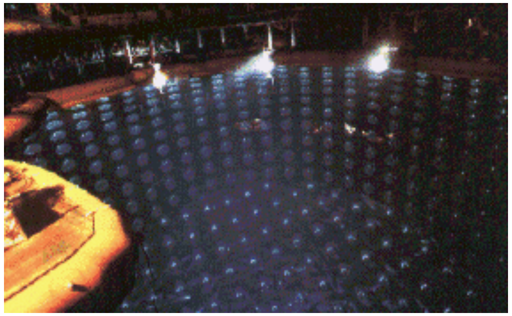
Atmospheric neutrino and proton decay at Super-Kamiokande and Hyper-Kamiokande

Zepeng Li, Duke University

For The Super-Kamiokande Collaboration
and The Hyper-Kamiokande Collaboration

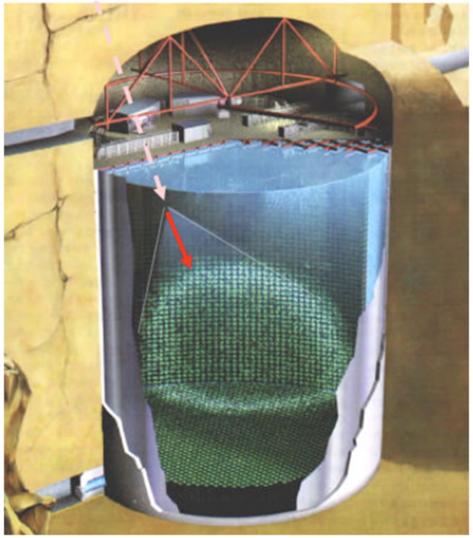
Three generations of Kamiokande

Kamiokande
(1983-1996)



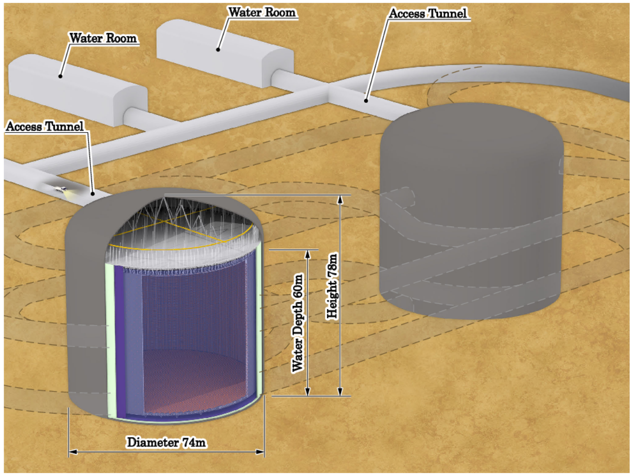
3 kton

Super-Kamiokande
(1996-)



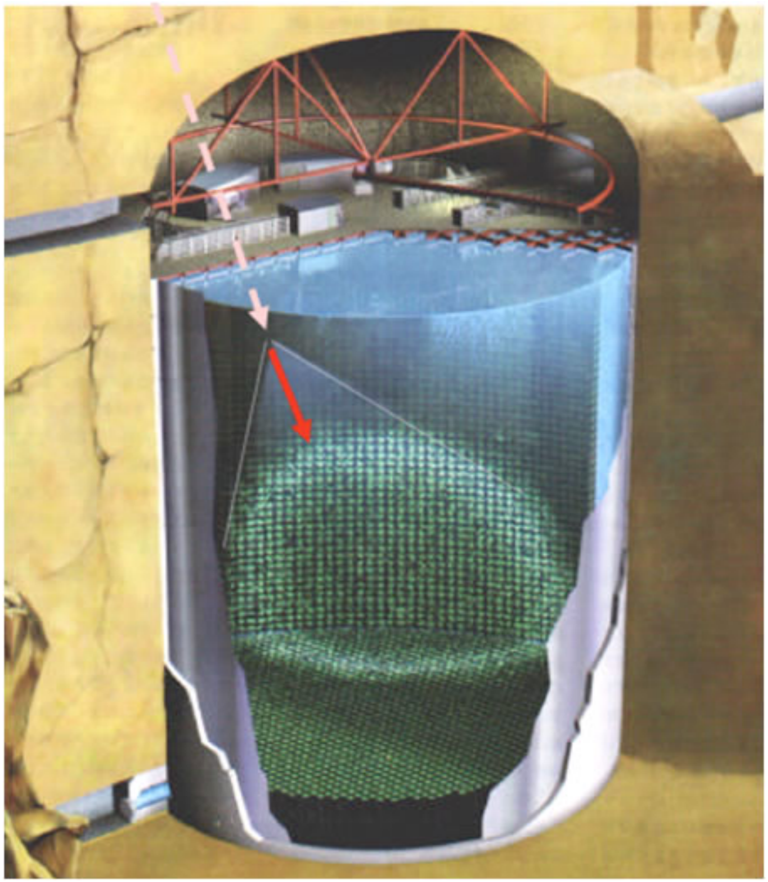
50 kton

Hyper-Kamiokande
(2026-)



520 kton

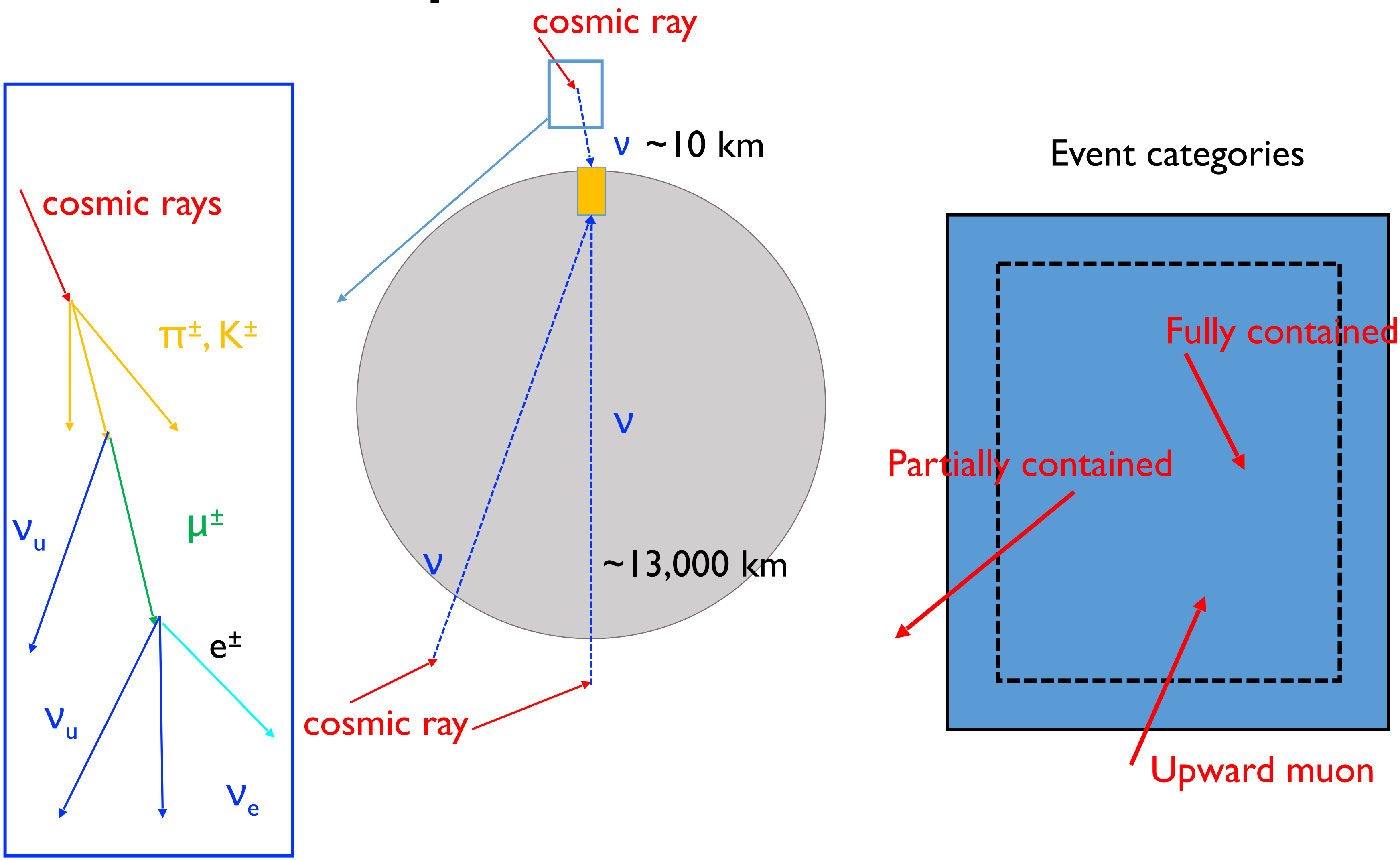
Super-Kamiokande



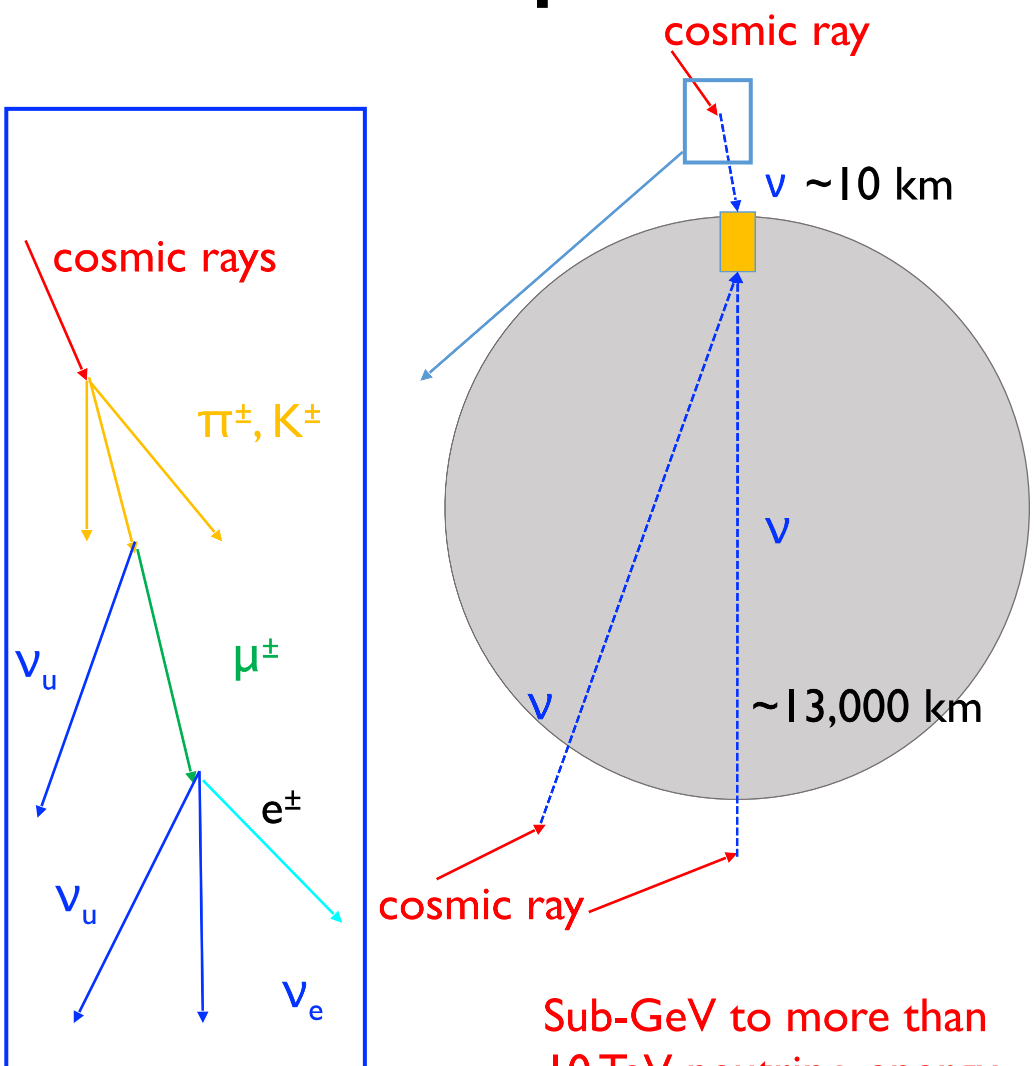
Four Run Periods:
SK-I (1996-2001) SK-II (2003-2005)
SK-III(2005-2008) SK-IV(2008-Present)

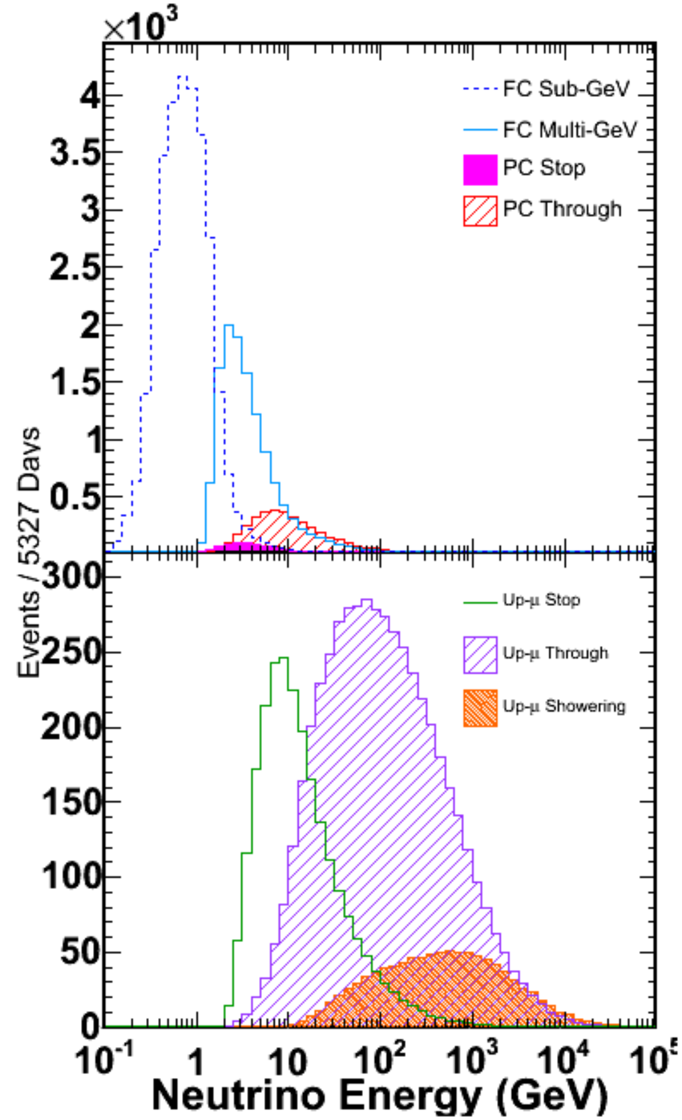
- Super-K is a 50 kton water Cherenkov detector with 22.5 kton of fiducial volume at 2,700 m.w.e underground.
- The detector is optically separated into ID and OD.
- Multi-purpose detector.
- Excellent detection of atmospheric neutrinos, >47,000 atmospheric neutrino events since 1996.
- A Nobel prize winning experiment!

Atmospheric neutrinos in SK



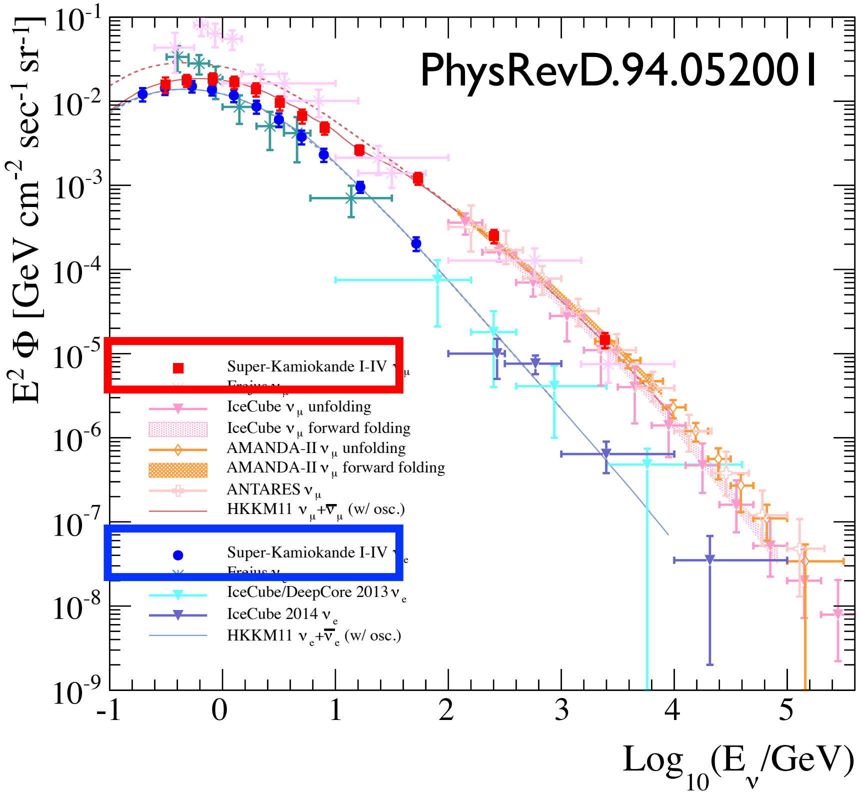
Atmospheric neutrinos in SK



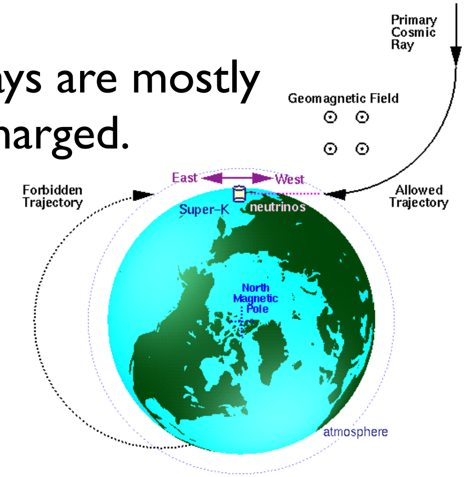


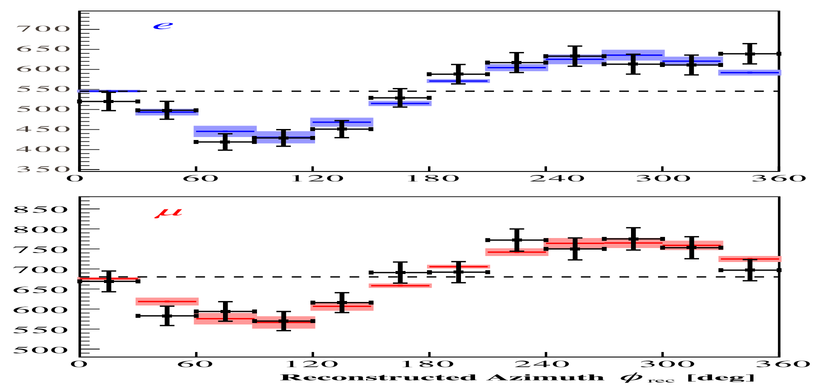
Sub-GeV to more than 10 TeV neutrino energy.

