Hyper-Kamiokande

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On behalf of the Hyper-Kamiokande Working Group

NUFACT 2014

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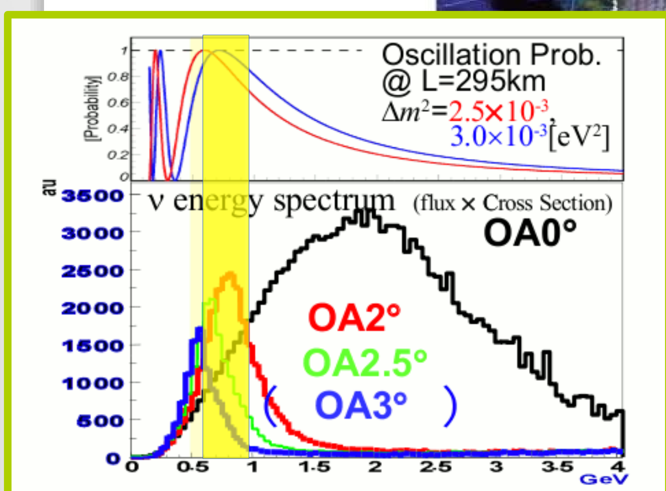
Tokai to Hyper-Kamiokande

- Use upgraded J-PARC neutrino beam line (same as T2K) with expected beam power ≥750kW, 2.5° off-axis angle.



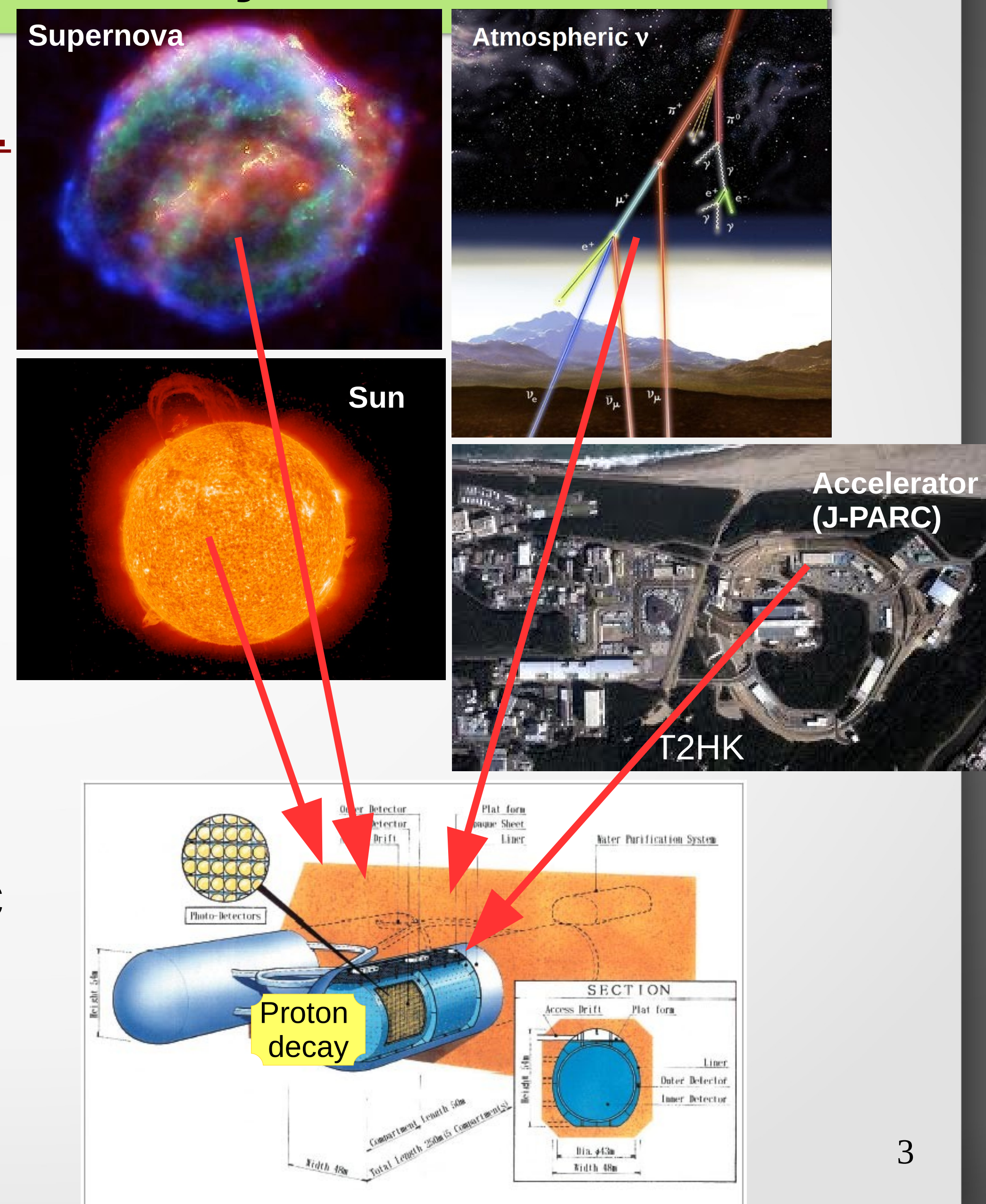
- Narrow-band beam at ~600MeV at 2.5° off-axis

- Take advantage of Lorentz Boost and 2-body kinematics in $\pi^+ \rightarrow \mu^+ \nu_\mu$
- Pure ν_μ beam with ~1% ν_e contamination

The Hyper-Kamiokande Project

Multi-purpose neutrino experiment.
Wide-variety of scientific goals:

- Neutrino oscillations:
  - Neutrino beam from J-PARC
  - Atmospheric neutrinos
  - Solar neutrinos
- Search for proton decay
- Astrophysical neutrinos (supernova bursts, supernova relic neutrinos, dark matter, solar flare, …)
- Neutrino geophysics



Hyper-K in the World

(http://www.hyperk.org)

- Selected one of the 27 'top projects' in the 'Japanese master plan for large scale research projects' by the Science Council of Japan.
- Open meetings held twice/year since Aug.2012
- International Board of Representatives formed to discuss contributions, cost-sharing and budget request.
- R&D work ongoing internationally.

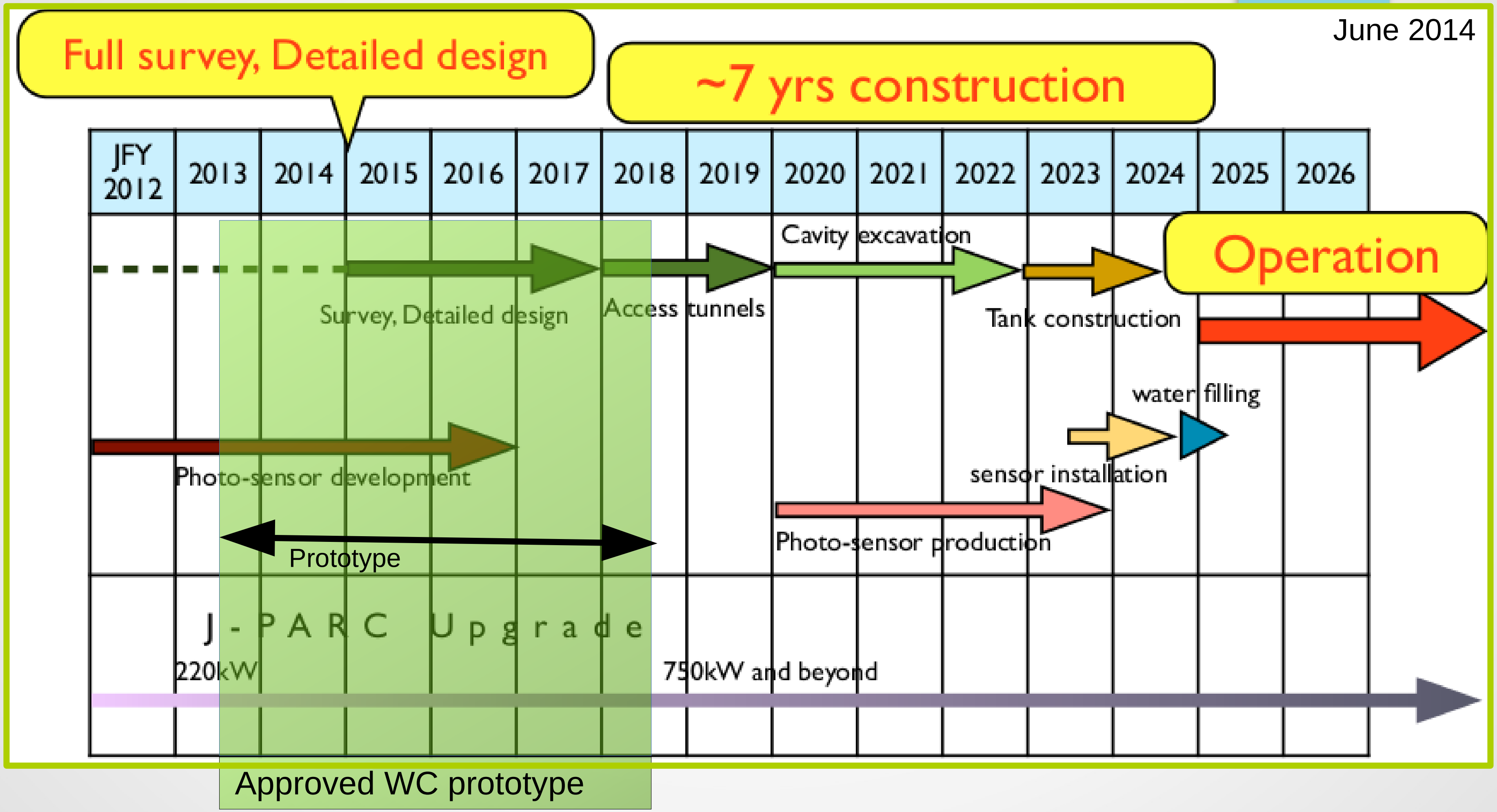
12 countries, 67 institutes, 240 people

Asia	72
Japan	64
Korea	8

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

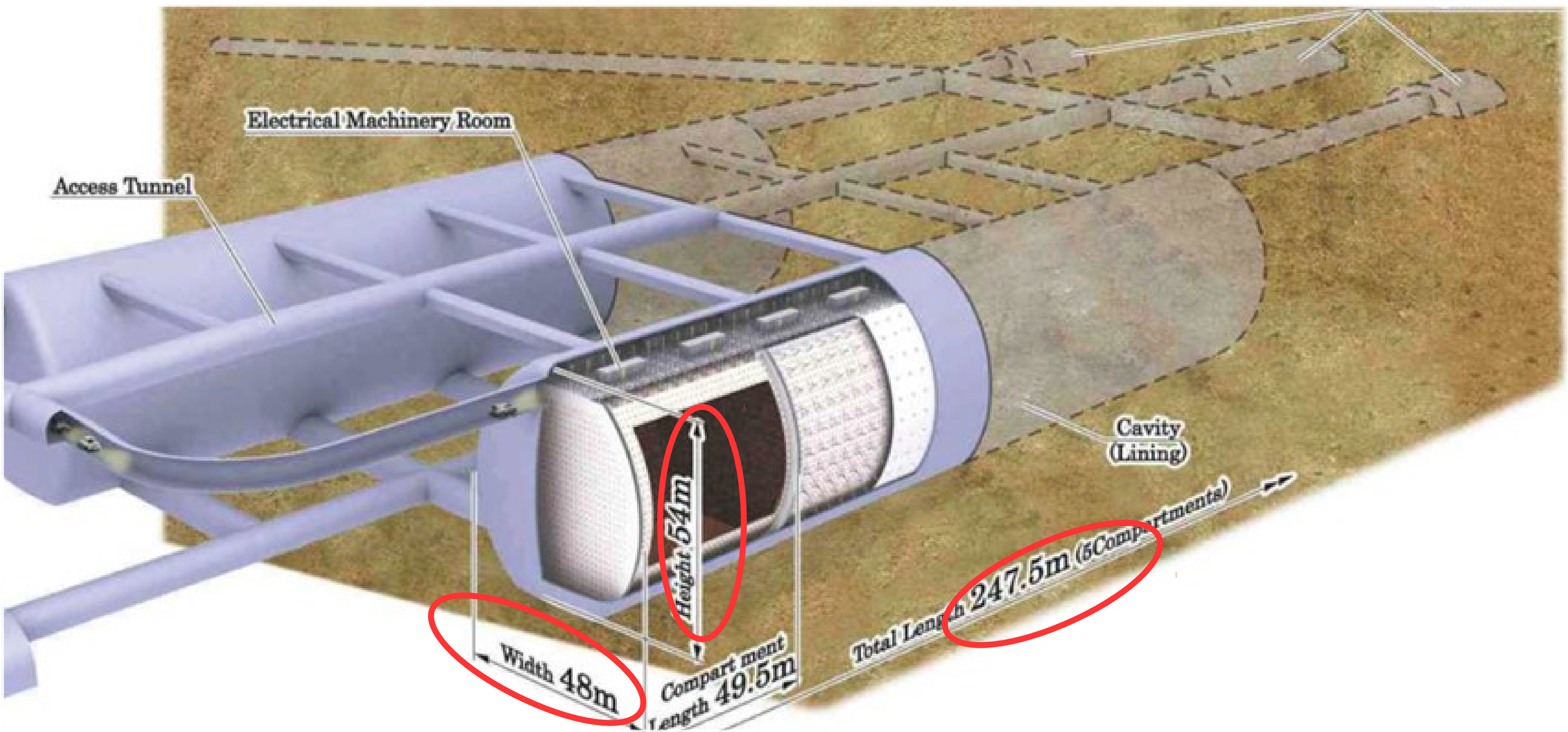
Americas	62
Brazil	2
Canada	19
USA	41

The Hyper-Kamiokande Timeline



- Approved WC prototype for technical studies (2013-2018) ~$1.2M
- Major decisions on experiment design expected before 2018.

The Hyper-Kamiokande Detector

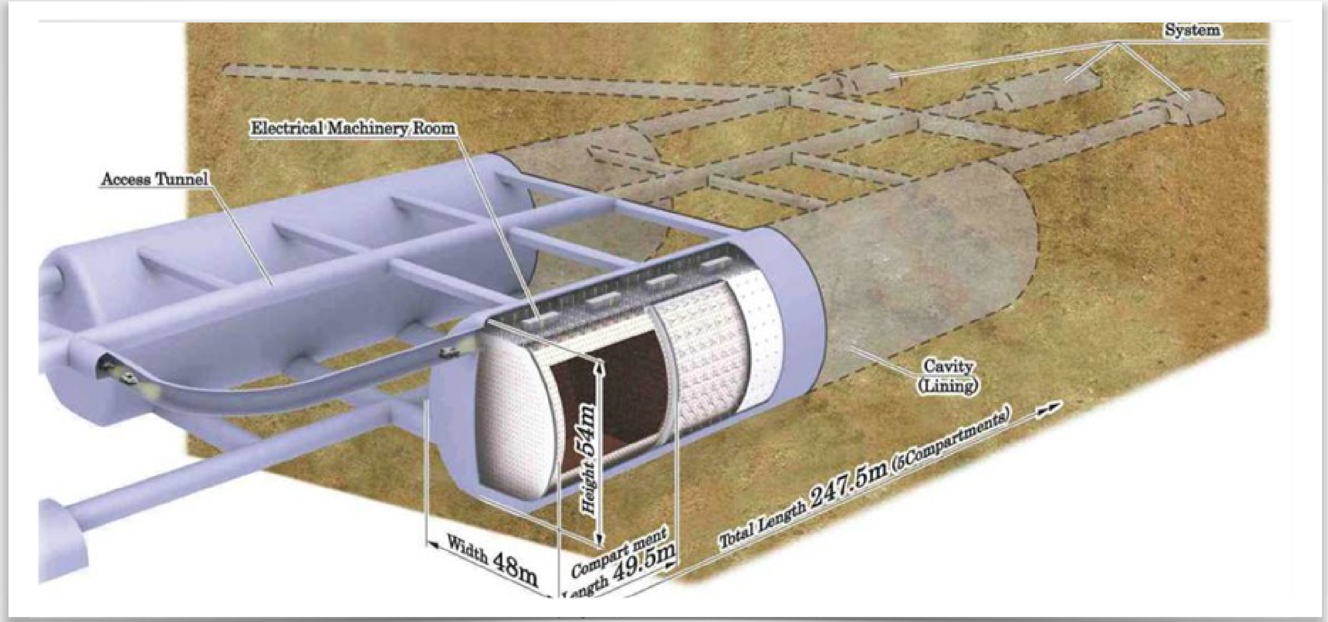


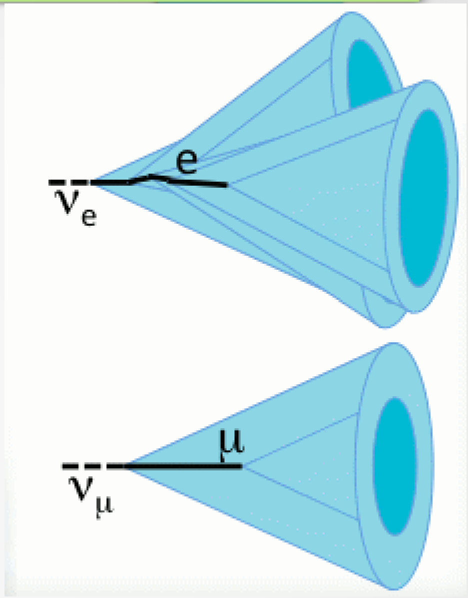
The Hyper-Kamiokande Detector

- Water Cherenkov, proven technology & scalability:
  - Excellent PID at sub-GeV region >99%
  - Large mass → statistics always critical for any measurements.

