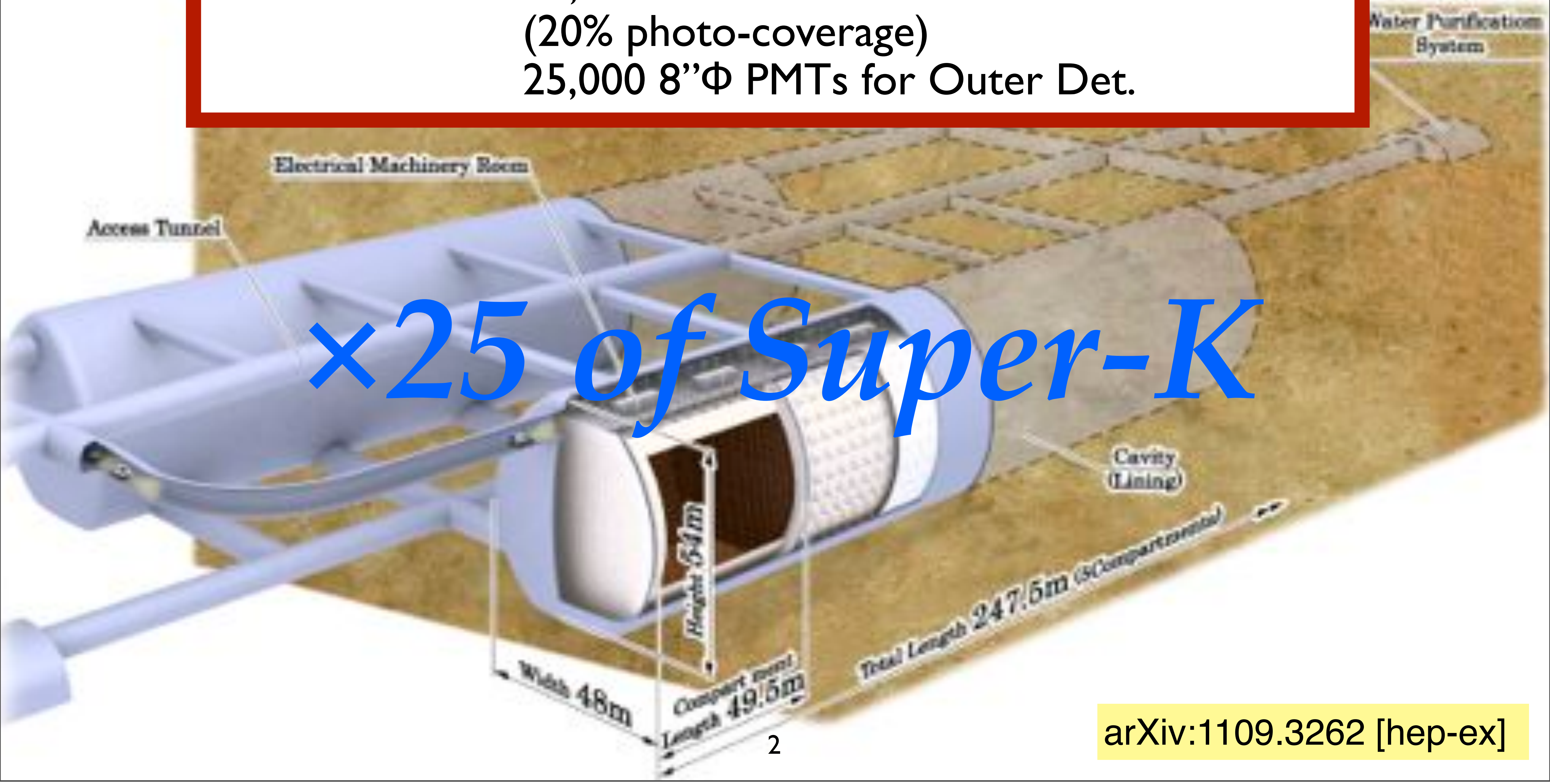
Neutrino Telescopes 2013
@Venice on March 14, 2013

Hyper-Kamiokande

T. Nakaya (Kyoto)
for the Hyper-K working group

Hyper-K Overview

Total Volume	0.99 Megaton
Inner Volume	0.74 Mton
Fiducial Volume	0.56 Mton (0.056 Mton × 10 compartments)
Outer Volume	0.2 Megaton
Photo-sensors	99,000 20”Φ PMTs for Inner Det. (20% photo-coverage) 25,000 8”Φ PMTs for Outer Det.



×25 of Super-K

arXiv:1109.3262 [hep-ex]

x50 for νCP to T2K

x25 Larger ν Target & Proton Decay Source

higher intensity ν by upgraded J-PARC

x2 (year or power)

831 citation

The JHF-Kamioka neutrino project

Y. Itow[1], T. Kajita[1], K. Kaneyuki[1], M. Shiozawa[1], Y. Totsuka[1],
Y. Hayato[2], T. Ishida[2], T. Ishii[2], T. Kobayashi[2], T. Maruyama[2],
K. Nakamura[2], Y. Obayashi[2], Y. Oyama[2], M. Sakuda[2], M. Yoshida[2],
S. Aoki[3], T. Hara[3], A. Suzuki[3],
A. Ichikawa[4], T. Nakaya[4], K. Nishikawa[4],
T. Hasegawa[5], K. Ishihara[5], A. Suzuki[5],
A. Konaka[6]

[1] Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan

[2] Inst. of Particle and Nuclear Studies, High Energy Accelerator Research Org. (KEK),
Tsukuba, Ibaraki 305-0801, Japan

[3] Department of Physics, Kobe University, Kobe, Hyogo 657-8501, Japan

[4] Department of Physics, Kyoto University, Kyoto 606-8502, Japan

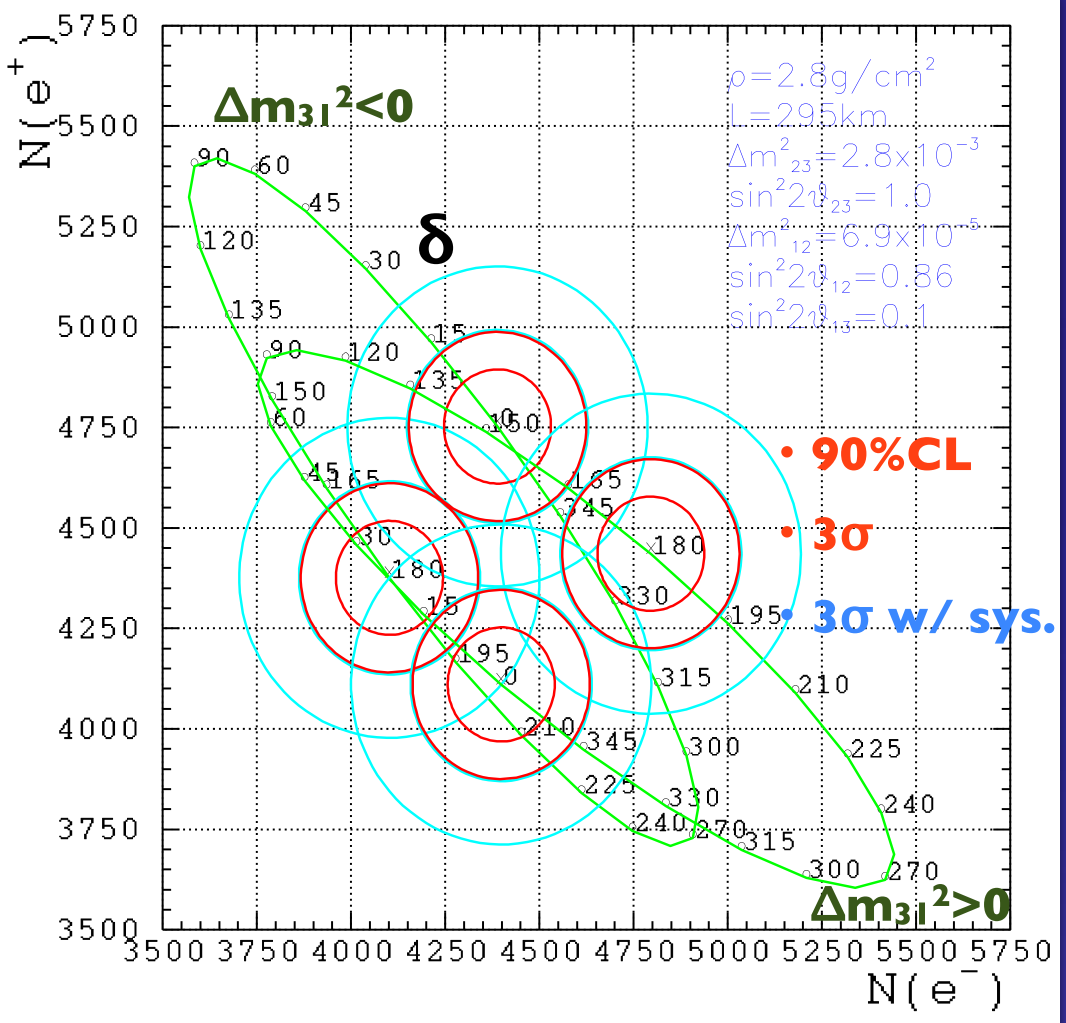
[5] Department of Physics, Tohoku University, Sendai, Miyagi, 980-8578, Japan

[6] TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada, V6T 2A3

arXiv:hep-ex/0106019v1 5 Jun 2001

Abstract

The JHF-Kamioka neutrino project is a second generation long base line neutrino oscillation experiment that probes physics beyond the Standard Model by high precision measurements of the neutrino masses and mixing. A high intensity narrow band neutrino beam is produced by secondary pions created by a high intensity proton synchrotron at JHF (JAERI). The neutrino energy is tuned to the oscillation maximum at ~1 GeV for a baseline length of 295 km towards the world largest water Čerenkov detector, Super-Kamiokande. Its excellent energy resolutio and particle identification enable the reconstruction of the initial neutrino energy, which i compared with the narrow band neutrino energy, through the quasi-elastic interaction. Th physics goal of the first phase is an order of magnitude better precision in the $\nu_\mu \to \nu_\tau$ oscillatio measurement ($\delta(\Delta m^2_{23}) = 10^{-4}$ eV^2 and $\delta(\sin^2 2\theta_{23}) = 0.01$), a factor of 20 more sensitiv search in the $\nu_\mu \to \nu_e$ appearance ($\sin^2 2\theta_{\mu e} \simeq 0.5 \sin^2 2\theta_{13} > 0.003$), and a confirmation of th $\nu_\mu \to \nu_\tau$ oscillation or discovery of sterile neutrinos by detecting the neutral current events. I the second phase, an upgrade of the accelerator from 0.75 MW to 4 MW in beam power an the construction of 1 Mt Hyper-Kamiokande detector at Kamioka site are envisaged. Anothe order of magnitude improvement in the $\nu_\mu \to \nu_e$ oscillation sensitivity, a sensitive search of the CP violation in the lepton sector (CP phase δ down to $10^\circ - 20^\circ$), and an order of magnitude improvement in the proton decay sensitivity is also expected.



(Fig. 20 at page 25)

a sensitive search of the CP violation in the lepton sector (CP phase δ down to 10°–20°), and an order of magnitude improvement in the proton decay

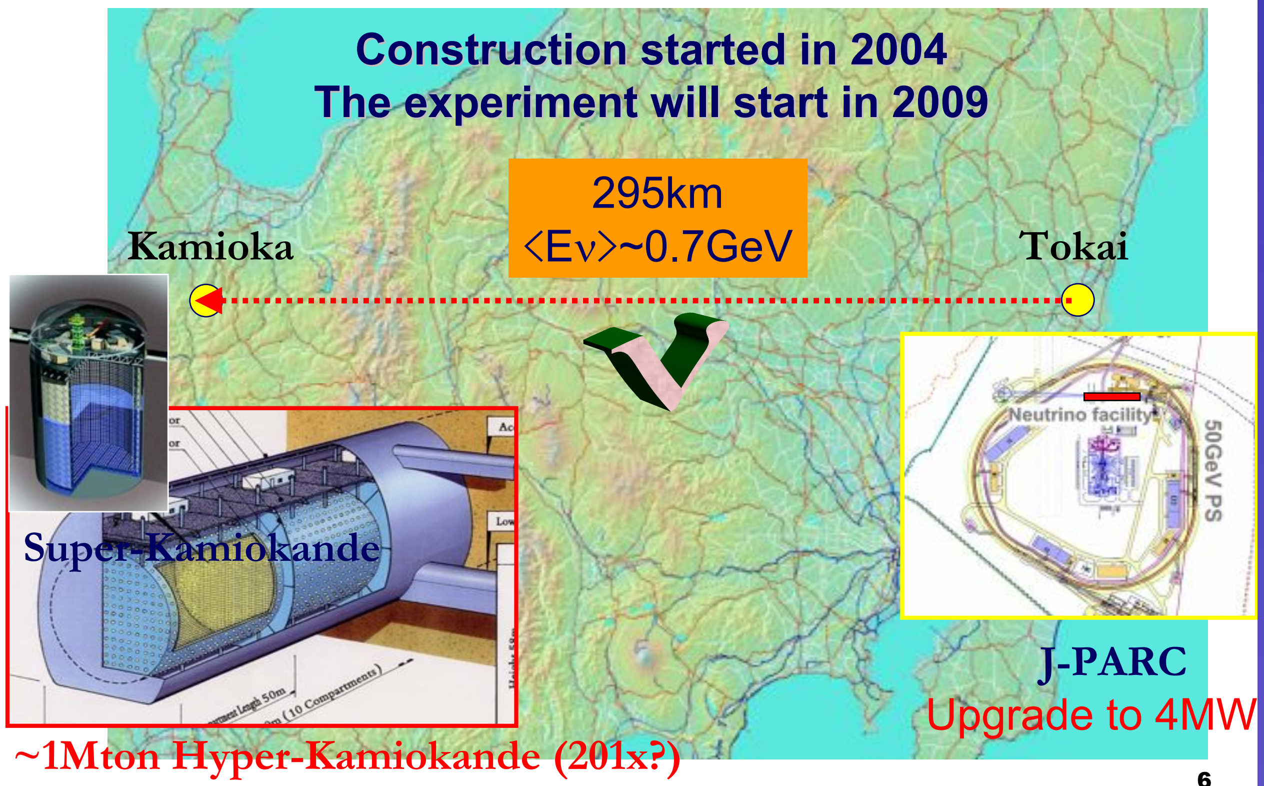
Neutrino Telescopes 2005
at Venice

The Neutrino Physics at Accelerators: the High Intensity Frontier

T. Nakaya (Kyoto Univ.)

1. Introduction

2. T2K Experiment -II



5. Summary

- Accelerator neutrino experiments including K2K and MINOS provide essential information for neutrino mixing and mass.
- The next generation experiments with a high intensity accelerator are sensitive to
  - ☐ $\delta\sin^2 2\theta_{23}$~1%; $\delta\Delta m^2 < 1\times10^{-4}$eV^2
  - ☐ $\sin^2 2\theta_{13} < 0.01$
- With a gigantic (100k~1Mtons) detector, the experiment has the sensitivity to the CP violation.
  - ☐ $\delta < 20°$ for $\sin^2 2\theta_{13} > 0.01$
- The experiments sensitive to the sign of Δm^2 is also under consideration (not T2K).

We are also looking forward an expected phenomena in the experiments.

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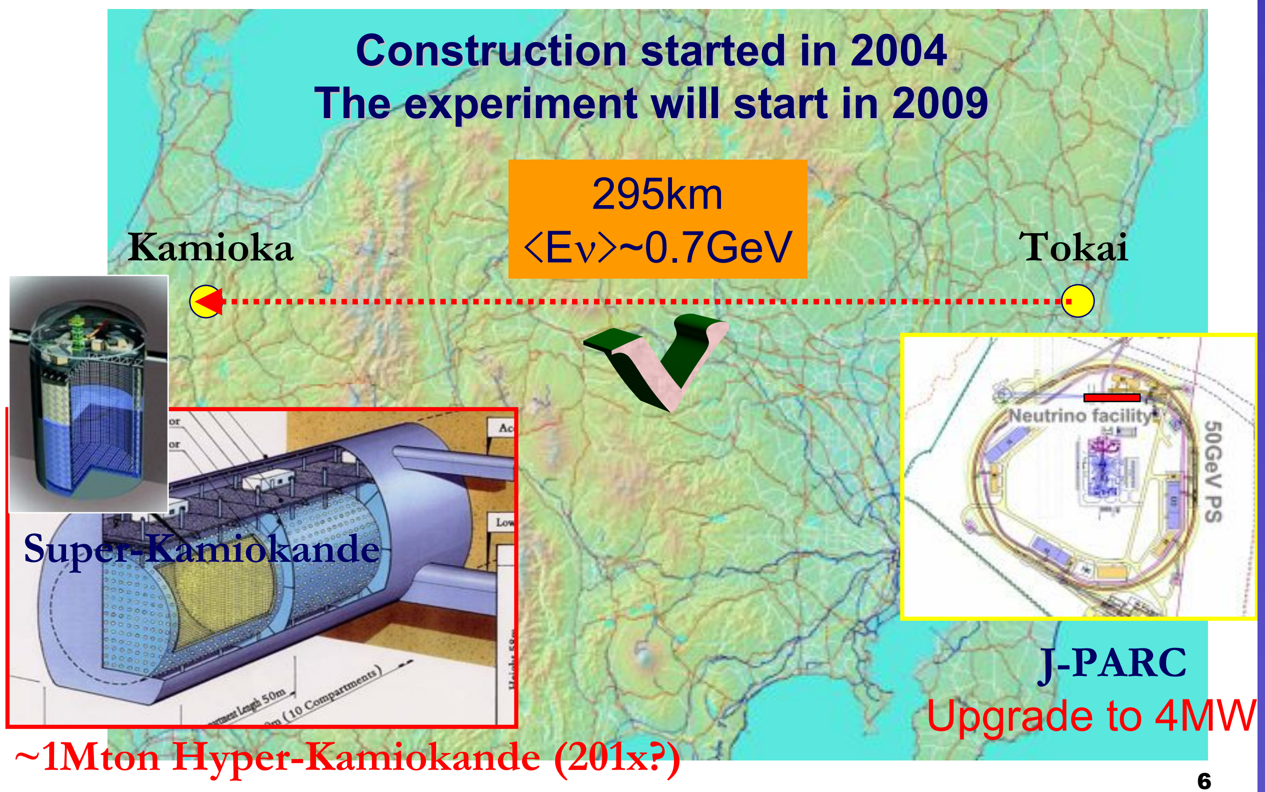
Construction started in 2004
The experiment will start in 2009

Upgrade to 4MW

~1Mton Hyper-Kamiokande (201x?)

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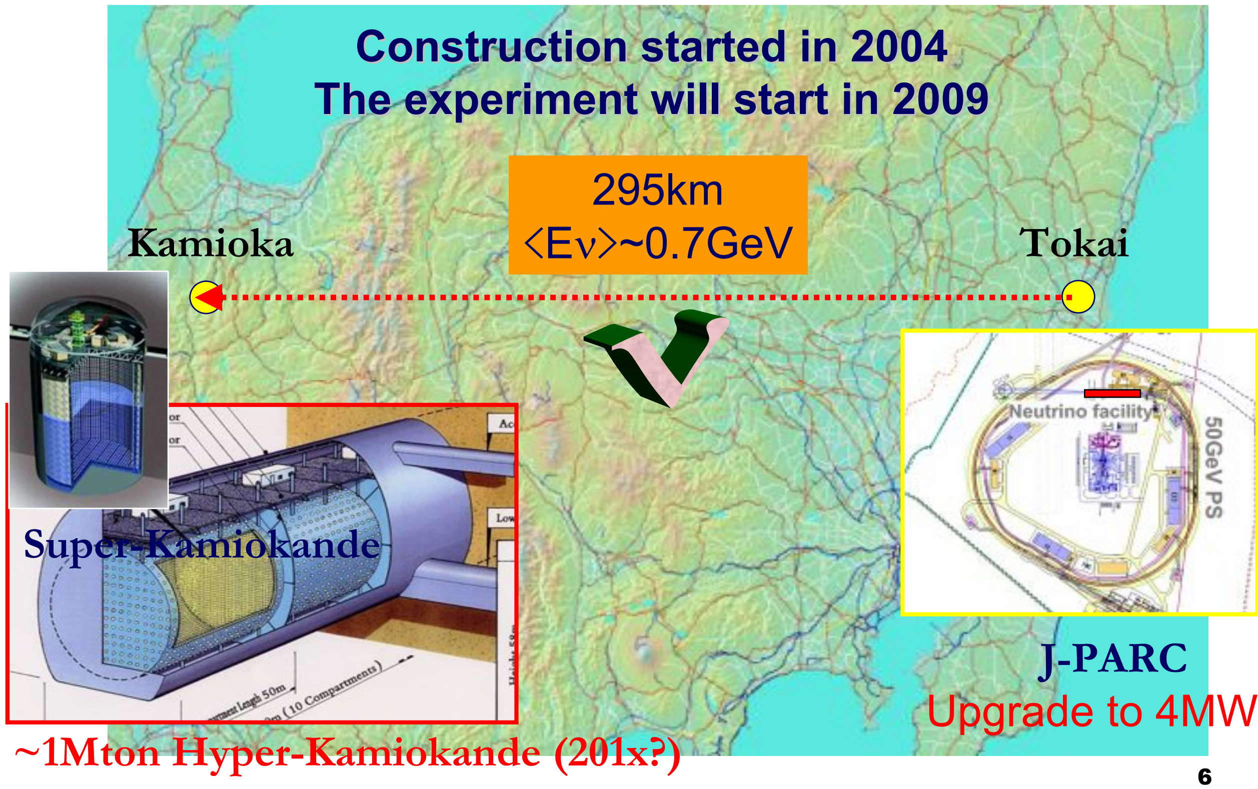

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Hyper-K in Japanese Future Strategy

