Plans and prospects for the Hyper-Kamiokande detector

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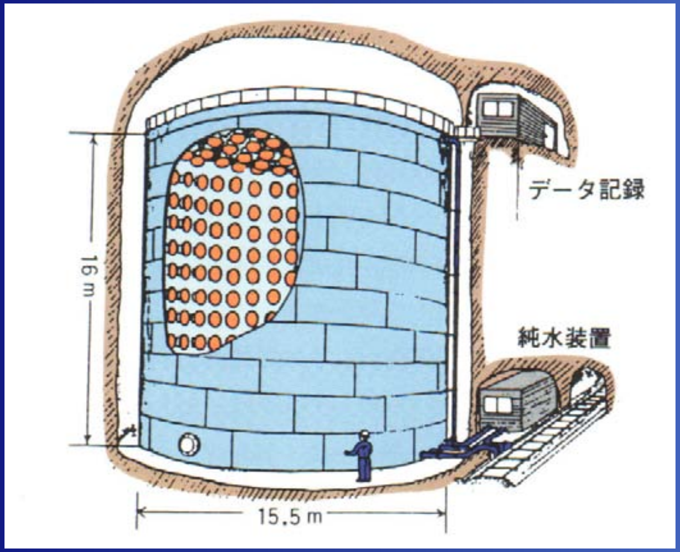
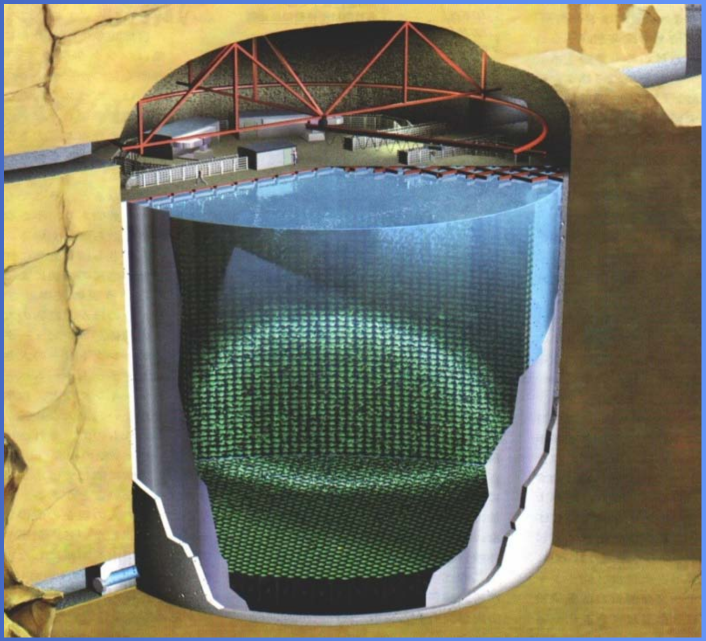
1. Introduction

Kamiokande
(1983-1996)



3000 ton, ~1000 PMTs
- Observed Super Nova neutrino.

Super-Kamiokande
(1996-Now)



50,000 ton, ~11,000 PMTs
- Found neutrino oscillations

?

Need larger detector

- Neutrino Oscillation

  - θ_{13} is measured in 2012, non-zero and not so small.

  - Long base line experiments have chance to measure δ_{CP}.

    ➔ use $\bar{\nu}_\mu$, cross section is lower than ν_μ

  - Mass hierarchy and Octant of θ_{13} ← Atmospheric ν with MSW effect.

  ➔ Statistics is crucial !

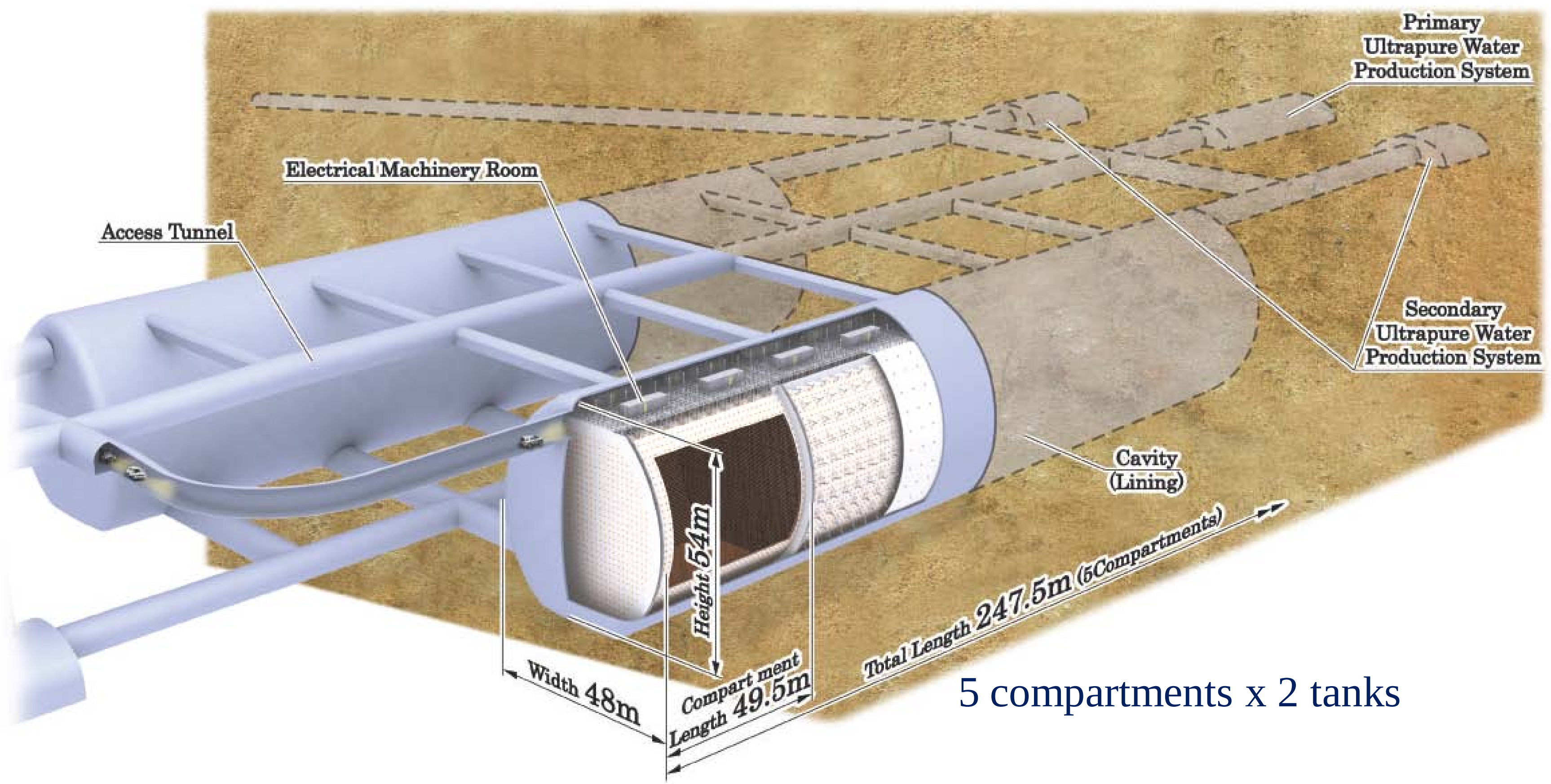
- Nucleon decay search

  - Explored until 0.2 Mton･year exposure in Super-K.

  - No evidence found yet.

  ➔ Need more exposure !

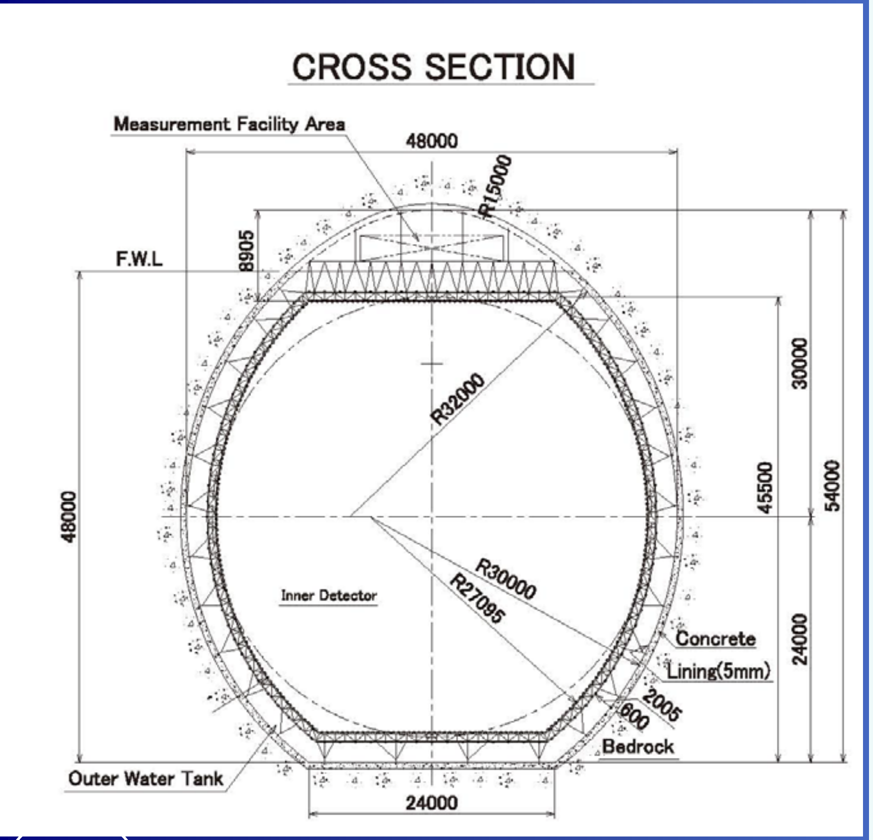
2. Hyper-Kamiokande



5 compartments x 2 tanks

1 Mega ton Water Chrenkov Detector

Base design



- Total Volume: 0.99 Mton
- Inner Volume: 0.74 Mton
- Fiducial volume: 0.56 Mton

  (0.056 Mton x 10 compartments)
- Outer volume: 0.2 Mton
- Photo-sensors:

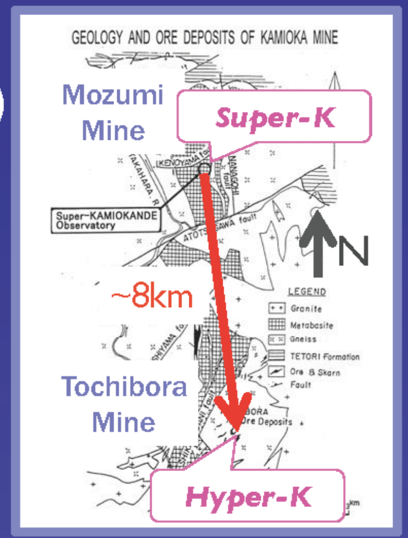
  99,000 20 inch PMT (ID)

