Nucleon Decay Searches in Super-Kamiokande

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High Sensitivity Experiments Beyond the Standard Model

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Thank you for giving me the opportunity to visit Quy Nhon again !

Outline

- Introduction
- Super-Kamiokande
- $p \rightarrow e^+\pi^0$, $\mu^+\pi^0$
- $p \rightarrow \nu K^+$
- Other modes
- Summary and prospects (SK-Gd, Hyper-K)

1. Introduction

Strong | Weak | EM
(Electroweak)

↓ ↓

Grand Unified Theories

The Standard Model has been successful!
… but why so many parameters?

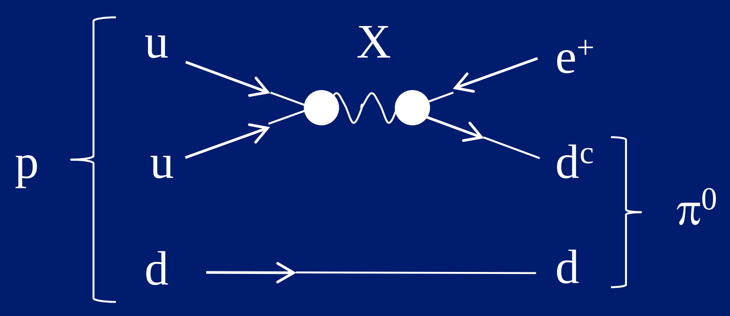
GUTs: attempt to unify Strong and Electroweak interactions.

GUTs scale: $10^{14\text{-}16}$ GeV ⇒ Cannot be reached by Accelerators.

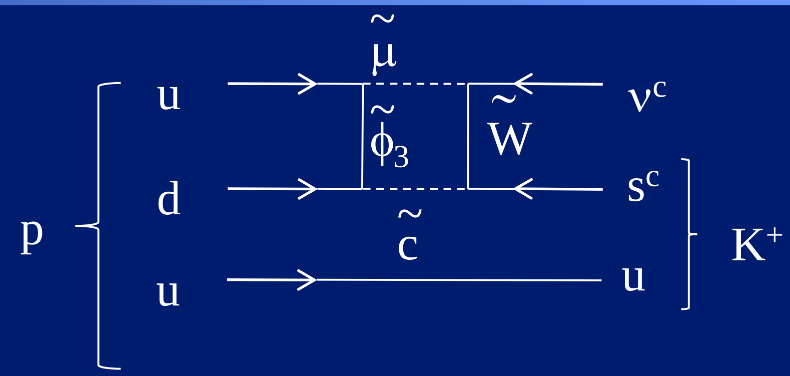
Lepton and baryon numbers are not conserved. ⇒ Proton decay is permitted !

Nucleon decay experiment is the direct probe for GUTs.

Examples of proton decay



Minimal SU(5) model



SUSY SU(5) model

Proton lifetime predictions

Model	Mode	Prediction (years)
Minimal SU(5)	$p \rightarrow e^+\pi^0$	$10^{28.5} \sim 10^{31.5}$ [1]
Minimal SO(10)	$p \rightarrow e^+\pi^0$	$10^{30} \sim 10^{40}$ [2]
Minimal SUSY SU(5)	$p \rightarrow \bar{\nu}K^+$	$\leq 10^{30}$ [3]
SUGRA SU(5)	$p \rightarrow \bar{\nu}K^+$	$10^{32} \sim 10^{34}$ [4]
SUSY SO(10)	$p \rightarrow \bar{\nu}K^+$	$10^{32} \sim 10^{34}$ [5]

[1] P. Langacker, Phys. Reports 72, 185 (1981)
[2] D.G. Lee, M.K. Parida, and M. Rani, Phys. Rev. D51, 229 (1995)
[3] H.Murayama and A. Pierce, Phys. Rev. D65, 55009 (2002)
[4] T. Goto and T. Nihei, Phys. Rev. D59, 115009 (1999)
[5] V. Lucas and S. Ruby, Phys. Rev. D55, 6986 (1997)

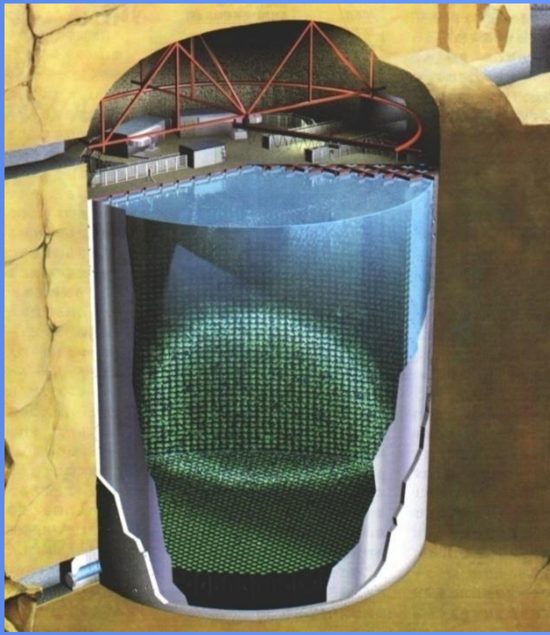
$> 10^{30}$ years !

It's REALLY rare decay.

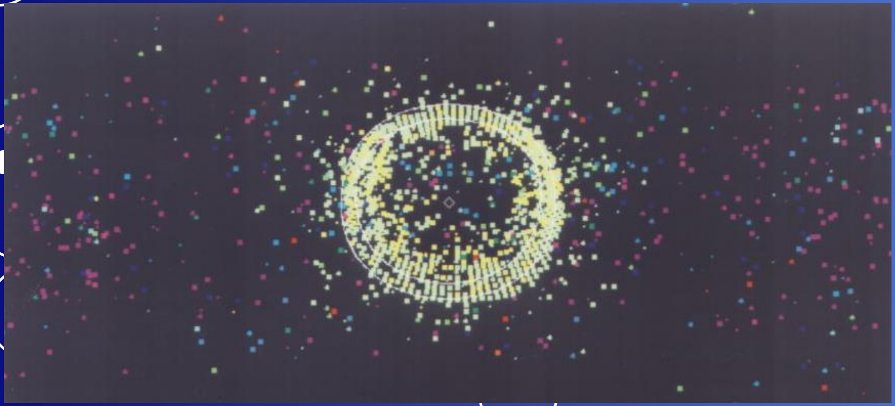
Nucleon Decay Experiment

2. Super-Kamiokande Detector

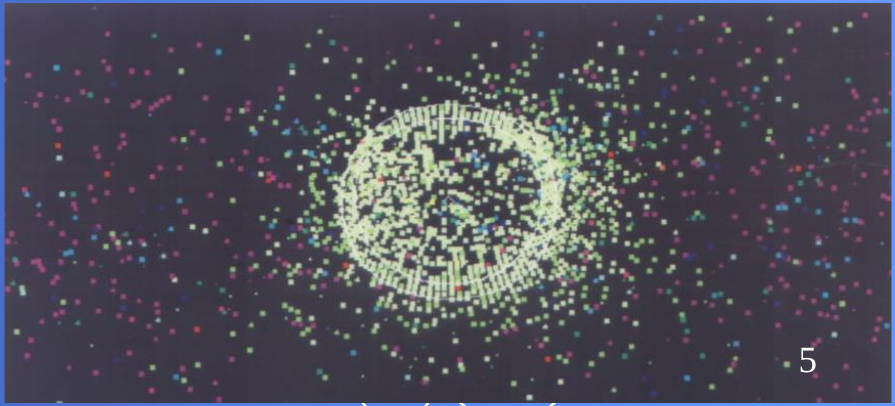
Location: Kamioka mine, Japan. ~1000 m under ground.
Size: 39 m (diameter) x 42 m (height), 50kton water. Optically separated into inner detector (ID) and outer detector (OD, ~2.5 m layer from tank wall.)
Photo device: 20 inch PMT (ID), 8 inch PMT (OD, veto cosmic rays).
Mom. resolution: 3.0 % for e 1 GeV/c (4.1%: SK-2).
Particle ID: Separate into EM shower type (e-like) and muon type (μ-like) by Cherenkov ring angle and ring pattern.



μ-like ($\mu^{\pm}$)



e-like ($e^{\pm}$, γ)



History of Super-Kamiokande

Accident

Reconstruction

Electronics upgrade

96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16

SK-1
Livetime:
- 1489.2 days
Exposure:
- 91.7 kton·yr
Inner PMT: 11146
Photo coverage:
40 %

SK-2
Livetime:
- 798.6 days
Exposure:
- 49.2 kton·yr
Inner PMT:5182
Photo coverage:
19 %

SK-3
Live time:
518 days
Exposure:
31.9kton･yr
ID PMT:11146
Photo coverage:
40 %

SK-4 (~Mar.16')
Live Time:
2520 days
Exposure:
155.2kton･yr

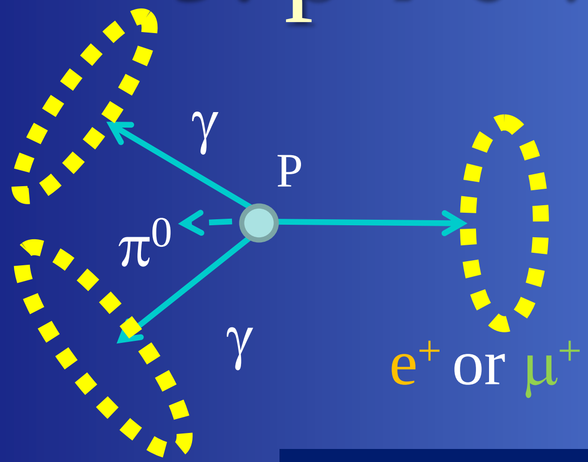
Same

- Run more than 20 years !
- Collected 328kton･year data in total.