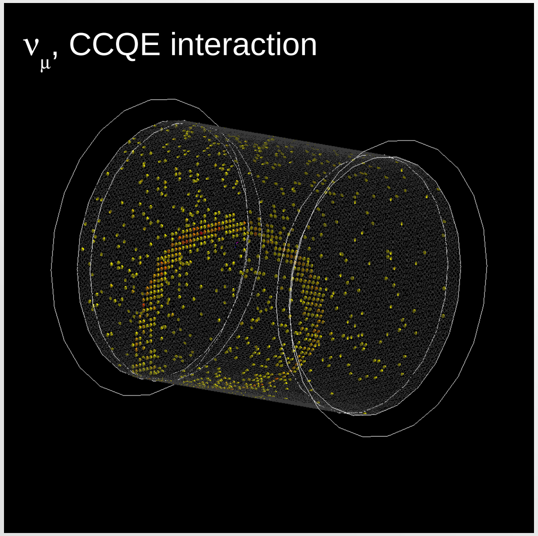
Total Volume	0.99 Megaton
Inner Volume	0.74 Mton
Fiducial Volume	0.56 Mton (0.056 Mton × 10 compartments)
Outer Volume	0.2 Megaton
Photo-sensors	•99,000 20”Φ PMTs for Inner Detector (ID) (20% photo-coverage) •25,000 8”Φ PMTs for Outer Detector (OD)
Tanks	•2 tanks, with egg-shape cross section ≈ 48m (w) × 50m (t) × 250 m (l) •5 optically separated compartments per tank

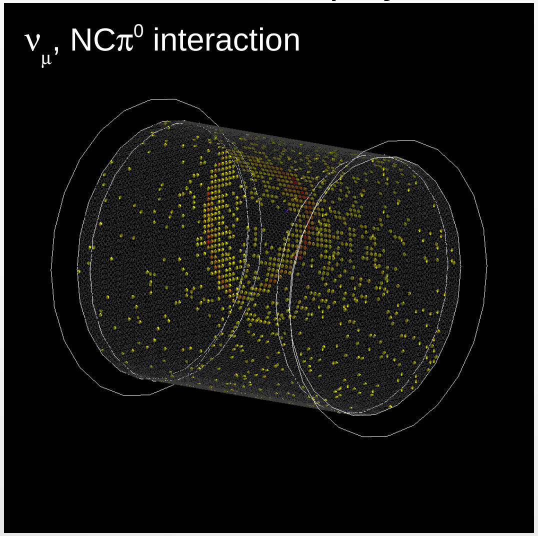
The Hyper-Kamiokande Detector

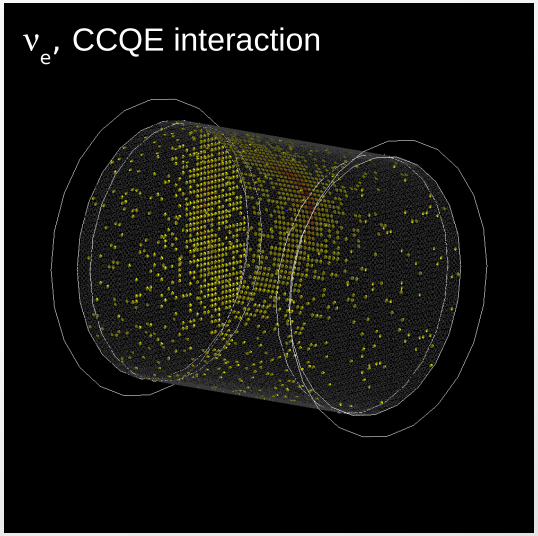




GEANT4 event displays

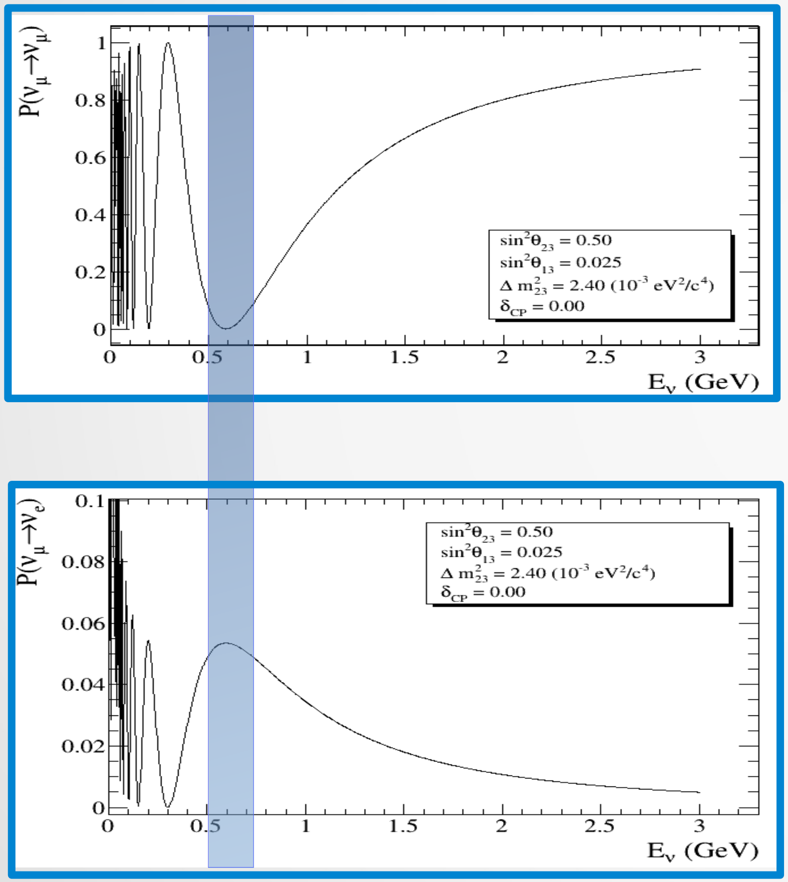






Oscillation Searches at Hyper-K

HK is optimized for both appearance and disappearance searches



T2K ν beam energy peak

ν_μ Disappearance: determine θ_{23} and Δm^2_{32}

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

ν_e Appearance: determine θ_{13}, constrain δ_{CP}

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)$$

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

$$\sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right) \sin^2\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) \sin\delta_{CP} + CPC$$

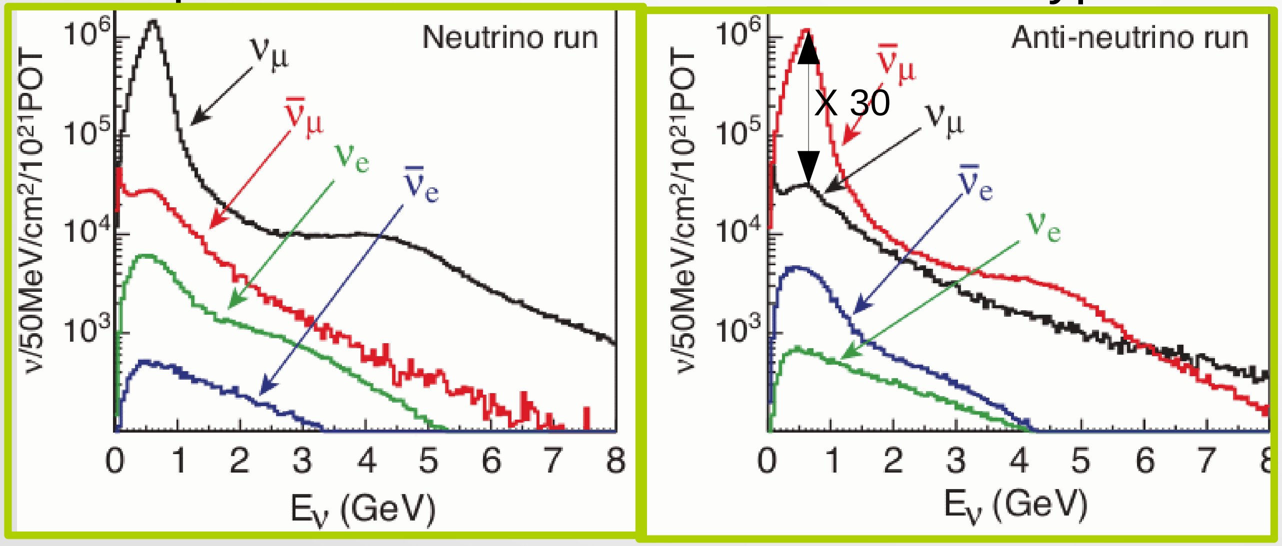
$$+ matter + solar\ terms$$

For maximum power fit both data samples **jointly**

Neutrino Beam for the Experiment

- Same beam configuration as for T2K
  - Same off-axis sub-GeV narrow-band beam.
  - Horn current 320kA
- At least 750kW expected at the starting of the experiment.
- Assumed **7.5MW × 10^7 s** (1.56 × 10^{22} POT) for the following sensitivity studies
  - 10 years are needed if 750kW per 10^7s/year
  - Higher beam power is under study

Expected unoscillated neutrino flux at Hyper-K

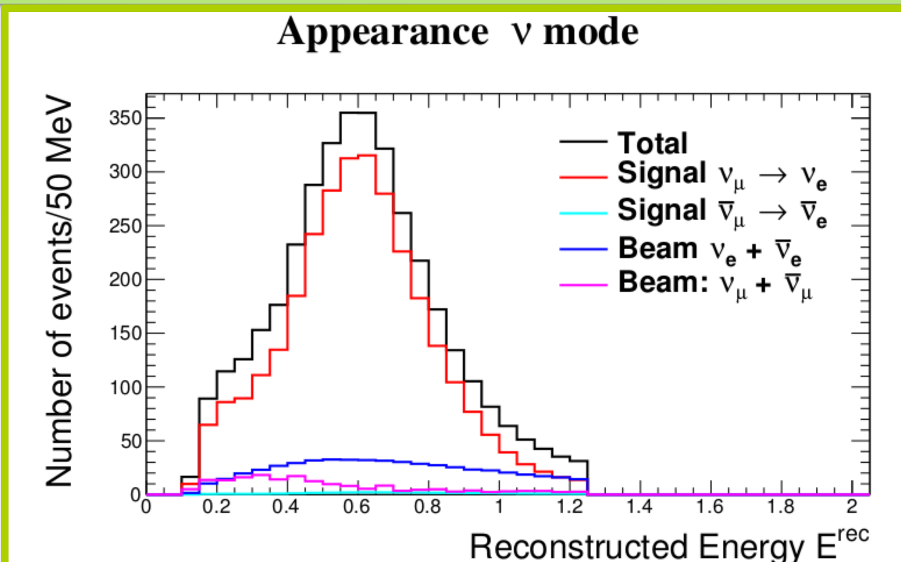


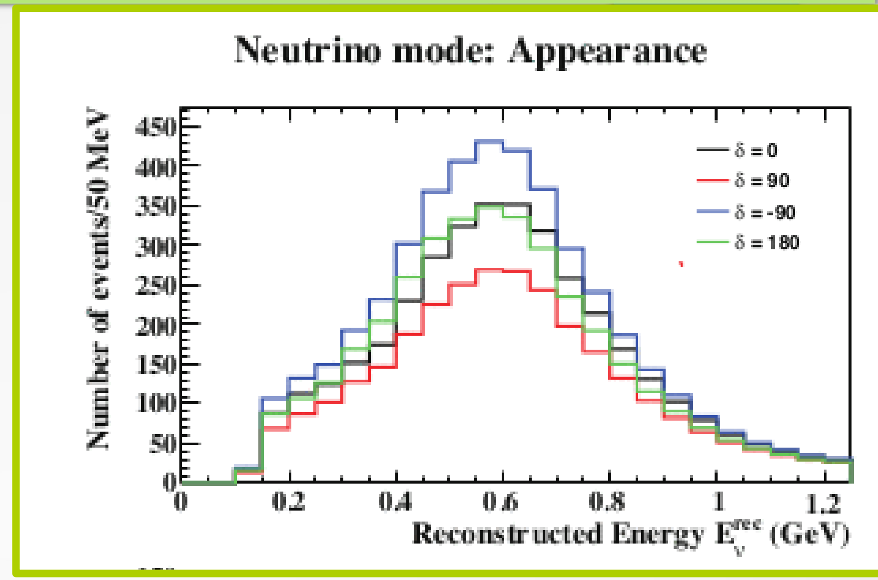
Nominal beam sharing between neutrinos and anti-neutrinos in the following sensitivity plots:

ν-mode: $\bar{\nu}$-mode
1y : 3y

Expected Events

Letter of Intent to J-PARC, April 2014





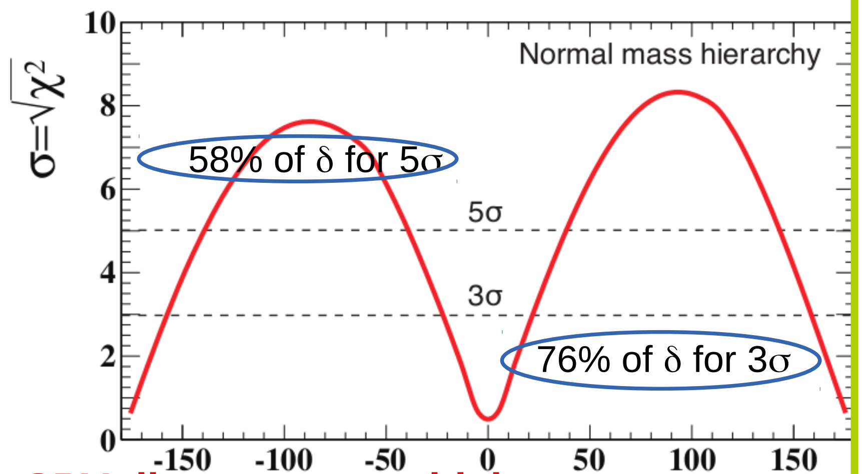
Appearance	Signal		Background					Total
	$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$	NC	
ν mode	3016	28	11	0	503	20	172	3750
$\bar{\nu}$ mode	396	2110	4	5	222	265	265	3397

Disappearance	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$	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

Large expected number of events. NH, $\sin^2 2\theta_{13} = 0{,}1$ and $\delta_{CP} = 0$

Hyper-K Sensitivity to δ_{CP}

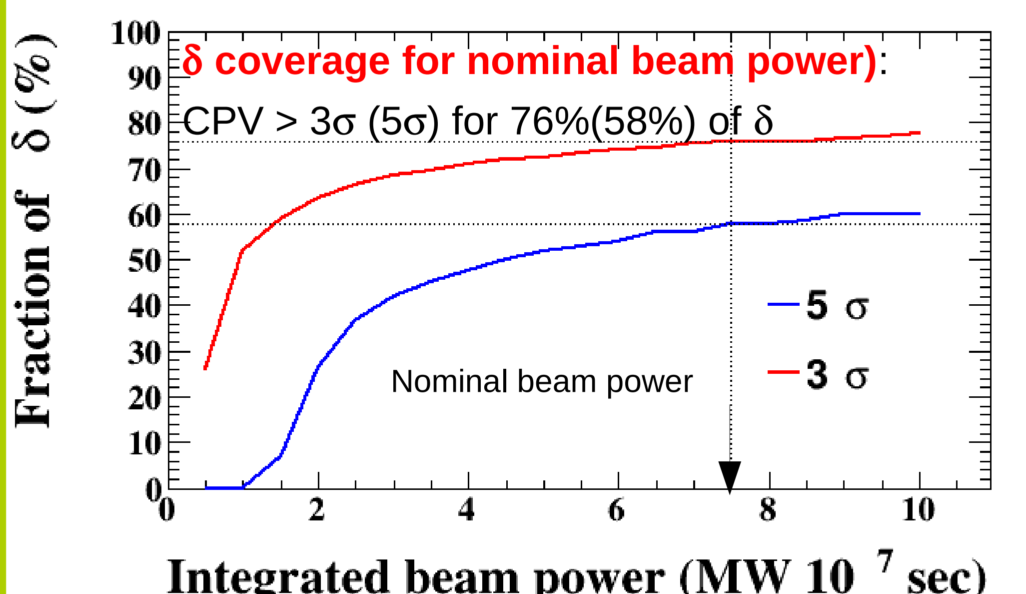
Letter of Intent to J-PARC, April 2014



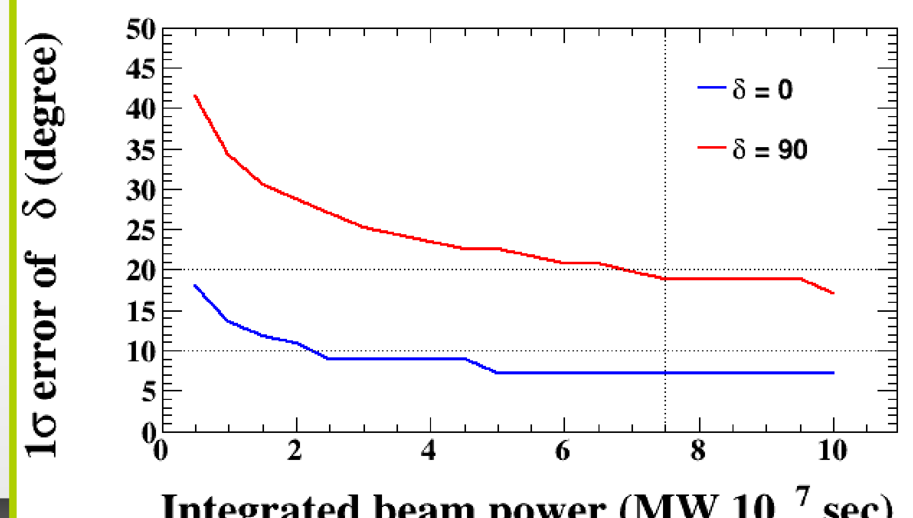
CPV discovery sensitivity
to δ_{CP}=0,π w/ MH known

Errors (%) on the expected number of events				
	ν mode		$\bar{\nu}$ mode	
	ν_e	ν_μ	ν_e	ν_μ
Flux & ND	3.0	2.8	5.6	4.2
ND-independ. xsect	1.2	1.5	2.0	1.4
Far Detector	0.7	1.0	1.7	1.1
Total	3.3	3.3	6.2	4.5

Fractional region of δ(%) for CPV (sin δ ≠0) > 3,5 σ



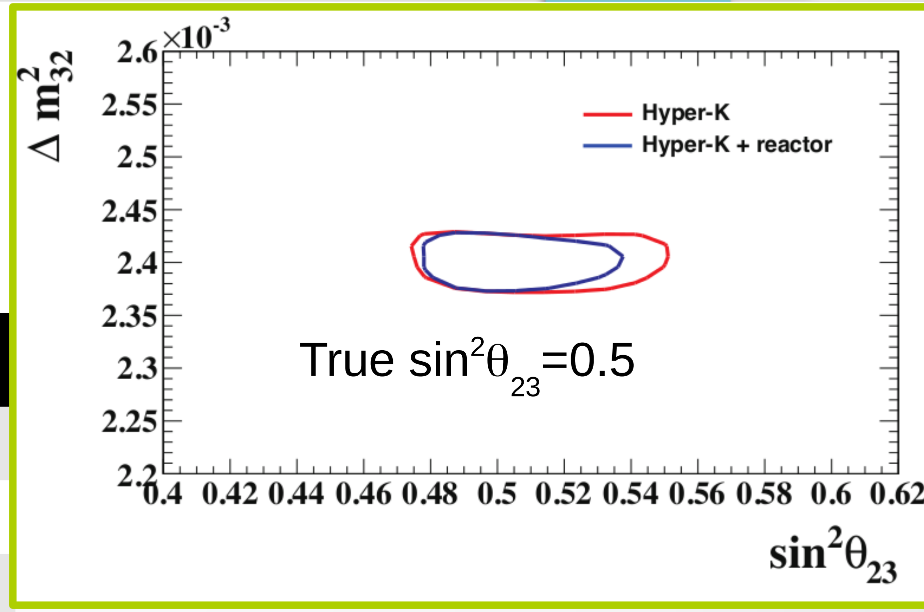
1σ uncertainty of δ as a function of the beam power: < 19°(6°) for δ = 90°(0°)

