Hyper-Kamiokande project

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Kashiwa, March-29-2012

Conditions for measuring CP δ

$$^{t}(\nu_e,\nu_\mu,\nu_\tau) = U_{\alpha i}^{MNS}\,{}^{t}(\nu_1,\nu_2,\nu_3)$$

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{j>i}\mathrm{Re}(U_{\alpha i}^{*}U_{\beta i}U_{\alpha i}^{*}U_{\beta j})\sin^2\frac{(m_j^2-m_i^2)L}{4E_\nu}$$

ν, anti-ν →

$$\mp 2\sum_{j>i}\mathrm{Im}(U_{\alpha i}^{*}U_{\beta i}U_{\alpha i}^{*}U_{\beta j})\sin\frac{(m_j^2-m_i^2)L}{2E_\nu}$$

$$\text{CPV term} \propto \sin\vartheta_{12}\cdot\sin\vartheta_{13}\cdot\sin\vartheta_{23}\cdot\sin\delta\cdot\Delta m_{12}^2$$

✓ $\sin\theta_{23}\sim 1/\sqrt{2}$	1998 atm-ν, accelerator-ν
✓ $\sin\theta_{12}\sim 0.5$, $\Delta m^2_{12}\sim 7.6\times10^{-5}\mathrm{eV}^2$	2001 solar-ν(LMA), reactor-ν
✓ $\sin\theta_{13}\sim O(0.1)$	2011 ~2.5σ(T2K), 2012 >5σ(Daya Bay), others

Nature gives us an opportunity of leptonic CPV measurement.

→Need larger detector.

Letter of Intent:

The Hyper-Kamiokande Experiment

— Detector Design and Physics Potential —

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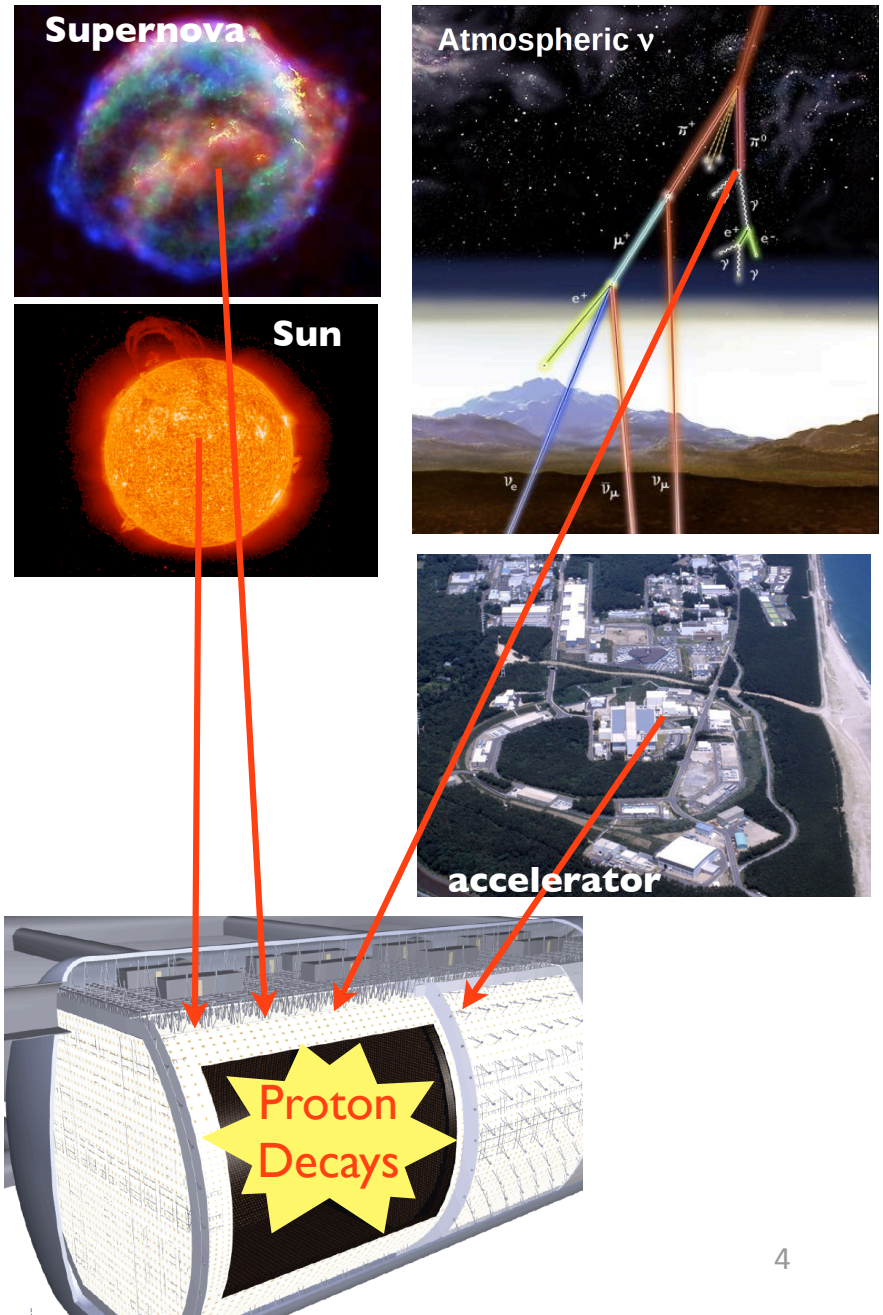
Hyper-K WG,
arXiv:1109.3262 [hep-ex]

Multi-purpose detector, Hyper-K

- Total (fiducial) volume is 1 (0.56) million ton
  - 25 × Super-K
- Explore full picture of neutrino oscillation parameters.
  - Discovery of leptonic CP violation (Dirac δ)
  - ν mass hierarchy determination(Δm^2_{32}>0 or <0)
  - θ_{23} octant determination (θ_{23}<π/4 or >π/4)
- Extend nucleon decay search sensitivity
  - $\tau_{proton}=10^{34}\sim10^{35}$ years
- Neutrinos from astrophysical objects
  - 200 ν's / day from Sun
  - 250,000 (50) ν's from Supernova @Galactic-center (Andromeda)
  - 830 ν's / 10 years Supernova relic ν
  - WIMP ν, solar flare ν, etc



ν physics targets of Hyper-K

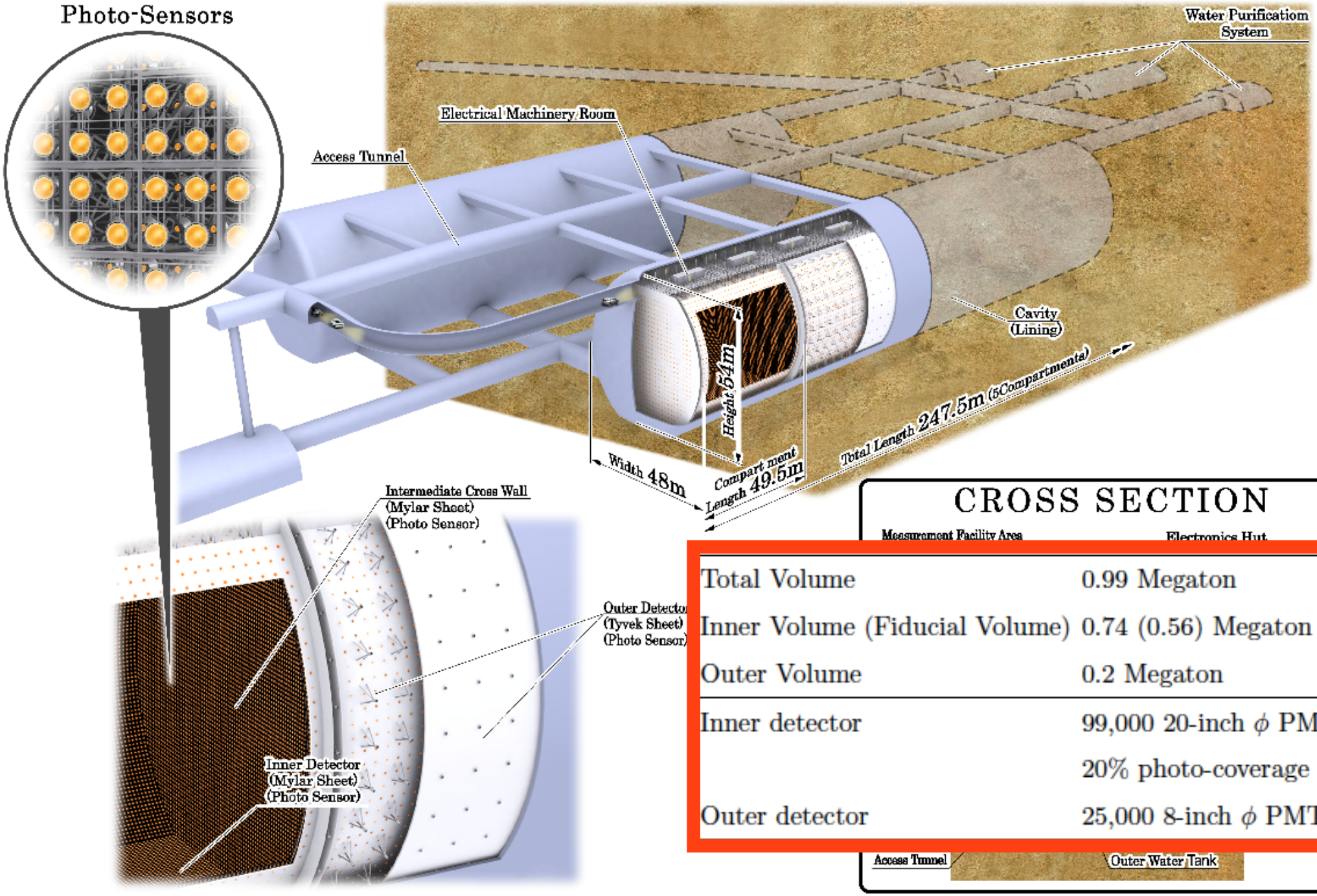
Given $\sin^2\theta_{13}$~a few %

Daya Bay: $\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$

- Leptonic CP violation, Dirac phase δ
- ν mass hierarchy, $\Delta m^2_{32}>0$ or $\Delta m^2_{32}<0$
- θ_{23} octant, $\theta_{23}<\pi/4$ or $\theta_{23}>\pi/4$

Proposal to explore full picture of neutrino oscillation parameters.

