Overview of Hyper-Kamiokande

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ANT11 Workshop, Oct.-10-2011

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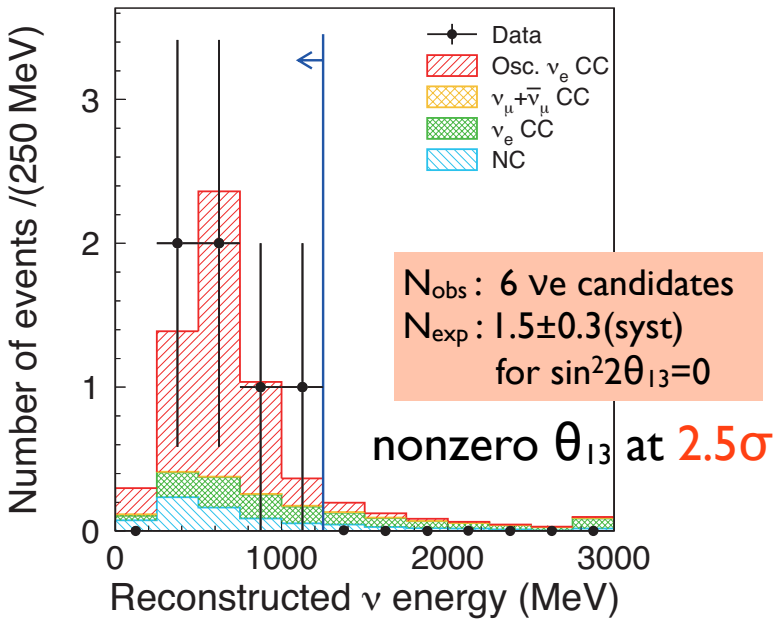
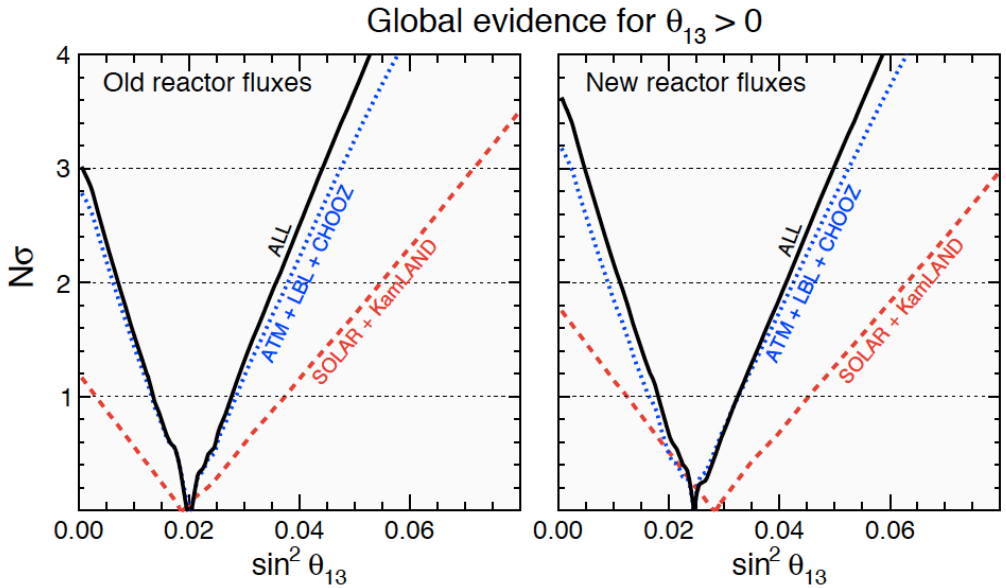
Establish θ_{13}, then CP violation

T2K collaboration, PRL107,041801(2011)

T2K observed indication of $\nu_\mu \rightarrow \nu_e$



Fogli et al., arXiv1106.6028
titled "Evidence of $\theta_{13}>0$ from global ν analysis"



nonzero θ_{13} is already >3σ w/ solar and reactorν

- T2K aims to establish nonzero θ_{13} and measure it w/ more data
- reactor experiments are starting data taking (Double CHOOZ, RENO, Daya Bay)

It's now time to seriously think about next generation experiments assuming $\theta_{13}\neq 0$ ($\sin^2\theta_{13}$= a few %).

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

arXiv:1109.3262v1 [hep-ex] 15 Sep 2011

Letter of Intent:

The Hyper-Kamiokande Experiment

— Detector Design and Physics Potential —

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

- Baseline design of the Hyper-K
- physics potential

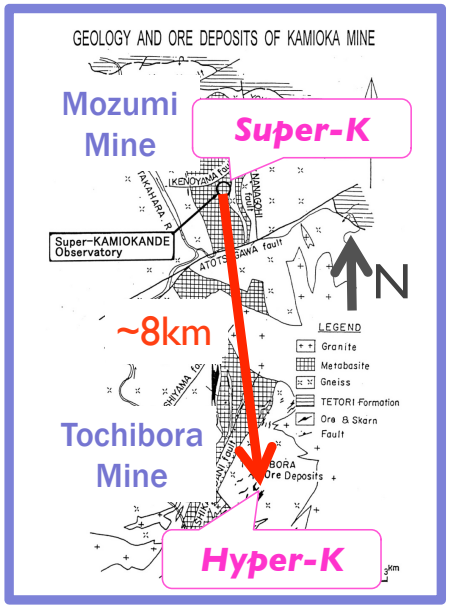
Explain them, especially physics case in this talk

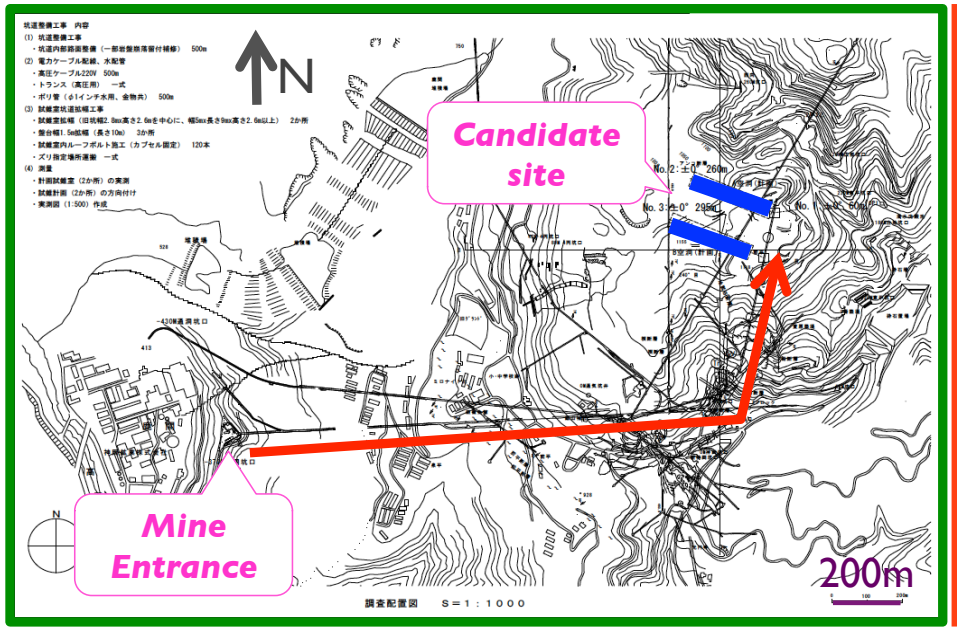
TABLE II. Physics targets and expected sensitivities of the Hyper-Kamiokande experiment. σ_{SD} is the WIMP-proton spin dependent cross section.

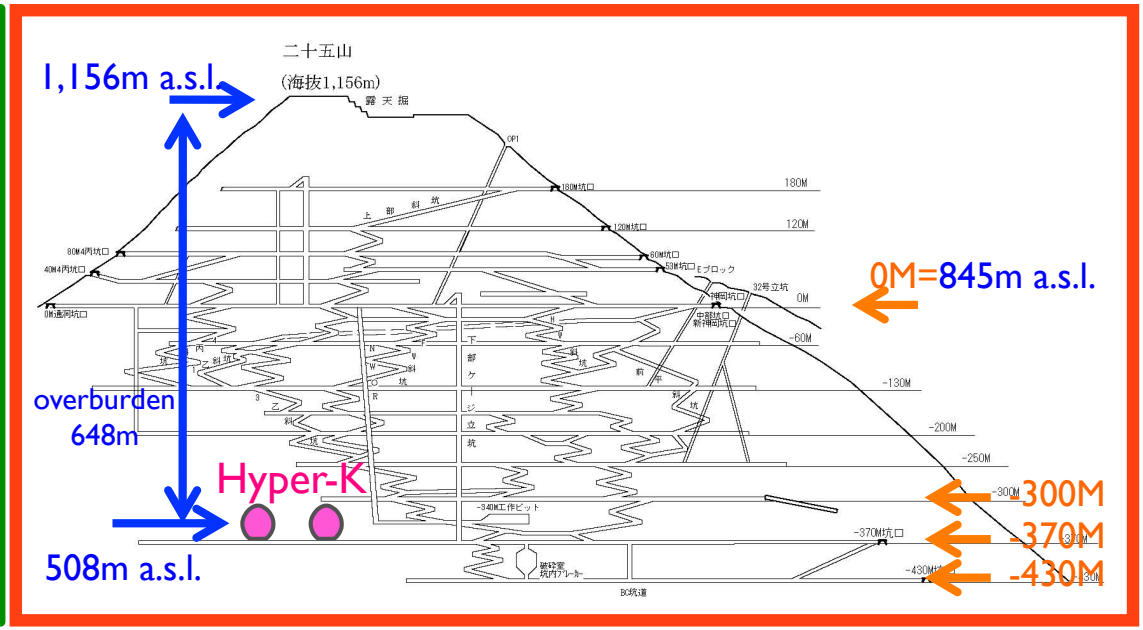
Physics Target	Sensitivity	Conditions
Neutrino study w/ J-PARC ν		1.66 MW $\times$ 5 years (1 year $\equiv 10^7$ sec)
– CP phase precision	$< 18°$	@ $s^2 2\theta_{13} (\equiv \sin^2 2\theta_{13}) > 0.03$ and mass hierarchy (MH) is known
– CPV 3σ discovery coverage	74% (55%)	@ $s^2 2\theta_{13} = 0.1$, MH known(unknown)
	74% (63%)	@ $s^2 2\theta_{13} = 0.03$, MH known(unknown)
	66% (59%)	@ $s^2 2\theta_{13} = 0.01$, MH known(unknown)
Atmospheric neutrino study		10 years observation
– MH determination	$> 3\sigma$ CL	@ $0.4 < s^2\theta_{23}$ and $0.04 < s^2 2\theta_{13}$
– θ_{23} octant determination	$> 90\%$ CL	@ $s^2 2\theta_{23} < 0.99$ and $0.04 < s^2 2\theta_{13}$
Nucleon Decay Searches		10 years data
– $p \to e^+ + \pi^0$	1.3×10^{35} yrs (90% CL)	
	5.7×10^{34} yrs (3σ CL)	
– $p \to \bar{\nu} + K^+$	2.5×10^{34} yrs (90% CL)	
	1.0×10^{34} yrs (3σ CL)	
Solar neutrinos		
– ^{8}B ν from Sun	200 ν's / day	7.0 MeV threshold (total energy) w/ osc.
– ^{8}B ν day/night accuracy	$< 1\%$	5 years, only stat. w/ SK-I BG $\times 20$
Astrophysical objects		
– Supernova burst ν	170,000$\sim$260,000 ν's	@ Galactic center (10 kpc)
	30$\sim$50 ν's	@ M31 (Andromeda galaxy)
– Supernova relic ν	830 ν's / 10 years	
– WIMP annihilation at Sun		5 years observation
	$\sigma_{SD} = 10^{-39}\text{cm}^2$	@ $M_{\text{WIMP}} = 10$ GeV, $\chi\chi \to b\bar{b}$ dominant
	$\sigma_{SD} = 10^{-40}\text{cm}^2$	@ $M_{\text{WIMP}} = 100$ GeV, $\chi\chi \to W^+W^-$ dominant

