Physics Potential of
Hyper-Kamiokande
for Neutrino Oscillation measurements

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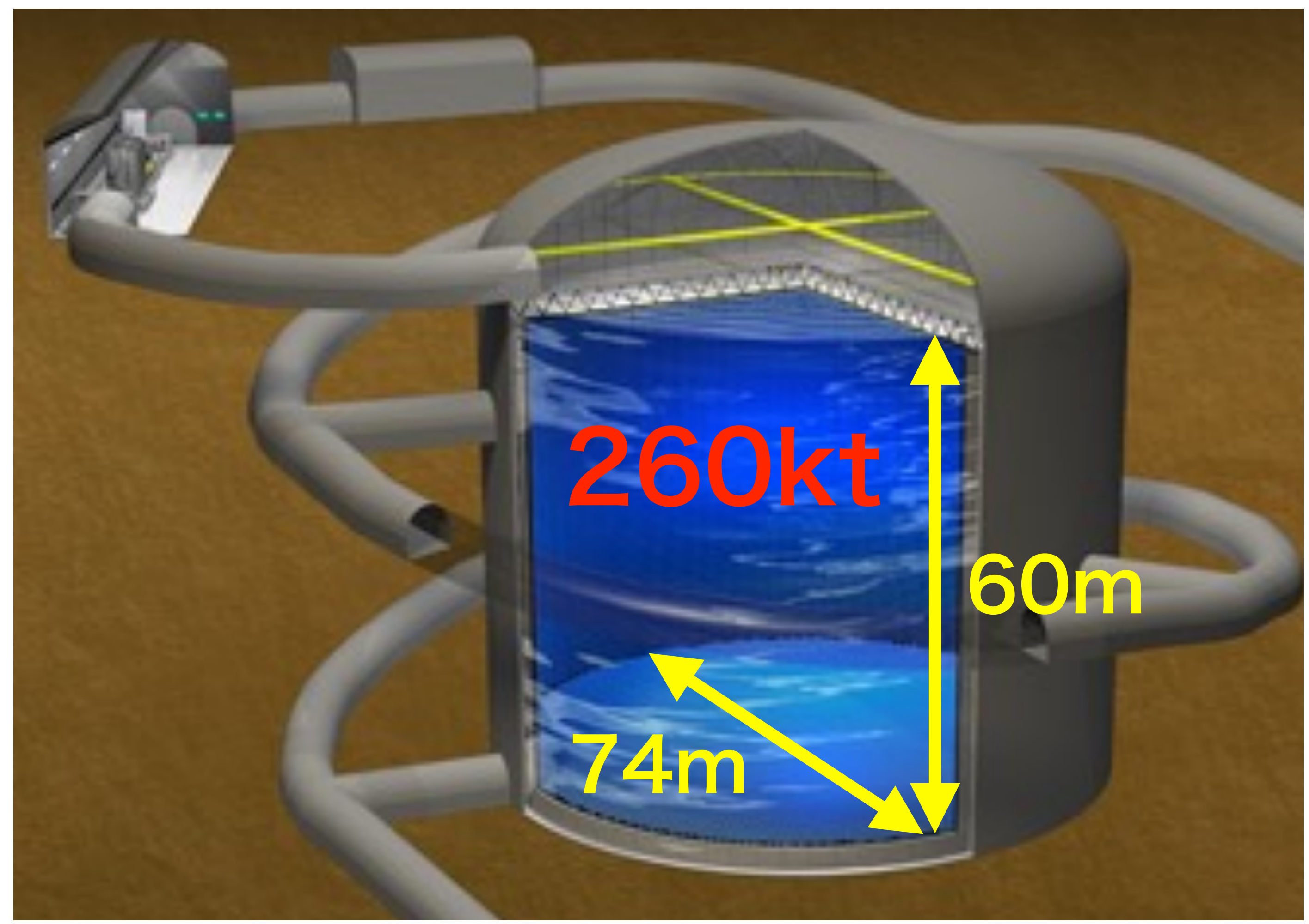
NuFact 2018, 20th workshop on neutrinos from accelerators, Virginia tech

Contents

Overview

Hyper-Kamiokande

- Next generation water Cherenkov detector
  - Construct two detectors in stage
    - Realize the first detector as soon as possible
    - An option of second detector in Korea
- Rich physics
  - Nucleon decay
  - Neutrino oscillation (CPV, MH)
  - Neutrino astronomy/Astrophysics
- Detector
  - Φ74m x H60m
  - 260 kton total mass
  - 190 kton fiducial volume
    - ~10 x Super-K
  - 40% Photo coverage (ID)
    - 40,000 x new 20” PMTs
      - x2 higher photon detection efficiency



Neutrino Oscillation Measurements

PMNS matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \boxed{\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}} \boxed{\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}} \boxed{\begin{pmatrix}\cos\theta_{12} & \cos\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Flavor eigen-state | θ_{23} factor | θ_{13} and δ factor | θ_{12} factor | Mass eigen-state

- **"ν_e appearance" : sensitive to θ_{13}, δ_{CP}, mass hierarchy**

$$P(\nu_\mu \to \nu_e) \quad \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\left(1+\frac{4\sqrt{2}G_F n_e E}{\Delta m^2_{31}}(1-2\sin^2\theta_{13})\right)$$

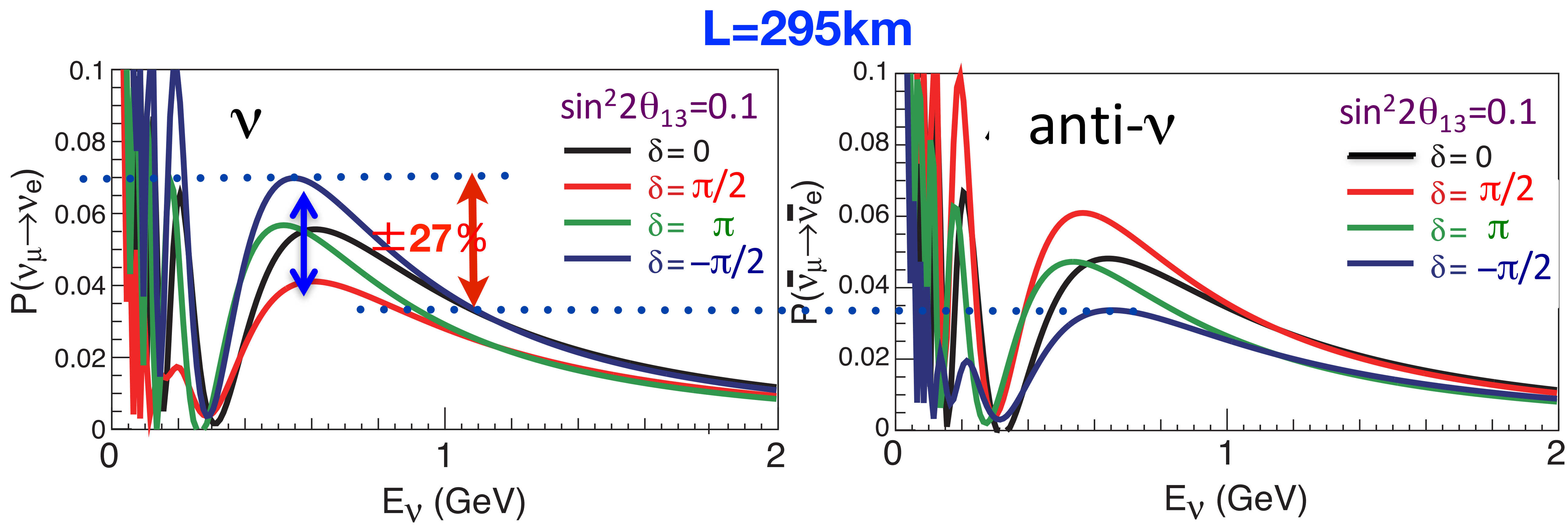
$$-\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\sin\delta\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\sin^2\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

- **"ν_μ disappearance" : sensitive to θ_{23}, Δm^2_{32}**

$$P(\nu_\mu \to \nu_\mu) \approx 1-(\cos^4\theta_{13}\sin^2 2\theta_{23}+\sin^2\theta_{23}\sin^2 2\theta_{13})\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)$$

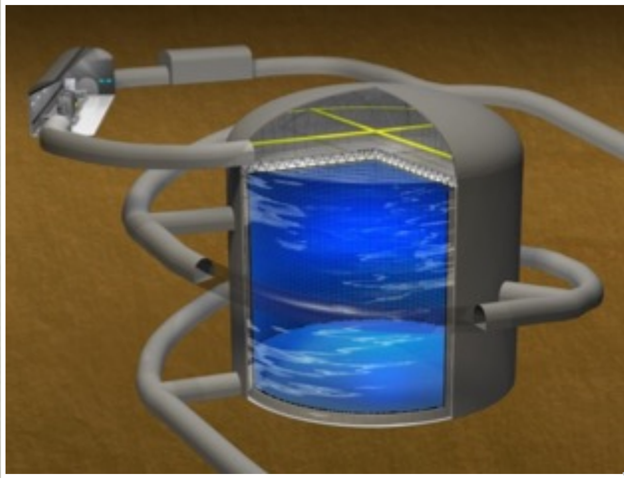
Accelerator-produced pure muon neutrino beam is quite beneficial !!

