Hyper-Kamiokande detector design and physics potential

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Letter of Intent:
The Hyper-Kamiokande Experiment
— Detector Design and Physics Potential —

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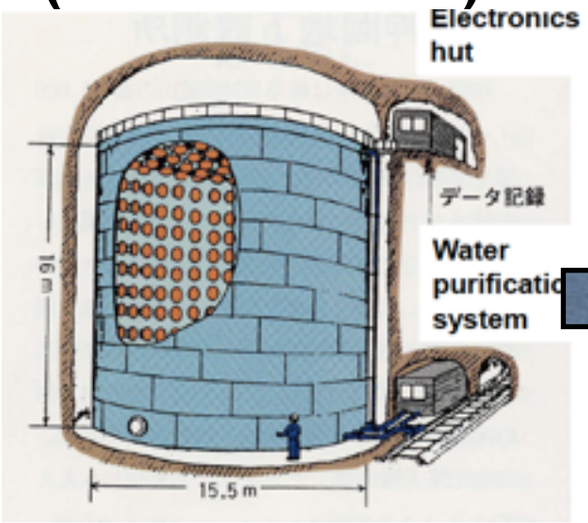
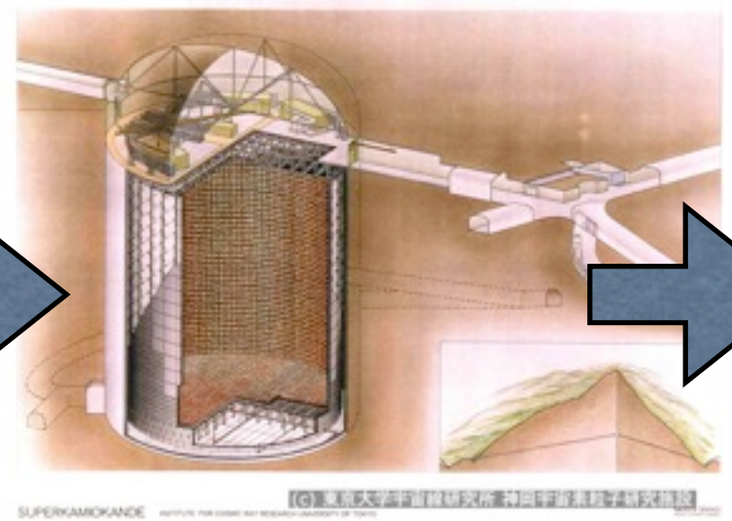
Three generations of Water Cherenkov Detectors at Kamioka

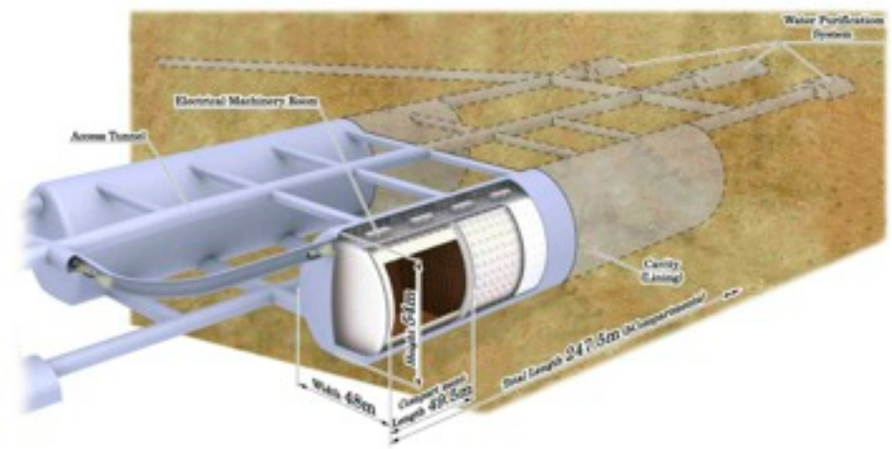
Kamiokande (1983-1996)



Super-Kamiokande (1996-)



Hyper-Kamiokande (201x?-)

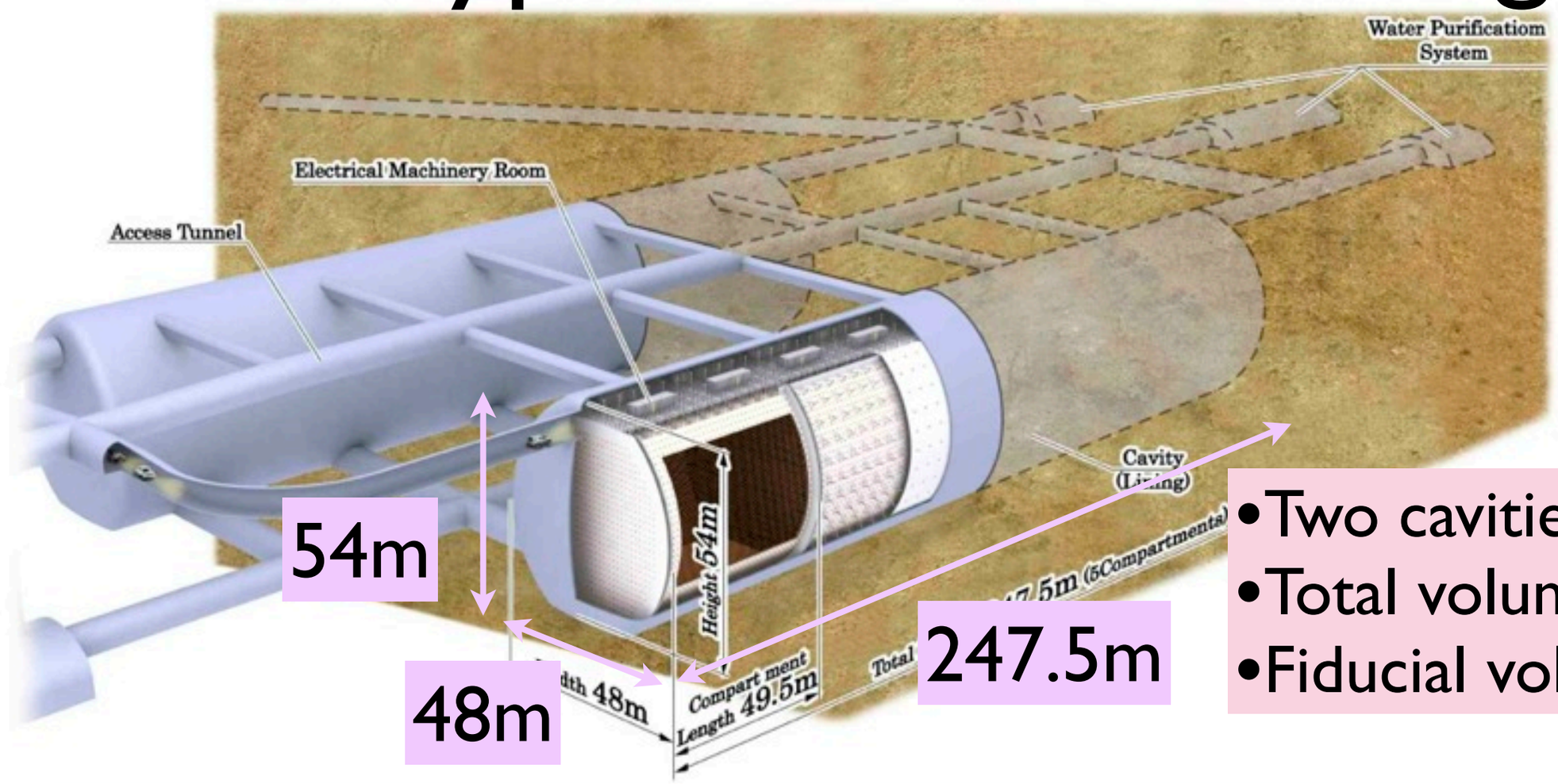


3kton → 50kton → 1Mton=1000kton

x17

x20
(x25 fid.)

Hyper-K: baseline design



- Two cavities
- Total volume: 0.99 Mton
- Fiducial volume: 0.56Mton

x25 Super-K

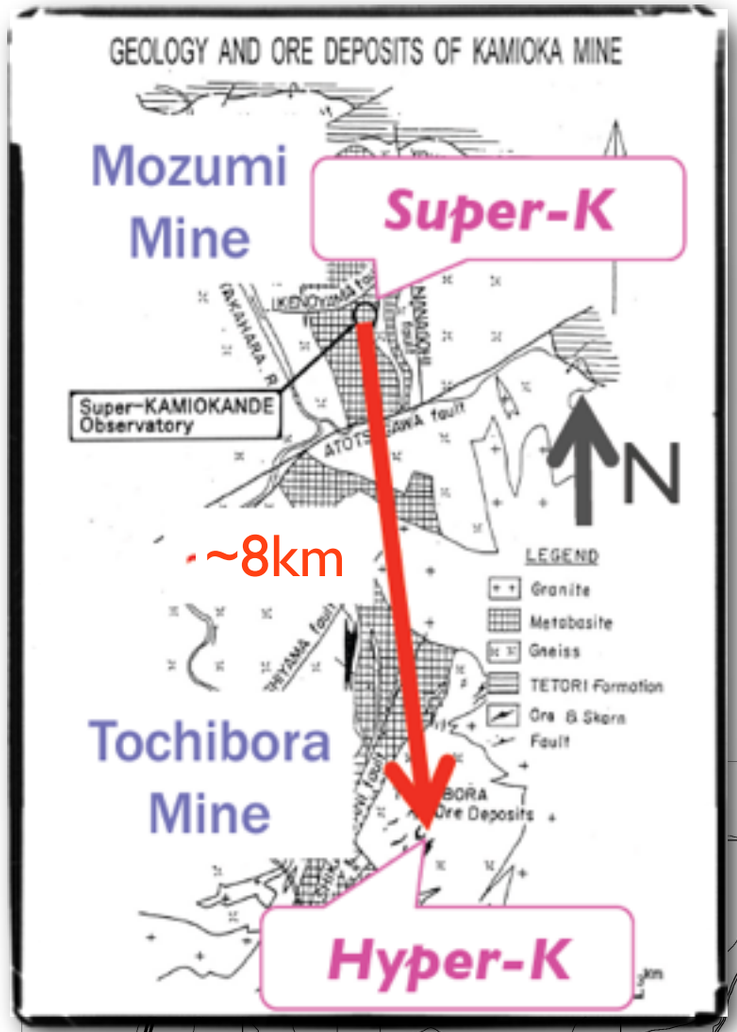
- Each cavity optically separated into five inner detector regions
  - Each has ~x2 volume compared to Super-K
  - Segmentation walls also instrumented