Hyper-Kamiokande candidate site

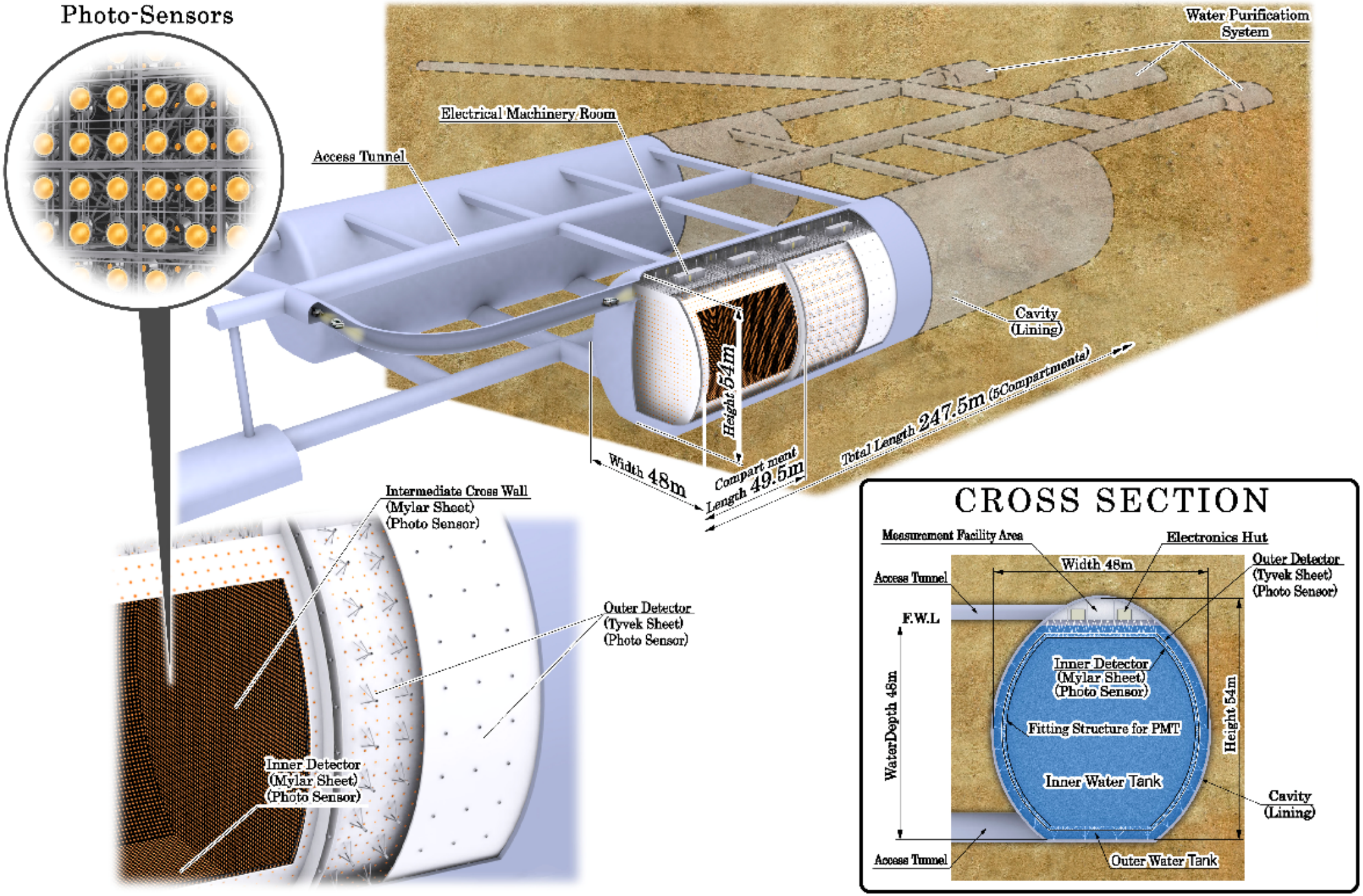
- ✦ 8km south from Super-K
  - ✦ same T2K beam off-axis angle
- ✦ 2.6km horizontal drive from entrance
- ✦ under the peak of Nijuugo-yama
  - ✦ 648m of rock or 1,750 m.w.e. overburden
  - ✦ 508m above sea level
- ✦ dominated by Hornblende Biotite Gneiss and Migmatite
- ✦ 2.3km from waste rock disposal place
- ✦ 13,000 m^3/day or 1megaton/80days natural water



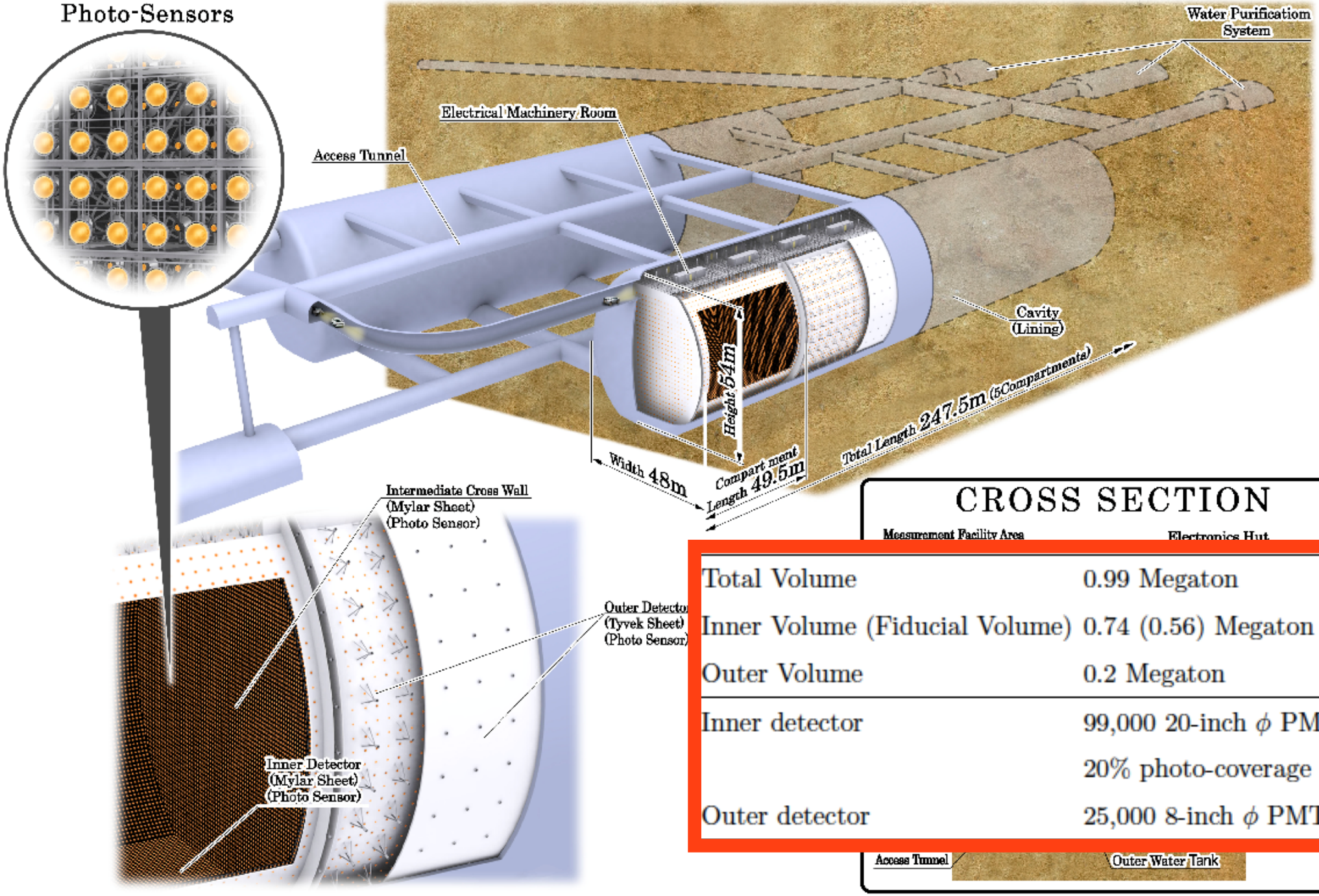




Schematic View of the Hyper-Kamiokande



Schematic View of the Hyper-Kamiokande

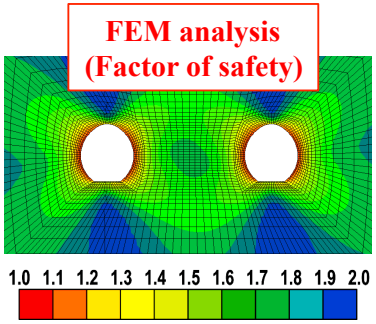


Total Volume	0.99 Megaton
Inner Volume (Fiducial Volume)	0.74 (0.56) Megaton
Outer Volume	0.2 Megaton
Inner detector	99,000 20-inch ϕ PMTs
	20% photo-coverage
Outer detector	25,000 8-inch ϕ PMTs

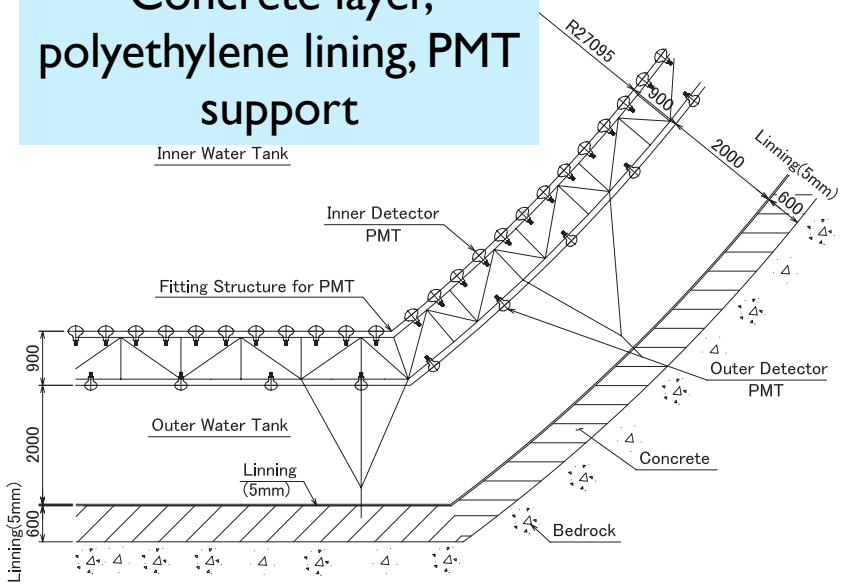
More on baseline design

Geological survey

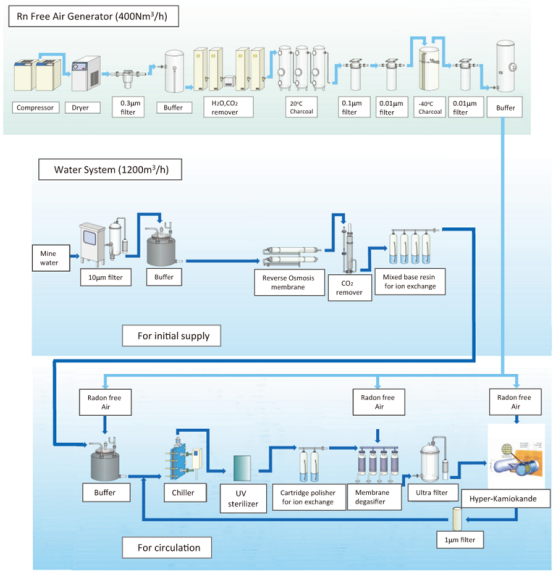
Twin cavern analysis



Concrete layer, polyethylene lining, PMT support

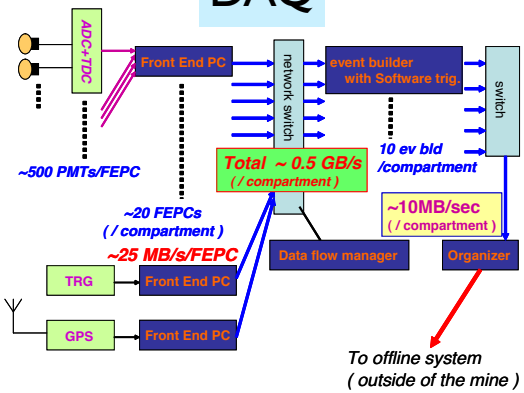


Water system



Gd loading test (Super-K collaboration)

DAQ



Photon sensor

Physics targets

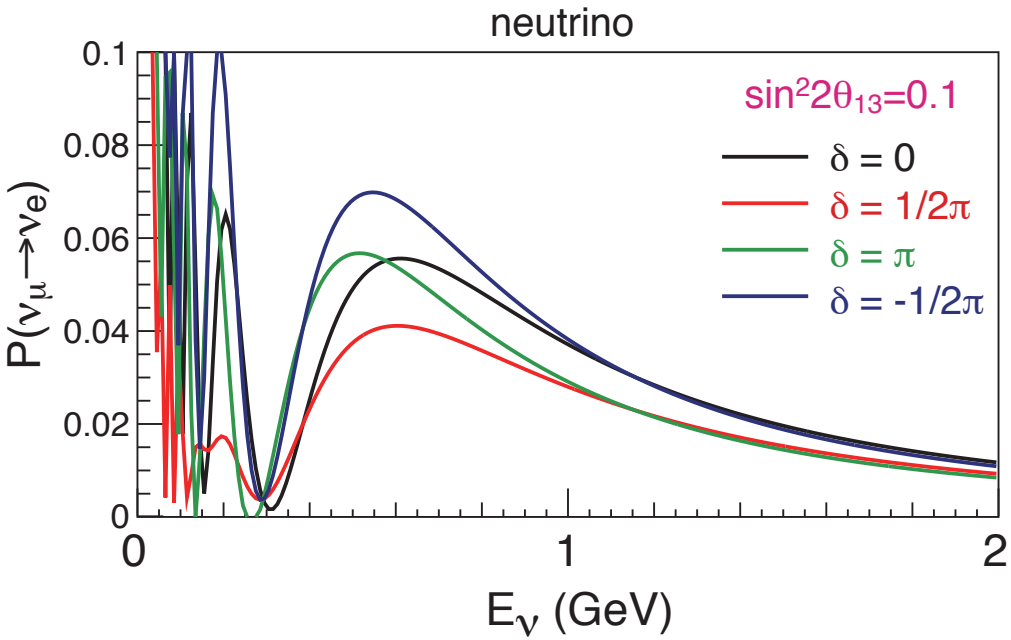
- explore full picture of neutrino mass&mixing
- explore unification picture of quarks and leptons

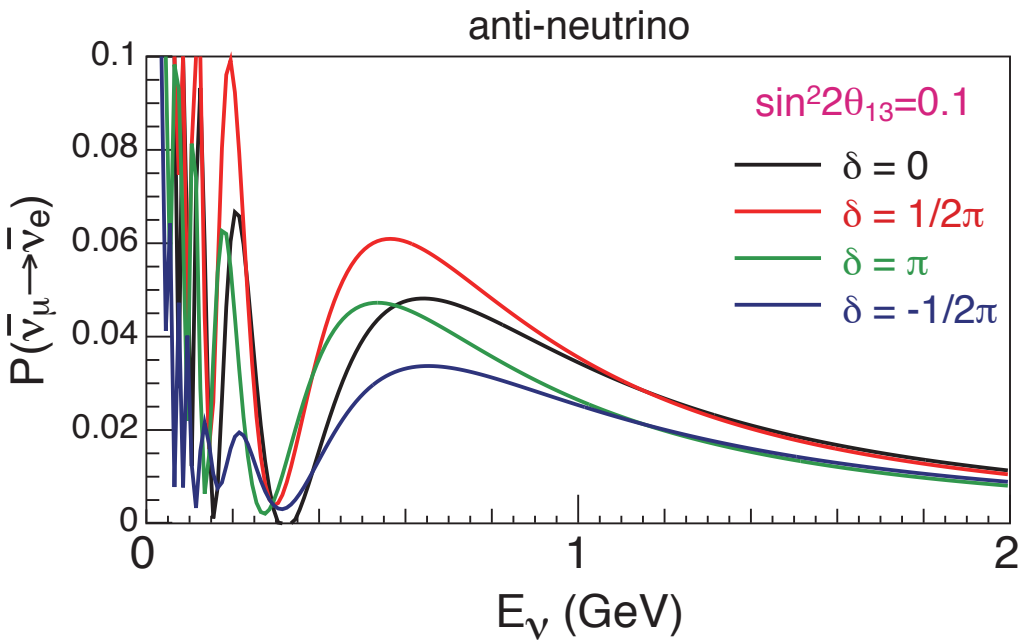
- J-PARC ν's
  - Discovery of Leptonic CP violation
  - ν mass hierarchy
- Atmospheric ν
  - supplemental information on ν properties
- Proton (or neutron) decays
- Solar ν
- Astrophysical objects
  - Supernova burst ν and Supernova relic ν
  - WIMP annihilation ν
  - Solar flare ν, GRB ν, ...
- Neutrino Geophysics

