19th International Workshop on Neutrinos from Accelerators

Physics potential of Hyper-Kamiokande for neutrino oscillations

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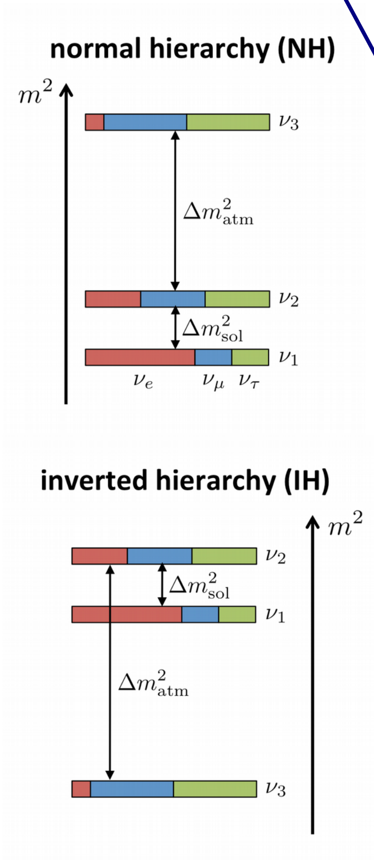
Outline

- Physics goals for neutrino oscillations
- Sensitivity with beam neutrinos and one detector
- Atmospheric neutrinos and combination with beam neutrinos
- Second tank: staging and Korean detector options
- Solar neutrino oscillations

Main physics goals (neutrino oscillations)

Mass hierarchy:
$m_3 > m_2, m_1$?



PDG 2016 summary table

Parameter	best-fit	3σ
Δm^2_{21} [10^{-5} eV ^{2}]	7.37	6.93 – 7.97
$\lvert\Delta m^2\rvert$ [10^{-3} eV ^{2}]	2.50 (2.46)	2.37 – 2.63 (2.33 – 2.60)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	0.437	0.379 – 0.616
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	0.569	0.383 – 0.637
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	0.0214	0.0185 – 0.0246
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	0.0218	0.0186 – 0.0248
δ/π	1.35 (1.32)	(0.92 – 1.99) ((0.83 – 1.99))

Octant of θ_{23}:
$\theta_{23} > \pi/4$?
$\theta_{23} < \pi/4$?

Violation of CP symmetry in neutrino oscillations?

+ improve measurements of oscillation parameters, tests of the 3 neutrino oscillation model

Looking for second order effects

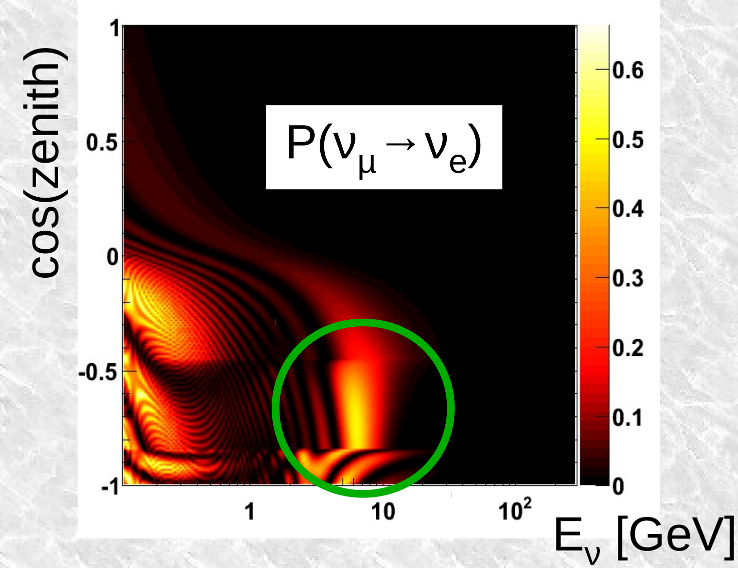
Look for subtle effects by comparing $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

CP violation: $\sin(\delta) \neq 0$?

$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) = & \, 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \\
& + 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta - s_{12} s_{13} s_{23}) \cos\Delta_{32} \sin\Delta_{31} \sin\Delta_{21} \\
& - 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin\Delta_{32} \sin\Delta_{31} \sin\Delta_{21} \\
& + 4s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta) \sin^2\Delta_{21}
\end{aligned}
$$

$$\sin^2\Delta_{ij} = \sin^2(1.27\,\Delta m_{ij}^2 \times L/E)$$

Mass hierarchy: $\Delta m^2_{32/31} > 0$?



Octant of θ_{23}: $\theta_{23}=\pi/4$? $\theta_{23}>\pi/4$? $\theta_{23}<\pi/4$?

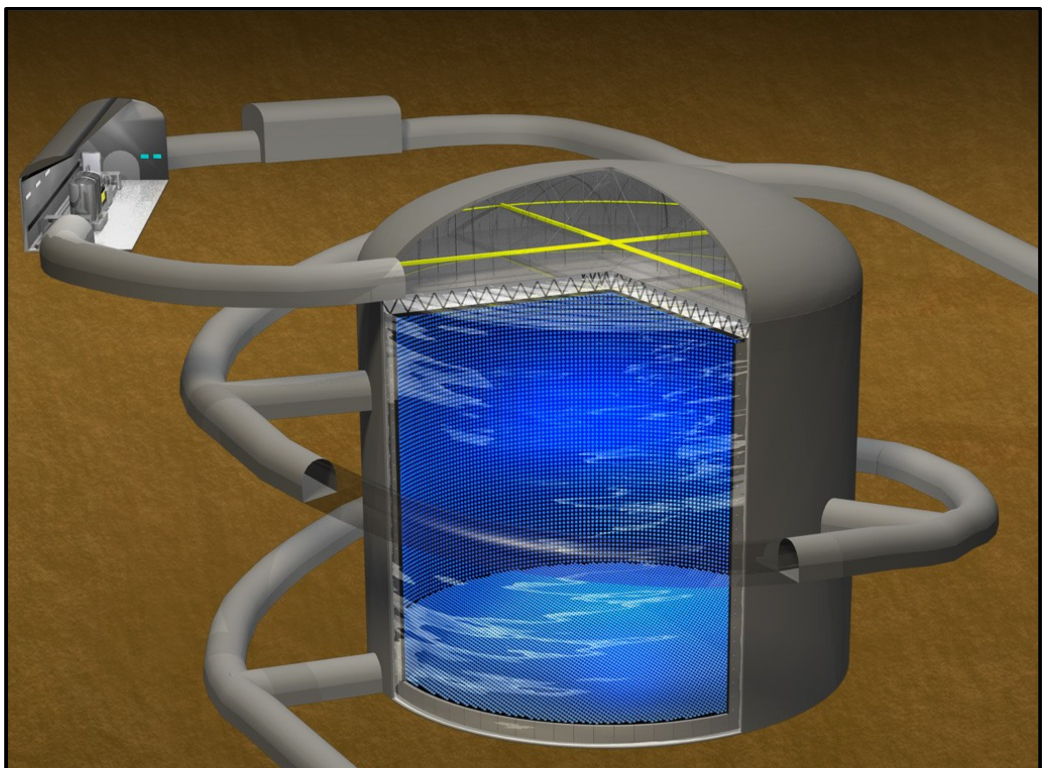
$$P(\nu_\mu \rightarrow \nu_\mu) \sim 1 - \left(\overbrace{\cos^4\theta_{13}}^{\sim 0.96} \times \sin^2 2\theta_{23} + \overbrace{\sin^2 2\theta_{13}}^{\sim 0.085} \times \sin^2\theta_{23} \right) \times \sin^2 \frac{\Delta m_{31}^2 \times L}{4E}$$

Need more neutrino events

Hyper-Kamiokande

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

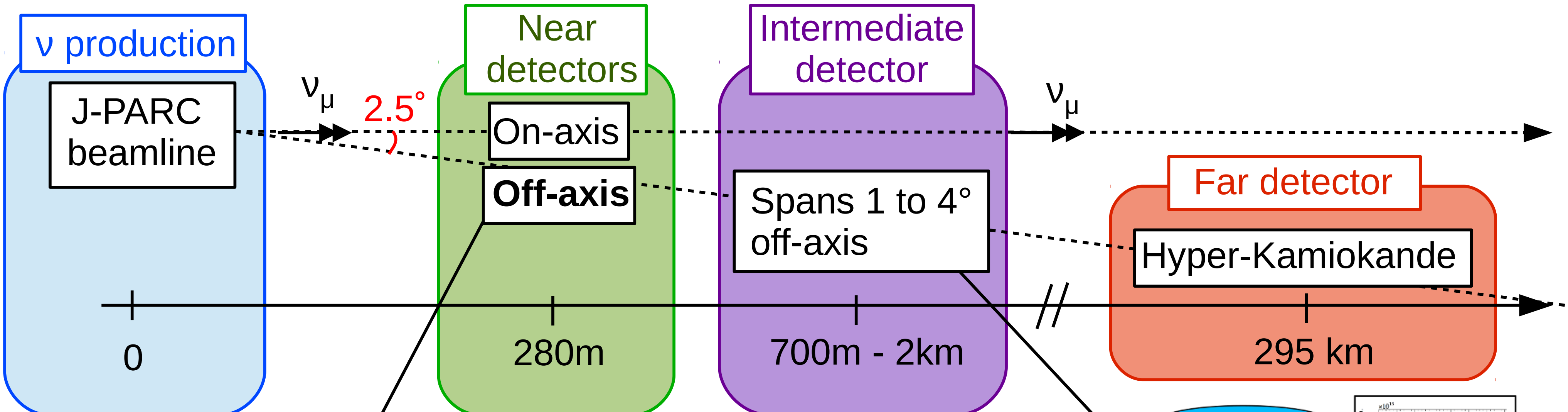
- Larger detector for increased statistics
- Improved photo-sensors for better efficiency
- Higher intensity beam and updated/new near detector for accelerator neutrino part

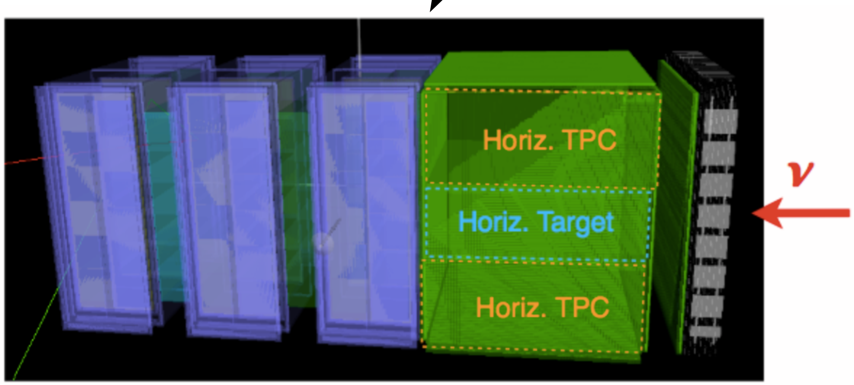


- 60m height x 74m diameter tank
- 190 kton fiducial volume (SK:22.5 kton)
- Construct first tank as soon as possible
- Proposals for a second tank:
  - 6 years later in Japan
  - as soon as possible in Korea

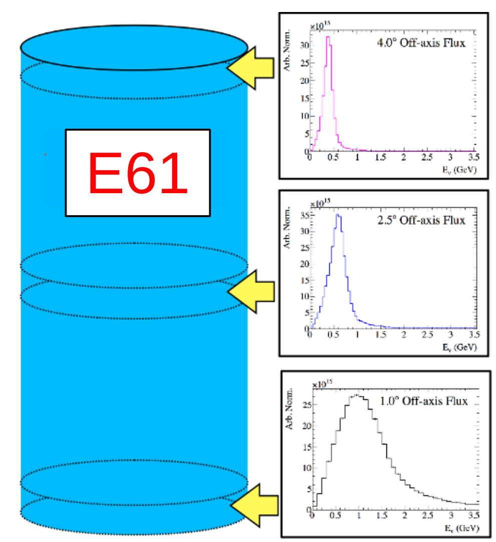
Long baseline oscillations: T2HK

- Candidate site for Hyper-K ~8km south of Super-K
- Baseline (295km) and off-axis angle (2.5°) for J-PARC beam identical to Super-K: very "T2K-like" experimental apparatus





