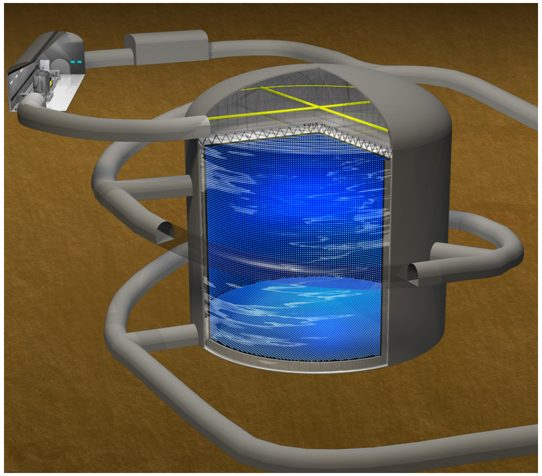
Higher energy physics at Hyper-Kamiokande

Higher energy ν physics at HK

- **Accelerator neutrinos (~0.6GeV)**
  - L=295km (fixed baseline)
  - Upgraded J-PARC ν beam
  - well understood beam at oscillation max.

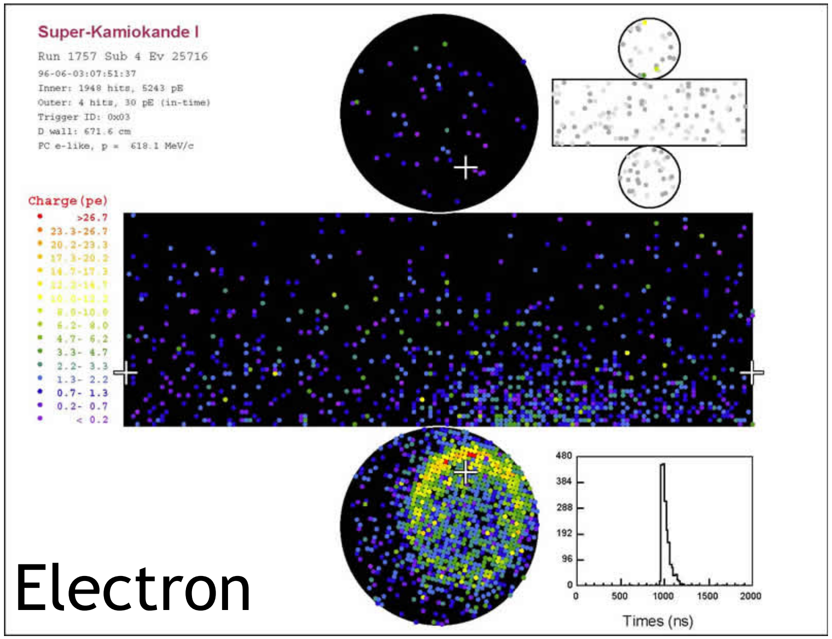


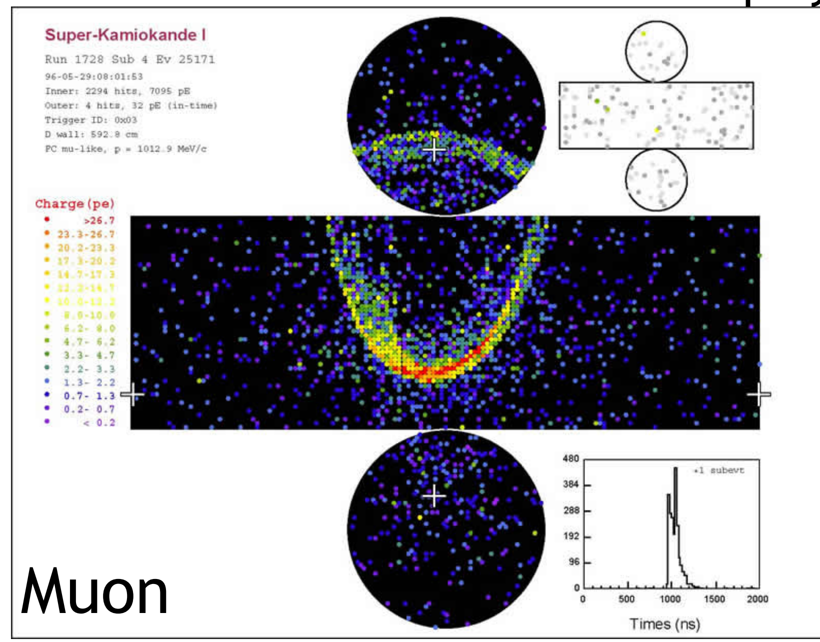
complementary

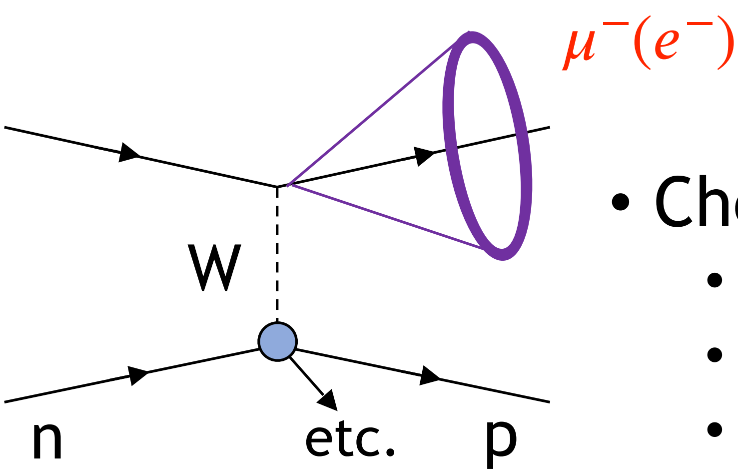
- **Atmospheric neutrinos (0.1GeV~TeV)**
  - 10km < L < 10^4km
  - Resonant oscillations due to Earth's matter effects
  - cover wide range of oscillation parameter space (e.g. NSI search)
- **Astrophysical neutrino sources (GeV~TeV)**
  - Neutrino from point sources: galactic centre, sun, earth
  - AGN/GRB/neutron star merger, dark matter annihilation
  - complementary to IceCube/KM3NeT (~TeV and above)
- **Nucleon decay search (~GeV)**
  - Probe to Grand Unified Theory at very high energy scale

Water Cherenkov detector for GeV scale

SK event displays





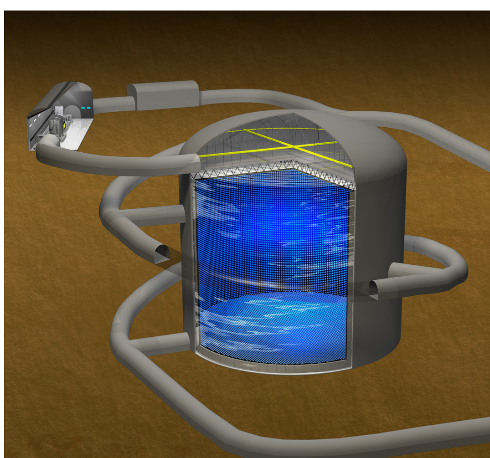


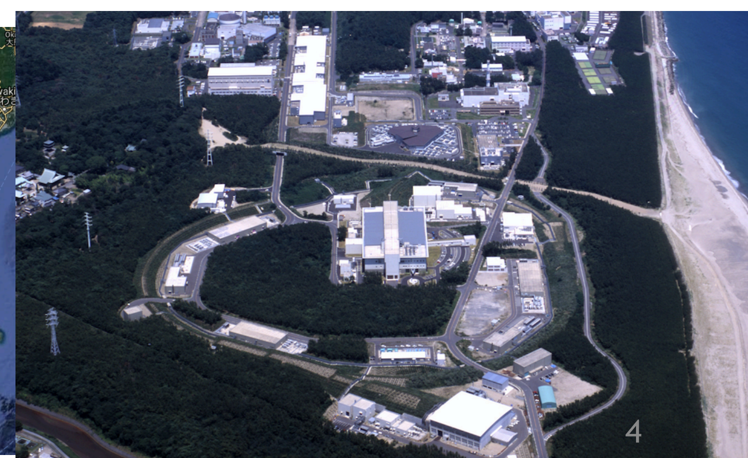
- Cherenkov ring
  - Particle identification (>99% efficiency)
  - Momentum reconstruction
  - Multi-rings for non-QE, proton decay

HK long baseline project

- **J-PARC neutrino beam**
  - off-axis ν beam peaked at ~600MeV (oscillation maximum)
    - CCQE dominant: suitable for water Cherenkov detector
    - Narrow band beam to suppress NC π^0 and CC non-QE
  - Recent news from T2K
    - 485kW stable run (500kW achieved)
    - Protons on target (POT) accumulated (1:1 for ν and anti-ν mode)
    - **Hint of CP violation** (δ_{CP}~—90^o favoured)

Good opportunity for CP measurement at HK



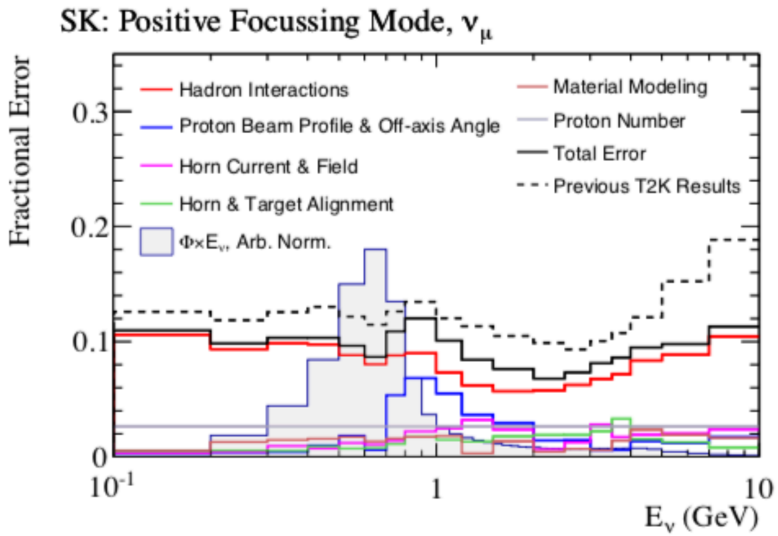


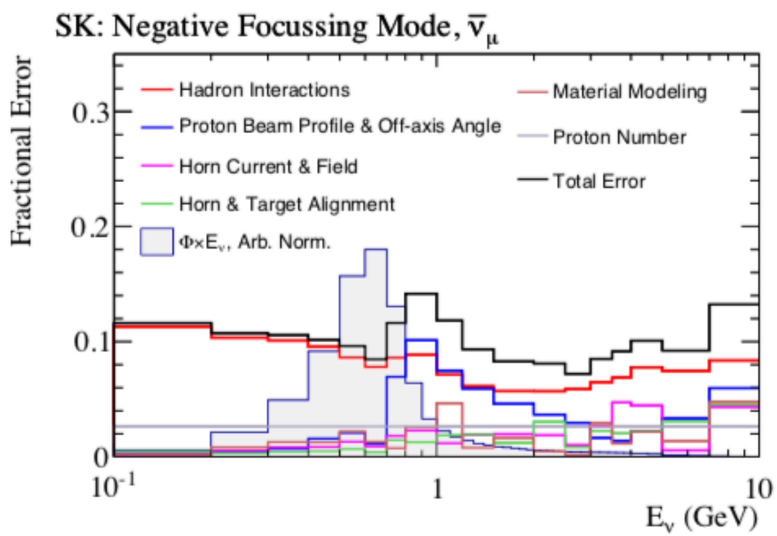
J-PARC neutrino beam

- **Upgrades plan for HK (500kW → 1.3MW)**
  - Replace MR power supply
  - Replace RF system
  - Upgrade injection/extraction devices
  - Upgrade the beam monitors