Water Cherenkov Detector for Nucleon Decay searches

- Easy to construct large detector .
  - Need huge number of nucleons.
  - SK: 22.5kton in fiducail = 7.5×10^{33} protons.
- High efficiency and low uncertainty.
  - Mesons from proton decay in oxygen suffer from nuclear interactions (absorption, scattering, charge exchange …) which are dominant sources of inefficiency.
  - 2 hydrogens in water act as free proton, free from nuclear interactions.
- Backgrounds (atmospheric ν) are well understood.
  - SK is the world largest Neutrino Detection Experiment.

3. $p \rightarrow e^+\pi^0$,$\mu^+\pi^0$ mode



Event features;

- e^+ ,$\mu^+$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

Selected by simple cuts!

$e^+\pi^0$ case;

- all e-like, w/o decay-e.

$\mu^+\pi^0$ case;

- one μ-like with decay-e.

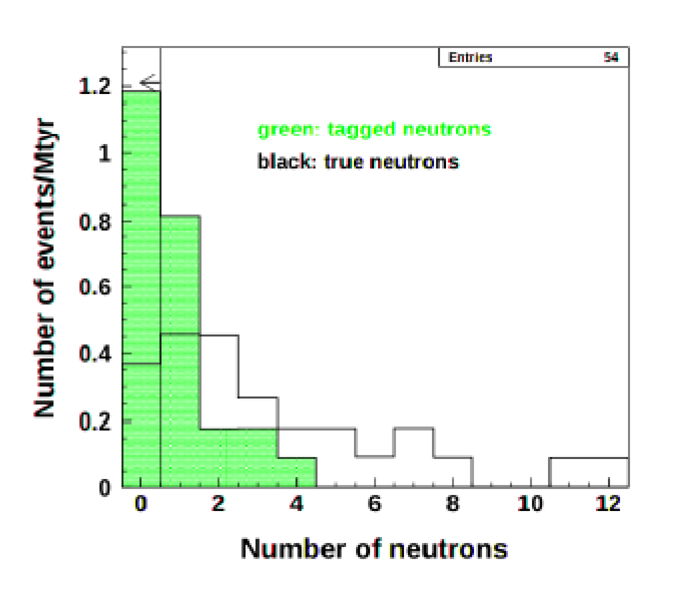
- $85 < M\pi^0 < 185$ MeV (for 3-ring event) .
- $800 < M_P < 1050$ MeV & $P_{tot} < 250$ MeV/c

New technique 1: Neutron tag

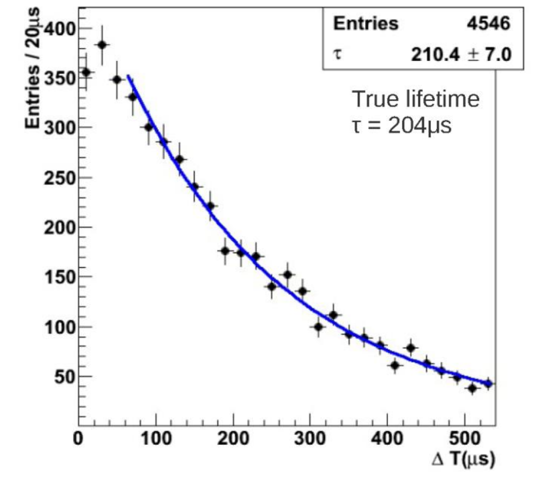
- Most of atmospheric ν BKG are accompanied by neutron.
- A neutron is captured by hydrogen (~200μsec) and emit γ ray;

$$n+p \rightarrow d+\gamma \text{ (2.2 MeV)}$$

- New electronics installed in SK4 enables to record all hits including this γ ray.
- Search for hit cluster N≥7 in 10 ns window after prompt signal, and neutrons are selected by neural network.
- Eff. 20.5 %, BKG 1.8 %.
- About half of backgrounds can be rejected by requiring no neutron.

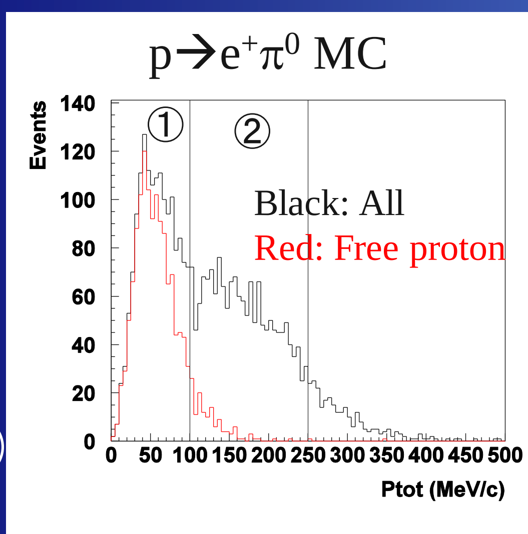


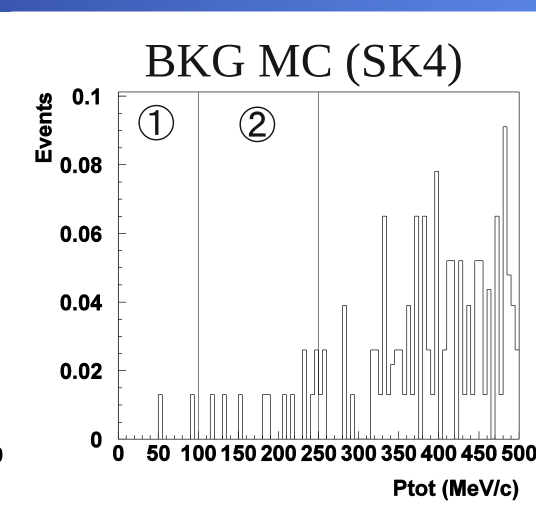
Time difference from prompt signal

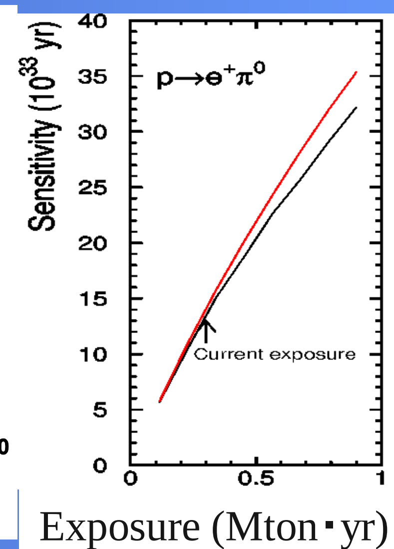


New technique 2: two box analysis

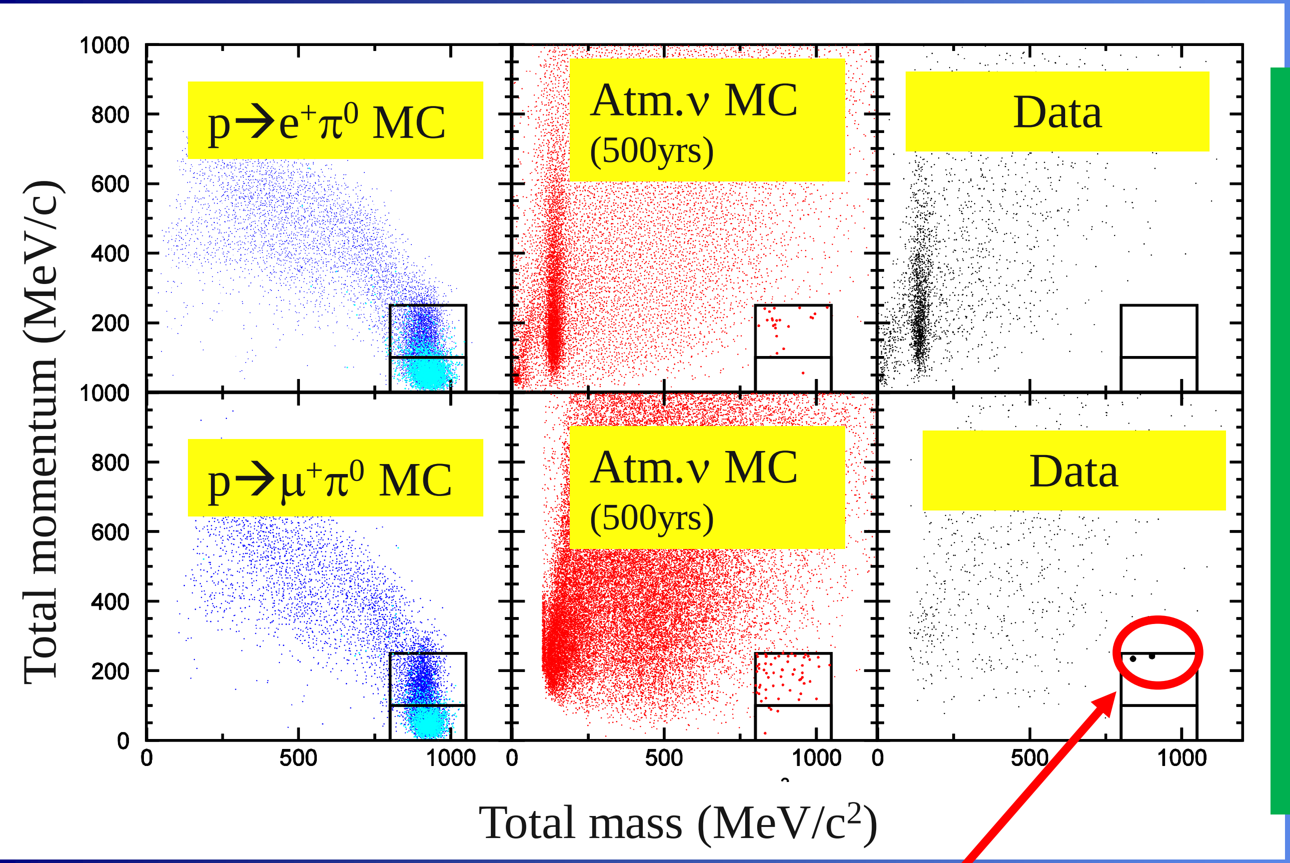
- Signal box defined by 800<Mtot<1050 MeV/c^2 and Ptot<250MeV/c is divided into two regions;
  ① Lower box: Ptot<100 MeV/c
    ✓ Signal: Dominated by free proton(H) decay, free from nuclear effects → Almost BKG free.
  ② Higher box: 100≤Ptot<250 MeV/c
    ✓ Signal: Dominated by bound proton (O) decay, more uncertainty due to nuclear effects. More BKG.
- Achieve better sensitivity.







