Proton decay search with water Cherenkov detectors

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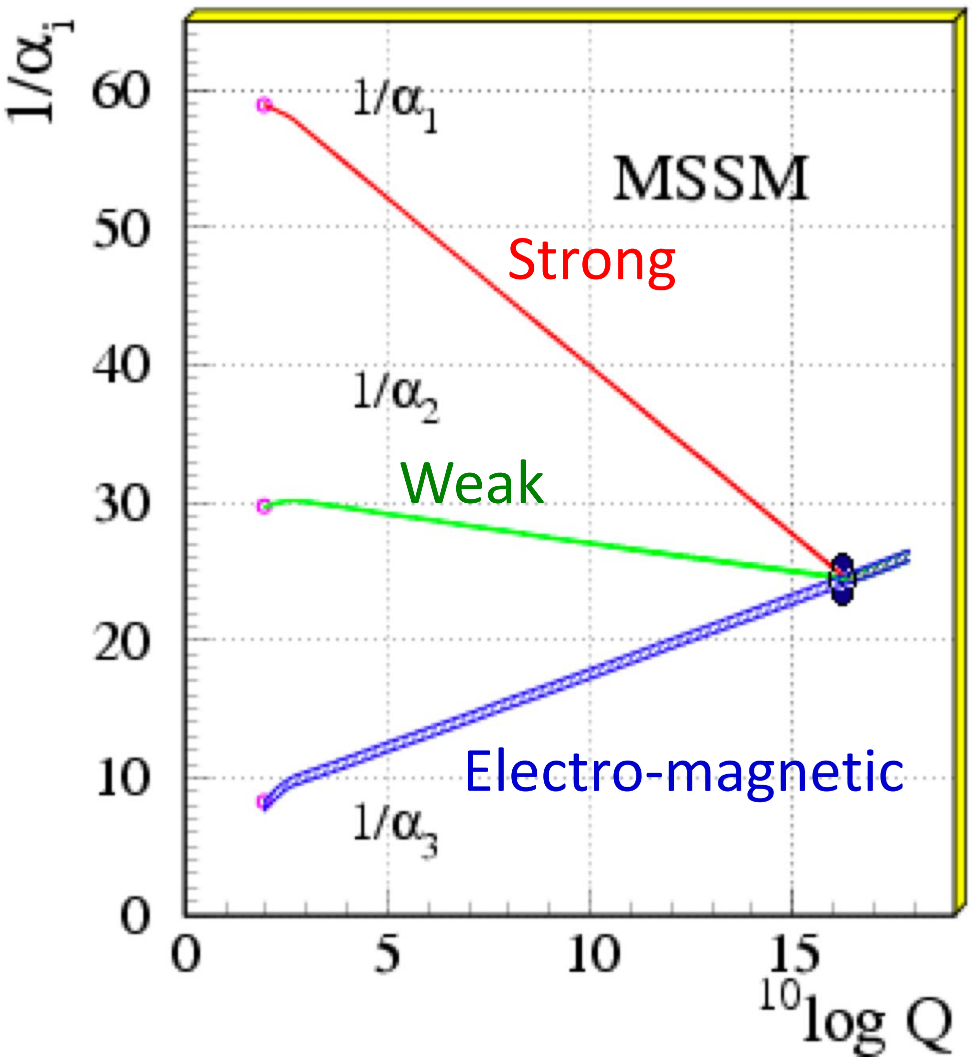
(Kamioka obs., ICRR, The Univ. of Tokyo)

Grand Unification

Running coupling constants seem to cross at single point
(unification scale)



↓

Unification of interactions
and
Unification of quark and lepton

↓

Possibility of transition
from quark to lepton

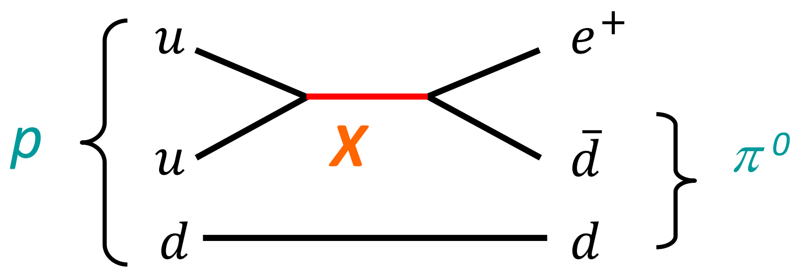
↓

Proton decay

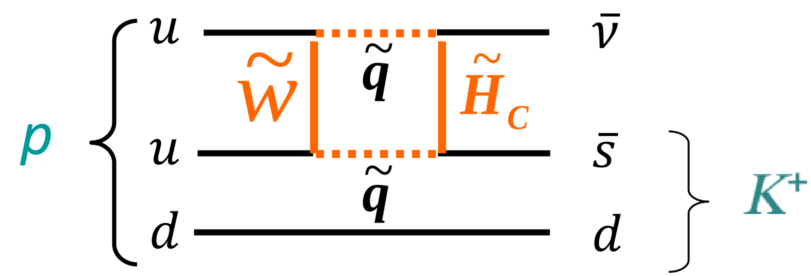
Predicted decay modes of proton

Two major decay modes

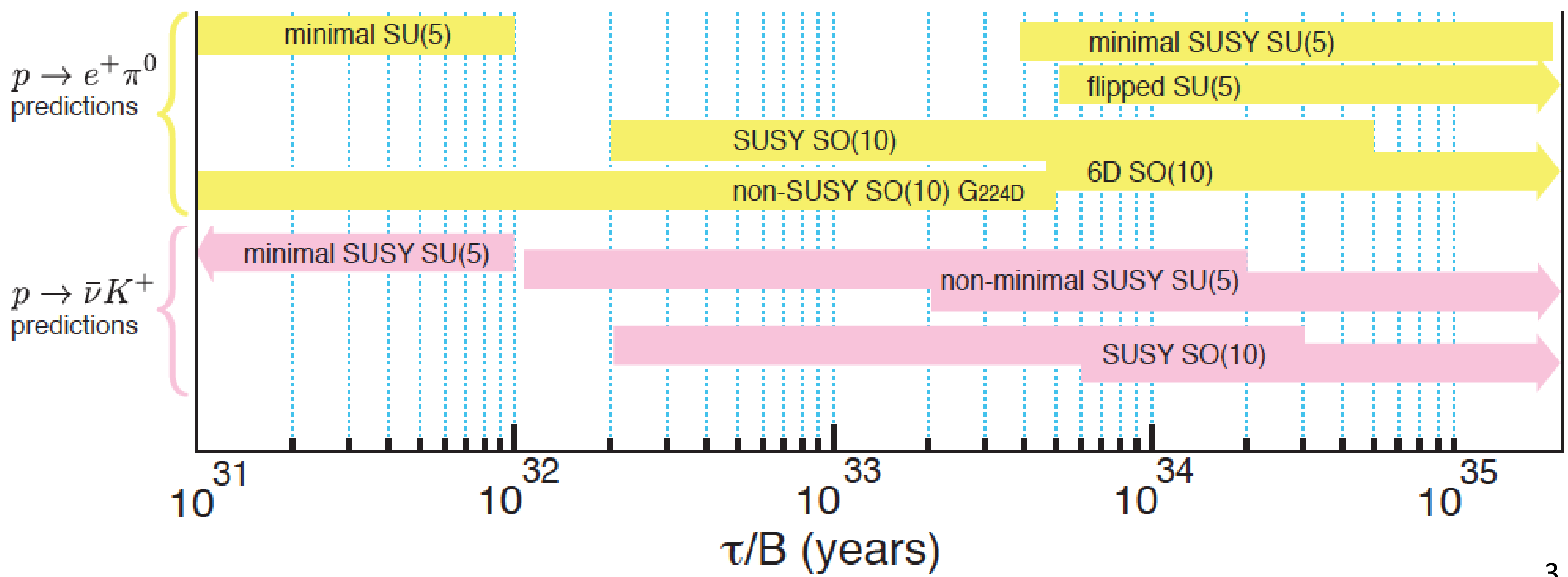
$p \to e^+\pi^0$



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

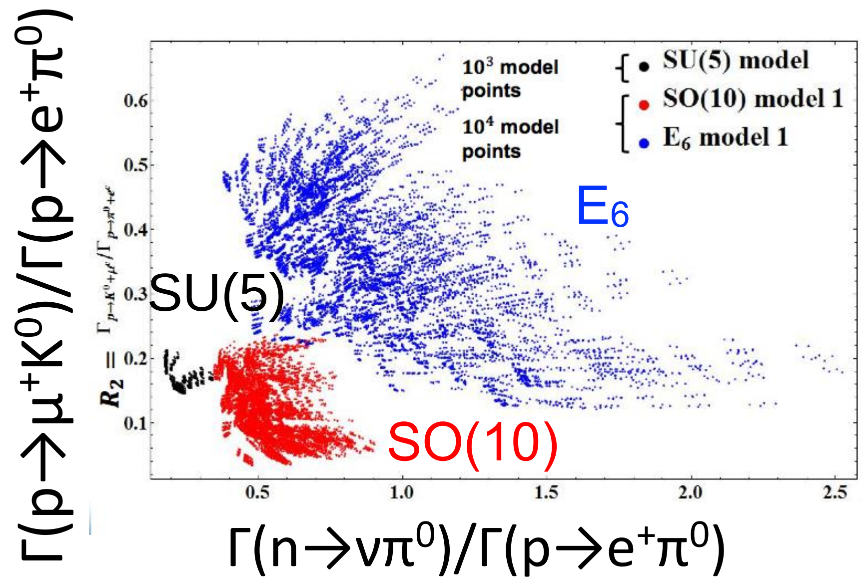


Theoretical predictions



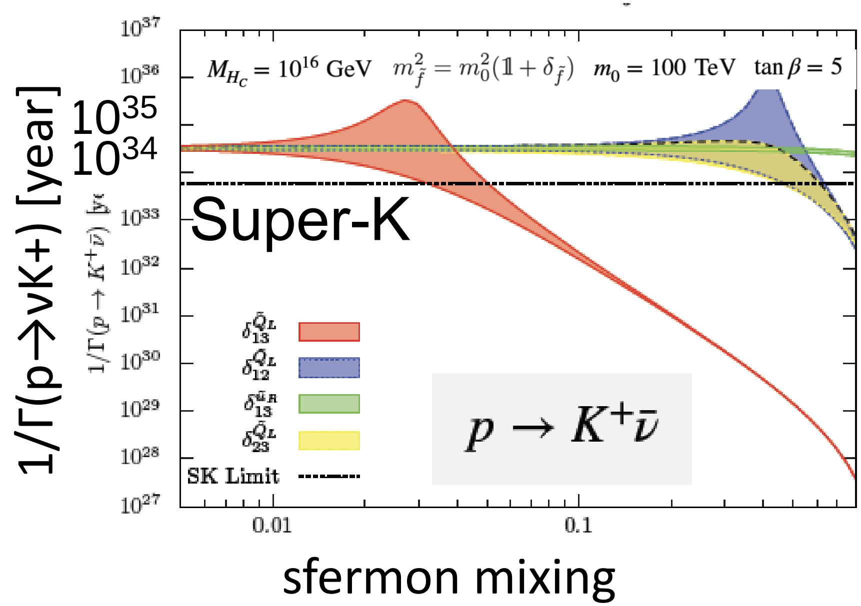
Predicted decay modes of proton

Model predictions
$\Gamma(n \to \nu\pi^0)/\Gamma(p \to e^+\pi^0)$
depends on the gauge groups
SU(5), SO(10), E_6
(Y. Muramatsu)



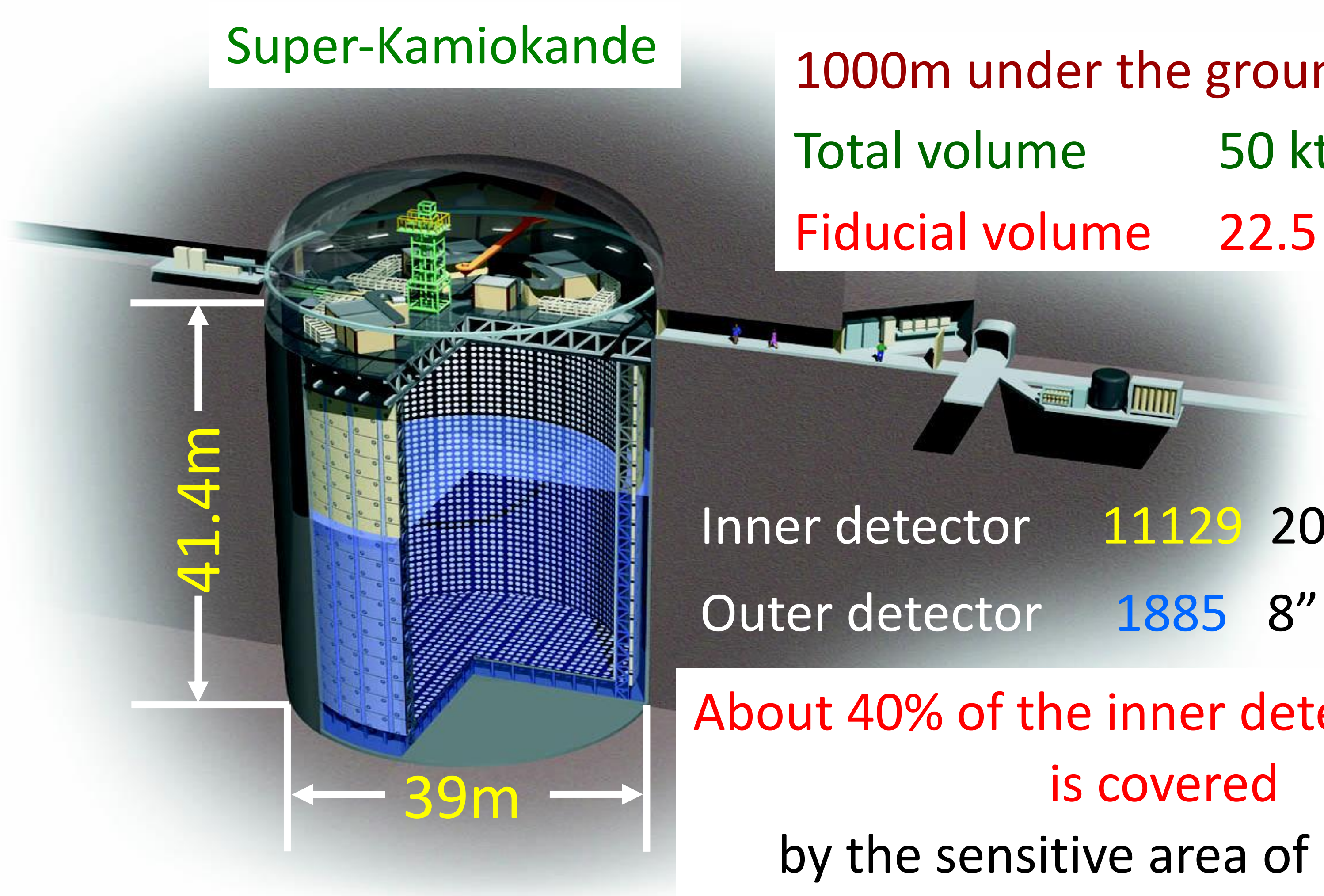
Decay branches depends on
the size of sfermion mixing.
(N.Nagata and S.Shirai,
JHEP 1403, 049 (2014))

Branching ratio may tell us
the flavor structure of
SUSY particles.



Super-Kamiokande detector

Ring imaging water Cherenkov detector ~ 22.5k ton



1000m under the ground

Total volume 50 ktons

Fiducial volume 22.5 ktons

Inner detector 11129 20” PMTs

Outer detector 1885 8” PMTs

About 40% of the inner detector is covered by the sensitive area of PMT.

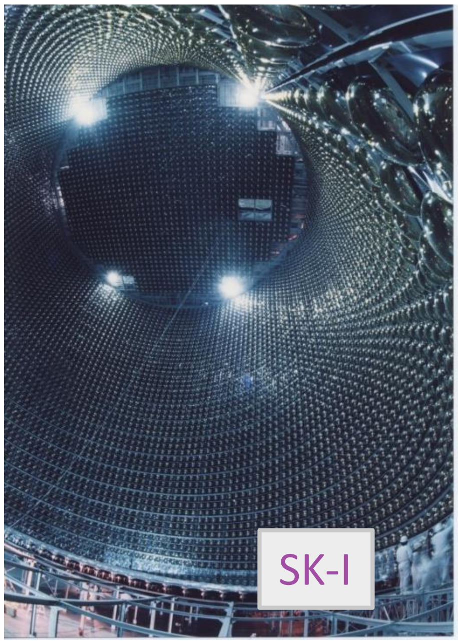
Every day, ~ 20 solar and atmospheric neutrinos are observed.

→ *Background of proton decay*

Super-Kamiokande detector

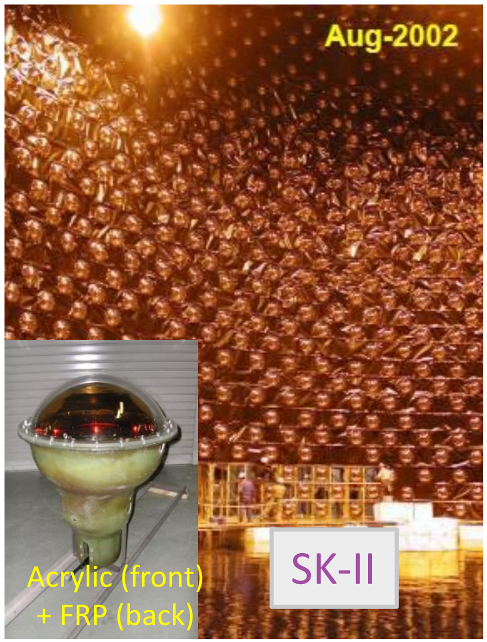
History of the SK detector

SK-I
April 1996
~ June 2001



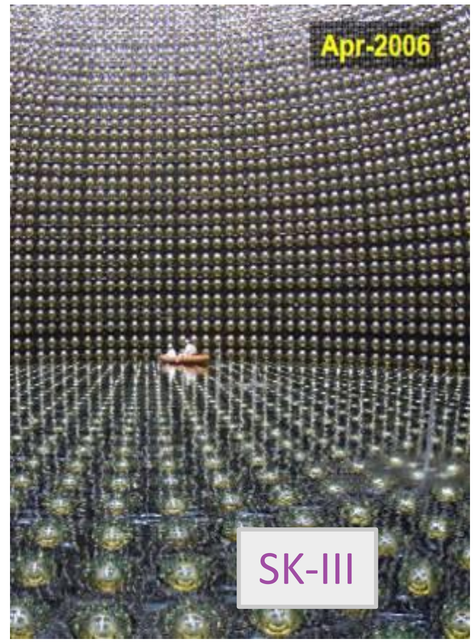
11146 ID PMTs
(40% coverage)

SK-II
October 2002
~ October 2005



5182 ID PMTs
(19% coverage)

SK-III
June 2006
~ September 2008



11129 ID PMTs
(40% coverage)

SK-IV
September 2008
~ running

Electronics
Upgrade

Ring imaging water Cherenkov detector

Event reconstruction

Amount of the Cherenkov photons

$\propto$ Momentum of the particle

➡ Use observed # of photons to reconstruct energy.