  Doubles repetition cycle (2.5s → 1.2s)

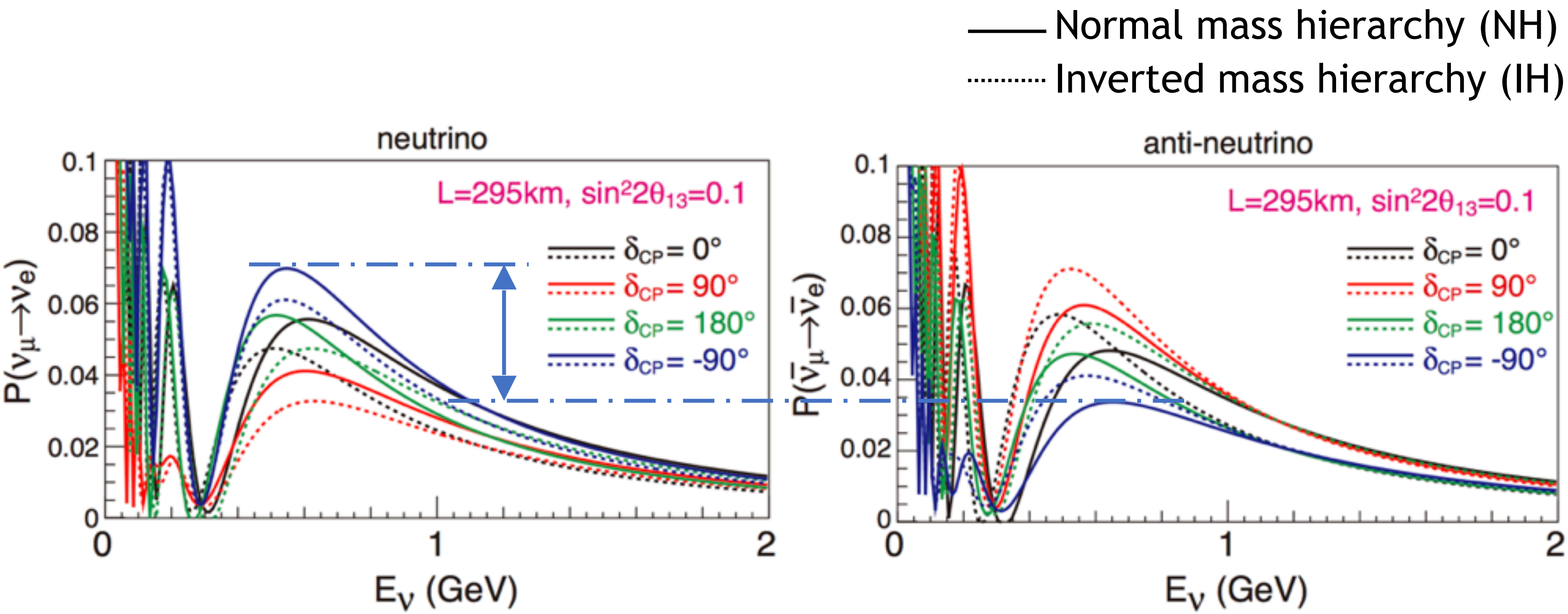
- **External measurements help to suppress flux systematic errors**
  - Flux uncertainty dominated by **hadron production model**





Measurement of CP asymmetry with neutrino and antineutrino beams

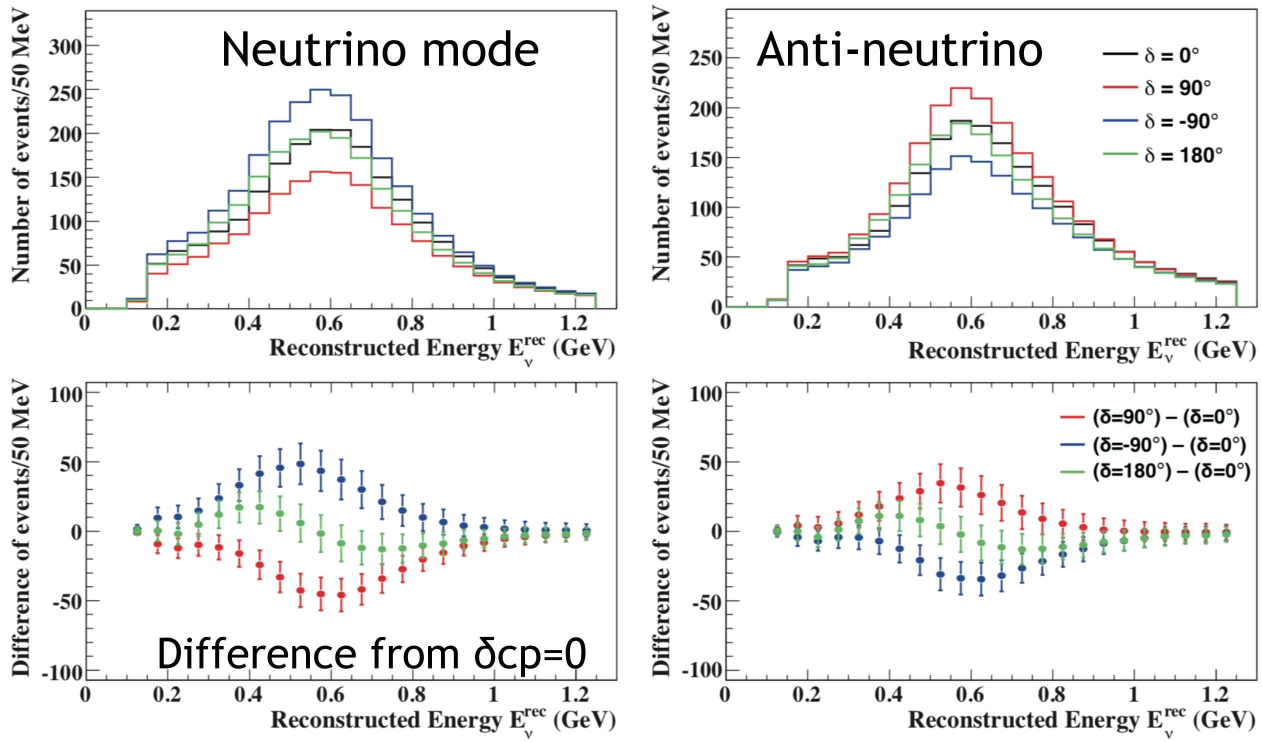
- CP violation emerges as different oscillation probabilities in neutrino and anti-neutrino



- Comparison of oscillation probabilities: $P(\nu_\mu \rightarrow \nu_e)$ vs. $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  - Up to ~30% variation at δ_{CP}~—90° in NH wrt $\sin\delta_{CP}$=0

Expected signal at HK

Normal hierarchy



Expected signals and background in 10 years with single tank + 1.3MW beam

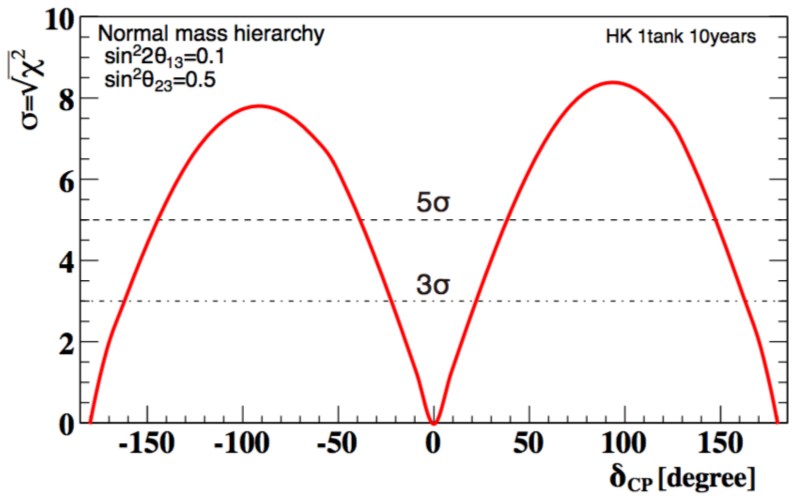
	Appearance signal	Wrong sign signal	Beam background	NC background
Neutrino mode	**1640**	20	260	130
Anti-neutrino mode	**1180**	210	320	200

Prospects for CP violation measurements

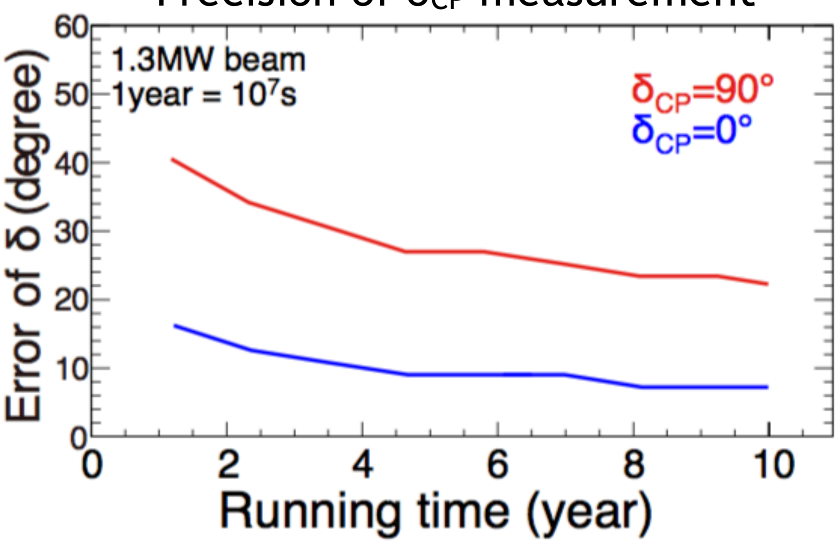
- Exclusion of sinδ_{CP}=0
  - −8σ for δ_{CP} = −90° (T2K favoured)
  - Good opportunity to make discovery of neutrino CP violation at > 5σ
- Measurement of neutrino δ_{CP}
  - 23° for δ_{CP} = 90°
  - 7° for δ_{CP} = 0°

  Input to Investigate origin of CPV

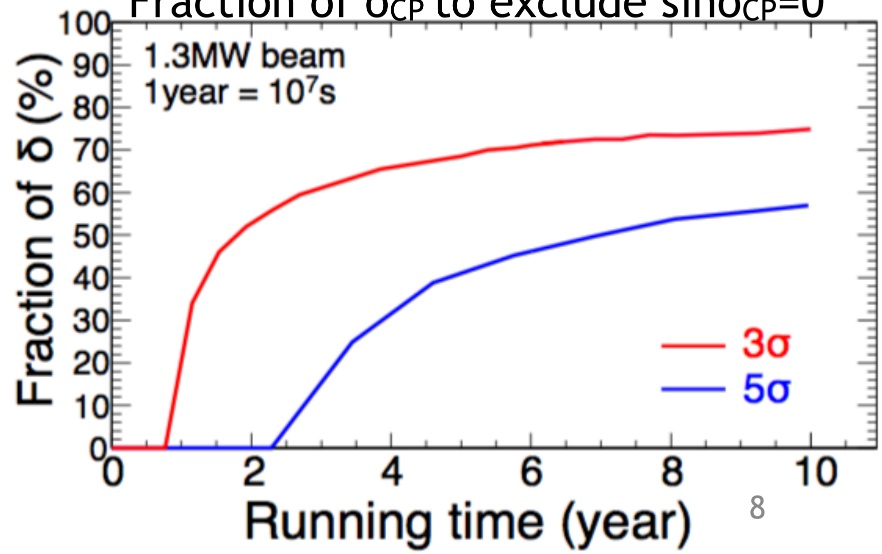
Significance of CP violation measurement