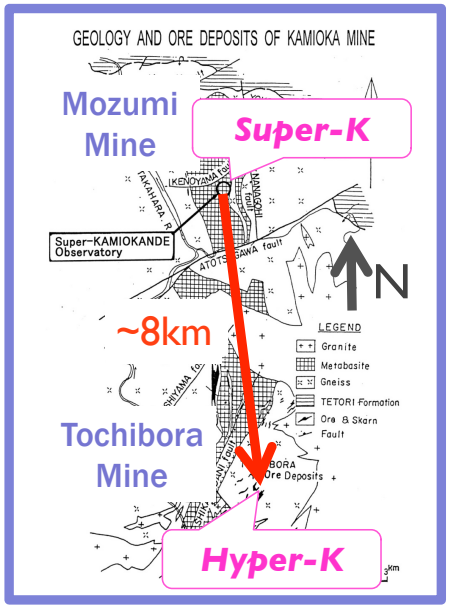
Schematic View of the Hyper-Kamiokande

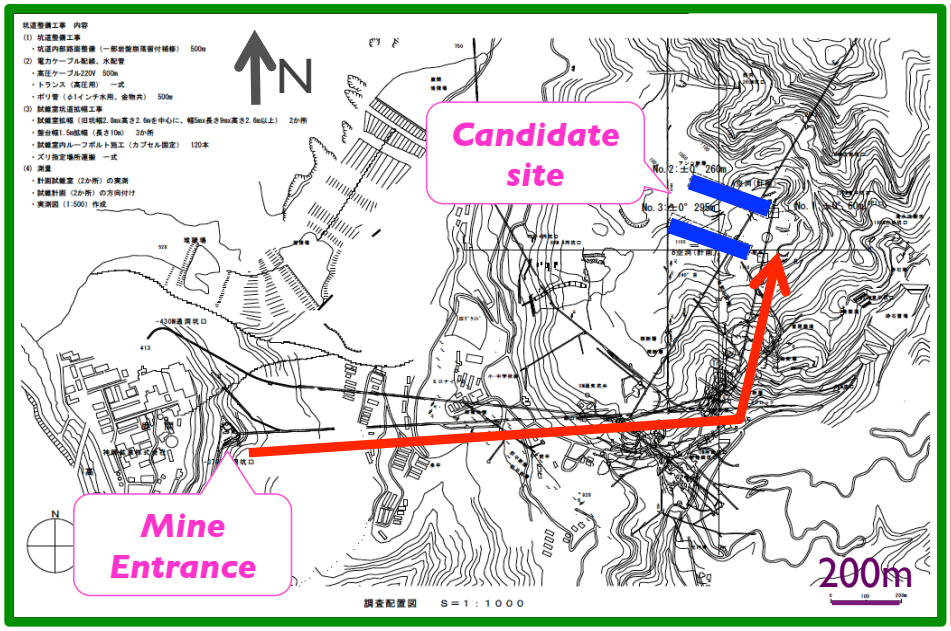


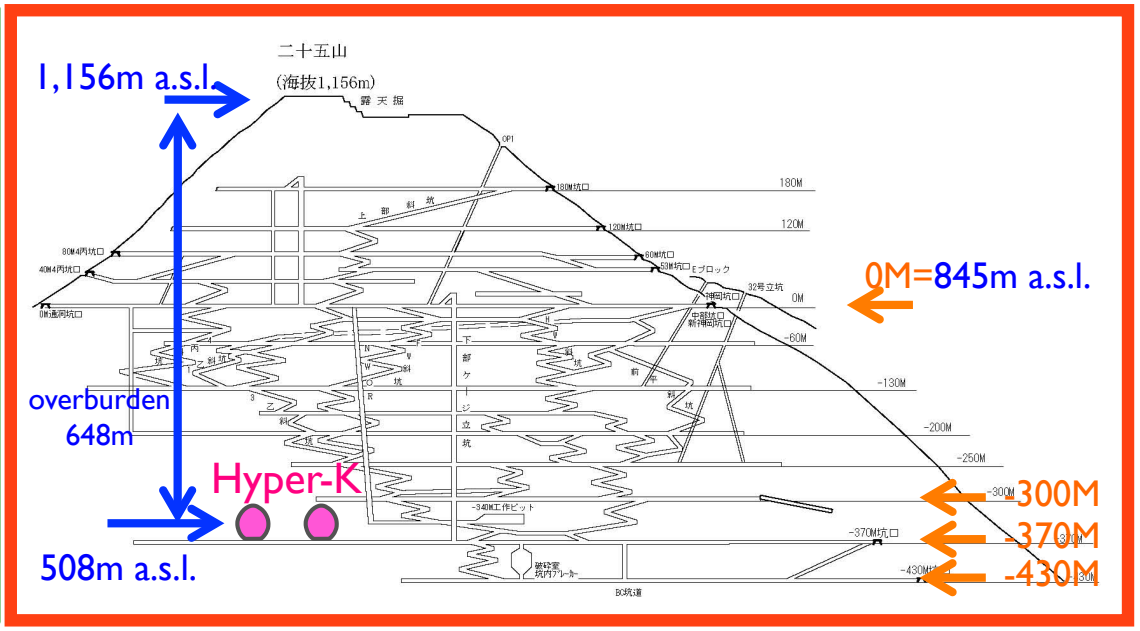
Total Volume	0.99 Megaton
Inner Volume (Fiducial Volume)	0.74 (0.56) Megaton
Outer Volume	0.2 Megaton
Inner detector	99,000 20-inch ϕ PMTs
	20% photo-coverage
Outer detector	25,000 8-inch ϕ PMTs

Hyper-Kamiokande candidate site

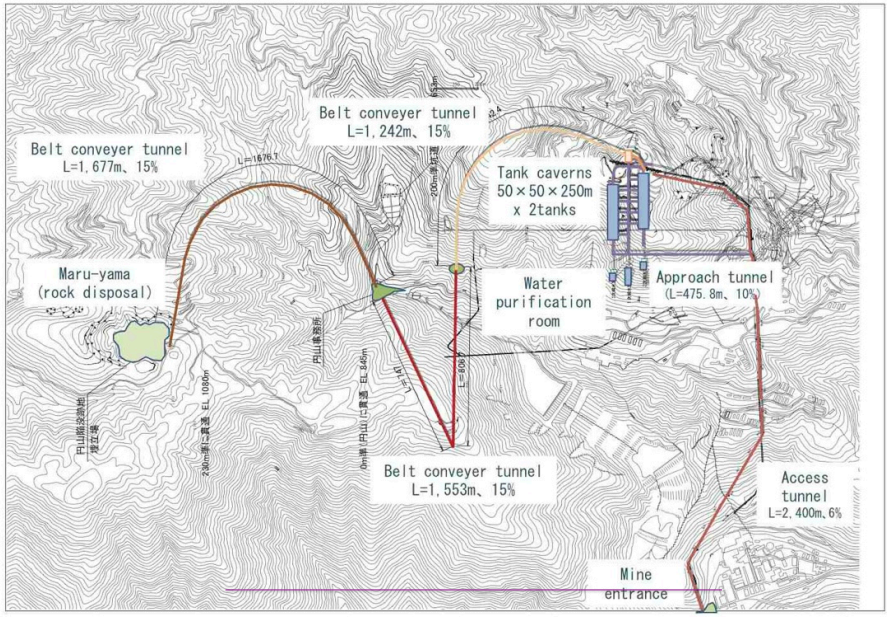
- 8km south from Super-K
  - same T2K beam off-axis angle (2.5 degree)
  - same baseline length (295km)
- 2.6km horizontal drive from entrance
- under the peak of Nijuugo-yama
  - 648m of rock or 1,750 m.w.e. overburden
- 13,000 m^3/day or 1megaton/80days natural water



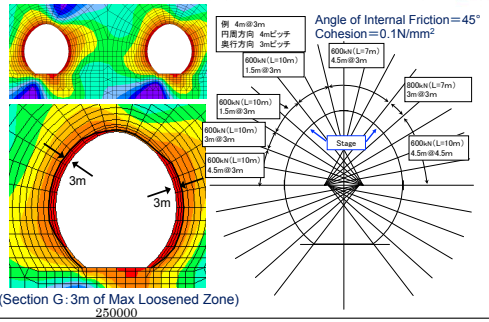




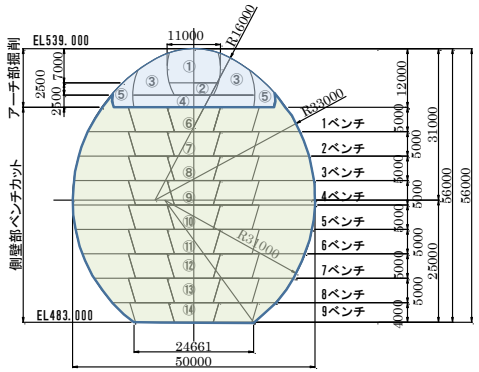
Cavern excavation

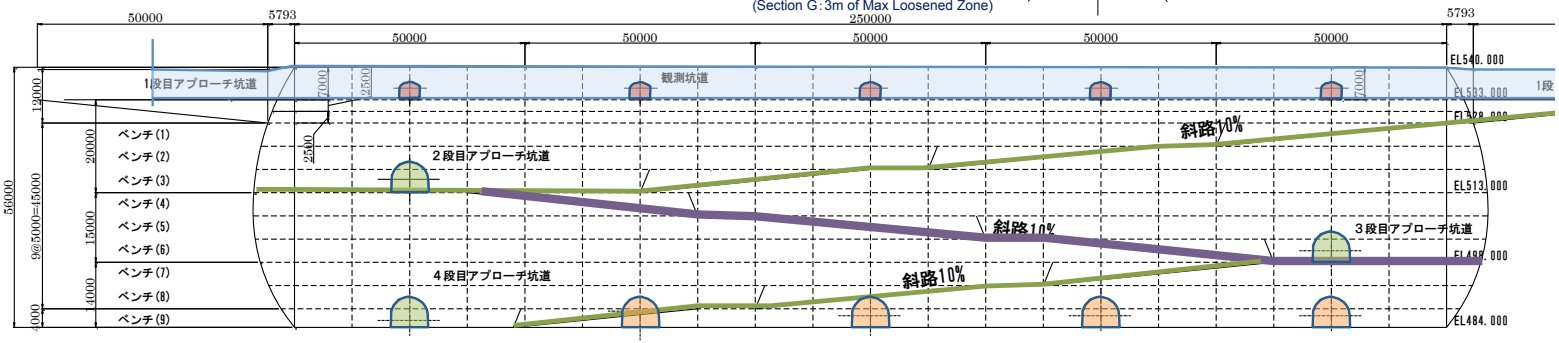


- geological survey, in-situ rock stress tests
- scheduling & costing ongoing



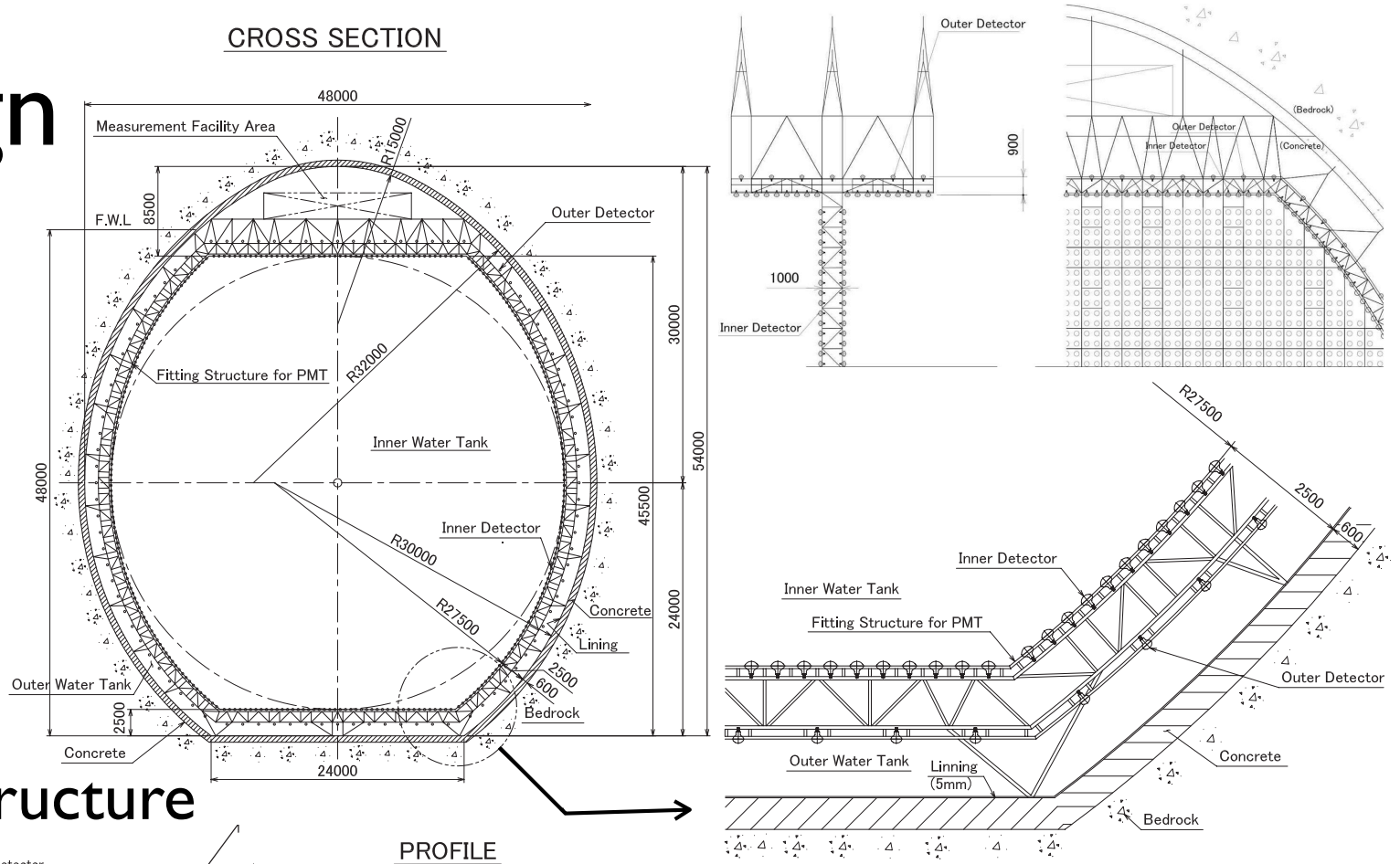
(Section G:3m of Max Loosened Zone)

