Recent results from Super-Kamiokande

~ dinucleon decay and $n - \bar{n}$ oscillation ~

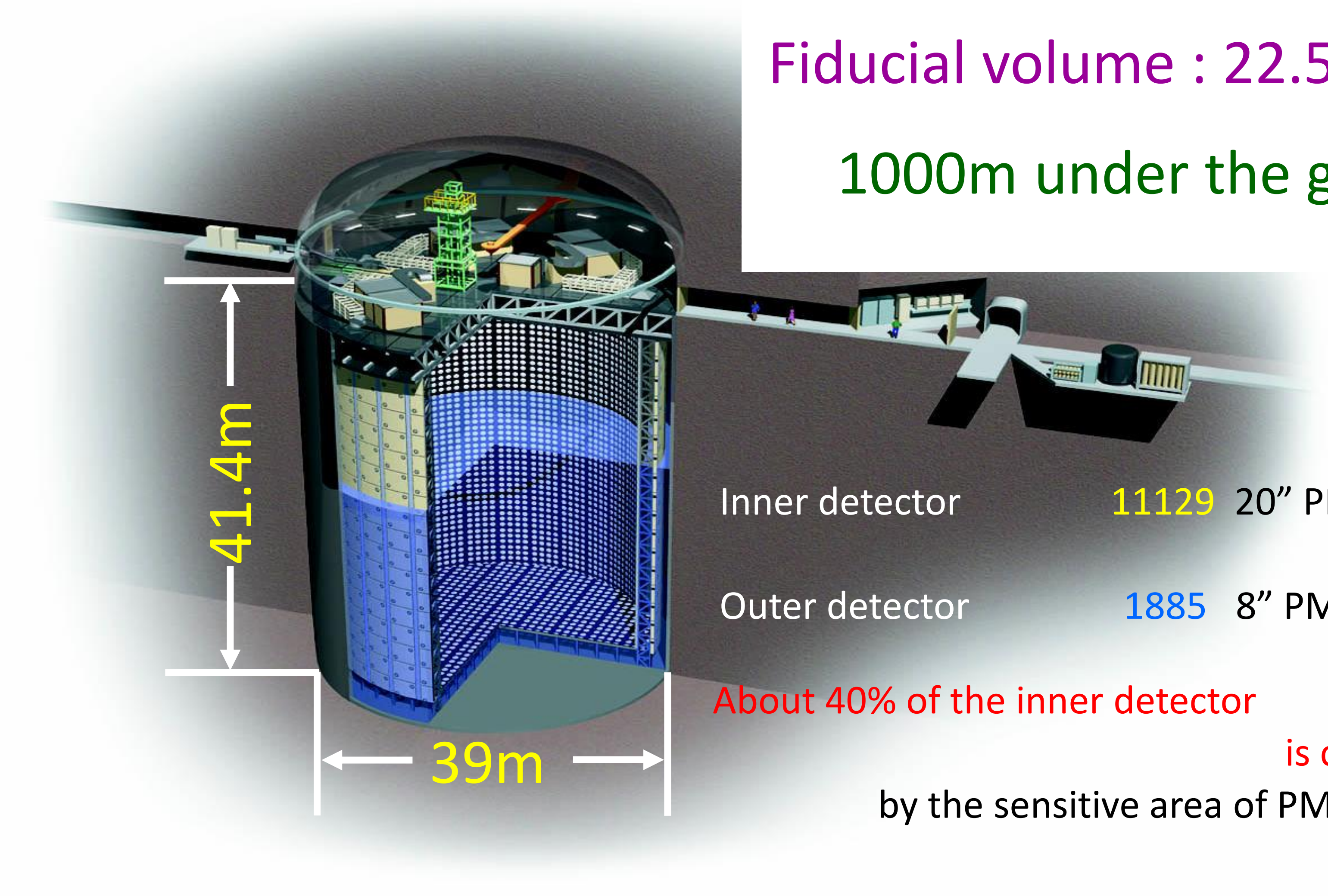
Yoshinari Hayato (Kamioka, ICRR, U-Tokyo)

Super-Kamiokande detector

50000 tons Ring imaging Water Cherenkov detector

Fiducial volume : 22.5 ktons

1000m under the ground



Inner detector 11129 20" PMTs

Outer detector 1885 8" PMTs

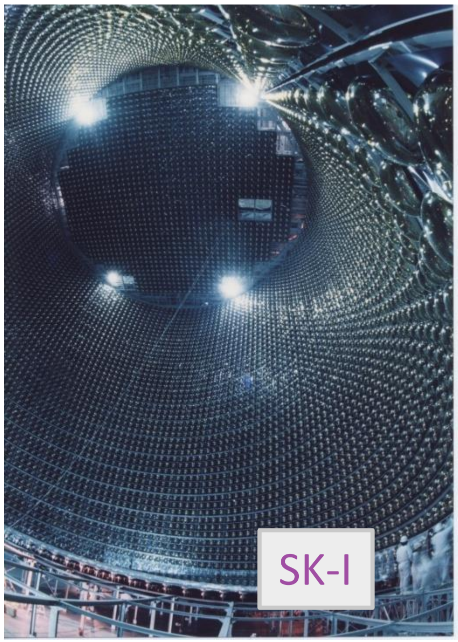
About 40% of the inner detector is covered by the sensitive area of PMT.

Operation started in Apr. 1996.