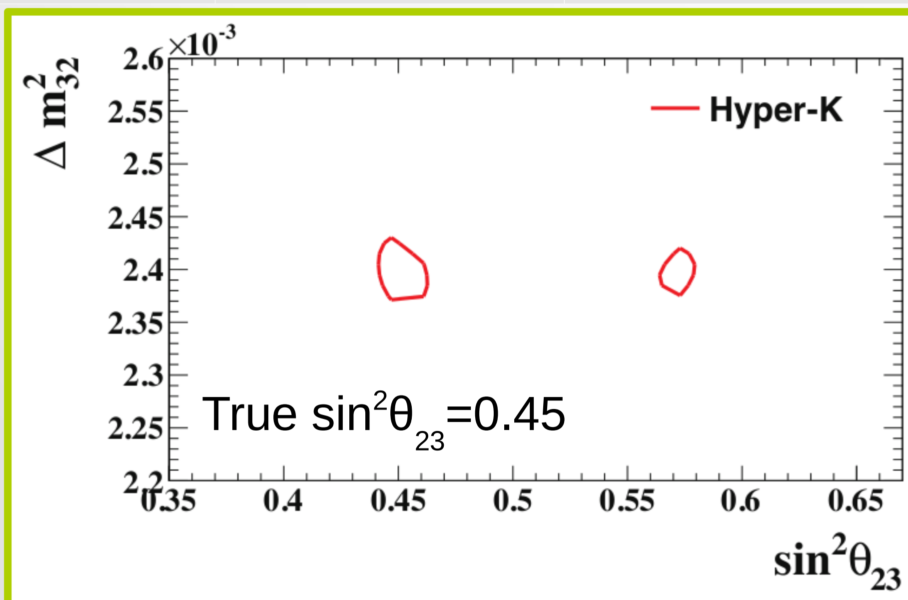


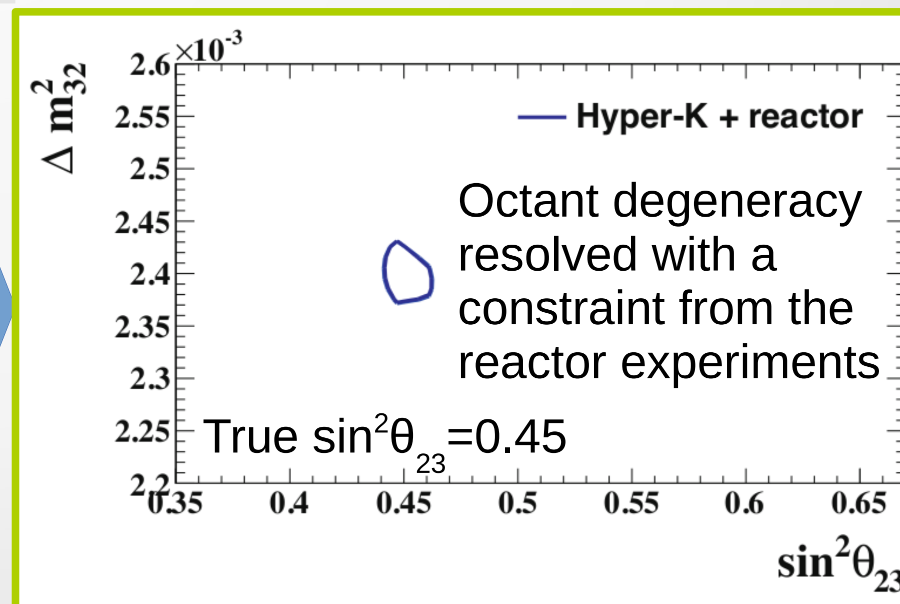
Sensitivity to θ_{23}

- $\sin^2 2\theta_{23}$ and Δm^2_{23} free parameters as well as $\sin^2 2\theta_{13}$ and δ_{CP} in the fit.
- Octant resolution w/ reactor θ_{13}: ~3σ wrong octact rejection for $\sin^2\theta_{23}$<0.46 or >0.56

True $\sin^2\theta_{23}$	1σ err $\sin^2\theta_{23}$	1σ err Δm^2_{23} (eV^2)
0.45	0.006	1.4
0.50	0.015	1.4
0.55	0.009	1.5



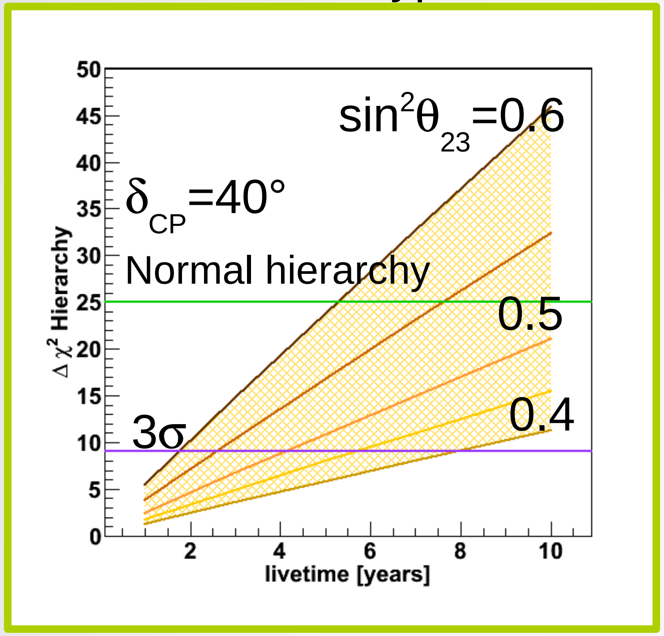


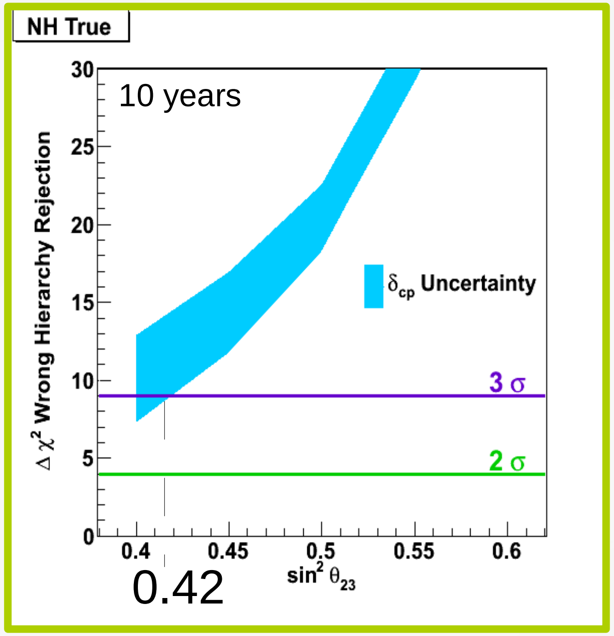


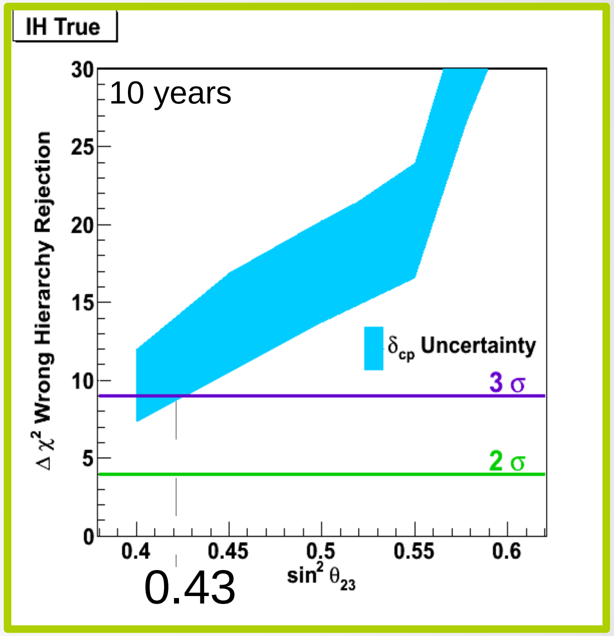
Hyper-K Sensitivity to MH

arXiv:1109.3262

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



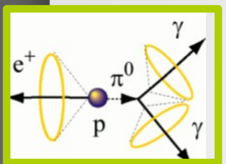


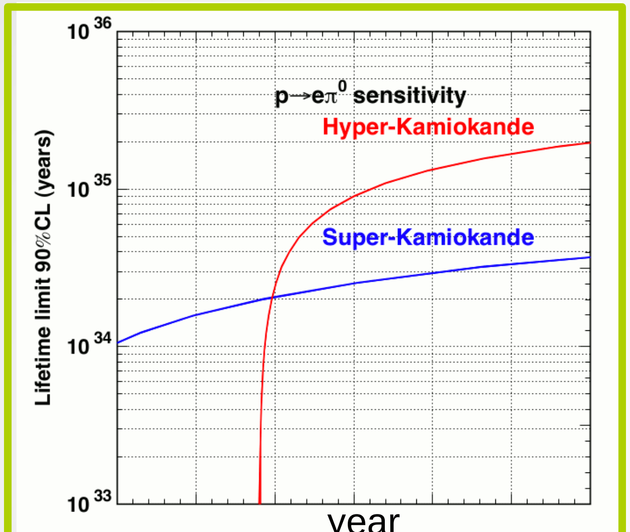


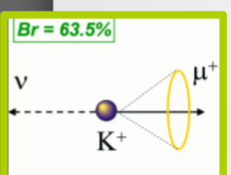
- Use atmospherics for 3σ mass hierarchy determination.
- 3σ mass hierarchy determination for $\sin^2\theta_{23}$ > 0.42 (0.43) for normal (inverted) hierarchy for 10y data taking.
- Also combine with beam data to enhance physics capability.

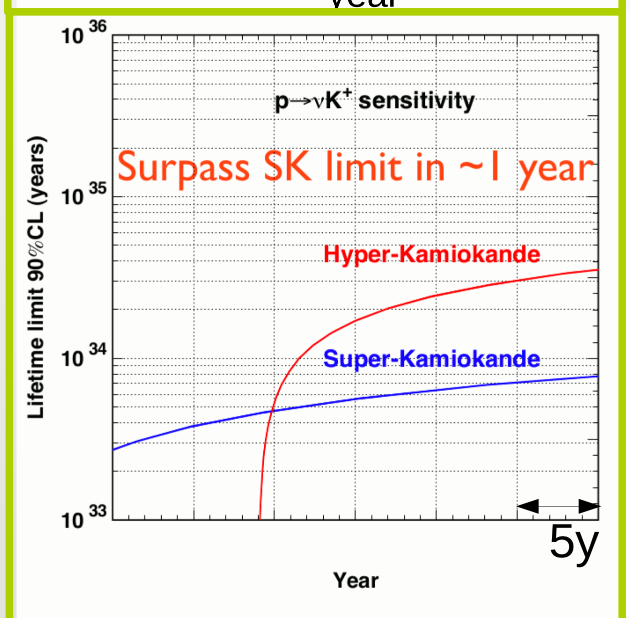
Proton Decay Sensitivity

Surpass SK limit in ~1 year

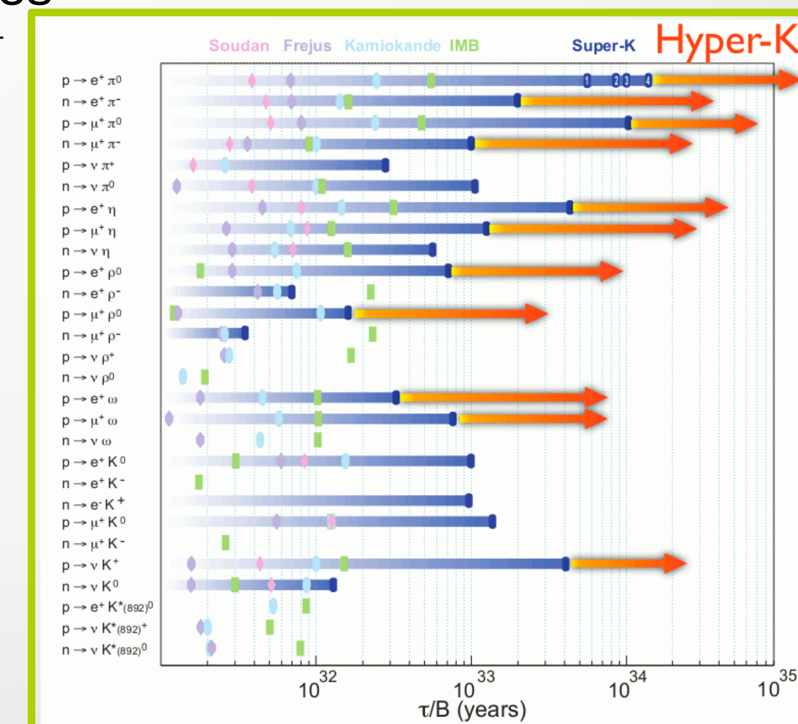








- 10 times better sensitivity than Super-K
- Hyper-K surpasses SK limits in ~1y
- Hyper-K is sensitive in every single mode
  - $p\to e^+\pi^0$: 1.3×10^{35} y at 90% CL
  - $p\to \bar{\nu}K^+$: 2.5×10^{34} y at 90% CL
  - Many other modes:
    - $p(n \to e,\mu) + (\pi,\rho,\omega,\eta)$; 10^{14}-10^{35}
    - K^0 modes
    - $\nu\pi^0$, $\nu\pi^+$
    - ….

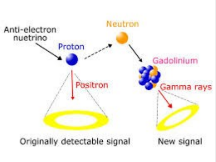


'Other' Physics Topics at Hyper-K

More physics topics can be investigated by Hyper-Kamiokande:

- Solar Neutrinos: 200 ν's / day from Sun → day/night asymmetry of the solar neutrinos flux can be precisely measured at HK.

- Astrophysical neutrinos:
  - 200k ν's from Supernova at Galactic center (10kpc) → time variation & energy can be measured with high statistics. Important data to cross check explosion models
  - Supernova relic neutrinos → possible G_d-doping of Hyper-K



- Indirect Searches for Dark Matter: 1) search for excess of neutrinos from the center of the Earth, Sun and galactic centre as compared to atmospheric neutrino background 2) Search for diffuse signal from Milky Way halo.

- Search for transient astrophysical phenomena: solar flares, GRBs, etc.

- Neutrino geophysics: neutrino radiography w/ atmospheric neutrinos for surveying the internal structure of the Earth.

Site(s) and Cavern(s)

Two sites are being investigated:

- Tochibora mine:
  - ~8km South from Super-K
  - Identical baseline (295km) and off-axis angle (2.5º) to Super-Kamiokande
- Mozumi mine (same as Super-K)
  - Deeper than Tochibora
  - Currently finishing design studies

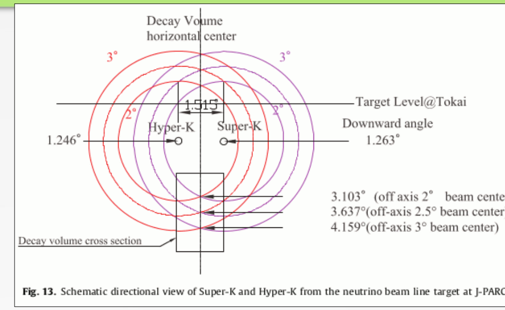
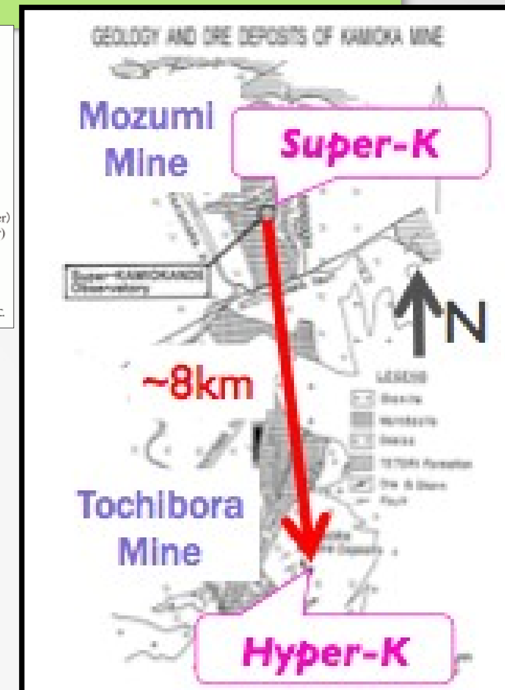
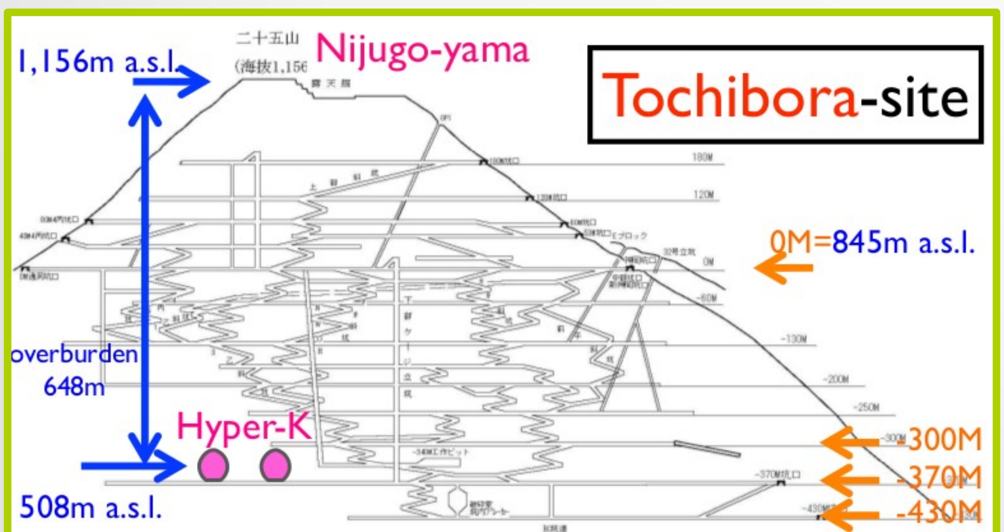
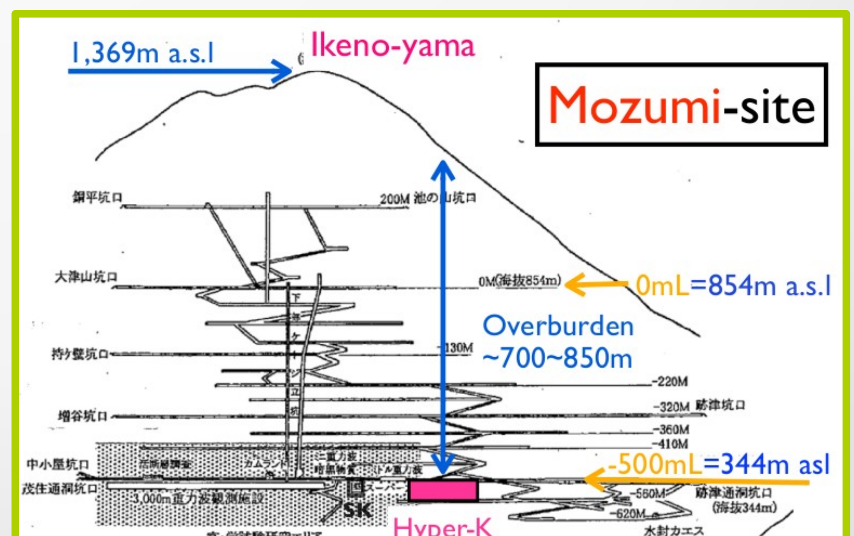


Fig. 13. Schematic directional view of Super-K and Hyper-K from the neutrino beam line target at J-PARC.



