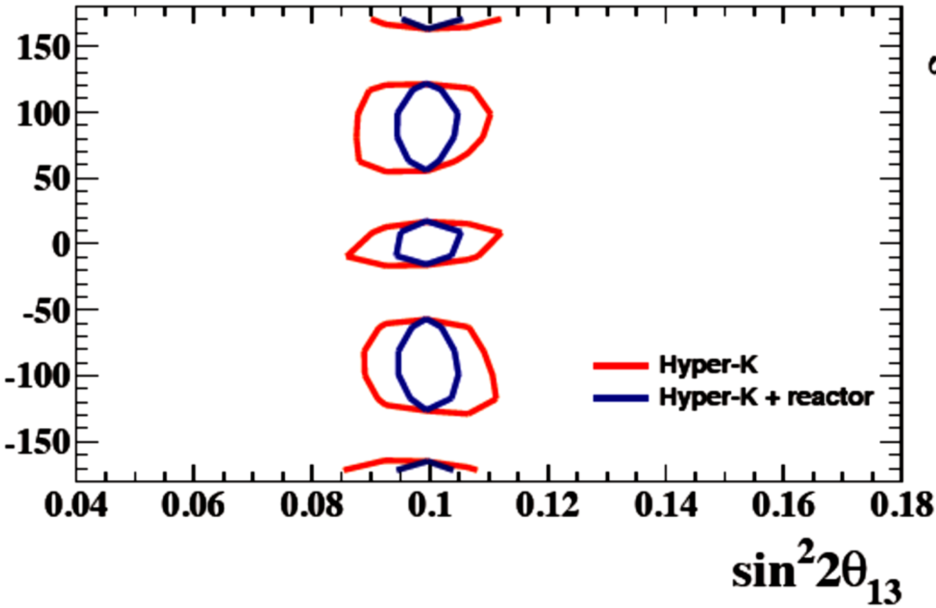
(incl. Water Cherenkov detector)

Neutrino physics of LBL J-PARC & HK ~ Determination of CP δ

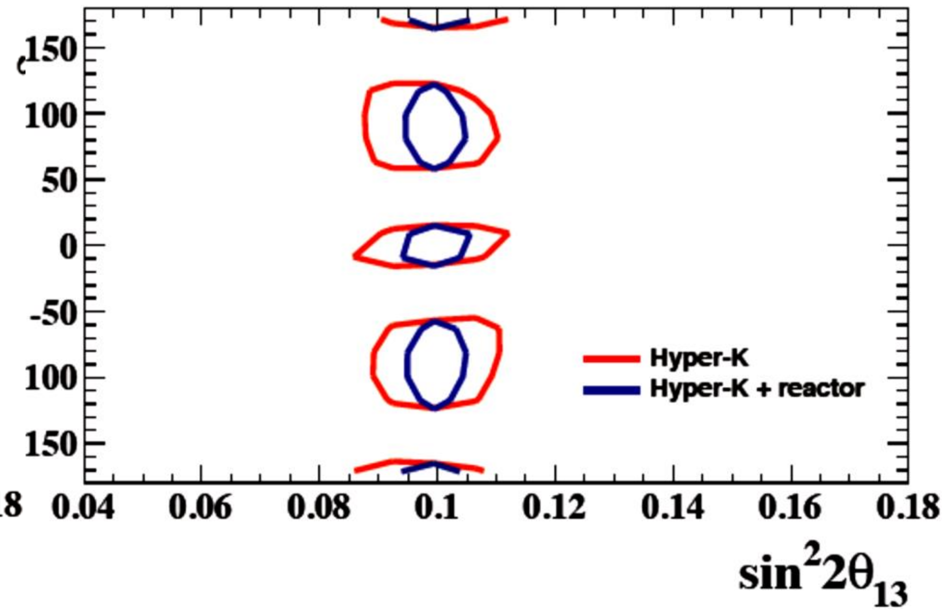
Use both # of observed events
and reconstructed energy spectra of ν and $\bar{\nu}$.

(@ 7.5 x 10^7 MW·sec , ν : $\bar{\nu}$ = 1 : 3)