Precision of δ_{CP} measurement

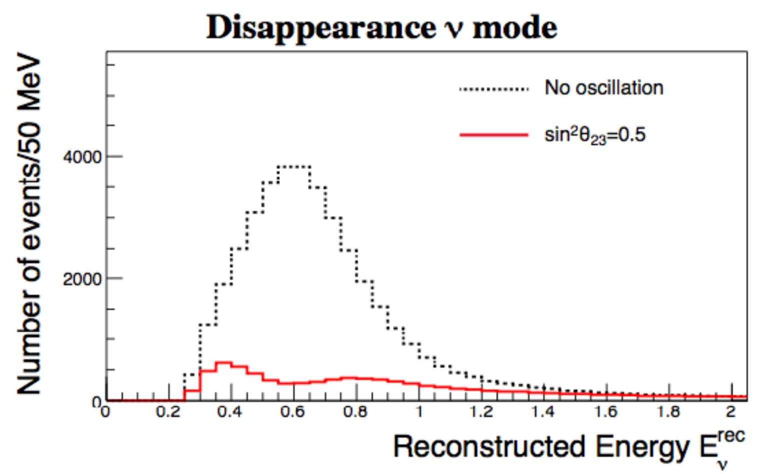


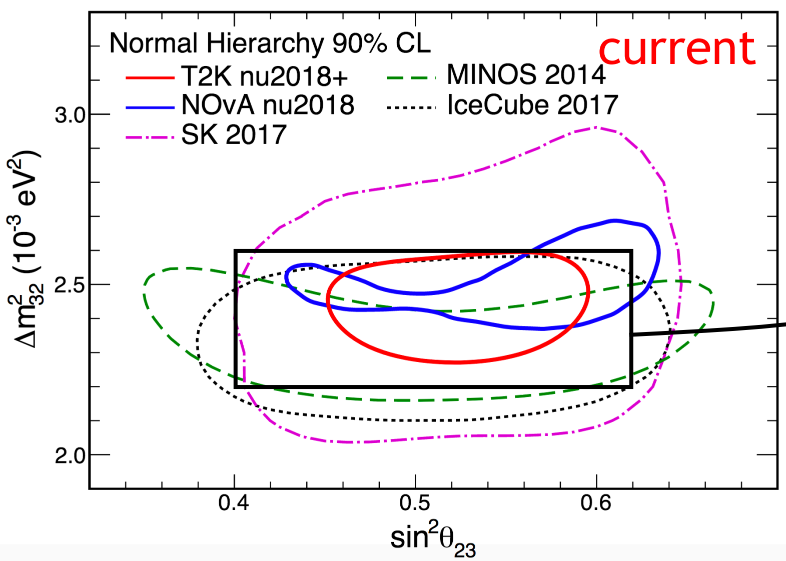
Fraction of δ_{CP} to exclude sinδ_{CP}=0

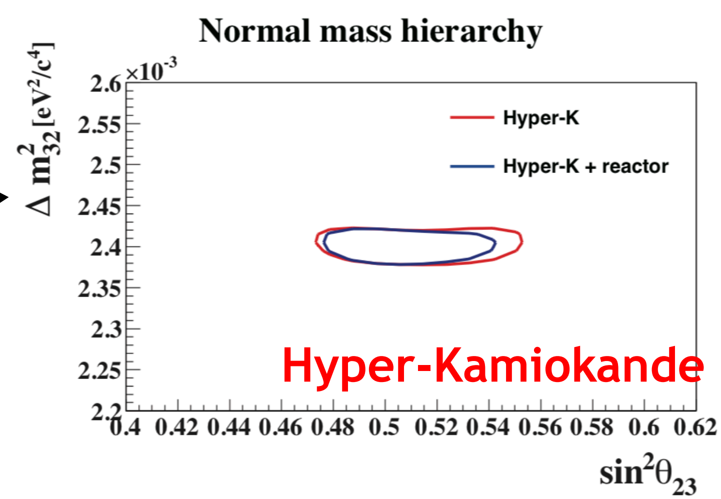


Precision measurement of ν_μ disappearance

- $\delta(\Delta m^2_{32}) \sim 1.4\times10^{-5}\mathrm{eV}^2$
- $\delta(\sin^2 2\theta_{23}) \sim 0.006$ at $\sin^2 2\theta_{23}=0.45$
  ~ 0.017 at $\sin^2 2\theta_{23}=0.50$



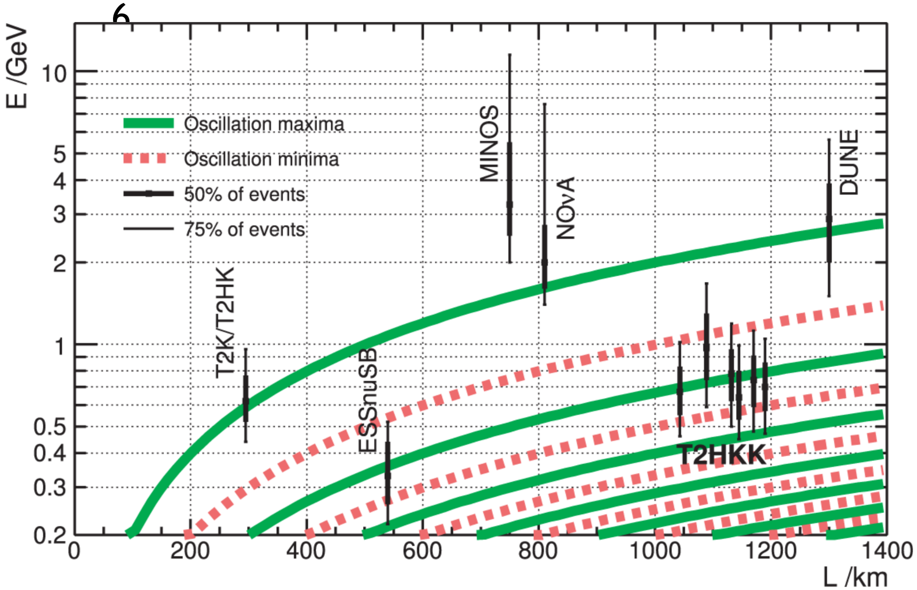




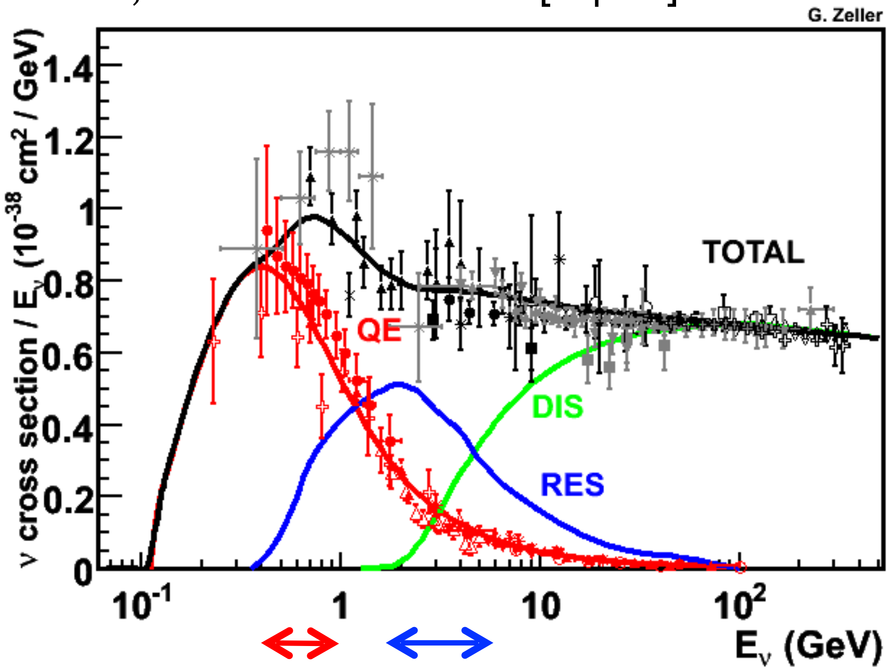
	CCQE	CCQE	CC non-QE	Others
Neutrino mode	6040	350	3180	520
Anti-neutrino mode	2700	6100	4300	610

DUNE and HyperK

HK Proto-Collaboration PTEP, Vol. 2018, Issue 6



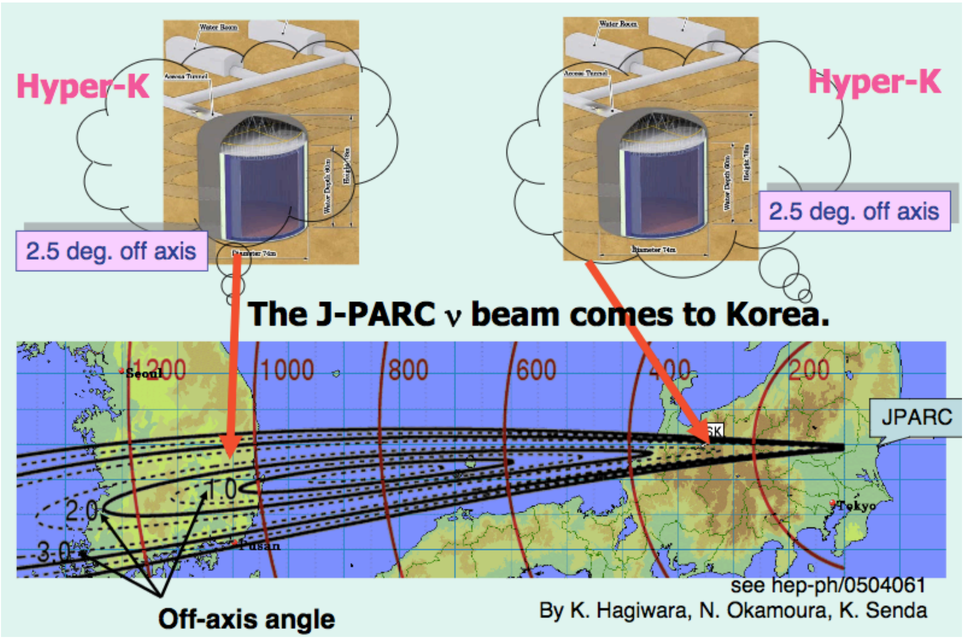
Fields, Laura arXiv:1212.0060 [hep-ex] PSNUM-18



*energy range which covers 75% of events

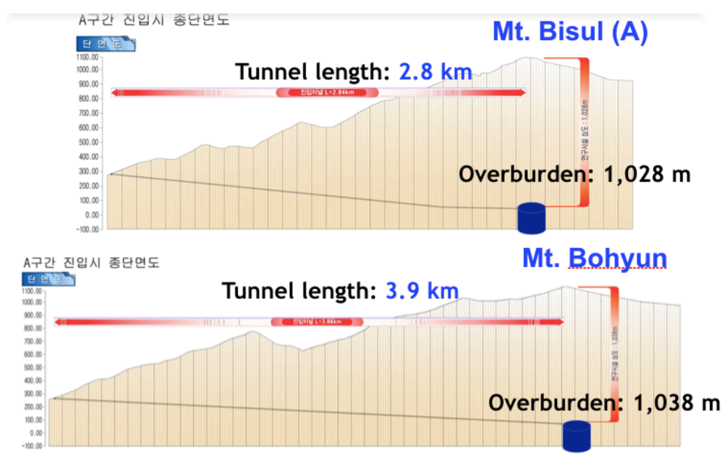
- Hyper-Kamiokande
  - Major component is QE: E_ν determined from (p,θ) of outgoing lepton
  - Suppress non-QE/NC by single Cherenkov ring and off-axis beam
- DUNE
  - Resonance and DIS dominant: E_ν from total lepton and hadron energy
  - Wide band beam and detect all charged particles by Liquid Argon