- **Recommendation by HEP community**
  - http://www.jahep.org/office/doc/201202_hecsubc_report.pdf
  - Recommendations for two large-scale projects
    - Linear Collider
    - **Large-scale Neutrino & Nucleon decay Detector**
- **KEK roadmap draft (Jan. 2013) includes Hyper-K**
  - http://kds.kek.jp/getFile.py/access?sessionId=1&resId=0&materialId=0&confId=11728
- **Cosmic Ray community endorses Hyper-K as a next large-scale project**
- **The master plan for large scale projects in Science Council of Japan**
  - A proposal of large neutrino/nucleon-decay detector will be submitted with Hyper-K. J-PARC neutrino beam operation w ~>1MW and a near detector complex are also packaged.
  - (Ref.) the master plan in 2010, Hyper-K was described in page 20
    - http://www.scj.go.jp/ja/info/kohyo/pdf/kohyo-21-t90-e2.pdf

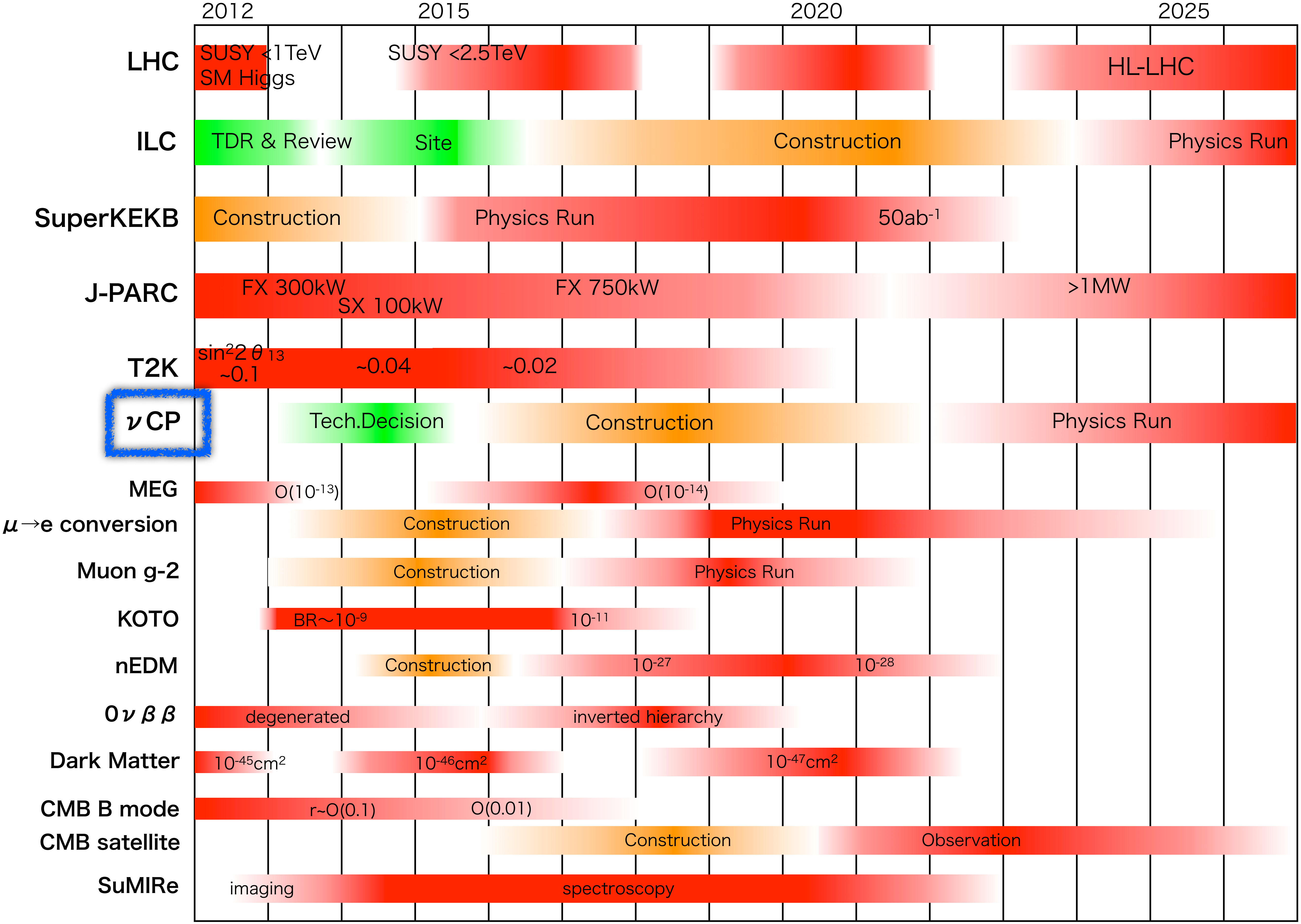
Japan HEP community

Recommendations

The committee makes the following recommendations concerning large-scale projects, which comprise the core of future high energy physics research in Japan.

- **Should a new particle such as a Higgs boson with a mass below approximately 1 TeV be confirmed at LHC, Japan should take the leadership role in an early realization of an e^+e^- linear collider.** In particular, if the particle is light, experiments at low collision energy should be started at the earliest possible time. In parallel, continuous studies on new physics should be pursued for both LHC and the upgraded LHC version. Should the energy scale of new particles/physics be higher, accelerator R&D should be strengthened in order to realize the necessary collision energy.
- **Should the neutrino mixing angle θ_{13} be confirmed as large, Japan should aim to realize a large-scale neutrino detector through international cooperation, accompanied by the necessary reinforcement of accelerator intensity, so allowing studies on CP symmetry through neutrino oscillations.** This new large-scale neutrino detector should have sufficient sensitivity to allow the search for proton decays, which would be direct evidence of Grand Unified Theories.

Timelines of Current/Future Projects



Physics

Nature is kind to neutrinos

- **Established**
  - Neutrino oscillations everywhere
  - Large mixing angles
  - not too small mass difference!

- **Will be established in the near future**
  - majonara mass
  - Inverted mass hierarchy
  - sterile neutrinos (w/ various mass scales)
  - **large CP violation** (w/ PMNS δ_{CP} and maybe from the sterile sectors...)
  - neutrino mass effects in cosmology

Physics Topics in Hyper-K

arXiv:1109.3262 [hep-ex]

- Accelerator Neutrino Beam
- Atmospheric Neutrinos

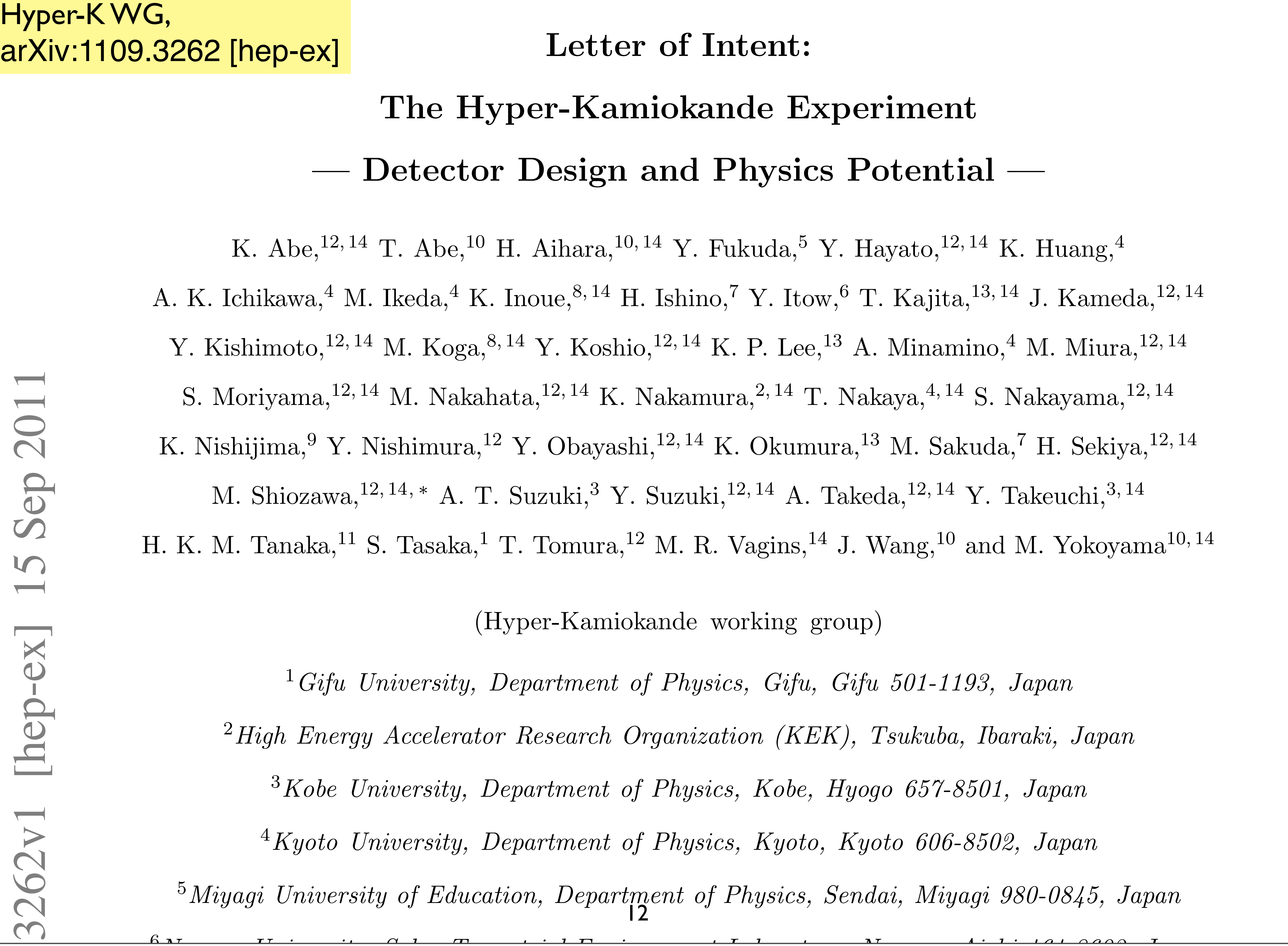
Neutrino Oscillations w/ CPV

- Solar Neutrinos
- Astrophysical Neutrinos
  - Supernova, Dark Matter, Solar flare, etc..
- Neutrino geophysics
- Nucleon Decay

GUT

- NOTE: Although some neutrino sources are free, the capability of the detector to catch free neutrinos are NOT free.

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



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

K. Abe,[12,14] T. Abe,[10] H. Aihara,[10,14] Y. Fukuda,[5] Y. Hayato,[12,14] K. Huang,[4] A. K. Ichikawa,[4] M. Ikeda,[4] K. Inoue,[8,14] H. Ishino,[7] Y. Itow,[6] T. Kajita,[13,14] J. Kameda,[12,14] Y. Kishimoto,[12,14] M. Koga,[8,14] Y. Koshio,[12,14] K. P. Lee,[13] A. Minamino,[4] M. Miura,[12,14] S. Moriyama,[12,14] M. Nakahata,[12,14] K. Nakamura,[2,14] T. Nakaya,[4,14] S. Nakayama,[12,14] K. Nishijima,[9] Y. Nishimura,[12] Y. Obayashi,[12,14] K. Okumura,[13] M. Sakuda,[7] H. Sekiya,[12,14] M. Shiozawa,[12,14,*] A. T. Suzuki,[3] Y. Suzuki,[12,14] A. Takeda,[12,14] Y. Takeuchi,[3,14] H. K. M. Tanaka,[11] S. Tasaka,[1] T. Tomura,[12] M. R. Vagins,[14] J. Wang,[10] and M. Yokoyama[10,14]

(Hyper-Kamiokande working group)

[1]*Gifu University, Department of Physics, Gifu, Gifu 501-1193, Japan*

[2]*High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, Japan*

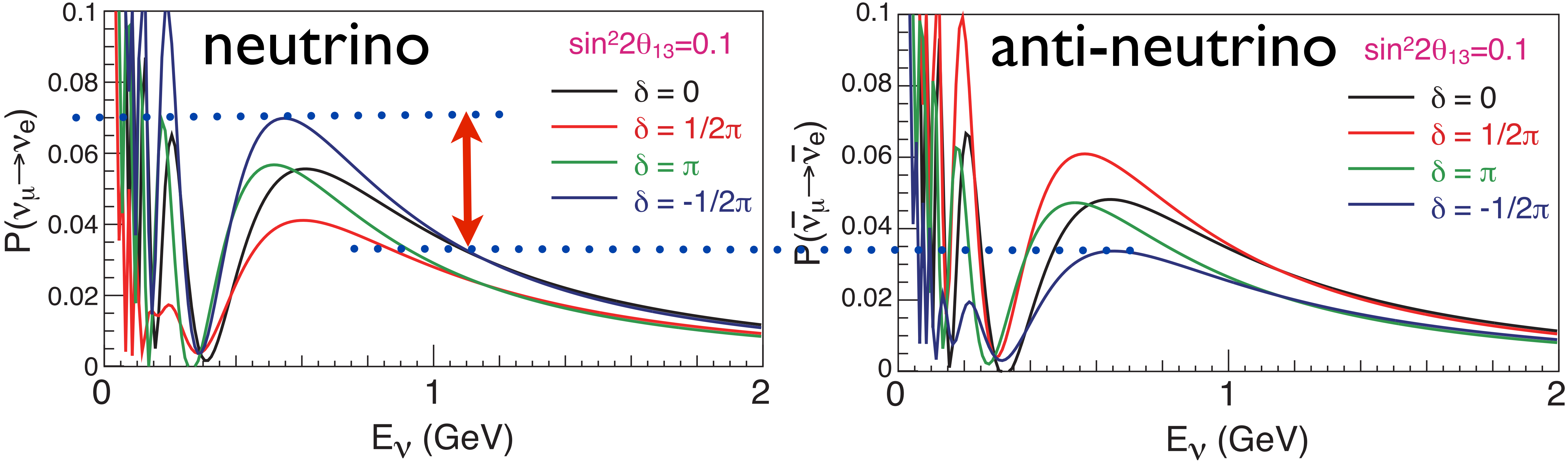
[3]*Kobe University, Department of Physics, Kobe, Hyogo 657-8501, Japan*

[4]*Kyoto University, Department of Physics, Kyoto, Kyoto 606-8502, Japan*

[5]*Miyagi University of Education, Department of Physics, Sendai, Miyagi 980-0845, Japan*

Measuring CP asymmetry w/ J-PARC ν beam

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



- Comparison between $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  - as large as ~25% from nominal.
  - also sensitive to exotic (non-MNS) CPV

Rich Physics in 3 generation mixings

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = \; & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31}
\end{aligned}
$$

Leading

CP violating (flips sign for $\bar{\nu}$)

$$
\begin{aligned}
& +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \boxed{\sin\delta} \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& +4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21}
\end{aligned}
$$

Solar

$$
\begin{aligned}
& -8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31}
\end{aligned}
$$

Matter effect

$$
\begin{aligned}
& +8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2} (1 - 2S_{13}^2) \sin^2 \Delta_{31}
\end{aligned}
$$

Leading

$$\boxed{\sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)}$$

CPV

$$\frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\boxed{\sin^2 2\theta_{13}\sin^2\frac{\Delta m_{31}^2 L}{4E}}\sin\frac{\Delta m_{21}^2 L}{4E}\sin\delta$$

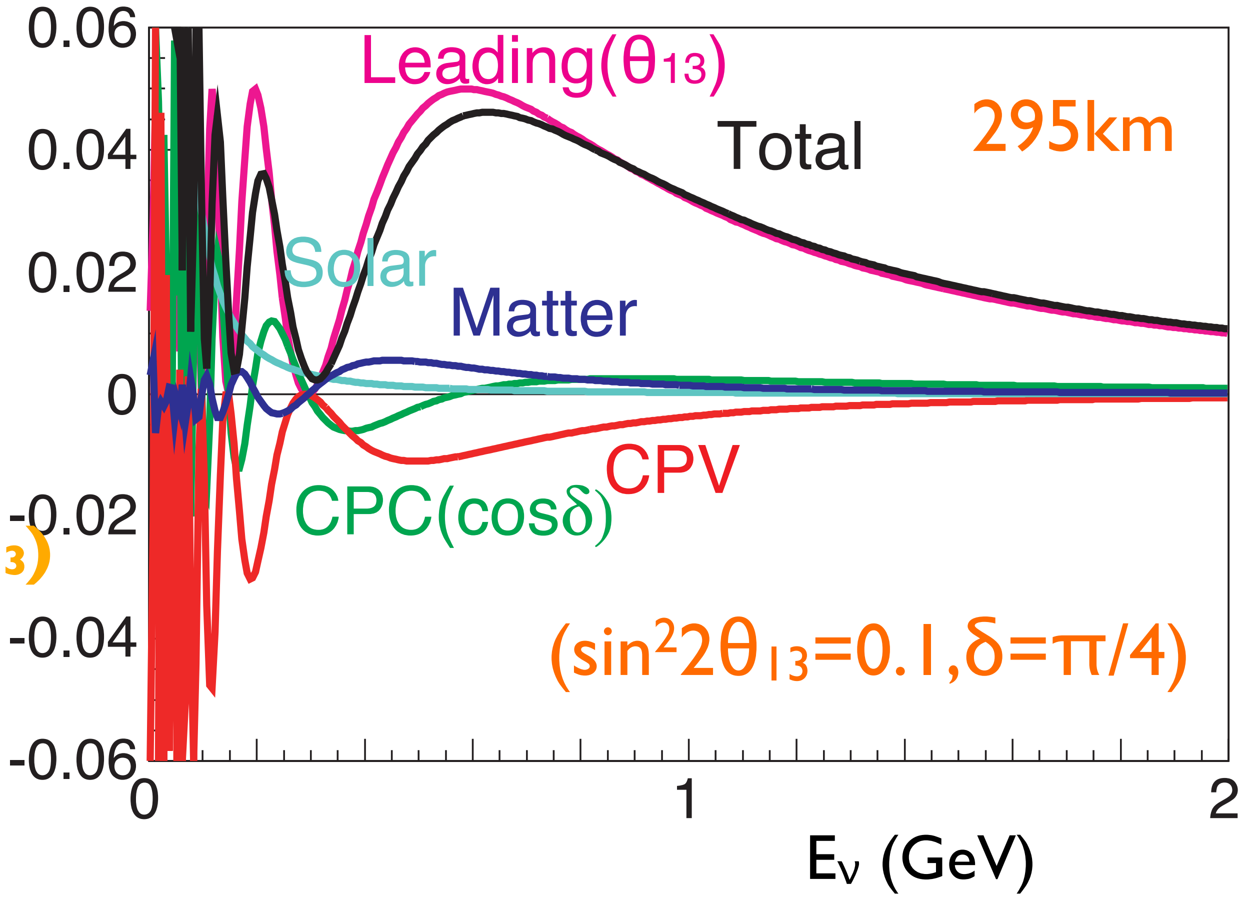
~0.03

~11.8 (6.4 from 1/sinθ$_{13}$)

$$\sim\frac{\pi}{4}\boxed{\frac{\Delta m_{21}^2}{\Delta m_{32}^2}}\boxed{\frac{\sin 2\theta_{12}\sin 2\theta_{23}}{\sin^2\theta_{23}\sin\theta_{13}}}\frac{E_{1st\max}}{E}\left[leading\right]\sin\delta$$

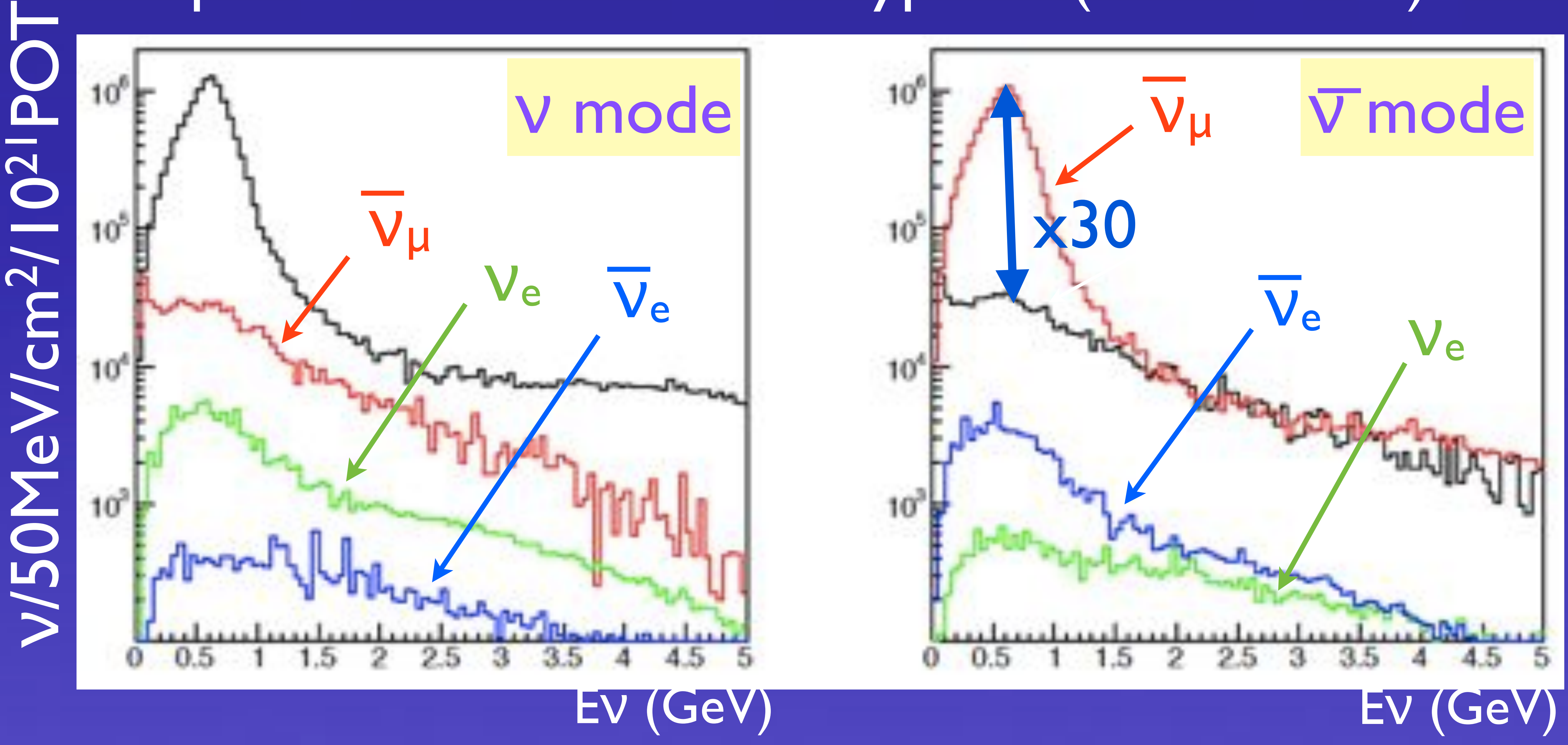
$$\underline{\sim 0.27\times\left[leading\right]}\times\frac{E_{1st\max}}{E}\times\sin\delta$$