Normal mass hierarchy



Inverted mass hierarchy



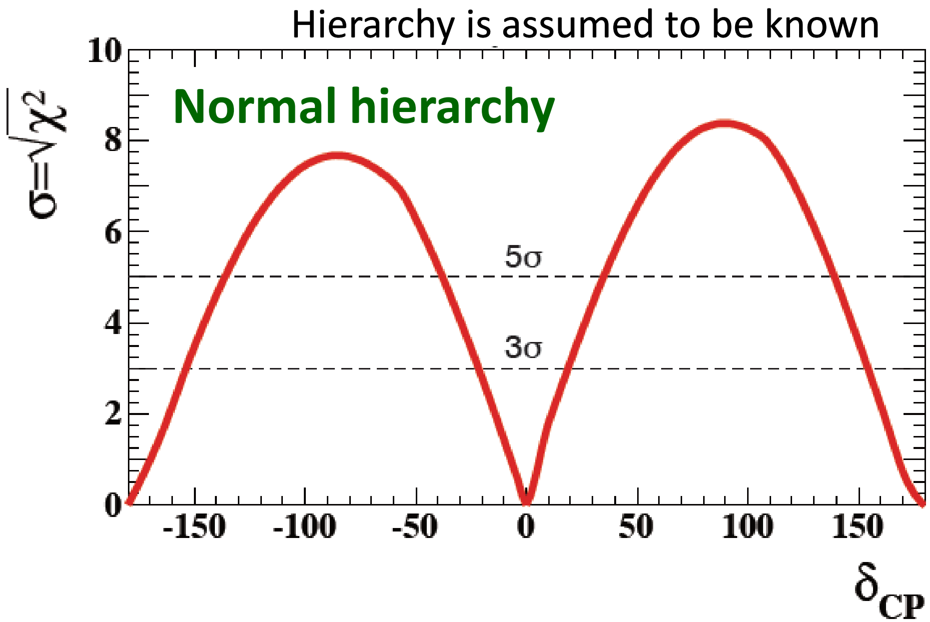
Determination power of CP δ parameter

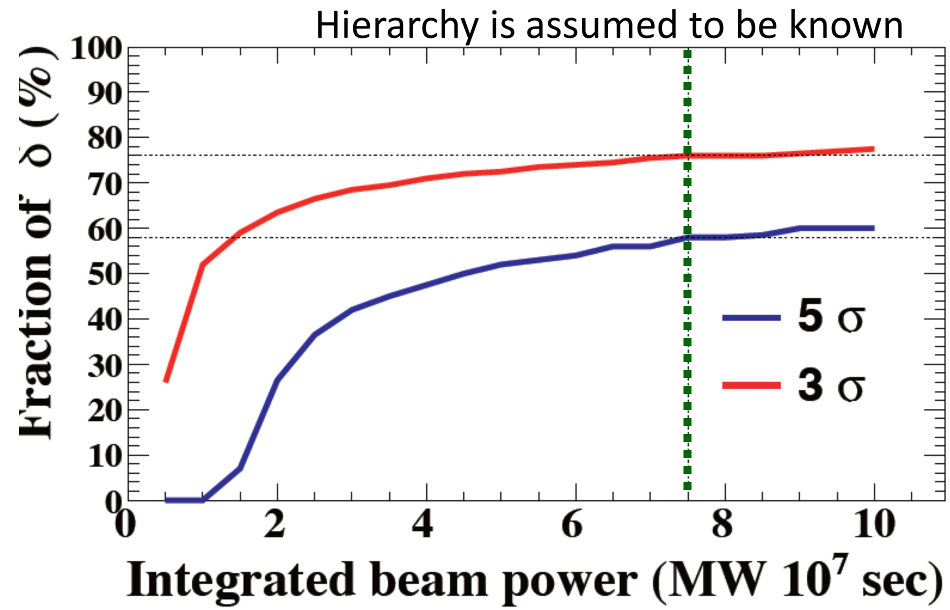
1σ error of δ is expected to be 8^o ~ 19^o.

Neutrino physics of LBL J-PARC & HK ~ Determination of CP δ

Sensitivity ~ Exclusion of sin δ = 0
(7.5 x 10^7 MW·sec)