Updated ND and new ID to reduce systematics



ND280 upgrade: official T2K project

E61: currently separate collaboration

Long baseline oscillations: T2HK Sensitivity studies

Setup similar to T2K: sensitivity studies based on framework used to evaluate T2K future sensitivity (PTEP 2015, 043C01 (2015))

- SK MC and reconstruction
- Scaled to one 187kton f.v. tank
- 10 years run with 1.3 MW beam
- Running mode ν:$\bar{\nu}$ is 1:3
- **Mass hierarchy assumed to be known**

Nominal values:
$\sin^2(2\theta_{13})=0.1$
$\sin^2(\theta_{23})=0.5$
$\Delta m^2_{32}=2.4\mathrm{x}10^{-3}$ ev^2/c^4
$\sin^2(2\theta_{12})=0.8704$
$\Delta m^2_{21}=7.6\mathrm{x}10^{-5}$ ev^2/c^4

Systematic uncertainties estimated based on T2K experience + expected improvement:

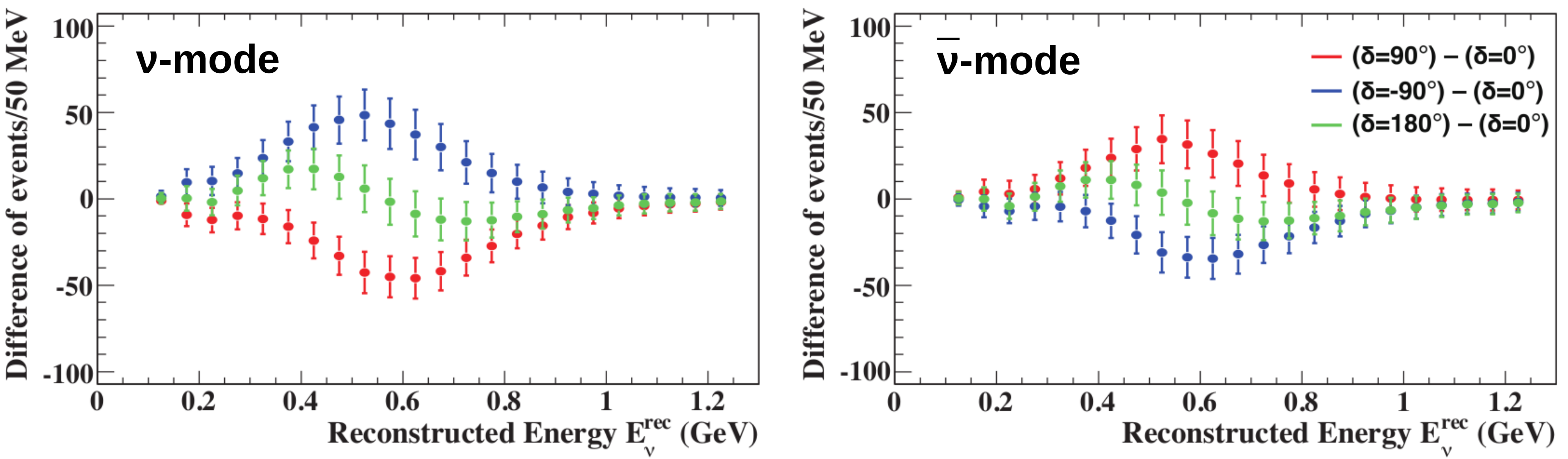
- ✓ Updated near detector and Intermediate detector
- ✓ Larger atmospheric control sample for far detector

	Sample	Flux + ND constrained xsec	x-sec ND independant	Far detector	Total	T2K 2017
ν mode	e-like	3.0%	0.5%	0.7%	**3.2%**	6.3%
	µ-like	3.3%	0.9%	1.0%	**3.6%**	4.4%
$\bar{\nu}$ mode	e-like	3.2%	1.5%	1.5%	**3.9%**	6.4%
	µ-like	3.3%	0.9%	1.1%	**3.6%**	3.8%

Long baseline oscillations: T2HK
Expected number of events: appearance

- Expect >1000 signal events in each running mode
- Differences between the different values of δ in terms of number of events and spectrum

	Signal		Background	Total
	$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$		
ν-mode	1643	15	400	2058
$\bar{\nu}$-mode	206	1183	517	1906

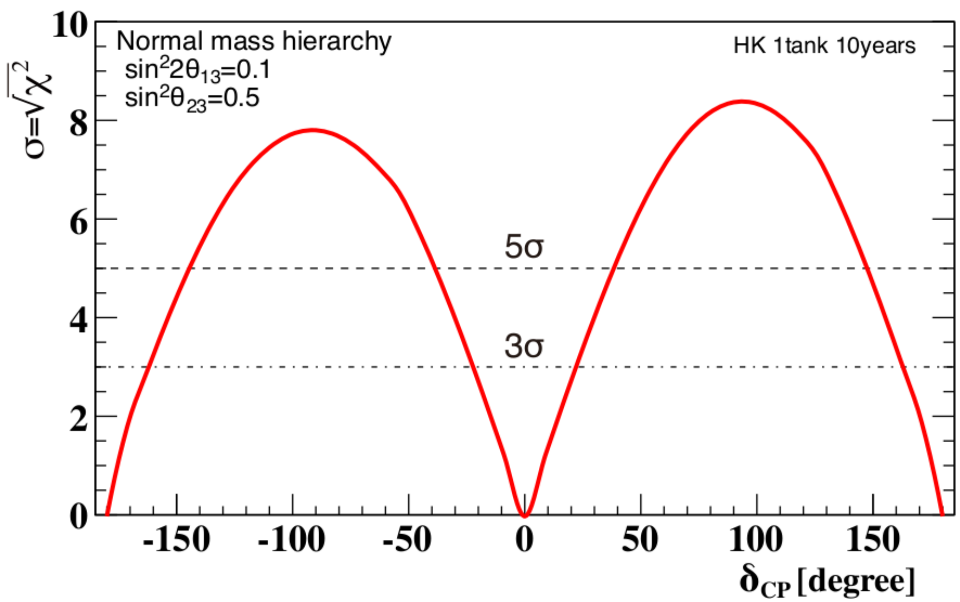


Long baseline oscillations: T2HK Sensitivity to CP-violation

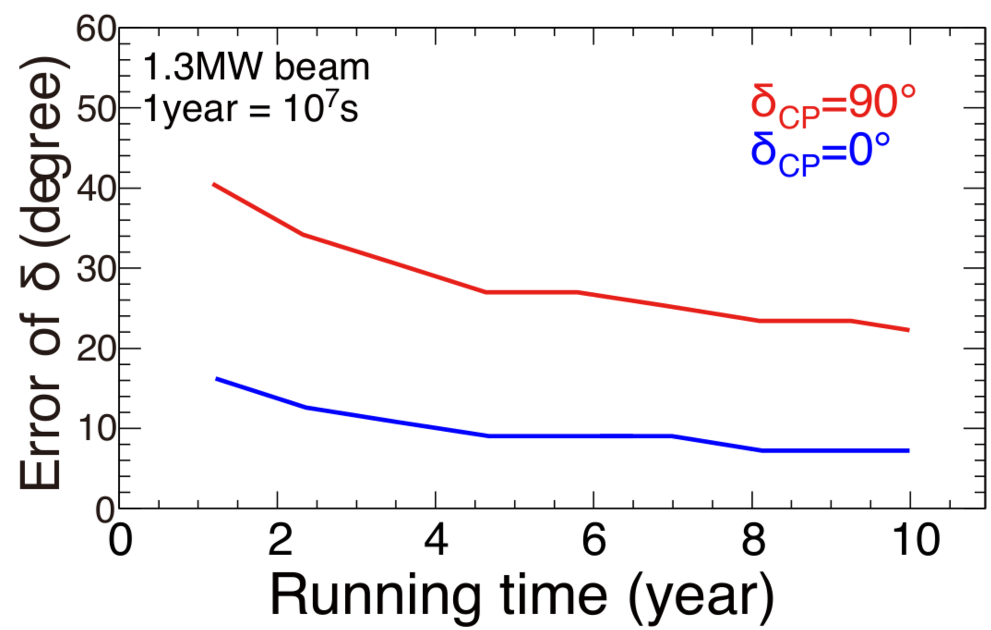
After 10 years of running:

- Exclude CP conservation at 5σ (3σ) for 57% (76%) of possible true values of δ
- Measure δ with 7° (true δ=0) to 23° (true δ=90°) precision

Ability to exclude CP conservation



Precision of δ measurement



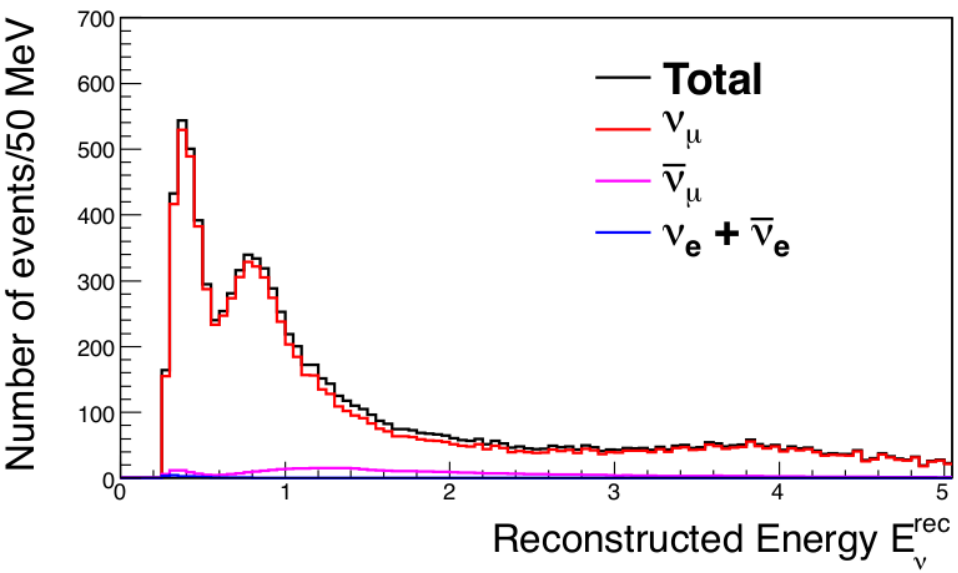
(Mass hierarchy assumed to be known)

Long baseline oscillations: T2HK
Expected number of events: disappearance

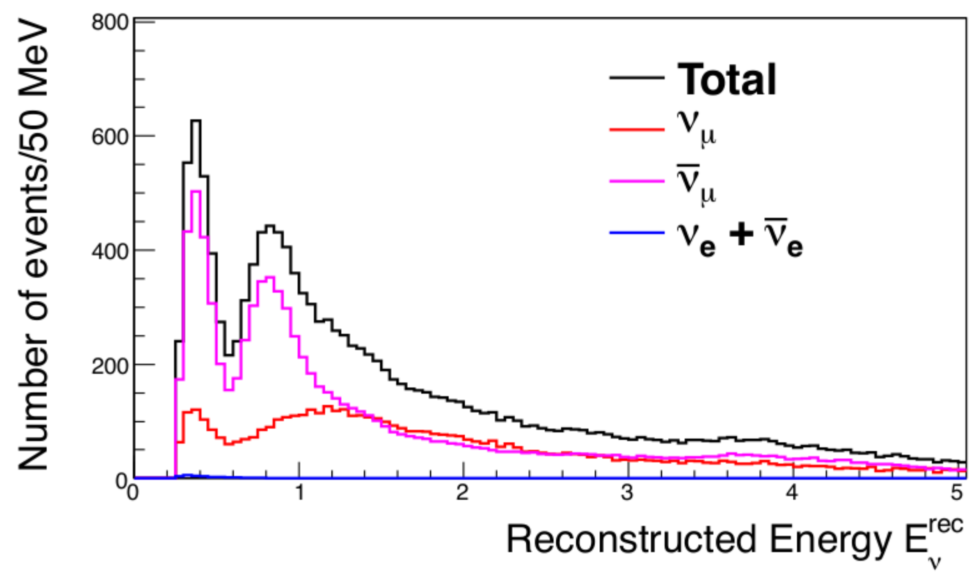
- Expect more than 10000 events in each running mode
- Clear oscillation pattern in the spectra
- Larger “wrong-sign” background in $\bar{\nu}$-mode