Atmospheric neutrinos measurement in SK



Cosmic rays are mostly positive charged.

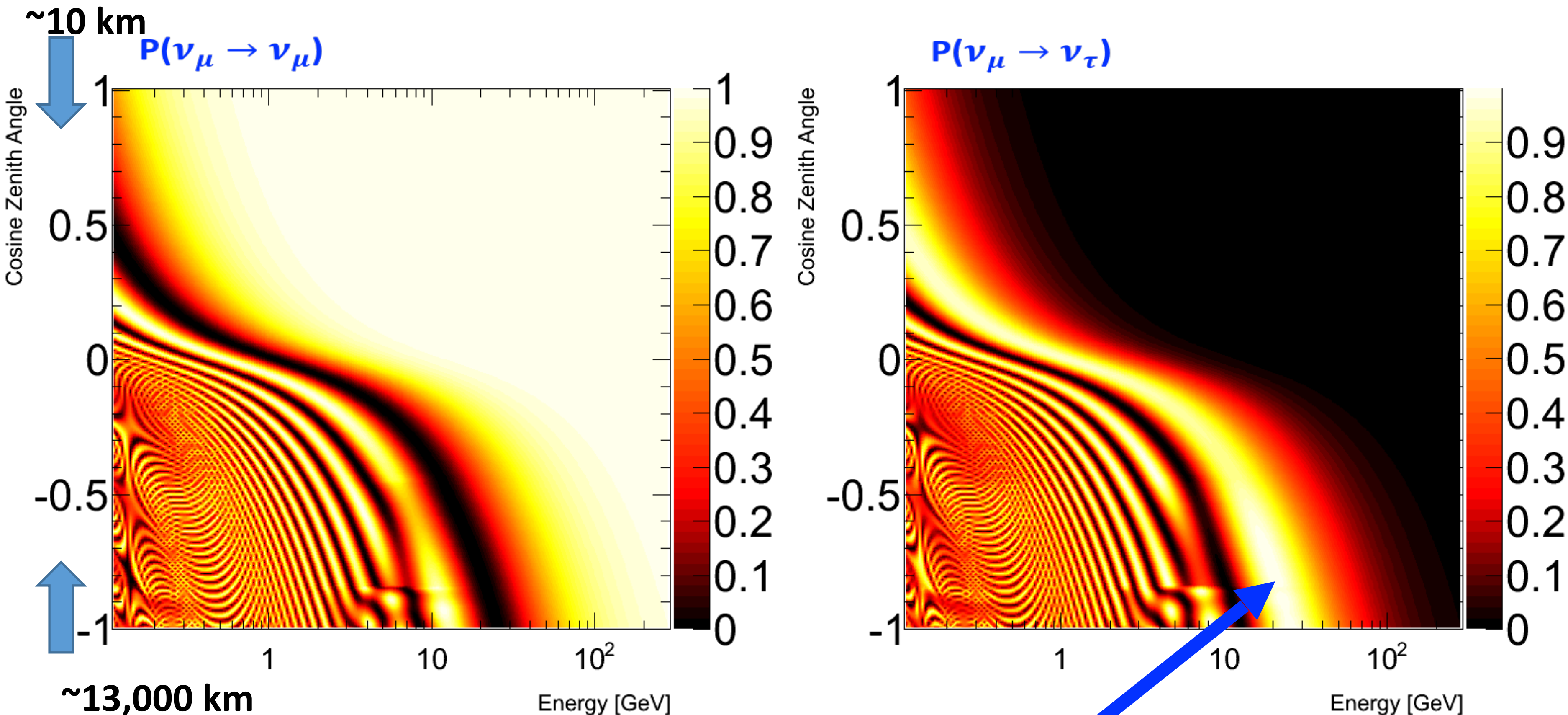




SK measures the flux of atmospheric neutrino with energy of sub-GeV to ~10 TeV. The measurement is consistent with Honda flux model prediction.

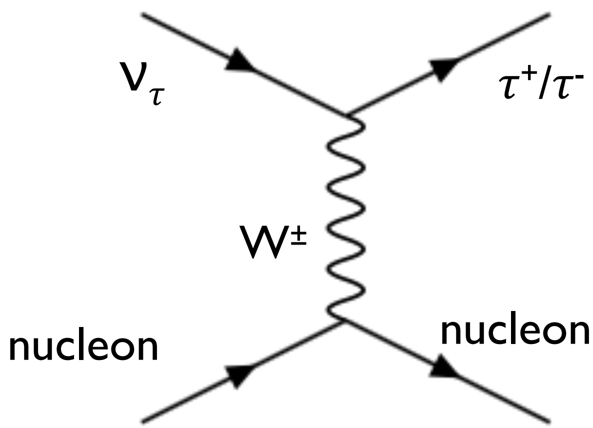
SK observes clear azimuthal dependence for both μ-like(6.0σ) and e-like(8.0σ) samples due to the effect of geo-magnetic field.

Neutrino oscillations at Super-K

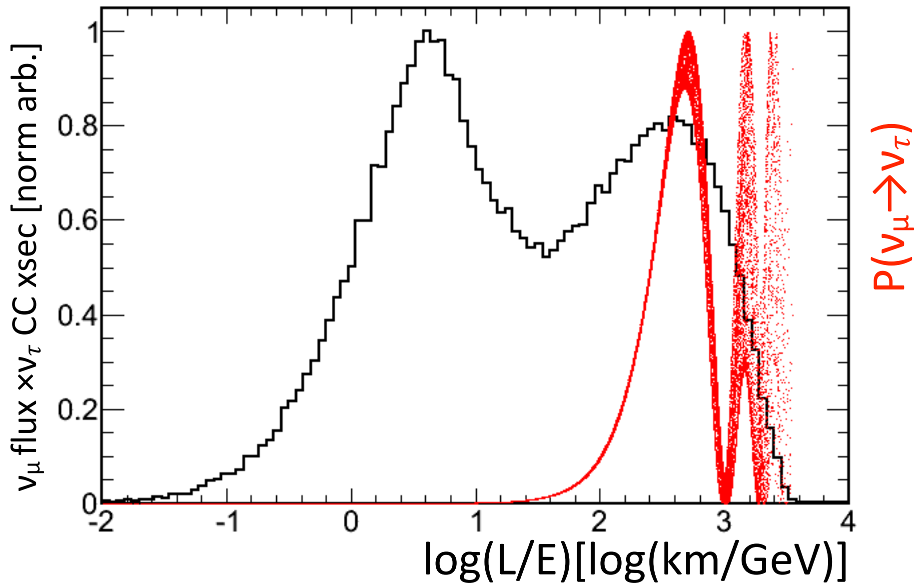


- Leading effect if ν_μ disappearance ($\nu_\mu \to \nu_\tau$).
- ν_τ appearance from neutrino oscillations could be detected by charged-current ν_τ interactions.

Tau neutrino appearance in Super-K



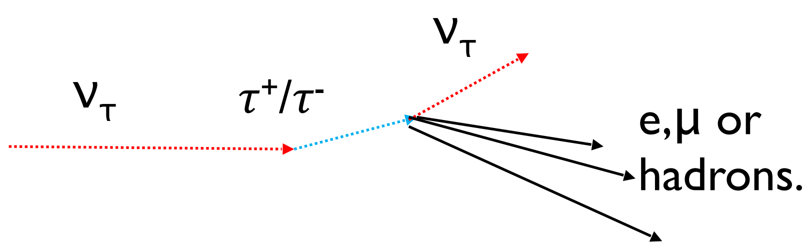
E_ν > 3.5GeV



To search for tau neutrino appearance from neutrino oscillation, high energy neutrino beam is necessary!

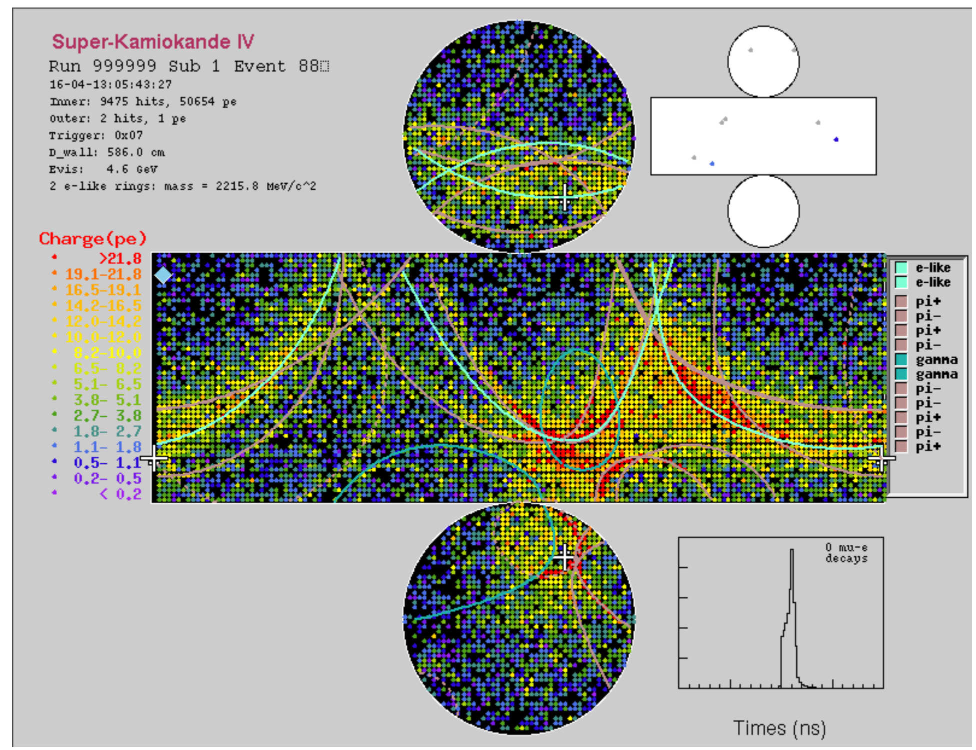
Atmospheric neutrinos have wide span of energy and path length. Large probability of ν_τ appearance with proper combination of L and E.

Tau neutrino appearance in SK

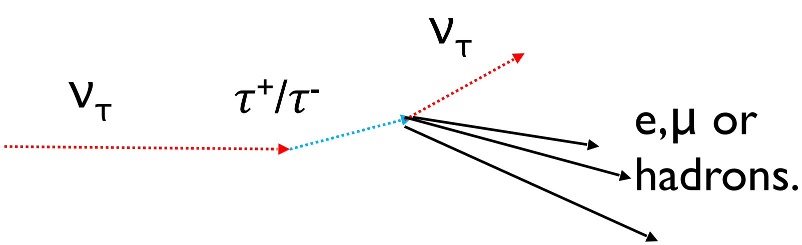


Tau lepton decays in ~10^{-13}s, tau lepton track is undetectable in SK detector.

- Tau lepton production is rare in SK due to 3.5 GeV energy threshold of charged-current ν_τ interaction, ~300 CC ν_τ events expected in SK FV.
- Multiple light-producing particles from tau decay.
- Neural network(input variables in backup) to select hadronic tau decay events.



Tau neutrino appearance in SK



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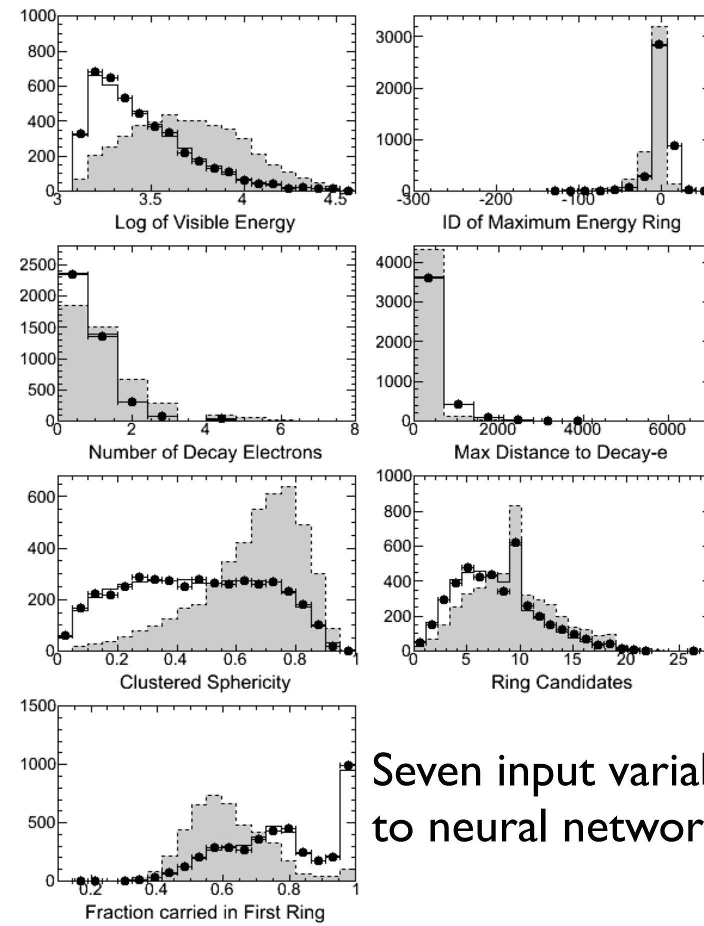
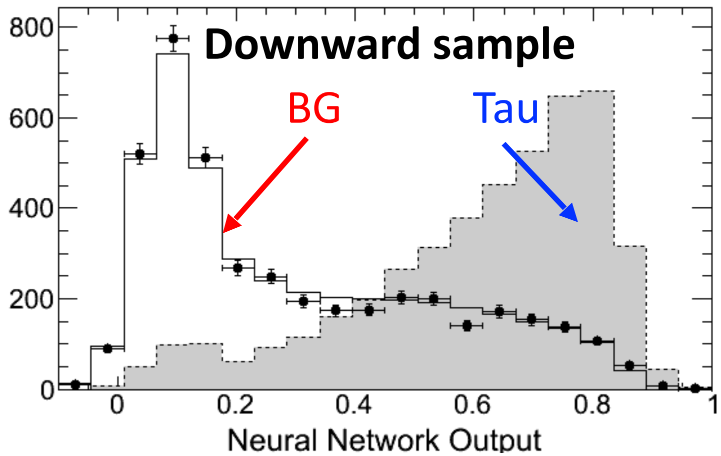
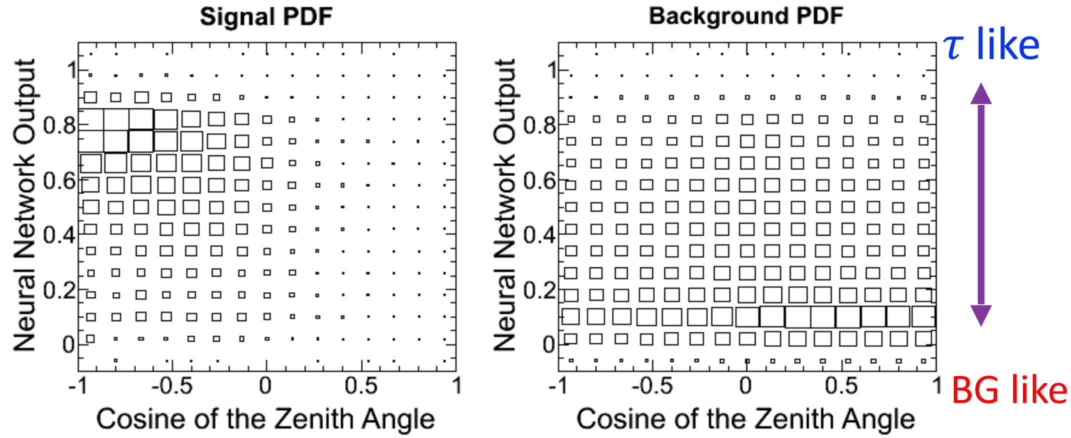
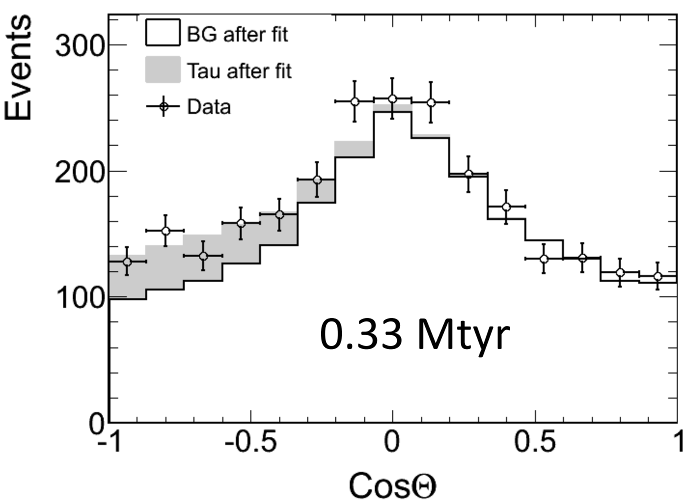


Seven input variables to neural network.