Fraction of δ
~ Exclusion of sin δ = 0





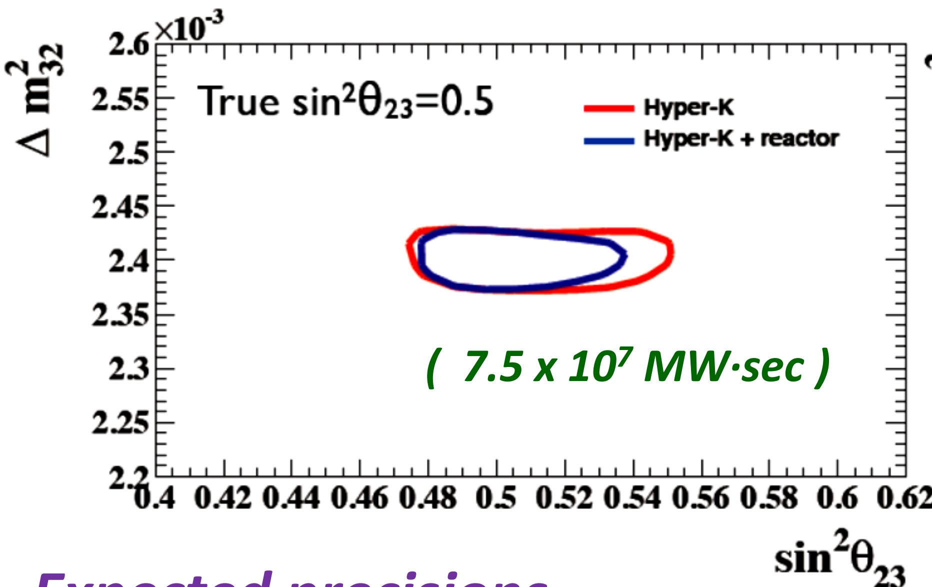
Exclusion of sin δ = 0

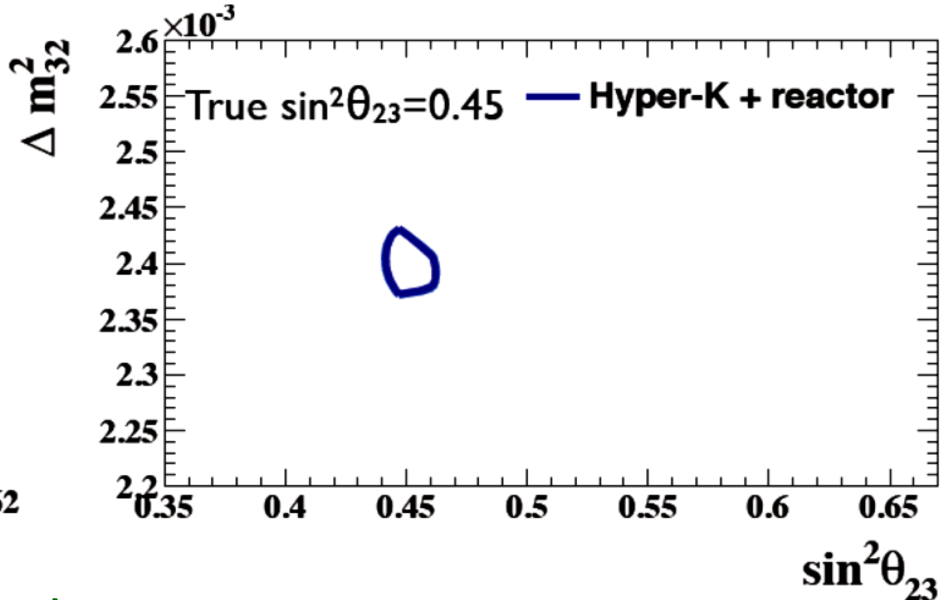
76% of δ at 3σ level and 58% of δ at 5σ level

with realistic systematic error estimations.

Neutrino physics of LBL J-PARC & HK

~ Measurements of $|\Delta m^2_{32}|$ and $\mathbf{sin^2 2\theta_{23}}$





Expected precisions *(7.5 x 10⁷ MW·sec)*

True Δm^2_{32} = 2.5×10^{-3} eV² $\pm 0.015 \times 10^{-3}$ eV² (0.6%)

True $\sin^2\theta_{23}$ =
- 0.55 ± 0.009 (1.6%)
- 0.50 (Full mixing) ± 0.015 (3%)
- 0.45 ± 0.006 (1.3%)

(T2K 2014 results $\Delta m^2_{32} = 2.51 \pm 0.10 \times 10^{-3}$ eV²
$\sin^2\theta_{23} = 0.514 \pm 0.055$)

Large improvements & good chance to identify non-maximal mixing.

MOMENT

~ a muon decay medium baseline neutrino facility ~

MOMENT ~ a muon decay medium baseline neutrino facility

Future accelerator based neutrino oscillation experiment in China

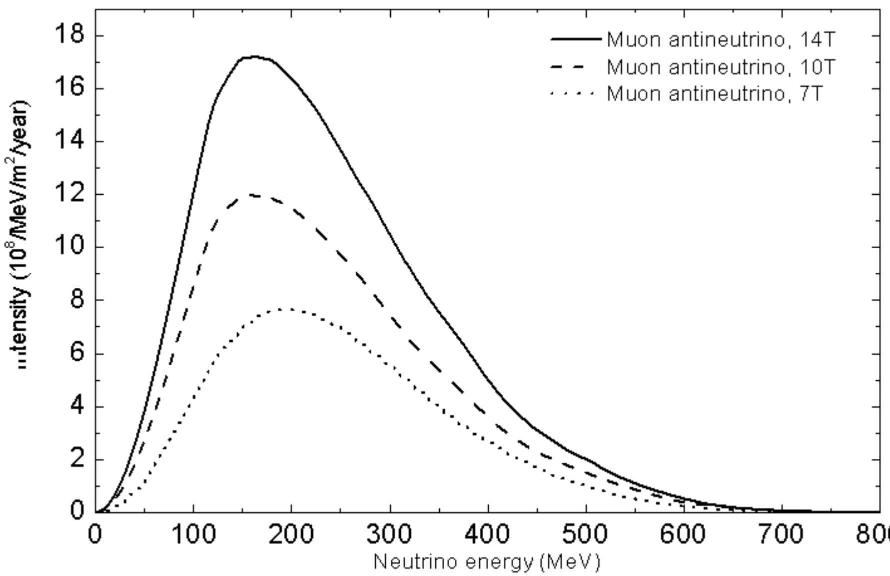
Intended to study CP violation in the lepton sector

Lowering the energy to largely reduce backgrounds from pion productions.

