Status and Neutrino Oscillation Physics Potential of the Hyper-Kamiokande Project in Japan

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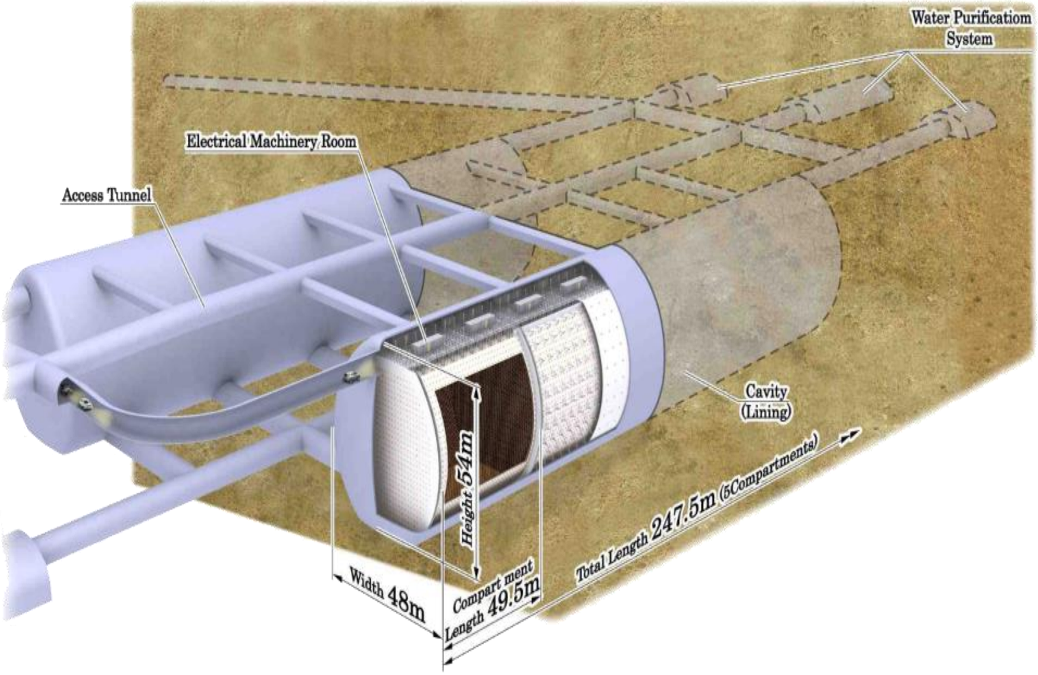
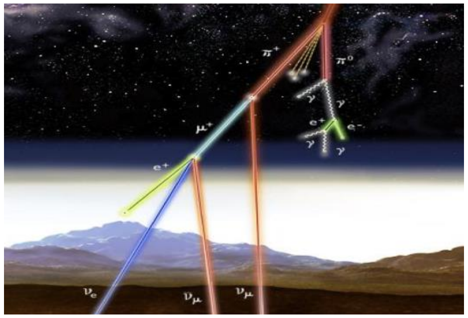
Hyper-Kamiokande: overview

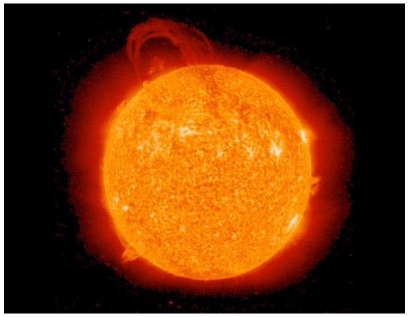


Hyper-Kamiokande is a multi-purpose **Water-Cherenkov detector** with a variety of scientific goals:

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

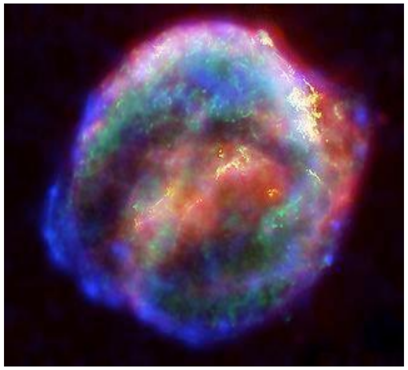
Atmospheric ν





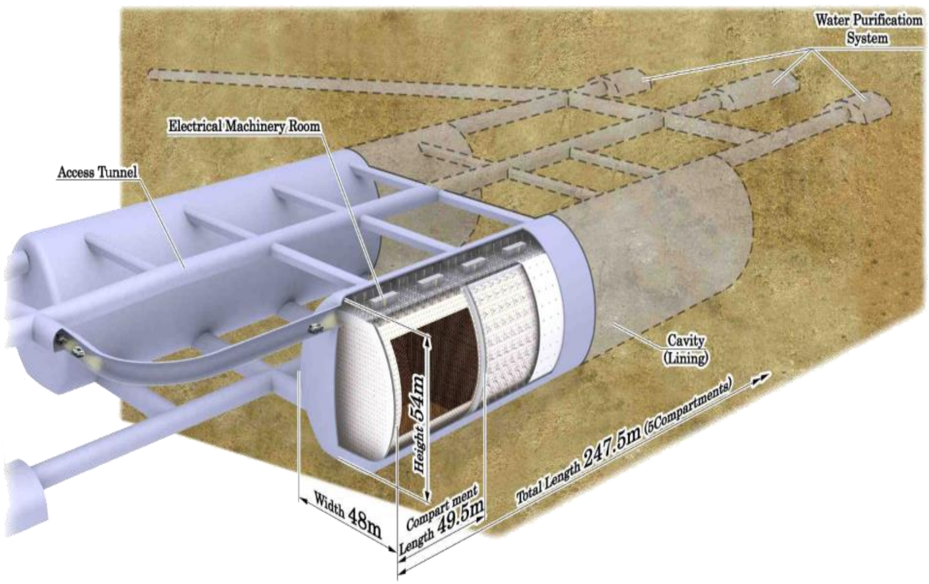
Solar ν

Supernova ν



Accelerator ν

Hyper-Kamiokande: overview



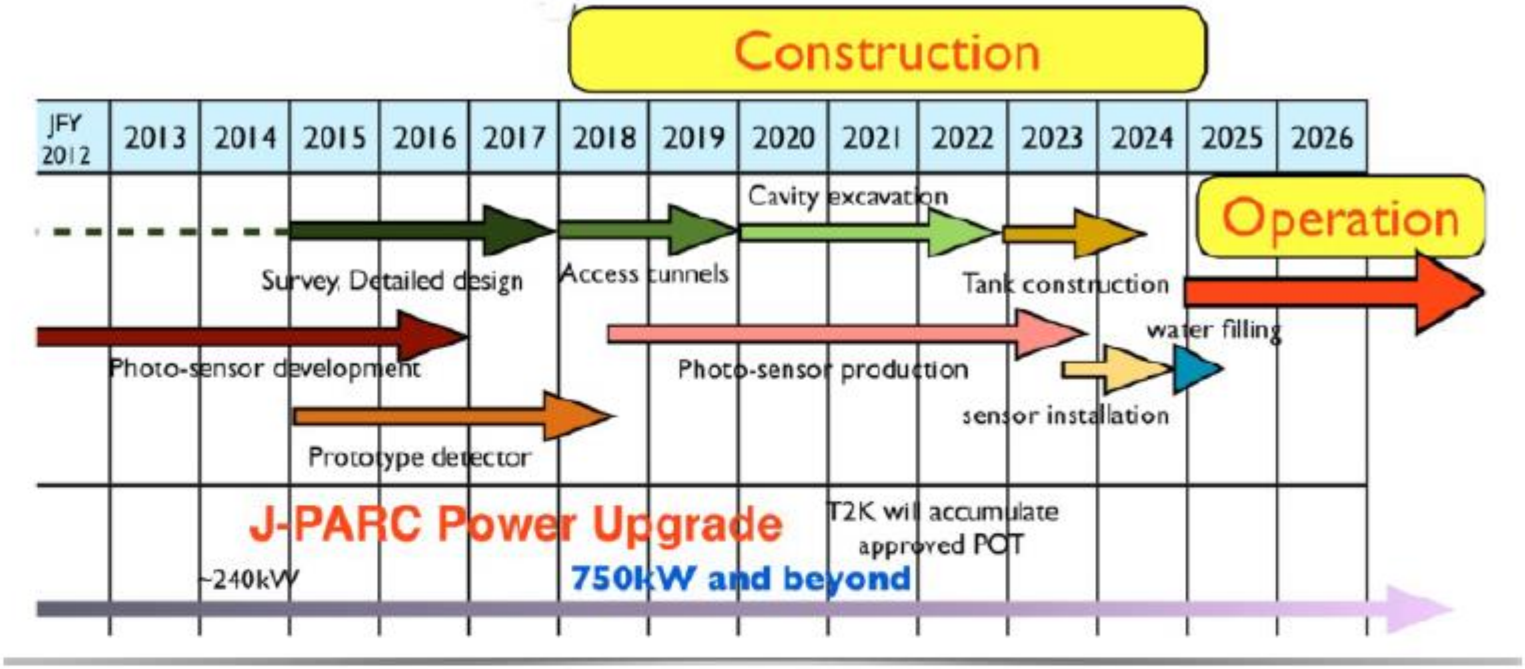
Total Volume :	0.99 Mton
Inner Volume :	0.75 Mton
Fiducial Volume :	0.56 Mton (0.056x10)
Photo sensors :	SK-type PMTs
Inner detector:	99,000 20″ PMTs
Outer detector:	25,000 8″ PMTs
Nominal site :	Tochibora mine

- 2 tanks lying along-side, divided in 10 compartments;
- Compartments are optically separated;
- egg-shape cross section;
- 20% photocatode-coverage;
- Fiducial volume: **25 times larger than Super-Kamiokande**;

Detector simulation studied with WCSim (open-source water Cherenkov detector Simulation program based on Geant4);

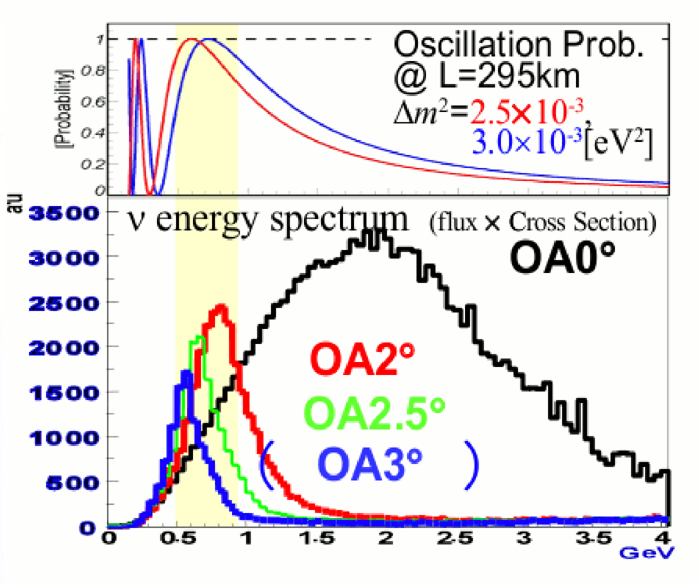
- Water Cherenkov: proved technology and scalability
- Excellent PID at sub-GeV region (quasi-elastic→single ring: PID > 99%);
- Large mass → statistics always critical for any measurement

Hyper-Kamiokande Timeline



- International proto-collaboration has been formed (13 countries, ≈250 members);
- Work ongoing worldwide in all the aspects of the experiment;
- Cooperation with KEK-IPNS/ICRR to develop the project;
- Design Report being prepared in 2015;
- Once the budget is approved, the construction can start in 2018 and data taking around 2025.