Tau neutrino appearance in SK







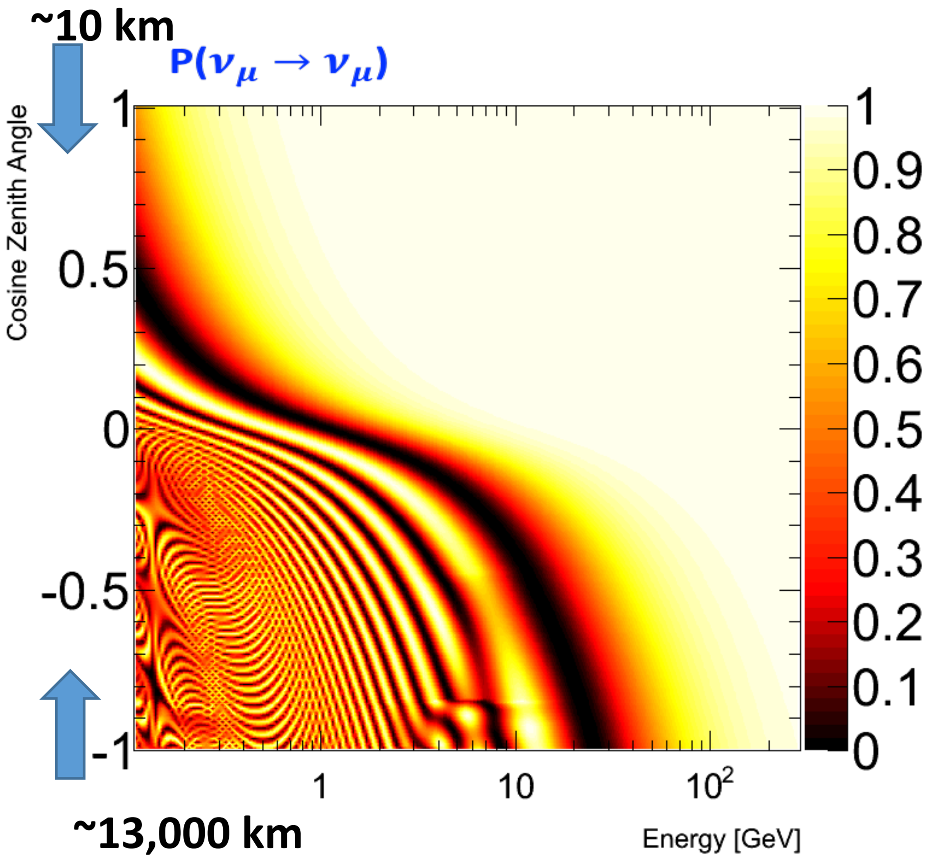
tau-like events after the fit

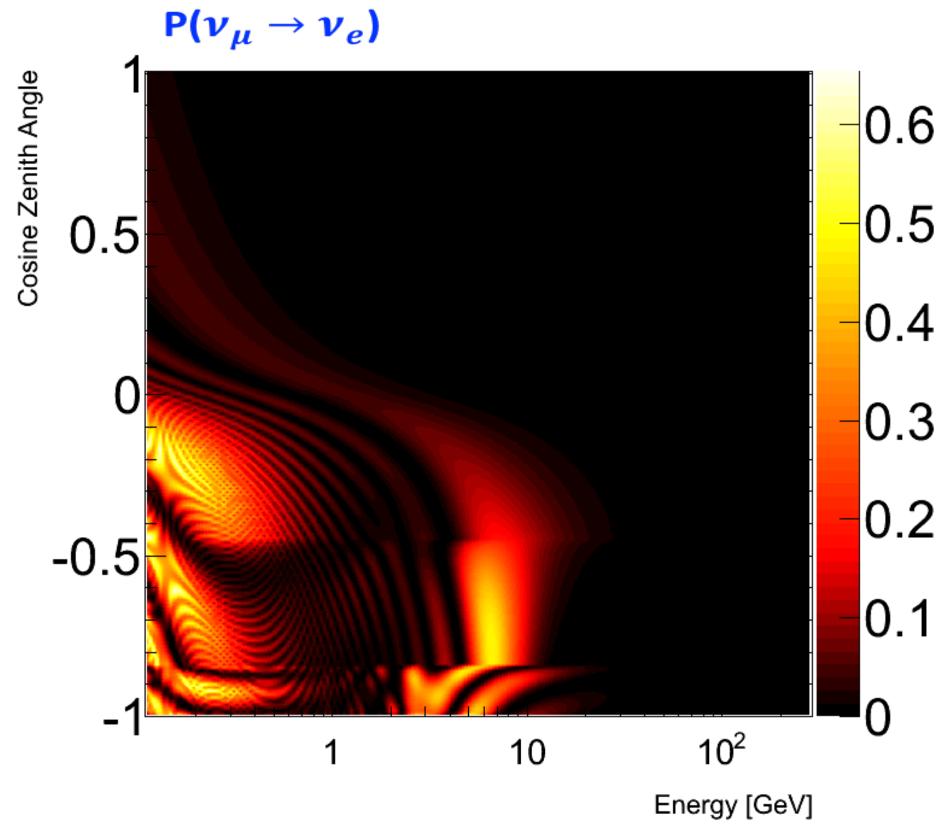
$$\mathbf{Data = PDF_{bg} + \alpha \times PDF_{tau} + \sum \varepsilon_i \times (tauPDF_i + bgPDF_i)}$$

α is the normalization of tau events.
$(tau, BG)PDF_i$ is the PDF of ith systematic error of shifting it by 1σ, ε_i is the magnitude of the systematic error.

α=1.47±0.32 preliminary
compared to simulation
(4.6σ from 0)assuming NH
Sensitivity at α=1: 3.3σ

Neutrino oscillations at Super-K

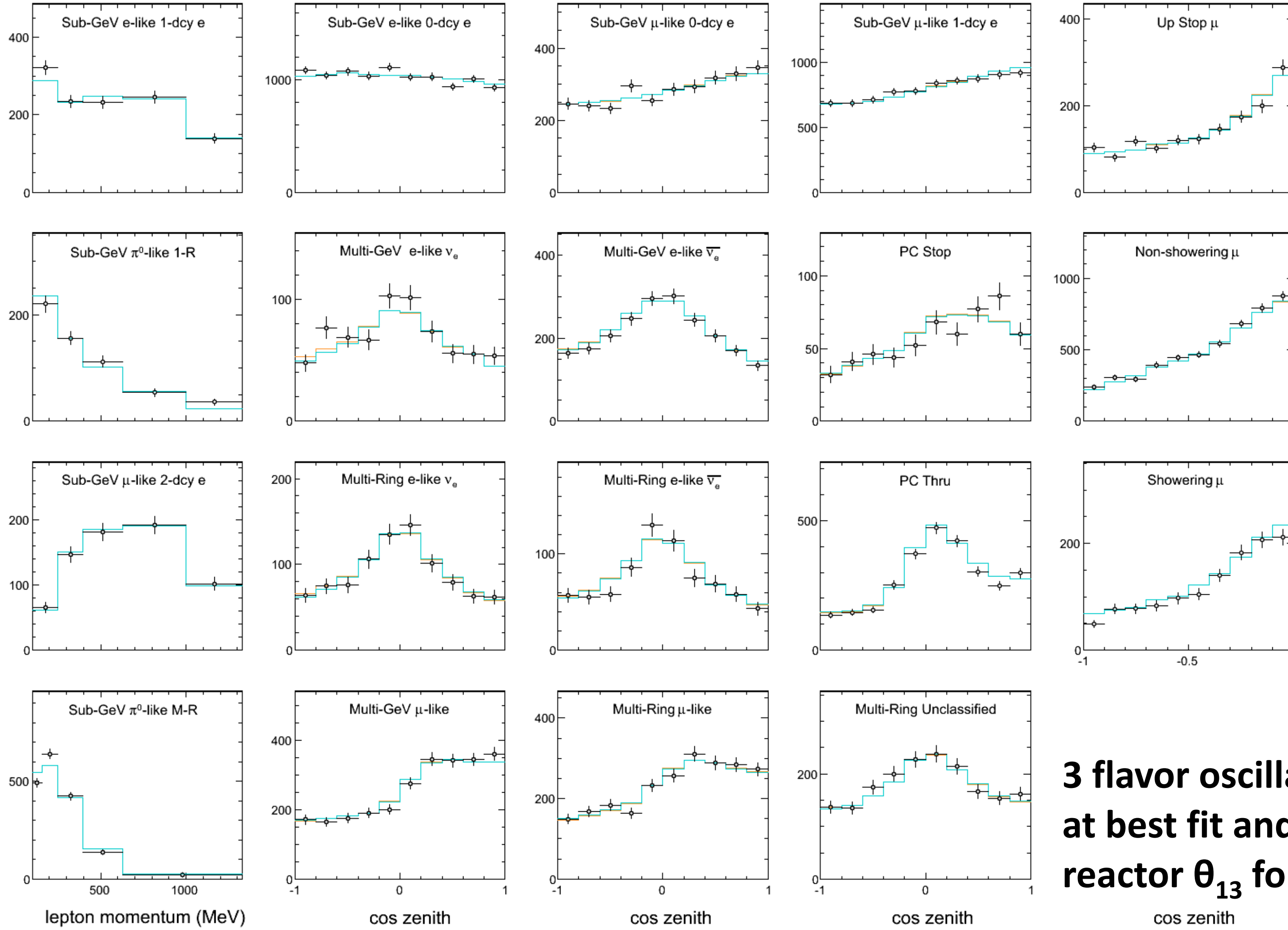




Leading effect is ν_μ disappearance.

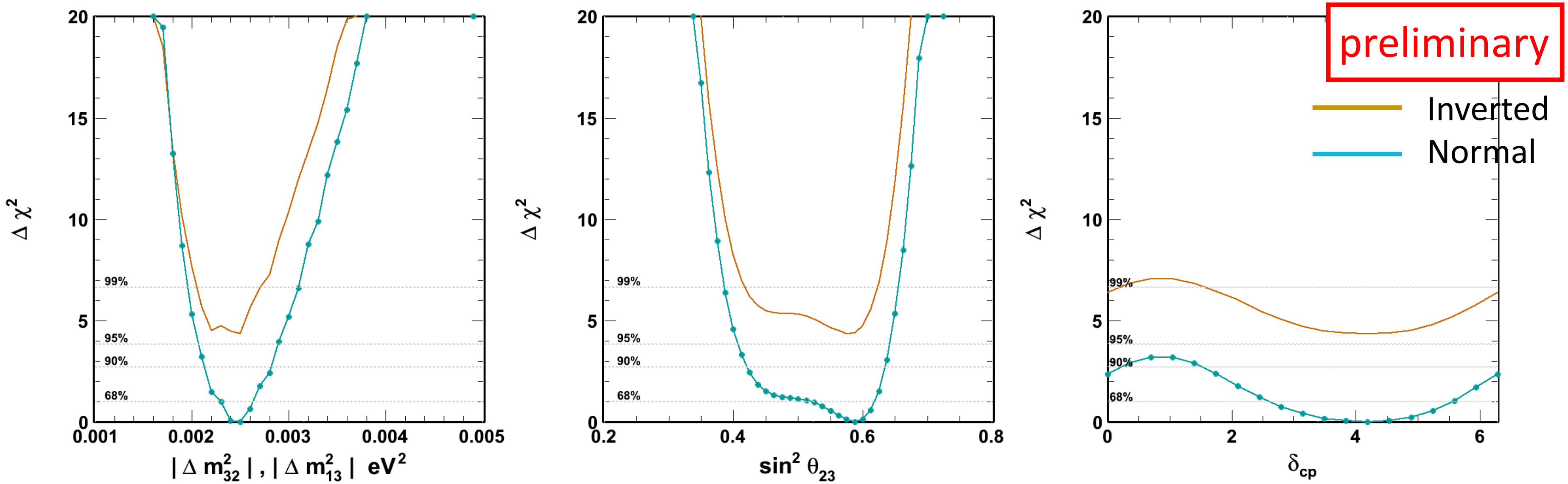
Sub-leading effects help to resolve θ_{23} octant, δ_{CP} and mass hierarchy.

SK1-4 0.33 Mtyr data and MC



3 flavor oscillation at best fit and reactor θ_{13} for MC.

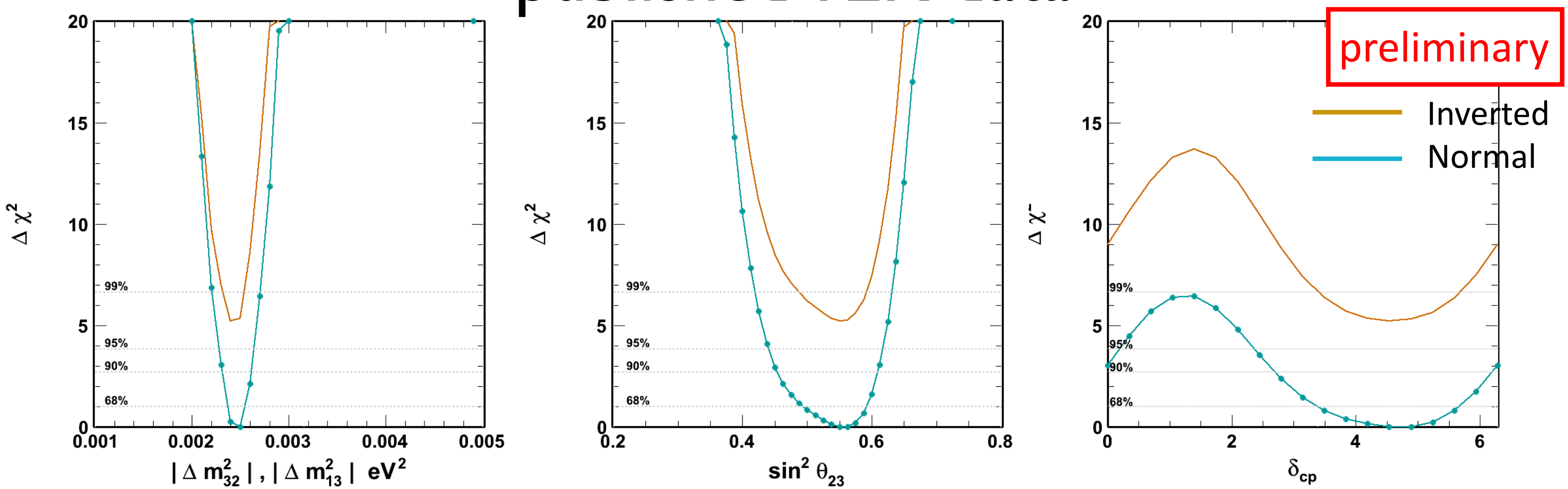
SK oscillation analysis-θ_{13} constrained



Fit (517 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$\|\Delta m^2_{32}\|$ eV^2
SK (IH)	576.0	0.0219	4.2	0.58	2.5×10^{-3}
SK (NH)	571.7	0.0219	4.2	0.59	2.5×10^{-3}

- θ_{13} is constrained at PDG average, uncertainty is included as a systematic error.
- $\Delta\chi^2 = \chi^2_{NH}-\chi^2_{IH}= -4.3$ (-3.1 of sensitivity)
- The p-value of obtaining $\Delta\chi^2$ of -4.3 or less is 0.031 ($\sin^2\theta_{23}$=0.6) and 0.007 ($\sin^2\theta_{23}$=0.4) in IH hypothesis. Under NH hypothesis, the p-value is 0.45 ($\sin^2\theta_{23}$=0.6).

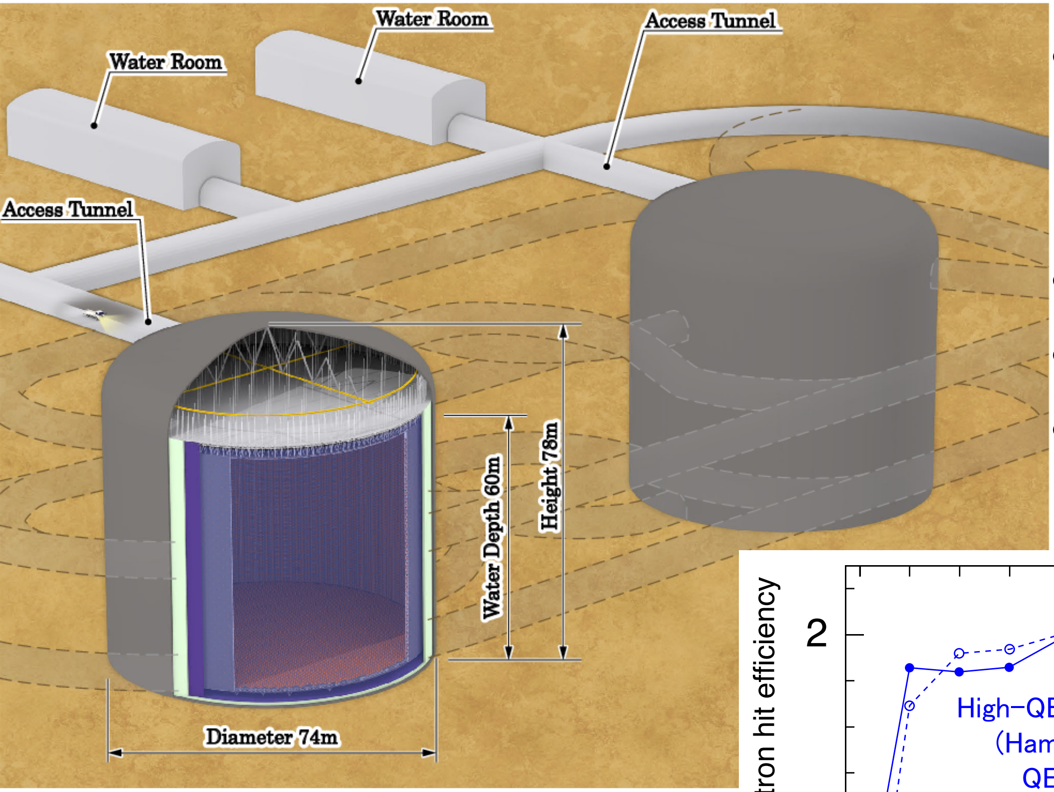
Oscillation analysis with constraint from published T2K data



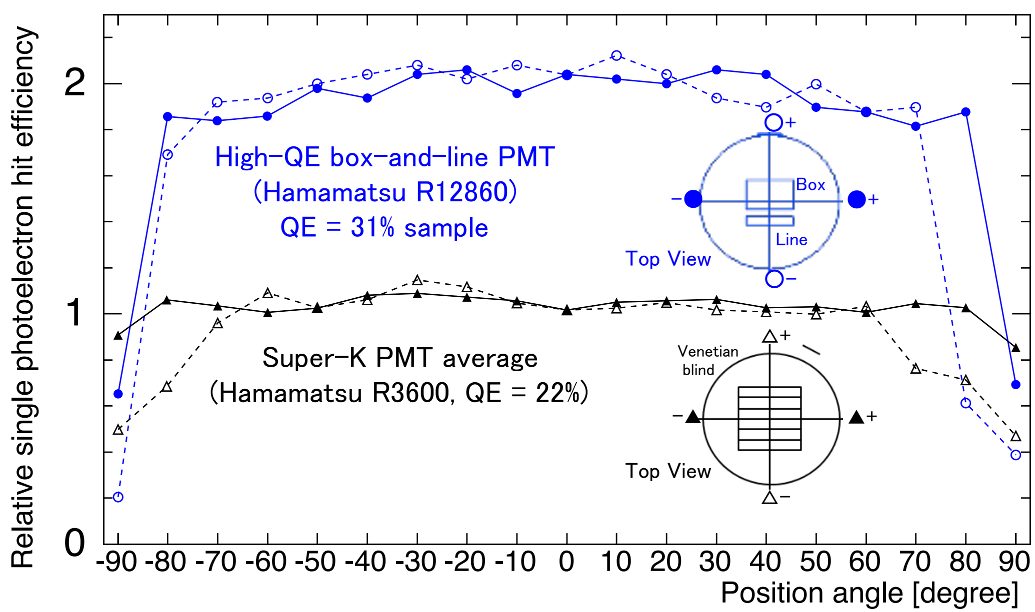
Fit (517 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32}\rvert eV^2$
SK (IH)	644.8	0.0219	4.5	0.55	2.5×10^{-3}
SK (NH)	639.6	0.0219	4.9	0.55	2.4×10^{-3}

- $\Delta\chi^2$ = -5.2 (-3.8 of sensitivity for SK best, -3.1 for combined best)
- The p-value of obtaining $\Delta\chi^2$ of -5.2 is 0.024 ($\sin^2\theta_{23}$=0.6) and 0.001 ($\sin^2\theta_{23}$=0.4). Under NH hypothesis, the p-value is 0.43 ($\sin^2\theta_{23}$=0.6).