Electrical Machinery Room
Access Tunnel
Cavity (Lining)
Height 54m
Width 48m
Compart-ment Length 49.5m
Total Length 247.5m (6Compartments)
Hyper-K
Super-K
x25 Larger Target
~0.6GeV νμ
295km
Quest for CP Violation in lepton sector
Higher Intensity
>1.66MW (KEK roadmap)
JPARC
© 2010 ZENRIN
Data © 2010 MIRC/JHA
© 2010 Cnes/Spot Image
© 2010 Mapabc.com
©2009 Google
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

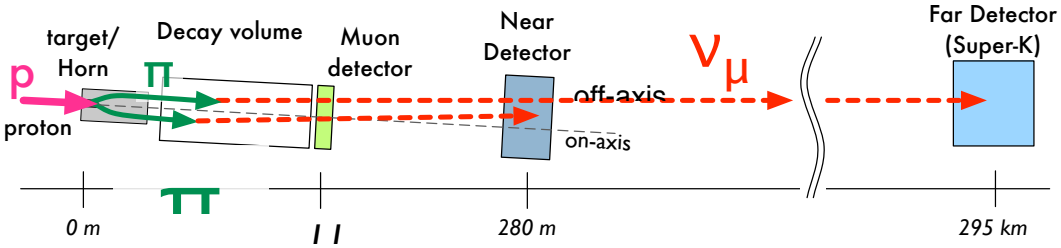
Normal hierarchy

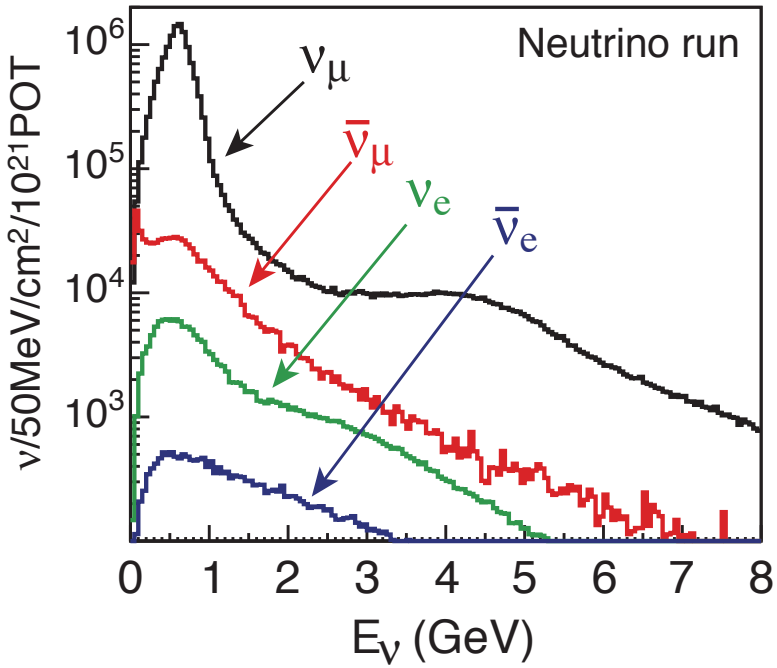


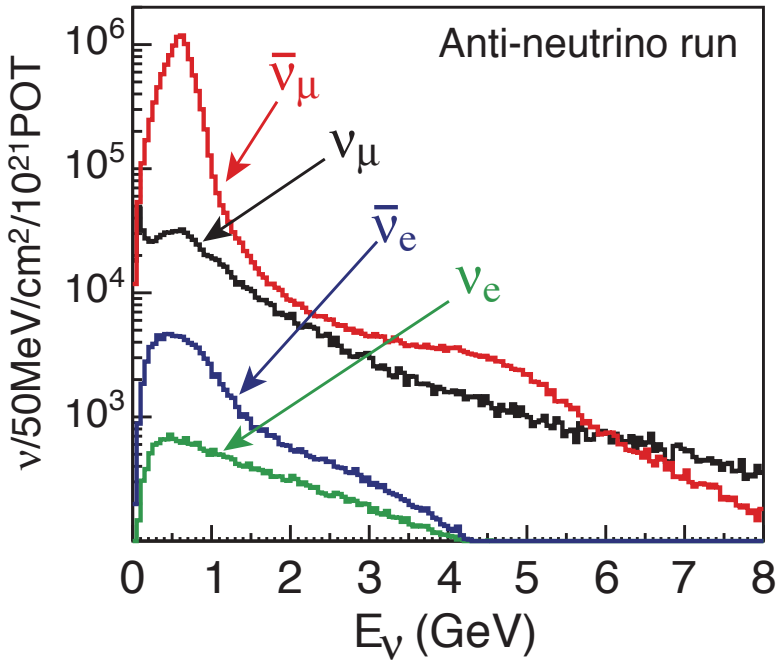


- CPV test by comparing $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  - sensitive to exotic (non MNS matrix origin) CPV
- Fake CPV effect by matter effect
  - P(matter)/P(δ)~1/3 for $\sin^2 2\theta_{13}=0.1$
  - P(matter)/P(δ)~1/10 for $\sin^2 2\theta_{13}=0.01$ (pure δ-driven CPV)

JPARC ν







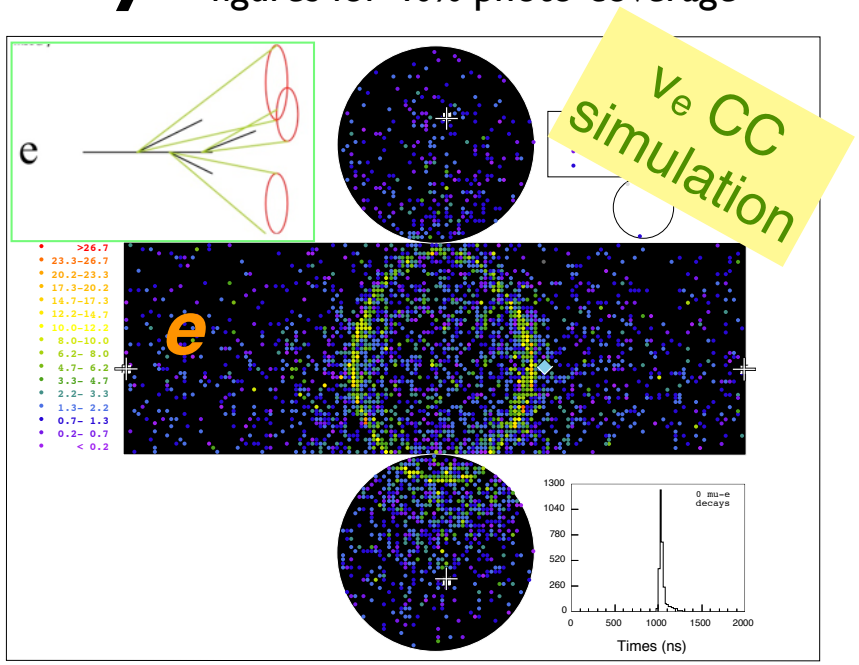
- J-PARC ν's
  - T2K flux based on beamline geometry, horn (320kA), hadron (π, K) production data, proton profile
  - anti-ν by inverted horn current

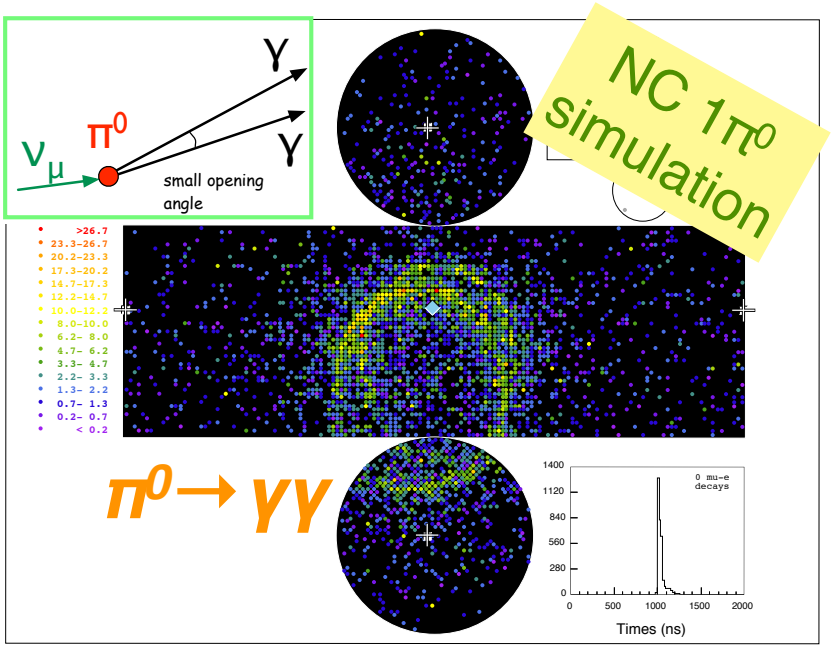
- Quasi-monochromatic ν w/ peak energy at oscillation maximum
- intrinsic beam ν_e (BG) is <1% at peak energy

Detailed study

figures for 40% photo-coverage

- Full simulation of ν interaction, hadron secondary interactions (NEUT)
- HK detector response by modified Super-K simulation
  - PMT density 40%→20%
  - light propagation, electronics response
  - small geometry difference (~35m(SK) ⇔50m(HK))





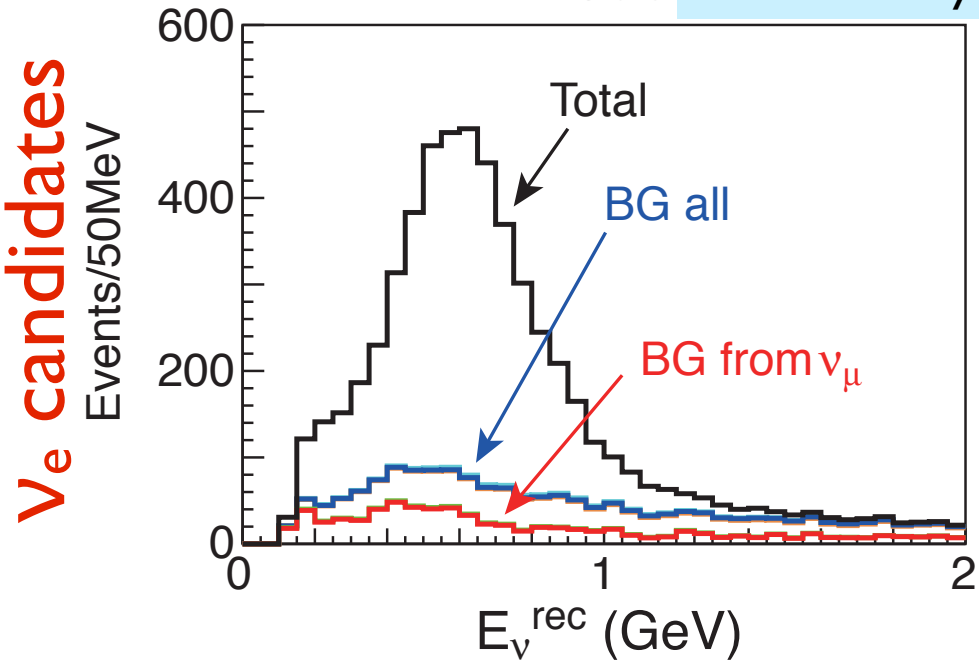
ν_e event selection

1. Fully Contained & in Fiducial Volume & Evis>100MeV
2. 1-ring
3. e-like
4. No muon decays
5. M_{inv} < 100 MeV/c^2
6. E^{rec}_{ν} < 2 GeV (looser cut to use spectrum information)

Selected ν_e candidates (and BG)

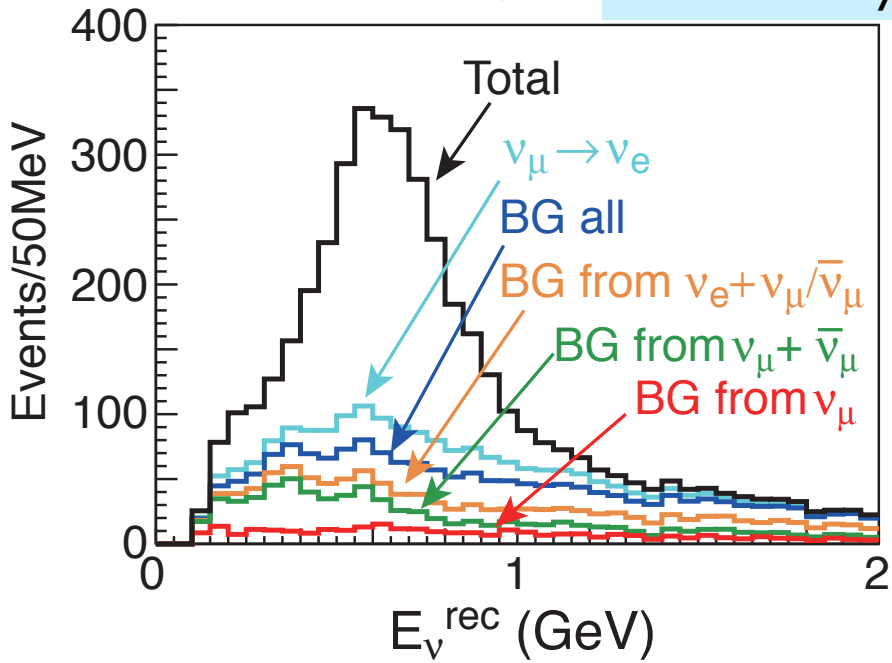
$\sin^2 2\theta_{13}=0.1, \delta=0$

ν mode 1.66MW×1.5yrs



$\nu_\mu \to \nu_e$CC: 3940 ev
$\bar{\nu}_\mu \to \bar{\nu}_e$CC: 51
$\nu_\mu + \bar{\nu}_\mu$CC : 39
$\nu_e + \bar{\nu}_e$CC :977
NC :718