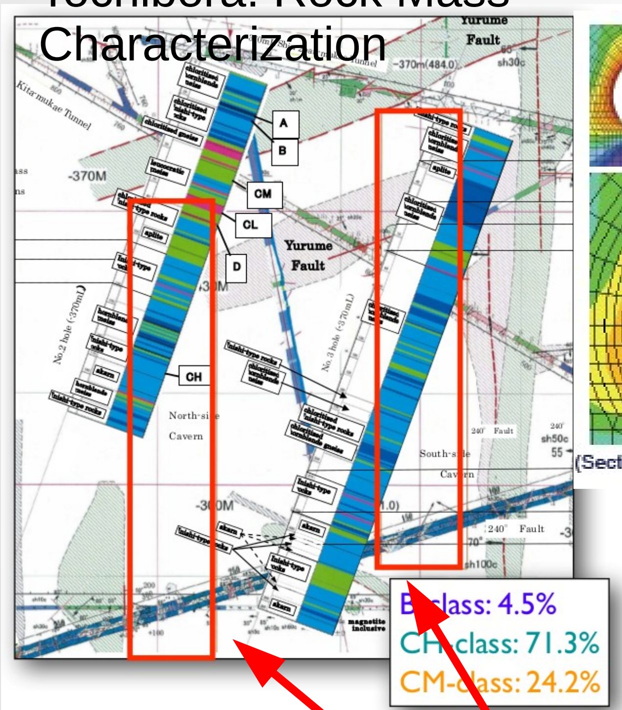




Site(s) and Cavern(s), cont'd

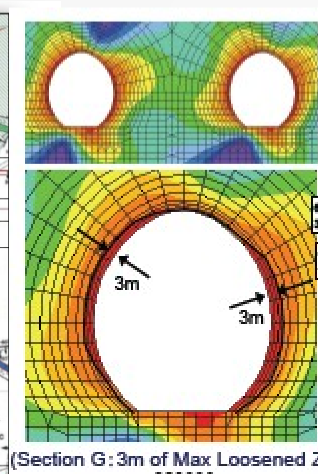
- Rock quality in the two sites is similar.
- Design of the cavity, support structure studies based on geological survey
- Confirmed that the HK cavern can be constructed w/ existing techniques
- Construction schedule for the Tochibora mine: ~2y tunnels, ~3y cavern

Tochibora: Rock Mass Characterization

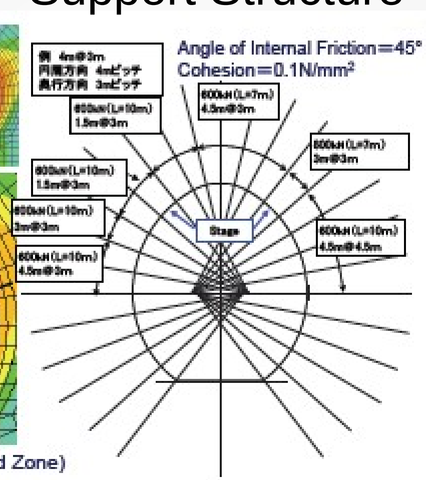


HK tank location

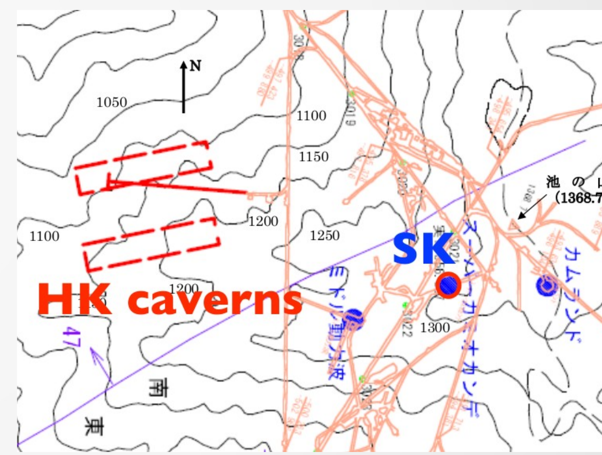
Cavern



Support Structure



Mozumi



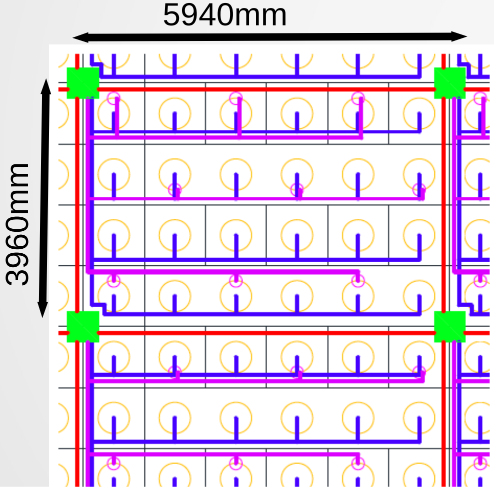
Mozumi:
- geological survey performed in 2013
- cavern stability analyses just completed
- Access and approach-tunnels being designed
- ..

Baseline design expected to finish soon

Tank Design Work

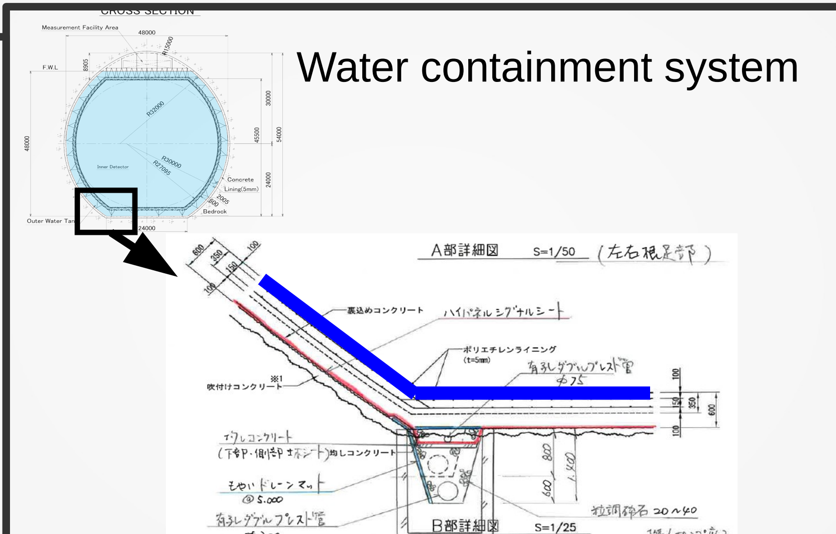
- All major parts of HK tank have been designed: water containment system, photosensors support, layout of water pipes, front-end electronics, cables, calibration holes, plug manholes, etc.

Electronics & cable layout



—: Support structure
—: Cable for inner PMT
—: Cable for outer PMT
—: Network/Power cable
■: Hub / Front End Electronics
○: Inner photo-sensor (20")
○: Outer photo-sensor (8")

Water containment system



Water piping layout

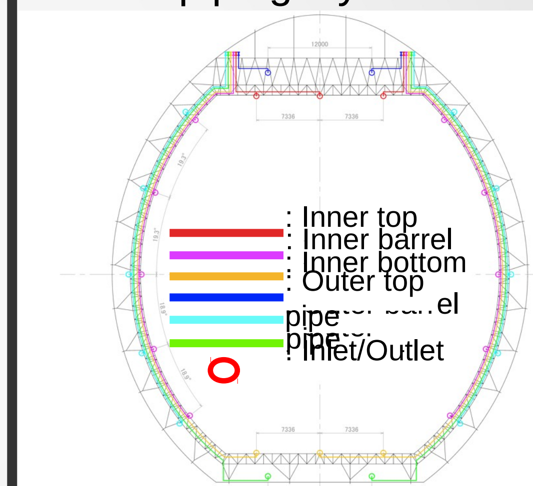
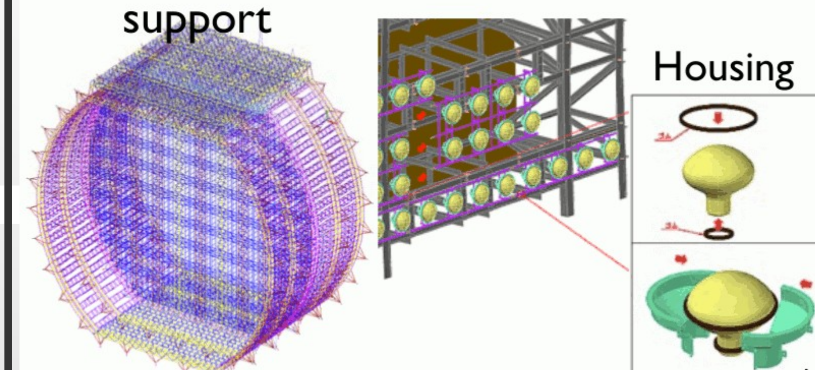


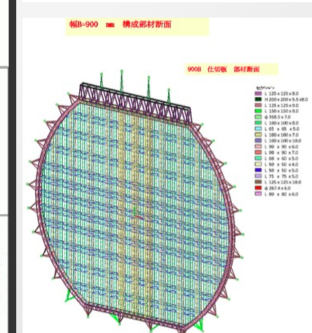
Photo-sensor support

Mounting Photo-sensor

Housing



Separation wall



Photodector Development

PMT
- Used in Super-K for 18 years
- High reliability

Venetian blind PMT
(50-cm ϕ Normal QE)

High QE photocathode

Under viability test
- Test in 200 ton tank

Venetian blind PMT
(50-cm ϕ High QE)

PMT improvement

Under development
- Under evaluation in the air

Box and Line PMT
(50-cm ϕ High QE)

New photosensor (HPD)

HPD (New)
(20-cm ϕ Normal QE)

High QE photocathode

Make larger

HPD
50-cm ϕ High QE)

Photodector Development

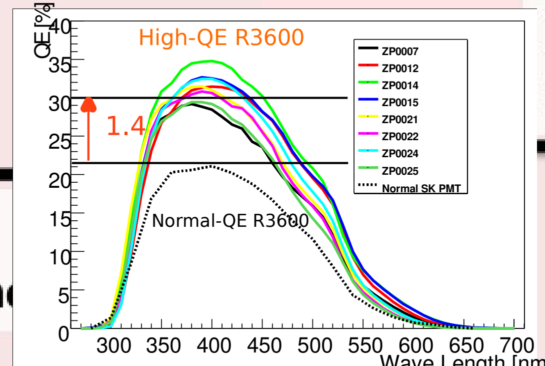
PMT
- Used in Super-K for 18 years
- High reliability

High QE photocath

Venetian blind PMT
(50-cm ϕ Normal QE)

Under viability test
- Test in 200 ton tank

High-QE SK PMT



Venetian blind PMT
(50-cm ϕ High QE)

PMT improvement

Under development
- Under evaluation in the air

Box and Line PMT
(50-cm ϕ High QE)

New photosensor (HPD)

HPD (New)
(20-cm ϕ Normal QE)

High QE photocathode

Make larger

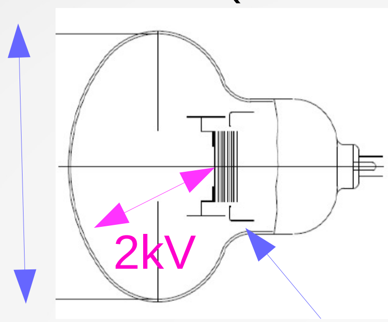
HPD
50-cm ϕ High QE)

700

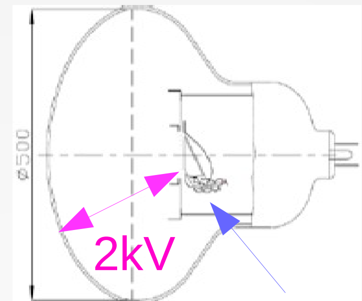
Photosensors Candidates

R&D going to get better perfomance and lower costs

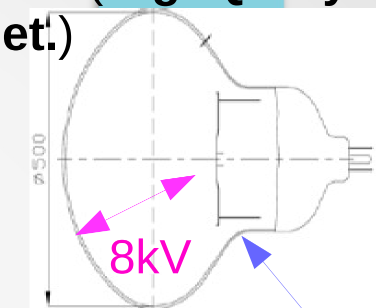
Established (**SK PMT**)



R&D (**HighQE/CE PMT**)



R&D (**HighQE hybrid det.**)



	SK PMT	HighQE/CE PMT	HighQE hybrid det.
Quantum Eff. (QE)	22%	30%	30%
Collection Eff. (CE)	80%	93%	95%
Timing resol (FWHM)	5.5 nsec	2.7nsec	1nsec

Established (SK PMT):

- Super-K ID PMTs
- Used for ~20 years
  → Guaranteed
- Complex production
  → Expensive

R&D (HighQE/CE PMT):

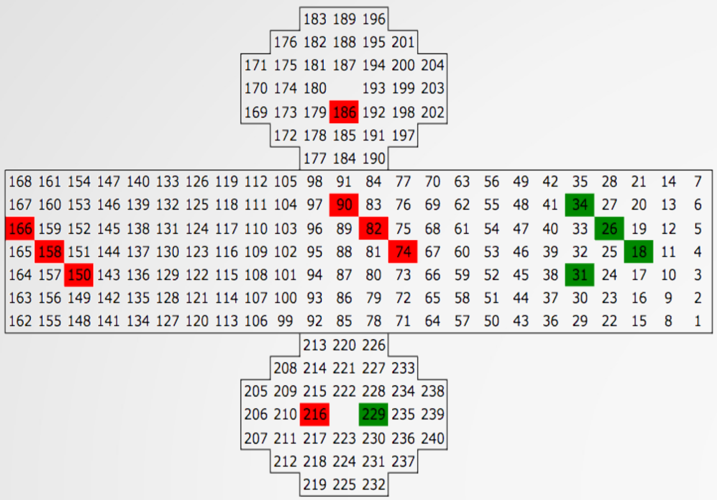
- Under development
- Better performance
- Same technology
  → Lower risk

R&D (HighQE hybrid det.):

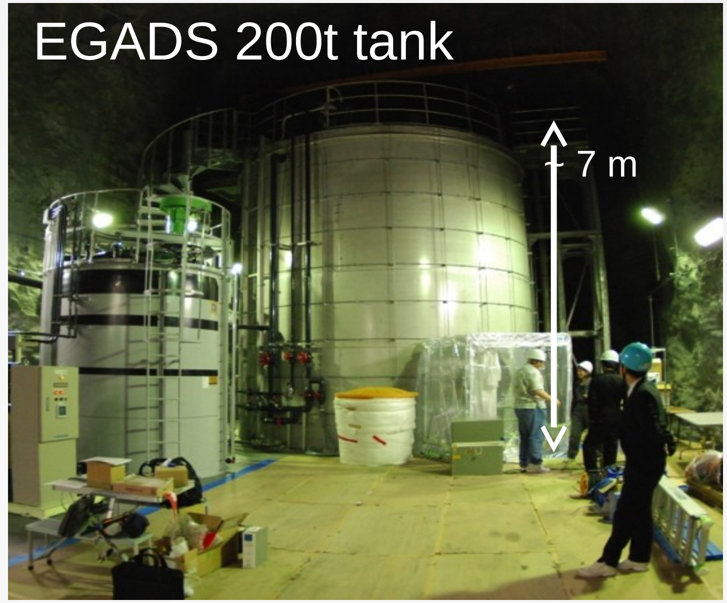
- Under development
- Far better performance
- Simple structure
  → Lower cost
- New technology
  → Higher risk

Lower Risk ⟵ ⟶ Higher Performance

Photosensors Tests in Water Tank

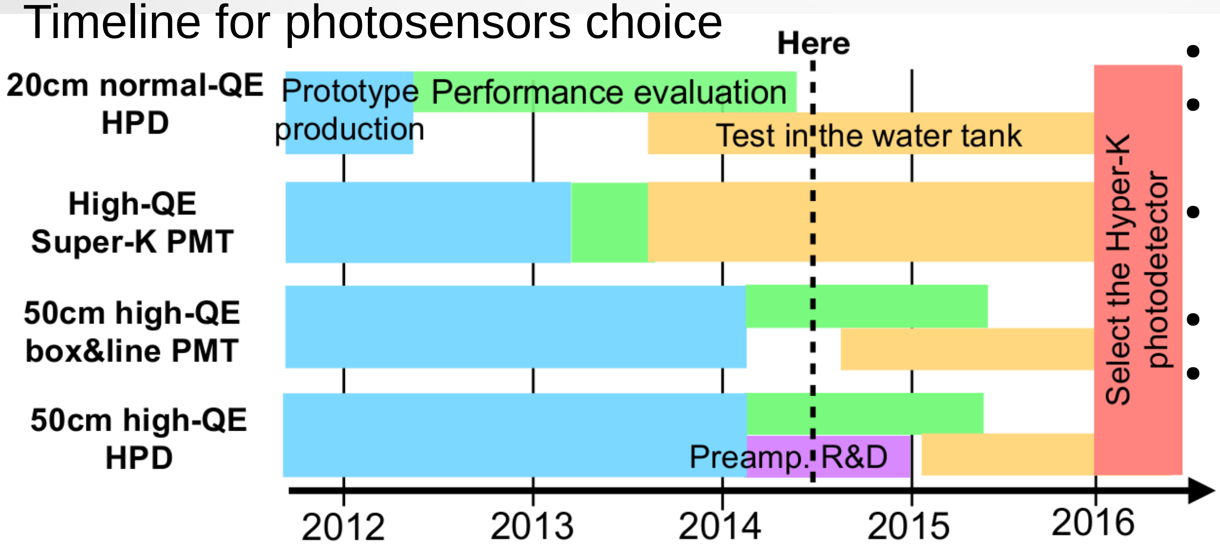


8″ HPDs
20″ high-QE PMTs



- EGADS (for G_d-doped water tests)
- 240 inward-facing PMTs
- EGADS used to test high-QE PMTs
- 227 PMTs (R3600; currently in SK) for reference for photo-detector evaluation
- 8" HPDs, 20" high-QE PMTs