	ν_μ CCQE	ν_μ CC non QE	$\bar{\nu}_\mu$ CCQE	$\bar{\nu}_\mu$ CC non QE	Bkg	Total
ν-mode	6043	2981	348	194	515	10080
$\bar{\nu}$-mode	2699	2354	6099	1961	614	13726

Disappearance ν mode



Disappearance $\bar{\nu}$ mode



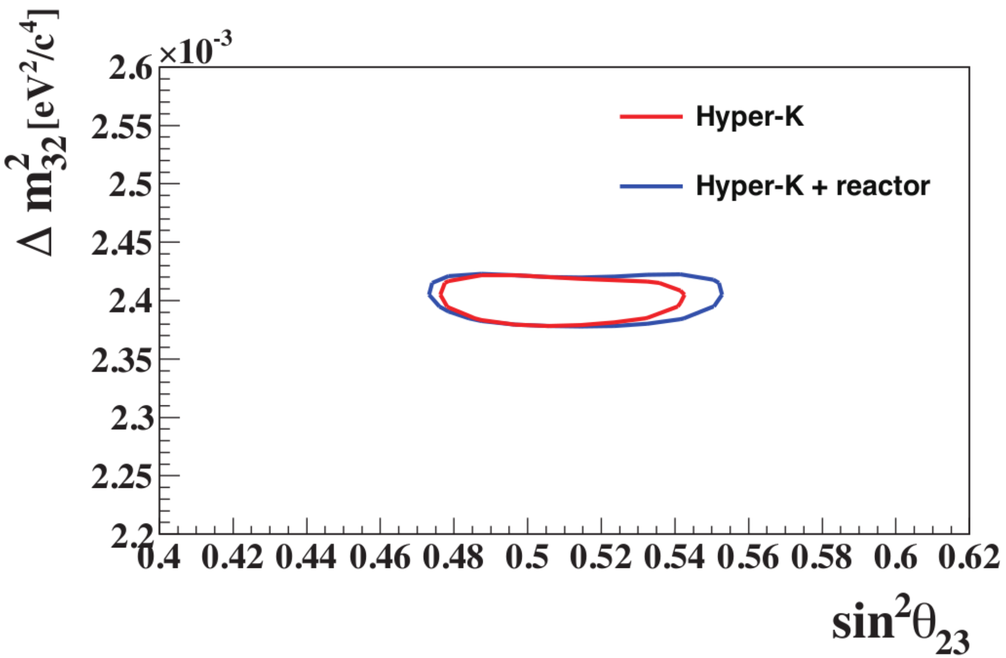
Long baseline oscillations: T2HK
Sensitivity to atmospheric parameters

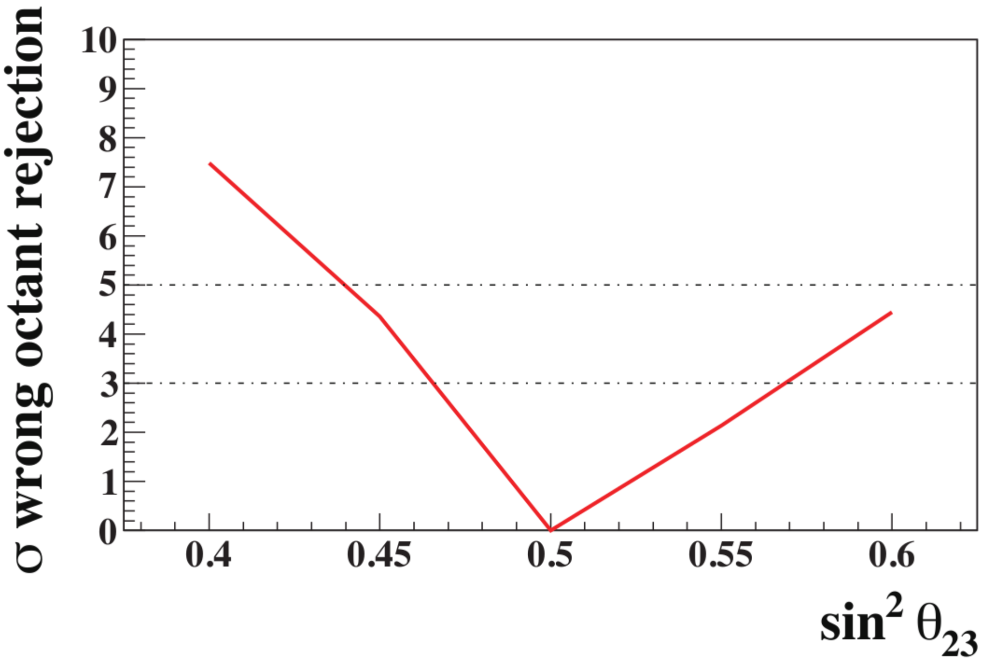
After 10 years:

- Measure Δm^2_{32} with 1.4×10^{-5} ev^2/c^4 precision
- Measure $\sin^2(\theta_{23})$ with precision 0.006 to 0.017
- Some ability to determine octant of θ_{23}

$\sin^2(\theta_{23})$ precision

True value	0.45	0.5	0.55
Precision	0.006	0.017	0.009

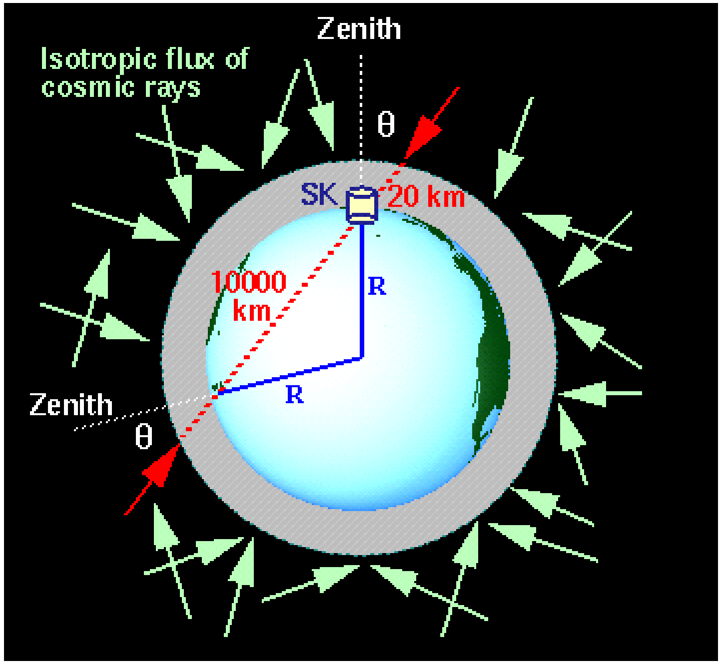


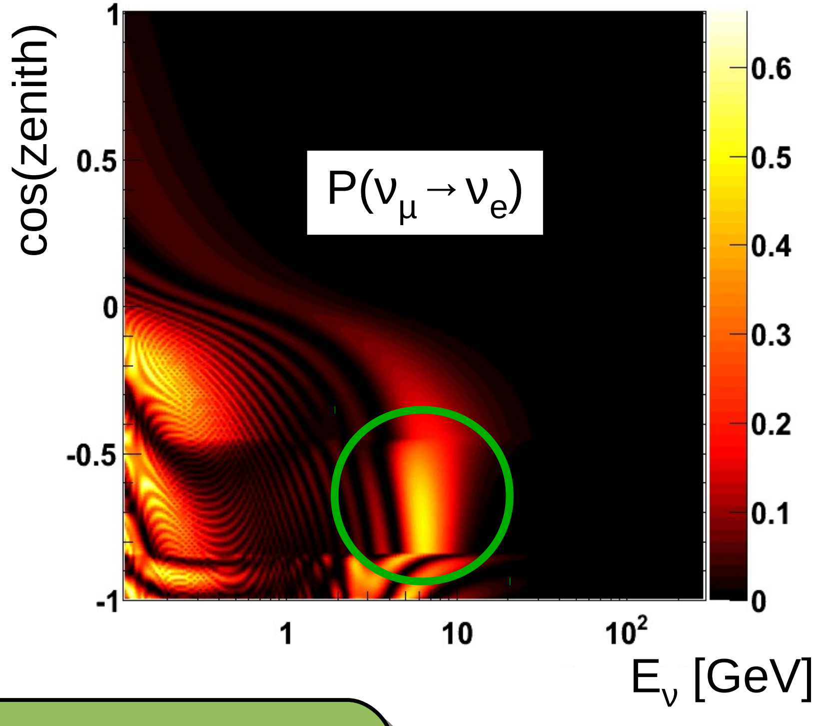


Normal hierarchy, "reactor constraint" $\sin^2(2\theta_{13}) = 0.1 \pm 0.005$

Atmospheric neutrinos

T2HK baseline is only 295km → limited sensitivity to mass hierarchy
Hyper-K can study oscillation of atmospheric ν's like Super-K





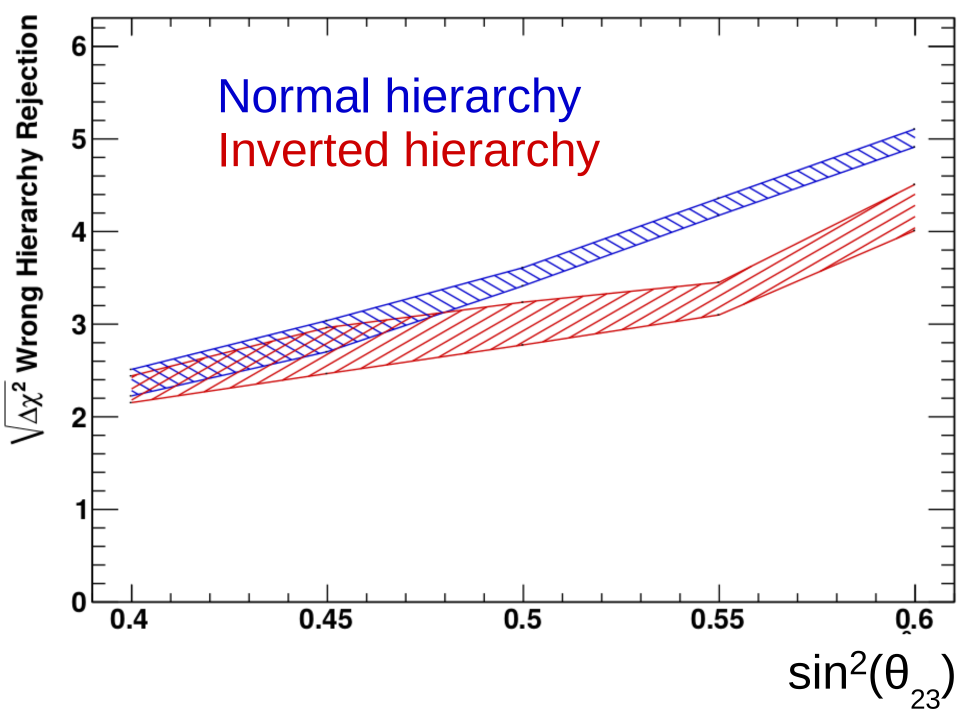
Sensitivity studies based on SK analysis
- Scaled SK MC
- 10 years running with one 186 kt fv detector
- No improvement of Super-K systematics assumed
- True mass hierarchy not assumed to be known