Results



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

	Eff. (%)	BKG	OBS
Low P_{tot}	18.7	0.07	0
High P_{tot}	19.9	0.54	0
Total	38.6	0.61	0

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

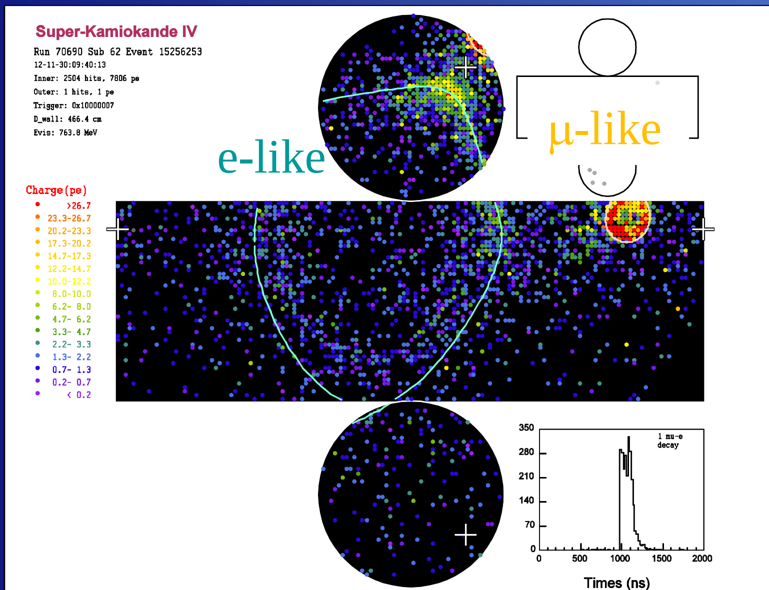
	Eff.(%)	BKG	OBS
Low P_{tot}	18.0	0.05	0
High P_{tot}	16.7	0.82	2
Total	34.7	0.87	2

(Poison(0.87,≥2) = 23%)

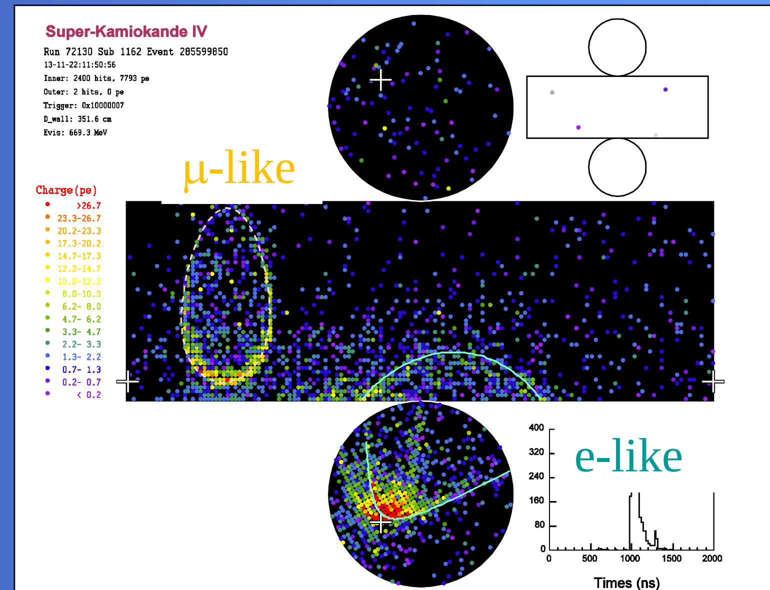
2 candidates for $p \to \mu^+\pi^0$!

Observed events (both are 2-ring events)

1st event



2nd event



	TotMass (MeV/c^2)	TotMom. (MeV/c)	Pe (MeV/c)	Pμ (MeV/c)	Ang. (deg.)
1st	903	248	375	551	158
2nd	832	238	461	391	149

Note1: Cut: Ptot <250MeV/c, they were really close to boundary.
Note2: The 2nd event will go out from signal box with updated gain correction.

Systematic errors

	$p \to e^+\pi^0$		$p \to \mu^+\pi^0$	
	low P_{tot}	high P_{tot}	low P_{tot}	high P_{tot}
Eff.				
π-FSI	2.8	10.6	2.9	12.1
Corr. decay	1.9	9.1	1.7	9.0
Fermi mom.	8.5	9.3	8.0	9.6
Reconstruction	4.6	5.6	3.7	3.3
Total	10.2	17.7	9.4	18.2
BKG				
Flux	7.0	6.9	7.0	7.0
Cross section	14.5	10.4	8.4	7.8
π-FSI	15.4	15.4	14.2	14.4
Reconstruction	21.7	21.7	21.7	21.7
(neutron tag)	10	10	10	10
Total (I/II/III)	31.2	29.4	28.1	28.1
(IV)	32.7	31.1	29.9	29.8

Life time limt (90% CL) with 306kton･yrs data

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

$> 1.6 \times 10^{34}$ years

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

$> 7.7 \times 10^{33}$ years

(will be published soon).

Coming soon: Improved reconstruction tool.

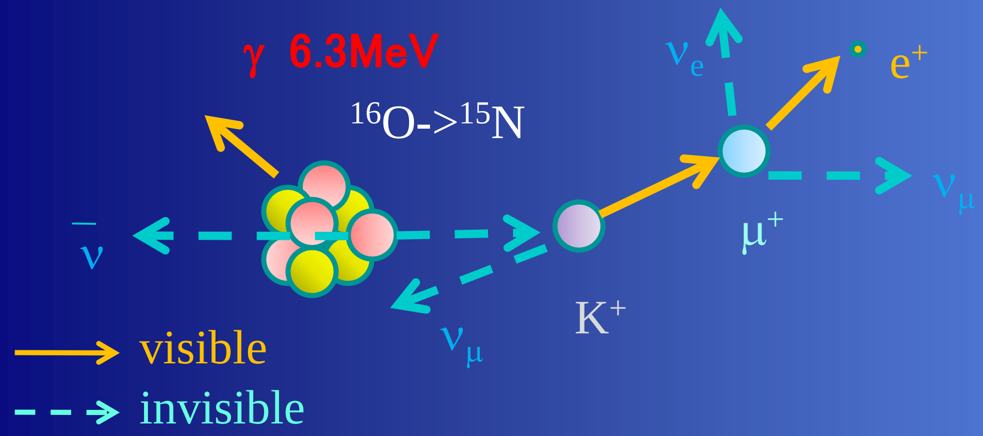
- Current one: decide step by step: VTX, # of rings, PID, Mom …
- New method: Fit everything at once by maximum likelihood.
- Higher resolution → Expect to improve discovery potential.

4. $p \rightarrow \bar{\nu} K^+$ mode

General features

- $\bar{\nu}$ cannot be detected = not reconstruct proton mass and momentum.
- Momentum of K^+ ~ 339MeV/c: below Cherenkov threshold and not visible by SK.
- K^+ stops in water and decay with $\tau = 12$ns:
  - $K^+ \rightarrow \nu\mu^+$: Br. 64 % (Method A)
  - $K^+ \rightarrow \pi^+\pi^0$: Br. 21 % (Method B)
- In these two body decay case, decayed particles have monochromatic momentum.

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



Event features;

- K^+ is invisible, stops and 2 body decay (P_μ = 236 MeV/c).

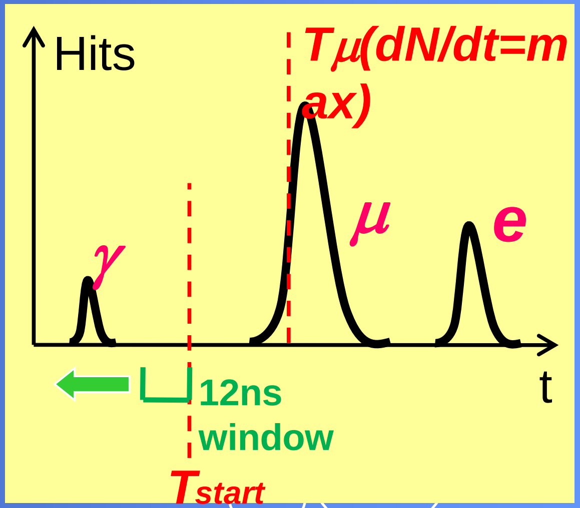
➔ Excess in P_μ.