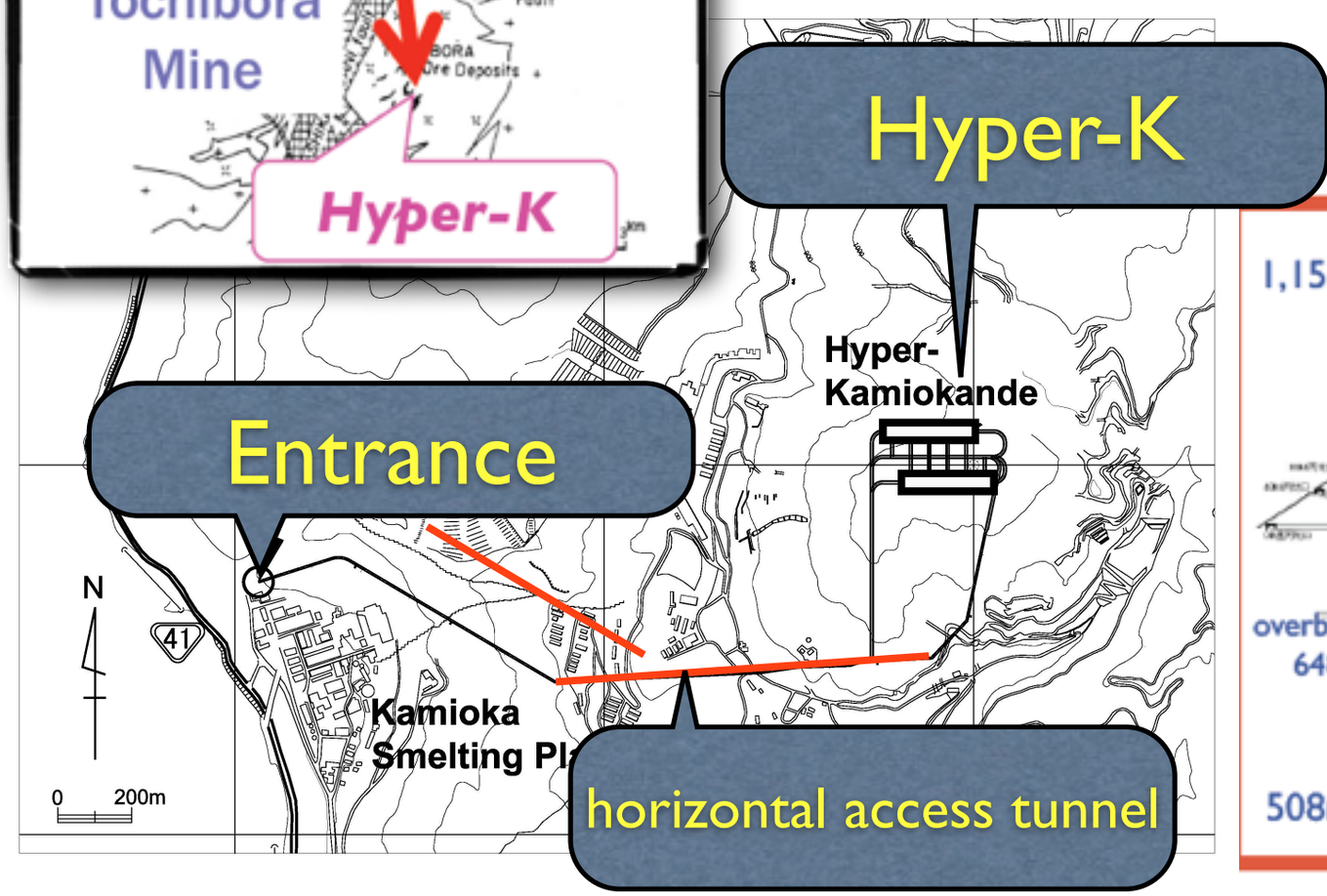
→ Performance the same as Super-K

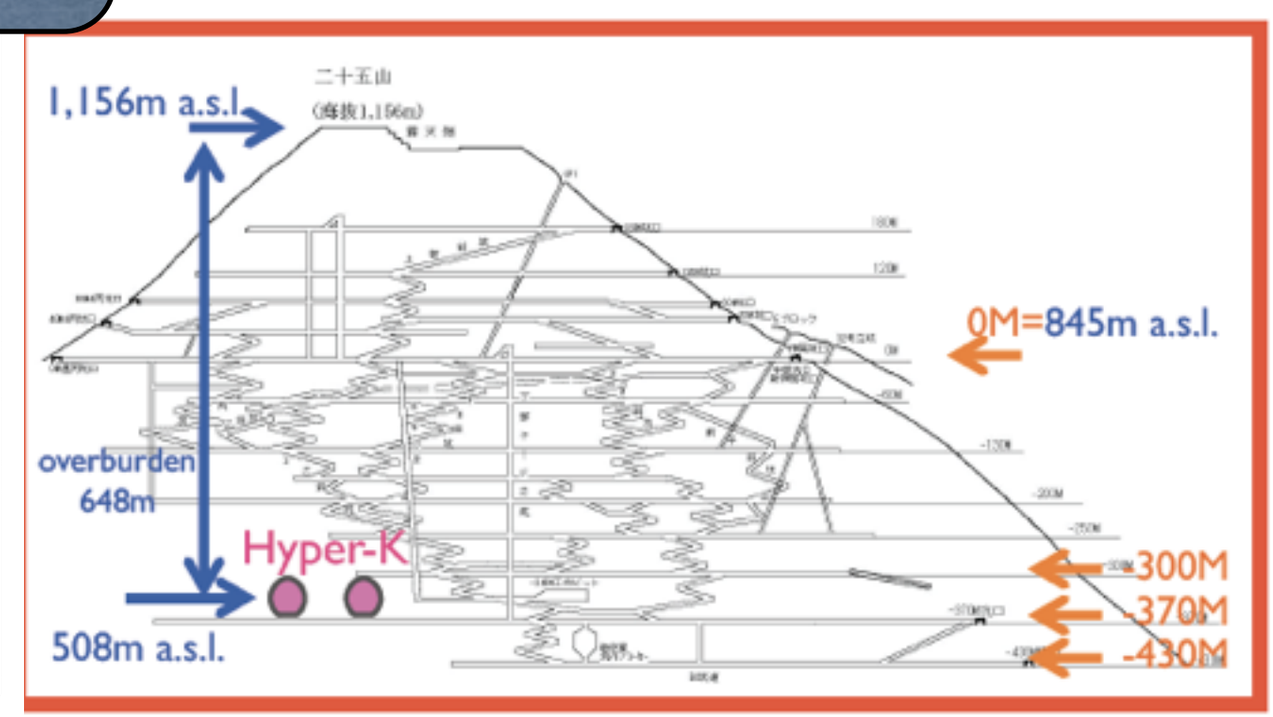
- Photo-coverage for ID: 20% (same as SK-II)
  - 99,000 20-inch PMTs
- Outer detector (2m) with 25,000 8-inch PMTs

Candidate site

- 8km south of Super-K
  - Same off-axis and baseline as T2K
- 648m of rock (1750m.w.e.) overburden
- 13,000m^3/day natural water (1Mt/80days)



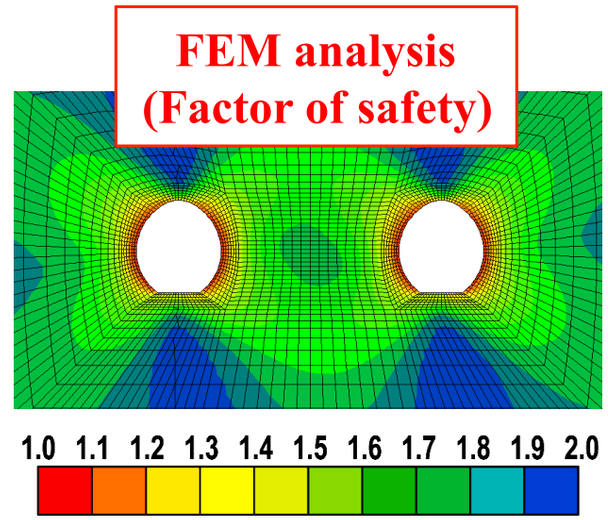




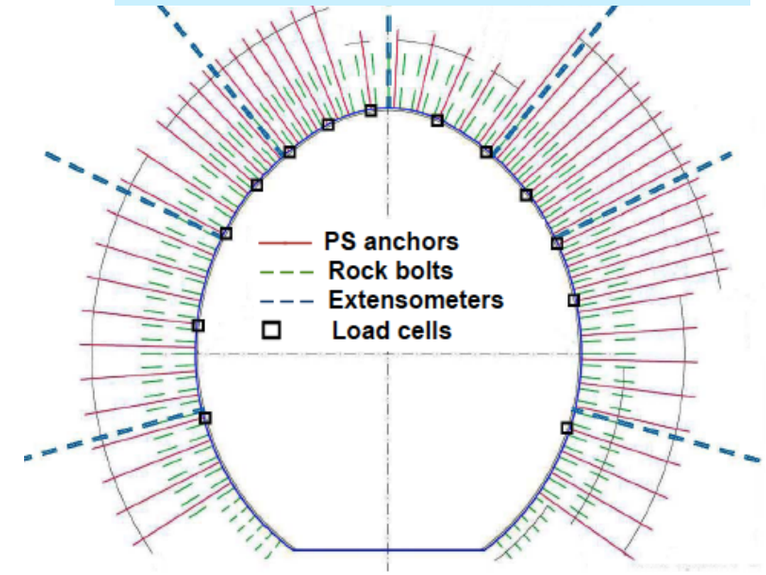
Cavity design based on measurements

Geological survey

Twin cavern analysis

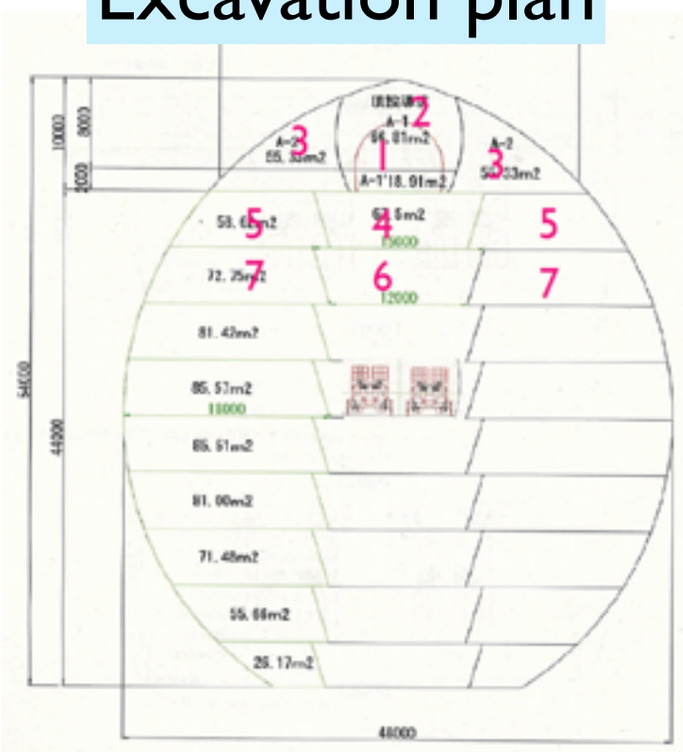


anchors, rock bolts design

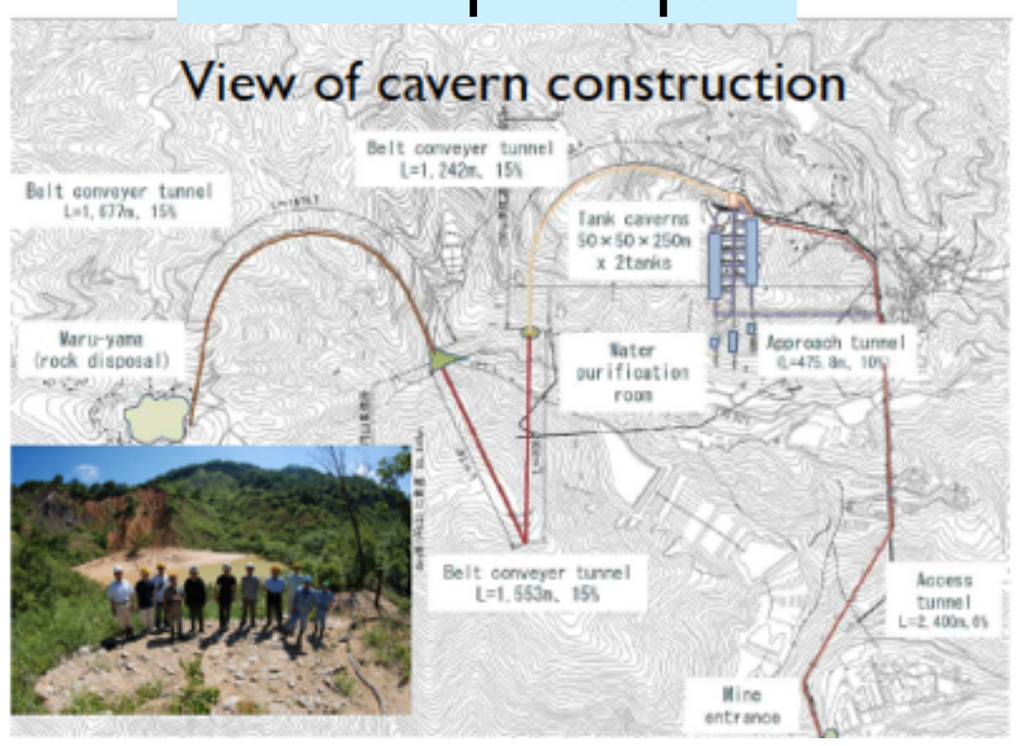


Construction procedure

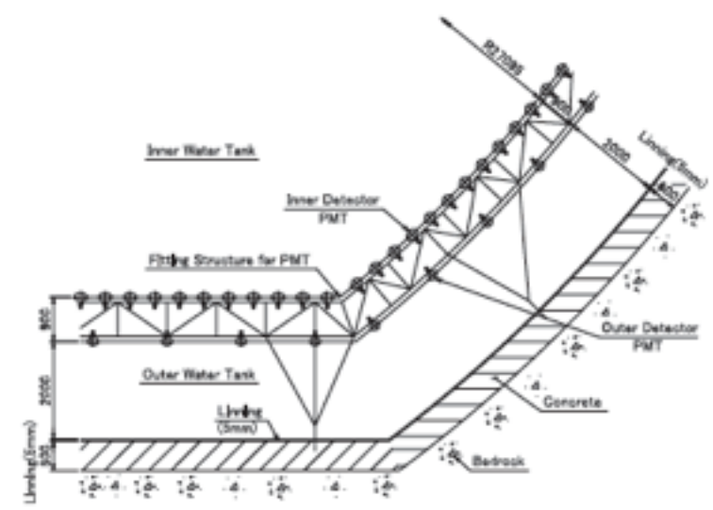
Excavation plan



Rock disposal plan



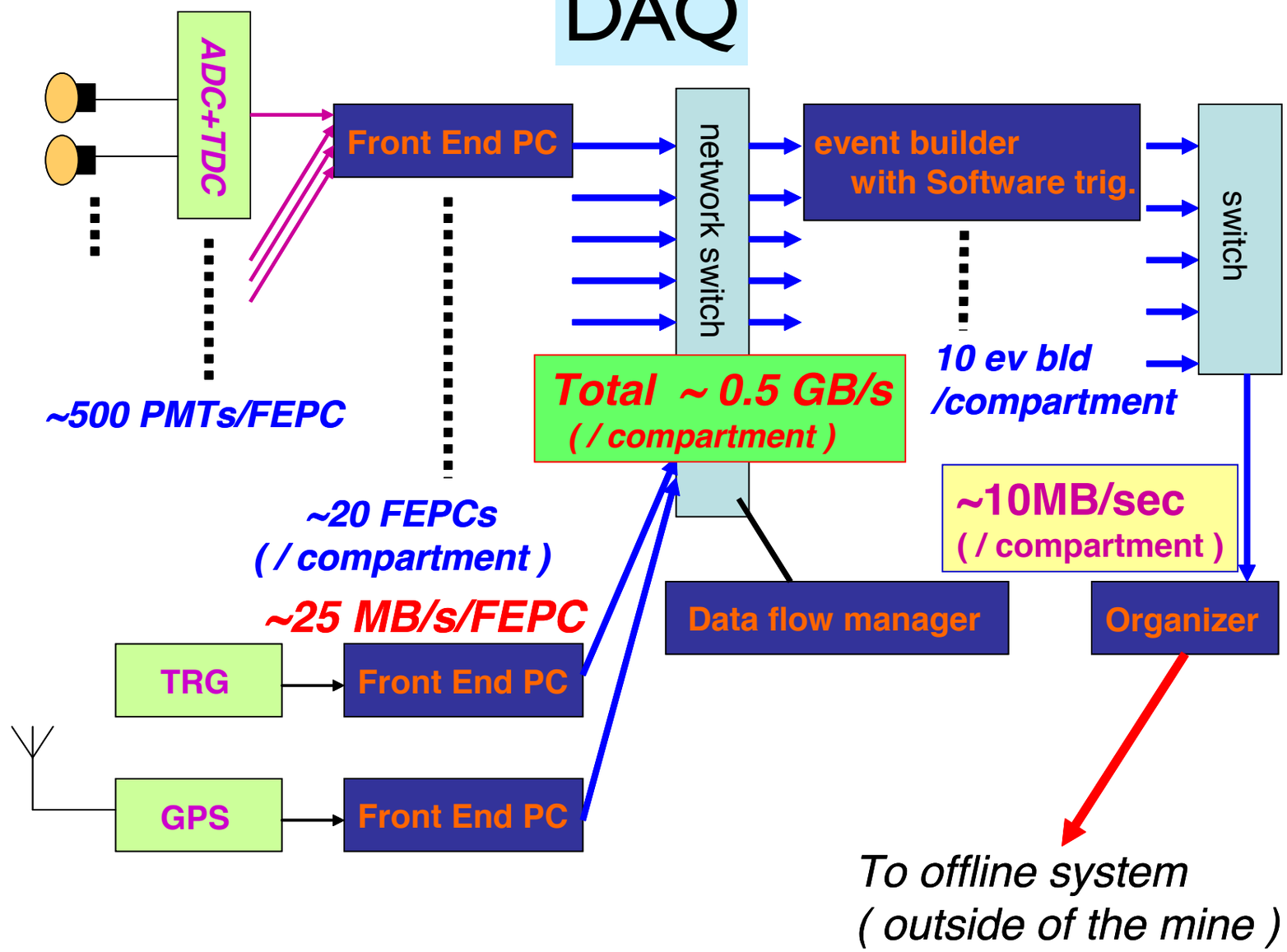
Concrete layer, polyethylene lining, PMT support



Baseline design based on experience and R&D

Photon sensor

DAQ



Detail scheduling / cost estimate on all elements underway
More R&D effort being planned/starting

Neutrino physics with Hyper-K

With "large" θ_{13} (indicated by T2K, MINOS, DC, solar, ..)