Atmospheric neutrinos

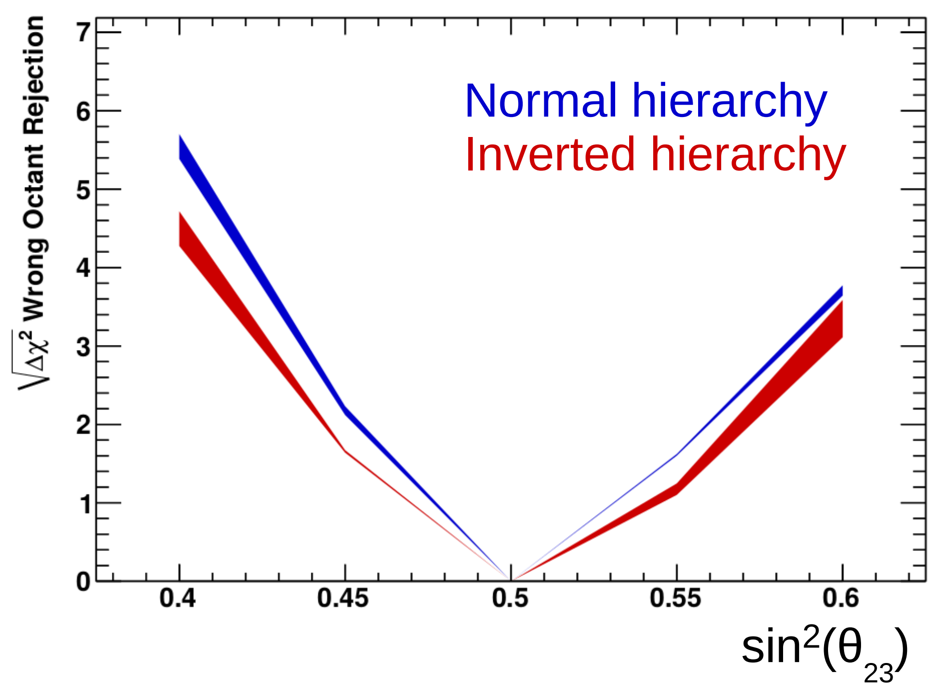
Using only atmospheric neutrinos:

- Can hope to determine mass hierarchy at 3σ in the NH case
- Some sensitivity to θ_{23} octant, but lower than beam neutrinos
- Sensitivities depend on true θ_{23} value

Mass hierarchy determination



Octant determination



Error bands: uncertainty due to unknown δ value

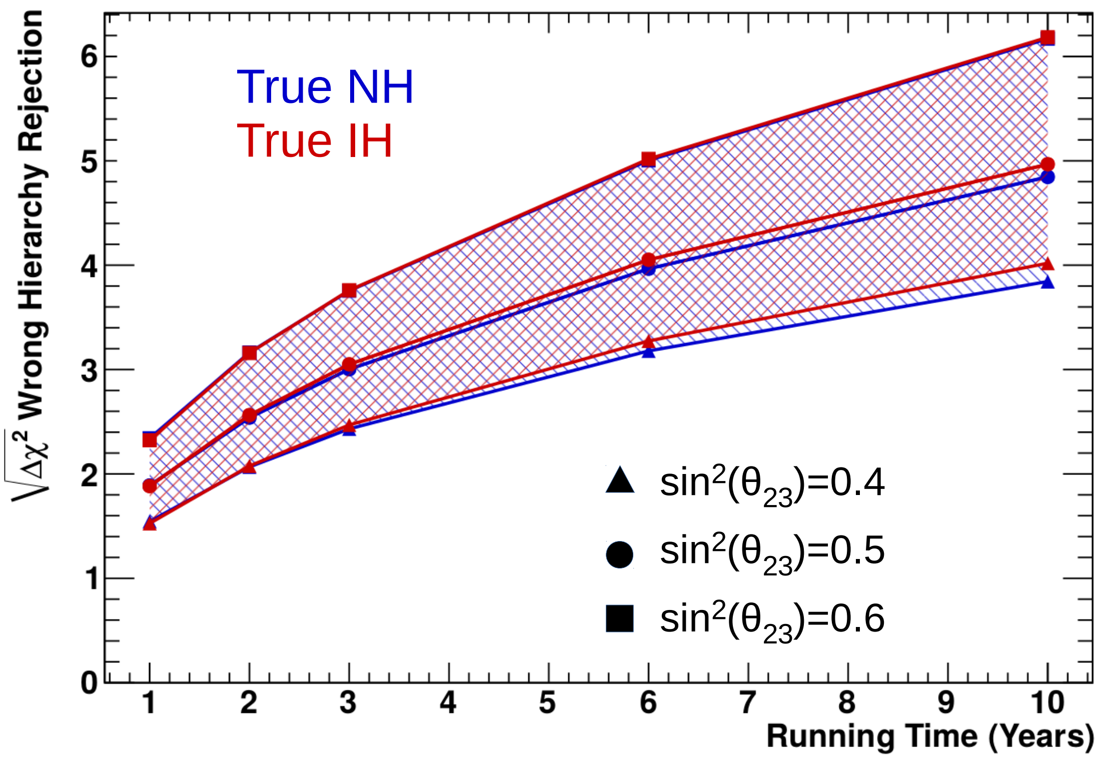
Atmospheric + beam neutrinos
Mass hierarchy

Atmospheric neutrinos

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

Beam neutrinos

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



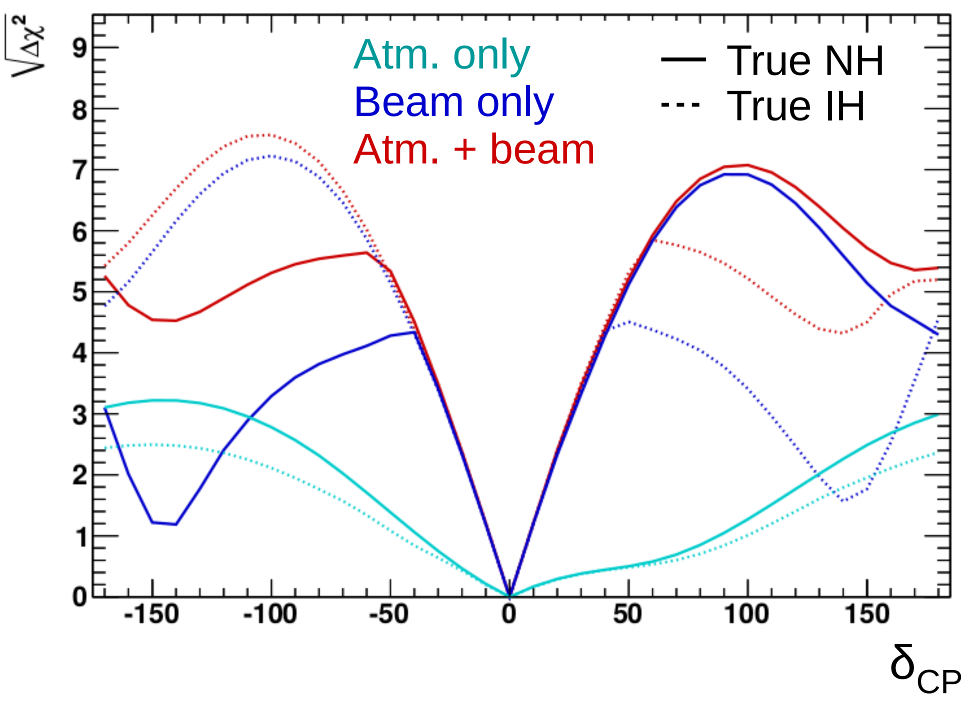
Combining the two:
- ✓ >3σ ability to reject wrong MH
- ✓ 5σ for larger values of $\sin^2(\theta_{23})$

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

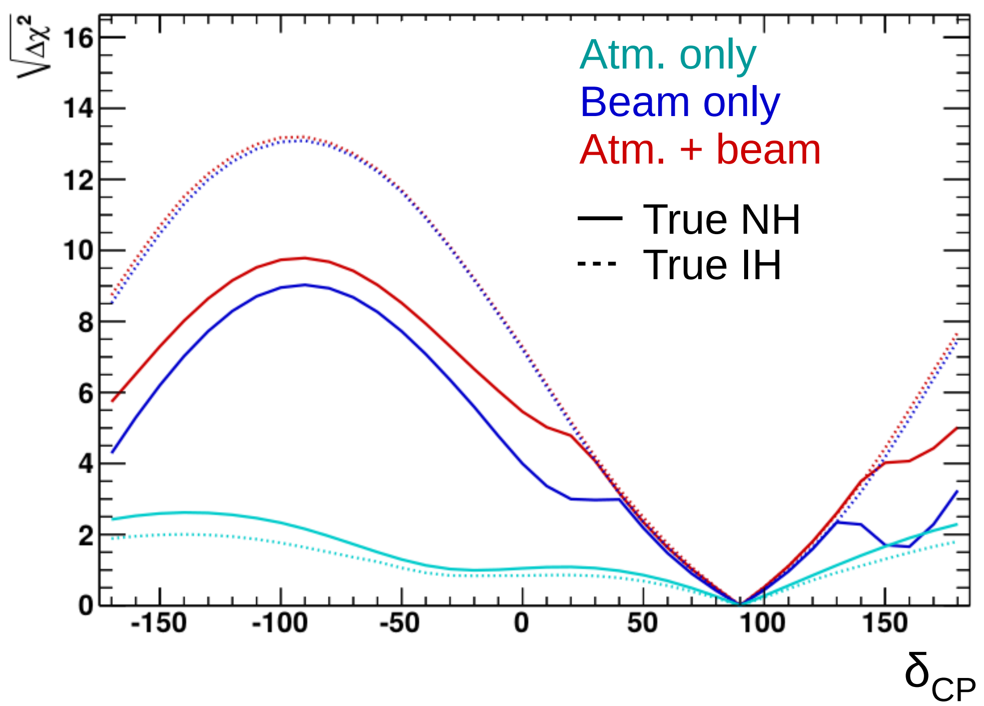
Atmospheric + beam neutrinos
Sensitivity to CP violation

- 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



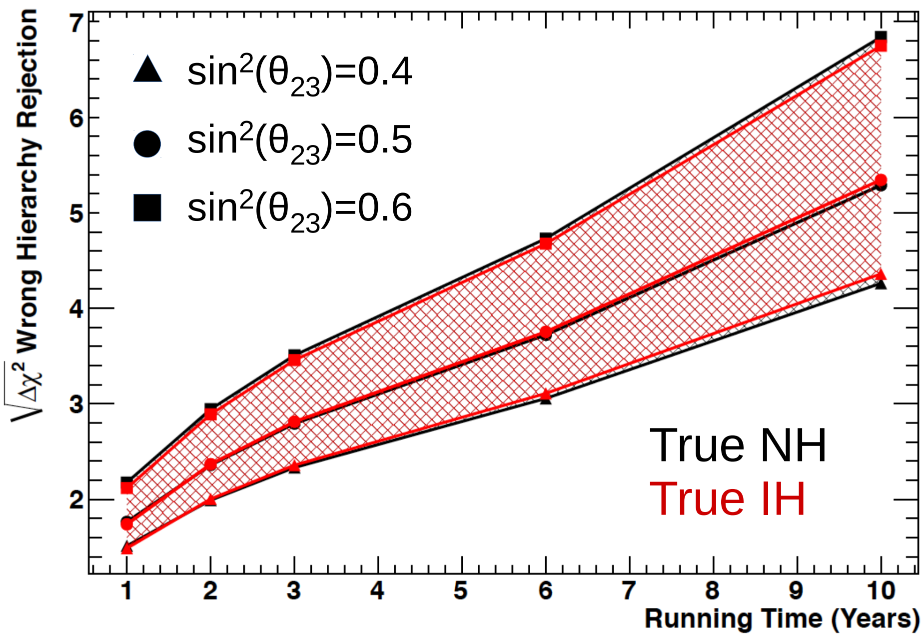
True δ=90º



Second detector
Staging approach

- Build first detector as soon as possible
- Second, identical detector coming later
- Assume here 2nd detector comes online 6 years later

Mass hierarchy determination
(beam + atmospheric)