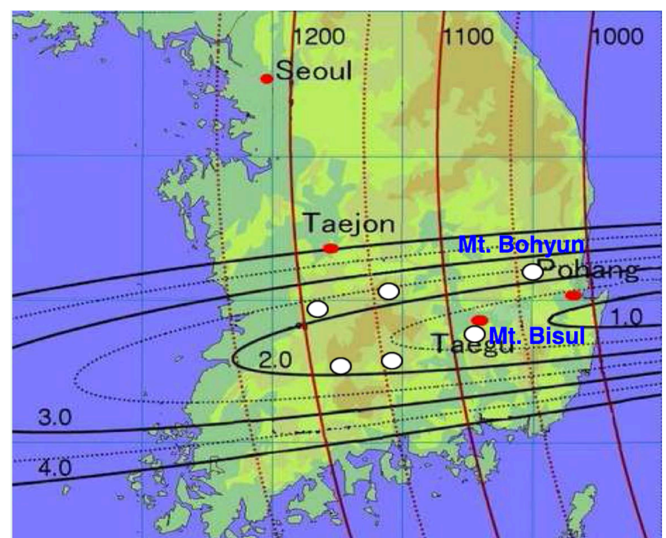
2nd HyperK detector in Korea



+ Longer baseline
  - more matter effects
  - sensitive to mass hierarchy

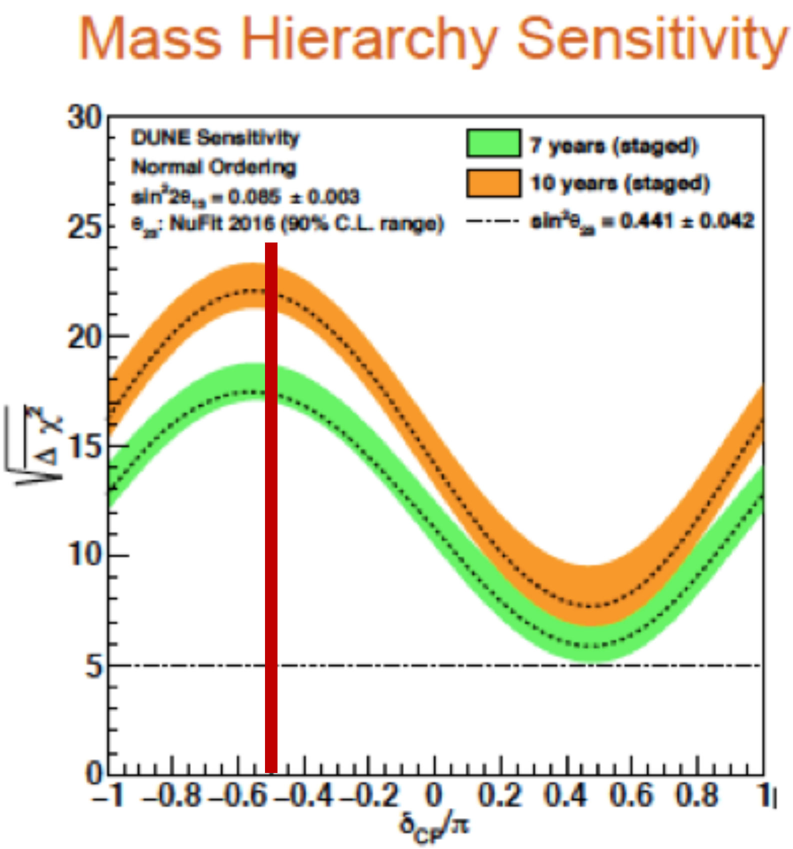
+ 2nd oscillation maximum
  - x2 CP enhancement
  - 1/9 in statistics
  - similar sensitivity as T2HK
  - less sensitive to systematics

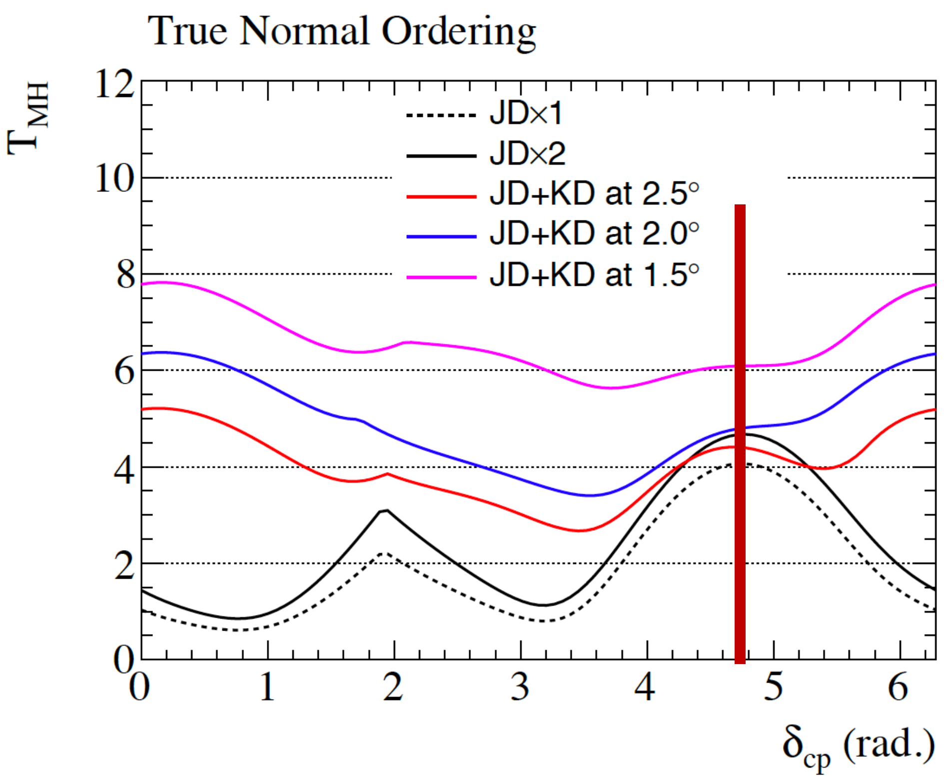




DUNE

Hyper-K





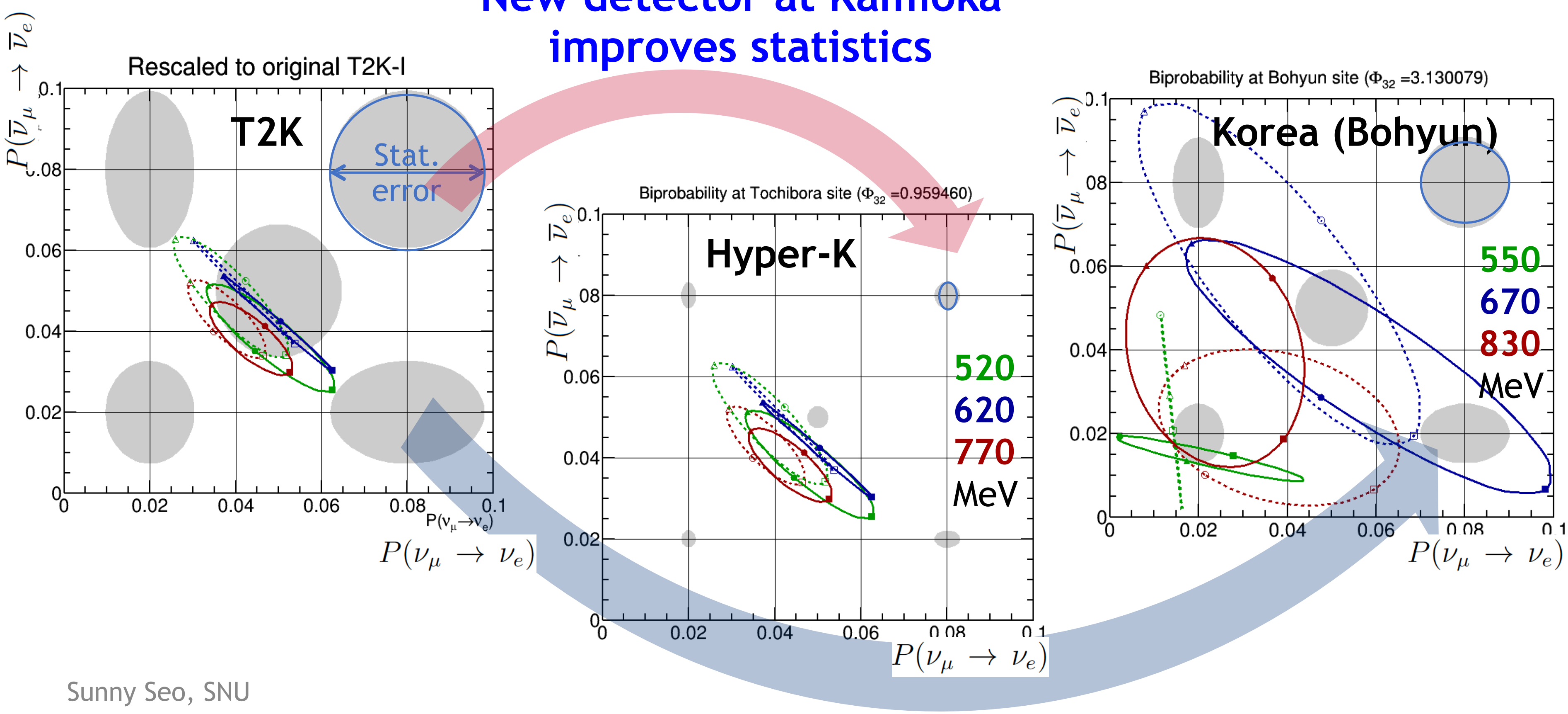
Sunny Seo, SNU

Unique benefits of a Korean Detector

Solid lines: Normal Hierarchy
Dotted lines: Inverted Hierarchy

Blue: Energy of peak QE rate
Red: median of high-energy tail
Green: " low-energy"