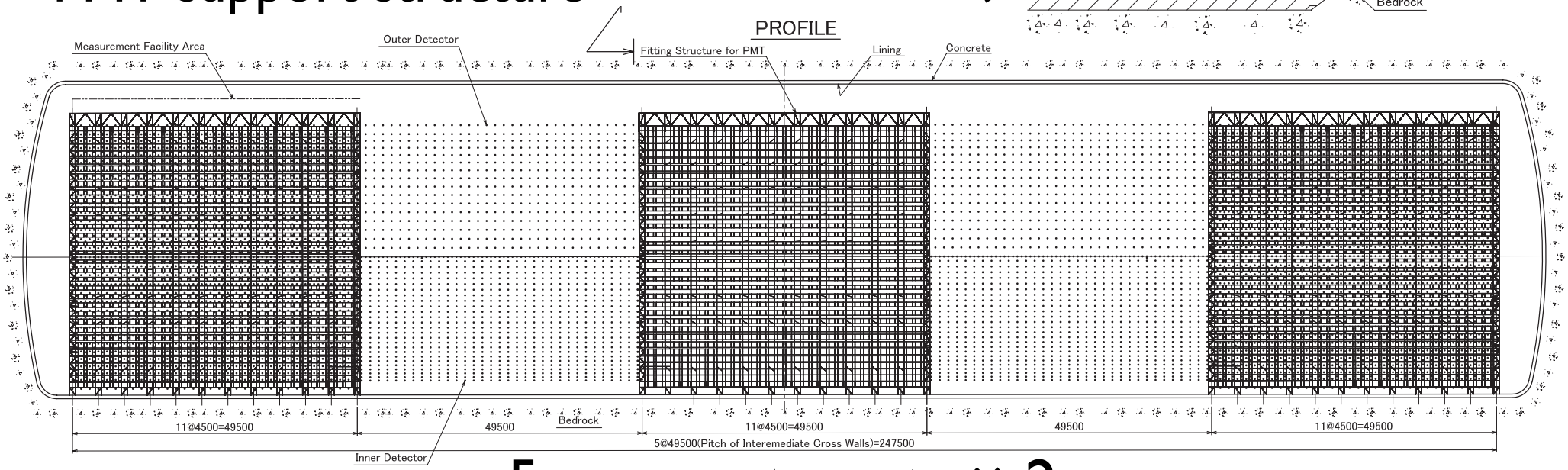




Tank Design

- liner
- PMT support structure

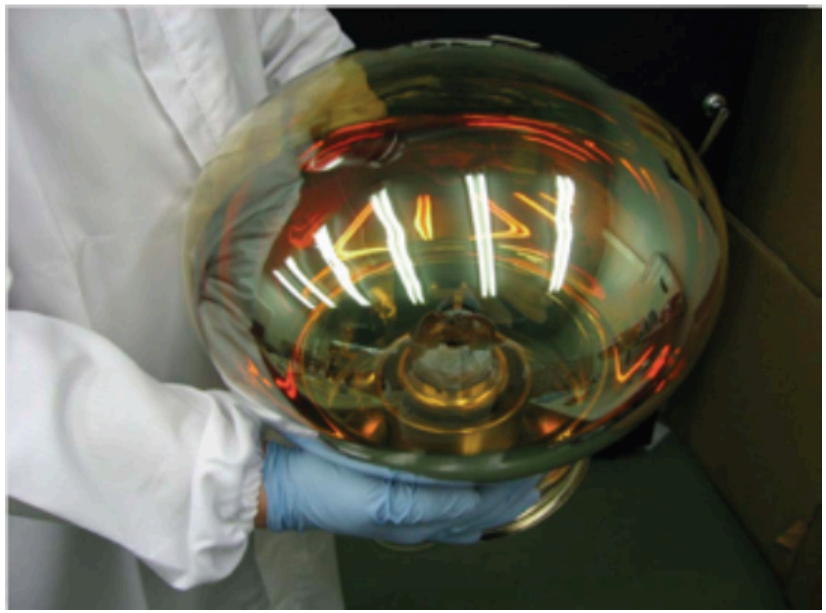




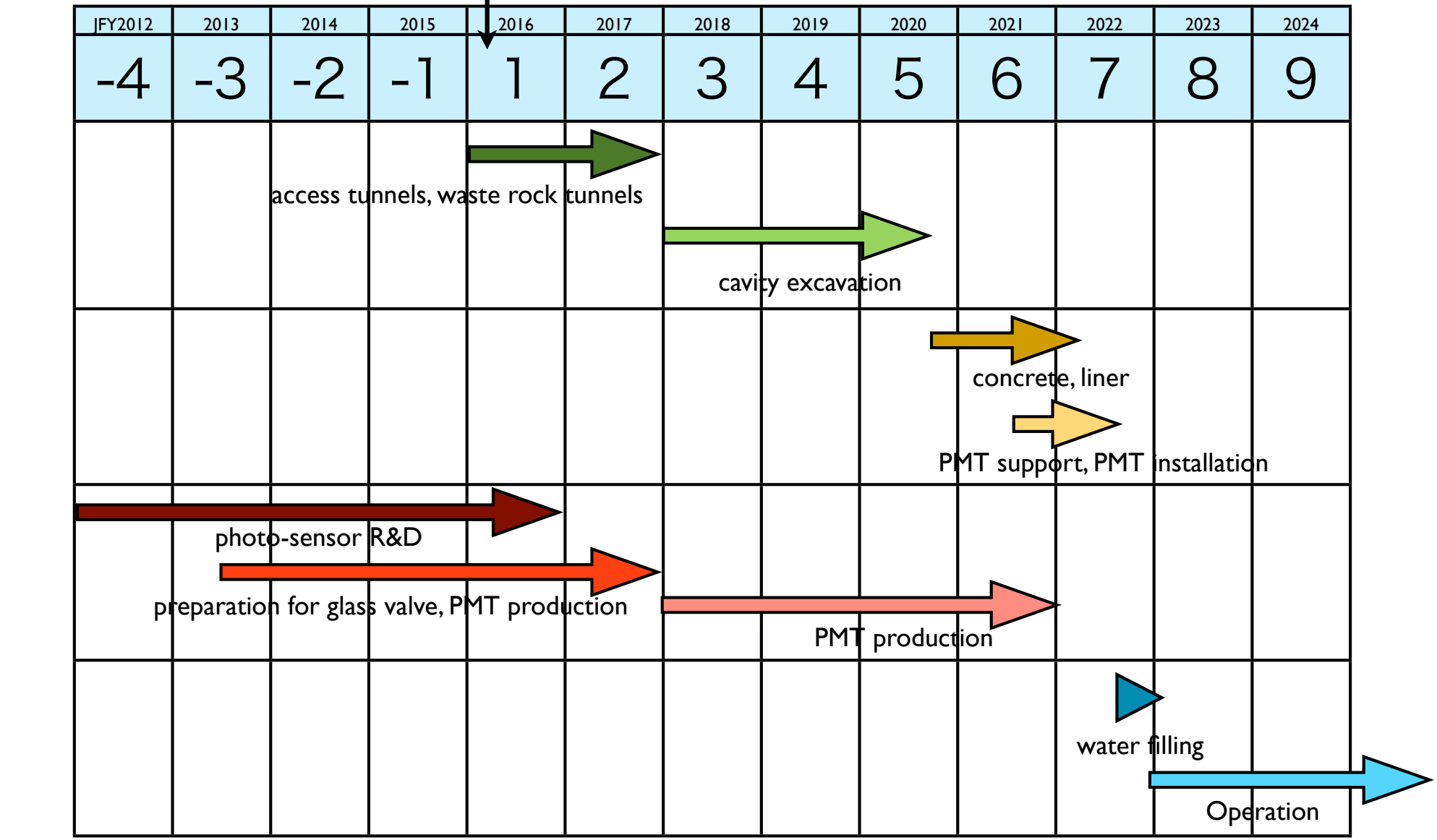
5 compartments × 2

More on developments

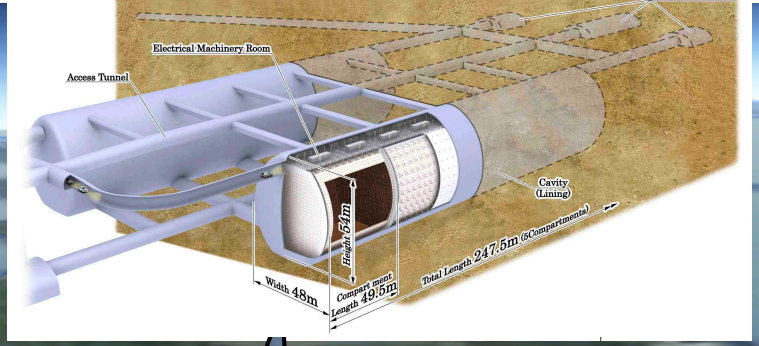
- sensors
  - –20 inch Hybrid PD
  - –New 20inch PMT
- proof test by 8inch HPD under preparation
- water-proof system for DAQ electronics
- water purification system, water quality control
- design optimization for lower cost, shorter construction period