CP Effect on Oscillation Probability



- ν_e **appearance probability changes as a function of** E_ν
  - **Depends on** δ_{CP} **(max. ±27% difference)**
  - **Comparing probabilities for neutrino and antineutrino gives sensitivity for CP violation**
  - **Matter effect is small (~10% contribution) compared to CP effect with ~300km baseline length**

Long Baseline Neutrino Oscillation Measurement



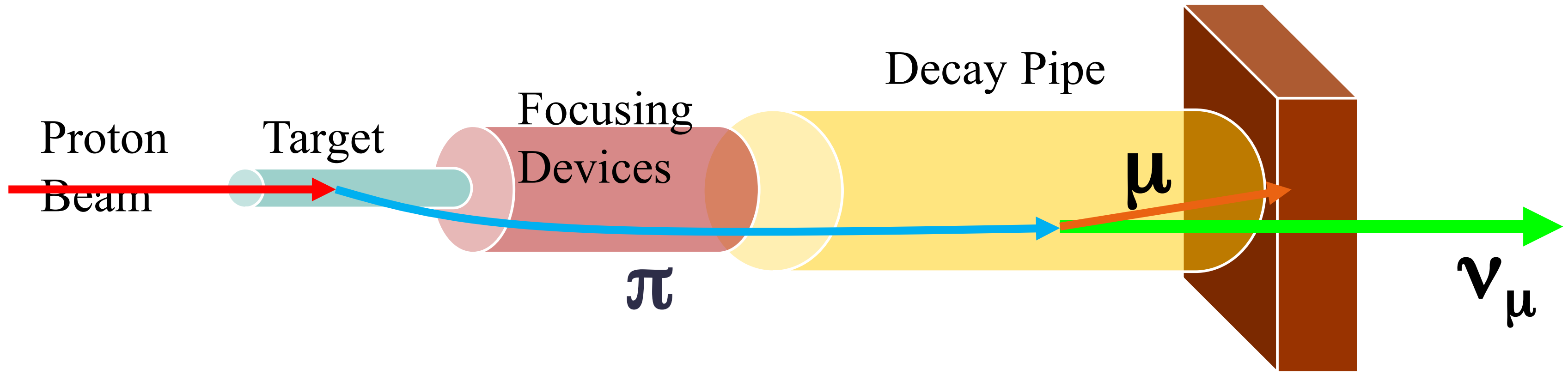
Hyper-K
(Water Č)

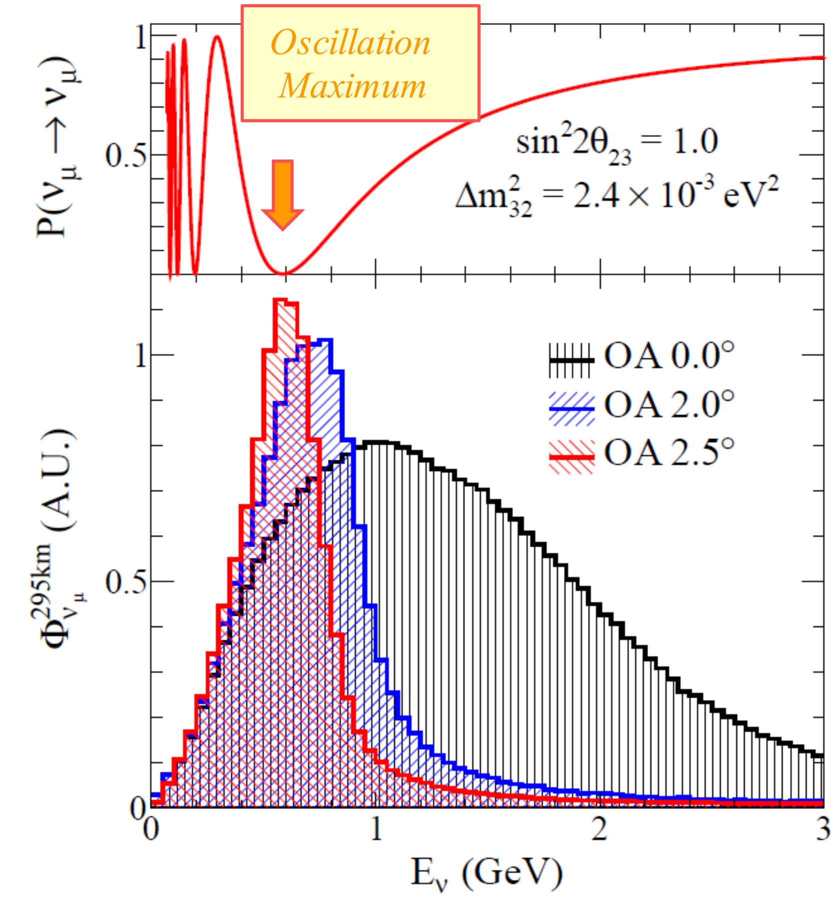
J-PARC
Accelerator Complex

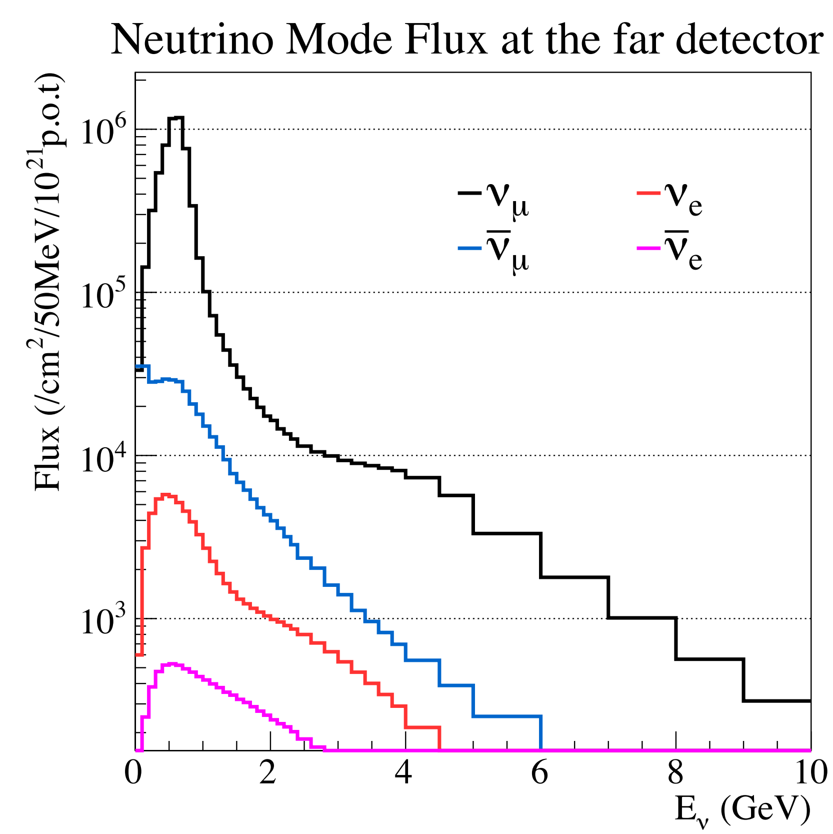
- **Revealing a full picture of neutrino oscillation with precise measurement of CP and mixing parameters**
- **J-PARC neutrino beam ⇒ upgrade to 1.3 MW for HK**
  - **Very reliable and well understood neutrino beam**