New detector at Kamioka improves statistics



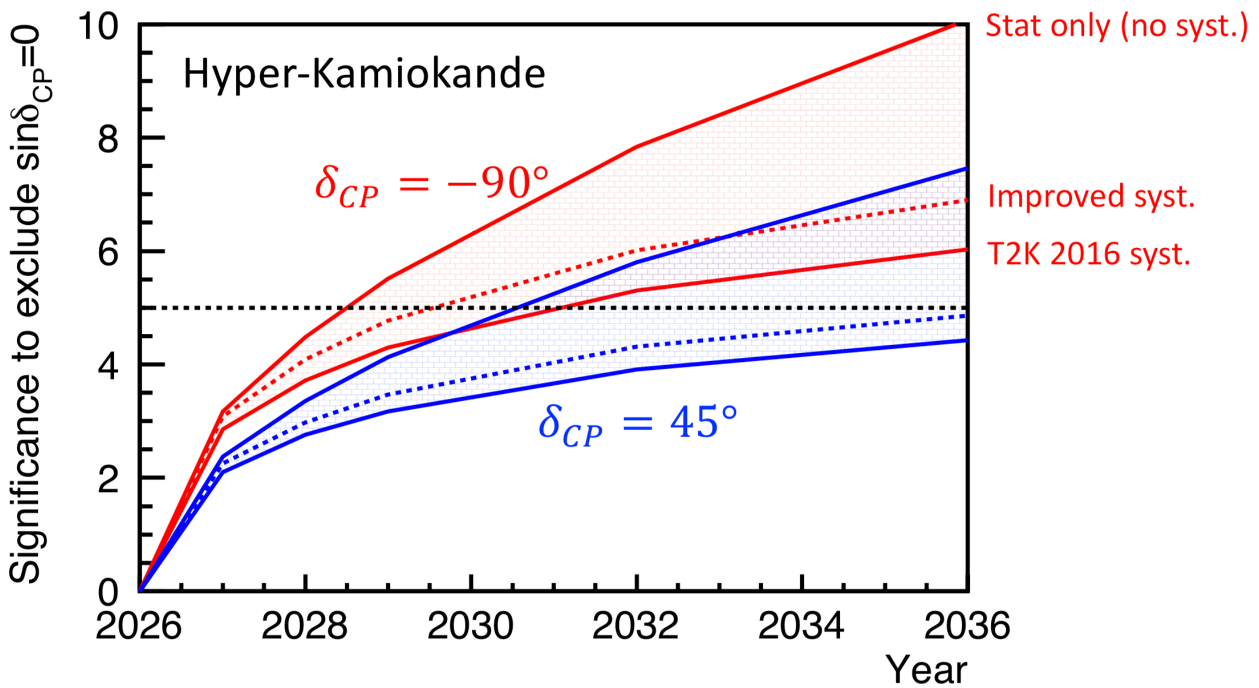
Sunny Seo, SNU

Detector in Korea measures parameters in a very different way

Systematic uncertainties

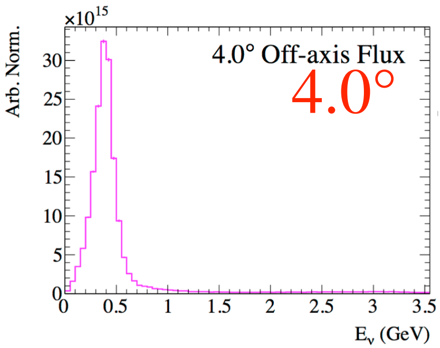
Discovery is difficult when experiment is limited by systematics:

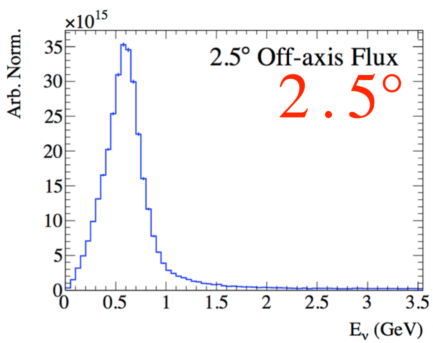
systemetics will not behave like gaussian unless constrained by data.

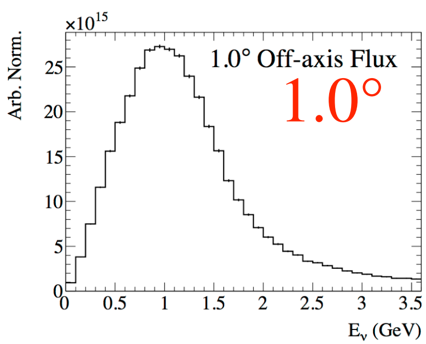


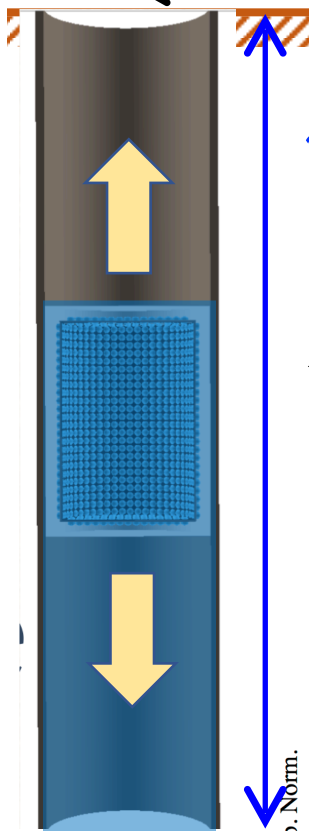
- **Reduction of systematic uncertainties is essential in CP violation measurement**
  - Neutrino-nucleus is the most challenging systematics
    - Data driven systematic error handling is required
    - **Intermediate water Cherenkov detector**

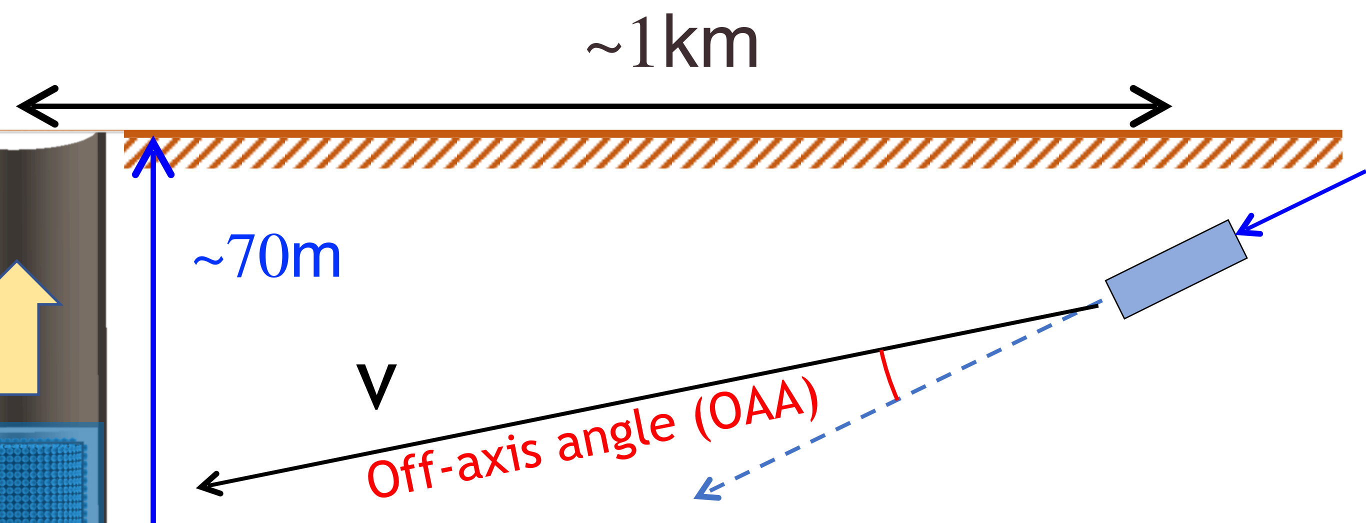
Intermediate water Cherenkov detector





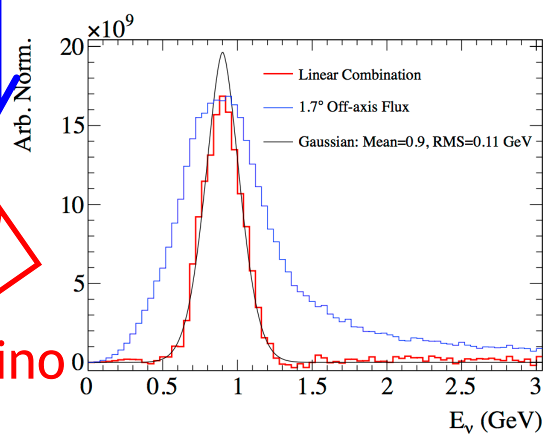




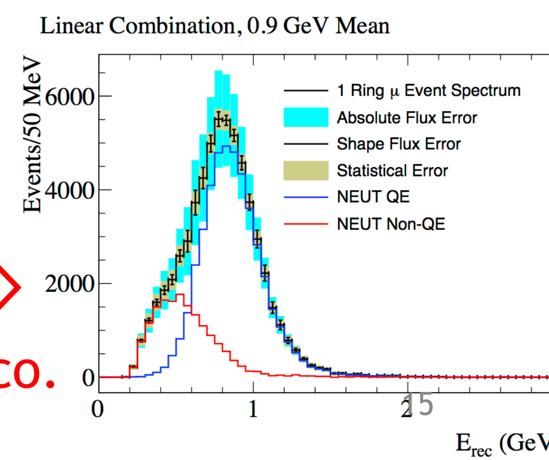


- **Off-axis spanning geometry (NuPRISM)**
  - Sampling different neutrino spectra at different off-axis positions

Linear sum makes monochromatic energy neutrino

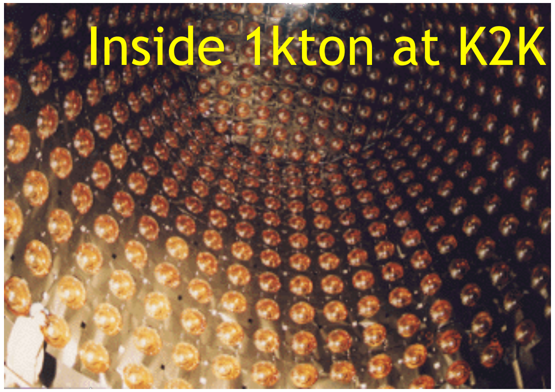


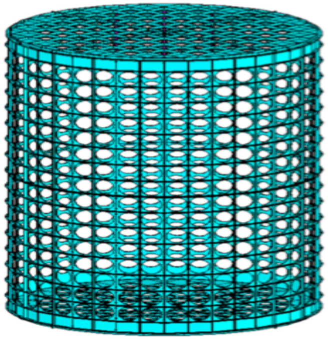
Reco.

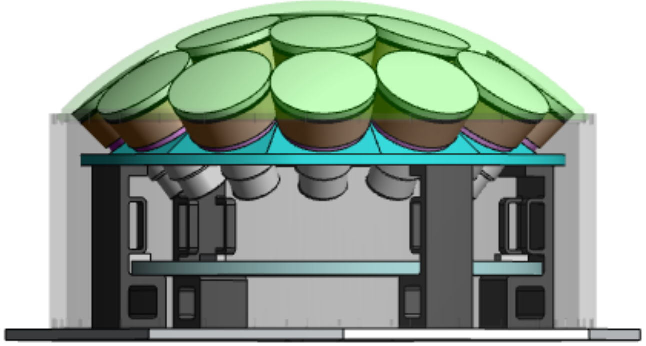


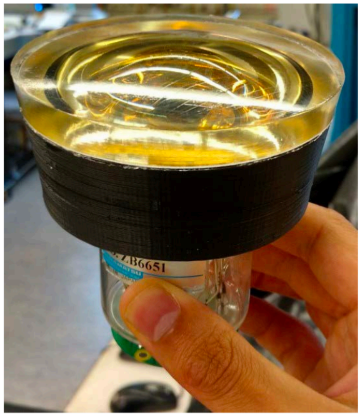
Intermediate water Cherenkov detector

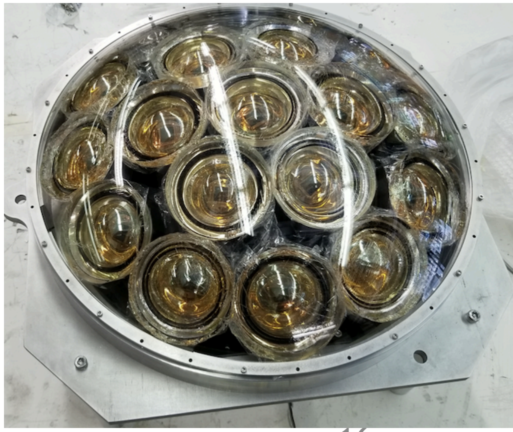
- 1kton(10m) scale water Cherenkov detector at ~1km distance
  - 10m diameter to contain muons
  - near/far variation and pile-up reduced at 1km
  - Small water Cherenkov:
    → **Higher granularity with mPMT modules**
  - Neutron measurement with Gd loading