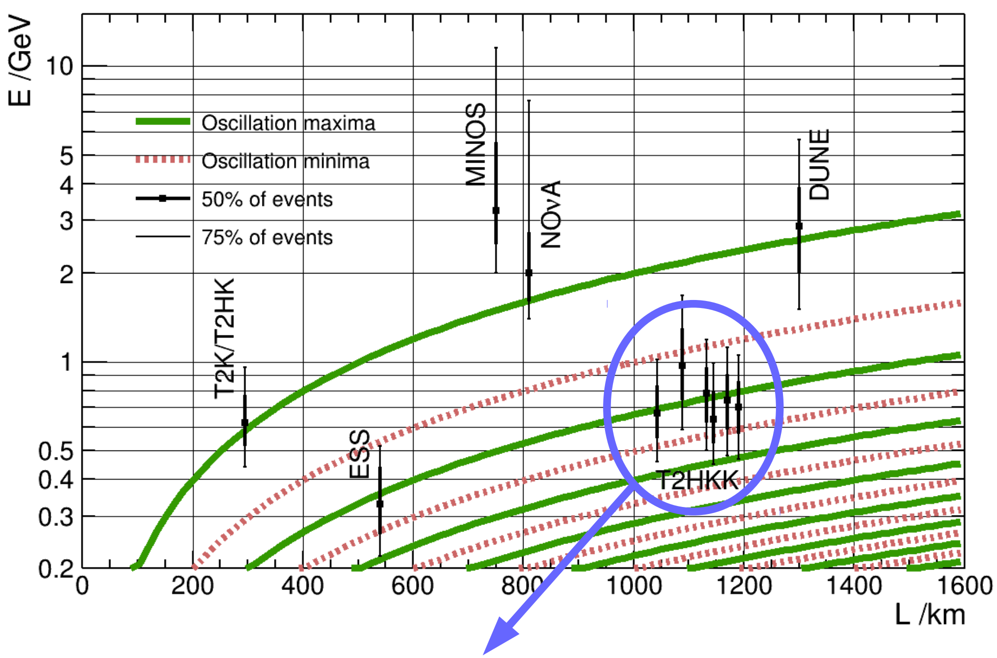


Sensitivity to CP violation
(beam only)

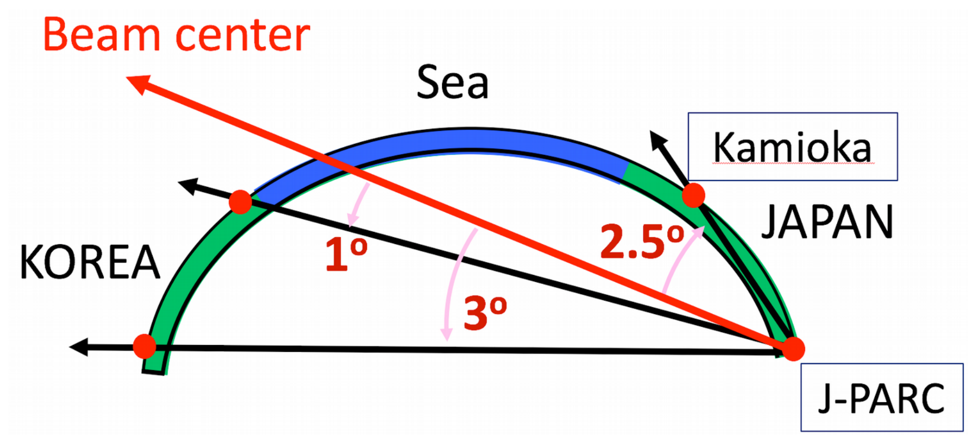
	Exclude CP conservation		Precision of δ measurement	
	> 3σ	> 5σ	δ=0	δ=90°
1 tank	76%	57%	7°	23°
Staging	78%	62%	7°	21°

Second detector
Second detector in Korea

Exploring the idea of putting second detector in Korea
- 2 identical detectors with different baseline
- Longer baseline to Korea: study mass hierarchy with beam neutrinos
- Different L/E regions



Look at oscillations at the 2nd oscillation maximum



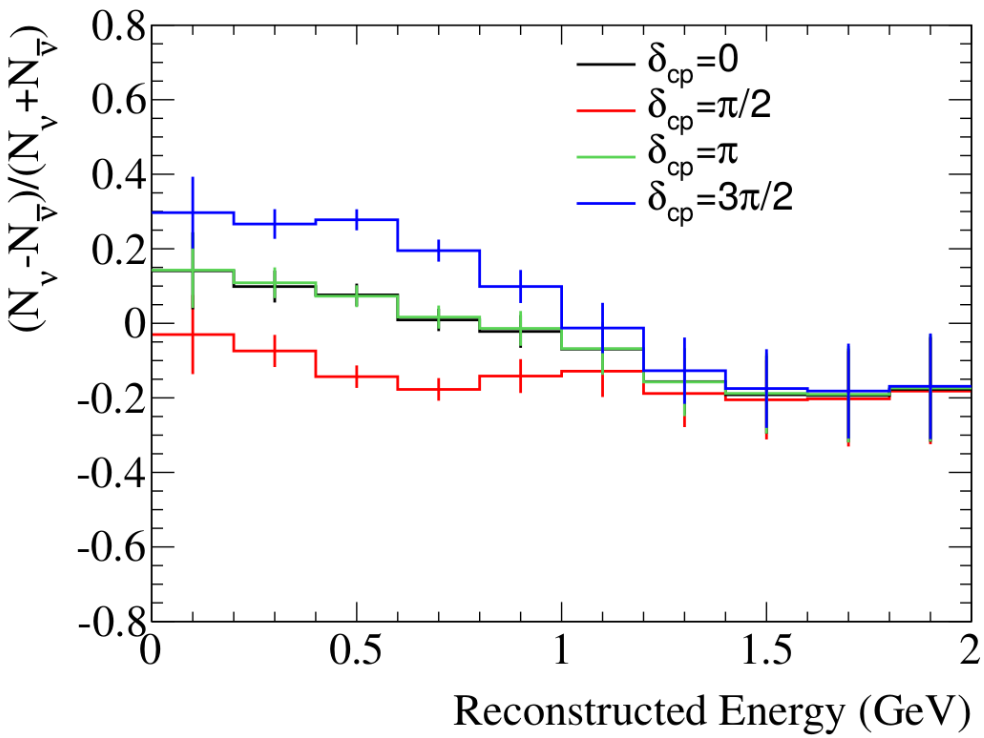
Candidate sites at different OAA and L

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

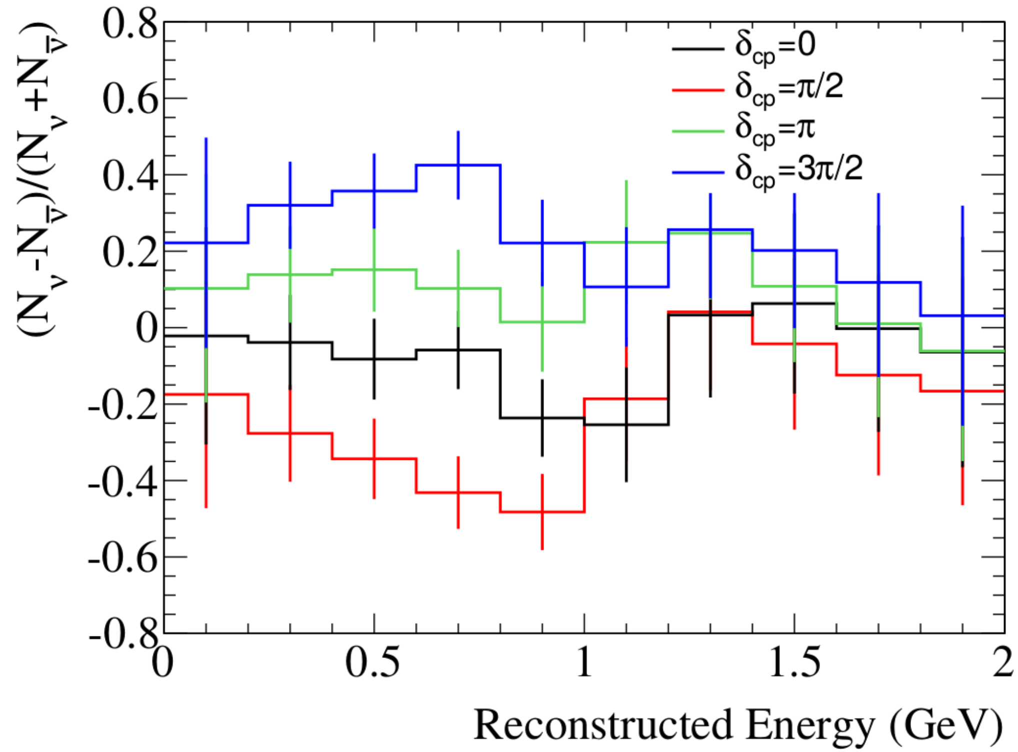
Second detector in Korea
Expected number of events

L=1100km OAA=1.5º δ=0	Signal		Background	Total
	$\nu_\mu \rightarrow \nu_e$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$		
ν-mode	140.6	2.4	81.8	224.8
$\bar{\nu}$-mode	159.1	23.9	95.5	278.5

OAA=2.5°, L=295 km, T2HK (Japan)



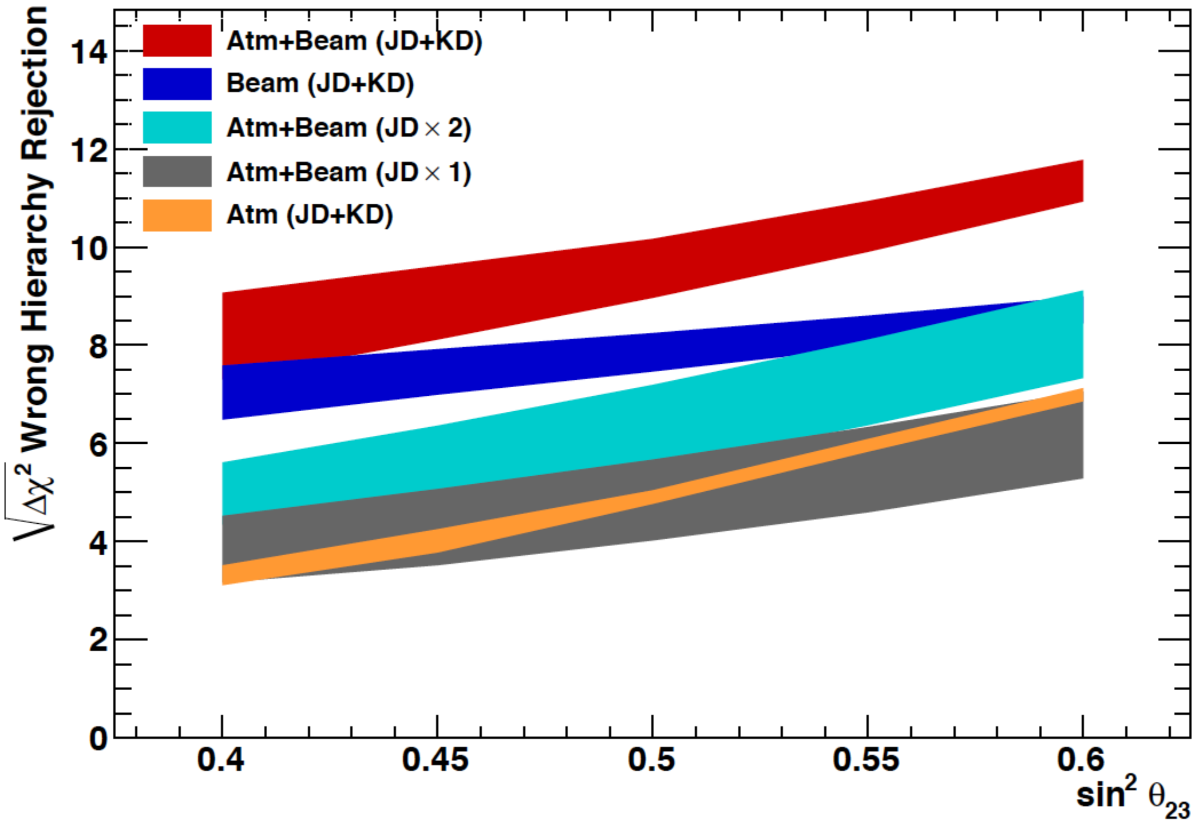
OAA=1.5°, L=1100 km, ~ Mt. Bisul (Korea)