Schedule



assuming budget being approved from JPY2016



Hyper-K

Super-K

x25 Larger ν Target

~0.6GeV νμ

295km

Quest for CP Violation in lepton sector

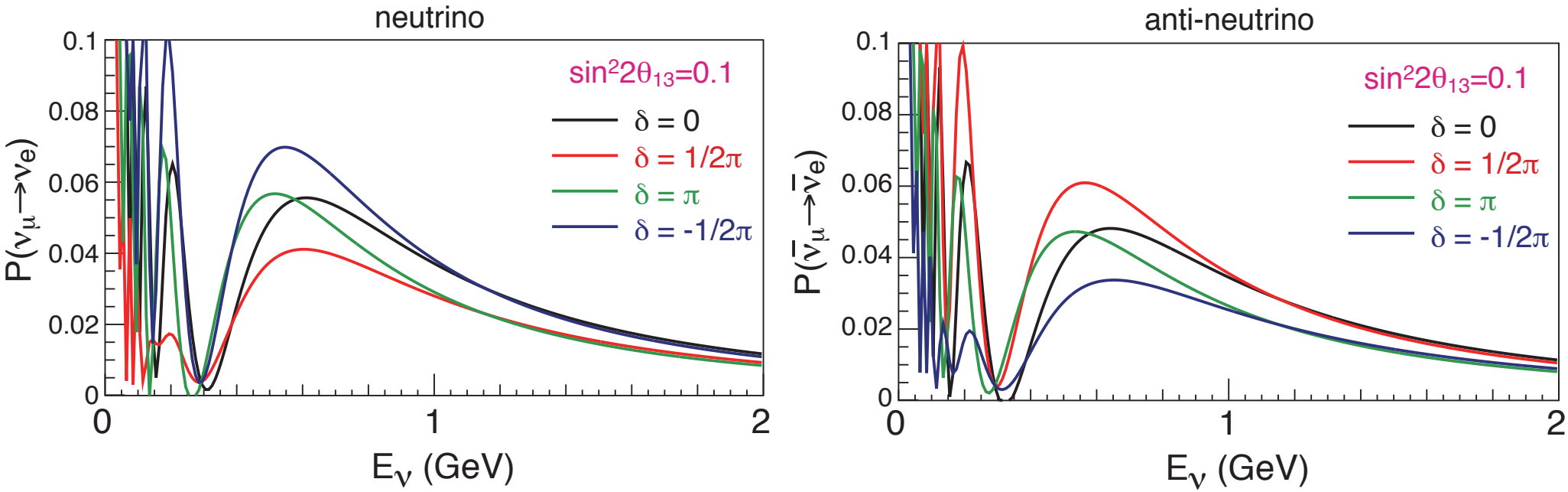
higher intensity ν by upgraded J-PARC

JPARC

36°24'46.66" N 139°18'01.27" E 標高 214 メートル 高度 188.55 キロメートル

$\nu_\mu \rightarrow \nu_e$ probability

Normal hierarchy



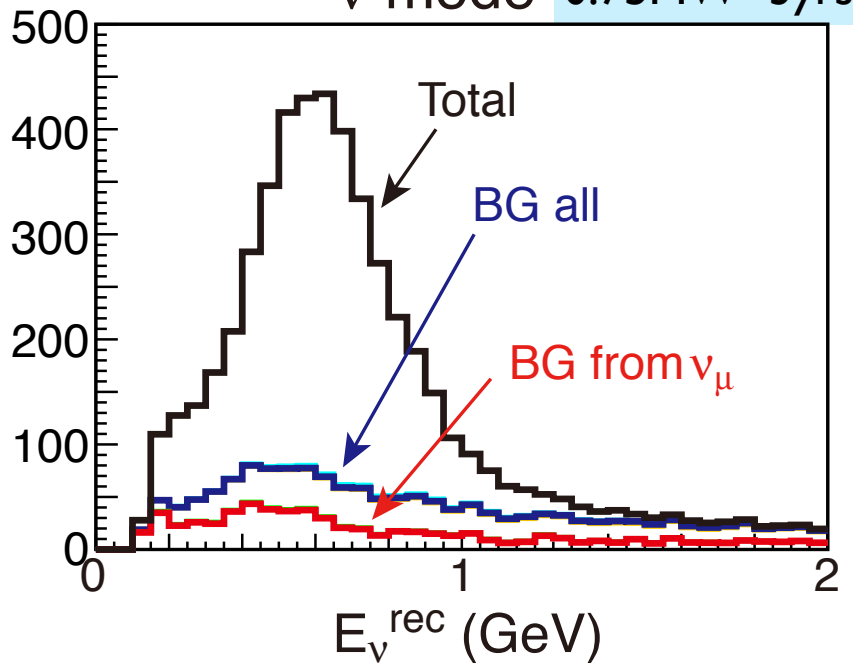
- CPV test by comparing $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- sensitive to exotic CPV (non MNS matrix origin)

Selected ν_e CC candidates

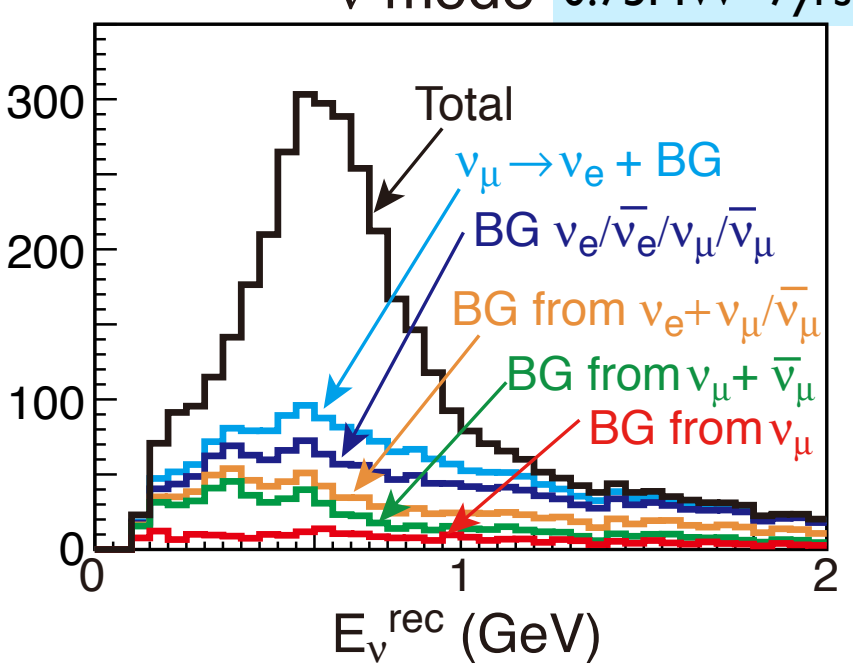
$\sin^2 2\theta_{13}=0.1, \delta=0$

ν_e CC candidates

ν mode 0.75MW×3yrs



$\bar{\nu}$ mode 0.75MW×7yrs



$\nu_\mu \rightarrow \nu_e$CC:	3,606 ev
$\nu_\mu+\bar{\nu}_\mu$CC :	35
$\nu_e+\bar{\nu}_e$CC :	880
NC :	649

$\nu_\mu \rightarrow \nu_e$CC:	2,339 ev
$\nu_\mu+\bar{\nu}_\mu$CC :	23
$\nu_e+\bar{\nu}_e$CC :	878
NC :	678

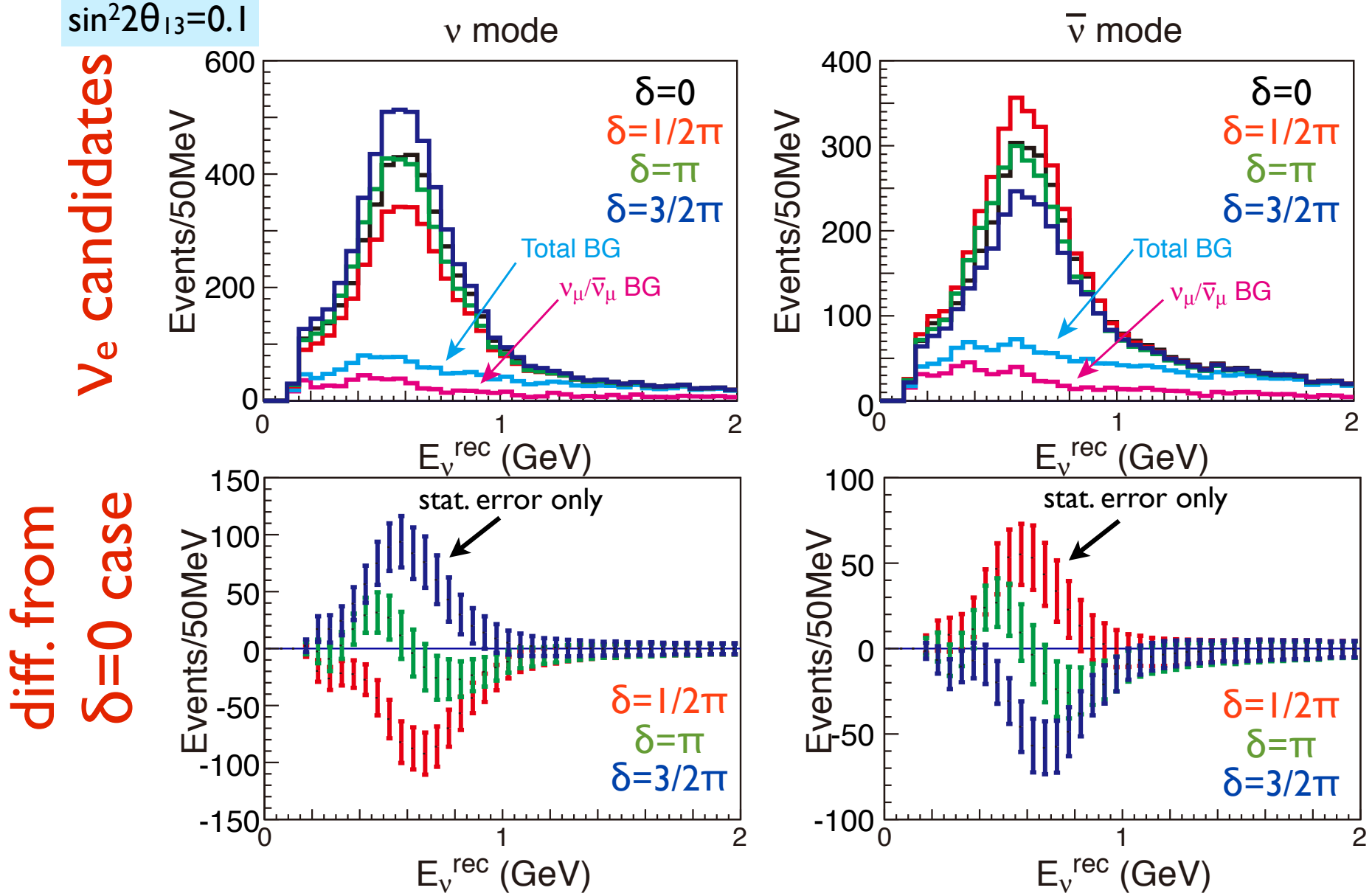
ν_e signal efficiency $\Leftrightarrow$ remaining BG

64% ν_μ+antiν_μCC <0.1%, NCπ^0 <5%

(0.1<E^{rec}_ν < 1.25 GeV)