- 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 < Pμ < 260 MeV/c
- Search Max hit cluster by sliding time window (12ns width);
  - 8 < Nγ < 60 hits for SK-1,3,4
  - 4 < Nγ < 30 hits for SK-2
  - $T_\mu - T_\gamma$ < 75 nsec
- No neutrons (only for SK-4)

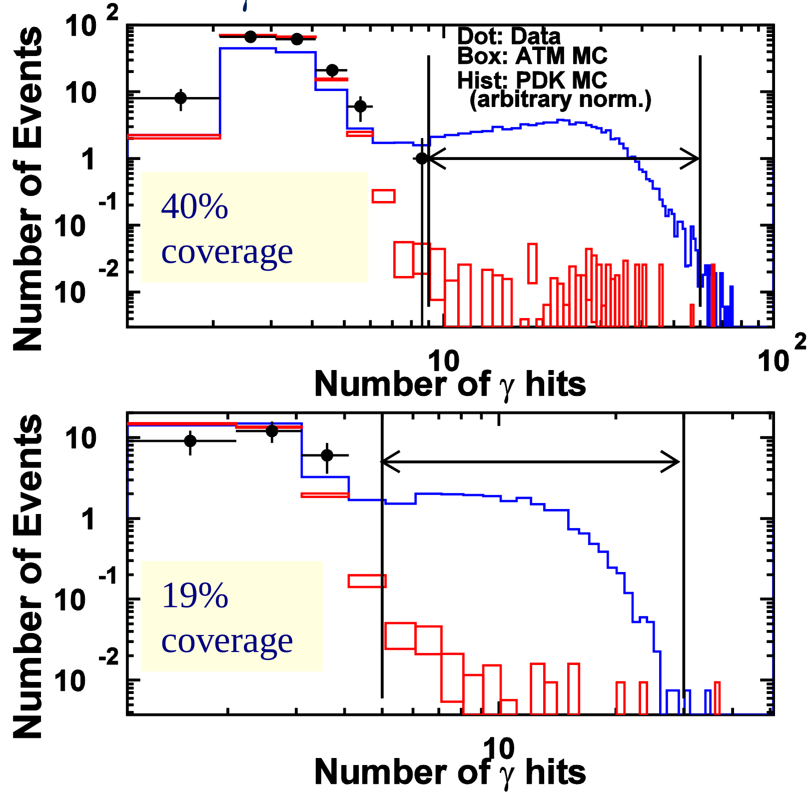


Results of Method (A)

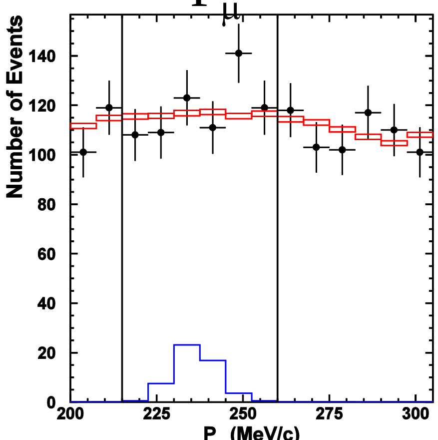
	Exp. (kton･yr)	Eff(%)	BKG	Data
SK1	91.7	7.9±0.1	0.08	0
SK2	49.2	6.3±0.1	0.14	0
SK3	31.9	7.7±0.1	0.03	0
SK4	133.5	8.5±0.1	0.14	0
Total	306.3		0.39	0

Black: Data
Red: ATM MC
Blue: PDK MC

N_γ distributions



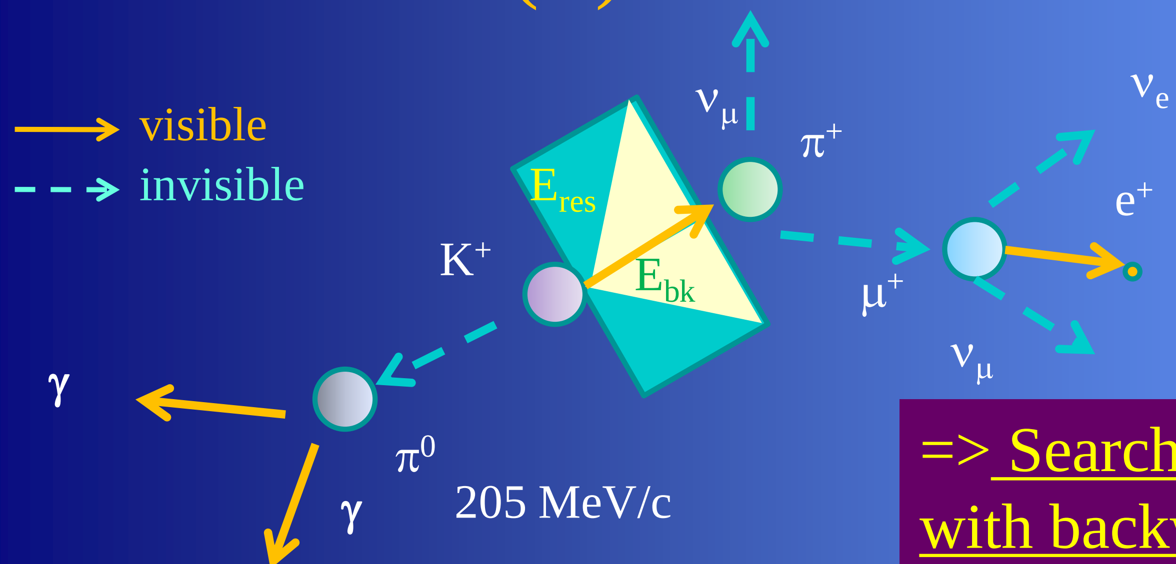
P_μ



Black: Data
Red: ATM MC
Blue: PDK MC

No candidates and no excess in P_μ.

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



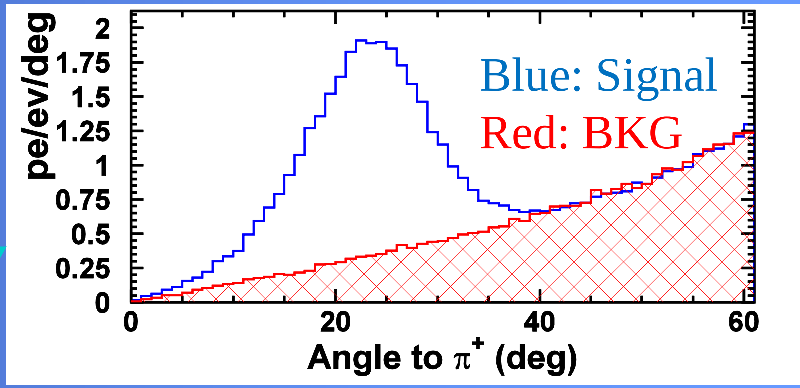
Event features;

- 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:

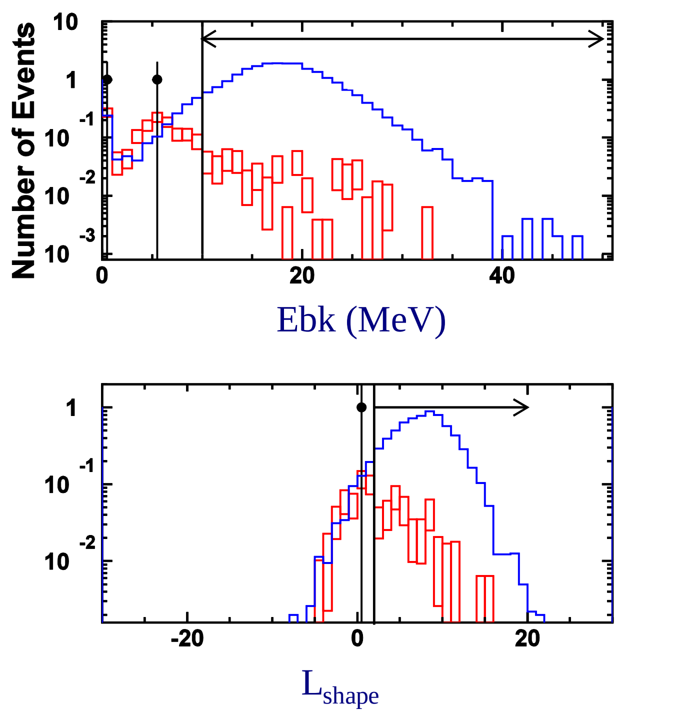
- 1 or 2 e-like rings with decay-e.
- $85 < M\pi^0 < 185$ MeV.
- $175 < P\pi^0 < 250$ MeV/c.
- E_{bk}: visible energy sum in 140-180 deg. of π^0 dir,
  E_{res}: in 90-140 deg,
  L_{shape}: Likelihood based on charge profile
  $10 < E_{bk} < 50$ MeV
  $E_{res} < 12$ MeV (20 MeV for 1ring)
  $L_{shape} > 2.0$ (3.0 for 1ring)
- No neutrons



Results of Method (B)

	Exp. (kton·yr)	Eff(%)	BKG	Data
SK1	91.7	7.8±0.1	0.18	0
SK2	49.2	6.7±0.1	0.17	0
SK3	31.9	7.9±0.1	0.09	0
SK4	133.5	9.0±0.1	0.12	0
Total	306.3		0.56	0

Black: Data
Red: ATM MC
Blue: PDK MC



No candidates.