Interaction position

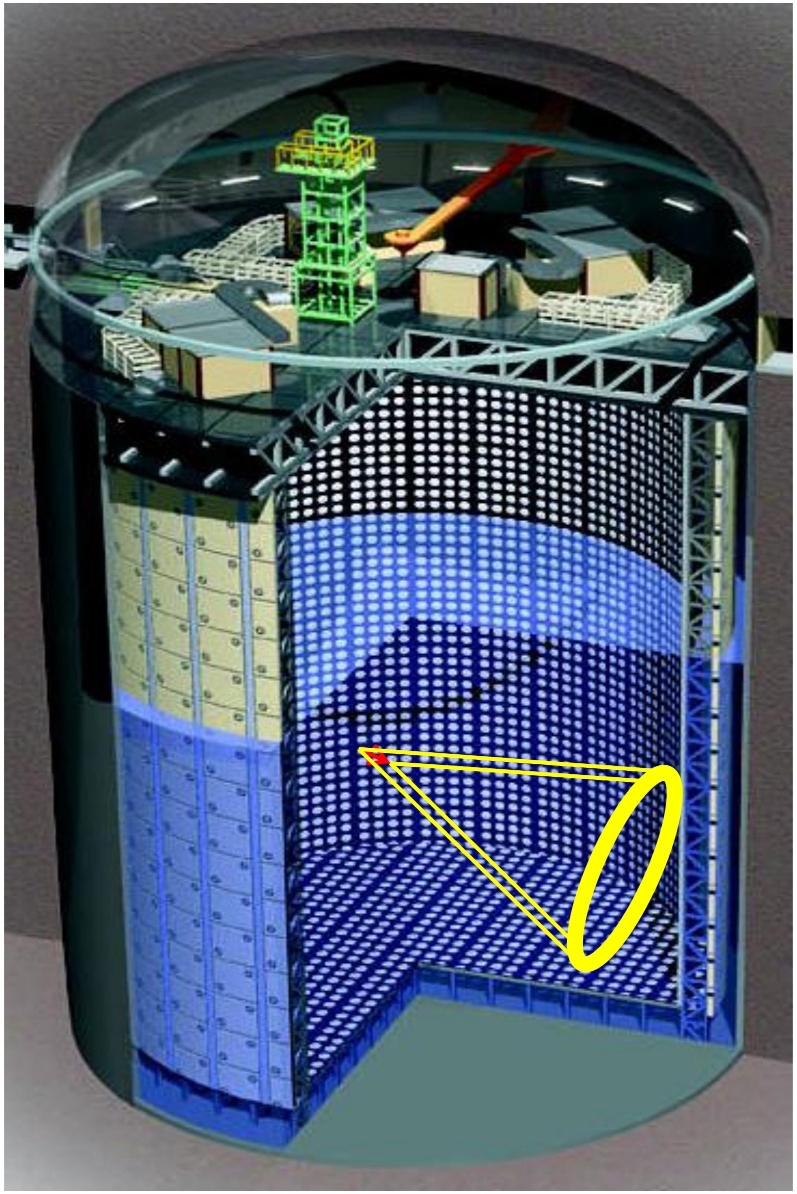
~ starting point of the charged particle

➡ Use photon arrival timing. Ring pattern is also used for the precise reconstruction.

of the charged particles & γ

➡ # of the Cherenkov rings

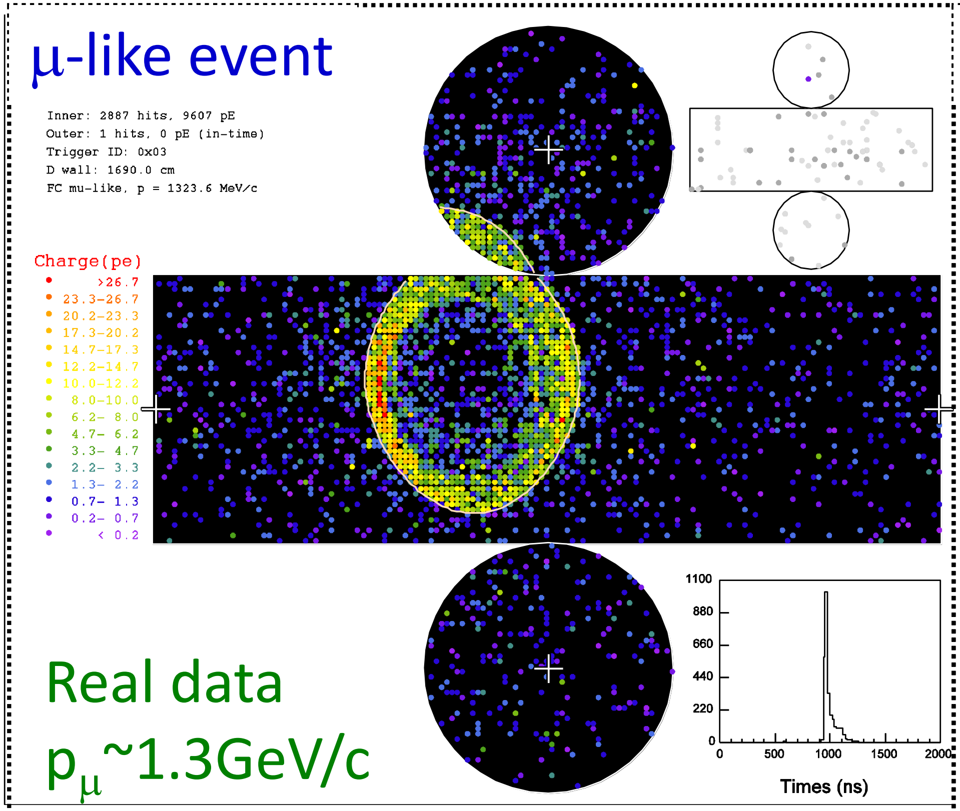
Also, electrons generated by the decay of μ, π etc. gives useful information.

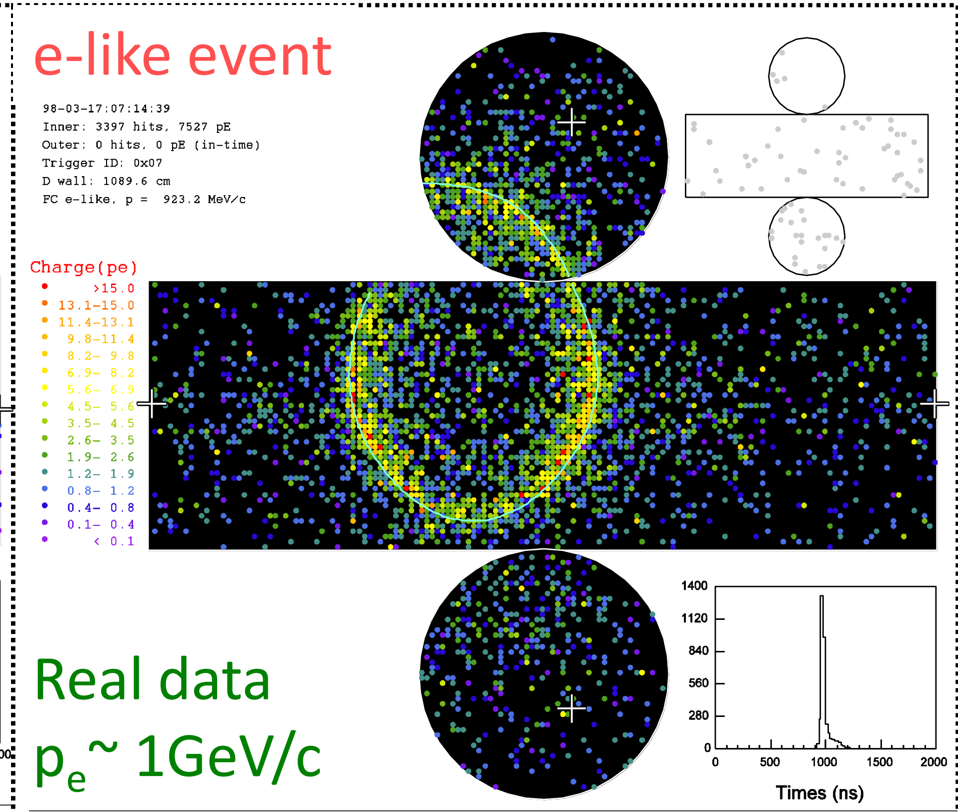


Ring imaging water Cherenkov detector

Particle types (e-like or μ-like) can be identified by the shape of the Cherenkov ring.

Electron (or gamma) generates electro-magnetic shower and ring is more diffused compared to the muon.



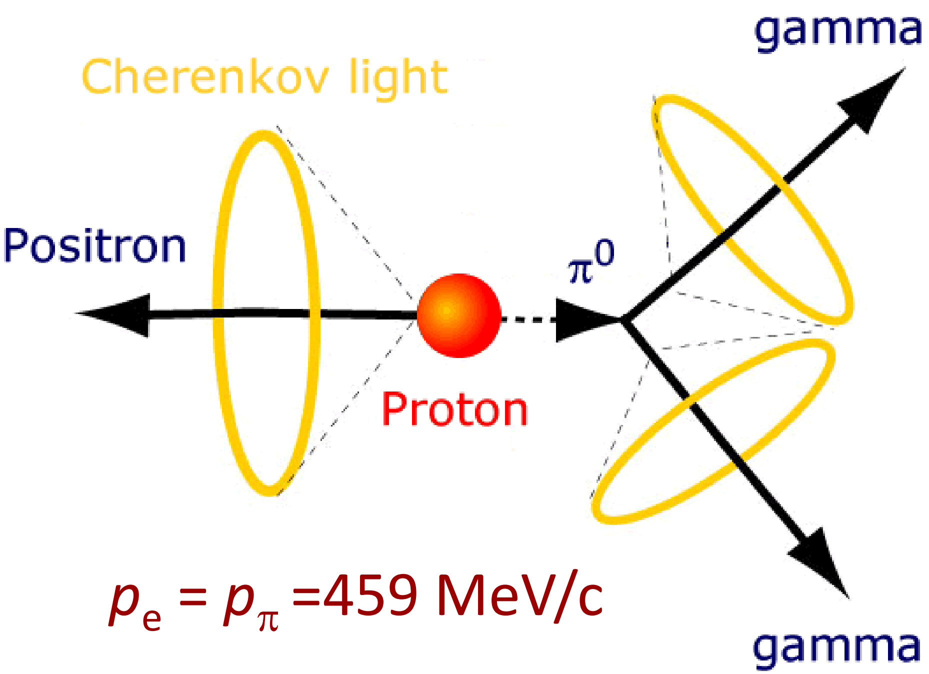


But weak in detecting low momentum heavy particles.

Proton decay search using ring imaging water Cherenkov detectors

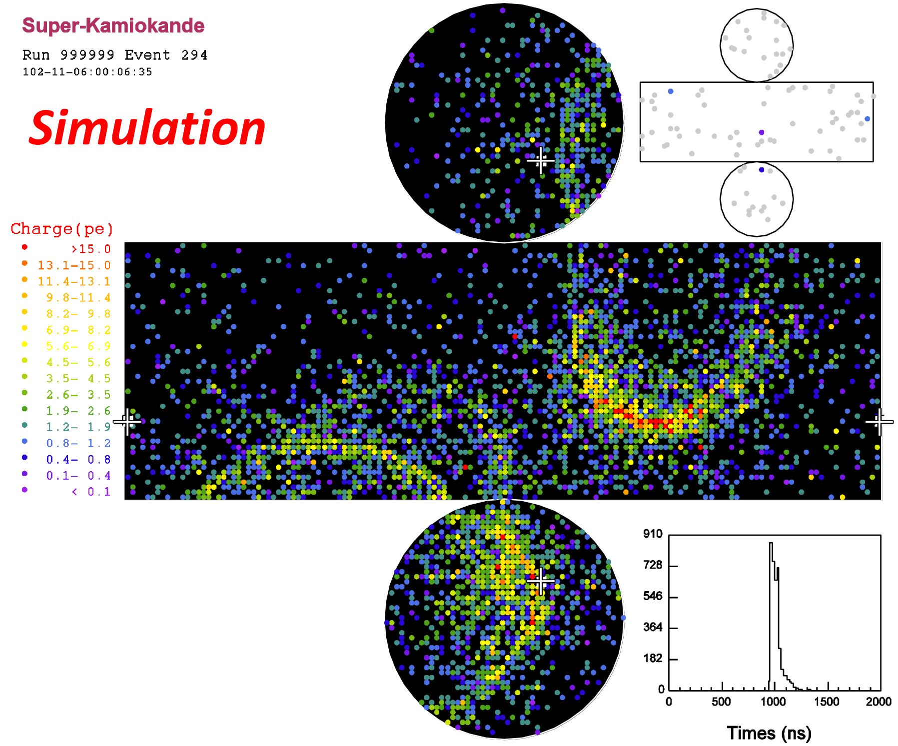
$p \rightarrow e^+ + \pi^0$

Ring imaging water Cherenkov detectors have very high efficiency in identifying both e^+ and π^0



$p_e = p_\pi$ =459 MeV/c

SK event display
$p \rightarrow e^+ + \pi^0$ (simulation)

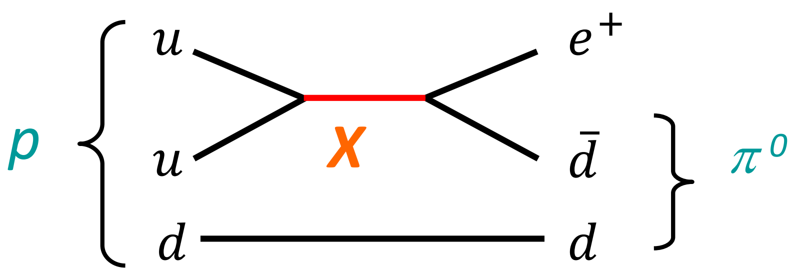


Clear 3 e-like rings are expected to be observed.

Proton decay search ~ signal and background ~

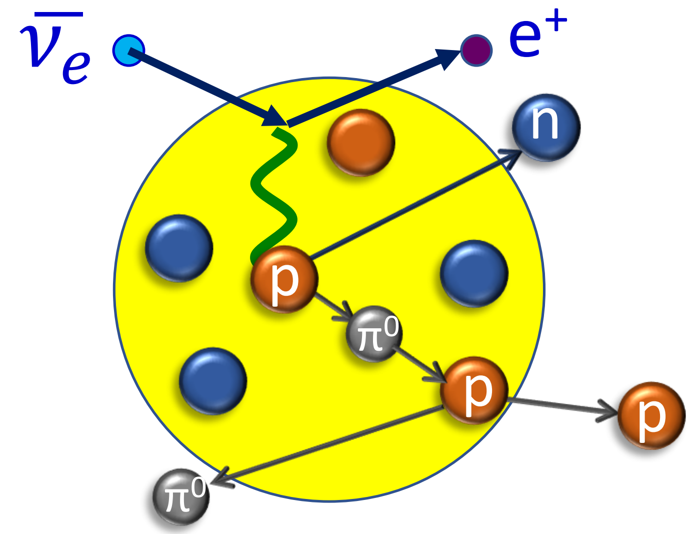
Proton decay signal

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



Background (example)

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

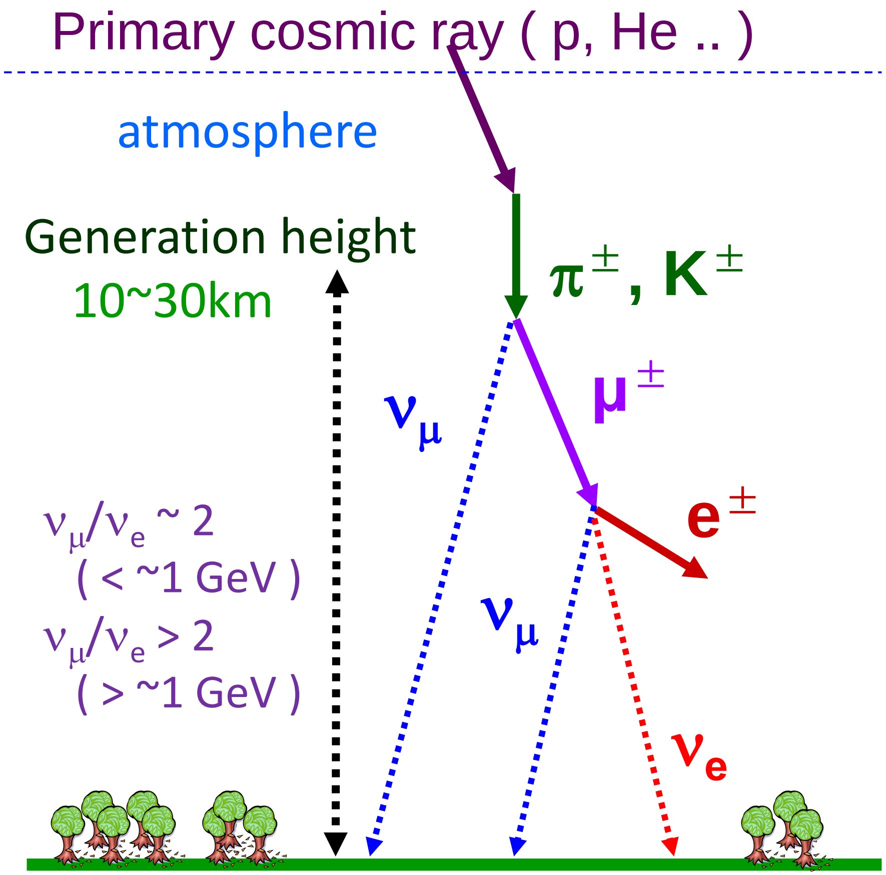


Background atmospheric neutrino events could be rejected if neutrons are tagged.

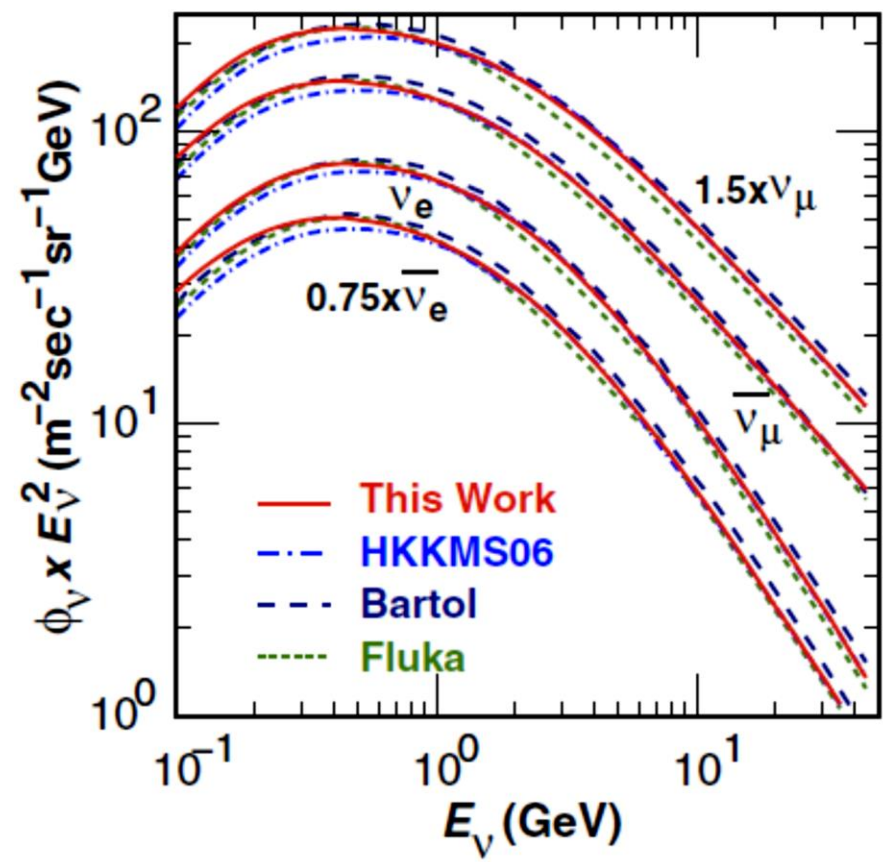
In the water, neutron is captured by hydrogen (~ 200 μs) and emit 2.2 MeV γ ray.

$$n + p \rightarrow d + \gamma$$

Proton decay search ~ background source ~
atmospheric neutrino



Atmospheric ν energy spectrum



Atmospheric neutrino energy spectrum
Peaked at *several hundreds of MeV.*
~ mass of nucleon ~

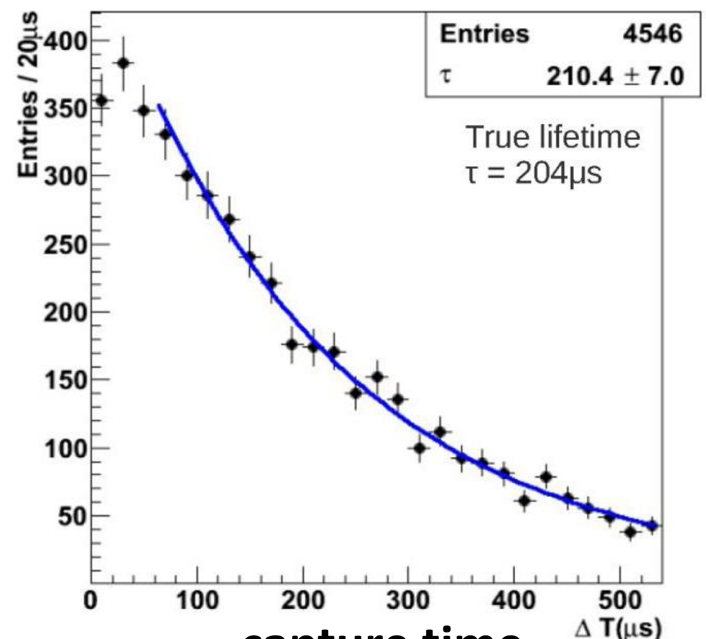
Proton decay search
~ background rejection using neutron tag method ~

New DAQ system installed for Super-K IV allows us
to store all the PMT hit information for > 500 μs
after the atmospheric ν or proton decay candidates.

→ Possible to search for 2.2 MeV γ,
which gives about 10 PMT hits.

Search for hit cluster
(N≥7 in 10ns)
after prompt event
and select candidates
using neural network.