Planned **baseline is ~ 150km**

Mean beam energy is tuned **~ 240 MeV.**

Neutrino beam from **muon decays**
(Conventional neutrino beam uses ν from pion decays)



Expected neutrino flux
(Depends on the level of the pion capture field at target)

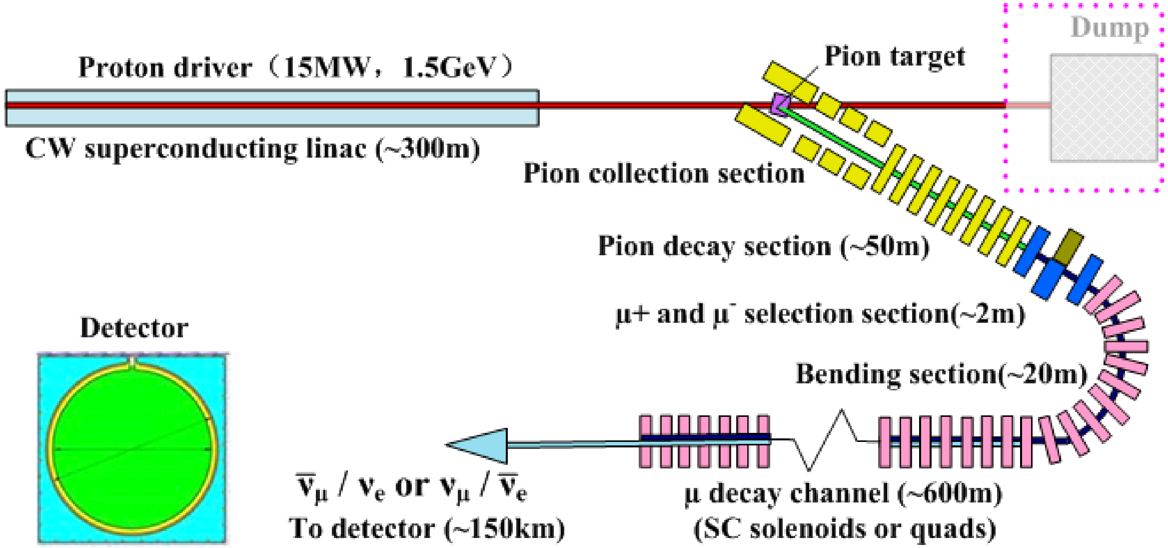
14T Field : **4.7×10^{11}** $\nu/m^2/year$
(7T Field : 2.1×10^{11} $\nu/m^2/year$)

MOMENT ~ a muon decay medium baseline neutrino facility

Use extremely intense proton beam (***15MW***)

from CW Superconducting LINAC

Accelerator : Use the same technology but different design for China-ADS (a funded R&D project)



Pion target

Mercury jet or fluidized tungsten powder

Detector : ** Need charge identification **

Various possibilities are considered

Water Cherenkov detector with Gd (like GAZOOKS)

Magnetized Iron detector (MIND)

Magnetized liquid Argon detector

Summary *~ It's time to start new experiments to explore CP violation in the lepton sector. ~*

J-PARC neutrino beam with Hyper-Kamiokande

- Utilize existing intense neutrino beamline with upgrades
  ~ Well understood and under control.
- Feasible Gigantic Water Cherenkov detector
  - Established detector technology ~ Feasible
    - Proven excellent performance in physics analyses
    - Proven long term stability
  - Further reduction of the cost & performance improvements
    - Realized by new technology and analysis methods
    - *(Will be confirmed with the test detectors and SK.)*
  - Broad physics opportunities
    - Various sources of neutrinos, nucleon decay etc..

MOMENT ~ a muon decay medium baseline neutrino facility

Different configuration of a new experiment with a new design of intense neutrino beam production

Fin.

Introduction

Neutrino oscillation ~ discovered in 1998 & extensively studied.

Flavor mixing & non-zero neutrino mass

~ Beyond the standard model ~

Parameters
- 3 oscillation angles(θ_{12}, θ_{23}, θ_{13})
- 2 mass differences(Δm^2_{12}, Δm^2_{32})
- **1 CP phase (δ)**