$\bar{\nu}$ mode 1.66MW×3.5yrs



$\nu_\mu \to \nu_e$CC: 421 ev
$\bar{\nu}_\mu \to \bar{\nu}_e$CC: 2168
$\nu_\mu + \bar{\nu}_\mu$CC : 25
$\nu_e + \bar{\nu}_e$CC :972
NC :750

ν_e signal efficiency ⇔ BG rejection

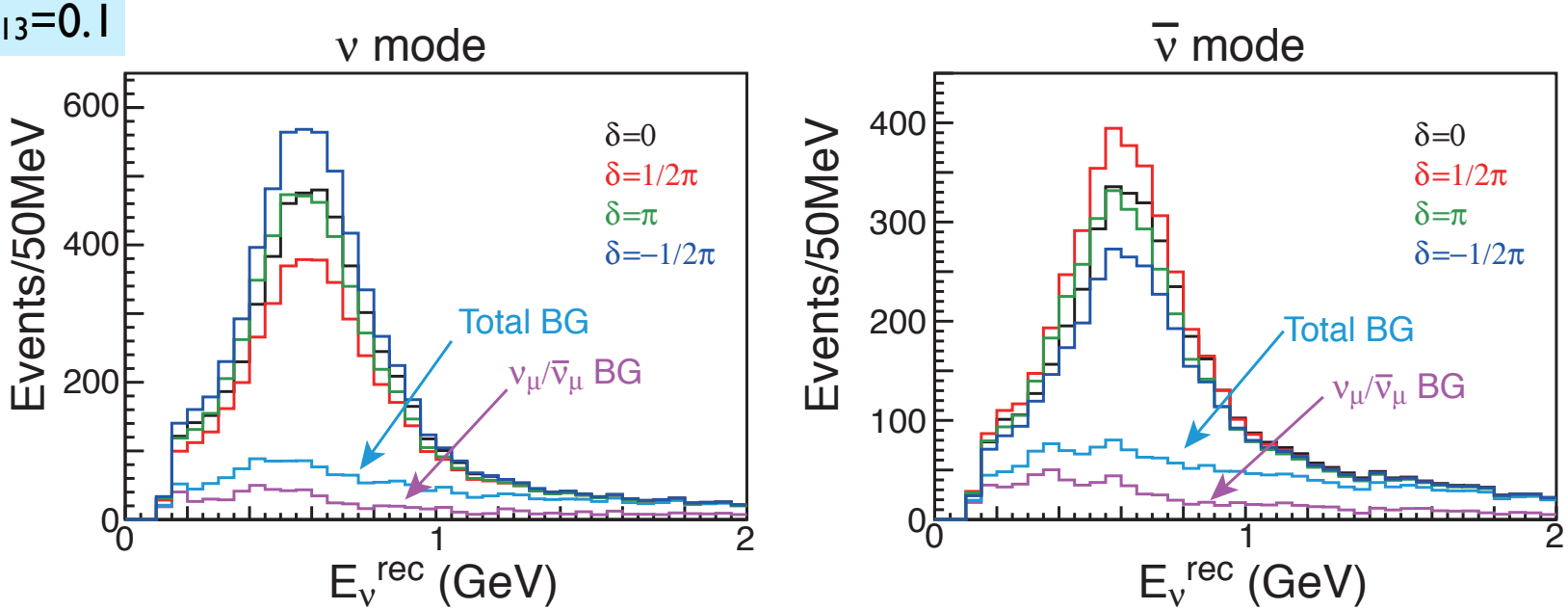
64% ν_μ+antiν_μCC <0.1%, NCπ^0 <5%

($0.1 < E^{rec}_\nu < 1.25$ GeV)

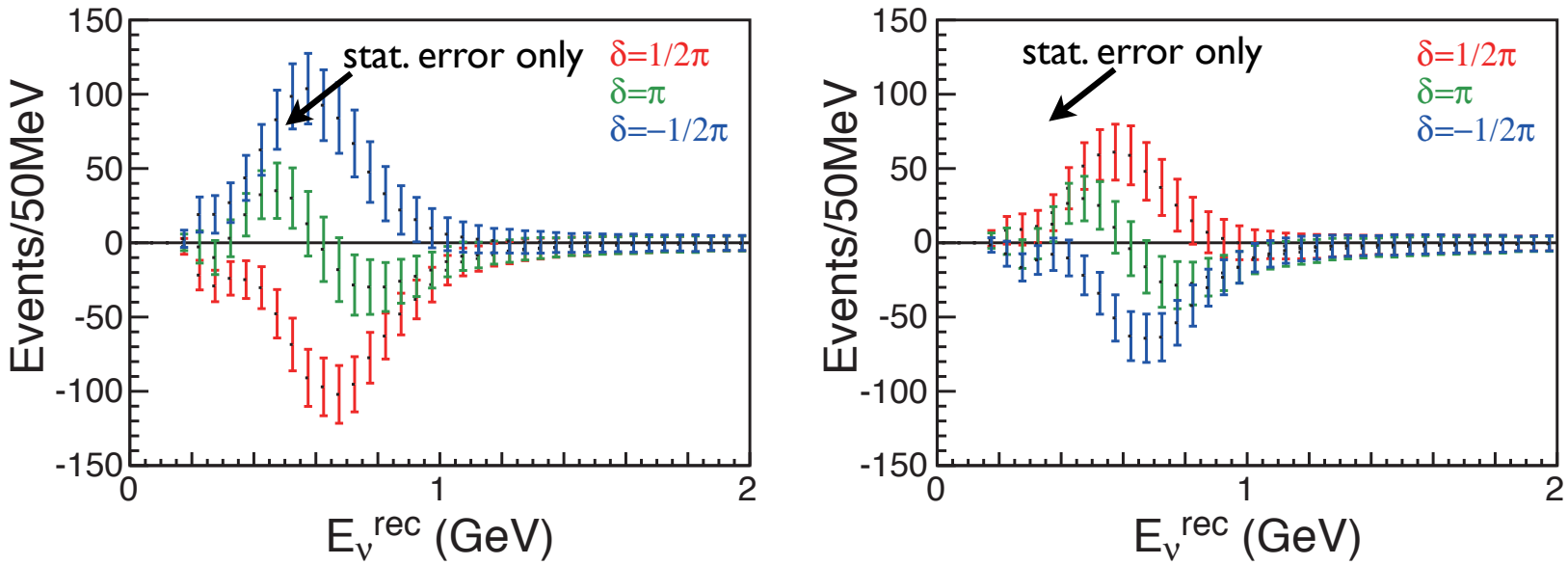
Expected ν_e candidates

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

ν_e candidates

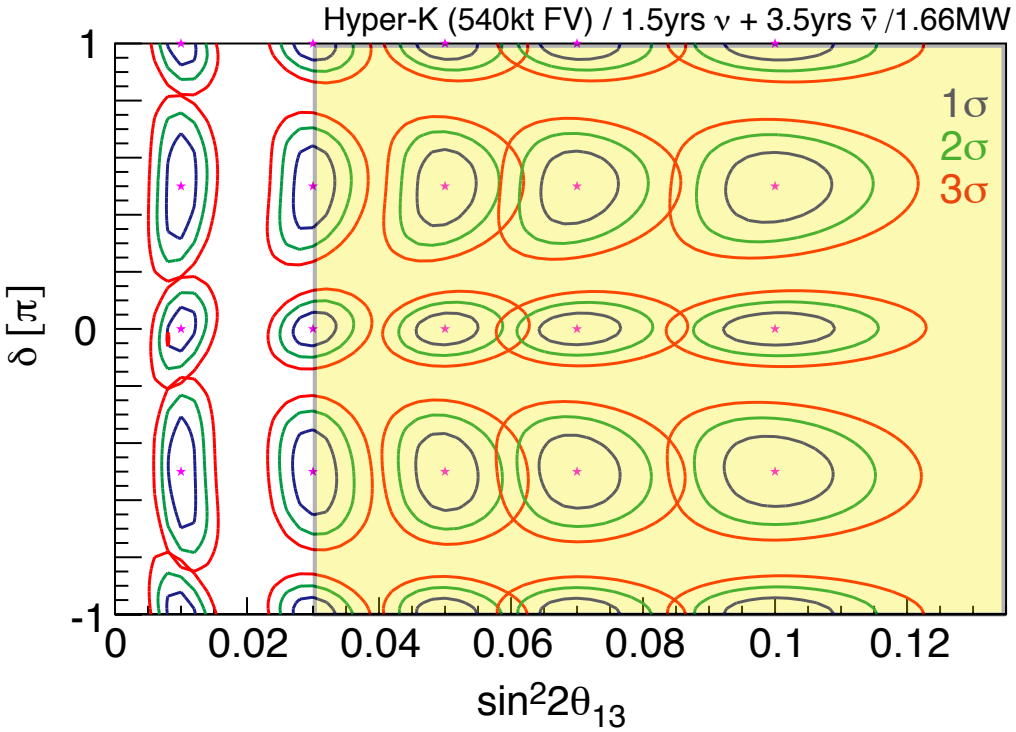


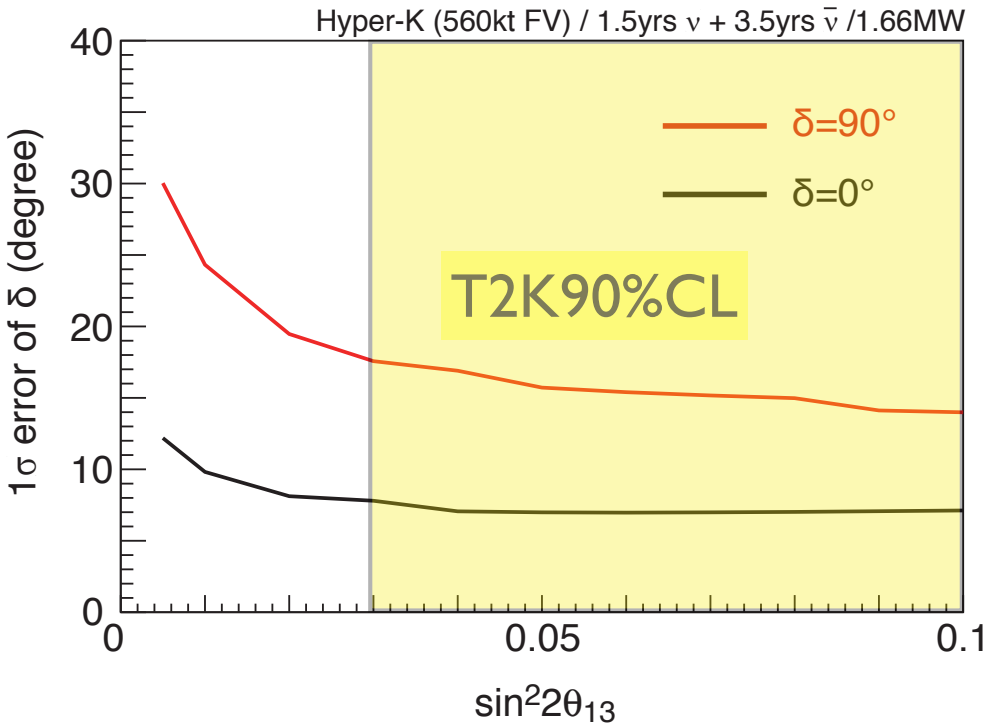
diff. from δ=0 case



Contours

Normal mass hierarchy (known)

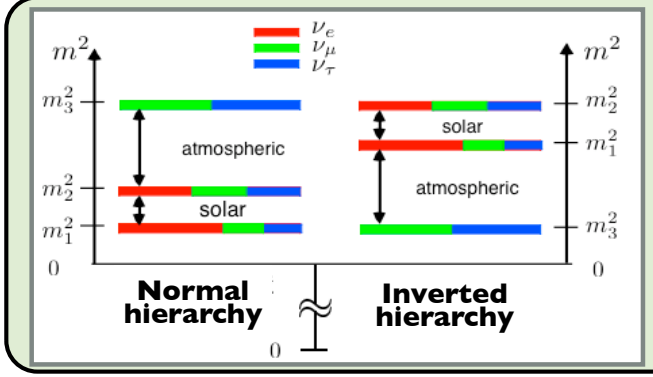




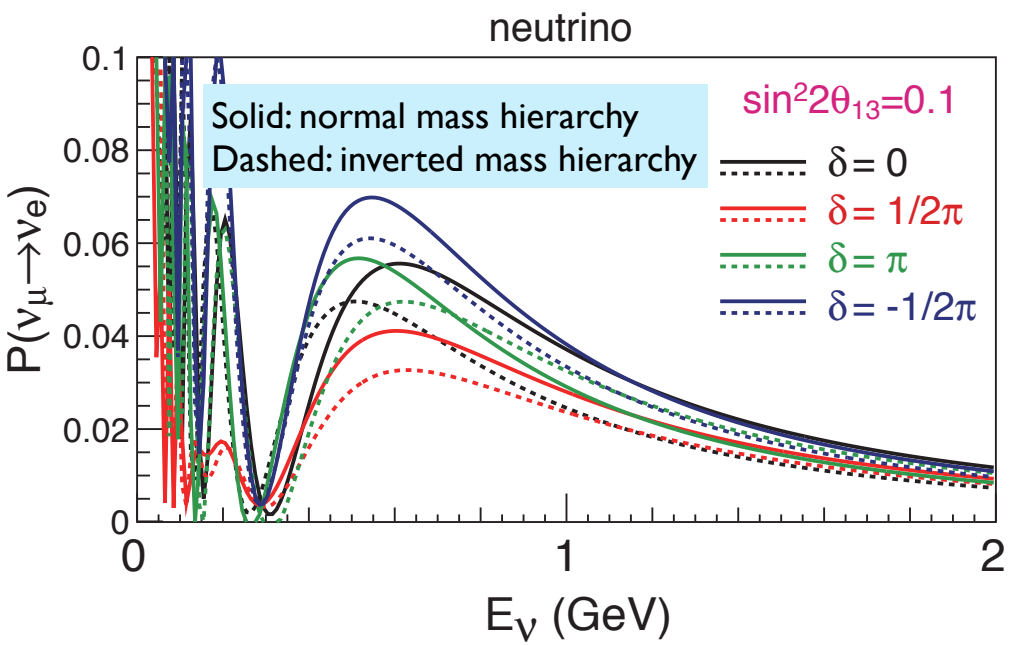
Good sensitivity in whole T2K's θ_{13} allowed region!