$p \rightarrow \bar{\nu} K^+$ Lifetime limit (90% CL) combining Method (A) and (B):

> 6.6 x10^{33} yrs @306 kton·yr

5. Other modes

N→ charged anti-lepton +meson

$p, n \rightarrow (e^+, \mu^+) + $ meson

- p: π^0, η, ρ^0, ω
- n: π^-, ρ^-

- Several mode in which a nucleon decays into a charged lepton and a meson (not only π^0) are proposed.
- Those searches were published with 141kton･yr exposure (PRD **85** 112001,(2012)).

Updated with 317kton･yrs exposure .

- ✓ Reduce BKG in SK4 by neutron tag.
- ✓ Two box analysis for $p \rightarrow e^+/\mu^+ + \eta^0$, $\eta^0 \rightarrow 2\gamma$
- ✓ And so on .

Event selection

1) Select rings (+ Michel electron cut)

$N \rightarrow$	lepton	meson	meson decay mode	(Br.)
$p \rightarrow$	e^+ (μ^+)	π^0	$\pi^0 \rightarrow 2\gamma$	(98.8%)
$p \rightarrow$	e^+ (μ^+)	η	$\eta \rightarrow 2\gamma$	(39.3%)
			$\eta \rightarrow 3\pi^0$	(32.6%)
$p \rightarrow$	e^+ (μ^+)	ρ^0	$\rho^0 \rightarrow \pi^+\pi^-$	($\sim$100%)
$p \rightarrow$	e^+ (μ^+)	ω	$\omega \rightarrow \pi^0\gamma$	(8.9%)
			$\omega \rightarrow \pi^+\pi^-\pi^0$	(89.2%)
$n \rightarrow$	e^+ (μ^+)	π^-		
$n \rightarrow$	e^+ (μ^+)	ρ^-	$\rho^- \rightarrow \pi^-\pi^0$	($\sim$100%)

Primary e/μ ring and
→ 2 e-like rings
→ 2 e-like rings
→ 4, 5 e-like rings
→ 2 μ-like rings
→ 2,3 e-like rings
→ 2 e-like and 1 μ-like

→ 2-elike and 1 μ-like

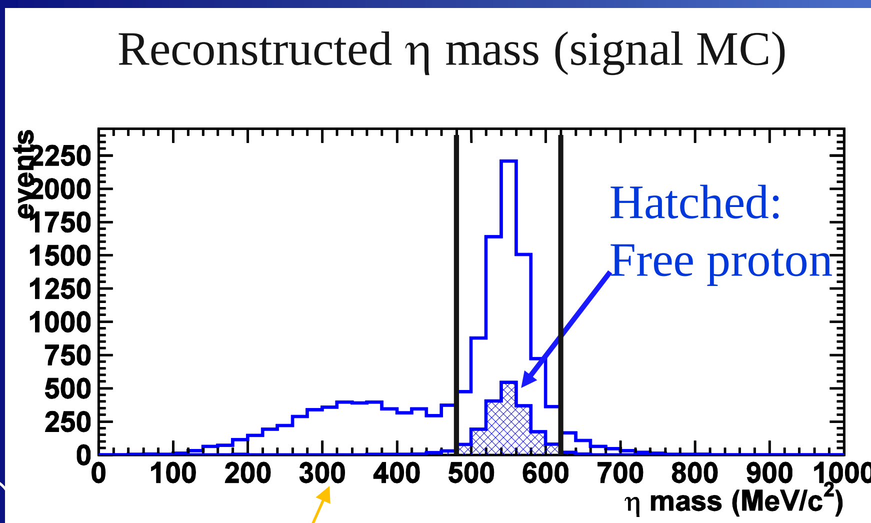
2) Reconstruct meson mass

η: 480 ~ 620 MeV/c^2
ρ^0 ,ρ^- : 600 ~ 900 MeV/c^2
ω: 650 ~ 900 MeV/c^2

3) Reconstruct nucleon mass and momentum

mass: 800 ~ 1050 MeV/c^2
(600~800MeV for p→eω, 450~700MeV for p→μω)
momentum: < 250 MeV/c
(<150 MeV/c for p→eη($3\pi^0$),eρ,eω($\pi^0\gamma$),
<200 MeV/c for p→ε/μω($\pi^+\pi^-\pi^0$))

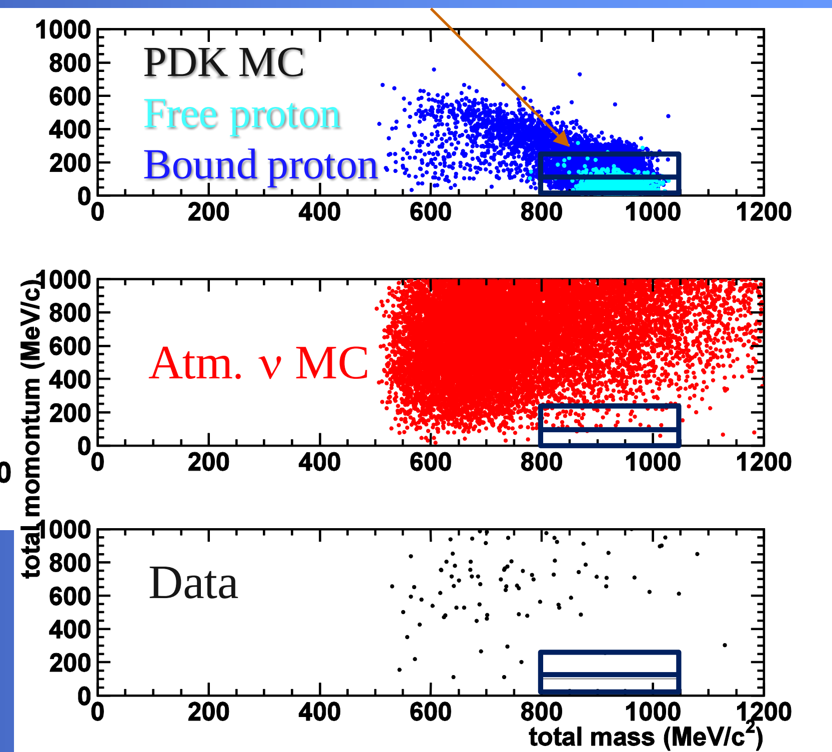
Example: p→e⁺η, η→2γ



Tail: Other decay modes of η
($\pi^0\pi^0\pi^0$, e.t.c.)

Can reconstruct meson mass!

Use two box: Ptot<100 MeV/c,
100≤Ptot<250 MeV/c



Results

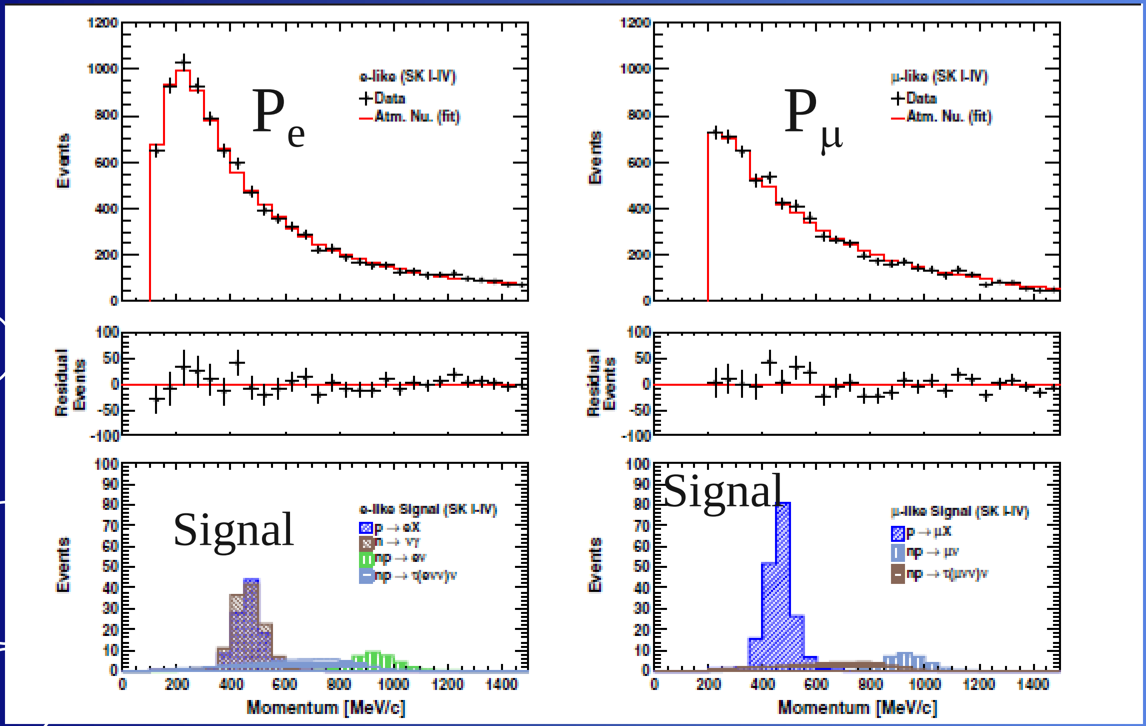
Mode	Eff.(%)	BKG	Obs.	Poisson Prob ≥Obs (%)	Lifetime limit (10^{33}yrs)
$p \rightarrow e^+\eta$	18.3	0.78	0	-	10.0 (prev.4.2)
$p \rightarrow e^+\rho^0$	3.7	0.64	2	13.5	0.72 (0.71)
$p \rightarrow e^+\omega^0$	4.9	1.35	1	74.1	1.6 (0.32)
$n \rightarrow e^+\pi^-$	12.7	0.41	0	-	5.3 (2.0)
$n \rightarrow e^+\rho^-$	1.4	0.87	4	1.2	0.03 (0.07)
$p \rightarrow \mu^+\eta$	21.3	0.85	2	20.9	4.7 (1.3)
$p \rightarrow \mu^+\rho^0$	1.8	1.3	1	72.7	0.57 (0.16)
$p \rightarrow \mu^+\omega^0$	6.7	1.09	0	-	2.8 (0.78)
$n \rightarrow \mu^+\pi^-$	12.2	0.77	1	53.7	3.5 (1.0)
$n \rightarrow \mu^+\rho^-$	1.1	0.96	1	61.7	0.06 (0.036)

Consistent with BKG, lifetime limits improved factor 2~3 in most of modes.