27%



The ν beam

Expected neutrino flux at Hyper-K (unoscillated)



2.5° off-axis beam from J-APRC
Peaked at oscillation maximum
Suppress BG from high energy component (ν_τ negligible)

CP measurement with J-PARC ν and Hyper-K

- Strength of water Cherenkov detector
  - LARGE mass – statistics is always critical
  - Excellent reconstruction/PID performance especially in sub-GeV region (quasi-elastic→single ring)
- Best matched with low energy, narrow band beam
  - Off-axis beam with relatively short baseline
    - Less matter effect
    - Complementary to other > ~1000km baseline experiments planned w/ Lq. Ar

(natural extension of technique proved by T2K)

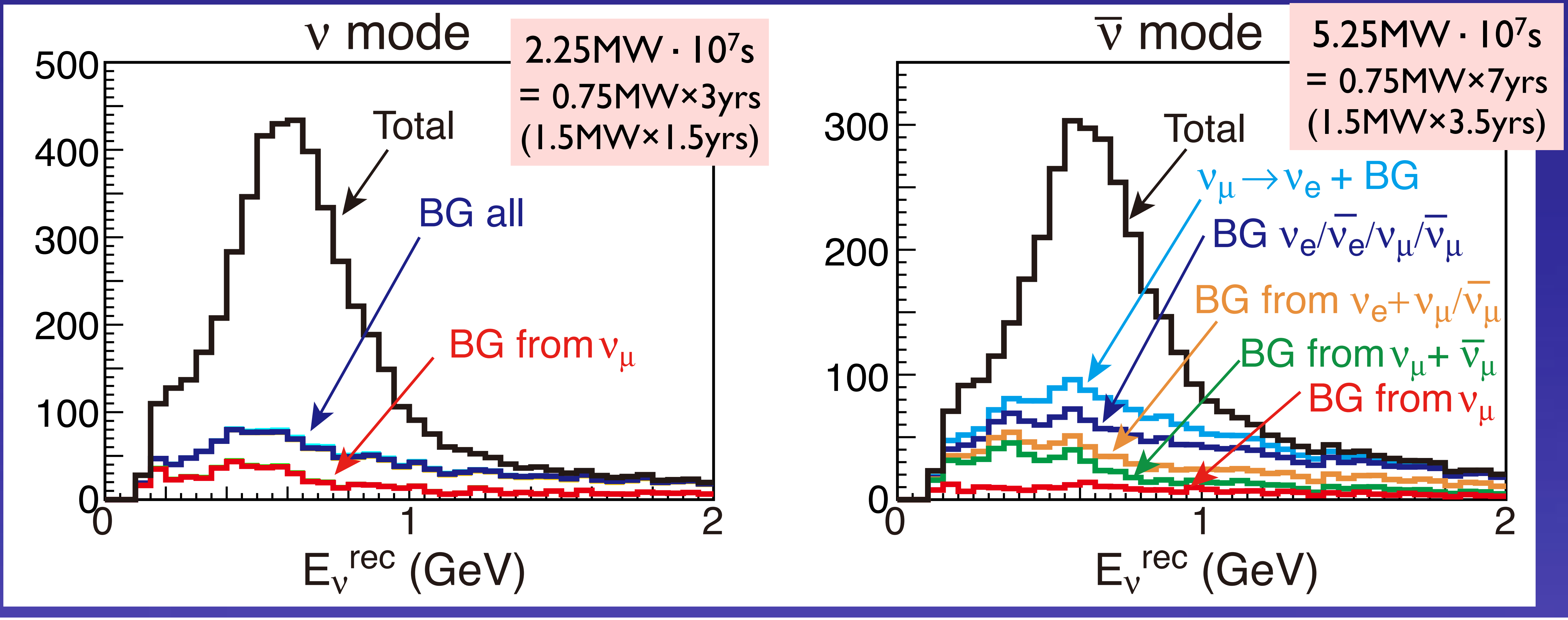
Full MC study

- 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 7.5MW・year beam exposure
  - We expect beam power upgrades beyond 750kW.
  - $\nu : \overline{\nu} = 3 : 7$

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

ν_e candidate events after selection

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



2.25MW · 10^7s
= 0.75MW×3yrs
(1.5MW×1.5yrs)

5.25MW · 10^7s
= 0.75MW×7yrs
(1.5MW×3.5yrs)

	Signal ($\nu_\mu \rightarrow \nu_e$ CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	beam $\nu_e/\bar{\nu}_e$ contamination	NC
ν (2.25MW · 10^7s)	3,560	46	35	880	649
$\bar{\nu}$ (5.25MW · 10^7s)	1,959	380	23	878	678

2000-4000 signal events expected for each of ν and $\bar{\nu}$

LARGE θ_{13} => good for Hyper-K

- High Signal ($\nu_\mu \rightarrow \nu_e$) and Low Background ($\pi^0$, beam ν_e, etc..)
  - Systematic error is more reliable (under control) for the ν_e signal than BG (example, π^0)
  - Assuming 5% sys. error for both ν_e signal and background (beam ν_e and NC π^0 dominant).

δ	**0**	**$\pi/6$**	**$\pi/3$**	**$\pi/2$**	**π**	**1.5π**
N(signal ν_e)	**3458**	**3059**	**2719**	**2597**	**3372**	**4233**
N/N(δ=0)± Stat	1.0±0.020	0.885±0.021	0.786±0.023	0.751±0.024	0.975±0.020	1.224±0.017
Sys (Sig)	0.038	0.037	0.035	0.035	0.037	0.039
Sys (BG)	0.012	0.013	0.015	0.015	0.013	0.011
N(signal $\bar{\nu}_e$)	**1900**	**2145**	**2335**	**2382**	**1830**	**1346**
N/N(δ=0)± Stat	1.0±0.030	1.13±0.028	1.23±0.026	1.25±0.026	0.96±0.031	0.71±0.040
Sys (Sig)	0.033	0.034	0.035	0.035	0.033	0.030
Sys (BG)	0.017	0.016	0.015	0.015	0.017	0.020

(*) Stat and Sys are the errors considering both signal and BG events.

- >10% larger variation relative to the expected number of events with δ=0 is expected for δ between $\pi/6$ and $5\pi/6$ ($7\pi/6$ and $11\pi/6$) which corresponds to ~70% region of δ.

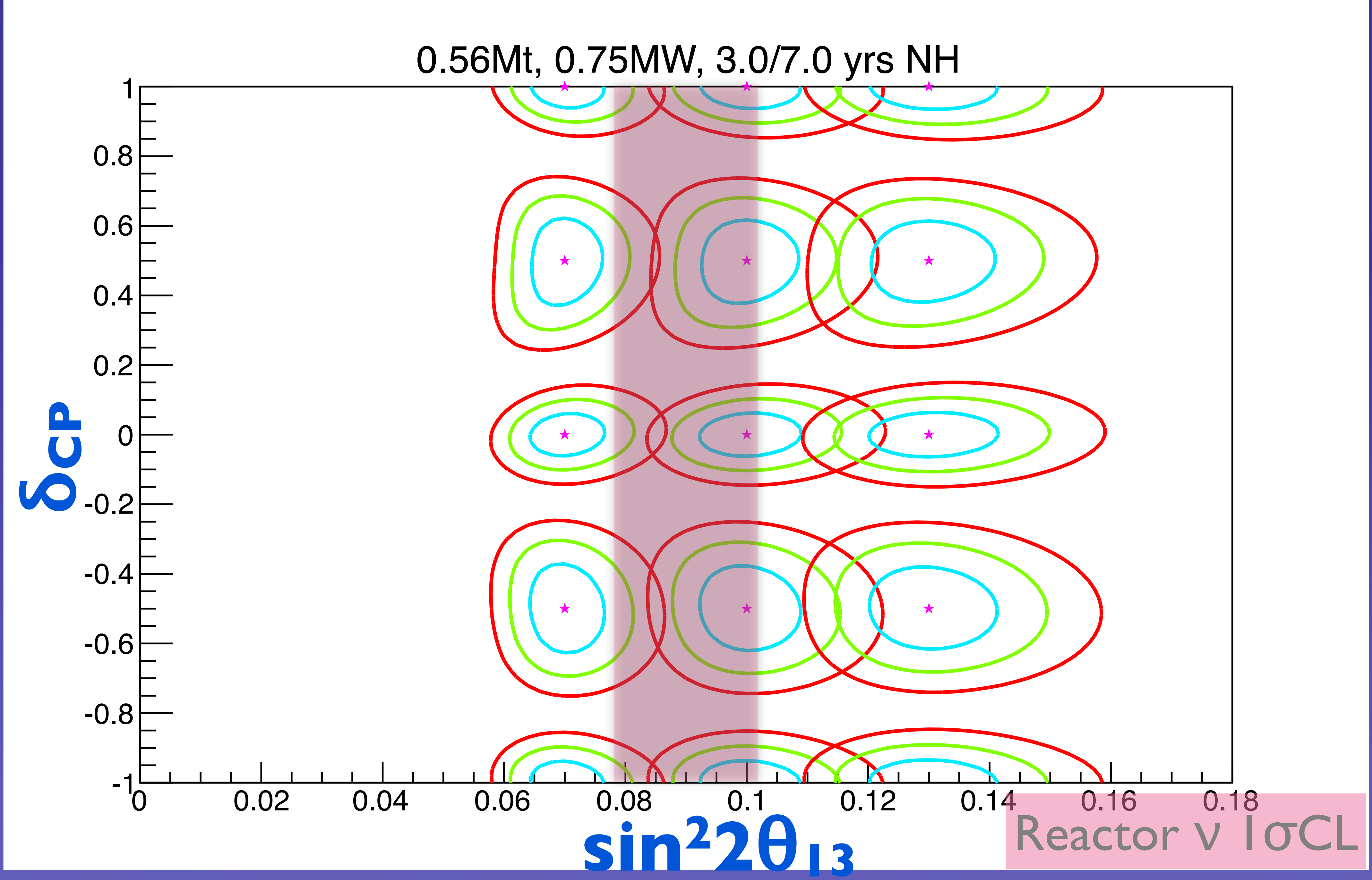
7.5MW・years

Contours

Normal mass hierarchy (known)

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

$\sin^2 2\theta_{23}=1$

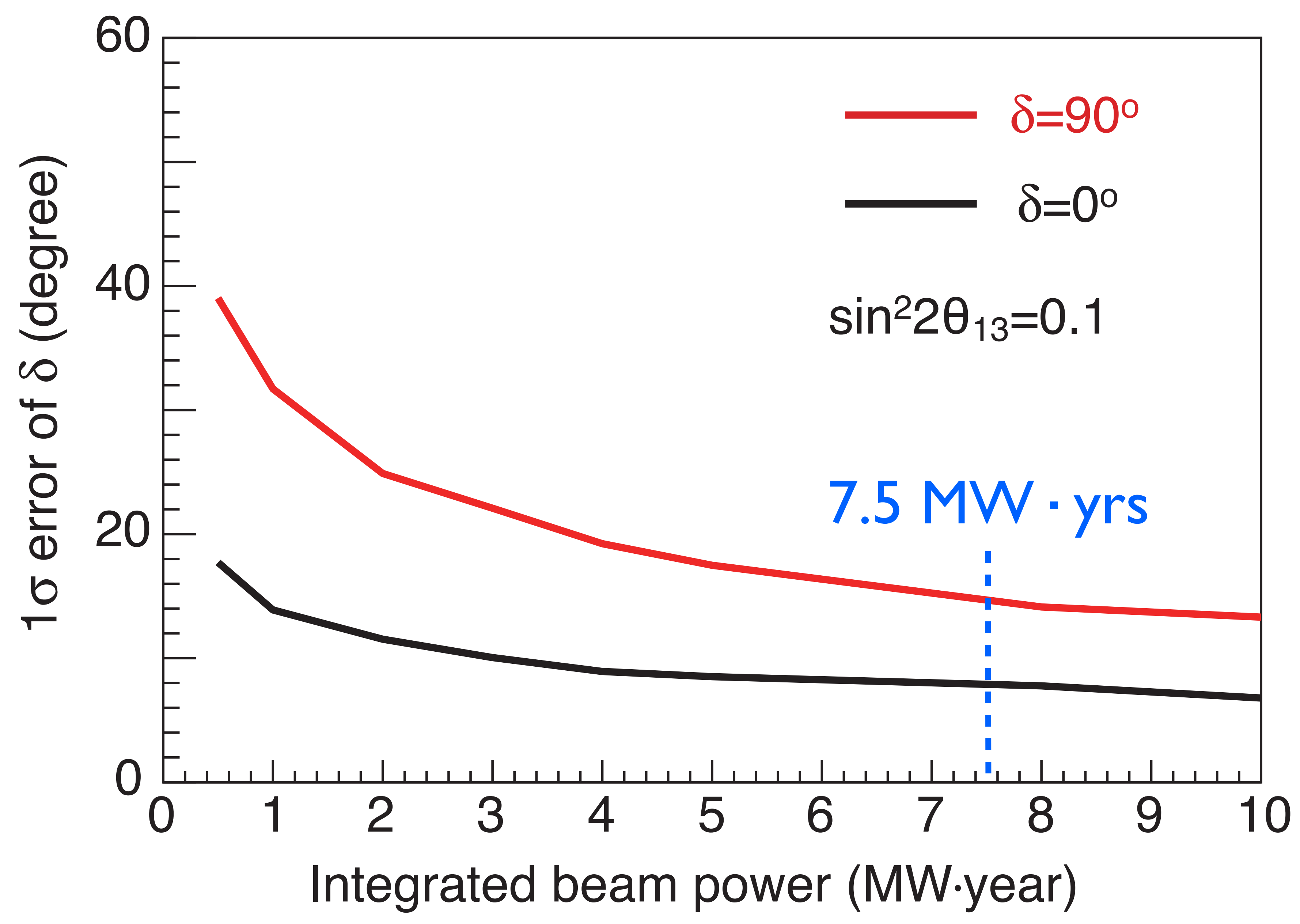


- Good sensitivity for CPV
- modest dependence on θ_{13} value

δ resolution

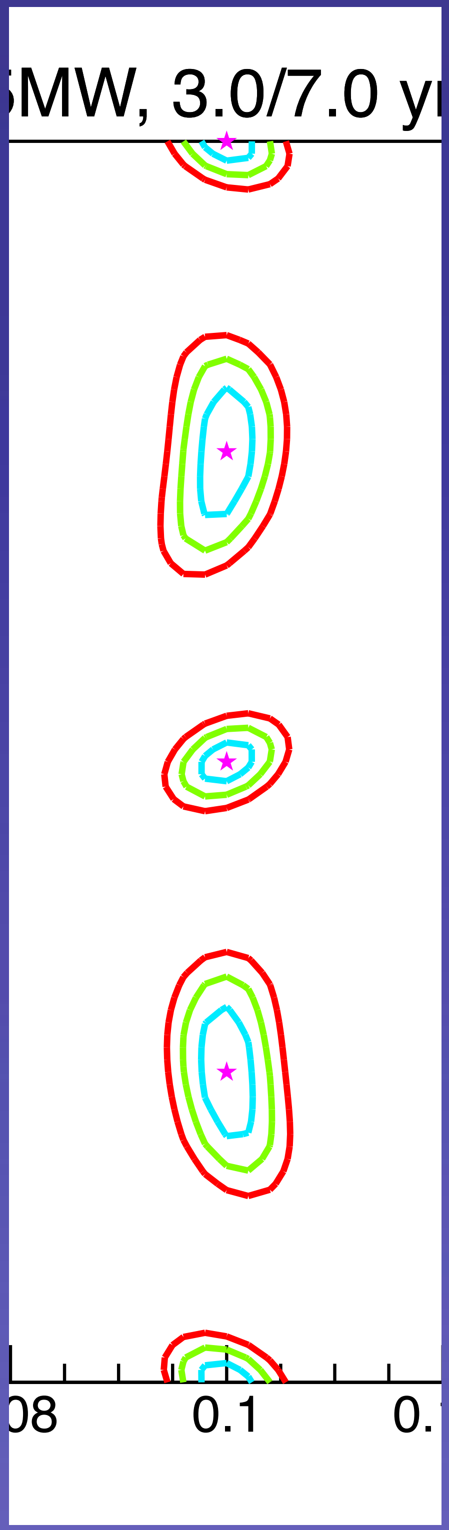
Normal mass hierarchy (known)