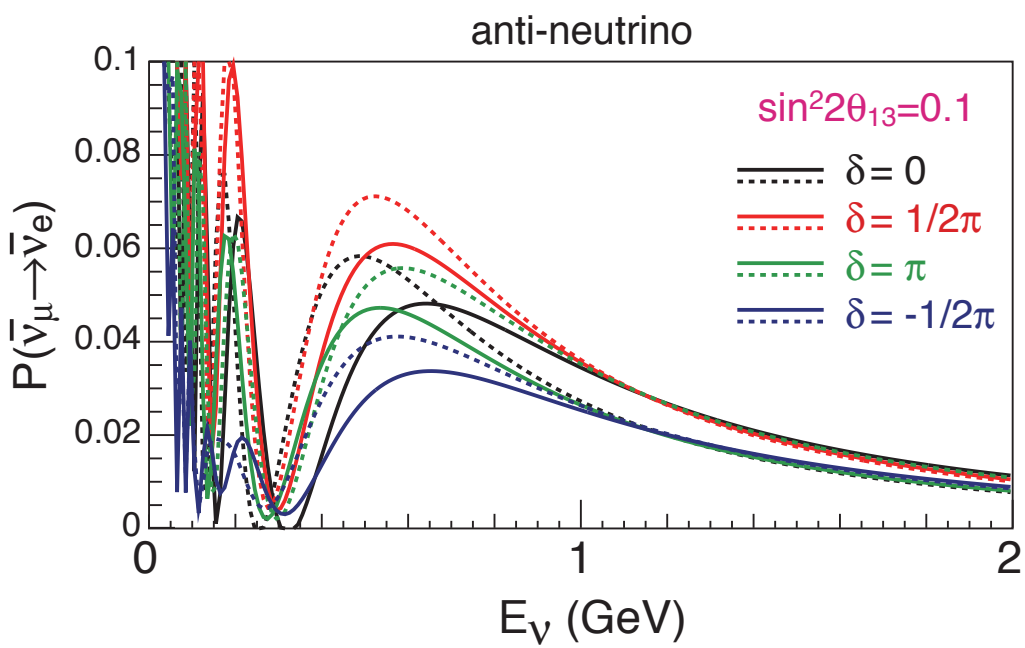
- δ precision < 18° (δ=90°)
  < 8° (δ= 0°)
- modest dependence on θ_{13} value

If mass hierarchy is unknown



- Normal hierarchy
  - m_3 is heaviest
- Inverted hierarchy
  - m_3 is lightest

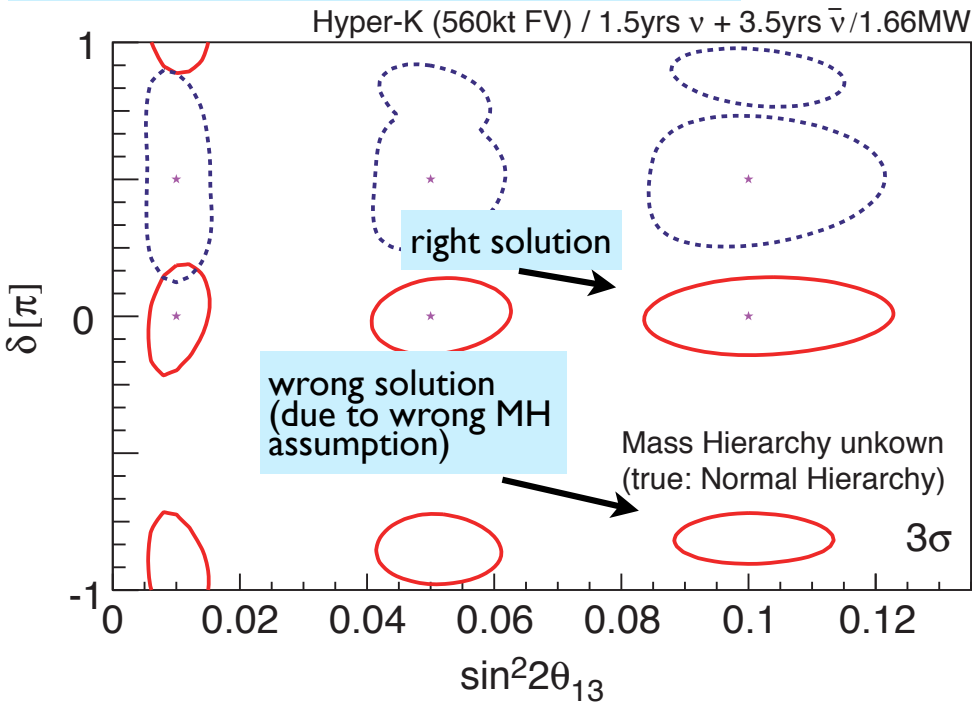




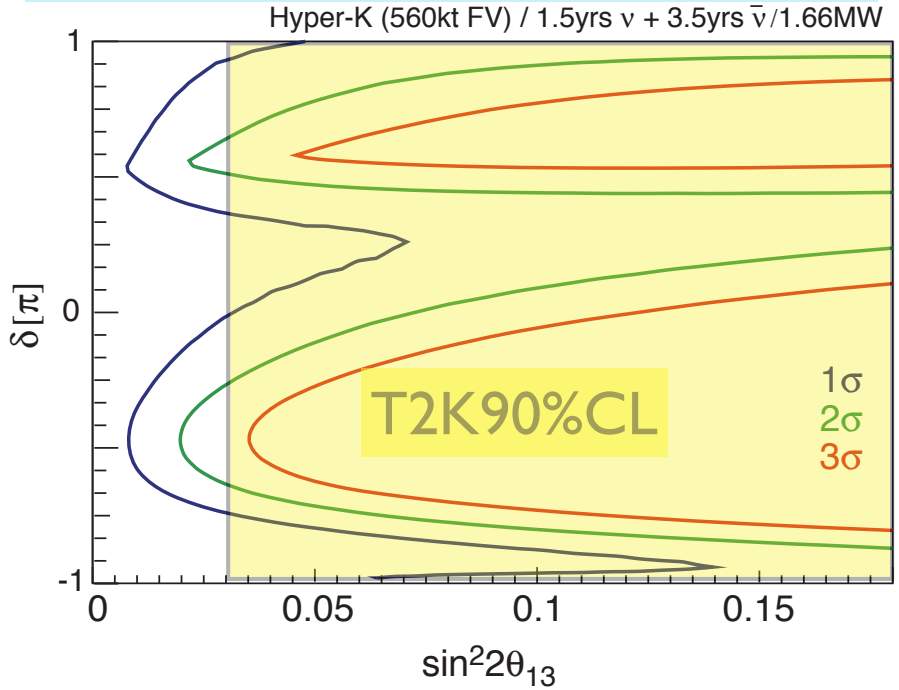
Degeneracy may occur if mass hierarchy is unknown JHEP10,001(2001)

If mass hierarchy is unknown

Normal mass hierarchy (unknown)



discrimination power of mass hierarchy



multiple solutions, wider allowed region due to wrong MH assumption

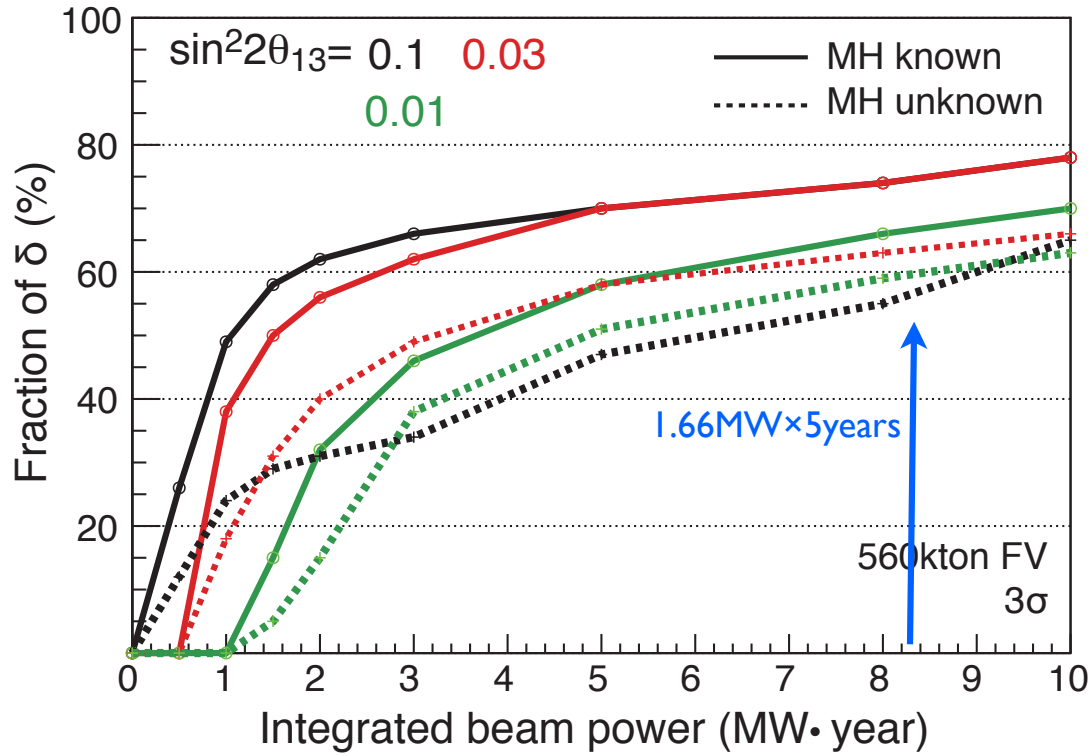
MH could be determined by HK-JPARC experiment

- Any improvement to resolve the degeneracy? Need more study.
- Input (mass hierarchy) from other experiments may become important.
  - from Nova? or ν-less DB? or...
- One possibility is to determine MH by atm. ν study (discuss later)

Fraction of δ (%) for CPV

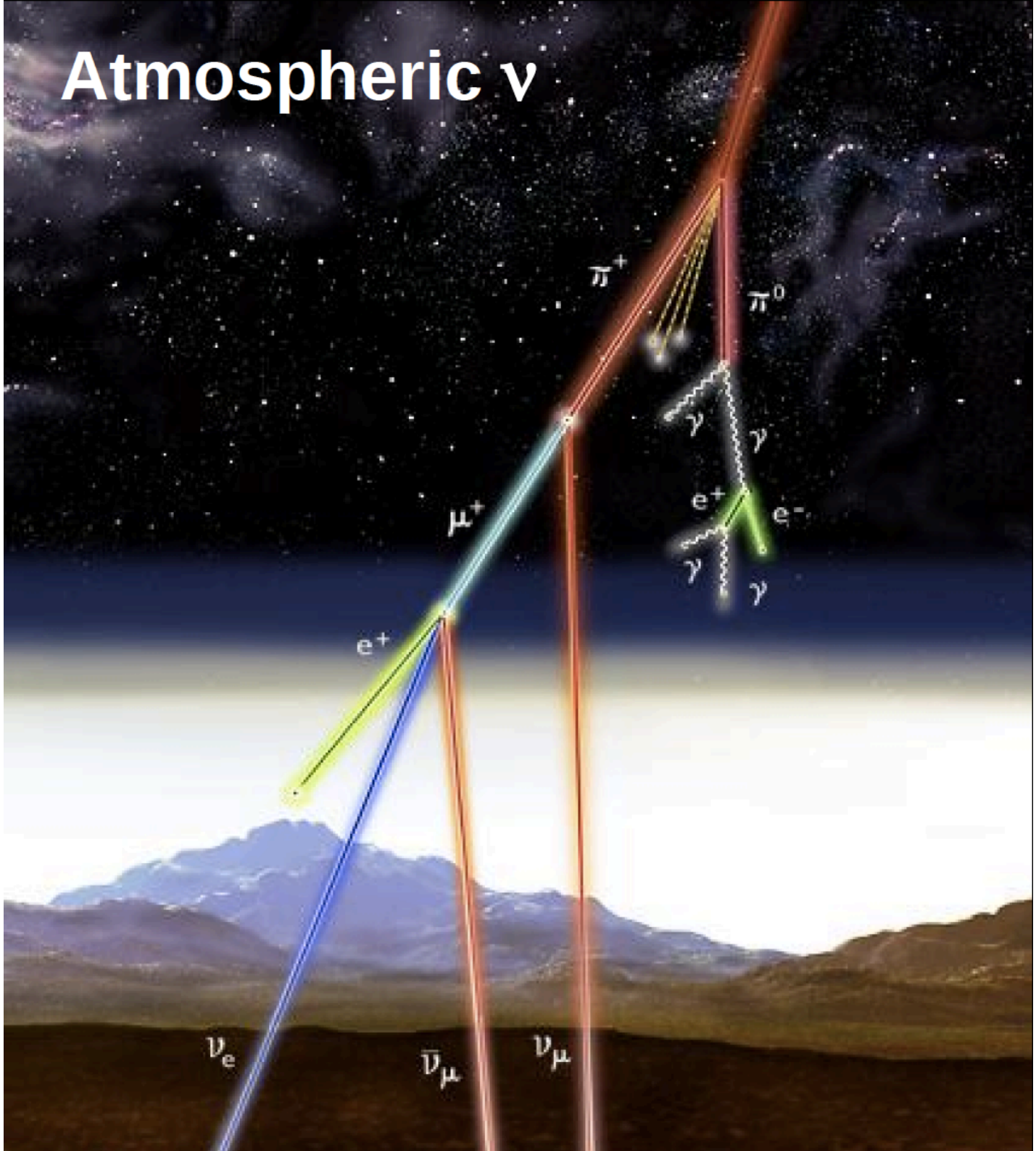
Fraction of δ in % for which expected CPV (sinδ≠0) significance is >3σ

		mass hierarchy	
		known	unknown
$\sin^2 2\theta_{13}$	0.1	74	55
	0.03	74	63
	0.01	66	59



CP violation can be observed with >3σ for 74% of the δ param. space.
If MH is assumed to be unknown, it degrades to ~60%.