J-PARC Neutrino Beam

Conventional neutrino beam from pion decay



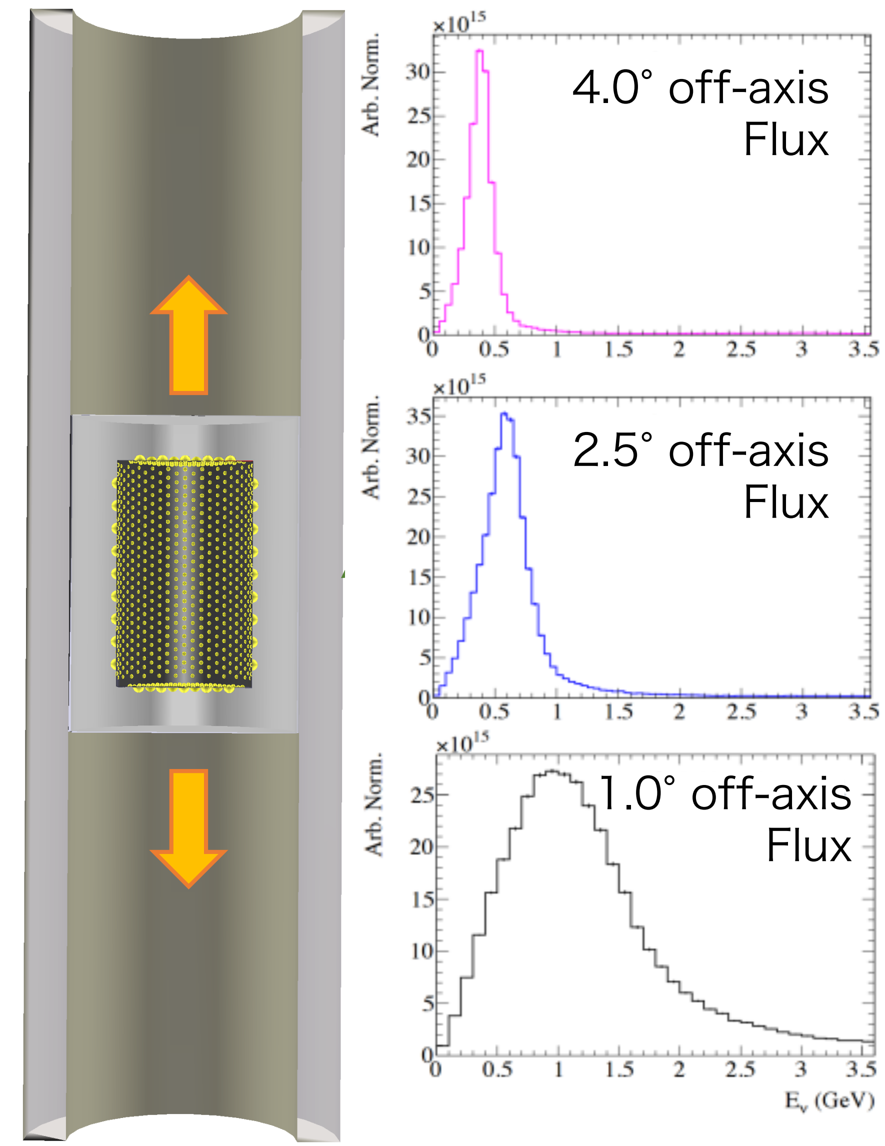


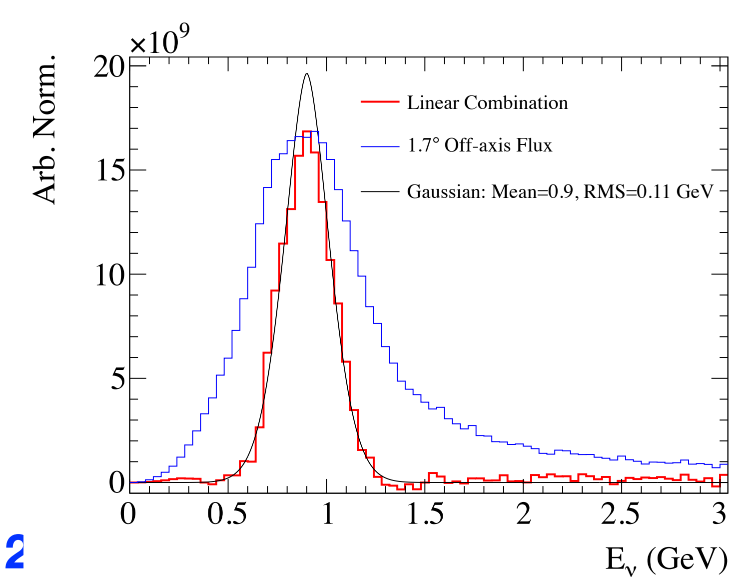


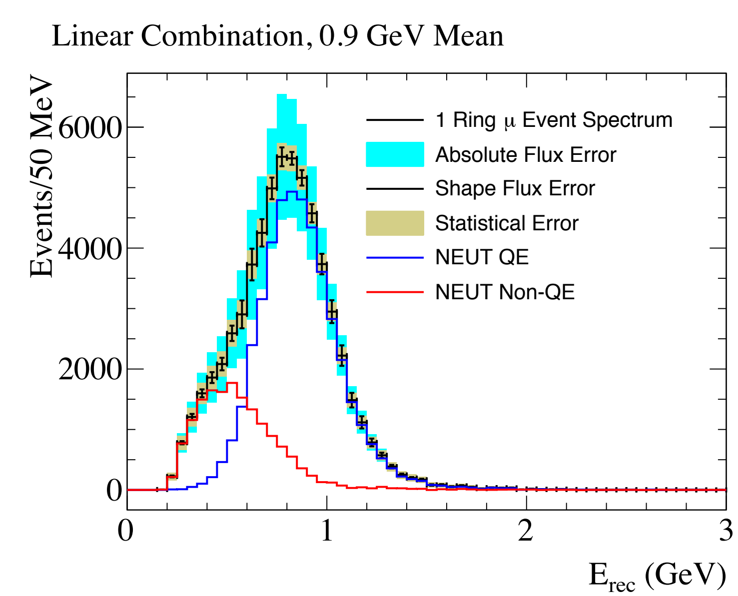
- **High intensity beam**
  - **30 GeV primary proton beam**
    - **Beam power upgrade 750 kW → 1.3 MW by 2026**
    - **3.2×10^{14} ppp beam intensity and 1.16s cycle**
- **Off-axis beam (2~2.5°)**
  - **Pure muon neutrino beam (96% ν_μ , 3% $\bar{\nu}_\mu$, 1% ν_e)**
  - **Select $\nu/\bar{\nu}$ beam by changing horn polarity**
  - **Low energy narrow-band beam ~ 0.6 GeV**
    - **peak at 1st osc. max. with L=295km.**

Intermediate Water Cherenkov Detector

- **~10kton water Cherenkov detector**
  - **Same technology as far detector (FD)**
    - **Water target**
    - **4π coverage**
- **Located 1~2km from target**
  - **Same neutrino energy spectrum as FD**
- **Vertically spanning (50~100m deep)**
  - **Linear combination of fluxes at different off-axis (1~4°) gives**
    - **Pseudo-monochromatic spectrum to estimate non-QE interaction**







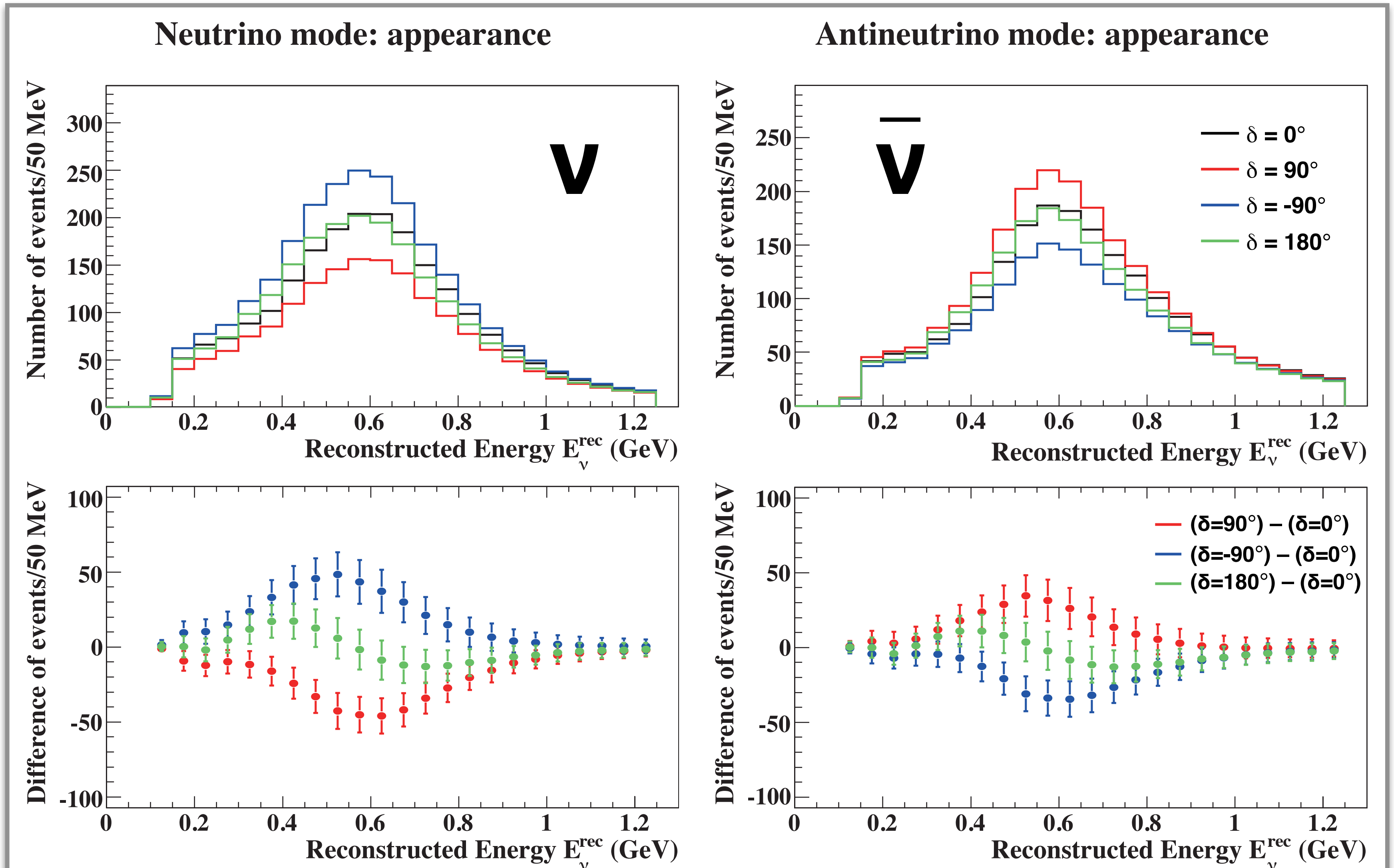
HK Sensitivity

Note :
The sensitivity studies shown here are based on single tank

Expected Events for CPV

Expected # of events in $\nu_e/\bar{\nu}_e$ appearance

(after applying ν_e selection criteria)