Super-Kamiokande detector

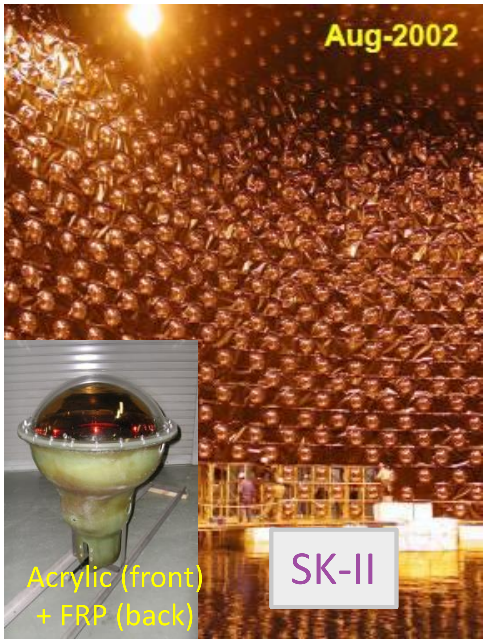
History of the SK detector

SK-I
April 1996
~ June 2001



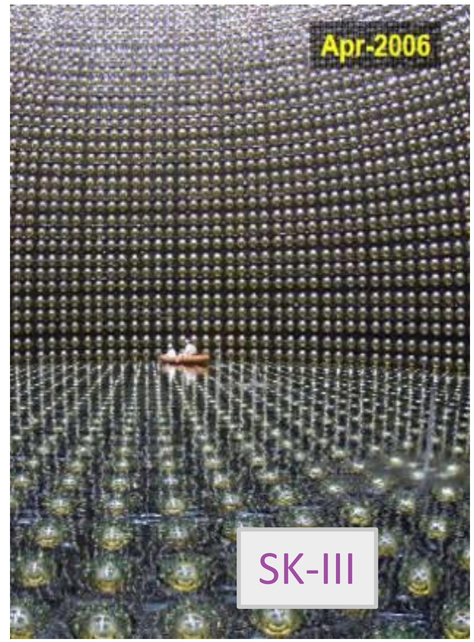
11146 ID PMTs
(40% coverage)

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

Physics in Super-Kamiokande

Neutrino oscillation

- Accelerator neutrinos
- Atmospheric neutrinos
- Solar neutrinos

GUT

Proton decay

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

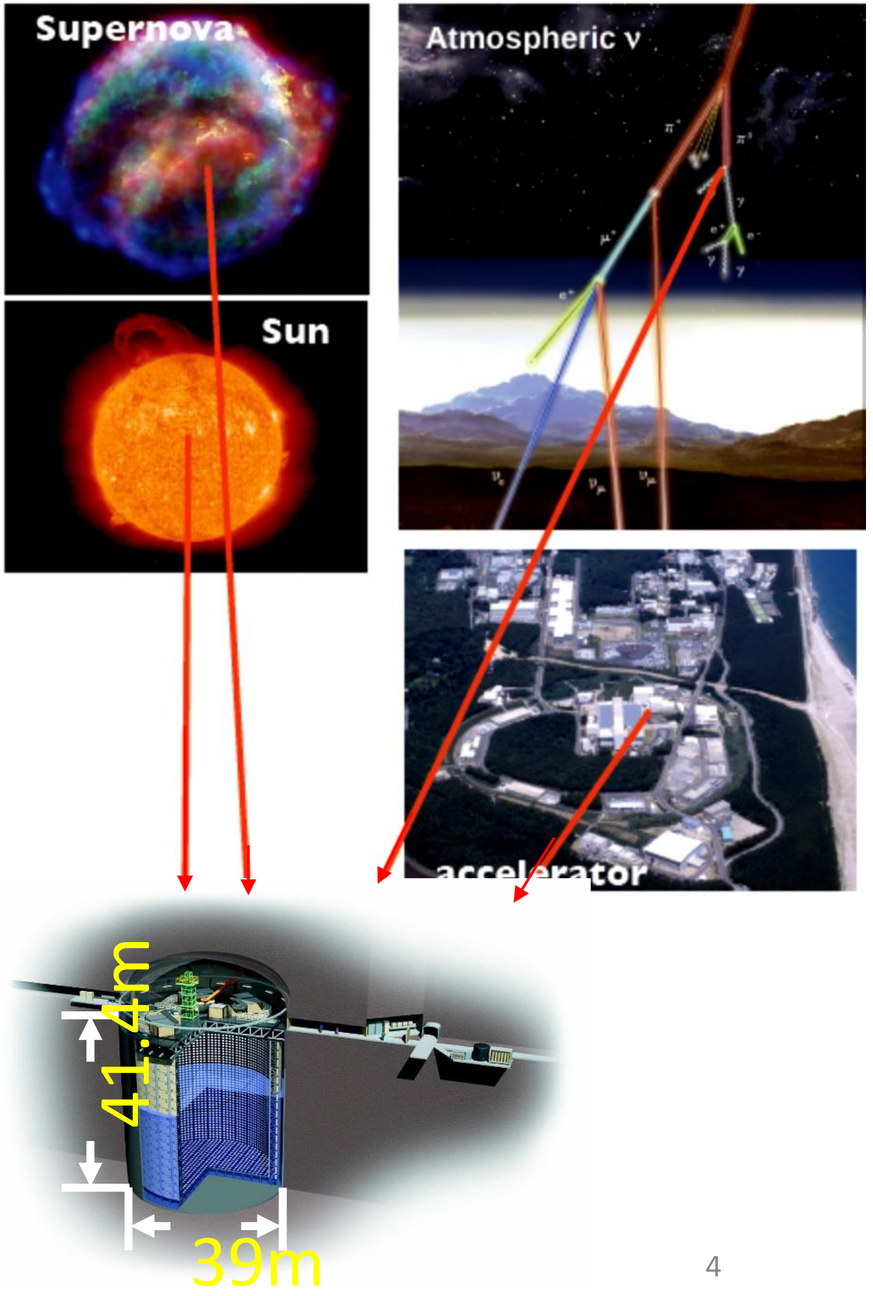
$p \rightarrow K^+ + \overline{\nu}$

New physics

- WIMP search
- n-$\overline{n}$ oscillation
- dinucleon decay etc….