Hyper-Kamiokande



- 60m(H)×74m(D) for 1 tank, with190 kton fiducial volume, ~10 × SK FV.
- 40% PMT coverage.
- Photon detection efficiency × 2.
- Time and charge resolution for single p.e. × 1/2.



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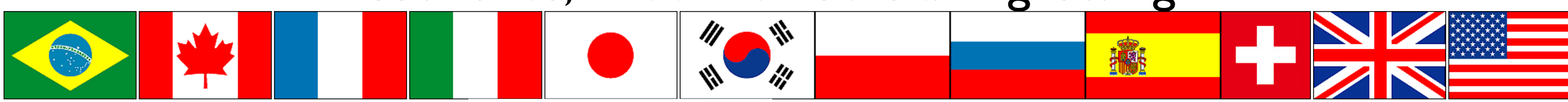
Hyper-Kamiokande proto-collaboration

12 countries, ~250 members and growing



KEK-IPNS and UTokyo-ICRR signed a MoU for cooperation on the Hyper-Kamiokande project.

MEMORANDUM OF UNDERSTANDING

of the cooperation in the Hyper-Kamiokande project

January 31, 2015

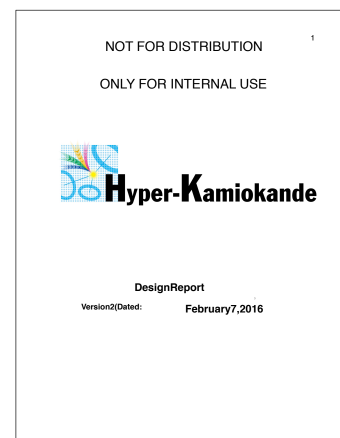
THE INSTITUTE FOR COSMIC RAY RESEARCH OF THE UNIVERSITY OF TOKYO and THE INSTITUTE OF PARTICLE AND NUCLEAR STUDIES OF THE HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION have reached agreement regarding cooperation in promoting the advanced nucleon decay and neutrino experiment program, Hyper-Kamiokande, by understanding that the program would make significant progress in a wide range of fields in physics and astronomy. It is also agreed to review and develop the program in its comprehensive aspects including promoting organization and budget measures.

This agreement is effective for two years from January 31, 2015 and is able to be updated upon the discussion between the two organizations.

Prof. Takaaki KAJITA
Director
Institute for Cosmic Ray Research,
The University of Tokyo

Prof. Masanori YAMAUCHI
Director
Institute of Particle and Nuclear Studies,
High Energy Accelerator
Research Organization

International Hyper-K Advisory Committee was formed under KEK-IPNS and UTokyo-ICRR.
First review report was delivered



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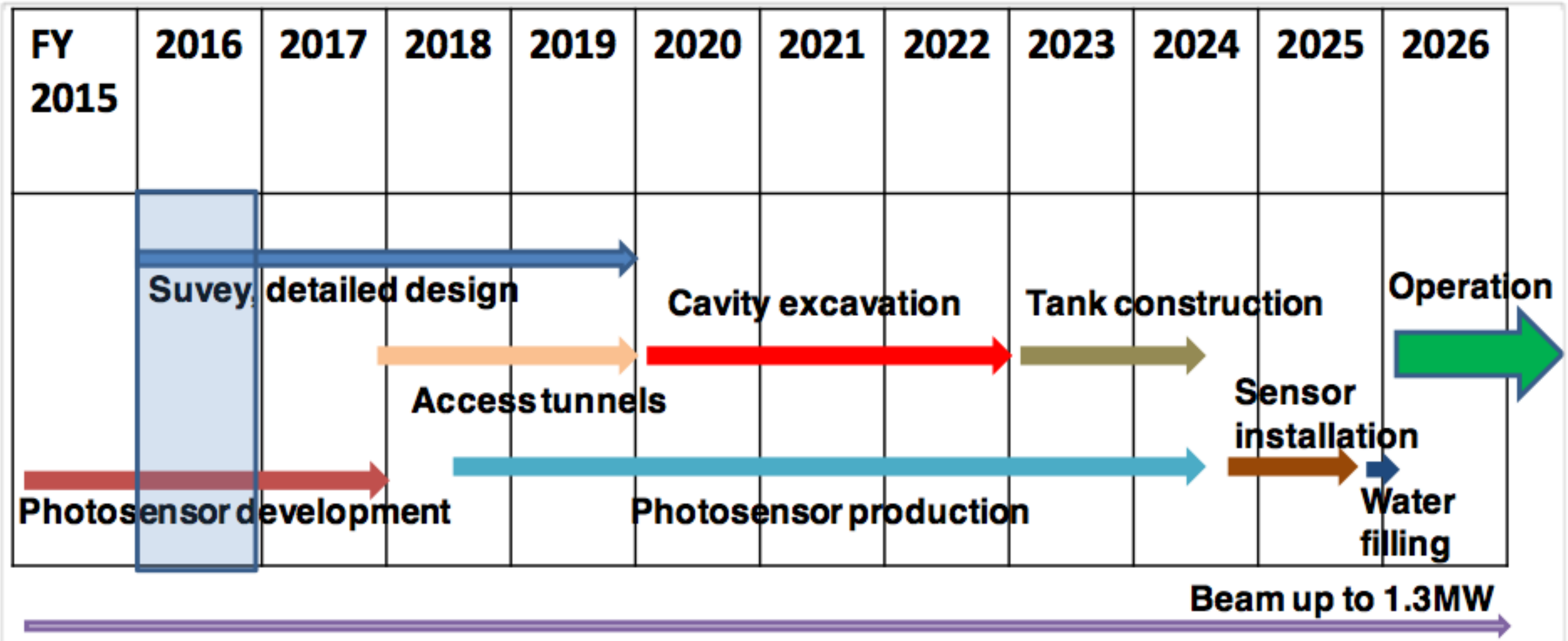
Hyper-Kamiokande

DesignReport
Version2(Dated: February7,2016

Notional Timeline (1st Tank)



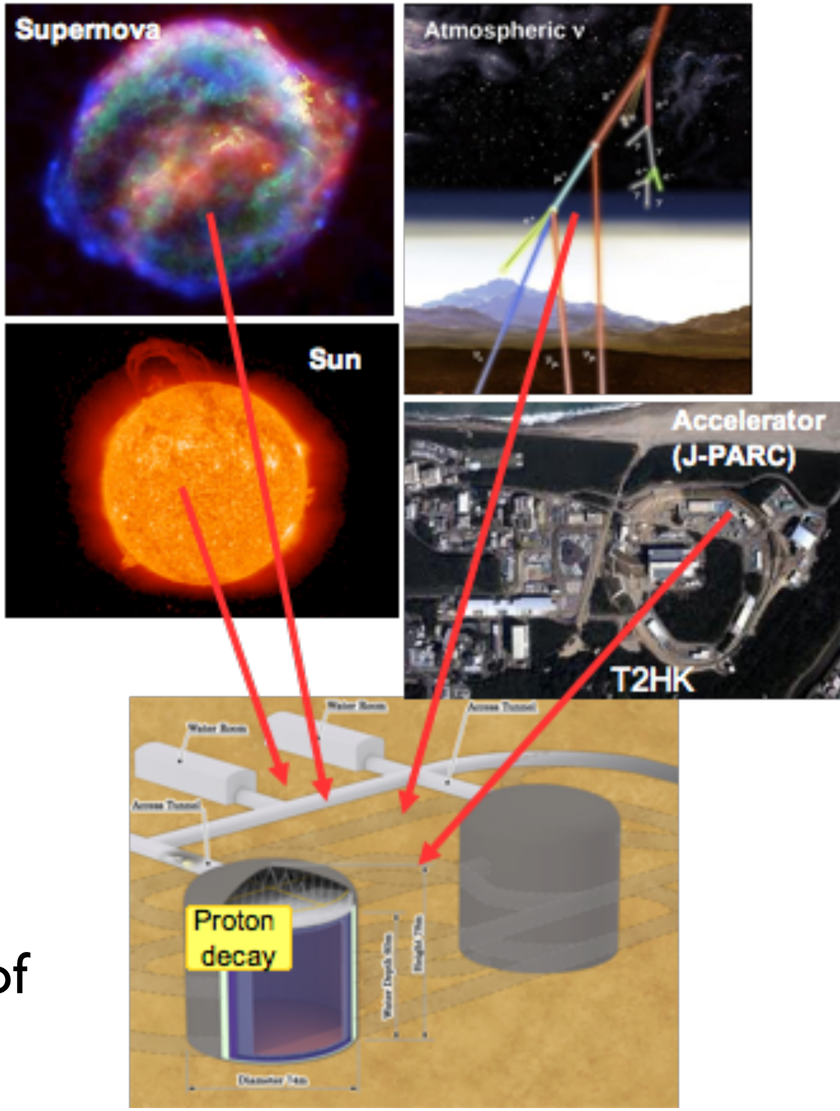
- 2018～2025 HK construction
- 2026～ CPV study

Atm・Solar・Supernova ν study, Proton decay searches

(Note) In the physics potential studies, the 2nd HK tank is assumed to come online 6 years after the start of the 1st tank.

Broad science program with Hyper-K

- Neutrino oscillation physics
  - Comprehensive study with beam and atmospheric neutrinos
- Search for nucleon decay
  - Possible discovery with ~×10 better sensitivity than Super-K
- Neutrino astrophysics
  - Precision measurements of solar ν
  - High statistics measurements of SN burst ν
  - Detection and study of relic SN neutrinos
- Geophysics (neutrinography of interior of the Earth)
- Maybe more (unexpected)

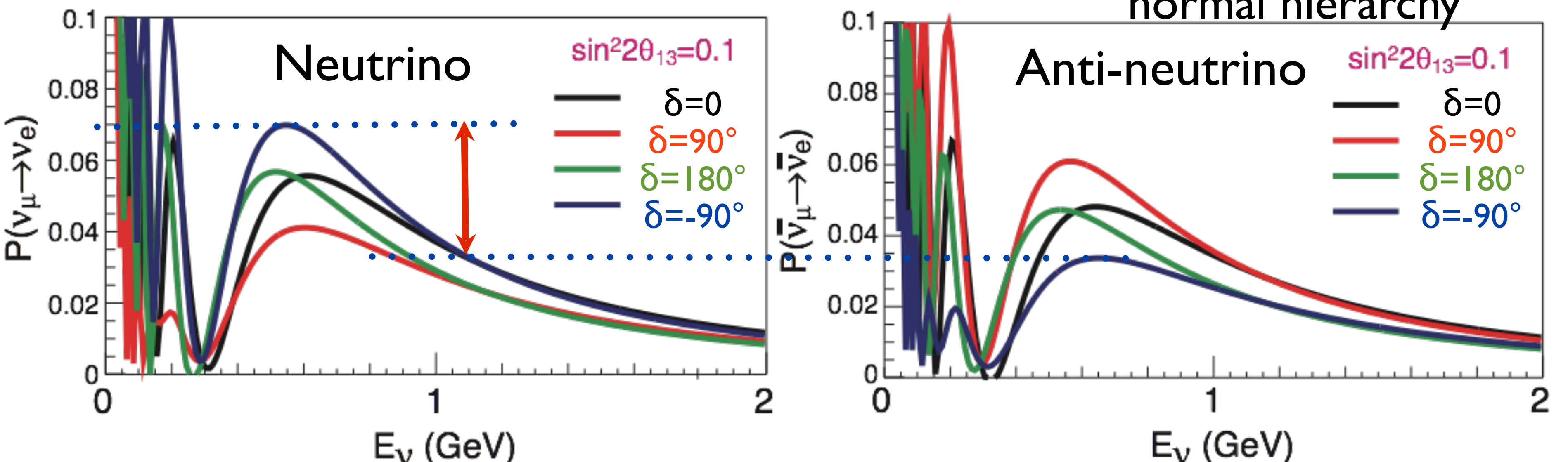


Measurement of *CP* asymmetry with ν beam

$P(\nu_\mu \rightarrow \nu_e)$: ν_e appearance probability

Expect 2000-3000 signal events for each of ν_e and $\bar{\nu}_e$ with HK + upgraded J-PARC neutrino beam (>1.3 MW).

for 295km baseline, normal hierarchy



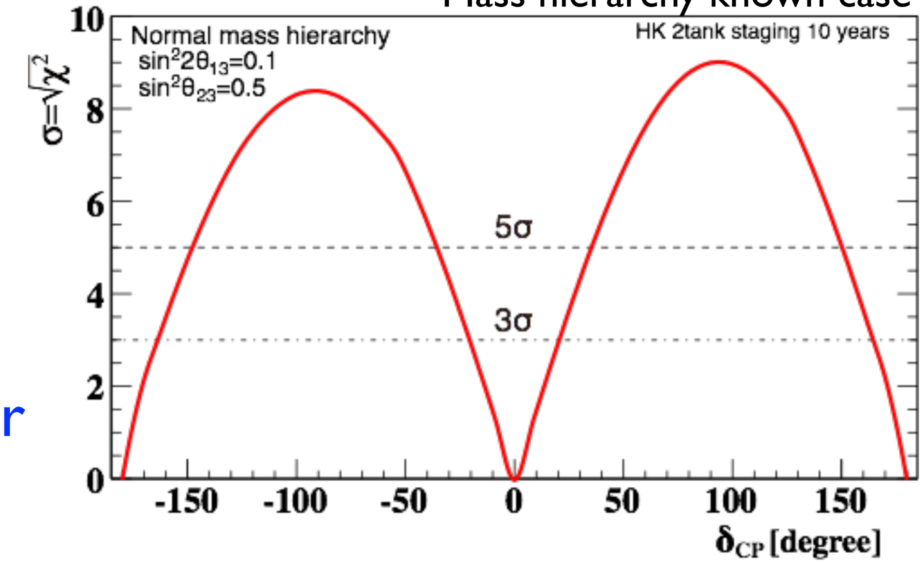
- Comparison of $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  - Max. ~±25% change from δ=0 case
  - Sensitive to exotic (non-MNS) CPV source

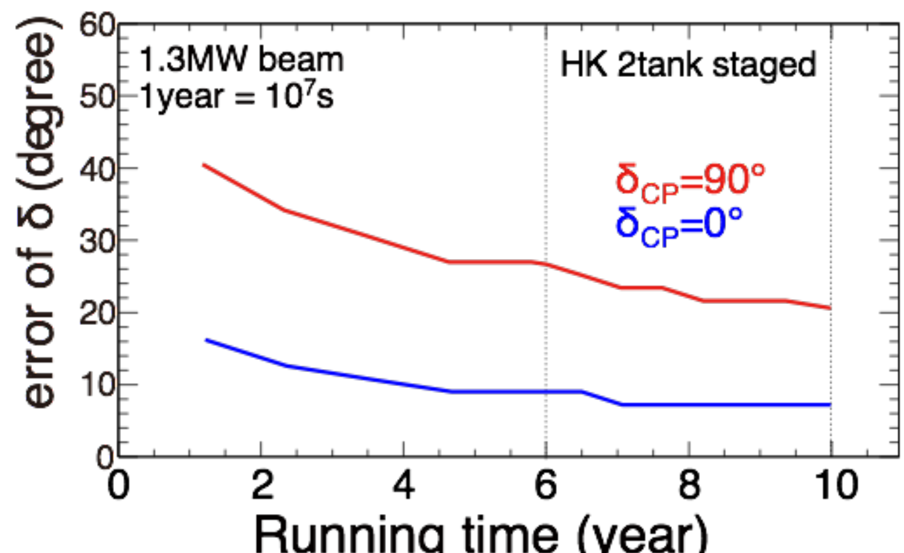
CPV sensitivity

Study CPV in lepton sector

- Exclusion of $\sin\delta_{CP}=0$ (CP conserved case)
  - $>8\sigma(6\sigma)$ for $\delta=-90°(-45°)$
  - ~80% coverage of δ parameter space with $>3\sigma$
- From discovery to δ_{CP} measurement:
  - ~7° precision possible

Mass hierarchy known case





Precision measurements too:

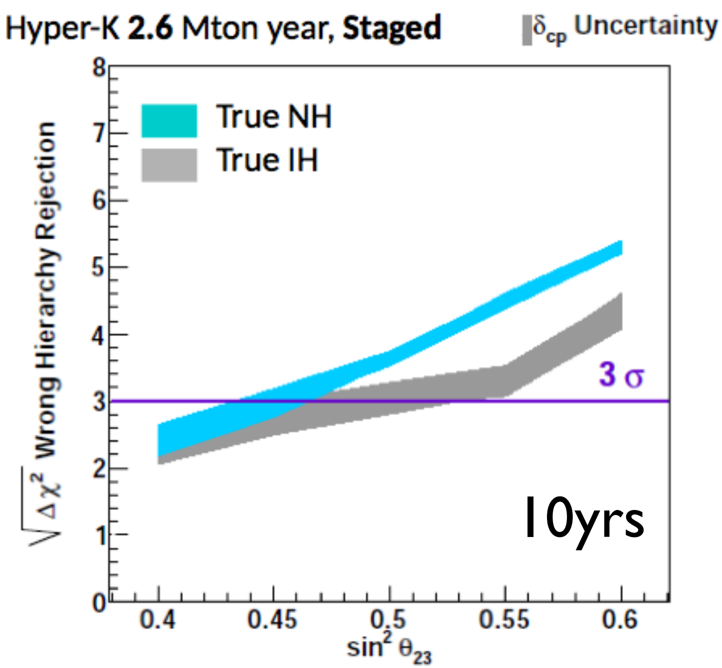
$\delta(\Delta m^2_{32})\sim 1.4\times 10^{-5} eV^2$

$\delta(\sin^2\theta_{23})\sim 0.015$ (for $\sin^2\theta_{23}=0.5$)

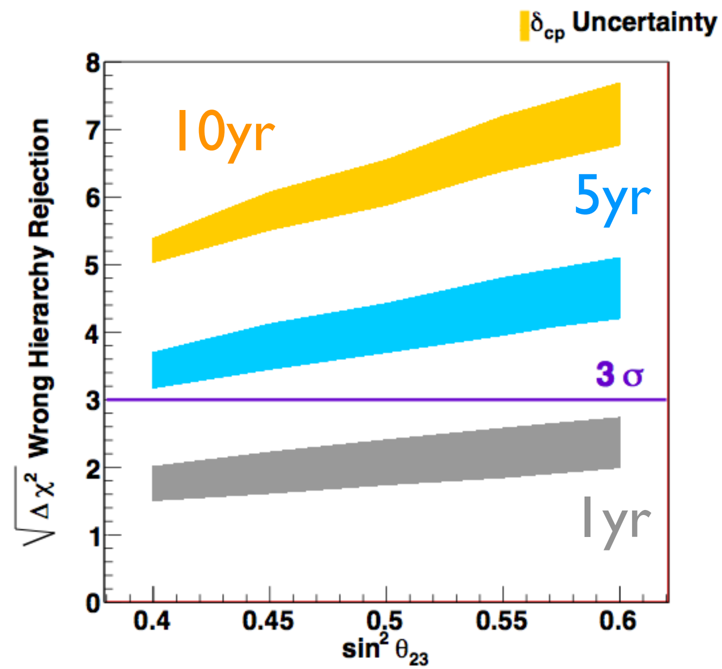
~ 0.006 (for $\sin^2\theta_{23}=0.45$)