Access to

- Leptonic *CP* violation
- ν mass hierarchy
- Octant of θ_{23}

Synergy of *accelerator* and *atmospheric* ν measurements

Explore full picture of neutrino oscillation

Accelerator ν: J-PARC to HK

x25 Larger Target

~0.6GeV νμ

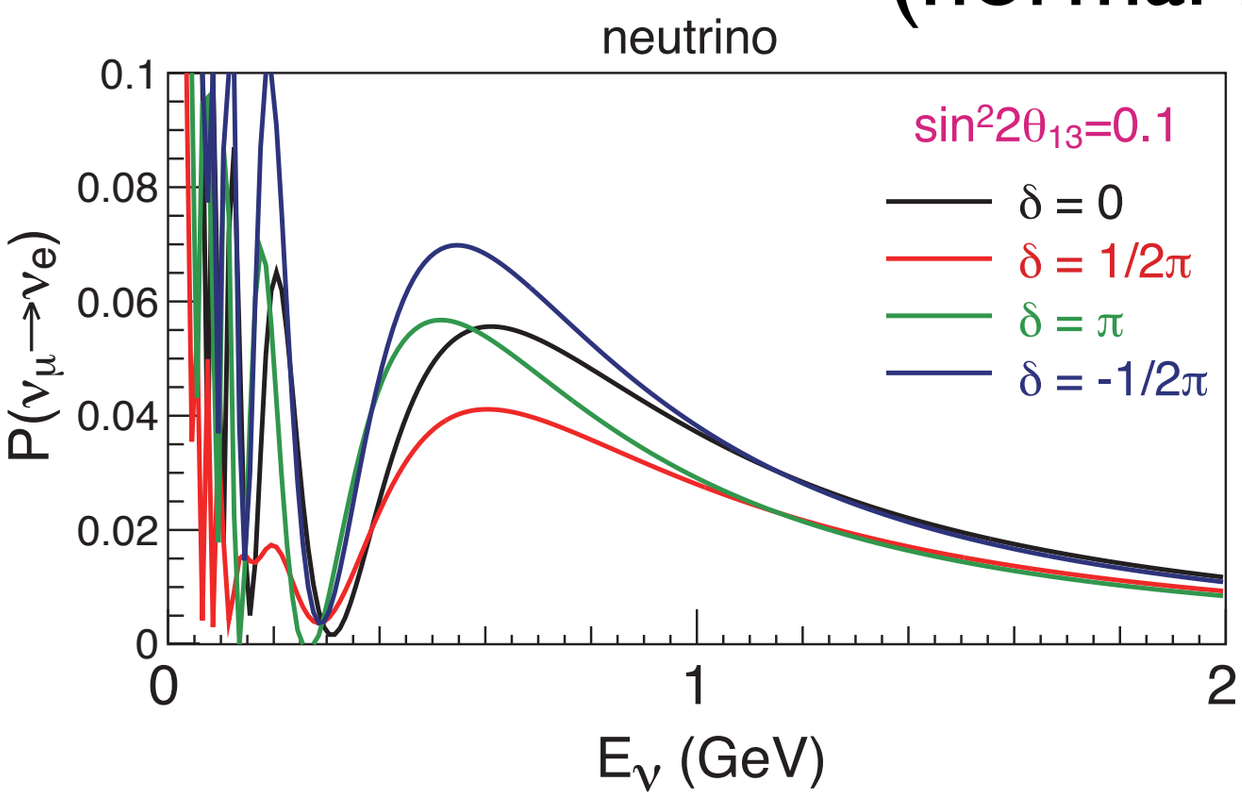
295km

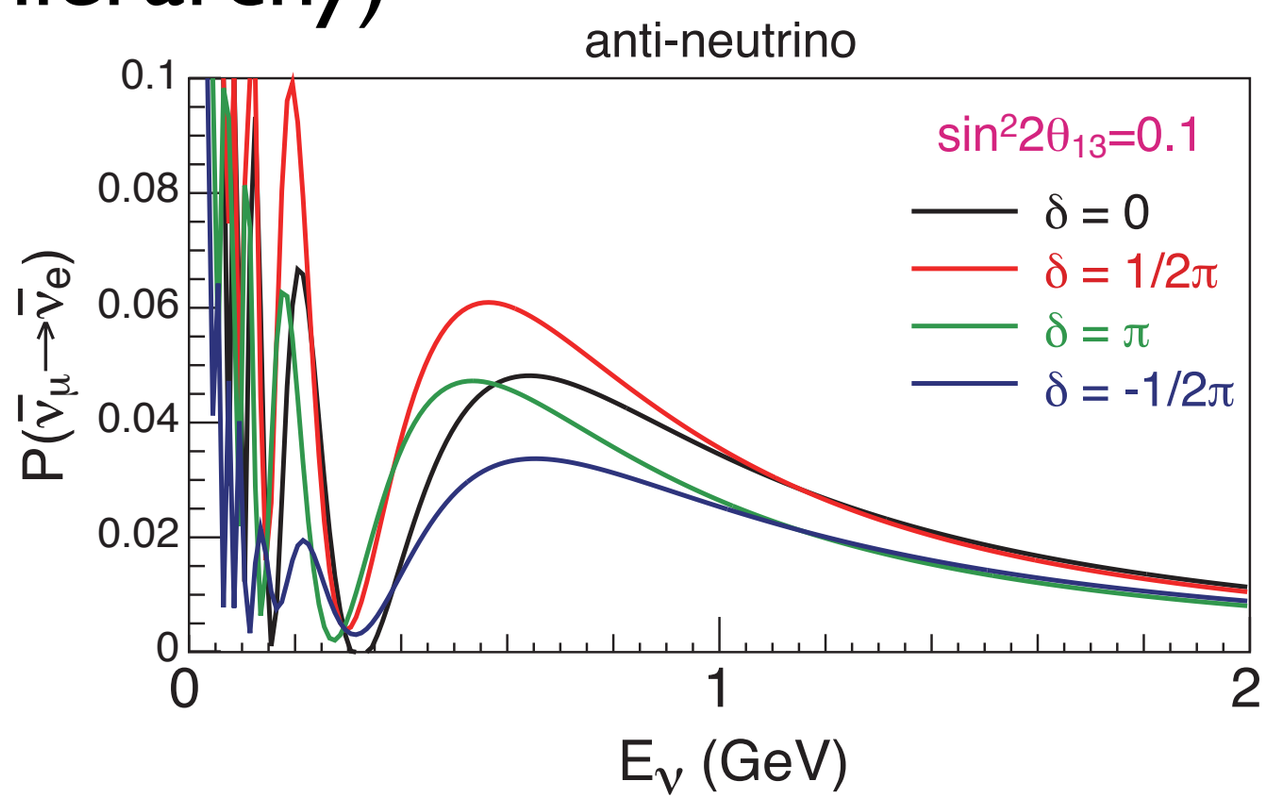
Quest for CP Violation in lepton sector

Higher Intensity
1.66MW (KEK roadmap)

Measuring *CP* asymmetry

$P(\nu_\mu \rightarrow \nu_e)$ appearance probability (normal hierarchy)





- Comparison of $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- In principle, sensitive to exotic (non-MNS) CPV

Full MC study

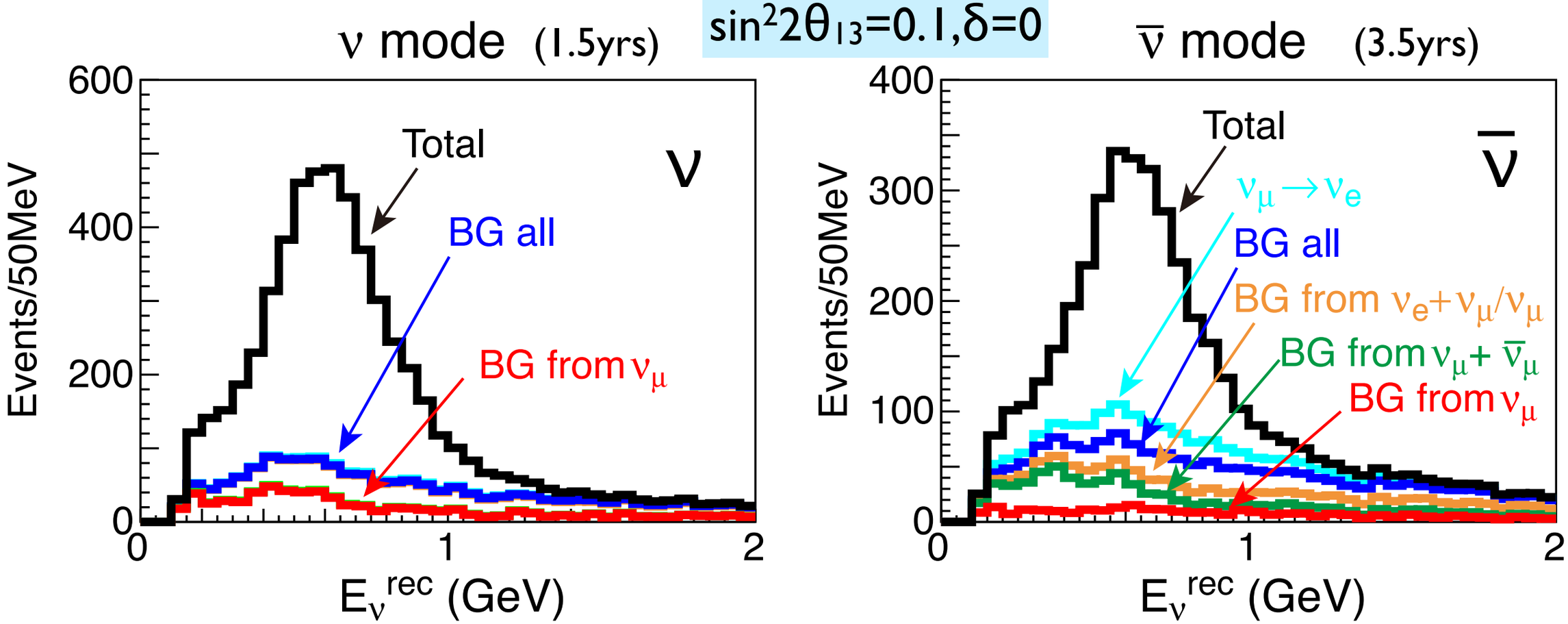
- Full simulation of ν beam, interaction, detector response and reconstruction
  - Number of PMT: half of SK-4 (20% coverage)
- Event selection almost the same as T2K
  - Loose cut on E_ν to utilize spectrum information
- Assumed total five year running
  - 1.5 year in ν / 3.5 year in $\bar{\nu}$
  - 1.66MW beam power for J-PARC assumed

(for E_ν^{rec}<1.25GeV)

Signal efficiency	64%
ν_μ CC BG rejection	>99.9%
NC π^0 BG rejection	95%

ν_e candidates after selection

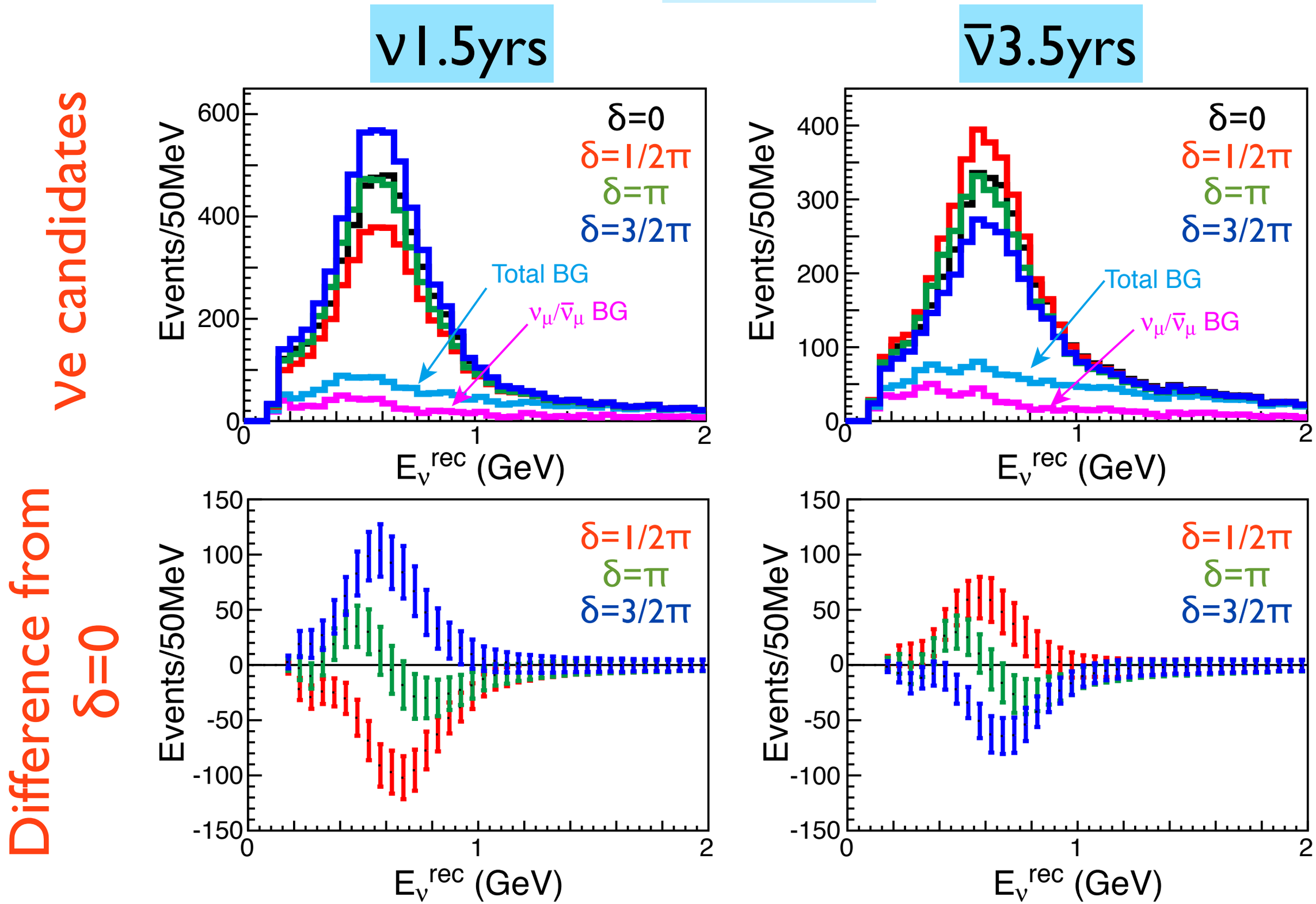
$\sin^2 2\theta_{13}=0.1, \delta=0$



	Signal ($\nu_\mu \to \nu_e$ CC)	ν_μ/ν_μ CC	ν_e/ν_e CC	NC
ν (1.5yrs)	3,991	39	974	718
$\bar{\nu}$ (3.5yrs)	2,589	25	972	750