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.

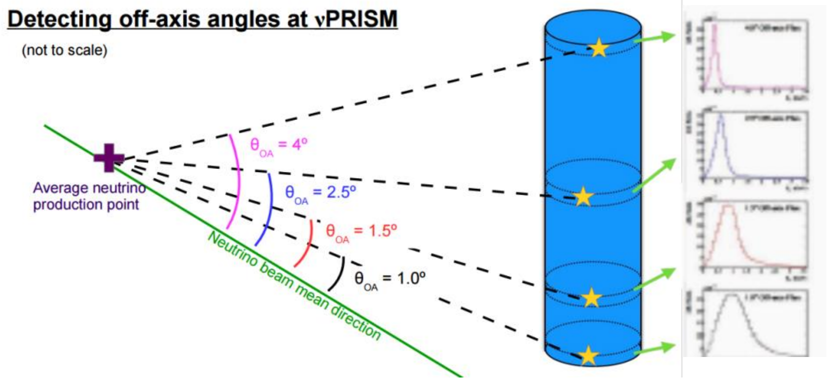
new power upgrade plan of J-PARC → we expect ~>900kW by 2020, and ~1.3MW by ~2024

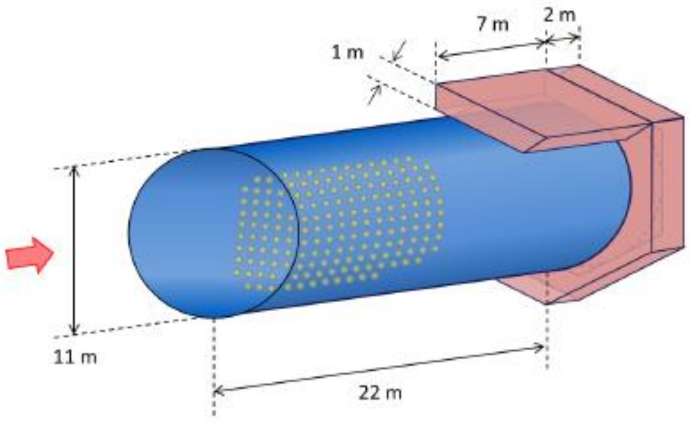
T2HK Near and intermediate detectors

- ✧ Different options for near detectors (at 280 m) are being investigated:
  - Upgraded INGRID (on axis detector for beam mean energy measurements) and ND280 (off axis detector for neutrino flux measurement and constraint of systematic uncertainties);
  - Addition of new detectors, like a 3D grid-like neutrino near detector with a water target (WAGASCI*), a high pressure TPC or a water-based liquid scintillation detector.
- ✧ Add new water-based intermediate (1-2 km) detector to better constraint uncertainties on flux and cross-section.

nuPRISM
(arXiv:1412.3086 [physics.ins-det])
Water column detector to minimise dependence on ν interaction sampling the beam at several off-axis angles

TITUS
(arXiv:1504.08272 [physics.ins-det])
A water Cherenkov detector Gd doped, surrounded by Muon Range Detector, to minimise systematic errors





Physics potential

- Sensitive to CPV with less matter effect
- Off-axis beam with relatively short baseline
- Best matched with low energy, narrow band beam

Assumptions:

- Integrated beam power: 7.5 MW$\times 10^7$ sec (i.e. 0.75 MW for 10 years running) → 1.56×10^{22} POT;
- ν running / $\bar{\nu}$ running → 1:3;

Physics potential evaluated with a simultaneous fit of the appearance and disappearance spectra;

Realistic estimation of the systematic uncertainties (based on the experience of T2K).

For details see *Prog. Theor. Exp. Phys. (2015) 053C02.*

Systematic uncertainties

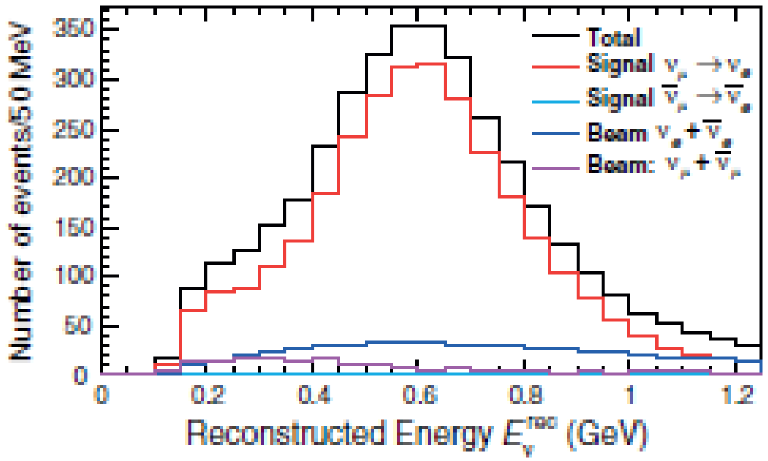
Systematic errors extrapolated from well-established T2K analysis, with reasonable improvements:

- ✧ Flux and ND constrained uncertainties → conservatively assumed to be the same as T2K;
- ✧ ND-independent cross-section uncertainties → assumed improvements due to availability of water target and new samples in ND;
- ✧ Far detector uncertainties → reduced due to availability of larger samples at HK near detectors and atmospheric events for systematics studies.

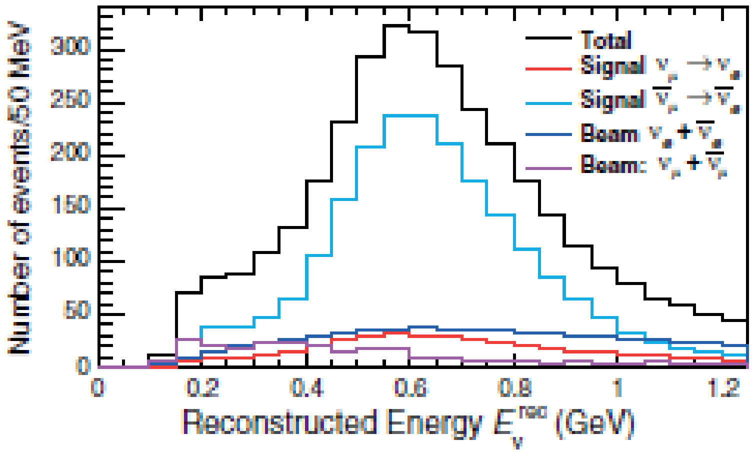
		Flux &ND-constrained	ND-independent cross section	Far detector	Total
ν mode	App	3.0%	1.2%	0.7%	3.3%
	Disapp	2.8%	1.5%	1.0%	3.3%
$\bar{\nu}$ mode	App	5.6%	2.0%	1.7%	6.2%
	Disapp	4.2%	1.4%	1.1%	4.5%

ν_e appearance

Appearance ν mode



Appearance $\bar{\nu}$ mode



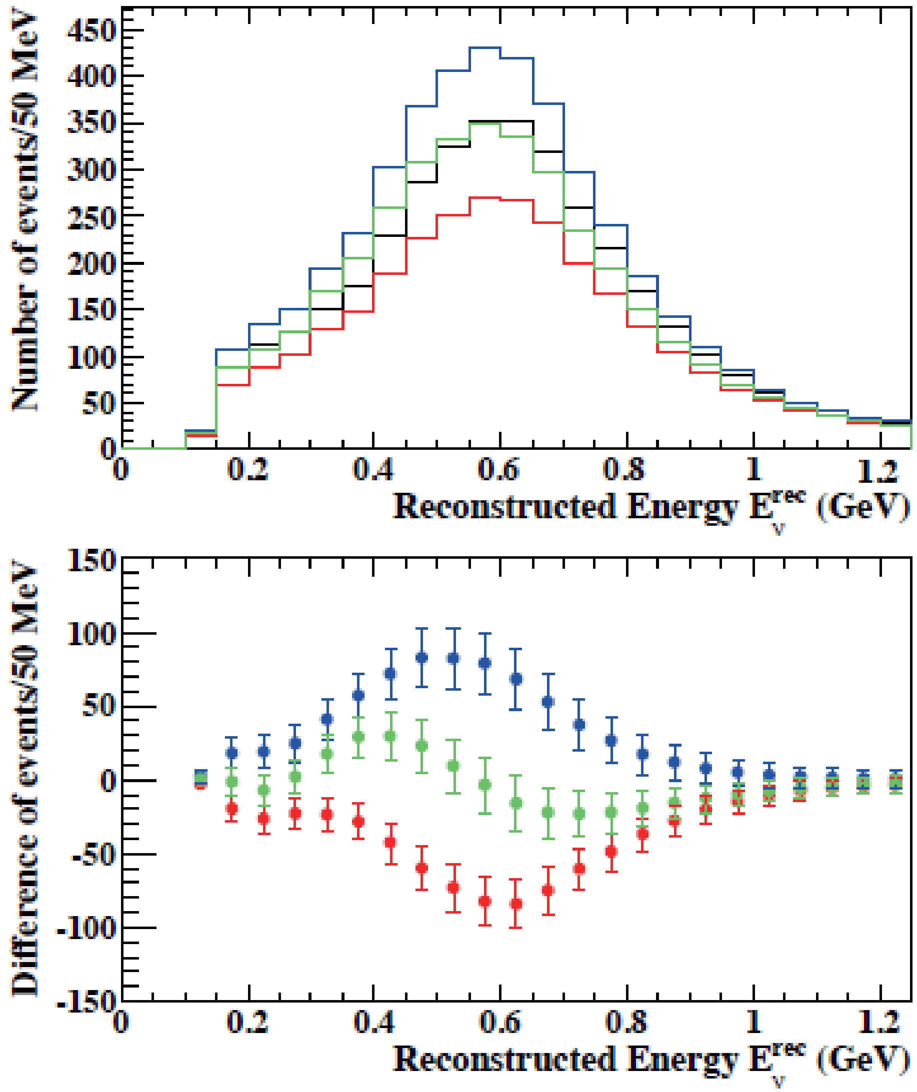
Normal mass hierarchy with $\sin^2 2\theta_{13} = 0.1$ and $\delta_{CP} = 0$ are assumed

large fiducial mass and high-power J-PARC neutrino beam → Large statistics!
Dominant background is intrinsic ν_e contamination in beam; In anti-neutrino mode also larger wrong-sign background.
Suppression of mis-identified π^0 from improved π^0 rejection.