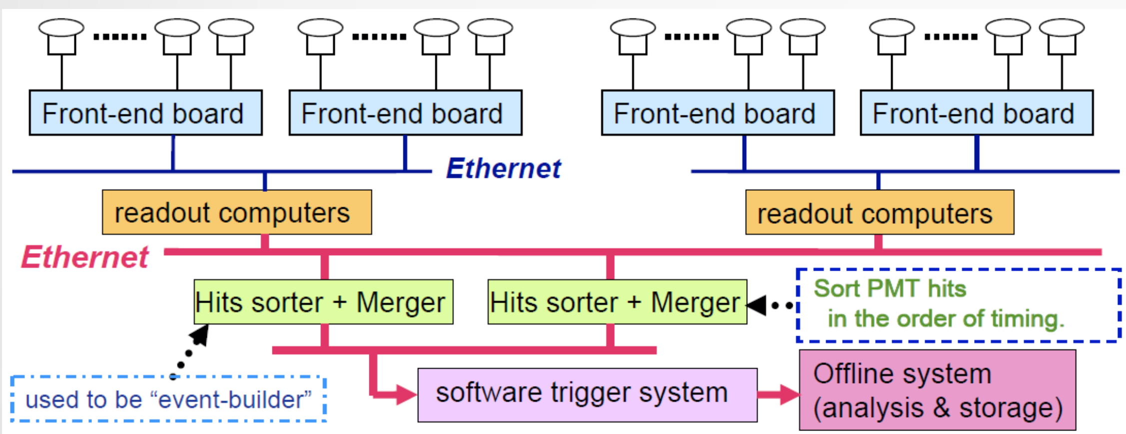
Timeline for photosensors choice



- **Data taking: Sept 2013, May 2014**
- Viability tests performed – ongoing process up to 2016.
- Adding (Aug 2014) Box-and-Line PMTs and 2 HPD.
- **More tests planned.**
- **Photosensor choice will be made in 2016**, needed to allow time for making mass production

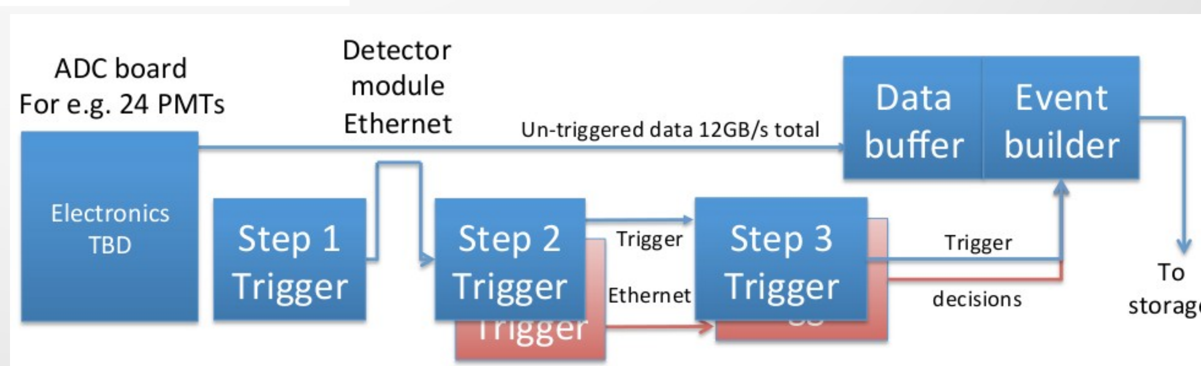
Electronics/DAQ

- Investigating a few approches for the electronics, eg:
  - QTC (ADC) + TDC (similar to SK4)
  - FADC
- Will evaluate their performance with the WC prototype detector
- Also working on the design of the DAQ



- Digitize all the signal (timing and charge) above ~ 1/4 p.e.
- Define events with software and store the event data.
- Nominal starting point: SK DAQ

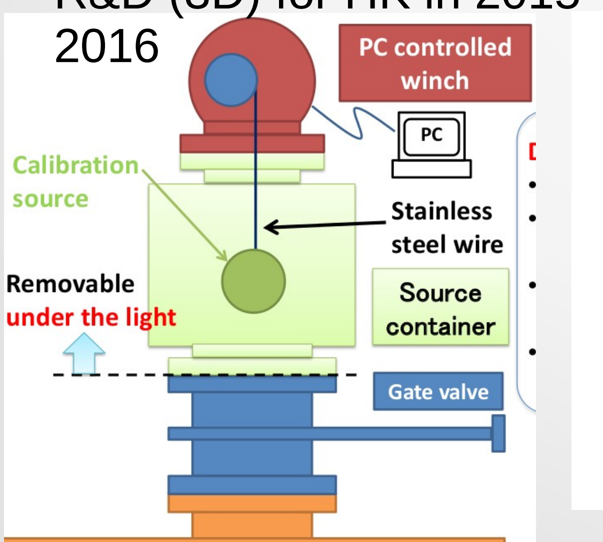
Investigating improved system for triggering (redundant, robust)



Calibration

- Review systems used by several experiments (SK, SNO, SNO+, Borexino, KamLAND, Daya Bay) to help in the design of the calibration system for Hyper-K
- Several ongoing R&D activities, some examples:

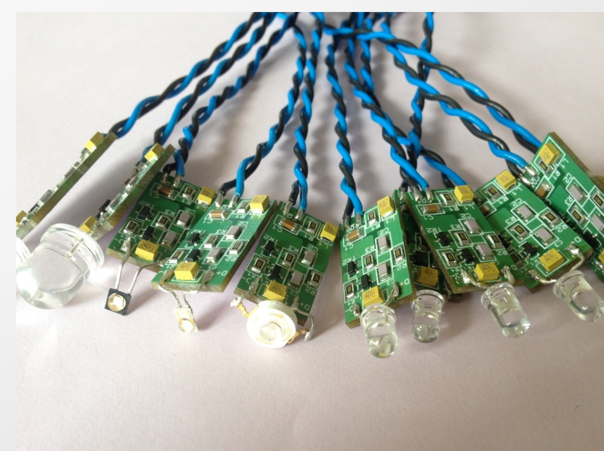
- Simple semi-automated calibration system (to be deployed in SK)
- Computed controlled.
- Compact and light-shielded.
- R&D (3D) for HK in 2015-2016



- Study response & reflection of large photosensors in water (Photosensor Testing Facility at TRIUMF)
- Optical system with laser, monitor and receiver PMTs in place and tested.


8” HPD in PTF

- Use LED as a light source for optical calibration.
- Can build an automated system that can illuminate each PMT with known sources
- Tests of LEDs underway



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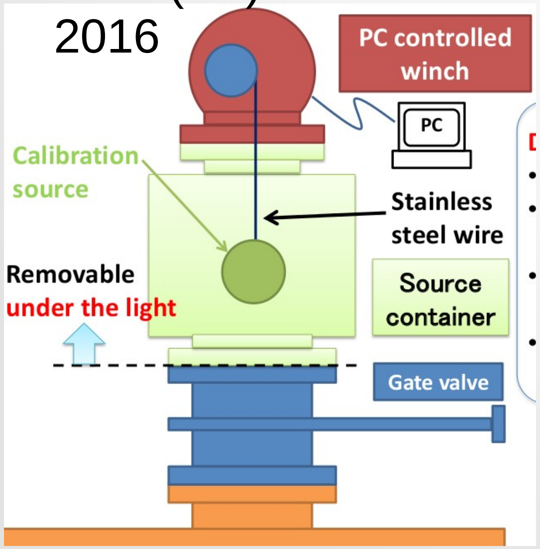

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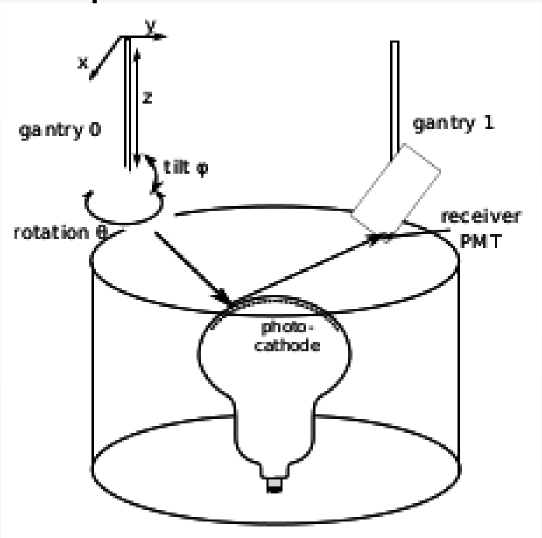

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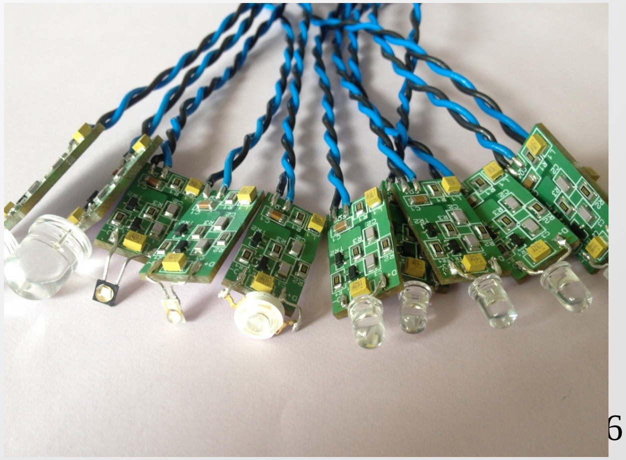
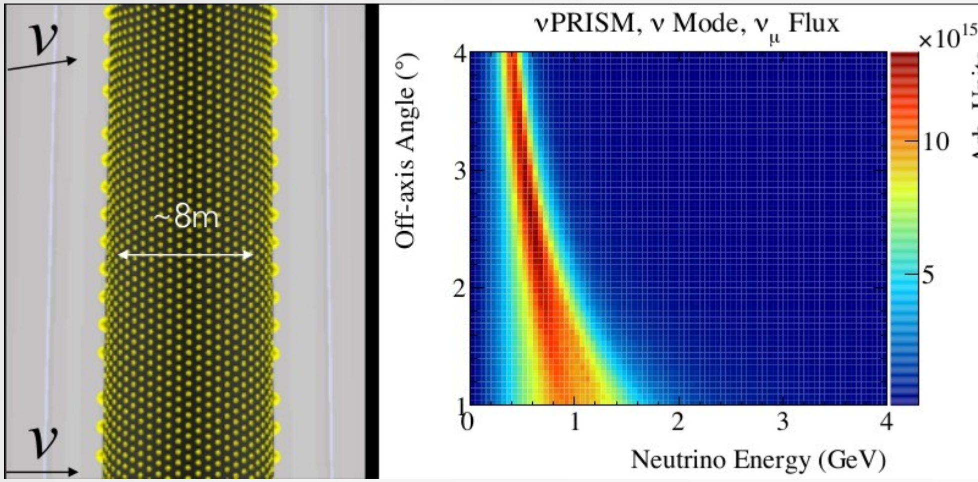


New Near Detector Concepts to further enhance the Hyper-K physics potential



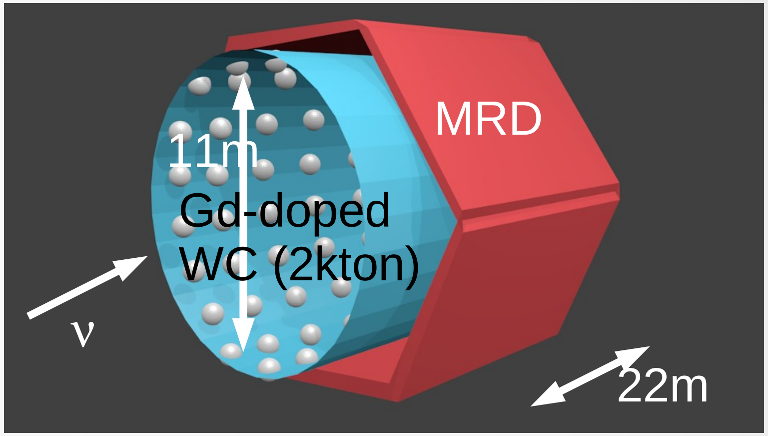
See M. Scott talk (WG2 parallel session - Monday)

"ν-PRISM" (~1km)

- tall (~50 m) WC detector spanning wide range of off-axis angles
- effectively isolate response in narrow band of energy by comparing interactions at different off-axis angles

"TITUS" (~2 km)

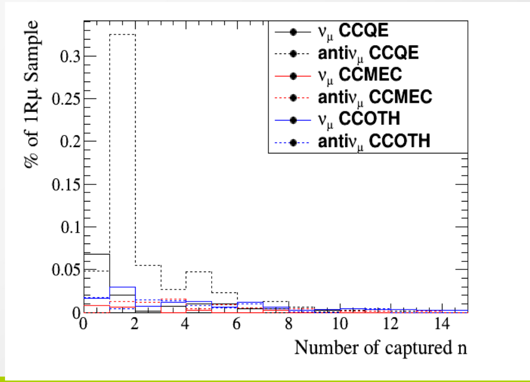
- 2 kt Gadolinium-doped WC detector with HPDs and LAPPDs



Muon range detector (MRD)

G_d for $\bar{\nu}/\nu$ discrimination

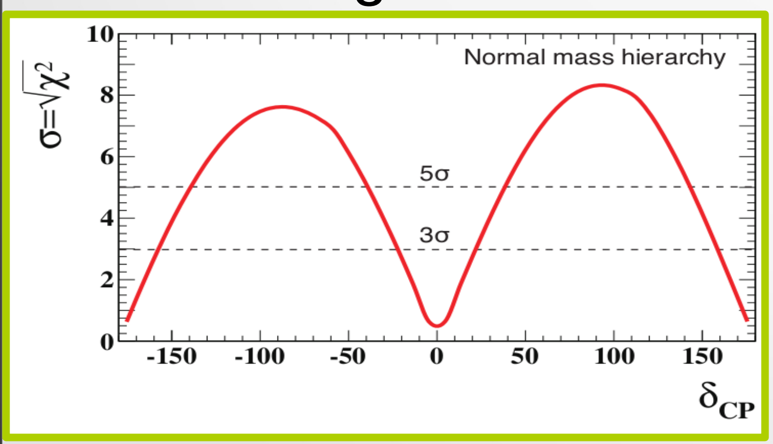
See M. Rayner poster (Tuesday)

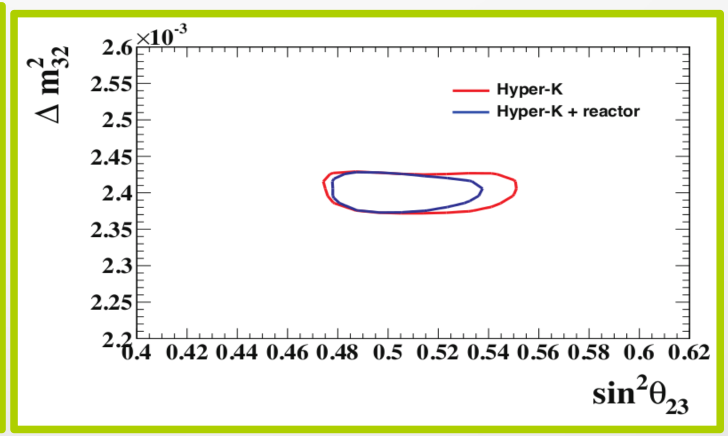


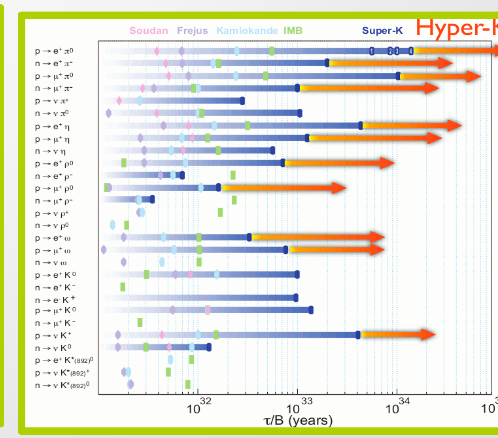
Several new upgrades planned at a 280m distance, either new detectors or upgrading ND280

Conclusions

- Next generation multi-purpose experiment
  - Oscillation physics:
    - able to measure δ_{CP} at 3σ for 76% of its phase space
    - solve octant degeneracy, mass hierarchy (atmospherics), θ_{32}, Δm^2_{32}
  - Astro and other physics:
    - very sensitive to all the proton decay channels, observe supernovas burst and relic supernova neutrinos, indirect dark matter, transient astrophysical phenomena, etc.
- Work ongoing worldwide in all the aspects of the experiment
- Data taking around 2025 with current schedule





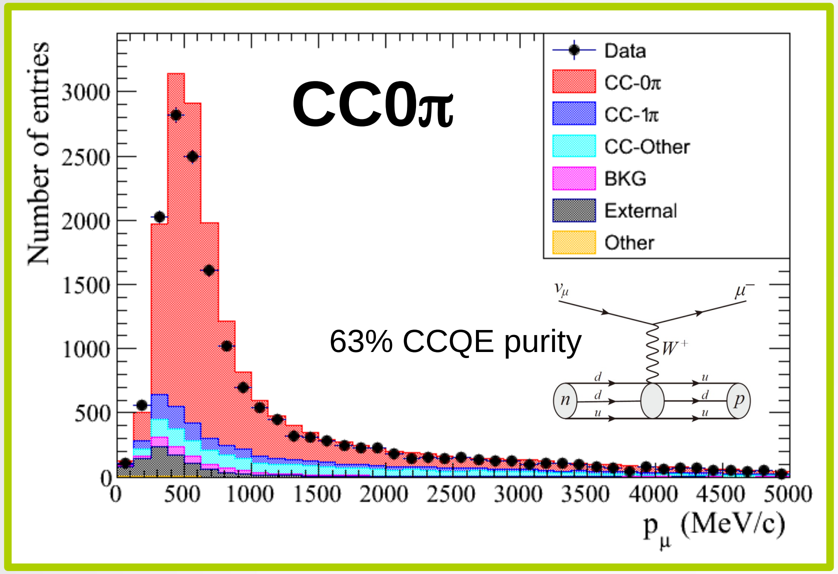


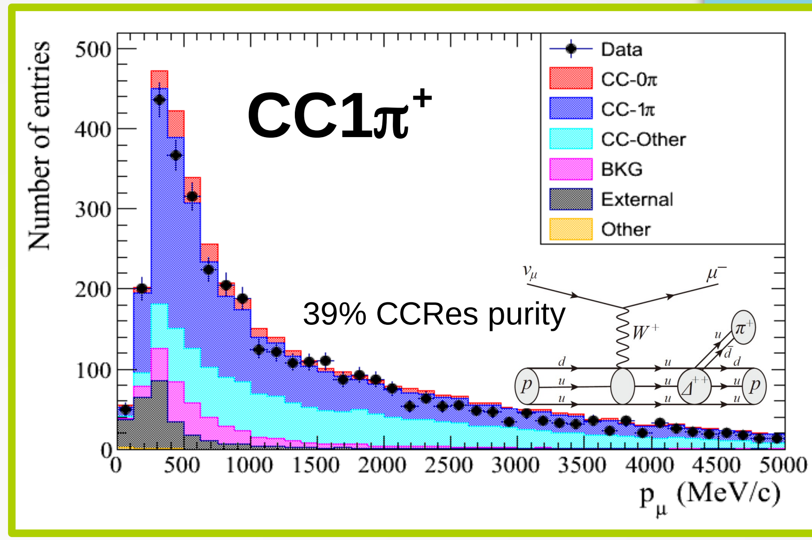
Stay tuned for many more exciting news from
Hyper-Kamiokande!