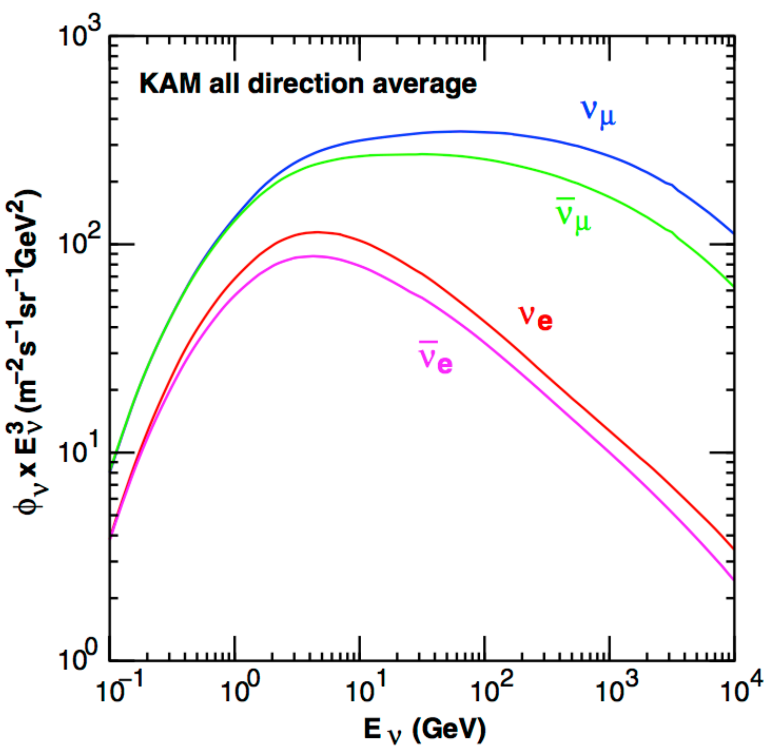
mPMT R&D actively on-going for IWCD and HK

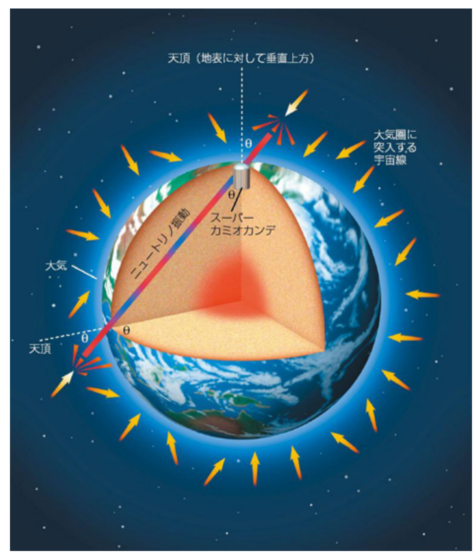
Atmospheric neutrinos

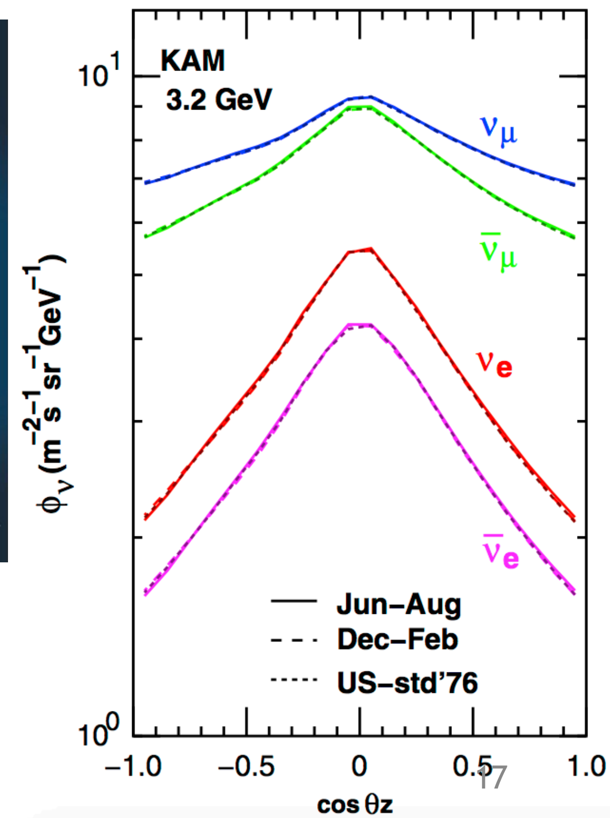
$$p \rightarrow \pi \rightarrow \mu + \nu_\mu$$
$$\hookrightarrow e + \nu_e + \nu_\mu$$

$$\frac{\phi(\nu_\mu)}{\phi(\nu_e)} \sim 2 \ (E_\nu < 1\text{GeV})$$

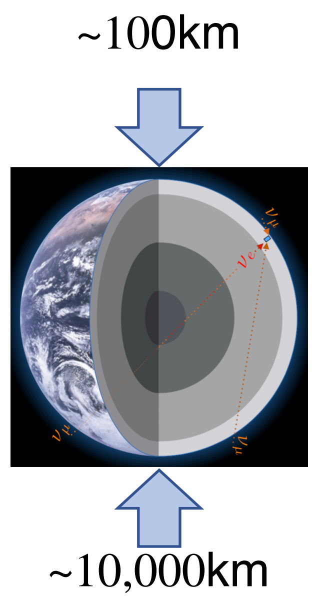
- Flux is up/down symmetric
- Normalization uncertainties cancelled in up/down ratio

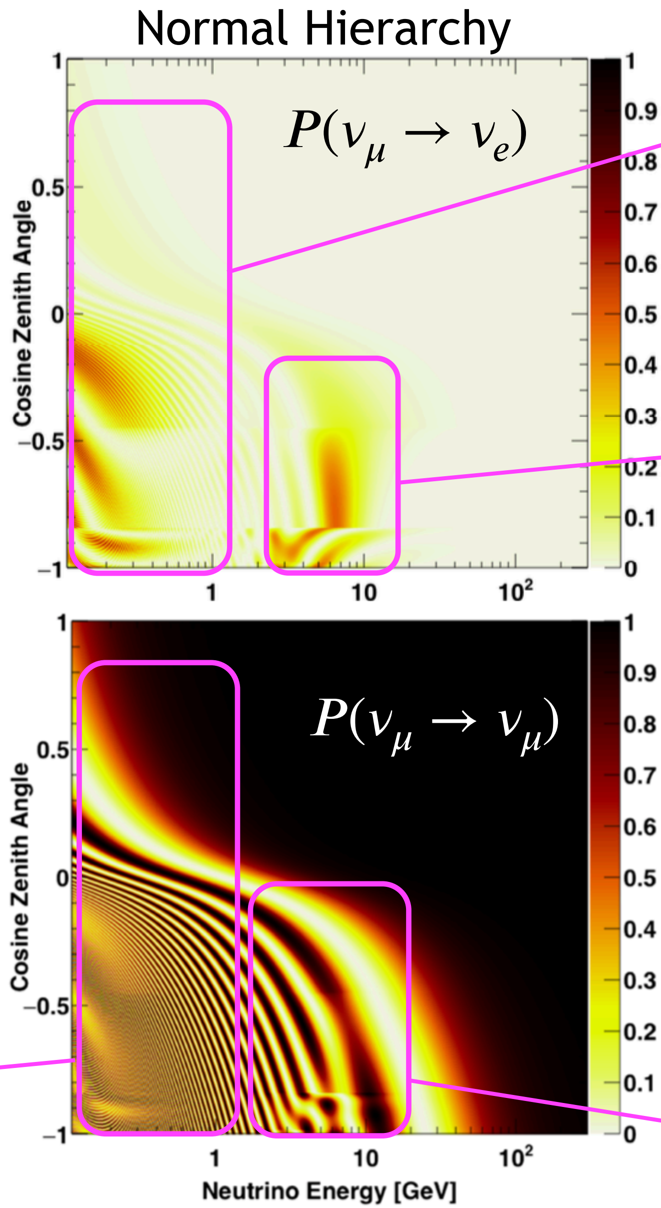


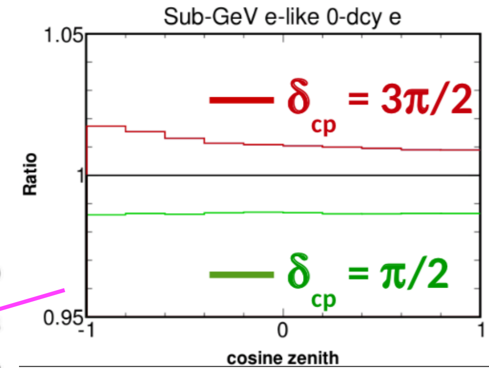


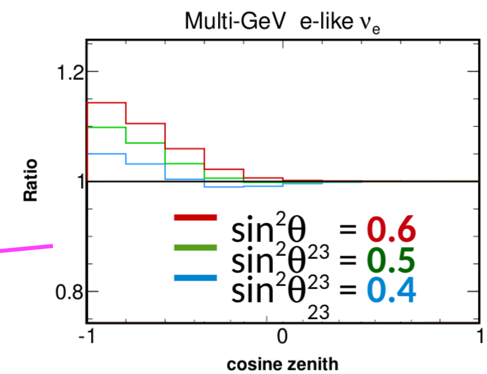


Three flavour oscillation

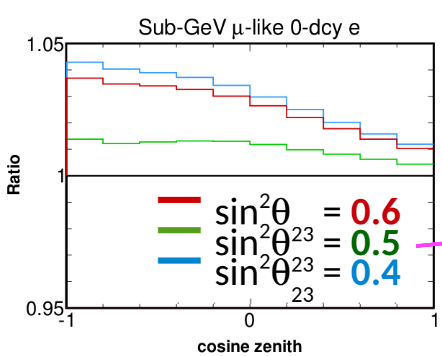


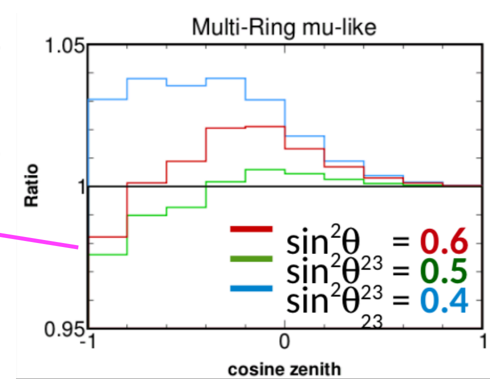




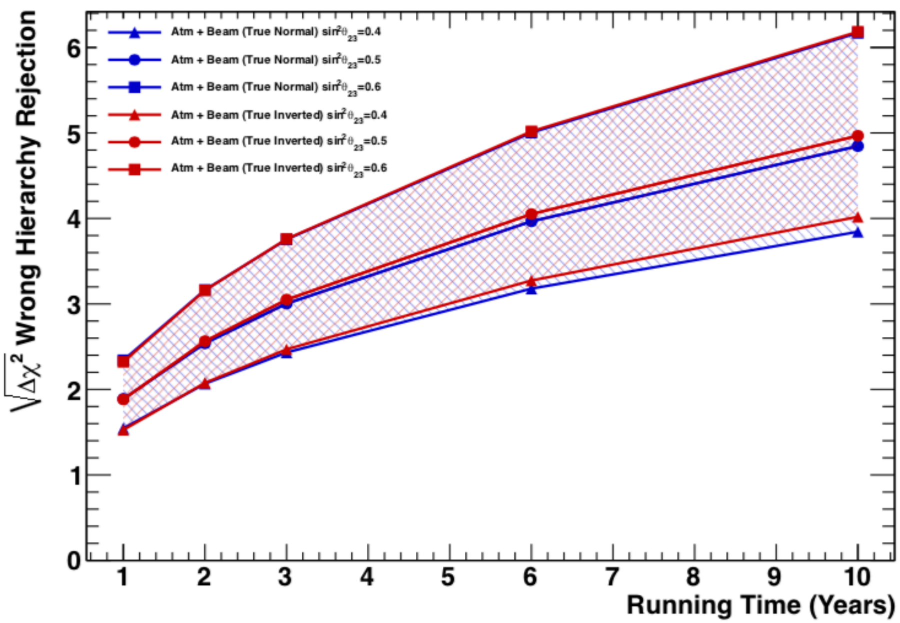


- Sensitive to δ_{CP}, θ_{23} octant ⇒parameter degeneracy
  - Benefit from combination with beam measurements