Assumption

- 1.3MW x 10years (10^8 s)
- $\nu : \bar{\nu}$ = 1 : 3
- $\sin^2 2\theta_{13}$=0.1
- Normal hierarchy

For δ=0	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 beam	1,643	15	7	259	134
$\bar{\nu}$ beam	1,183	206	4	317	196

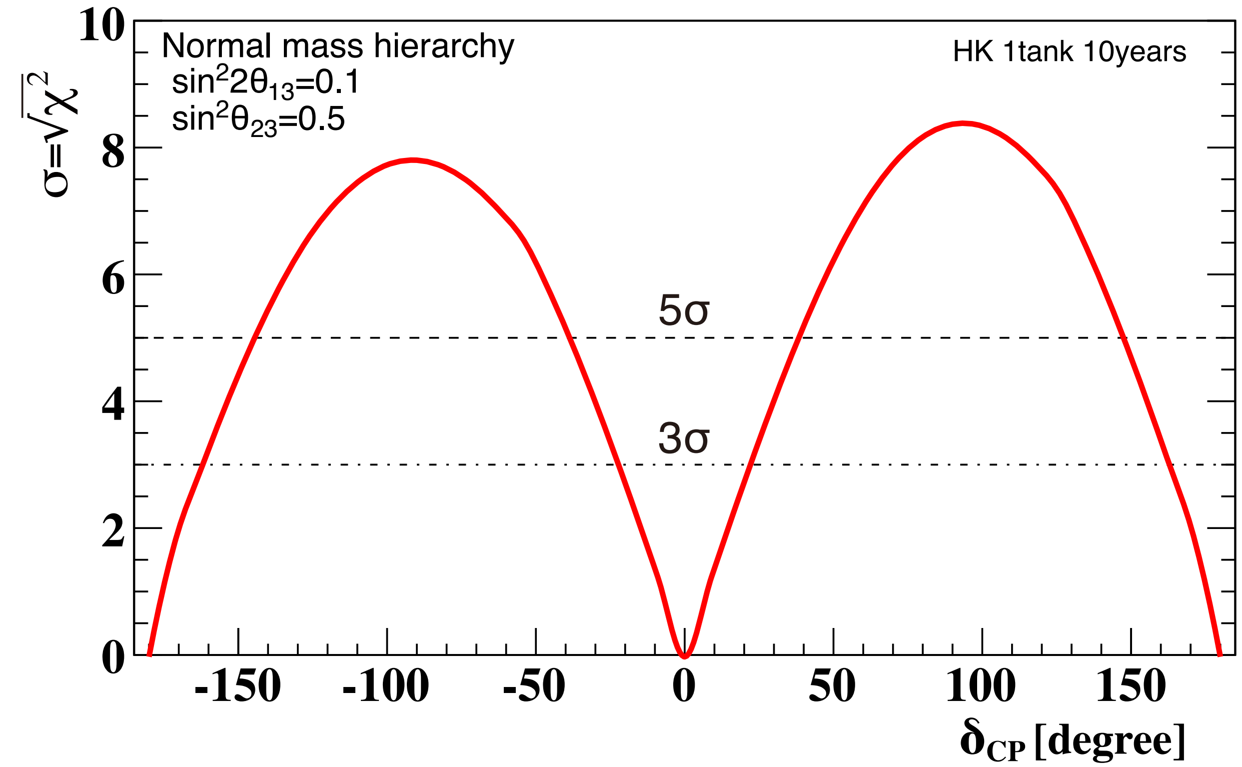
CPV Sensitivity

- **Exclusion of $\sin\delta_{CP}=0$**
  - **>8σ (6σ) for δ=-90° (-45°)**
  - **~80% coverage of δ parameter space with >3σ**
- **δ_{CP} measurement precision**
  - **22° at δ=±90°**
  - **7° at δ=0°, 180°**

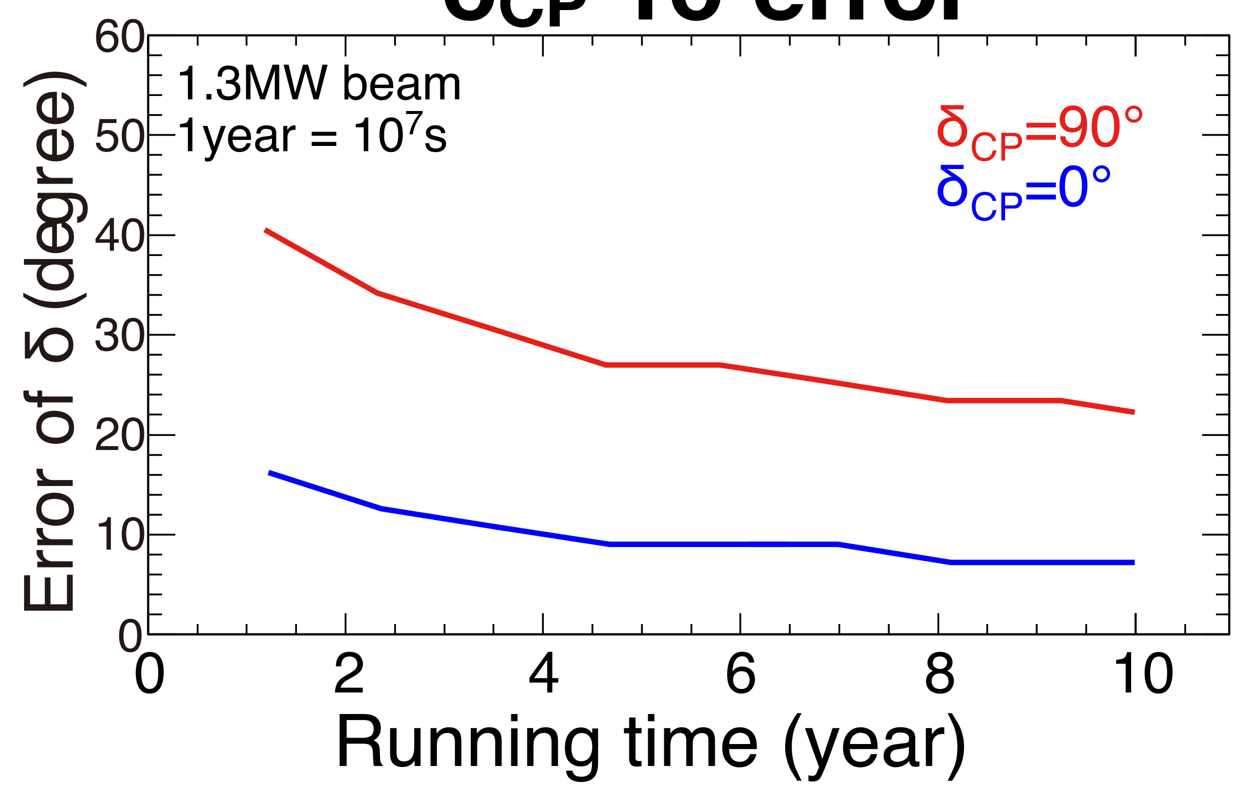
Sensitivity study adopt analysis techniques and systematic uncertainties used in T2K

- **Realistic systematic uncertainties plus expected reduction of errors**
- **3~4% syst. Error (6~7% in T2K)**