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

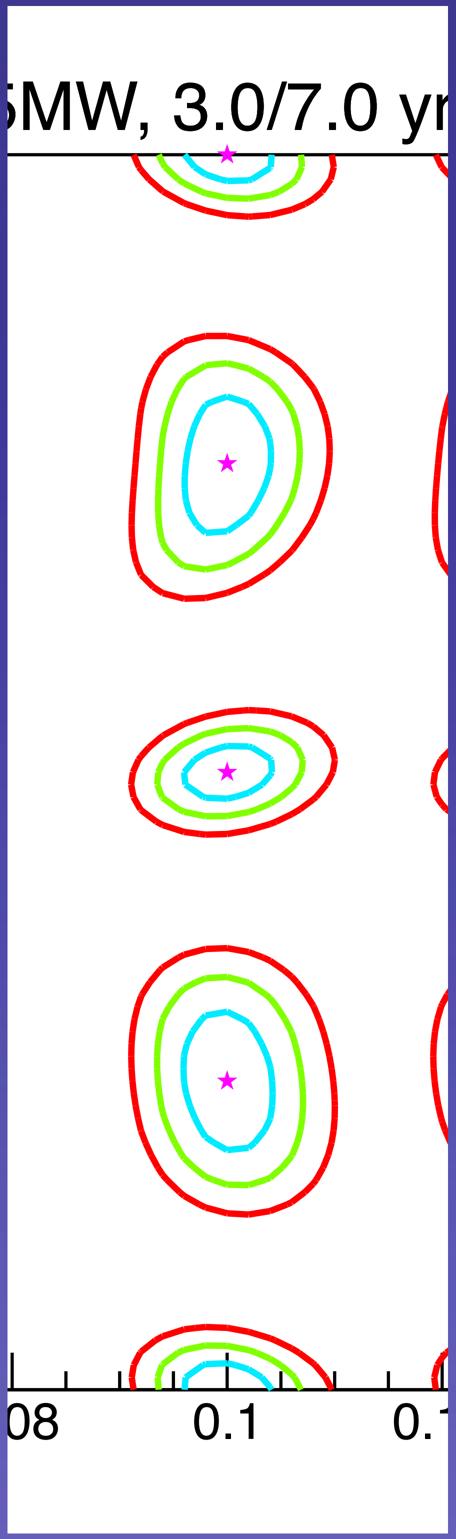


- δ precision < 20° (δ=90°)
  < 10° (δ= 0°)
- modest dependence on θ_{13}

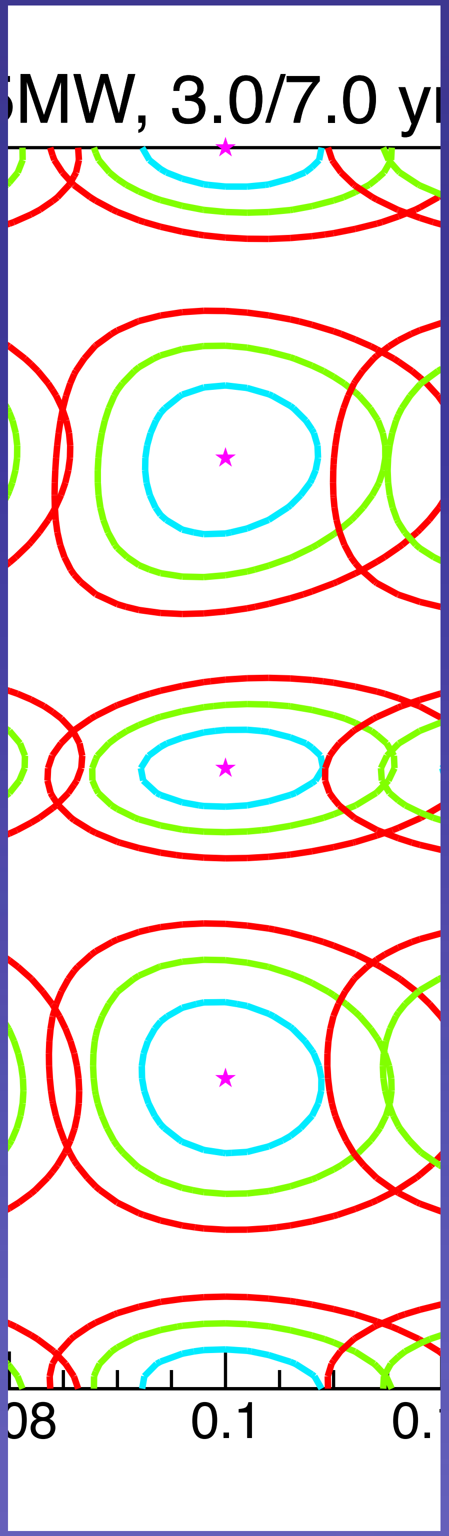
Effect of systematic errors



0%

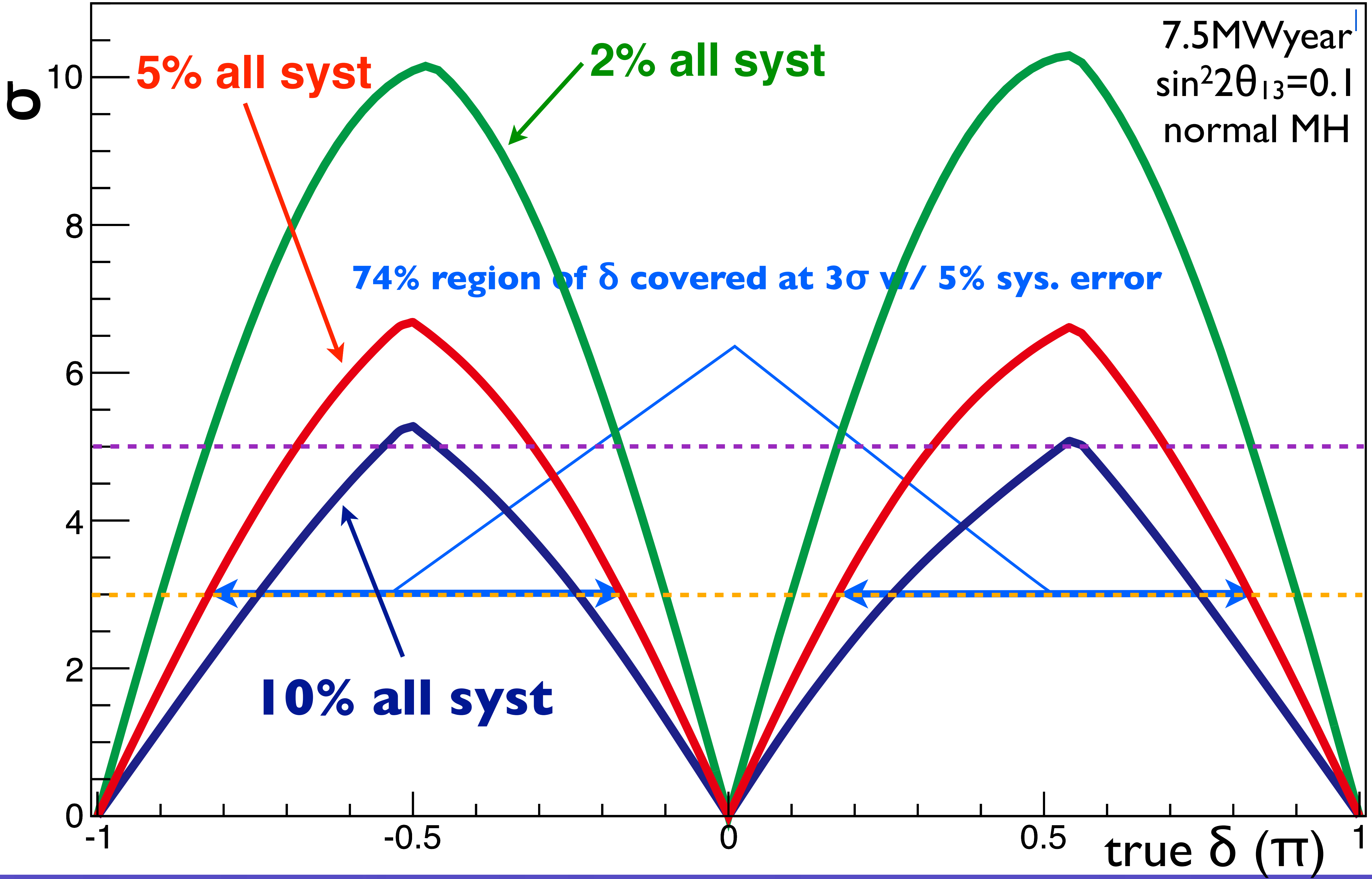


2%



5%

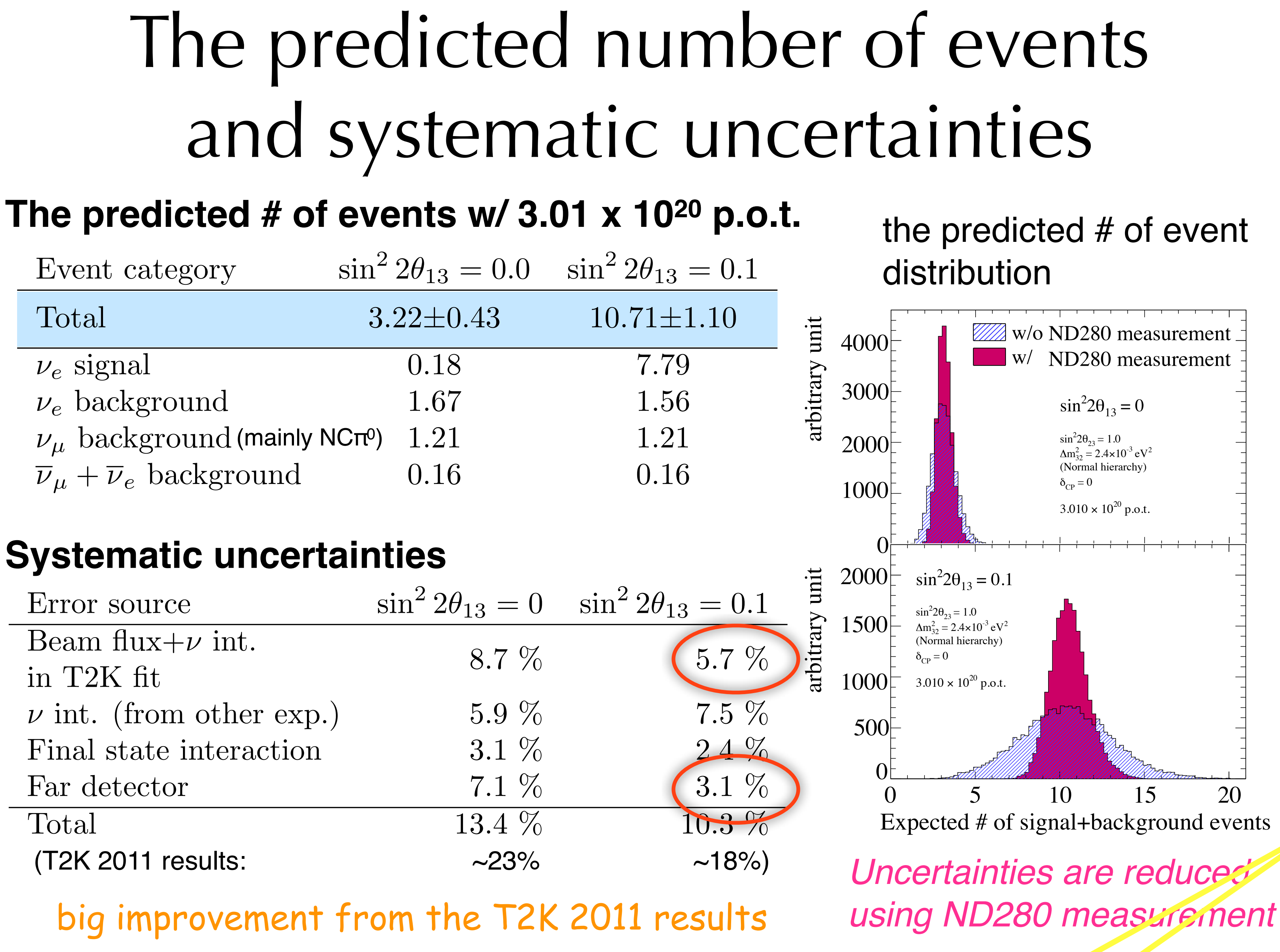
CPV Discovery Sensitivity (w/ Mass Hierarchy known)



High Sensitivity to CPV w/ <~5% sys. error

K. Sakashita@ICHEP2012

T2K Experience



The predicted number of events and systematic uncertainties

The predicted # of events w/ 3.01 x 10^{20} p.o.t.

Event category	$\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
Total	3.22±0.43	10.71±1.10
ν_e signal	0.18	7.79
ν_e background	1.67	1.56
ν_μ background (mainly NCπ⁰)	1.21	1.21
$\overline{\nu}_\mu + \overline{\nu}_e$ background	0.16	0.16

Systematic uncertainties

Error source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
Beam flux+ν int. in T2K fit	8.7 %	5.7 %
ν int. (from other exp.)	5.9 %	7.5 %
Final state interaction	3.1 %	2.4 %
Far detector	7.1 %	3.1 %
Total	13.4 %	10.3 %
(T2K 2011 results:	~23%	~18%)

big improvement from the T2K 2011 results

the predicted # of event distribution

Uncertainties are reduced using ND280 measurement

10

- **Total Sys. error for $\sin^2 2\theta_{13}$=0.1: ~10%**
  - Beam flux + ν int. constraint in T2K: 5.7%
  - External ν cross section uncertainty from other experiment: 7.5%
  - Super-K detector uncertainty: 3.1%

T2K flux extrapolation and the detector uncertainties almost reach the Hyper-K requirement.

Upcoming Cross section measurements in T2K-ND280 and the cross section model improvements are critical.

Atmospheric Neutrino Oscillations at Hyper-Kamiokande

Covered by C.Walter

Roger Wendell, ICRR
2012.08.22
Hyper-K Open Meeting, Kashiwa

3-flavor oscillations in atmospheric ν

NuclPhysB669,255(2003)

NuclPhysB680,479(2004)

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

Solar term

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

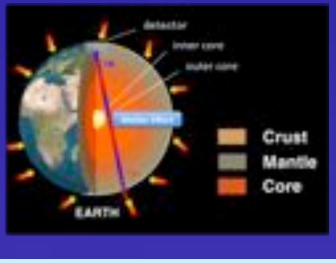
Interference term (δCP)

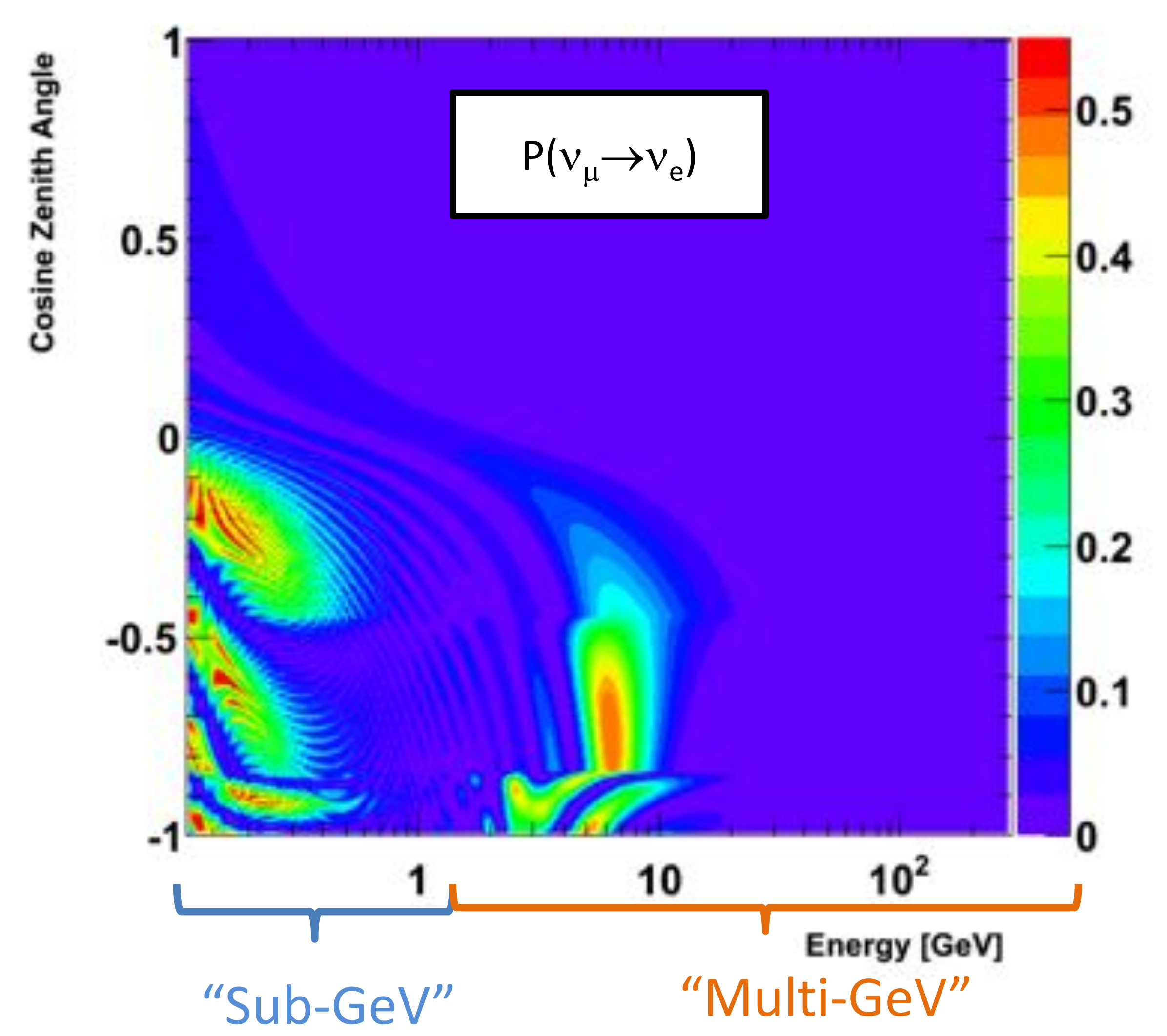
$$+2\sin^2\tilde{\theta}_{13}(r \cdot \sin^2\theta_{23} - 1) \quad (3)$$

θ_{13} resonance term

$\mathbf{r}$: μ/e flux ratio (~2 at low energy)

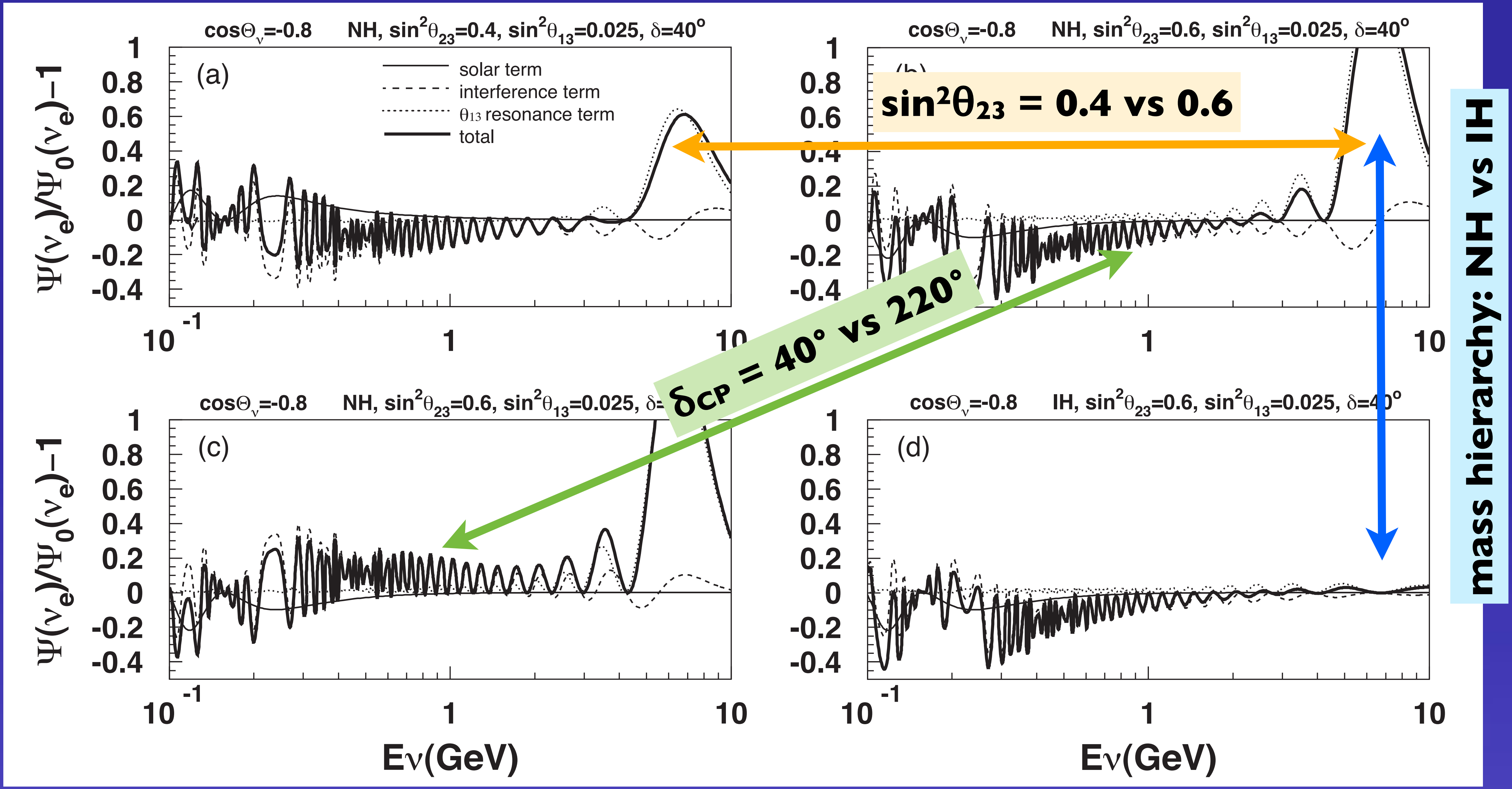
$P_2 = |A_{e\mu}|^2$: 2ν transition probability $\nu_e \rightarrow \nu_{\mu\tau}$ in matter
$R_2 = \mathrm{Re}(A^*_{ee}A_{e\mu})$
$I_2 = \mathrm{Im}(A^*_{ee}A_{e\mu})$
A_{ee} : survival amplitude of the 2ν system
$A_{e\mu}$: transition amplitude of the 2ν system





ν_e appearance (and ν_μ distortion) is expected due to MSW effect in the Earth's matter
- 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.



$\sin^2\theta_{23}$ = 0.4 vs 0.6

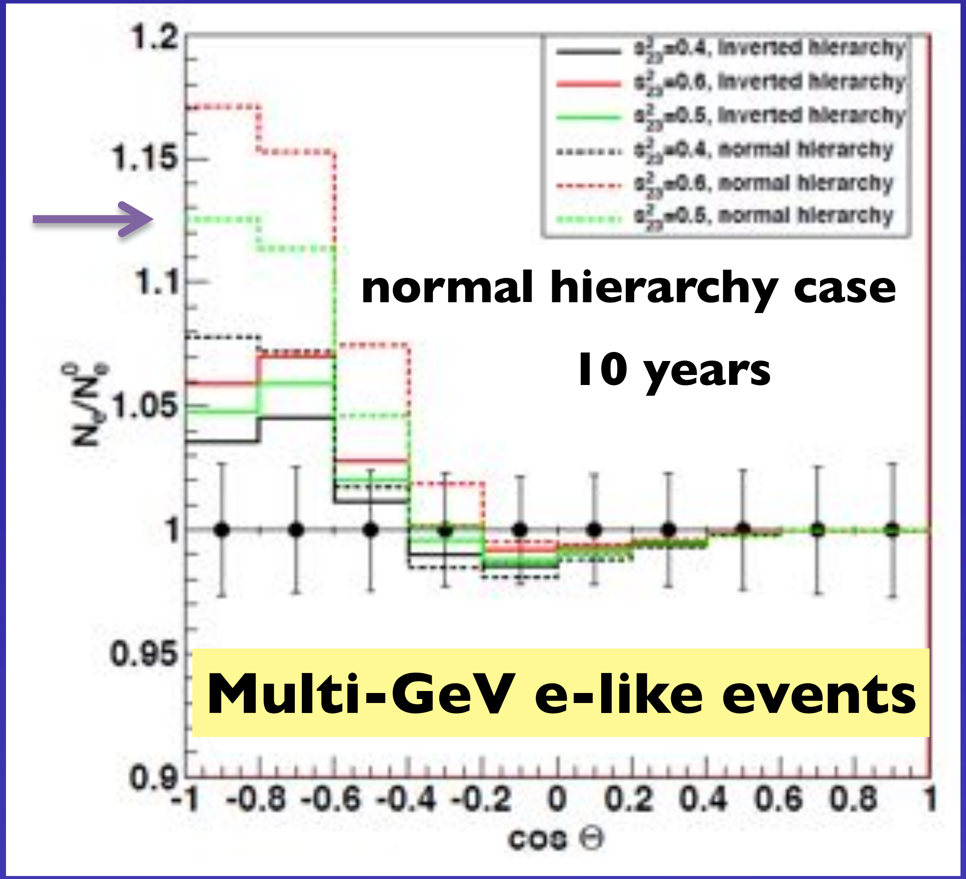
δ_{CP} = 40° vs 220°

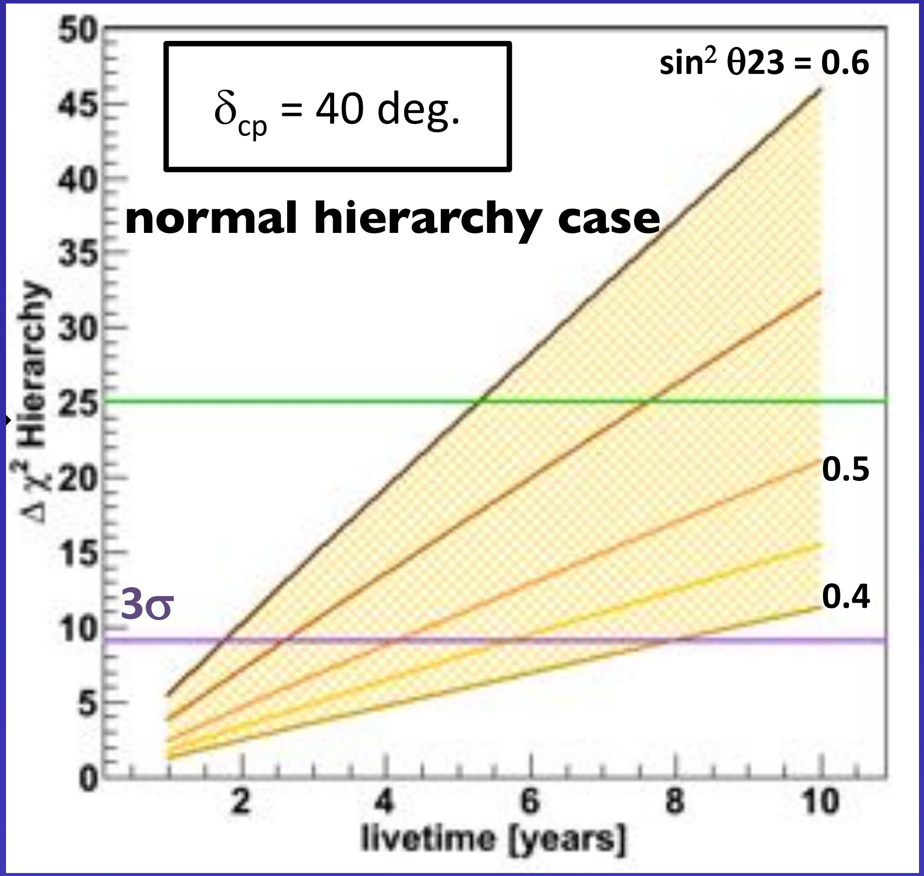
mass hierarchy: NH vs IH

- Through matter effect (MSW), we study
  - Mass hierarchy ⟹ Asymmetry between neutrinos and antineutrinos.
  - Octant of θ_{23} ⟹ Magnitude of resonance effect