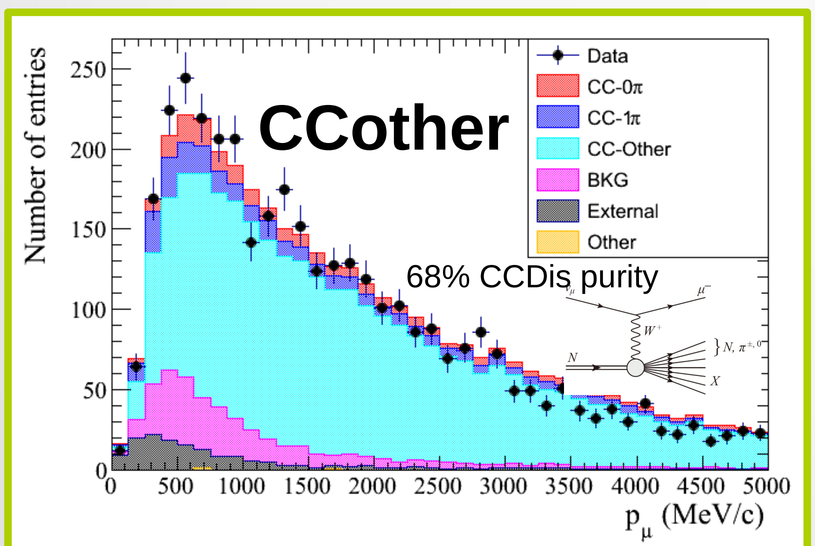
Additional Slides

Phys. Rev. Lett. 112, 061802 (2014)

Muon Momentum in ND280





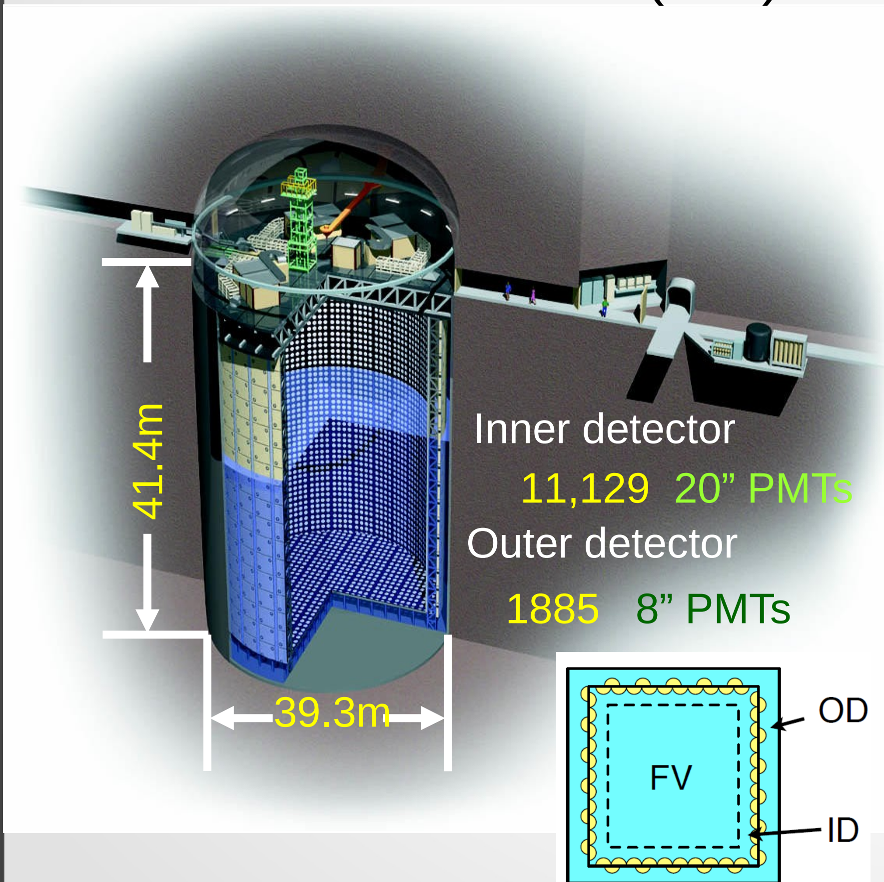


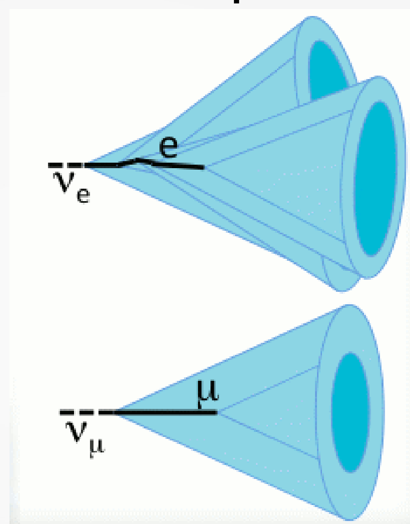
Purity of each sample

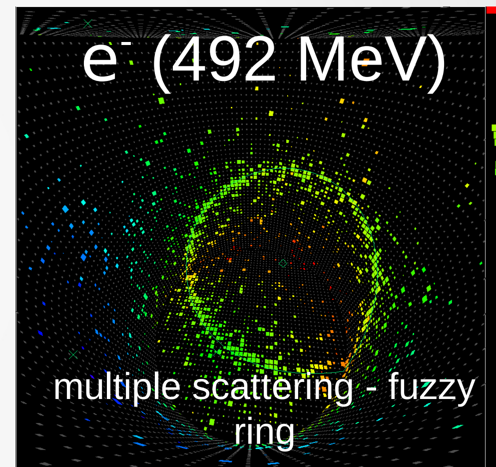
	CC0π	CC1π	CCother
CC0π	72.6%	6.4%	5.8%
CC1π	8.6%	49.4%	7.8%
CCother	11.4%	31%	73.8%
Bkg(NC+anti-nu)	2.3%	6.8%	8.7%
Out of FGD1 Fid Vol	5.1%	6.5%	3.9%

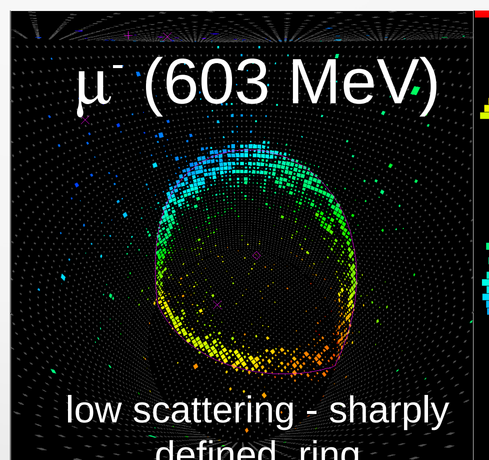
T2K Far Detector: Super-Kamiokande

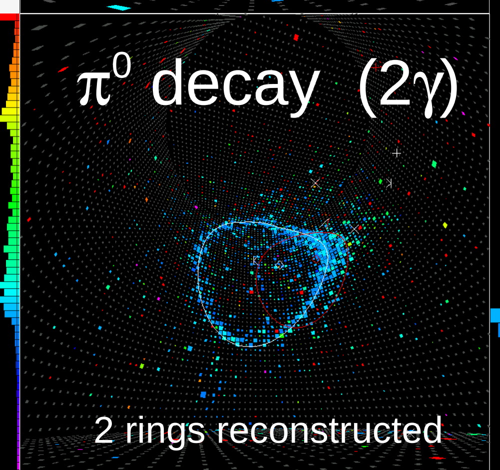
- 50 kton (22.5 kton fiducial) water Cherenkov detector
- Good reconstruction for T2K energy range
- Particle Identification (PID) based on shape of Cherenkov rings





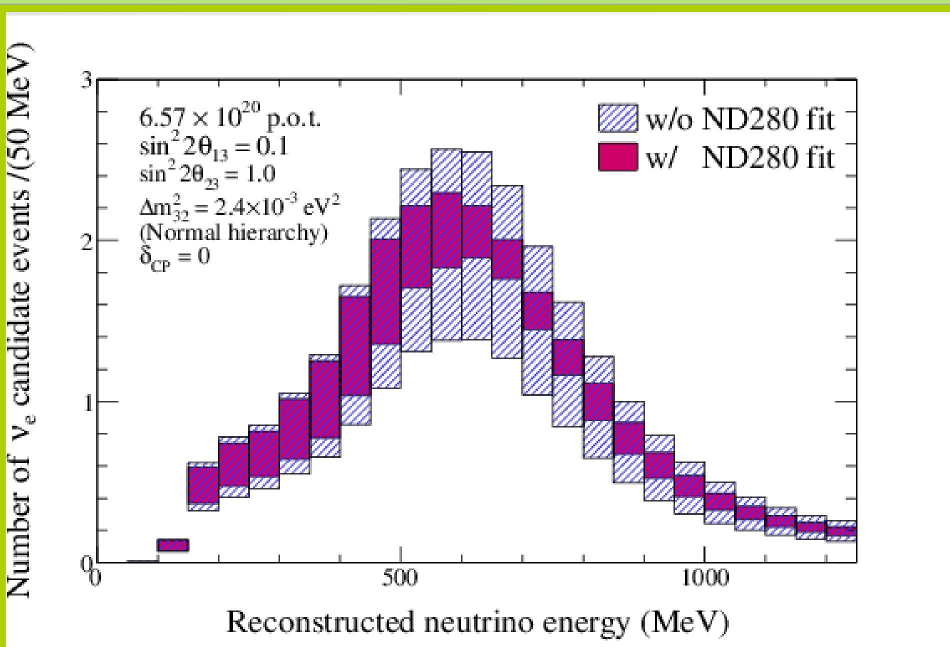


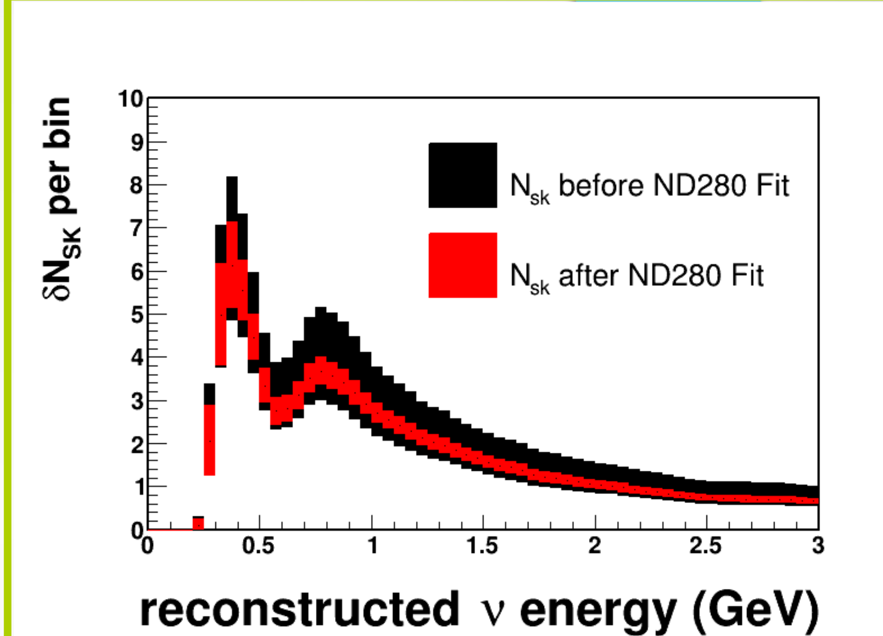




Event displays show Monte Carlo

Results Systematic Errors w/ ND280 Fit





Relative uncertainty (%) on the expected number of events

($\sin^2 2\theta_{13} = 0.1$, $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{32} = 2.4\times10^{-3}eV^2$, $\delta CP = 0$, NH)

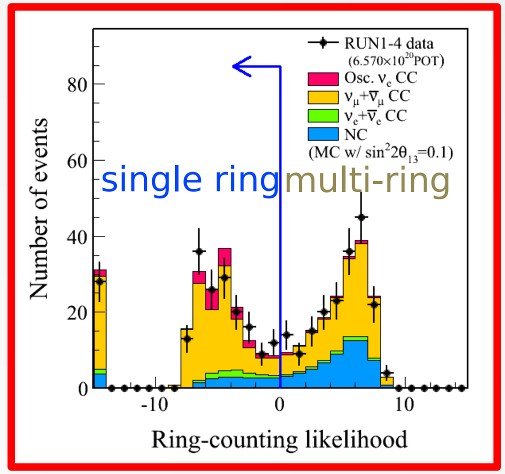
ν_e	Systematic sources	ν_μ
3.1	Flux & Combined Cross-Sections	2.7
4.7	Independent Cross Sections	5.0
2.4	π Hadronic Interactions (FSI)	3.0
2.7	SK Detector Efficiencies	4.0
6.8	**TOTAL**	**7.6**

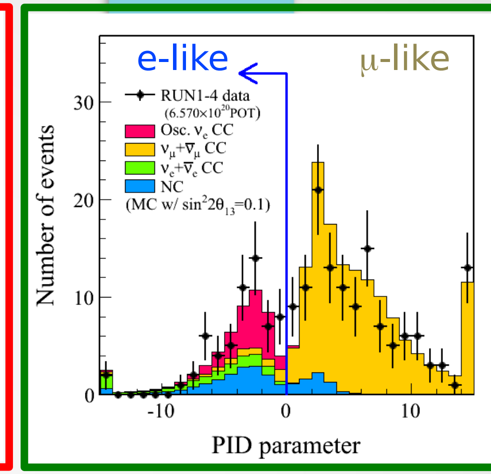
Phys. Rev. Lett. 112, 061802 (2014)

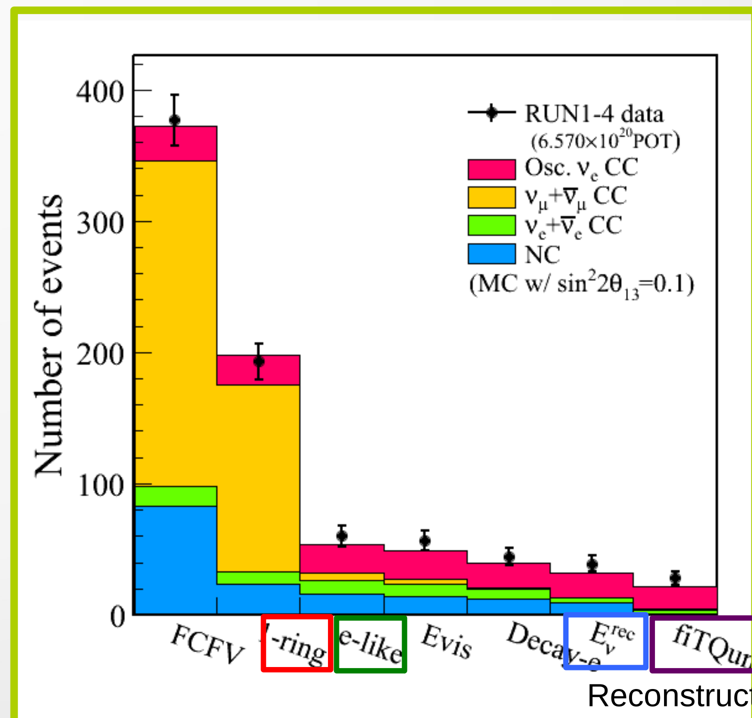
$\nu_\mu \rightarrow \nu_e$ Event Selection

Event selection:

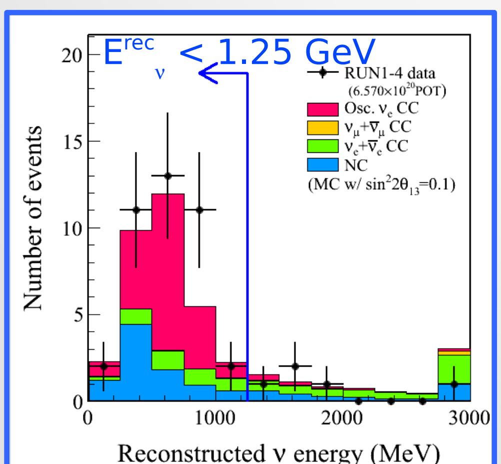
- Fully contained in fid. volume
- Only one reconstructed ring
- Ring is electron-like
- Visible energy > 100MeV
- No Michel Electrons
- Reconstructed energy < 1.25 GeV
- New SK reconstruction (~30% reduction in π^0 background)
- 28 events in 6.57×10^{20} POT