$\sin\delta_{CP}=0$ exclusion

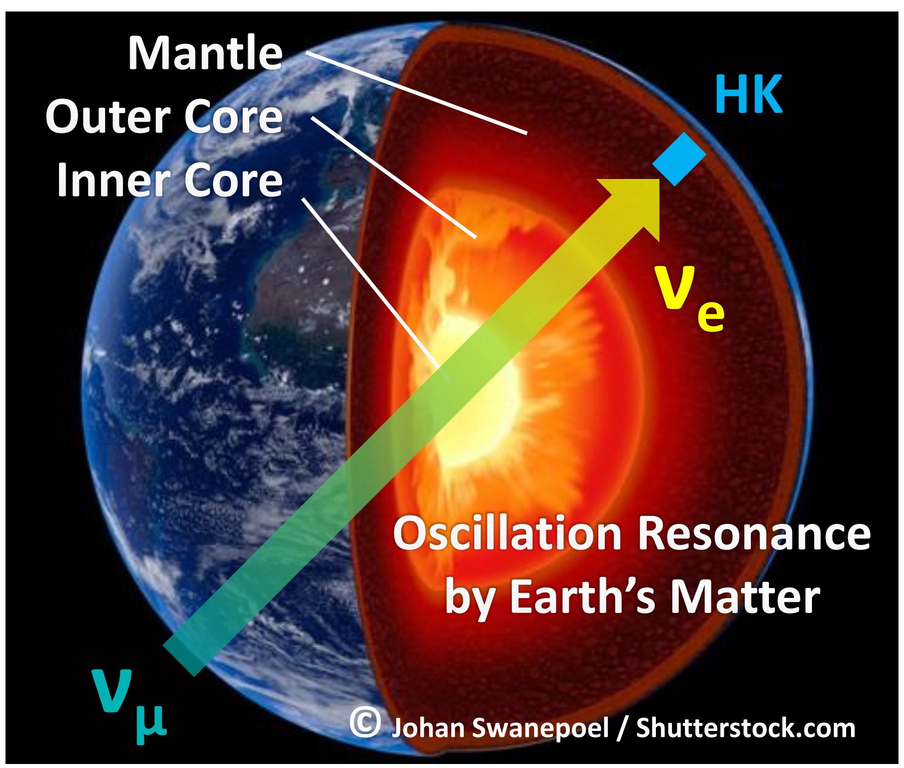


δ_{CP} 1σ error

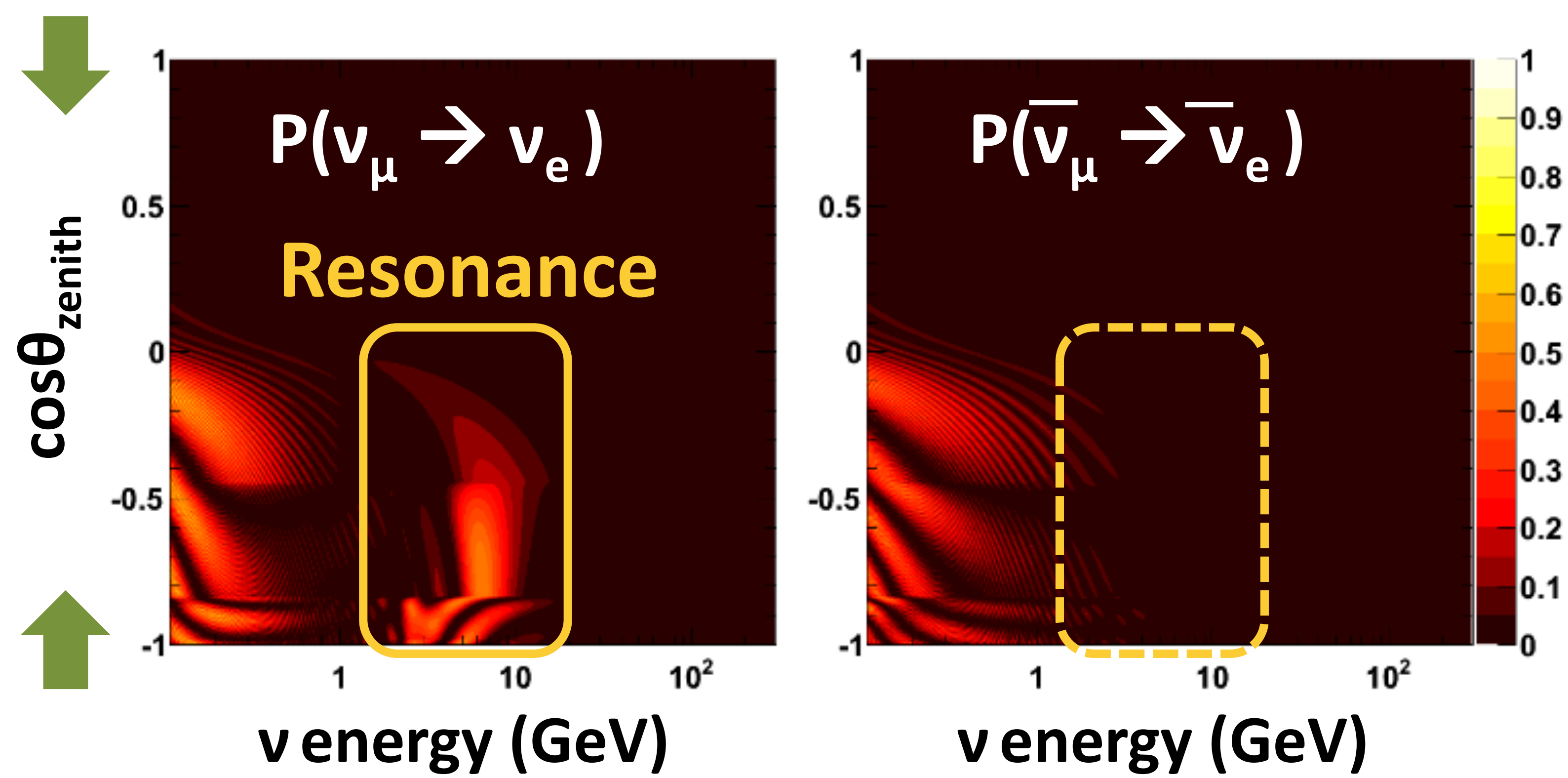


Mass Hierarchy Determination

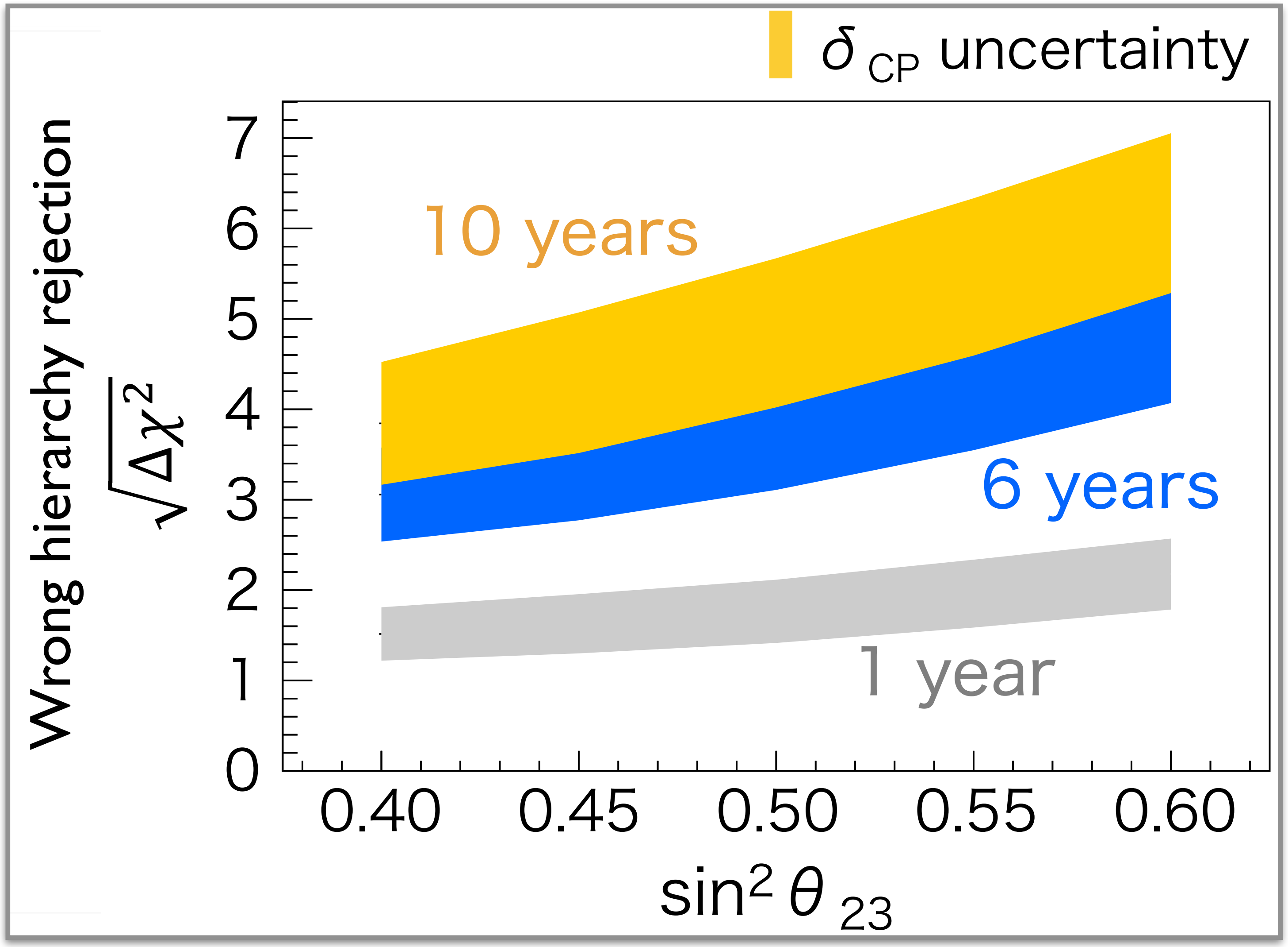
- Earth matter effect in upward-going multi-GeV ν_e sensitive to mass hierarchy
  - "Resonance" pattern appears in ν_e ($\bar{\nu}_e$) appearance for NH (IH)
- Combination of atmospheric ν and beam ν to determine mass hierarchy