PMNS Matrix ($U_{\alpha i}$)

$$|\nu_\alpha\rangle = \sum U_{\alpha i} |\nu_i\rangle$$

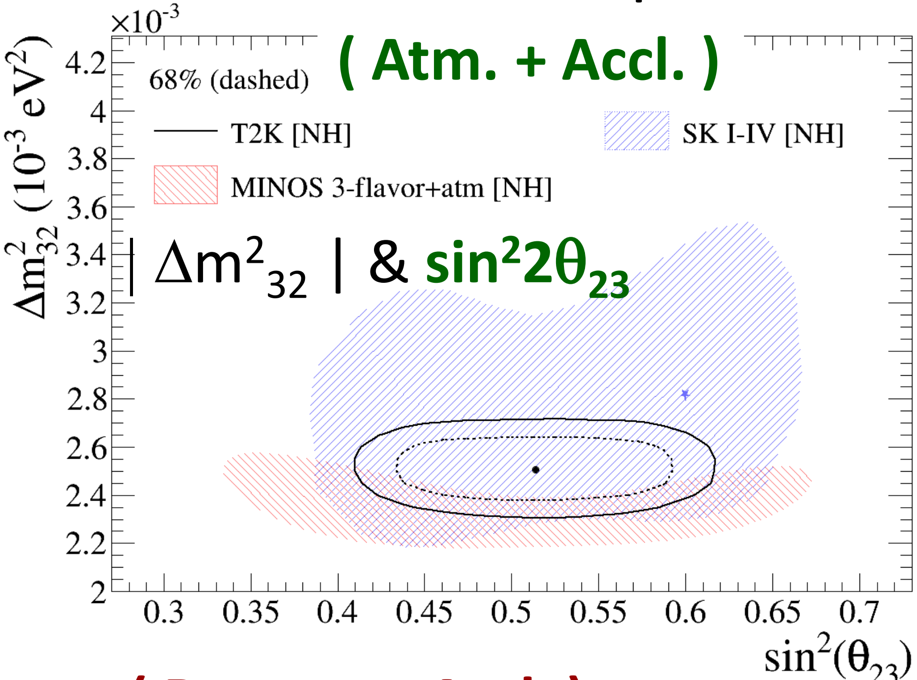
Weak ***Mass eigenstates***

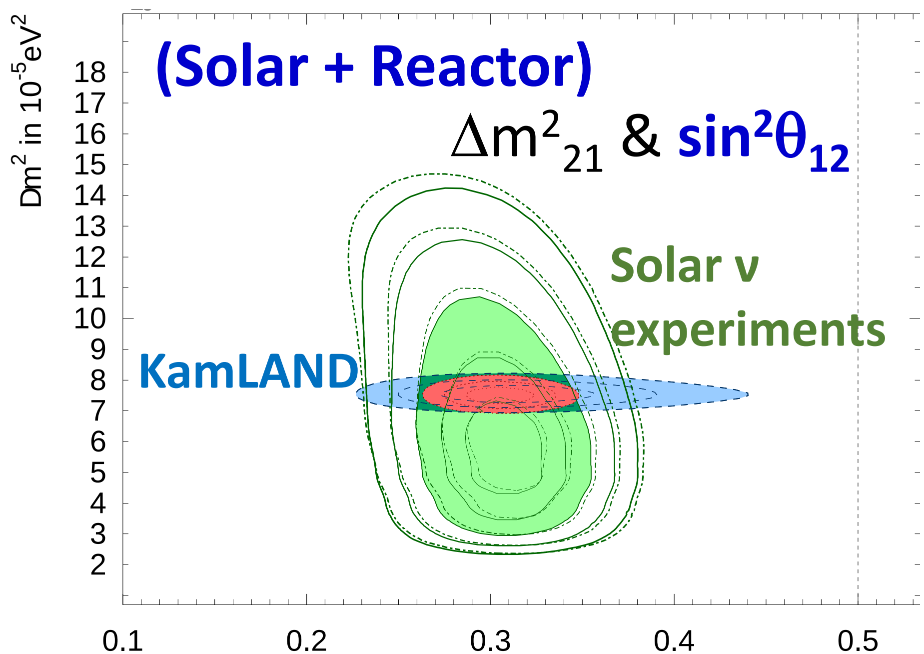
$s_{ij}=\sin\theta_{ij}$, $c_{ij}=\cos\theta_{ij}$

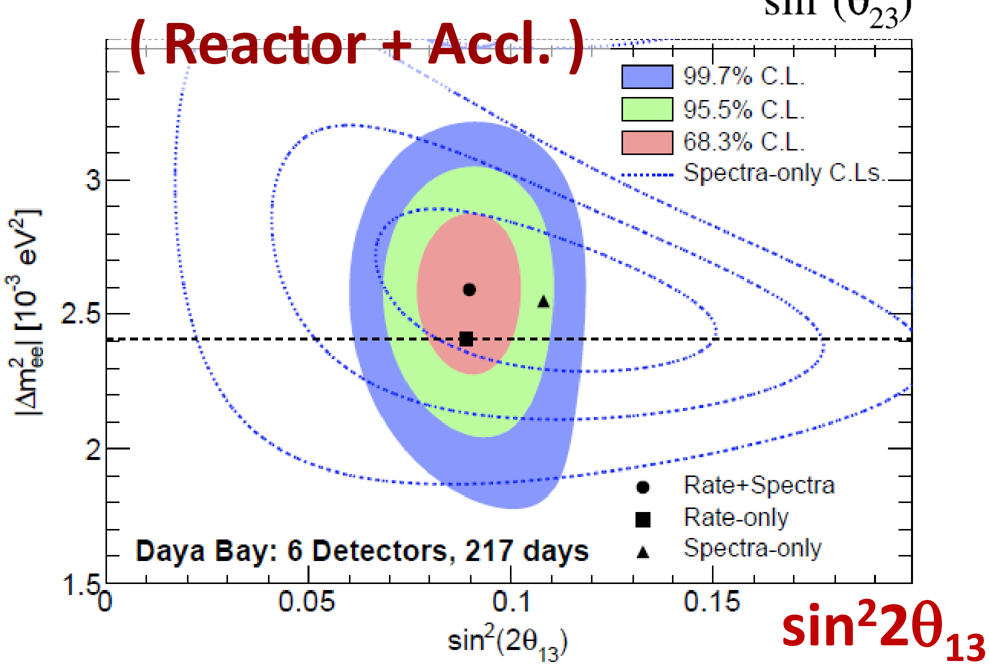
$$U \doteq \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}$$