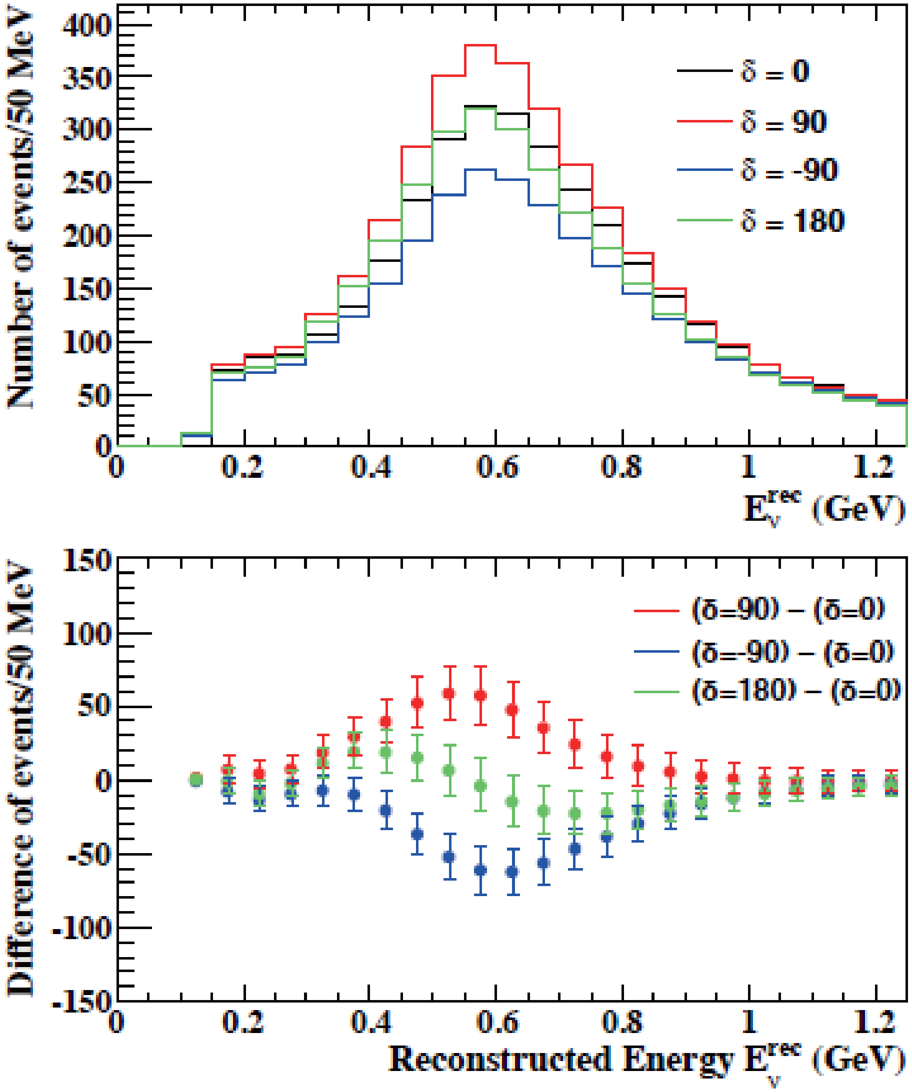
	signal		Background			BGTotal	Total
	$\nu_\mu \rightarrow \nu_e$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$\nu_\mu/\bar{\nu}_\mu$ CC	$\nu_e/\bar{\nu}_e$ CC	NC		
ν mode	3016	28	11	523	172	706	3750
$\bar{\nu}$ mode	396	2110	9	618	265	891	3397

Effect of δ_{CP} at Hyper-Kamiokande

Neutrino mode: Appearance

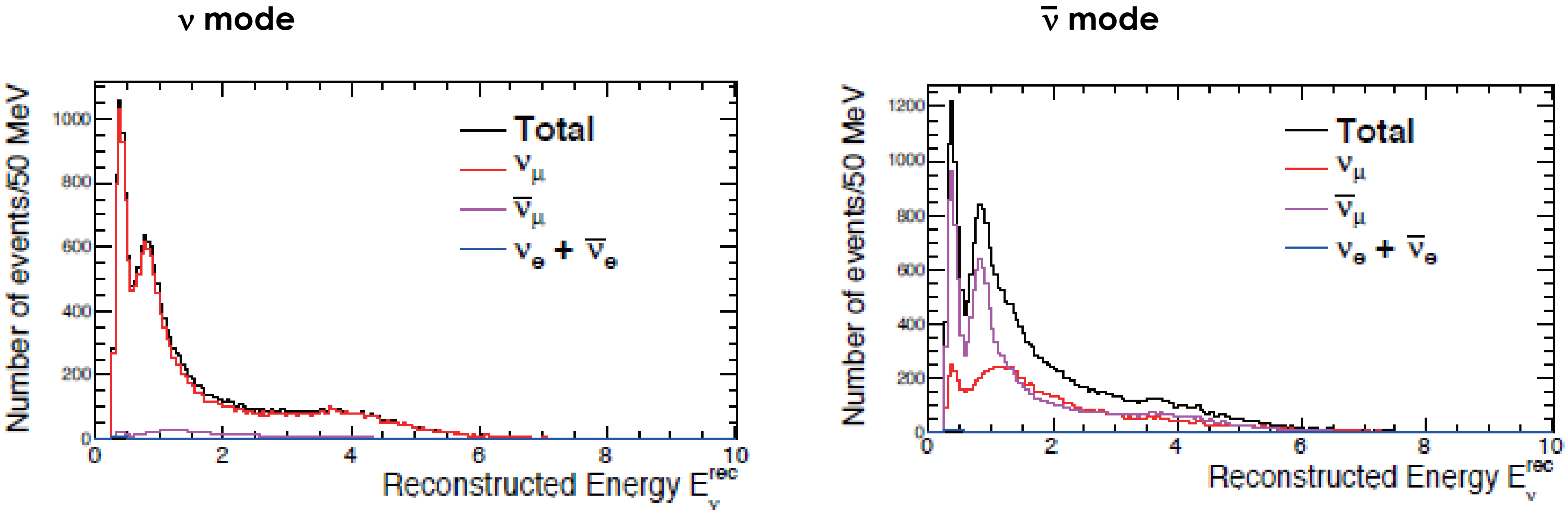


Antineutrino mode: Appearance



ν_μ disappearance

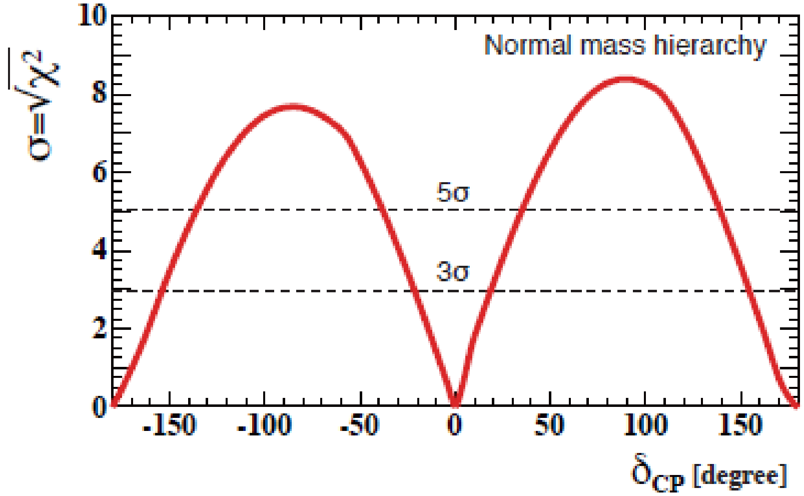
expected number of ν_μ candidate events

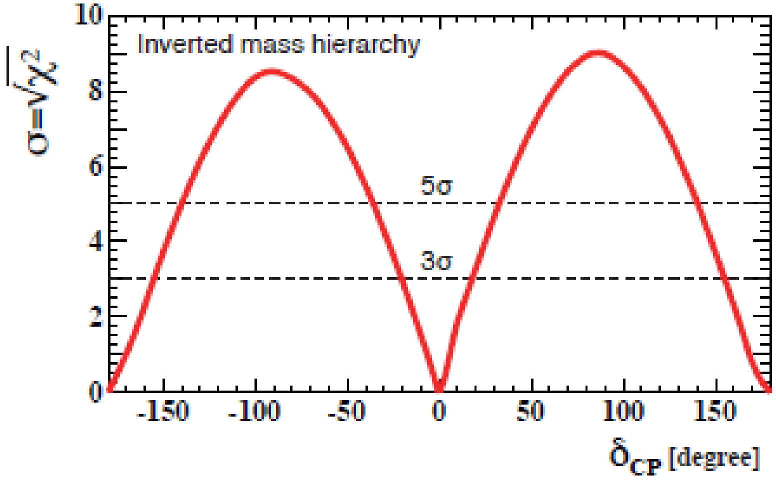


	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC	NC	$\nu_\mu \rightarrow \nu_e$	total
ν mode	17225	1088	11	1	999	49	19372
$\bar{\nu}$ mode	10066	15597	7	7	1281	6	26964

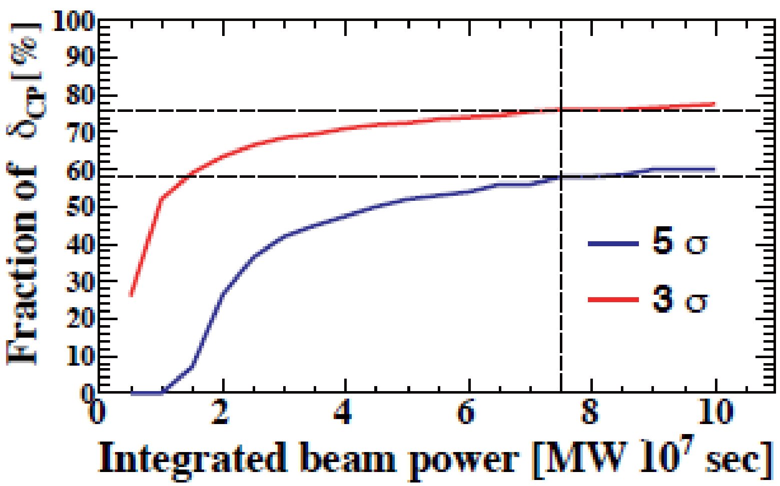
Sensitivity to δ_{CP}

76% (58%) of δ_{CP} space covered at 3σ (5σ) with better than 19 degrees uncertainty for 7.5MW10^{7}s

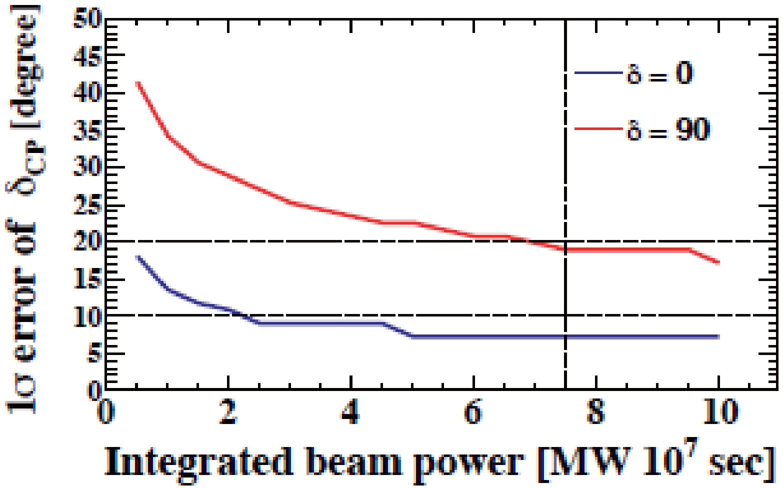




- Assuming $\sin^2 2\theta_{13} = 0.1$, $\sin^2 \theta_{23} = 0.5$ and $\Delta m^2 = 0.0024$ eV



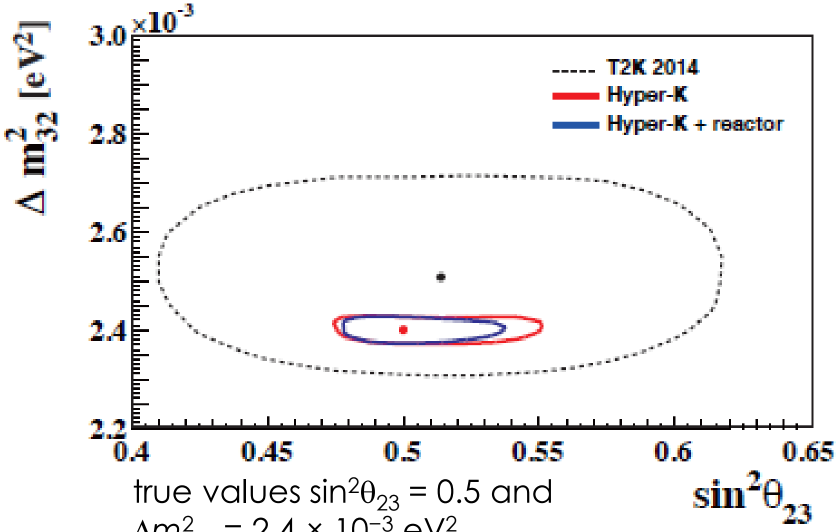
- Fraction of δ_{CP} space for which $\sin \delta_{CP} = 0$ can be excluded with 3σ/5σ



- 1σ uncertainty as a function of the integrated beam power.

