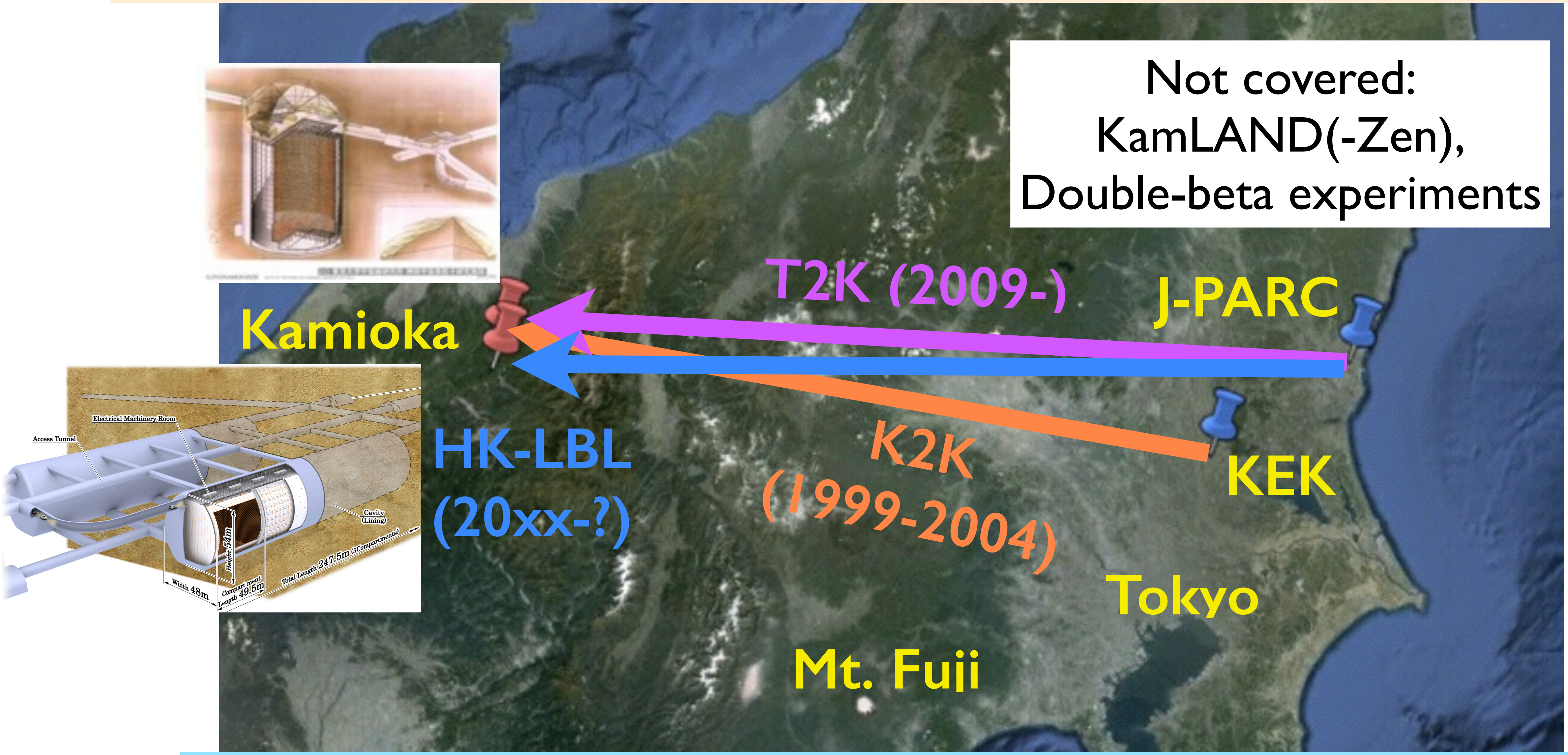
The Japanese future neutrino program

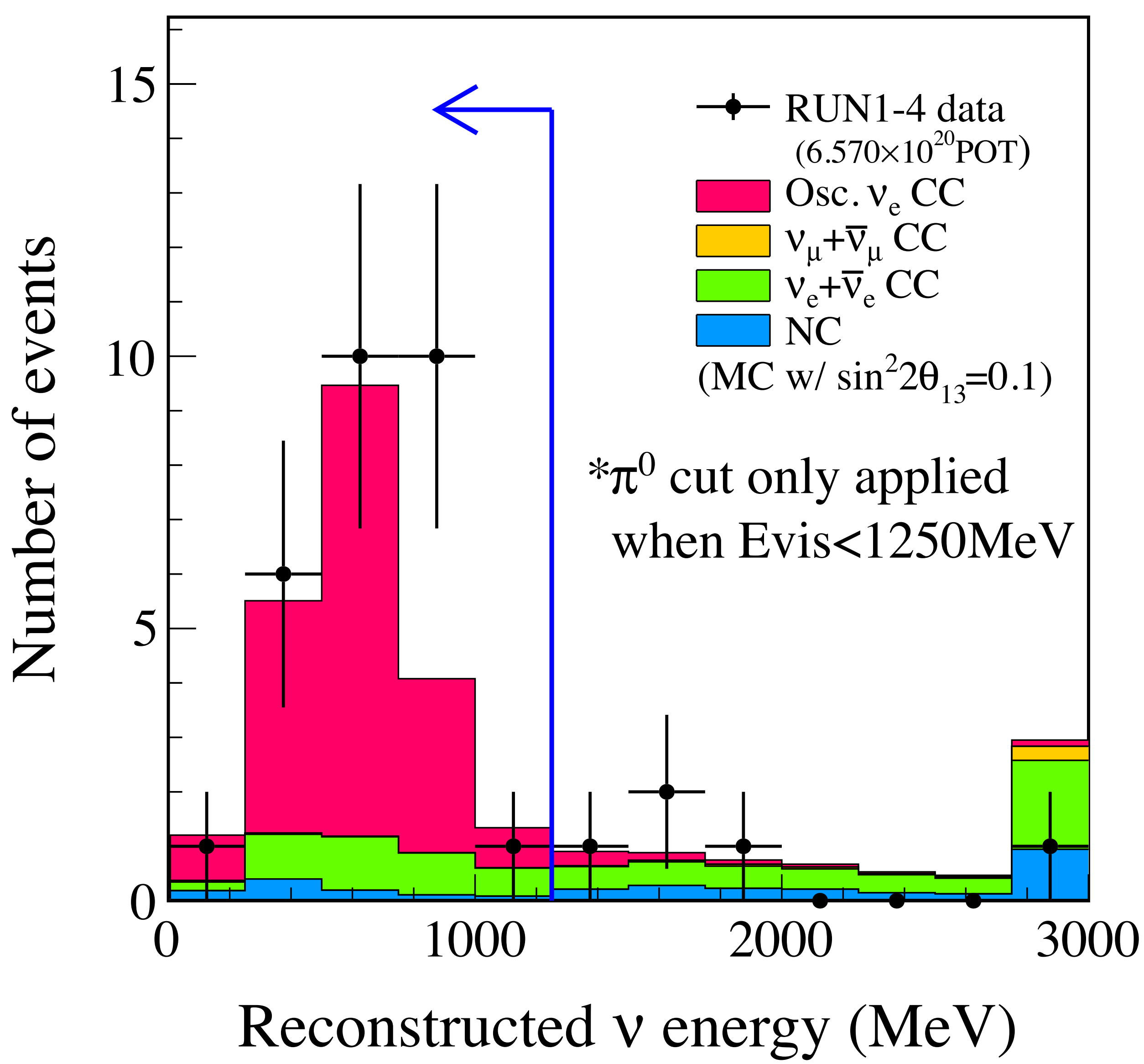


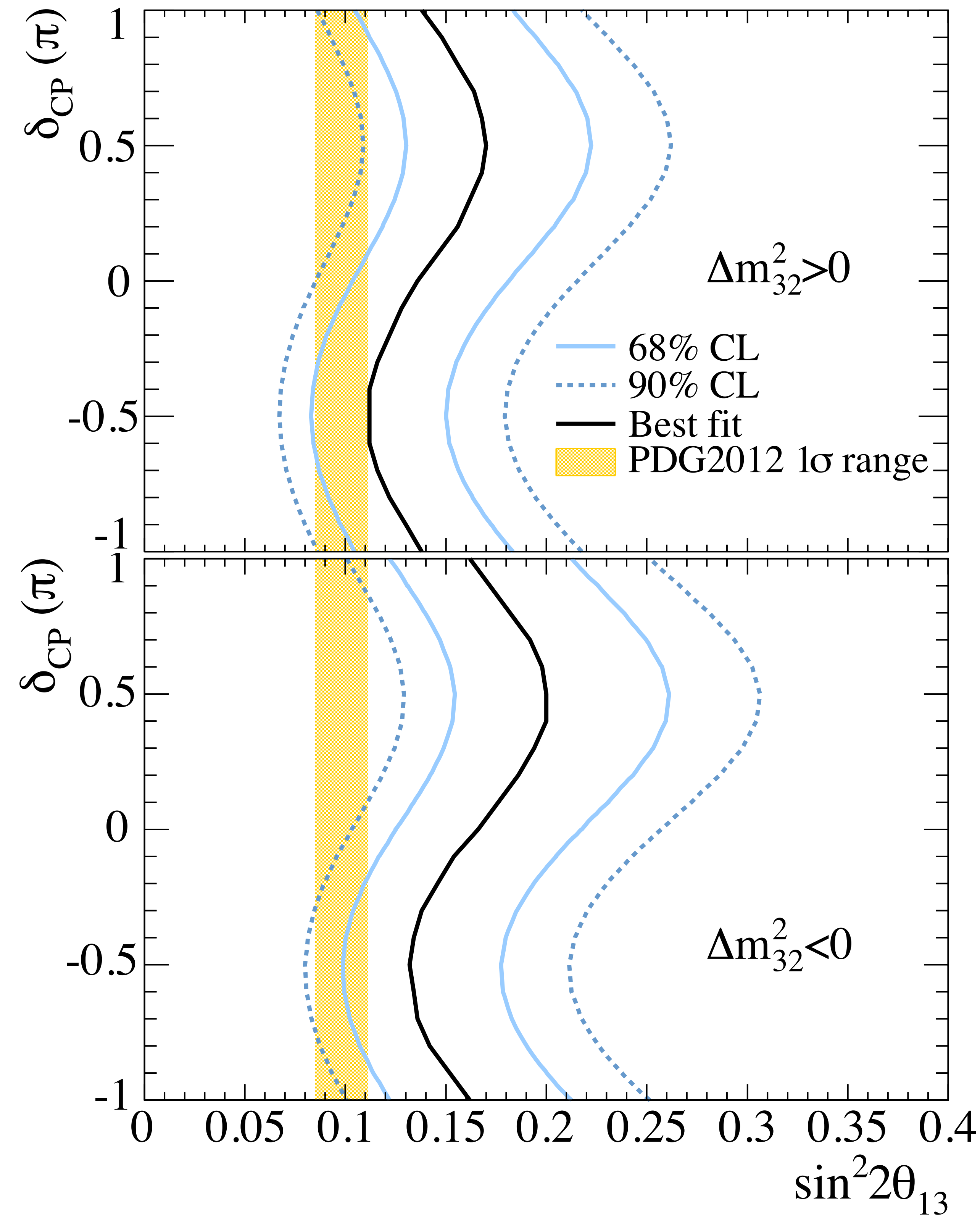
Masashi Yokoyama
masashi@phys.s.u-tokyo.ac.jp
Department of Physics, the University of Tokyo

SWAPS2014
June 12, 2014, Cartigny, Switzerland

Observation of ν_e appearance by T2K

[PRL 112, 061802(2014)]



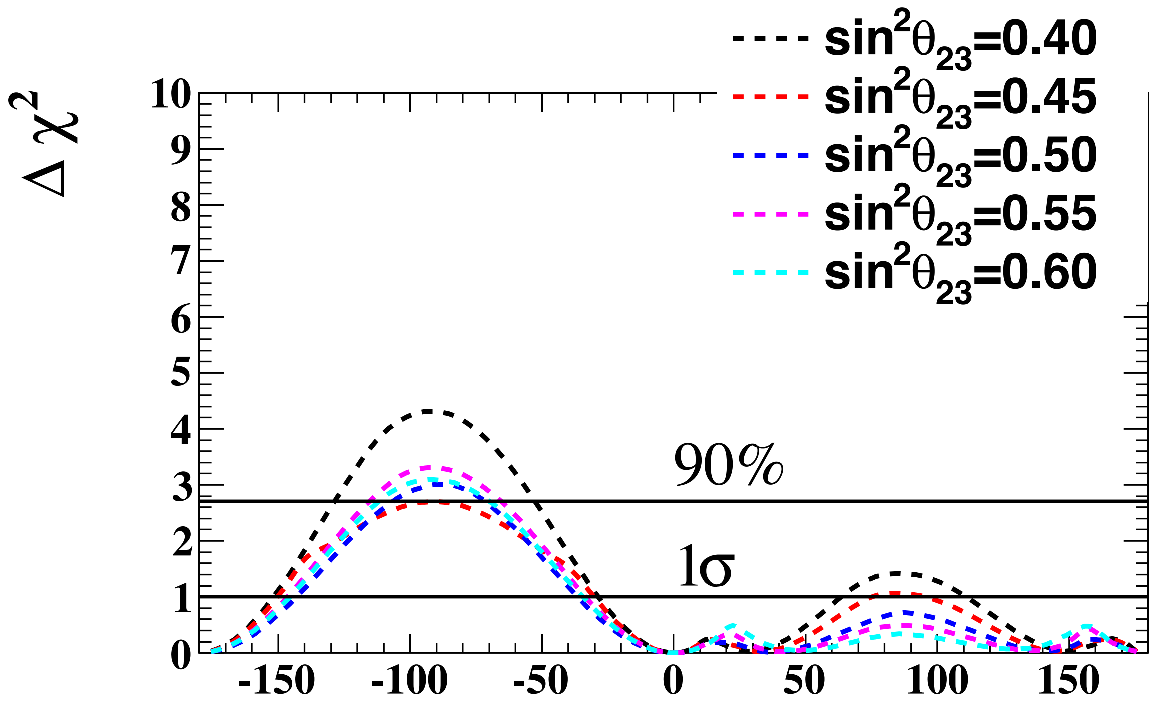


Opened a door to the next step!

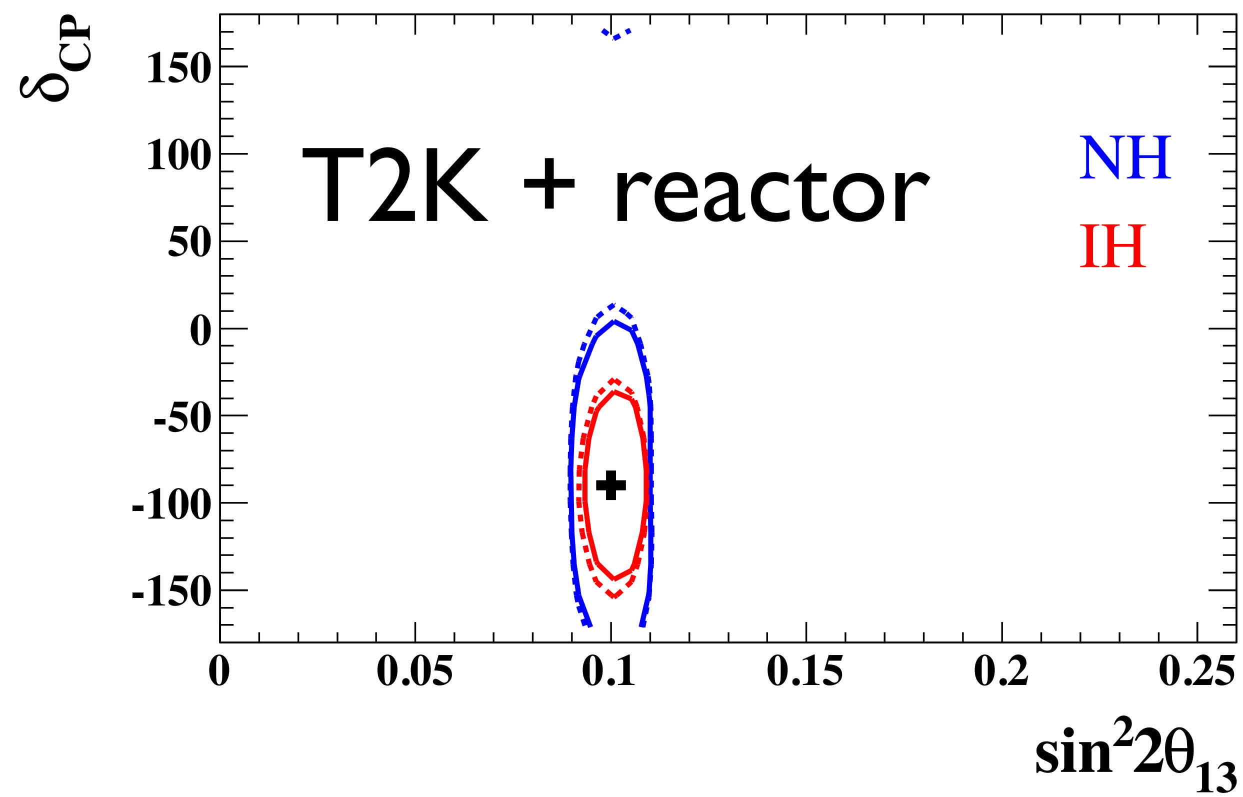
T2K future sensitivity to CPV

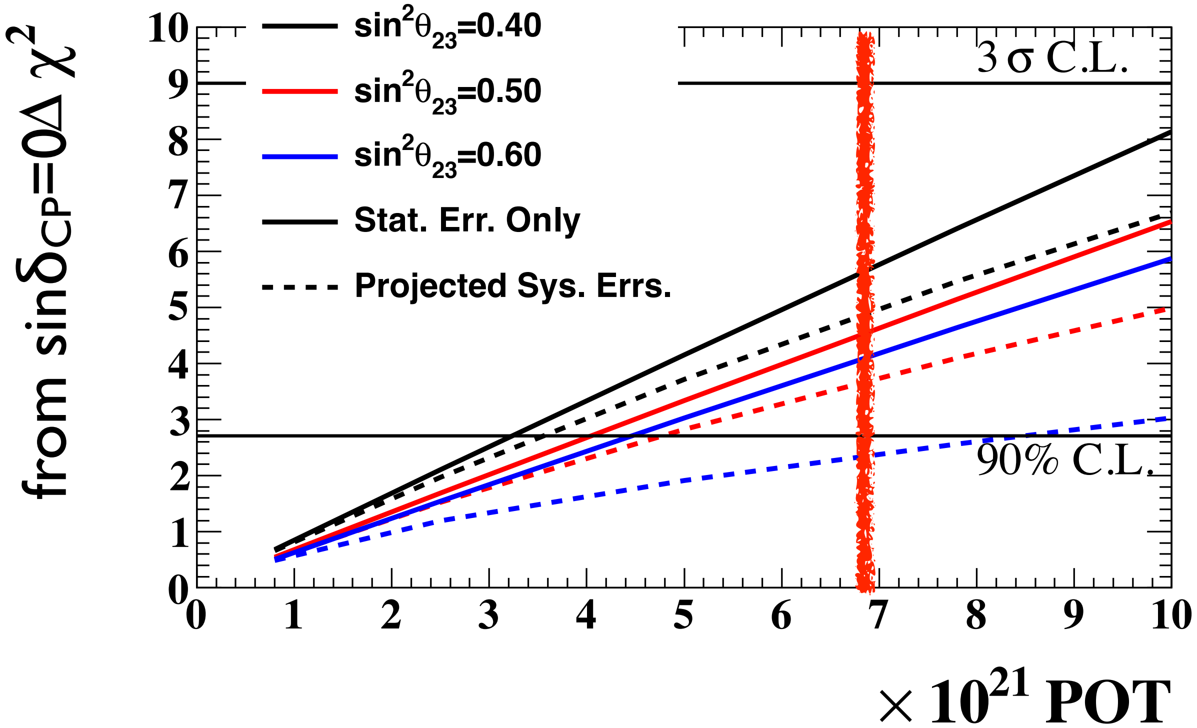
3.9×10^{21} POT each for ν and $\bar{\nu}$

2012 T2K systematics included (dashed lines)



$\sin^2 2\theta_{13}=0.1$, $\delta_{CP}=-90°$, $\sin^2\theta_{23}=0.5$, $\Delta m^2_{32}=2.4E\text{-}3$ (NH)





Current T2K data:
~8% of approved POT

Future run including
anti-neutrino beam will probe CPV

Next generation project in Japan

One Megaton Water Cherenkov Detector
Hyper-Kamiokande

Recommendation by Japanese HEP community (Feb. 2012)

- **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.

One of 27 top projects in Japanese Master Plan for Large Scale Projects by Science Council of Japan (Feb. 2014)


提 言

第 22 期学術の大型研究計画に関する
マスタープラン
（マスタープラン 2014）

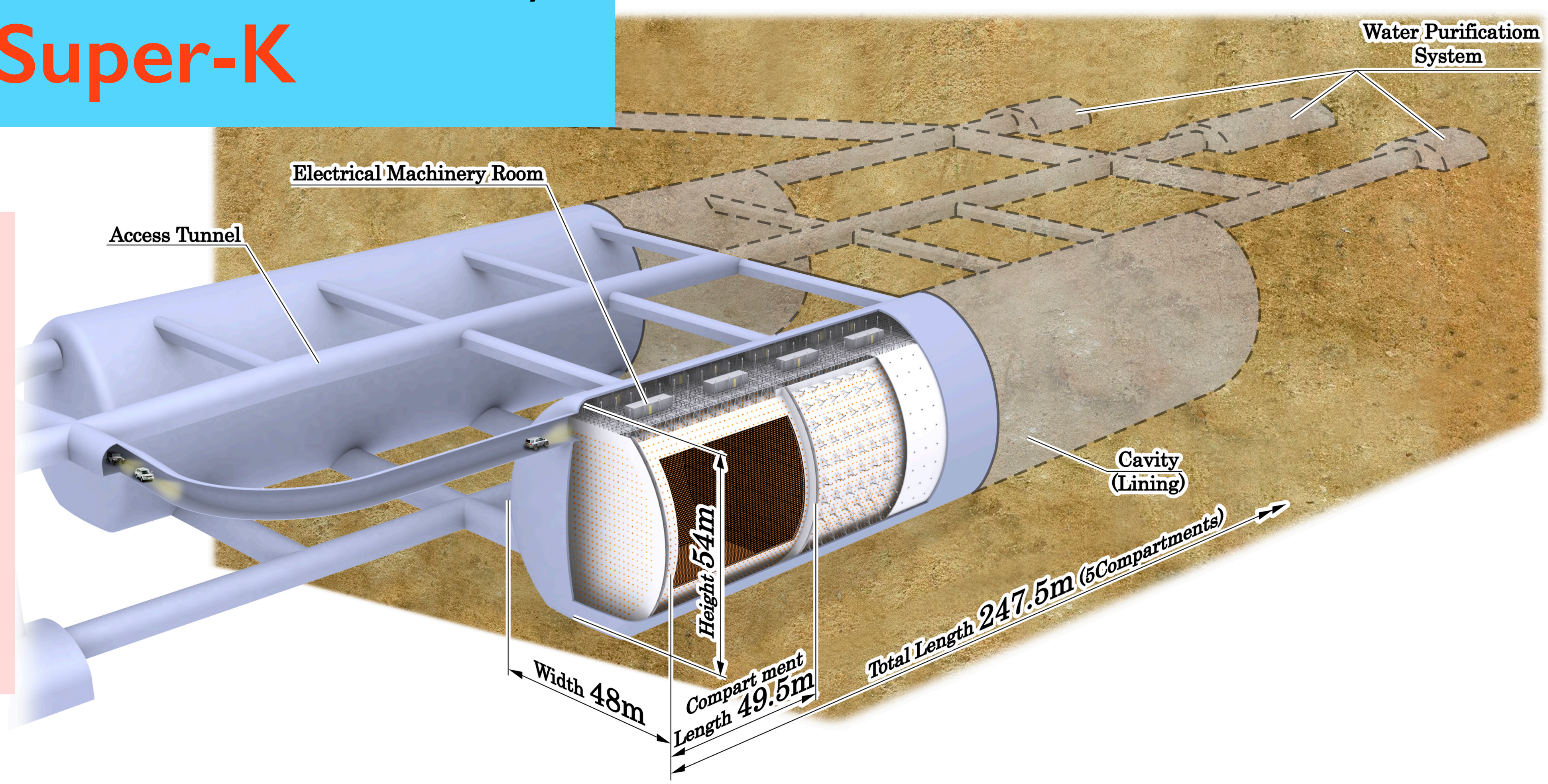
平成２６年（２０１４年）２月２８日
日 本 学 術 会 議
科学者委員会
学術の大型研究計画検討分科会

Hyper-Kamiokande Detector

Total volume: 0.99 Mton
Inner volume: 0.74 Mton
Outer volume: 0.2 Mton
Fiducial volume: 0.56 Mton
(0.056Mton × 10 compartments)
x25 of Super-K

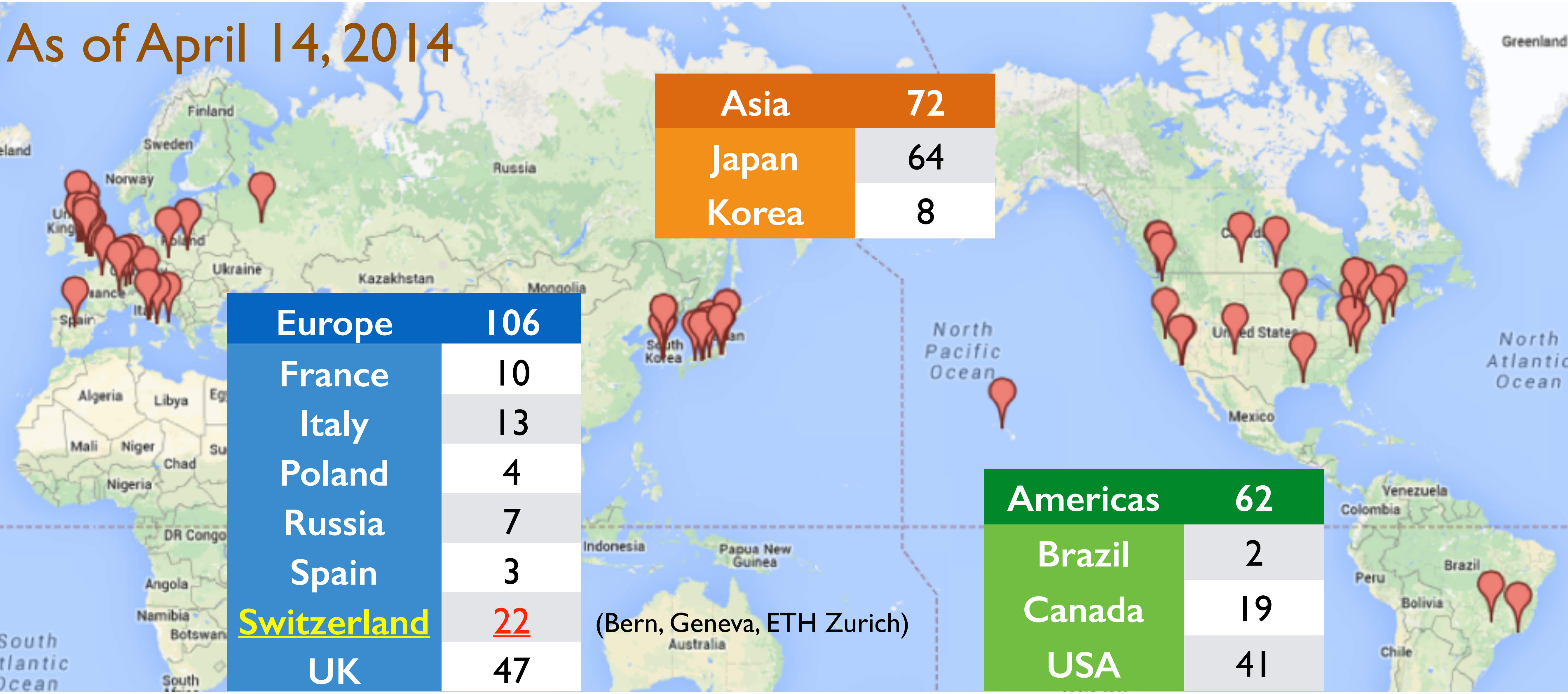
Hyper-K WG,
arXiv:1109.3262 [hep-ex]
arXiv:1309.0184 [hep-ex]

- 99,000 20” PMT for inner-det. (20% coverage)
- 25,000 8” PMT for outer-det.