Normal hierarchy case (opposite in inverted case)



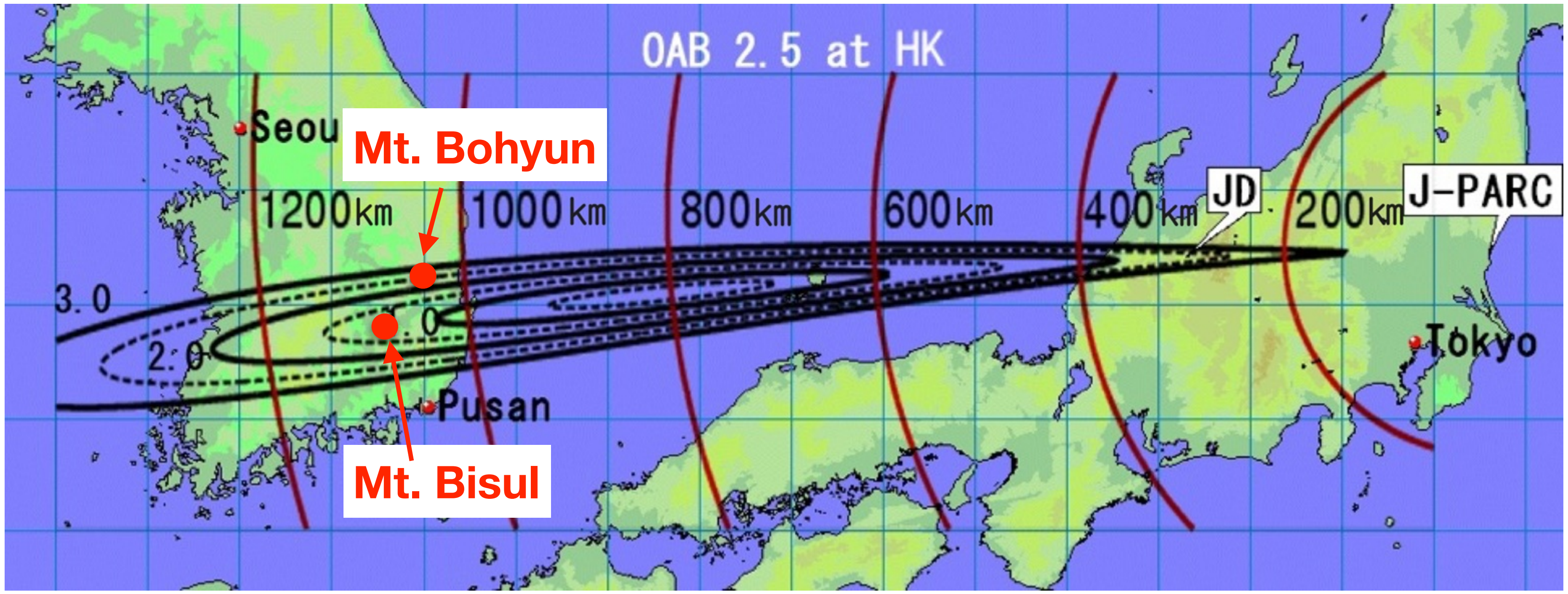
Sensitivity for Mass Hierarchy



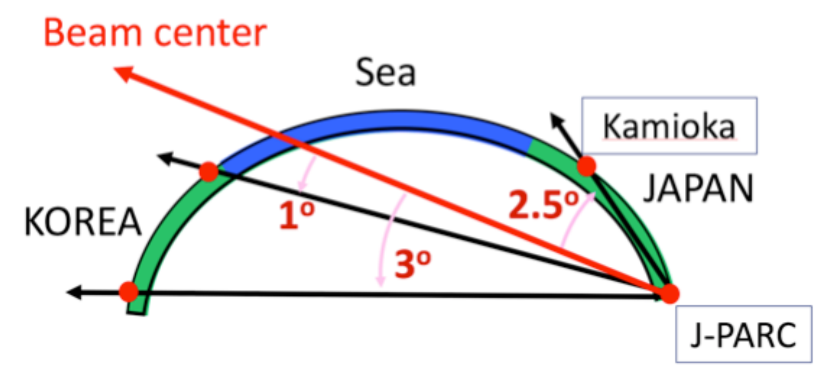
- **Hyper-K can determine Mass hierarchy in ~5 years ($\sin^2\theta_{23}$=0.5) using atmospheric and beam neutrinos, even if MH not determined before Hyper-K era**
  - **cf. Super-K suggests Normal Hierarchy with ~2σ**
    - **Phys. Rev. D97, 072001 (2018)**