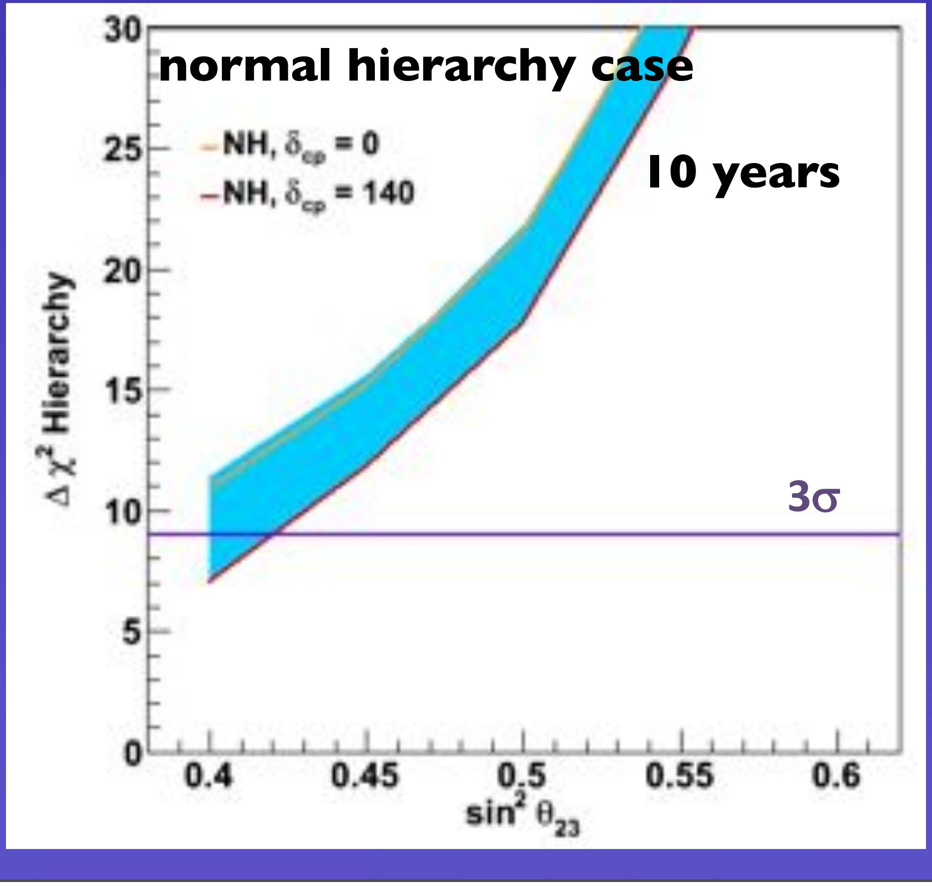
    Appearance (and $\nu_\mu \rightarrow \nu_\mu$ disappearance) interplay
  - δ_{CP} (and θ_{13}) ⟹ Interference effects in ~GeV energy region

Mass Hierarchy Sensitivity





- Sensitivity depends on θ_{23}, δ and mass hierarch (a little).
- 3σ mass hierarchy determination for $\sin^2\theta_{23}>0.42$ (0.43) in the case of normal (inverted) hierarchy.

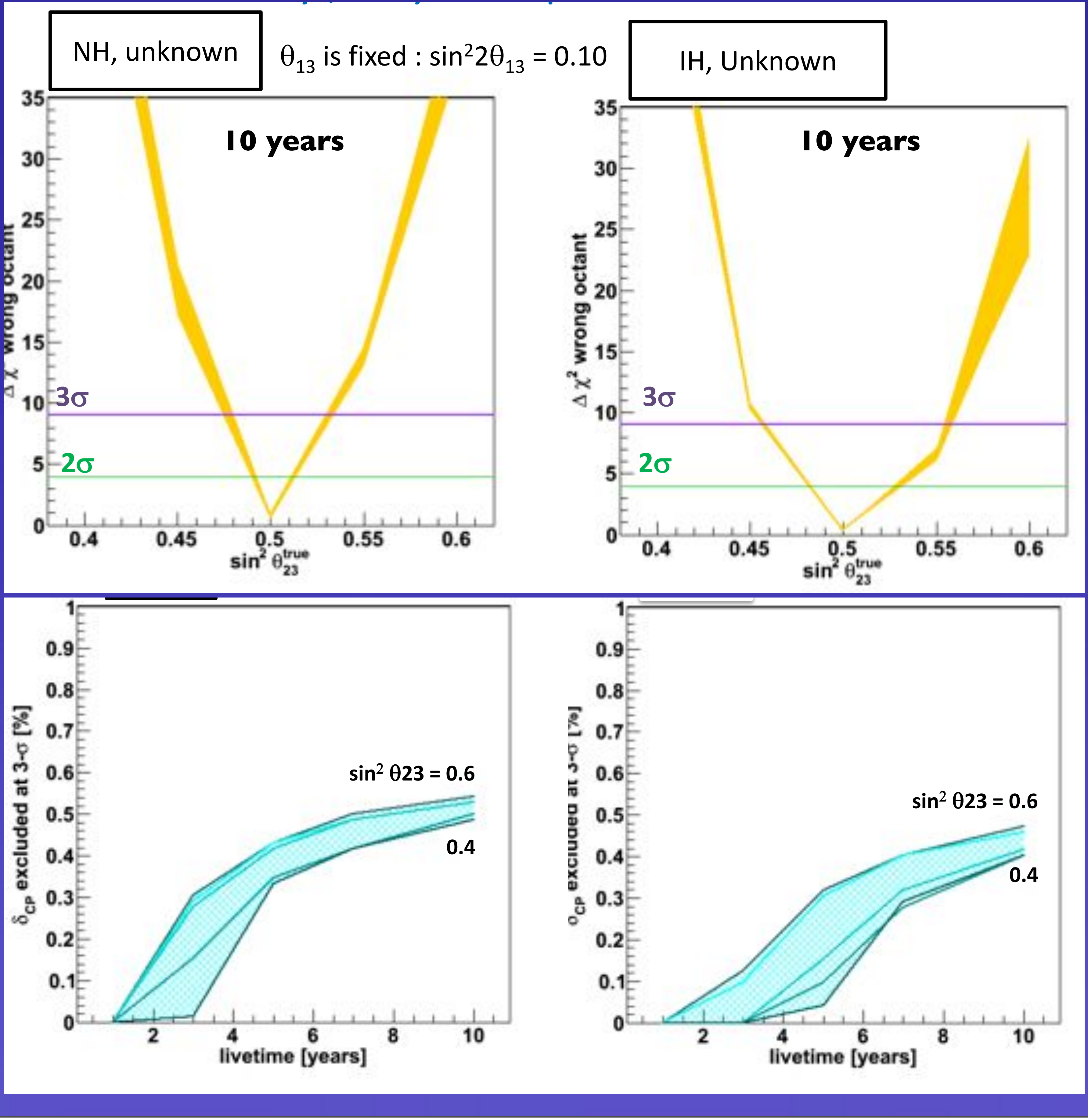


Sensitivity for θ_{23} octant and CPV

θ_{23} octant sensitivity

- (band depends on δ)

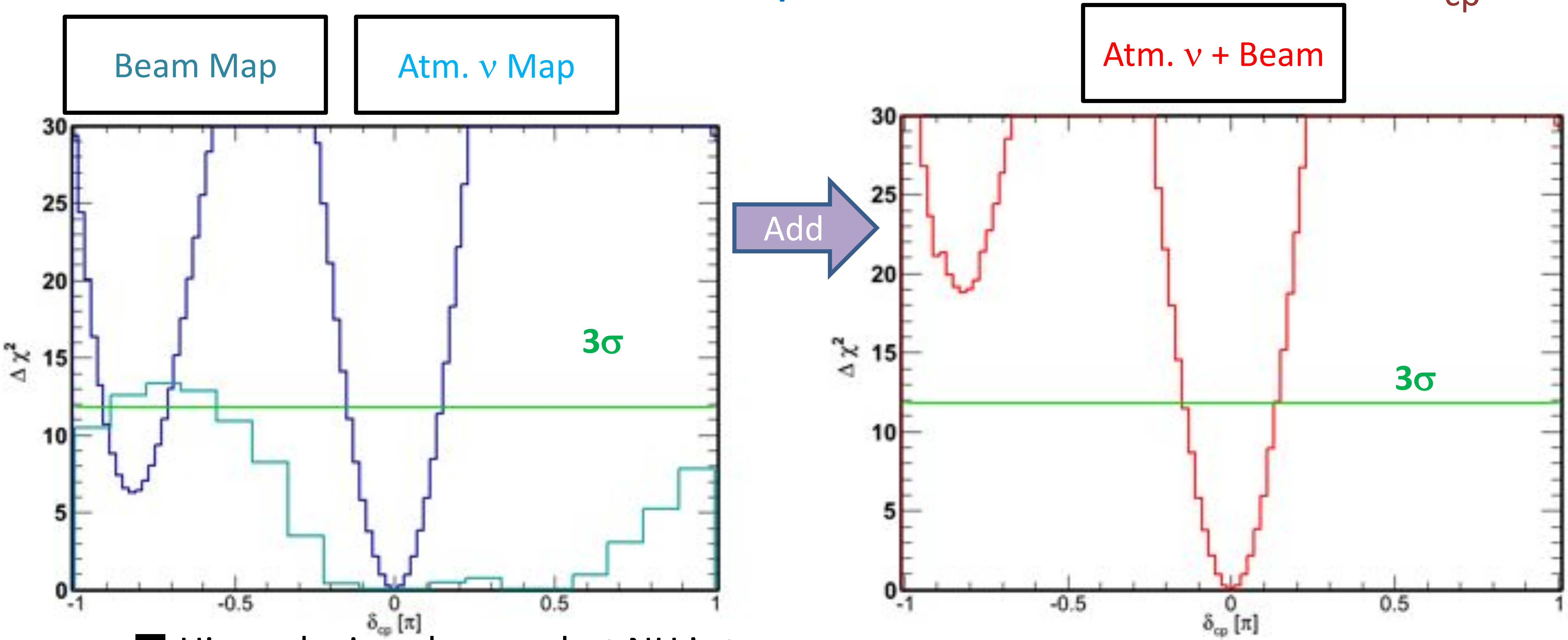
Fraction of δ_{CP} excluded (3 σ)



Combination of Beam and Atmospheric Neutrinos

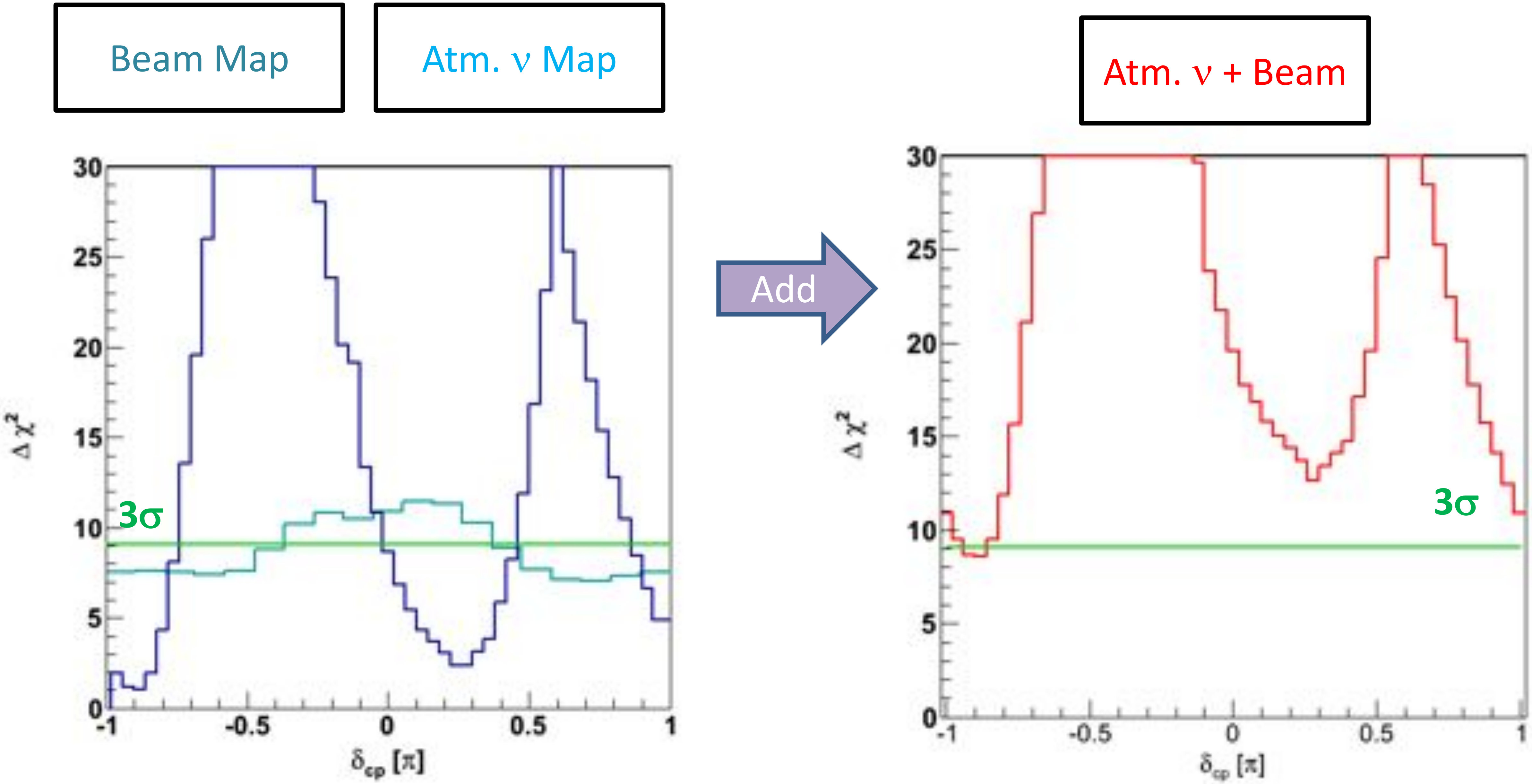
Resolve mass hierarchy and the regeneracy w/ >3σ!

Combination of Beam and Atmospheric Neutrinos : Allowed δ_{cp}



- ☐ Hierarchy is unknown, but NH is true
- ☐ True $\delta_{cp} = 0.0$
- ☐ True $\sin^2 2\theta_{13} = 0.10$
- ☐ Maximal mixing , $\sin^2 2\theta_{23} = 1.0$
- ☐ Degenerate solution exists at 3σ in the beam only case - just add the χ^2 maps
- ☐ In the real world, something more sophisticated is in order

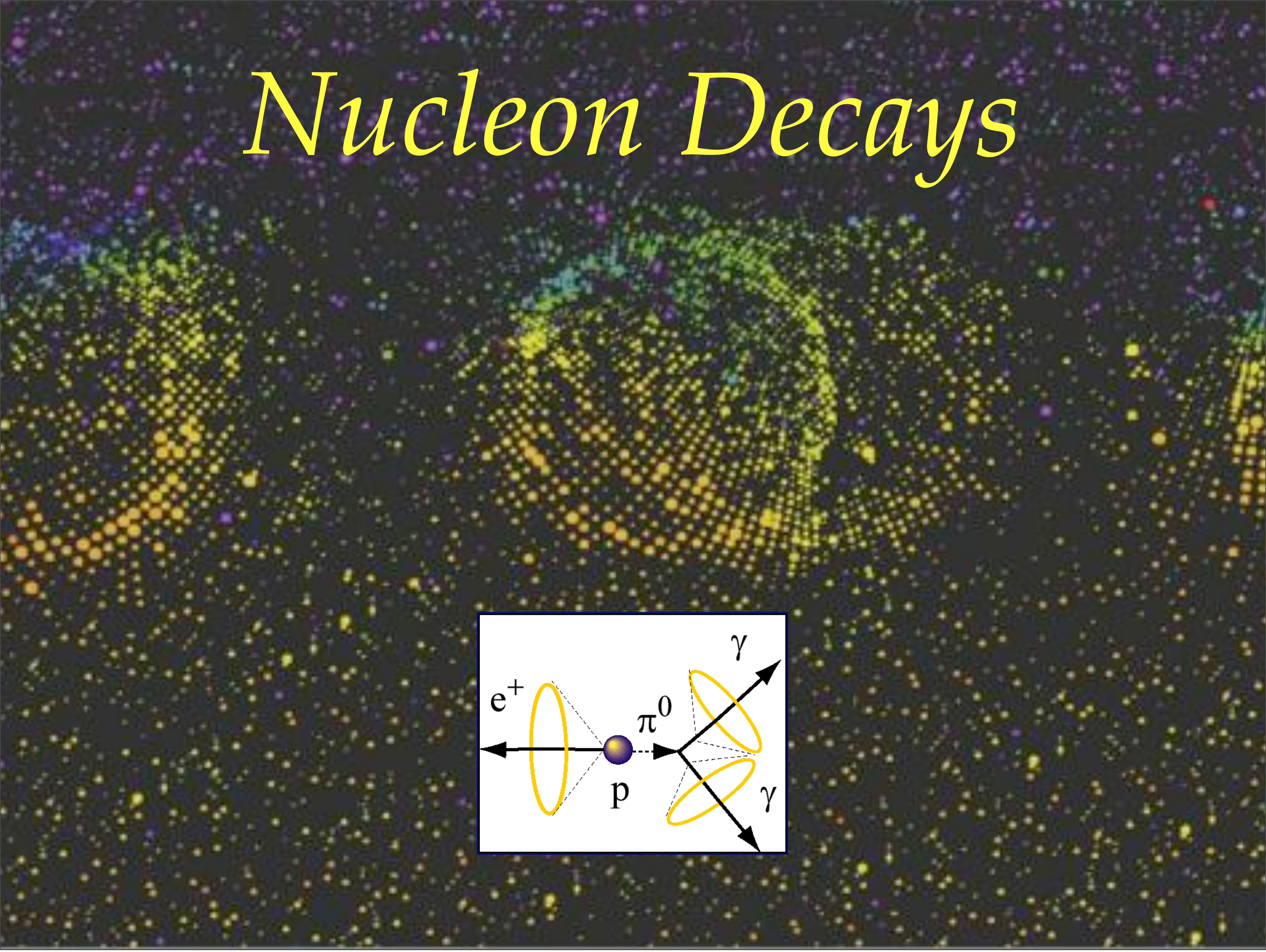
Hierarchy sensitivity : Combination of Beam and Atm. Neutrinos



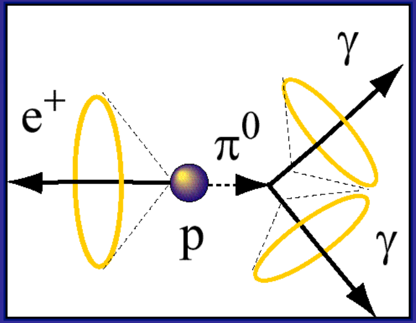
- ☐ Hierarchy is unknown, but the NH is true
- ☐ True $\sin^2 2\theta_{13} = 0.10$
- ☐ Using $\sin^2\theta_{23} = 0.4$
- ☐ Even under a conservative assumption its possible to achiev ~3σ discrimination or all values of δ_{cp} if the true hierarchy is normal