Sensitivity to θ_{23} and Δm^2_{32}

Octant degeneracy resolved with a constraint from reactor experiments

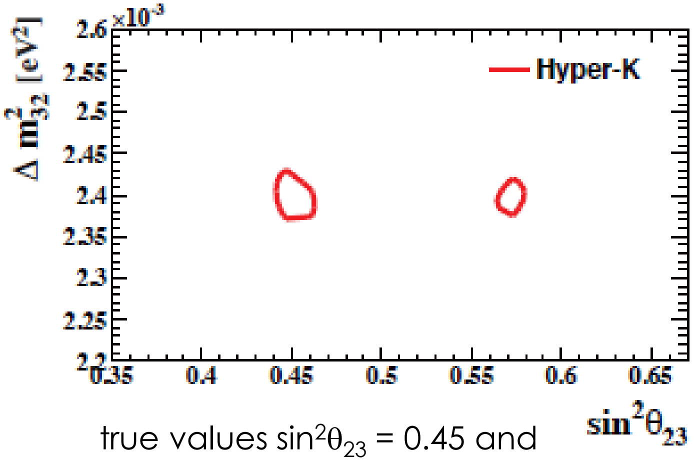


true values $\sin^2\theta_{23} = 0.5$ and
$\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2

- Expected 1σ uncertainty of $\sin^2\theta_{23}$ and Δm^2_{32}
- uncertainty of Δm^2_{32} better than 1.5×10^{-5} eV^2 for NH/IH

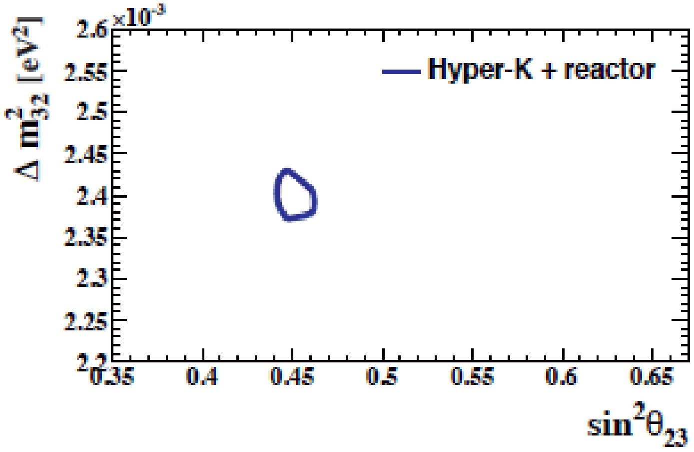
True $\sin^2\theta_{23}$	$\sin^2\theta_{23}$	Δm^2_{32} (10^{-5})
0.45	0.006	1.4
0.50	0.015	1.4
0.55	0.009	1.5

Without reactor



true values $\sin^2\theta_{23} = 0.45$ and
$\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2

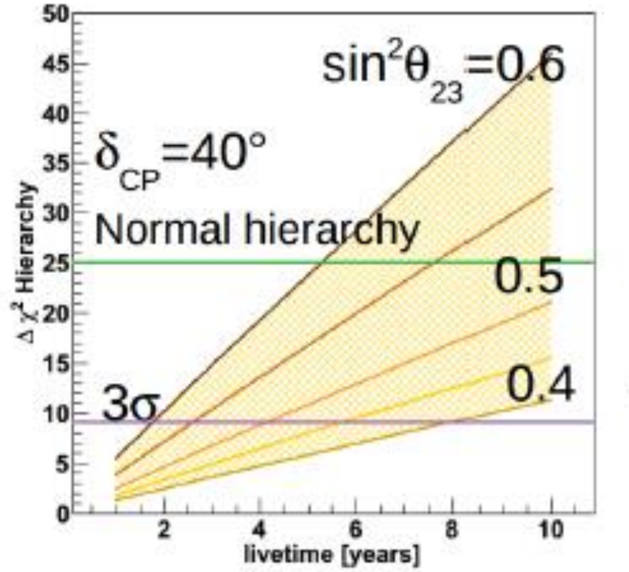
With reactor



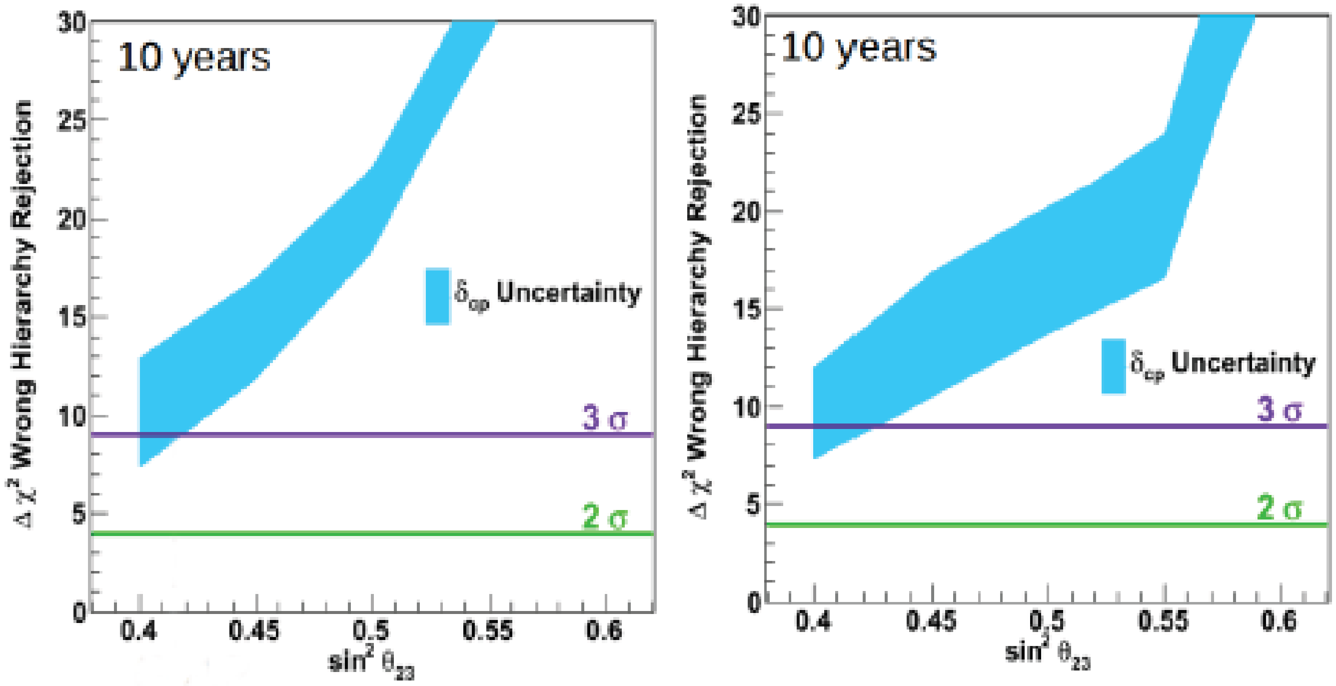
Reactor constraint on $\sin^2 2\theta_{13} = 0.1 \pm 0.005$ *is imposed*

Sensitivity to Mass Hierarchy

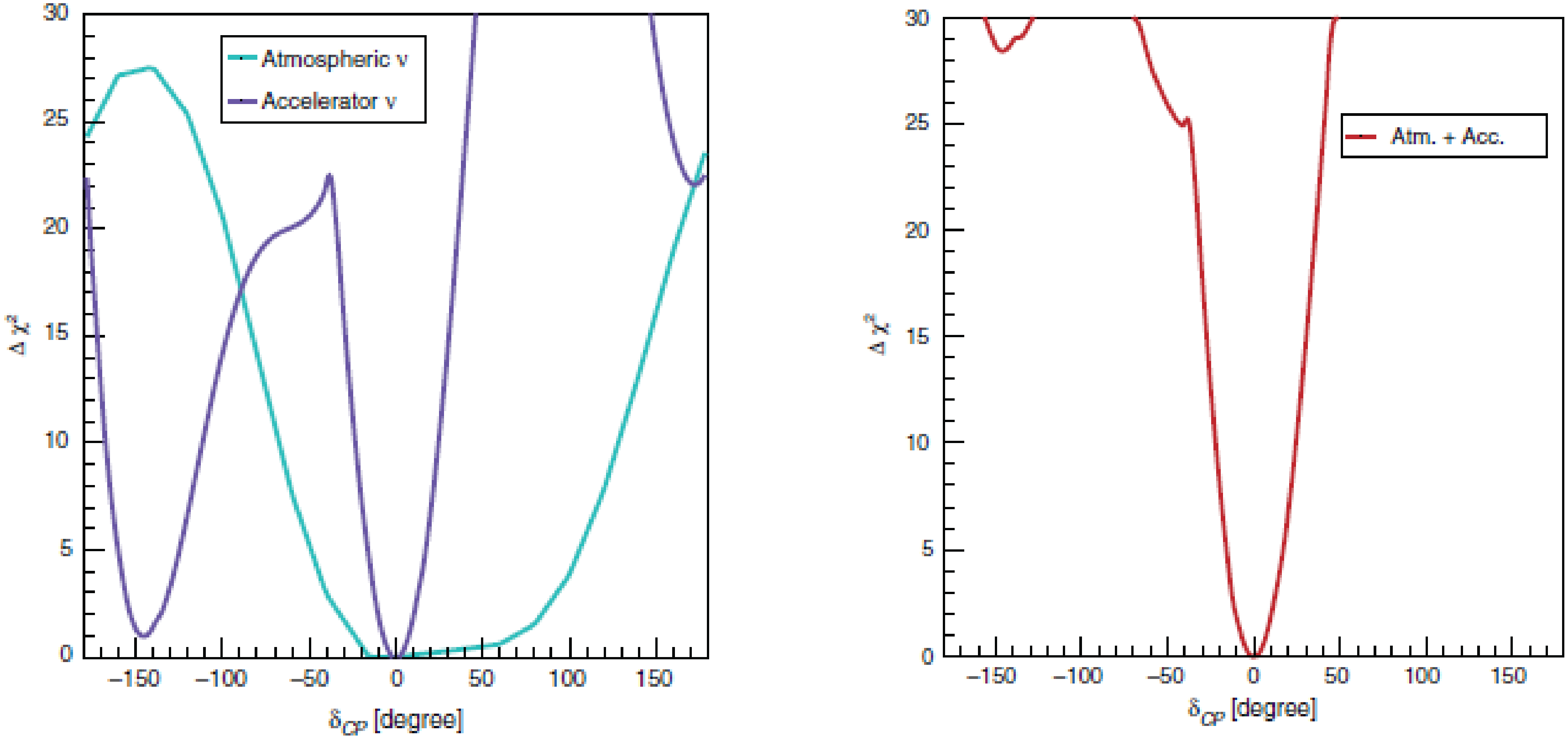
Use atmospheric neutrinos to determine mass hierarchy;
3σ after 10 years data taking for $\sin^2\theta_{23} > 0.42$ (0.43) for NH (IH)



Significance of MH determination as a function of the Hyper-K lifetime



Accelerator and Atmospheric data



If mass hierarchy unknown, several minima because unable to separate CP violation from matter effects.
Combination of accelerator and atmospheric data resolves ambiguity!