Second tank option in Korea

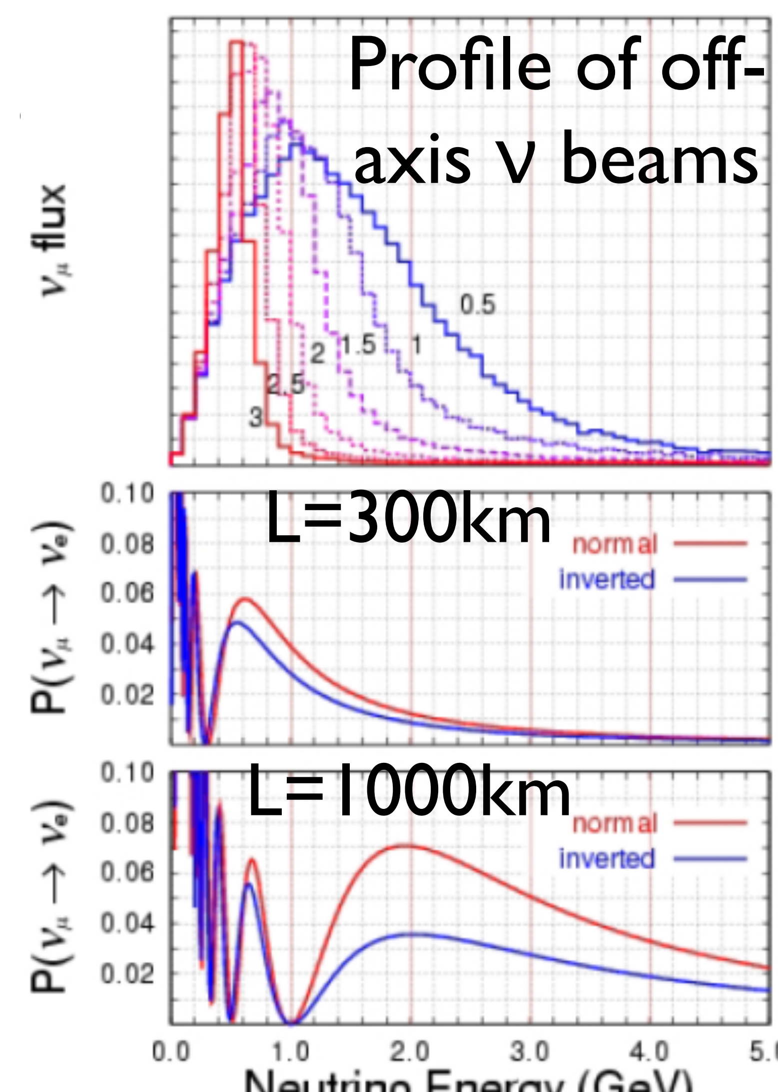
Korean Option for 2nd Tank



PTEP 2018, 063C01



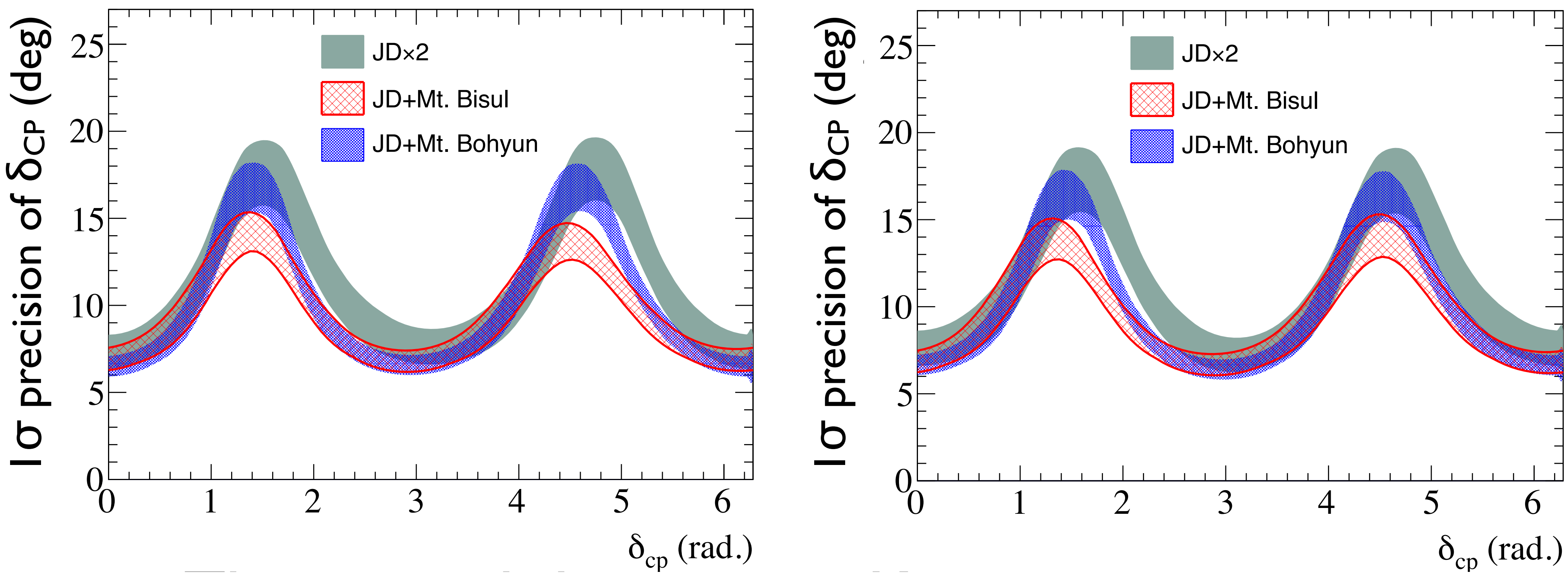
- **Second tank option in Korea is being considered**
- **Advantage**
  - **Large CP effect at second oscillation maximum**
  - **Higher mass hierarchy sensitivity with longer baseline**
- **Possible site**
  - **Mt. Bisul at L=1,088km, OA=1.3°**
  - **Mt. Bohyun at L=1,043km, OA=2.3°**



Physics Sensitivity w/ Korean Detector

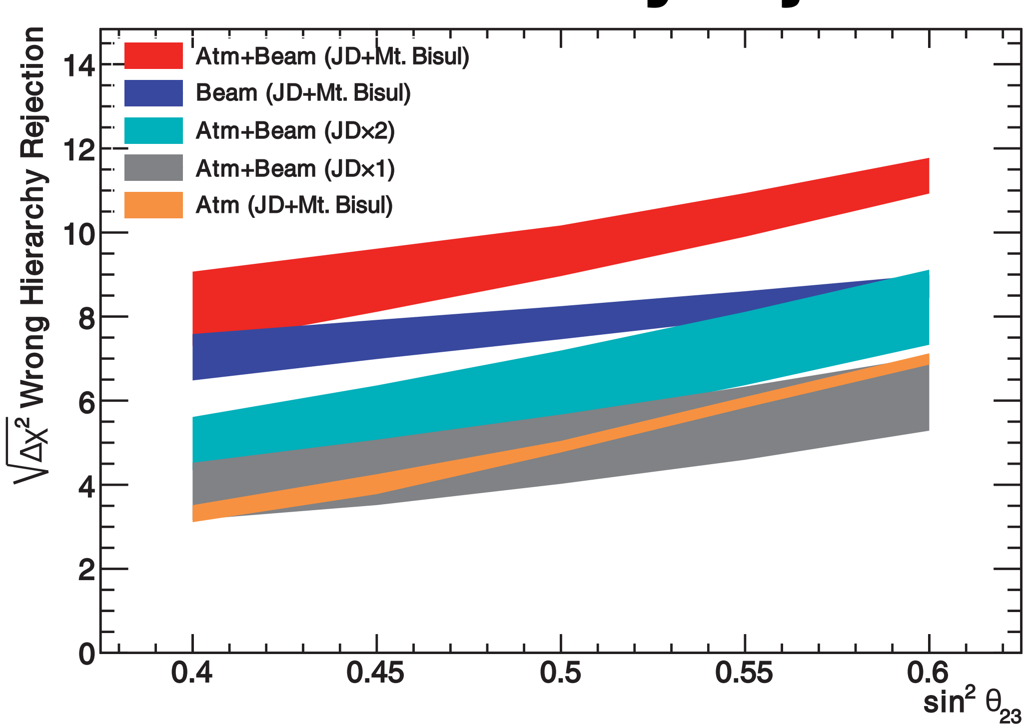
δ_{CP} 1σ precision

PTEP 2018, 063C01



Band indicates range $0.4<\sin^2\theta_{23}<0.6$

Mass hierarchy rejection



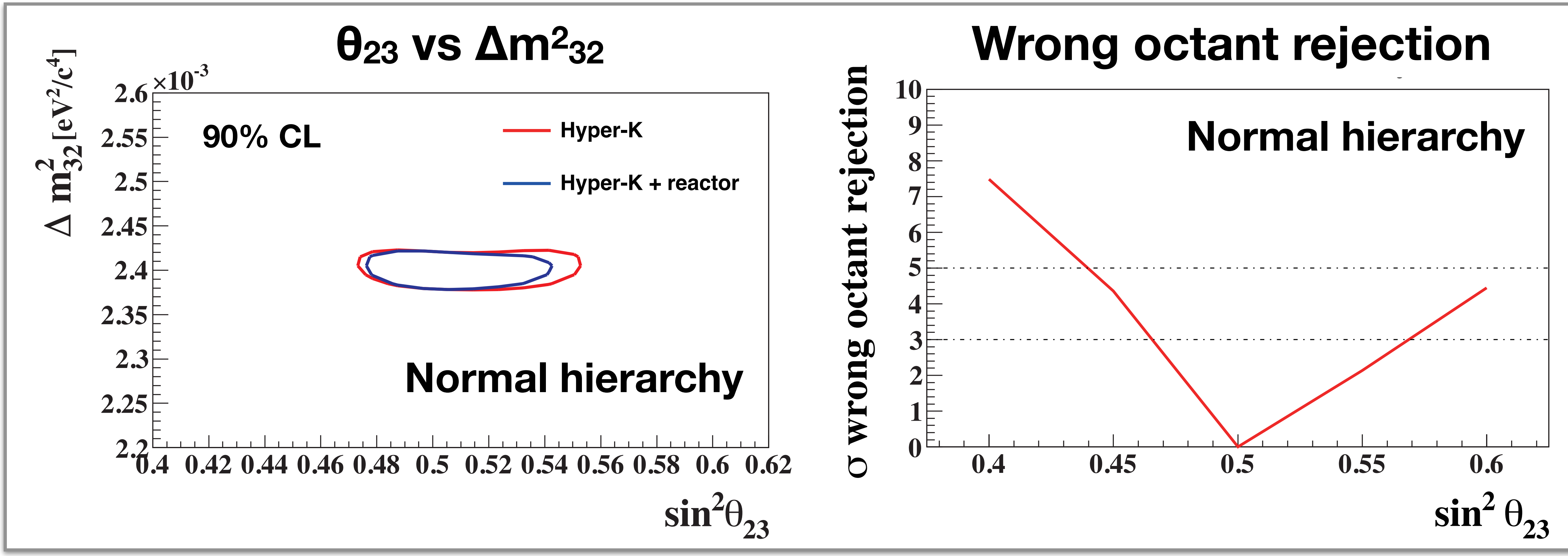
- **Korean detector gives us**
  - **better δ_{CP} measurement precision**
    22°(1tank)→<15° at δ_{CP}=-90°
  - **higher mass hierarchy sensitivity**
    4.5σ(1tank)→9σ at $\sin^2\theta_{23}$=0.5

Summary

- Hyper-Kamiokande
  - Next generation water Cherenkov detector
  - 260 kton total volume with Φ74m x H60m → 190 kton fiducial volume
  - 2 tanks with stating (to start as early as possible)
- HK sensitivity
  - CPV sensitivity
    - >8σ at δ=-90° & 80% coverage for >3σ
    - δ_{CP} resolution : 22°(7°) for δ=±90° (0, 180°)
  - Mass hierarchy can be determined within ~5 years
  - Second tank in Korea can improve δ_{CP} resolution down to 15° and mass hierarchy sensitivity

Backup

θ_{23}, Δm^2_{32}, and Octant



assumption for reactor : $\sin^2\theta_{13}=0.1\pm0.005$

True $\sin^2\theta_{23}$	0.45		0.50		0.55	
Parameter	Δm^2_{32} (eV^2)	$\sin^2\theta_{23}$	Δm^2_{32} (eV^2)	$\sin^2\theta_{23}$	Δm^2_{32} (eV^2)	$\sin^2\theta_{23}$
NH	1.4×10^{-5}	0.006	1.4×10^{-5}	0.017	1.5×10^{-5}	0.009
IH	1.5×10^{-5}	0.006	1.4×10^{-5}	0.017	1.5×10^{-5}	0.009