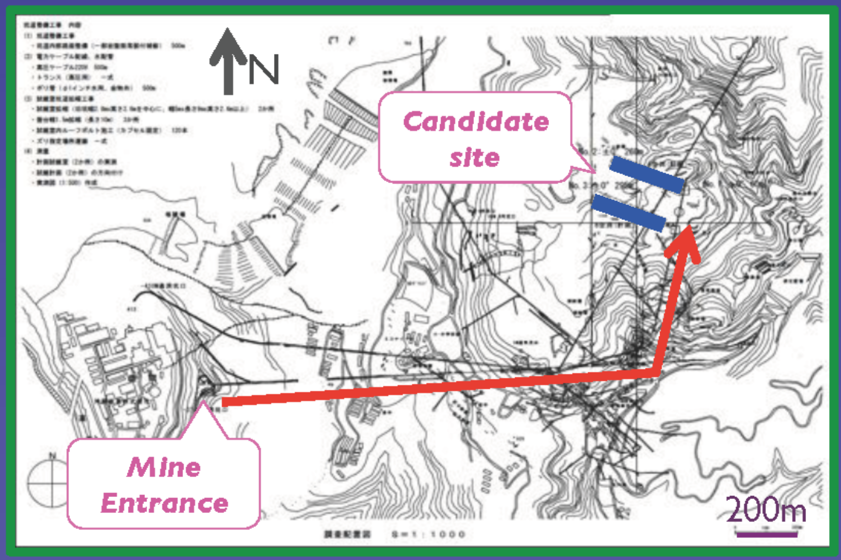
  (20 % photo coverage)

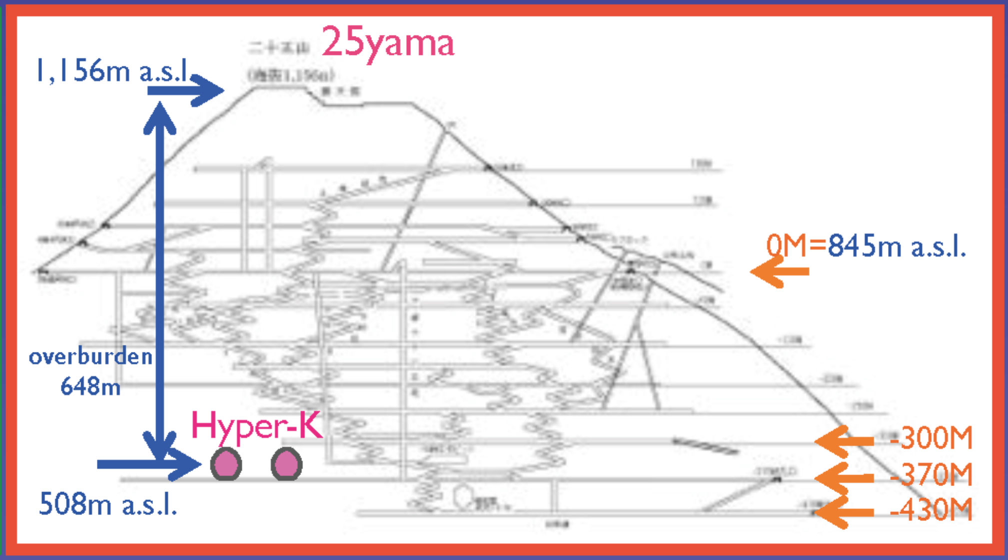
  25,000 8 inch PMT (OD)

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 m³/day or 1megaton/80days natural water







Physics Topics in Hyper-K

- Accelerator ν beam
- Atmospheric ν
- Solar ν
- Astrophysical ν (Super Nova, Dark matter, e.t.c.)
- ν geophysics
- Nucleon decay

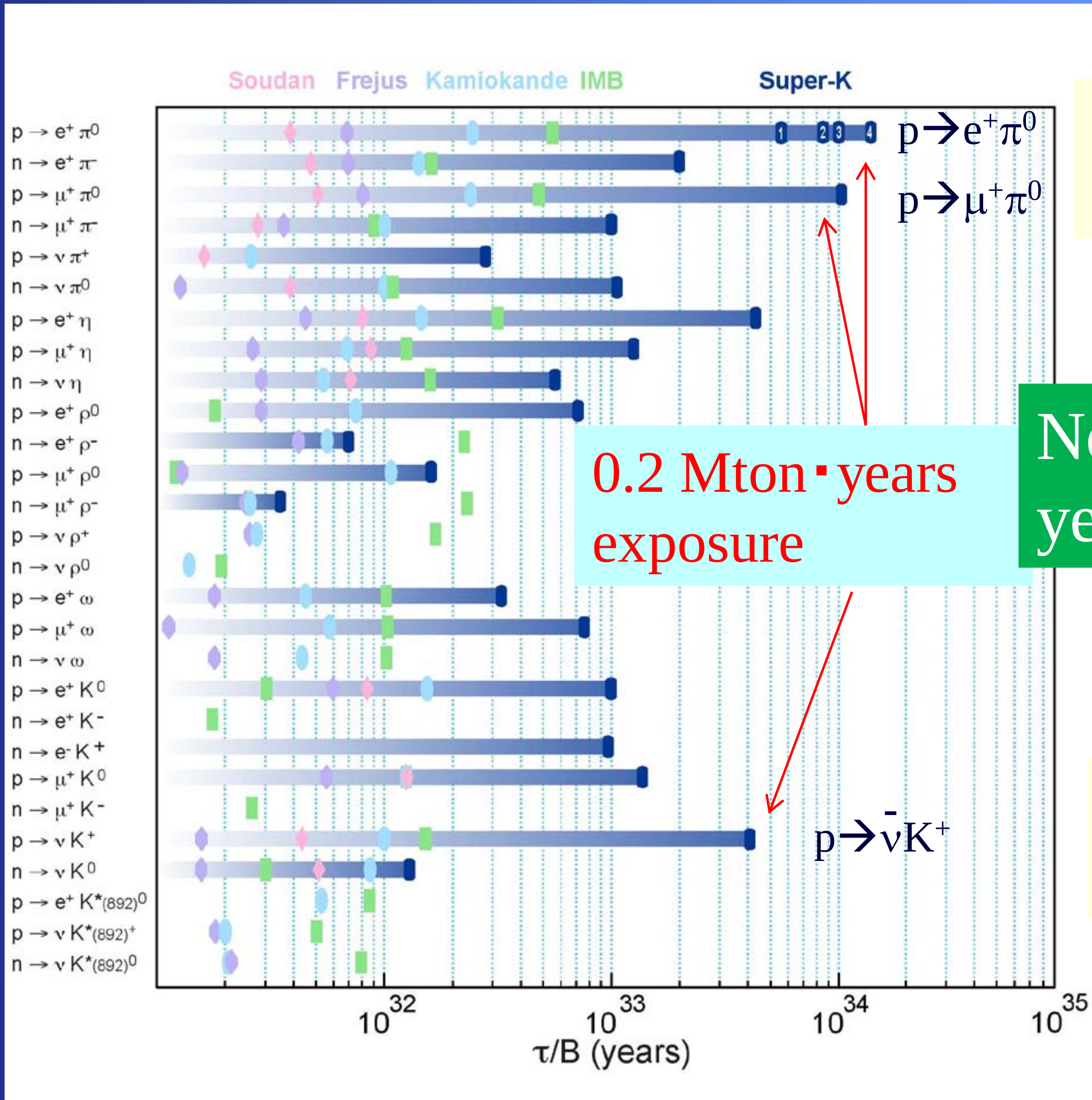
ν oscillation with CP violation

GUTs,
B&L Violation

3. Prospect for nucleon decay by Hyper-K

- Nucleon decay experiment is the direct probe for GUTs.
- $p \rightarrow e^+\pi^0$ (non-SUSY GUTs), $p \rightarrow \bar{\nu}K^+$ (SUSY-GUTs) are regarded as the dominant mode.
- Why water cherenkov detector ?
  - ➢ Nucleon decay is extremely rare event. Need large number of nucleon.
    - ➔ (relatively) easy to enlarge detector size.
  - ➢ Two free protons, without interaction in nucleus.
    - ➔ High efficiency for $p \rightarrow e^+\pi^0$,e.t.c. .

How far we have explored by Super-K



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

> 1.3 x 10^{34} years

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

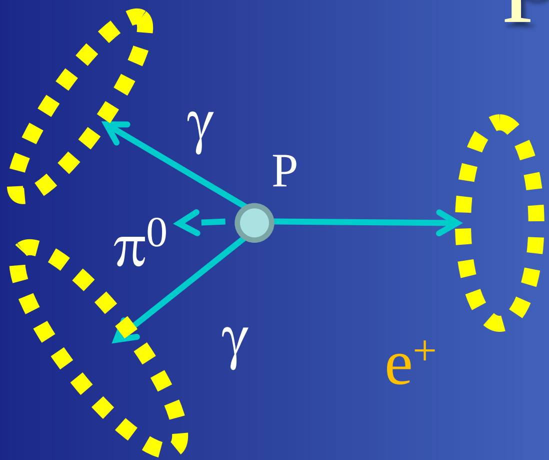
0.2 Mton・years exposure

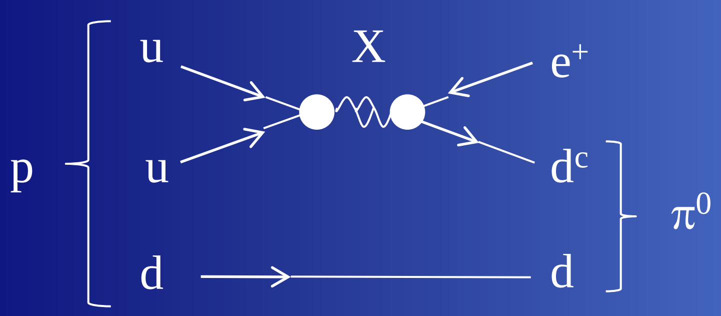
No evidence yet

$p \rightarrow \bar{\nu}K^+$

> 4 x 10^{33} years

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





Minimal SU(5) model

Event features;

- e^+ and π^0 are back-to-back (459 MeV/c)
- $\pi^0 \rightarrow 2\ \gamma$s : all particles can be detectable.