Summary

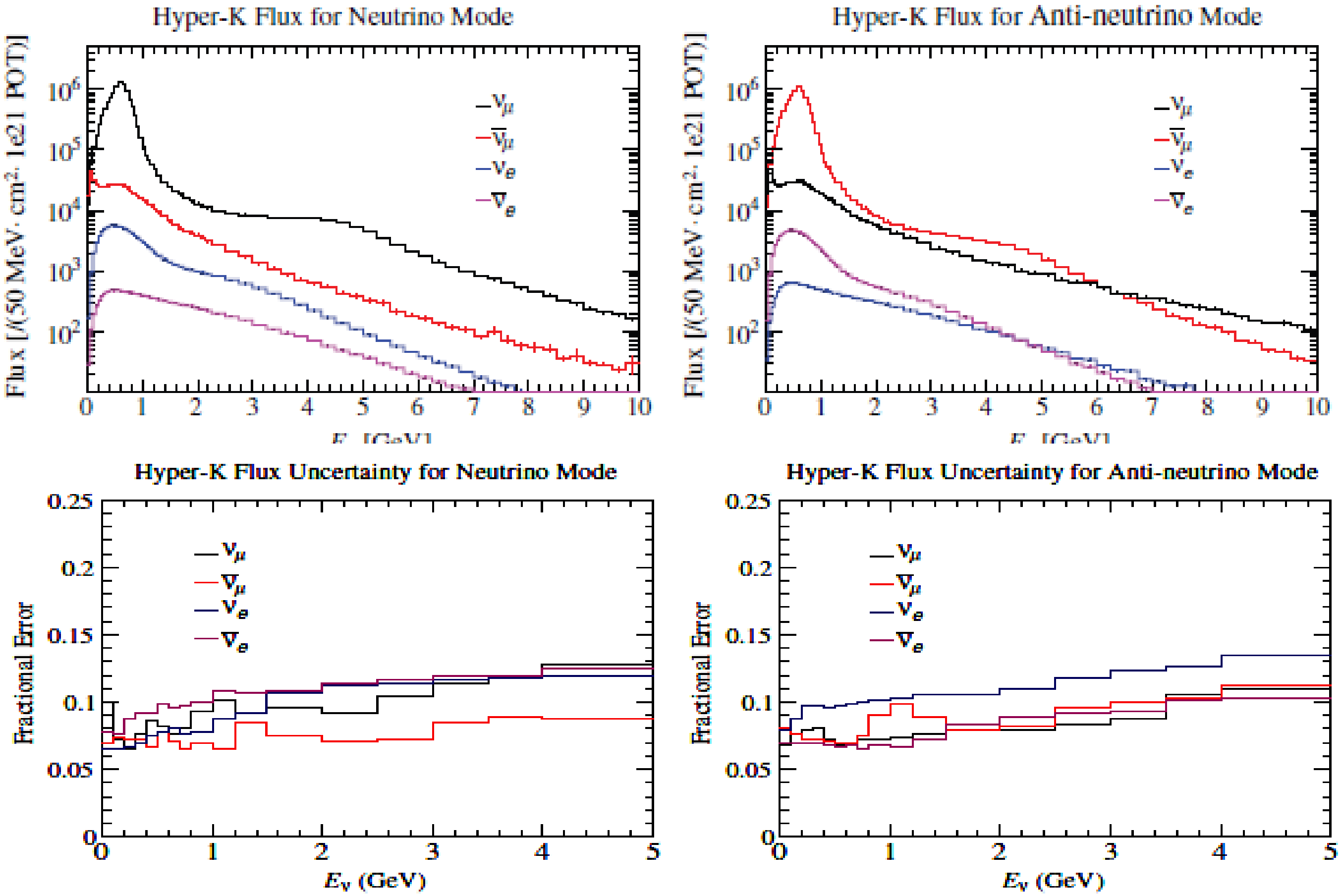
- ✧ The Hyper-Kamiokande experiment offers a variety of physics goals, in particular measurement of neutrino oscillation:
- ✧ 76% (58%) of δ_{CP} space covered at 3σ (5σ) with better than 19 degrees uncertainty;
- ✧ If mass hierarchy is not known, Hyper-K can reject wrong hierarchy with more than 3σ;
- ✧ Resolve θ_{23} octant degeneracy with help of reactor constraint on θ_{13};
- ✧ Very broad physics potential (solar neutrinos, supernova neutrinos, proton decay, etc.);
- ✧ Data taking starts around 2025 according to current schedule.

Backup slides

SK vs. HK

	SK	HK	
Total volume	50 kT	990 kT	20x SK
Fiducial volume	22.5 kT	560 kT	25x SK
PMTs	11k 20”	99k 20” (20% coverage)	

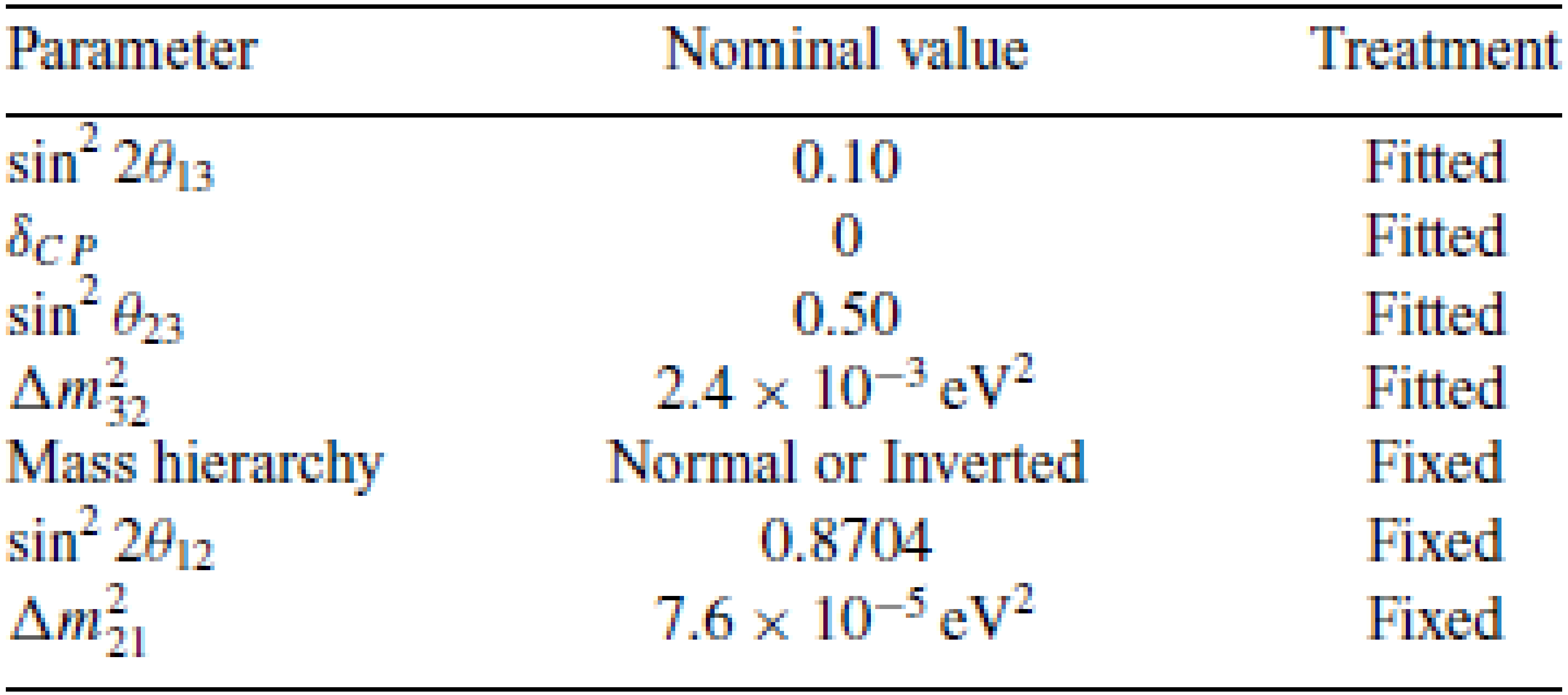
Neutrino and anti-neutrino flux with J-PARC beam



- Neutrino flux is estimated by T2K collaboration by tuning MC modeling of hadronic interactions to NA61/SHINE data.
- T2K flux simulation used with the horn currents raised from 250 kA to 320 kA
- Predicted uncertainty on the neutrino flux calculation assuming that replica target hadron production data are available