Atmospheric ν



Oscillated ν_e flux

NuclPhysB680,479(2004)

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

$$+2\sin^2\tilde{\theta}_{13}(r \cdot \sin^2\theta_{23} - 1) \quad (3)$$ θ_{13} resonance term

r : μ/e flux ratio (~2 at low energy)

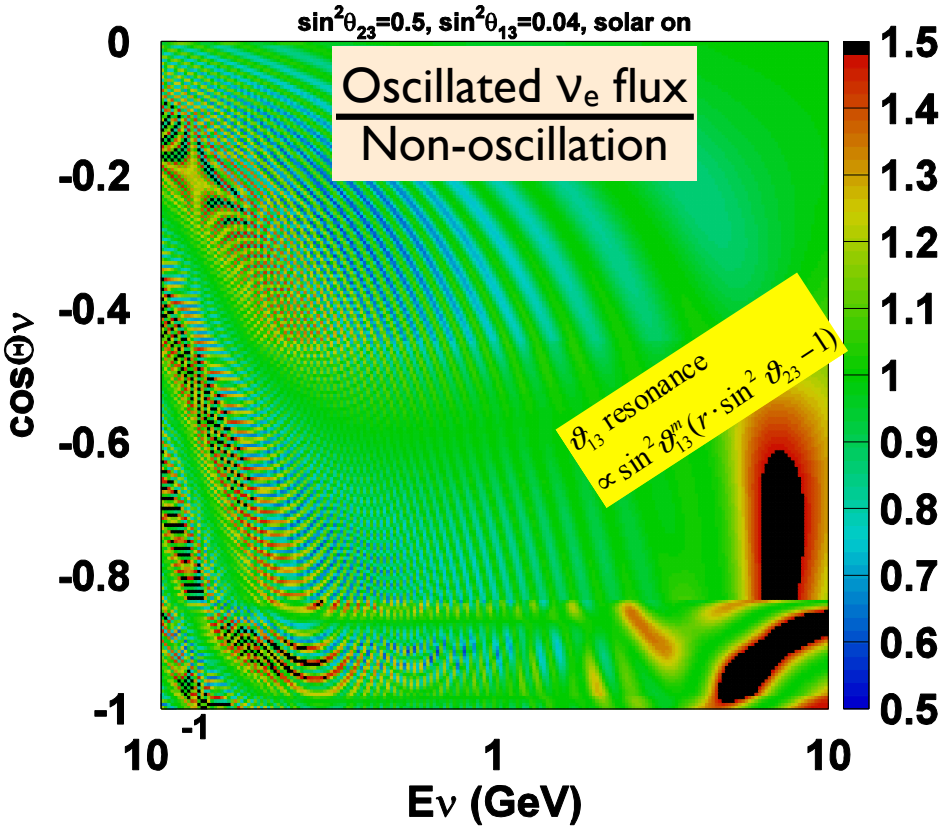
$P_2 = |A_{e\mu}|^2$: 2ν transition probability $\nu_e \rightarrow \nu_{\mu\tau}$ in matter

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

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

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

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



Relevant ν oscillation parameters

- Solar term
  - $\sin^2\theta_{23}$
- Interference term
  - δ, matter effect (θ_{13}, Mass Hierarchy)
- θ_{13} resonance term
  - $\sin^2\theta_{23}$, matter effect (θ_{13}, Mass Hierarchy)

Effective θ_{13} becomes large due to Earth's matter potential ⇨ more ν_e appearance

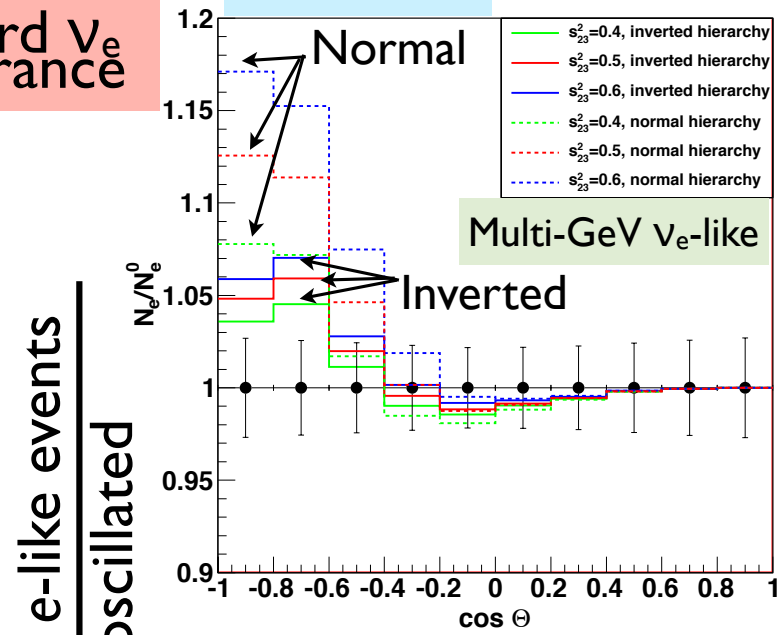
- happens in ν in the case of normal mass hierarchy
- in anti-ν in inverted mass hierarchy

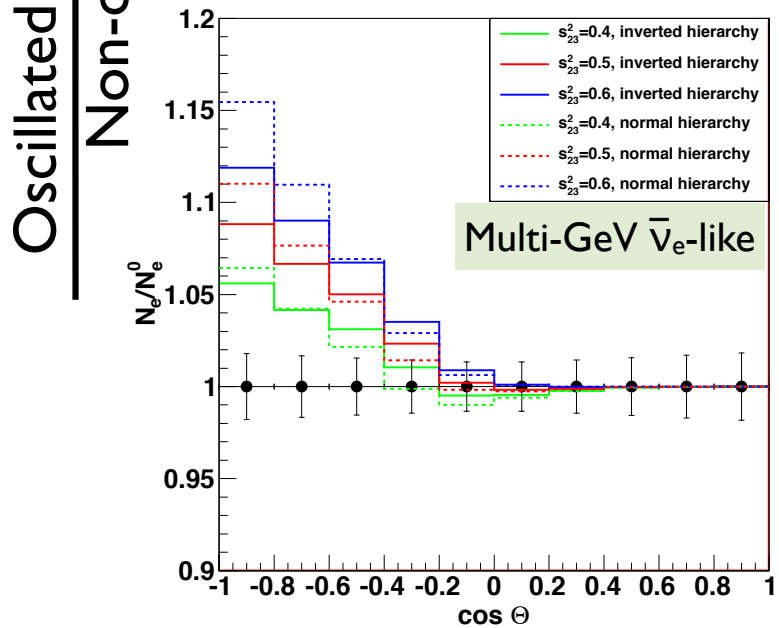
ν_e-like and anti-ν_e-like sample

$$\nu_e + N \rightarrow e^- + X$$
$$\bar{\nu}_e + N \rightarrow e^+ + X$$

Upward ν_e appearance

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





Oscillated e-like events

Non-oscillated

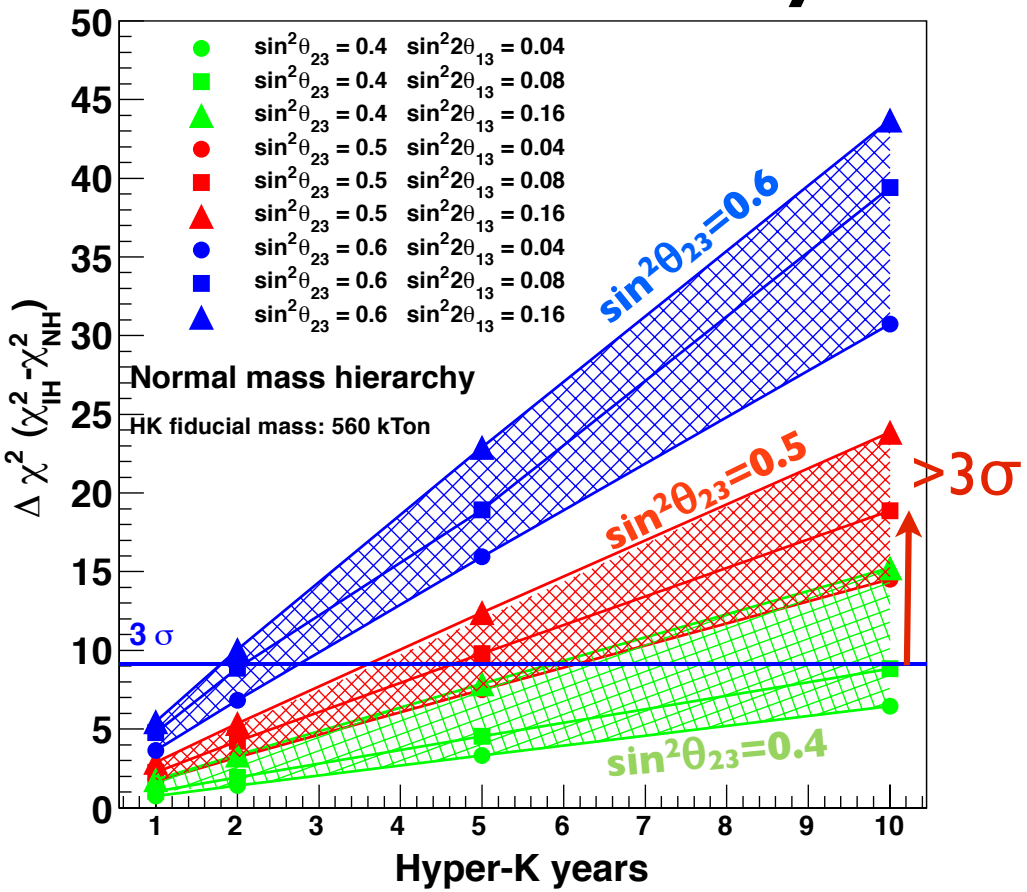
- ν_e CC produce more π^+
  - more muon decays
- More energy transfer to hadronic system
  - lower charged lepton energy
  - more pions (muon decays)

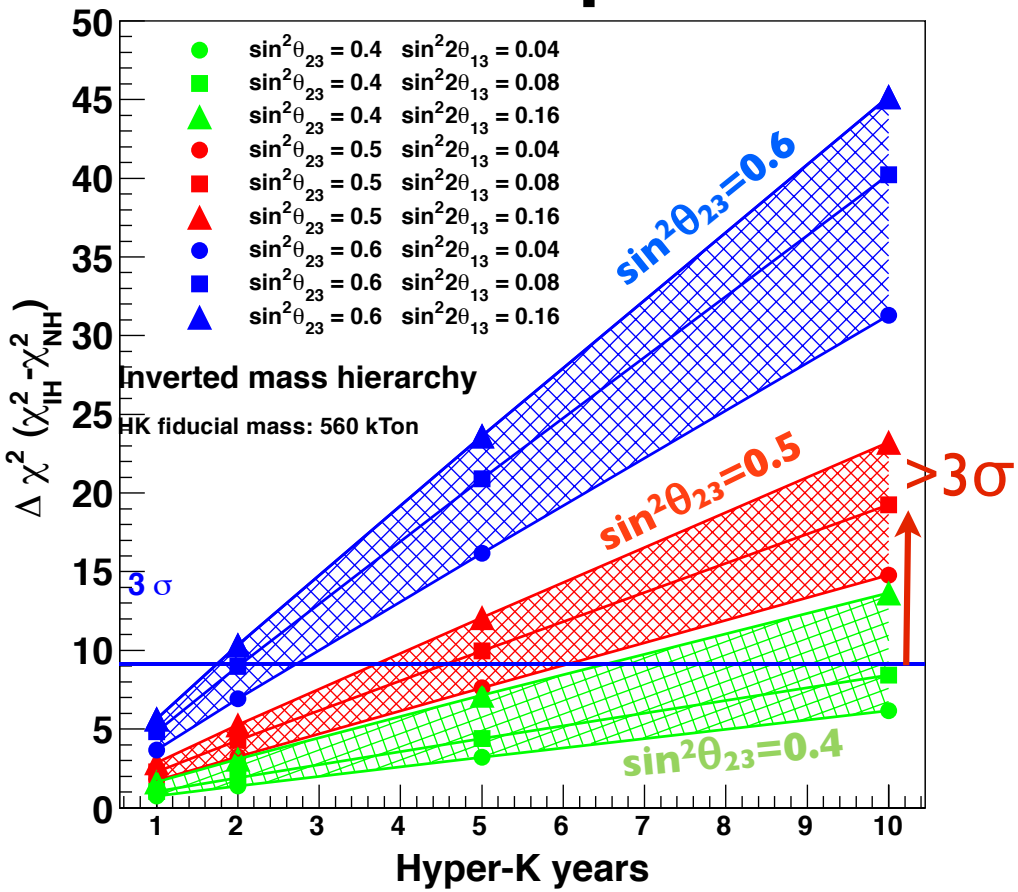
enrichment by variables

- # of rings
- # of muon decay electrons
- Lepton energy fraction
- transverse momentum