$\sin^2(2\theta_{13})=0.085$, $\sin^2(\theta_{23})=0.5$, $\Delta m^2_{32}=2.5\text{x}10^{-3}$ ev^2/c^4, normal hierarchy

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

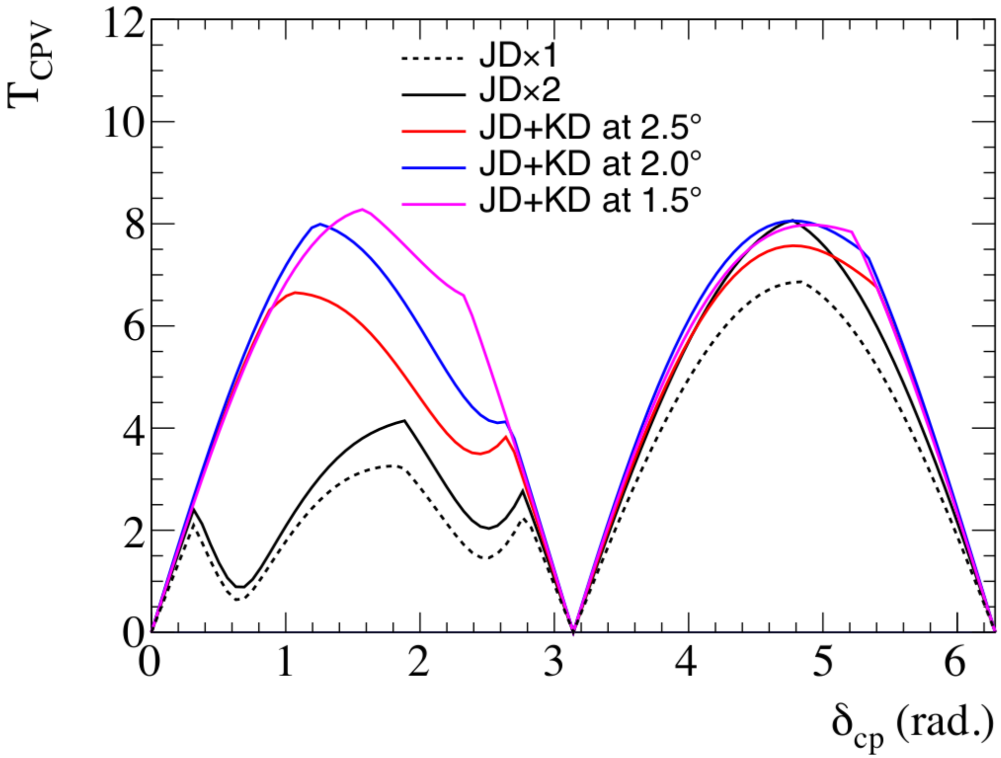
JD: Japanese Detector, KD: Korean detector, JDx2 does not assume staging

True normal mass hierarchy

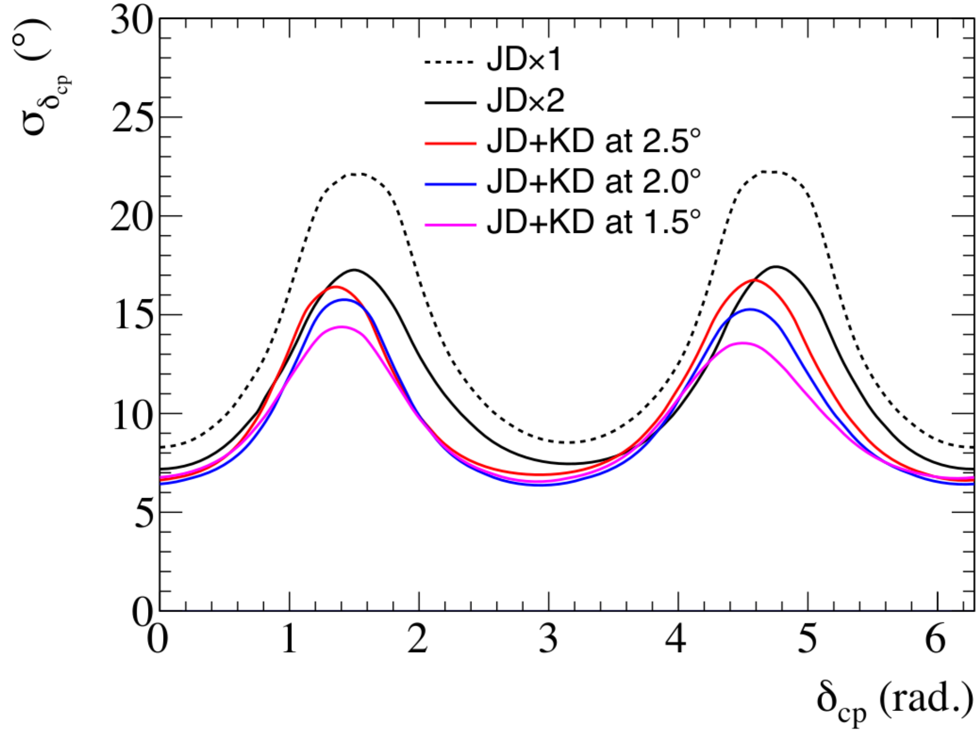
Second detector in Korea
Sensitivity to CP violation

With only beam neutrinos:
- Solve degeneracy between δ and MH if MH is unknown
- Increased precision on δ measurement around ±π/2

Ability to exclude CP conservation



Precision of δ measurement

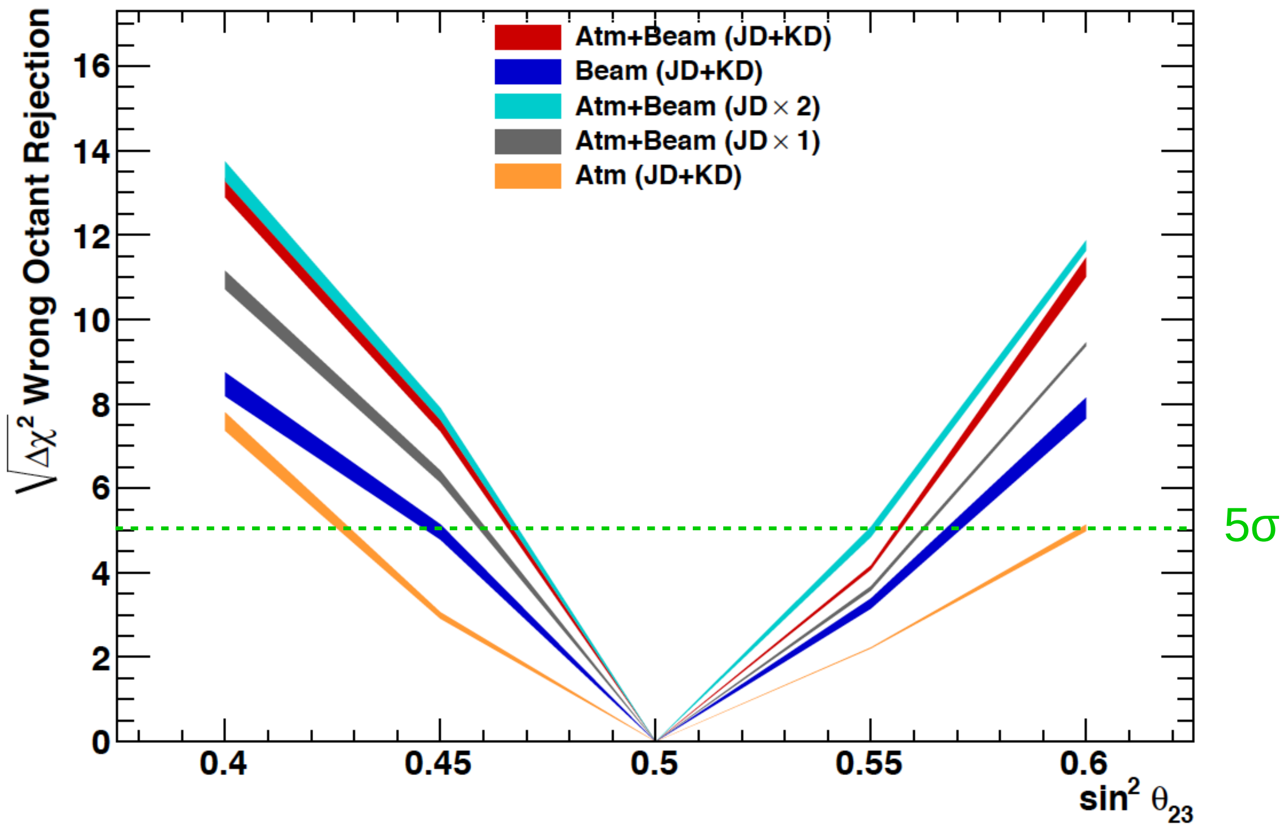


True hierarchy: NH
Different analysis than beam only for one Japanese detector showed in previous slides

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



Error bands: uncertainty due to unknown δ value

JD: Japanese Detector, KD: Korean detector, JDx2 does not assume staging

Future improvements

So far, sensitivities evaluated with tools from current experiments (T2K, SK)
→ a number of developments planned

Updates form recent T2K analyses

- New reconstruction algorithm and analysis at far detector
- Extended fiducial volume
- Additional appearance sample(s)
- Additional shape information for appearance samples

Systematic uncertainties

- Move to more detailed systematic model
- Reduction with updated near and intermediate detectors
- Improvement on far detector calibration
- Flux uncertainties using external data

Updates from SK analysis

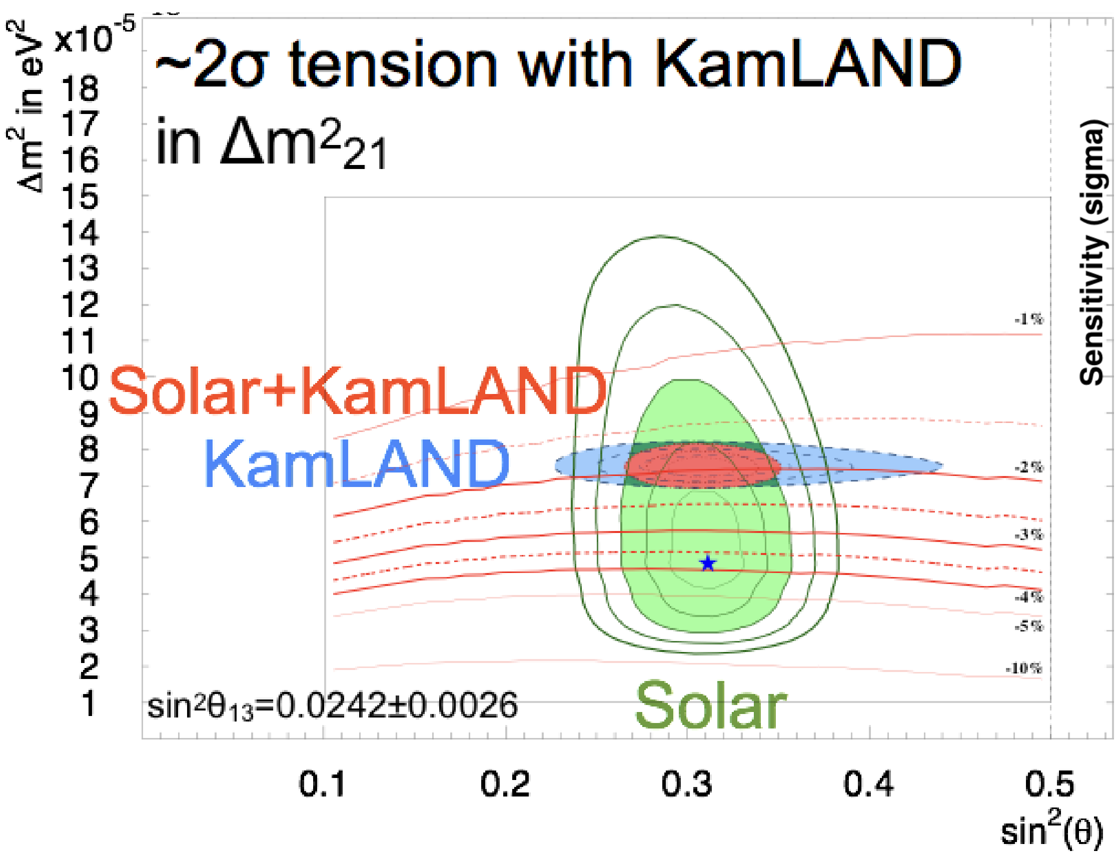
- Use of neutron tagging
- Extension of fiducial volume
- Constraint on tau appearance background for electron samples