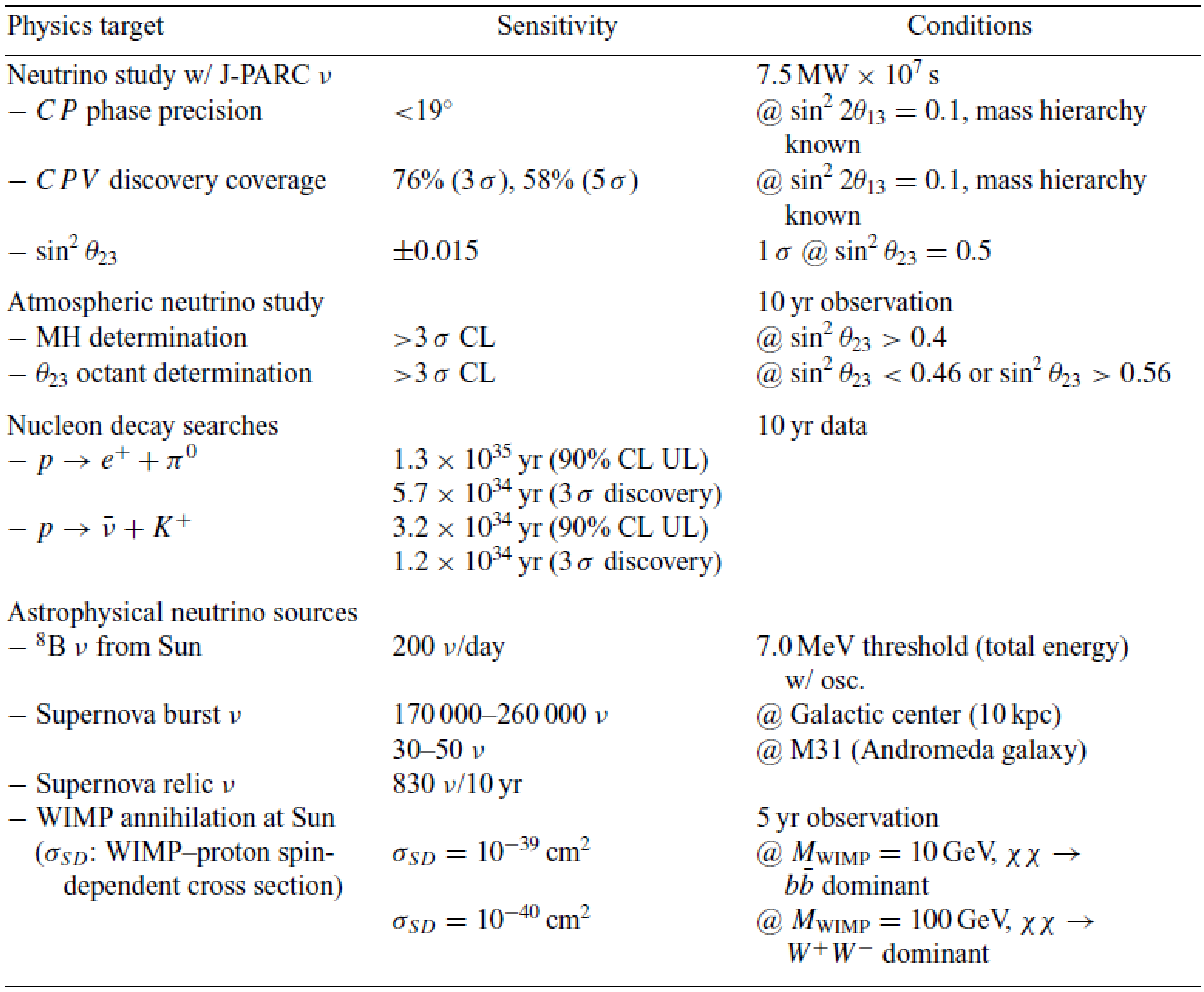
Oscillation parameters in the fit

Oscillation parameters used for the sensitivity analysis and treatment in the fitting



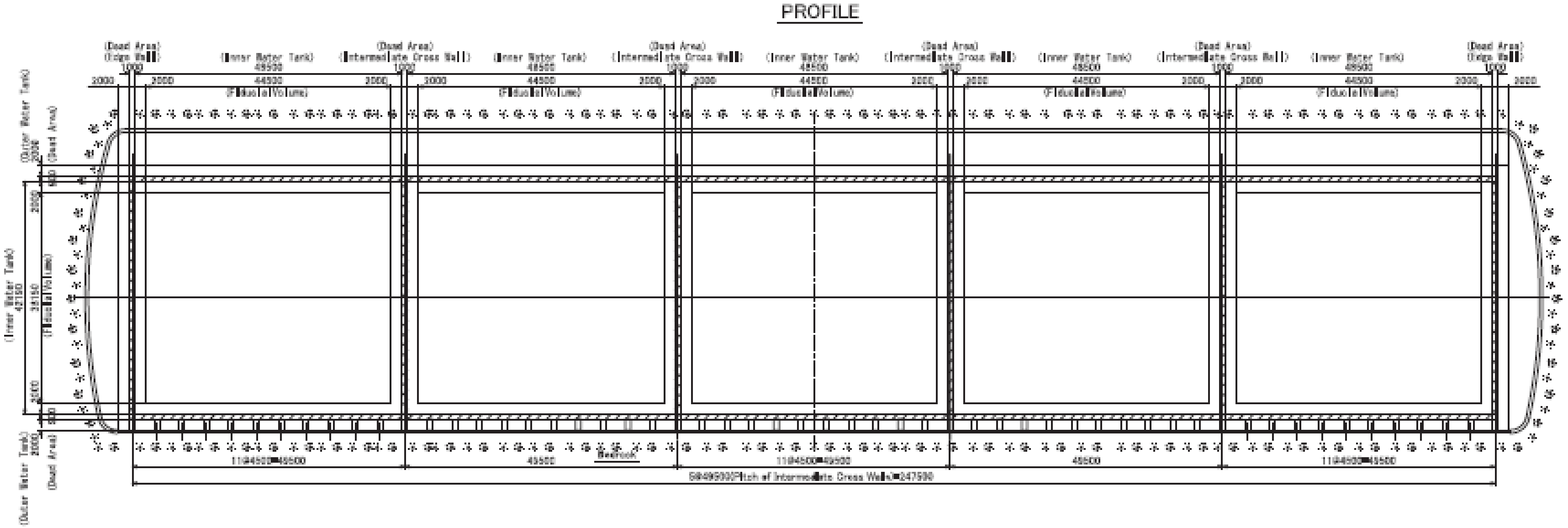
Parameter	Nominal value	Treatment
$\sin^2 2\theta_{13}$	0.10	Fitted
δ_{CP}	0	Fitted
$\sin^2 \theta_{23}$	0.50	Fitted
Δm^2_{32}	$2.4 \times 10^{-3}\ \mathrm{eV}^2$	Fitted
Mass hierarchy	Normal or Inverted	Fixed
$\sin^2 2\theta_{12}$	0.8704	Fixed
Δm^2_{21}	$7.6 \times 10^{-5}\ \mathrm{eV}^2$	Fixed

Expected sensitivities of the Hyper-K



Physics target	Sensitivity	Conditions
Neutrino study w/ J-PARC ν		7.5 MW × 10^7 s
– CP phase precision	$<19^\circ$	@ $\sin^2 2\theta_{13} = 0.1$, mass hierarchy known
– CPV discovery coverage	76% ($3\,\sigma$), 58% ($5\,\sigma$)	@ $\sin^2 2\theta_{13} = 0.1$, mass hierarchy known
– $\sin^2\theta_{23}$	± 0.015	$1\,\sigma$ @ $\sin^2\theta_{23} = 0.5$
Atmospheric neutrino study		10 yr observation
– MH determination	$>3\,\sigma$ CL	@ $\sin^2\theta_{23} > 0.4$
– θ_{23} octant determination	$>3\,\sigma$ CL	@ $\sin^2\theta_{23} < 0.46$ or $\sin^2\theta_{23} > 0.56$
Nucleon decay searches		10 yr data
– $p \to e^+ + \pi^0$	1.3×10^{35} yr (90% CL UL) 5.7×10^{34} yr ($3\,\sigma$ discovery)	
– $p \to \bar{\nu} + K^+$	3.2×10^{34} yr (90% CL UL) 1.2×10^{34} yr ($3\,\sigma$ discovery)	
Astrophysical neutrino sources		
– ^{8}B ν from Sun	200 ν/day	7.0 MeV threshold (total energy) w/ osc.
– Supernova burst ν	170 000–260 000 ν 30–50 ν	@ Galactic center (10 kpc) @ M31 (Andromeda galaxy)
– Supernova relic ν	830 ν/10 yr	
– WIMP annihilation at Sun (σ_{SD}: WIMP–proton spin-dependent cross section)		5 yr observation
	$\sigma_{SD} = 10^{-39}$ cm^2	@ $M_{\text{WIMP}} = 10$ GeV, $\chi\chi \to b\bar{b}$ dominant
	$\sigma_{SD} = 10^{-40}$ cm^2	@ $M_{\text{WIMP}} = 100$ GeV, $\chi\chi \to W^+W^-$ dominant

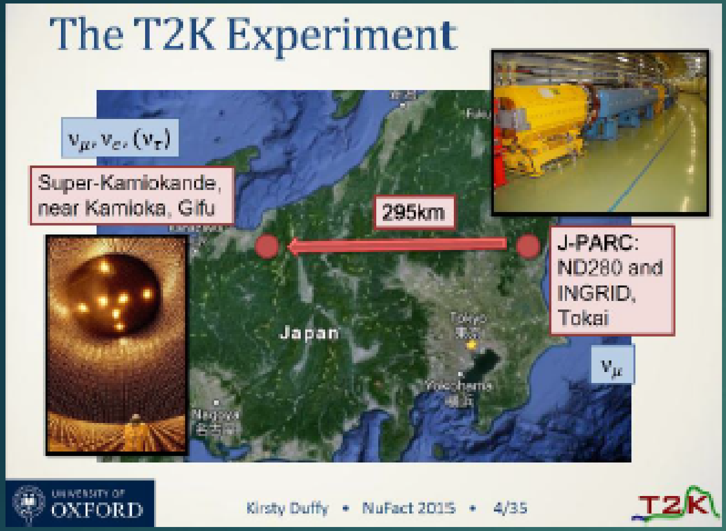
HyperK detector



Each tank will be optically separated by segmentation walls located every 49.5 m to form 5 (in total 10) compartments, as shown in Fig. 4, such that event triggering and event reconstruction can be performed in each compartment separately and independently. Because the compartment dimension of 50 m is comparable with that of Super-K (36 m) and is shorter than the typical light attenuation length in water achieved by the Super-K water filtration system (>100 m @ 400 nm), we expect that the detector performance of Hyper-K for beam and atmospheric neutrinos will be effectively the same as that of Super-K.

The estimated cosmic-ray muon rate around the Hyper-K detector candidate site is $\sim 8 \times 10^{-7}$ s^{-1} cm^{-2}, which is roughly 5 times larger than the flux at Super-K's location ($\sim 1.5 \times 10^{-7}$ s^{-1} cm^{-2}). The expected deadtime due to these muons is less than 1% and is negligible for long-baseline experiments, as well as nucleon decay searches and atmospheric neutrino studies.