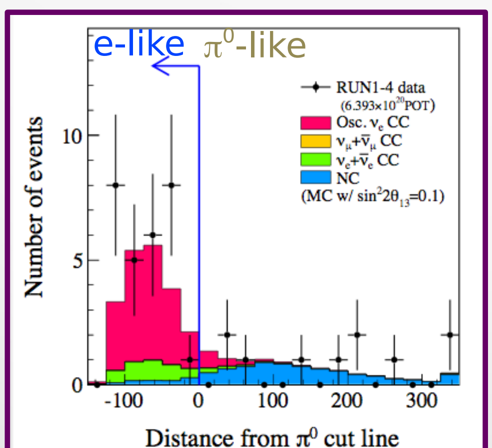




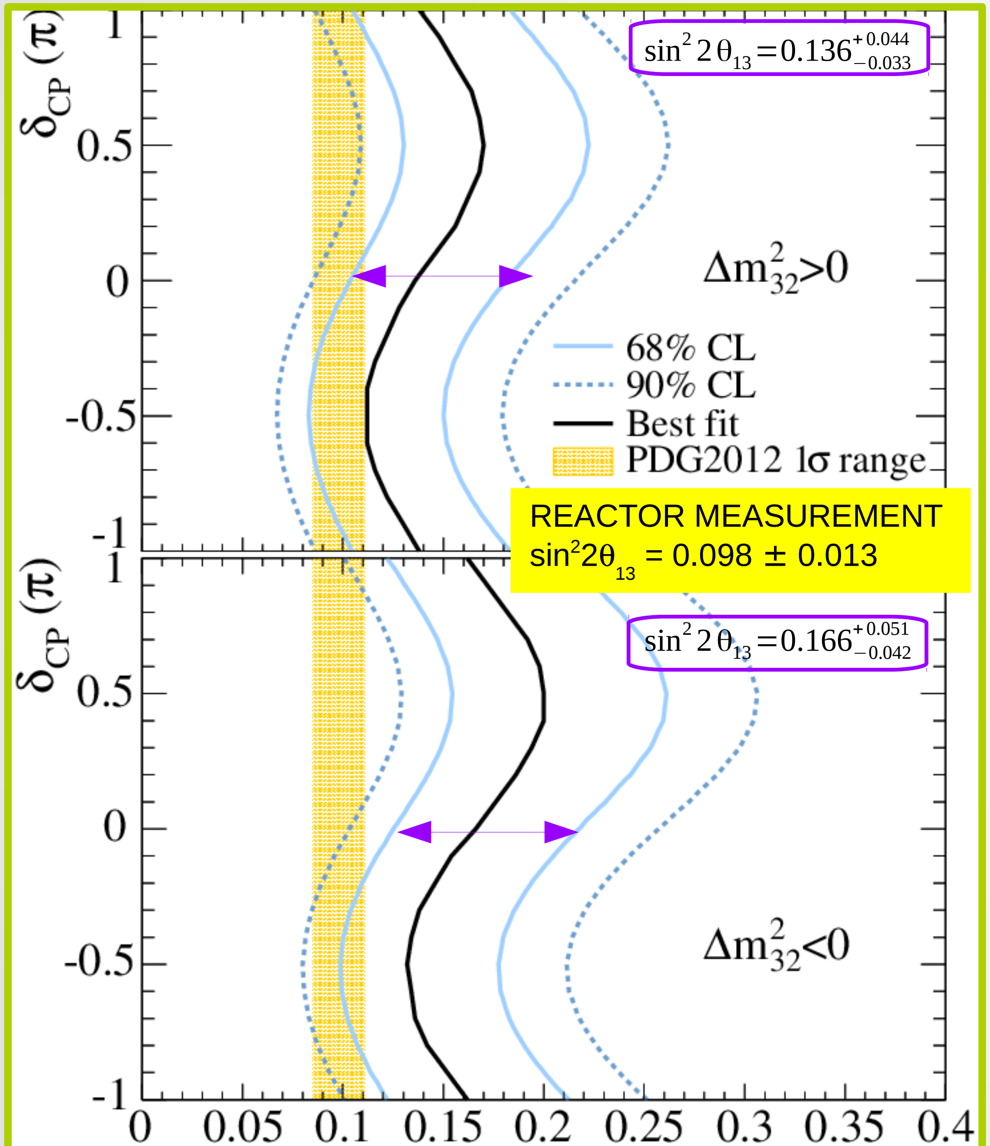


Reconstruction algorithm



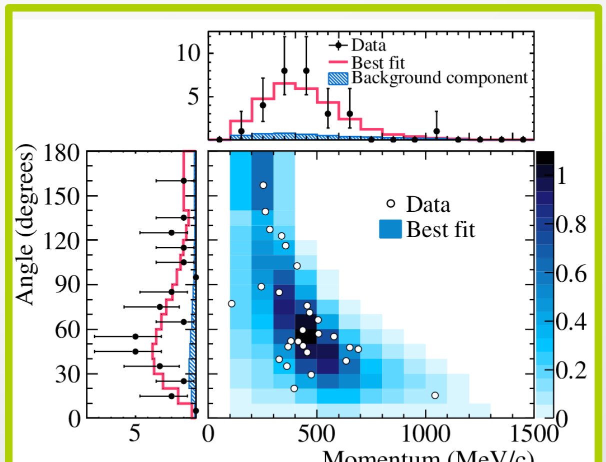


T2K Observation of ν_e Appearance



Marginalized over θ_{23} and Δm^2_{32}

- ν_e appearance in a ν_μ beam with 7.3σ significance
- Best fit value for $\sin^2 2\theta_{13}$ larger than the reactor value
- Due to δ_{CP}-$\sin^2\theta_{13}$ correlation, when applying the reactor constraint, region with $\sin^2 2\theta_{13}$ small as possible is favoured.



Maximum likelihood fit in (p_e,θ_e)

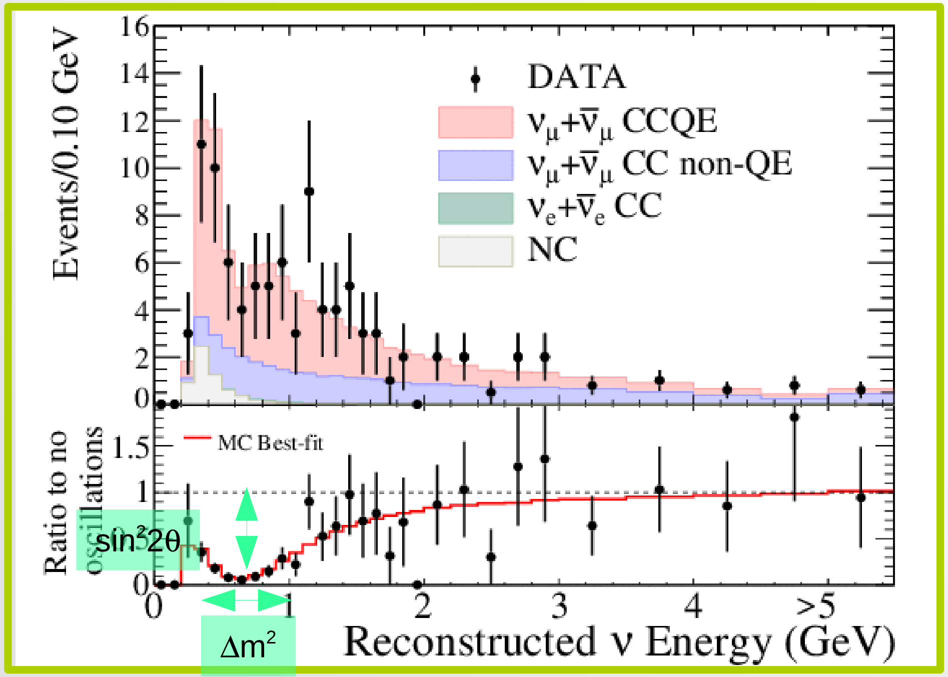
Phys. Rev. Lett. 112, 181801 (2014)

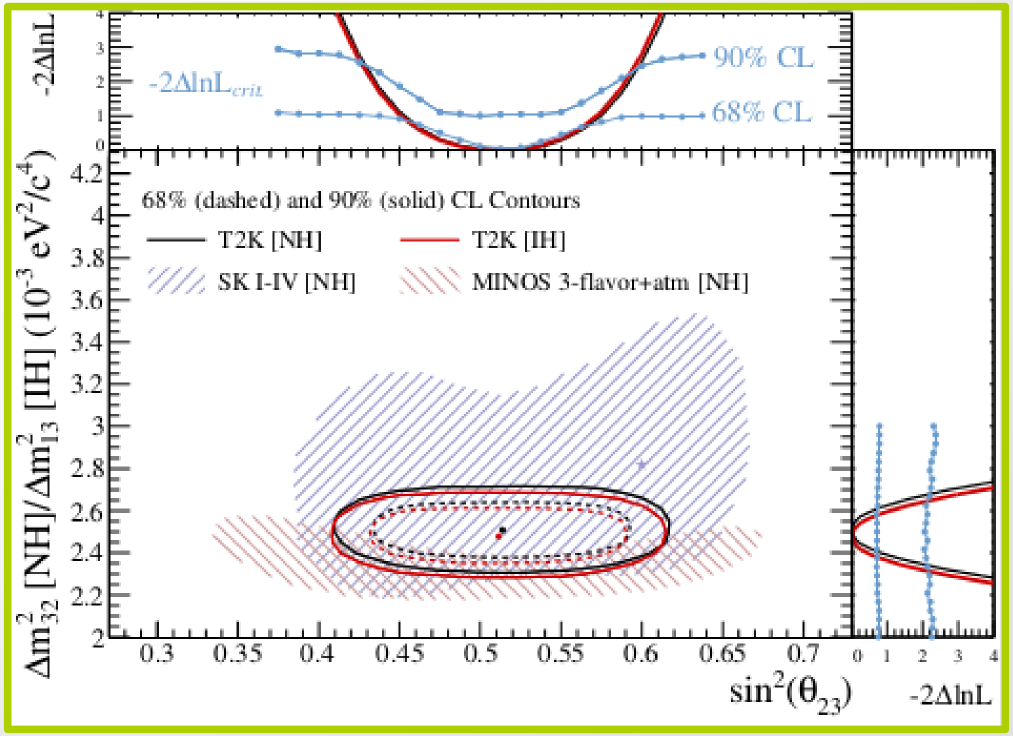
$\nu_\mu \rightarrow \nu_\mu$ T2K Result

- Best-fit oscillation parameter values:

Oscillation parameter	NH	IH
$\sin^2\theta_{23}$	$0.514^{+0.055}_{-0.056}$	0.511 ± 0.055
Δm^2_{32} ($\times 10^{-3}$ eV^2)	2.51 ± 0.10	2.48 ± 0.10

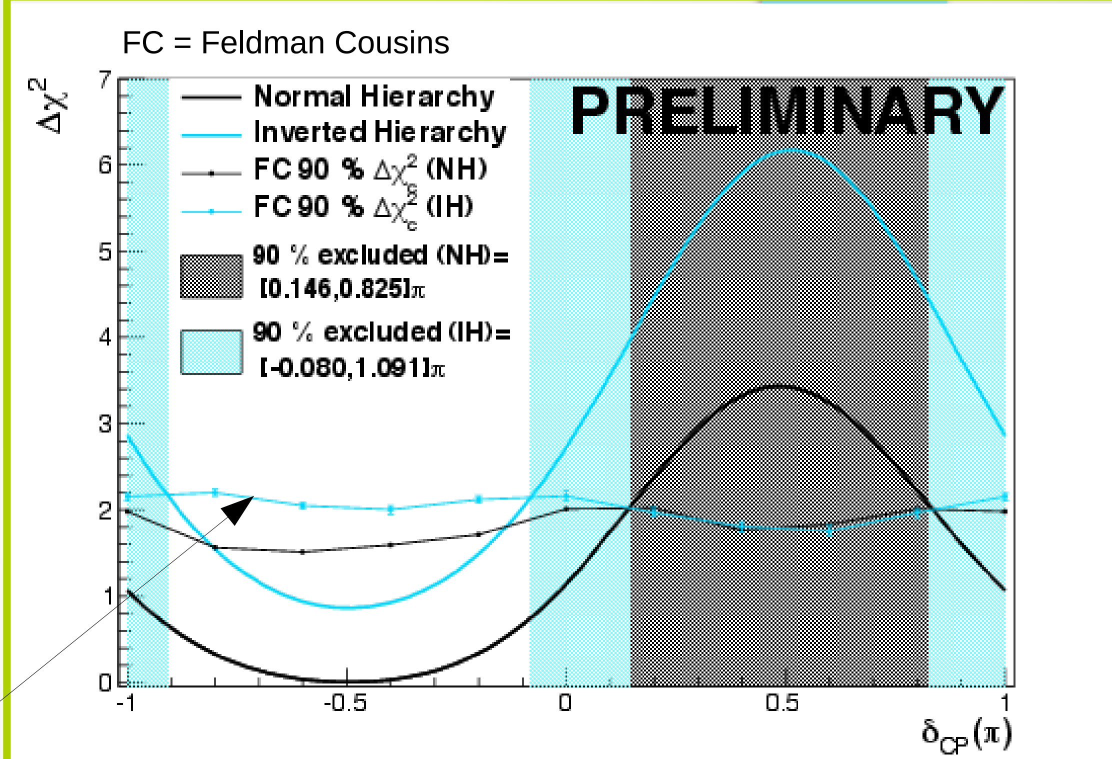
- Events: 120 (observed), 446.0 ± 22.5 (no oscillation)
- Most precise measurement of $\sin^2\theta_{23}$ and favours Maximal Mixing





T2K Joint $\nu_\mu + \nu_e$ Analysis

- Likelihood ratio fit to both ν_μ + ν_e event samples
- Plot includes constraint from reactor experiments as given by the PDG2013 ($\sin^2 2\theta_{13}$ = 0.095 ± 0.01)
- Consistent results with a Bayesian analysis



$\sin^2\theta_{23}$, Δm^2_{32} and $\sin^2 2\theta_{13}$ are marginalized following the 3D $\Delta\chi^2$ surface from Run1+2+3+4

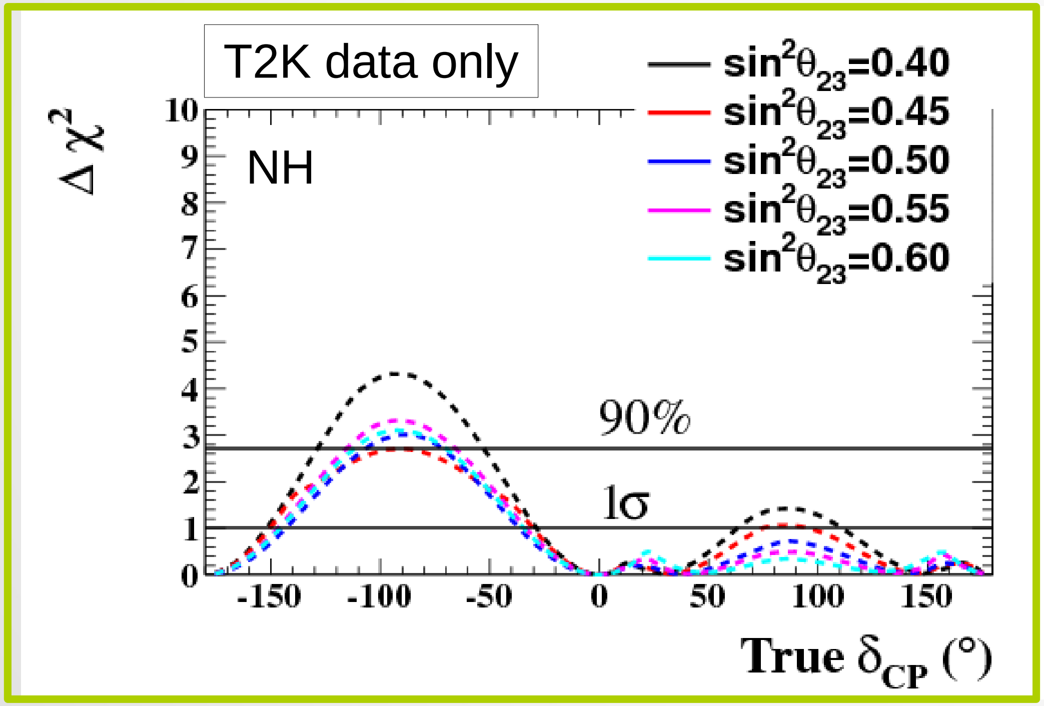
T2K has a slight hint for $\delta_{CP} \sim -\pi/2$

δ_{CP} excluded regions	Preliminary	
	Best fit	90%CL (π)
NH	-0.495	[0.146;0.825]
IH	-0.495	[-0.080;1.091]

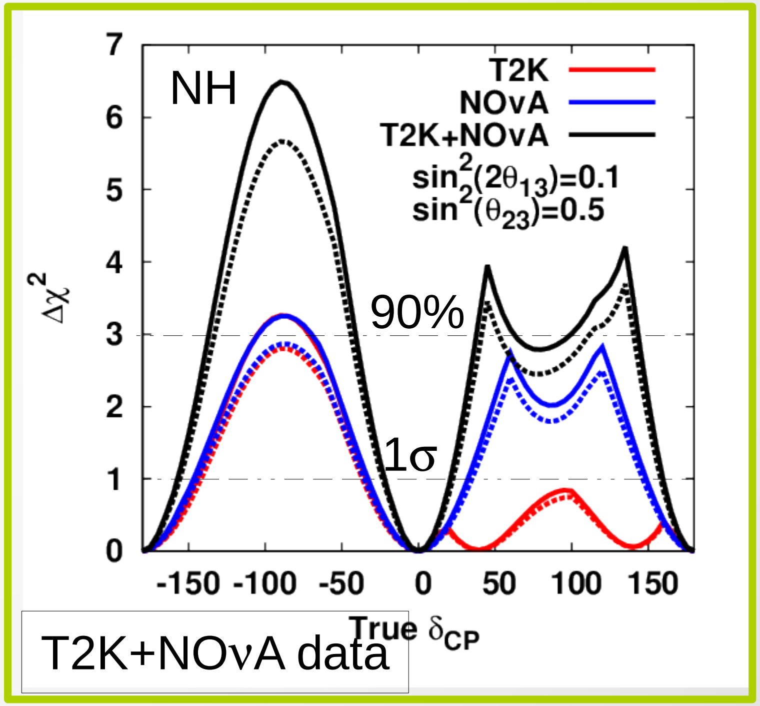
Future: Neutrino & Anti-neutrino running

T2K Future Sensitivity to δ_{CP}

Sensitivity studies to resolve $\sin\delta_{CP} \neq 0$ with 7.8×10^{21} POT. Best sensitivity expected for 50% ν and 50% anti-ν beam running. Projected reactor constraint $\sin^2 2\theta_{13} = 0.1 \pm 0.005$.



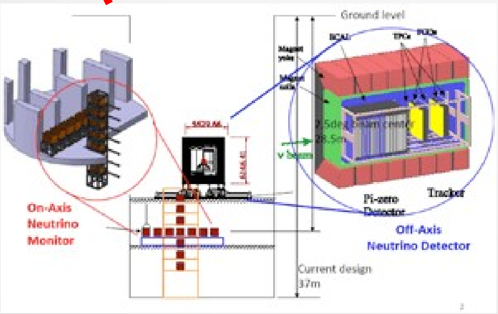
Using joint oscillation analysis with realistic 2012 systematic errors (~10% ν_e, ~13% ν_μ)



Using GloBES, with 50% ν and anti-ν running for NOvA too. Solid lines: no syst. error.