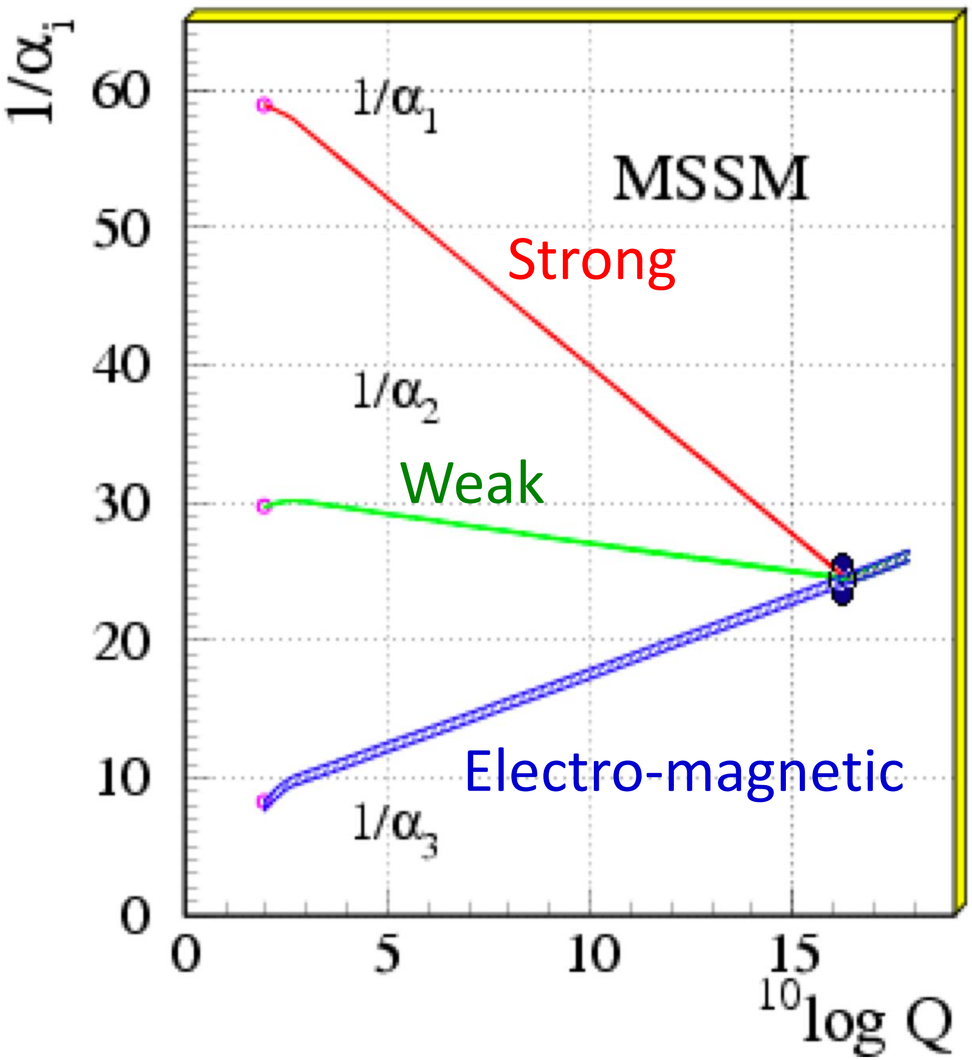
Neutrino astrophysics

- Super nova burst neutrino
- Super nova relic neutrino



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

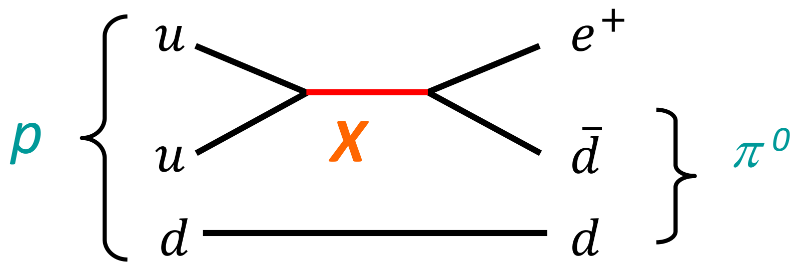
↓

Proton decay

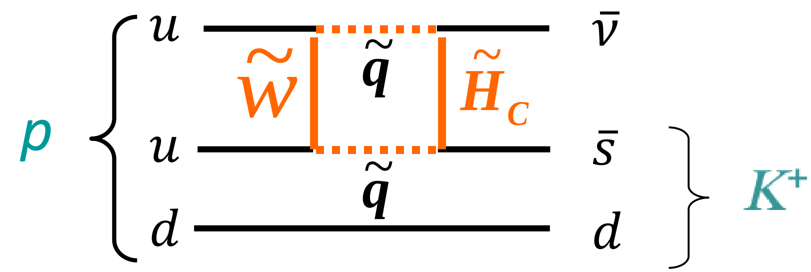
Predicted decay modes of proton