T2K latest achievements



The T2K Experiment

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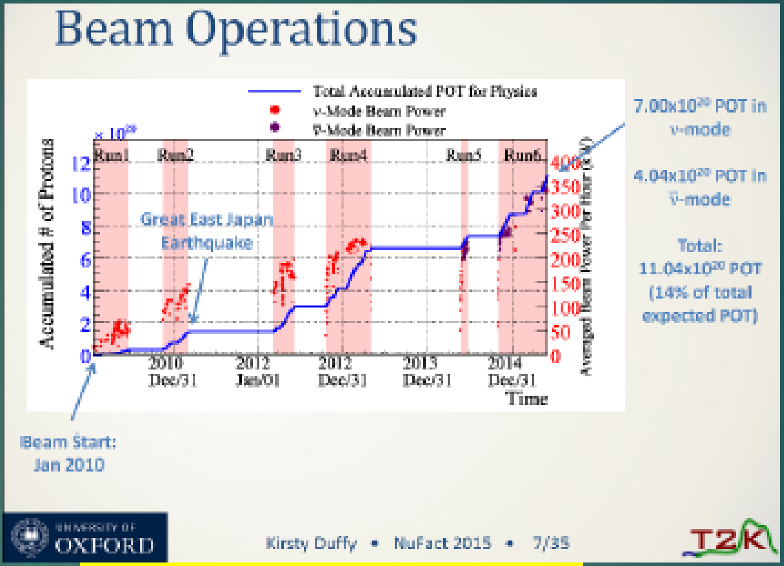

Beam Operations

7.00×10^{20} POT in ν-mode

4.04×10^{20} POT in ν̄-mode

Total: 11.04×10^{20} POT (14% of total expected POT)

Beam Start: Jan 2010

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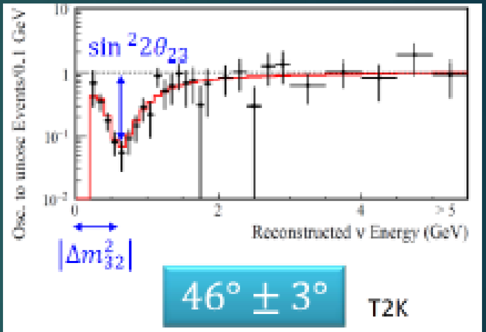
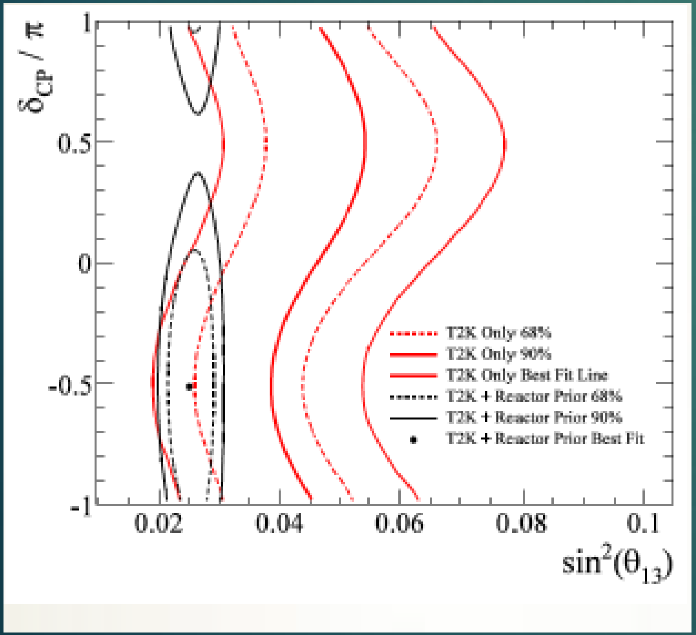
Stable operation at **345kW**

Maximum beam power: **371kW**

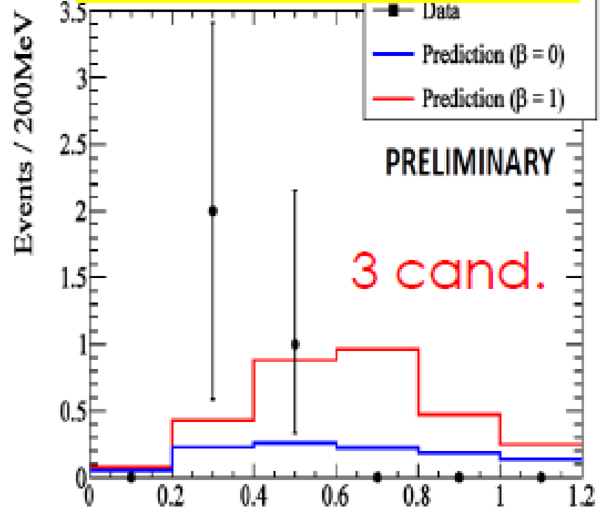


46° ± 3° T2K

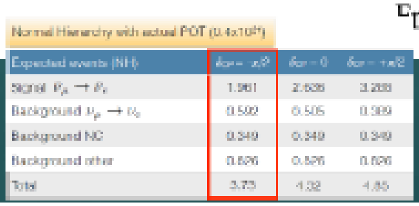


Start measuring CPV phase

First $\overline{\nu}_e$ app search



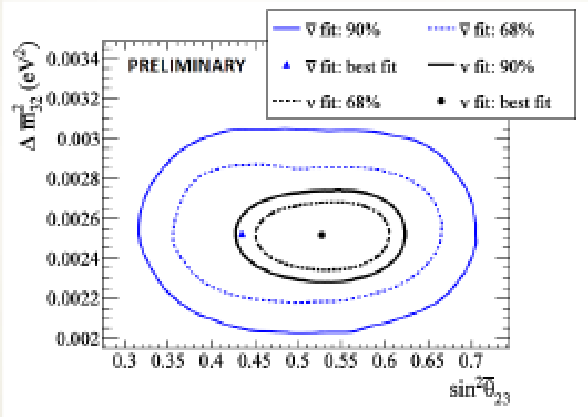
3 cand.



Normal Hierarchy with actual POT (0.4×10^{21})

Expected events (NH)	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$
Signal $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	1.961	2.636	3.288
Background $\nu_\mu \rightarrow \nu_e$	0.592	0.505	0.389
Background NC	0.349	0.349	0.349
Background other	0.826	0.826	0.826
Total	3.73	4.32	4.85

$\overline{\nu}_\mu$ disapp. meas.



Best fit values: $\sin^2\overline{\theta}_{23} = 0.46^{+0.14}_{-0.06}$

$\Delta\overline{m}^2_{32} = 2.50^{+0.3}_{-0.2} \times 10^{-3} eV^2$

Start world leading meas.

Expected T2K sensitivities

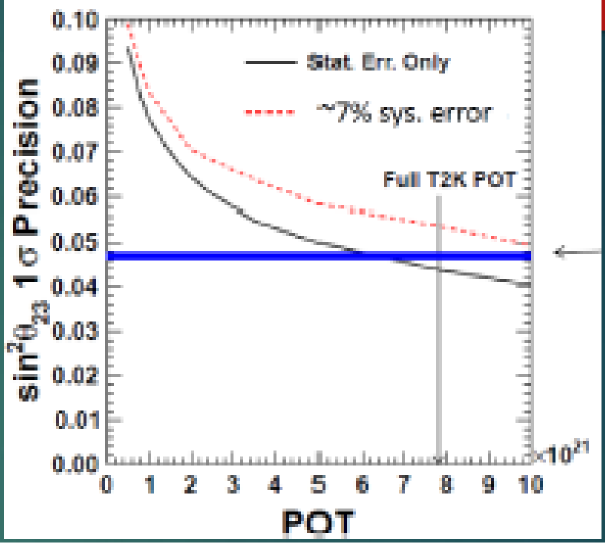
ν_e appearance sample

* bkg includes wrong-sign

	ν_e signal	ν_e bkg.	$\bar{\nu}_e$ signal	$\bar{\nu}_e$ bkg.
$\delta = 0$	98.2	26.8	25.6	16.3
$\delta = -90°$	121.4	26.4	19.0	17.2

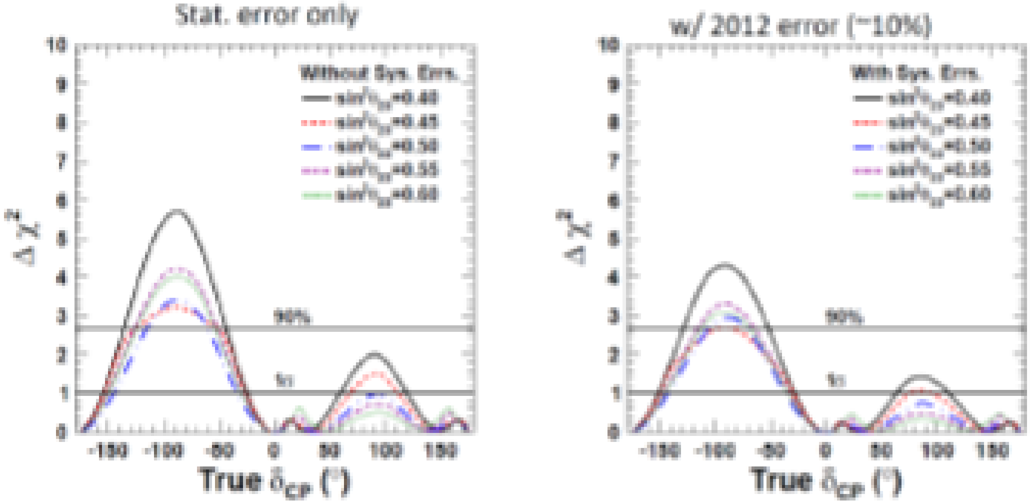
ν_μ disappearance sample

	ν_μ-mode	$\bar{\nu}_\mu$-mode
w/o oscillation	2,648	1,007
w/ oscillation	741	342



Sensitivity to CP violation at 7.8E21 POT

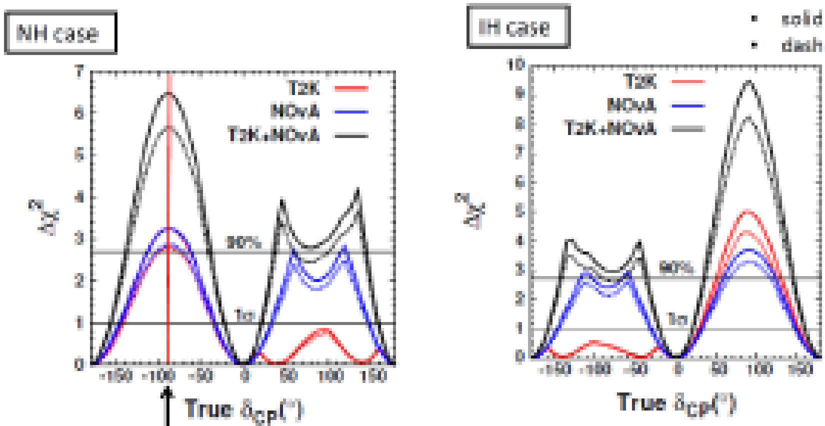
NH case (IH case gives better sensitivity)
1:1 ν-mode:ν̄-mode running



T2K has > 90% C.L. sensitivity if $\delta_{CP} = -90°$

combining w/ NOvA

- $\sin^2\theta_{23} = 0.5$
- solid : stat. only
- dash: 5% sys. error

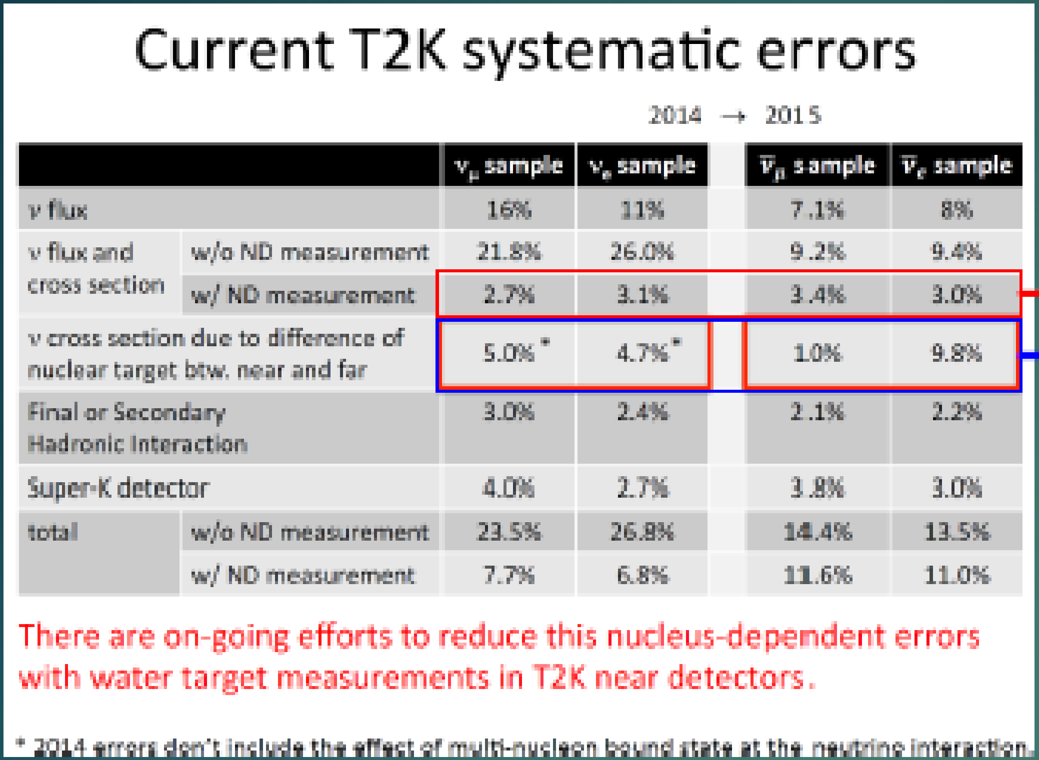


Current most probably situation. (NH, $\delta_{CP} = -90°$)