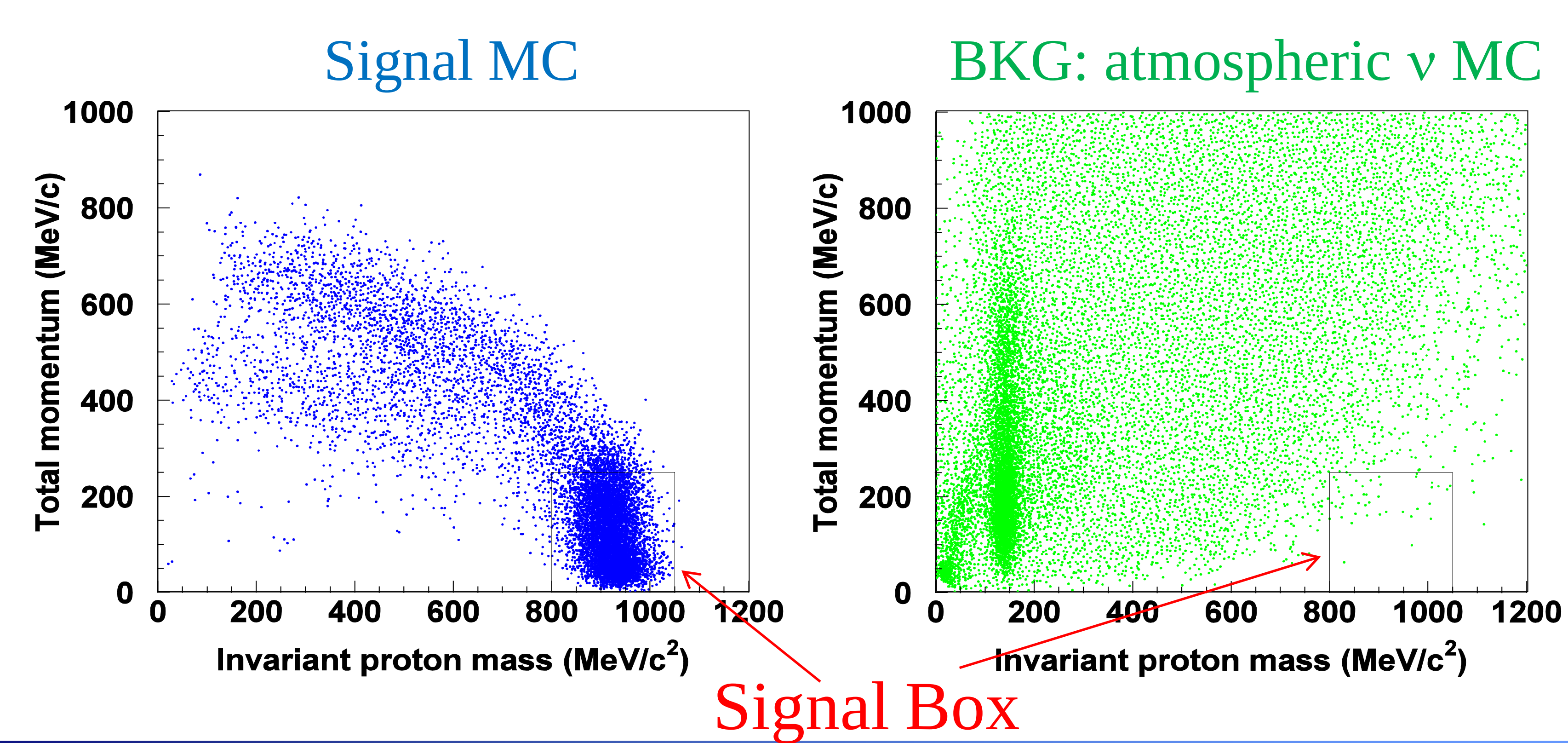
➔ Reconstruct proton mass and momentum.

Selection;

- Fully contained, VTX in fiducail volume.
- 2 or 3 ring .
- all e-like, w/o decay-e.
- $85 < M\pi^0 < 185$ MeV (for 3-ring event) .
- $800 < M_P < 1050$ MeV & $P_{tot} < 250$ MeV/c

All particles can be seen by water cherenkov detector

M_{tot} vs P_{tot} (after all other cuts)



* Inefficiency mostly due to π^0 interaction in nucleus (absorption, scattering, charge exchange).

* Dominant BKG: CC1π

$\bar{\nu}_e p \rightarrow e^+ n \pi^0$

$\nu_e n \rightarrow e^- n \pi^+$ +charge exchange

Performance of Hyper-K for $p \rightarrow e^{+}\pi^{0}$

Efficiency: 45 % (87 % for free proton)

* photo coverage 20 % , but almost same performance is expected with current SK case (40 %). Phys.Rev.Lett. 102,141801(2009)

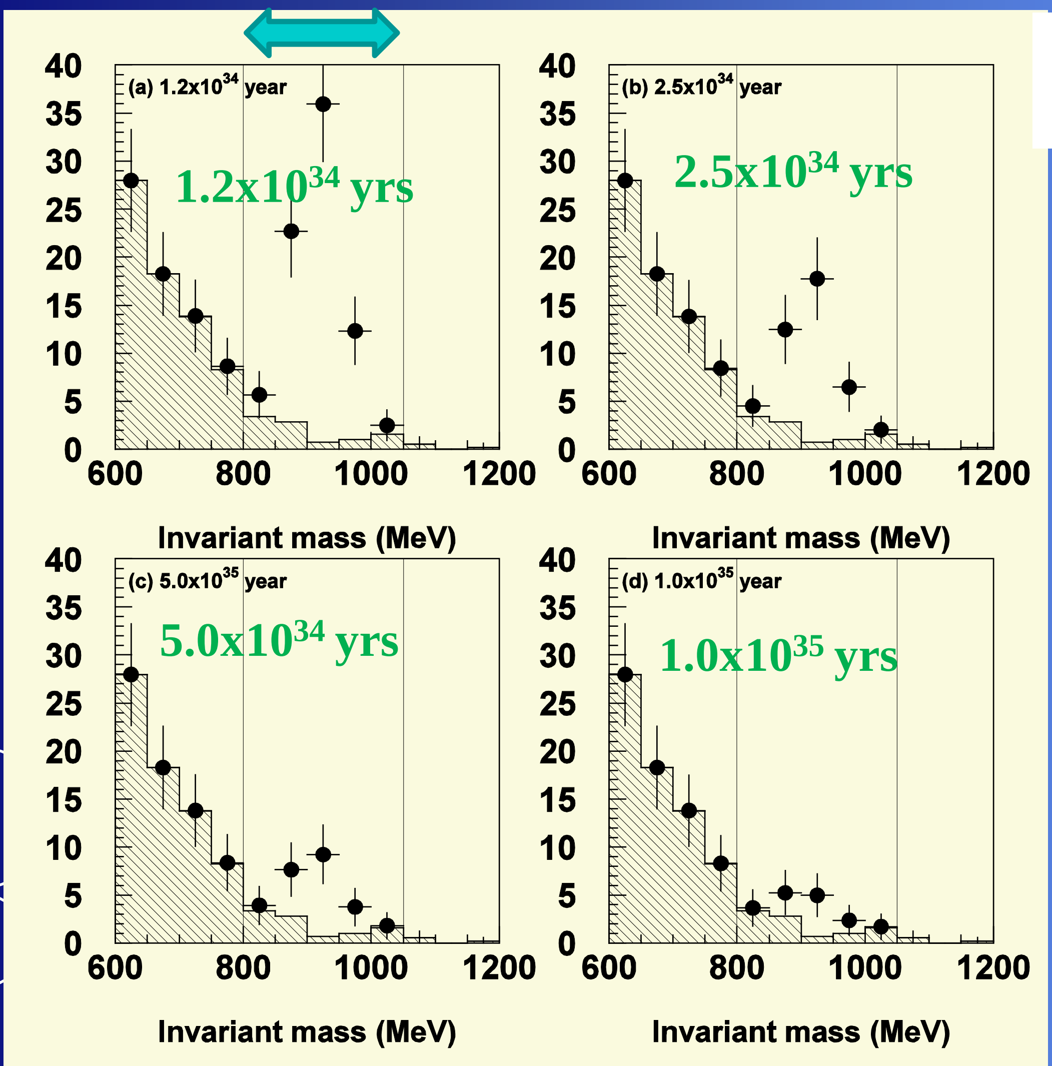
Background rate: 1.6 events/Mton・year

* Consistent with the estimation by using Acc. ν data (K2K), $1.63^{+0.62}_{-0.61}$ events/Mton・year. Phys.Rev.D77,032003 (2008)

* Room for improvement if neutron can be tagged (neutron is captured by water after a few 100 μsec and 2.2 MeV γ is emitted).

Discovery potential for $p \rightarrow e^+\pi^0$

Total mass with 10yrs run assuming life time

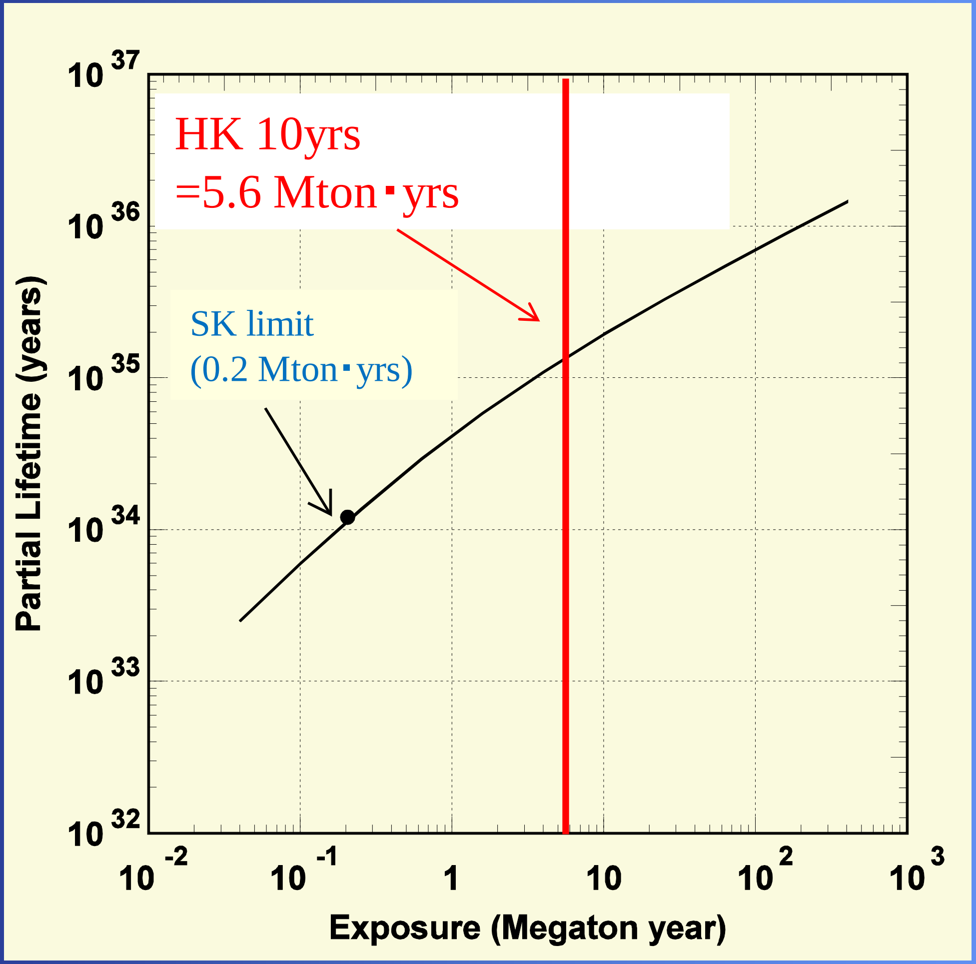


Dot: Signal+BKG
Hist: BKG

Discovery potential (3σ)
< 5.6×10^{34} years

* Counting event only.