Two major decay modes

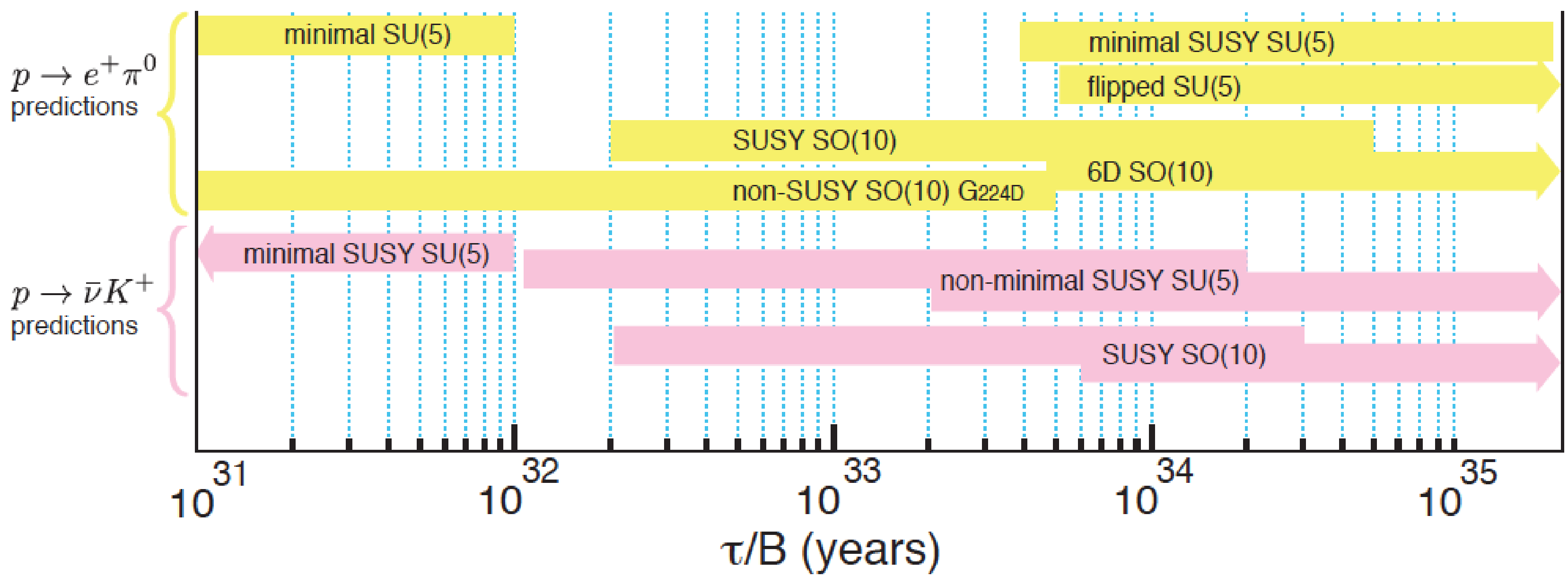
$p \to e^+\pi^0$



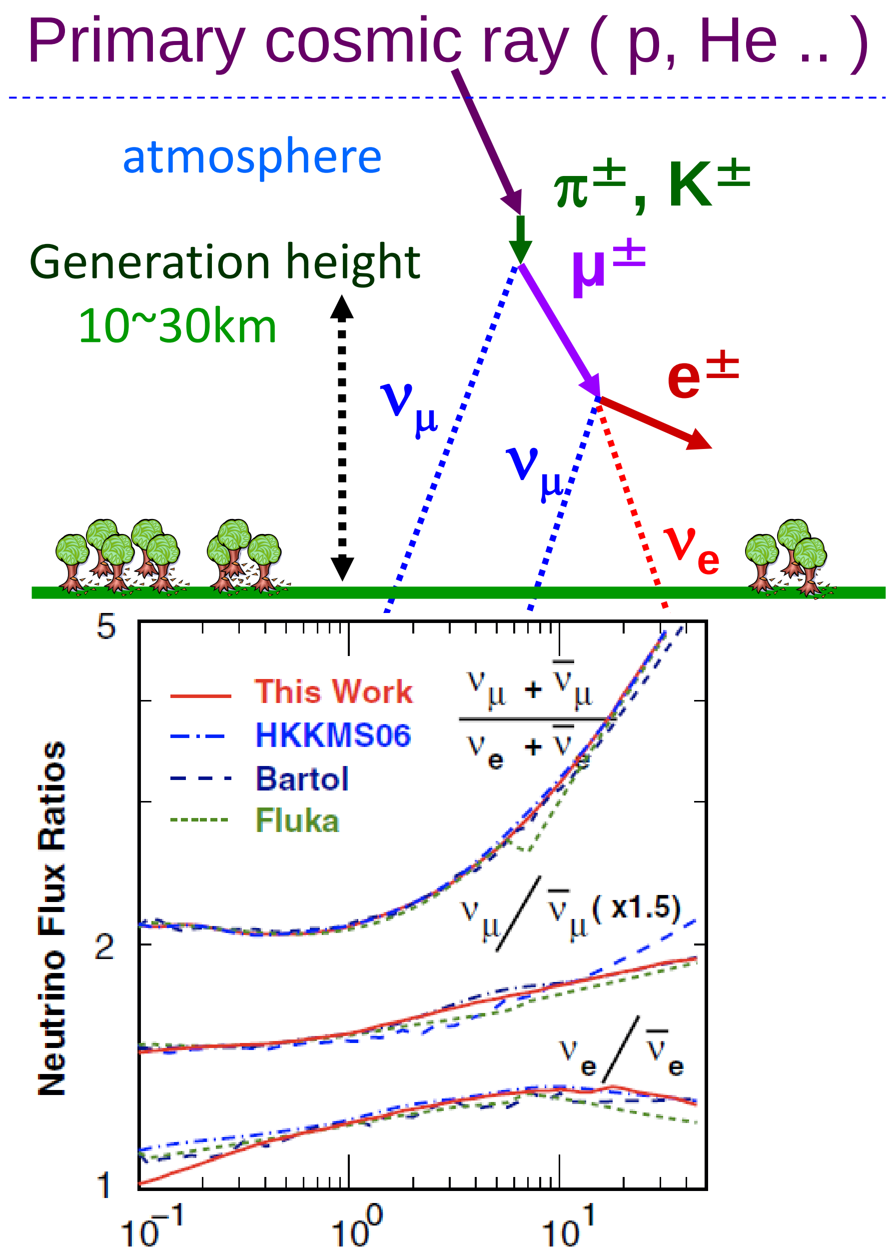
$p \to \bar{\nu} K^+$



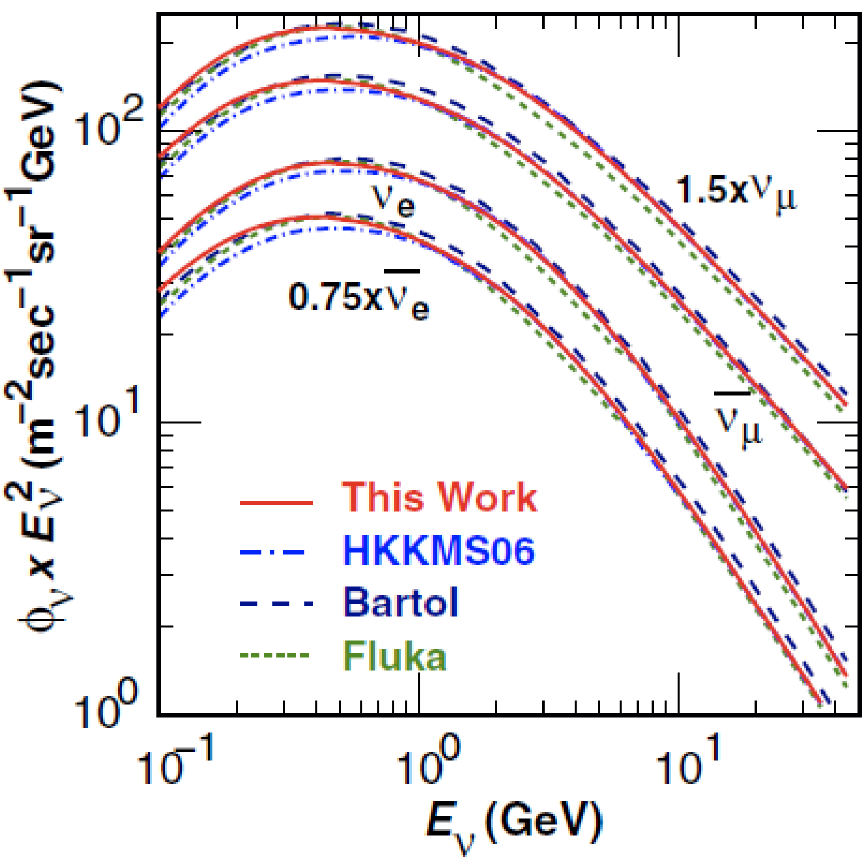
Theoretical predictions



Source of background ~ atmospheric neutrino

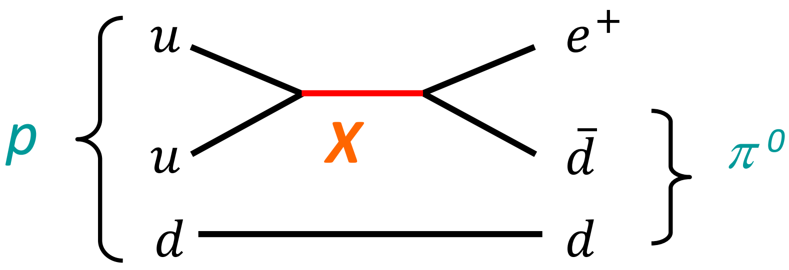