Expected ν_e CC candidates

$\sin^2 2\theta_{13}=0.1$



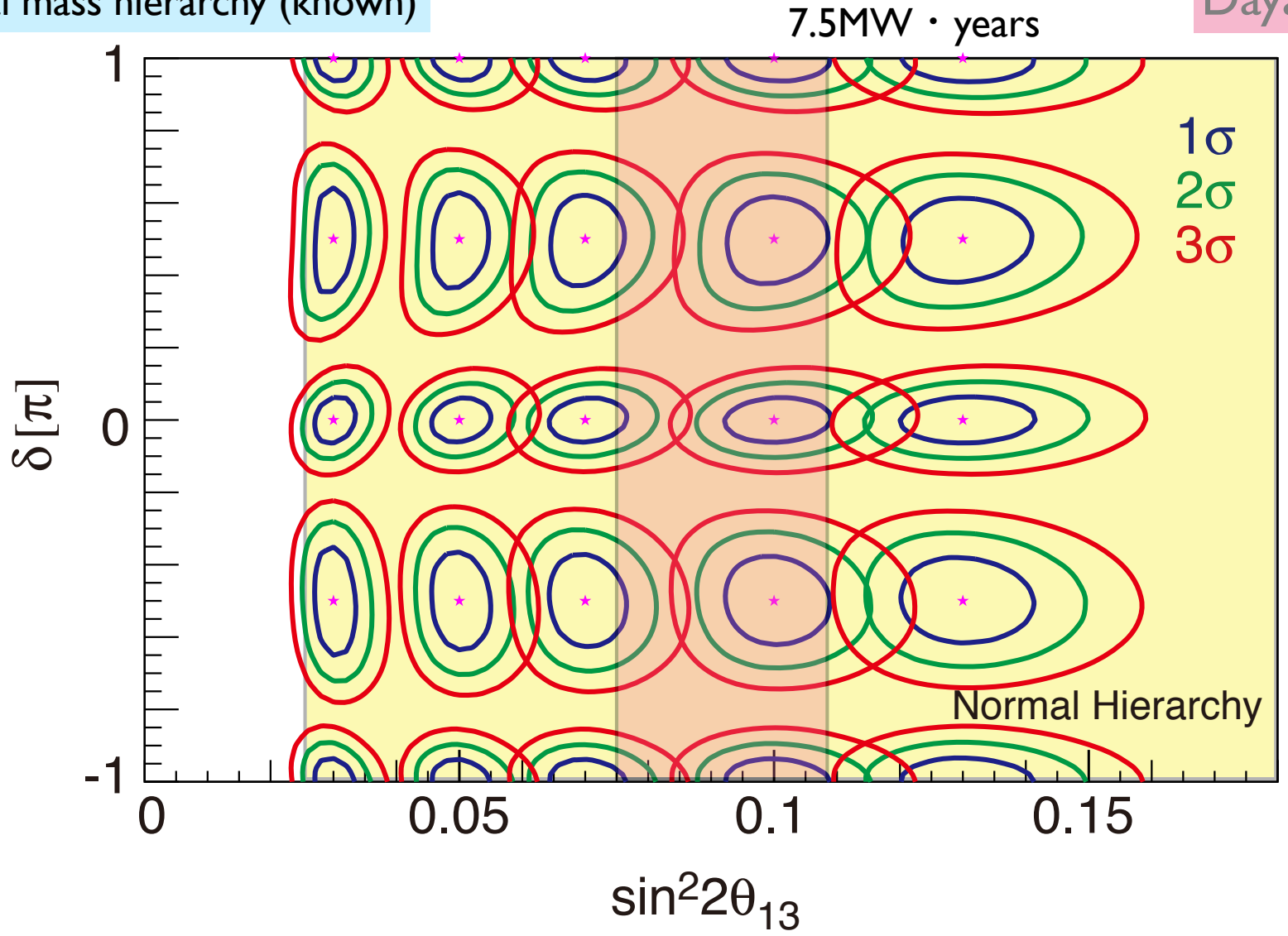
Numbers and shape for CP measurement

Contours

T2K90%CL

DayaBay1σCL

Normal mass hierarchy (known)

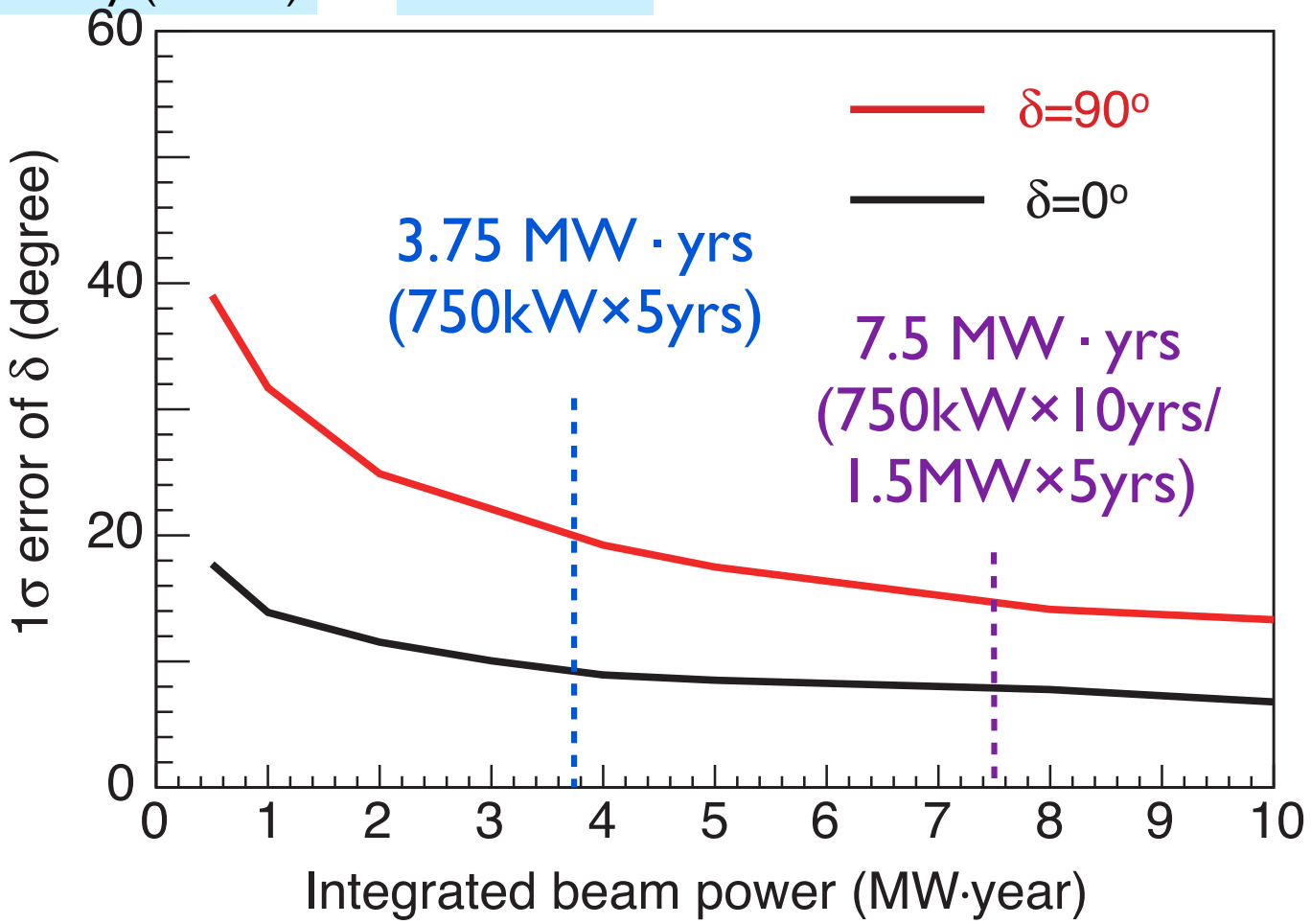


Good sensitivity in whole θ_{13} allowed region!

δ resolution

Normal mass hierarchy (known)

$\sin^2 2\theta_{13}=0.1$



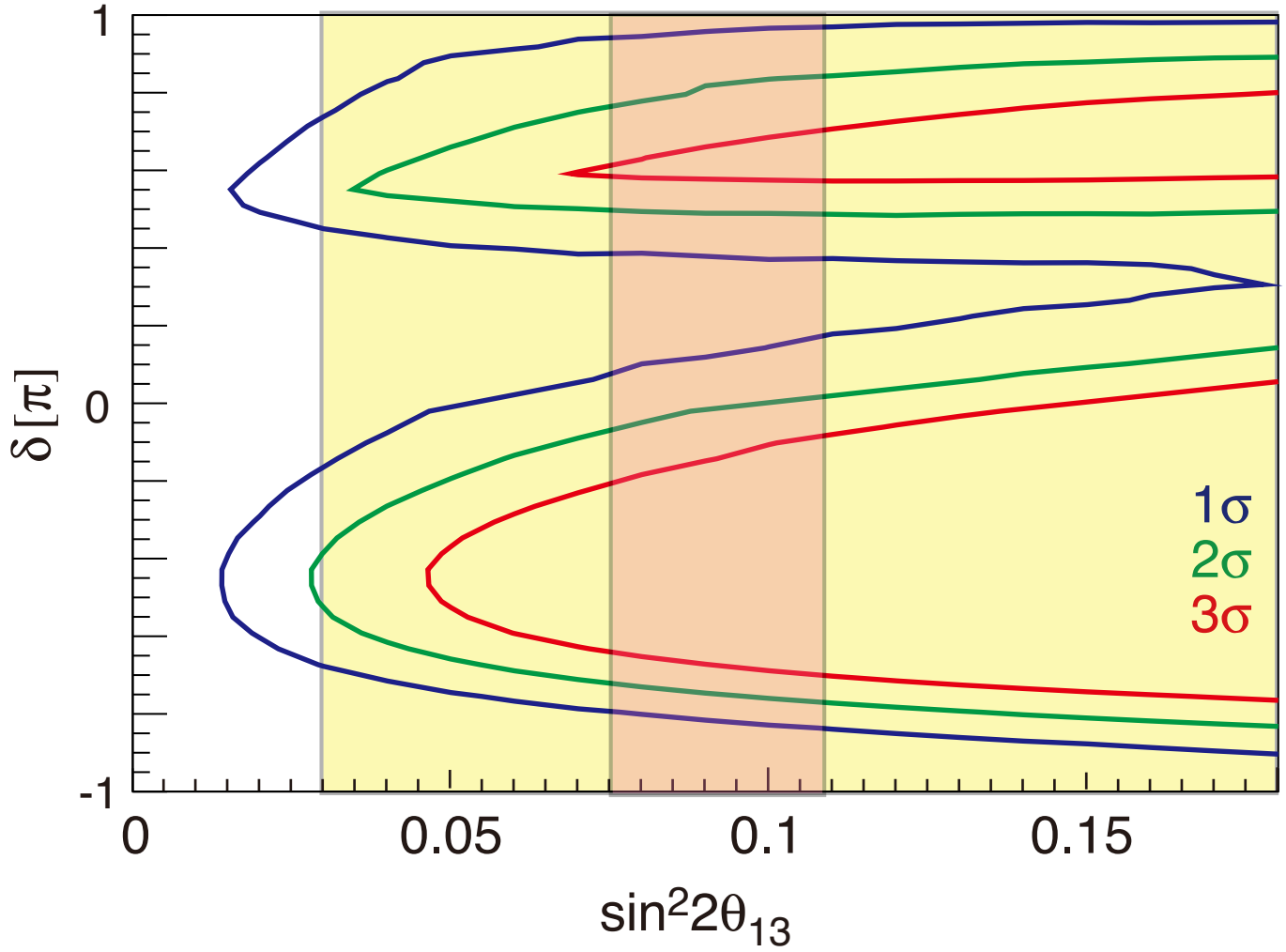
- δ precision < 20° (δ=90°)
  < 10° (δ= 0°)
- modest dependence on θ_{13} value

mass hierarchy determination

discrimination power of mass hierarchy

T2K90%CL

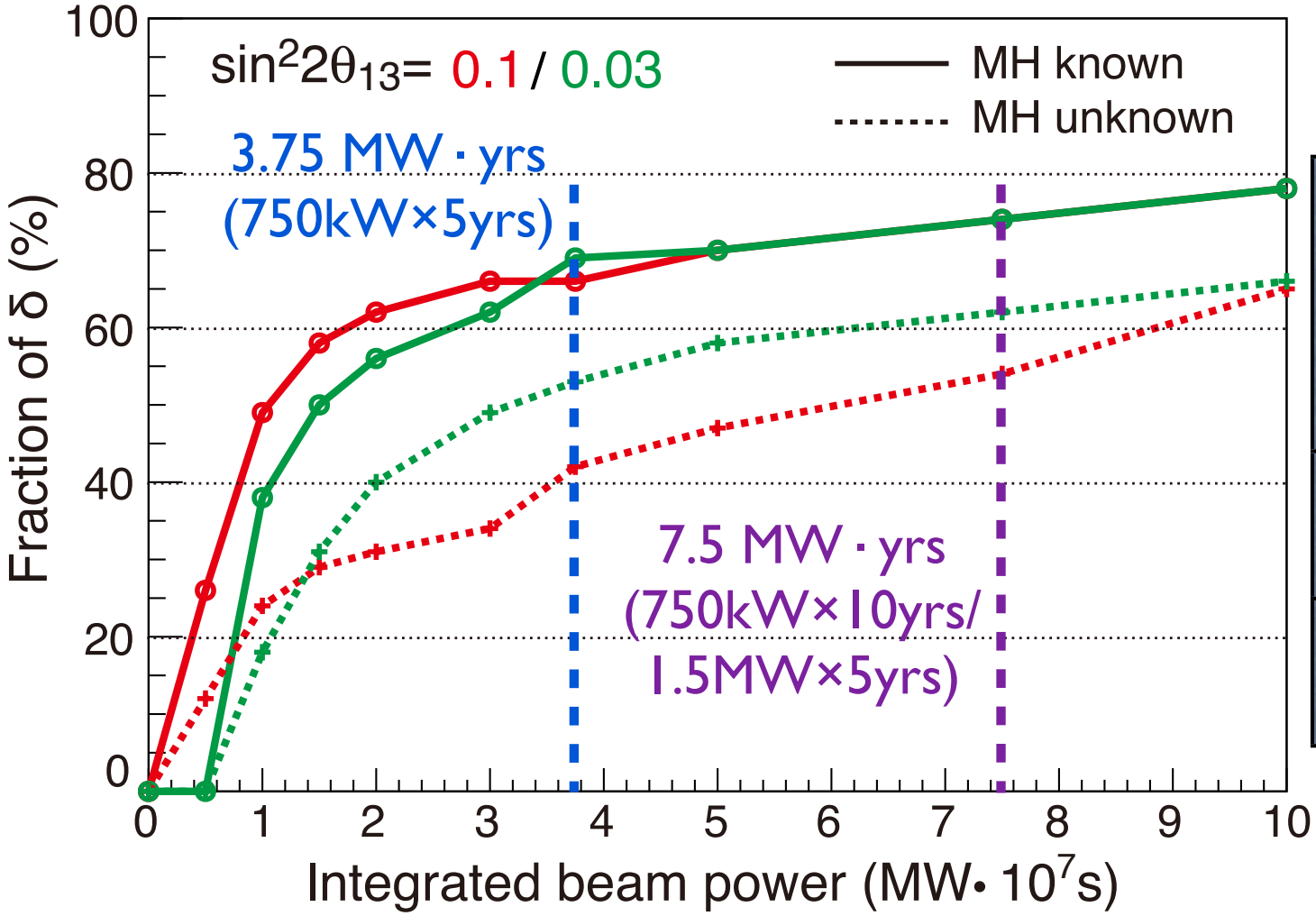
DayaBay1σ



Chance to determine MH by HK-JPARC experiment !

Fraction of δ (%) for CPV discovery

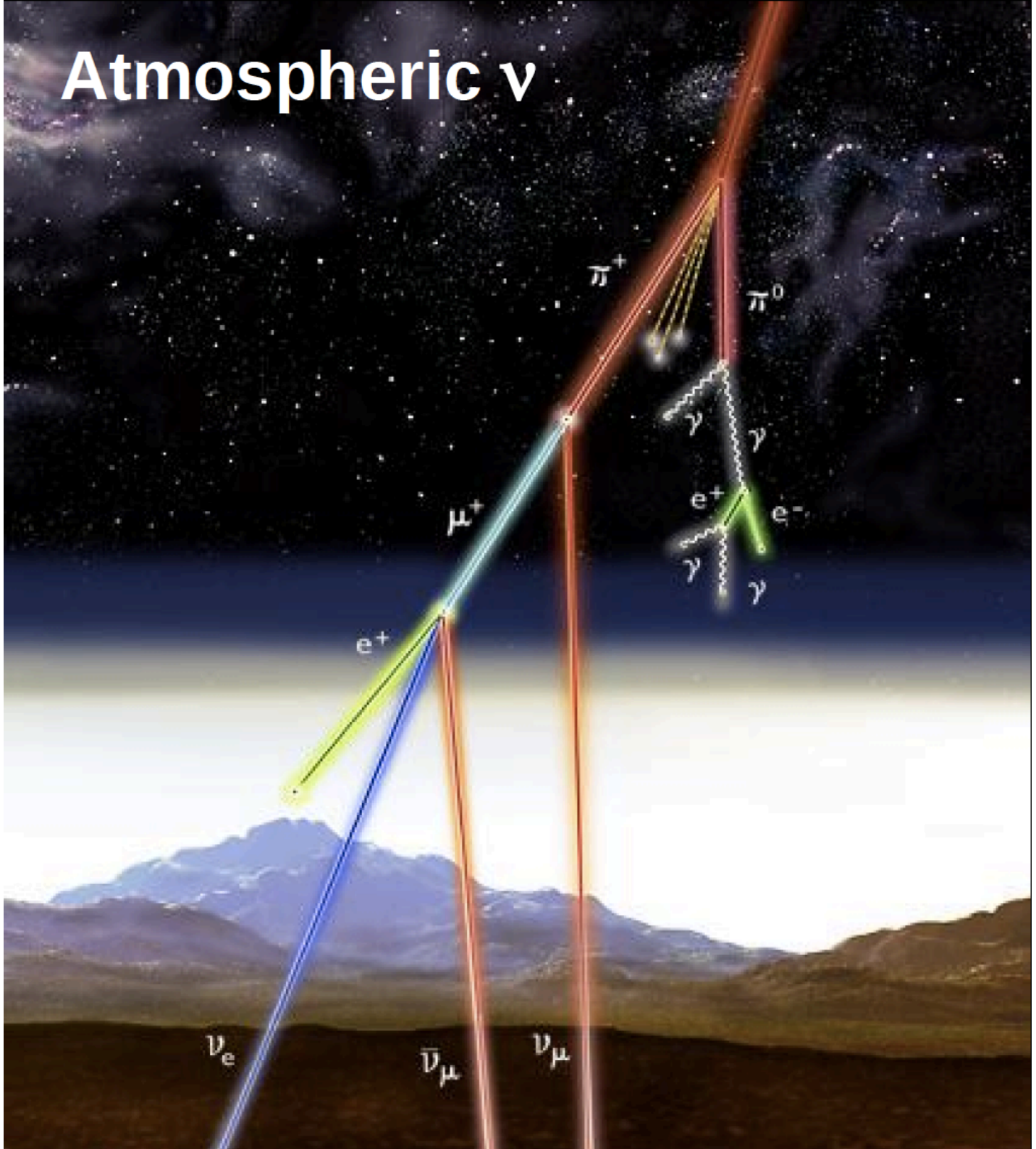
Fraction of δ in % for which expected CPV (sinδ≠0) significance is >3σ

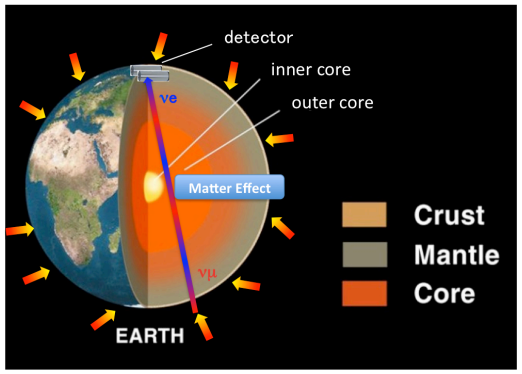


$\sin^2 2\theta_{13}$=0.1

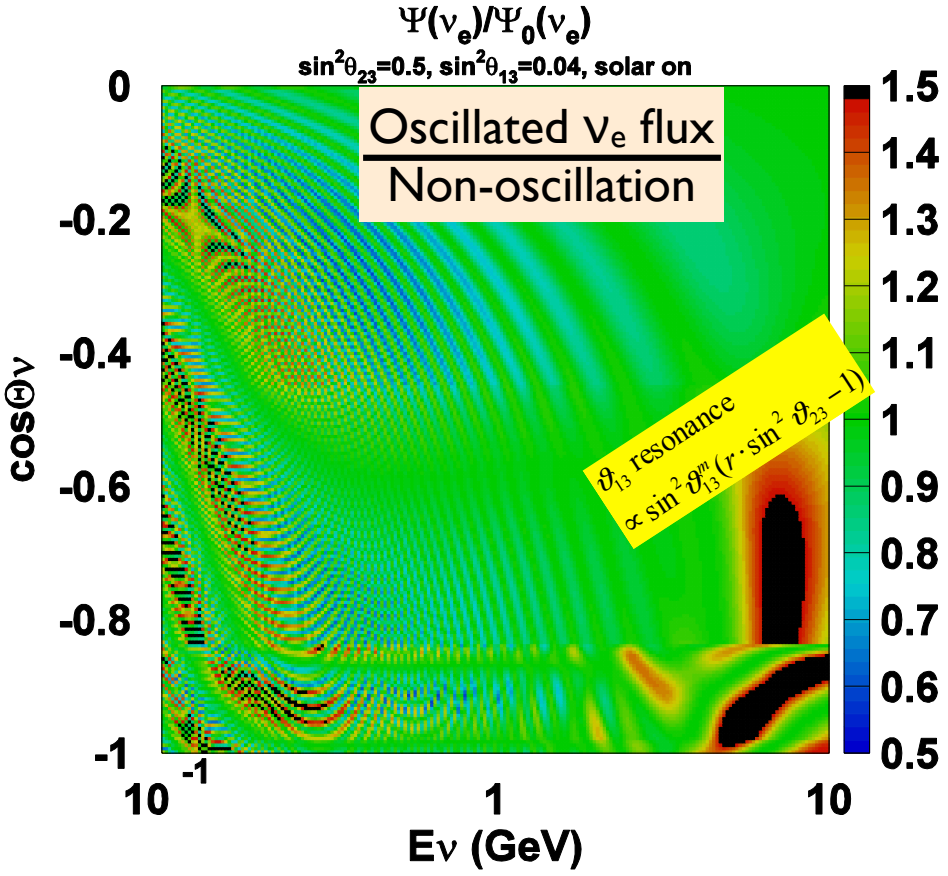
(MW× yrs)	Mass hierarchy	
	known	unknown
3.75	69%	42%
7.5	74%	54%

- Effect of unknown mass hierarchy is limited
  - Input from atm ν and other experiments also expected for MH


Atmospheric ν
π+
π0
γ
γ
e+
e-
γ
γ
μ+
e+
νe
ν̄μ
νμ



Atmospheric ν_e flux



NuclPhysB669,255(2003)

NuclPhysB680,479(2004)

r : μ/e flux ratio (~2 at low energy)

$P_2 = |A_{e\mu}|^2$: 2ν transition probability $\nu_e \rightarrow \nu_{\mu\tau}$ in matter

$R_2 = \mathrm{Re}(A^*_{ee}A_{e\mu})$

$I_2 = \mathrm{Im}(A^*_{ee}A_{e\mu})$

A_{ee} : survival amplitude of the 2ν system

$A_{e\mu}$: transition amplitude of the 2ν system

$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx P_2(r \cdot \cos^2\theta_{23} - 1)$$ Solar term