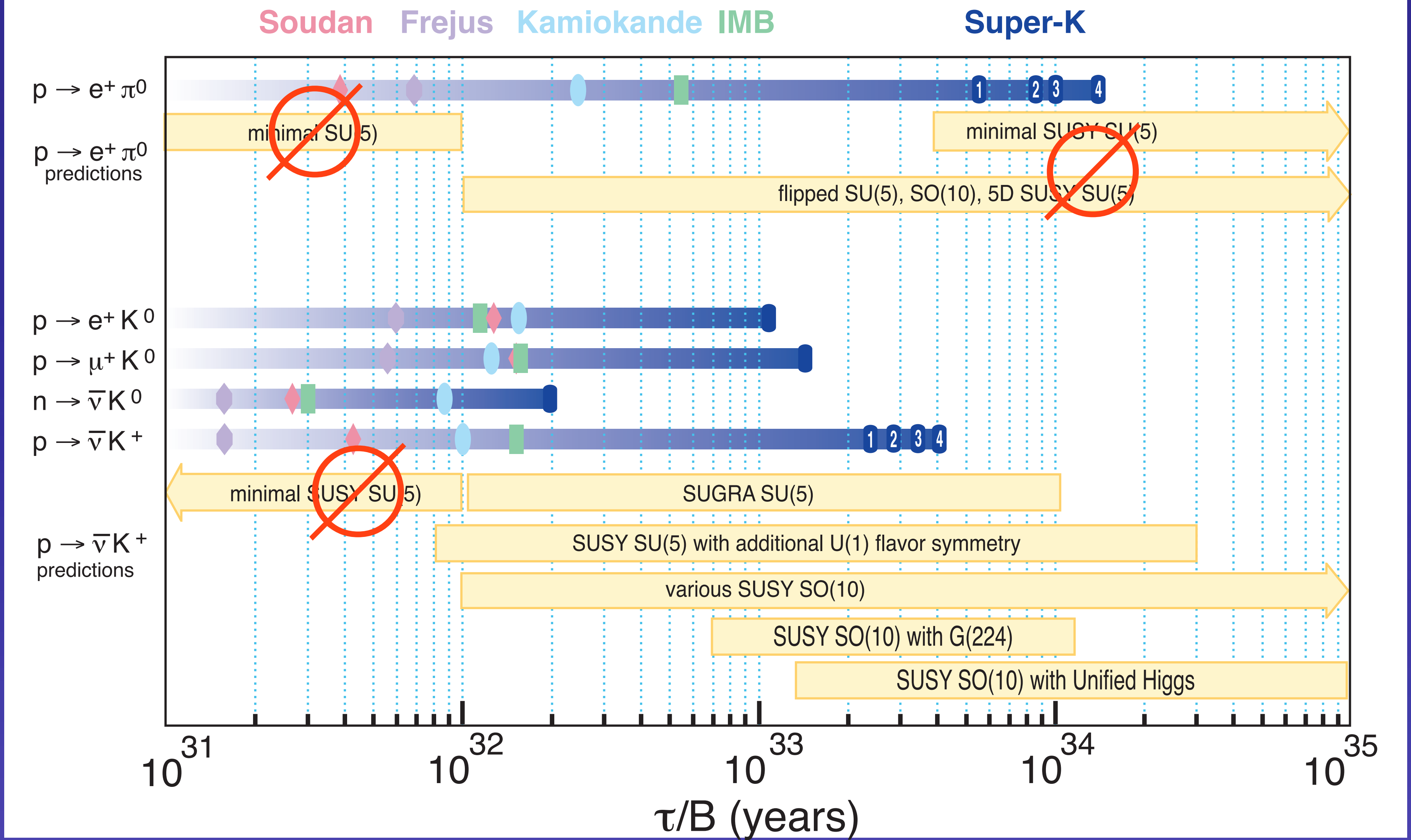
δ_{CP}=40 degree

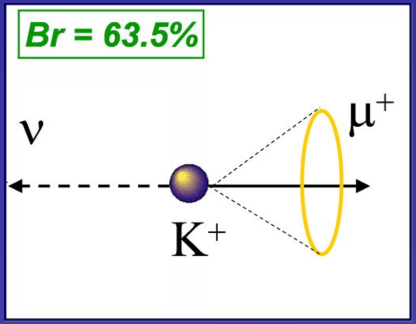
Nucleon Decays



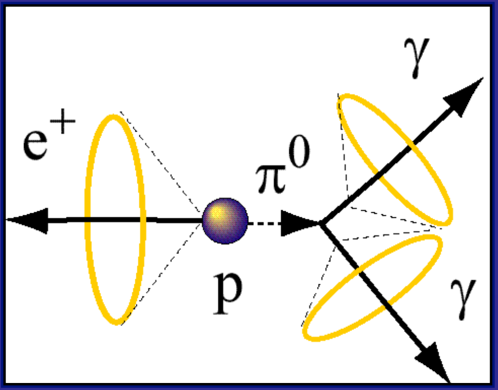
Experimental Limits







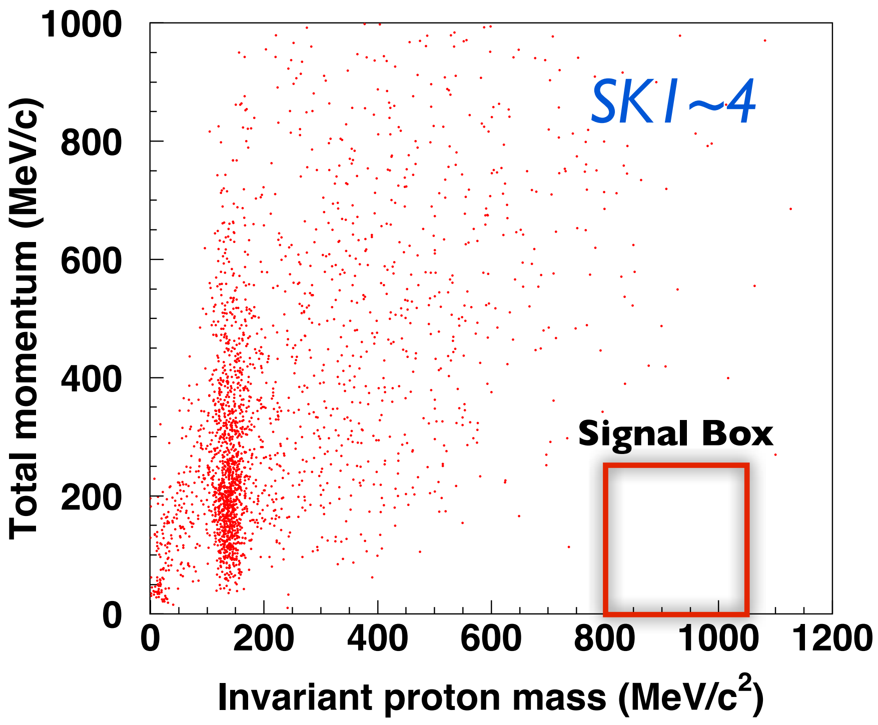
- Super-K gives most stringent limits for many decay modes.
  - $\tau(p \rightarrow e^+\pi^0) > 1.3\times10^{34}$years (90%C.L. by 220kton・yrs data)
  - $\tau(p \rightarrow \nu K^+) > 4.0\times10^{33}$years (90%C.L. by 220kton・yrs)
- No signal evidence has been found ➡ giving constraints on models (GUTs)
  - Constraints on SUSY models (ex: R-parity conservation)
  - Exclude minimal *SU(5)* and minimal SUSY *SU(5) models.*

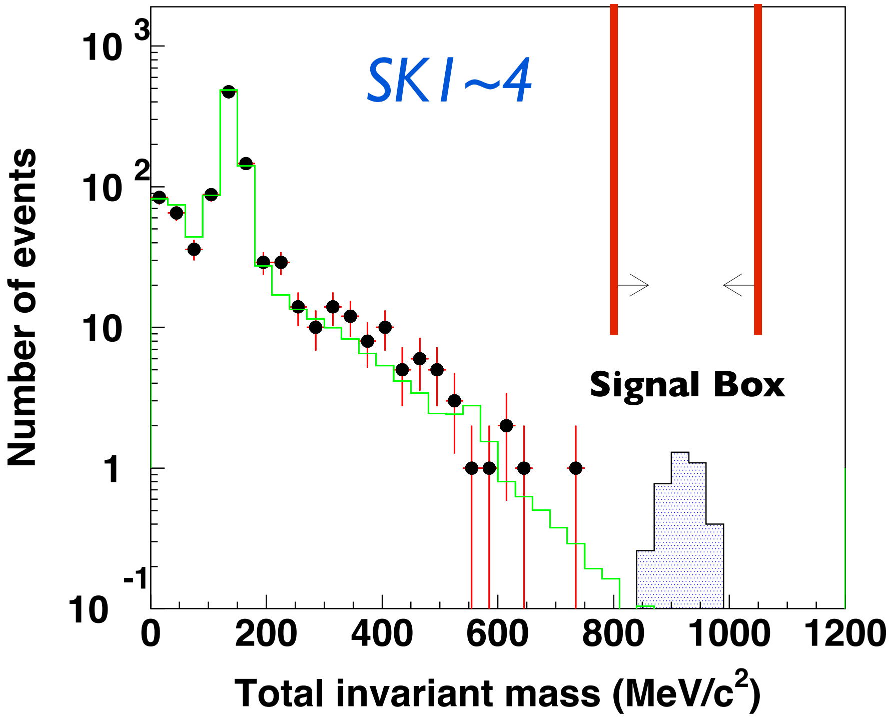


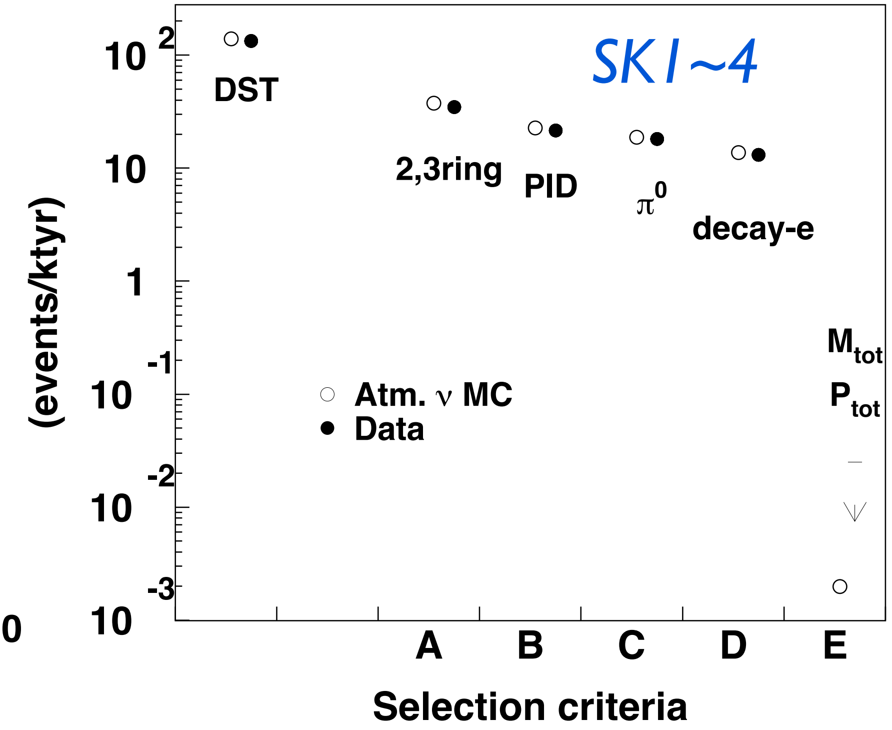
$p \rightarrow e^+ + \pi^0$ searches

Super-K data are consistent with BG MC.

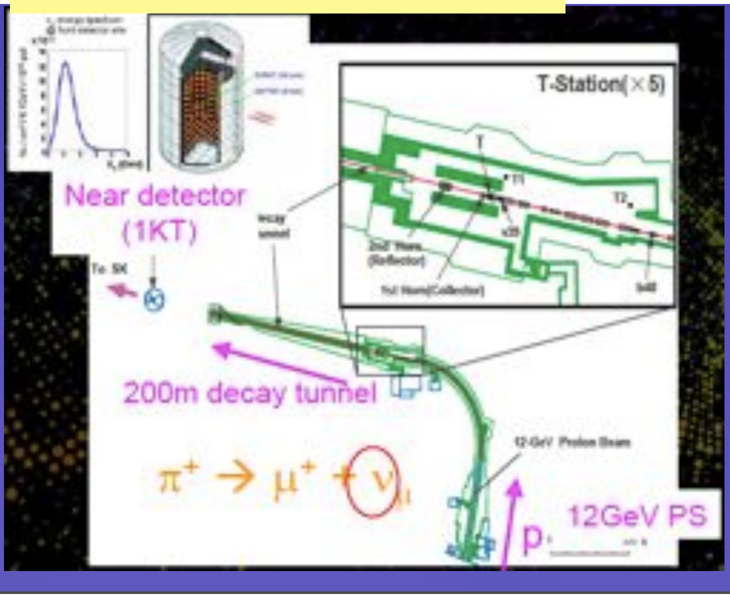
Super-K cut
- 2 or 3 Cherenkov rings
- All rings are showering
- $85 < M_{\pi 0} < 185 \mathrm{MeV/c^2}$ (3-ring)
- No decay electron
- $800 < M_{proton} < 1050 \mathrm{MeV/c^2}$ $P_{total} < 250 \mathrm{MeV/c}$







PRD77:032003,2008

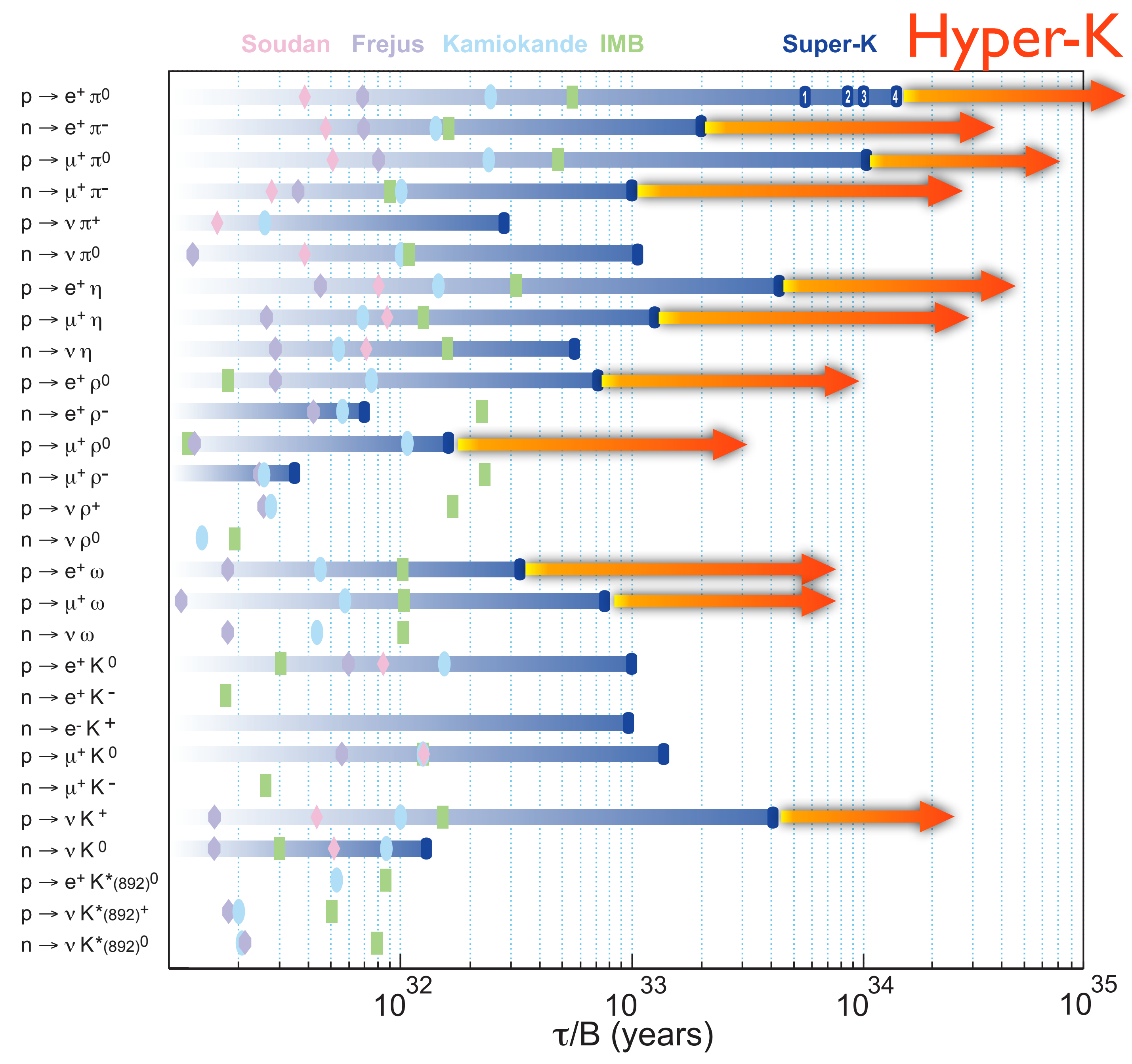


- BG measurement by accelerator ν (K2K)
  - BG=1.63+0.42/-0.33(stat.)+0.45/-0.51(syst.) $(\mathrm{Mt}\times\mathrm{yrs})^{-1}$ (Eν<3GeV)
  - Consistent w/ simulation 1.8±0.3(stat.)

BG in Hyper-K is under control.

Search for nucleon decays

- 10 times better sensitivity than Super-K.
  - only realistic plan to go beyond 10^{35} years for $p \rightarrow e^{+}+\pi^{0}$
- $>3\sigma$ discovery is possible for lifetime beyond Super-K limits.



Hyper-K sensitivities

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

Status of R&D

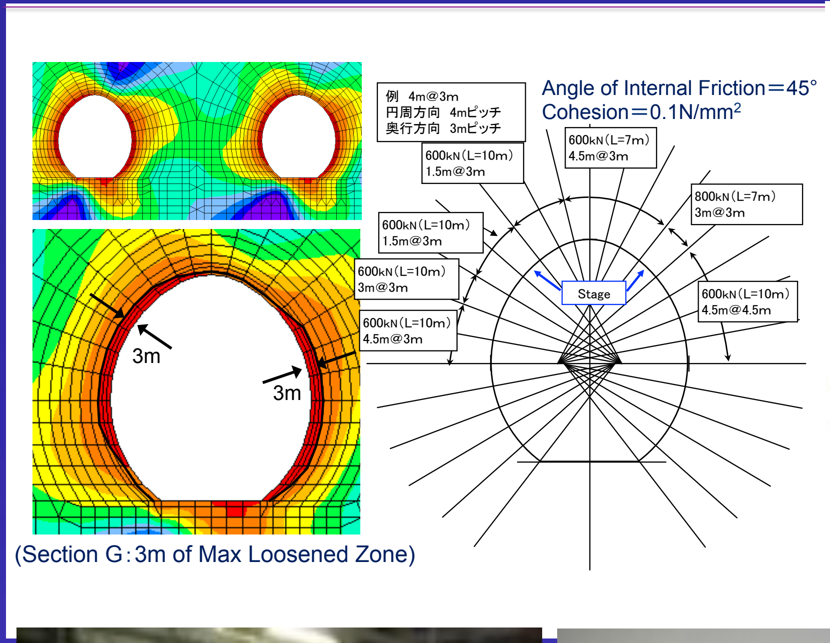
Two Hyper-K meetings (Aug. 23-24, 2012: Jan. 14-15, 2013)


~100 participants (~50 non-Japanese members)

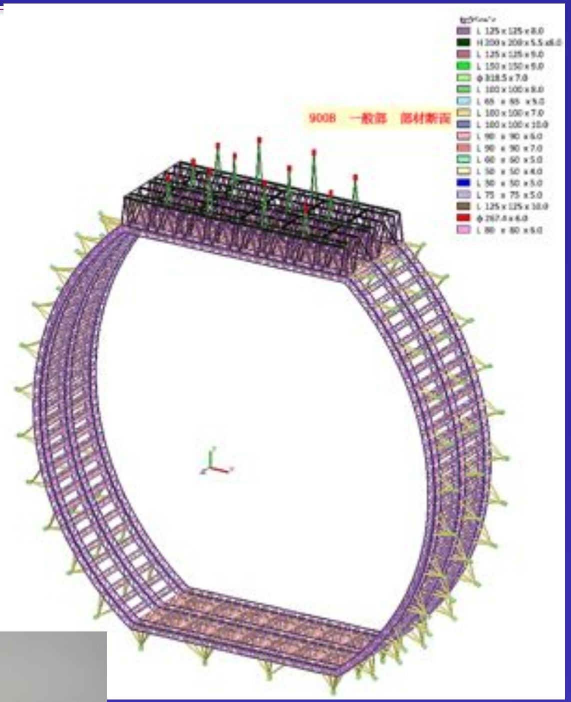
- http://indico.ipmu.jp/indico/conferenceDisplay.py?ovw=True&confId=7
- Review the current status of the project and discuss the strategy to realize Hyper-K.
- The next meeting will be on June 21 and 22, 2013.

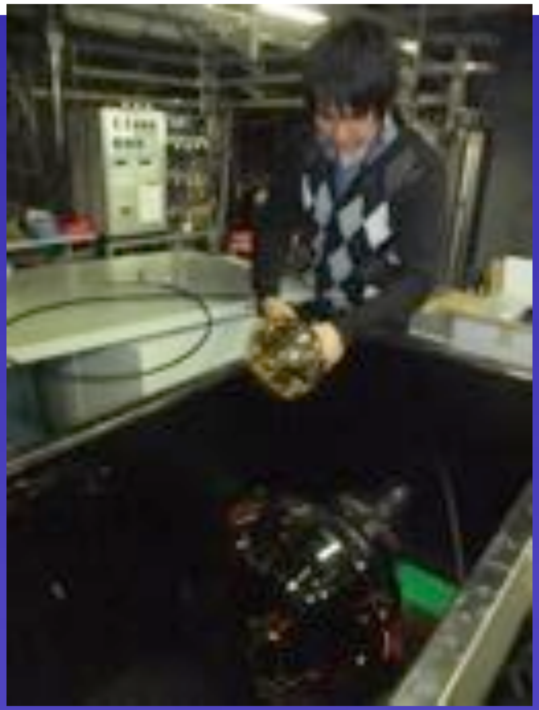
Development works

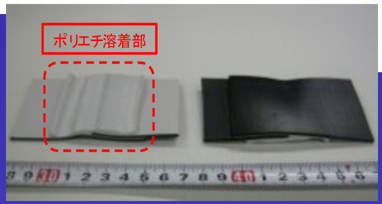
- Detector design optimization
    - tank shape, segmentation wall, tank liner, PMT support structure
- Water purification system, water quality control
- DAQ electronics (under water?)
- Calibration source deployment system
    - automated, 3D control
- Software development
    - Detector geometry optimization, enhance physics capabilities
- Physics potential studies
    - requirements for near detectors
- works in the international working group

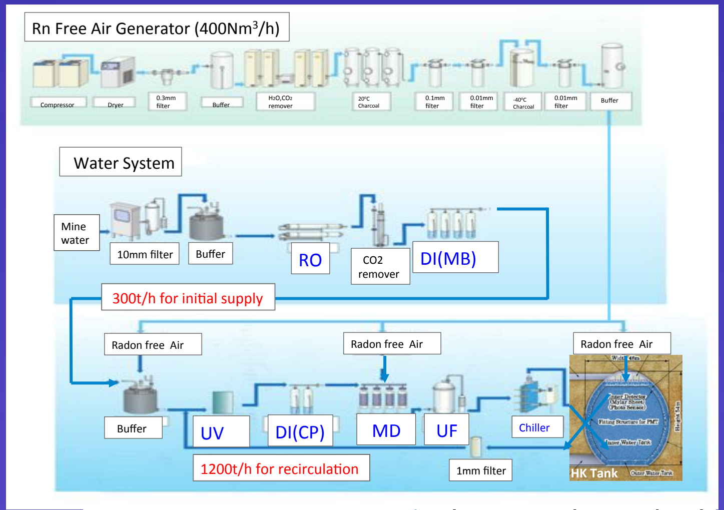


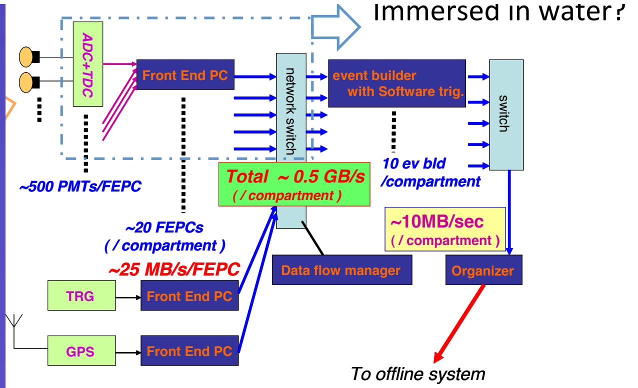
(Section G：3m of Max Loosened Zone)