Atmospheric ν energy spectrum

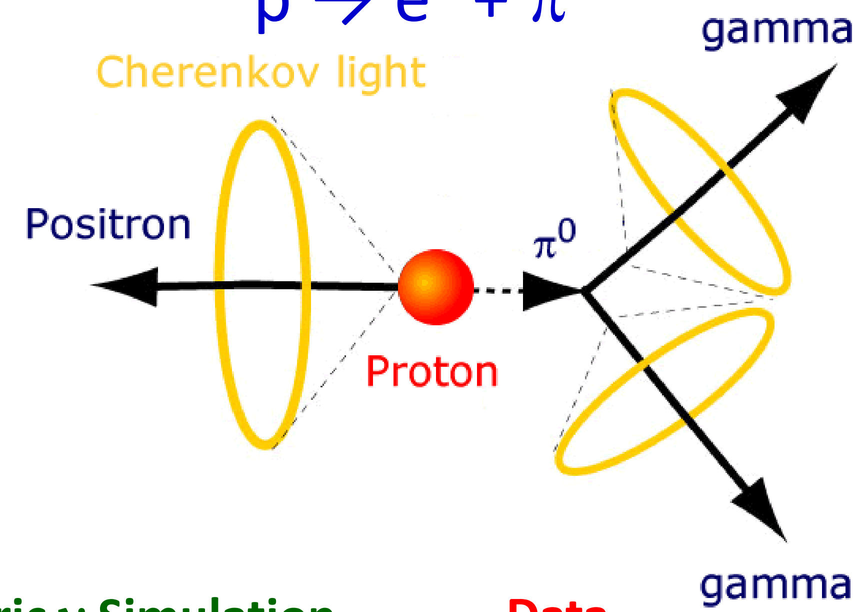


- Broad energy spectrum
- ν_μ/ν_e ~ 2 (< ~1 GeV)
- ν_μ/ν_e > 2 (> ~1 GeV)

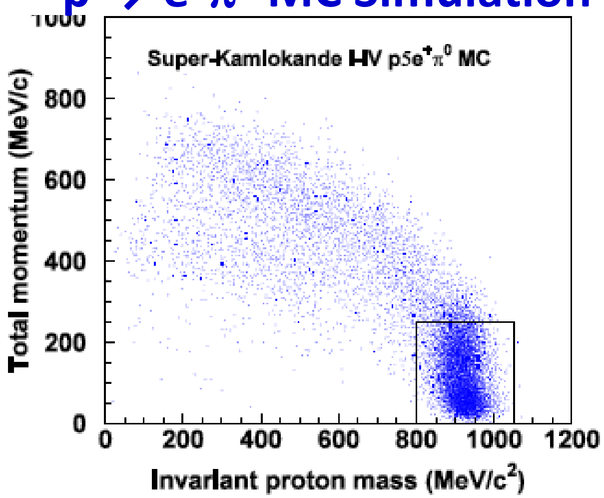
Proton decay search in SK



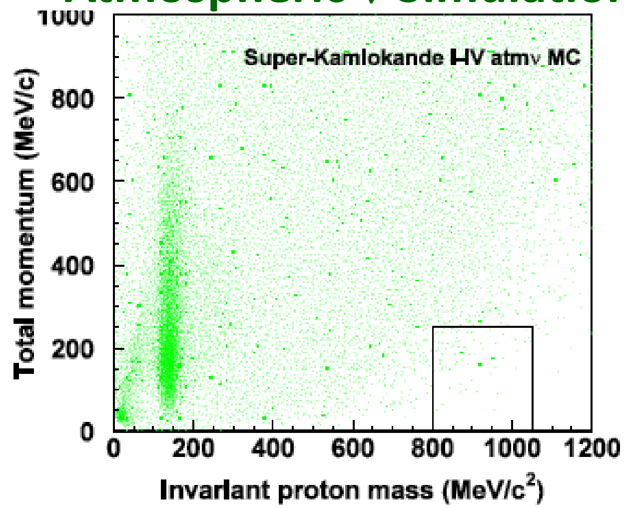
p → $e^+ + \pi^0$