Mass hierarchy determination with atmospheric neutrinos

HK atmospheric only



HK atmospheric + beam

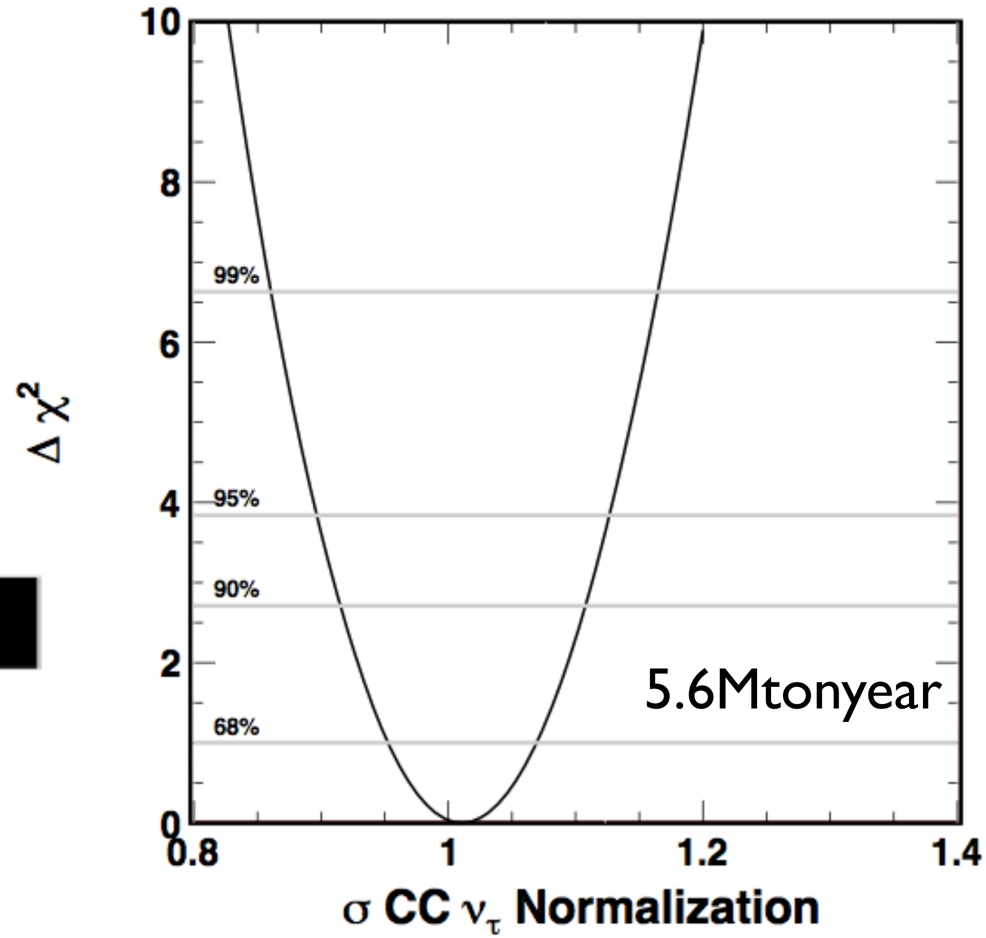


- ~>3σ sensitivity to the mass hierarchy with atm ν only
- Complementary information from beam and atm ν
- Sensitivity enhanced by combining two sources!

Oscillation-induced ν_τ measurements

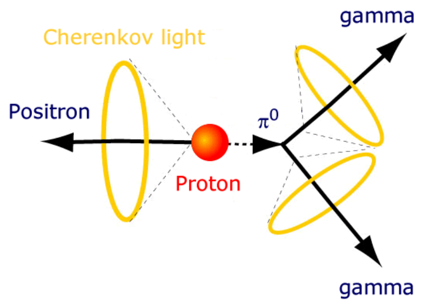
- After 10 years Hyper-K will have O(1,000) ν_τ CC events that can be used to study CC ν_τ cross section, leptonic universality, etc.

per/ 100 kton yr.	Hyper-K
Signal CC $\nu\tau$	40.2
Background	448.7
S /$\sqrt{B}$, 10 years	9.6

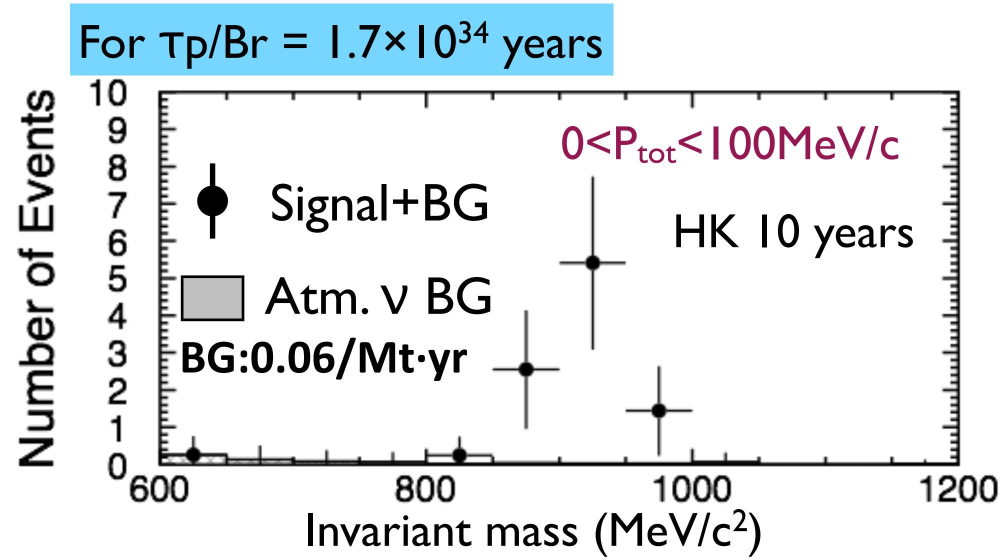


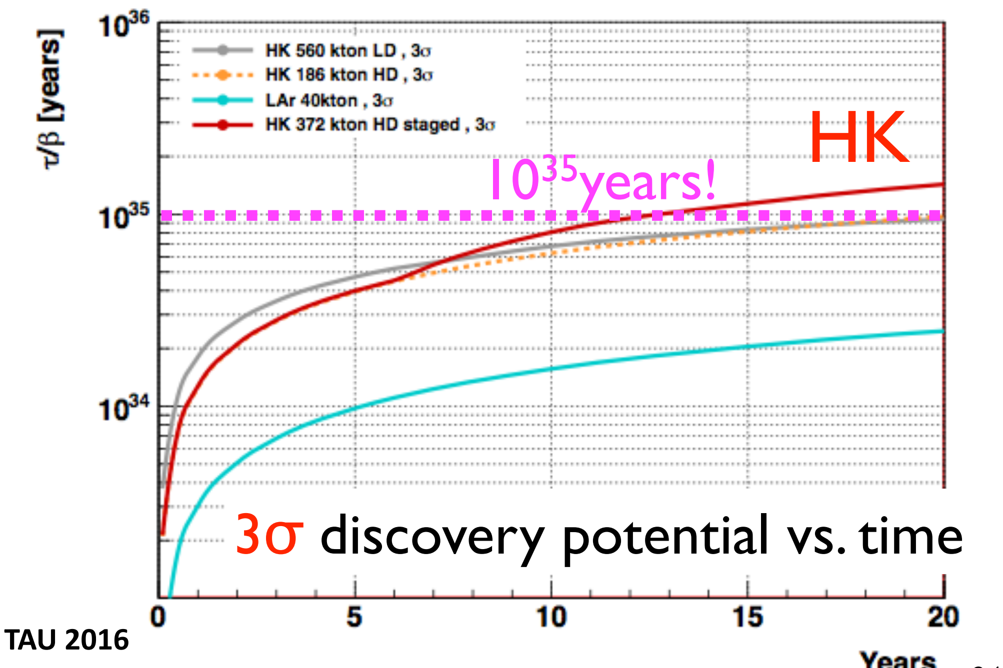
<10% constraint to ν_τ cross section

Searches for $p \rightarrow e^+\pi^0$ in HK



- For lifetime just above the current limit, clear signal can be seen
- Negligible background in the free proton enhanced region
- BG suppression by neutron tagging (thanks to improved photosensor)
- 3σ discovery potential will reach $>10^{35}$ years!





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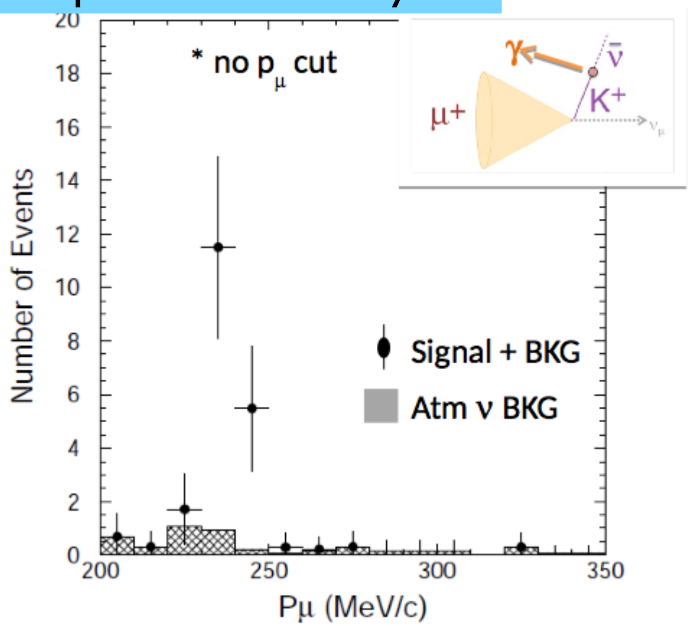
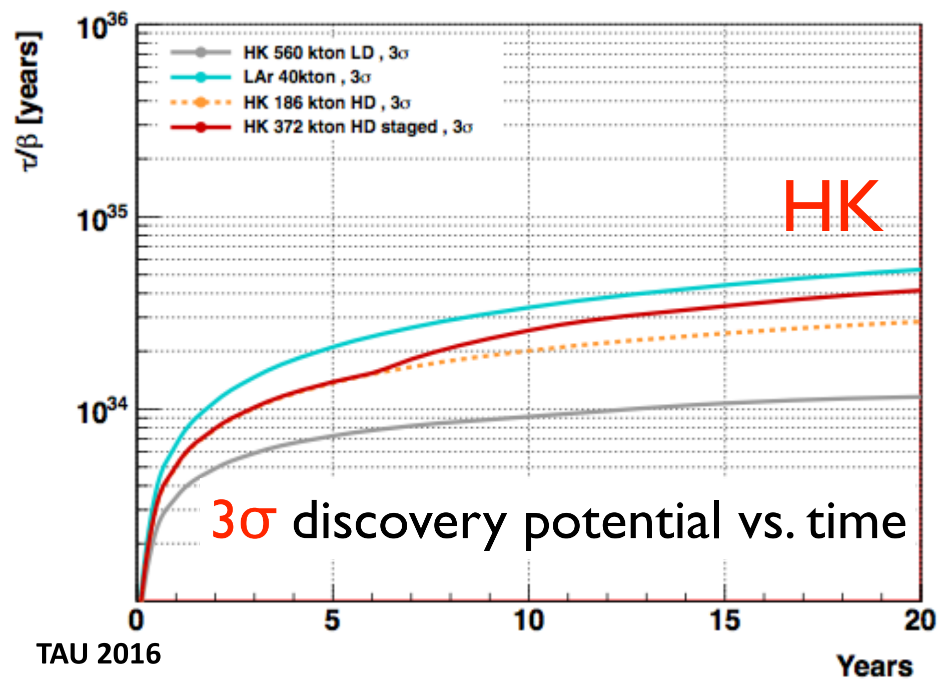
Searches for $p \to \bar{\nu} K^+$ in HK

- K^+ invisible (below Cherenkov threshold) but can be reconstructed via (like in Super-K)
  - $K \to \mu\nu$ tagged by de-excitation γ
  - $K \to \pi^+\pi^0$
- Sensitivity enhanced by improved timing and photon yield
- Clear signal expected for lifetime just above current limit

For $\tau p/Br = 6.6\times10^{33}$ years





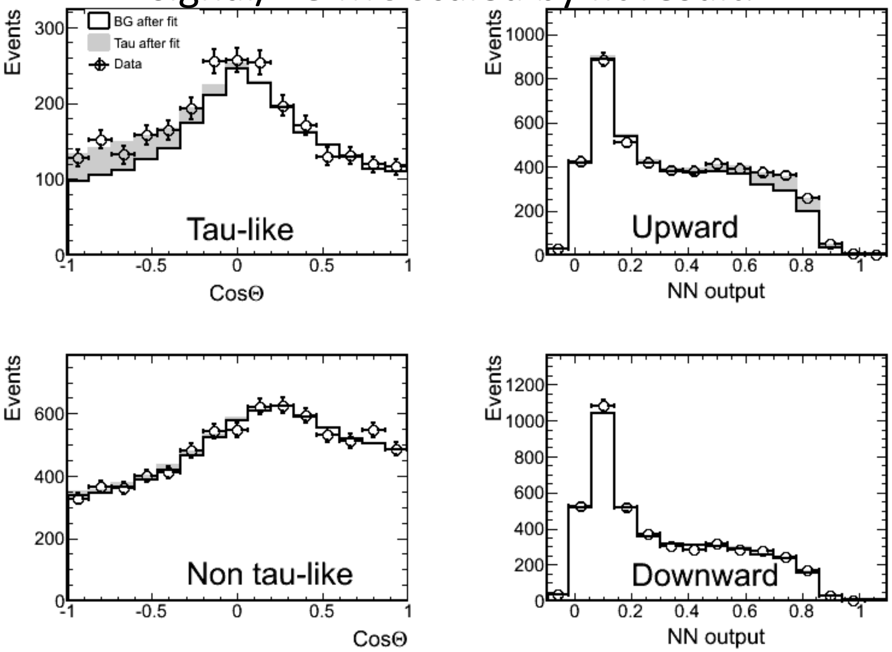
Summary

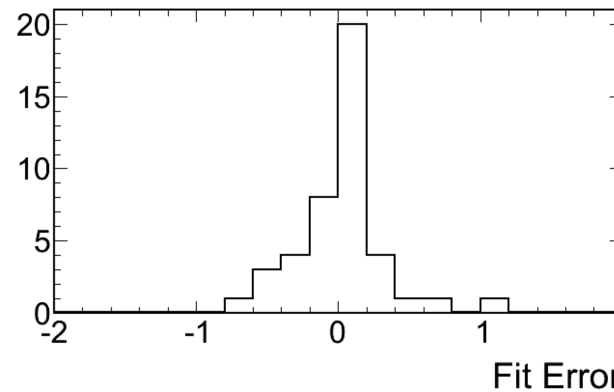
- Super-Kamiokande
  - Tau neutrino appearance with significance of 4.6σ.
  - Normal hierarchy preferred by $\Delta\chi^2 = -4.3$ (p-value between 0.031 and 0.007 in IH hypothesis, 0.45 in NH hypothesis).
  - Weak preference of second octant and δ_{CP} near $3/2\pi$.
- Hyper-Kamiokande
  - Next generation water Cherenkov detector, ~10 times larger volume and better PMTs.
  - Broad science program on neutrino physics, proton decay, geo-physics, etc.

Backups

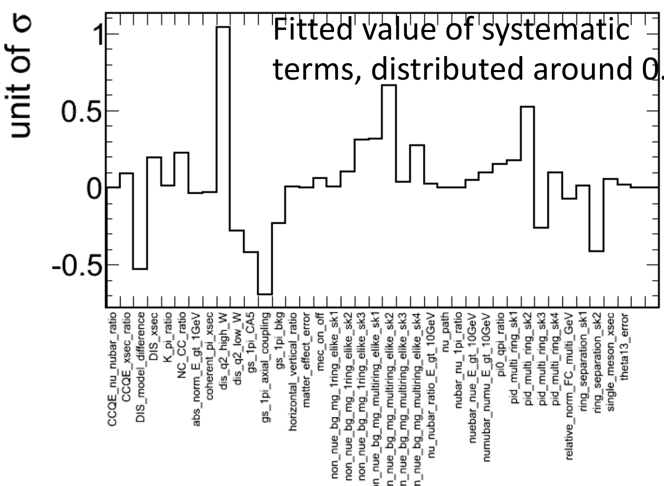
Fit results of tau analysis

Fit result for different samples,
signal/BG MC scaled by fit result.

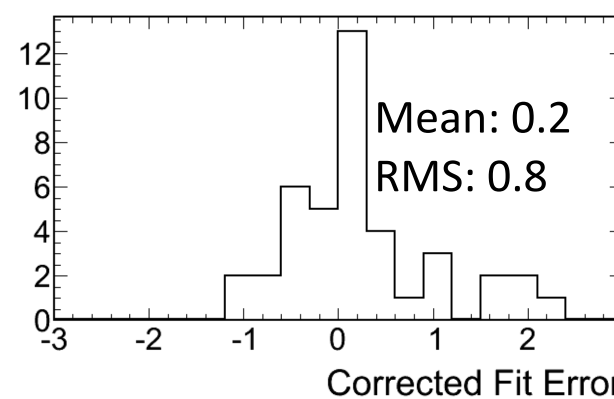




Fitted deviation in unit of σ of systematic errors



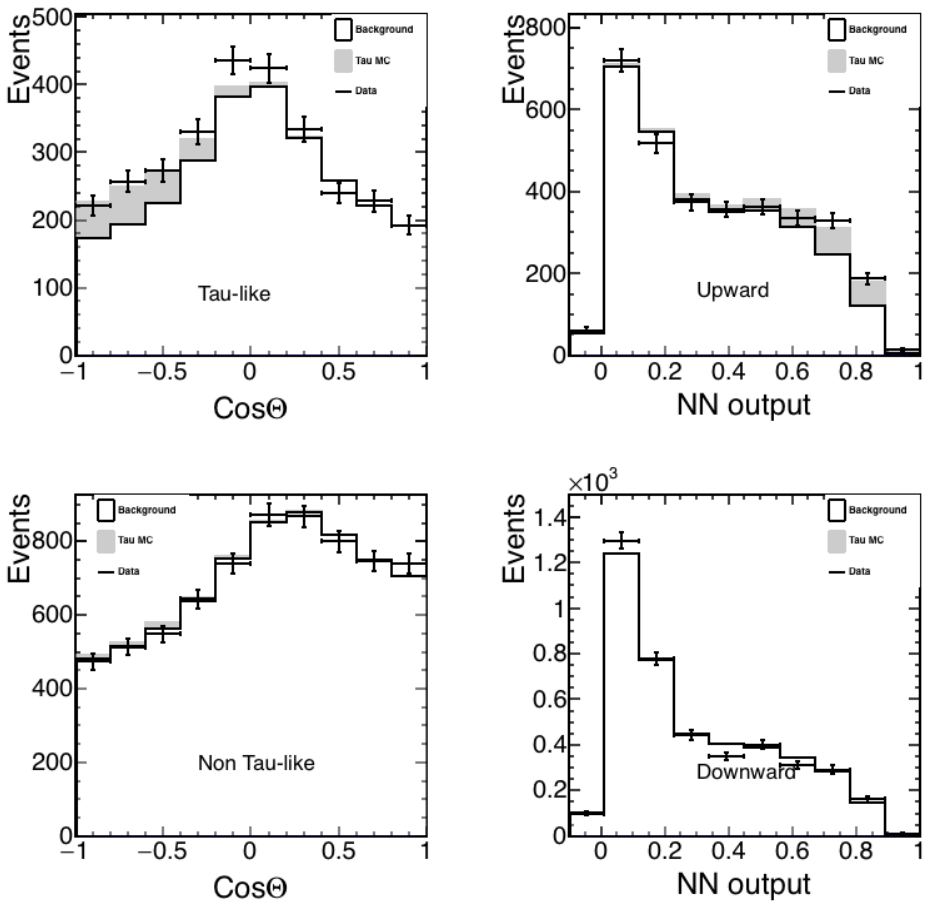
Fitted value of systematic terms, distributed around 0.