Atmospheric & Accelerator **Reactor & Accelerator** **Solar & Reactor**

Neutrino oscillation parameter measurements







Δm^2_{21} = $\mathbf{7.49^{+0.19}_{-0.17} \times 10^{-5}}$ (eV/c^2)^2

$|\Delta m^2_{32}|$ ~ $\mathbf{2.5 \pm 0.2 \times 10^{-3}}$ (eV/c^2)^2

$\sin^2 2\theta_{23} > 0.9$

$\sin^2\theta_{12} \sim 0.305 \pm 0.013$

$\sin^2 2\theta_{13} = 0.098 \pm 0.013$

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$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$

Next step ~ Prospects of the current experiment

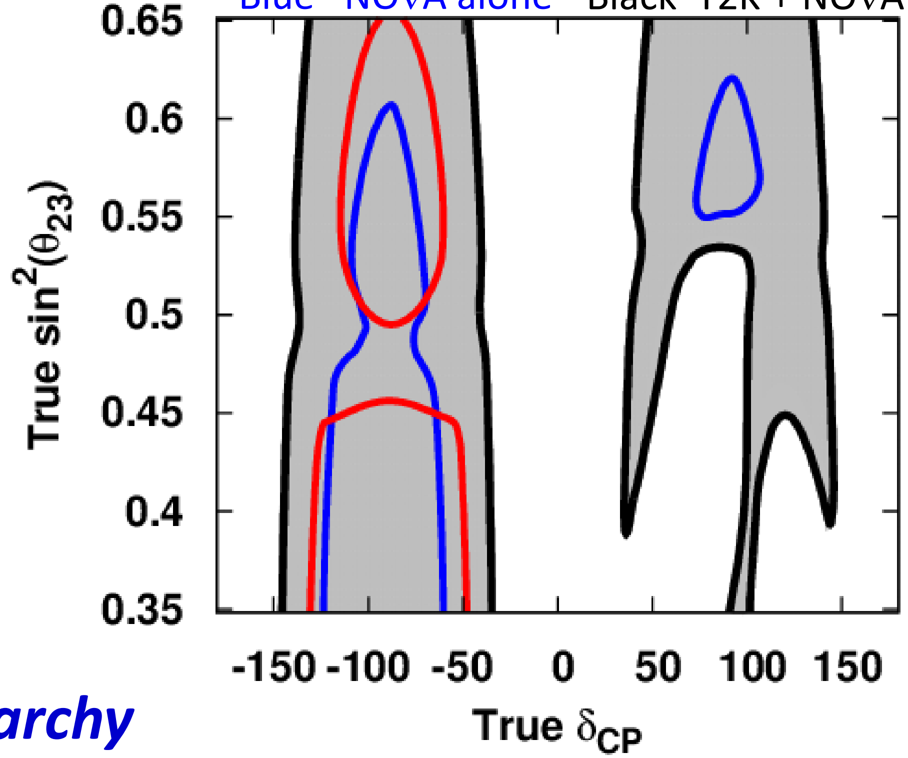
- Current generation experiments (T2K and NOνA) are expected to lead the study of the CP violation in the lepton sector.
- However, the expected sensitivity of CPV is **~ 2σ** level

Next generation experiments are essential for the study of CPV and mass hierarchy

Region where sinδ=0 can be excluded by 90% C.L.