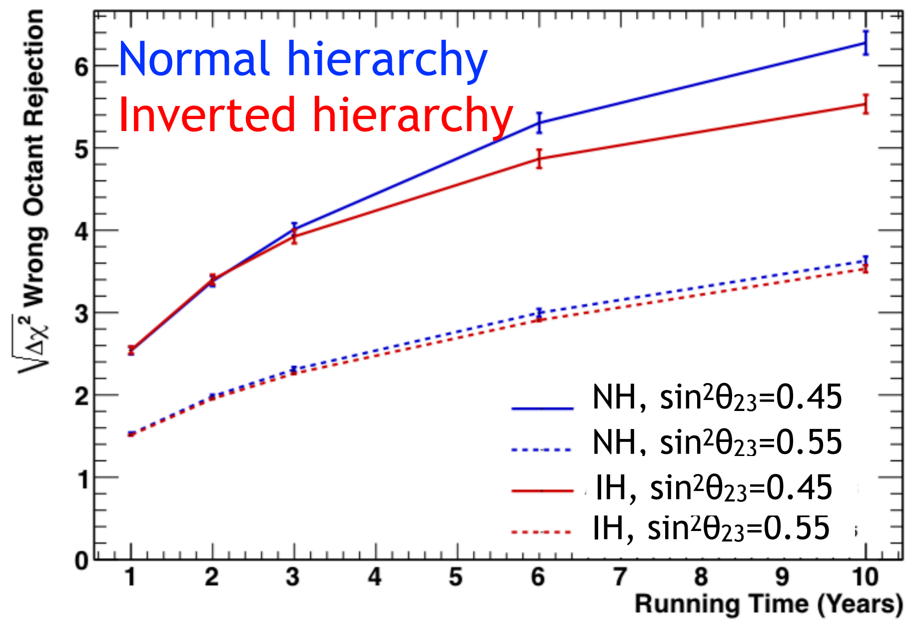




Mass hierarchy



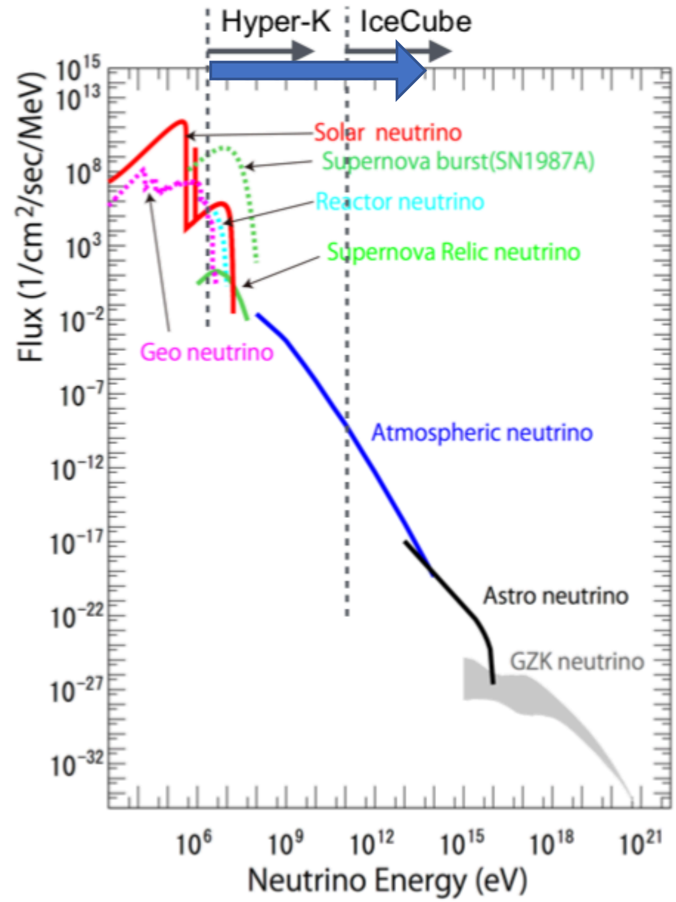
θ_{23} octant

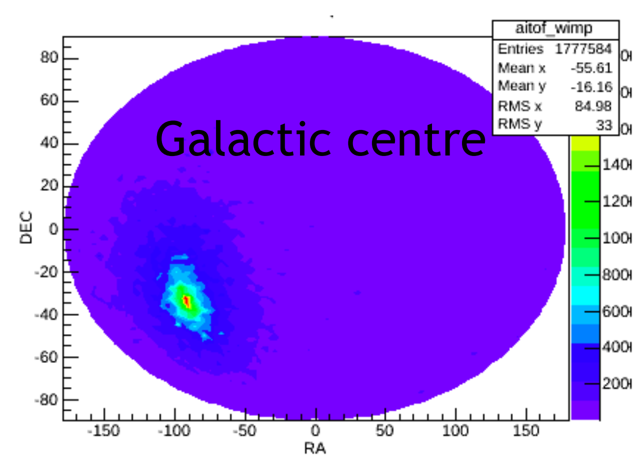


- Mass hierarchy
  - Super-K favours normal hierarchy at ~2σ level
  - 3σ mass hierarchy after 5 years of HK ($\sin^2\theta_{23}$ = 0.5)
- θ_{23} octant
  - Resolve θ_{23} octant in 5-10 years or nearly maximal θ_{23} mixing

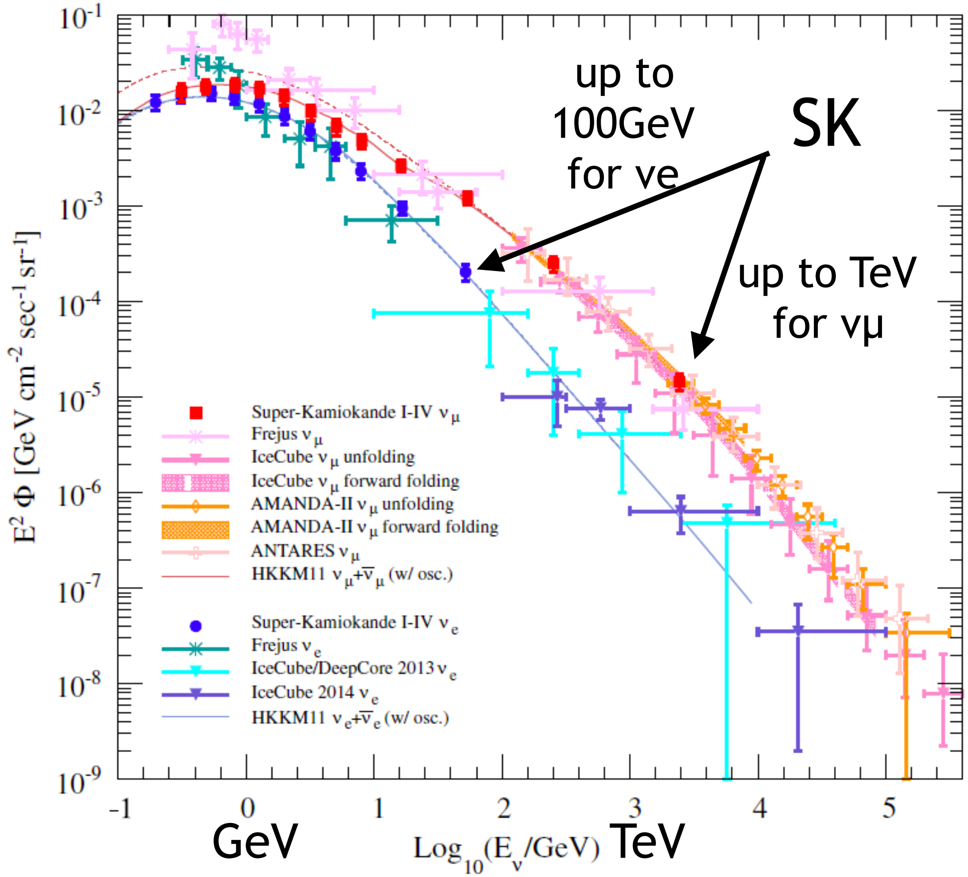
Astrophysical neutrinos

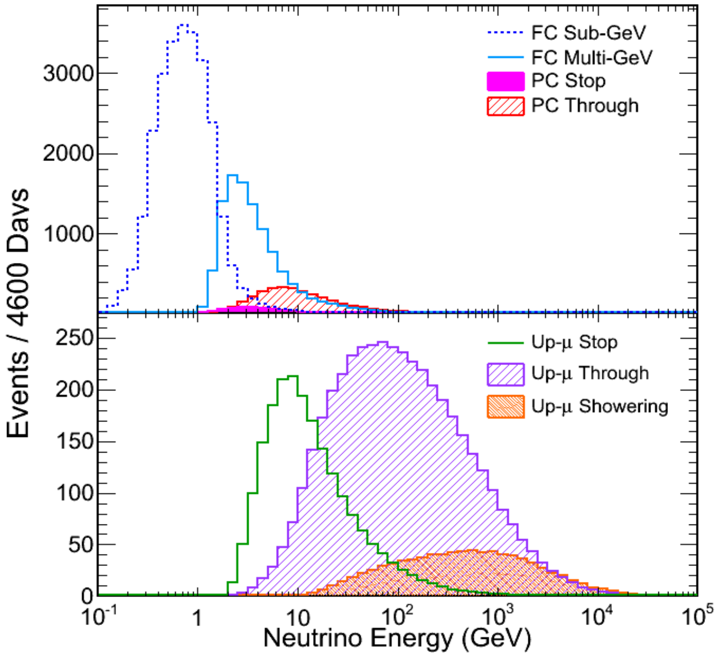
- **Hyper-K has potential to expand the window in GeV-TeV neutrinos**
  - WIMP annihilation from the galactic centre, Sun and Earth
  - Gamma-Ray Burst Jets
  - Gravitational-wave sources (multi-messenger)
- **Backgrounds: atmospheric neutrinos**
  - Excellent directionality (1-3 degrees) to look for point source.
    - burst timing gives another handle
  - Electron neutrinos detection, an order of magnitude less backgrounds