(E_ν^{rec}<2GeV)

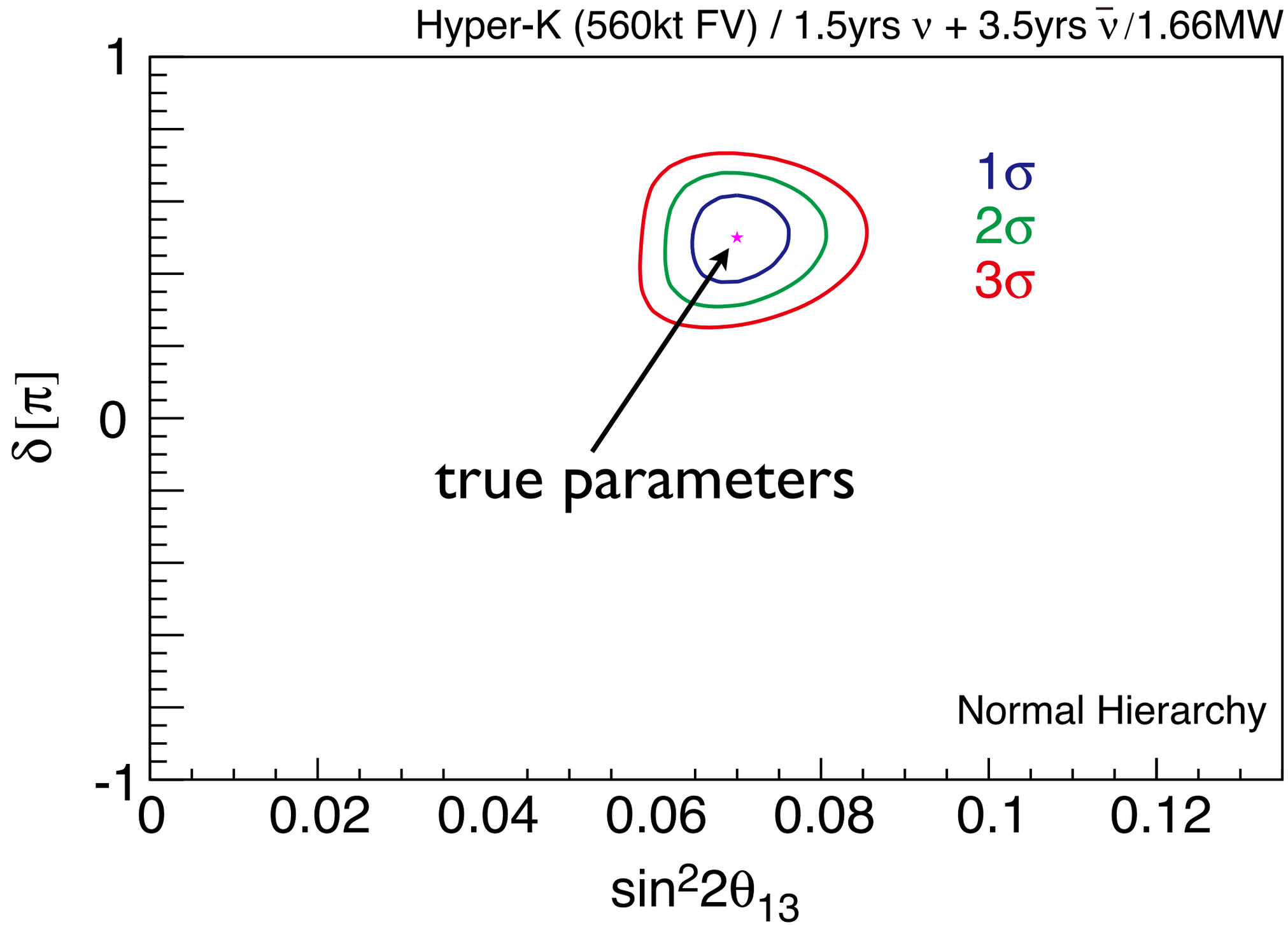
$\sin^2 2\theta_{13}=0.1$



Sensitive to all values of δ (including δ=0,π)

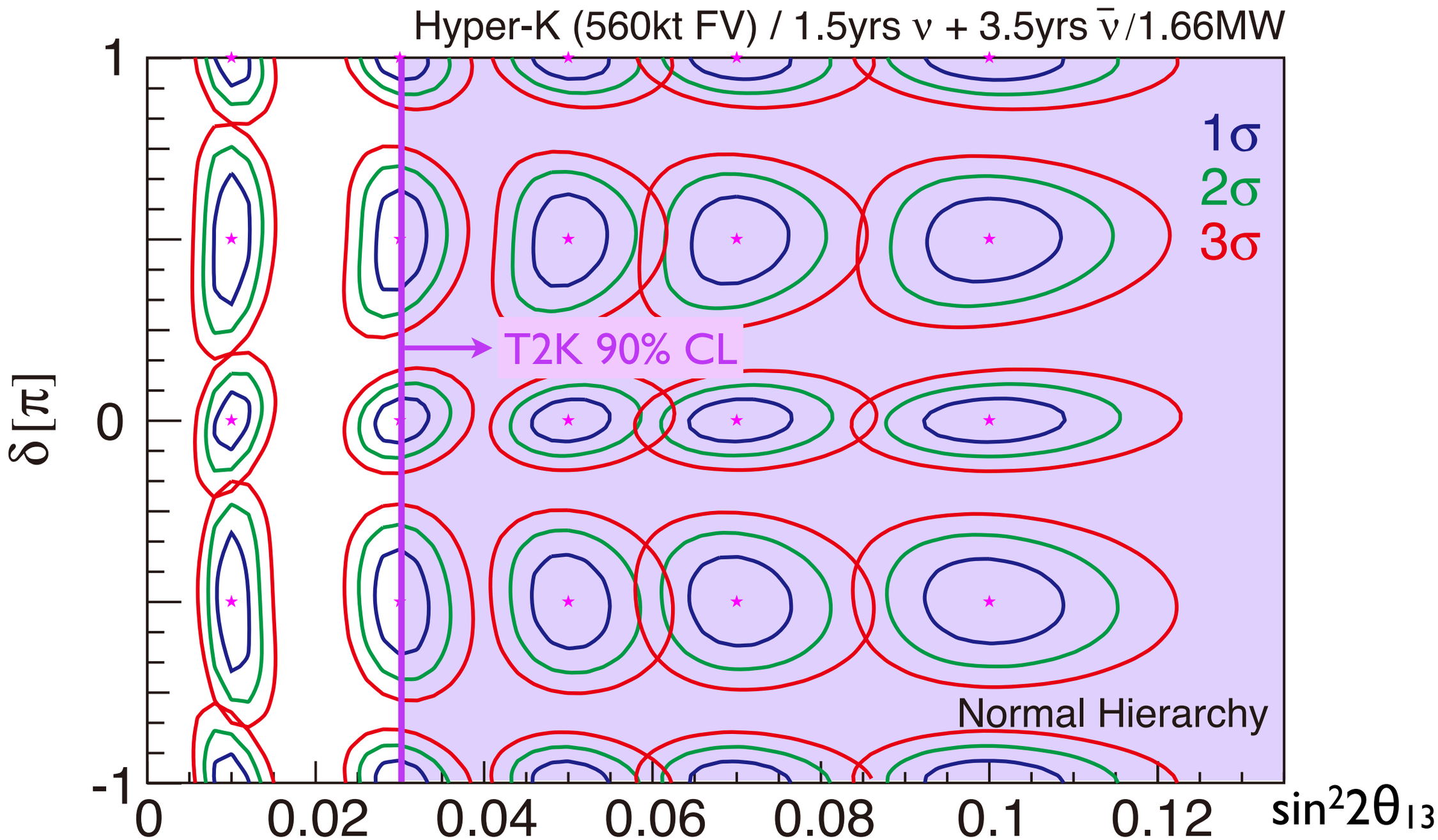
Expected contour

5% systematics on signal, ν_μ BG, ν_e BG, $\nu/\bar{\nu}$



Expected contours

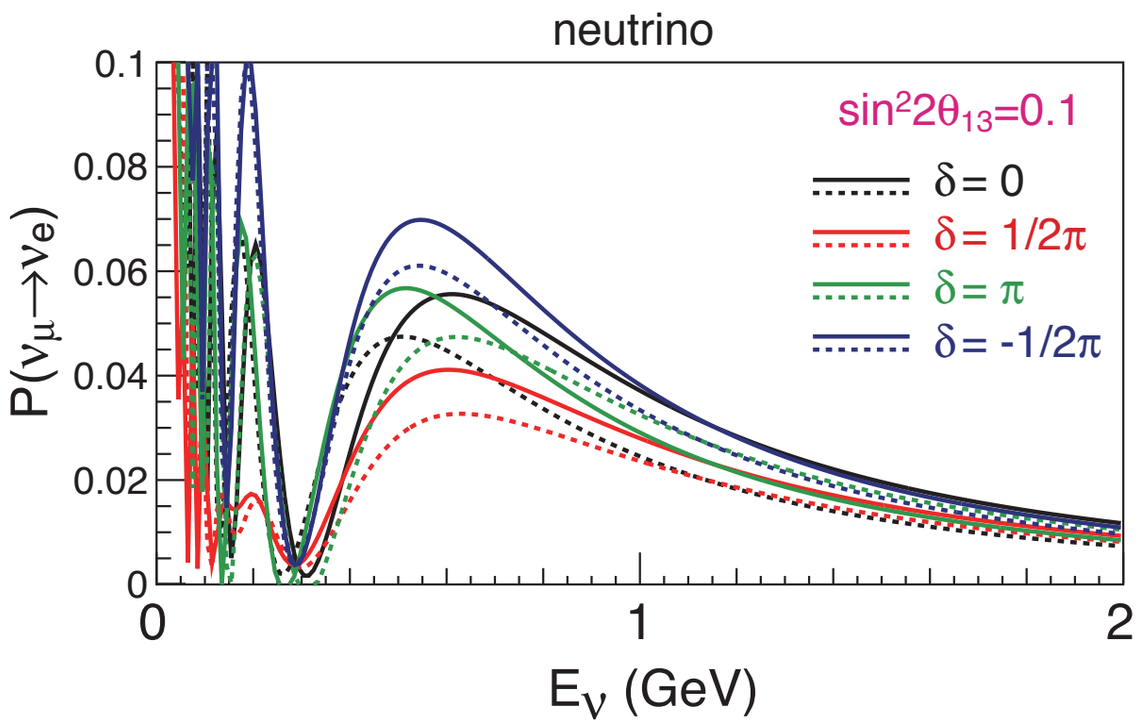
5% systematics on signal, ν_μ BG, ν_e BG, $\nu/\bar{\nu}$