Δm^2_{32} precision : 0.6% ⇒ comparable with reactor measurement

Comparison will enable a significant consistency check

Systematic Uncertainties

- **Syst. Errors based on SK/T2K experience and prospect**
  - **Error matrices of T2K adopted in HK sensitivity**
  - **Near detector : constrain cross section error w/ water target**
  - **Far detector : systematic error reduced by large stat. of atm-ν**

Assumed systematic uncertainties for sensitivity studies

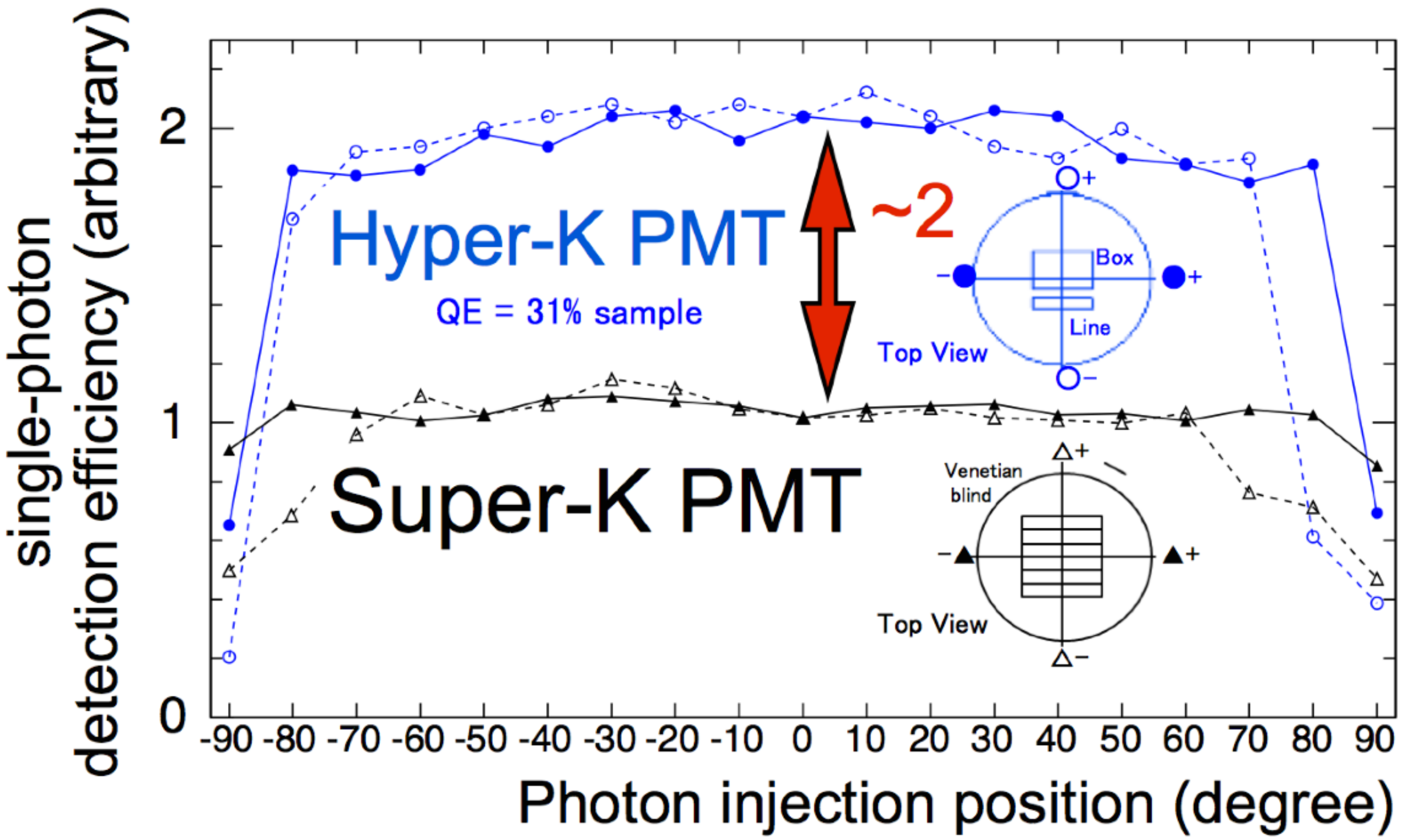
		Flux & ND-constrained cross section	ND-independent cross section	Far detector	Total	T2K (2017)
ν mode	Appearance	3.0%	0.5%	0.7%	3.2%	**6.1%**
	Disappearance	3.3%	0.9%	1.0%	3.6%	**4.4%**
$\overline{\nu}$ mode	Appearance	3.2%	1.5%	1.5%	3.9%	**6.5%**
	Disappearance	3.3%	0.9%	1.1%	3.6%	**3.8%**

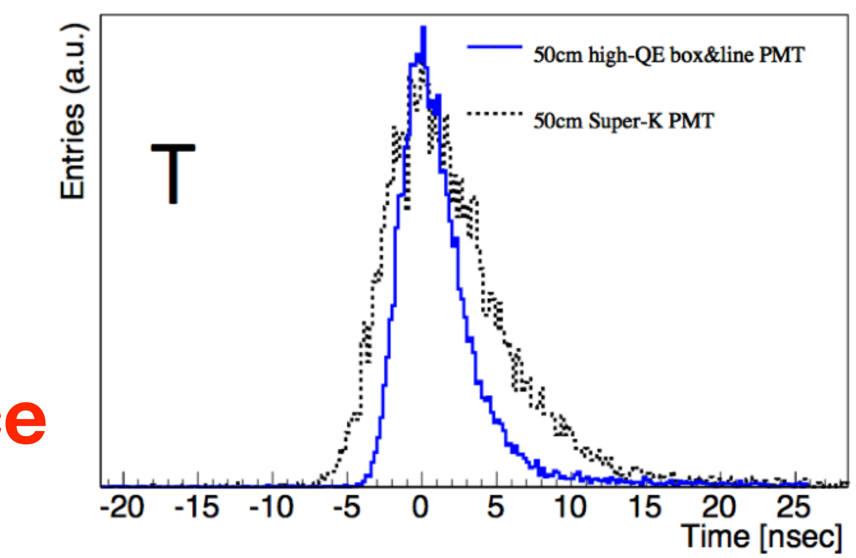
HK sensitivity studies assume uncertainties at 3~4% level

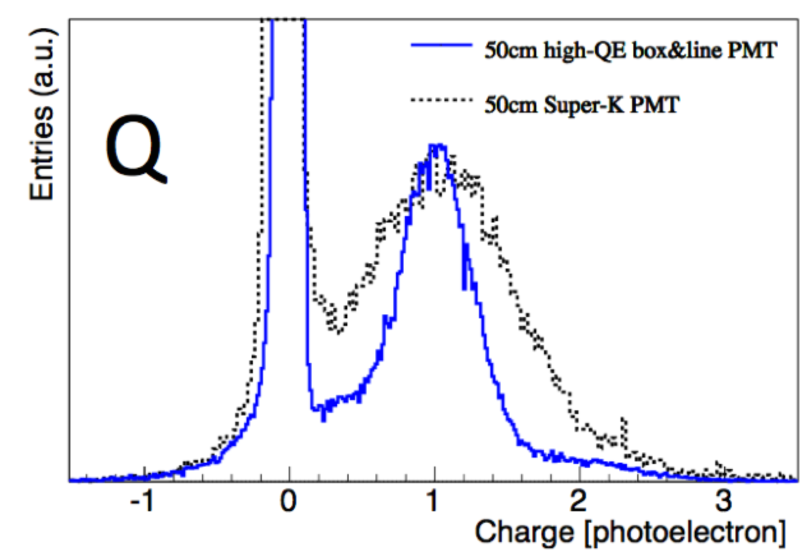
(cf. uncertainties at 6~7% level in T2K)

Dominant errors : electron (anti-)neutrino cross section, near-to-far extrapolation of event rates, far detector modeling

New Photo-Sensor







- New 20-inch photo-sensors: higher performance
  - Single-photon efficiency: x2
  - 1 p.e. timing resolution: 2ns → 1ns
  - 1 p.e. charge resolution: 53% → 35%
- Large impact on detector performance/physics sensitivity

CP Violation Search in Neutrino Sector

- Leptonic (ν) CPV search is very important
  - The only known CPV source = CKM phase
  - Need other CPV source to explain the matter-antimatter asymmetry in the universe.
- Leptogenesis scenario only with Dirac CP phase
  - S. Pascoli et al., PRD 75, 083511 (2007) PDG review 2014
    - $|\sin\delta_{CP}|>\sim0.6$
- Flavor symmetry prediction on δ_{CP}
  - e.g. Petrov 1504.02402v1
- Precise measurement is also important!