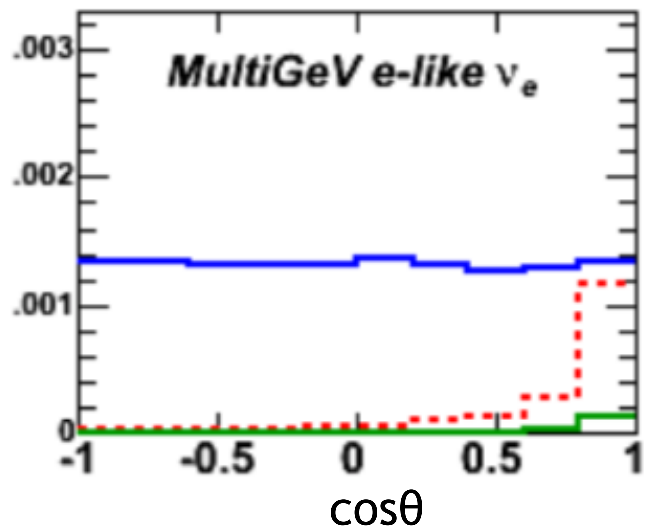




GeV-TeV neutrino in SK

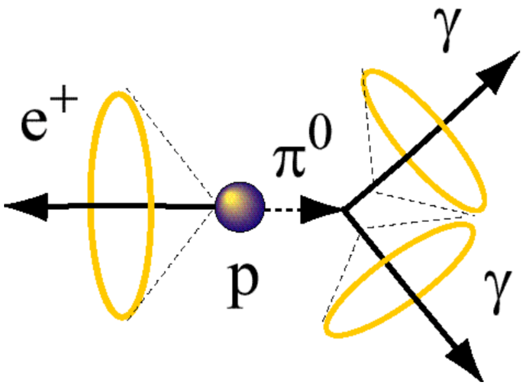




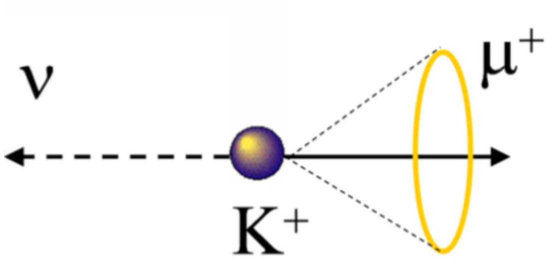


x8 more brightness for Hyper-K
Improved pointing with better reconstruction
will further reduce the atmospheric backgrounds

Proton decay search



- $p \rightarrow e^+ + \pi^0$ mediated by gauge boson
  - Observed as 2 or 3 ring e-like
  - Momentum balance and proton mass selection in particular for free proton decays



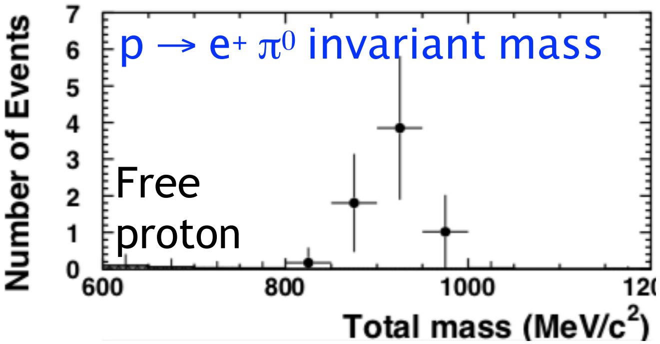
- $p \rightarrow \nu + K^+$ mediated by SUSY particle
  - p_K ~ 339MeV below Cherenkov threshold
    → search for two body decay of K^+
    - $K^+ \rightarrow \nu + \mu^+$ (BR: 64%) (+ de-excitation γ)
    - $K^+ \rightarrow \pi^+ + \pi^-$ (BR: 21%)

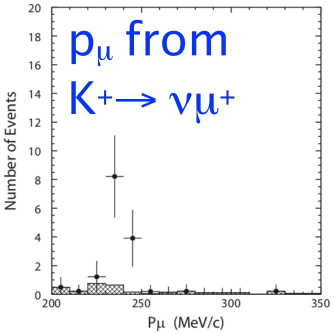
- Improvement of multi-ring reconstruction to enhance acceptance and rejection
- Atmospheric neutrino background rejection by neutron tag

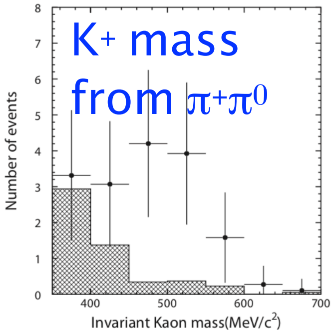
Proton decay search

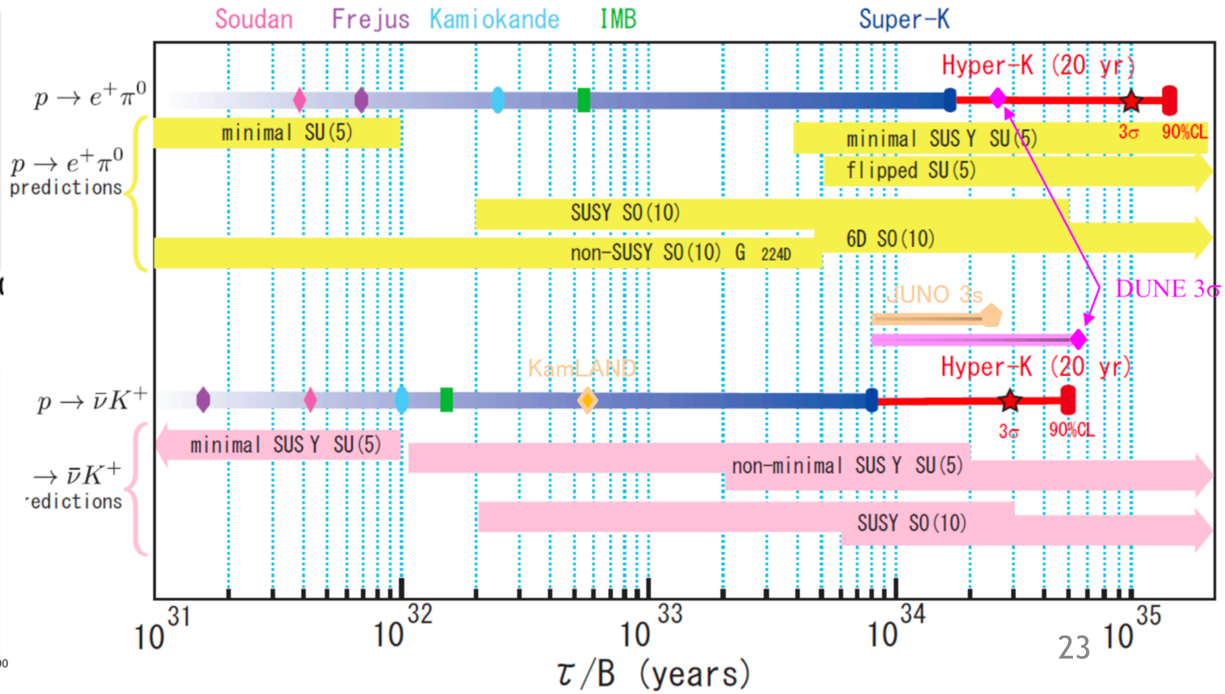
- Extend proton decay search for various decay modes
  - **x8 Larger fiducial volume** than Super-Kamiokande
  - **BG free search** (0.06BG/Mton・yr) by neutron tagging and improved multi-ring event reconstruction
- **Sensitivity reaches ~10^{35}yr**

If proton lifetime is at SK limit,



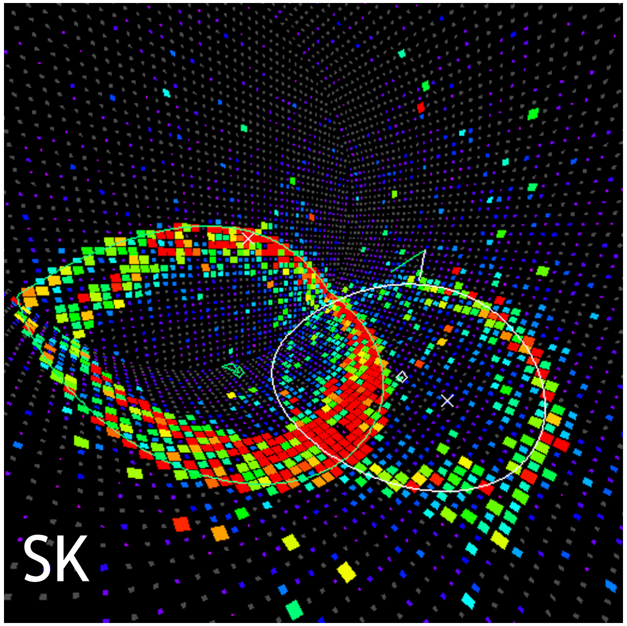


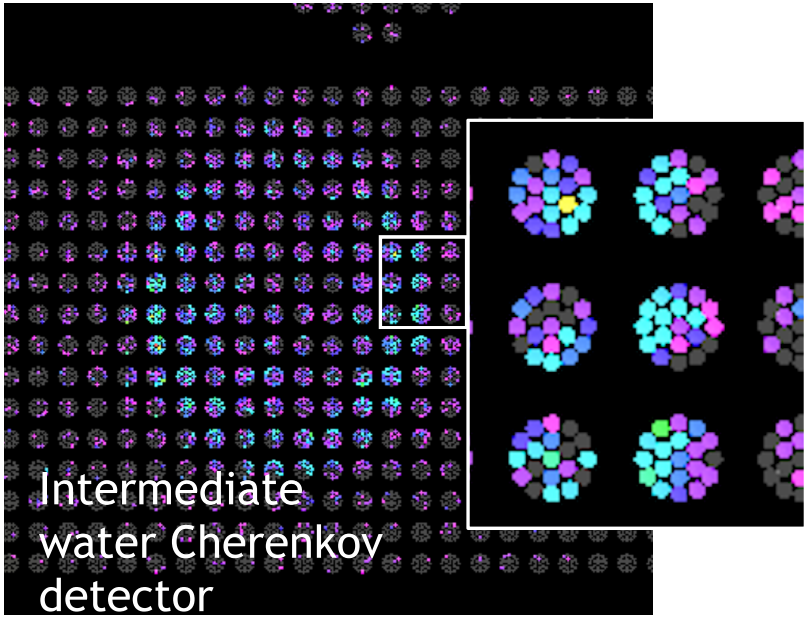




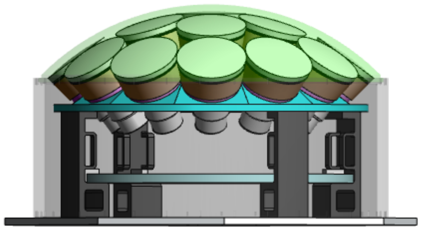
Reconstruction software improvements

- **Potential software developments/improvements**
  - Geant-4 based Hyper-Kamiokande simulation (in progress)
  - Sophisticated multi-ring reconstruction (machine learning)
    - Use of both 20 inch PMTs and mPMT modules
  - Neutrino / antineutrino separation
    - Development of neutron tagging analysis





mPMT module



Summary

- Hyper-K is unique detector in subGeV to TeV range
  - High statistics data with large fiducial volume
  - Precision event reconstruction with large photo-coverage
- Rich physics targets in this higher energy region
  - **Precision neutrino oscillation studies with J-PARC beam**
    CP violation, maximal θ_{23} mixing or not
    Further improvements by the Korean detector at 2nd oscillation max.
  - **Expand oscillation studies with atmospheric neutrinos**
    Larger energy range, Longer baseline, Matter effects
    → Mass hierarchy, τ appearance, Non-standard interactions
  - **Nucleon decay** search to 10^{35} years in life time
  - **Astrophysical neutrino search** in GeV-TeV window
- Innovative contributions are required to achieve the goal
  - **Intermediate detector** to constrain neutrino interactions
  - **Additional detector and calibration system** for detector systematics
  - **Hadron production measurements** for beam and atmospheric ν flux
  - **Event reconstruction** for multi-ring events (machine learning)