Detection efficiency ~ 20.5%
(mis-tag ~ 1.8%)



capture time

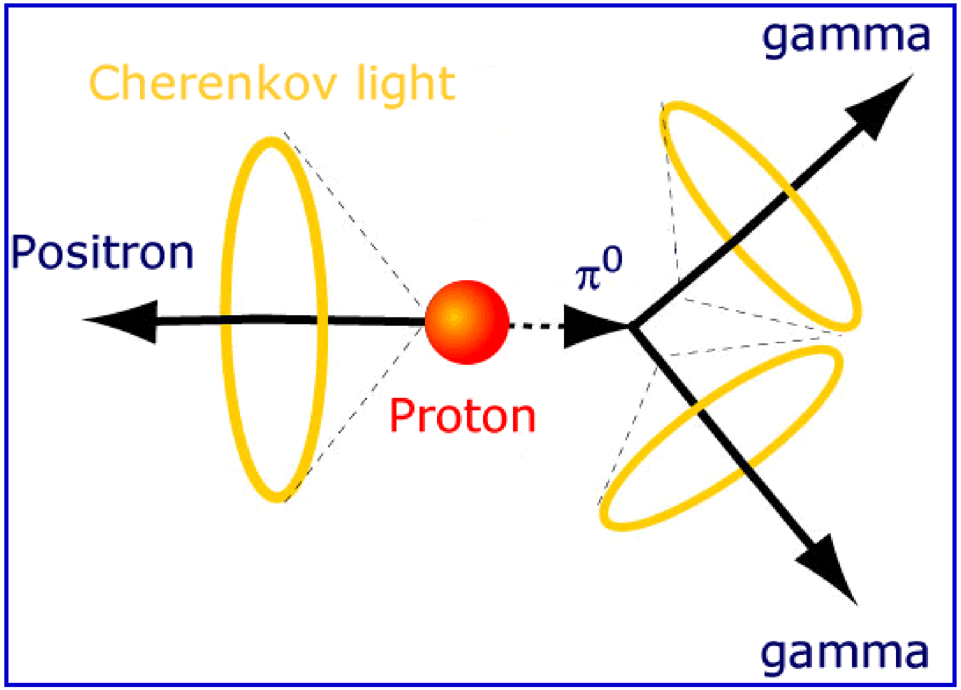
About half of the background events
could be rejected by requiring no neutron candidates.

Proton decay search in SK $p \to e^+ + \pi^0$

Event selection criteria

- No activity in the outer detector
- Vertex in the fiducial volume
- No decay electron
- 2 or 3 e-like ring
  ($e^+ + 1$ or 2γ)

  ~ one of the γs may have low energy or overlap with the other rings
- Reconstructed π^0 mass
  $85 \sim 185$ MeV/c^2
  (for 3 ring events)
- Reconstructed proton mass
  $800 \sim 1050$ MeV/c^2
- Reconstructed total (proton) momentum
  $p_{tot} < 250$ MeV/c
- No tagged neutron (only for SK4)



Proton decay search in SK $p \to e^+ + \pi^0$

Source of the background events

$\to$ atmospheric ν

~ 1.5 events / Mt·year

30% from CC single π

(ν_e N $\to$ e N' π)

20% from CC multi π

(ν_e N $\to$ e N' mπ)

30% from CC QE

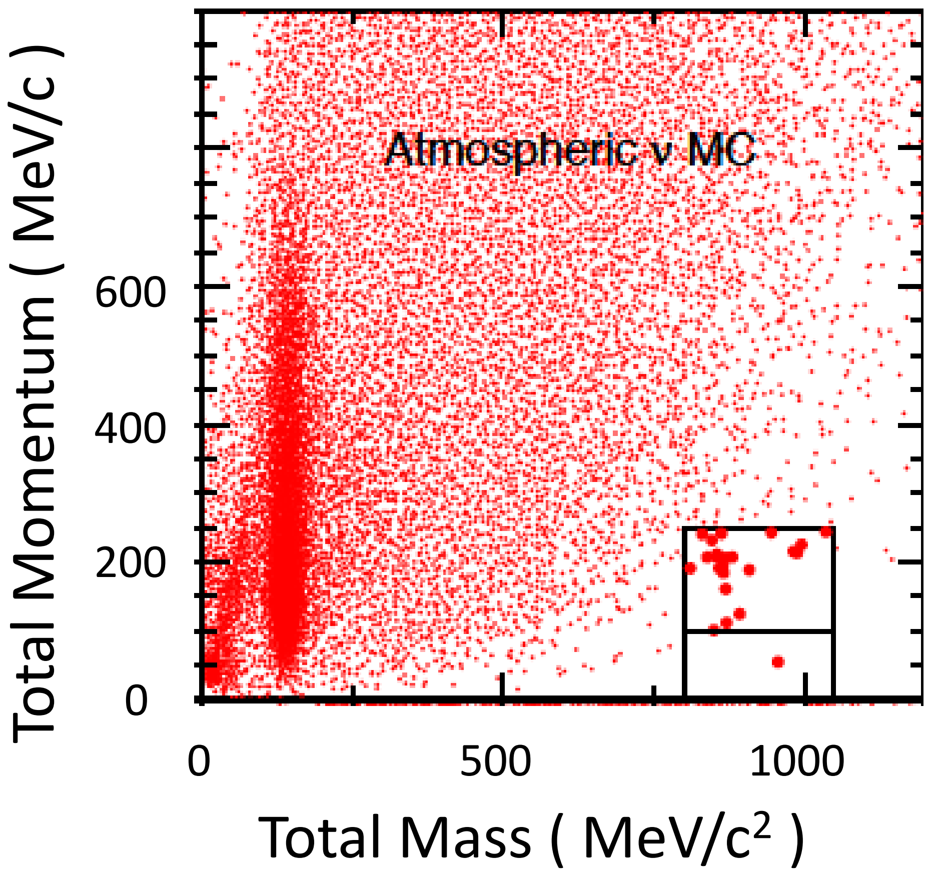
π^0 from secondary interactions of nucleon

(ν_e N $\to$ e N' + secondary π^0)

20% from NC

(ν N $\to$ ν N' X)

Total mass and total momentum atmospheric ν MC sample



π interaction in Oxygen or in the detector changes the charge, momentum and direction of π.

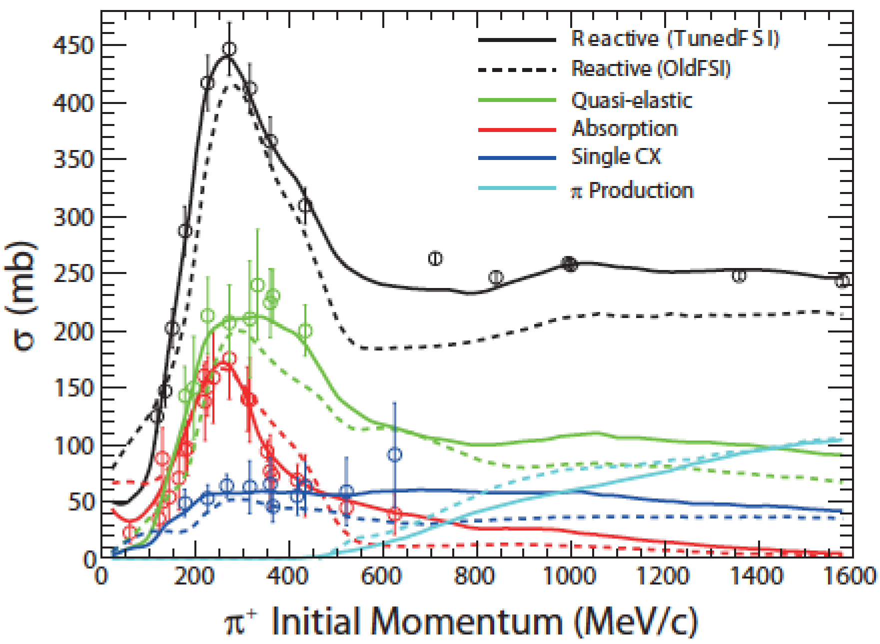
Proton decay search in SK $p \rightarrow e^+ + \pi^0$

One of the major sources of inefficiency

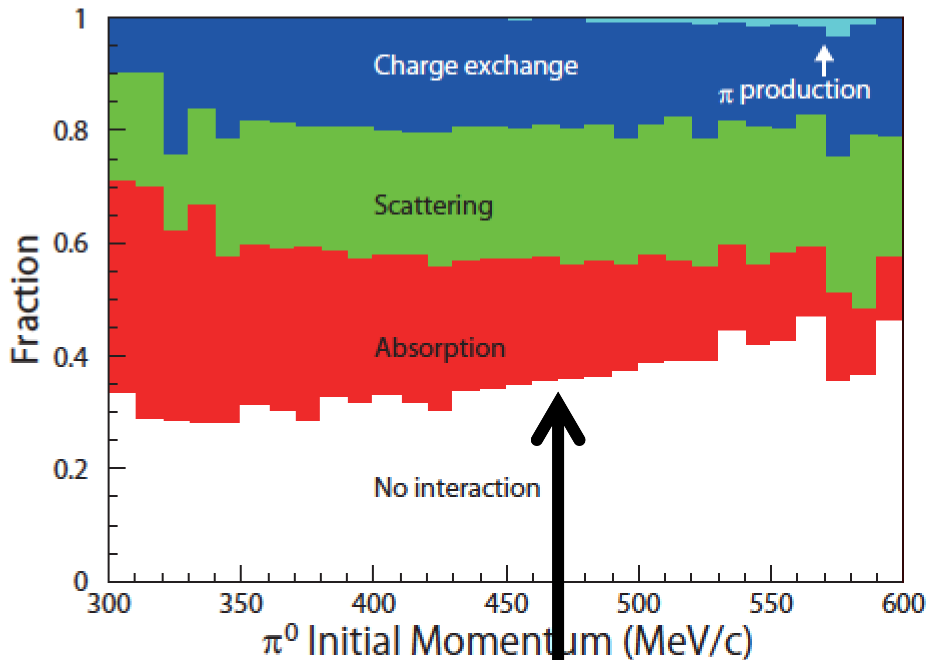
π interaction in Oxygen (before escaping from ^{16}O)

- charge exchange ($\pi^0 \rightarrow \pi^{\pm}$)
- inelastic scattering ~ change momentum and direction of π^0

π^+ interaction cross-section on carbon



π^0 interaction probability in ^{16}O



momentum of π^0
(from stationary proton's decay)

Proton decay search in SK $p \rightarrow e^+ + \pi^0$

Toward the precise estimation of the background

Data from the accelerator experiments are very useful.

For the SK analysis,

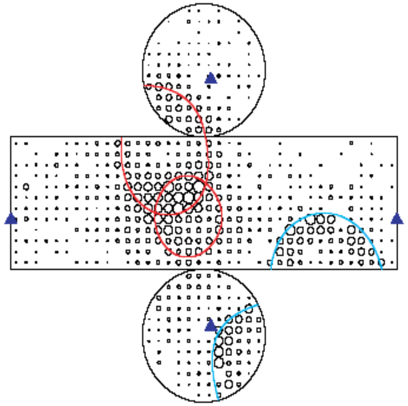
data from the 1kt water Cherenkov detector

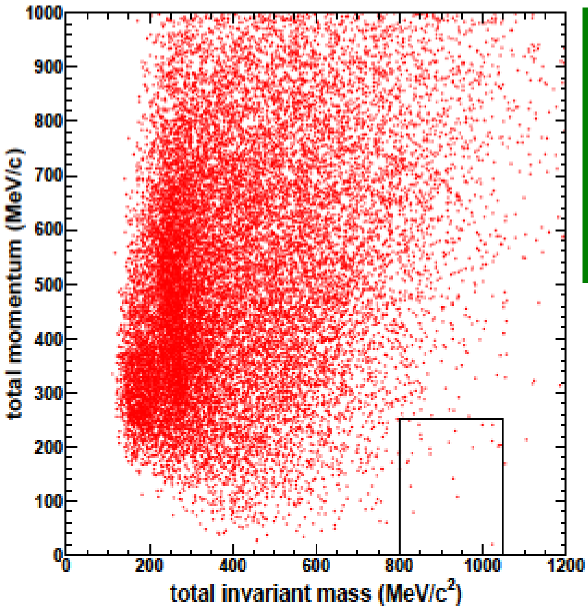
in the K2K experiment

were used to check our estimations.

K2K : ν_μ beam, E_ν ~ a few hundreds of MeV ~ a few GeV.

2- or 3-ring $\mu\pi^0$ events





K2K ($p \rightarrow e^+ + \pi^0$ BG by $E\nu$<3GeV)

1.63 +0.42/-0.33 (stat.)

+0.45/-0.51 (sys.)

events / Mt·yr

Good agreement

Simulation, E_ν<3GeV

1.8 +/- 0.3(stat.)

events / Mt·yr

Data from π beam experiments are also useful.

Proton decay search in SK $p \rightarrow e^+ + \pi^0$

One of the major sources of inefficiency

π interaction in Oxygen (before escaping from ^{16}O)

- charge exchange ($\pi^0 \rightarrow \pi^\pm$)
- inelastic scattering ~ change momentum and direction of π^0

Further reduction of background

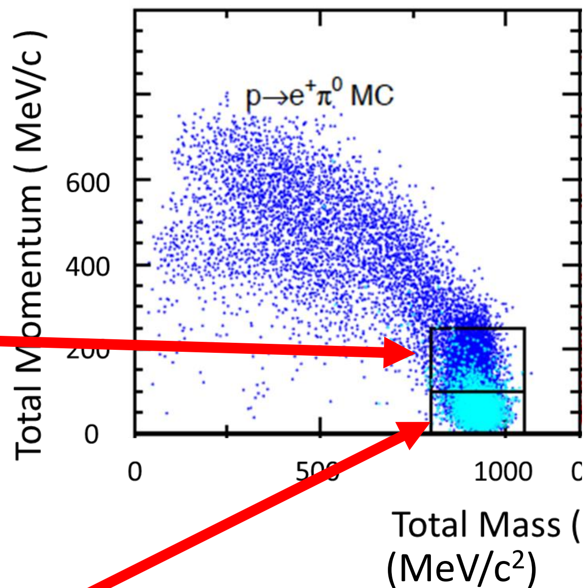
Divide the sample into two.

- High momentum sample ($100 < p < 250$ MeV/c) to search for the decay of proton in Oxygen

  Larger # of backgrounds

- Low momentum sample ($p < 100$MeV/c) to search for the decay of Hydrogen

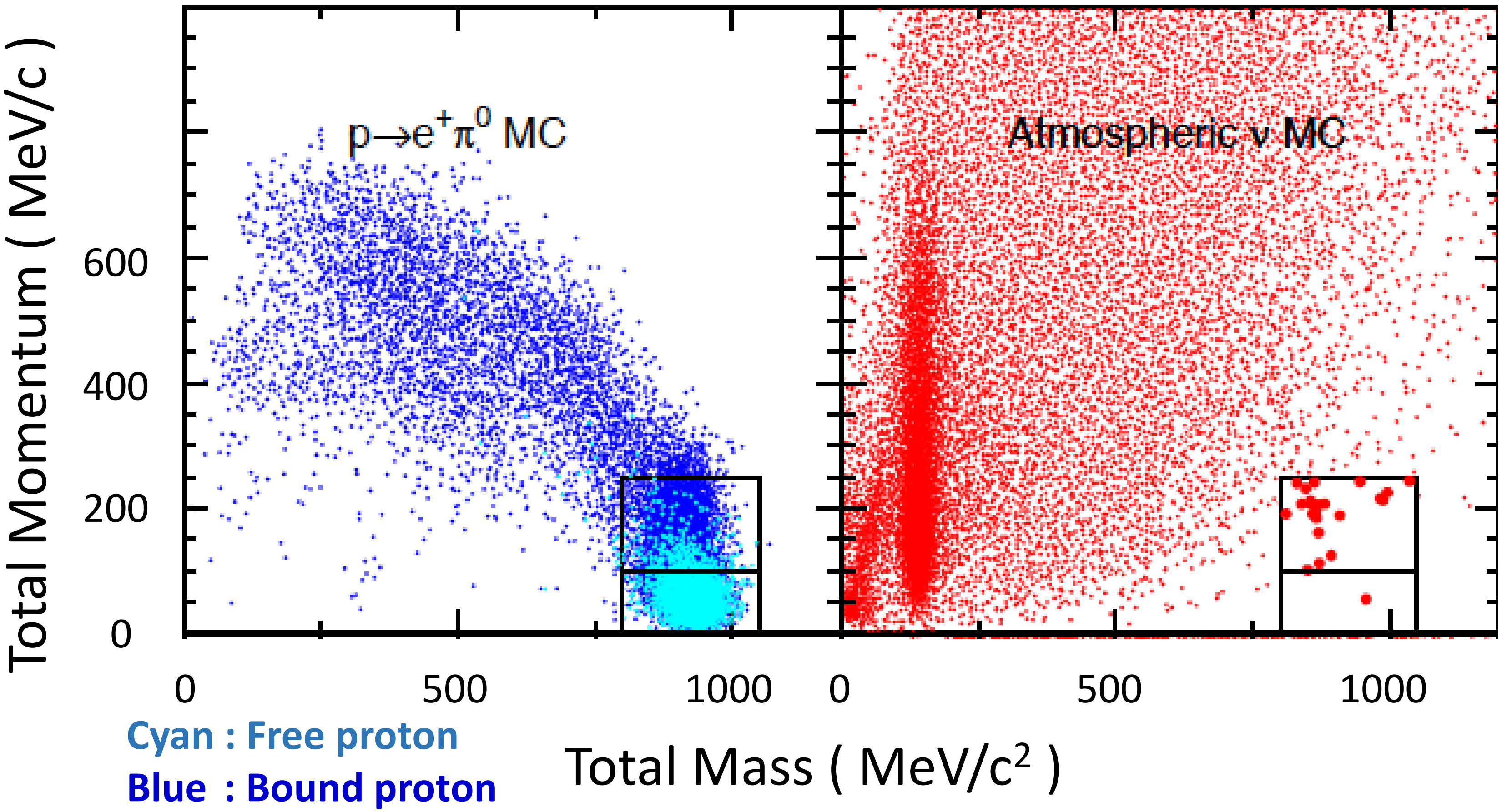
  Smaller # of backgrounds



Cyan : Free proton

Blue : Bound proton

Proton decay search in SK $p \to e^+ + \pi^0$

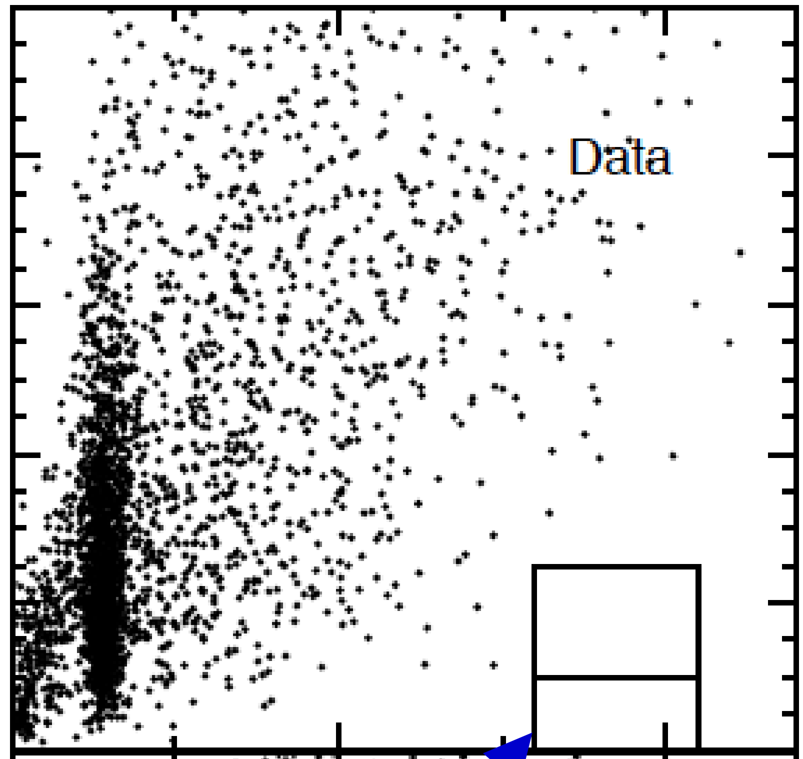


SK-IV	Low P_{tot}	High P_{tot}
Signal efficiency	18.7 (±1.9) %	19.4 (± 3.4) %
Background (/Mt*yr)	$0.18^{+0.25}_{-0.13}$	1.1 ± 0.3

Proton decay search in SK $p \rightarrow e^+ + \pi^0$

	SK-I	SK-II	SK-III	SK-IV
kt·yrs	91.7	49.2	31.9	133.5
Eff.(%)	18.8±1.9	18.3±1.9	19.6±2.0	18.7±1.9
BKG	$0.03^{+0.03}_{-0.02}$	<0.01	<0.01	$0.02^{+0.03}_{-0.02}$
(/Mt·yr)	$0.36^{+0.30}_{-0.20}$	$0.26^{+0.27}_{-0.17}$	$0.09^{+0.21}_{-0.08}$	$0.18^{+0.25}_{-0.13}$
OBS	0	0	0	0
Eff.(%)	20.4±3.6	20.2±3.6	20.5±3.6	19.4±3.4
BKG	0.22±0.08	0.12±0.04	0.06±0.02	0.15±0.06
(/Mt·yr)	2.4±0.8	2.5±0.9	1.8±0.7	1.1±0.3
OBS	0	0	0	0

Upper block : Low momentum region
Lower block : High momentum region



So far, no candidate events have been observed.