Hyper-Kamiokande International Working Group

As of April 14, 2014



Asia	72
Japan	64
Korea	8

Europe	106
France	10
Italy	13
Poland	4
Russia	7
Spain	3
Switzerland	22
UK	47

(Bern, Geneva, ETH Zurich)

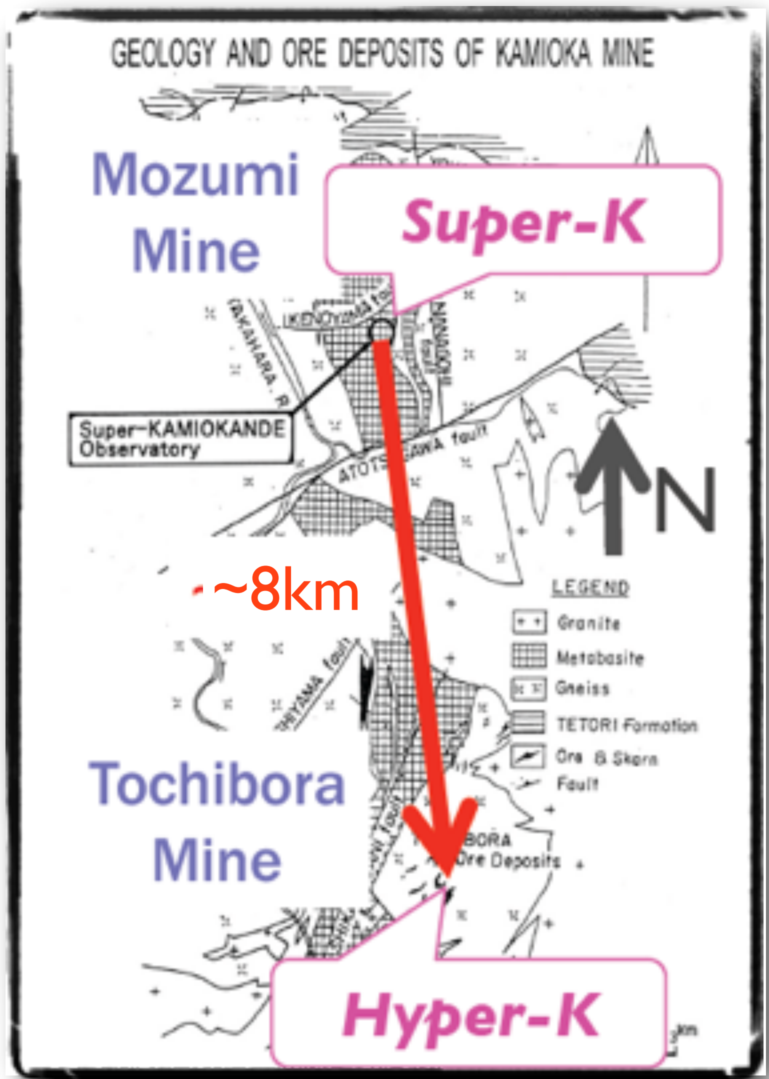
Americas	62
Brazil	2
Canada	19
USA	41

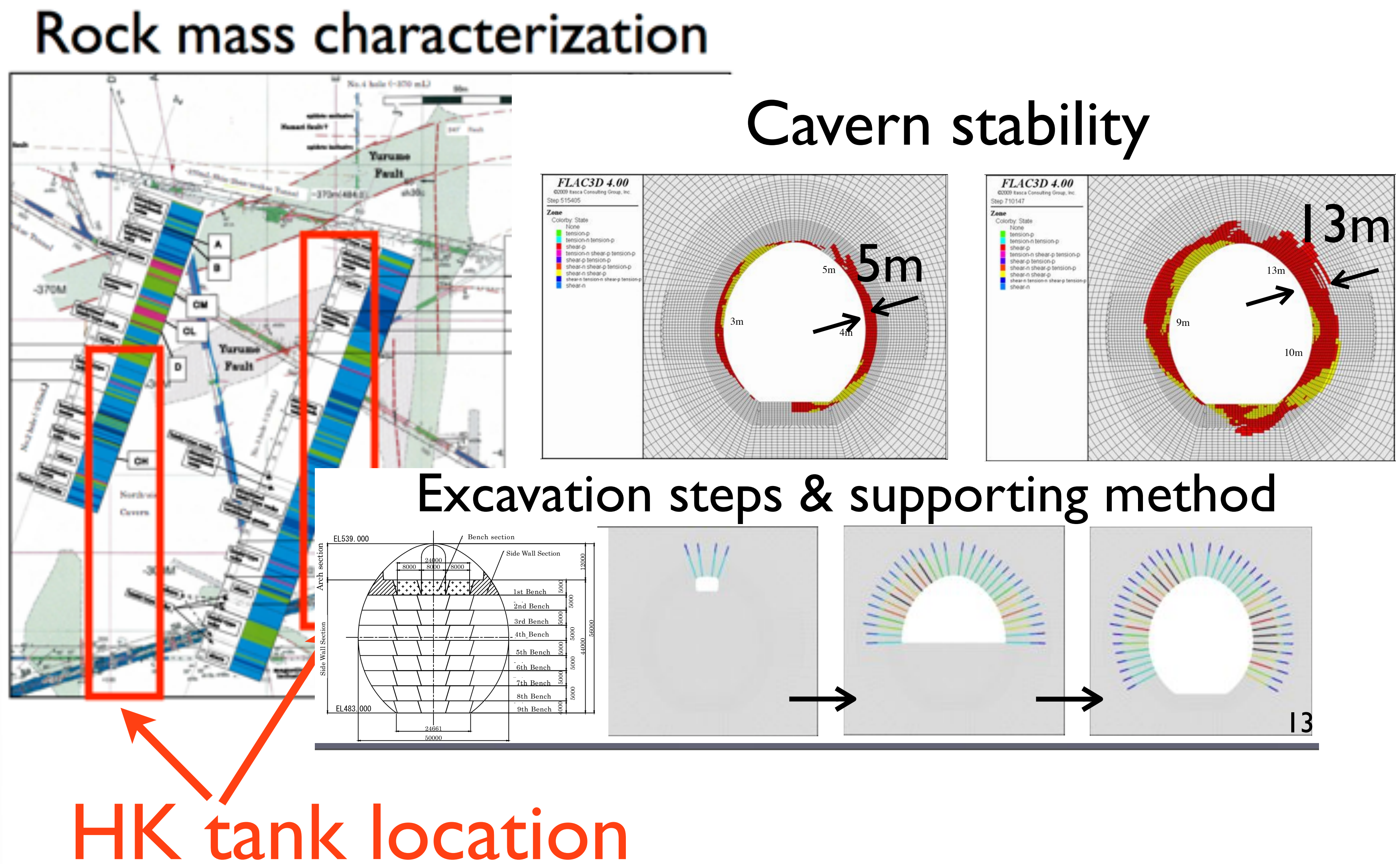
12 countries, 67 institutes, 240 people

(authors of proposal for J-PARC PAC in May 2014)

Site and Cavern

Candidate site:
~8km south of SK

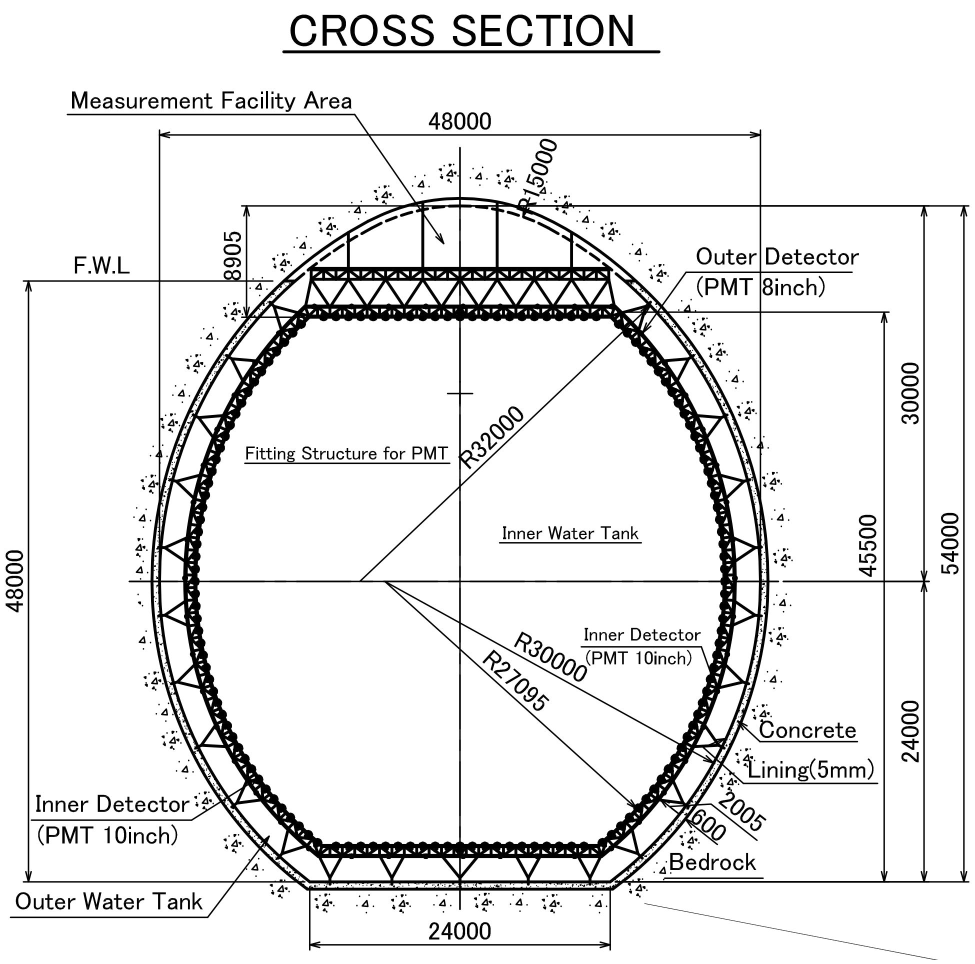




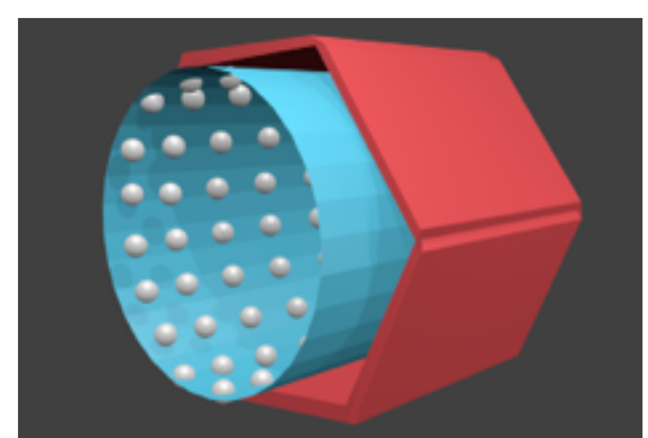
Cavity design studied based on the in-situ measurements of rock quality and stress

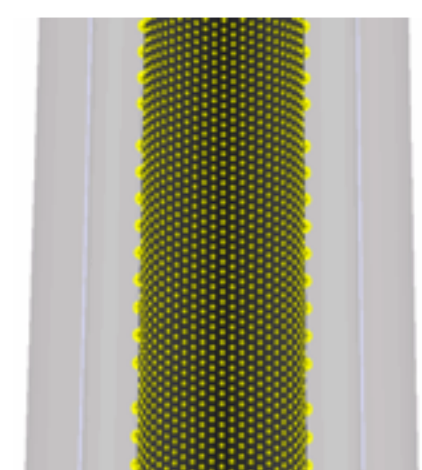
HK caverns can be constructed with existing technology

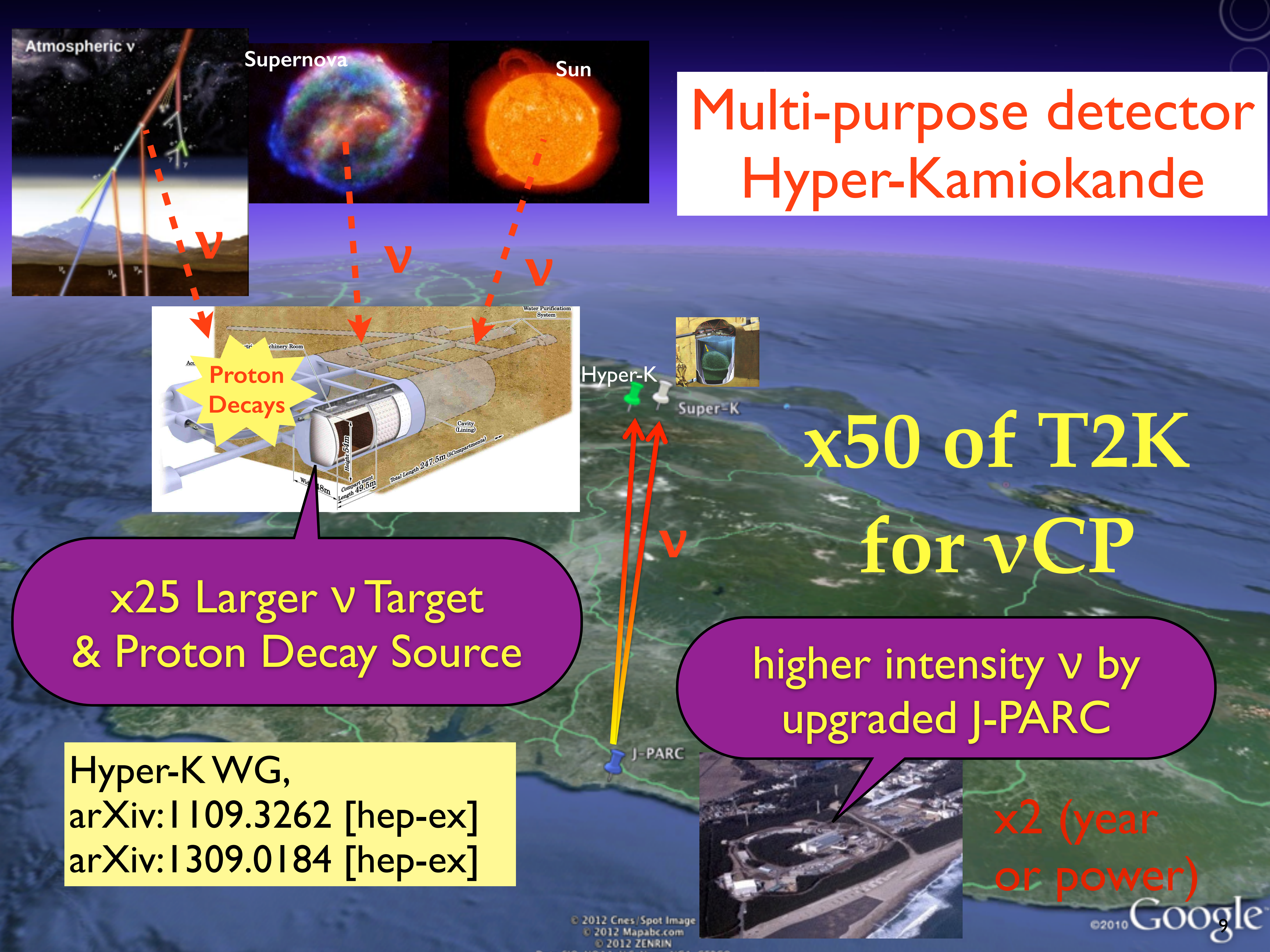
Detector design



- Baseline design established
  - Construction possible with current technology
- Some R&D for enhancing the capability and reduction of the cost
  - New photo-sensor development
  - Possible new near and intermediate detectors






Multi-purpose detector
Hyper-Kamiokande
Atmospheric ν
Supernova
Sun
ν
ν
ν
Water Purification System
Proton
Decays
Cavity (Lining)
Total Length 247.5m (8Compartments)
Compartment Length 49.5m
Height 64m
Hyper-K
Super-K
x50 of T2K
for νCP
ν
x25 Larger ν Target
& Proton Decay Source
J-PARC
higher intensity ν by
upgraded J-PARC
x2 (year
or power)
Hyper-K WG,
arXiv:1109.3262 [hep-ex]
arXiv:1309.0184 [hep-ex]
© 2012 Cnes/Spot Image
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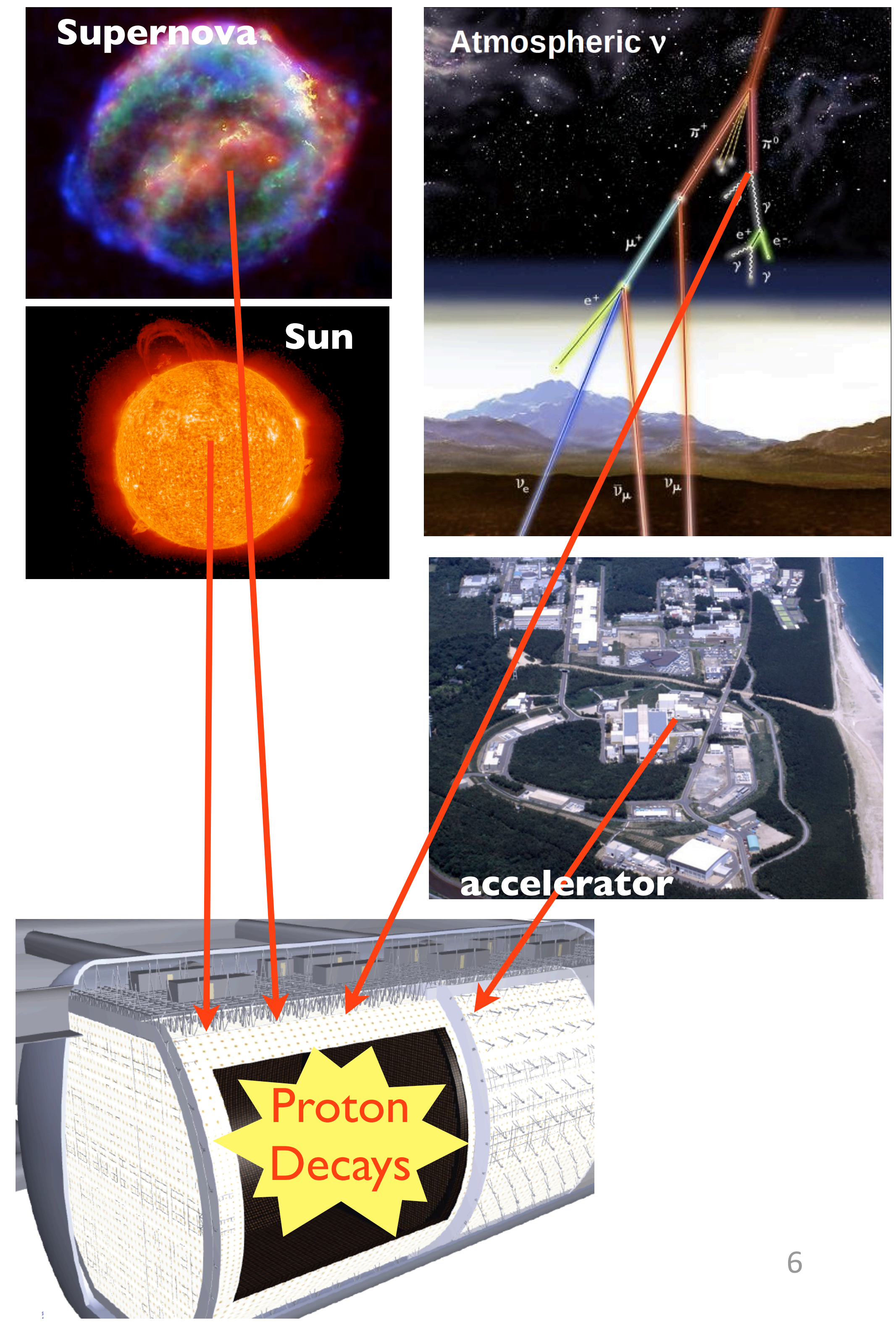
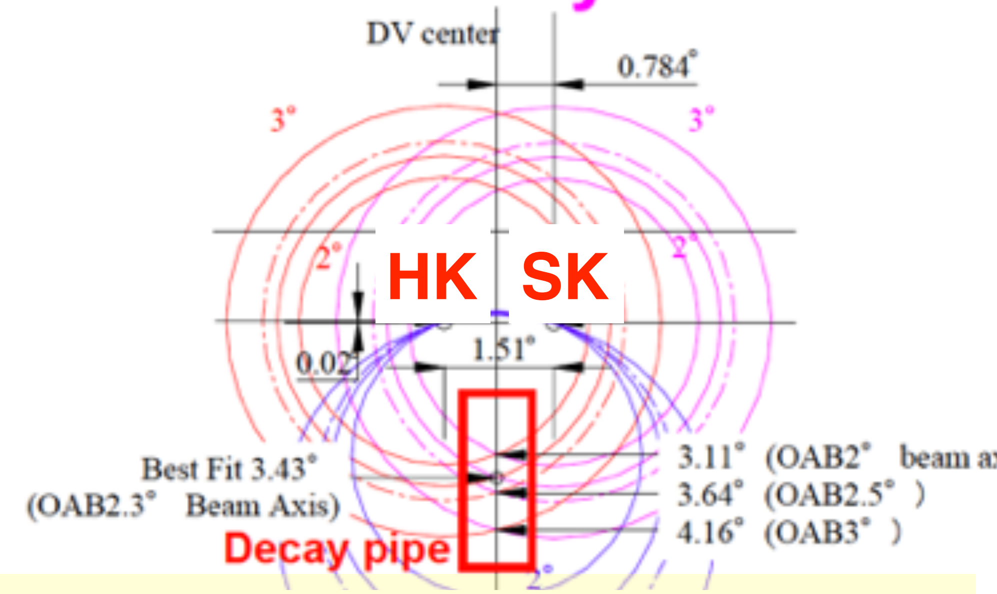
Broad science program with Hyper-K