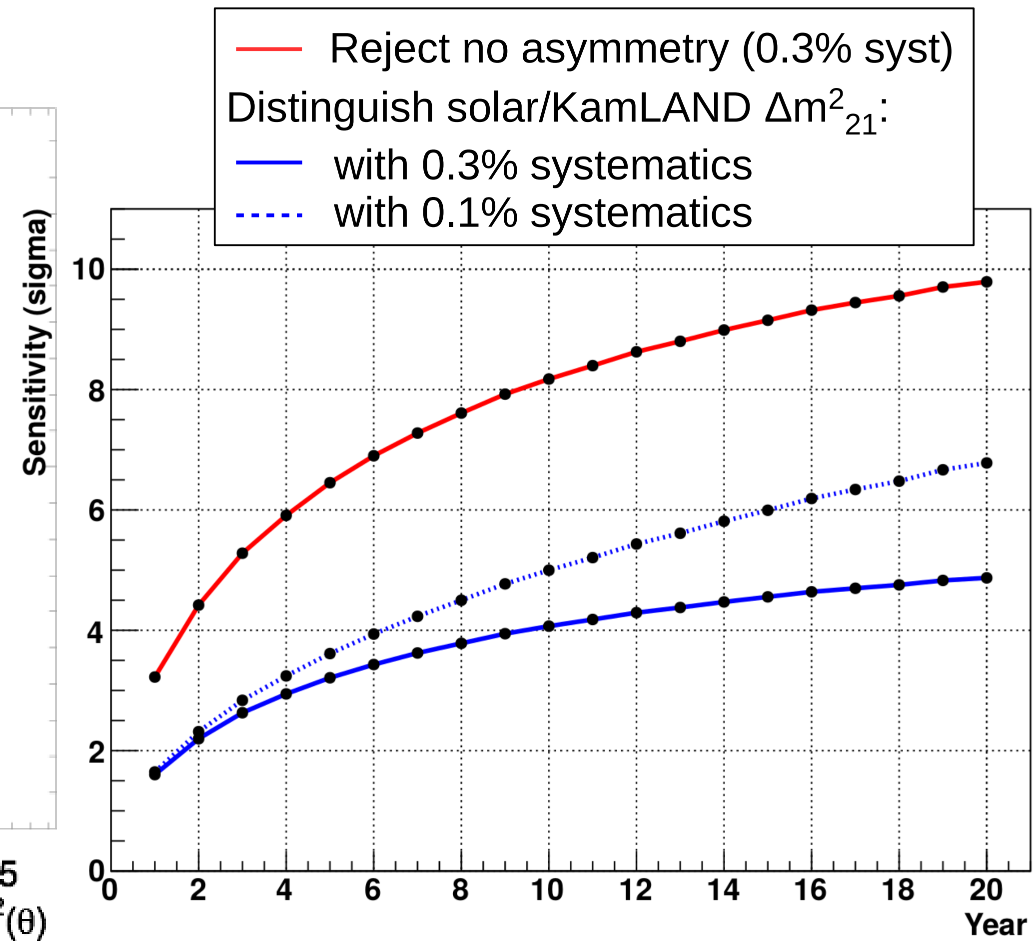
Simulation

- Move from scaled SK MC (SKDetsim) to real HK (WCSim) MC
- Effect of improved photosensors

Solar neutrino oscillations
Day/night asymmetry

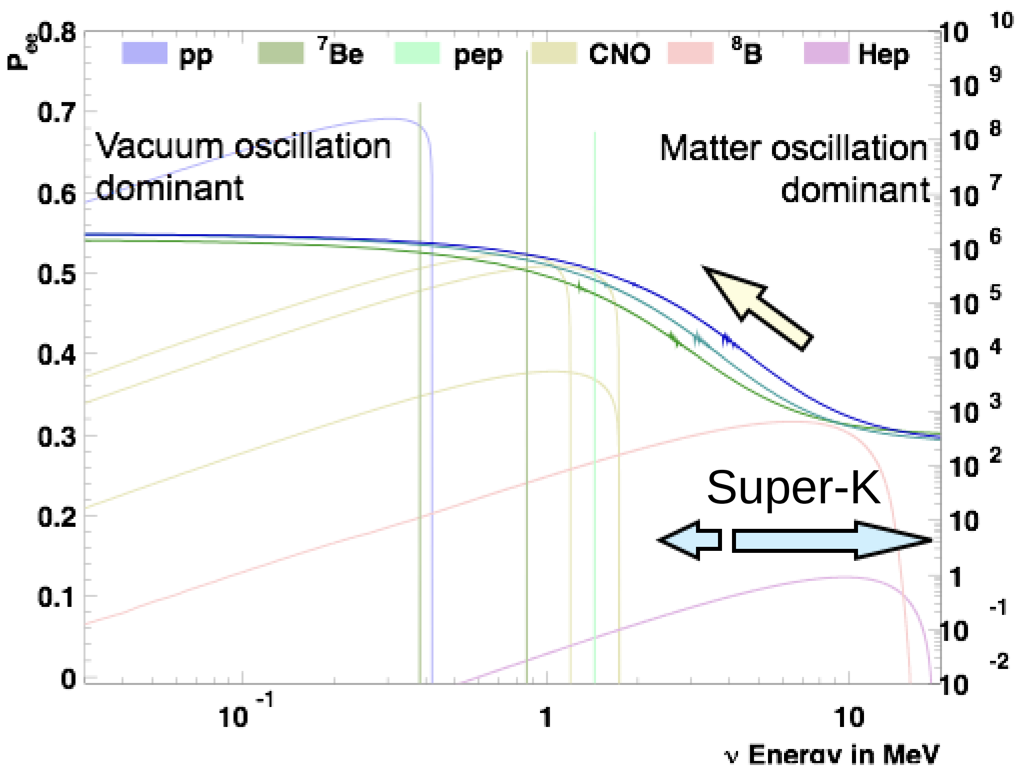
- Due to matter effects, expected rate of solar neutrinos is higher during night time
- Observing this asymmetry can allow to resolve tension between solar neutrino and KamLAND measurements of Δm^2_{21}



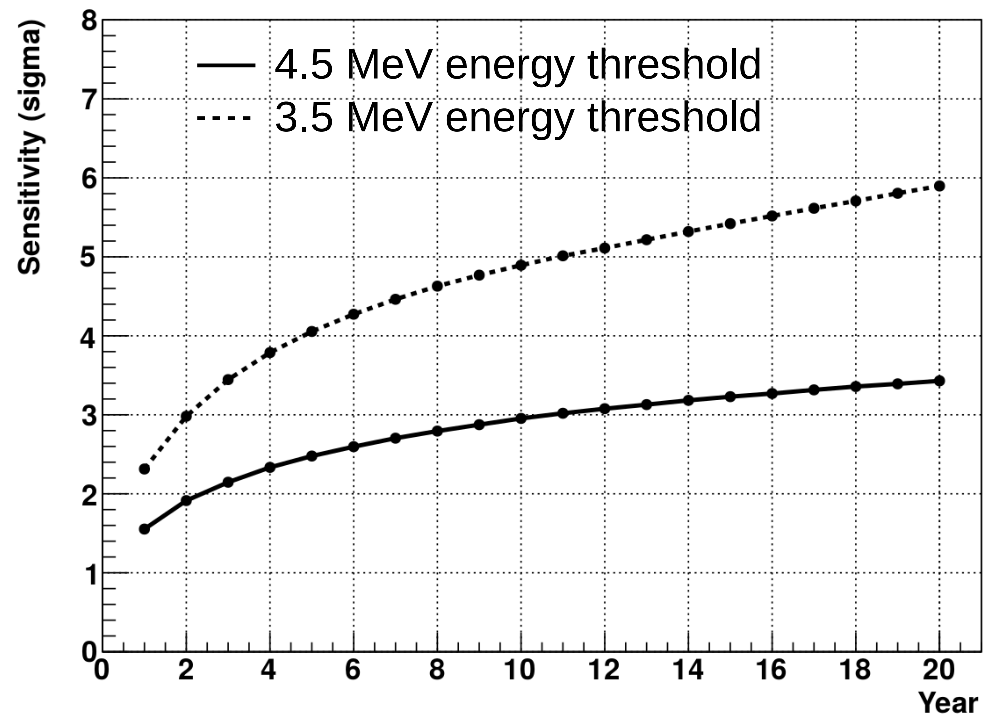


Solar neutrino oscillations
Spectrum upturn

- Transition from matter-dominated energy region to vacuum-dominated one for ν_e survival probability creates an upturn in the spectrum
- Precise measurements of the spectrum allows to confirm MSW-LMA model and distinguish between standard oscillations and new physics
- Key parameter is the energy threshold (reduce radon background)



Upturn observation sensitivity

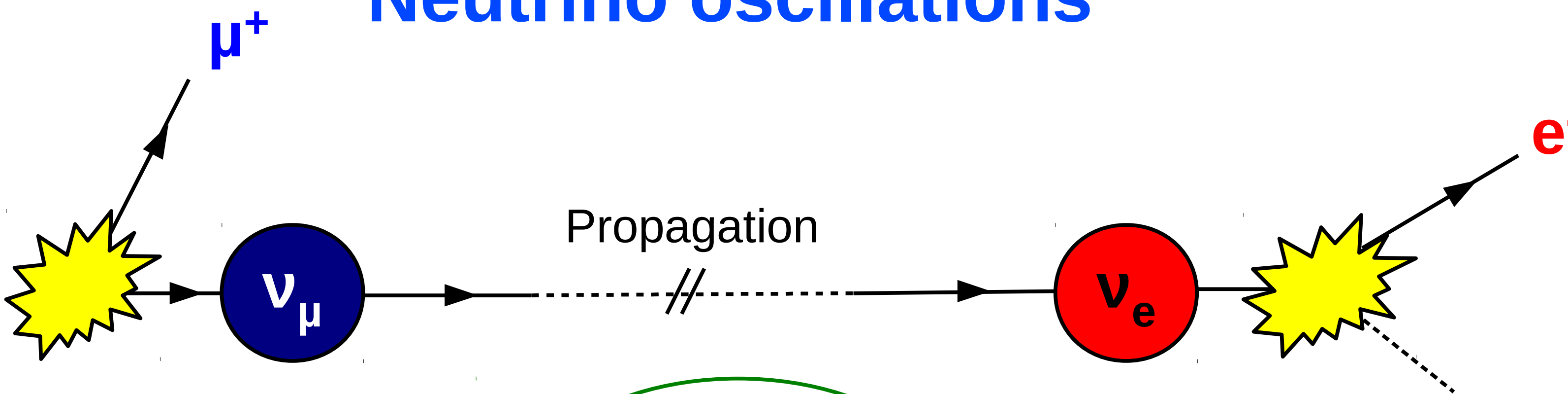


Summary

- Hyper-Kamiokande will allow to study the three main open questions in neutrino oscillations: CP violation, mass hierarchy and octant of θ_{23}
- With one detector and 10 years of beam and atmospheric neutrino data:
  - Exclude CP conservation at 5σ (3σ) for 57% (76%) of possible true values of δ
  - Measure δ with 7° (true δ=0) to 23° (true δ=90°) precision
  - Can determine mass hierarchy with $>3\sigma$ significance
  - Can determine octant at 5σ if $\sin^2(\theta_{23})<0.46$ or $\sin^2(\theta_{23})>0.56$
- Increased sensitivity with a second detector
  In particular second detector in Korea would give access to mass hierarchy with beam neutrinos, and study oscillations at the second maximum

Additional slides

Neutrino oscillations



Flavor eigenstates
(interaction)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass eigenstates
(propagation)