Partial lifetime limit = 1.6x10^{34}year

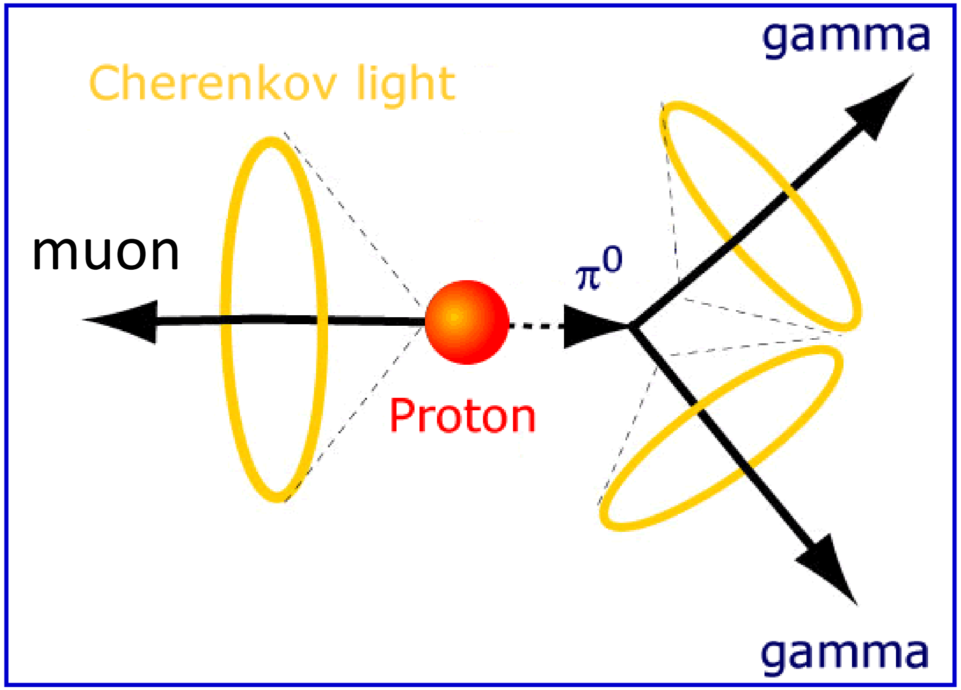
Proton decay search in SK $p \to \mu^+ + \pi^0$

Event selection criteria

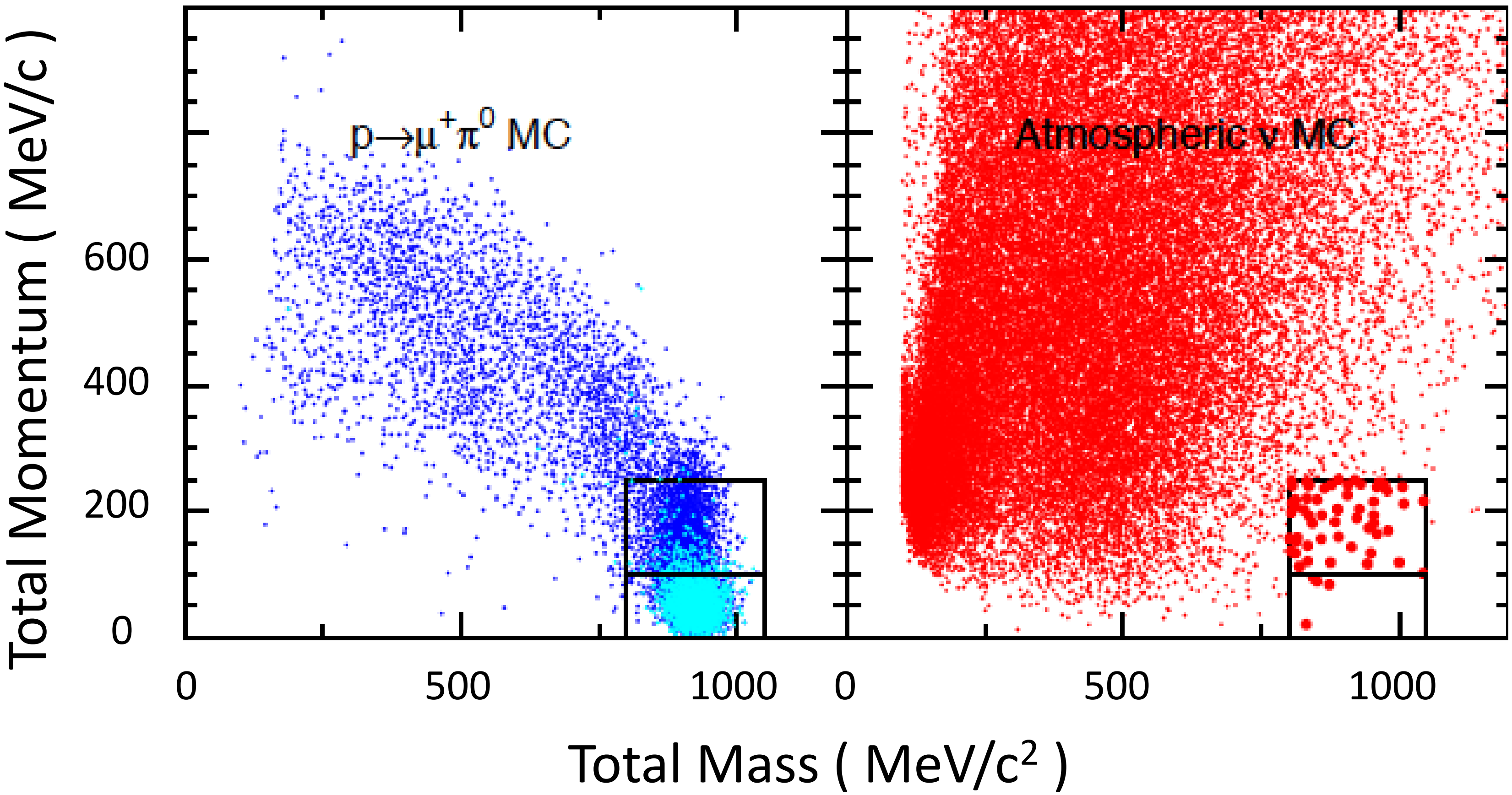
- No activity in the outer detector
- Vertex in the fiducial volume
- No decay electron
- 2 or 3 rings and only 1 μ-like
  (μ^+ + 1 or 2 γ)

~ one of the γs may have low energy or overlap with the other rings

- Reconstructed π^0 mass
  85 ~ 185 MeV/c^2
  (for 3 ring events)
- Reconstructed proton mass
  800 ~ 1050 MeV/c^2
- Reconstructed total (proton) momentum
  p_{tot} < 250 MeV/c
- No tagged neutron (only for SK4)



Proton decay search in SK $p \rightarrow \mu^+ + \pi^0$

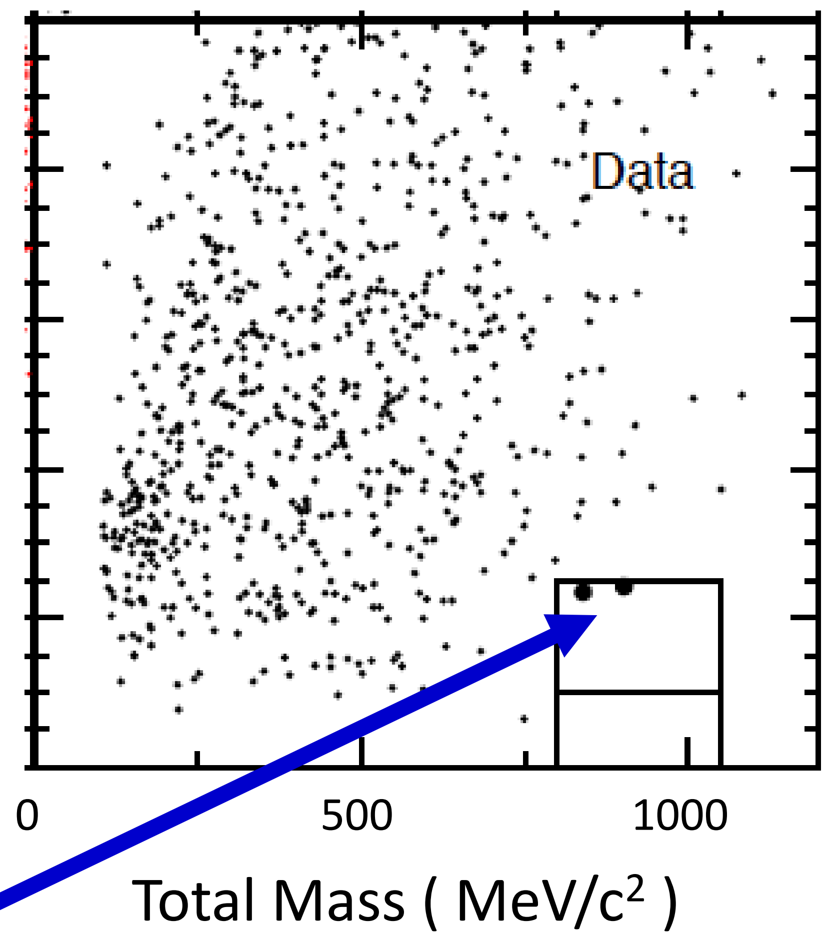


SK-IV	Low P_{tot}	High P_{tot}
Signal efficiency	20.1 (± 1.9) %	18.2 (± 3.3) %
Background (/Mt*yr)	$0.09^{+0.21}_{-0.08}$	1.7 ± 0.6

Proton decay search in SK $p \rightarrow \mu^+ + \pi^0$

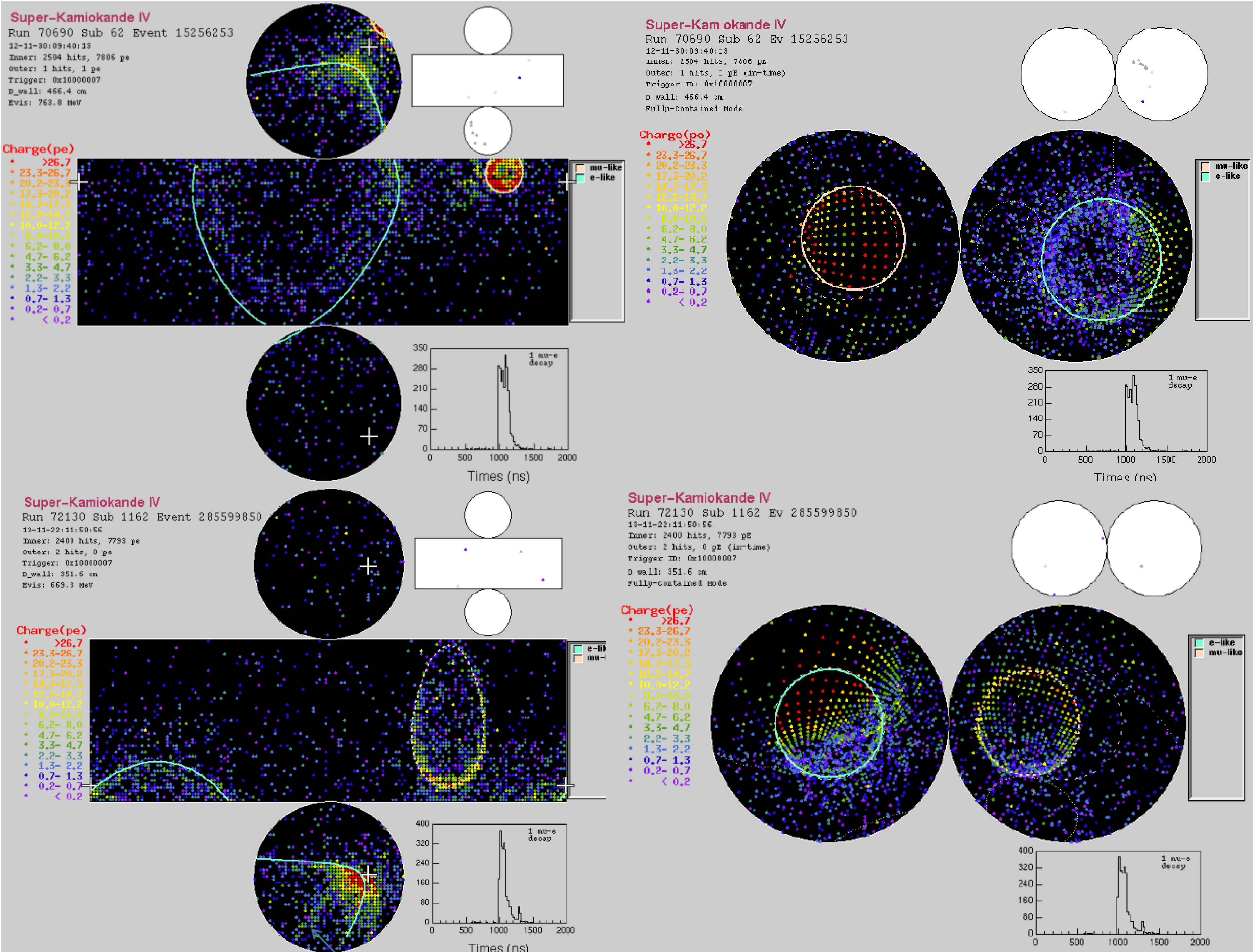
	SK-I	SK-II	SK-III	SK-IV
kt·yrs	91.7	49.2	31.9	133.5
Eff.(%)	16.4±1.5	16.0±1.5	16.4±1.5	20.1±1.9
BKG	$0.03^{+0.02}_{-0.02}$	<0.01	<0.01	$0.01^{+0.02}_{-0.01}$
(/Mt·yr)	$0.31^{+0.26}_{-0.17}$	$0.10^{+0.13}_{-0.07}$	$0.22^{+0.22}_{-0.14}$	$0.09^{+0.21}_{-0.08}$
OBS	0	0	0	0
Eff.(%)	15.3±2.8	15.3±2.8	16.5±3.0	18.2±3.3
BKG	0.33±0.10	0.14±0.05	0.12±0.04	0.23±0.08
(/Mt·yr)	3.6±1.1	2.9±0.9	3.7±1.2	1.7±0.6
OBS	0	0	0	2

Upper block : Low momentum region
Lower block : High momentum region



2 candidate events have been observed in high momentum region.

Partial lifetime limit = 7.7x10^{33}year


Super-Kamiokande IV
Run 70690 Sub 62 Event 15256253
12-11-30:09:40:13
Inner: 2504 hits, 7806 pe
Outer: 1 hits, 1 pe
Trigger: 0x10000007
D_wall: 466.4 cm
Evis: 763.8 MeV
Charge(pe)
>26.7
23.3-26.7
20.2-23.3
17.3-20.2
14.7-17.3
12.2-14.7
10.0-12.2
8.0-10.0
6.2- 8.0
4.7- 6.2
3.3- 4.7
2.2- 3.3
1.3- 2.2
0.7- 1.3
0.2- 0.7
< 0.2
mu-like
e-like
1 mu-e decay
Times (ns)
Super-Kamiokande IV
Run 70690 Sub 62 Ev 15256253
12-11-30:09:40:13
Inner: 2504 hits, 7806 pE
Outer: 1 hits, 1 pE (in-time)
Trigger ID: 0x10000007
D wall: 466.4 cm
Fully-Contained Mode
Super-Kamiokande IV
Run 72130 Sub 1162 Event 285599850
13-11-22:11:50:56
Inner: 2400 hits, 7793 pe
Outer: 2 hits, 0 pe
Trigger: 0x10000007
D_wall: 351.6 cm
Evis: 669.3 MeV
Super-Kamiokande IV
Run 72130 Sub 1162 Ev 285599850
13-11-22:11:50:56
Inner: 2400 hits, 7793 pE
Outer: 2 hits, 0 pE (in-time)
Trigger ID: 0x10000007
D wall: 351.6 cm
Fully-Contained Mode

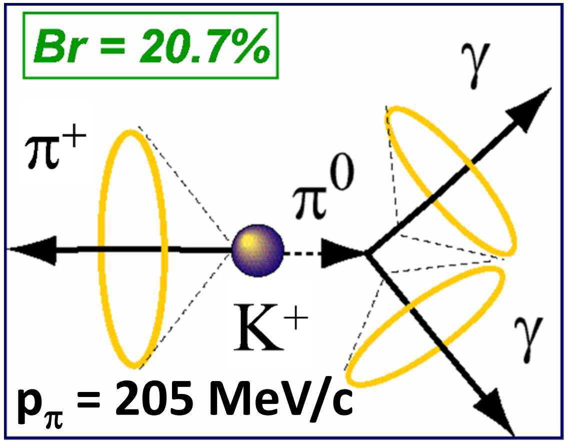
Proton decay search in SK $p \rightarrow \bar{\nu} + K^+$

Ring imaging water Cherenkov detectors
can not detect K+ from proton decay directly
due to its small momentum. (p_K = 339 MeV/c)

Interaction probability of low momentum K^+ is small
and most of K^+ are expected to decay at rest.

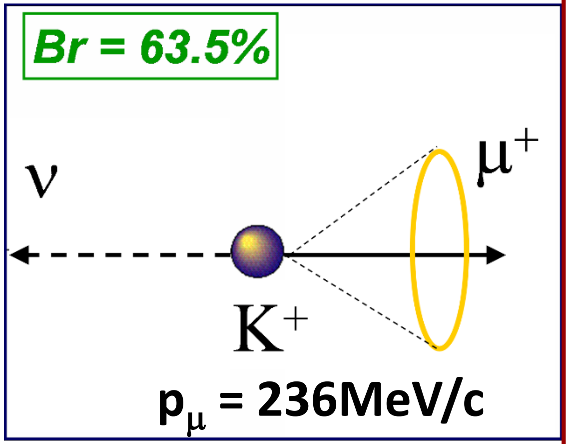
→ Use decay products of K^+
for the identification of the candidate events

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



- Two e-like rings with 1 decay-e
- Small activity (from π^+) in the opposite direction of π^0

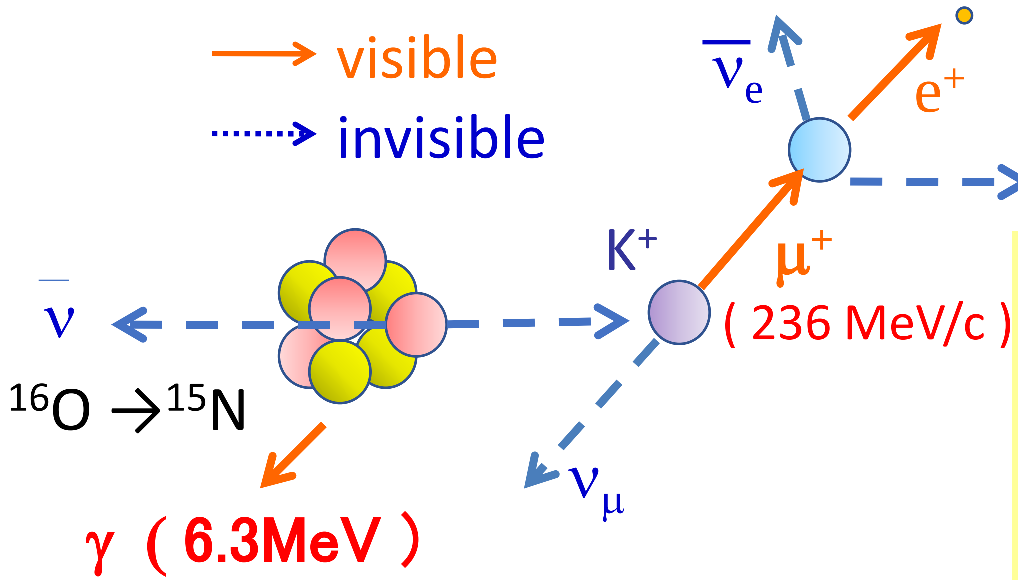
$K^+ \rightarrow \mu^+ + \bar{\nu}$

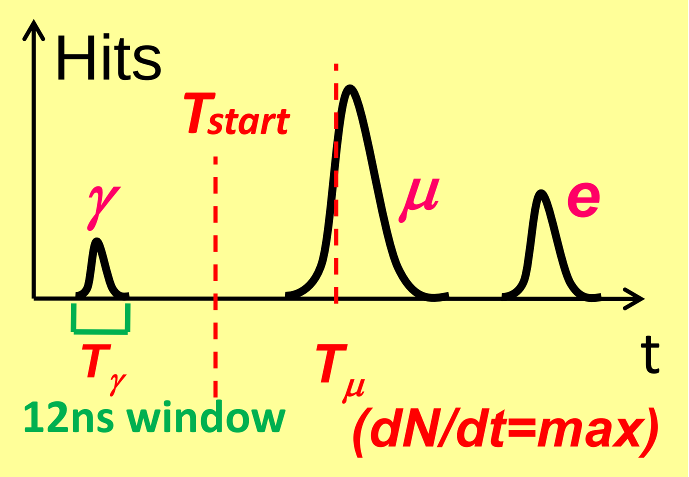


- Single μ-like ring with 1 decay electron

Proton decay search in SK $p \rightarrow \bar{\nu} + K^+$

$K^+ \rightarrow \mu^+ + \nu$ with prompt γ tag.