- Neutrino oscillation physics
- Search for nucleon decay
  - Possible discovery with ~×10 better sensitivity than Super-K
  - $e^+\pi^0$: 5.7×10^{34} years,
    $K^+\overline{\nu}$: 1.2×10^{34} years (3σ)
- Neutrino astrophysics
  - ~200,000 ν events for SN @ 10kpc (Galactic center)
  - Detection (~830 ν) and study of relic SN neutrinos
- Geophysics (neutrinography of interior of the Earth)
- Maybe more (unexpected)

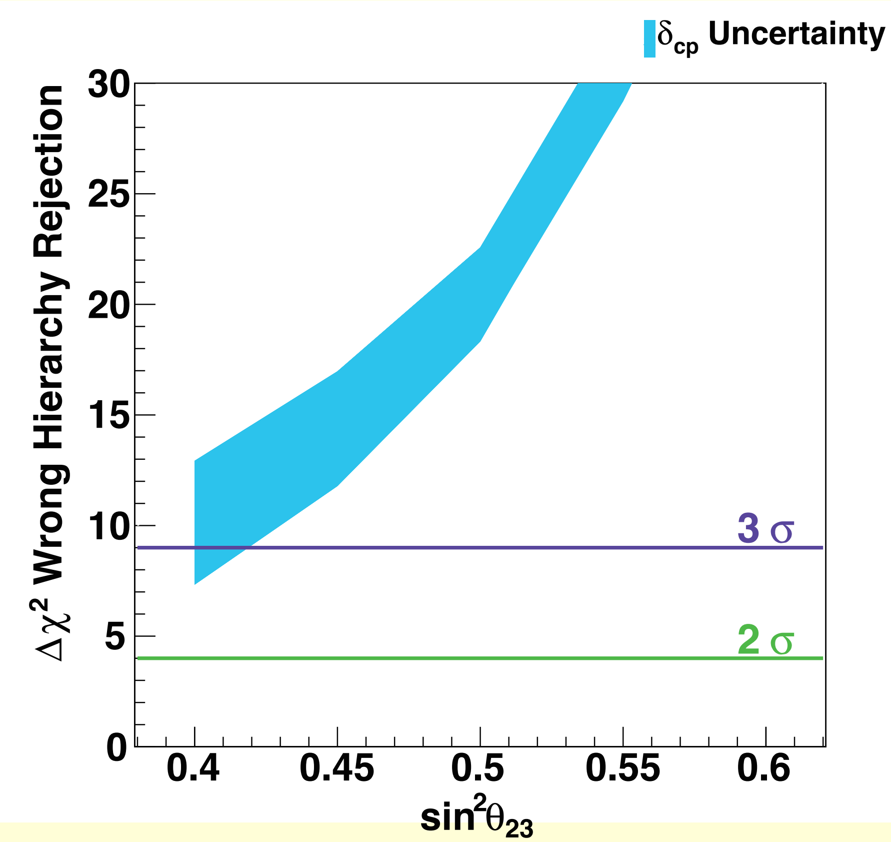


ν oscillation study w/ Hyper-K

- Long baseline experiment with J-PARC neutrino beam
  - Same configuration as T2K
    - Well understood beam and systematics (NA61 etc.)
    - Reliable sensitivity estimate based on T2K results
  - Main focus on CP asymmetry
- Atmospheric neutrino
  - >3σ determination of mass hierarchy and θ_{23} octant



J-PARC ν beamline designed to have the same off-axis for Super-K & Hyper-K

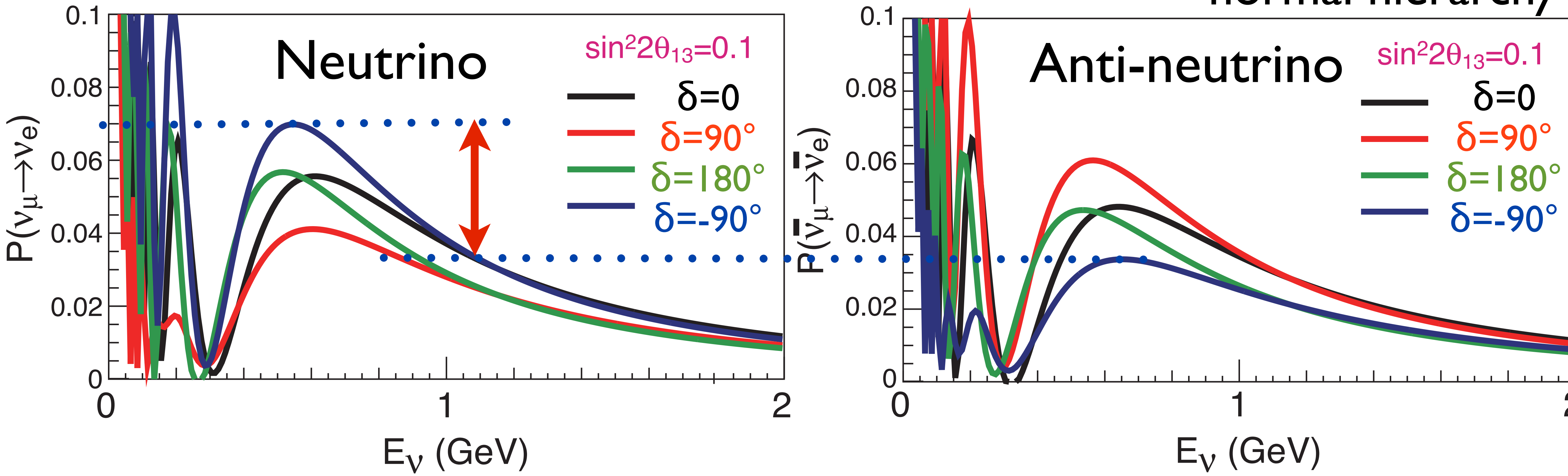


Mass hierarchy sensitivity by atm ν

Measurement of *CP* asymmetry with ν beam

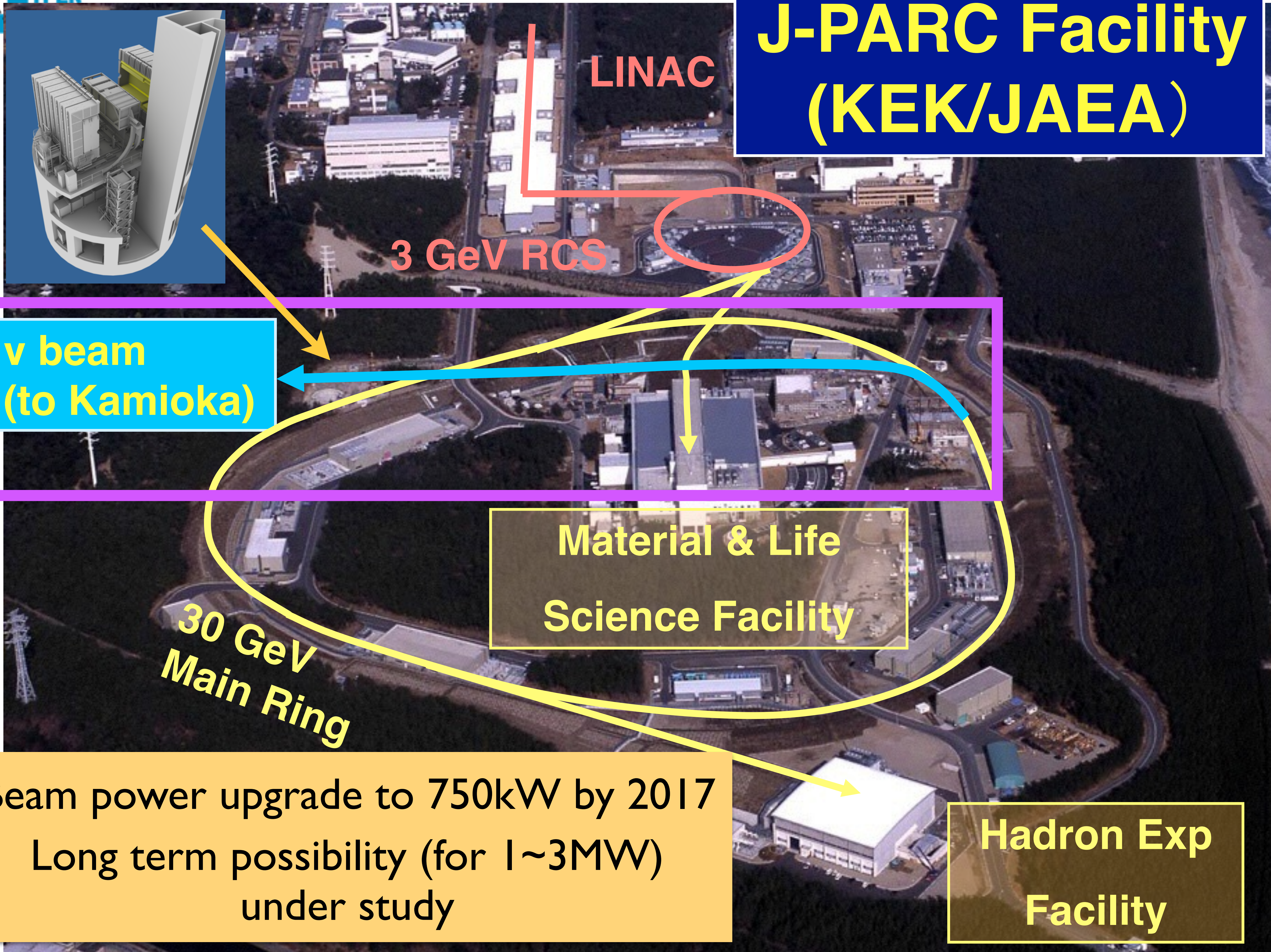
$P(\nu_\mu \to \nu_e)$: ν_e appearance probability

for 295km baseline,
normal hierarchy



- Comparison of $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$
  - Max. ~±25% change from δ=0 case
  - Sensitive to exotic (non-MNS) CPV source

J-PARC Facility (KEK/JAEA)



Beam power upgrade to 750kW by 2017
Long term possibility (for 1~3MW) under study

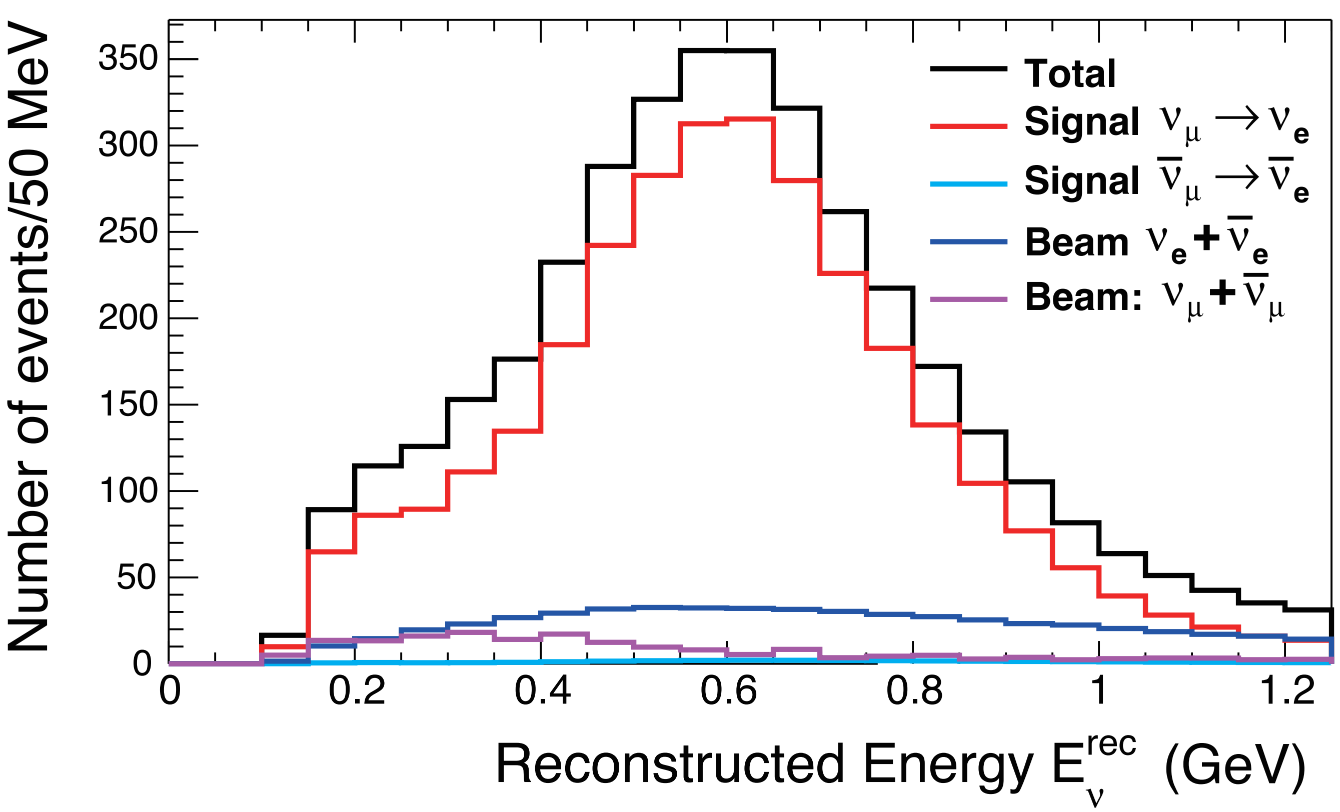
Reconstructed energy distributions

$7.5\text{MW} \times 10^7\text{s}$ (1.56×10^{22} POT)

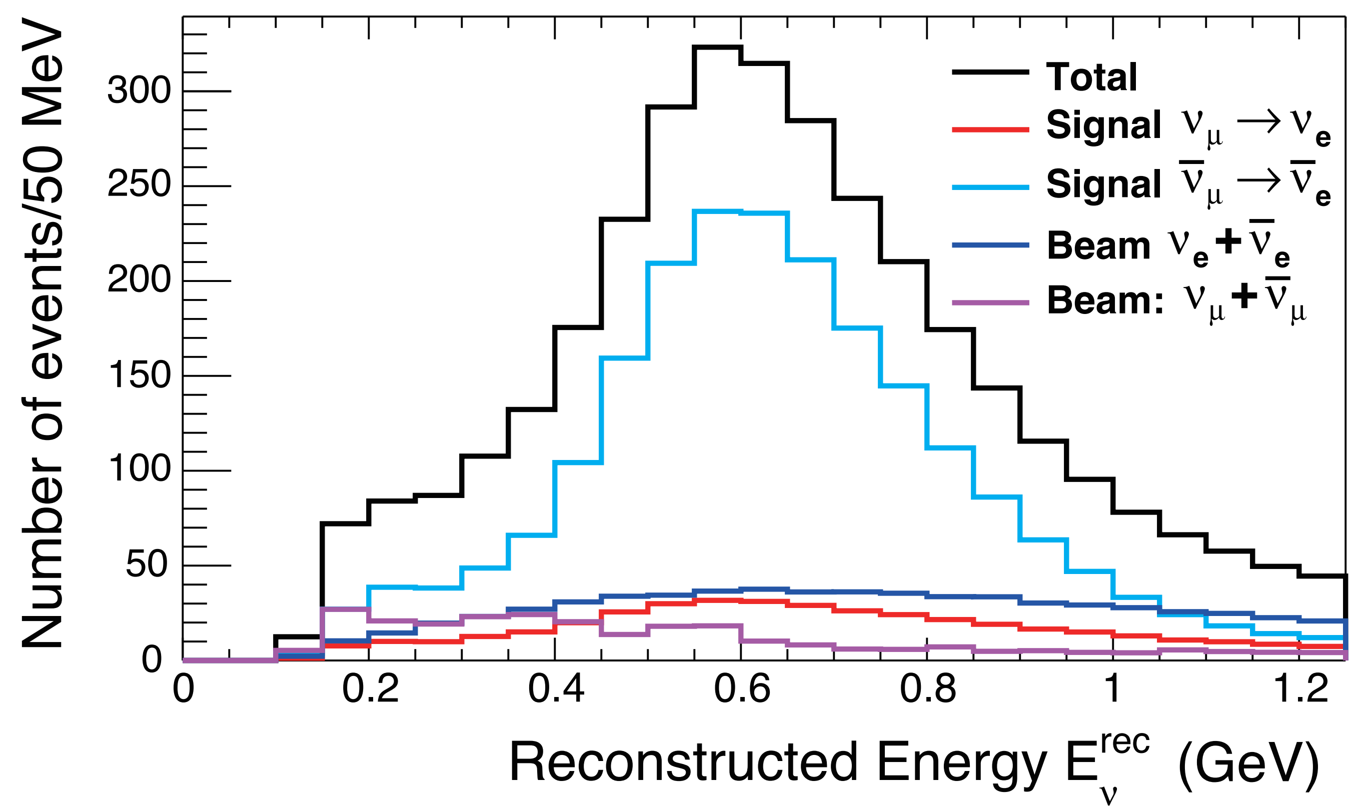
$\sin^2 2\theta_{13}=0.1, \delta=0$, normal MH

$\nu:\bar{\nu}=1:3$

Appearance ν mode



Appearance $\bar{\nu}$ mode



	Signal (νμ→νe CC)	Wrong sign appearance	νμ/$\bar{\nu}$μ CC	beam νe/$\bar{\nu}$e contamination	NC
ν	3,016	28	11	523	172
$\bar{\nu}$	2,110	396	9	618	265

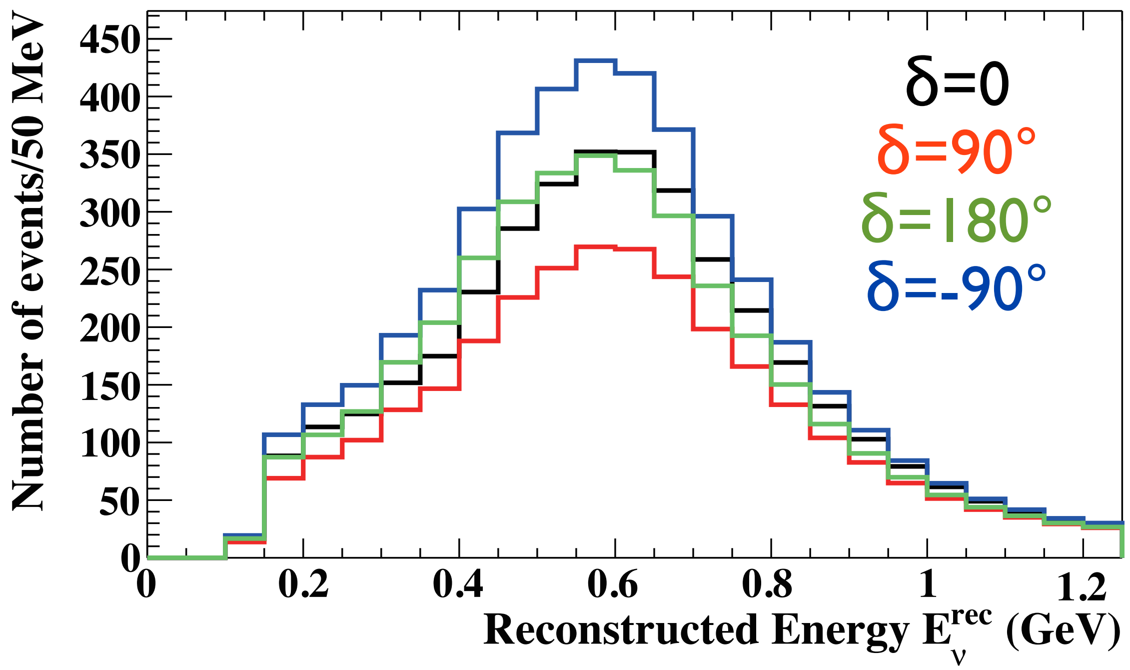
New π^0 rejection (fiTQun) applied

δ_{CP} dependence of observables

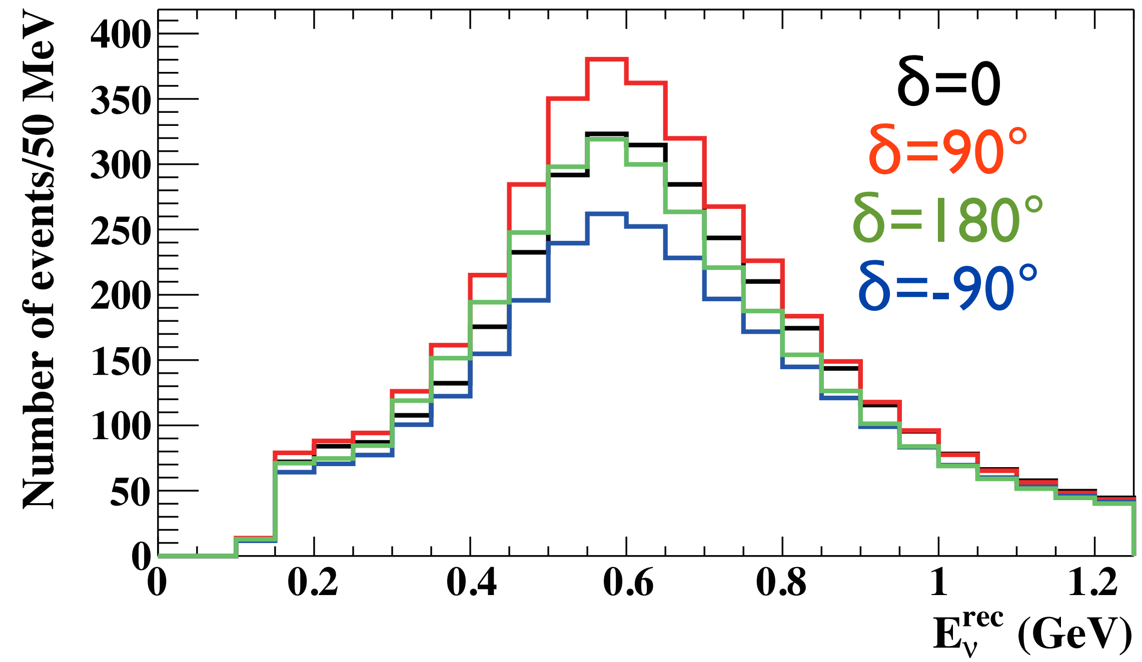
7.5MW×10^7s (1.56×10^{22} POT)