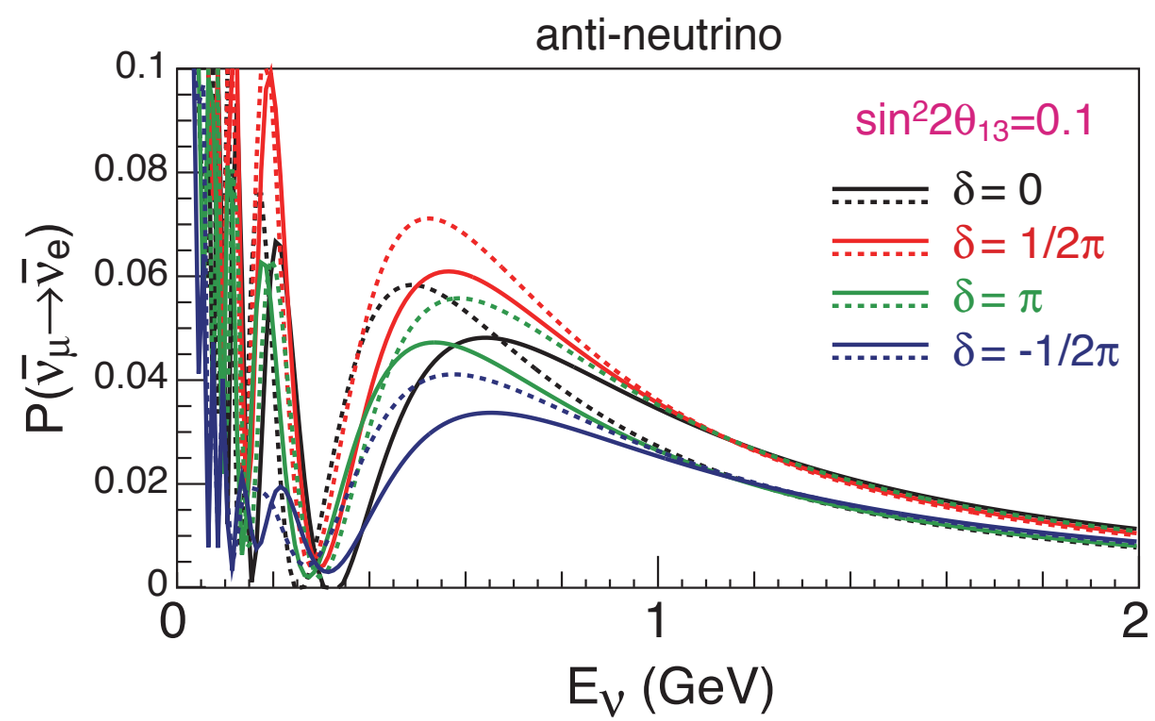


Good sensitivity over allowed region of T2K

Mass hierarchy

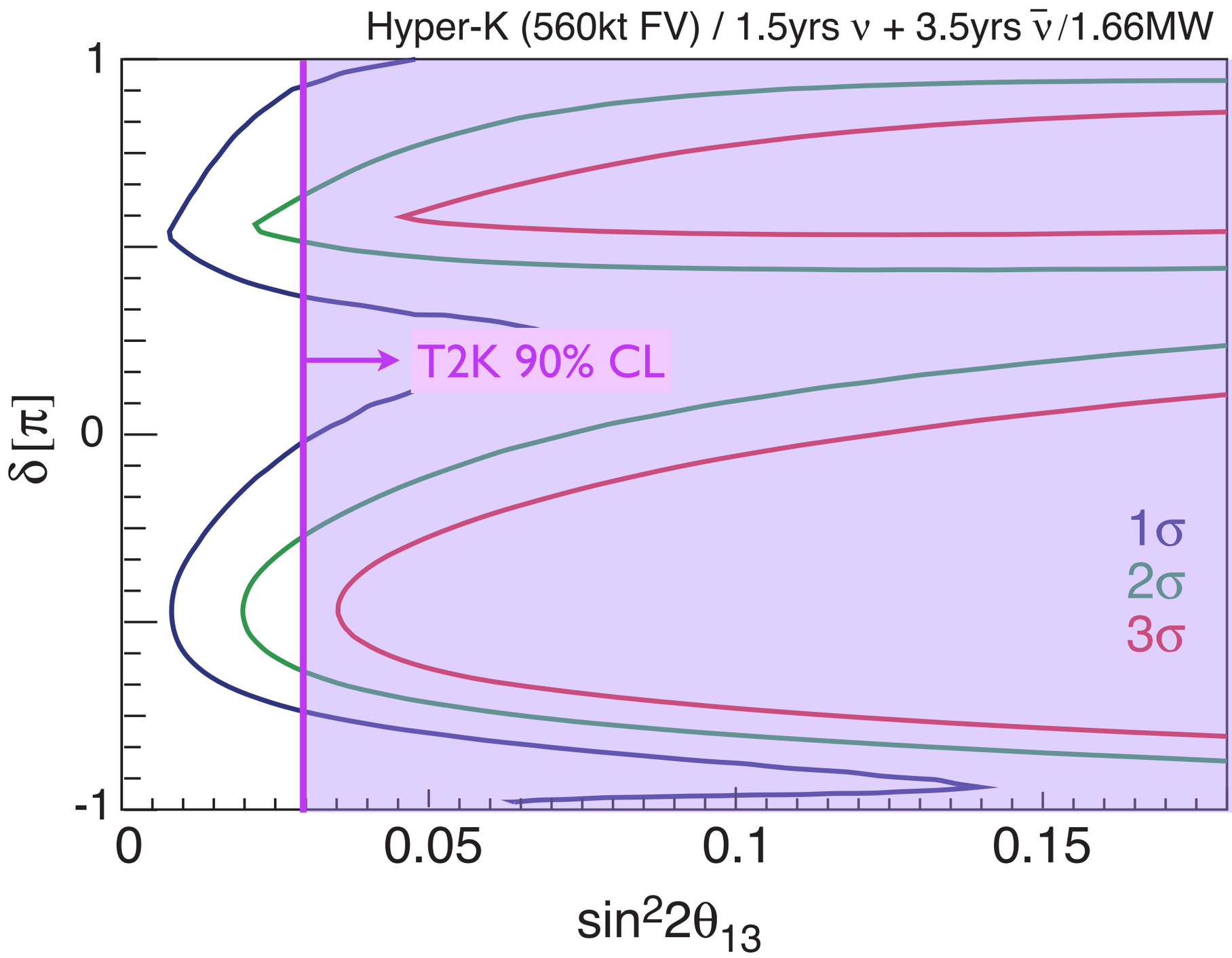
Solid: normal
Dashed: inverted





- Fake CPV effect by matter effect
- Some sensitivity using shape information

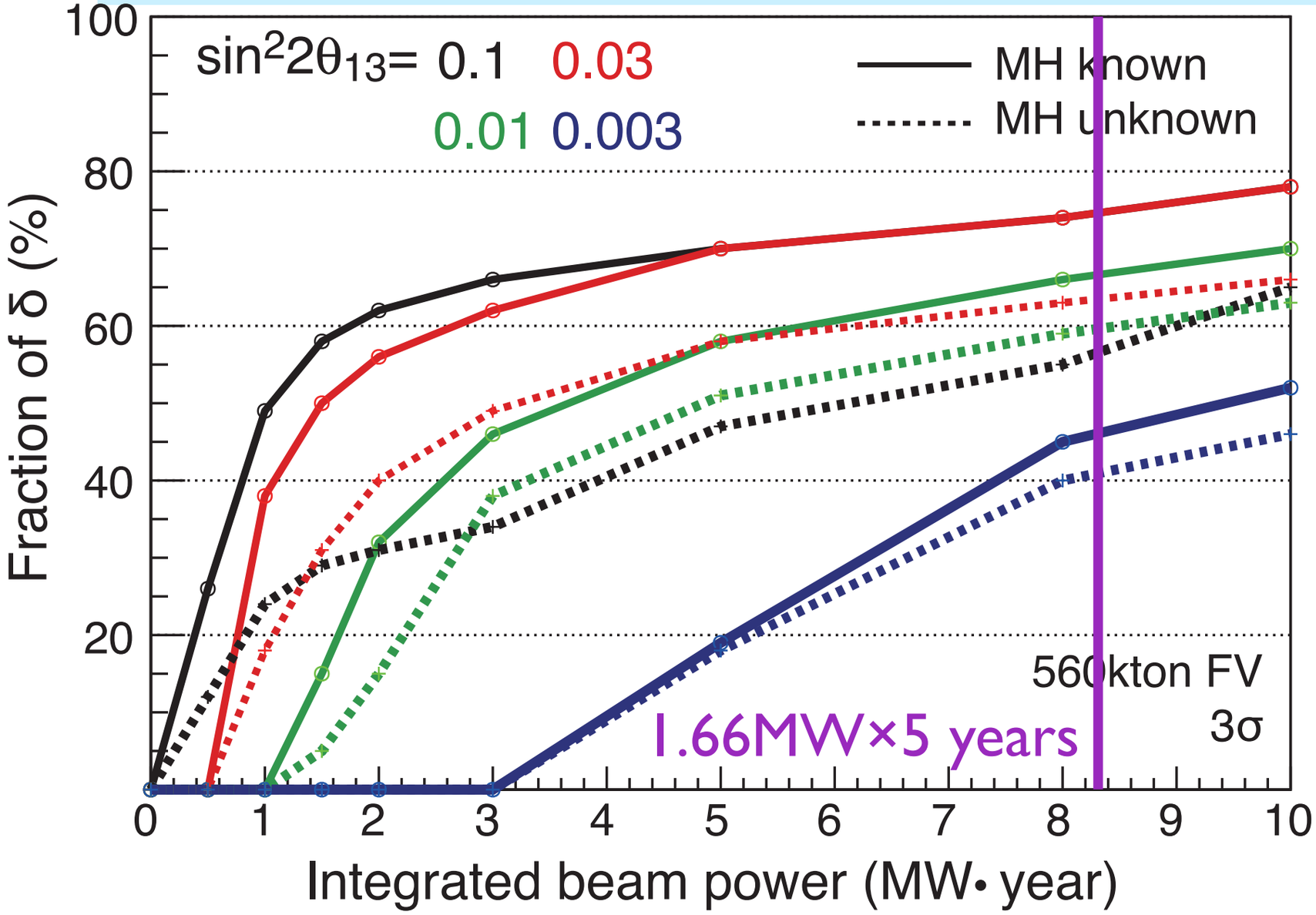
Mass hierarchy



J-PARC HK experiment has sensitivity to mass hierarchy

CPV sensitivity

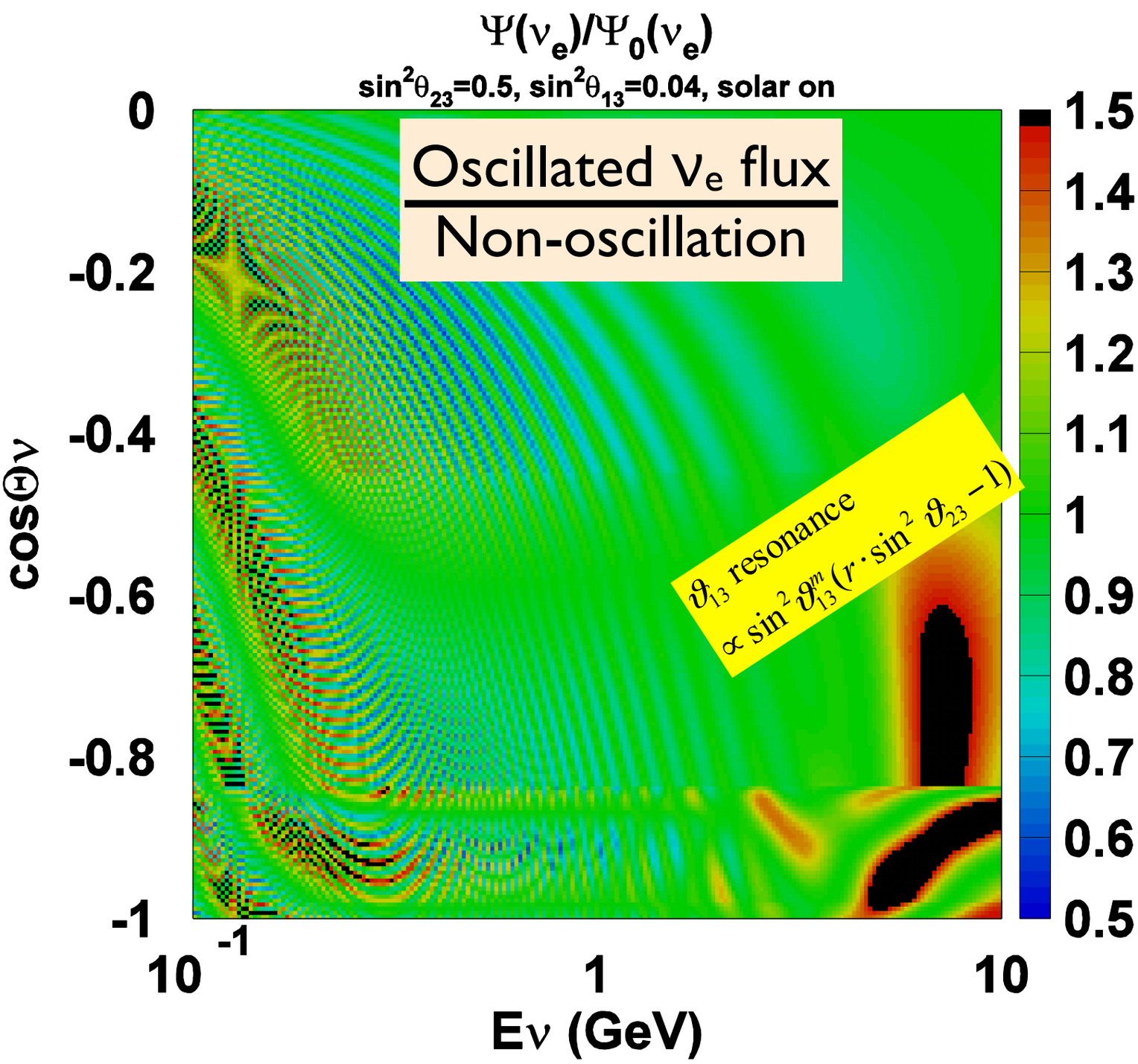
Fraction of δ parameter for which CPV can be observed with >3σ



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

- CPV can be observed with >3σ for 74% of δ ($\sin^2 2\theta_{13}$>0.03)
- Effect of unknown mass hierarchy is limited
  - Input from atm ν and other experiments also expected for MH

Atmospheric ν



$\nu_\mu \rightarrow \nu_e$ appearance resonance either ν or $\bar{\nu}$ depending on mass hierarchy

Sensitive to

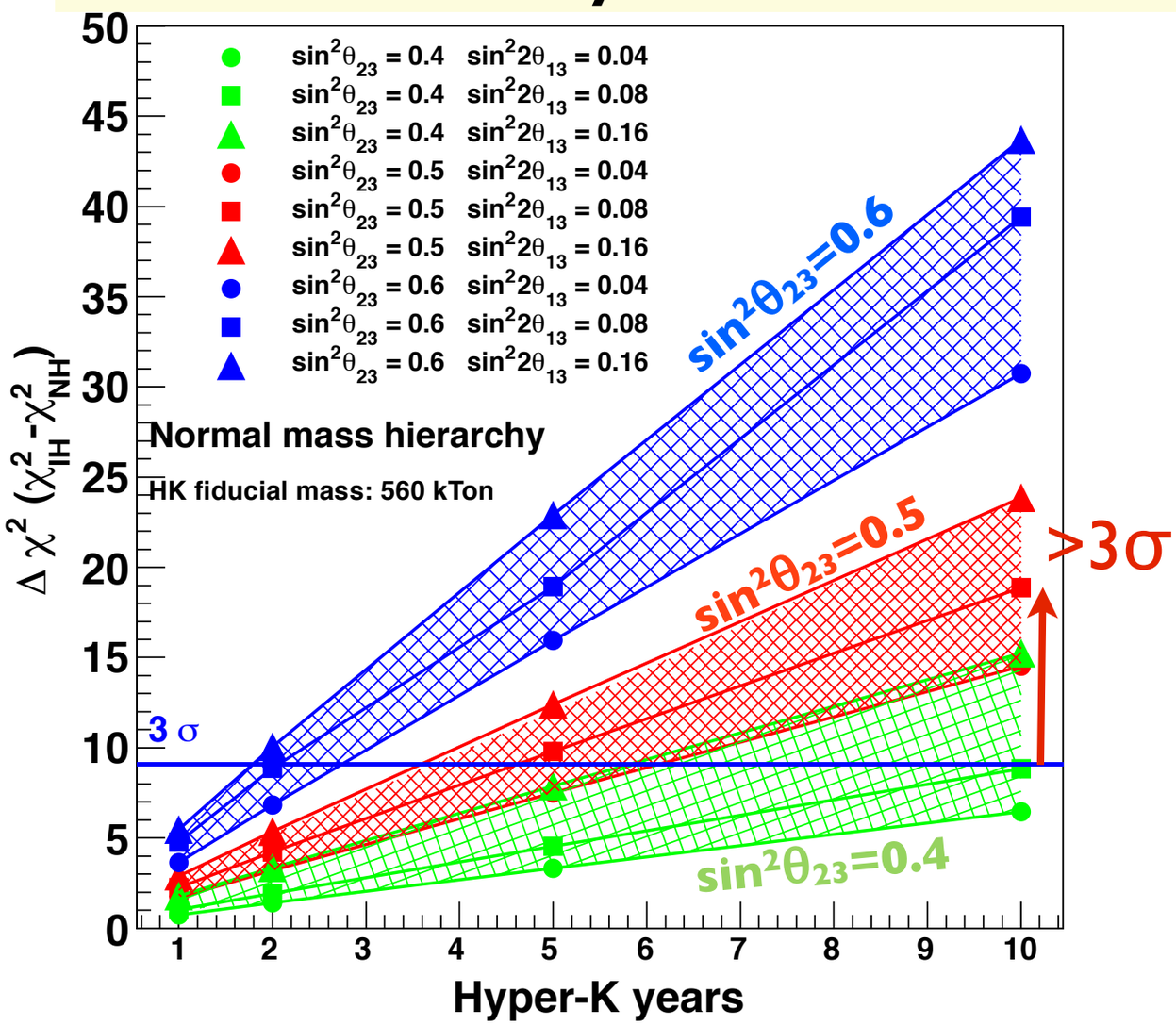
- Mass hierarchy
- θ_{23} octant
- CP asymmetry