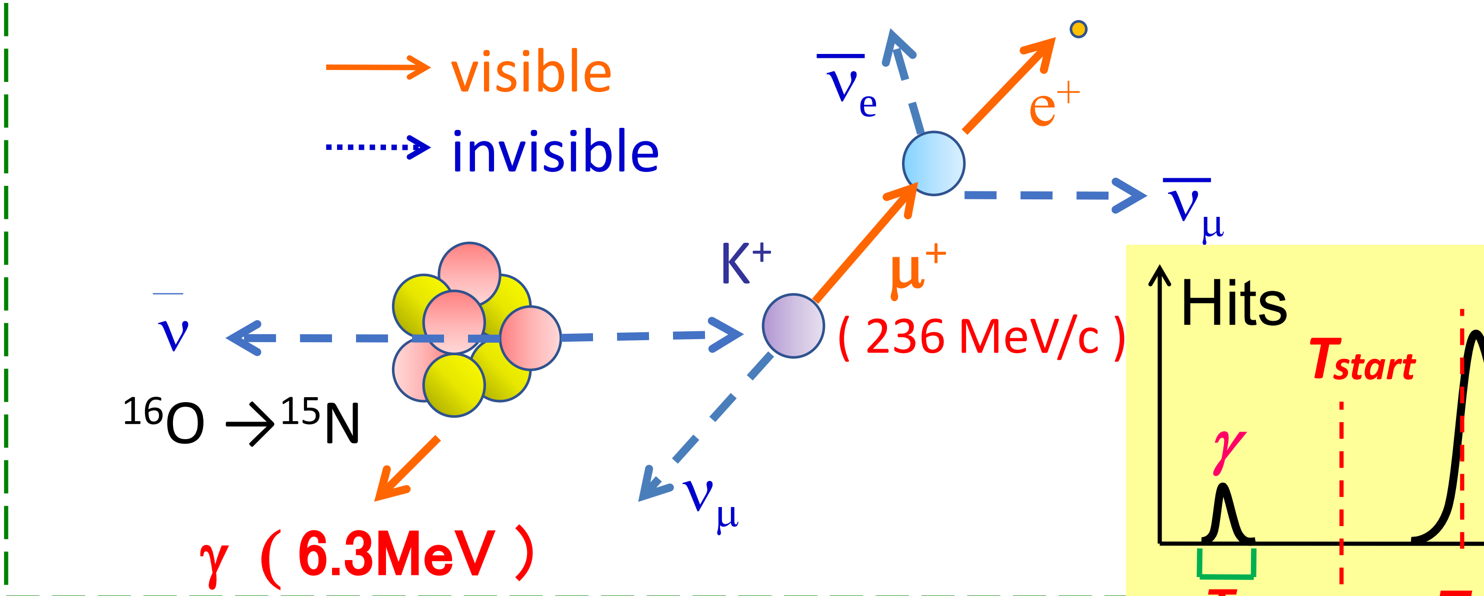


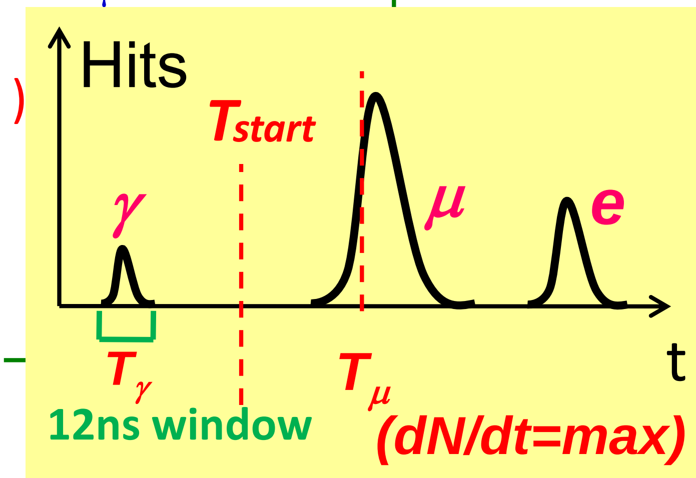
When a proton in oxygen decays,
6.3MeV de-excitation γ is also emitted
with probability of ~ 40 %.

- Search for 1 ring μ-like events with p_μ ~ 236 MeV/c with 1 decay electron
- Additionally, search for the pre-activity from prompt de-excitation 6.3 MeV γ

Proton decay search in SK $p \to \bar{\nu} + K^+$

$K^+ \to \mu^+ + \nu$ with prompt γ tag.





Event selection criteria

- No activity in the outer detector
- Vertex in the fiducial volume
- 1 decay electron
- 1 μ-like ring
- No tagged neutron (only for SK4)

- Maximum # of hit cluster in 12ns after prior to the μ signal (N_{12})

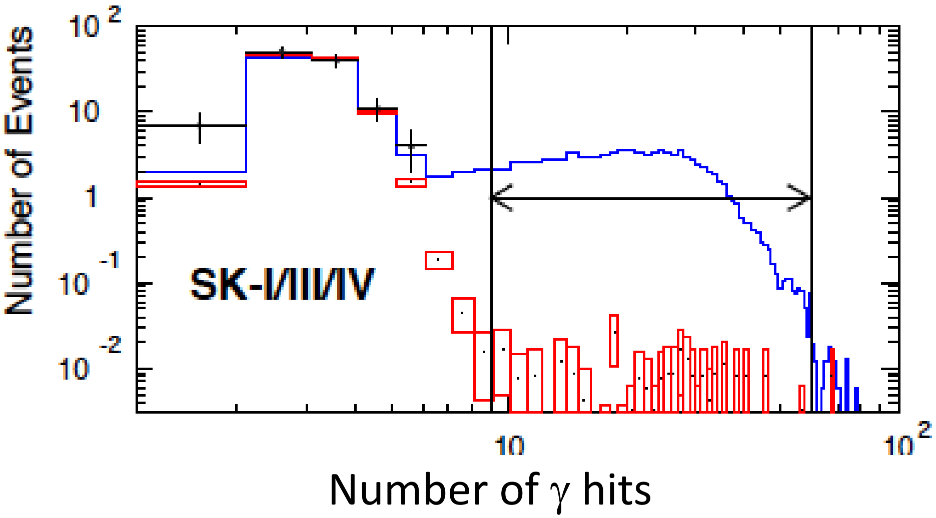
  $8 < N_{12} < 60$ (SK1,3,4)

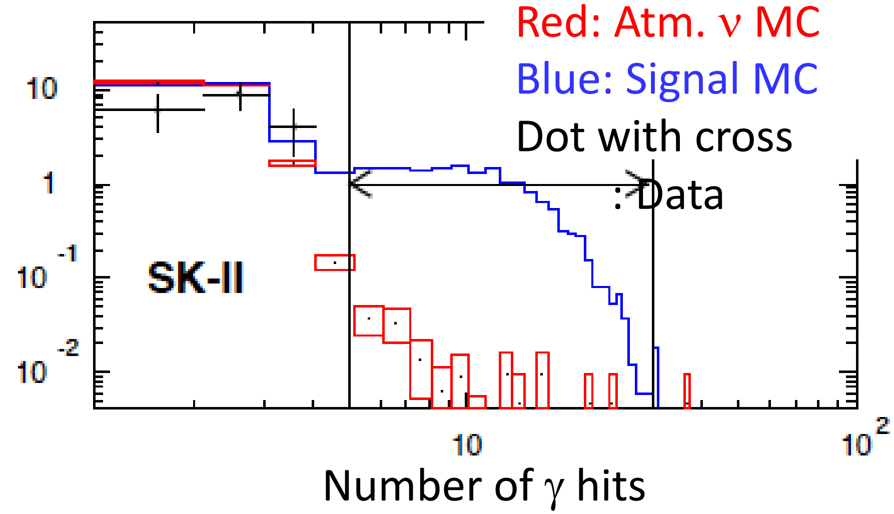
  $4 < N_{12} < 30$ (SK2)

  $T_\mu - T_\gamma < 75$ns

Proton decay search in SK $p \rightarrow \bar{\nu} + K^{+}$

$K^{+} \rightarrow \mu^{+} + \bar{\nu}$ with prompt γ tagging



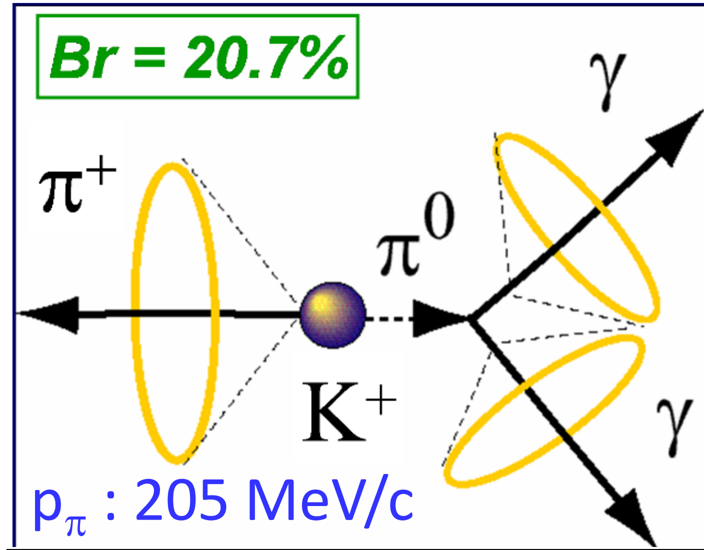


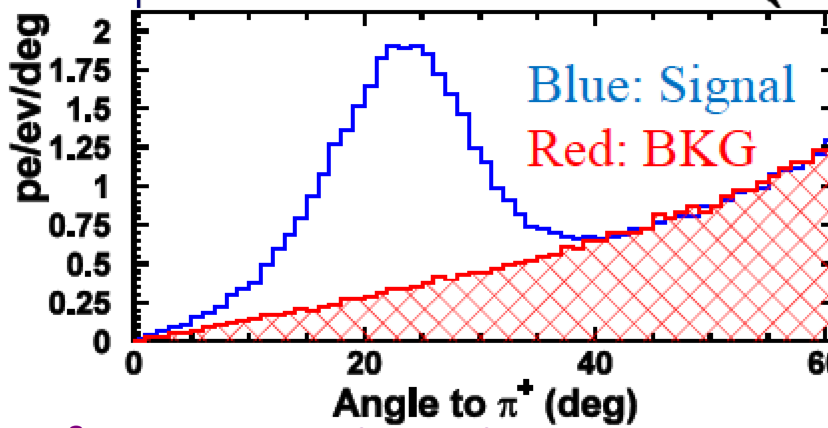
	Exposure (kt.yr)	Efficiency (%)	Background	Data
SK1	91.7	7.9 ± 0.1	0.08	0
SK2	49.2	6.3 ± 0.1	0.14	0
SK3	31.9	7.7 ± 0.1	0.03	0
SK4	133.5	8.5 ± 0.1	0.14	0
Total	306.3		0.39	0

Proton decay search in SK

Event selection criteria $K \rightarrow \pi^+ + \pi^0$

- No activity in the outer detector
- Vertex in the fiducial volume
- 1 decay electron
- 1 or 2 e-like rings (from π^0)
- Reconstructed π^0 mass
  85 ~ 185 MeV/c^2
- Reconstructed π^0 momentum
  175 ~ 250 MeV/c
- Visible energy sum in 140~180° from π^0 direction (E_{bk})
  $10 < E_{bk} < 50$ MeV

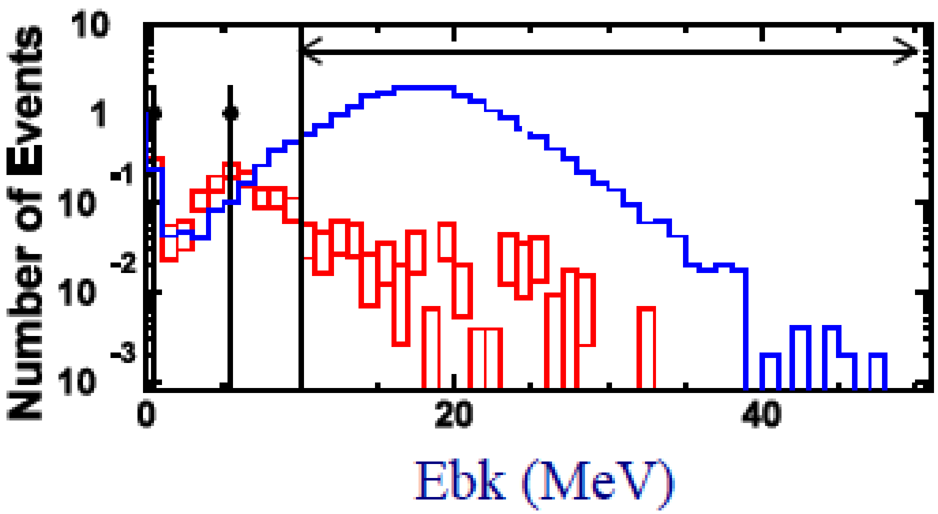


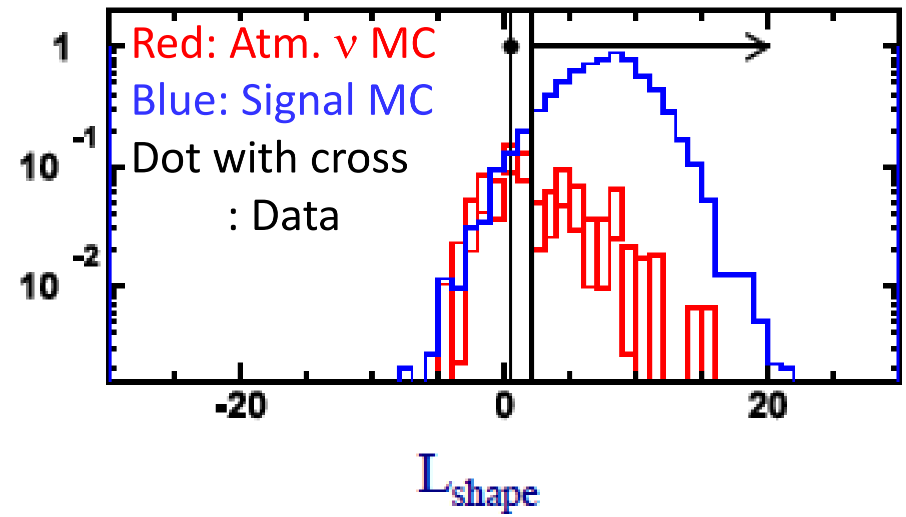


- Visible energy sum in 90~140° from π^0 direction (E_{res})
  $E_{res} < 12$ MeV (2 rings), 20 MeV (1 ring)
- Charge distribution likelihood cut
- No tagged neutron (only for SK4)

Proton decay search in SK $\quad p \rightarrow \bar{\nu} + K^+$

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





	Exposure (kt.yr)	Efficiency (%)	Background	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

Proton decay search in SK $p \rightarrow \bar{\nu} + K^+$

$K^+ \rightarrow \mu^+ + \bar{\nu}$ with prompt γ tag.

	Exposure (kt.yr)	Efficiency (%)	Background	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

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

	Exposure (kt.yr)	Efficiency (%)	Background	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

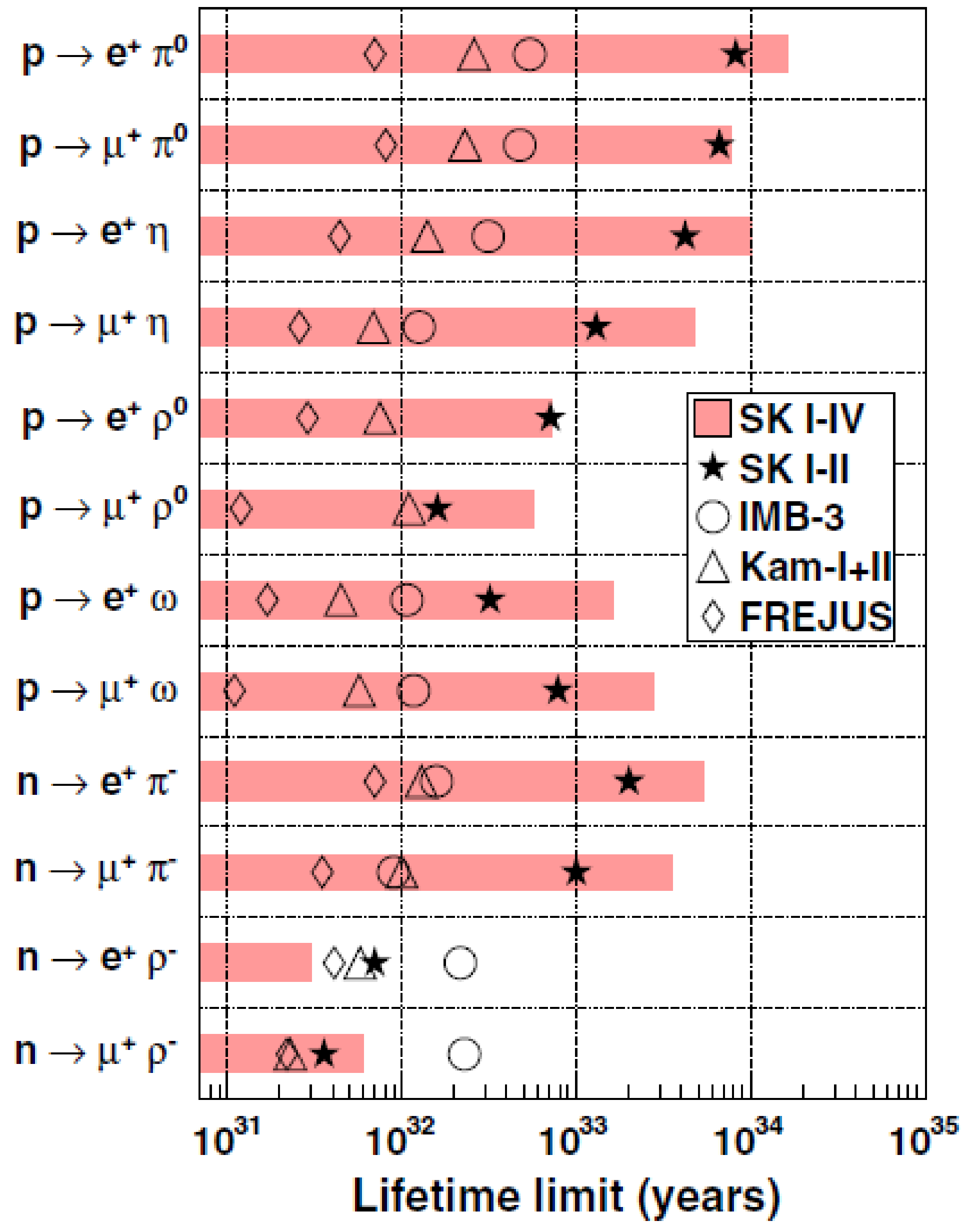
Partial lifetime limit (combined) = 6.6 $\times 10^{33}$ year @ 306.3 kt·yr

More nucleon decay searches in SK

Decay modes	Background events	Candidate events	Probability (%)	Lifetime limit (10^{33}yrs) 90%C.L.
$p \rightarrow e^{+} + \eta$	0.78 ± 0.30	0	---	10.
$p \rightarrow \mu^{+} + \eta$	0.85 ± 0.23	2	20.9	4.7
$p \rightarrow e^{+} + \rho^{0}$	0.64 ± 0.17	2	13.5	0.72
$p \rightarrow \mu^{+} + \rho^{0}$	1.30 ± 0.33	1	72.7	0.57
$p \rightarrow e^{+} + \omega$	1.35 ± 0.43	1	74.1	1.6
$p \rightarrow \mu^{+} + \omega$	1.09 ± 0.52	0	---	2.8
$n \rightarrow e^{+} + \pi^{-}$	0.41 ± 0.13	0	---	5.3
$p \rightarrow \mu^{+} + \pi^{-}$	0.77 ± 0.20	1	53.7	3.5
$n \rightarrow e^{+} + \rho^{-}$	0.87 ± 0.26	4	1.2	0.03
$n \rightarrow \mu^{+} + \rho^{-}$	0.96 ± 0.28	1	61.7	0.06

Nucleon decay searches in SK

Extensive studies have been performed.
However, no signature of nucleon decay was observed.

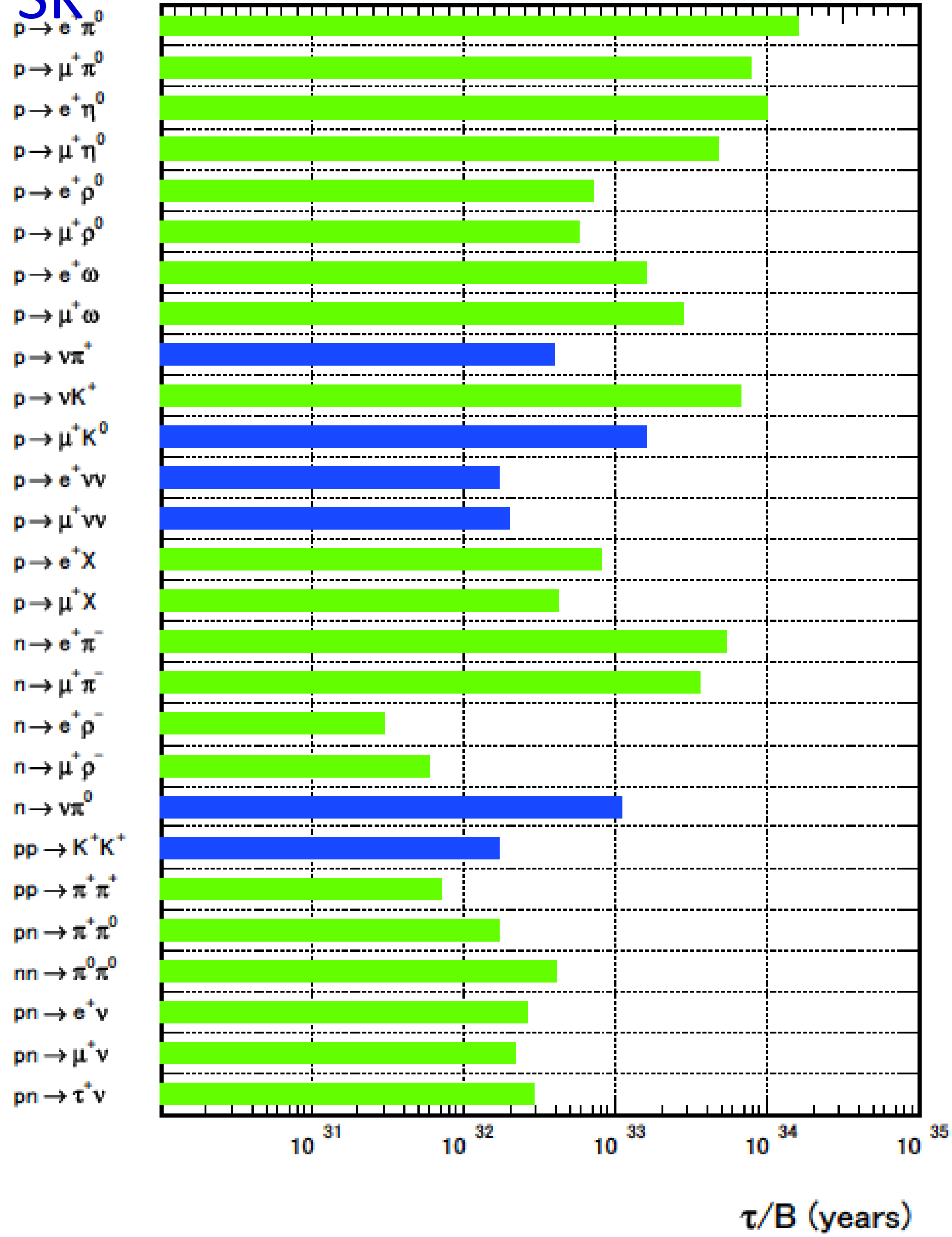


Nucleon decay searches in SK

Extensive studies have been performed.