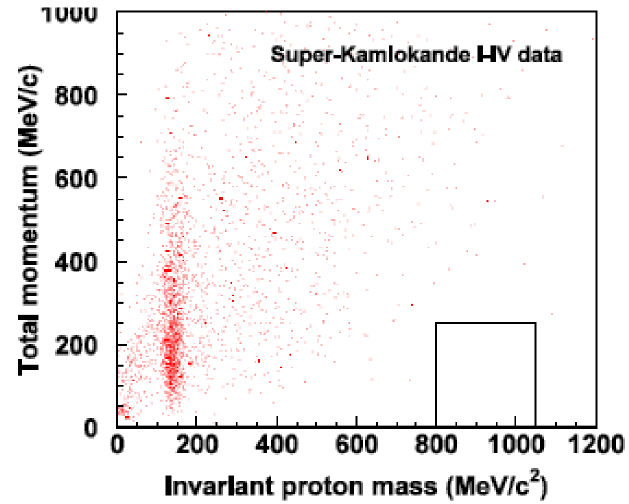
p → $e^+\pi^0$ MC Simulation



Atmospheric ν Simulation



Data



Efficiency ~ 40%, expected Background ~ 0.7 events

No signal candidate : ***$\tau/B > 1.4 \times 10^{34}$ yr***

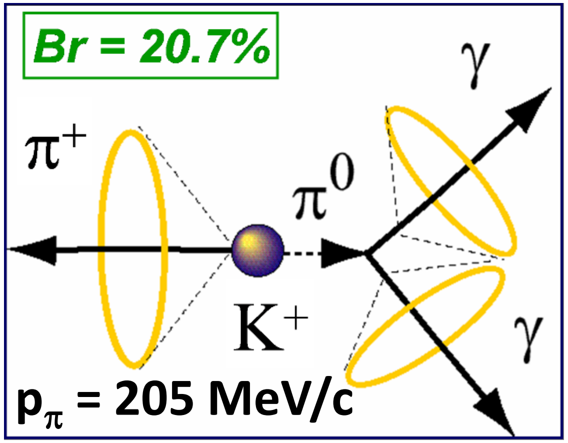
Proton decay search in SK $p \rightarrow \bar{\nu} + K^+$