νe candidates

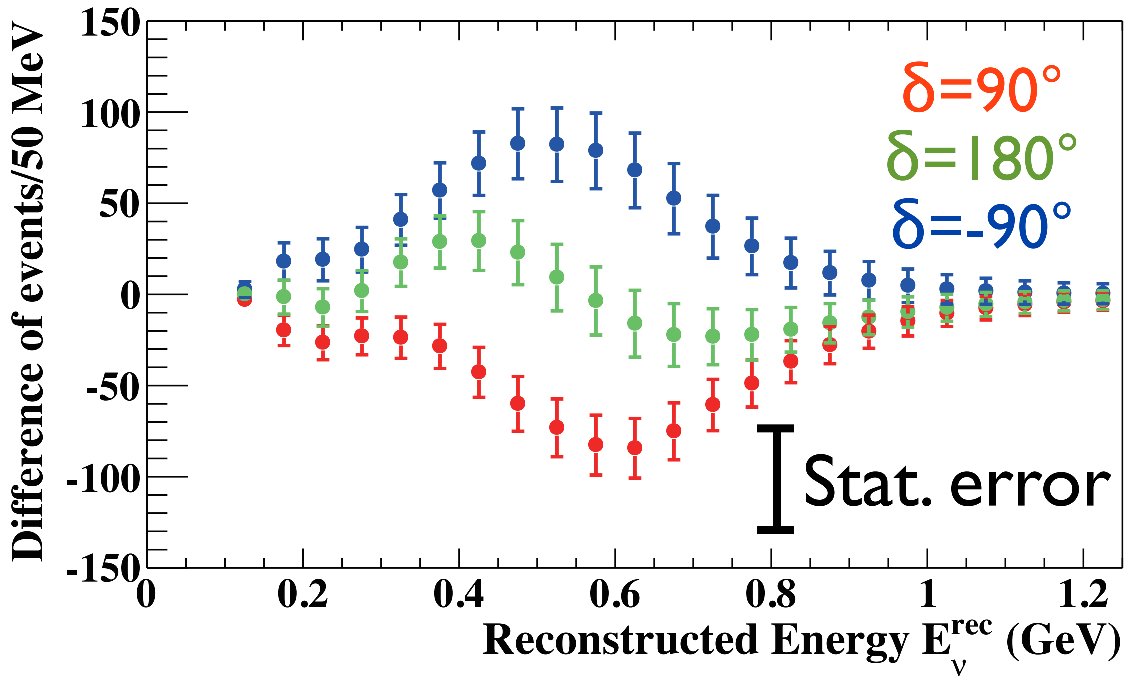
Neutrino mode: Appearance

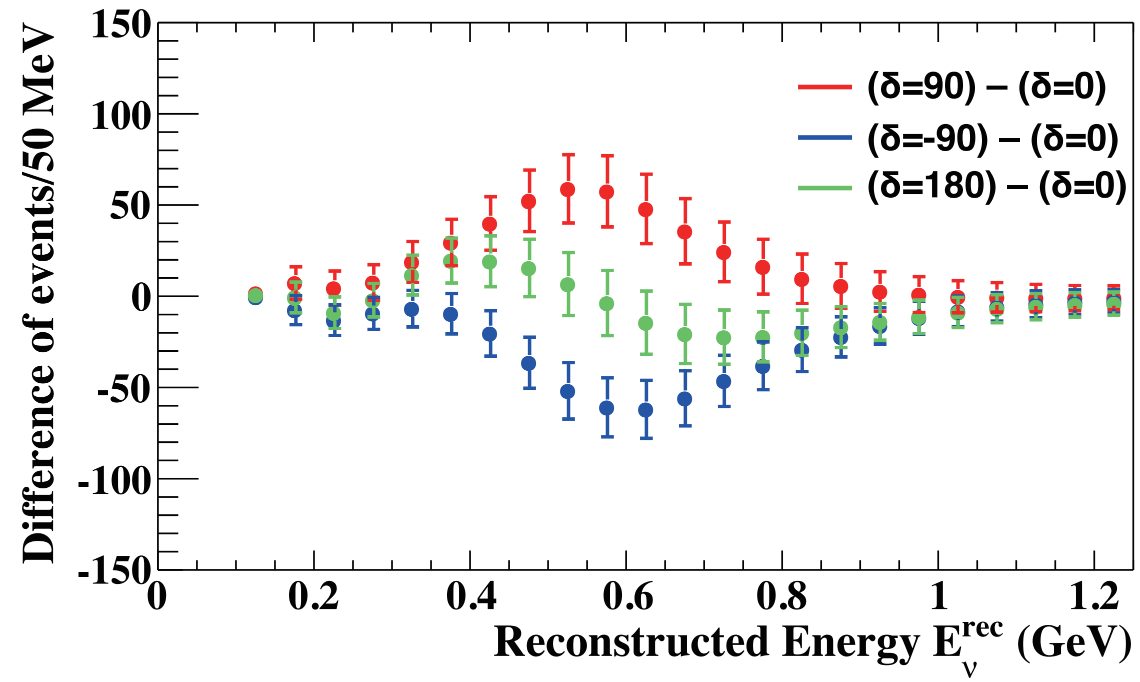


Antineutrino mode: Appearance



Difference from δ=0





Sensitive to all values of δ with numbers + shape

Sensitivity study

Updated in May 2014

- Based on the framework developed for T2K future sensitivity study
  - Fit reconstructed E_ν distributions
  - Both ν_e and ν_μ samples, for ν and anti-ν run
  - Fit $\sin^2\theta_{23}$, Δm^2_{32}, $\sin^2 2\theta_{13}$, δ_{CP}
  - Mass hierarchy assumed to be known (from other experiments and/or HK atmospheric ν)
- Systematic error estimated based on T2K experience/ prospects
  - Implemented as covariance matrix, including correlation between energy/flavor bins

Assumed systematic uncertainties

- Beam flux + near detector constraint
  - Conservatively assumed to be the same
- Cross section uncertainties not constrained by ND
  - Nuclear difference removed assuming water measurements
- Far detector
  - Reduced by increased statistics of atmospheric ν control sample

Uncertainty on the expected number of events at Hyper-K (%)

	ν mode		anti-ν mode	
	νe	νμ	νe	νμ
Flux&ND	3.0	2.8	5.6	4.2
XSEC model	1.2	1.5	2.0	1.4
Far Det. +FSI	0.7	1.0	1.7	1.1
Total	3.3	3.3	6.2	4.5

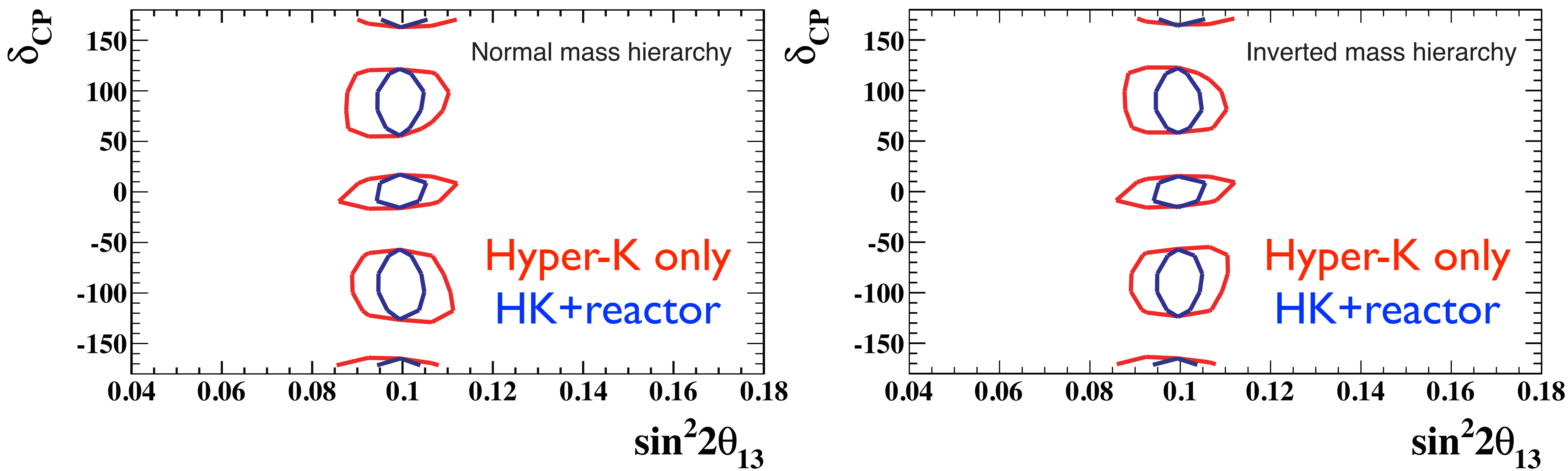
(T2K 2014)	
νe	νμ
3.1	2.7
4.7	5.0
3.7	5.0
6.8	7.6

- Further reduction by new near detectors under study

Expected sensitivity to CP asymmetry

Mass hierarchy assumed to be known

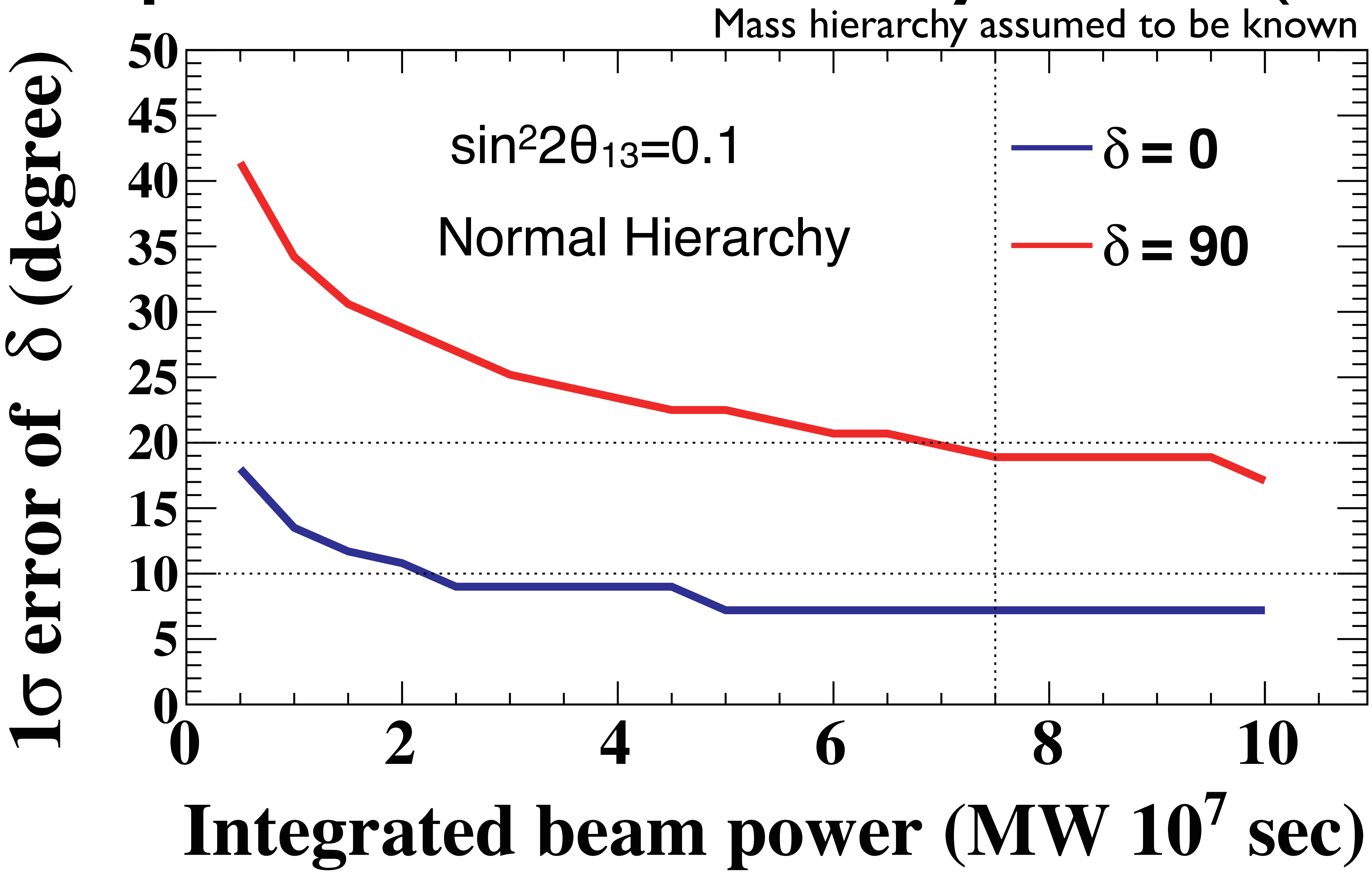
90% CL contour on $\sin^2 2\theta_{13}$-δ plane
(δ=0°, 90°, 180°, -90° overlaid)



$7.5\text{MW} \times 10^7\text{s}$ (1.56×10^{22} POT)

- Excellent δ_{CP} measurement capability

Expected uncertainty of δ (1σ)

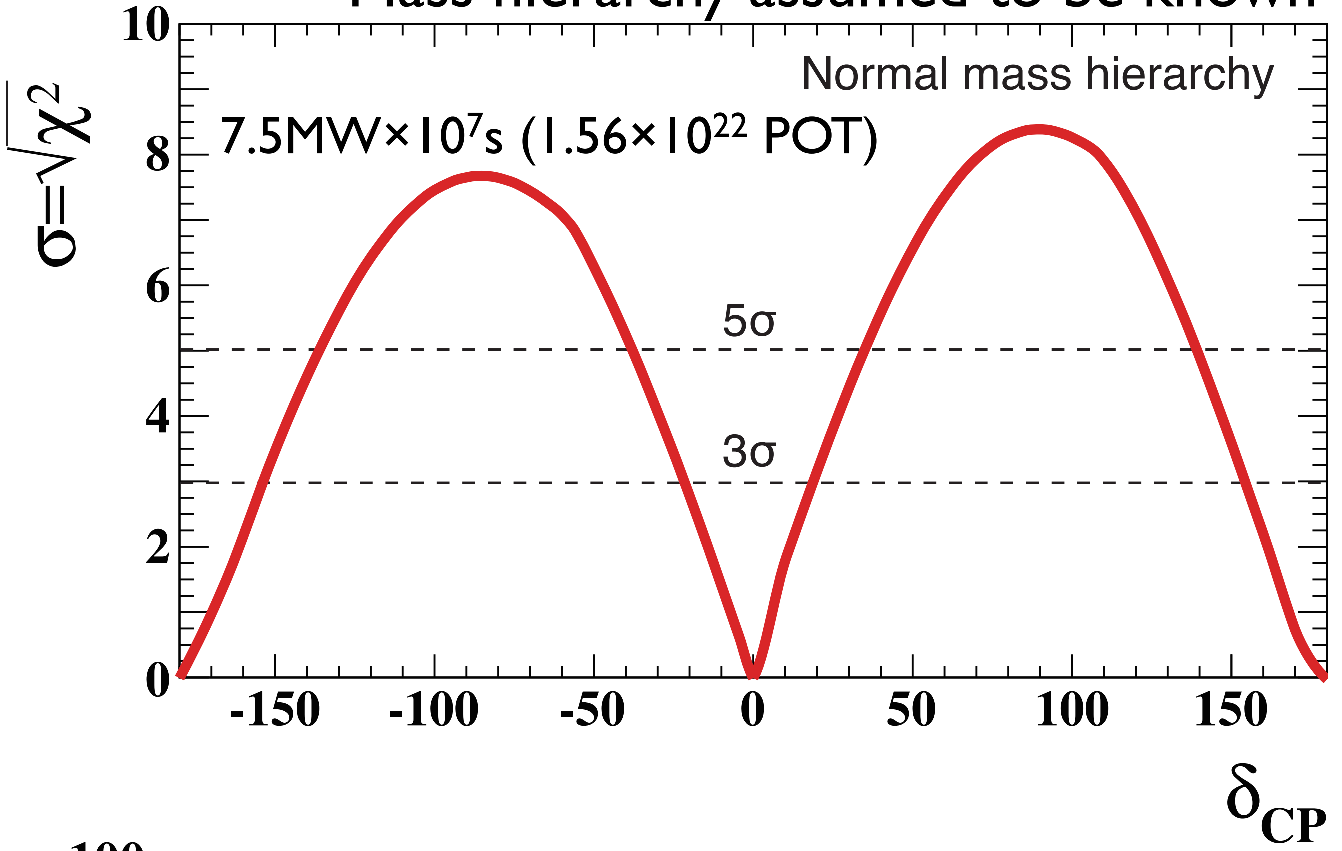


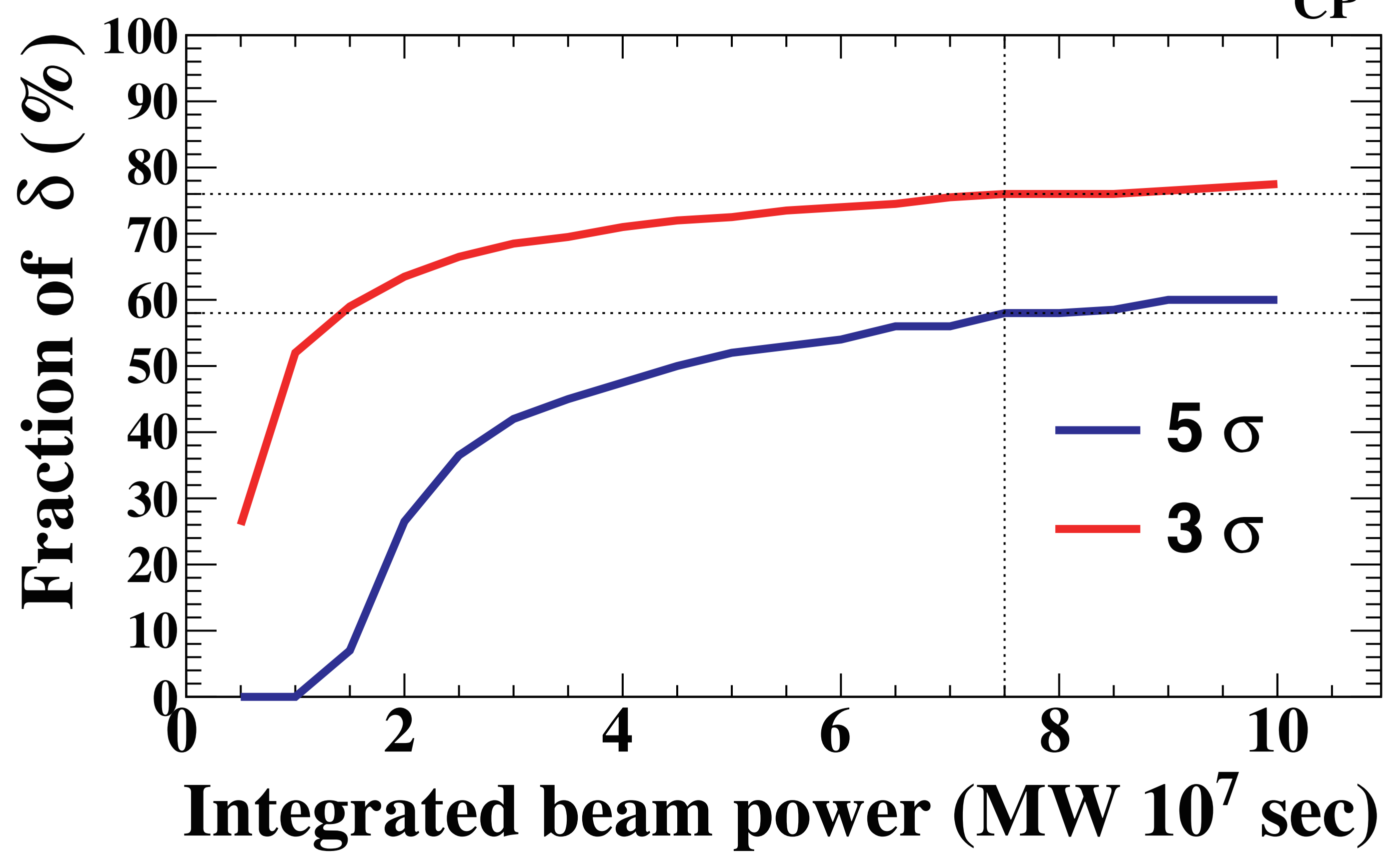
- 8°-19° depending on the true value of δ

Sensitivity to CP violation

- Exclusion of sinδ=0
  - >3σ for 76% of δ
  - >5σ for 58% of δ
- Possible to establish CP violation in the lepton sector!

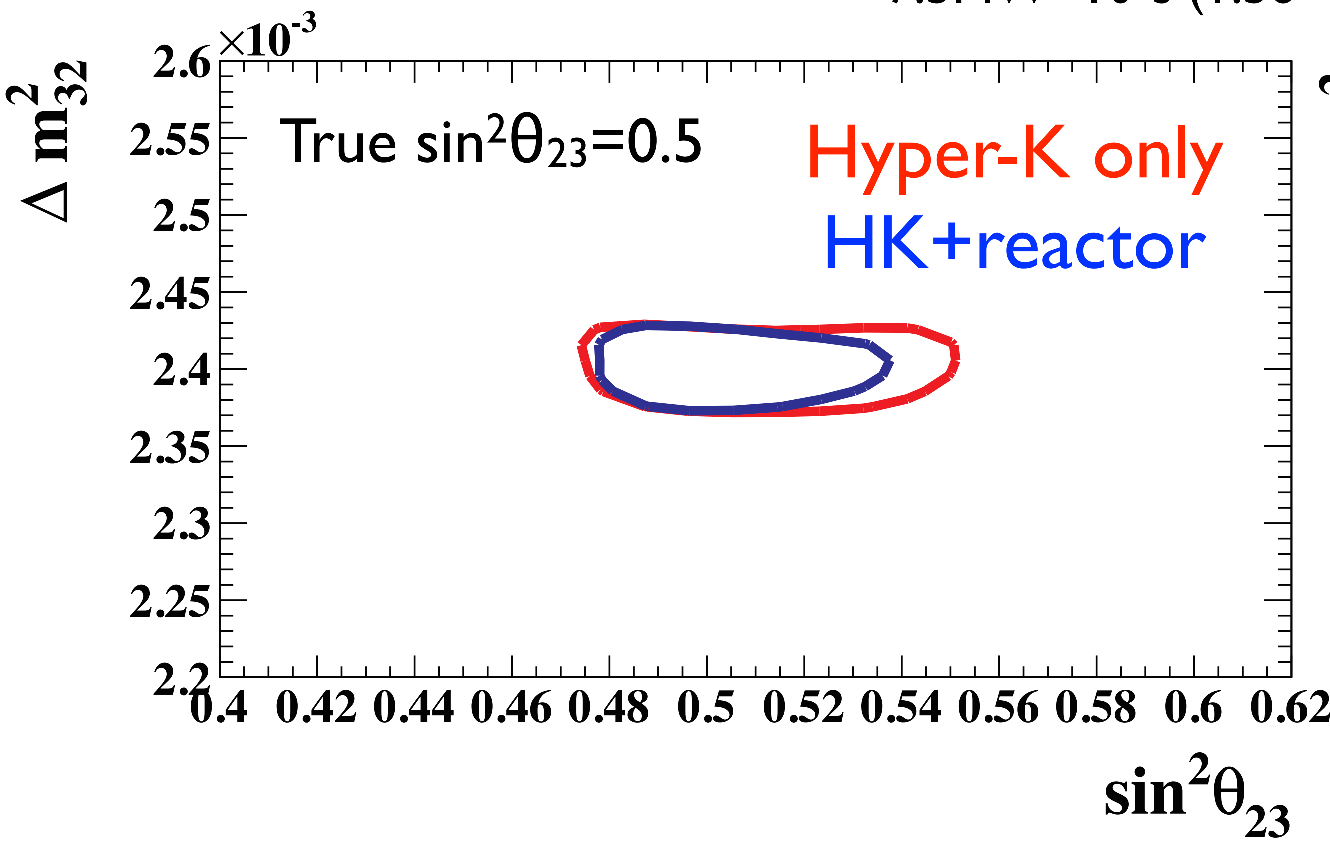
Mass hierarchy assumed to be known

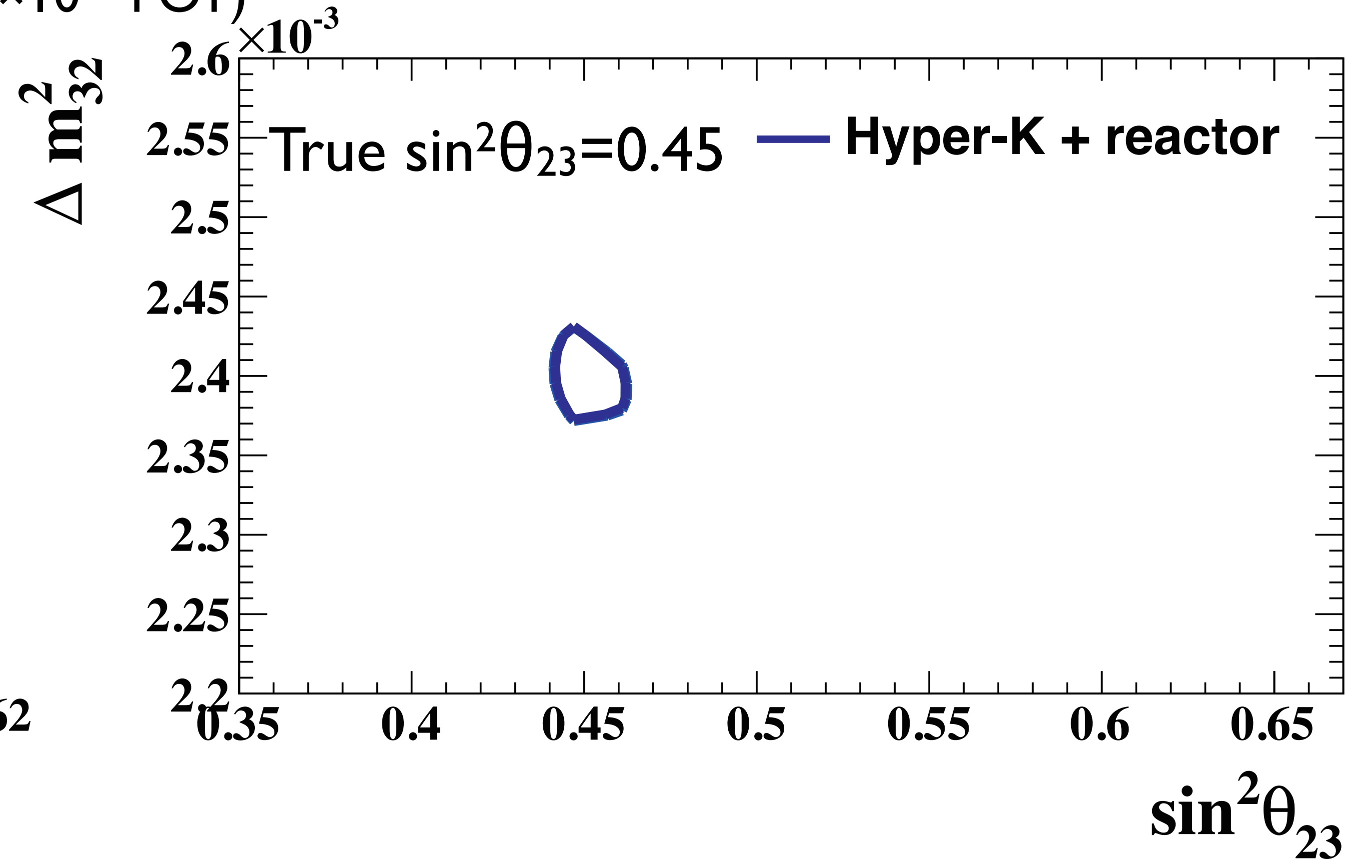




Measurement of Δm^2_{32}, θ_{23}

$7.5\text{MW}\times10^7\text{s}$ (1.56×10^{22} POT)