However, no signature of nucleon decay was observed.

*) Blue lines are analysis with less than 300kt yr data and we can improve with revised analyses.



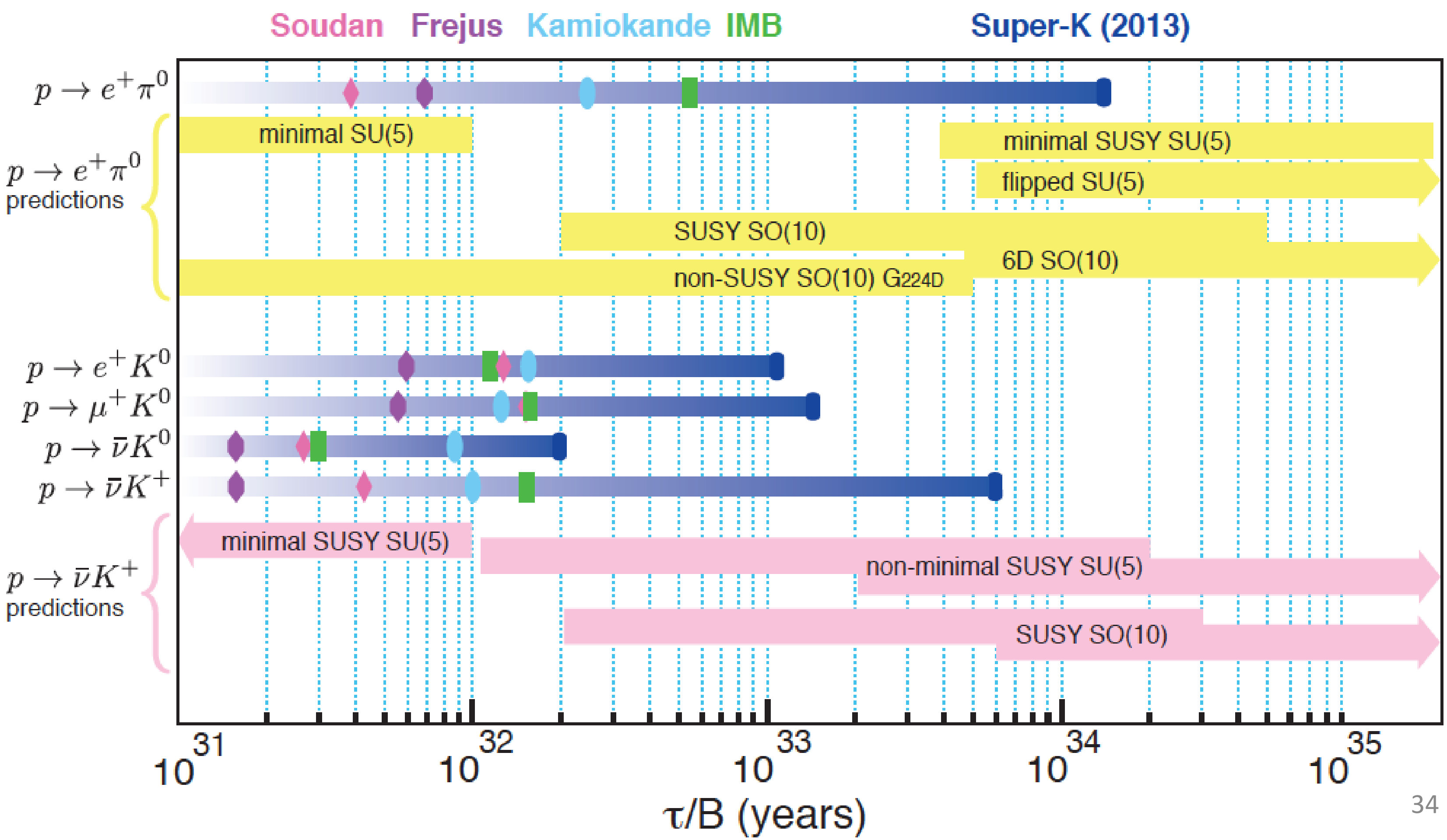
Proton decay searches in SK

So far, we have not found no indication of nucleon decay.

Latest lifetime limits from SK

$p \rightarrow e^+ \pi^0$ $\tau/B > 1.6 \times 10^{34}$ yr

$p \rightarrow \bar{\nu} K^+$ $\tau/B > 6.6 \times 10^{33}$ yr



Search for dinucleon decay and $n - \bar{n}$ oscillation

Sakharov conditions

Three minimum properties of Nature
for any baryogenesis to occur.

1. *At least one B-number violating process*.
2. C- and CP-violation
3. Interactions outside of thermal equilibrium.

No experimental signature of $|\Delta B| = 1$ baryon number violation
(proton decay) until now.

→ Other possibilities of $|\Delta B| = 2$

dinucleon decay

$n - \bar{n}$ oscillation etc...

References

Search for n – nbar oscillation in Super-Kamiokande,
K. Abe et al., Phys. Rev. D 91, 072006 (2015)

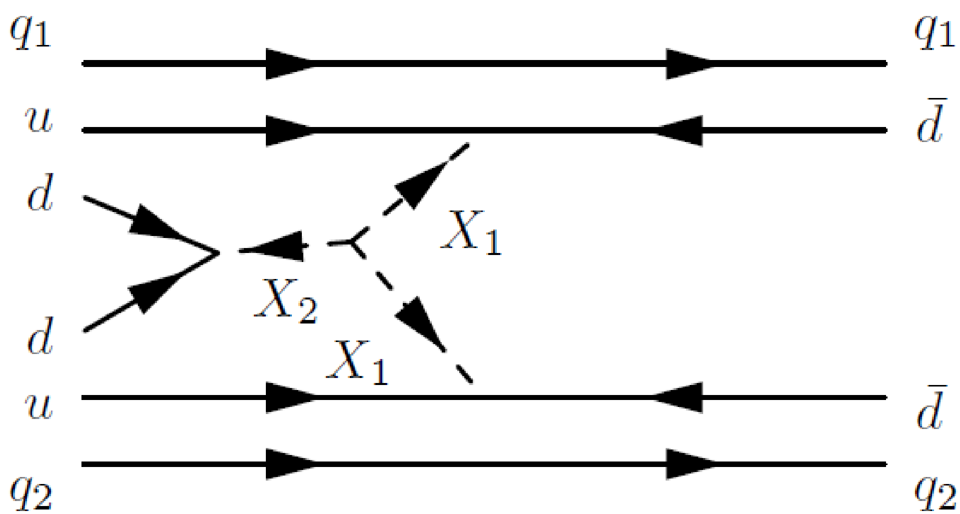
Search for dinucleon decay into pions at Super-Kamiokande
J. Gustafson et al, Phys. Rev. D91, 072009 (2015)

Search for dinucleon decay

Search for NN → $\pi\pi$ in Oxygen

One example of Feynman diagram for dinucleon decay

Ref. J. M. Arnold, B. Fornal, and M. B. Wise
Phys. Rev. D 87, 075004 (2013)



q_1 , q_2 : u or d

X_1, X_2 : Scalar particle

→ Search for 3 channels using SK data

pp → $\pi^+\pi^+$

pn → $\pi^+\pi^0$

nn → $\pi^0\pi^0$

Search for dinucleon decay

Basic Idea : Search for two back-to back pions in an event
and calculate the reconstruct invariant mass.

Signal : Reconstructed Invariant mass ~ ($2xM_p - 2xM_\pi$)

In SK, π^+ is identified as non-showering ring (μ-like ring)
π^0 could be reconstructed from 2 showering rings
(e-like rings)

Background

Atmospheric ν events ($\nu N \to \nu N' \pi \pi$ etc..)

Difficulties

μ is also identified as non-showering ring
dinucleon decay occurs in Oxygen and go through water
→ pions interact with the other nucleons.
= May change charge, direction and momentum.
In the worst case, pions are absorbed.

Simple cut-based analysis results in poor efficiency and poor background rejection power.

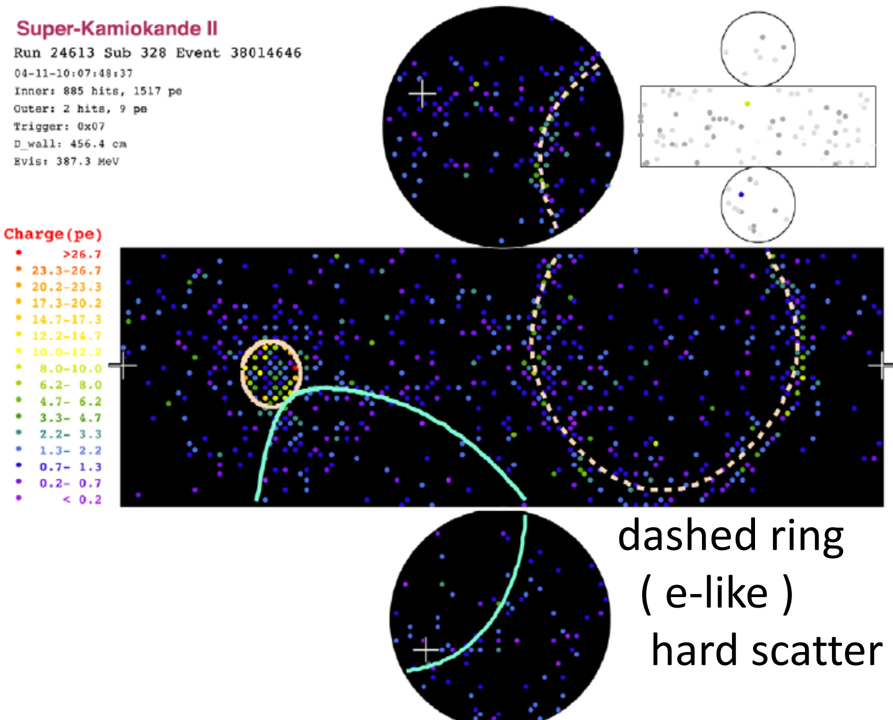
Search for dinucleon decay in Super-Kamiokande (I)

$pp \rightarrow \pi^+\pi^+$

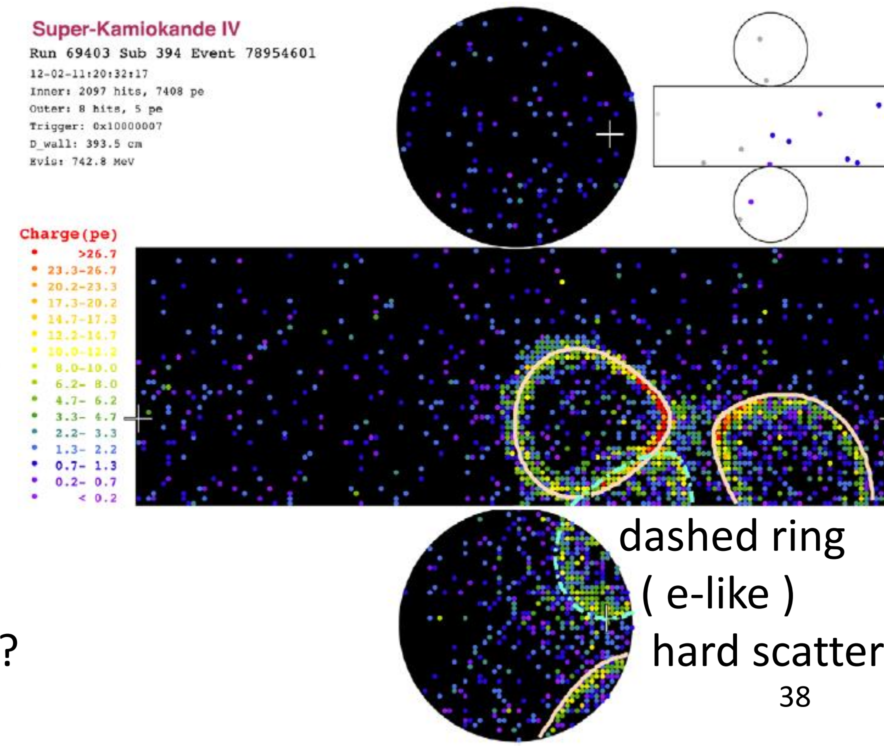
	SK-I	SK-II	SK-III	SK-IV
Eff. (%)	6.1 ± 0.2	5.3 ± 0.2	6.4 ± 0.2	5.8 ± 0.2
Bkg. (MT-yr)	17.8 ± 1.8	14.3 ± 1.6	17.4 ± 1.7	14.2 ± 1.6
Bkg. (SK live.)	1.6	0.70	0.56	1.6
Candidates	0	1	0	1

4.5 background expected, 2 observed. (bkg. consistent …)

Event displays (remained as candidates)



dashed ring
(e-like)
hard scatter ?



dashed ring
(e-like)
hard scatter ?

Search for dinucleon decay in Super-Kamiokande (I)

$pp \rightarrow \pi^+\pi^+$

Remaining background events

~ 45% : Charged current single π production (ν N $\rightarrow$ *l*- N' π^+ etc.)

~ 30% : Charged current deep inelastic scattering (DIS)

(ν N $\rightarrow$ *l*- N' $\pi^+ \pi^+$ etc.)

Systematic uncertainties

	$pp \rightarrow \pi^+\pi^+$			
Signal (%)	SK-I	SK-II	SK-III	SK-IV
Simulation	35.2	35.1	33.6	38.5
Reconstruction	6.0	8.6	4.0	3.2
BDT	3.6	2.2	4.4	2.0
Total	35.9	36.2	34.1	38.7
Background (%)	SK-I	SK-II	SK-III	SK-IV
Simulation	29.1	29.1	35.8	26.5
Reconstruction	6.1	8.1	4.1	3.2
BDT	6.8	1.0	4.3	1.4
Total	30.5	30.3	36.4	26.8

Major uncertainty (Simulation) π interactions in/with nucleus

Obtained lifetime limit : $\tau_{pp \rightarrow \pi+\pi+}$ > 7.22 x 10^{31} yrs

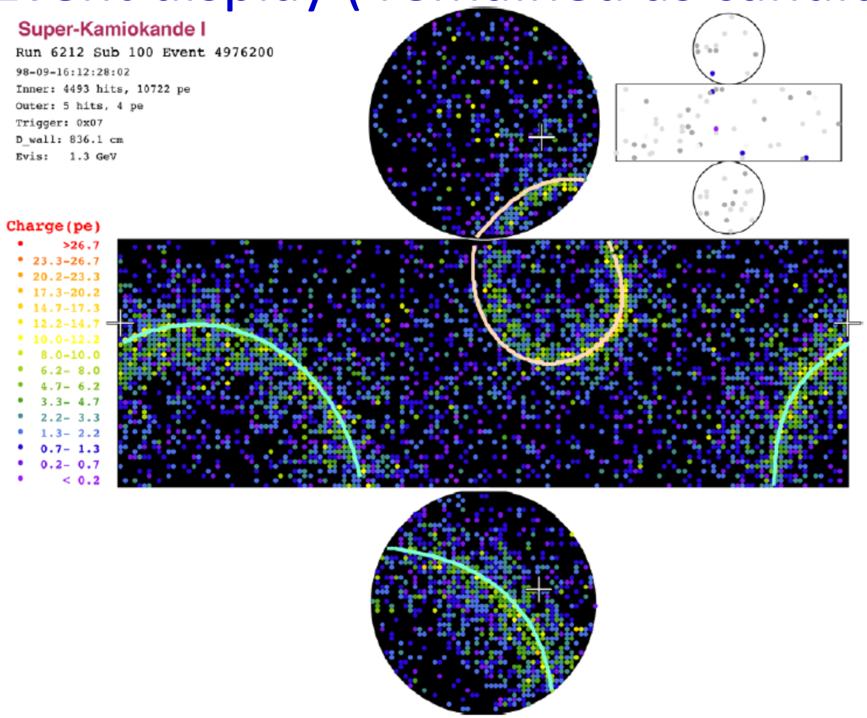
Search for dinucleon decay in Super-Kamiokande (II)

$pn \rightarrow \pi^+\pi^0$

	SK-I	SK-II	SK-III	SK-IV
Cut	0.19	0.24	0.20	0.17
Eff. (%)	10.2 ± 0.2	10.0 ± 0.2	9.4 ± 0.2	10.4 ± 0.2
Bkg. (MT-yr)	2.7 ± 0.7	2.3 ± 0.7	2.2 ± 0.7	2.9 ± 0.8
Bkg. (SK live.)	0.25	0.11	0.07	0.32
Candidates	1	0	0	0

0.75 background expected, 1 observed. (bkg. consistent…)

Event display (remained as candidates)



2 ring event

Opening angle = 140 deg.

p_e = 987 MeV/c

p_μ = 460 MeV/c

Reconstructed π^0 mass = 10MeV/c^2

No decay electron

Search for dinucleon decay in Super-Kamiokande (II)

$pn \rightarrow \pi^+\pi^0$

Remaining background events

30 ~ 45% : Charged current single π production

($\nu N \rightarrow l^- N' \pi^+$ etc.)

30 ~ 45% : Charged current deep inelastic scattering (DIS)

($\nu N \rightarrow l^- N' \pi^+ \pi^+$ etc.)

Systematic uncertainties

	$pn \rightarrow \pi^+\pi^0$			
Signal (%)	SK-I	SK-II	SK-III	SK-IV
Simulation	33.3	32.2	28.4	35.0
Reconstruction	3.3	1.7	5.6	5.6
BDT	<1	1.6	<1	<1
Total	33.4	32.3	28.9	35.3
Background (%)	SK-I	SK-II	SK-III	SK-IV
Simulation	22.1	19.9	24.0	27.8
Reconstruction	1.8	1.8	3.3	3.8
BDT	6.3	7.4	10.3	11.3
Total	23.1	21.3	26.3	28.6

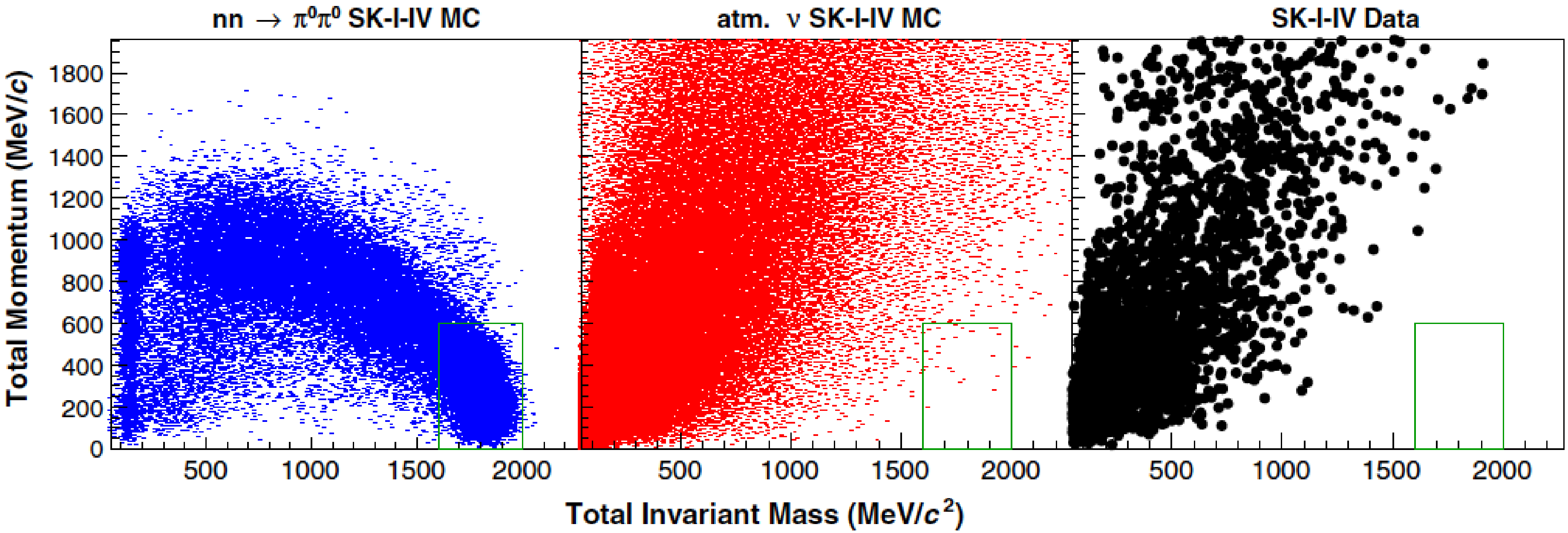
Major uncertainty (Simulation) π interactions in/with nucleus

Obtained lifetime limit : $\tau_{pn \rightarrow \pi+\pi0}$ > 1.70 x 10^{32} yrs

Search for dinucleon decay in Super-Kamiokande (III)

$nn \rightarrow \pi^0\pi^0$

	SK-I	SK-II	SK-III	SK-IV
Eff. (%)	22.1 ± 0.3	18.8 ± 0.3	20.9 ± 0.3	21.4 ± 0.3
Bkg.	0.05 ± 0.02	0.04 ± 0.01	0.03 ± 0.01	0.02 ± 0.01
Data	0	0	0	0



0.14 background expected, 0 observed.