Sensitivity for $p \rightarrow e^+\pi^0$ (90 %CL)



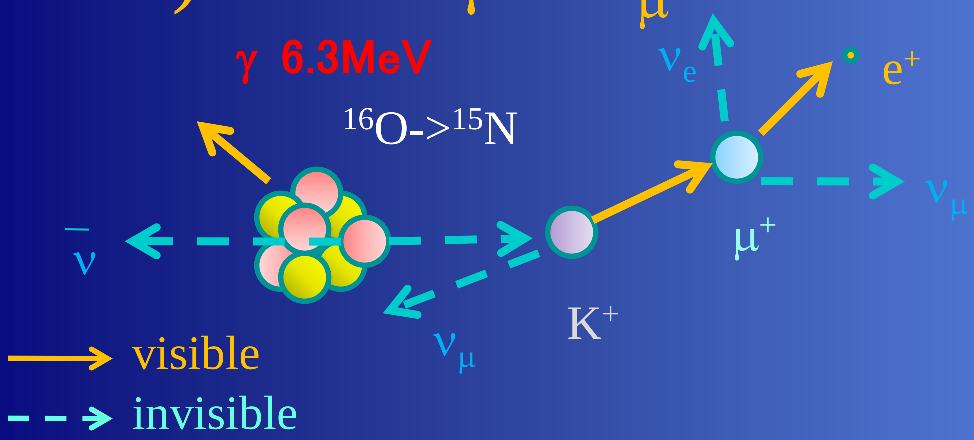
10 yrs run (5.6 Mton・yrs)

➔ reach to 1.3×10^{35} yrs (90 %CL)

$p \rightarrow \bar{\nu} + K^+$

* Cannot see K^+, stop in water ➔ use decay products

A) $K^+ \rightarrow \mu^+ + \nu_\mu$



Event features;

- 2 body decay (P_μ = 236 MeV/c).

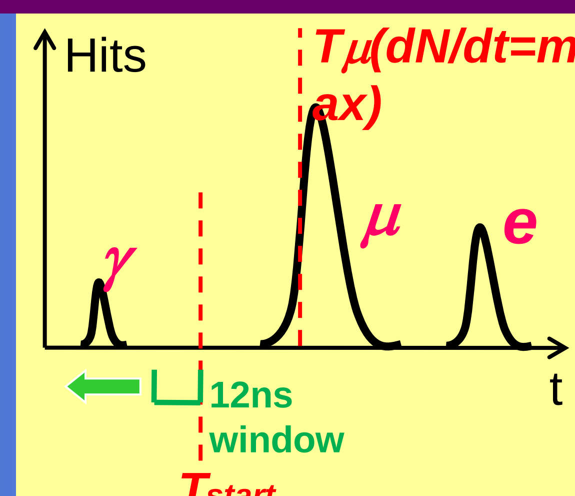
➔ Excess in P_μ.

- Proton in ^{16}O decays and excited nucleus emits 6 MeV γ (Prob. 41%, not clear ring).

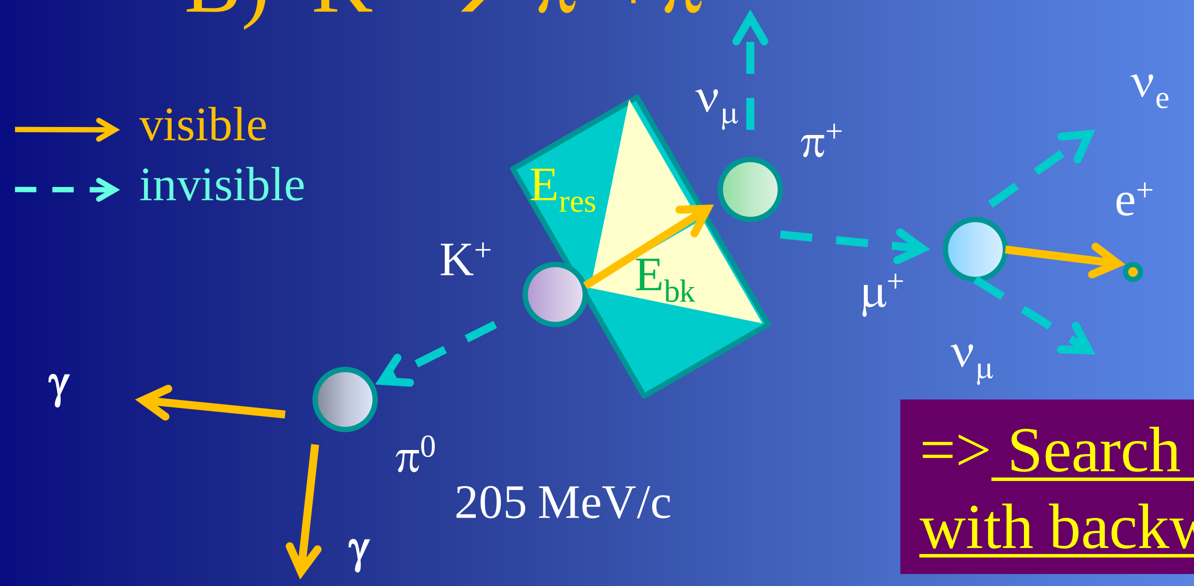
➔ Tag γ to eliminate BKG.

Selection:

- 1 μ-like ring with decay-e.
- $215 < P\mu < 260$ MeV/c
- Search Max hit cluster by sliding time window (12ns width);
  - $4 < N\gamma < 30$ hits
  - $T_\mu - T_\gamma < 75$ nsec



B) $K^+ \rightarrow \pi^+ + \pi^0$



Event features;

- Br. 21 %.
- π^0 and π^+ are back-to-back and have 205 MeV/c.
- $P\pi^+$ is just above Č thres. (not clear ring).

=> Search for monochromatic π^0 with backward activities.

Selection:

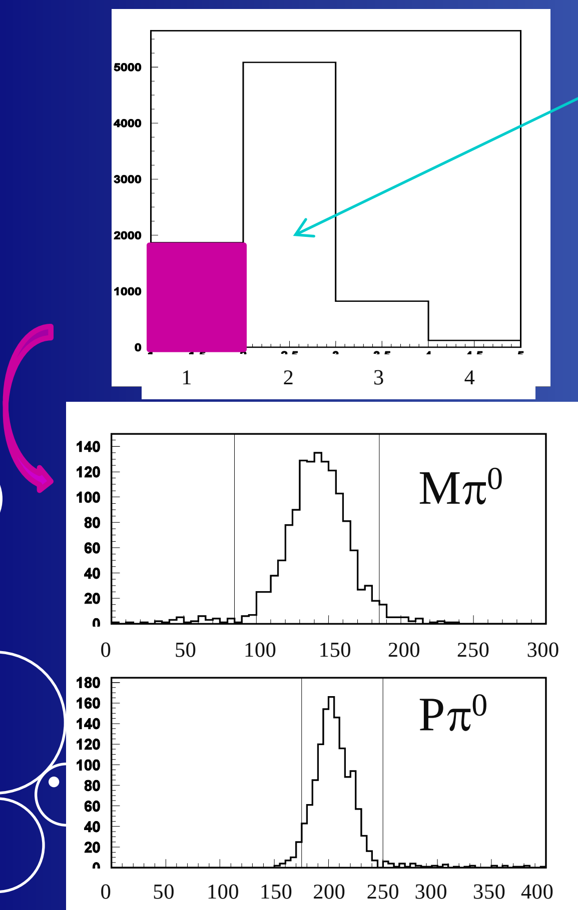
- 2 e-like rings with decay-e.
- $85 < M\pi^0 < 185$ MeV.
- $175 < P\pi^0 < 250$ MeV/c.
- E_{bk}: visible energy sum in 140-180 deg. of π^0 dir,

  E_{res}: in 90-140 deg.

  $7 < E_{bk} < 17$ MeV & $E_{res} < 12$ MeV

Recent improvement(1): $p \rightarrow \bar{\nu} K^+, K^+ \rightarrow \pi^+ \pi^0$

of Ring: $K^+ \rightarrow \pi^+ \pi^0$



Judge as 1 ring if opening angle of 2 γs is small or momentum of one γ is small,

Use "π^0 fitter"

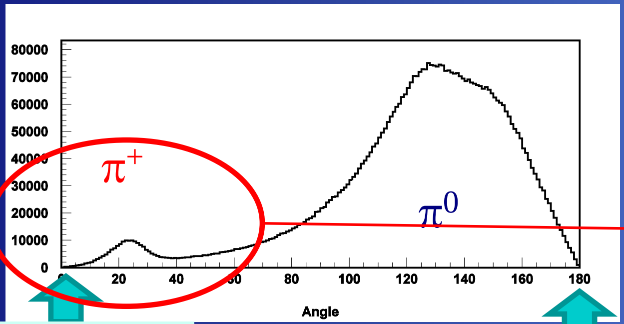
- Make likelihood assuming π^0 and search for missing ring.
- It is used for ν_e appearance analysis of T2K to reduce BKG.

It makes 1 ring sample available for this analysis!

→ efficiency increased.

Recent improvement(2): $p \rightarrow \bar{\nu} K^+, K^+ \rightarrow \pi^+ \pi^0$

Charge distribution in angle

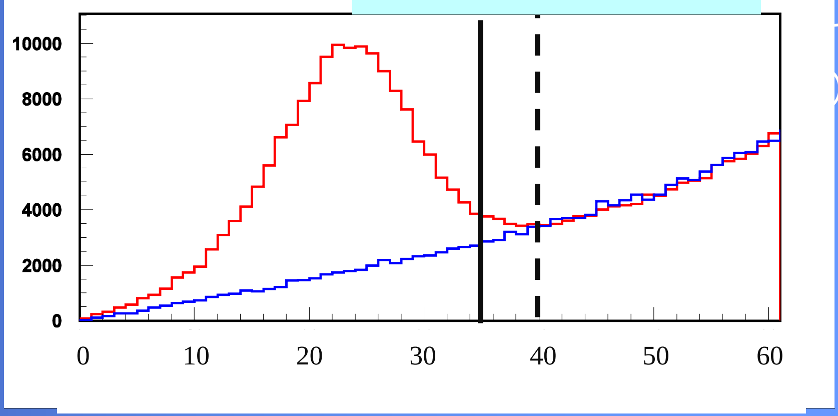


Opposite of π^o dir $= \pi^+$ dir

π^0 dir

zoom

Red: PDK MC
Blue: BKG



Conventional method: Use charge sum in <40°

New method: Use charge sum in < 35°

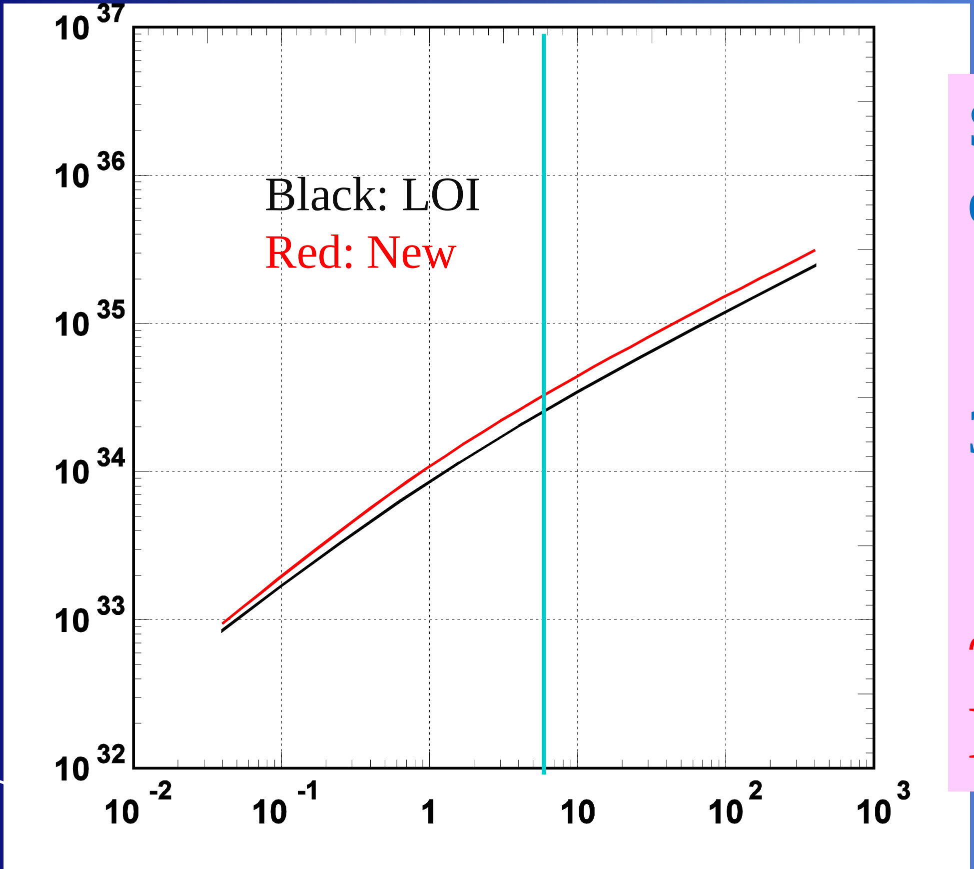
and compare shape by likelihood assuming signal and BKG.