Normal hierarchy

Red T2K alone
Blue NOνA alone Black T2K + NOνA

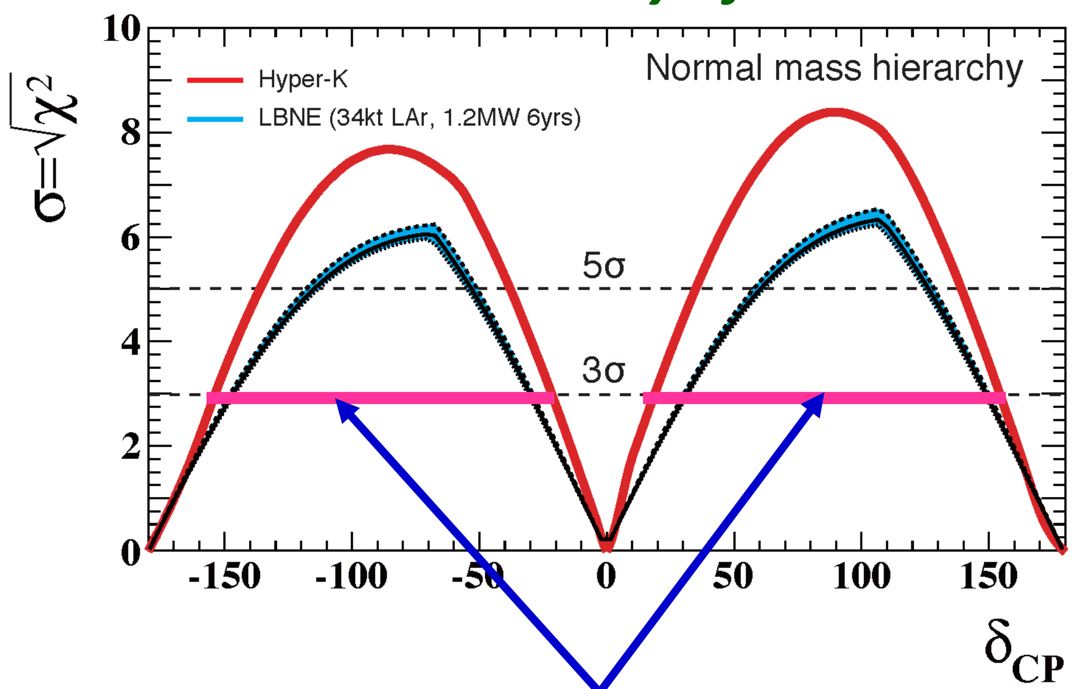


Both T2K / NOνA : full POT (POT fraction : 50% ν + 50% anti-ν)
Assuming 5% (10%) normalization uncertainty on signal (background)
Assuming true: $\sin^2 2\theta_{13}=0.1$, $\Delta m^2_{32}=2.4\times10^{-3}$ eV^2
θ_{13} constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$

Excerpts from the P5 report

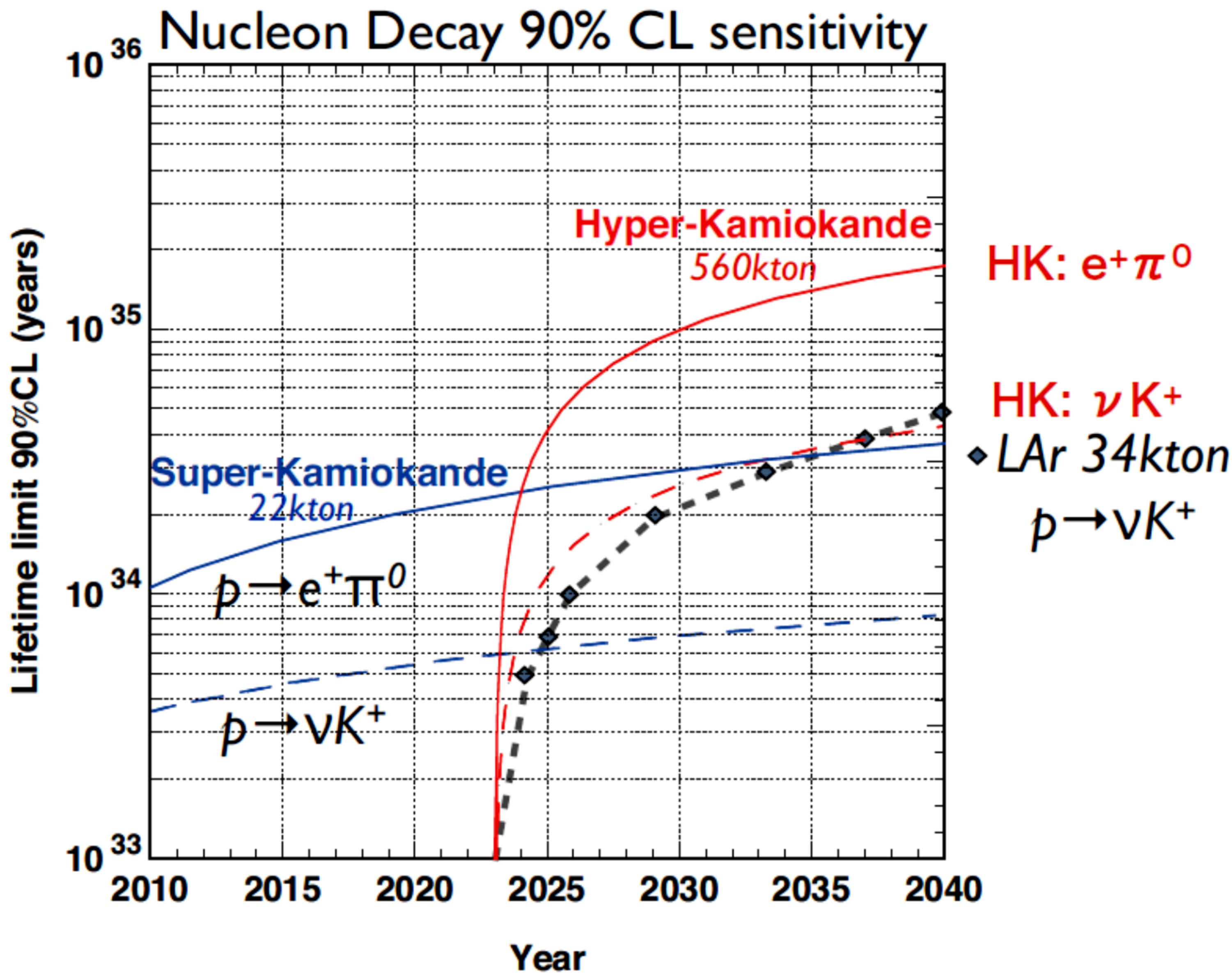
For a long-baseline oscillation experiment, based on the science Drivers and what is practically achievable in a major step forward, we set as the goal a mean sensitivity to CP violation of better than 3σ (corresponding to 99.8% confidence level for a detected signal) over more than 75% of the range of possible values of the unknown CP-violating phase δ_{CP}.