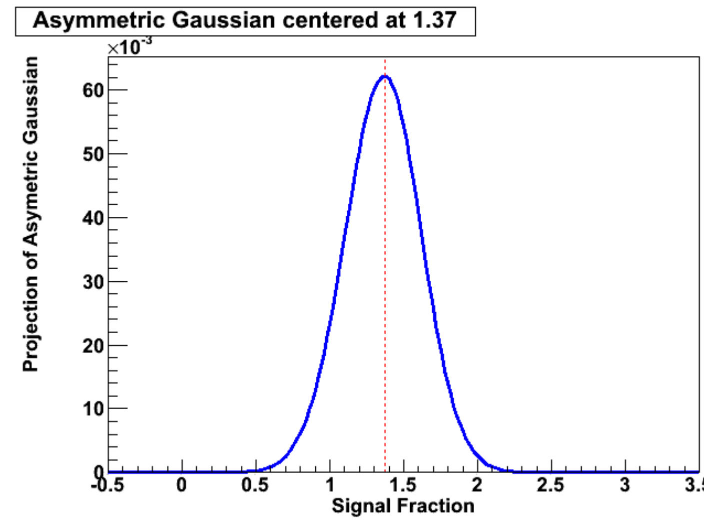


Mean: 0.2
RMS: 0.8

$$\frac{error_{fit} - mean}{sigma_{input} - sigma_{fit}}$$

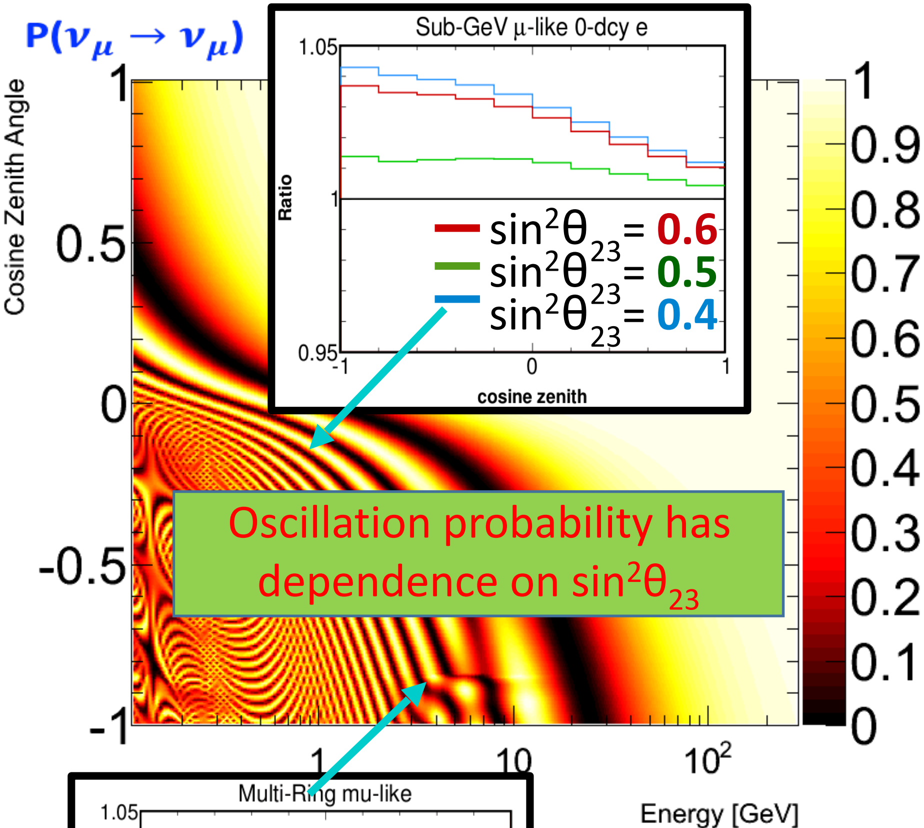
Paper fit update of tau analysis

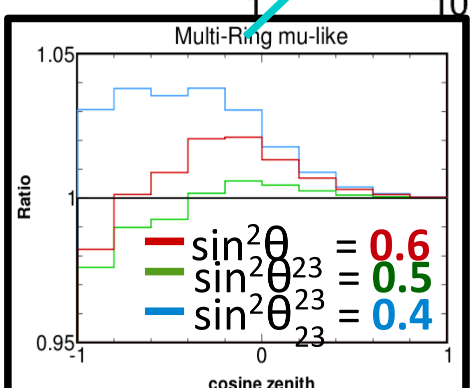




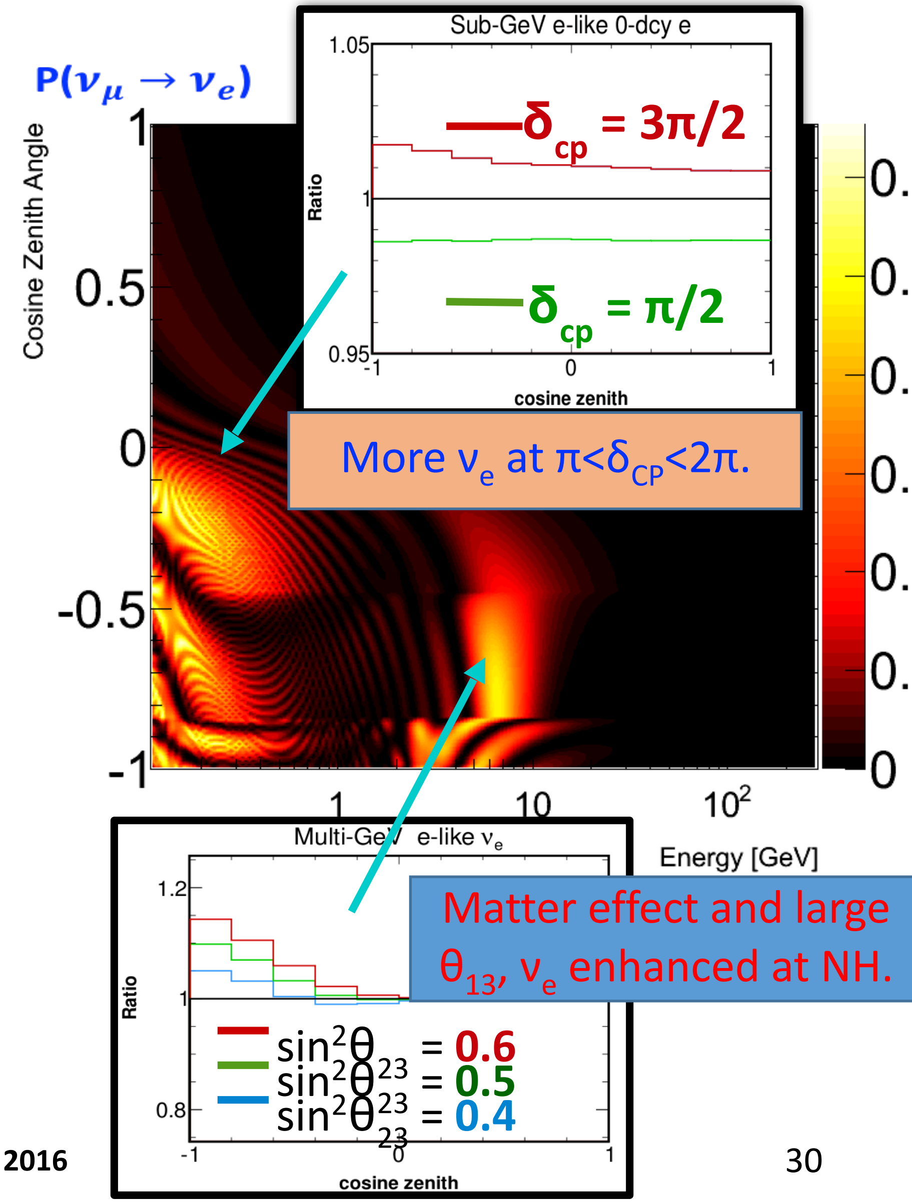
Tau fraction:$1.37 \pm 0.23^{+0.13}_{-0.11}$, the significance is 5.1σ.

Neutrino oscillations at Super-K

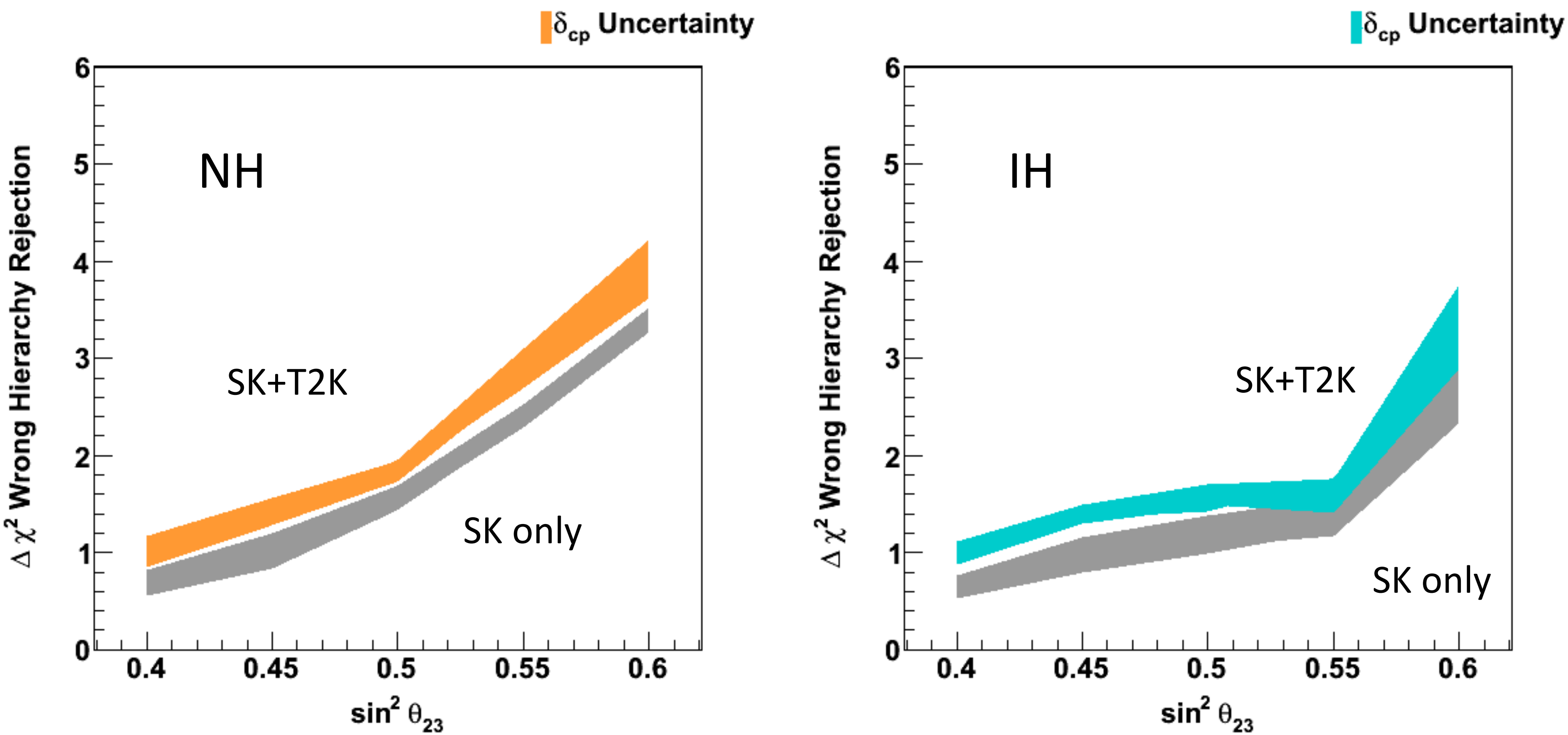




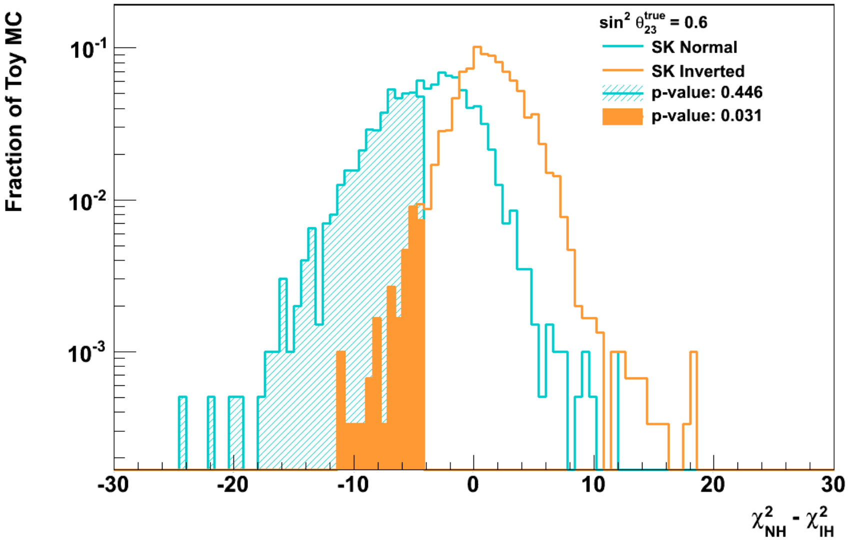
Ratio to two-flavor oscillations shown. Multiple samples used in the analysis.

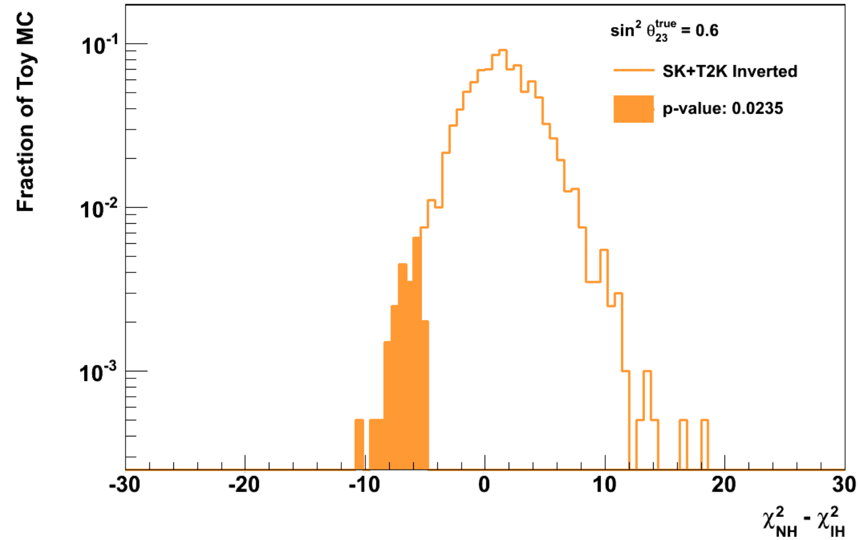


Improved MH sensitivity with T2K constraint

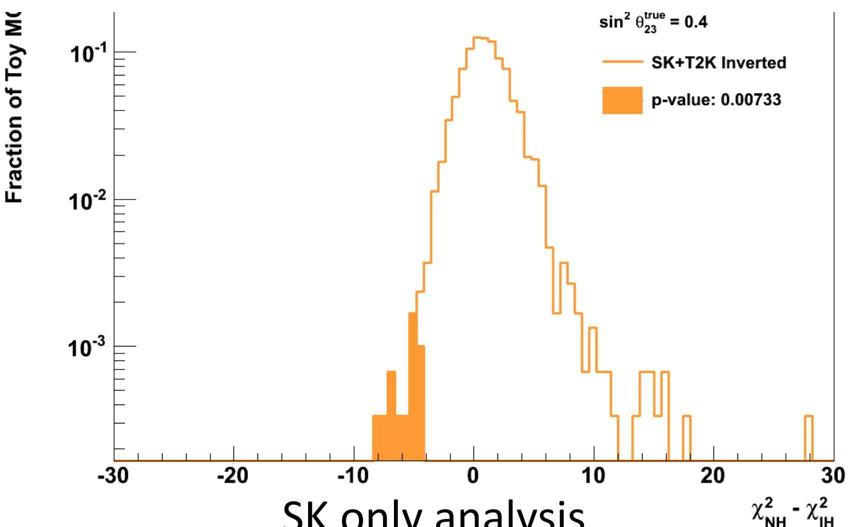


p-value for MH preference



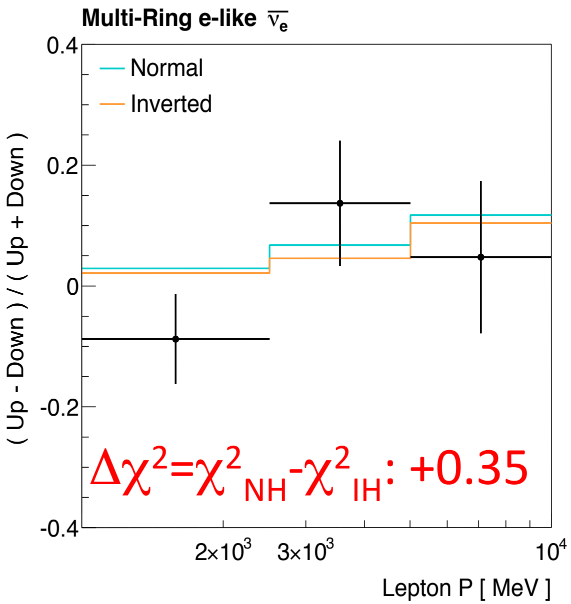


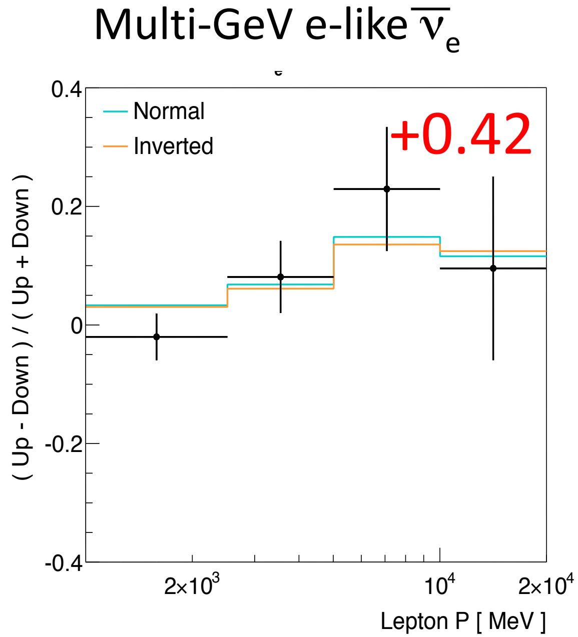
SK analysis with T2K constraint.