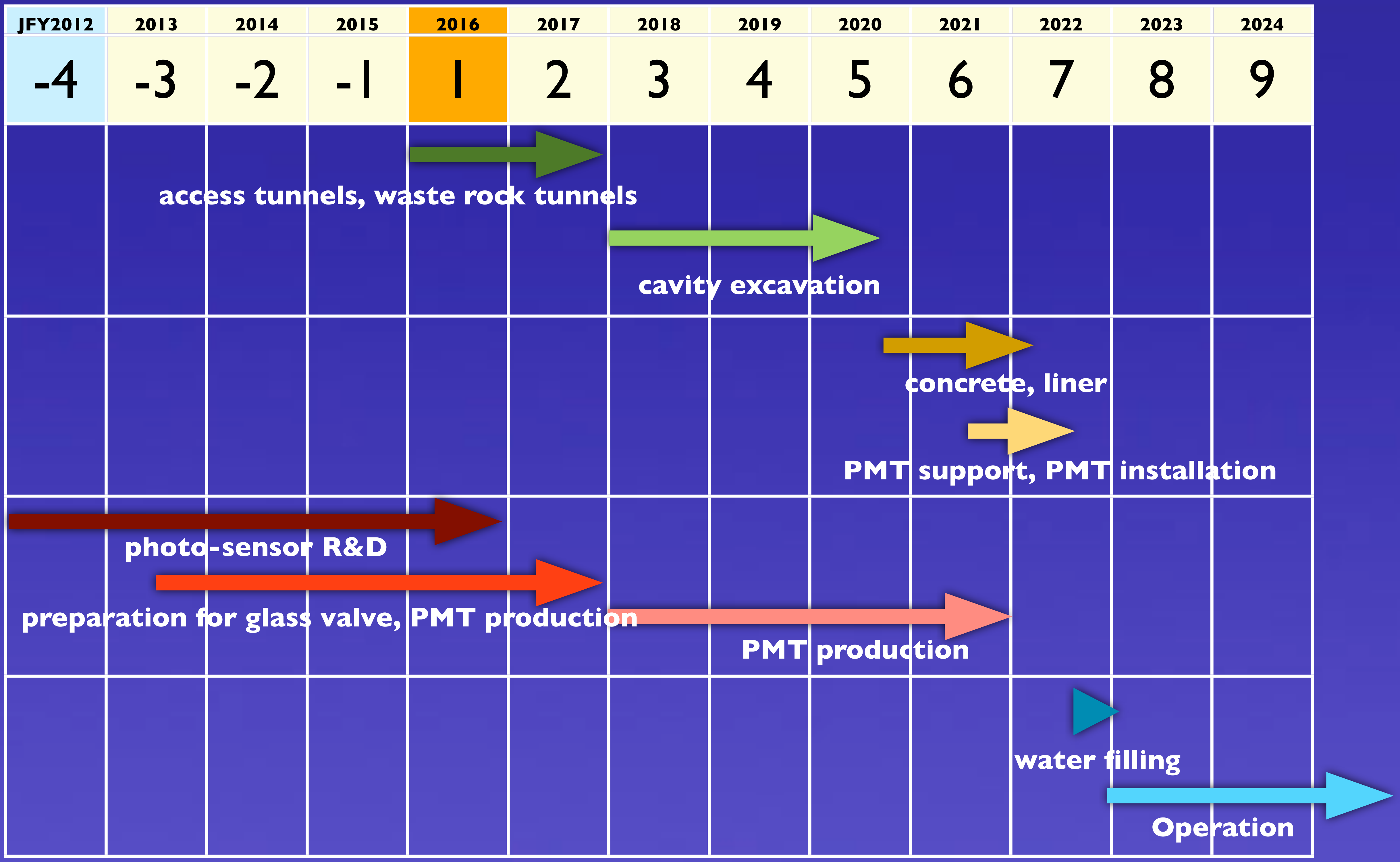






Target Schedule

Construction start



JFY2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
-4	-3	-2	-1	1	2	3	4	5	6	7	8	9

access tunnels, waste rock tunnels

cavity excavation

concrete, liner

PMT support, PMT installation

photo-sensor R&D

preparation for glass valve, PMT production

PMT production

water filling

Operation

assuming budget being approved from JPY2016

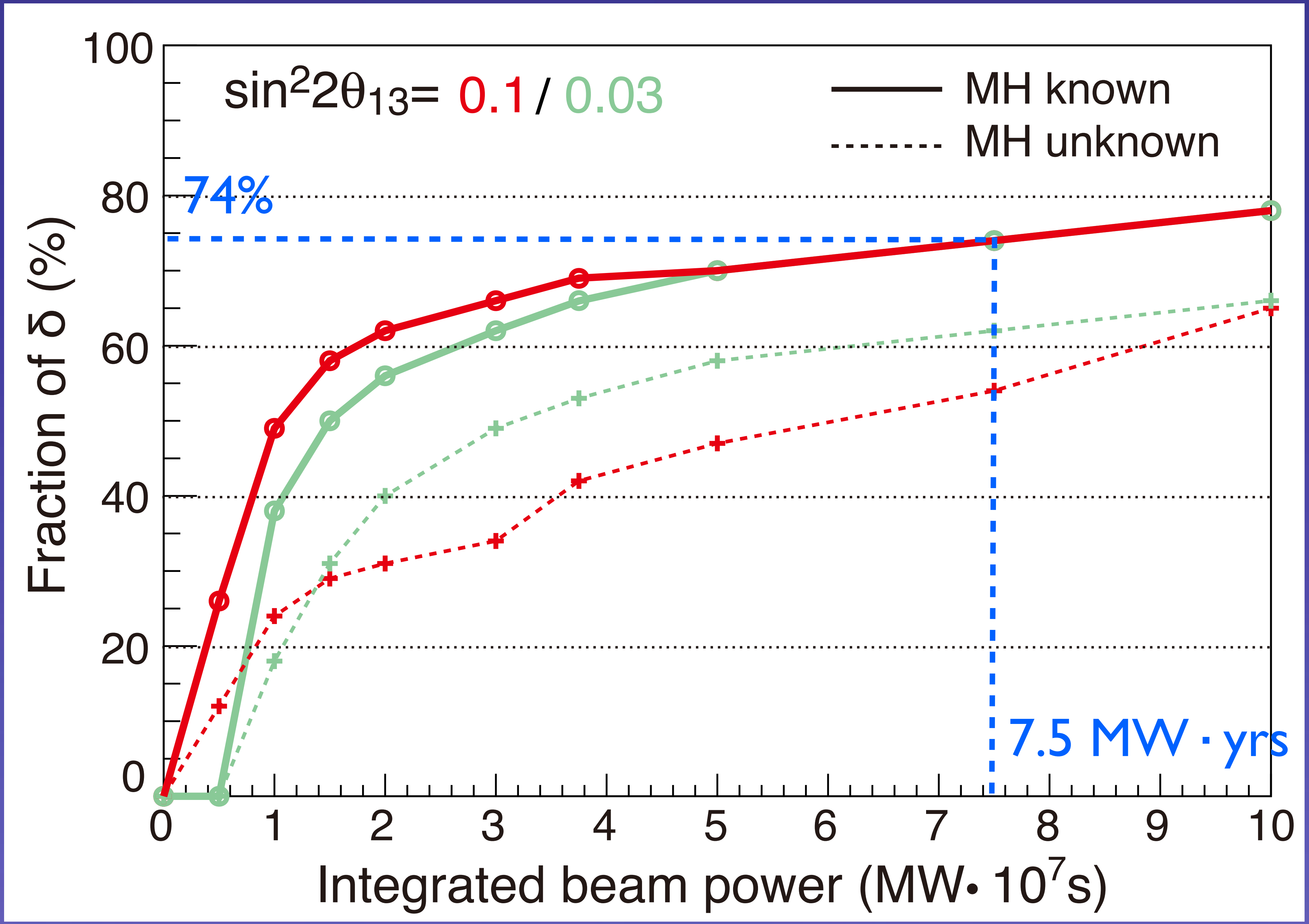
Let’s realize the Detector

- ***The next open Hyper-K meeting will be on June 21-22, 2013 in Japan.***
- ***All you are WELCOME!***

Backup

Fraction of δ (%) for CPV discovery

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



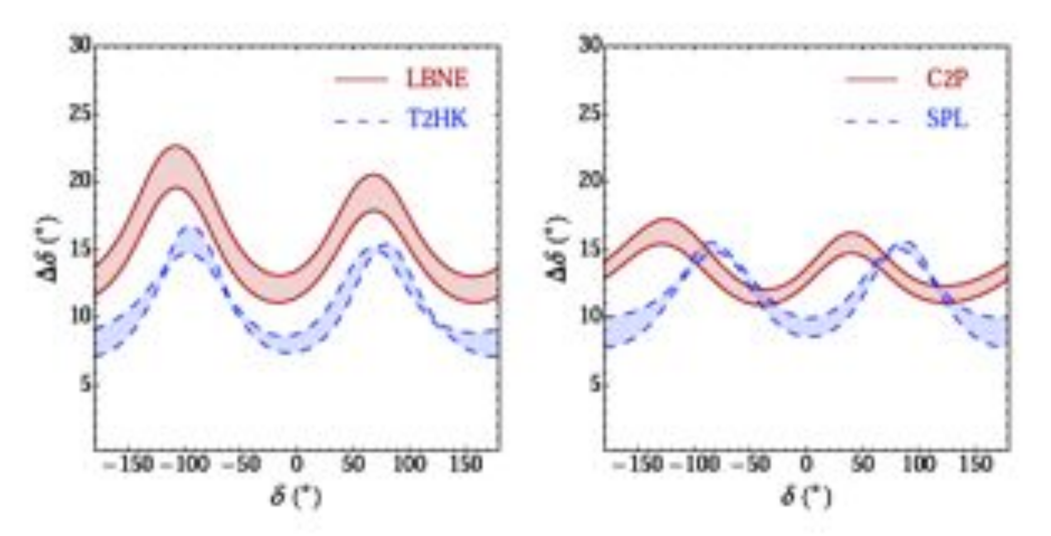
- Although the sensitivity is degraded if mass-hierarchy is unknown, the mass-hierarchy could be determined by other LBL experiments and Hyper-K atmospheric neutrino measurements at the time of CP discovery.

Long baseline projects

Project	Beam power MW	Fiducial Mass kt	Baseline km	MH	CPV 90%CL, (3σ)	Physics starts	Astrophysical program
LBNO	0.8	20->100	2300	Excellent	71 (44)	2023	Yes
T2HK	0.75	500	295	Little	86 (74)*	2023	Yes
LBNE	0.7	10	1300	OK	69 (43)	2022	No
Lund	5	440	365	Some	86 (70)	>2019	Yes
CERN-Canfranc	0.8-4	440	650	Some	80-88(80)	>2020	Yes

*: if mass hierachy is known

P. Coloma et al.hep-ph:1203.5651



T2HK: 4MW, 500 kt
LBNE: 0.8 MW,33 kt
C2P=LBNO : 0.8 MW, 100 kt

$\nu_\mu \rightarrow \nu_e$ probability

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) = \; & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \quad \text{Leading} \qquad \text{CP violating (flips sign for } \bar{\nu}\text{)} \\ & +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\ & -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \boxed{\sin\delta} \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\ & +4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \quad \text{Solar} \\ & -8C_{13}^2 S_{12}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu}(1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\ & +8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2}(1 - 2S_{13}^2) \sin^2 \Delta_{31} \quad \text{Matter effect} \end{aligned}$$

Rich physics (with precise θ_{13} expected from reactor)