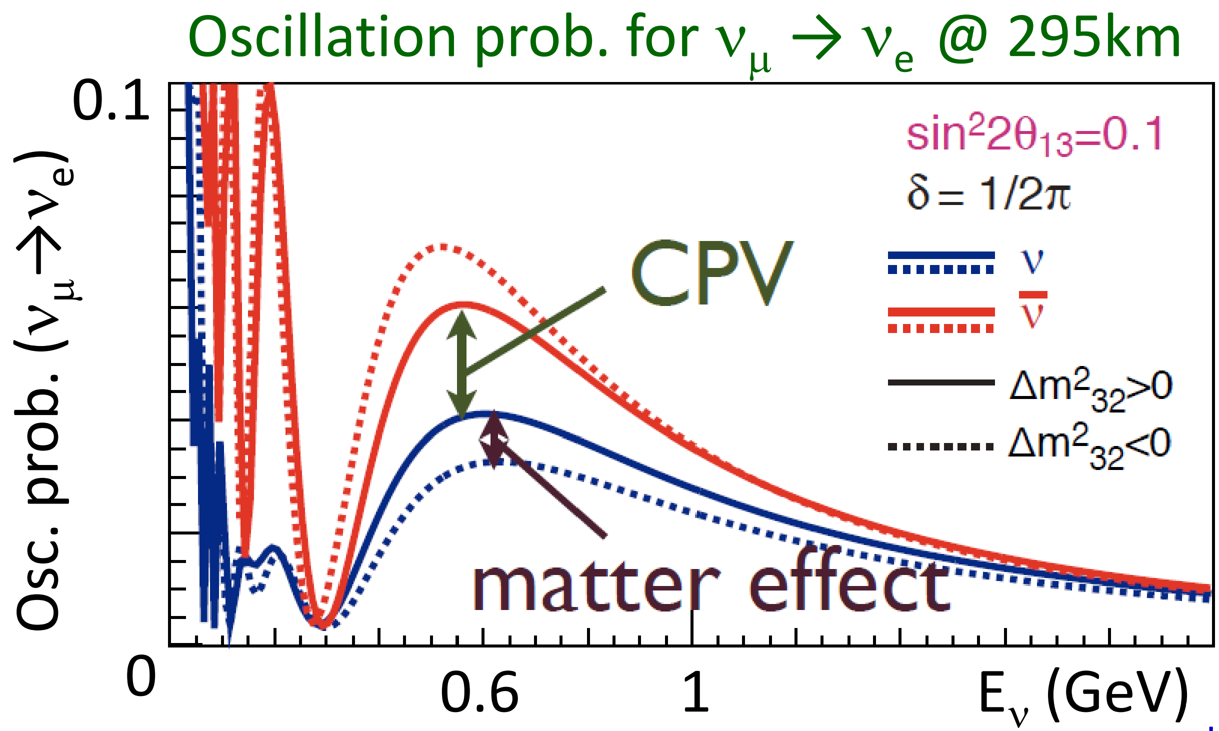
Sensitivity of δ



76% (3σ) of the δ is covered by J-PARC + Hyper-Kamiokande

Sensitivity of proton decays





$\Delta m^2_{21}=7.6\times10^{-5}eV^2$

$|\Delta m^2_{32}|=2.4\times10^{-3}eV^2$

$\sin^2\theta_{12}=0.31$

$\sin^2\theta_{23}=0.5$

$\rho=2.6g/cm^3$

Hierarchy is assumed to be known