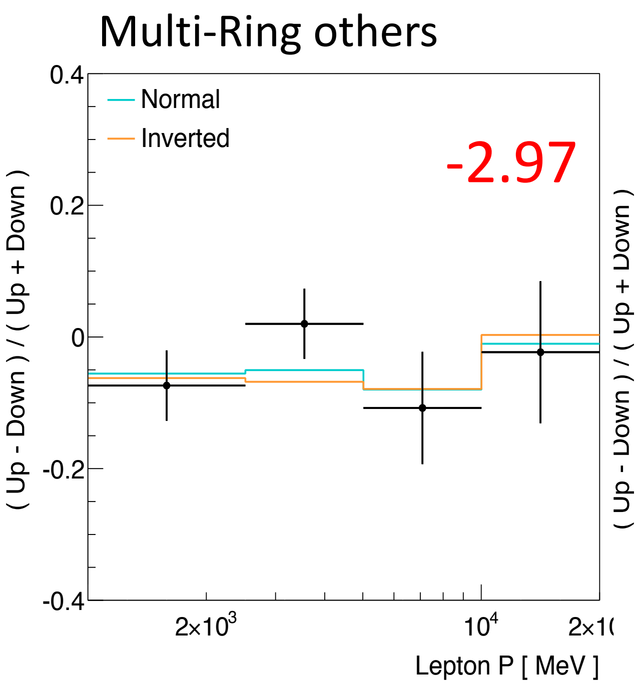


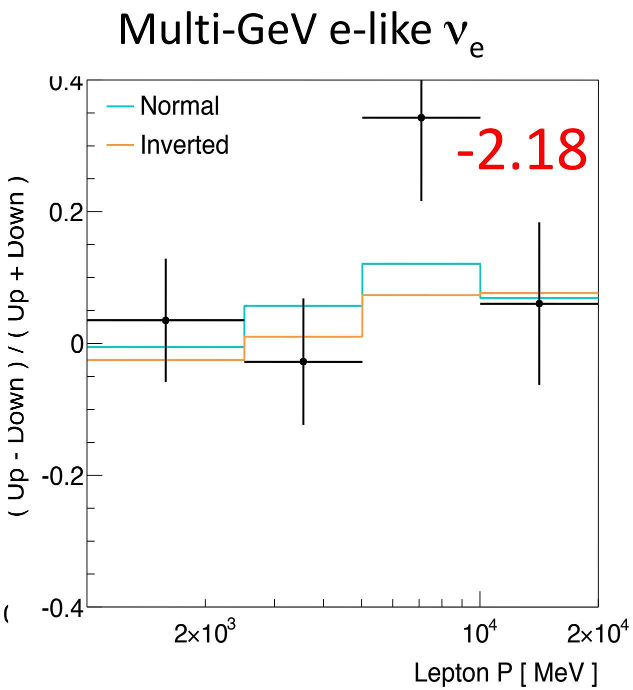
SK only analysis

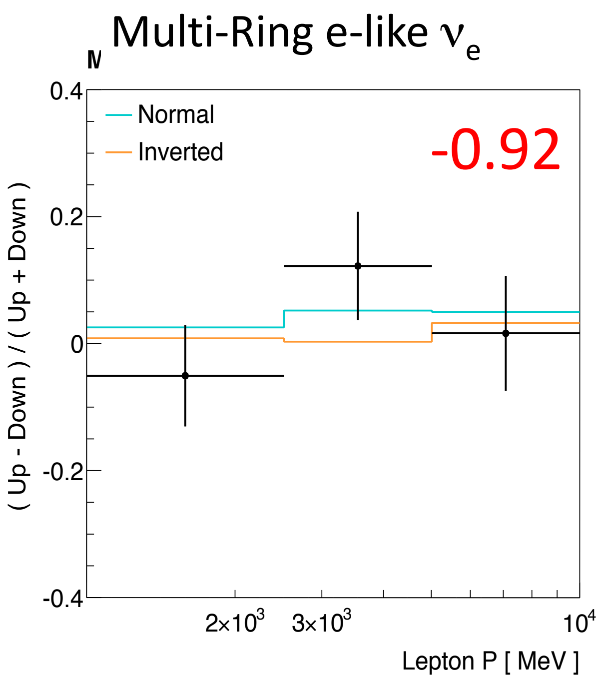
Hierarchy preference in sub-samples



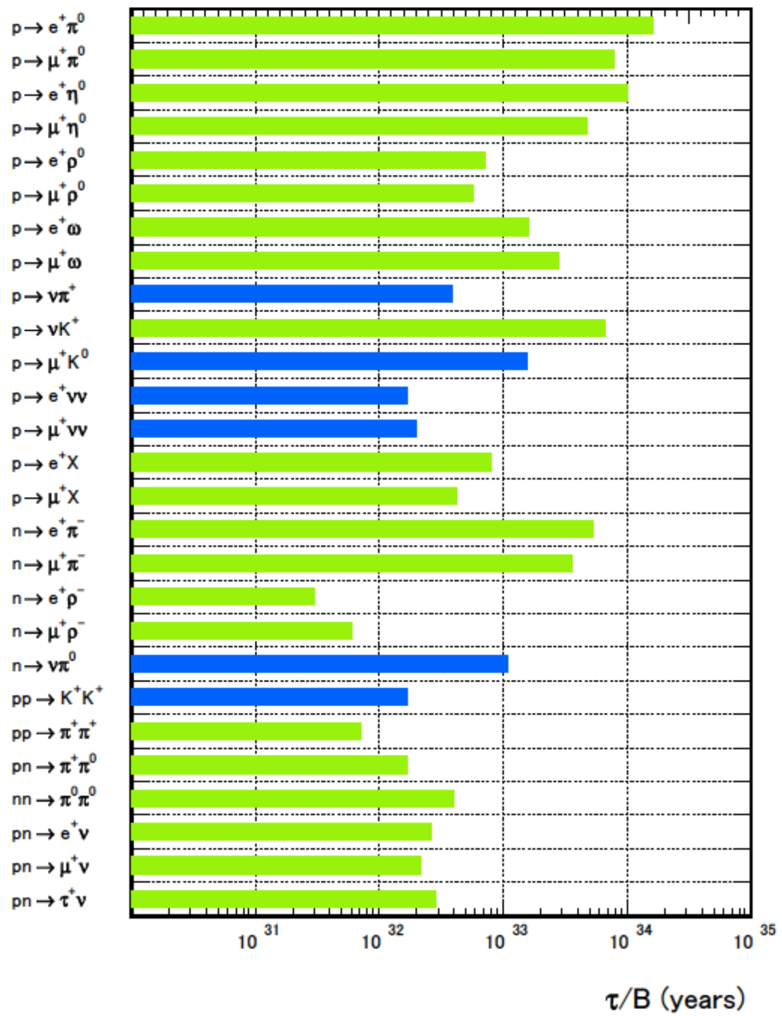








Proton decay results from SK



- Update nucleon decay results by more than 0.3 Mton▪year exposure (green in the left figure).
- Super-Kamiokande can cover large number of decay modes.
- All of them are the most stringent limits on nucleon lifetime.
- We observed some candidates, but still consistent with expected backgrounds and no evidences of nucleon decay have been observed.

Hyper-K backup

Strength of Hyper-K

- Best sensitivity for CP measurement
  - Relatively short baseline (~300km): less matter effect
  - Off axis beam at 1st oscillation maximum
- Large statistics with good S/N
  - ~2000 appearance signal events expected
  - S/N~10 at appearance peak
- Performance proven with real data
  - Building on experience from T2K/Super-K
  - Further improvement expected as we go

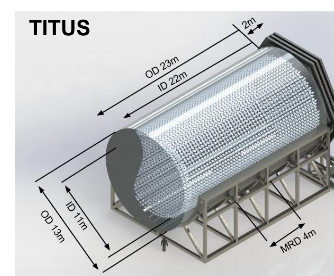
Long baseline experiment using a beam from J-PARC

- The same configuration as T2K (2.5° off-axis beam)
  - Well understood systematics
- Upgraded J-PARC and neutrino beamline
  - >1.3MW expected (current T2K:420kW)

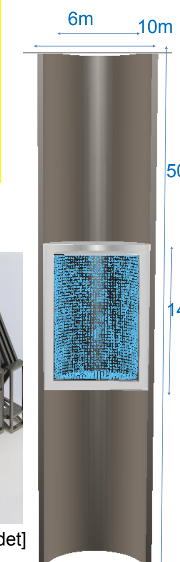
J-PARC upgrade for HK is given the highest priority in KEK Project Implementation Plan (June 2016)

http://www.kek.jp/en/About/Roadmap/

- Near detectors for T2K (with upgrade) will continue for Hyper-K
- New intermediate detector with water Cherenkov technique being investigated



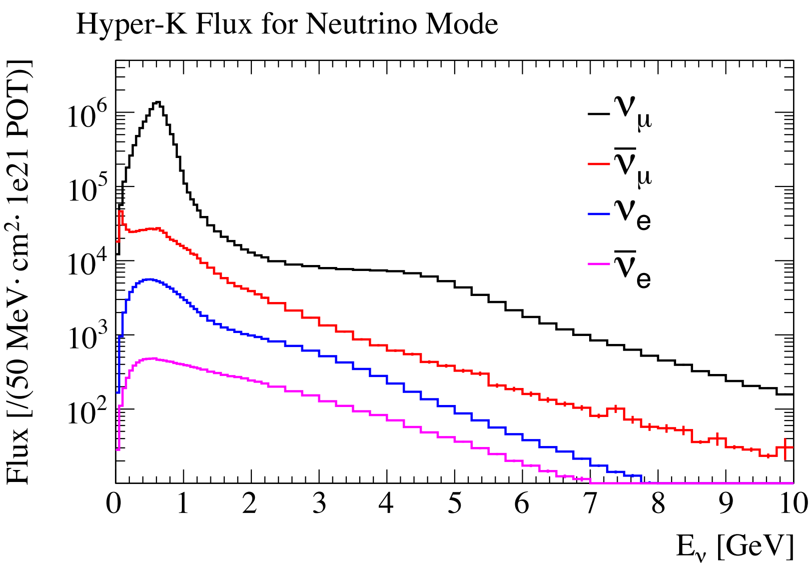
arXiv:1606.08114 [physics.ins-det]

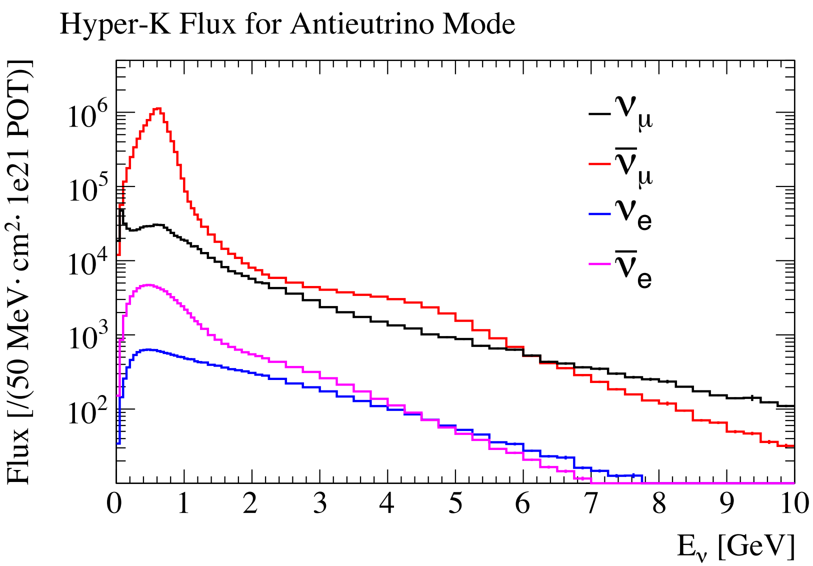


arXiv:1412.3086 [physics.ins-det] **NuPRISM**

Neutrino energy spectrum

- Well understood by NA61@CERN and T2K
- Anti-ν flux ~80% of ν @peak
  - π production multiplicity
  - Of course, cross section on nucleus differs (by ×~3)
- Beam time ratio of ν:$\bar{\nu}$=1:3 is assumed in sensitivity study
  - Different ratio studied but dependence not large for CPV sensitivity





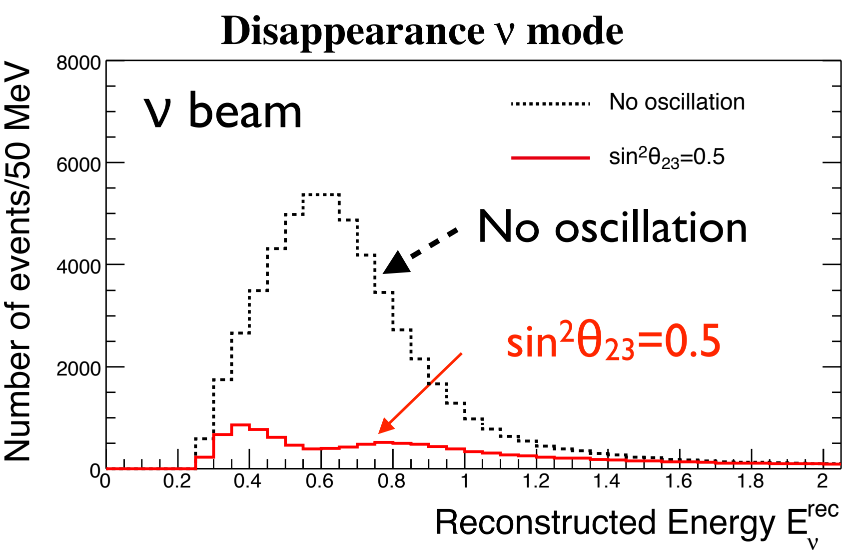
Sensitivity study

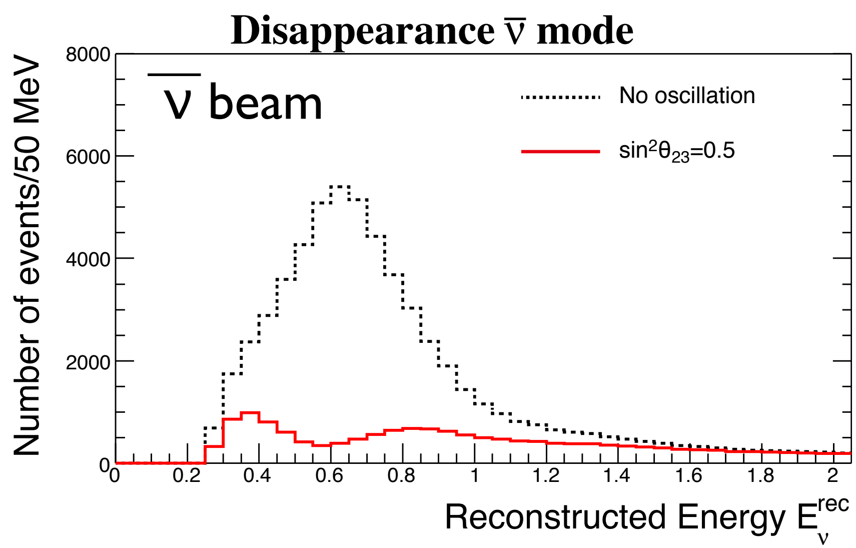
- Based on a framework developed for T2K future sensitivity study (PTEP 2015, 043C01)
  - Fit reconstructed E_ν distributions
  - Both ν_e and ν_μ samples, for ν and anti-ν run
  - Fit $\sin^2\theta_{23}$, Δm^2_{32}, $\sin^2 2\theta_{13}$, δ_{CP}
  - Mass hierarchy assumed to be known (from other experiments and/or HK atmospheric ν)
- Systematic error estimated based on T2K experience/prospects
  - Implemented as covariance matrix, including correlation between energy/flavor bins
  - Compared to published (PTEP 2015, 053C02) result which used a conservative estimate, anti-ν error is improved based on progress in T2K anti-ν data analysis
- Assuming 2Tank HD staging (2nd tank from 7th year), 10 years total run

Expected events

1.3MW, 10×10^7sec, $\nu:\bar{\nu}=1.3$

ν_μ disappearance





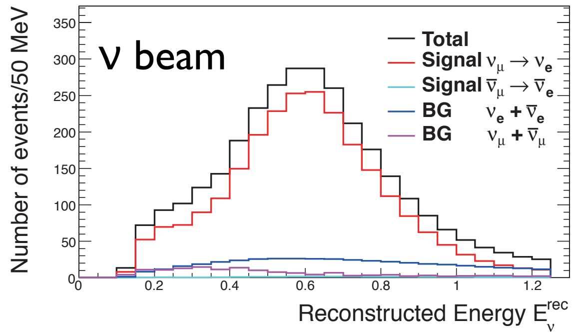
	$\nu_\mu+\bar{\nu}_\mu$ CCQE	ν_μCC nonQE	Others
ν beam	8947	4444	721
$\bar{\nu}$ beam	12317	6040	859