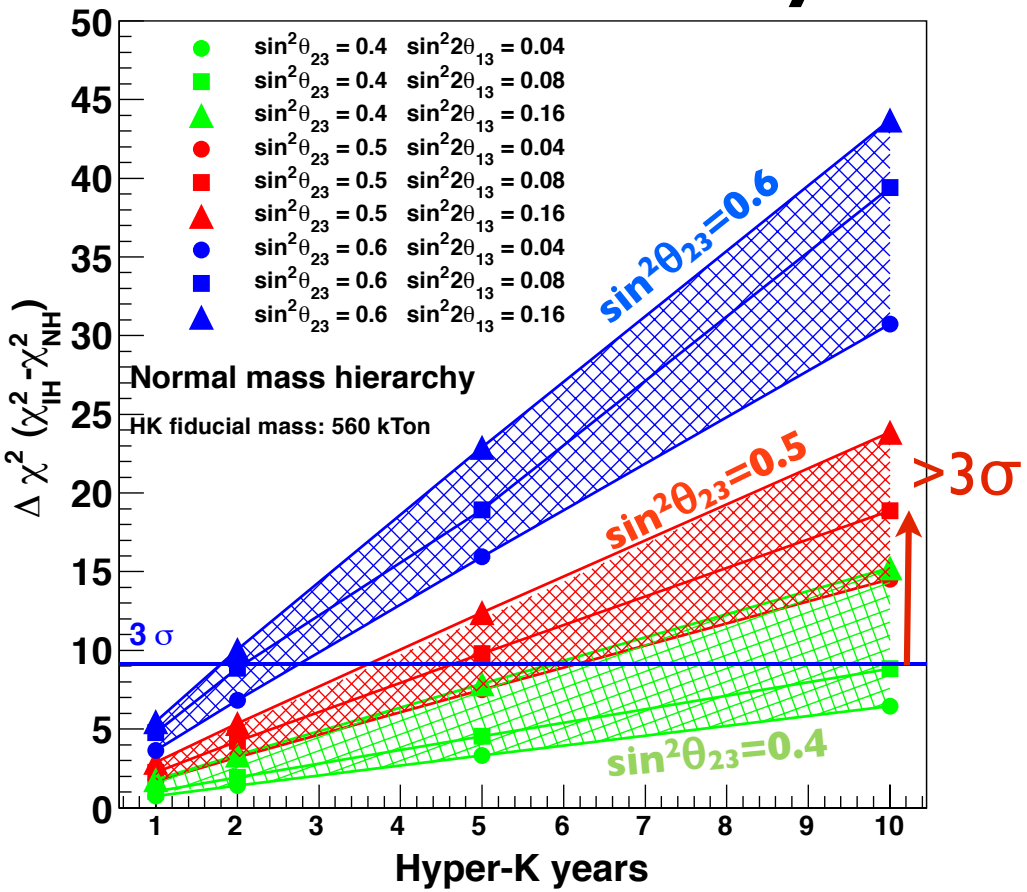
$$-r \cdot \sin\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin 2\theta_{23}(\cos\delta \cdot R_2 - \sin\delta \cdot I_2)$$ Interference term

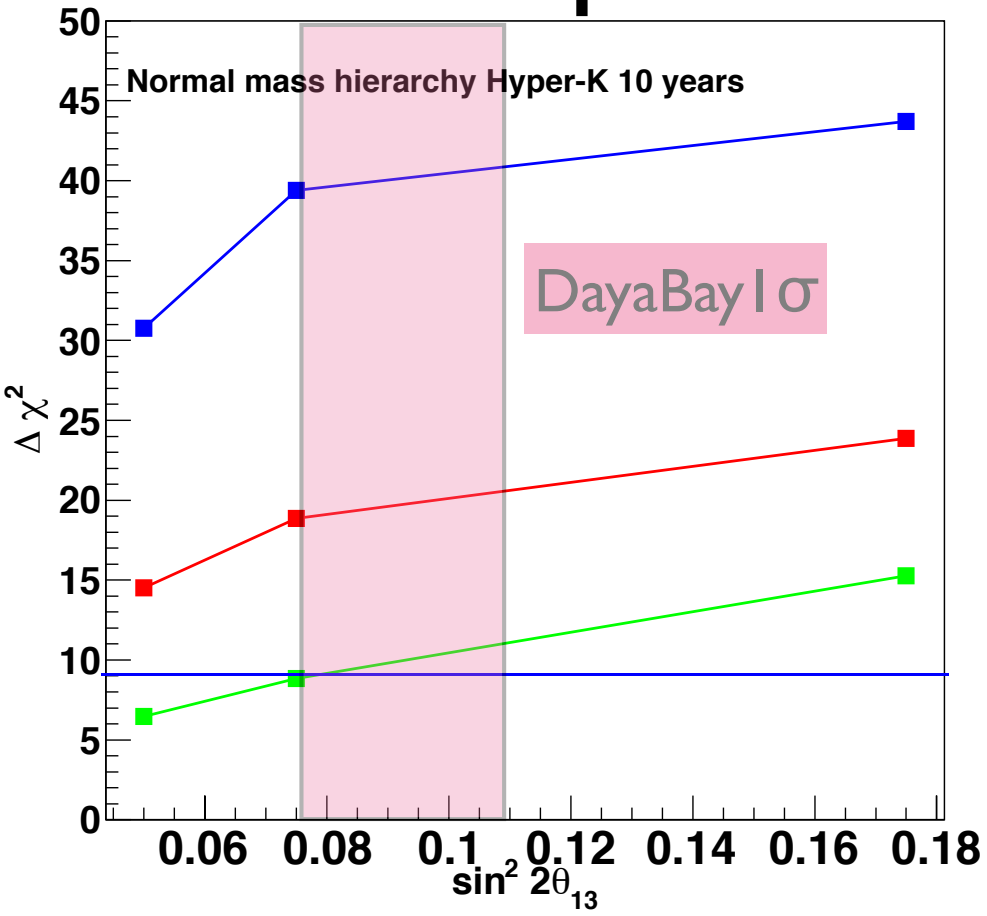
$$+2\sin^2\tilde{\theta}_{13}(r \cdot \sin^2\theta_{23} - 1)$$ θ_{13} resonance term

ν_e appearance is expected due to Earth's matter potential
- happens in ν in the case of normal mass hierarchy
- in anti-ν in inverted mass hierarchy

Large θ_{13} value gives us a good chance to discriminate mass hierarchy.

Mass hierarchy discrimination power



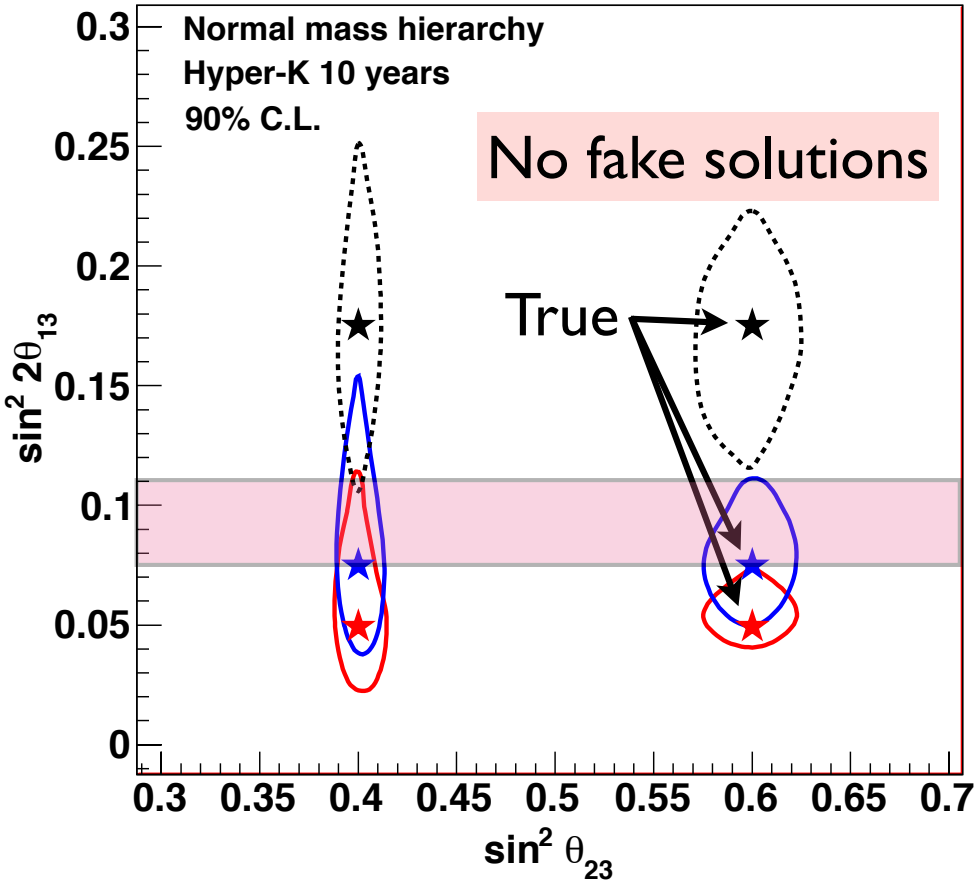


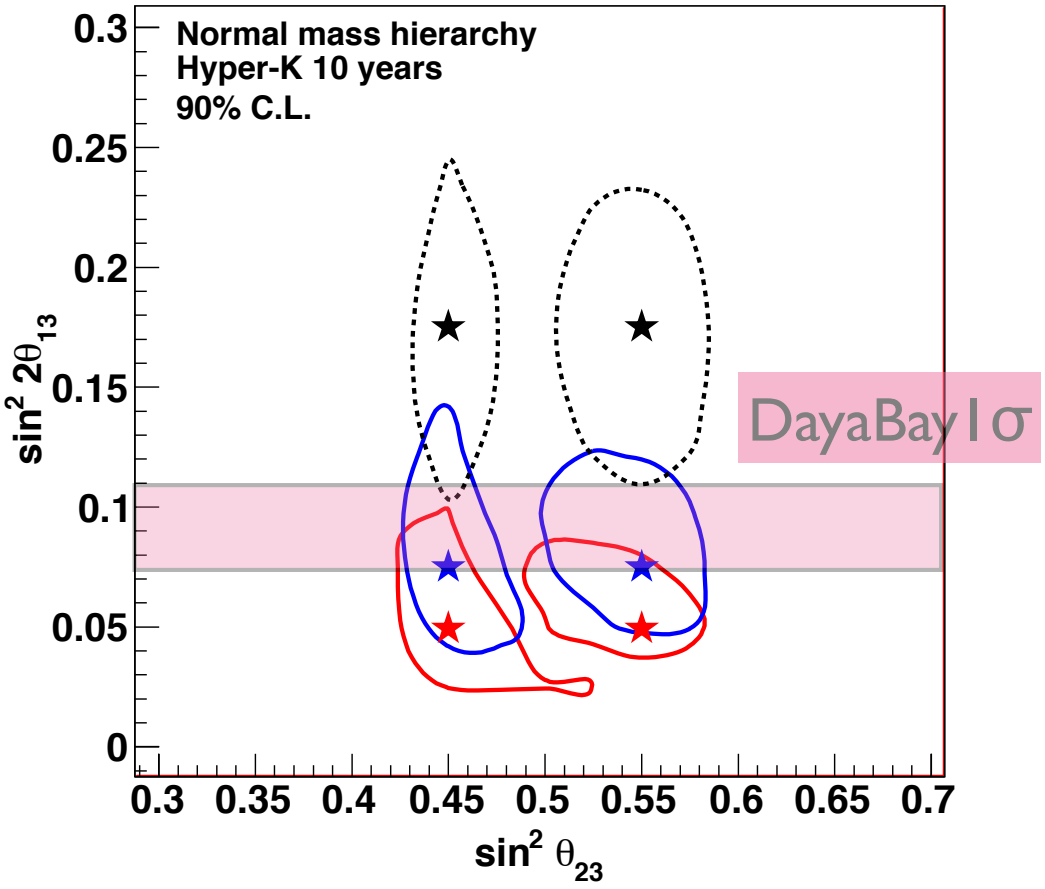
- expect to discriminate normal from inverted hierarchy w/ 3σ significance by ~5years data.
- Large θ_{13} (and θ_{23}) values are encouraging.