- Both competition and cooperation with NOvA are really important.
- combination w/ SuperK etc. would also enhance the sensitivity

Where we are & Where we go

Minamino (Kyoto)
M.Hartz(KavliIPMU/TRIUMF)
K.Mahn (MSU)
In NuFact15



Current T2K systematic errors

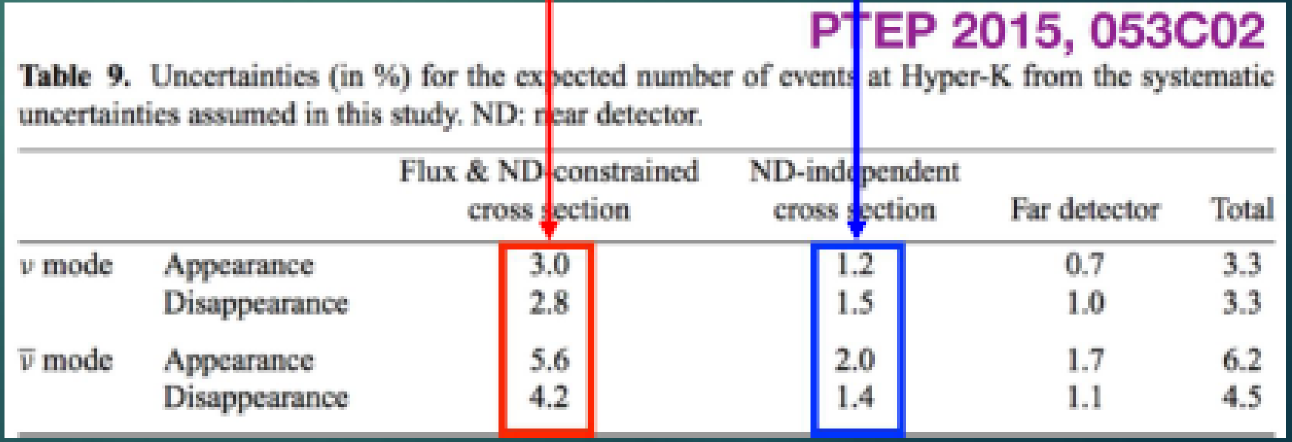
2014 → 2015

		ν_μ sample	ν_e sample	$\overline{\nu}_\mu$ sample	$\overline{\nu}_e$ sample
ν flux		16%	11%	7.1%	8%
ν flux and cross section	w/o ND measurement	21.8%	26.0%	9.2%	9.4%
	w/ ND measurement	2.7%	3.1%	3.4%	3.0%
ν cross section due to difference of nuclear target btw. near and far		5.0% *	4.7% *	1.0%	9.8%
Final or Secondary Hadronic Interaction		3.0%	2.4%	2.1%	2.2%
Super-K detector		4.0%	2.7%	3.8%	3.0%
total	w/o ND measurement	23.5%	26.8%	14.4%	13.5%
	w/ ND measurement	7.7%	6.8%	11.6%	11.0%

There are on-going efforts to reduce this nucleus-dependent errors with water target measurements in T2K near detectors.

* 2014 errors don't include the effect of multi-nucleon bound state at the neutrino interaction.

- Need to aim at a few % level
- Cannot achieve in "1day", need learning process
- "T2K-extended" can provide important opportunity



PTEP 2015, 053C02

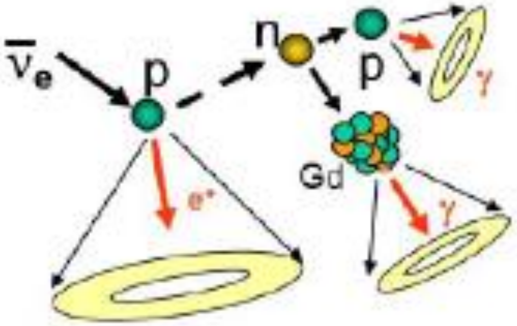
Table 9. Uncertainties (in %) for the expected number of events at Hyper-K from the systematic uncertainties assumed in this study. ND: near detector.

		Flux & ND-constrained cross section	ND-independent cross section	Far detector	Total
ν mode	Appearance	3.0	1.2	0.7	3.3
	Disappearance	2.8	1.5	1.0	3.3
$\overline{\nu}$ mode	Appearance	5.6	2.0	1.7	6.2
	Disappearance	4.2	1.4	1.1	4.5

Gadolinium Option

Beacom and Vagins, *Phys. Rev. Lett.*, 93:171101, 2004 [226 citations]

- Gd-doping proposed in 2004 mainly to greatly enhance supernova neutrino detection.
- It can help also other physics
  - Beam physics → distinguish ν and $\bar{\nu}$; CCQE and other ν-interactions
  - Proton decays → reduce background
- R&D programme started with EGADS (200ton scale model of Super-K)
- Now finishing → Super-K will run with the Gd-doping
- Considered as possible option for Hyper-K



EGADS Facility in Kamioka Mine

SK will have Gd. It could be an option for HK

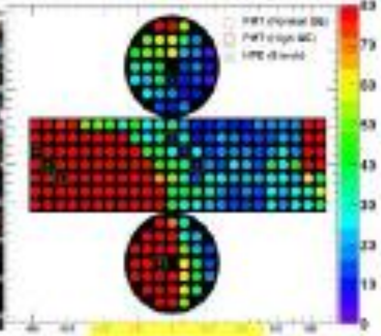
April 2015: fully loaded (0.2%) with Gd sulfate, and functioning perfectly.

EGADS:

12/2009

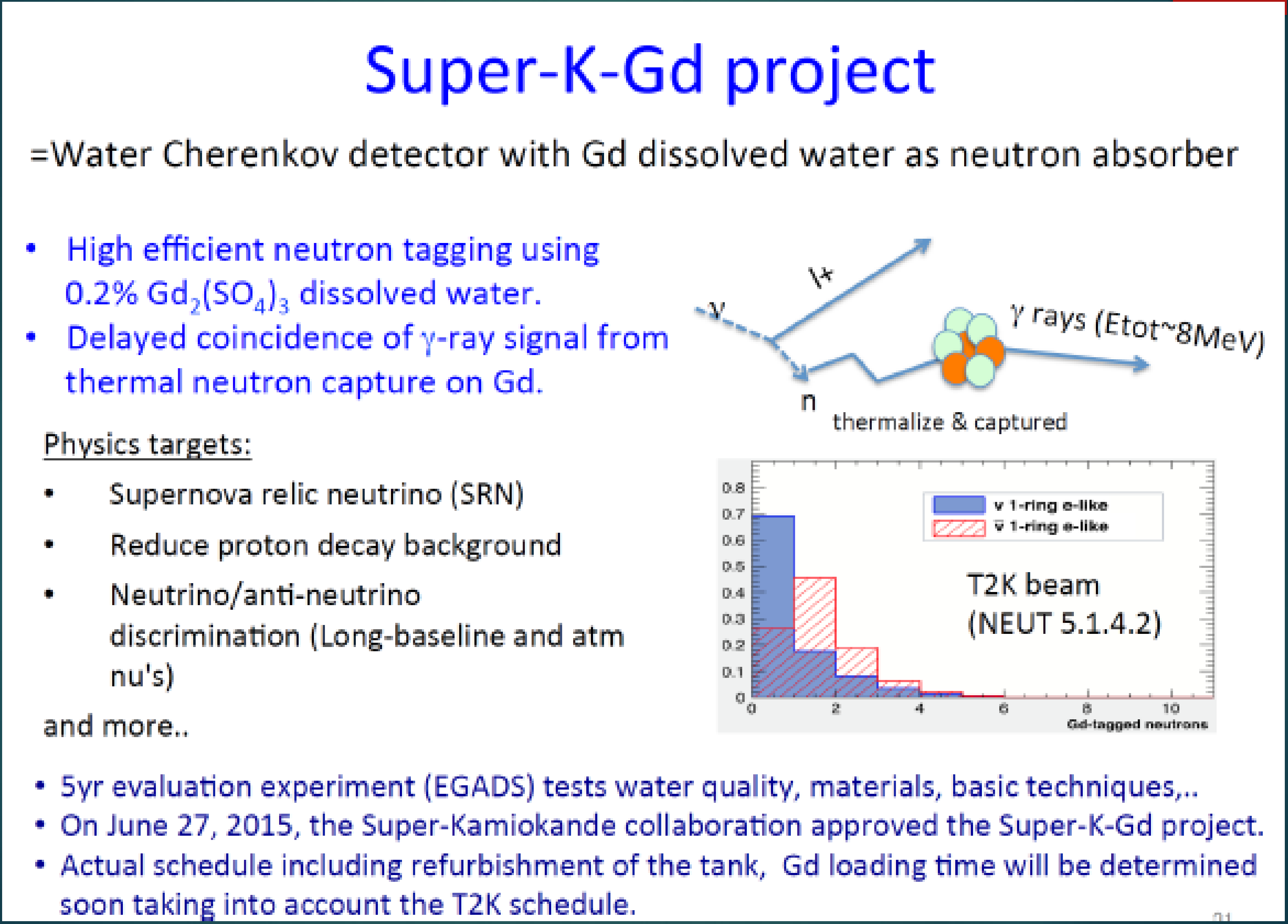
11/2011

8/2013



6/2015

Super-K upgrade: Gd



Super-K-Gd project

=Water Cherenkov detector with Gd dissolved water as neutron absorber

- High efficient neutron tagging using 0.2% $Gd_2(SO_4)_3$ dissolved water.
- Delayed coincidence of γ-ray signal from thermal neutron capture on Gd.

Physics targets:

- Supernova relic neutrino (SRN)
- Reduce proton decay background
- Neutrino/anti-neutrino discrimination (Long-baseline and atm nu's)

and more..

- 5yr evaluation experiment (EGADS) tests water quality, materials, basic techniques,..
- On June 27, 2015, the Super-Kamiokande collaboration approved the Super-K-Gd project.
- Actual schedule including refurbishment of the tank, Gd loading time will be determined soon taking into account the T2K schedule.