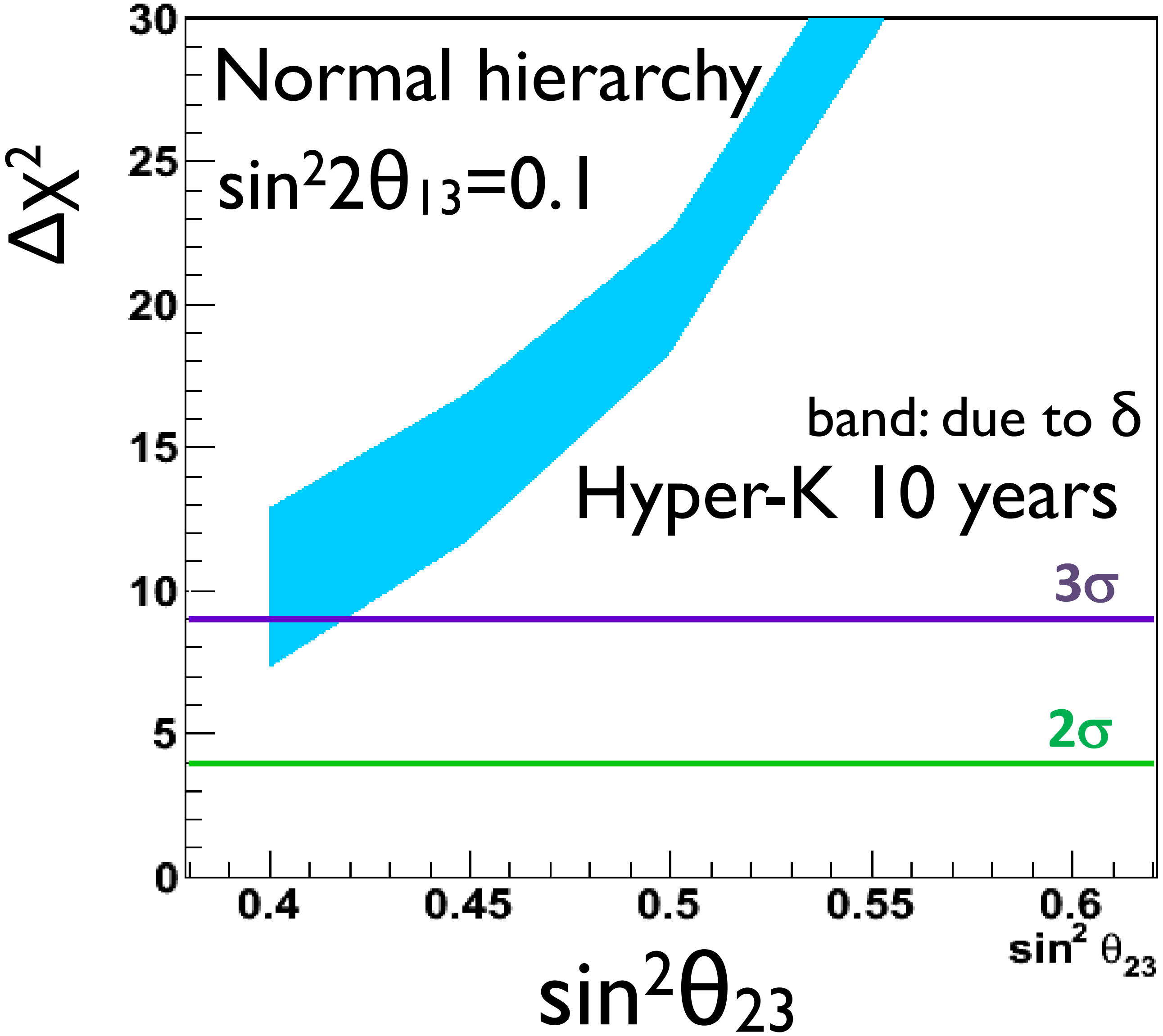
Expected 1σ uncertainty

True $\sin^2\theta_{23}$	0.45		0.50		0.55	
Parameter	Δm^2_{32}	$\sin^2\theta_{23}$	Δm^2_{23}	$\sin^2\theta_{23}$	Δm^2_{32}	$\sin^2\theta_{23}$
Normal hierarchy	1.4×10^{-5} eV^2	0.006	1.4×10^{-5} eV^2	0.015	1.5×10^{-5} eV^2	0.009
Inverted hierarchy	1.5×10^{-5} eV^2	0.006	1.4×10^{-5} eV^2	0.015	1.5×10^{-5} eV^2	0.009

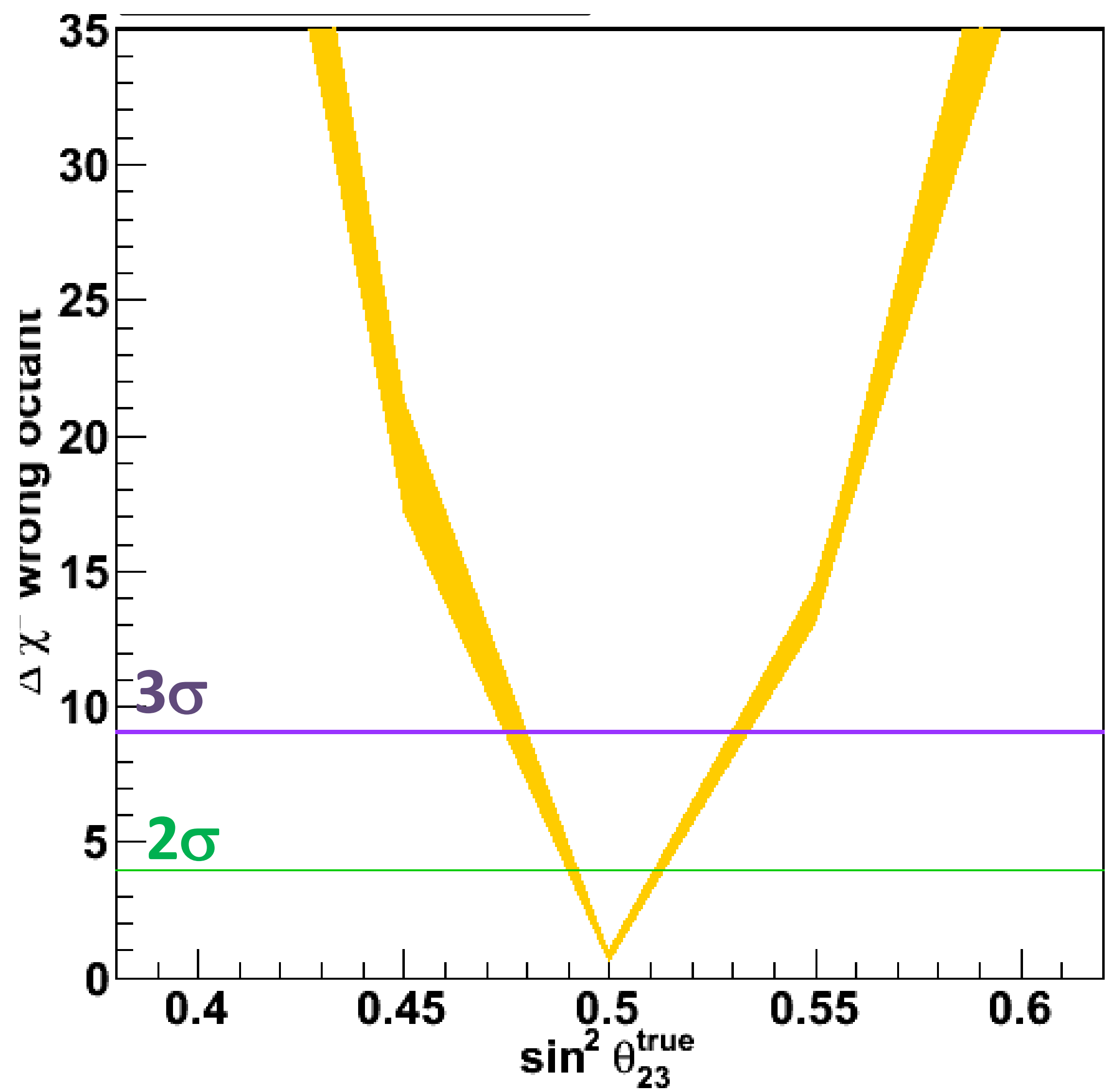
cf. T2K 2014 result: $\Delta m^2_{32}=2.51\pm0.10\times10^{-3}\text{eV}^2$, $\sin^2\theta_{23}=0.514\pm0.055$

Atmospheric ν

Mass hierarchy



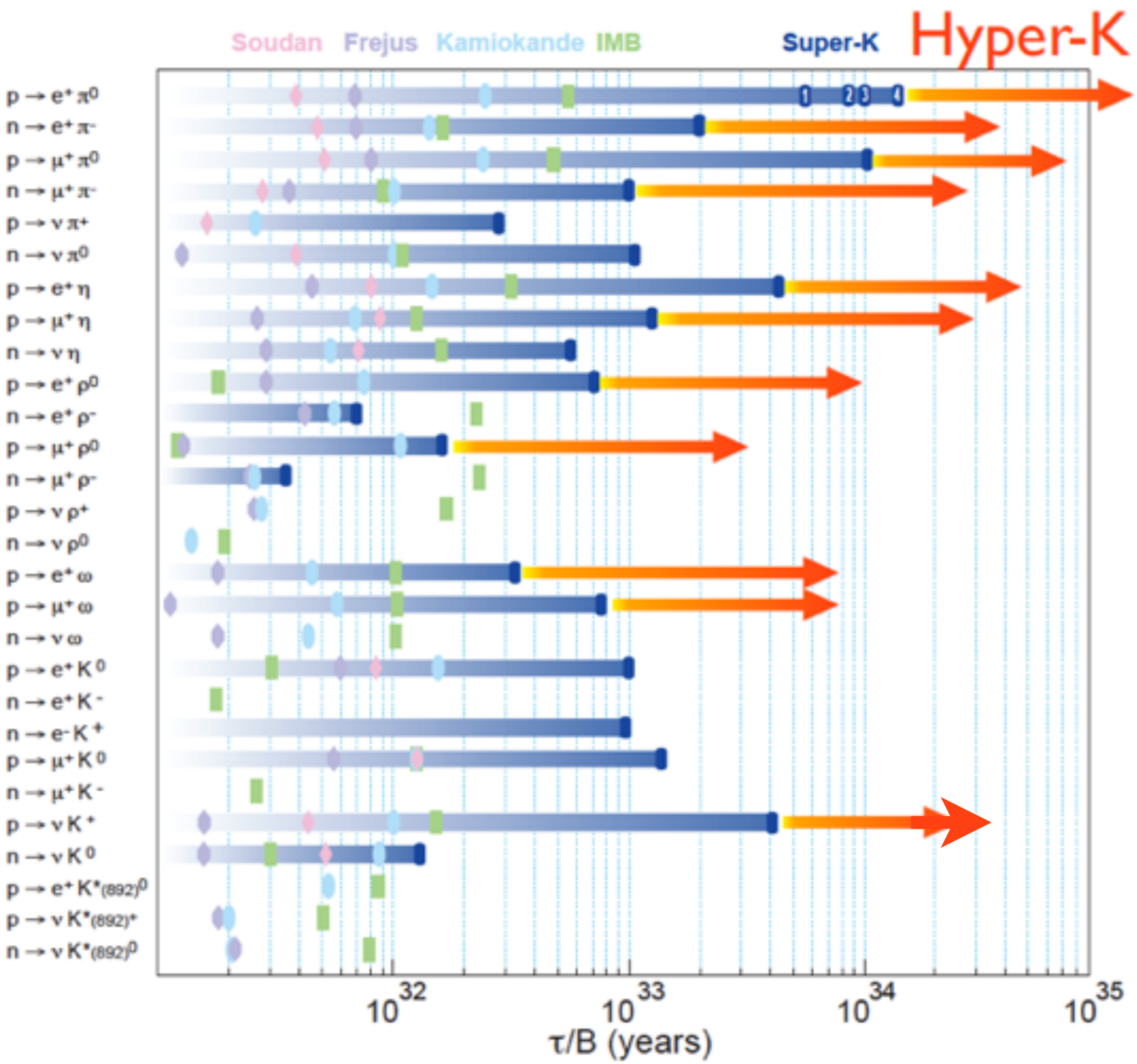
θ_{23} octant



Complementary measurements to accelerator ν
Combined analysis of acc + atm ν will enhance capability

Proton decay sensitivity

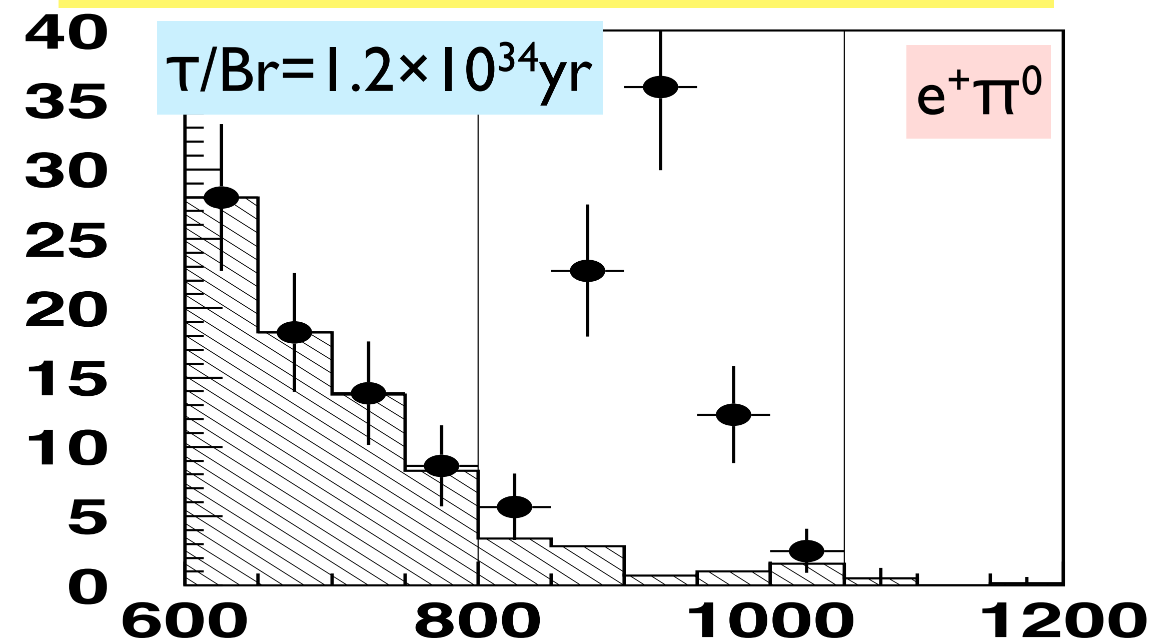
~10 times better sensitivity than current Super-K limits!



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

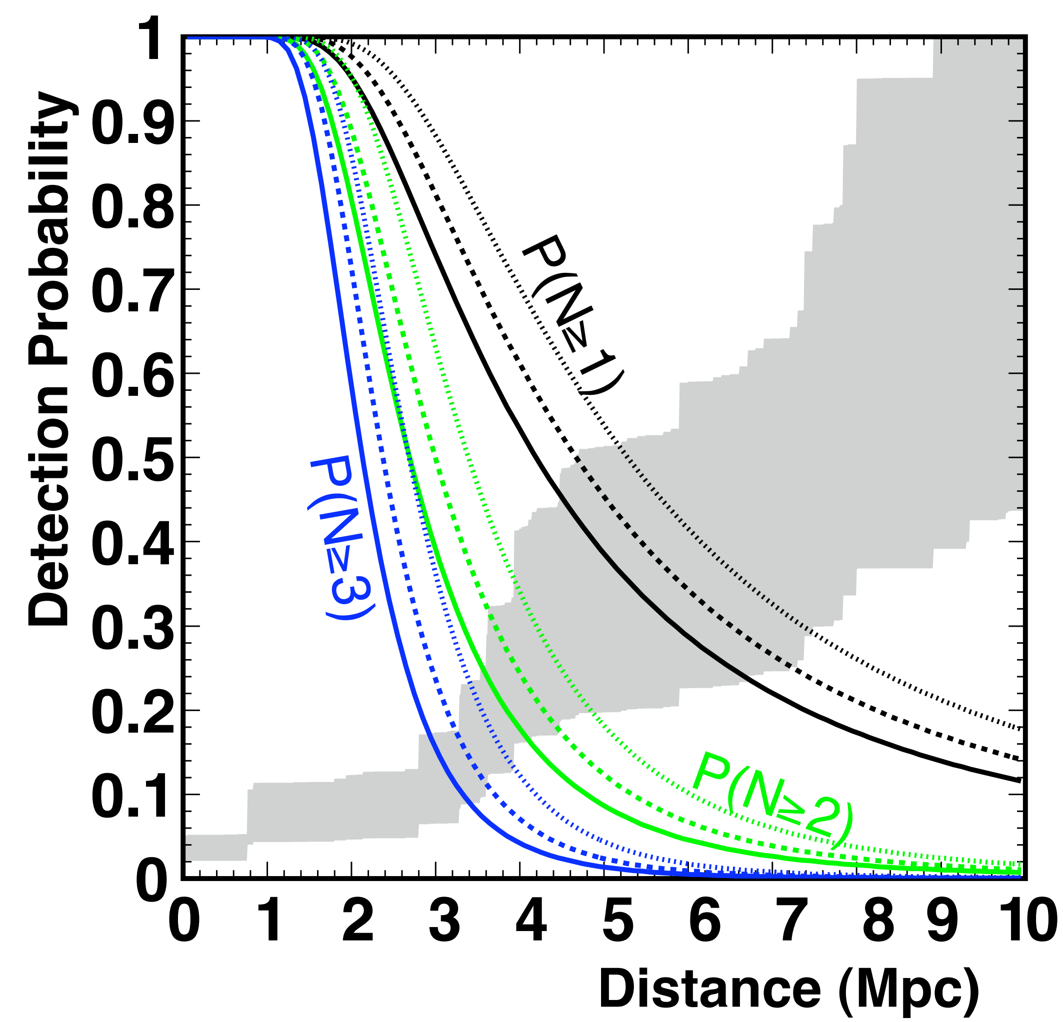
$p \to \bar{\nu}K^+$:
  - 3.2×10^{34}yrs (90%CL)
  - 1.2×10^{34}yrs (3σ)

>3σ possible for lifetime above current SK limits



Neutrino astrophysics

- **Supernova burst neutrino**
  - >50% efficiency with >3 multiplicity for <2Mpc SN (~1/10yrs expected)
  - Huge statistics if SN in our Galaxy
    - ~250k events @ 10kpc



- **Supernova relic neutrino**
  - ~800 events in 10 years
  - History of heavy element synthesis in the universe
- Precision measurements of solar neutrino
  - Spectrum upturn, day/night asymmetry
- Indirect WIMP Search

Hyper-K Working Group Organization

Steering Committee
Nakaya (chair)
Aihara, Nakahata, Shiozawa, Yokoyama
+ a few more

- oversee the HK group
- channel for contacting to the group
- involve non-Japanese in future

International board of representative (IBR)
a few members from each country

- represent each countries
- budget request in each countries

Project Leader
Shiozawa

- PL oversees the sub-WGs
- WG conveners may be composed of one Japanese plus some non-Japanese.

WG1: Shiozawa

WG2: Sekiya, Vagins

WG3: Nakayama, Nishimura

WG4: Hayato

WG5: Miura, Walter, F.D.Lodovico

WG6: Hide Tanaka, Hiro Tanaka, Koshio, Mine, Mccauley

WG7: Hartz

Physics WG conveners: Yokoyama

- **Phys-WG1**: Yokoyama
- **Phys-WG2**: Wendell
- **Phys-WG3**: Takeuchi

WG1: Cavity and Tank
WG2: Water
WG3: Photo-sensor
WG4: DAQ
WG5: Software
WG6: Calibration
WG7: Beam & Near Detectors

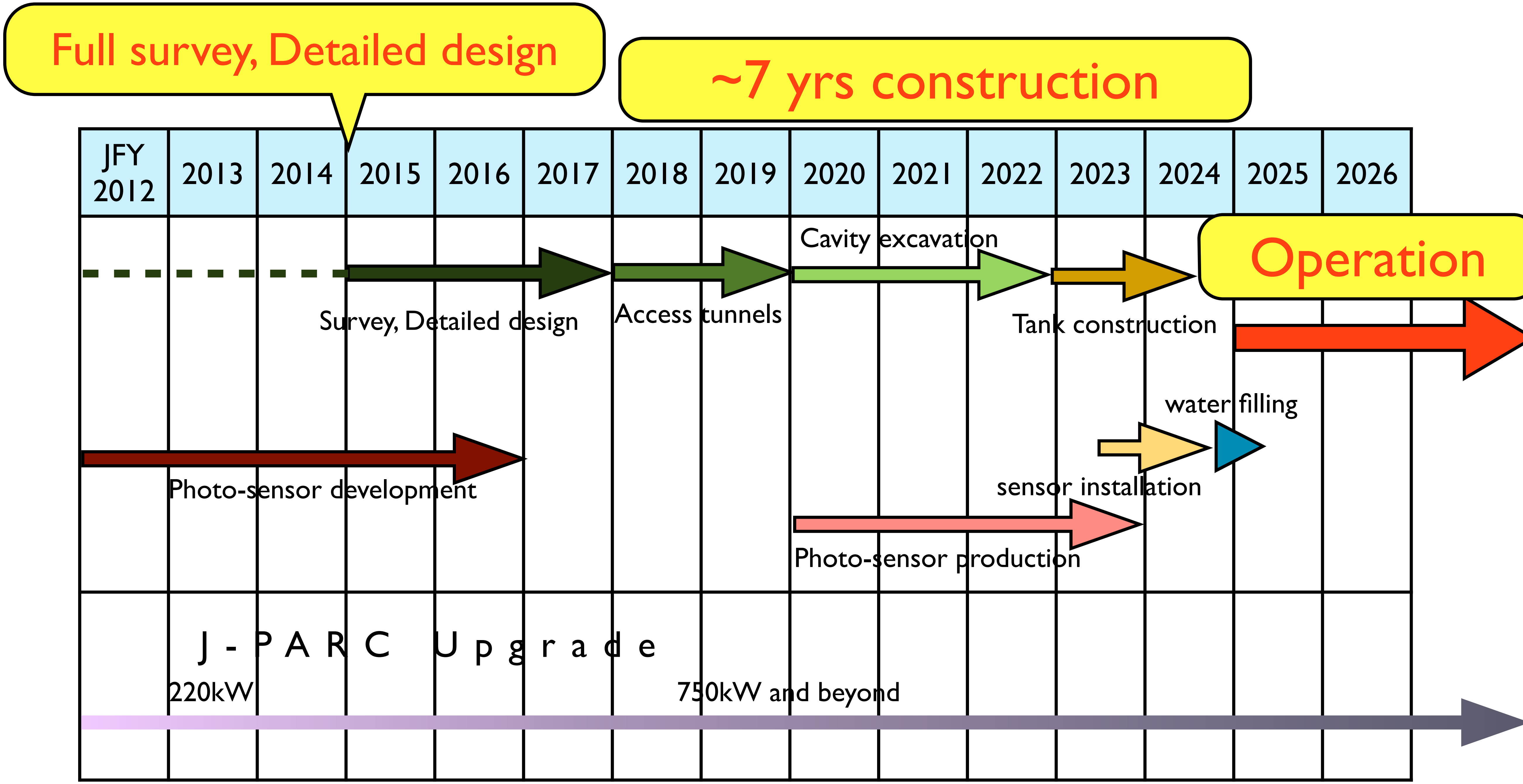
Phys-WG1: Accelerator
Phys-WG2: Atmν+Nucleon decays
Phys-WG3: Astroparticle Physics (SN, solarν, etc)

International working group

- Open meetings: twice/year since Aug. 2012
  - ~100 participants each time (~half from outside Japan)
  - Next: Jul.19-22 @ Vancouver, Canada
    http://bit.ly/5th-hyperk
  - EU-HK meeting: June 18 @ CERN
    http://bit.ly/HK-EU2

- International Board of Representative
  - Representatives from 13 countries:
    Brazil, Canada, France, Italy, Japan, Korea, Poland, Portugal, Russia, Spain, Switzerland, UK, USA
  - Seriously discussing contributions and cost sharing
- In Japan, Grant-in-aid for R&D program from JFY2013 (5 years)
- In Switzerland, included in the SERI inventory of planned research infrastructures
- Budget request for Hyper-K R&D projects being submitted in Canada and UK
- Travel grant request submitted in EU (UK, France, Italy, Poland, Spain)

Notional Timeline



-2015 Full survey, Detailed design (3 years)
-2018 Excavation start (7 years)
-2025 Start operation

Summary

- Hyper-Kamiokande will provide excellent opportunities for wide range of physics topics
  - Neutrino mixing and CP violation
  - Nucleon decays
  - Neutrino astronomy
- J-PARC ν beam + Hyper-K: with 7.5MW$\times 10^7$s beam (1.56×10^{22} POT), CP violation in the lepton sector can be established ($>3\sigma$) for 76% of the δ_{CP} space.

Backup

The Hyper-Kamiokande Working Group

Boston University (USA): E. Kearns, J.L. Stone

Chonnam National University (Korea): K.K. Joo, J.Y. Kim, I.T. Lim

Dongshin University (Korea): M.Y. Pac, J.H. Choi

Duke University (USA): A. Himmel, K. Scholberg, C.W. Walter

Earthquake Research Institute, The University of Tokyo (Japan): A. Taketa, H.K.M. Tanaka

ETH Zurich (Switzerland): F Bay, S Di Luise, A. Rubbia

Imperial College London (UK): M. Malek, Y. Uchida, M.O. Wascko

Institute for Particle Physics Phenomenology, Durham University (UK): P. Ballett, S. Pascoli, M. Ross-Lonergan

INFN and Dipartimento Interateneo di Fisica di Bari (Italy): V. Berardi, M.G. Catanesi, R.A. Intonti, L. Magaletti, E. Radicioni

INFN-LNF (Italy): A. Longhin

INFN and Università di Napoli (Italy): G. De Rosa, V. Palladino, C. Riccio

INFN and Università di Padova (Italy): G. Collazuol, M. Laveder, M. Mezzetto

INFN Roma (Italy): L. Ludovici

Institute for Nuclear Research (Russia): A. Izmaylov, M. Khabibullin, A. Khotjantsev, Y. Kudenko, O. Mineev, A. Shaikhiev, N. Yershov

Iowa State University (USA): I. Anghel, G. Davies, M.C. Sanchez, T. Xin

IRFU, CEA Saclay (France): S. Bolognesi, S. Emery, V. Galymov, E. Mazzucato, G. Vasseur, M. Zito

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Kobe University (Japan): A. T. Suzuki, Y. Takeuchi, T. Yano

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Los Alamos National Laboratory (USA): G. Sinnis

Louisiana State University (USA): F.d.M. Blaszczyk, J. Insler, T. Kutter, O. Perevozchikov, M. Tzanov

Miyagi University of Education (Japan): Y. Fukuda

Nagoya University (Japan): K. Choi, T. Iijima, Y. Itow

National Centre for Nuclear Research (Poland): J. Lagoda, E. Rondio

Okayama University (Japan): D. Fukuda, H. Ishino, Y. Koshio, T. Mori, M. Sakuda

Osaka City University (Japan): Y. Seiya, K. Yamamoto

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Queen Mary, University of London (UK): L. Cremonesi, F. Di Lodovico, T. Katori, P.P.J. Martins, R.A. Owen, R. Sacco, S. Short, R. Terri, J.R. Wilson

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University of California, Irvine (USA): G. Carminati, S. Horiuchi, W.R. Kropp, S. Mine, M.B. Smy, H.W. Sobel

University of Edinburgh (UK): P. Beltrame, G. Cowan, F. Muheim, M. Needham

University of Geneva (Switzerland): A. Blondel, A. Bravar, Y. Karadhzov, A. Korzenev, E. Noah, M. Ravonel, M. Rayner, R. Asfandiyarov, L. Haegel, A. Haesler, C. Martin, E. Scantamburlo

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University of Liverpool (UK): C. Andreopoulos, N. McCauley, D. Payne, H.J. Rose, C. Touramanis

University of Oxford (UK): G. Barr, D. Dewhurst, D. Wark, A. Weber

University of Pittsburgh (USA): V. Paolone

University of Regina (Canada): M. Barbi, R. Tacik

University of Rochester (USA): K.S. McFarland

Universidade de São Paulo (Brazil): H. Minakata

University of Sheffield (UK): S.L. Cartwright, J.D. Perkin, L.F. Thompson

University of Tokyo (Japan): H. Aihara, Y. Suda, M. Yokoyama

University of Toronto (Canada): J.F. Martin

University of Warsaw (Poland): M. Posiadala-Zezula

University of Warwick (UK): J.J. Back, G.J. Barker, S.B. Boyd, D.R. Hadley

University of Washington (USA): J. Detwiler, N. Tolich, R.J. Wilkes

University of Winnipeg (Canada): B. Jamieson

Virginia Tech (USA): C. Mariani, S.D. Rountree, R.B. Vogelaar

Wroclaw University (Poland): J. Sobczyk

York University (Canada): S. Bhadra

$\nu_\mu \rightarrow \nu_e$ Oscillation and CP violation

Leading

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

$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) = \; & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \\
& +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& +4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \\
& -8C_{13}^2 S_{12}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
& +8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2} (1 - 2S_{13}^2) \sin^2 \Delta_{31}
\end{aligned}
$$

Solar

Matter effect

$$a = G_F N_e \sqrt{2} \simeq (4000 \text{ km})^{-1}$$

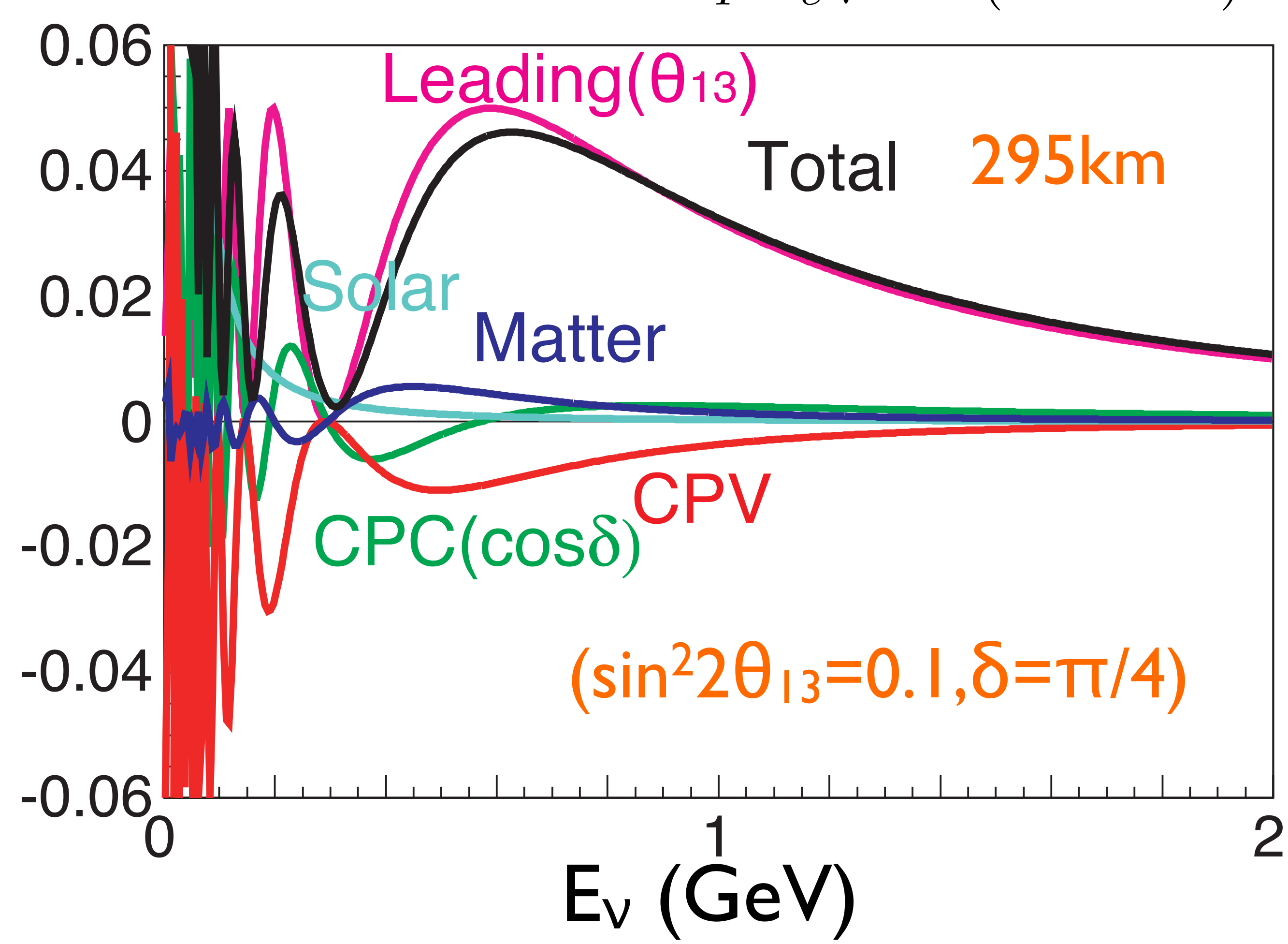
Leading term $\propto \sin^2 2\theta_{13}$

CPV term $\propto \sin 2\theta_{13}$

Matter effect $\propto \sin^2 2\theta_{13}$

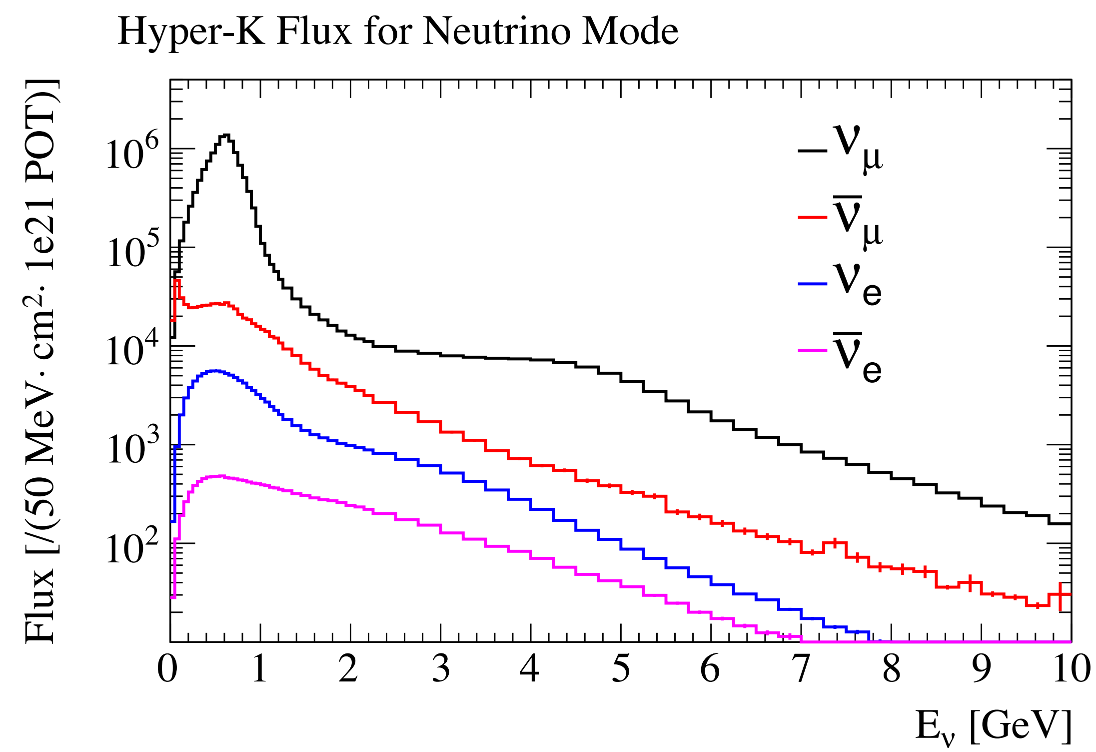
For larger $\sin^2 2\theta_{13}$
signal ↑, CP asymmetry ↓
matter/CP ↑

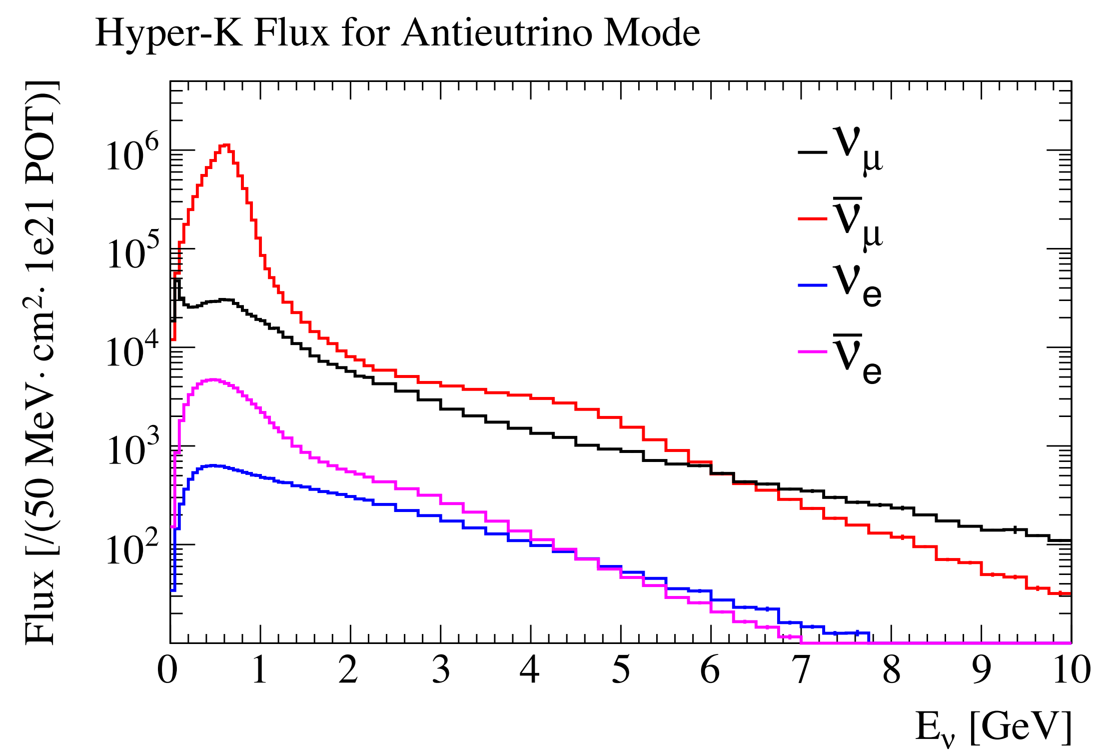
matter/CP~0.3 for $\sin^2 2\theta_{13}=0.1$ @L=295km



Neutrino beam

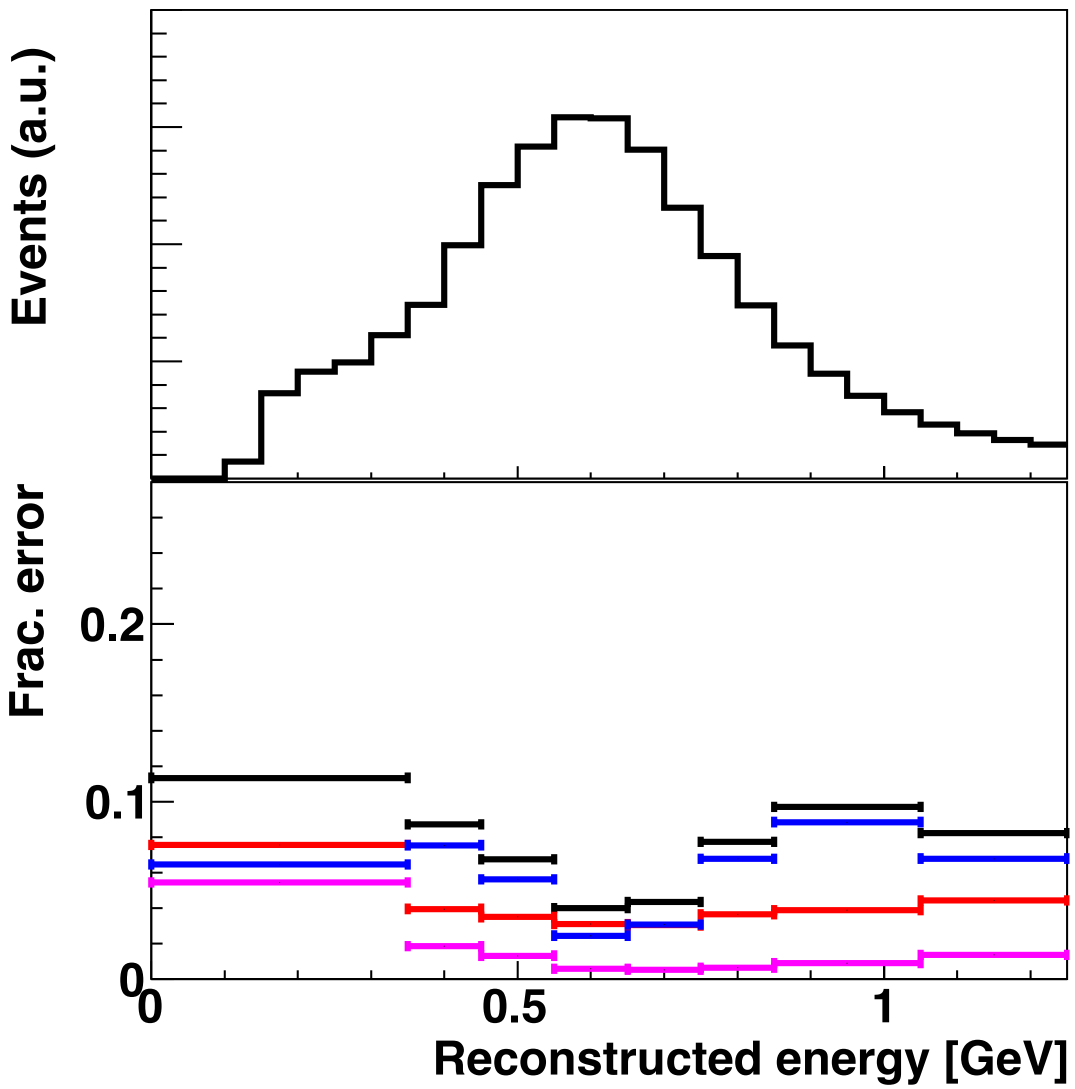
- The same beam as T2K
  - Horn current 320kA
  - Systematics well understood
- ≥750kW operation expected in Hyepr-K era
- Sensitivity estimated with 7.5MW×10^7s (1.56×10^{22} POT) as a baseline
  - 10 years if 750kW, 10^7s/year
  - More beam power strongly desired



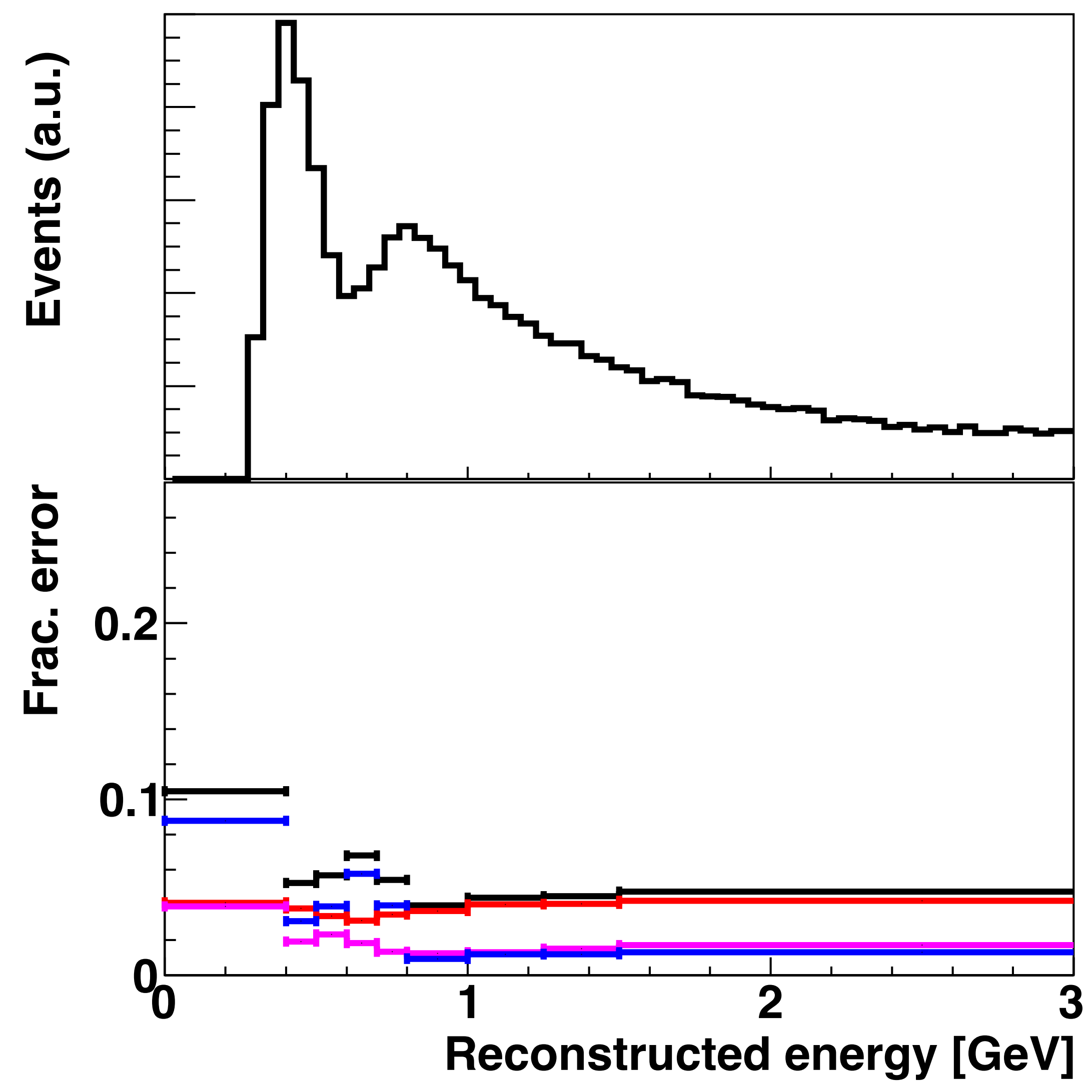


Fractional uncertainty

ν_e sample

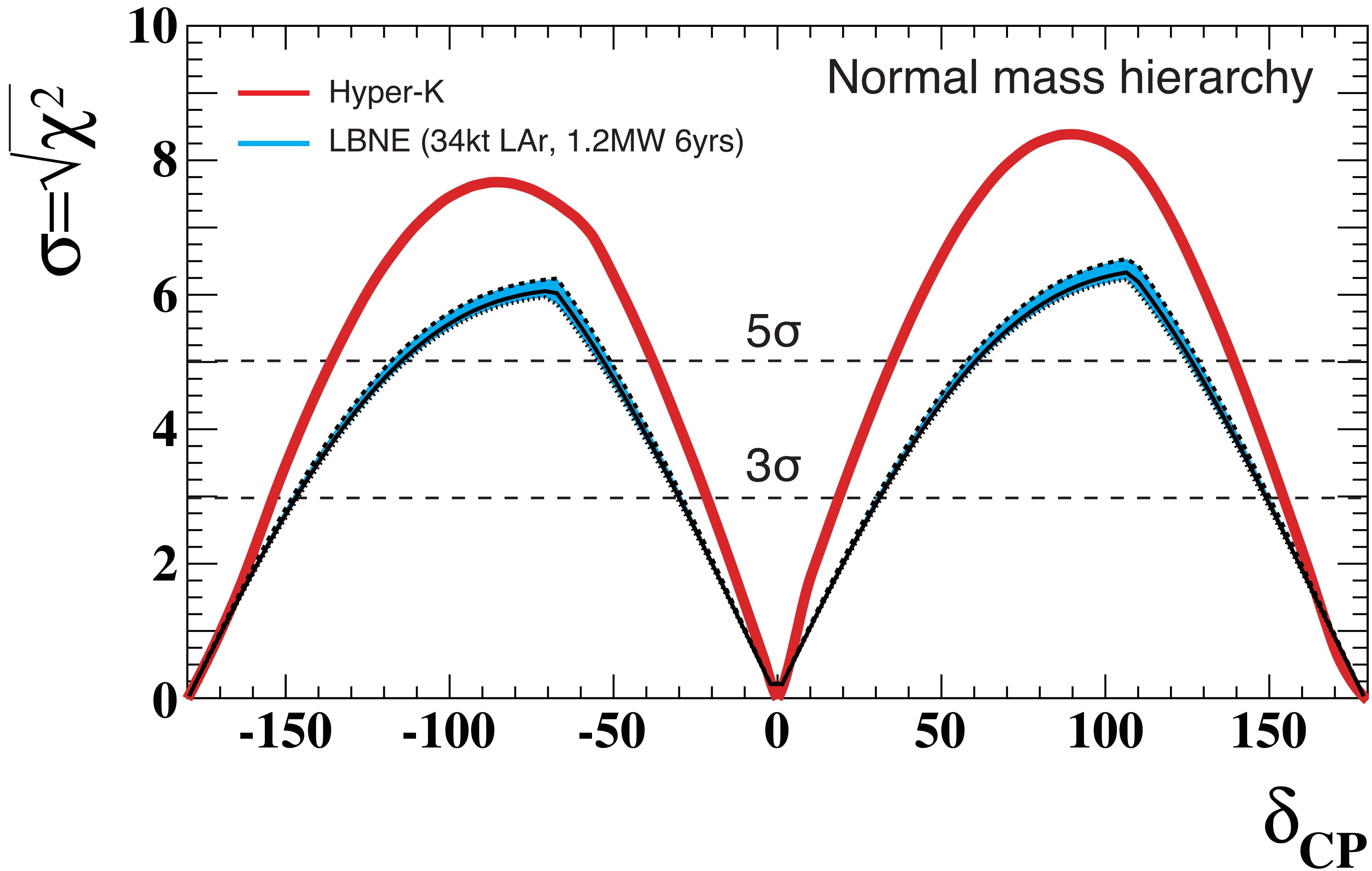


ν_μ sample



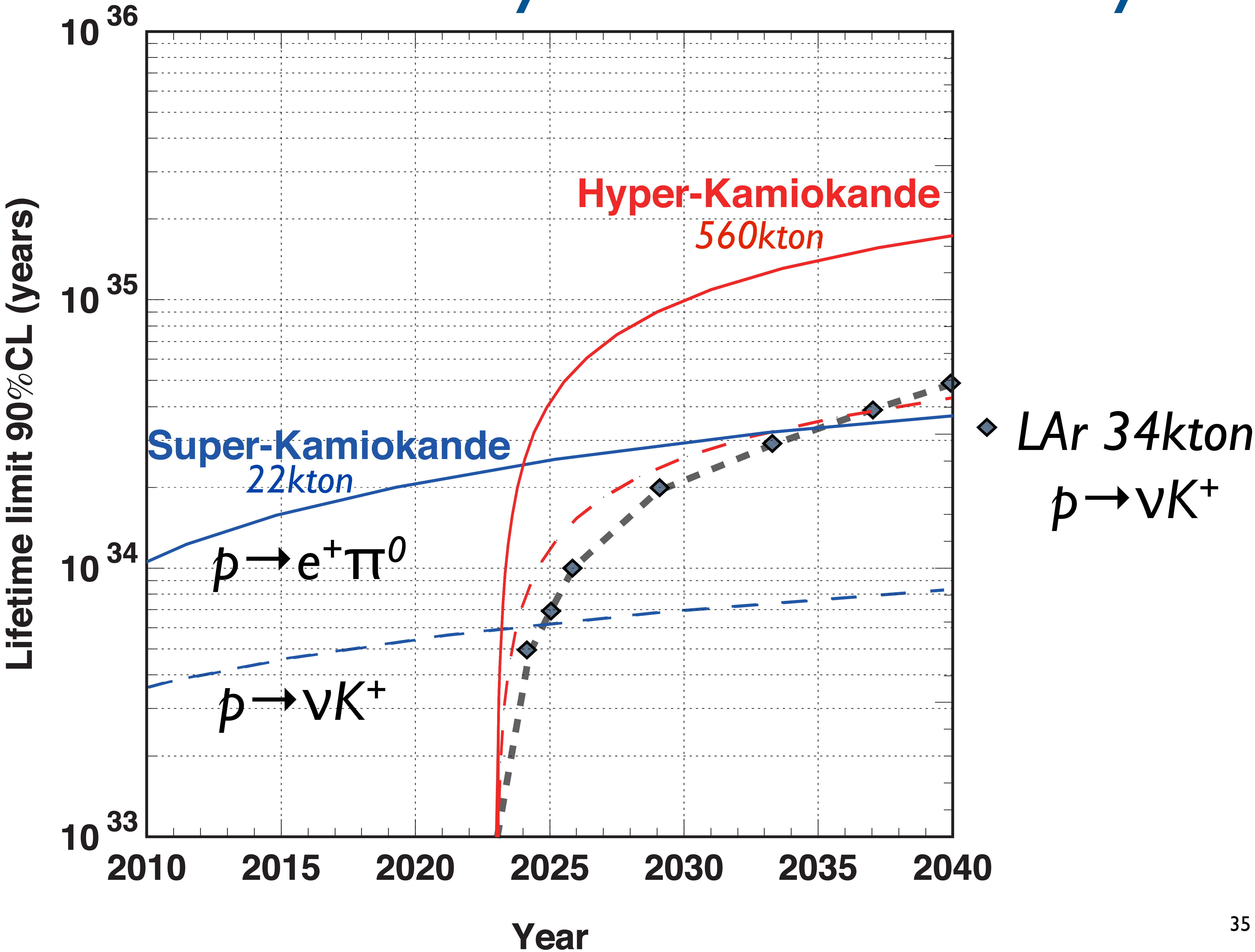
Total
Beam+ND
XSEC
Far detector (HK)

Comparison to LBNE



LBNE sensitivity from Fig.4.11 of arXiv:1307.7335

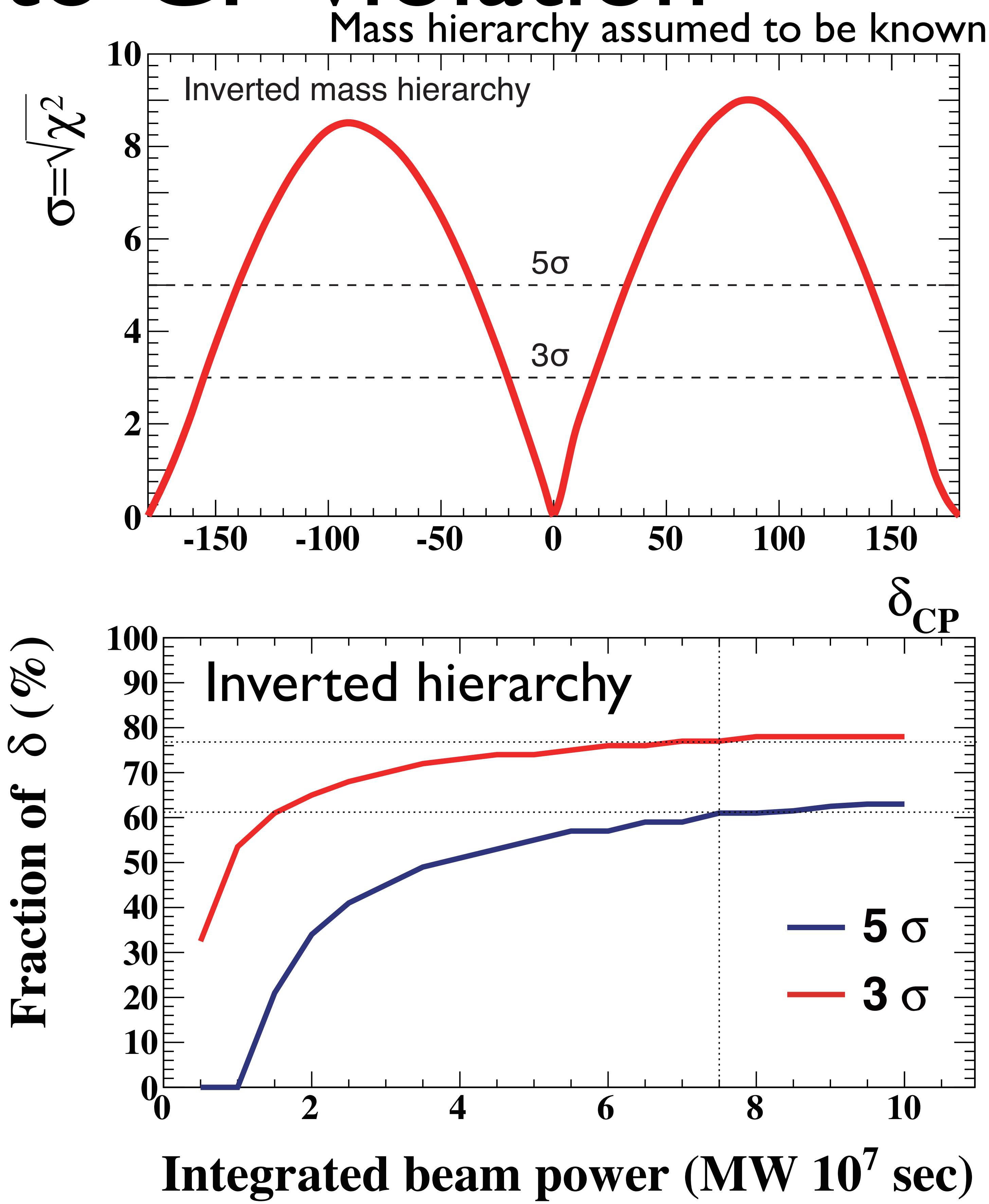
Nucleon Decay 90% CL sensitivity



Sensitivity to CP violation

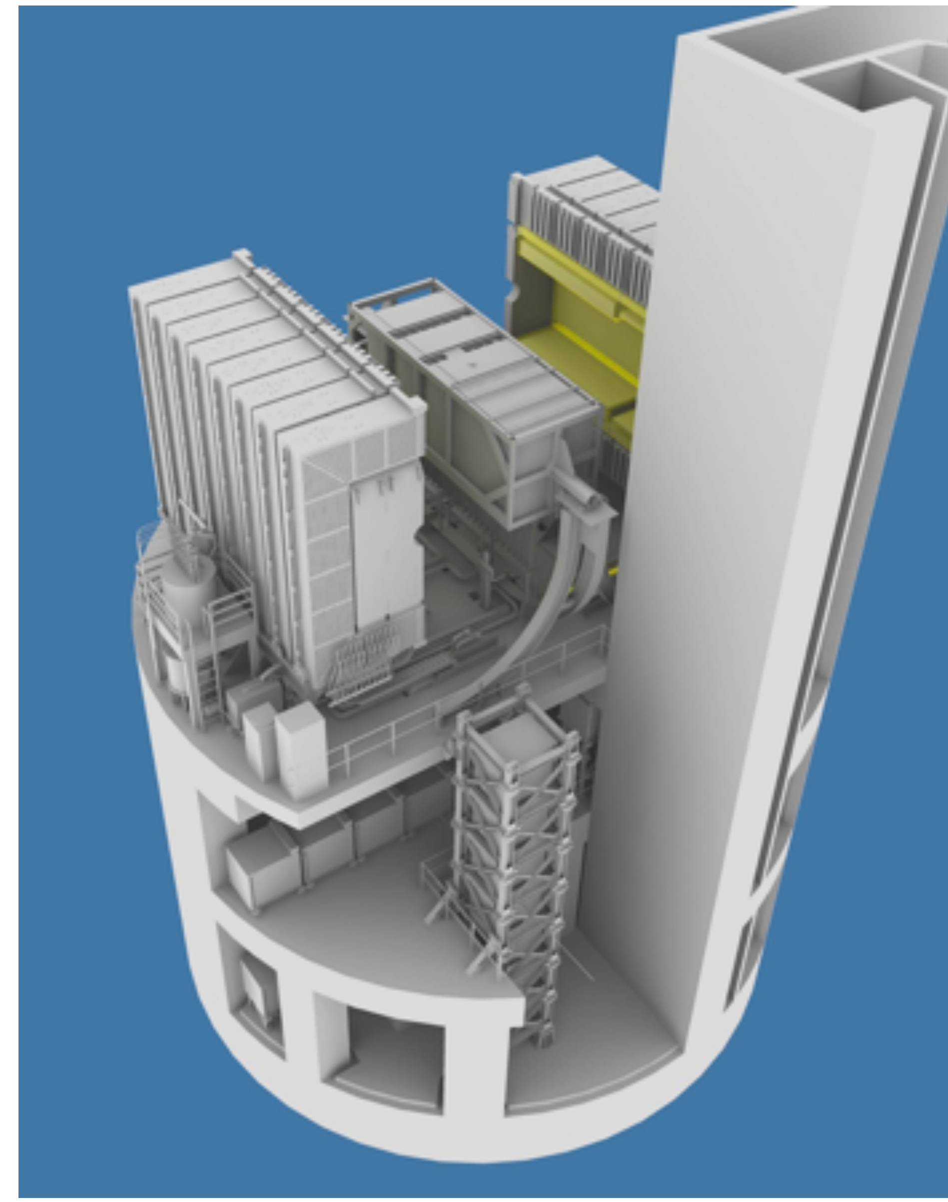
For inverted hierarchy

- Exclusion of sinδ=0
  - >3σ for 77% of δ
  - >5σ for 61% of δ
- Possible to establish CP violation in the lepton sector!



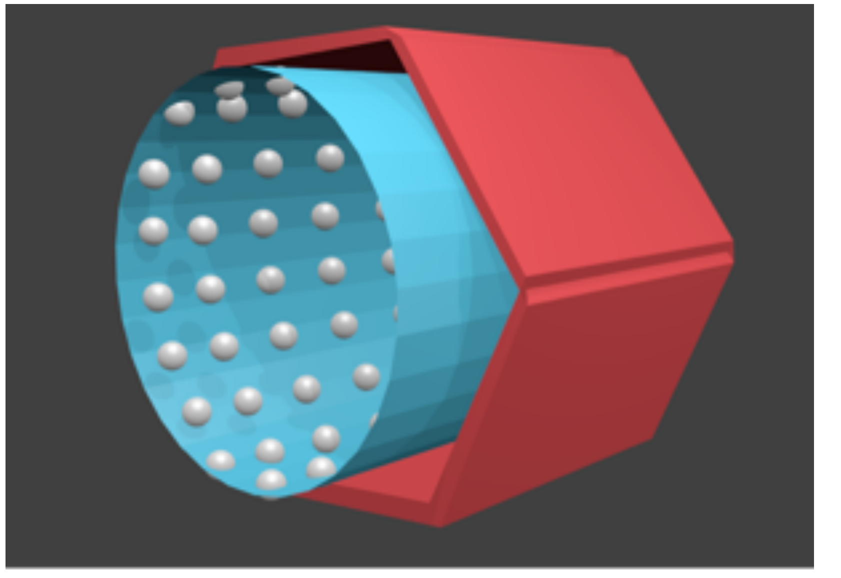
Near detectors

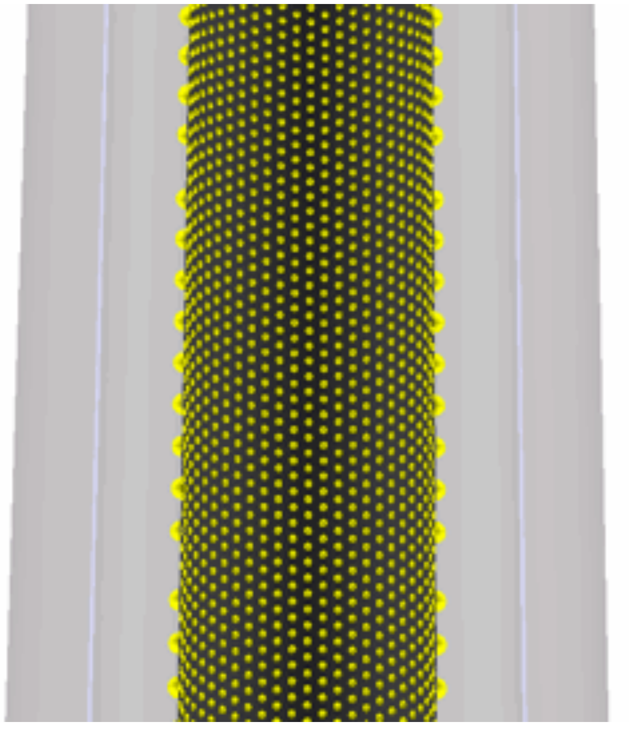
- For this sensitivity study, we assume T2K ND280 detector with expected improvements
  - Measurement of water cross section reduces uncertainties due to different target nucleus
  - Detector systematics conservatively assumed to stay at the current level



Study of new near detectors

- Possible new near detectors under study
  - Aim for further reducing systematics
- Upgrade of T2K ND280 detectors
- New water Cherenkov detector at ~1-2km distance
  - The same technology as the far detector
  - E_ν spectrum almost the same as HK
  - Water Cherenkov + muon range detector (TITUS)
  - Utilize off-axis dependence of spectrum (nuPRISM)





Selected as one of 27 top projects in Japanese Master Plan for Large Scale Research Projects by Science Council of Japan (Feb. 2014)

提　言

第 22 期学術の大型研究計画に関する
マスタープラン
（マスタープラン 2014）

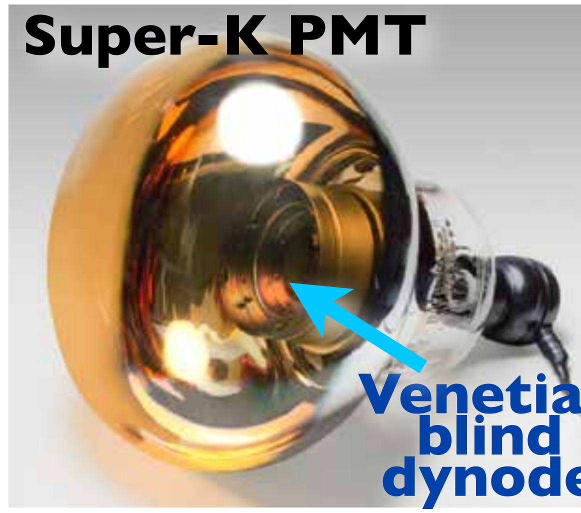
平成２６年（２０１４年）２月２８日
日　本　学　術　会　議
科学者委員会
学術の大型研究計画検討分科会

No.	Scien-tific Field No.	Project Name	Project Summary	Scientific Significance	Social Value	Project Duration	Financial Requirement (1billion yen)	Implementing Institution, or Affiliation of Proposer
85	23-2	Nucleon decay and neutrino oscillation experiment with an advanced large detector	The project aims to construct a one million ton-scale water Cherenkov detector, Hyper-Kamiokande, to succeed Super-Kamiokande and to perform world-leading neutrino and nucleon decay research in conjunction with the J-PARC accelerator facility.	The project will explore CP violation (matter-antimatter asymmetry) in neutrinos in order to help understand the evolution of the universe. Additionally, with the world's best nucleon decay searches it also aims to establish the unification of elementary particles and their forces.	Addressing profound questions concerning the elementary structure and evolution of the universe appeals directly to the inherent intellectual curiosity mankind harbors for comprehension of its origins and future. Additionally, dramatic advances in neutrino research with a world-leading project in Japan represent society's dreams for a rich program in basic science.	2015 to 2038	Total:1,880 Construction of Hyper-Kamiokande 800, Operating cost of Hyper-Kamiokande 450, Operating cost of J-PARC 600, Neutrino monitor 30	Lead by the Institute for Cosmic Ray Research, University of Tokyo and the High Energy Accelerator Research Organization. Participation from domestic and foreign universities and research institutions is anticipated.

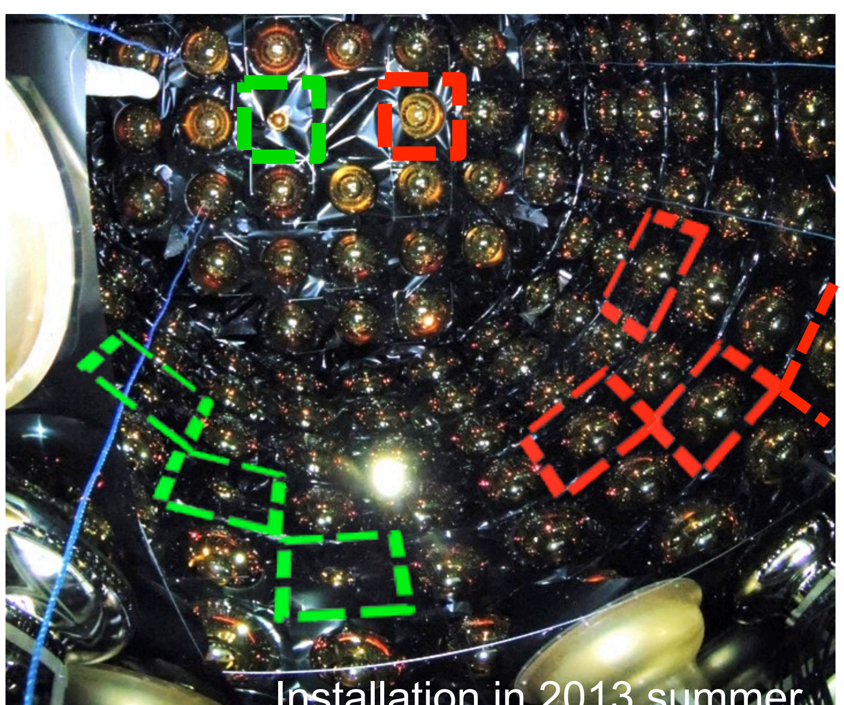
Photo-sensor R&D

R&D going on to get better performance and lower cost.

Established	*R&D*	*R&D*



quantum eff. (QE)	22%	30%	30%
collection eff. (CE)	80%	93%	95%
timing resolution (FWHM)	5.5 nsec	2.7 nsec	1 nsec



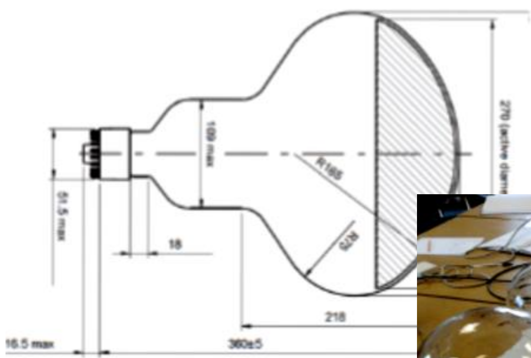
- 50cmΦ Box&Line PMT and HPD prototypes have been delivered last month, start basic performance test
- 20cmΦ HPD and HQE Super-K PMT have been tested in 200 ton water tank
- R&D to be completed in 2016

6

Hyper-Kamiokande detector ~ Activities in the world ~

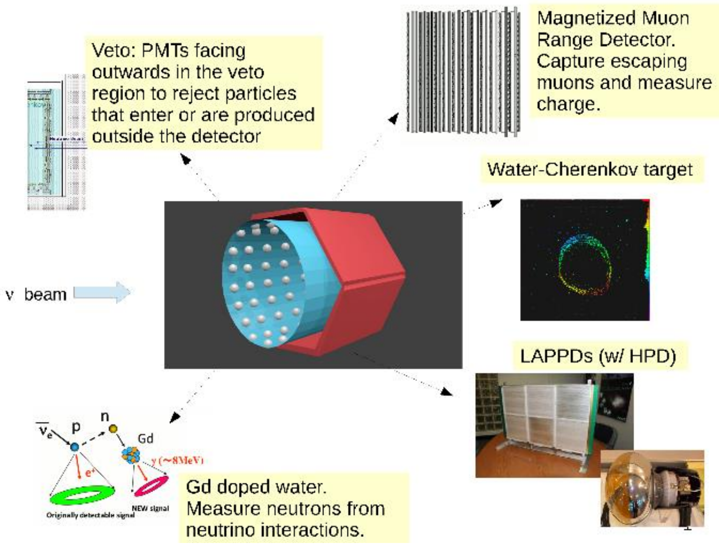
USA ~ New PMT R&D

First WATCHMAN/Hyper-K
11" ETEL/ADIT PMT envelopes
prior to glass finishing

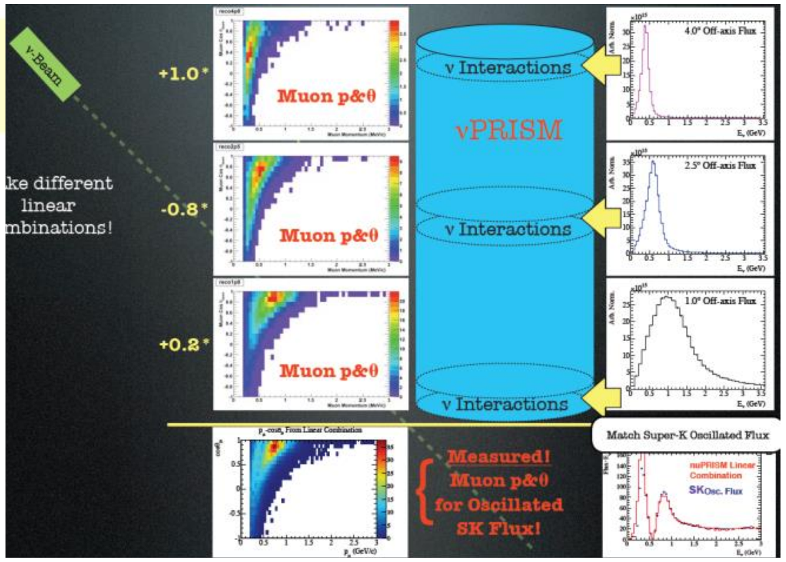


Europe & Canada
~ Near detector designs

TITUS



νPRISM

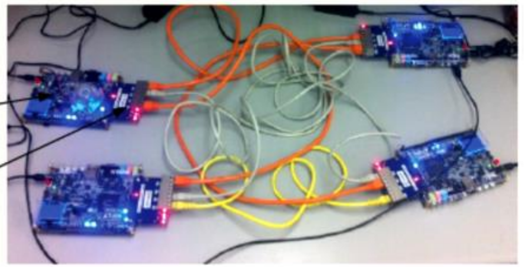


Canada

Photo sensor test facility

Network I/O module study

- Implemented 4 RapidIO cores in FPGA on each board; each RapidIO core has associated DMA engine.
- Managed to get each of 4 links running at 135MB/s; can also run faster, near 250MB/s, but needs to tweak DMA.
- Starting to work on the routing functionality; did some tests already, checking fail-over when cables are detached.



UK DAQ system, HPD/LAPPD, Calibration system R&D etc..

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Mid-term plan of MR

FX : The high repetition rate scheme is adopted to achieve the design beam intensity, 750 kW. Rep. rate will be increased from ~ 0.4 Hz to ~1 Hz by replacing magnet PS's and RF cavities.

SX : After replacement of stainless steel ducts to titanium ducts to reduce residual radiation dose, 50 kW operation for users will be started. Beam power will be gradually increased toward 100 kW carefully watching the residual activity. Local shields will also be installed if necessary.

JFY	2011	2012	2013	2014	2015	2016	2017
			Li. energy upgrade	Li. current upgrade			
FX power [kW] (study/trial) SX power [kW] (study/trial)	150 3 (10)	200 10 (20)	200 - 240 25 (30)	200 –300 (400) 20-50	→	→	750 100
Cycle time of main magnet PS New magnet PS for high rep.	3.04 s	2.56 s R&D →	2.48 s →	→	Manufacture installation/test	→	1.3 s →
Present RF system New high gradient rf system	Install. #7,8 R&D →	Install. #9 R&D →	→	Manufacture installation/test	→	→	
Ring collimators	Additional shields	Add.collimators and shields (2kW)	Add.collimators (3.5kW)				
Injection system FX system	Inj. kicker	Kicker PS improvement, Septa manufacture /test → Kicker PS improvement, LF septum, HF septa manufacture /test →	→	→	→	→	
SX collimator / Local shields	SX collimator					Local shields →	→
Ti ducts and SX devices with Ti chamber		SX septum endplate	Beam ducts	Beam ducts ESS			

Atmospheric neutrinos

ν_e appearance prob. in 3 flavor oscillation / no oscillation

r: μ/e flux ratio
P_2: $\nu e \to \nu x$ prob. in matter
$R_2 = \mathrm{Re}(A^*_{ee}A_{e\mu})$, $I_2 = \mathrm{Im}\,(A^*_{ee}A_{e\mu})$

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

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

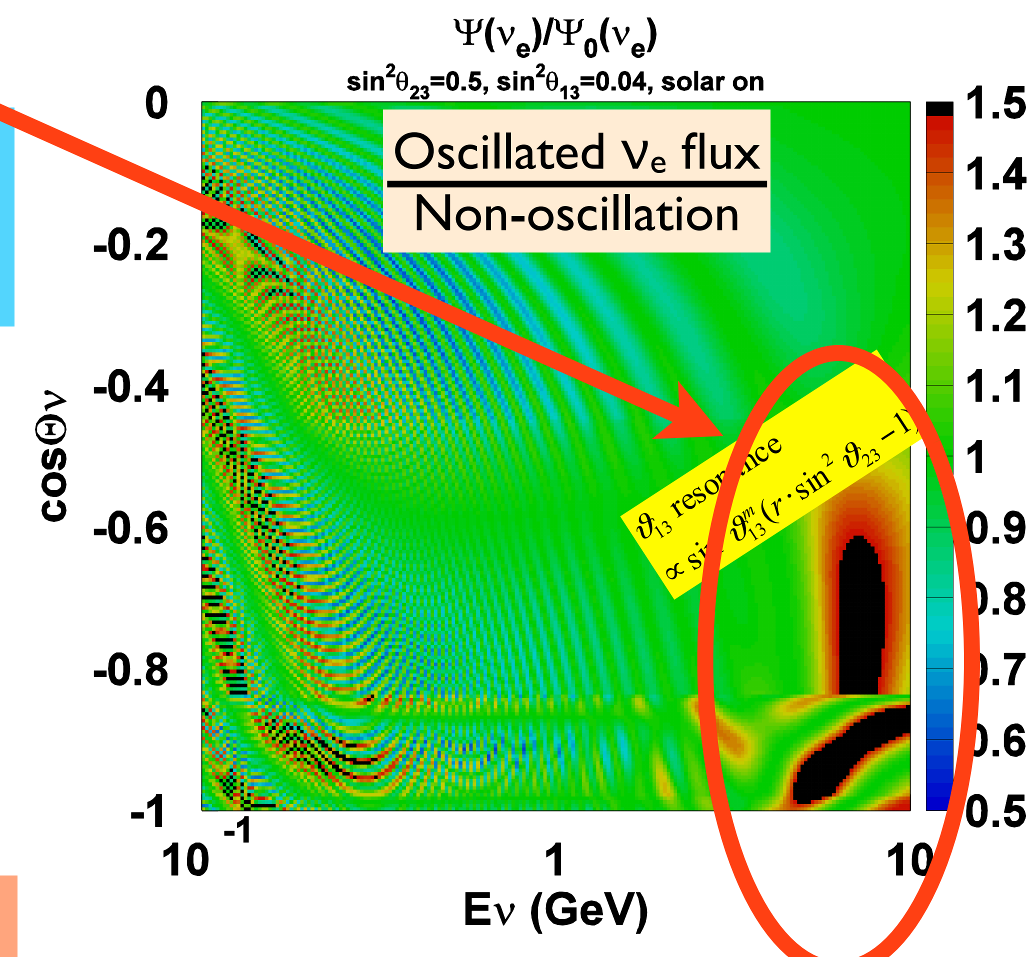
$$+2\sin^2\tilde{\theta}_{13} \cdot (r \cdot \sin^2\theta_{23} - 1) \quad \text{Matter}$$

$\nu_\mu \to \nu_e$ appearance resonance in earth's core
either ν or $\bar{\nu}$ depending on mass hierarchy

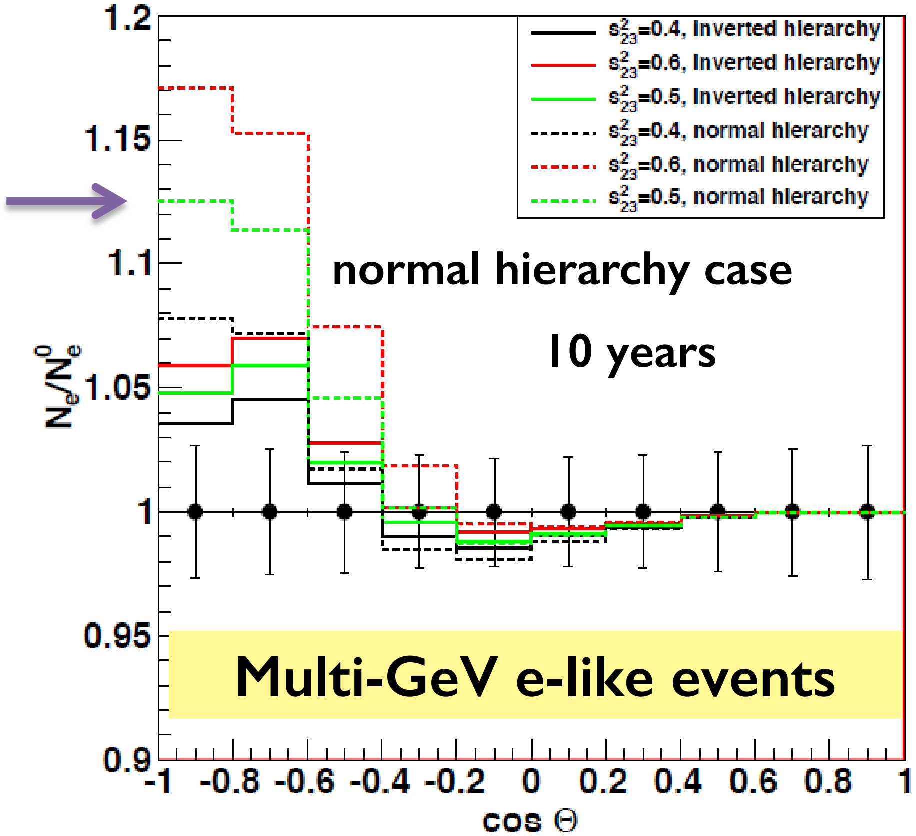
Sensitive to

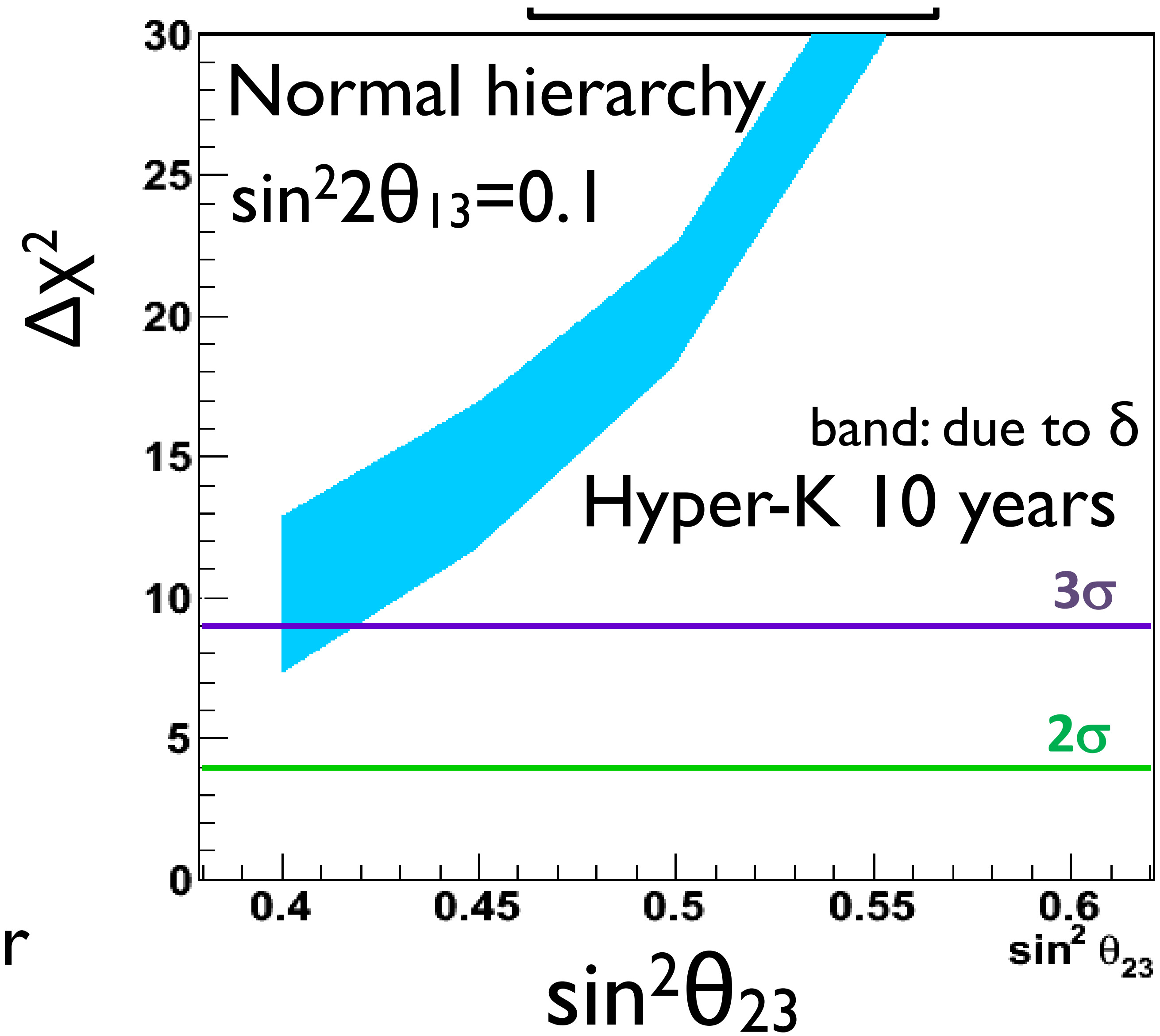
- Mass hierarchy
- θ_{23} octant
- CP asymmetry

larger θ_{13} gives better sensitivity



Mass hierarchy determination with atmospheric neutrinos

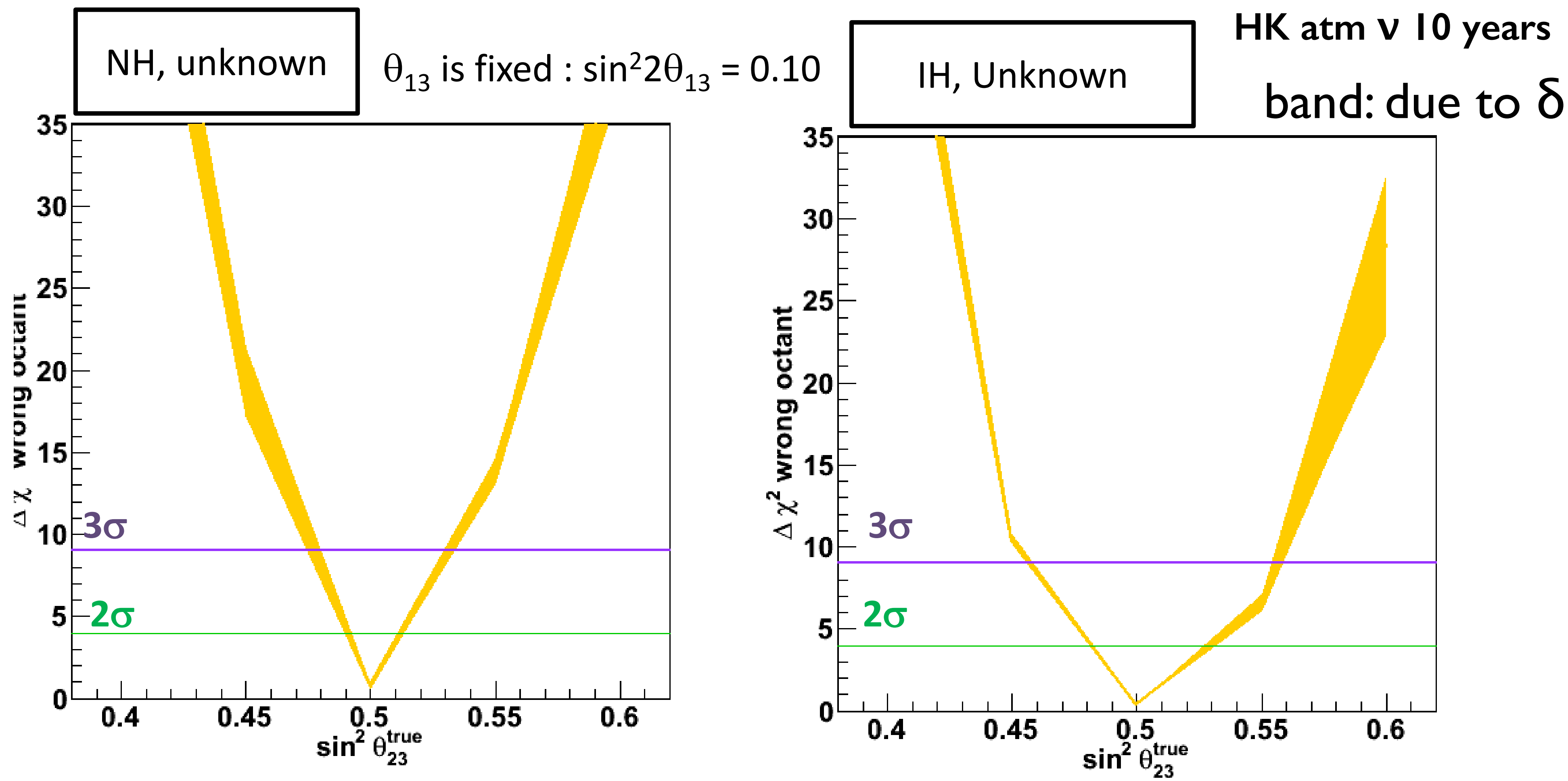




MSW effect in Earth's core
→ resonance effect on either
ν or anti-ν

3σ determination with <10 year observation
(better sensitivity depending on the value of θ_{23})

θ_{23} octant determination

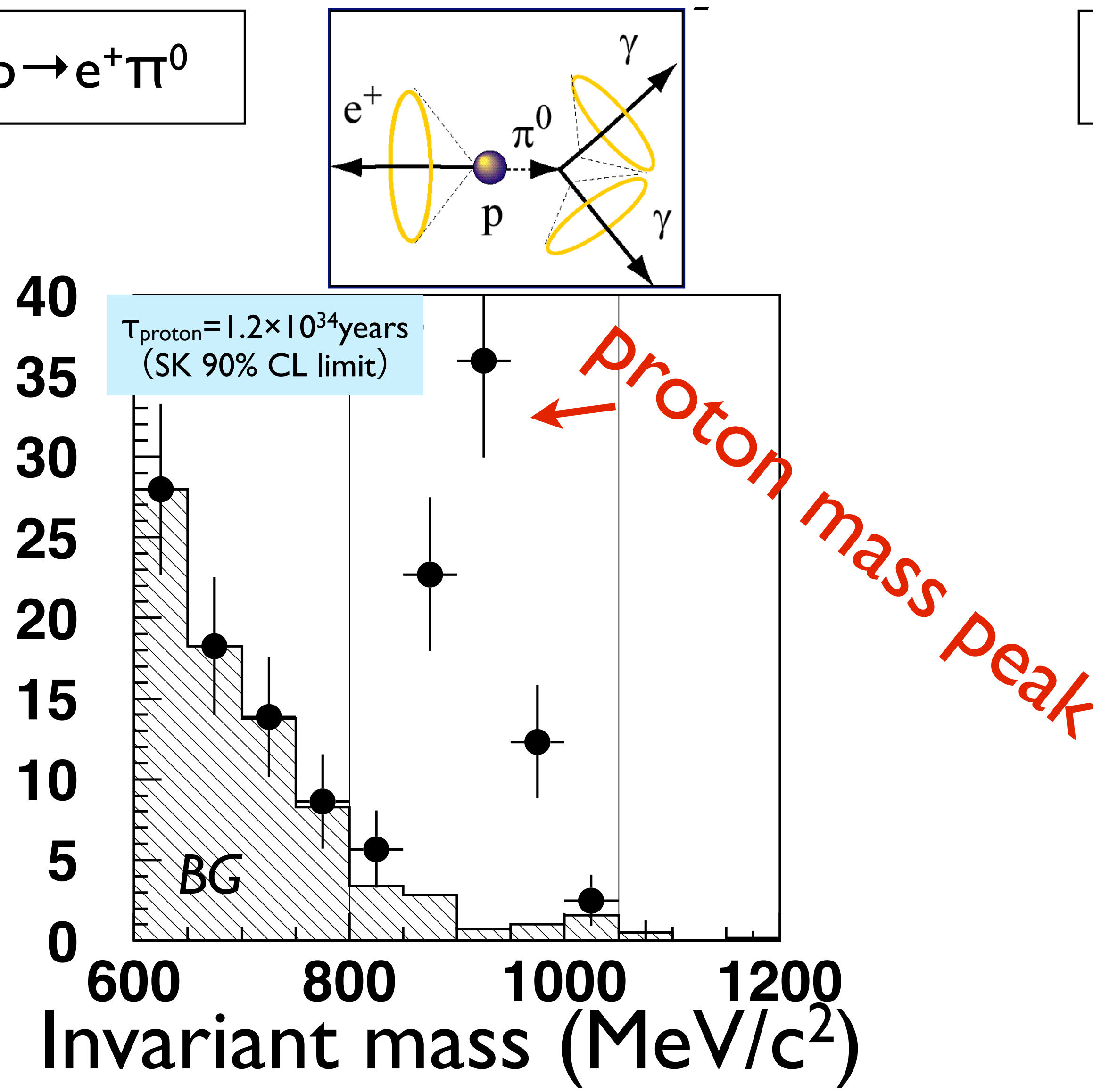


>3σ discrimination
for $\sin^2\theta_{23}<0.47(0.45)$ or $\sin^2\theta_{23}>0.53(0.0.56)$
for normal (inverted) MH

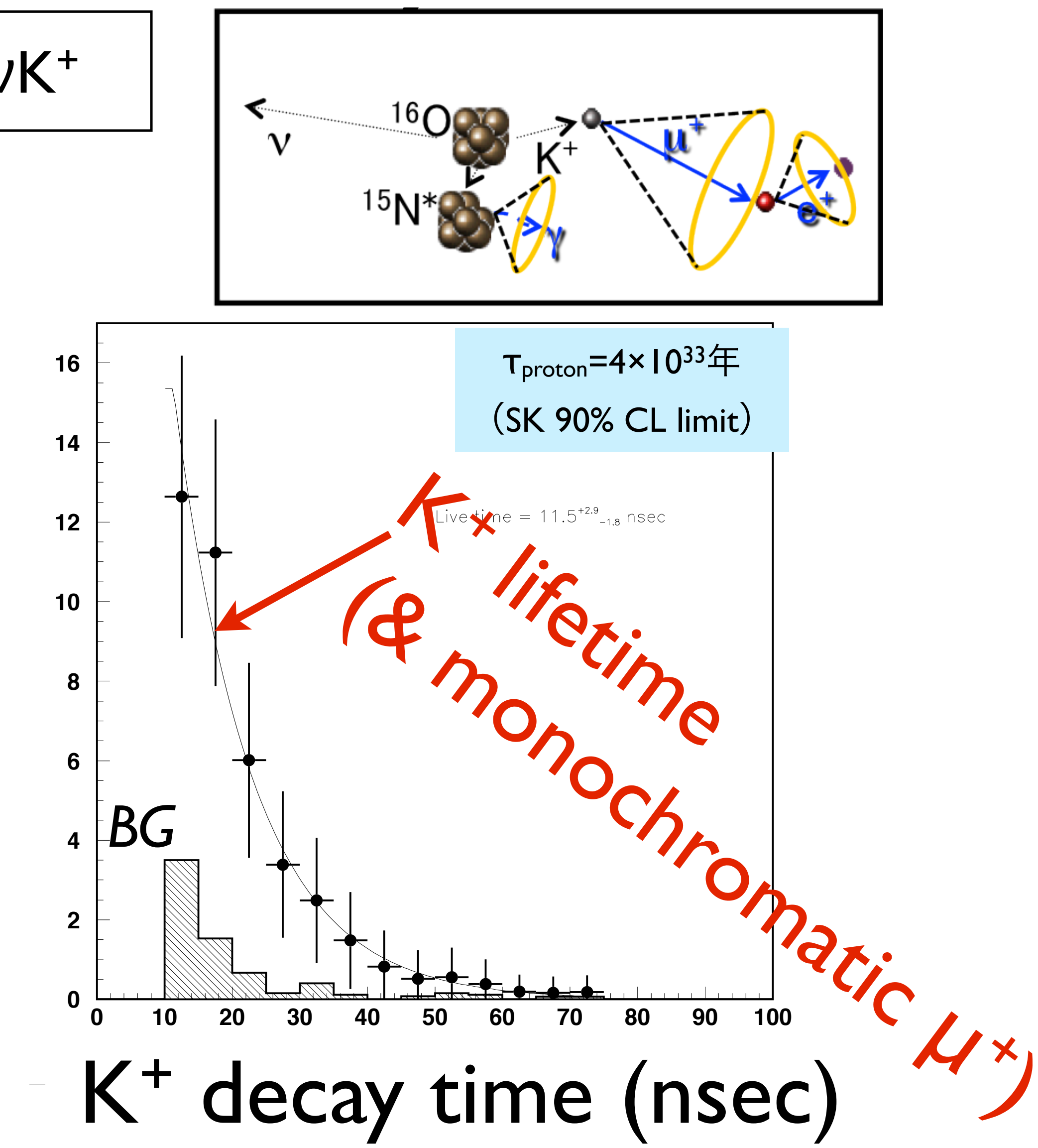
Complementary measurements to accelerator ν
Combined analysis of acc + atm ν will enhance capability

Proton decay sensitivity with Hyper-K

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



$p \rightarrow \nu K^+$



- Discovery reach (3σ)
  - $\tau(p \rightarrow e^+\pi^0) \sim 5.4\times10^{34}$ years (HK 10yrs)
- Limit (90%CL)
  - $\tau(p \rightarrow e^+\pi^0) > 1.3\times10^{35}$ years (HK 10yrs)

- Discovery reach (3σ)
  - $\tau(p \rightarrow \nu K^+) \sim 1.2\times10^{34}$ years (HK 10yrs)
- Limit (90%CL)
  - $\tau(p \rightarrow \nu K^+) > 3.2\times10^{34}$ years (HK 10yrs)

Good discovery potential, 90% CL sensitivity of 10^{34}~10^{35} yrs