θ_{23} octant

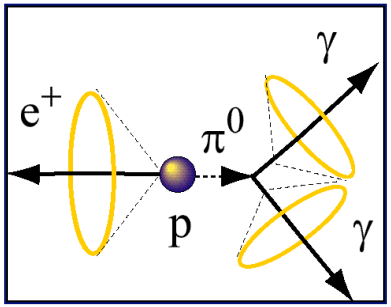
$\sin^2 2\theta_{23}=0.96$
↓
$\sin^2\theta_{23}=0.4$ or 0.6

$\sin^2 2\theta_{23}=0.99$
↓
$\sin^2\theta_{23}=0.45$ or 0.55





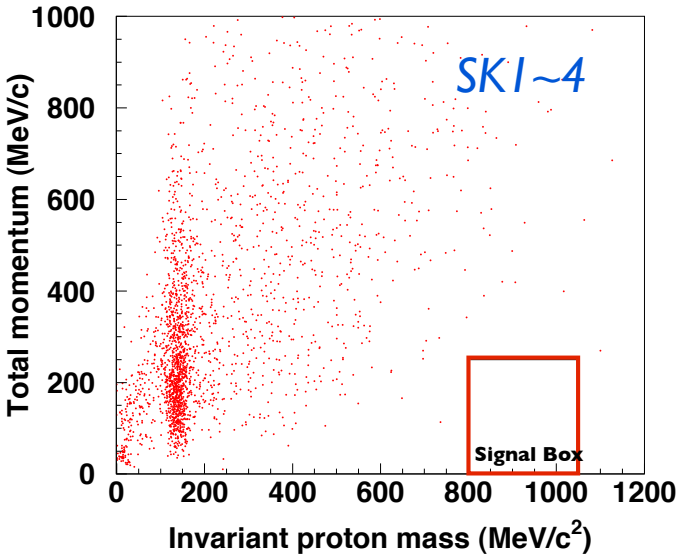
If $\sin^2 2\theta_{23}<0.99$, θ_{23} octant can be determined.

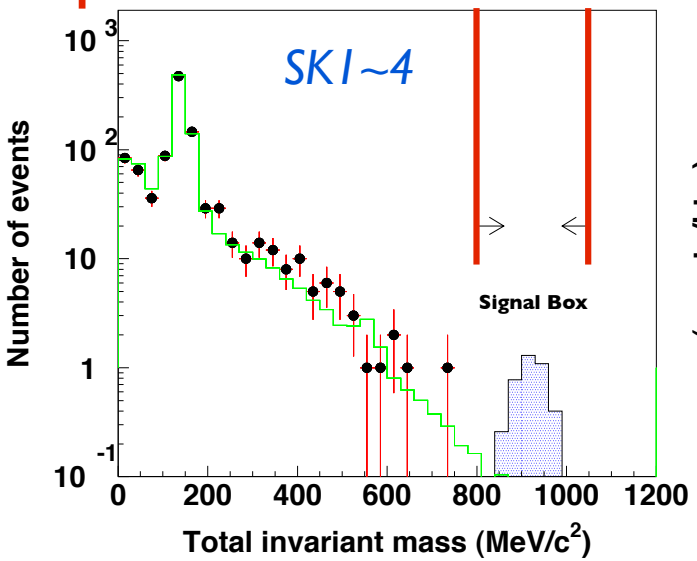


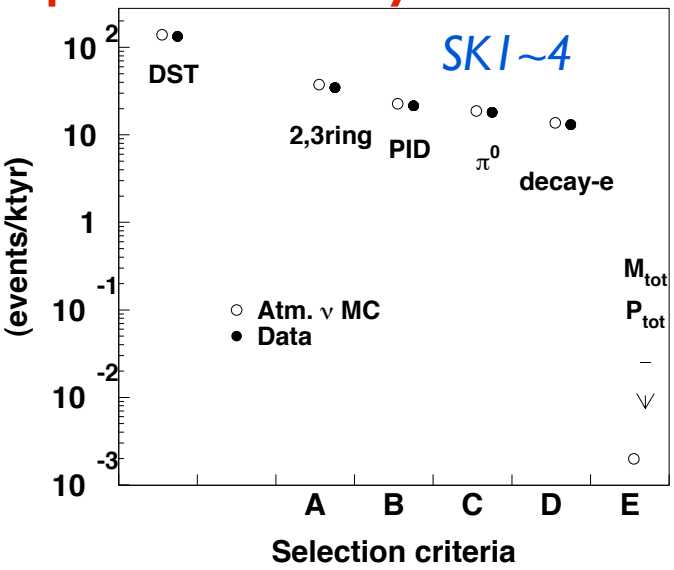
$p \rightarrow e^+ + \pi^0$ searches

Super-K cut
- 2 or 3 Cherenkov rings
- All rings are showering
- $85 < M_{\pi 0} < 185 MeV/c^2$ (3-ring)
- No decay electron
- $800 < M_{proton} < 1050$ MeV/c^2
  $P_{total} < 250$ MeV/c

Super-K data are well reproduced by BG MC.

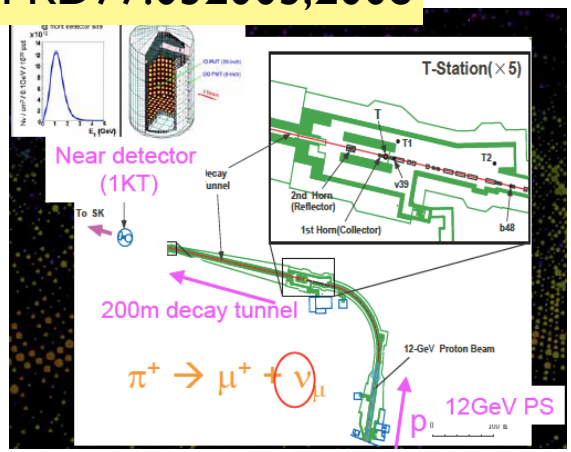






- detection efficiency = 45%
- atmospheric ν BG = 2.1±0.3(stat.)±0.8(syst.) (Mton×years)$^{-1}$
- $\tau_{proton}/Br > 1.3 \times 10^{34}$ years @ 90%CL

PRD77:032003,2008

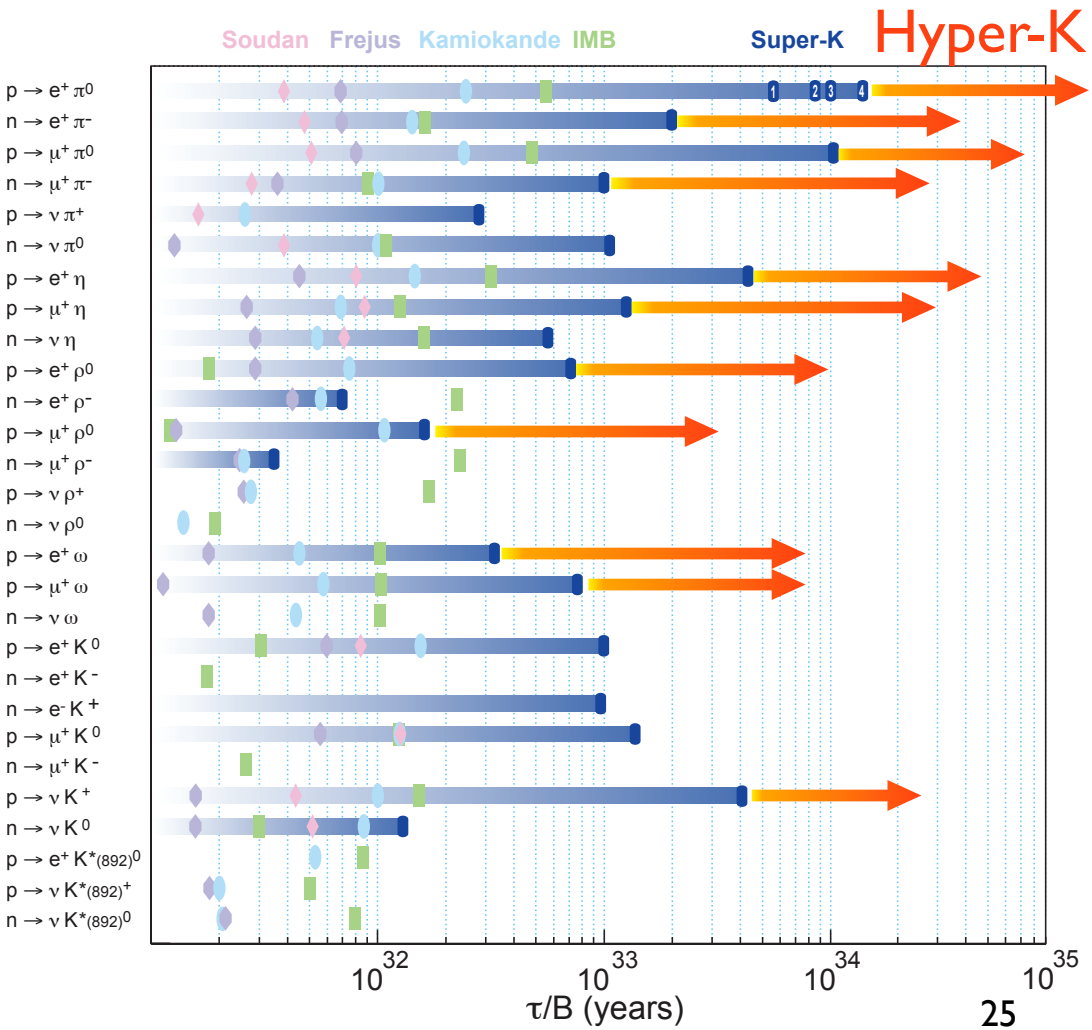


- BG measurement by accelerator ν (K2K)
  - BG=1.63+0.42/-0.33(stat.)+0.45/-0.51(syst.) (Mt×yrs)$^{-1}$ (Eν<3GeV)
  - Consistent w/ simulation 1.8±0.3(stat.)

Quality of next generation search is guaranteed.

Search for various decay modes

- many models predicts branching ratio of $p \to e^+\eta$, $e^+\rho$, $e^+\omega$ are 10~20%
- Flipped SU(5) (Ellis) predicts $Br(p \to e^+\pi^0) \sim Br(p \to \mu^+\pi^0)$
- (B-L) violated mode, e.g. $|\Delta B|=2$.



Hyper-K sensitivities

- $p \to e^+ + \pi^0$
  - $\tau_{proton}/Br > 1.3 \times 10^{35}$ years @90%CL
  - 5.6Mton×years (10 Hyper-K years)
- $p,n \to (e^+,\mu^+)+(\pi,\rho,\omega,\eta)$
  - $O(10^{34\sim35})$years
- *SUSY favored* $p \to \nu + K^+$
  - 2.5×10^{34} years
- K^0 modes, $\nu\pi^0$, $\nu\pi^+$ possible
- Other various decay modes.
  - (B-L) violated modes
  - radiative decays $p \to e^+\gamma$, $\mu^+\gamma$
  - neutron-antineutron振動 ($|\Delta B|=2$)
  - di-nucleon decays ($|\Delta B|=2$)
    - $pp \to XX\ldots$, $nn \to XX\ldots$

Summary

- Hyper-Kamiokande will cover rich physics topics.
  - discovery reach for leptonic CP violation.
  - good chance to discriminate hierarchy and θ_{23} octant.
  - ~10 times better sensitivity for nucleon decays.
  - various astrophysical objects.

- Effect of large $\sin^2 2\theta_{13}$ (~0.1)
  - JPARC-HK
    - small effect on CPV test if mass hierarchy is known.
    - $(\delta, \mathrm{sign}(\Delta m^2_{23}))$ degeneracy may happen.
    - Chance to determine the mass hierarchy.
  - Atmospheric ν
    - Good chance to determine the mass hierarchy and θ_{23} octant