	νe CC	anti-νe CC	others	Total
νe-like	57%	11%	32.0%	100%
anti-νe-like	55%	34%	11%	100%

Mass hierarchy discrimination power



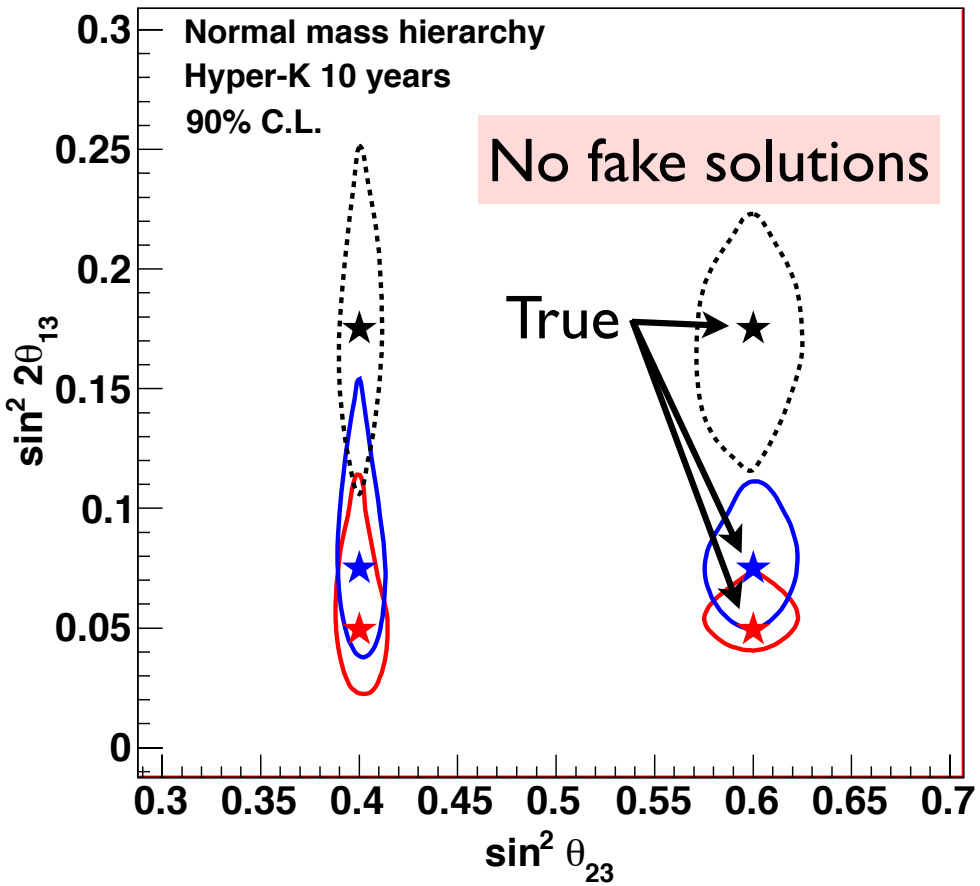


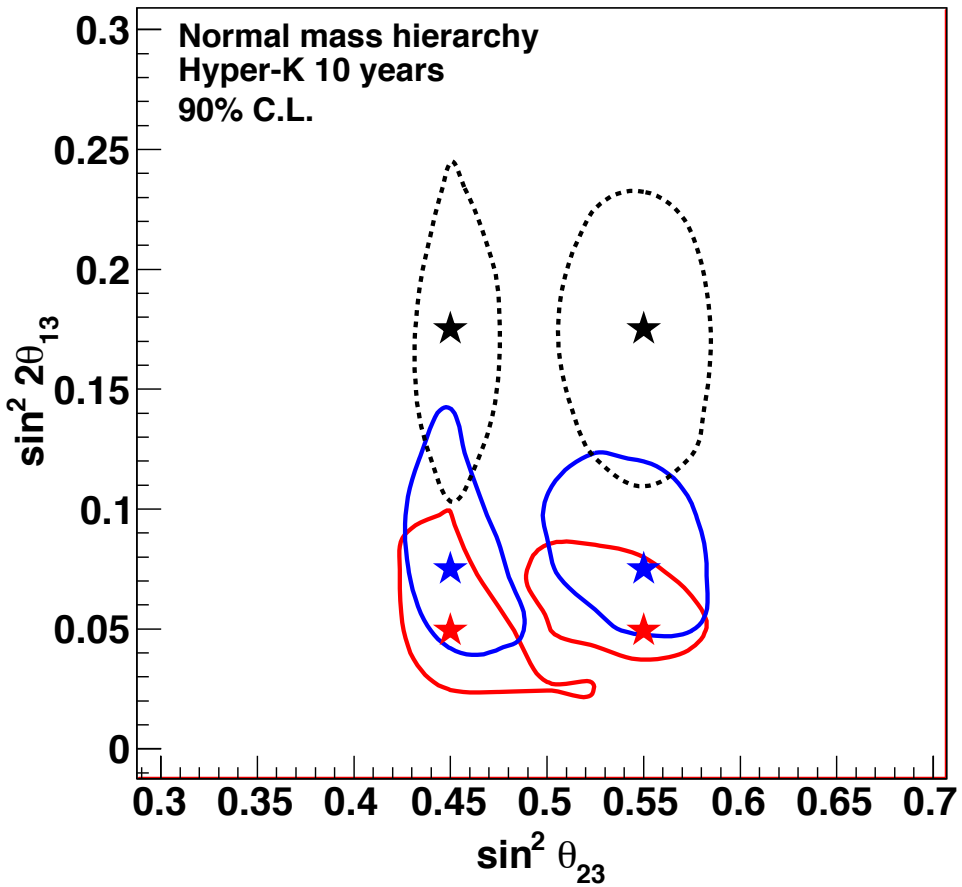
- expect to discriminate normal from inverted hierarchy w/ 3σ significance by ~5years data.
- If $\sin^2\theta_{23}$ is as small as 0.4 or less, we may need >10years.($\sin^2\theta_{23}$=0.4 ⇔ $\sin^2 2\theta_{23}$=0.96)
- θ_{23} (and θ_{13}) measurements in near future will make the sensitivity more accurate.

θ_{23} octant

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

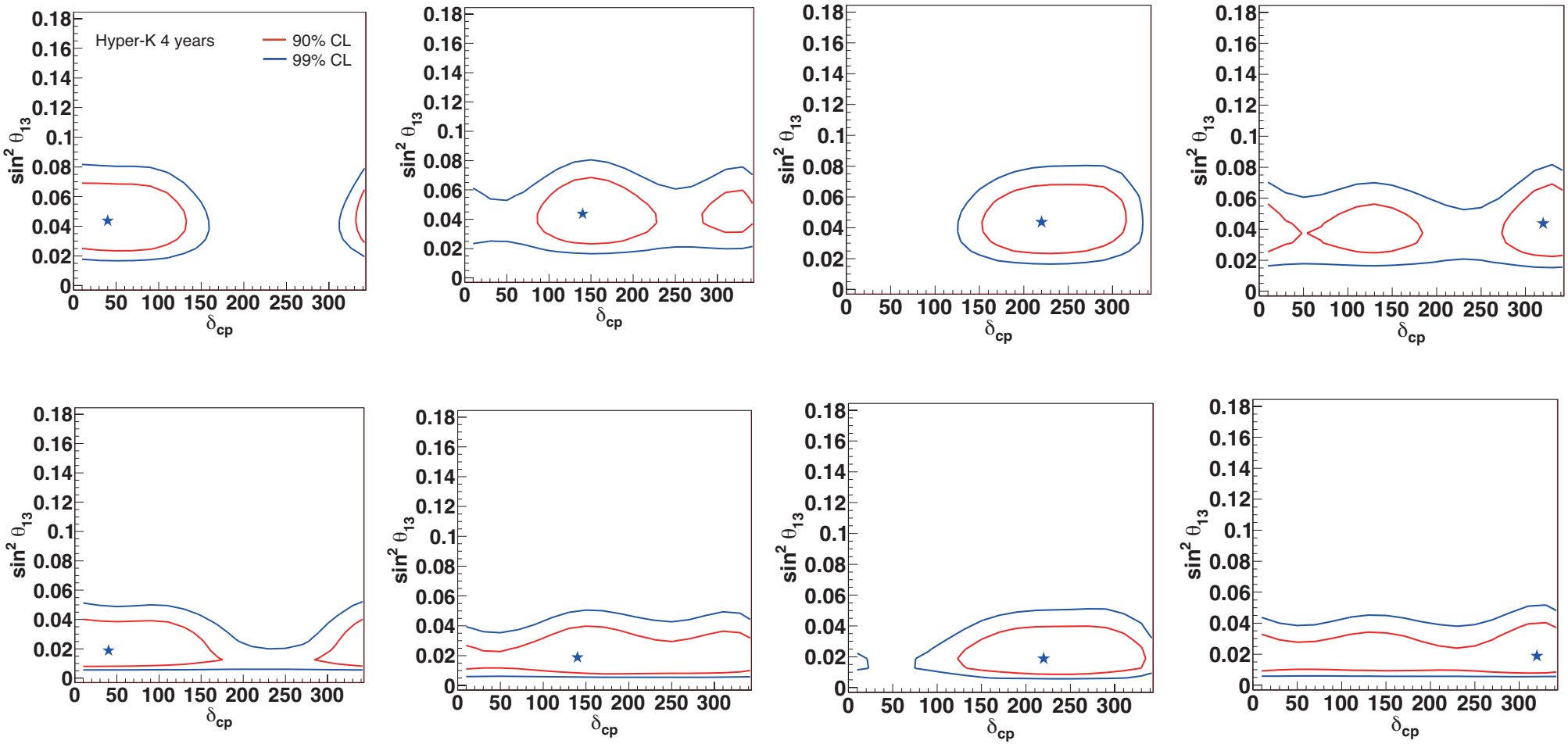
$\sin^2 2\theta_{23}=0.99$
↓
$\sin^2\theta_{23}=0.45$ or 0.55





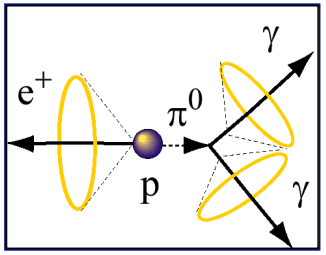
If $\sin^2 2\theta_{23}<0.99$, θ_{23} octant can be determined.