Complementary to accelerator ν

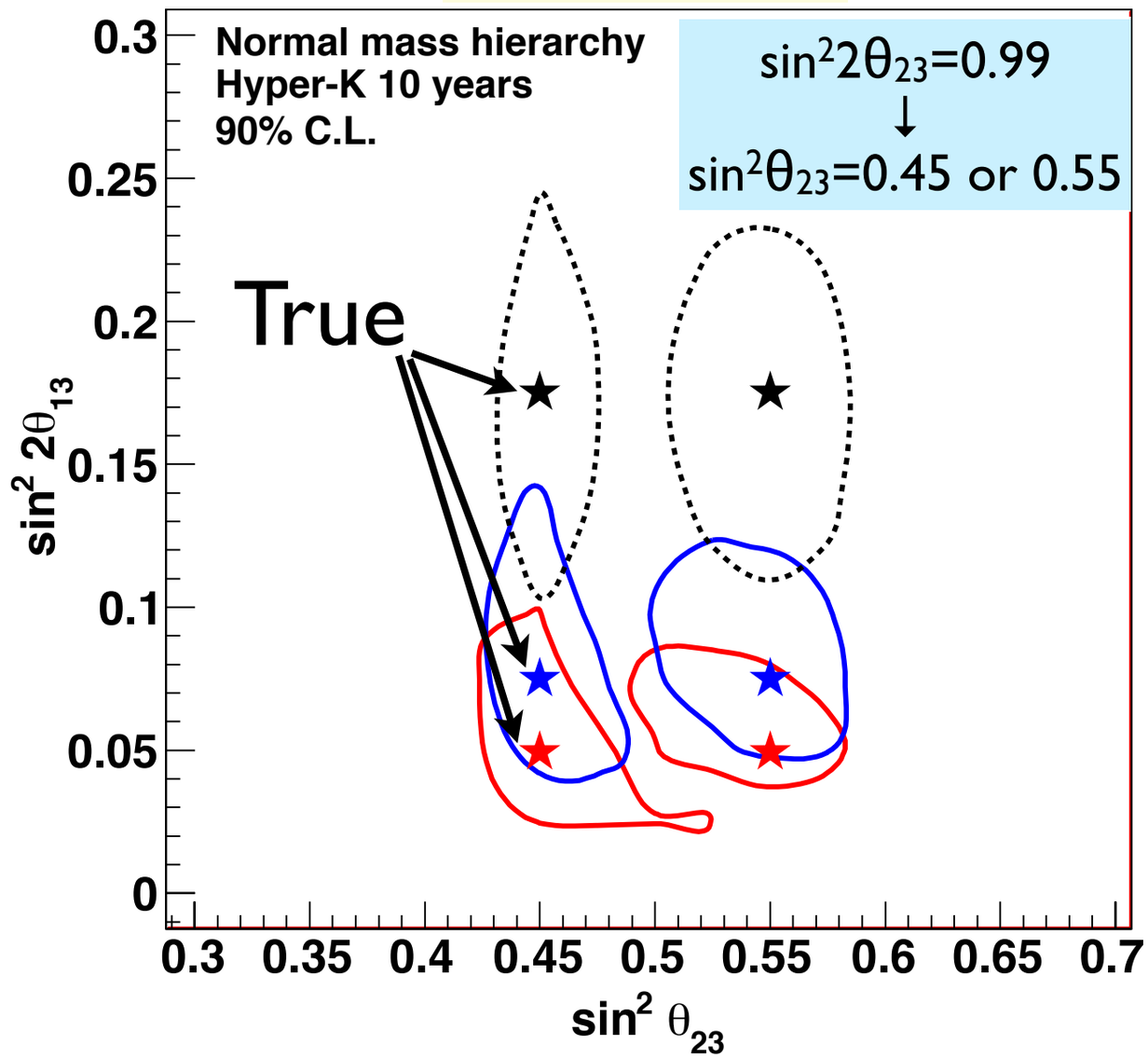
Large θ_{13} gives better sensitivity

Atmospheric ν

Mass hierarchy determination



θ_{23} octant



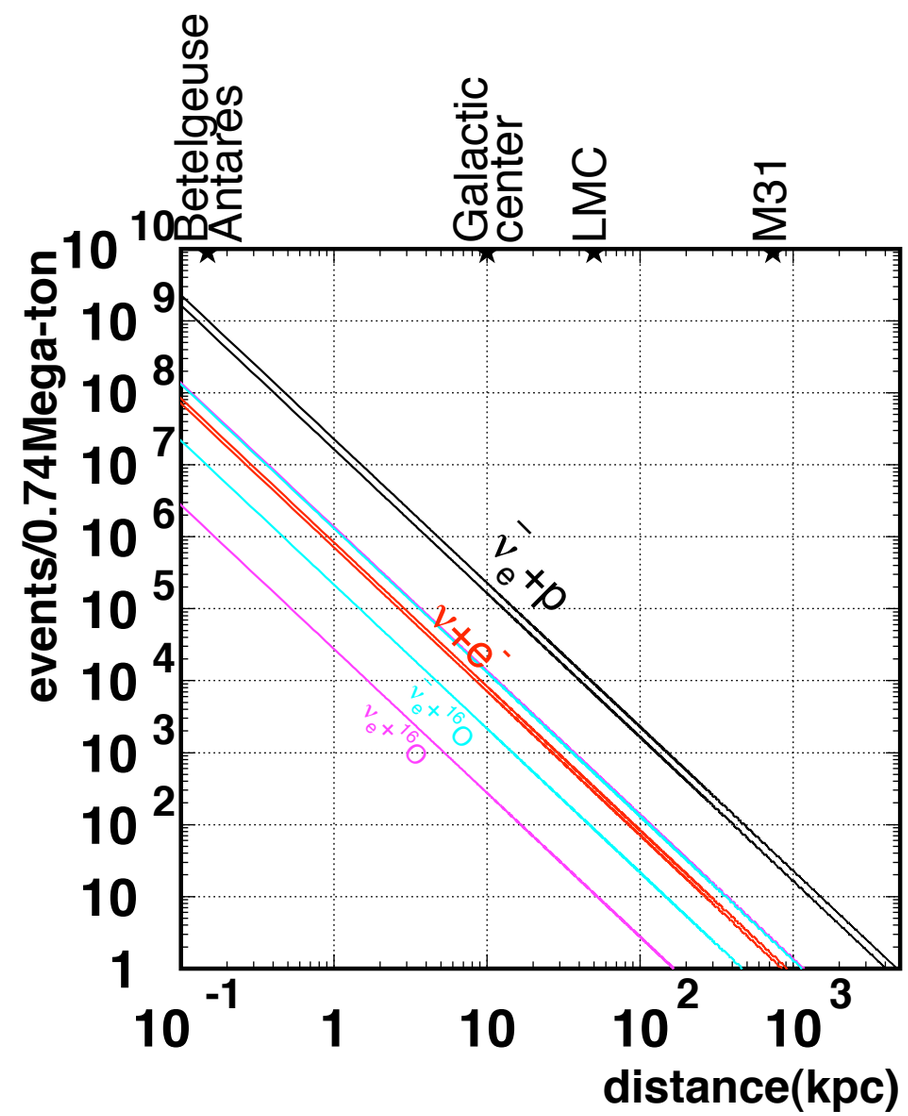
>3σ in 5-10 years

Resolved if $\sin^2 2\theta_{23}$<0.99

Complementary to accelerator ν

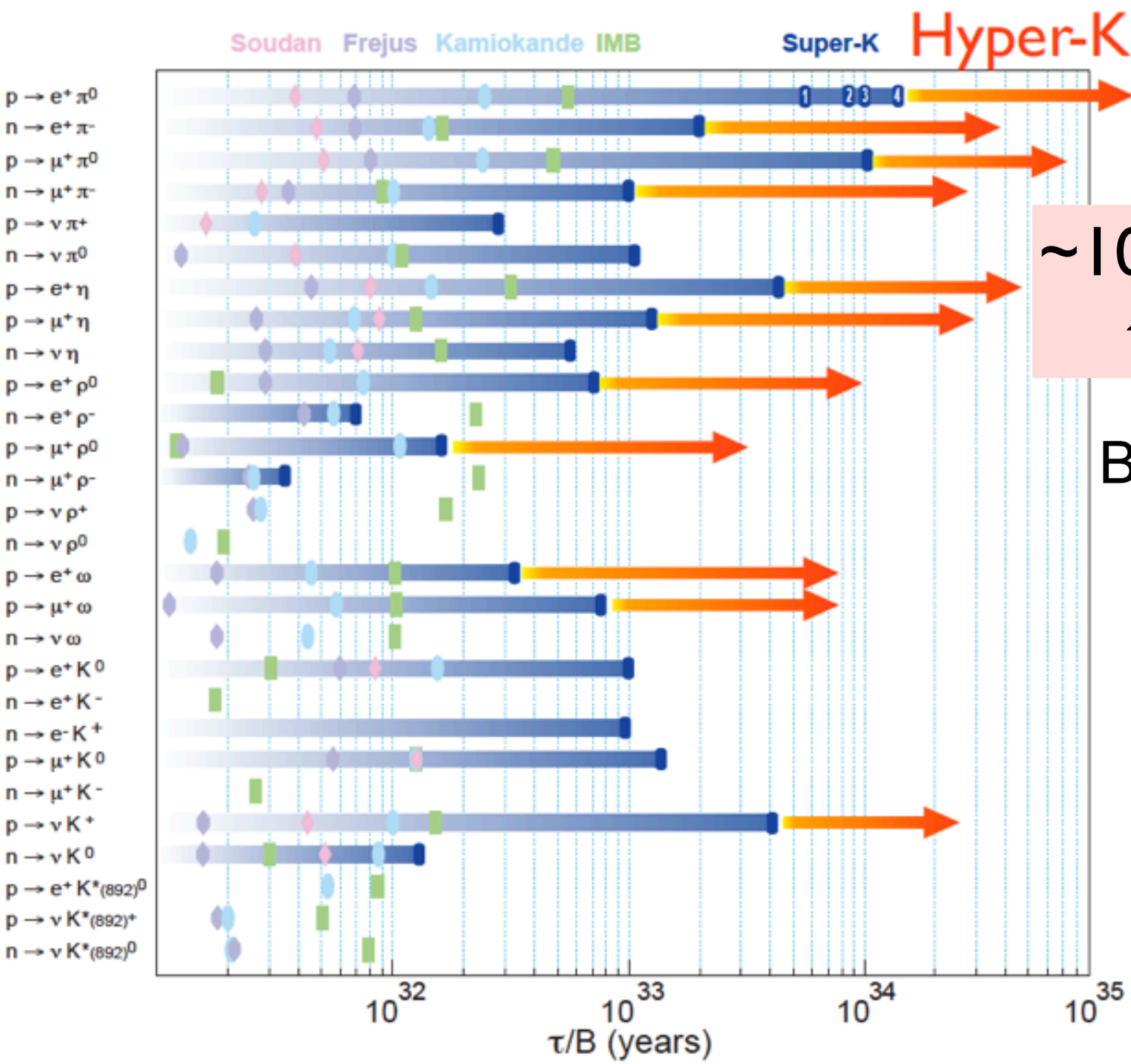
Other science with ν's in HK

- Supernova core collapse ν
  - ~200k events for 10kpc SN
- Relic supernova ν (with Gd?)
- Solar ν precise measurements
- WIMP, GRB, solar flare...
- Geophysics (ν tomography of Earth)



covering a wide range of particle physics/astrophysics topics

Nucleon decay with HK



Talk by Y. Obayashi
in nucleon decay session

~10 times better sensitivity than current Super-K

Based on full simulation

- $p \to e^+\pi^0$:
  - 1.3×10^{35}yrs (90%CL)
  - 5.7×10^{34}yrs (3σ)
- $p \to \nu K^+$:
  - 2.5×10^{34}yrs (90%CL)
  - 1.0×10^{34}yrs (3σ)

(10 years)

Summary

- Baseline design and physics potential of Hyper-Kamiokande are presented. [arXiv:1109.3262]
  - excellent sensitivity to leptonic CP violation.
  - discrimination of mass hierarchy and θ_{23} octant.
  - order of magnitude better sensitivity for nucleon decays.
  - astrophysical ν observation.
- Next step:
  - Detailed, realistic cost and schedule.
  - Optimization of design, more R&D.

Backup

ν physics case of Hyper-K

Assuming $\sin^2\theta_{13}$~a few % (suggested by T2K, MINOS, DC)

- 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.

Proton Decay searches w/ ~10 times better sensitivity than Super-K, astrophysical ν etc.