Mixing (or Pontecorvo-Maki-Nagawa-Sakata) matrix
link between the two sets of eigenstates

P($\nu_\alpha \rightarrow \nu_\beta$) oscillates as a function of distance L traveled by the neutrino with periodicity $\mathbf{\Delta m^2_{ij} L/E}$

($\Delta m^2_{ij} = m^2_i - m^2_j$)

Neutrino oscillations
Parameters

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

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

$P(\nu_\alpha \rightarrow \nu_\beta)$ depends on 6 parameters:

- 3 **mixing angles** : **θ_{12}, θ_{23}, θ_{13}**
- 2 **mass splittings** : **Δm^2_{ij}**
- 1 (complex) phase : The **CP phase δ**

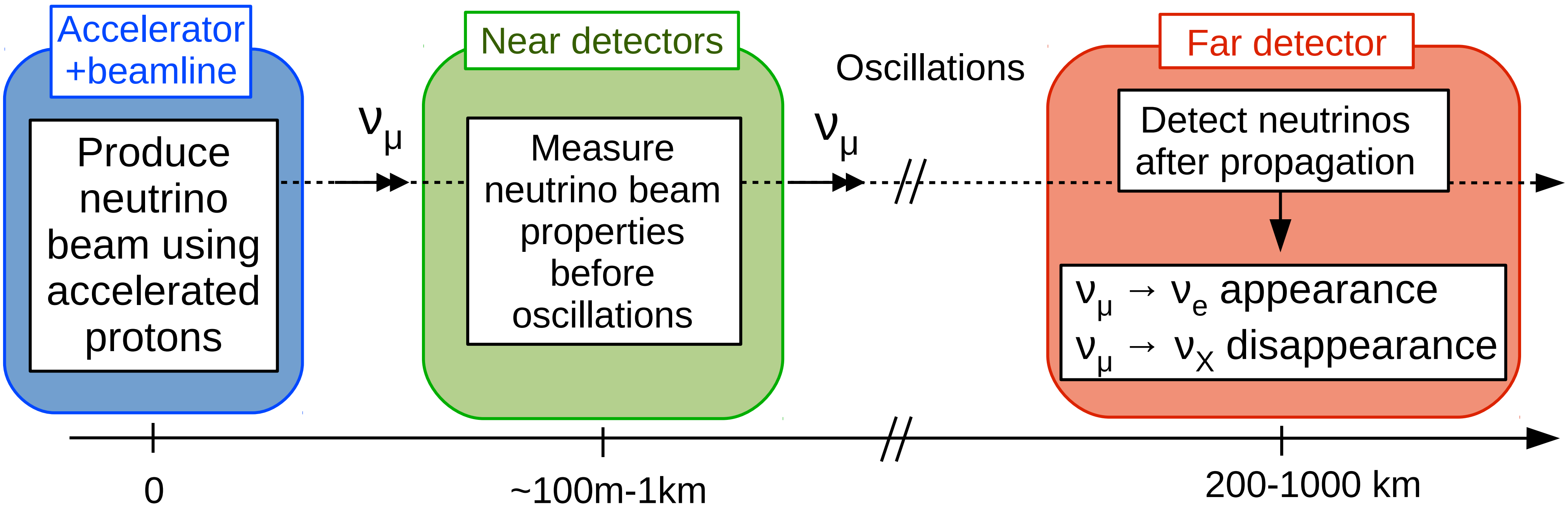
Amplitude

Periodicity

Difference in oscillations $\nu/\bar{\nu}$
(matter / anti-matter)

Long baseline experiments
Concept

Man-made neutrino beam produced by an accelerator

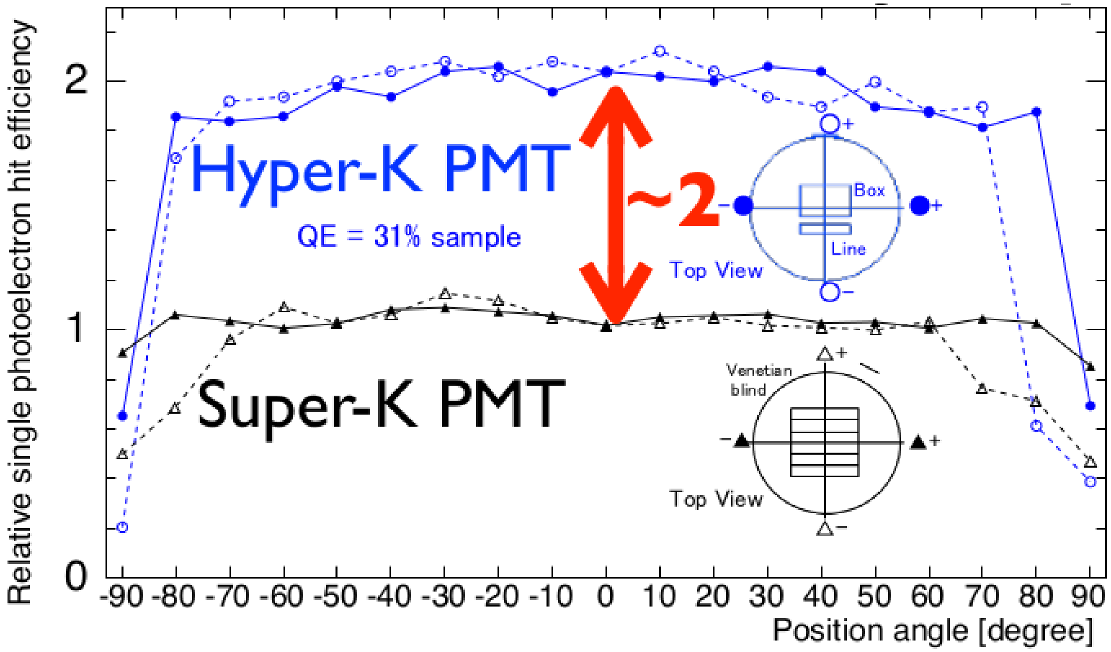


Several advantages:

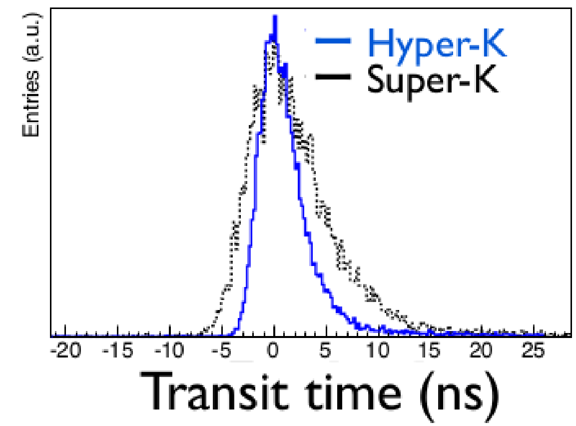
- Better knowledge and control of neutrino flux
- Can select neutrino energy range
- Can use near detectors to reduce uncertainties
- Know direction of neutrinos reaching far detector
- Can produce either neutrino or anti-neutrino beam (compare oscillations of neutrinos and anti-neutrinos)

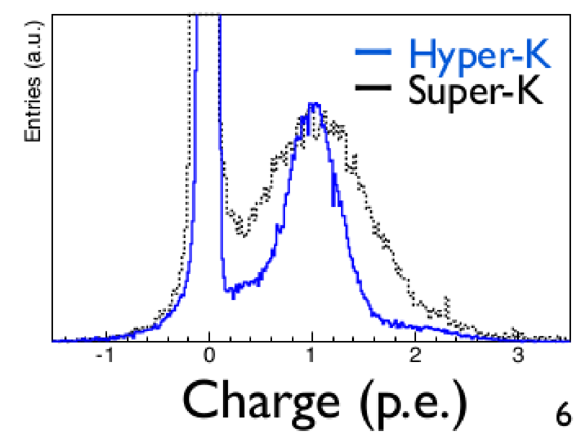
New 50cmΦ PMT for Hyper-K

Photo-detection efficiency (1p.e.)



Box & line dynode PMT

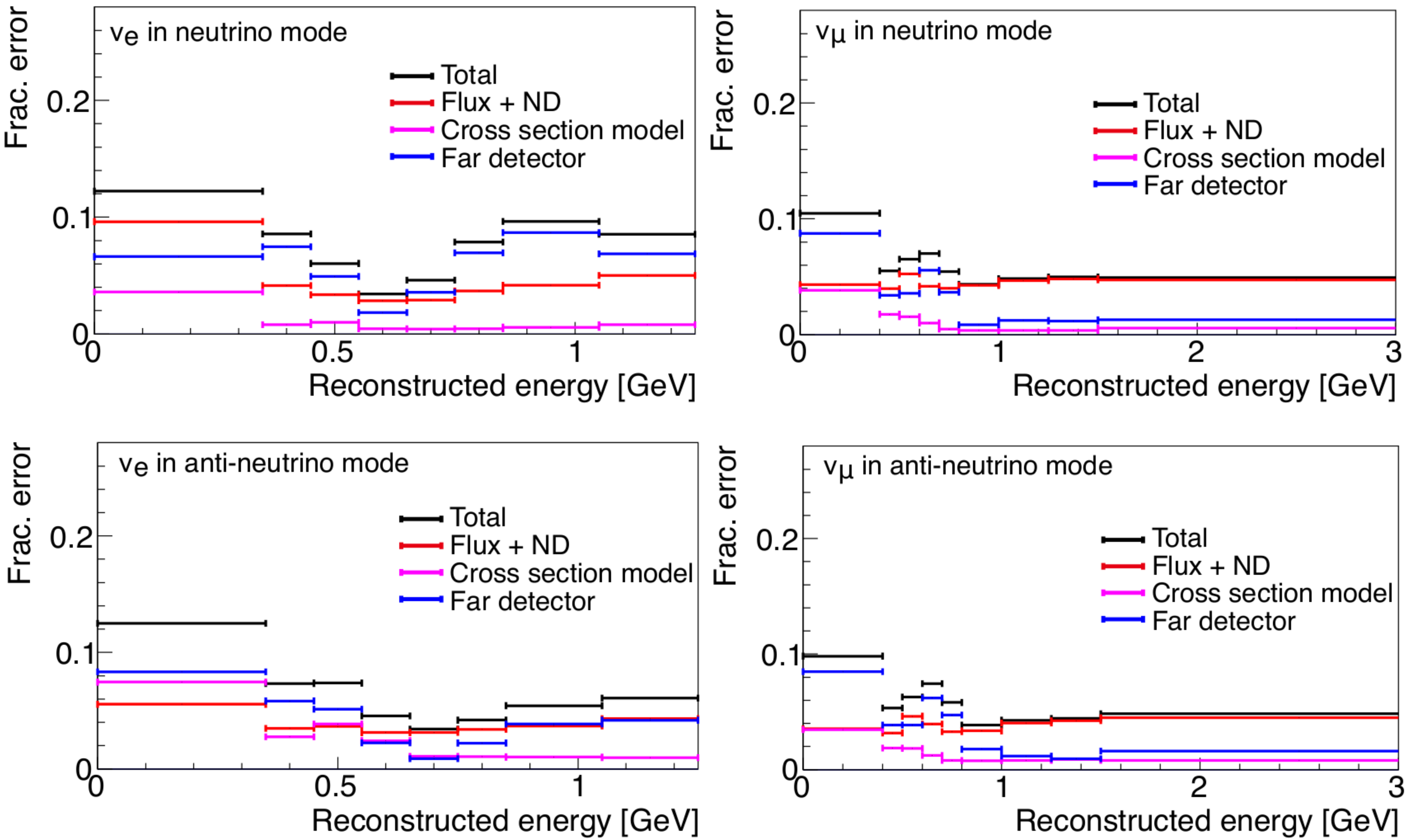




- Twice better photo-detection efficiency than SK PMTs
- Timing resolution (TTS): 1.1ns
  - cf. SK PMT: 2.1ns
- Higher pressure tolerance: >80m

H. Tanaka @ TAUP2017

Long baseline oscillations: T2HK Systematic uncertainties used



Long baseline oscillations: T2HK
Systematic uncertainties used

Correlation between the systematic uncertainties in the different Erec bins: