Neutrino oscillation physics potential of Hyper-Kamiokande

Linda Cremonesi[1],
for the Hyper-Kamiokande Collaboration

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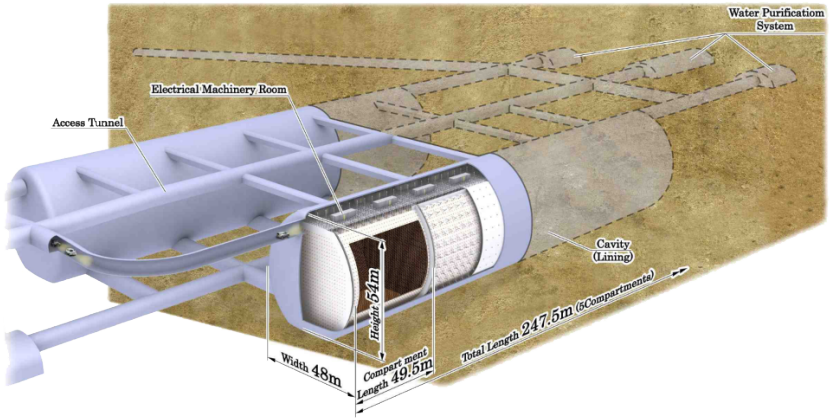
[1] currently at University College London

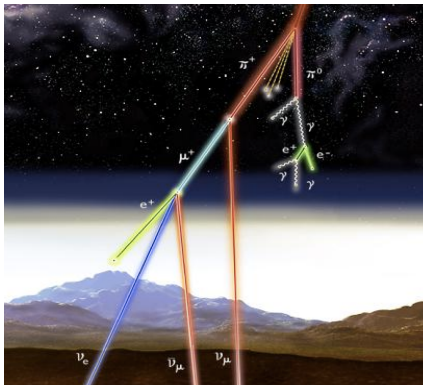
Hyper-Kamiokande: overview



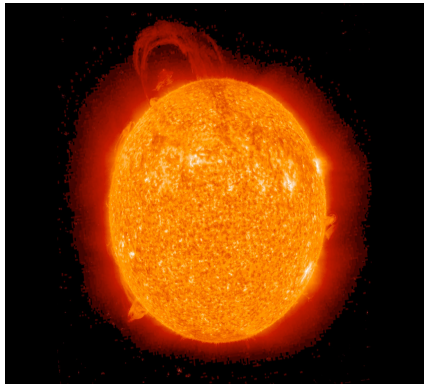
Hyper-Kamiokande is a multi-purpose **Water-Cherenkov detector** with a variety of scientific goals:

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

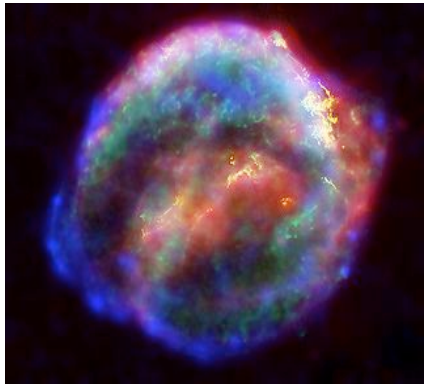
Atmospheric ν



Solar ν

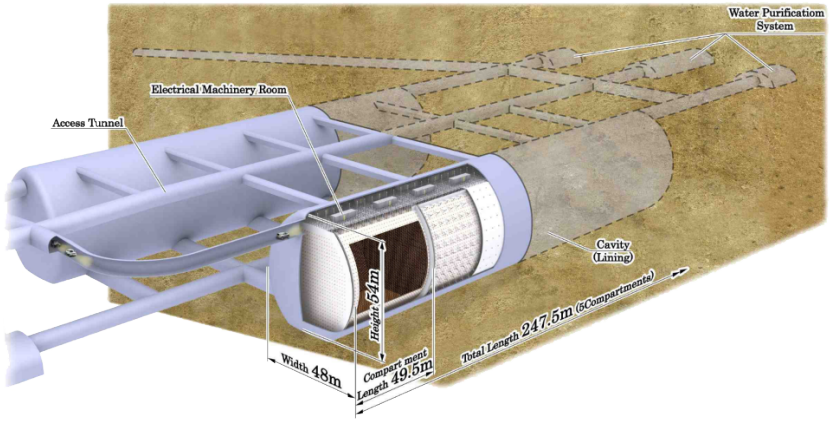


Supernova ν



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
Reconstruction :	fiTQun/BONSAI

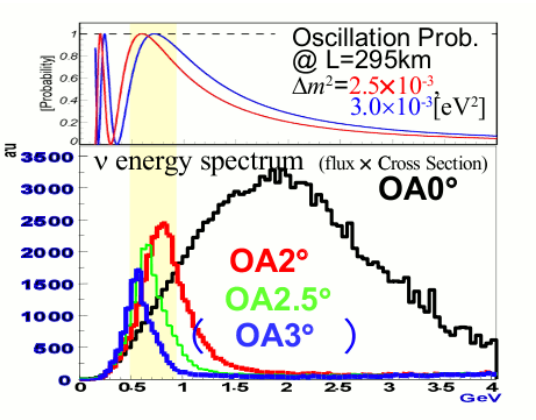
- 2 tanks lying along-side, divided in 10 compartments;
- Compartments are optically separated;
- egg-shape cross section;
- 20% photocatode-coverage;
- Fiducial volume: 25 times larger than Super-Kamiokande;
- Detector simulation studied with WCSim (Geant4, Water Cherenkov simulation programme);

Water Cherenkov: proved technology and scalability

- Excellent PID at sub-GeV region ($> 99\%$);
- Large mass $\rightarrow$ statistics always critical for any measurement

Tokai to Hyper-K long-baseline experiment

Natural extension of T2K experiment



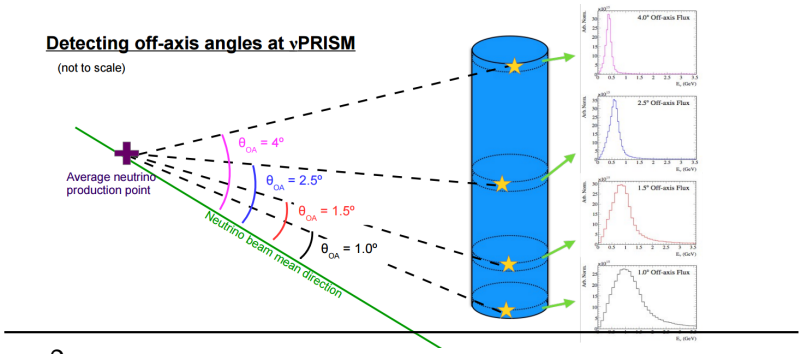
- Upgraded facility at J-PARC will deliver a muon (anti-)neutrino beam towards Hyper-K (≈0.75-1 MW);
- 2.5° off-axis narrow-band beam:
  - Suppresses high energy background;
  - $E_\nu \approx 0.6$ GeV peak at oscillation maximum;
- Pure ν_μ beam with $< 1\%$ ν_e contamination.