How much improved ?

	Effi (%)	**BKG/Mton·yr**
$K^+ \rightarrow \pi^+\pi^0$	6.6 (LOI) → 7.6	6.6 (LOI) → 1.8
$K^+ \rightarrow \mu\nu$+nuclear γ	7.1	1.6
$K^+ \rightarrow \mu\nu$, $P\mu$	43	1940

- Efficiency increased by 15 %, due to 1R sample.
- BKG reduced by 72 %, due to angle cut and shape likelihood.
- $\pi^+\pi^0$ method become comparable to prompt γ method !

Sensitivity curve for $p \rightarrow \bar{\nu} K^+$ (90 % C.L.)



Sensitivity for 5.6 Mton・year exposure (10 years run)

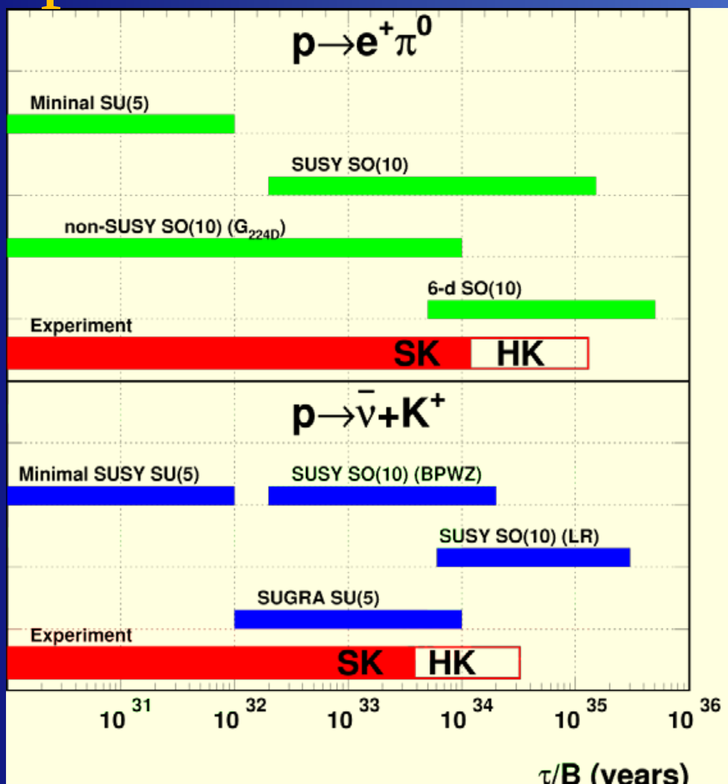
$2.5 \times 10^{34} \rightarrow 3.2 \times 10^{34}$ year

3σ discovery potential

$0.95 \times 10^{34} \rightarrow 1.23 \times 10^{34}$ year

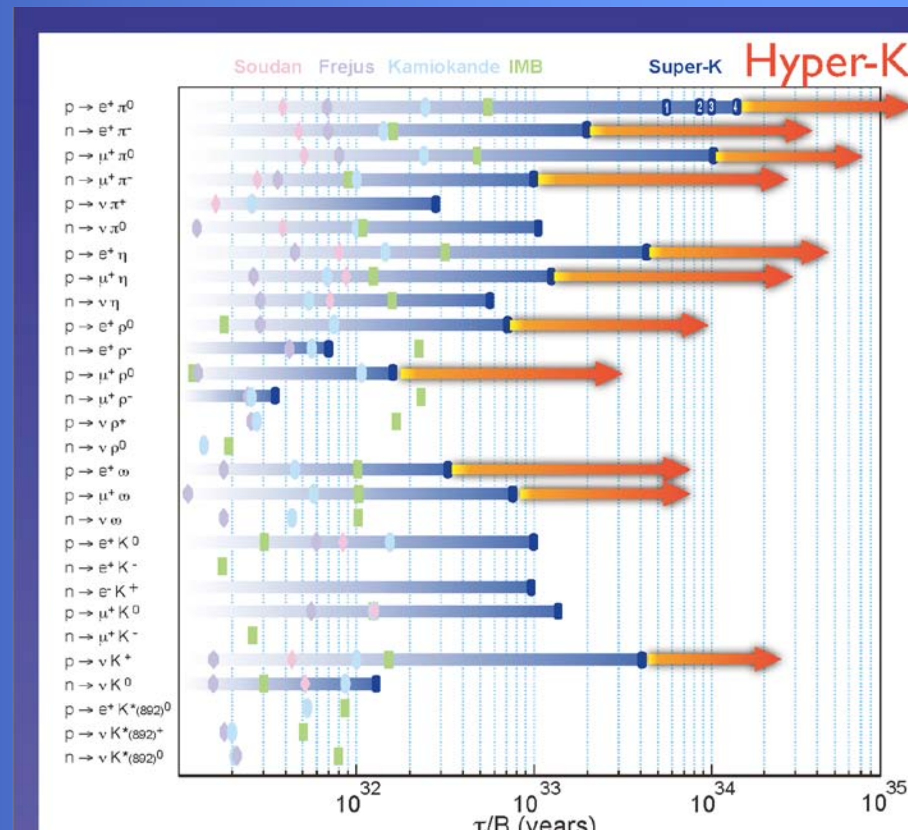
~ 30 % improved from LOI !

Comparison with predictions



Can cover major models.

Other modes



~ 10 times better than SK with 10 year run.

Other physics potential

- δ_{CP} precision <20°

  with 7.5 MW ･years , $s^2 2\theta_{13}$>0.03 with MH known

- MH determination > 3σ CL

  with 10 yrs run, 0.4 < $s^2\theta_{23}$ and 0.04 < $s^2 2\theta_{13}$

- θ_{23} octant determination > 90% CL

  with 10 yrs run, $s^2 2\theta_{23}$ <0.99and 0.04 < $s^2 2\theta_{13}$

- Solar ν from ^{8}B 200 events/day

  with 7 MeV threshold

- Super Nova ν 170,000~200,000 events

  @ Galactic center (10kpc)

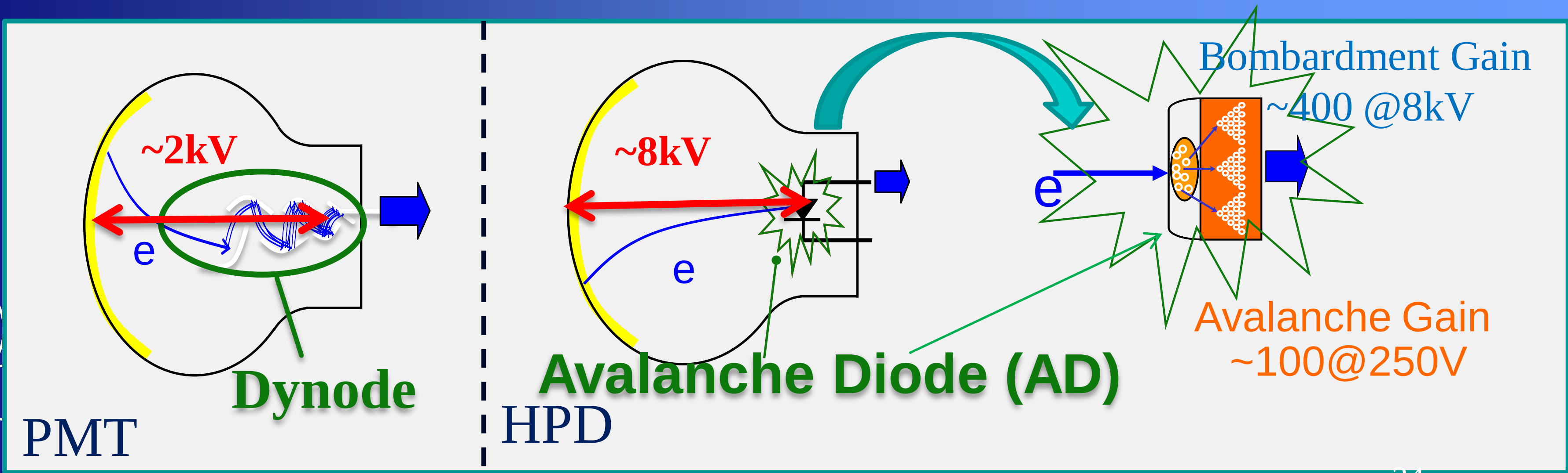
4. R&D status and plans

Photo sensors:

20 inch PMT in baseline design

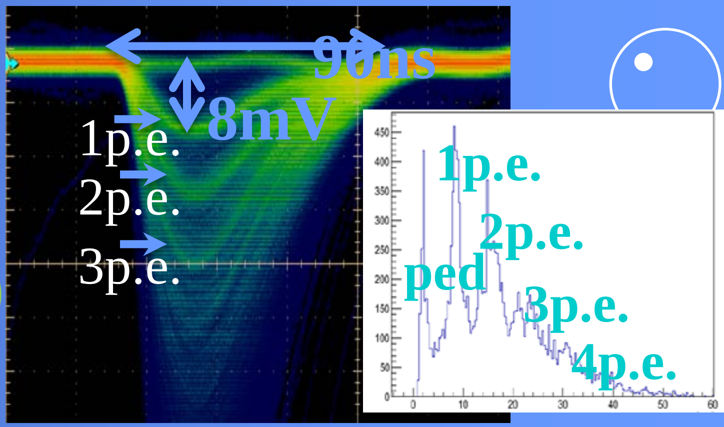
- It is almost hand-made (even in electrics parts).
- Expensive and not suitable for mass production.
- But we need 99,000 PMTs.