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

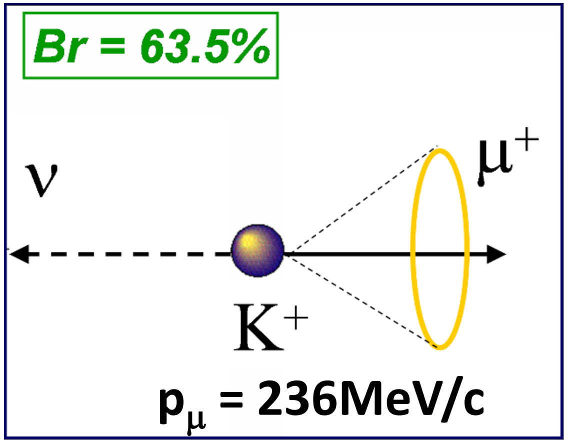
Interaction probability of low momentum K^+ is small
and most of K^+ are expected to decay at rest.

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

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



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

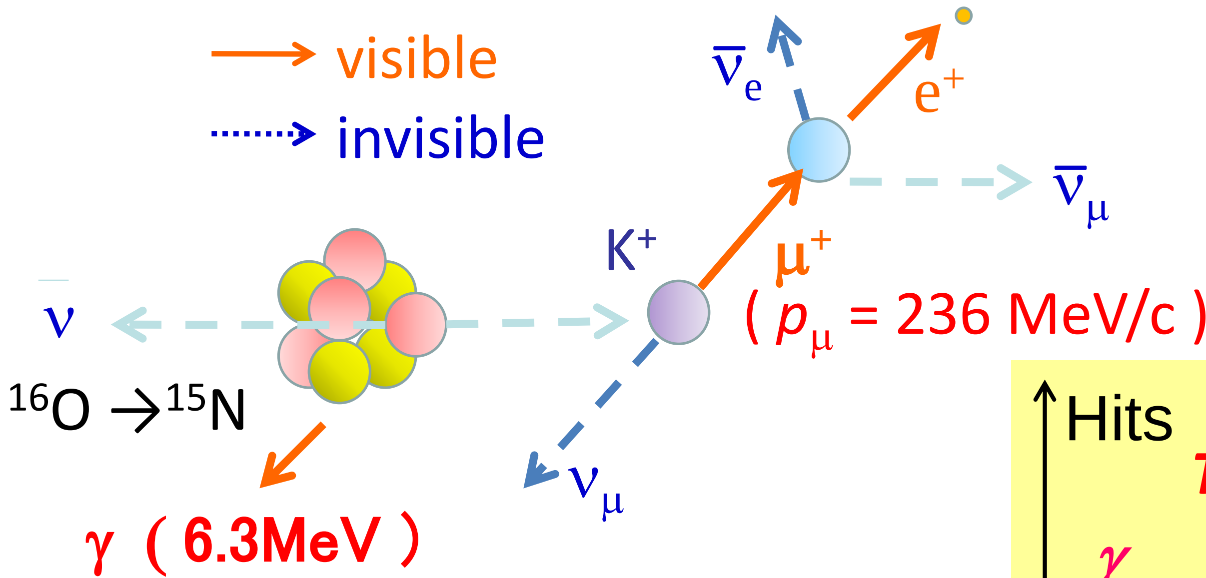


- Two e-like rings with 1 decay-e
- Small activity (from π^+) in the opposite direction of π^0

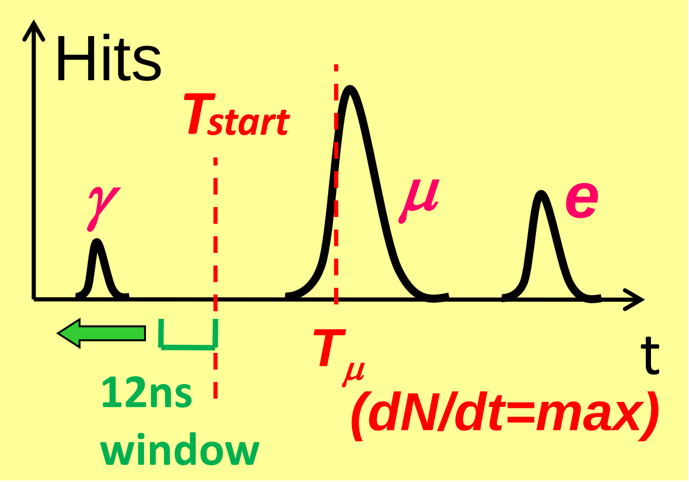
- Single μ-like ring with 1 decay electron