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, see poster session), a high pressure TPC[2] or a water-based liquid scintillation detector[3].
- Add new water-based intermediate (1-2 km) detector to better constraint uncertainties on flux and cross-section.

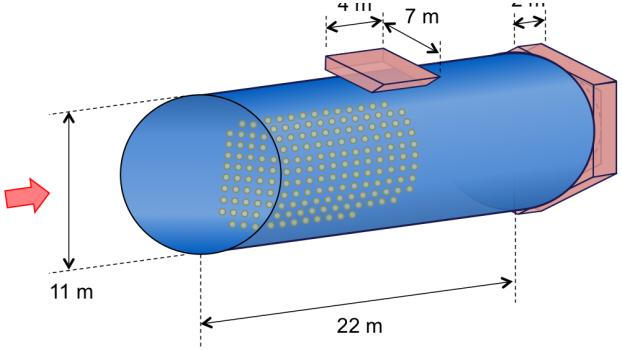
nuPRISM
(arXiv:1412.3086 [physics.ins-det])

- 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 Cherekov detector Gd doped, surrounded by Muon Range Detector, to minimise systematic errors;



[2] M. Ravonel, F. Sanchez, "High Pressure Gas TPC", at Near detector workshop 19th January 2014, Tokai.
[3] M. Yeh, S. Hans, W. Beriguete, R. Rosero, L. Hu, et al., Nucl. Instrum. Meth., A660, 51-56 (2011).

Physics potential

- All results shown today are reported in **Prog. Theor. Exp. Phys. (2015) 053C02**.
- Assumptions:
  - Integrated beam power: 7.5 MW$\times 10^7$ sec (i.e. 0.75 MW for 10 years running) $\rightarrow$ 1.56 10^{22} POT;
  - ν : running/ $\overline{\nu}$ running $\rightarrow$ 1:3;
  - Normal mass hierarchy with $\sin^2 2\theta_{13} = 0.1$ and $\delta_{CP} = 0$ are assumed.
- 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);

Systematic uncertainties assumptions

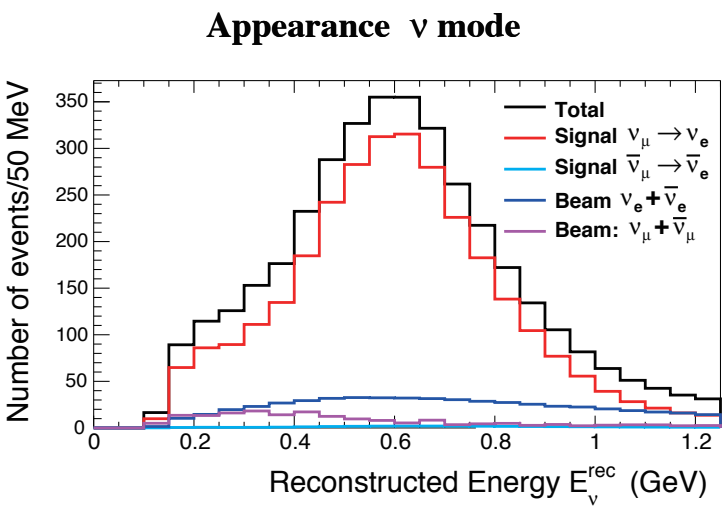
Systematic uncertainties assumptions

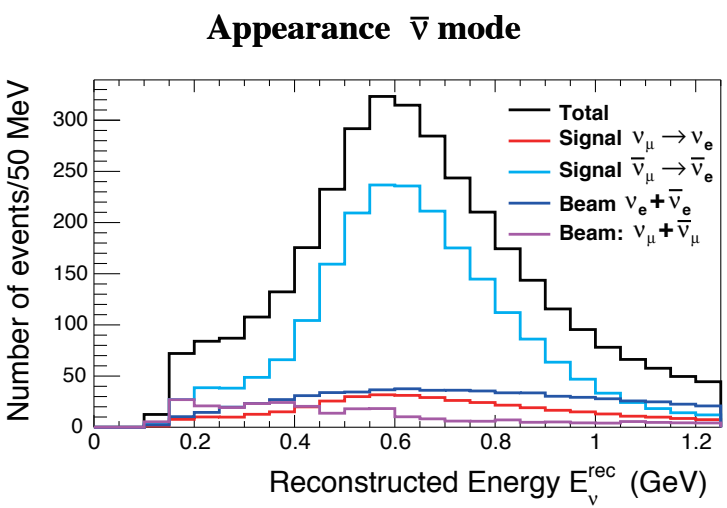
1. Flux and ND constrained uncertainties → conservatively assumed to be the same as T2K;
2. ND-independent cross-section uncertainties → assumed improvements due to availability of water target and new samples in ND;
3. Far detector uncertainties → reduced due to availability of larger atmospheric sample 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%
$\overline{\nu}$ mode	App	5.6%	2.0%	1.7%	6.2%
	Disapp	4.2%	1.4%	1.1%	4.5%

ν_e appearance

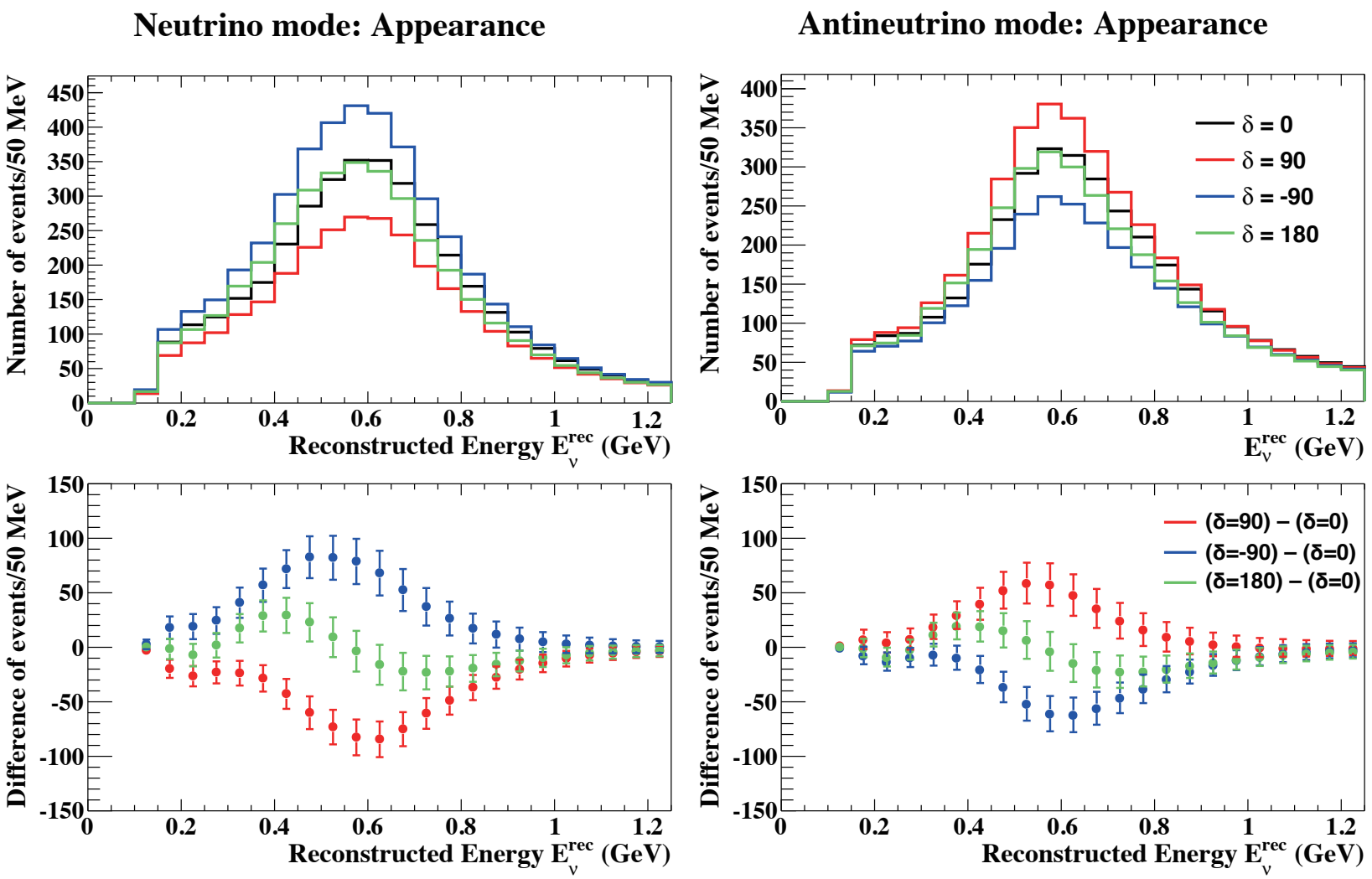
The expected number of ν_e candidate events.





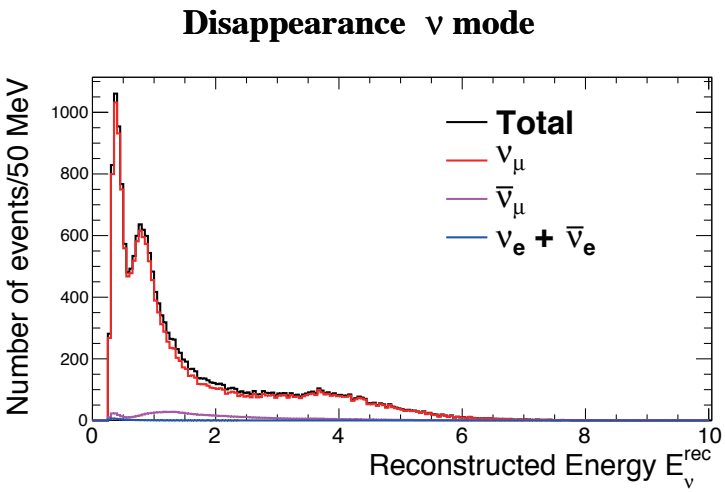
	signal		Background				Total
	$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu/\bar{\nu}_\mu$ CC	$\nu_e/\bar{\nu}_e$ CC	NC	BG Total	
ν mode	3016	28	11	523	172	706	3750
$\bar{\nu}$ mode	396	2110	9	618	265	891	3397

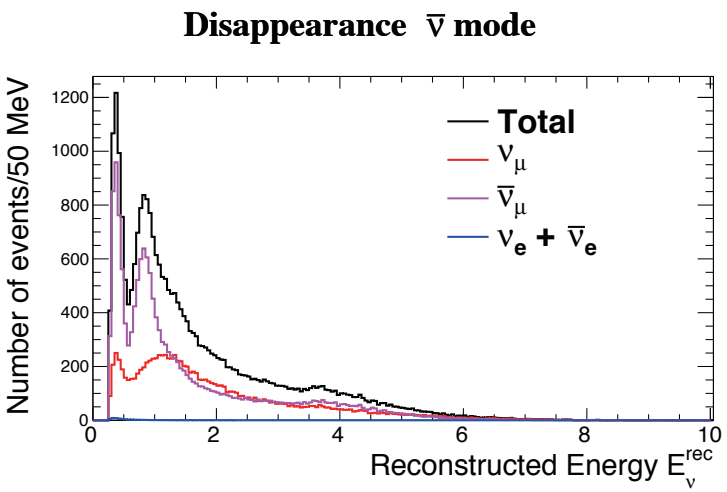
Effect of δ_{CP} at Hyper-K



ν_μ disappearance

The expected number of ν_μ candidate events.

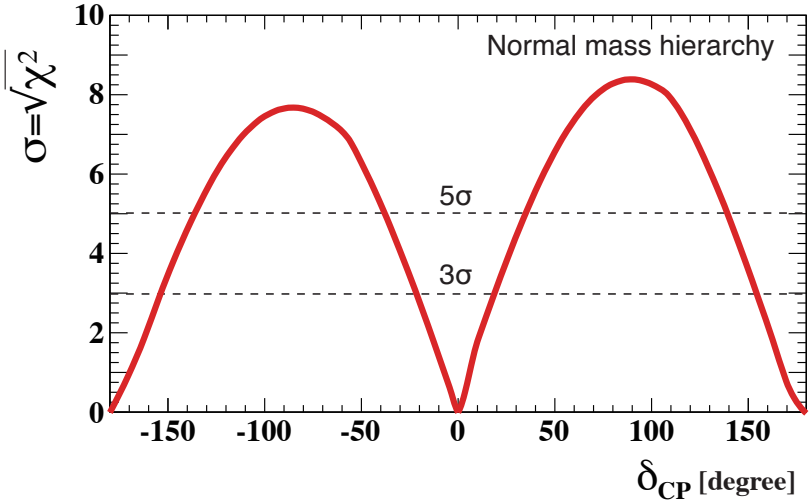




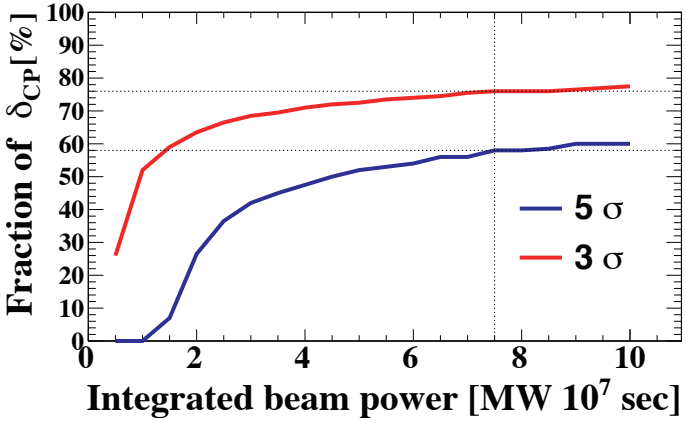
	ν_μ CC	$\overline{\nu}_\mu$ CC	ν_e CC	$\overline{\nu}_e$ CC	NC	$\nu_\mu \to \nu_e$	total
ν mode	17225	1088	11	1	999	49	19372
$\bar{\nu}$ mode	10066	15597	7	7	1281	6	26964

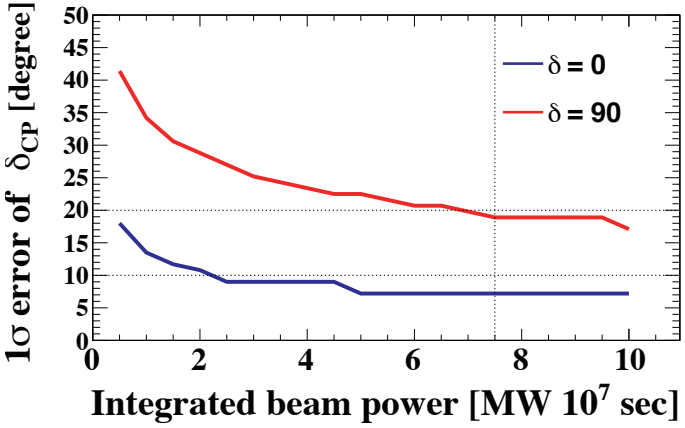
Sensitivity to δ_{CP}

76% (58%) of δ_{CP} space covered at 3σ (5σ) with better than 19 degrees uncertainty



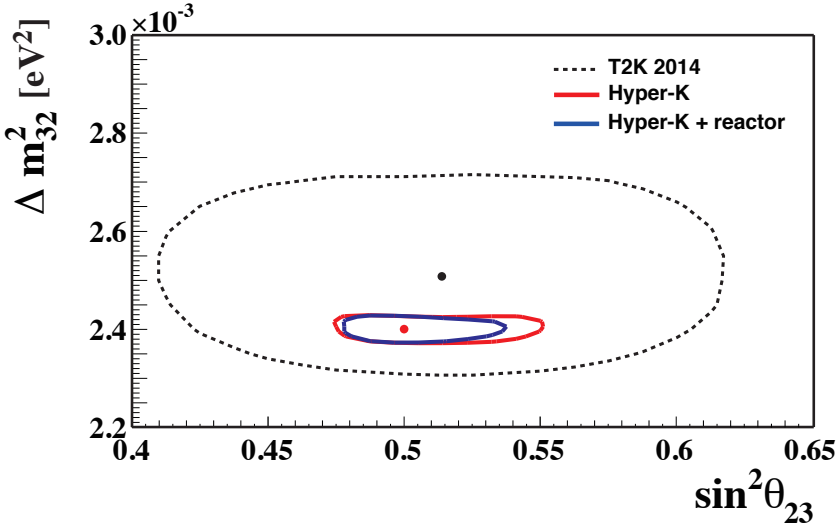
- Assuming normal MH, $\sin^2 2\theta_{13} = 0.1$, $\sin^2\theta_{23} = 0.5$ and $\Delta m^2_{32} = 0.0024\,\text{eV}$
- (left) Fraction of δ_{CP} space for which $\sin\delta_{CP} = 0$ can be excluded with $3\sigma/5\sigma$.
- (right) 1 σ uncertainty as a function of the integrated beam power.





Sensitivity to θ_{23}

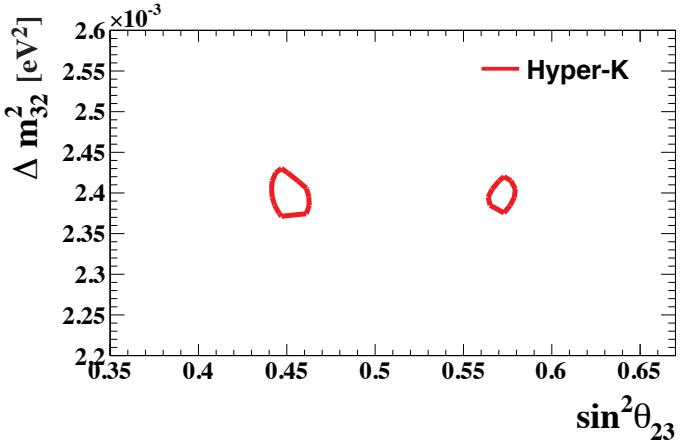
Octant resolution w/ reactor θ_{13} → wrong octant rejection for $\sin^2\theta_{23} < 0.46$ or > 0.56.



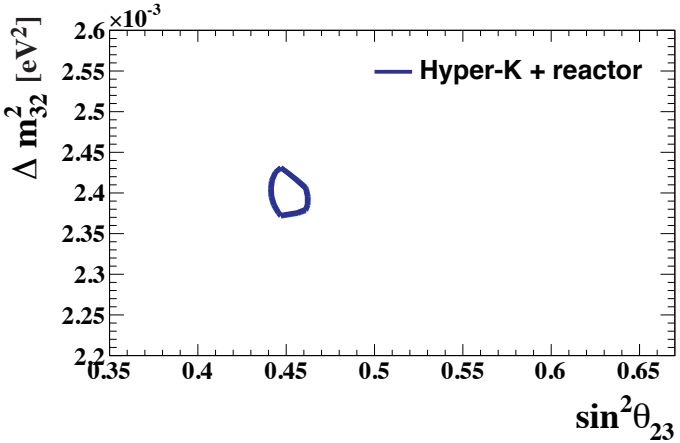
- Expected 1σ uncertainty of Δm^2_{32} better than 1.5×10^{-5} eV^2 for NH/IH.
- Expected 1σ uncertainty of $\sin^2\theta_{23}$:

True $\sin^2\theta_{23}$ Parameter	0.45	0.50	0.55
NH	0.006	0.015	0.009
IH	0.006	0.015	0.009

Without reactor



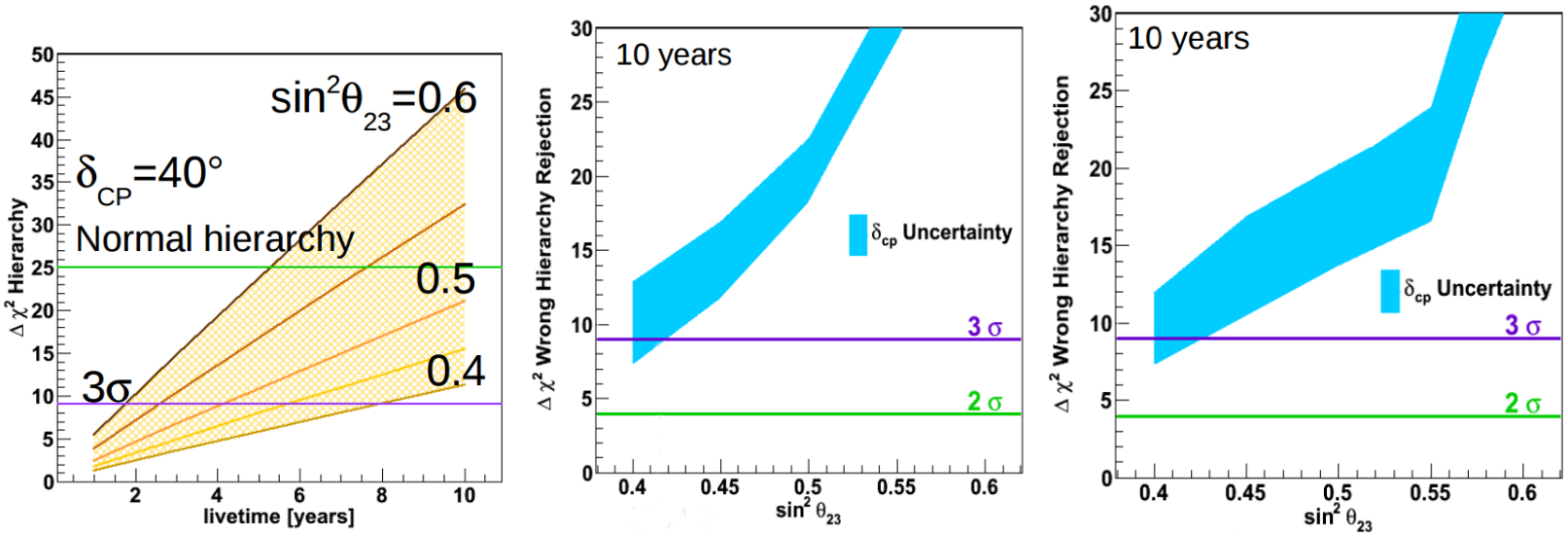
With reactor



Sensitivity to Mass Hierarchy

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

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

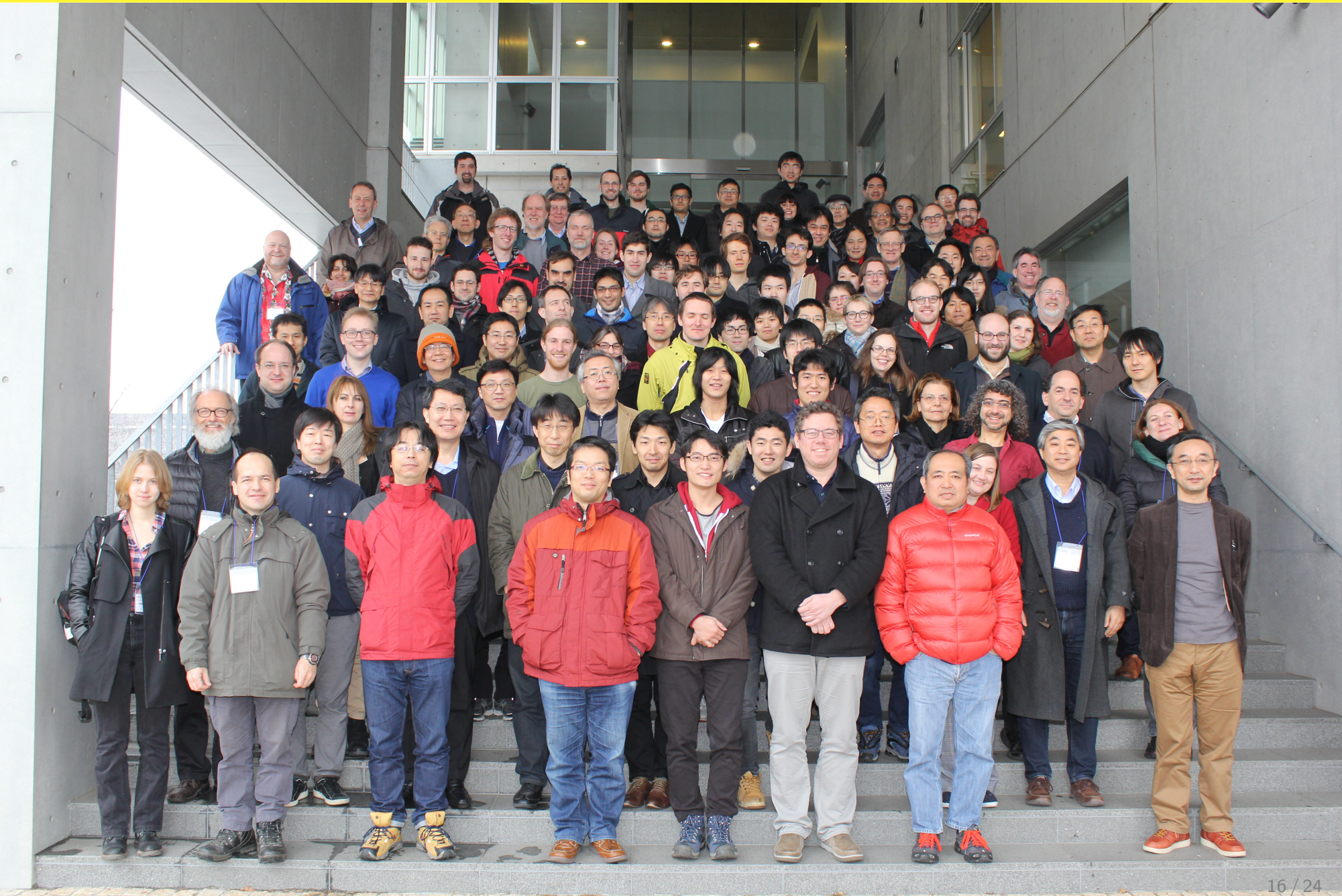


Summary

- 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, supepernova neutrinos, proton decay, etc.);
- Find out more during the Poster session $\rightarrow$ Mark Rayner "Status of the Hyper-Kamiokande Project".

- International proto-collaboration has been formed (13 countries, $\approx$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.

THANK YOU



BACK UP SLIDES

Sensitivitity studies

- Sensitivity to oscillation parameters evaluated using a binned likelihood based on the reconstructed neutrino energy distribution developed for the T2K experiment;
- Fit is performed using both ν_e ($\bar{\nu}_e$) appearance and ν_μ ($\bar{\nu}_\mu$) disappearance samples simultaneously.
- Systematic uncertainties are implemented as a covariance matrix based on the experience and prospects of T2K experiment;
- Event selection is the same as T2K official selection for ν_e appearance and ν_μ disappearance analysis

- Integrated beam power: 7.5 MW$\times 10^7$ sec (i.e. 0.75 MW for 10 years running) $\rightarrow$ 1.56 10^{22} POT;
- Horn current: $\pm$320 kA;
- $\nu : \bar{\nu} \rightarrow$ 1:3;

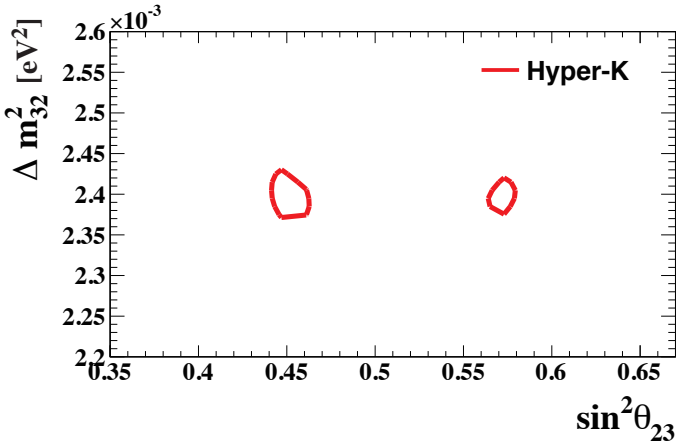
Parameter	$\sin^2 2\theta_{13}$	δ_{CP}	$\sin^2 \theta_{23}$	Δm^2_{32}	$\sin^2 2\theta_{12}$	Δm^2_{12}
Nominal	0.10	0	0.5	2.4 $\times 10^{-3}$	0.8794	7.6 $\times 10^{-5}$
Treatment	Fitted	Fitted	Fitted	Fitted	Fixed	Fixed

Sensitivity to θ_{23}

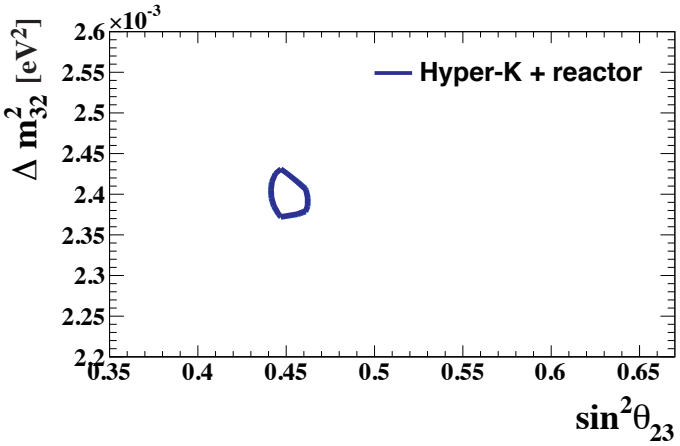
Table : Expected 1σ uncertainty of Δm^2_{32} and $\sin^2\theta_{23}$ for true $\sin^2\theta_{23} = 0.45, 0.50, 0.55$. Reactor constraint on $\sin^2 2\theta_{13} = 0.1 \pm 0.005$ is imposed.