➔ **Other possibility: Hybrid Photo Detector (HPD)**

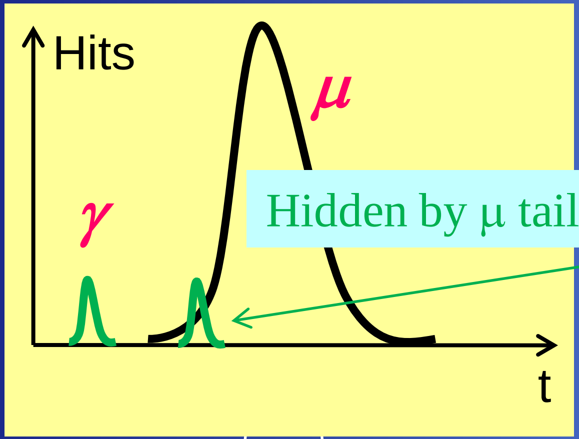


Advantage of HPD

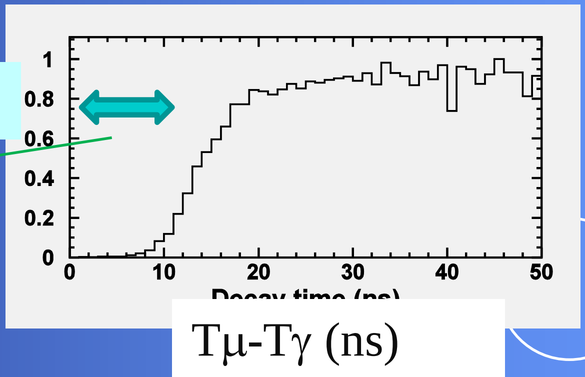
- **Avalanche Diode** is suitable for mass production.
  ➔ lower cost.
- Better photon counting.
- Better collection efficiency .
  (20 inch PMT~75 %→HPD ~95%)
- Better timing resolution
  (20 inch PMT ~2.2 nsec → HPD ~1.1 ns in TTS)



➔ Expect to improve nuclear γ tagging efficiency in $p \rightarrow \bar{\nu} K^+$



γ tagging efficiency



HPD for Hyper-K

- Target: 20 inch HPD, but no such a large one in the world.

  ➔ Made 8 inch with Hamamatu photonics as test module. Now checking basic performance.

- Never used in water (~8kV)

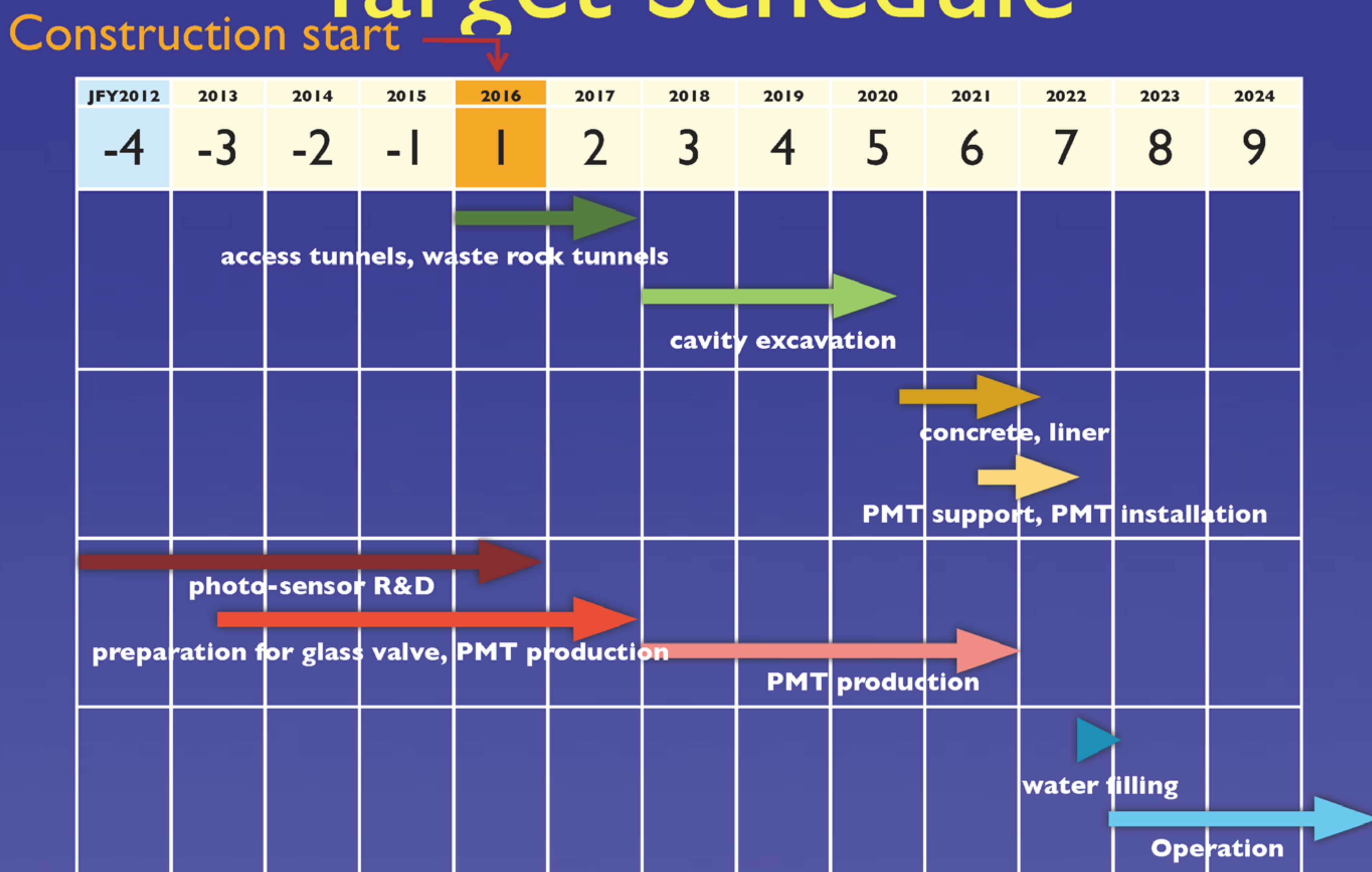
  ➔ Install to test tank (200 ton) in this summer. Check water proof, long term stability, e.t.c.

Software development

- SK detector simulation : Based on GEANT3
  Reconstruction tool: written in Fortran
- Now start to making Hyper-K detector simulation based on GEANT4.
- New reconstruction algorism written in C++:
  developing for SK and T2K analysis, also for Hyper-K.

➔ Evolving to improve physics reach!

Target Schedule



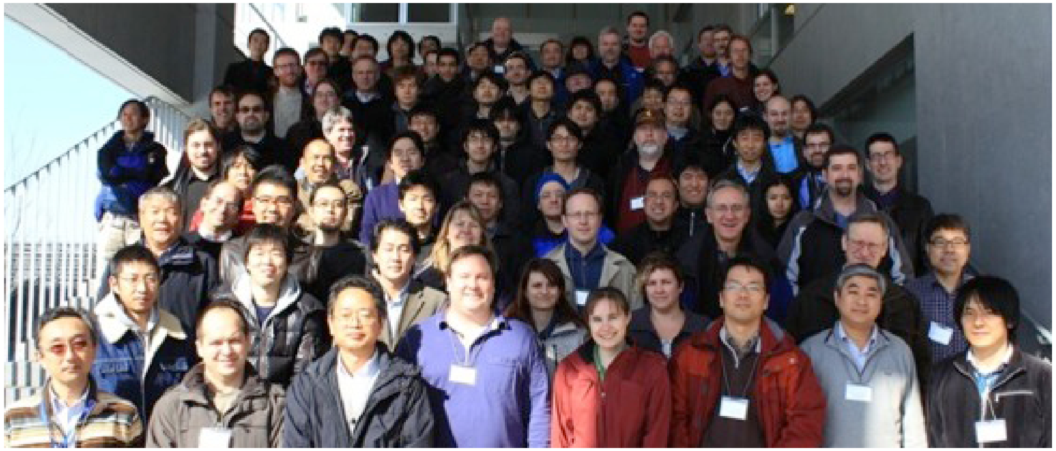
assuming budget being approved from JPY2016

International Hyper-K meetings

First meeting: Aug. 23-24, 2012

http://indico.ipmu.jp/indico/conferenceTimeTable.py?confId=7

Second meeting: Jan. 14-15, 2013



http://indico.ipmu.jp/indico/conferenceTimeTable.py?confId=10

Hyper-K is completely open to the international community

~100 participants for each of two meetings (~half from abroad)