Assumed parameters

- $L = 295$ km
- $\Delta m^2_{12} = 7.6 \times 10^{-5}$ eV^2
- $|\Delta m^2_{23}| = 2.4 \times 10^{-3}$ eV^2
- $\sin^2\theta_{12} = 0.31$
- $\sin^2\theta_{23} = 0.50$ ($\sin^2 2\theta_{23} = 1.0$)
- $\rho = 2.6$ [g/cm^3]

χ^2 definition

Fake data

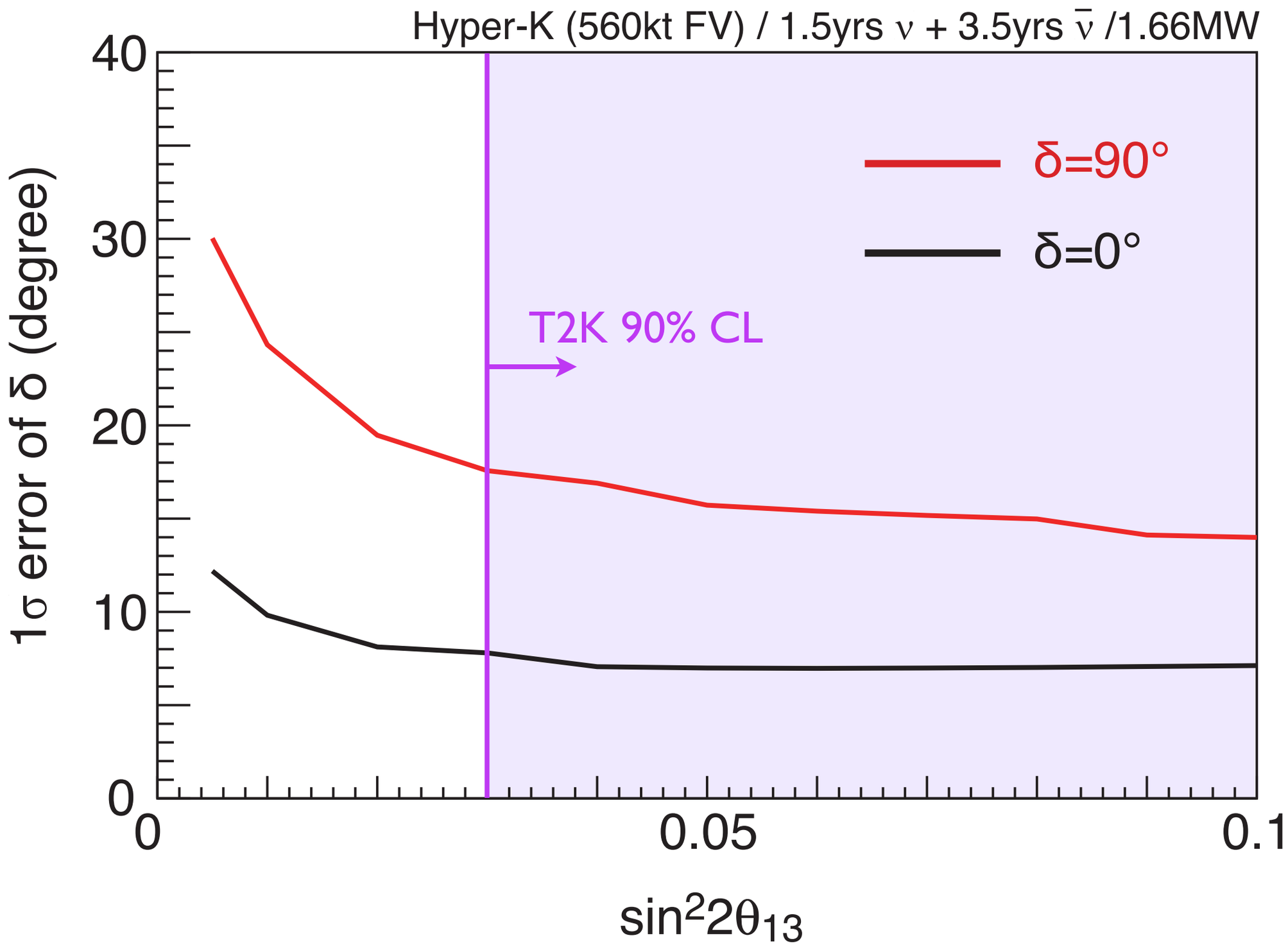
Oscillated MC w/ syst. error

$$\chi^2 = \sum_{\nu,\overline{\nu}} \sum_i \left[N^i - \left\{ 1 \pm \frac{1}{2} f_{\nu/\overline{\nu}} \right\} \cdot \left((1 + f_{\rm sig}) \cdot n^i_{\rm sig} + (1 + f_{\nu_\mu}) \cdot n^i_{\nu_\mu} + (1 + f_{\nu_e}) \cdot n^i_{\nu_e} \right) \right]^2 / N^i$$
$$+ \frac{{f_{\rm sig}}^2}{{\sigma_{\rm sig}}^2} + \frac{{f_{\nu_\mu}}^2}{{\sigma_{\nu_\mu}}^2} + \frac{{f_{\nu_e}}^2}{{\sigma_{\nu_e}}^2} + \frac{{f_{\overline{\nu}/\nu}}^2}{{\sigma_{\nu/\overline{\nu}}}^2},$$

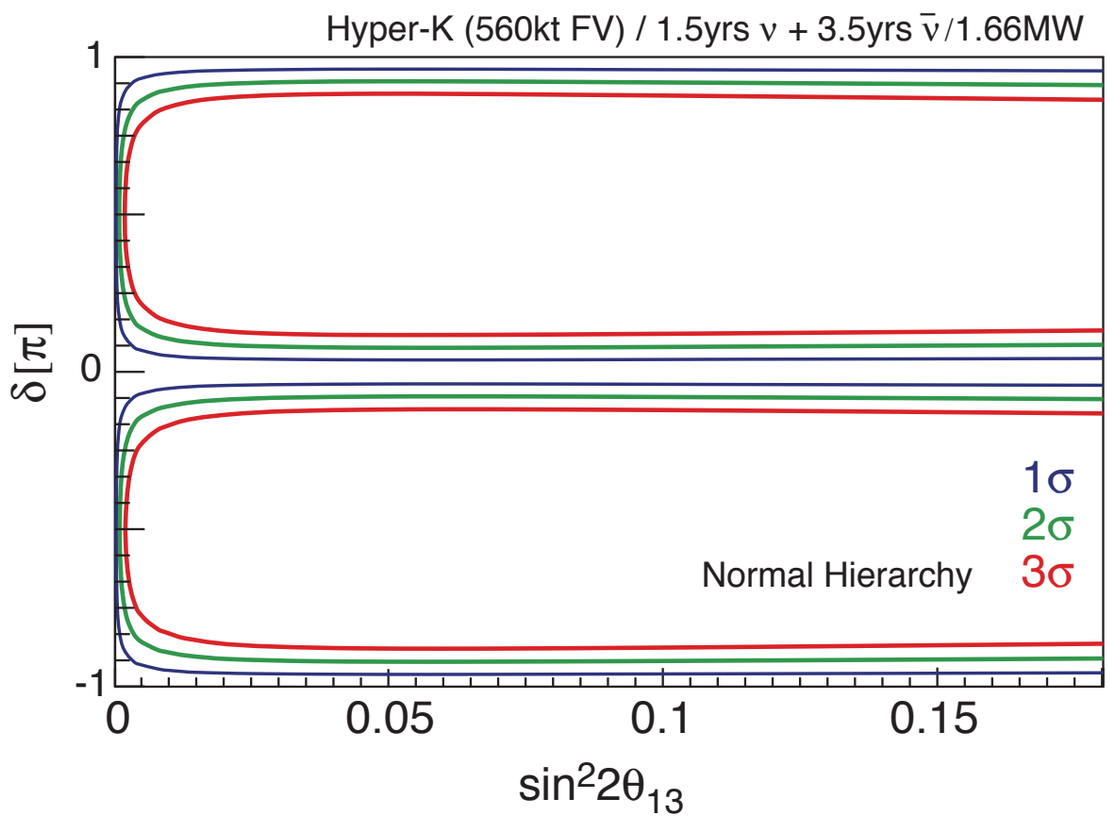
assumed syst. errors (all 5%)

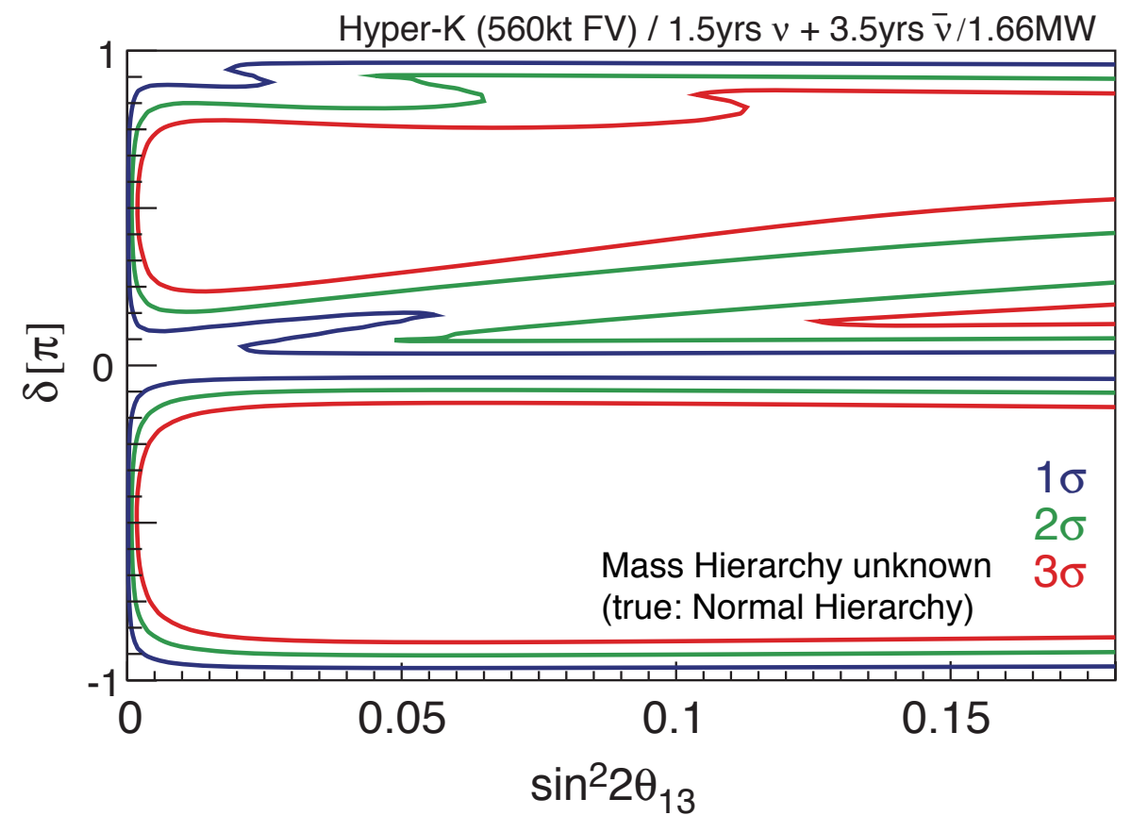
signal eff., ν_μBG, ν_eBG, ν/anti-ν ratio

1σ error of δ


Hyper-K (560kt FV) / 1.5yrs ν + 3.5yrs ν̄ /1.66MW
δ=90°
δ=0°
T2K 90% CL
1σ error of δ (degree)
40
30
20
10
0
0
0.05
0.1
sin²2θ13