PRL **115**, 121803(2015)

N (NN)→ charged lepton +X

- Search for
  - ➢ p→ e^+/μ^+ + X, n→γ+X (X: invisible massless particle, ΔB=1)
  - ➢ pn→$e^+/\mu^+/\tau^+$ + ν (di-nucleon decay, ΔB=2)
- Test momentum distributions of single ring events.



- Data and Atm.ν MC agree well.
- Lifetime limits: fit data by Atm.ν and signal MC.
  - ➢ p→e^+X: > 7.9x10^{32} yrs
  - ➢ p→μ^+X: > 4.1x10^{32} yrs
  - ➢ n→γX: > 5.5x10^{32} yrs
  - ➢ pn→e^+ν: > 2.6x10^{32} yrs
  - ➢ pn→μ^+ν: > 2.2x10^{32} yrs
  - ➢ pn→τ^+ν: > 2.9x10^{32} yrs

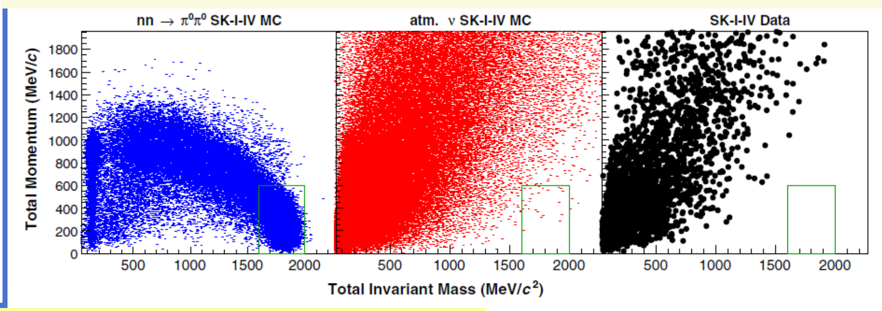
PRD **91**, 072009 (2015)

Di-nucleon decays: NN→ ππ

- Search for $^{16}O(pp) \rightarrow {}^{14}C\pi^+\pi^+$, $^{16}O(pn) \rightarrow 14N\pi^+\pi^0$, $^{16}O(nn) \rightarrow {}^{14}O\pi^0\pi^0$.
- $\Delta B=2$
- Tag pions in back-to-back. Pions are affected by nuclear interactions in nucleus and water.
  - Use Boosted Decision Tree for $pp \rightarrow \pi^+\pi^+$ and $pn \rightarrow \pi^+\pi^0$
- For $nn \rightarrow \pi^0\pi^0$, use total mass and total momentum cuts, as same as $p \rightarrow e^+\pi^0$.

Mode	Eff.(%)	BKG	Obs	Limit (10^{32}yr)
$pp \rightarrow \pi^+\pi^+$	5.9	4.5	2	0.72
$pn \rightarrow \pi^+\pi^0$	10.2	0.75	1	1.7
$nn \rightarrow \pi^0\pi^0$	21.1	0.14	0	4.0

Mtot vs Ptot for $nn \rightarrow \pi^0\pi^0$



Observation is consistent with BKG.

PRD **91**, 072006 (2015)

$n\bar{n}$ oscillation

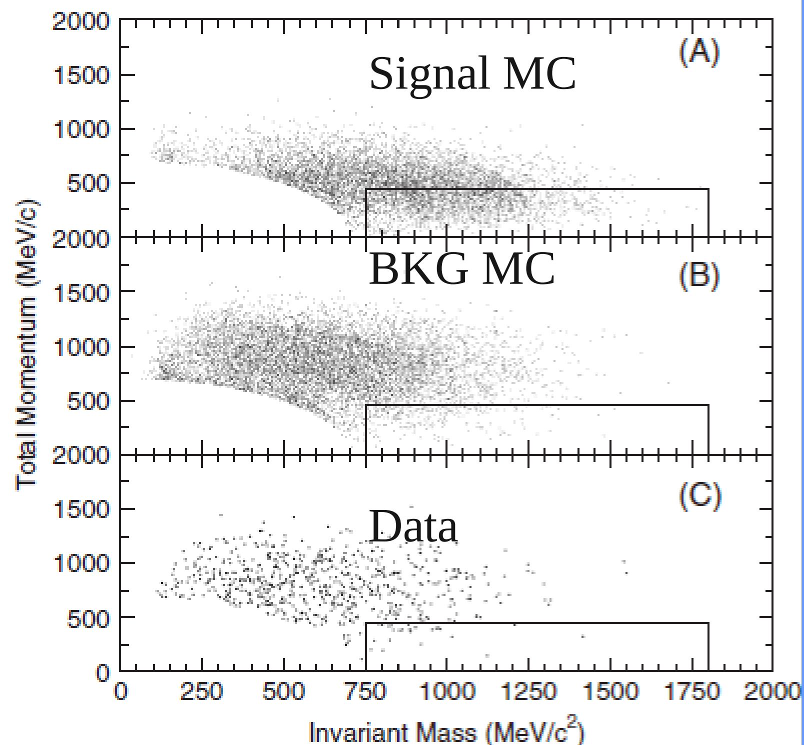
- $\Delta B=2$
- $\bar{n}$ annihilates immediately.
- Apply total momentum (P_{tot}< 450 MeV/c) and total mass cut (750 < M_{tot} <1800 MeV/c^2) to multi-ring.
- Use only SK1 data (91.7kton･yr).
  - Eff. 12.1 %
  - BKG: 24.1 events
  - Observed: 21 event
- Lifetime limt: > 1.9×10^{32} yrs

→ oscillation time (free neutron):

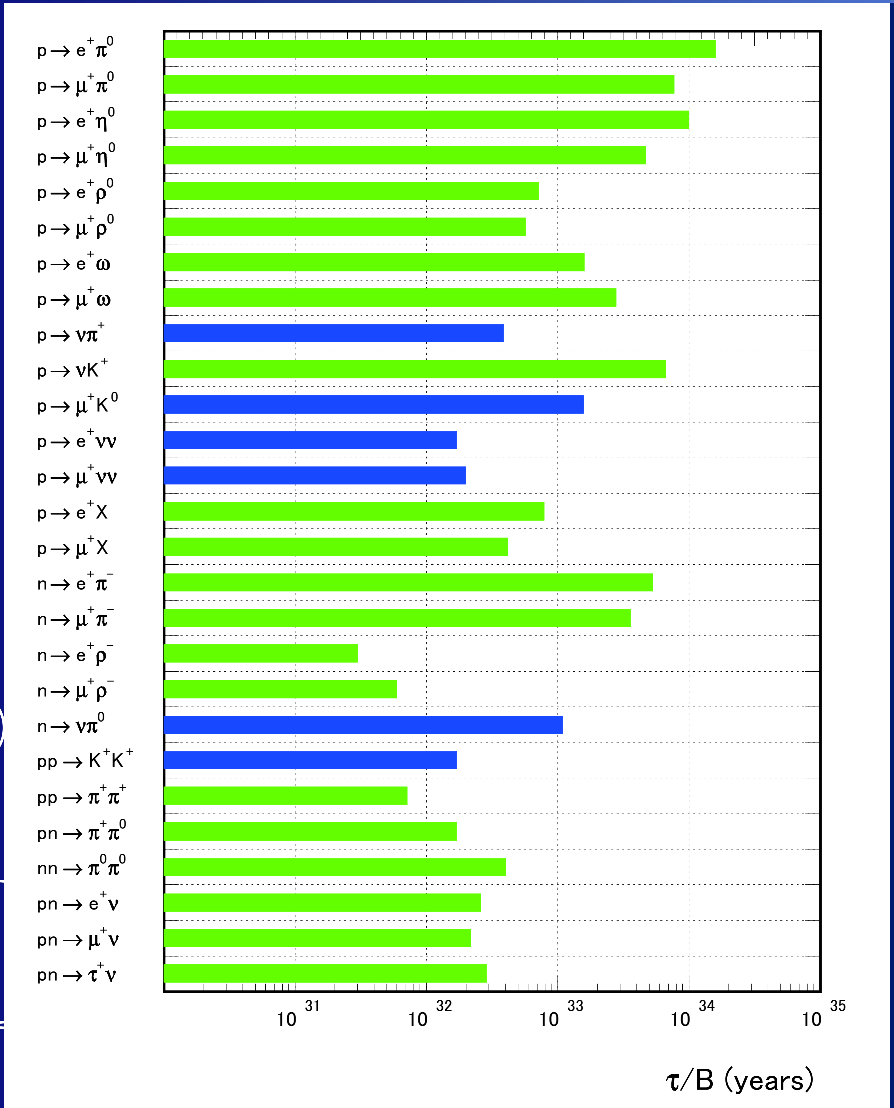
 > 2.7×10^{8} sec

(using nuclear suppressing factor by Freedman&Gil, PRD 78, 016002(2008), with 20~30% theoretical error)

$\bar{n}+p$		$\bar{n}+n$	
$\pi^+\pi^0$	1%	$\pi^+\pi^-$	2%
$\pi^+2\pi^0$	8%	$2\pi^0$	1.5%
$\pi^+3\pi^0$	10%	$\pi^+\pi^-\pi^0$	6.5%
$2\pi^+\pi^-\pi^0$	22%	$\pi^+\pi^-2\pi^0$	11%
$2\pi^+\pi^-2\pi^0$	36%	$\pi^+\pi^-3\pi^0$	28%
$2\pi^+\pi^-2\omega$	16%	$2\pi^+2\pi^-$	7%
$3\pi^+2\pi^-\pi^0$	7%	$2\pi^+2\pi^-\pi^0$	24%
		$\pi^+\pi^-\omega$	10%
		$2\pi^+2\pi^-2\pi^0$	10%



5. Summary



- Update nucleon decay results by more than 0.3 Mton・year exposure (green in the left figure).
- Super-Kamiokande can cover large number of decay modes.
- All of them are the most stringent limits on nucleon lifetime.
- We observed some candidates, but still consistent with expected backgrounds and no evidences of nucleon decay have been observed.