International working group was formed

Current members from Japan, Canada, Spain, Switzerland, Russia, UK, and US

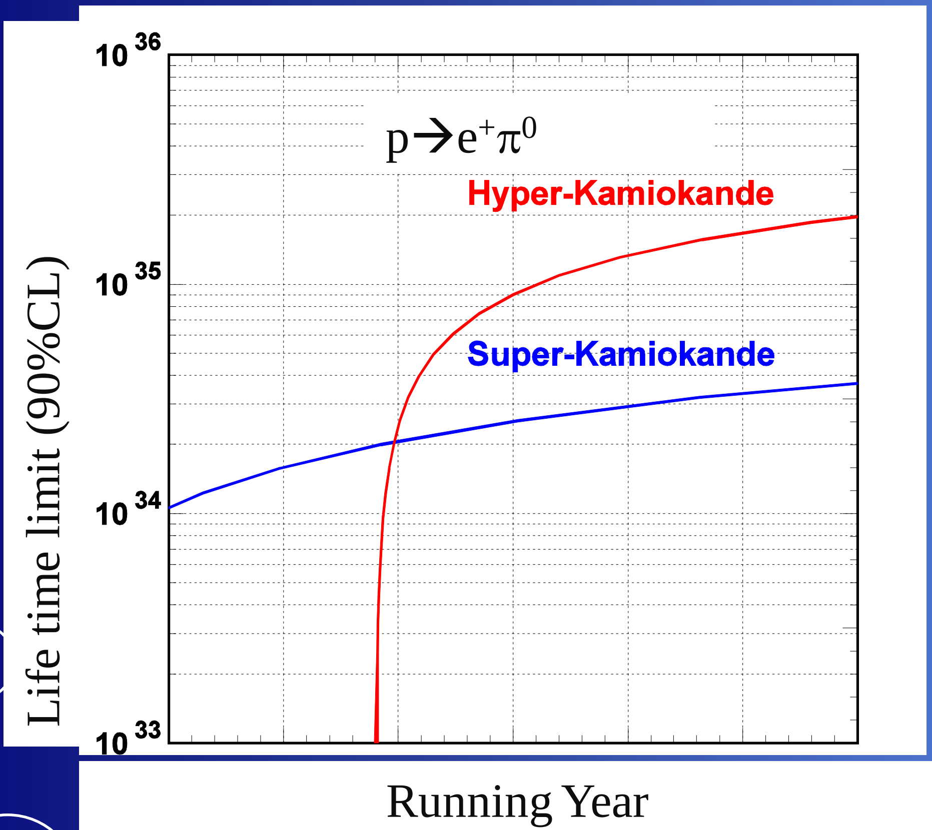
Next meeting: Jun. 21-22

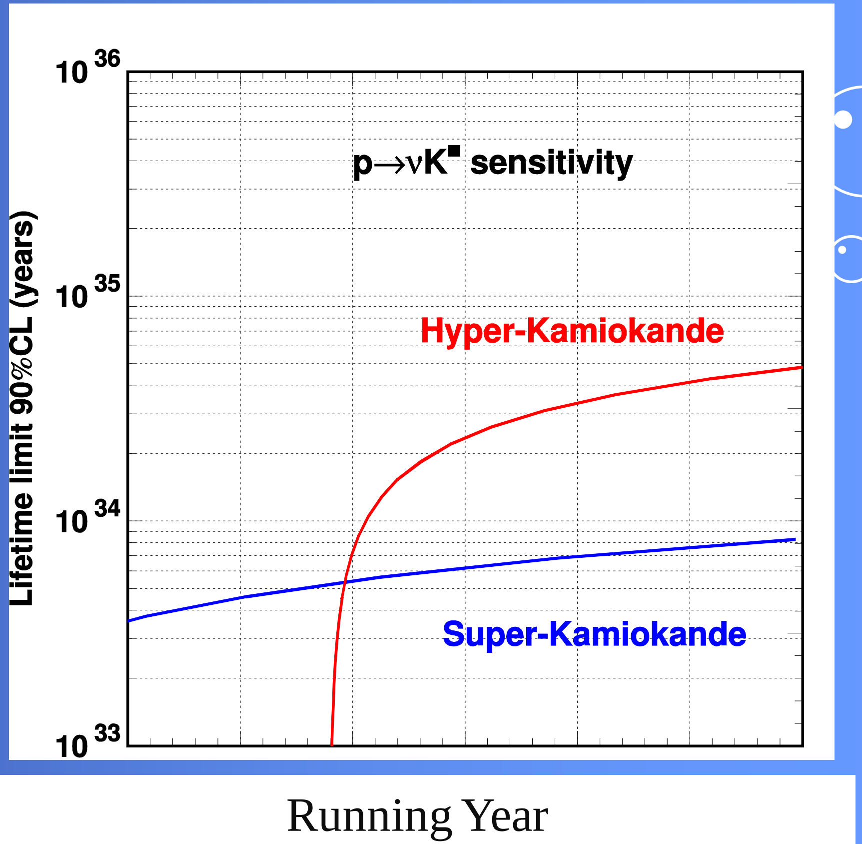
5. Summary

- We are planning to build Hyper-Kamiokande, 1Mton class water cherenkov detector.
- Hyper-Kamiokande can explore one order longer nucleon lifetime than Super-K.
- Now international working group is forming and we welcome your join.

Backup

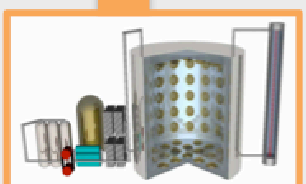
Comparison with Super-K





- HK Overtakes SK by ~one year run.
- Explore one order longer lifetime than SK by 10 years run.

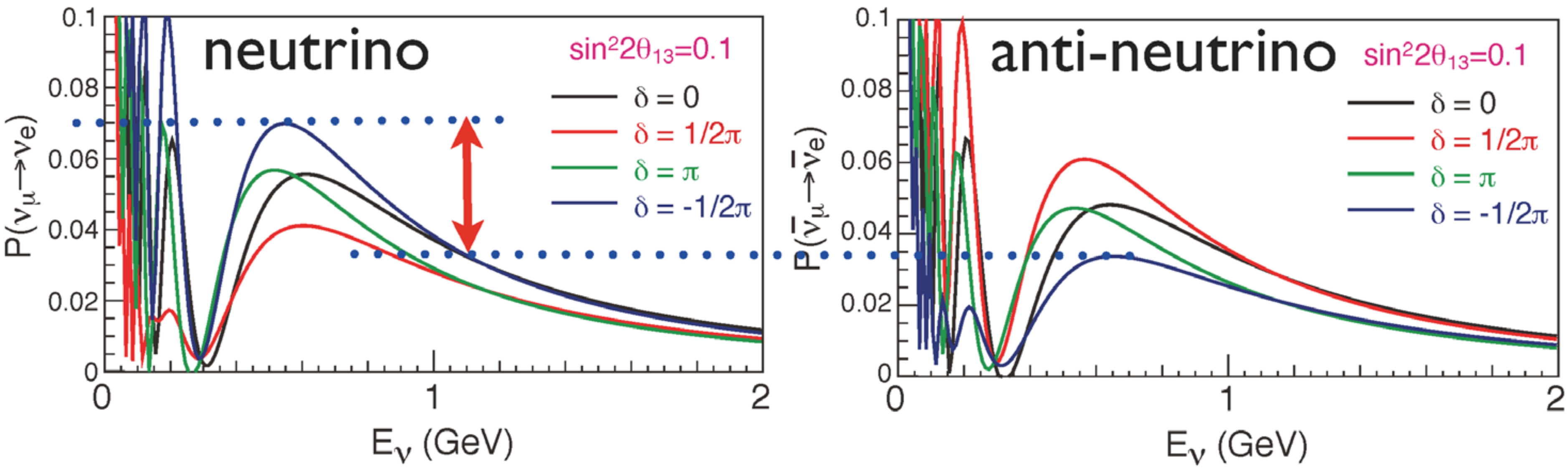
Schedule of HPD R&D

Year	Season.	8 inch HPD	20 inch HPD
2013	Spring	Proof test 200t tank Performance Evaluation (detail)	Prototype Performance Evaluation
2014		• Uniformity • B-field/Temp. dependence	
2015	Spring		Proof Test in 200t tank
2016	Determine HK photo sensor !		

We plan to finish our HPD study until 2016.

Measuring CP asymmetry w/ J-PARC ν beam

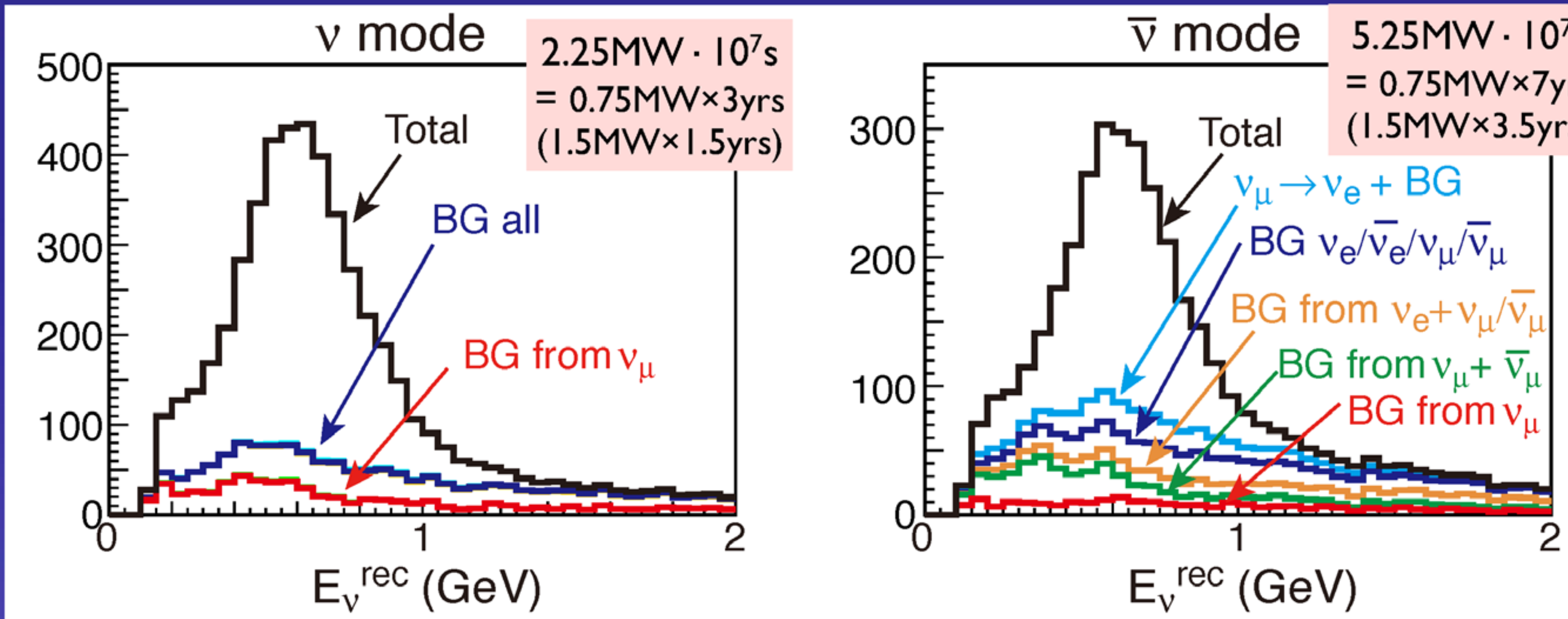
$P(\nu_\mu \rightarrow \nu_e)$ appearance probability (normal hierarchy)



- Comparison between $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

ν_e candidate events after selection

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



	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 ($2.25\text{MW} \cdot 10^7\text{s}$)	3,560	46	35	880	649
$\bar{\nu}$ ($5.25\text{MW} \cdot 10^7\text{s}$)	1,959	380	23	878	678