Obtained lifetime limit : $\tau_{nn \rightarrow \pi 0 \pi 0} > 4.04 \times 10^{32}$ yrs

Search for dinucleon decay in Super-Kamiokande

Search for 3 channels using SK data (282.1 kt·yr)

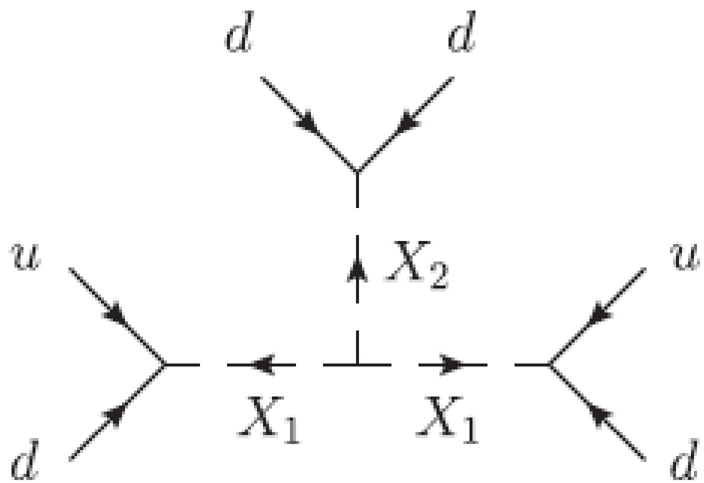
$pp \rightarrow \pi^+\pi^+$, $pn \rightarrow \pi^+\pi^0$, $nn \rightarrow \pi^0\pi^0$

All modes are consistent with background
(atmospheric neutrino interactions)
No signature was observed.

Mode	Frejus limit (^{56}Fe)	This analysis (^{16}O)
$pp \rightarrow \pi^+\pi^+$	7.0×10^{29} yrs	7.22×10^{31} yrs
$pn \rightarrow \pi^+\pi^0$	2.0×10^{30} yrs	1.70×10^{32} yrs
$nn \rightarrow \pi^0\pi^0$	3.4×10^{30} yrs	4.04×10^{32} yrs

Search for n – $\bar{n}$ oscillation

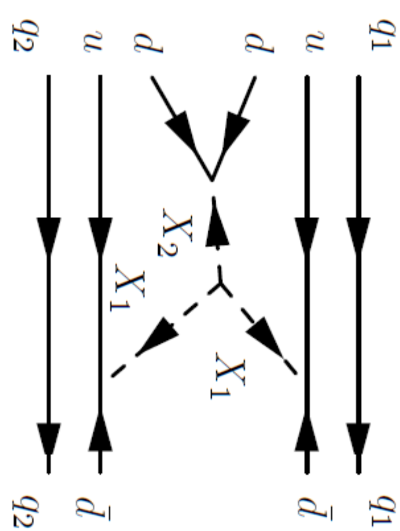
One example of Feynman diagram for dinucleon decay



Ref. J. M. Arnold, B. Fornal, and M. B. Wise
Phys. Rev. D 87, 075004 (2013)

X_1, X_2 : Scalar particle

Basically same as the diagram for dinucleon decay.



Search for n – $\bar{n}$ oscillation

Once an anti-neutron is produced,
it annihilates with one the surrounding nucleon
and produce pions.

Estimated branching ratio after annihilation.

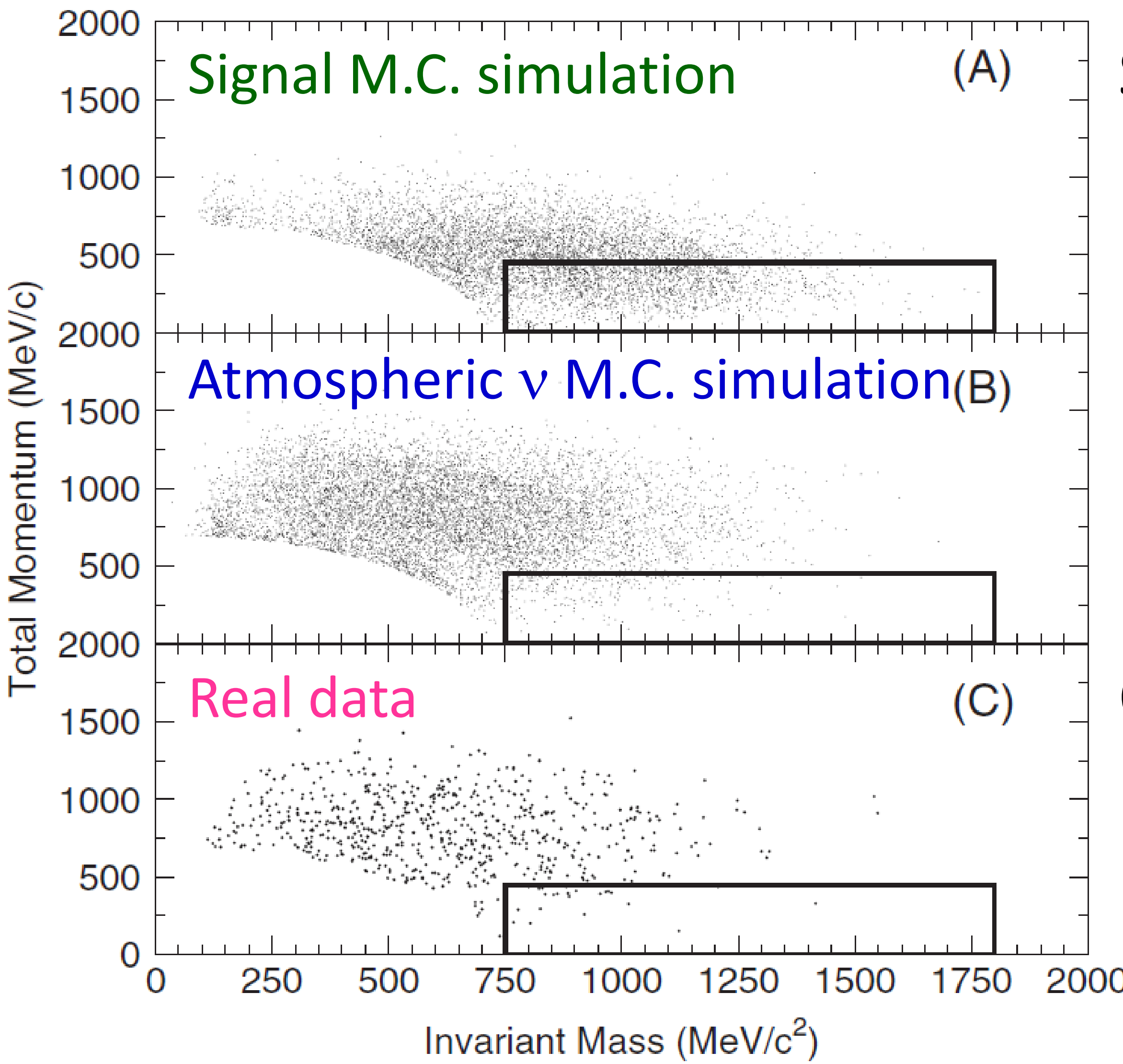
$\bar{n} + p$		$\bar{n} + n$	
$\pi^+\pi^0$	1%	$\pi^+\pi^-$	2%
$\pi^+2\pi^0$	8%	$2\pi^0$	1.5%
$\pi^+3\pi^0$	10%	$\pi^+\pi^-\pi^0$	6.5%
$2\pi^+\pi^-\pi^0$	22%	$\pi^+\pi^-2\pi^0$	11%
$2\pi^+\pi^-2\pi^0$	36%	$\pi^+\pi^-3\pi^0$	28%
$2\pi^+\pi^-2\omega$	16%	$2\pi^+2\pi^-$	7%
$3\pi^+2\pi^-\pi^0$	7%	$2\pi^+2\pi^-\pi^0$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

(Estimated based on the $\bar{p}$ p & $\bar{p}$ d bubble chamber experiments)

Search for n – n̄ oscillation in Super-Kamiokande

Used data set

SK 1 (1489 days) 92 kt·yr = 2.45 x 10^{34} neutron·year



Signal efficiency

12.1 %

Expected # of background events

24.1

Observed # of events

24

(background consistent….)

$\overline{T}_{n\text{-}\bar{n}}$ > 1.9x10^{32} years

Search for n – n̄ oscillation in Super-Kamiokande

Relation between oscillation time of a free neutron ($\tau^2_{n\text{-}\bar{n}}$)
and lifetime of a bound neutron ($T_{n\text{-}\bar{n}}$)

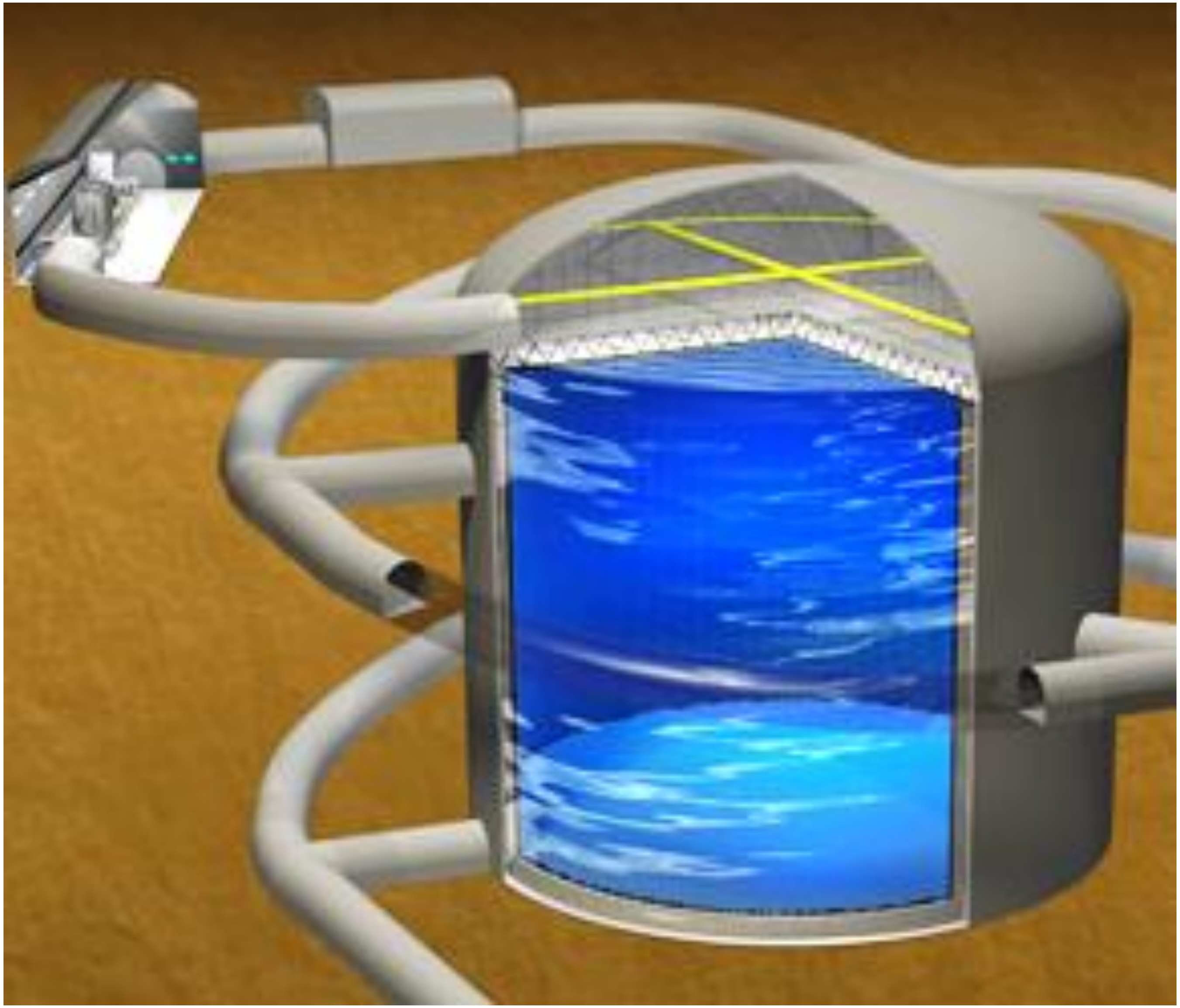
$$T_{n\text{-}\bar{n}} = R \cdot \tau^2_{n\text{-}\bar{n}} \Leftrightarrow \tau_{n-\bar{n}} = \sqrt{T_{n-\bar{n}}/R}$$

R : Nuclear suppression factor ($O(10^{23})$ sec^{-1})
Recent calculation : R = 0.571 x 10^{23} sec^{-1}

$T_{n\text{-}\bar{n}}$ > 1.9 x 10^{32} years
⇒ $\tau_{n\text{-}\bar{n}}$ > 2.7 x 10^{8} sec.

Experiment	SK	SD2	Frejus	KAM	IMB
Source of neutrons	Oxygen	Iron	Iron	Oxygen	Oxygen
Exposure (10^{32} neutron · yr)	245	21.9	5.0	3.0	3.2
Efficiency(%)	12.1	18.0	30.0	33.0	50.0
Candidates	24	5	0	0	3
Backgrounds	24.1	4.5	2.5(2.1)	0.9	–
$T_{n-\bar{n}}$ (10^{32} yr)	1.9	0.72	0.65	0.43	0.24
Suppression factor (10^{23} sec^{-1})	0.517	1.4	1.4	1.0	1.0
$\tau_{n-\bar{n}}$ (10^{8} sec)	2.7	1.3	1.2	1.2	0.88

Hyper-Kamiokande



Hyper Kamiokande project

What is not sufficient in SK? => ~ Statistics = target mass ~

→ ***260 kton (Fiducial volume ~ 186 kton) scale detector***

Expand the size of the cylindrical (SK-like) detector

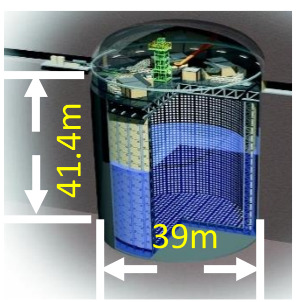
Effective photo sensitive area ~ 40%

Higher sensitivity PMTs (~2 times)

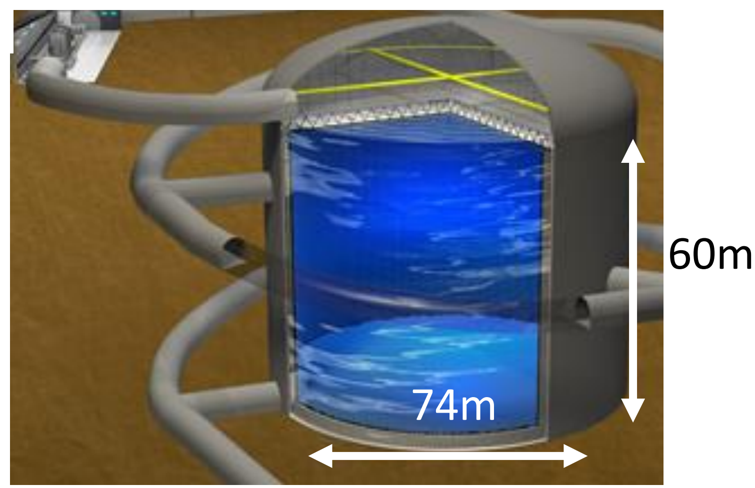
Maximum utilization of resources and experiences in SK

~ Use established technology for the long term operation to achieve physics goal in timely manner.

SK : Fiducial 22.5 kton



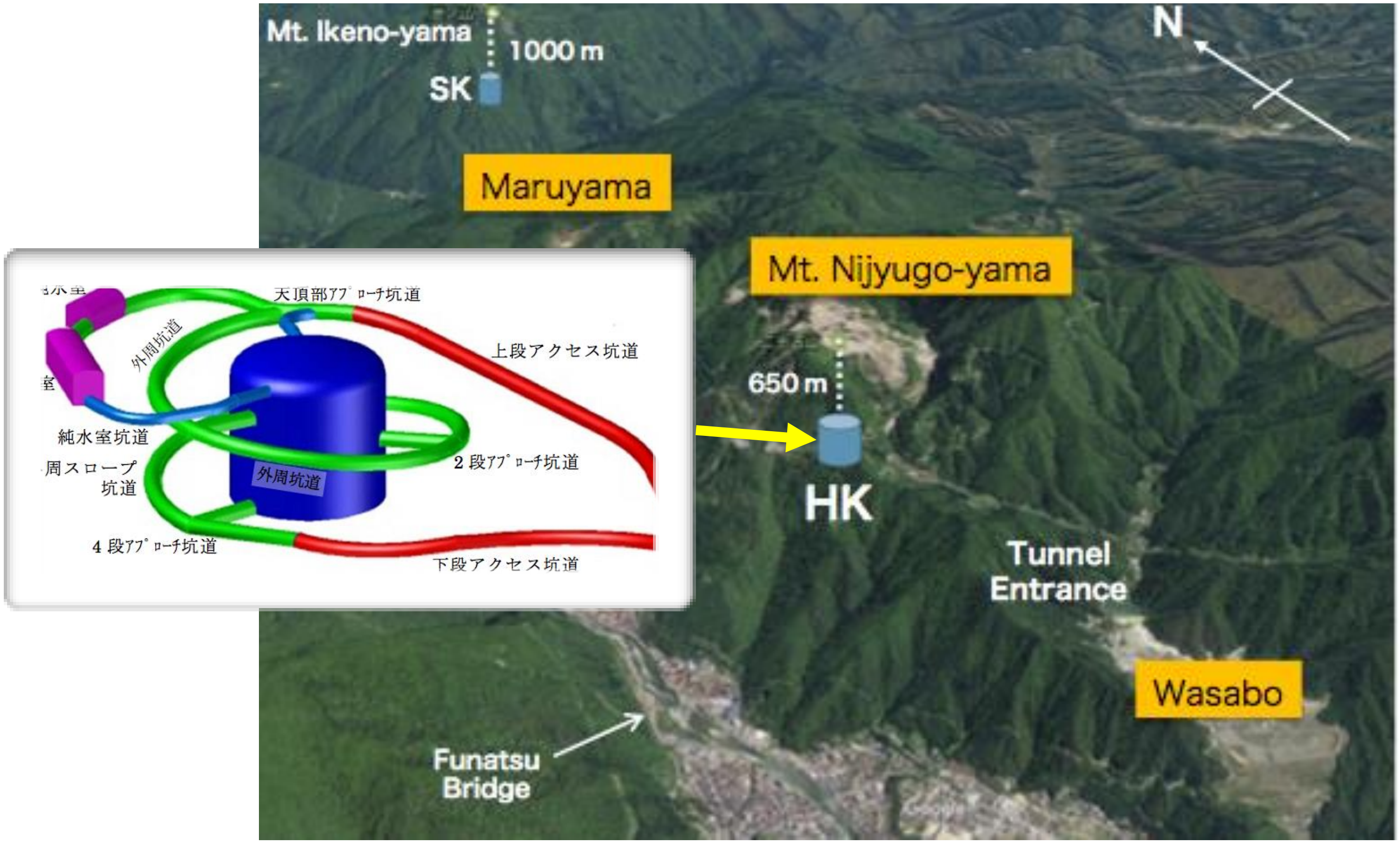
HK : Fiducial 186 kton **~ 8 x SK**



Hyper-Kamiokande detector

Is it possible to construct such gigantic detectors?

Candidate site : Tochibora mine in Kamioka



→ Based on the geological survey and analyses,
the cavern and the supporting structures were designed.

Possible to construct HK Caverns with existing technology.