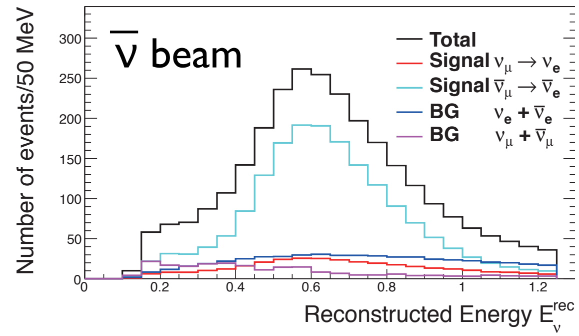
Expected events

1.3MW, 10×10[7]sec, $\nu:\bar{\nu}$=1.3

ν_e appearance

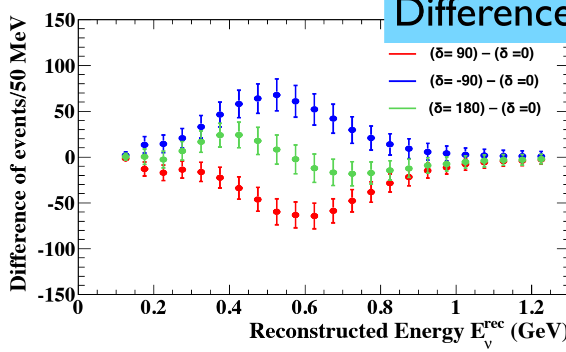
Using fiTQun for π^0 rejection

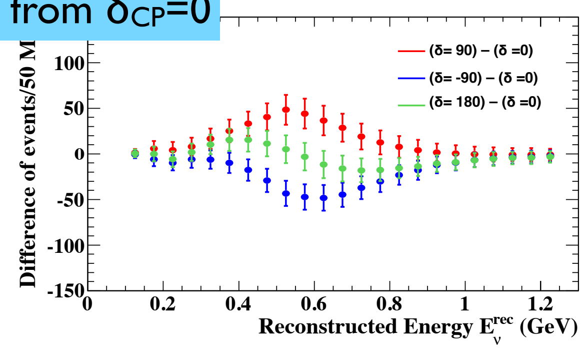




for δ=0	Signal ($\nu\mu \to \nu e$ CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	beam $\nu e/\bar{\nu} e$ contamination	NC
ν beam	2,300	21	10	362	188
$\bar{\nu}$ beam	1,656	289	6	444	274

Difference from δ_{CP}=0





δ=0 and 180° can be distinguished using shape information

Assumed systematic uncertainties

Extrapolation from T2K experience

- Beam flux + near detector constraint
  - Conservatively assumed to be the same
- Cross section uncertainties not constrained by ND
  - Nuclear difference removed assuming water measurements
- Far detector
  - Reduced by increased statistics of atmospheric ν control sample and fundamental detector response understanding with improved calibration

Uncertainty on the expected number of events at Hyper-K (%)

	ν mode		anti-ν mode	
	νe	νμ	νe	νμ
Flux&ND	3.0	3.3	3.2	3.3
XSEC model	0.5	0.9	1.5	0.9
Far Det. +FSI	0.7	1.0	1.5	1.1
Total	3.2	3.6	3.9	3.6

- Further reduction by new near detectors under study
- Benefit from experience with T2K(-II)

θ_{23} and Δm^2_{32}

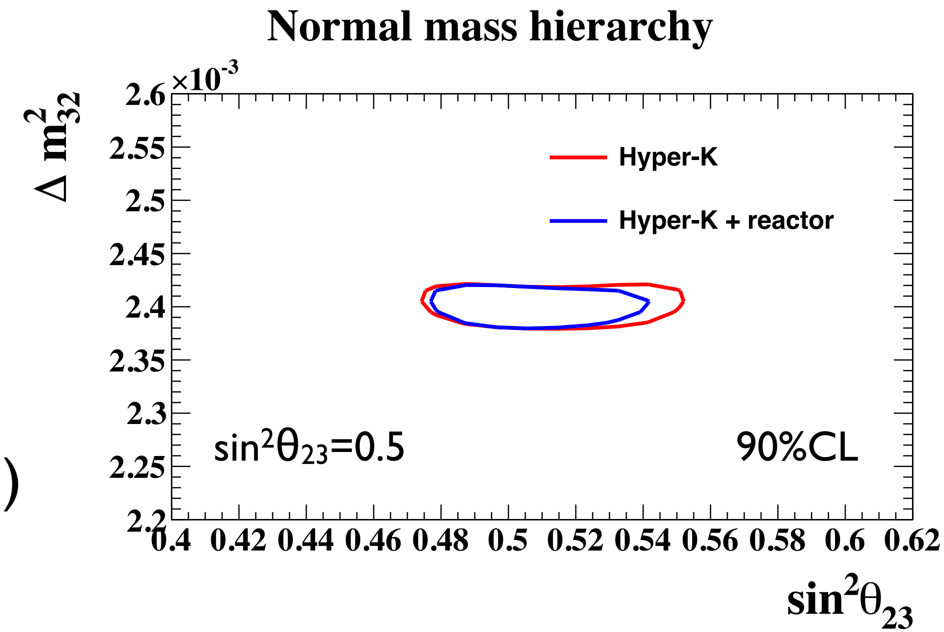
$\delta(\Delta m^2_{32}) \sim 1.4\times10^{-5}\mathrm{eV}^2$

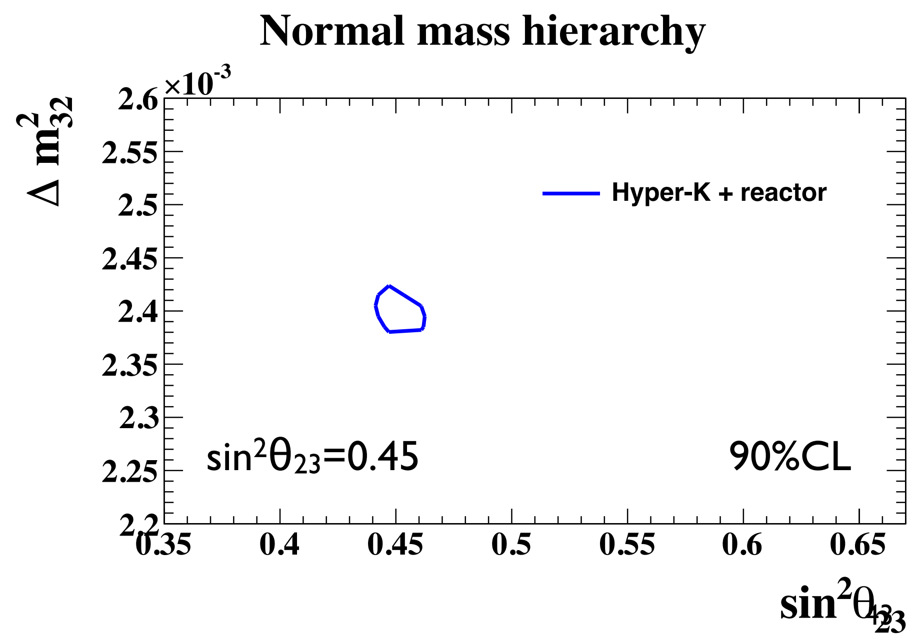
→ Mass hierarchy sensitivity in combination with reactor

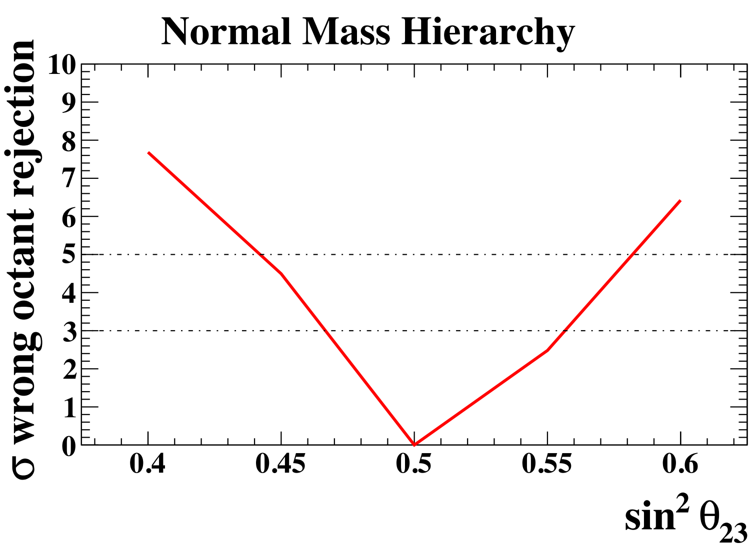
$\delta(\sin^2\theta_{23}) \sim 0.015$ (for $\sin^2\theta_{23}=0.5$)

~ 0.006 (for $\sin^2\theta_{23}=0.45$)

→Octant determination, input to models



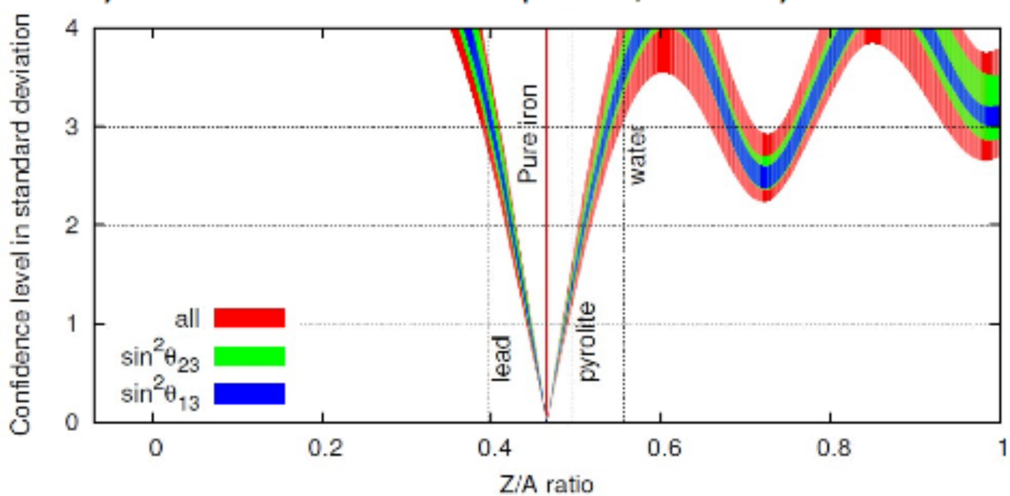


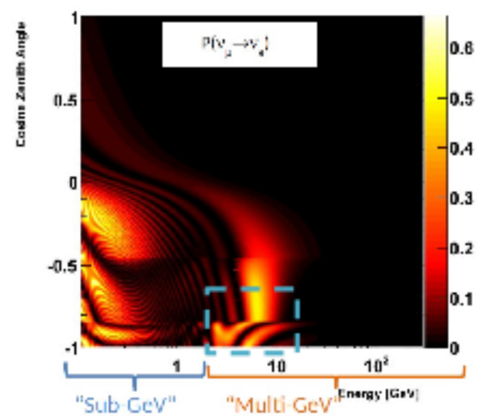


Atmospheric neutrinos

- Large statistics sample of neutrinos with a wide range of energy, path length, and flavor provide sensitivities to many physics topics
  - Neutrino oscillation measurements
    - Precision measurement of standard oscillation parameters (mass hierarchy, θ_{23} octant)
    - Search for exotics (sterile neutrinos, Lorentz violation)
  - Study of the interior of Earth by oscillography
    - Chemical composition of the Earth's core (Z/A ratio) using matter effect ($\propto$electron density)

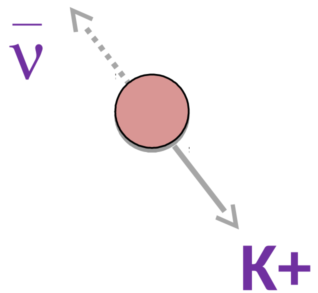
Sensitivity to Outer Core Chemical Composition, 10 Mton yr





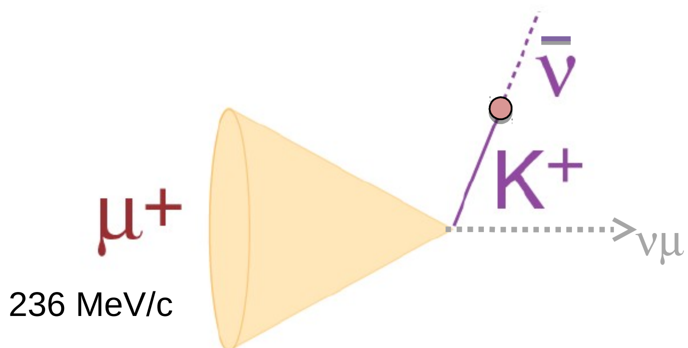
TAU 2016

Proton Decay : $p \rightarrow \bar{\nu} K^+$



- K+ momentum is 340 MeV/c [Cherenkov threshold (749 MeV/c)]
- However, K+ experiences no nuclear interactions and escapes
- Strategy: search for evidence of isolated K+ via its decays
- Cannot reconstruct the original proton mass

$K^+ \rightarrow \mu^+ \nu_\mu$ BR: 65%

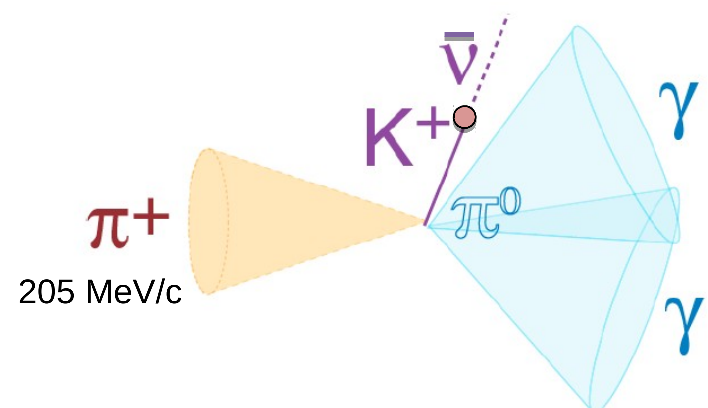


Search Methods

- 1) Nuclear deexcitation γ, μ, and decay e+
- 2) Monochromatic μ from K+ decay

Faster PMT timing and higher photon yield in the Hyper-K HD design improve signal efficiency

$K^+ \rightarrow \pi^+ \pi^0$ BR: 21%



Search Method

- 3) π^+ and two γ from π^0 decay

Nucleon decay searches

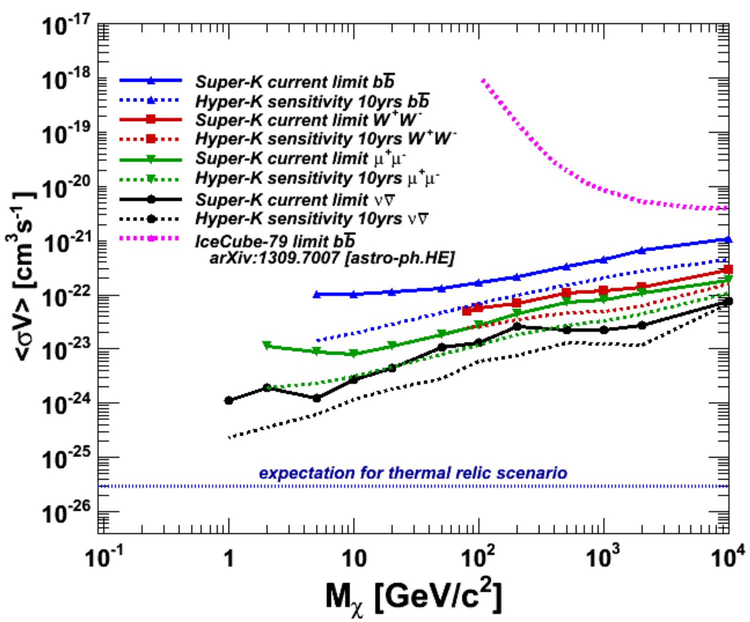
- Will be sensitive to a wide variety of nucleon decay modes
- 3σ potential exceeds current limits by an order of magnitude (or more)

	3σ discovery potential (10yrs)	Current limit (90%CL)
$p \to e^+\pi^0$	8.0×10^{34}	1.4×10^{34}
$p \to \nu K^+$	2.5×10^{34}	0.7×10^{34}
$p \to \mu^+\pi^0$	8.7×10^{34}	1.1×10^{34}
$p \to e^+\eta^0$	4.0×10^{34}	0.4×10^{34}
$p \to \mu^+\eta^0$	8.3×10^{34}	0.1×10^{34}
$n \to e^+\pi^-$	1.7×10^{34}	0.2×10^{34}
$p \to \mu^+\pi^-$	1.1×10^{34}	0.1×10^{34}

Indirect DM searches

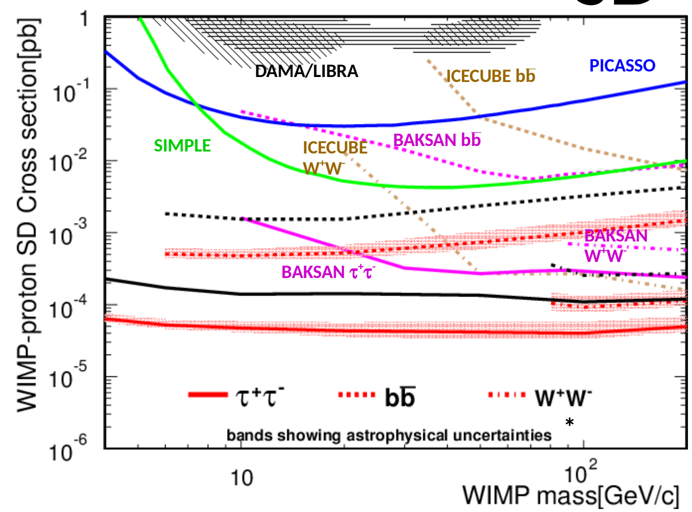
- Unique sensitivities, especially for low mass region
- Improve ×3-10 over SK limit

From Galactic center

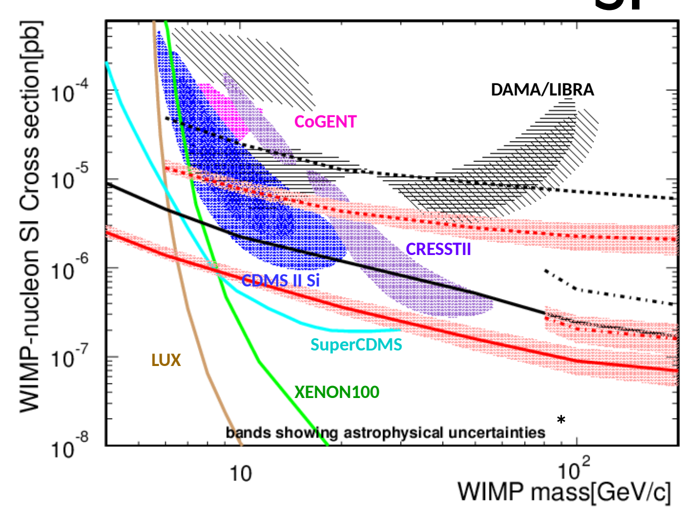


From Sun

SD



SI



Summary of physics potential

		2TankHD w/ staging
LBL (13.5MWyr)	δ precision	7°-21°
	CPV coverage (3/5σ)	78%/62%
	$\sin^2\theta_{23}$ error (for 0.5)	±0.017
ATM+LBL (10 years)	MH determination	>5.3σ
	Octant ($\sin^2\theta_{23}$=0.45)	5.8σ
Proton Decay (10 years)	$e^+\pi^0$ 90%CL	1.2×10^{35}
	νK 90%CL	2.8×10^{34}
Solar (10 years)	Day/Night (from 0/from KL)	6σ/12σ
	Upturn	4.9σ
Supernova	Burst (10kpc)	104k-158k
	Nearby	2-20 events
	Relic (10 yrs)	98evt/4.8σ