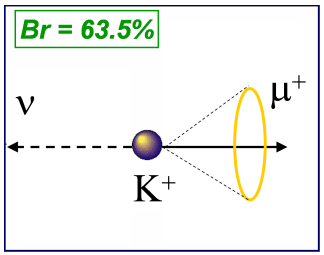
δ_{CP}

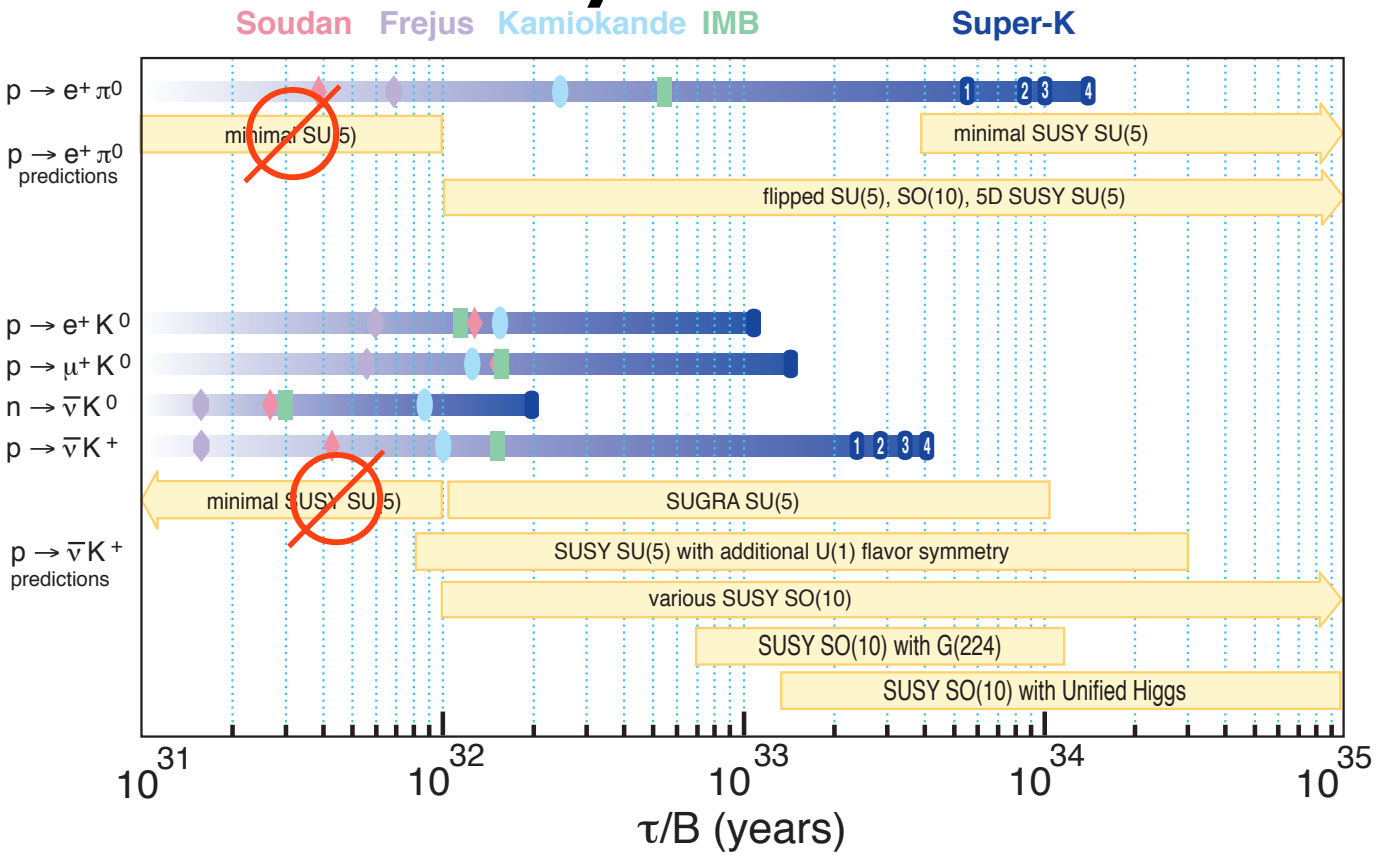


Supplemental information on Dirac δ

Nucleon decay searches





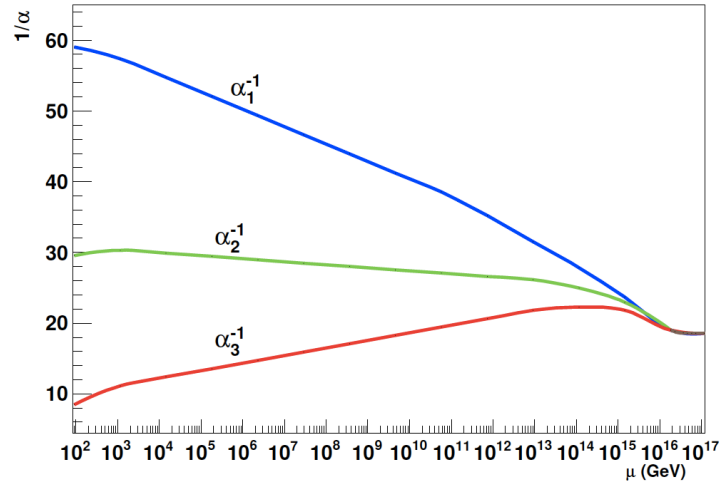


- Super-Kamiokande provides stringent limits for many decay modes.
  - $\tau(p \to e^+\pi^0) > 1.3\times10^{34}$ years (90%CL w/ 220kton · years)
  - $\tau(p \to \nu K^+) > 4.0\times10^{33}$ years (90%CL w/ 220kton · years)
- gives constraints on Grand Unification picture.
  - constraints on SUSY models e.g. R-parity conservation
  - excludes minimal *SU(5)*, minimal SUSY *SU(5)*. Next candidate is SUSY SO(10)?

class of SUSY *SO(10)* GUT

Babu et al. JHEP06(2010)084

- Characteristics
  - Low dimension Higgs: {45+16+16*+10}
  - Avoid Triplet-Doublet problem
  - Account for quark&lepton masses
    - tiny neutrino mass←Seesaw mechanism
    - Mixing←Q4 flavor symmetry

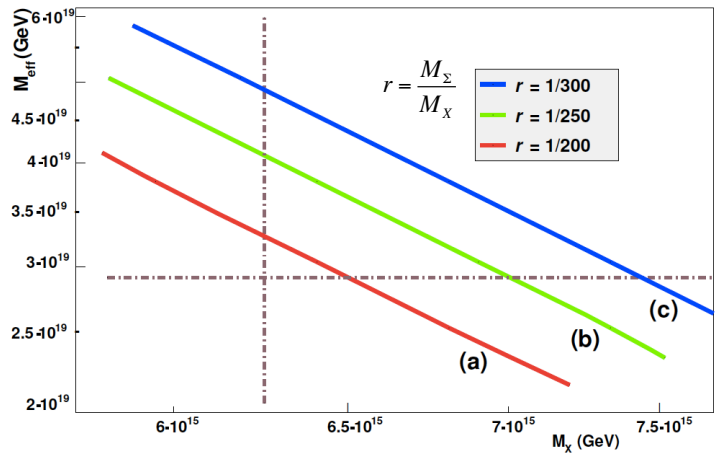


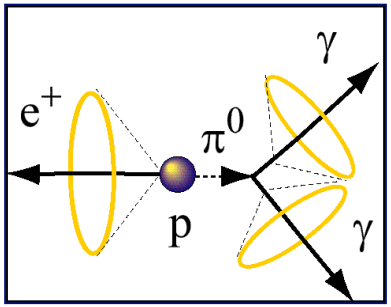
- Predicted decay rates

$$\Gamma^{-1}_{d=6}(p \to e^+\pi^0) \lesssim 5.3 \times 10^{34} \text{ yrs}$$

$$\Gamma^{-1}(p \to \overline{\nu} K^+) \lesssim (3.1 \times 10^{34} \text{ yrs}) \times \left(\frac{m_{\tilde{q}}}{1.5 \text{ TeV}}\right)^4 \left(\frac{130 \text{ GeV}}{m_{\tilde{W}}}\right)^2 (3/\tan\beta)^2$$

Both decays are reachable by Hyper-K.

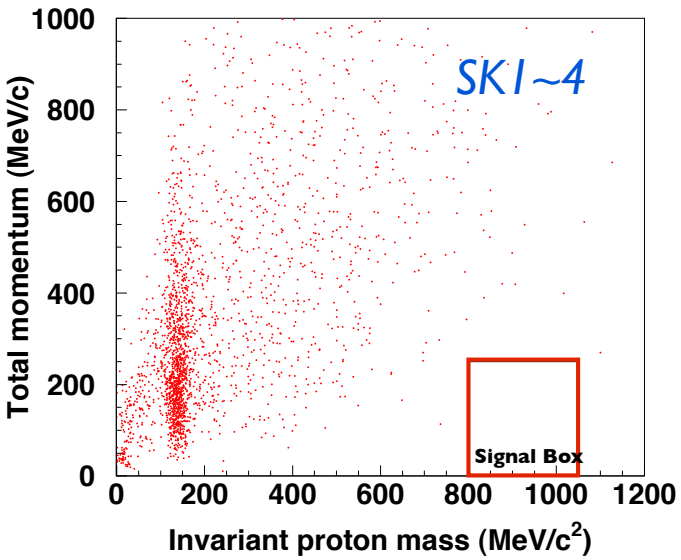


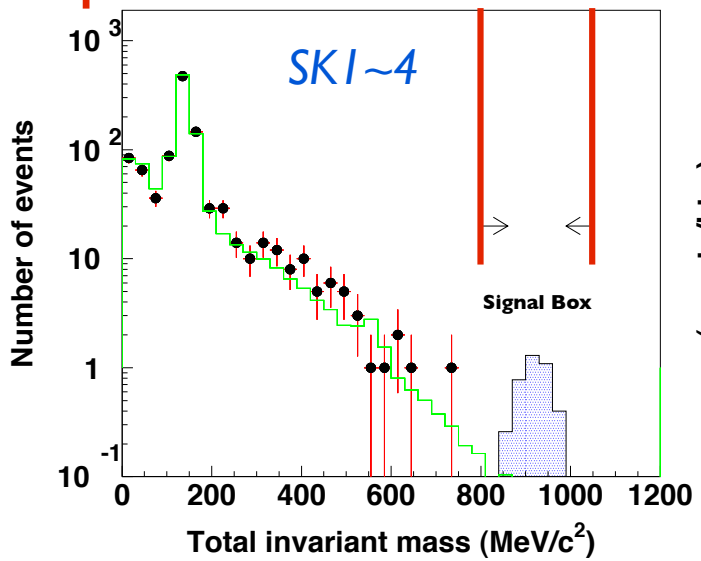


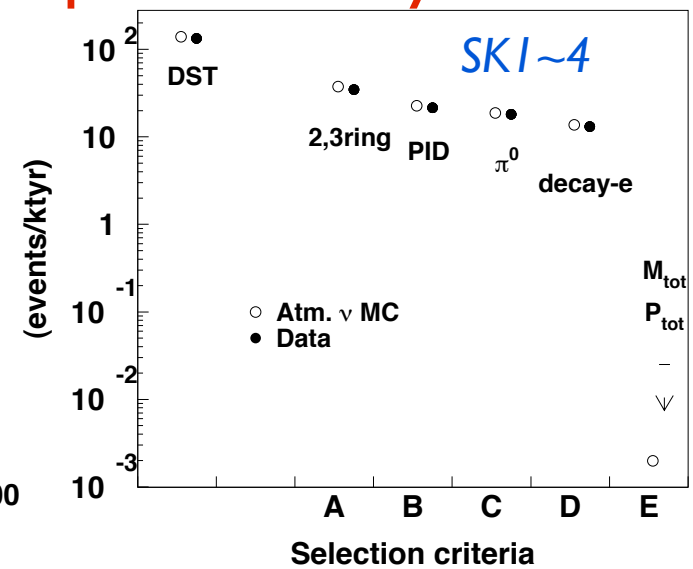
$p \rightarrow e^+ + \pi^0$ searches

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.

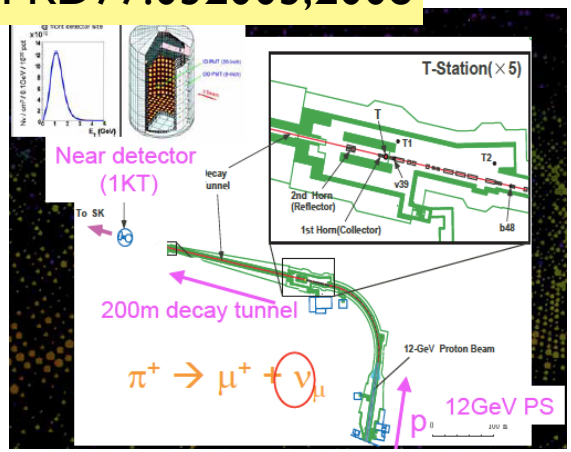






- detection efficiency = 45%
- atmospheric ν BG = 2.1±0.3(stat.)±0.8(syst.) (Mton×years)$^{-1}$
- $\tau_{proton}/Br > 1.3 \times 10^{34}$ years @ 90%CL

PRD77:032003,2008

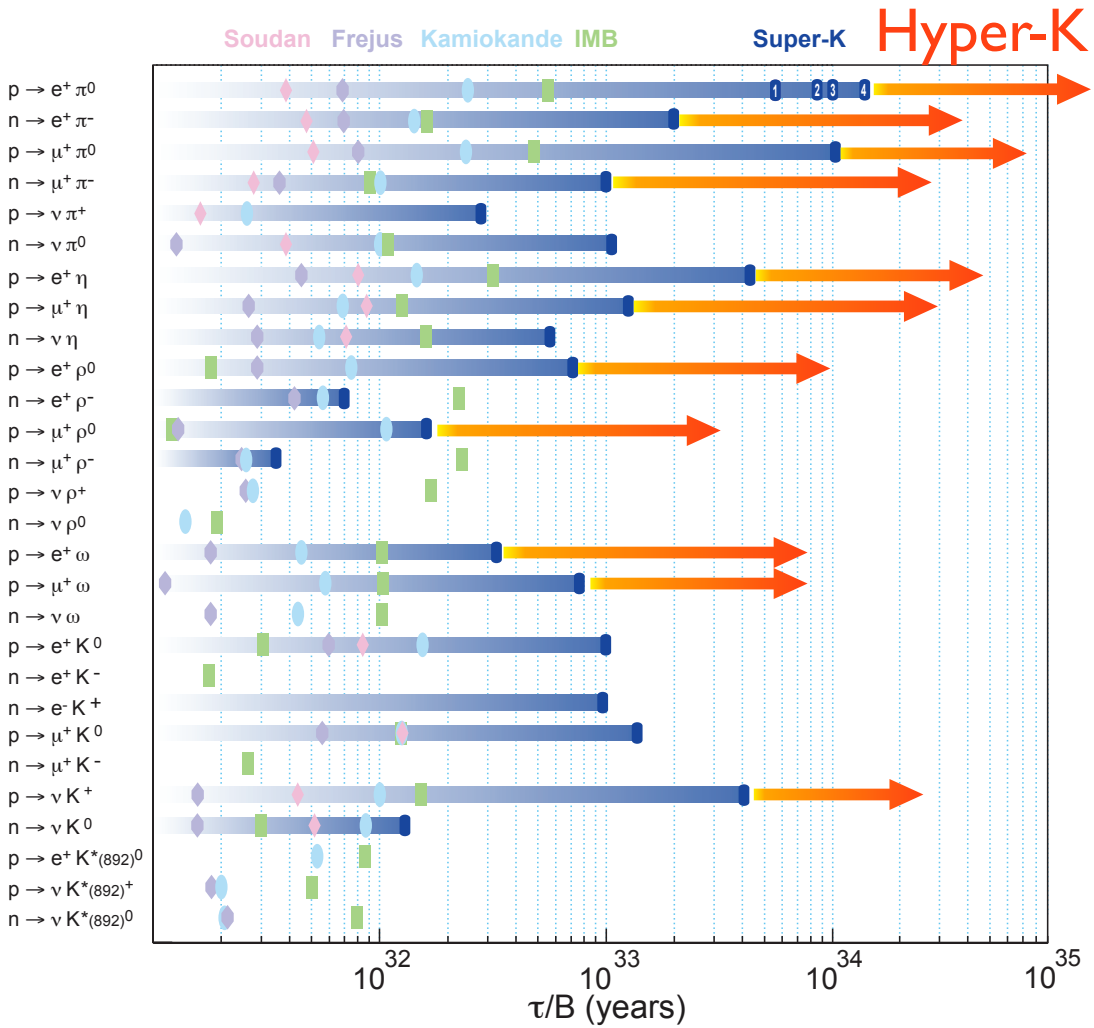


- BG measurement by accelerator ν (K2K)
  - BG=1.63+0.42/-0.33(stat.)+0.45/-0.51(syst.) (Mt×yrs)$^{-1}$ (Eν<3GeV)
  - Consistent w/ simulation 1.8±0.3(stat.)

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 ($|\Delta B|=2$)
    - $pp \to XX$..., $nn \to XX$...

Summary

- Baseline design and physics potential are described for Hyper-K.
  - based on well proven technology (water Cherenkov)
  - discovery reach for leptonic CP violation.
  - precision measurement of neutrino property.
  - unprecedented sensitivity for nucleon decays.
  - astrophysical ν etc.

- Next step:
  - Maximize (Physics sensitivity) / (cost)
  - New technology is a key to realize the project.