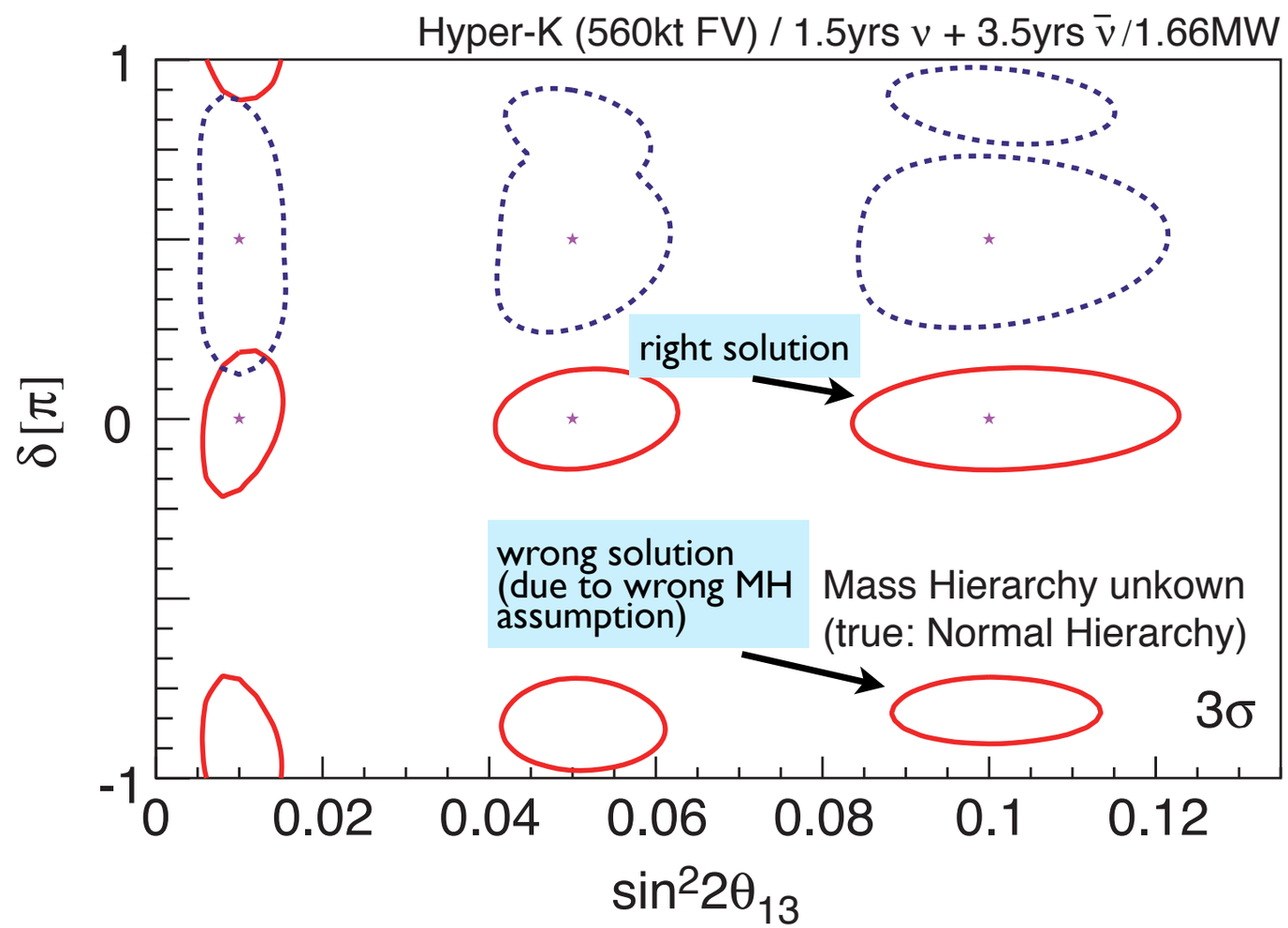
δ coverage for CPV





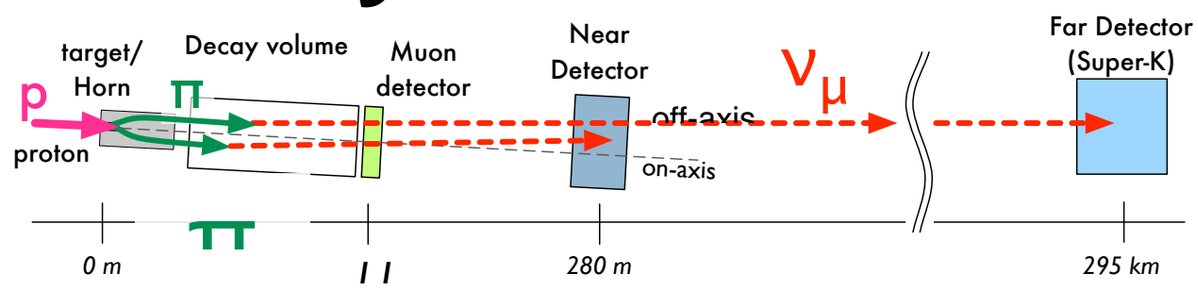
If mass hierarchy is unknown

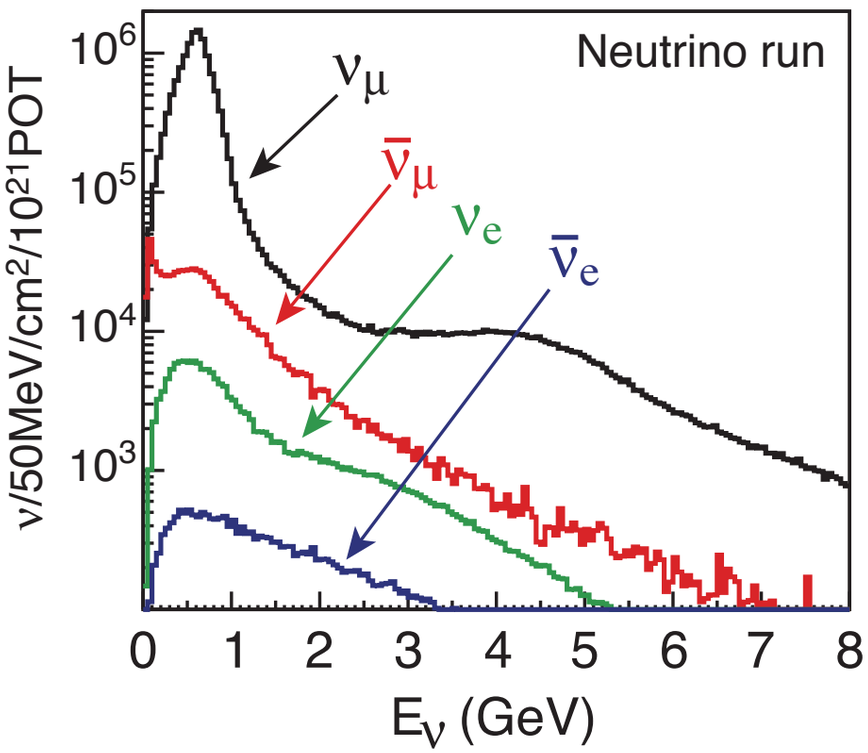
Normal mass hierarchy (unknown)

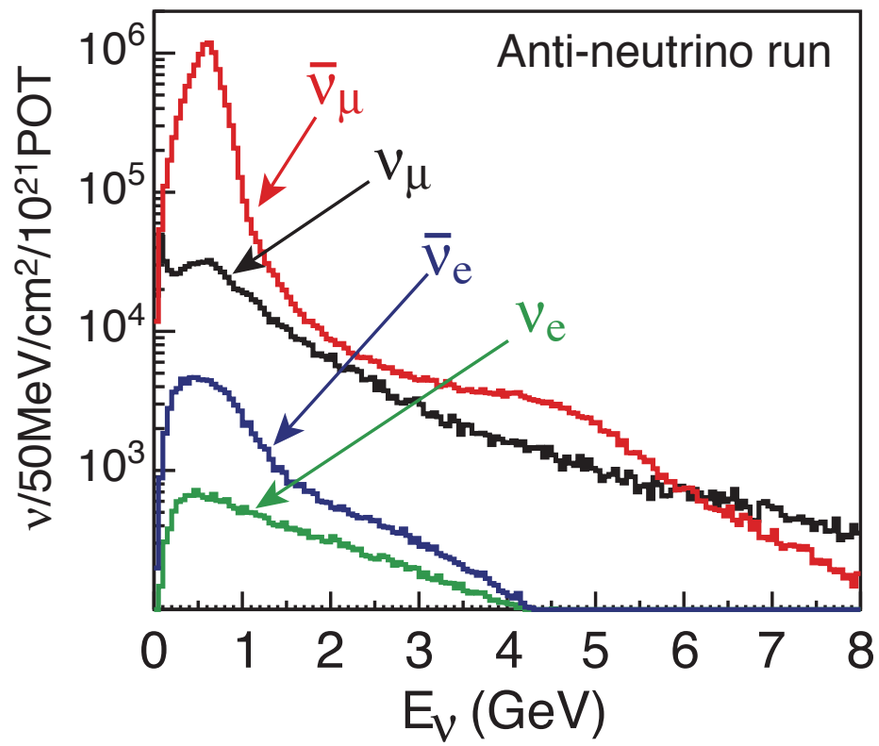


- multiple solutions, wider allowed region due to wrong MH assumption.
- Input (mass hierarchy) from other experiments may become important.
  - from NoνA? or ν-less DB? or...
- One possibility is to determine MH by atm. ν study (discuss later)

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

MR Power Improvement Scenario

	Day1 (up to Mar.2011) Achieved!	Next Step	KEK Roadmap
Power(MW)	0.145	0.45	>1.66
Energy(GeV)	30	30	30
Rep Cycle(sec)	3.04	2.2	1.92～0.5
No. of Bunch	8	8	8
Particle/Bunch	1.2×10^{13}	2.5×10^{13}	$4.1\sim8.3\times10^{13}$
Particle/Ring	9.2×10^{13}	2.0×10^{14}	$3.3\sim6.7\times10^{14}$
LINAC(MeV)	181	181	400
RCS	h=2	h=2	h=2 or 1

Combination of High rep. cycle and High beam density

15

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)

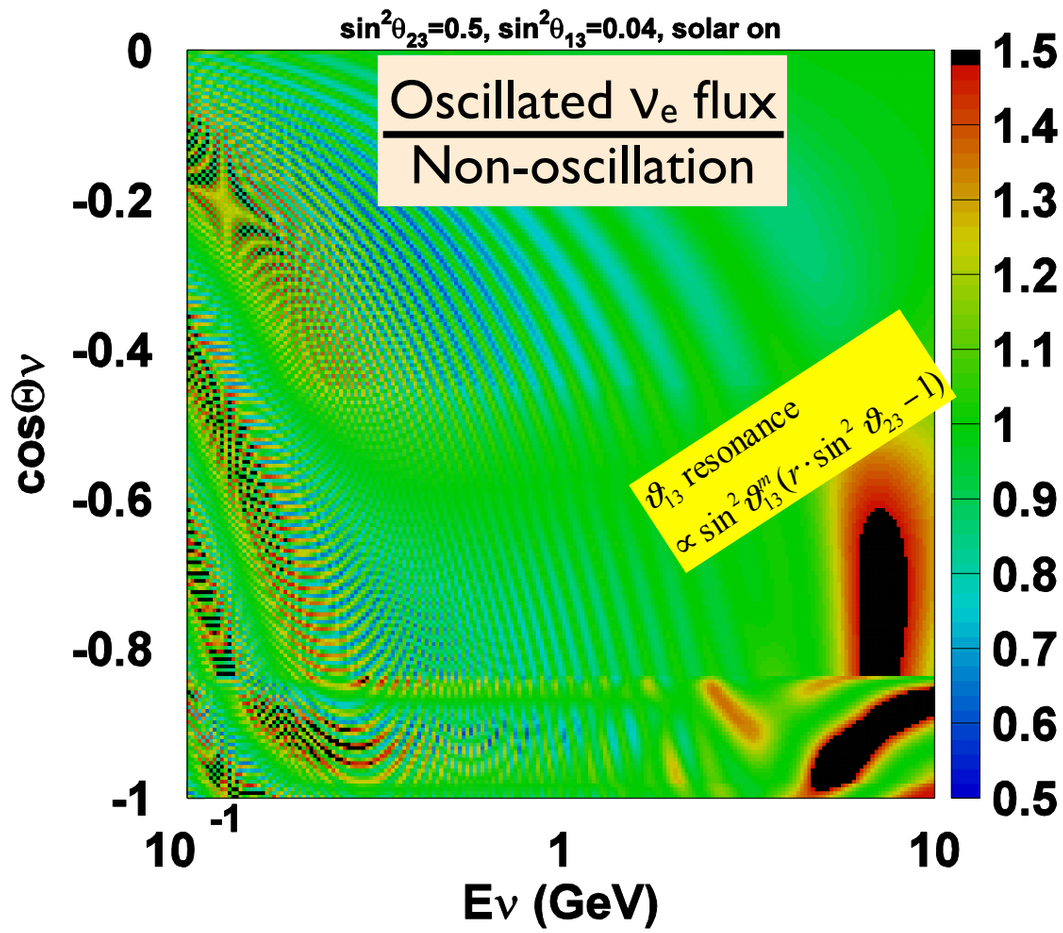
$P_2 = |A_{e\mu}|^2$: 2ν transition probability $\nu_e \rightarrow \nu_{\mu\tau}$ in matter

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

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

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

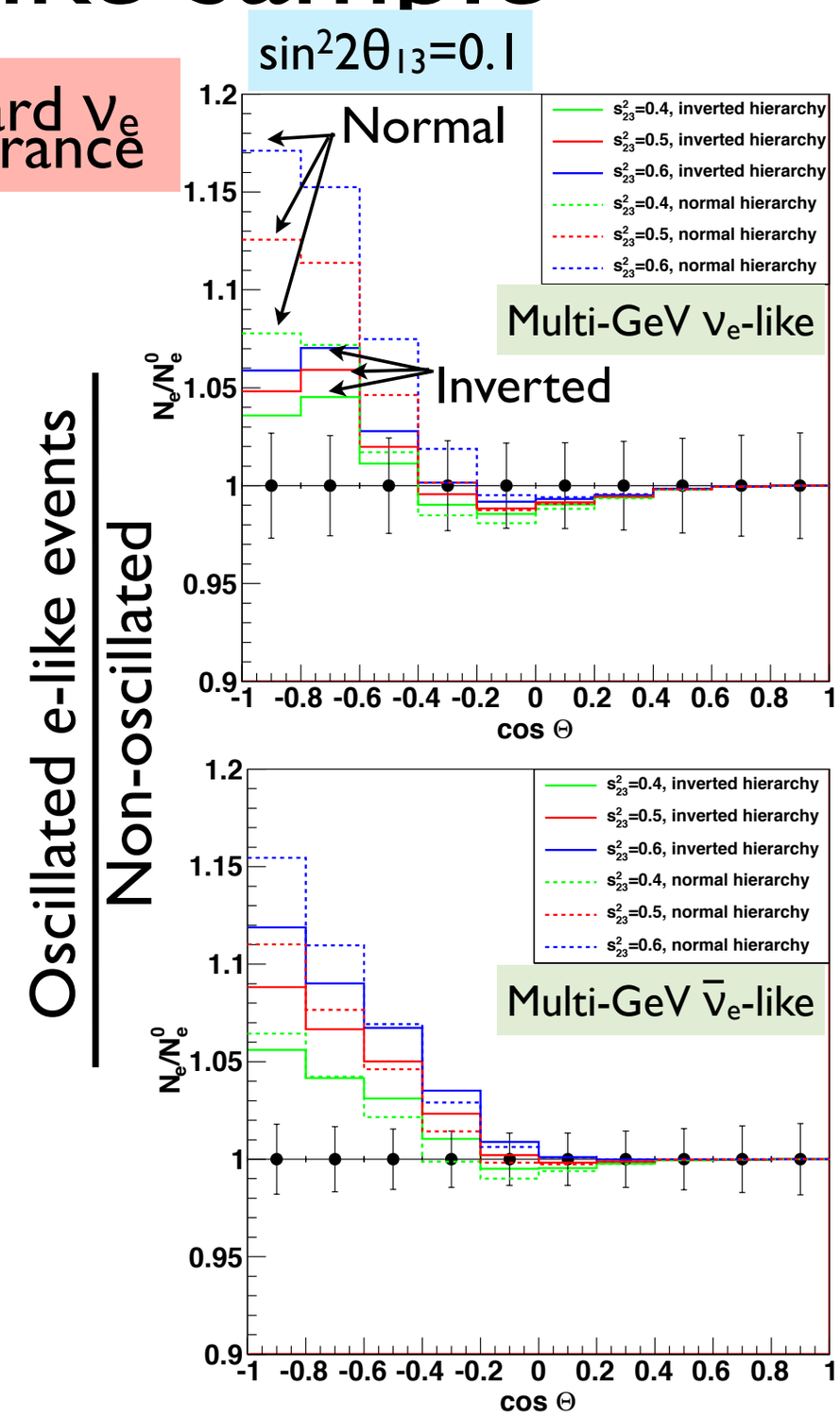
ν_e-like and anti-ν_e-like sample

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

Upward ν_e appearance

- 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%