5. Future prospects

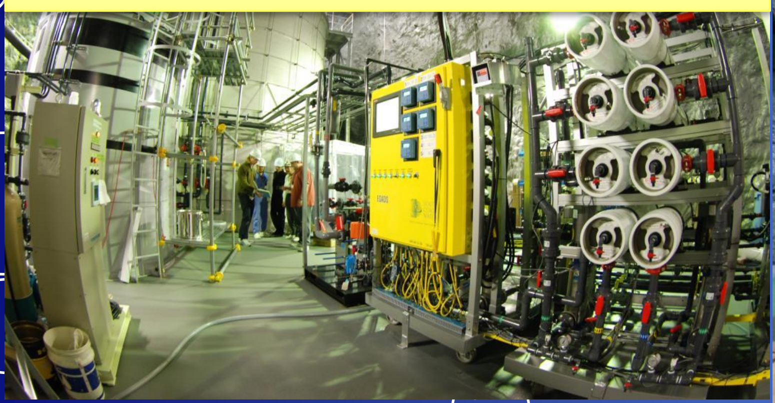
Near term: SK-Gd project

- Need more exposure, but suppress background.
- We have learned neutron tagging is a powerful tool to reject atmospheric neutrino backgrounds.
  - 20.5% tagging efficiency of neutron capture by hydrogen (2.2 MeV γ).
  - Atmospheric ν background can be reduced to ~50%
- Planning to add Gd into water (SK-Gd project).
  - 0.2% $Gd_2(SO_4)_3$
  - Emit 8 MeV γs after neutron capture by Gd.
  - Expect higher neutron tagging efficiency ~ 80%!

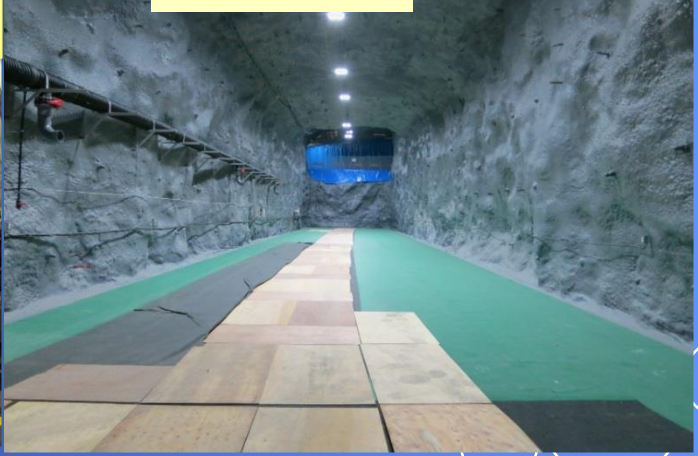
- Several R&D towards SK-Gd are going on.
  - Built test tank (EGADS).
  - Developed Gd dissolved water purification system.
  - Light attenuation check.
  - …. and more.
- Excavated a new hall for water purification system.
- Expect to start refurbishment in 2018.
  - T2K is ongoing now, but they also have plan to upgrade accelerator.
- Stay tuned !

200 m^3 tank with 240 PMTs

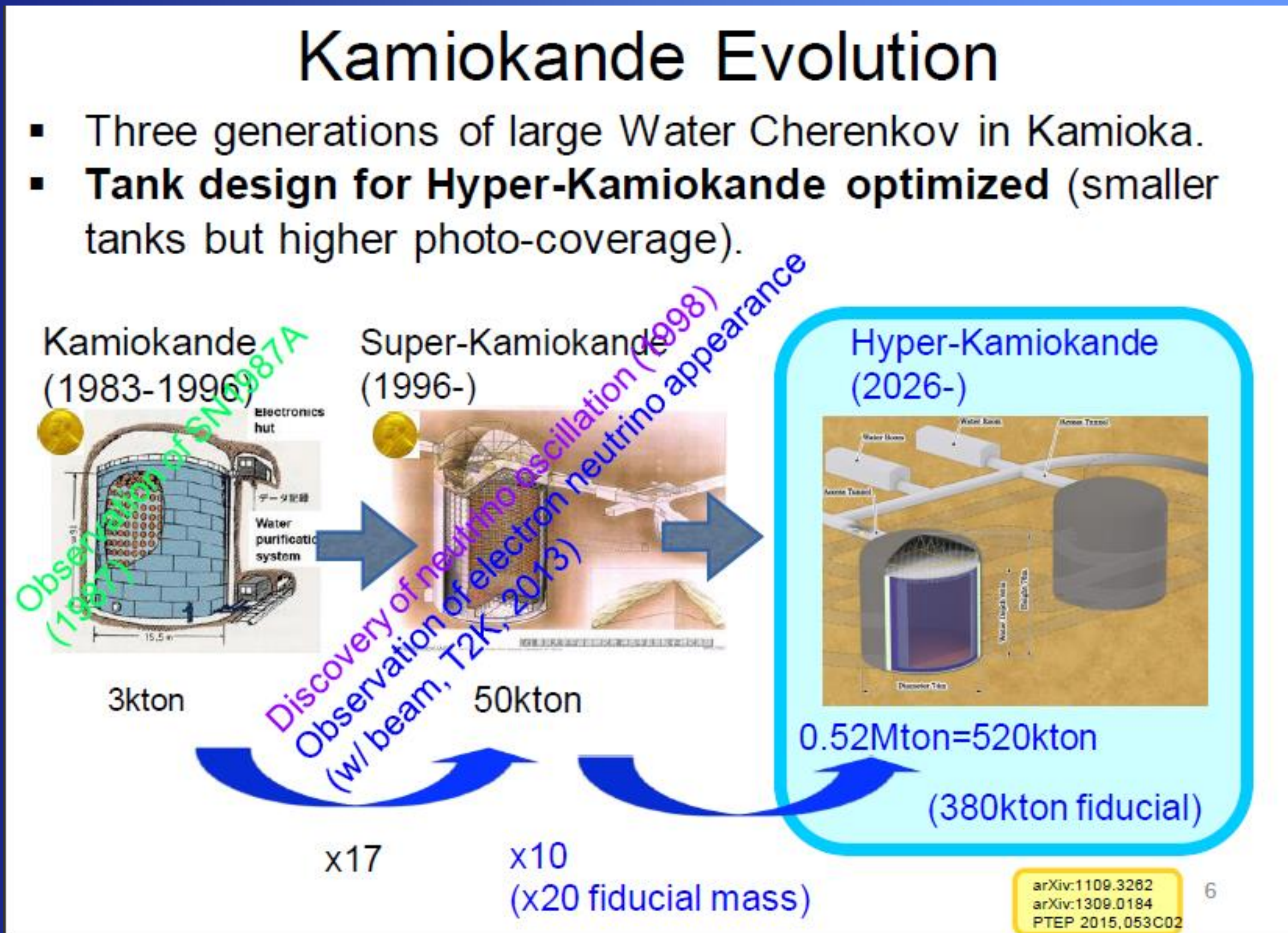
Gd water circulation system
(purify water with keeping Gd)