J-PARC ν-Beamline

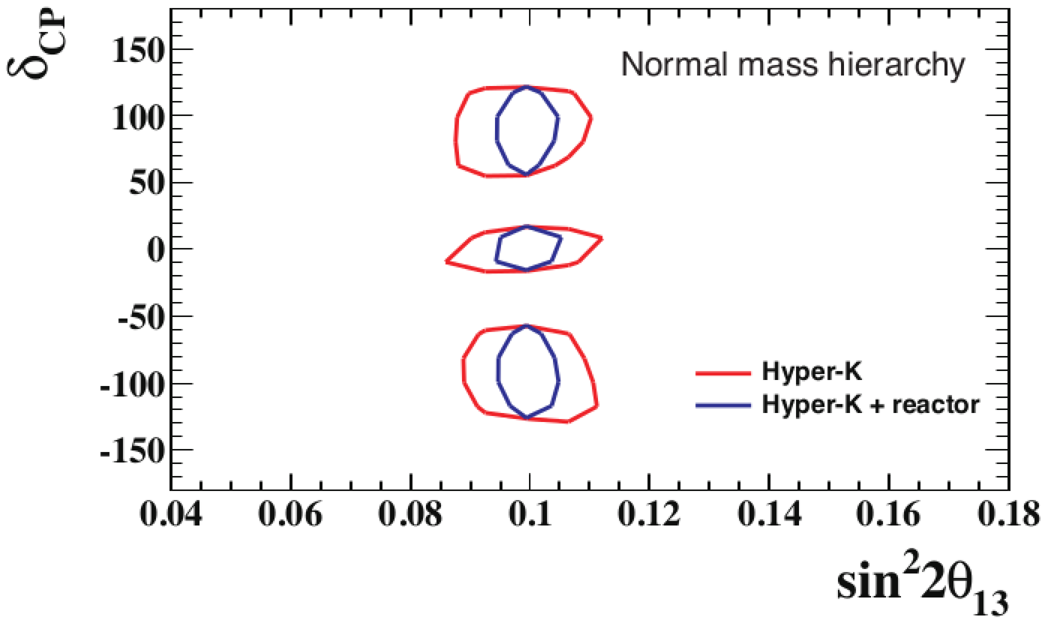
INGRID
on-axis

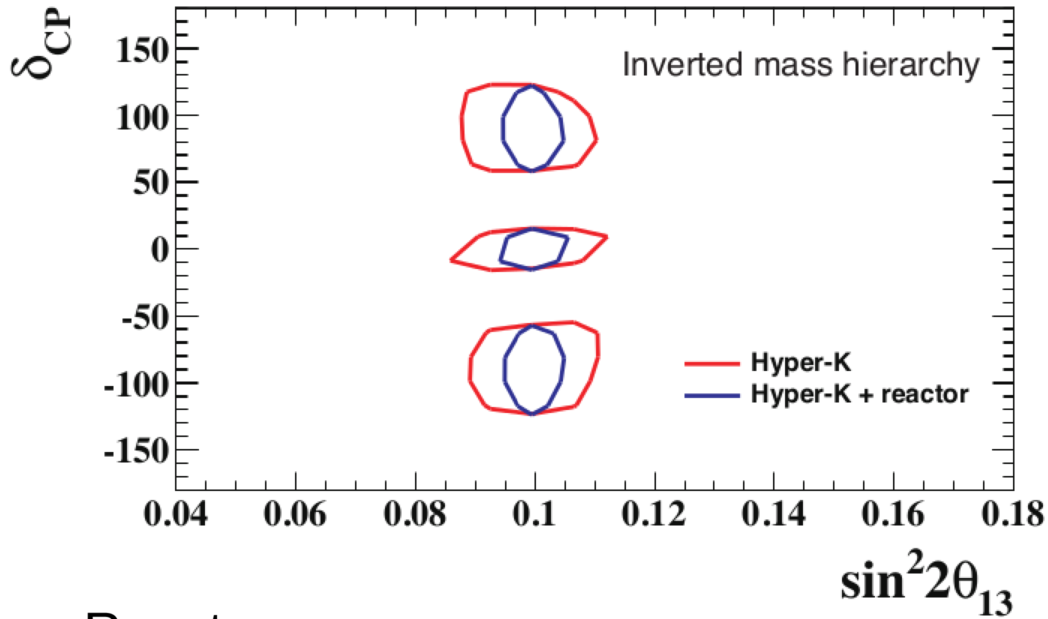


ND280
off-axis

θ_{13}-δ_{CP} allowed region (90%)

7.5MW×10^7sec, ν:anti-ν=1:3





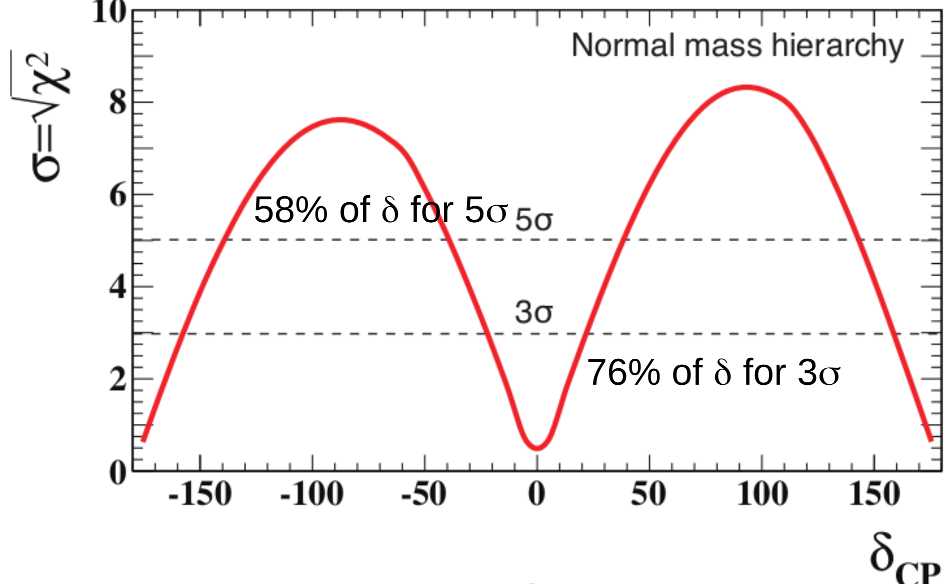
Reactor error:
$\delta\sin^2 2\theta_{13}$ = 0.005

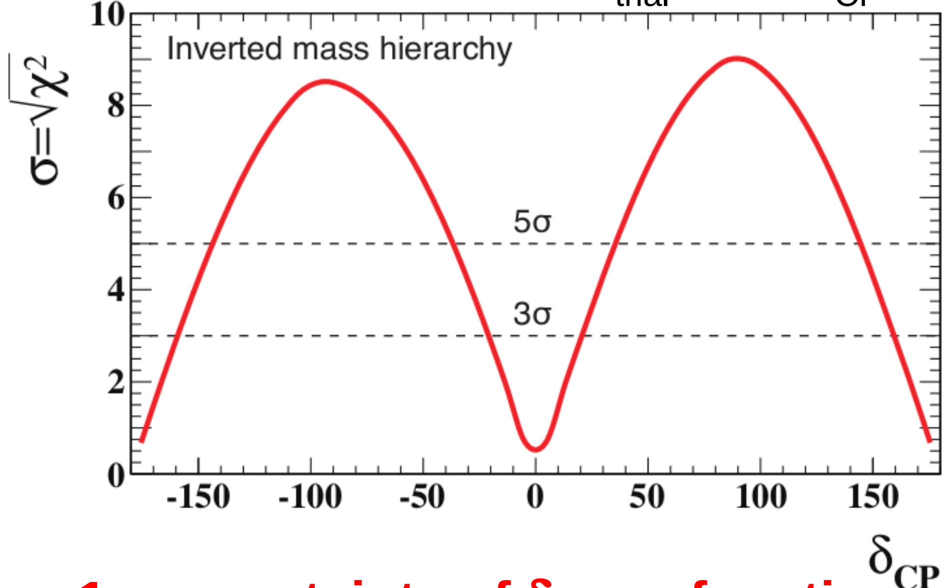
Parameter	$\sin^2 2\theta_{13}$	δ_{CP}	$\sin^2 2\theta_{23}$	Δm^2_{32}	Mass hierarchy	$\sin^2 2\theta_{12}$	Δm^2_{12}
Nominal	0.10	90, 0, -90	0.50	2.4×10^{-3}	Nominal, Inverted	0.8704	7.6×10^{-5}
Treatment	Fitted	Fixed	Fitted	Fitted	Known	Fixed	Fixed

40

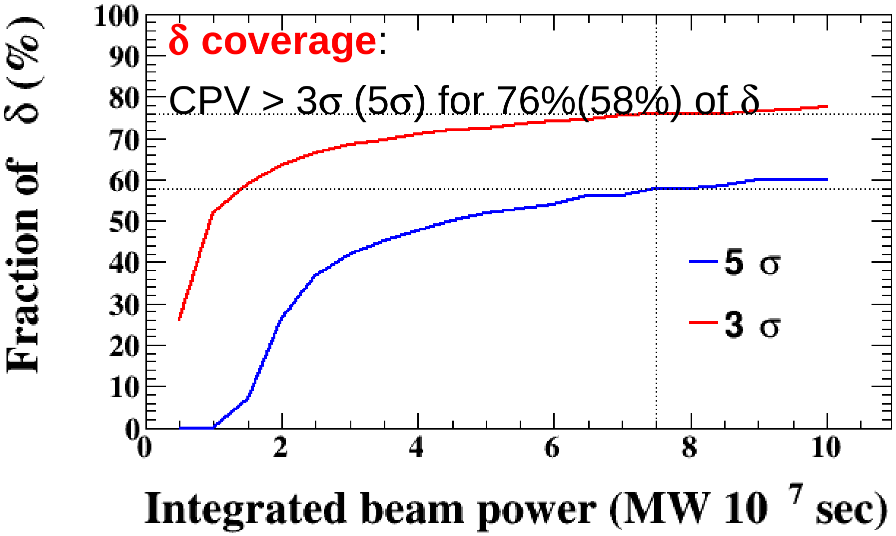
Significance of δ_{CP}=0

CPV discovery sensitivity w/ mass hierarchy known: $\Delta\chi^2 = \chi^2_{trial} - \chi^2(\delta_{CP}=0,180)$

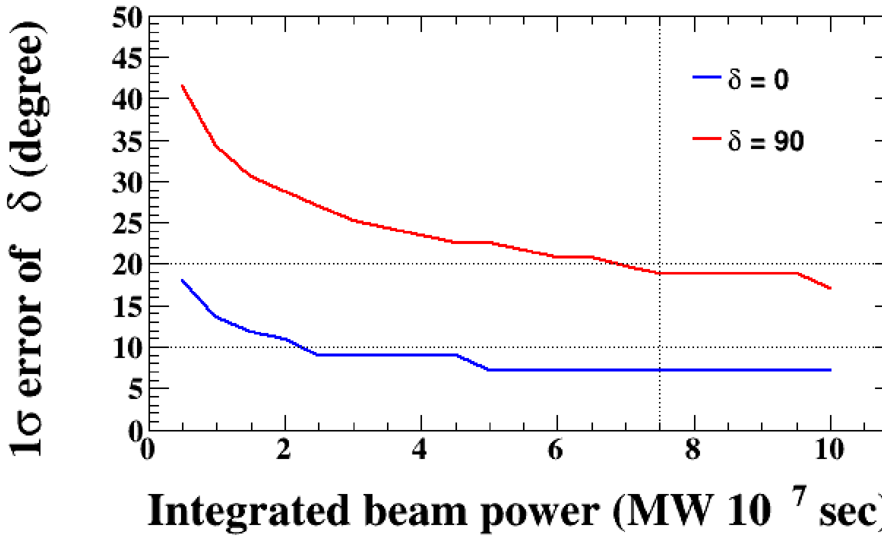




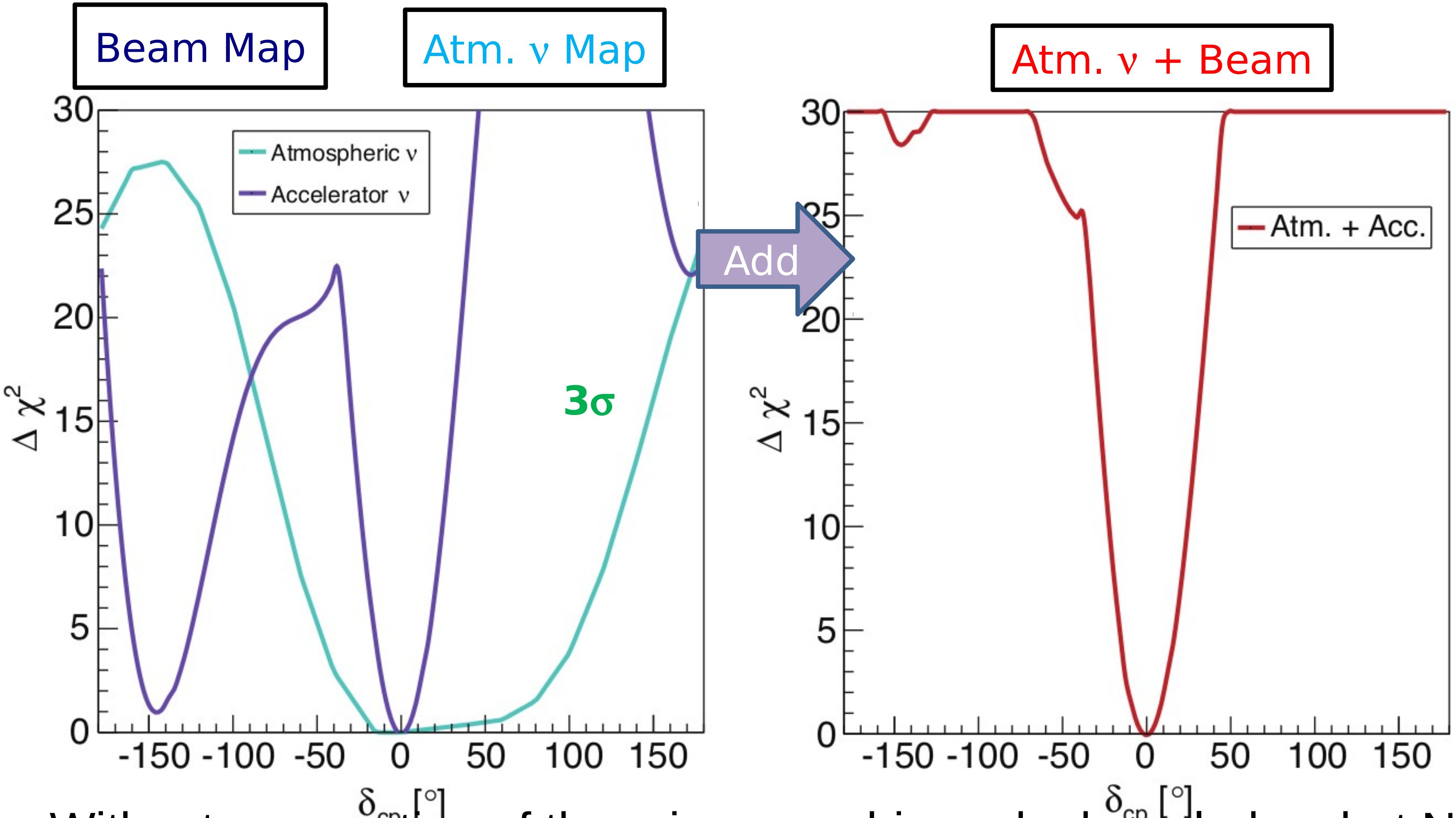
Fractional region of δ(%) for which the CPV (sin δ ≠0) significance is > 3σ



1σ uncertainty of δ as a function of the beam power: < 19°(6°) for δ = 90°(0°)



Beam + Atmospheric ν: Allowed δ_{CP}



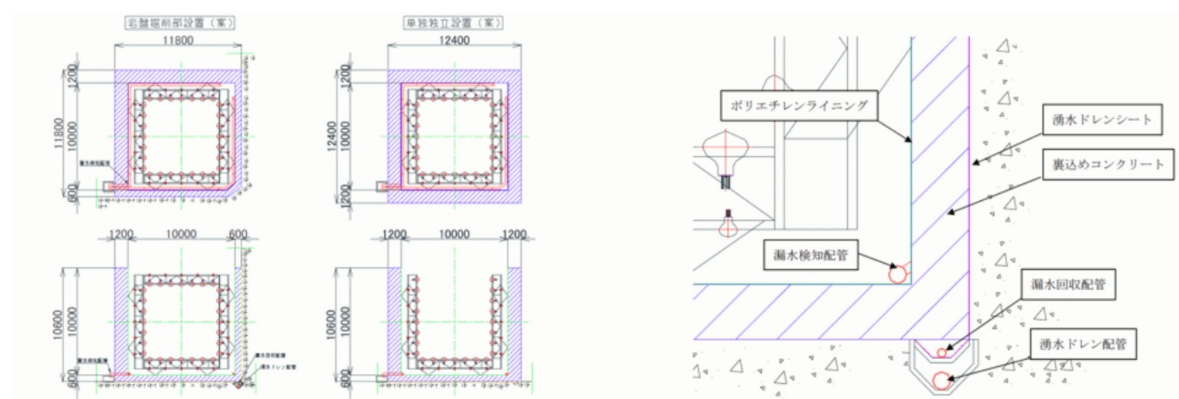
- Without assumption of the prior mass hierarchy knowledge, but NH is true.
- True δ_{CP} = 0.0; $\sin^2 2\theta_{13}$ = 0.10; Maximal mixing $\sin^2 2\theta_{23}$ = 1.0
- Degenerate solution exists at 3σ in the beam only case.
- The physics capability of the project can be enhanced by combining two complementary measurements.

1kton WC Prototype

- Prototype (1kton, ~10×10×10 m^3) for R&D test approved in Japan as Grant-in-Aid: ~ USD 1.2M/5 years (2013-18).

- It's one of the 27 proposals selected each year from all areas in science.

- Main feasibility studies:
  - Photosensor and corresponding support structure
  - Liners
  - Leak water collection detection
  - DAQ
  - Electronics
  - Calibration system
  - ….



Overall Cost Estimate

Total	800M USD	
Cavern	300M USD	
Tank & structure	200M USD	
Photo-sensors	200M USD	High QE HPD
Near Detector	30M USD	@Tokai

- Costs estimated based on the current design and including a new near detector.
- Proportional sharing of costs between the interested Countries is expected.