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

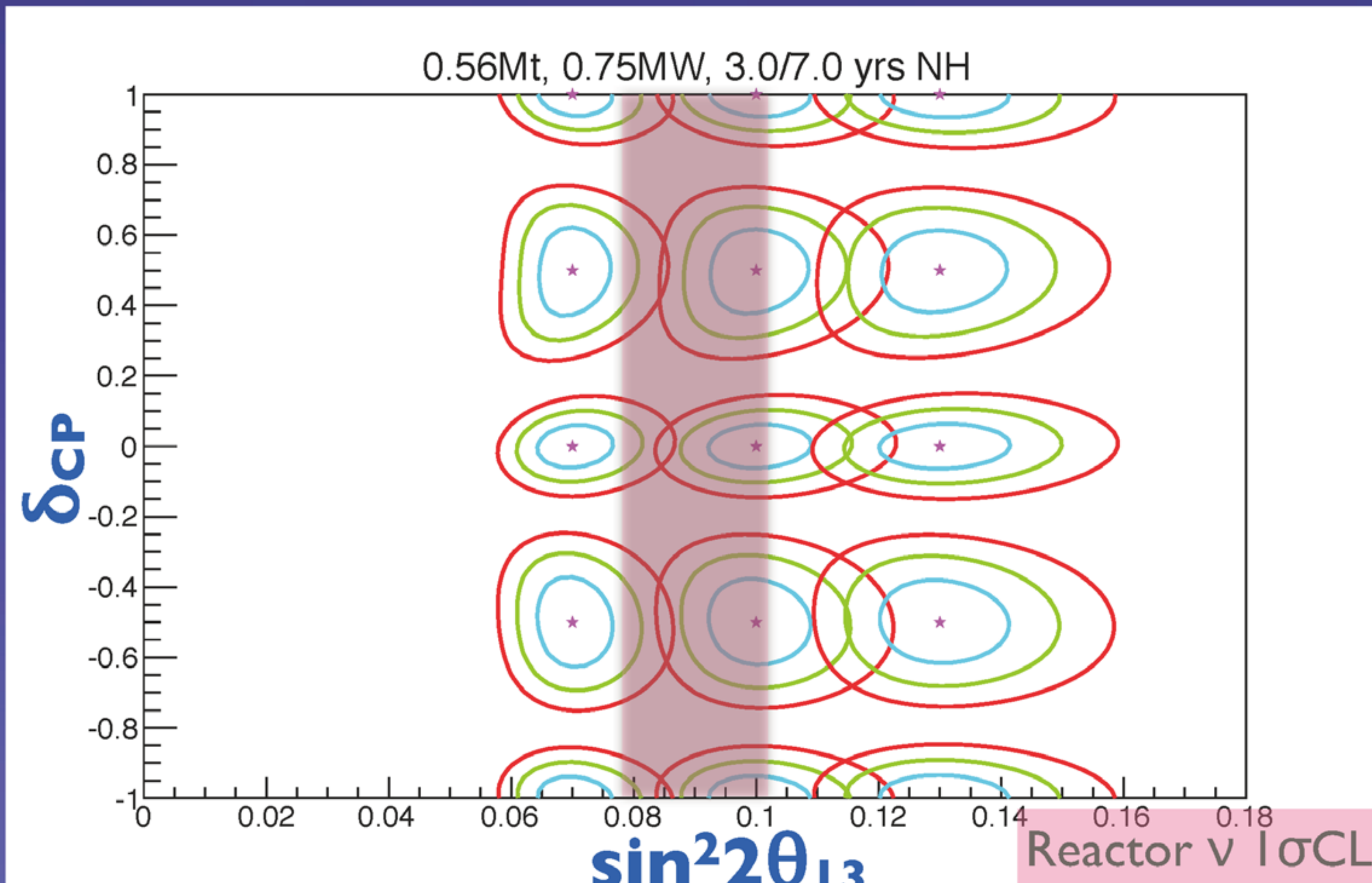
Contours

7.5MW · years

Normal mass hierarchy (known)

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

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

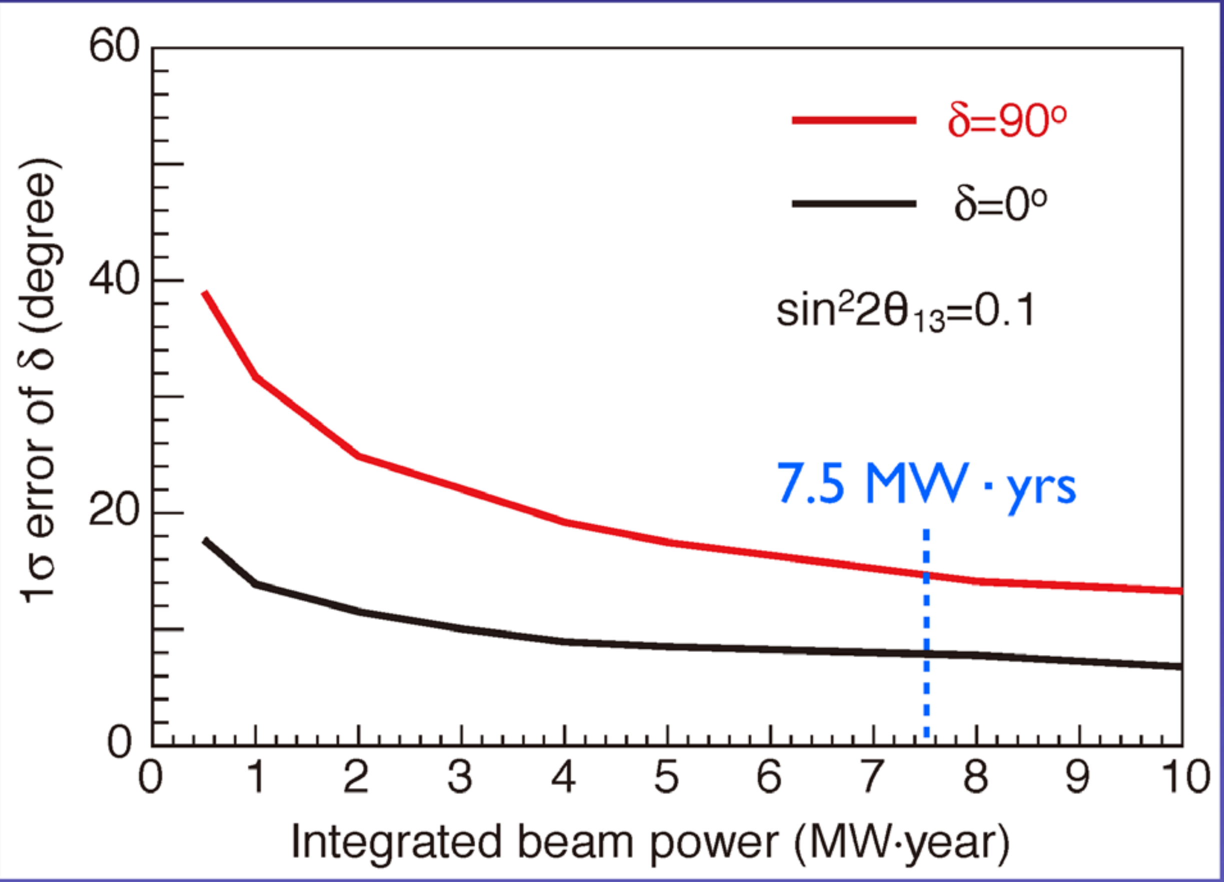


- Good sensitivity for CPV
- modest dependence on θ_{13} value

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}

3-flavor oscillations in atmospheric ν

NuclPhysB669,255(2003)

NuclPhysB680,479(2004)

$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx P_2(r \cdot \cos^2\theta_{23} - 1) \quad \text{Solar term}$$
$$- r \cdot \sin\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin 2\theta_{23}(\cos\delta \cdot R_2 - \sin\delta \cdot I_2) \quad \text{Interference term } (\delta CP)$$
$$+ 2\sin^2\tilde{\theta}_{13}(r \cdot \sin^2\theta_{23} - 1) \quad \theta_{13} \text{ resonance term} \qquad (3)$$

r : μ/e flux ratio (~2 at low energy)

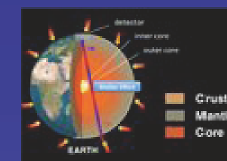
$P_2 = |A_{e\mu}|^2$: 2ν transition probability $\nu_e \to \nu_{\mu\tau}$ in matter

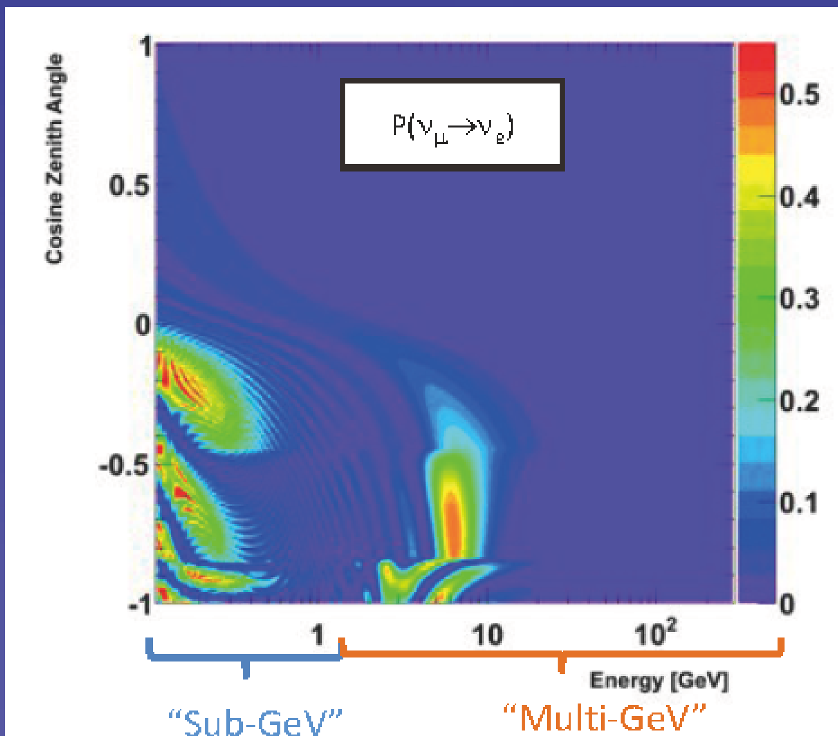
$R_2 = \mathrm{Re}(A^*_{ee}A_{e\mu})$

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

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

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



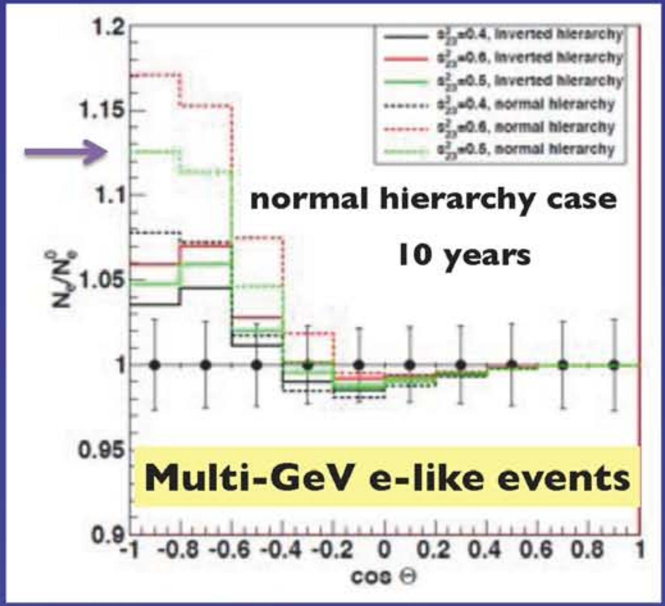


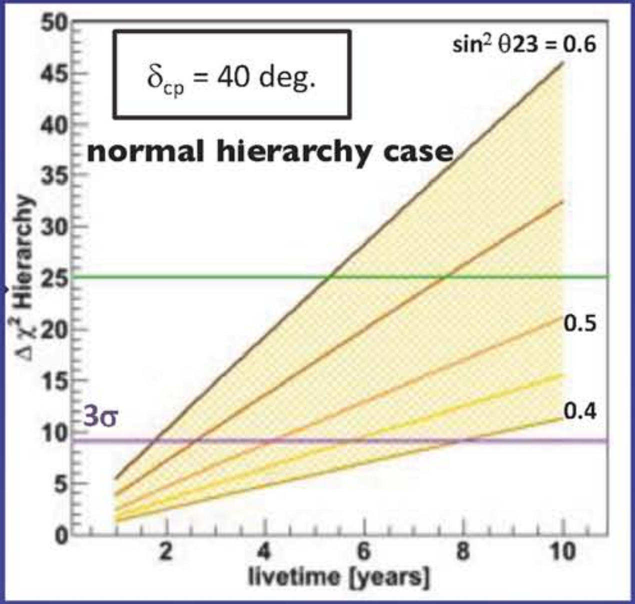
ν_e appearance (and ν_μ distortion) is expected due to MSW effect in the Earth's matter

- 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.

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.