Leading term ∝ $\sin^2 2\theta_{13}$

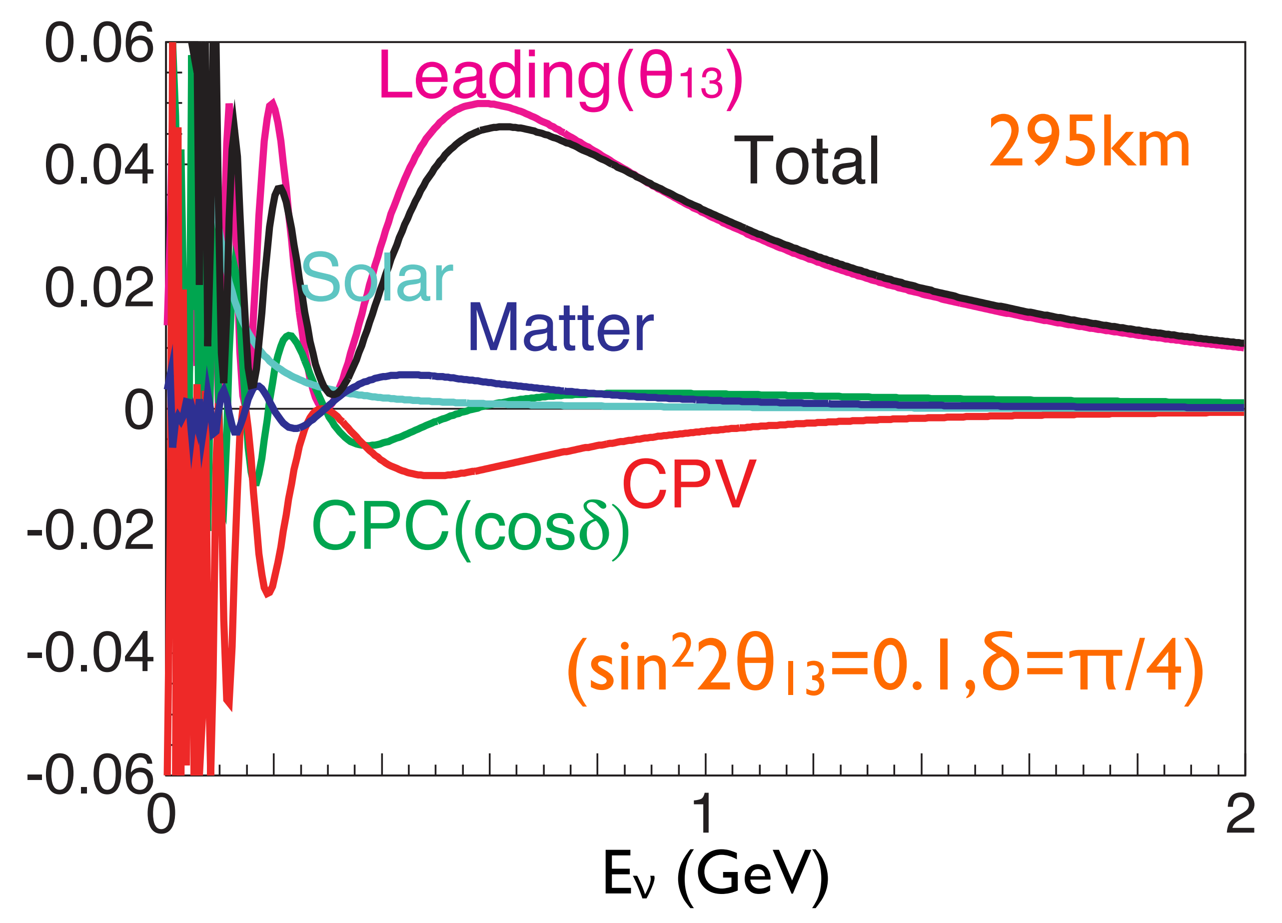
CPV term ∝ $\sin 2\theta_{13}$

Matter effect ∝ $\sin^2 2\theta_{13}$

For larger $\sin^2 2\theta_{13}$

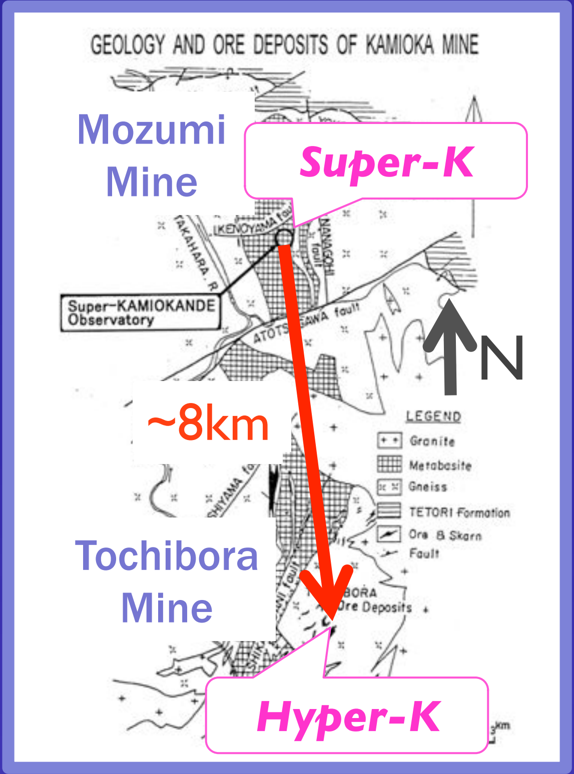
signal ↑, CP asymmetry ↓

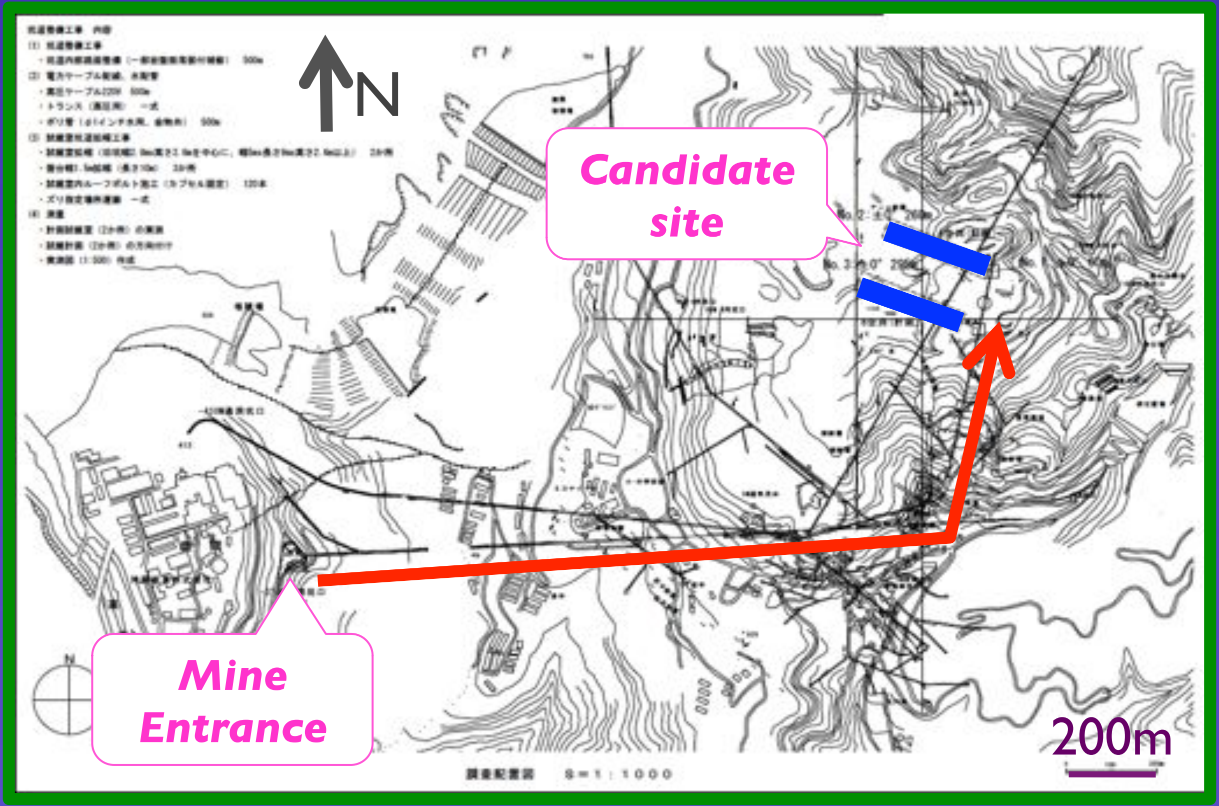
matter/CP ↑

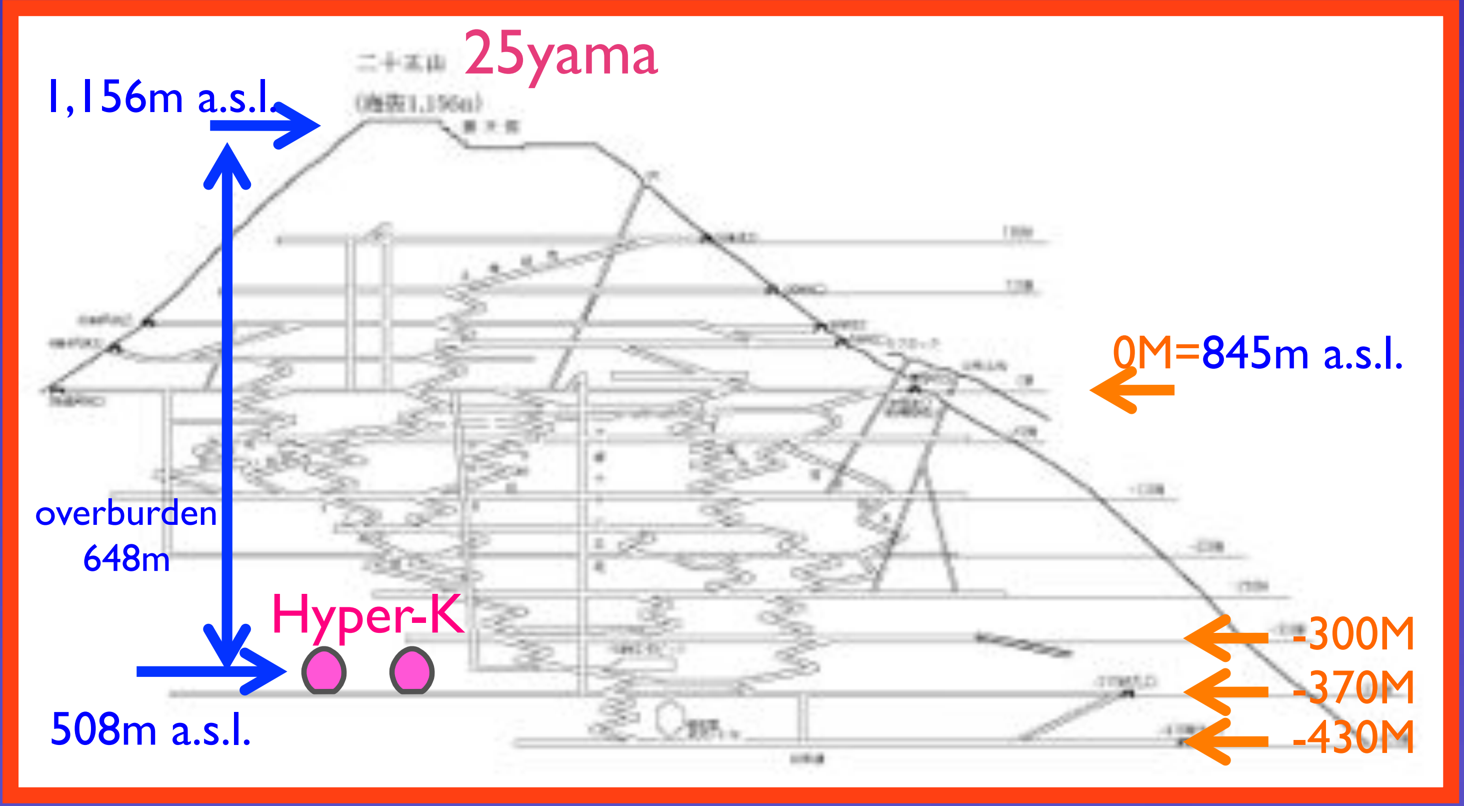


Hyper-K candidate site

- 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

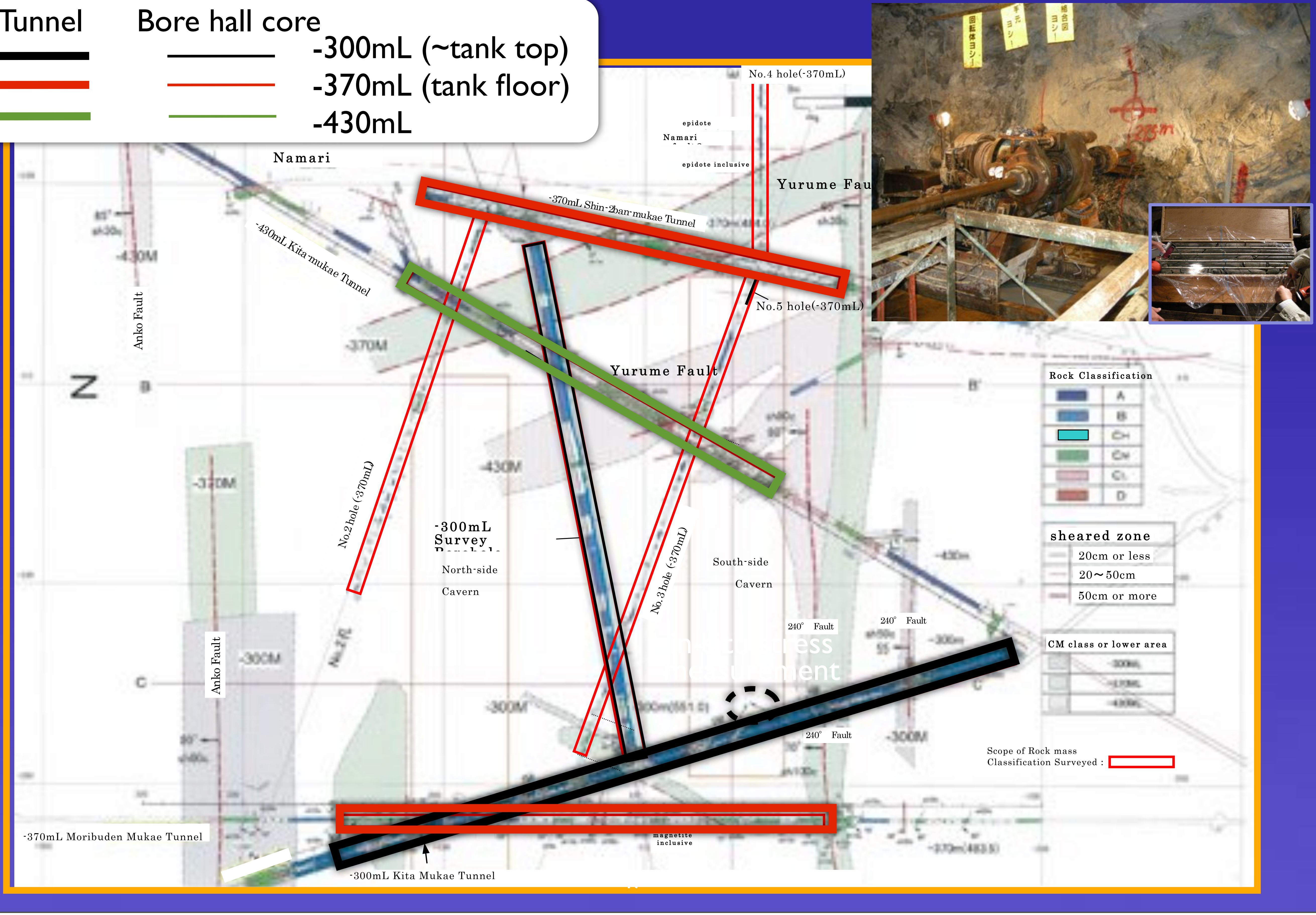




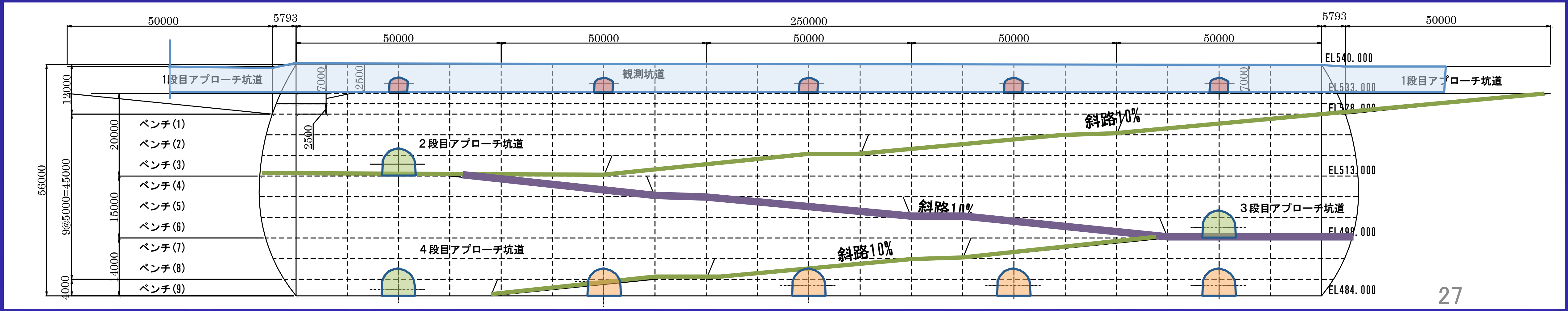


Overview of the geological survey

Tunnel	Bore hall core	
⬛	⬛	-300mL (~tank top)
🟥	🟥	-370mL (tank floor)
🟩	🟩	-430mL



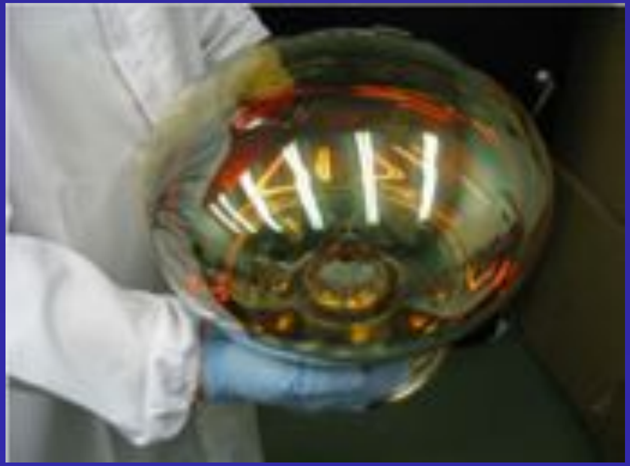
Cavern analysis



step-by-step calculations for each excavation benches

- cavity analysis (and PS anchor design) going on
- scheduling & costing ongoing

Photo-sensor



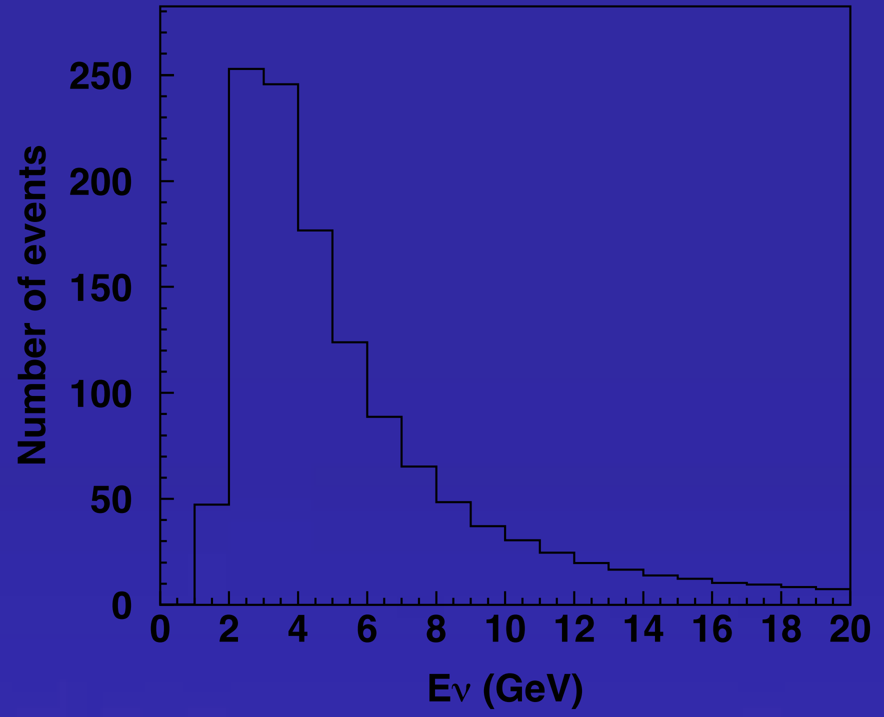
- Candidates for ID sensor
  - 20” Hybrid Photo Detector (HPD)
  - (New 20” PMT as backup)
- Proof test of 8” HPD in a water tank from this winter
- 20” HPD prototype is expected in ~a half year

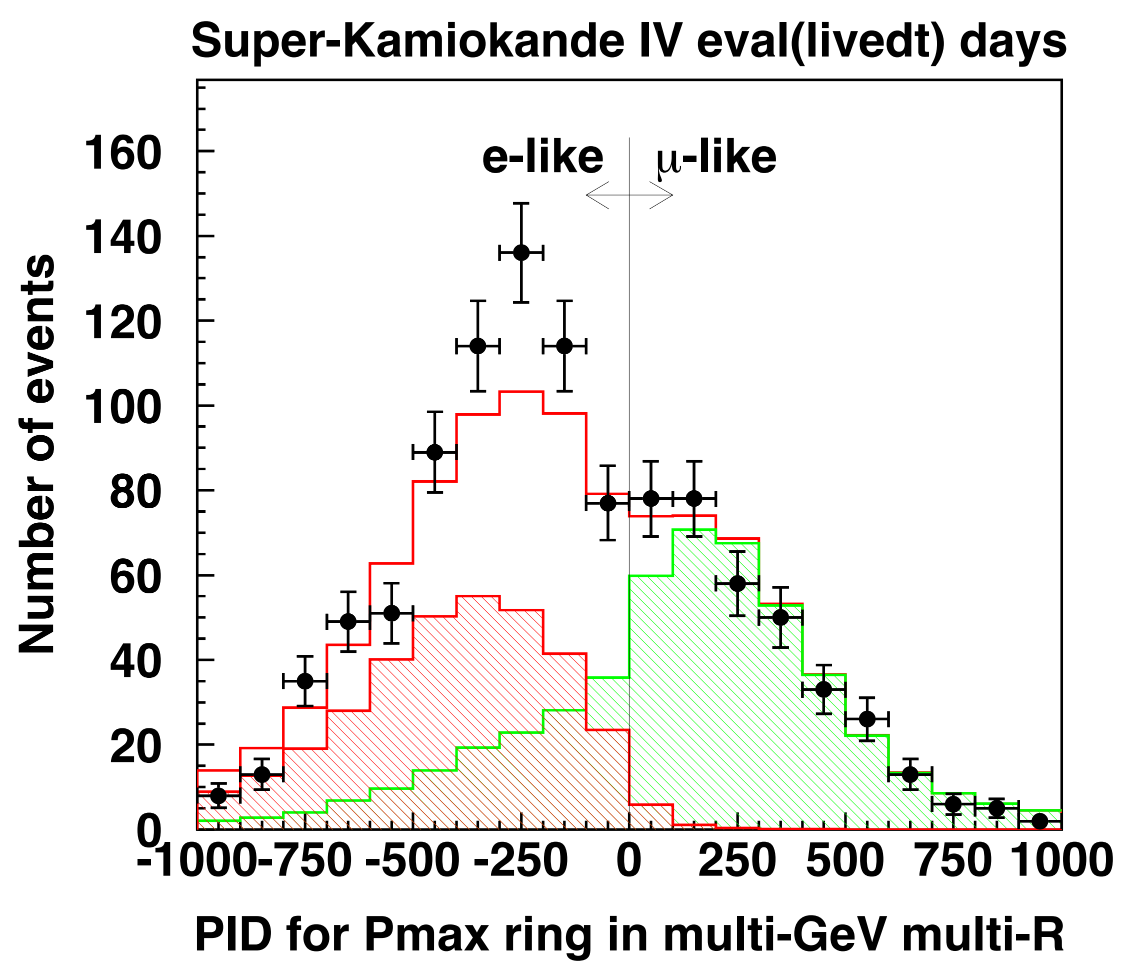
EGADS 200 ton tank
@Kamioka

Preparation @ Kamioka

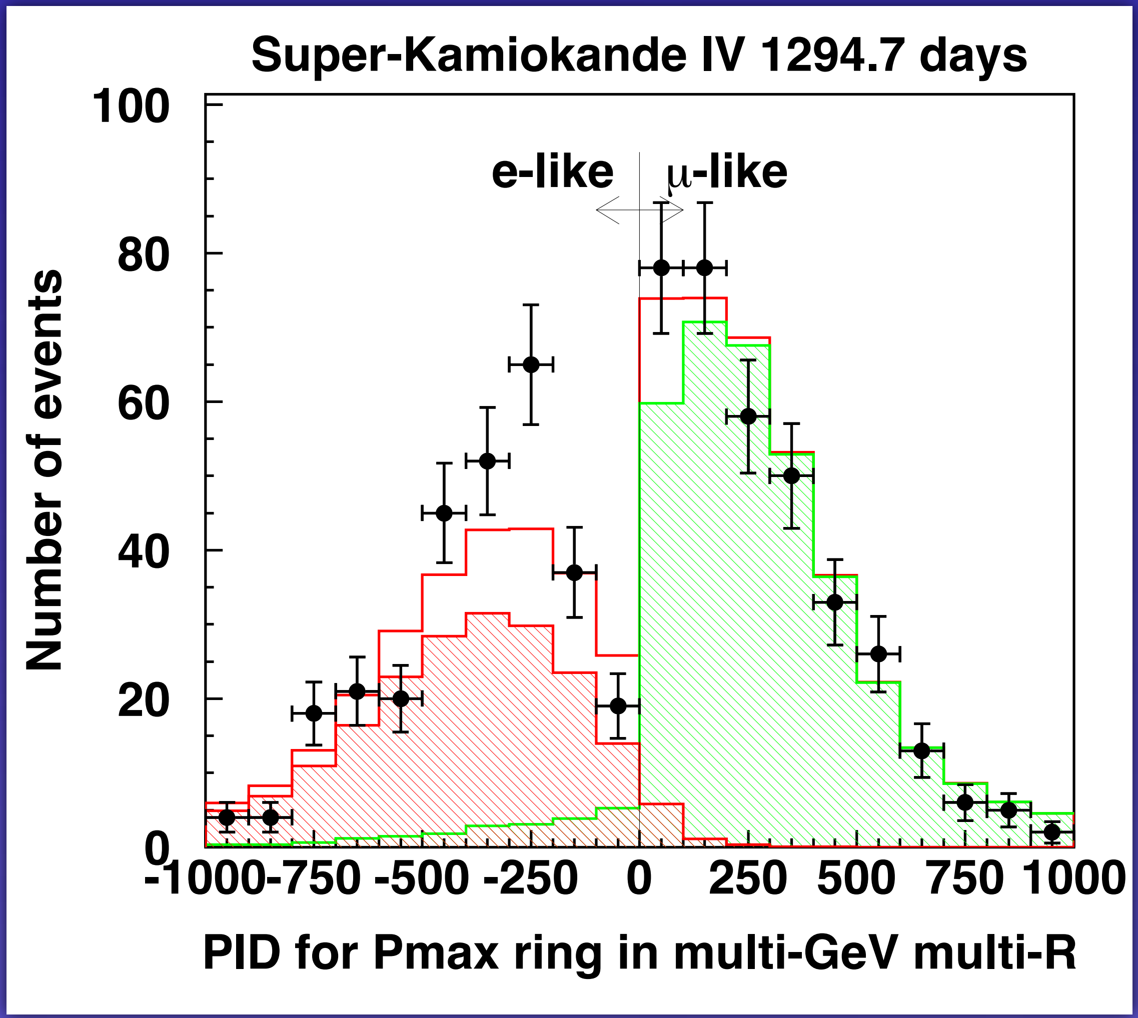
Multi-GeV reconstruction

- Multi-GeV PID for atm ν sample





Tighter Cut

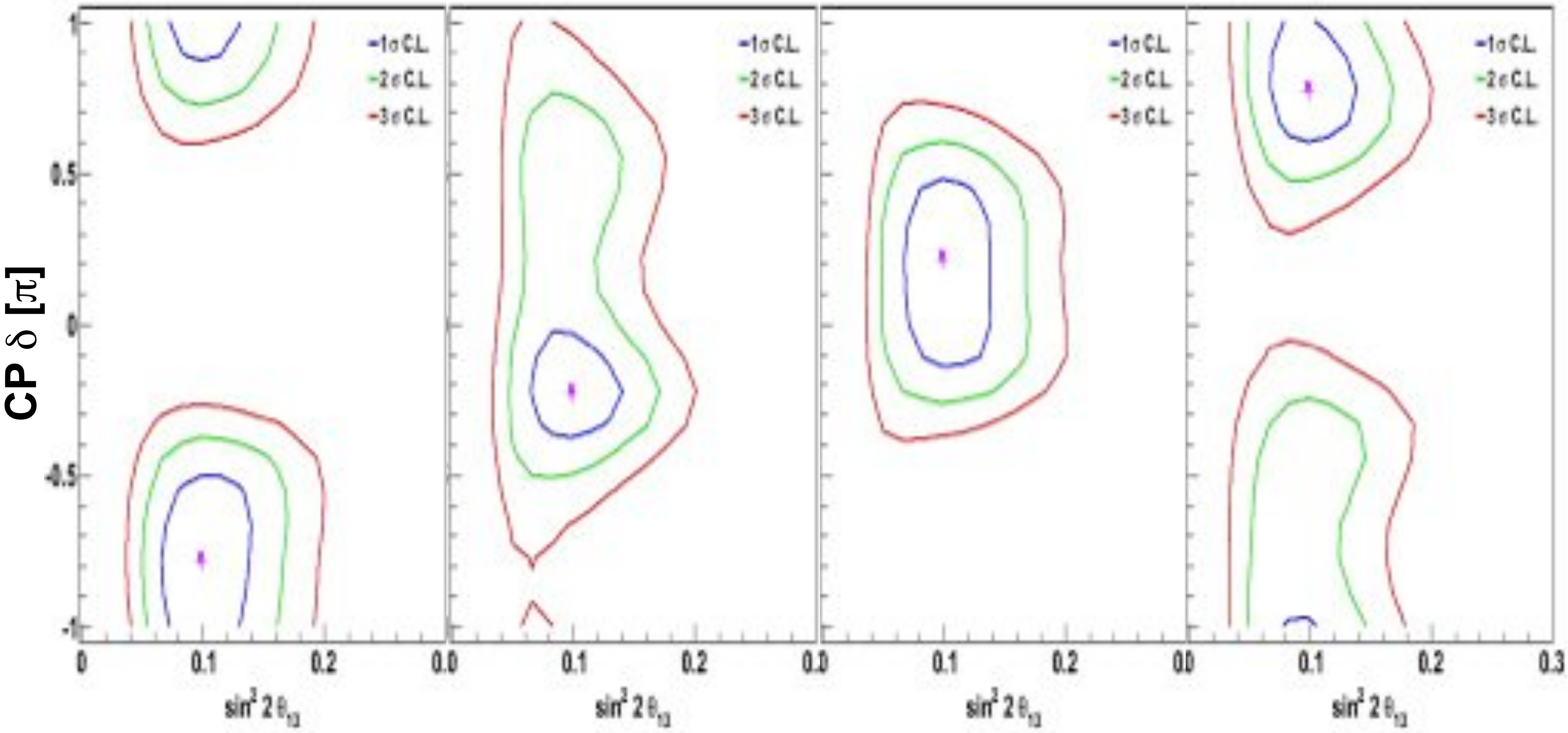


Sensitivity for CP δ and $\sin^2 2\theta_{13}$

Atmospheric neutrinos of Hyper-K 10 years

1σ CL
2σ CL
3σ CL

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



Give supplemental information to the CP study conducted by the J-PARC beam