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}	0.015	1.5×10^{-5}	0.009
IH	1.5×10^{-5}	0.006	1.4×10^{-5}	0.015	1.5×10^{-5}	0.009

Withour reactor

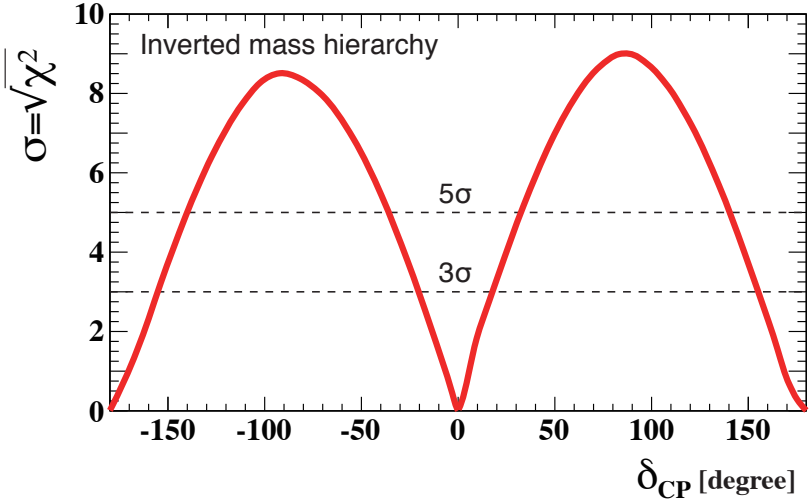


With reactor



Sensitivity to δ_{CP}

77% (61%) of δ_{CP} space covered at 3σ (5σ) with better than 19 degrees uncertainty



- Assuming inverted MH, $\sin^2 2\theta_{13} = 0.1$, $\sin^2 \theta_{23} = 0.5$ and $\Delta m^2_{32} = 0.0024\,\text{eV}$
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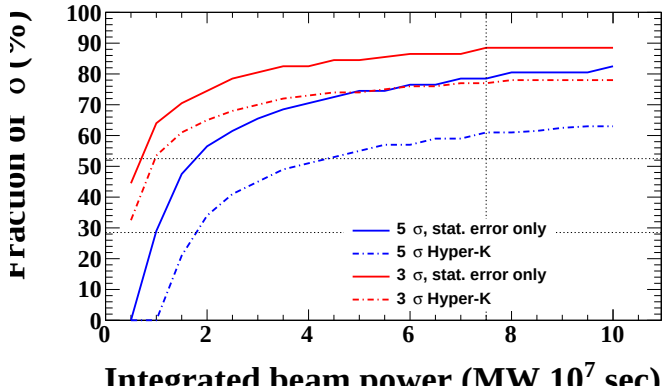
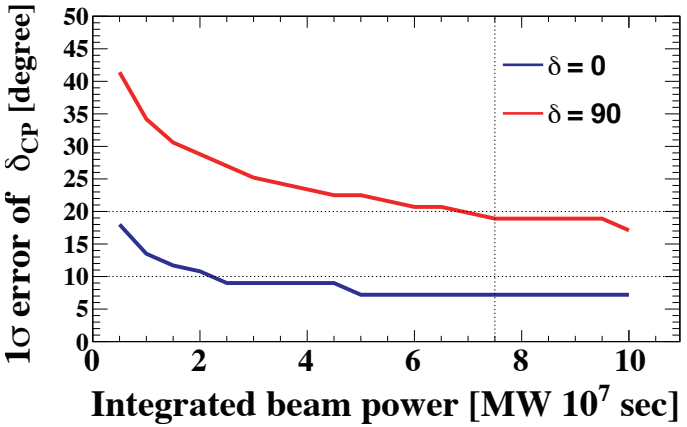
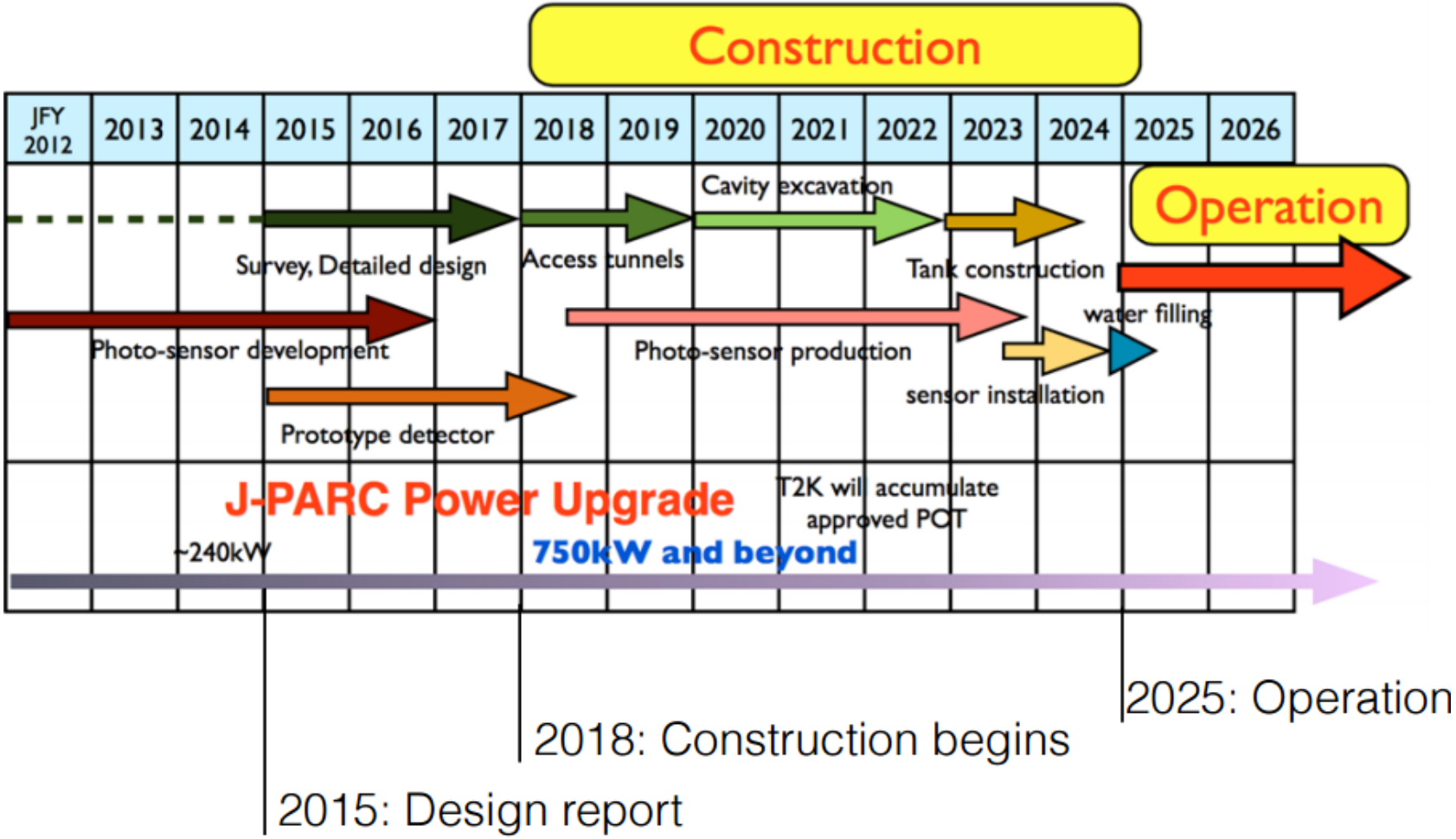


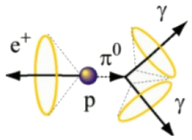


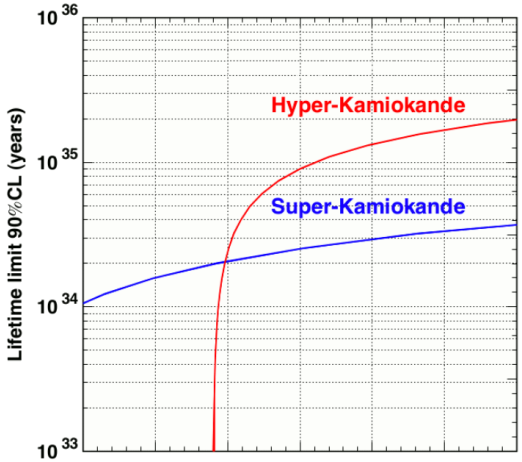
Hyper-K schedule



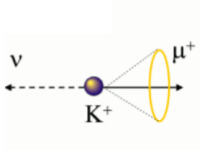
Proton decay

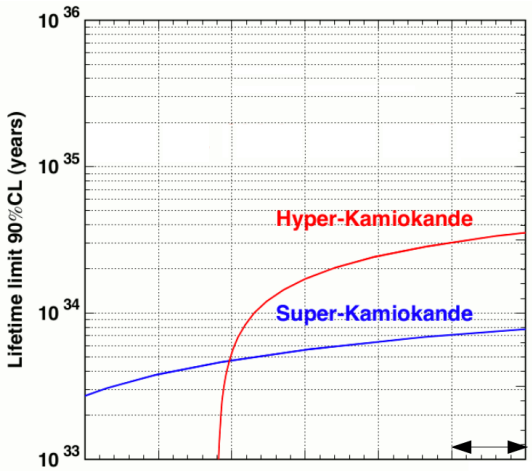
$p \to e^+\pi^0$





$p \to \overline{\nu}K^+$





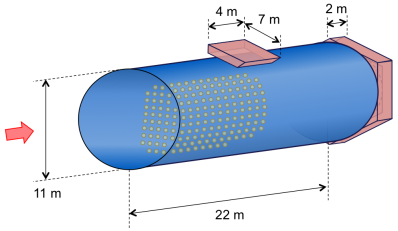
- 10 times better sensitivity than Super-K;
- Hyper-K surpasses SK limits in ≈ 1 year;
- Hyper-K is sensitive in many different modes:
  - $p \to e^+\pi^0$: 1.3×10^{35} years at 90% CL;
  - $p \to \overline{\nu}K^+$: 3×10^{34} years at 90% CL;
  - $p, n \to (e^+, \mu^+) + (\pi, \rho, \omega, \eta)$: 10^{34-35} years;
  - K^0 modes;
  - $\nu\pi^0, \nu, \pi^+$;
  - ...

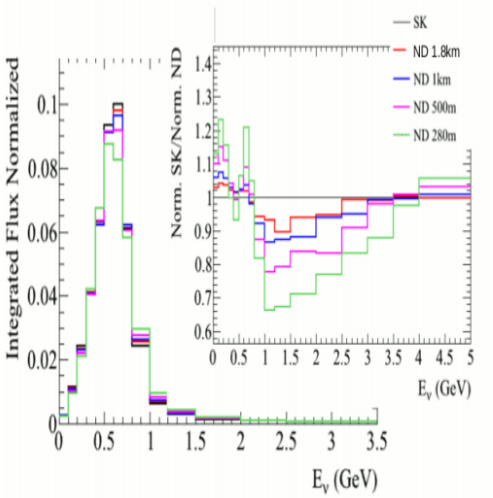
Other physics topics at Hyper-K

- Solar Neutrinos: 200 νs / day from Sun $\rightarrow$ day/night asymmetry of the solar neutrinos flux can be precisely measured at Hyper-K ($< 1\%$);
  - Currently tank optimisation ongoing to reach 6 MeV threshold (same as Super-K-2).
- Solar flares can be discovered at Hyper-K (important information about particle acceleration at work in solar flares);
- Supernova burst neutrinos: 200k νs from Supernova at Galactic center (10kpc) $\rightarrow$ time variation and energy can be measured with high statistics;
- Supernova relic neutrinos: possible with Gd doping of Hyper-K. $\approx$830 events in 10 years in 10-30 MeV energy range.

TITUS

Tokai Intermediate Tank for Unoscillated Spectrum





2-kton Gd-doped water Cherekov tank (9.75 m x 9.75 m x 22 m) surrounded by a Muon Range Detector (MRD) covering 3/4 on the length of the sides and the downstream of the detector

- size and shape optimised looking at muon containment and pile-up;

- located at $\approx$ 2 km from interaction point $\rightarrow$ TITUS detector sees almost the same spectrum as at Hyper-K:
  - The maximum difference in shape is 5% at the peak energy instead of almost 20% with ND280;
- Photosensors: LAPPDs (provide excellent time/space resolution and reduce NCπ^0 background) and HPDs $\rightarrow$ ANNIE experiment;
- Gd doped $\rightarrow$ 8 MeV cascade of 2/3 gammas from neutron capture:
  - reduce $\nu/\bar{\nu}$ uncertainty to less than a percent;
  - reduce ν_e/ν_μ uncertainty to 1-2%;
  - NCπ^0 rate will be known better than the current error on the axial mass;
- Can be included in the SuperNova Early Warning system;