Hyper-Kamiokande detector ~ Further improvements ~

Photo sensors ~ ***R&D to improve the detector performance***

Better timing resolution ~ better vertex resolution

Higher quantum efficiency

New photo sensor

Higher quantum efficiency 22% → > 30%

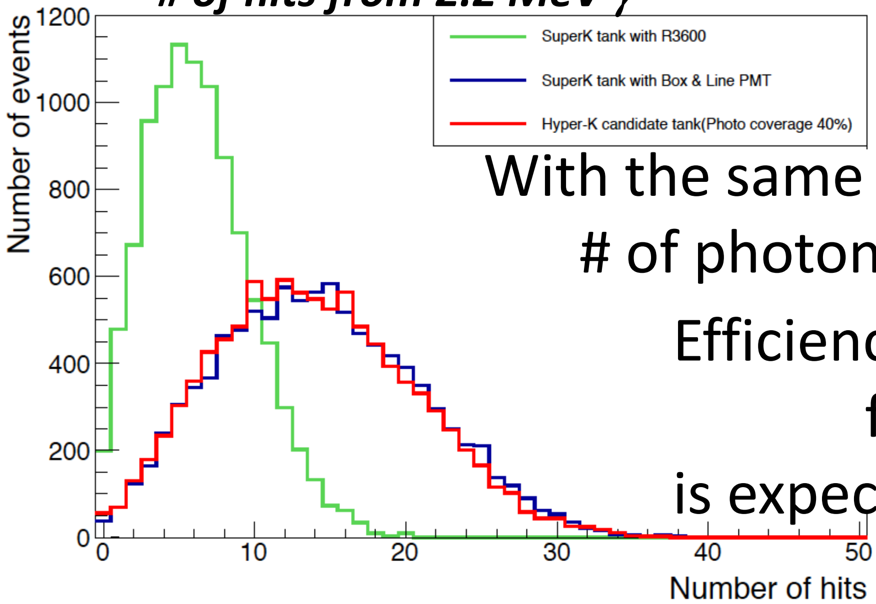
Higher collection efficiency 80% → ~ 90%

Photon detection efficiency

is expected to be improved by **> 50%**

20" Box&line PMT

# of hits from 2.2 MeV γ



With the same photo sensitive coverage,

# of photons expected to be larger.

Efficiency to detect 2.2 MeV γ

from neutron capture

is expected to be improved by ~ 3 times.

Proton decay search @ Hyper-K

$p \rightarrow e^+\pi^0$ # of background is further reduced with `improved' neutron tag efficiency.

$p \rightarrow e^+\pi^0$	$0 < p_{tot} < 100$ MeV/c		$100 < p_{tot} < 250$ MeV/c	
	Signal efficiency	# of background (/Mton·yr)	Signal efficiency	# of background (/Mton·yr)
SK IV	19%	0.2	19%	1.1
Hyper-K	19%	0.06	19%	0.6

$p \rightarrow \bar{\nu} K^+$: Efficiencies are improved owing to higher photon detection efficiency.

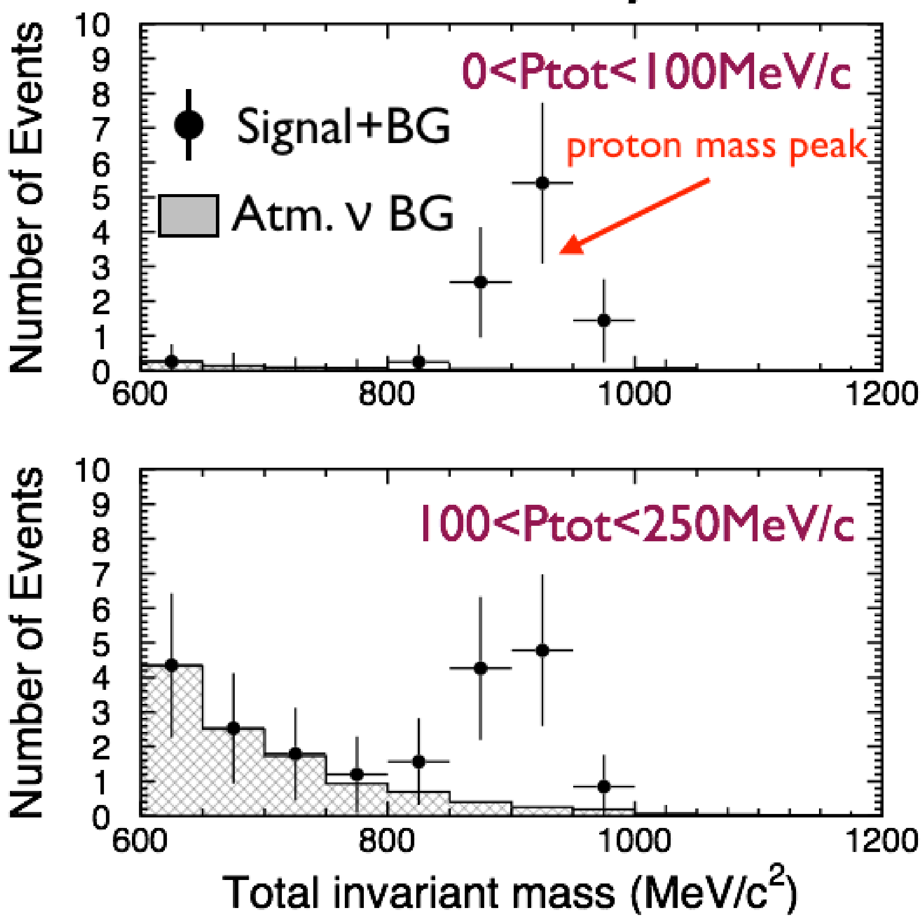
$p \rightarrow \bar{\nu} K^+$	$K^+ \rightarrow \mu^+\nu_\mu$ with prompt γ		$K^+ \rightarrow \pi^+\pi^0$	
	Signal efficiency	# of background (/Mton·yr)	Signal efficiency	# of background (/Mton·yr)
SK IV	8.5%	1.1	9%	0.9
Hyper-K	13%	0.9	11%	0.7

Proton decay search @ Hyper-K

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

For $\tau p/Br = 1.7\times10^{34}$ years

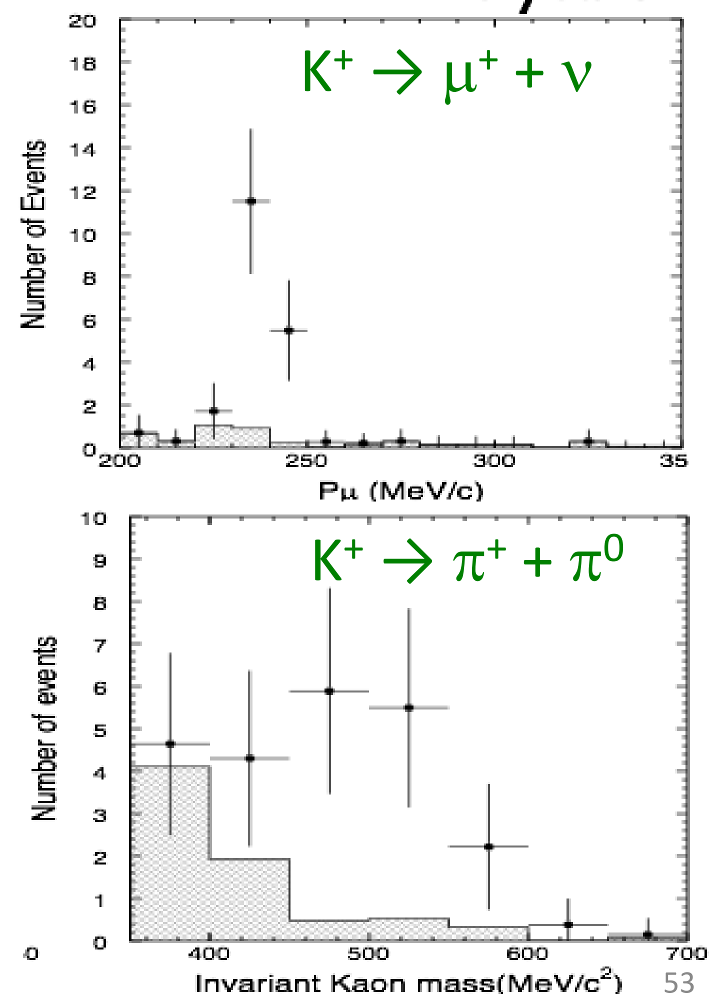
HK 10 years MC



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

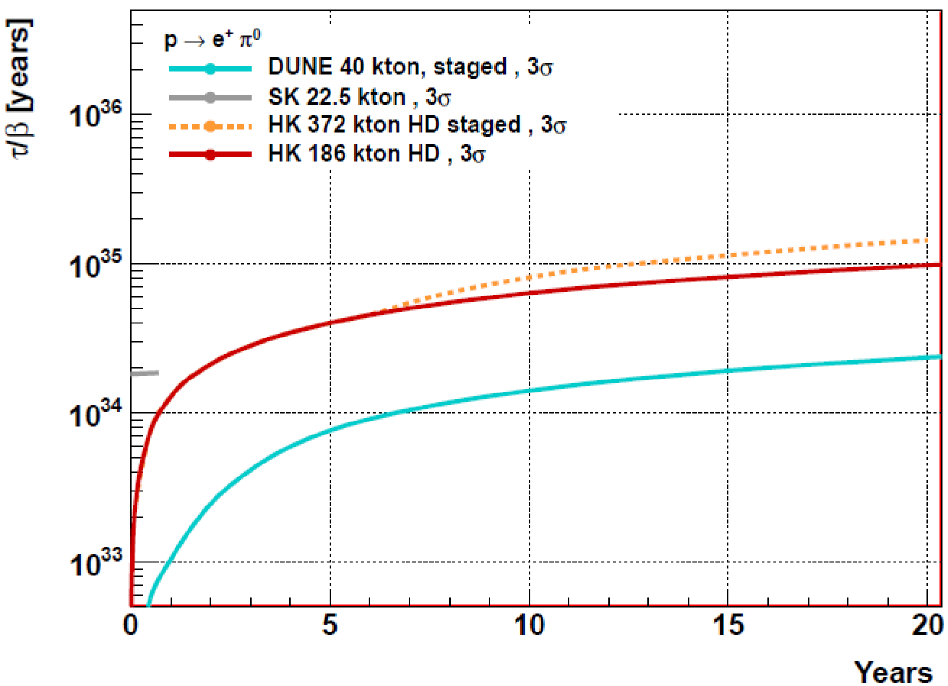
For $\tau p/Br = 6.6\times10^{33}$ years

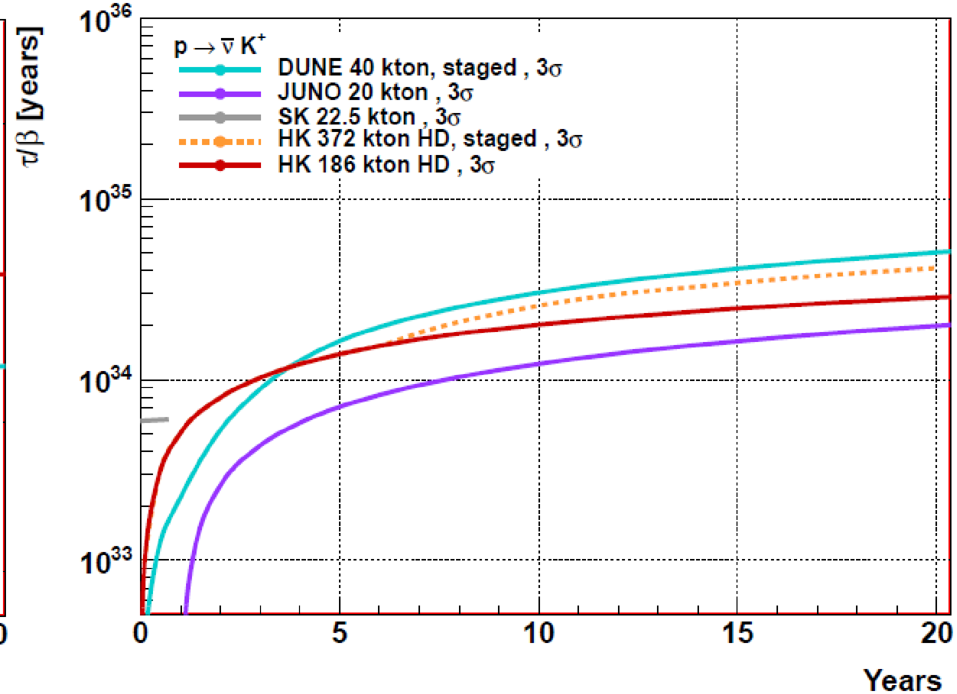
HK 10 years MC



Proton decay search @ Hyper-K

$p \rightarrow e^+\pi^0$ | $p \rightarrow \bar{\nu} K^+$





For $p \rightarrow e^+\pi^0$ 3σ discovery will reach ~ 10^{35} years

Funding outlook in Japan

- For FY 2019, "funding for feasibility study" was approved.

  Past examples include;

  Super-Kamiokande received the "funding for feasibility study" in 1990,
  and the construction budget was approved in 1991.
  Subaru telescope (8m telescope at Hawaii),
  ALMA telescope in Chili (for 2 years), and
  TMT (30 meter telescope in Hawaii).

- Then, **the President of the Univ. of Tokyo**, in recognition of both the project's importance and value both nationally and internationally, **pledged to ensure construction of the Hyper-Kamiokande detector commences as scheduled in April 2020.**

Hyper-K excavation will be started in 2020
and start observation in ~2027.

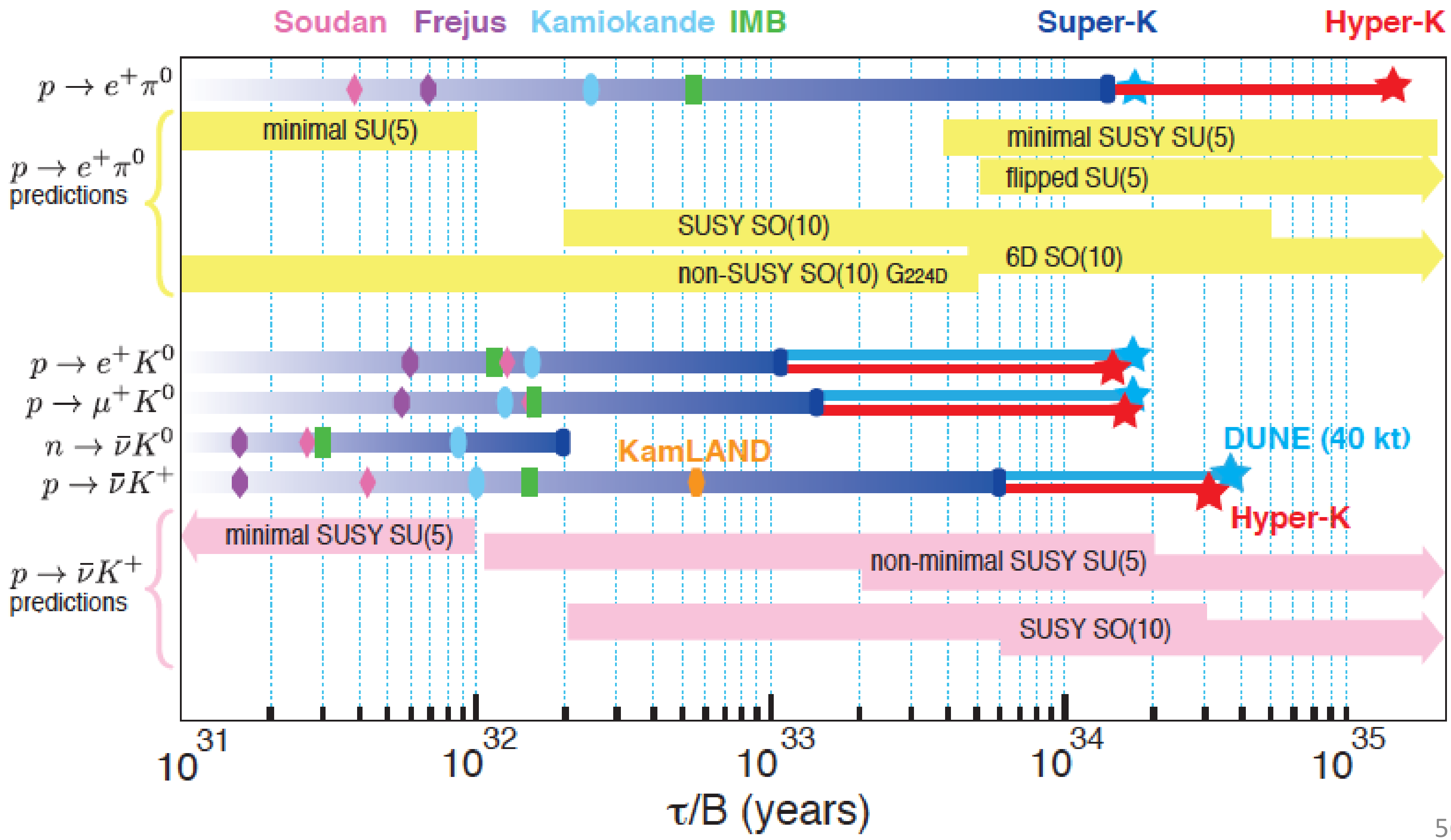
Summary

So far, we have not found no indication of nucleon decay.

Latest lifetime limits from SK

$p \to e^+ \pi^0$ $\tau/B > 1.6 \times 10^{34}$ yr

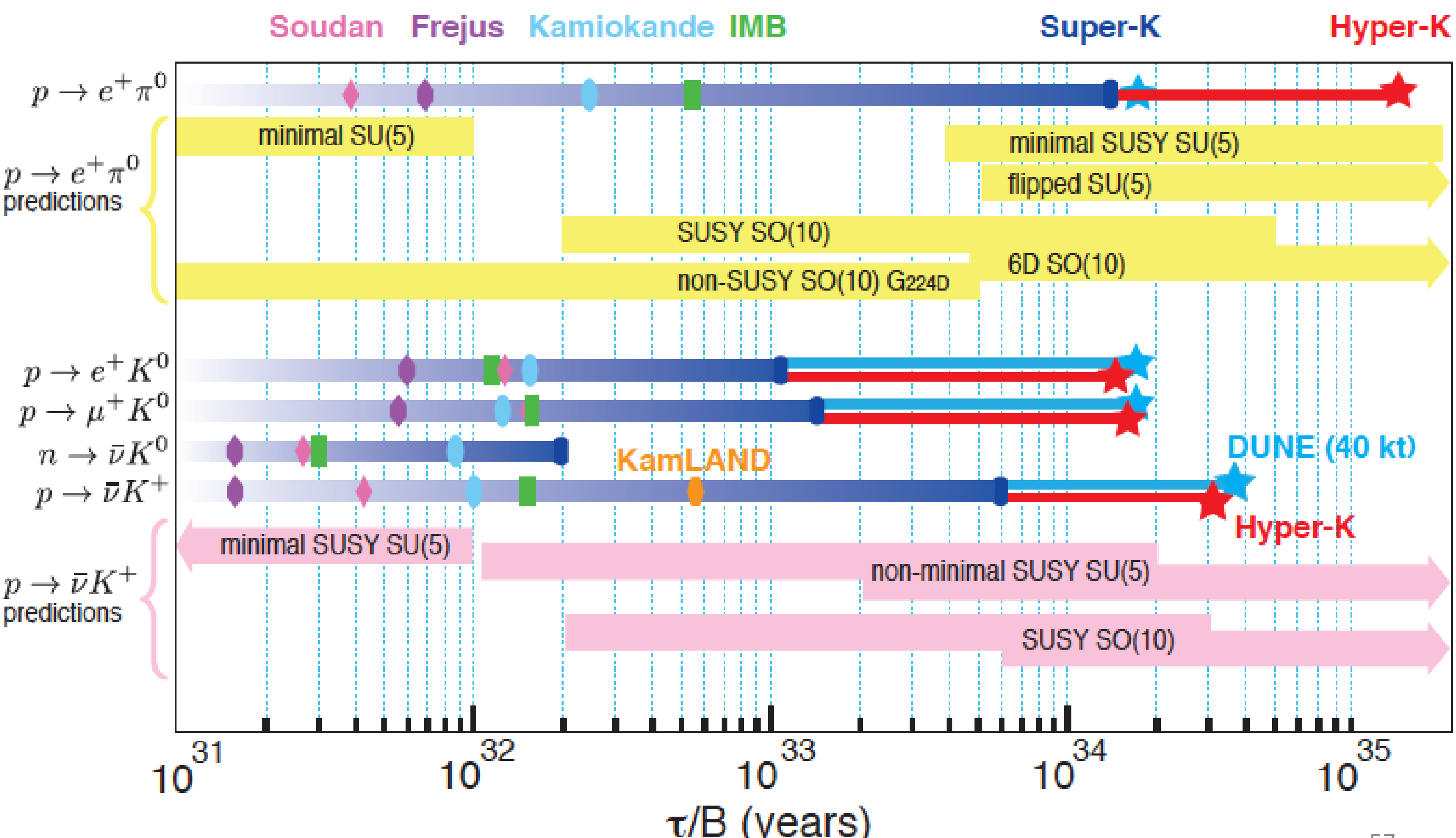
$p \to \bar{\nu} K^+$ $\tau/B > 6.6 \times 10^{33}$ yr



Summary

With Hyper-Kamiokande detector,

$p \to e^+\pi^0$ 3σ discovery will reach ~ 10^{35} years



fin.