New Hall

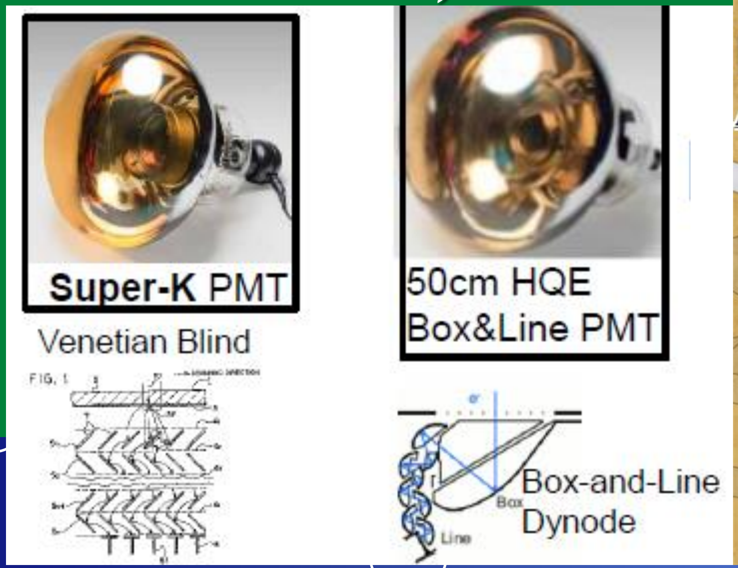


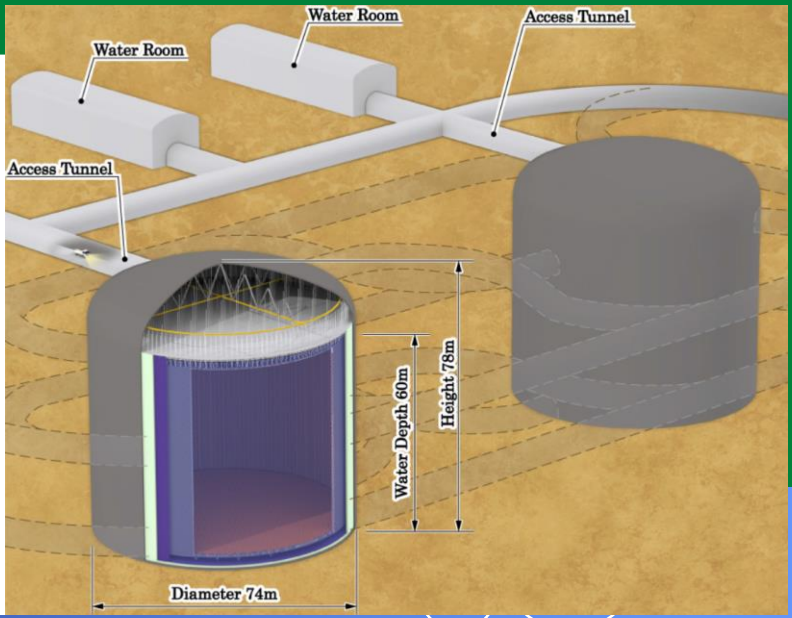
Longer term: Hyper-Kamiokande project



Current baseline design

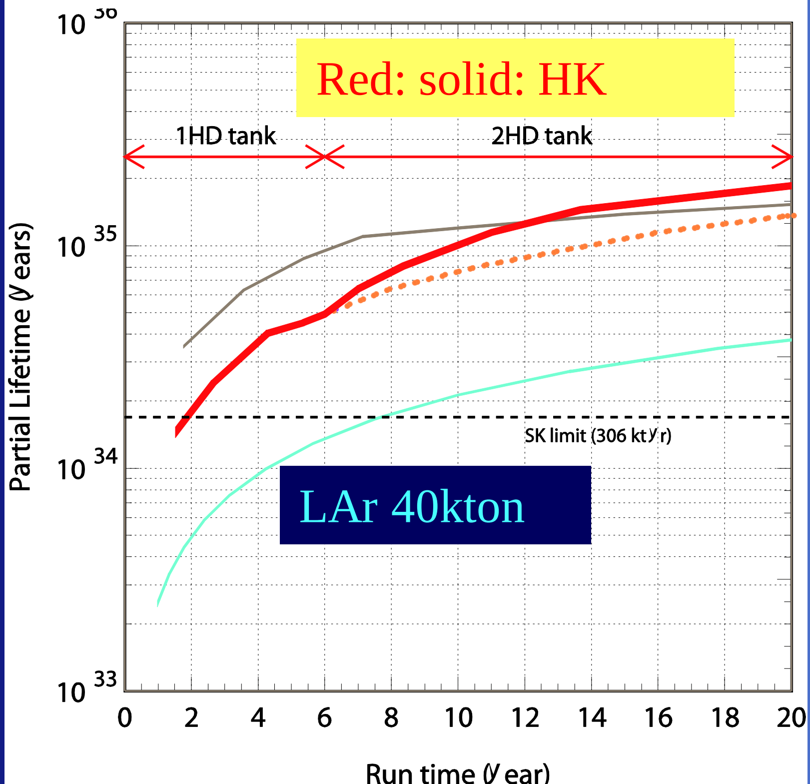
- Photosensor: Box&Line PMT, x2 photon counting efficiency, ½ time resolution than SK PMT.
- Photo-coverage: 40 %, same as the current SK.
- Tank size: 60m (H)x74m(D), upright cylindrical.
- Number of tank: 2 (the 2nd tank will be built after 6 years of the 1st tank).



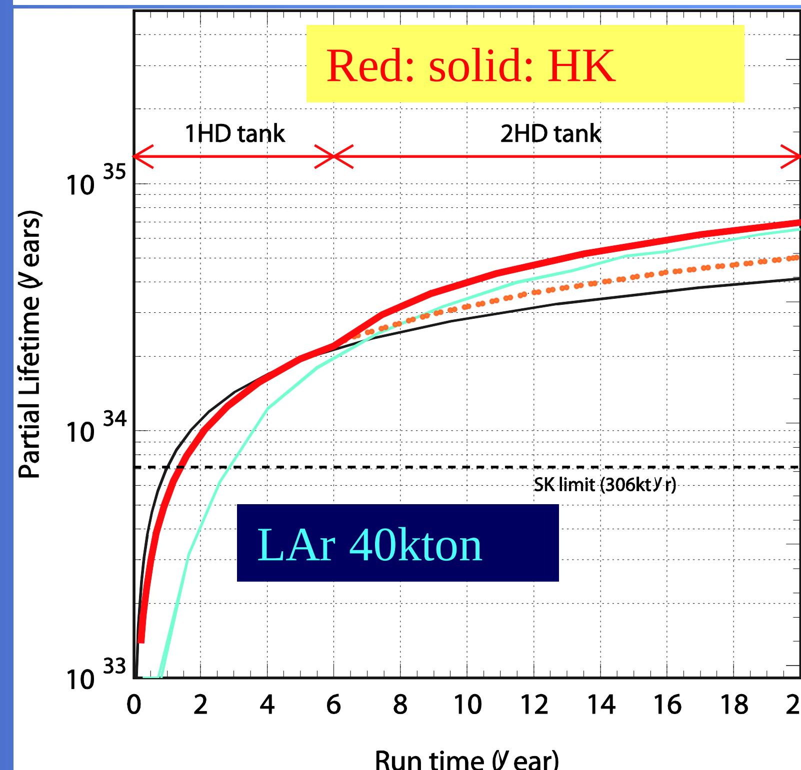


Expected reach in nucleon decay

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

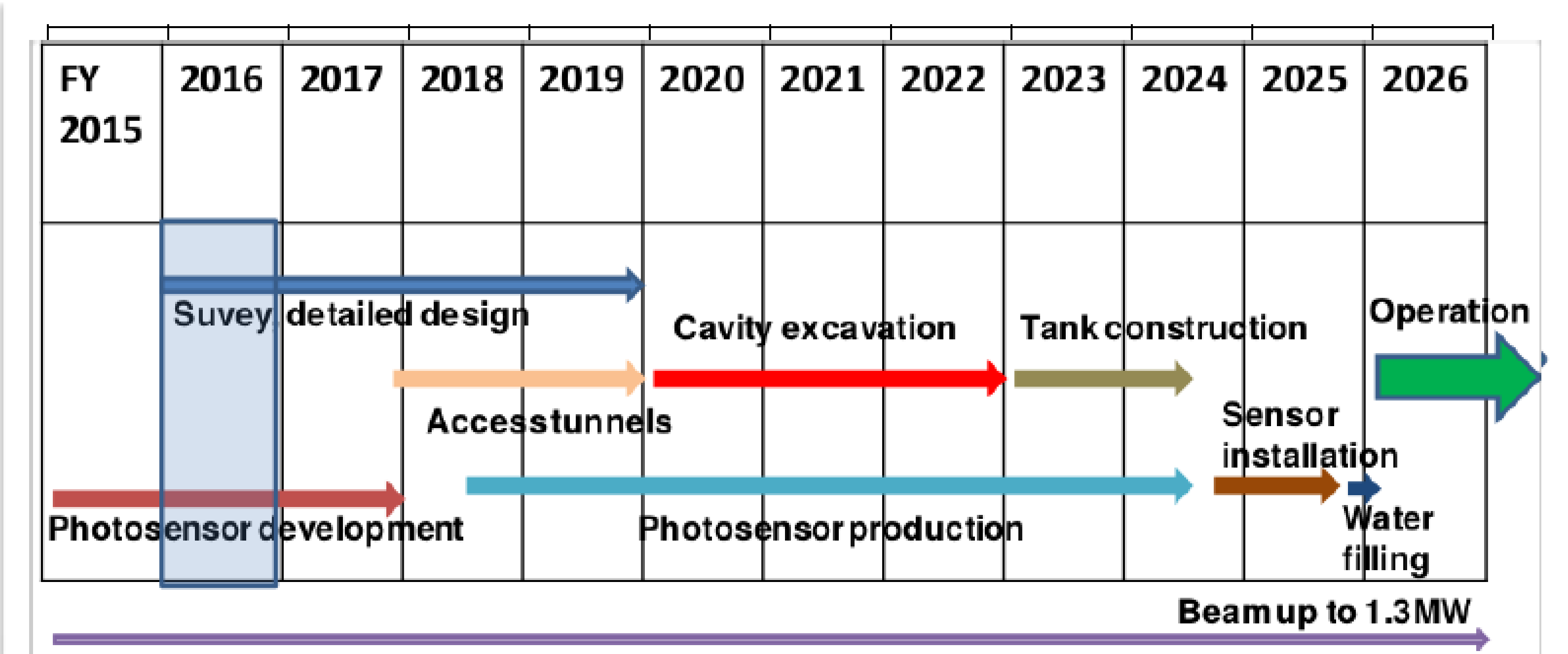


Sensitivity for $p \rightarrow \bar{\nu}K^+$ (90%CL)



After 10 years run, sensitivity of HK reaches to 1×10^{35} years for $e^+\pi^0$ and 4×10^{34} years for νK^+.

The Hyper-Kamiokande Timeline



Let’s built Hyper-Kamiokande !

- Forming proto-collaboration.
- If you are interested in, contact to me.