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

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



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



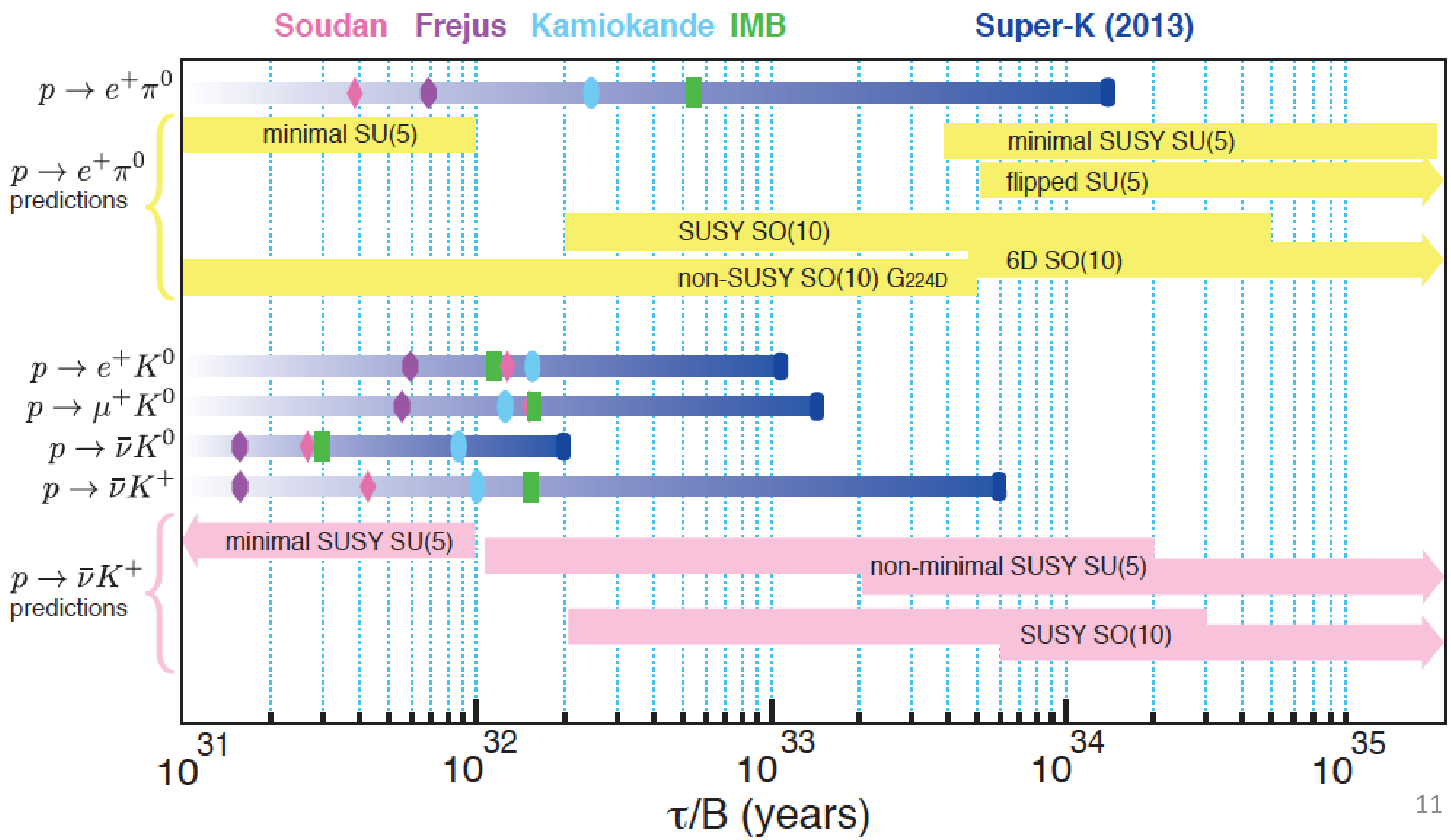
- Search for 1 ring μ-like events with p_μ ~ 236 MeV/c with 1 decay electron
- Additionally, search for the pre-activity from prompt de-excitation 6.3 MeV γ

Proton decay search in SK

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

Latest lifetime limits from SK

$p \to e^+ \pi^0$	$\tau/B > 1.4 \times 10^{34}$ yr
$p \to \bar{\nu} K^+$	$\tau/B > 5.9 \times 10^{33}$ yr



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 and n – π oscillation in Super-Kamiokande

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 – π oscillation etc...

References

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

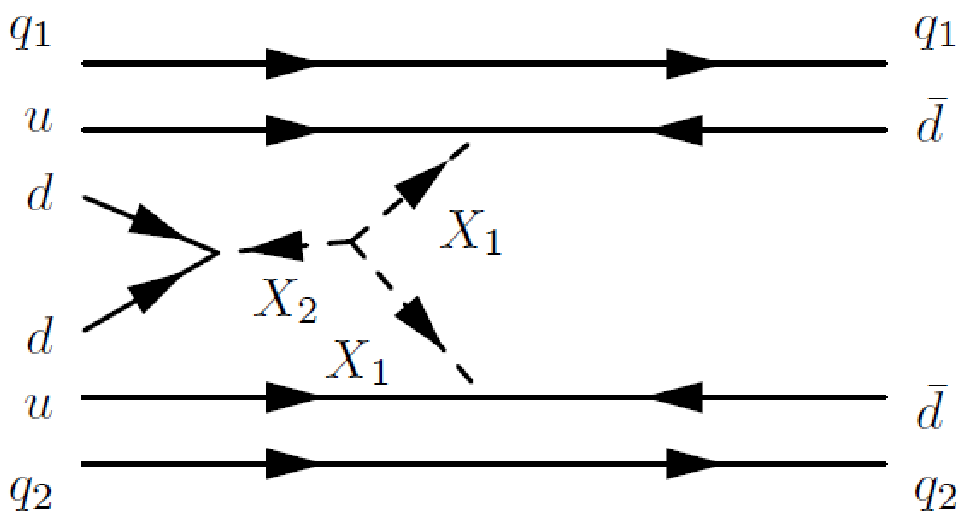
Search for dinucleon decay into pions at Super-Kamiokande J. Gustafson et al, Phys. Rev. D91, 072009 (2015)

Search for dinucleon decay in Super-Kamiokande

Search for NN → ππ 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 in Super-Kamiokande

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 (ν N → ν N' π π 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.

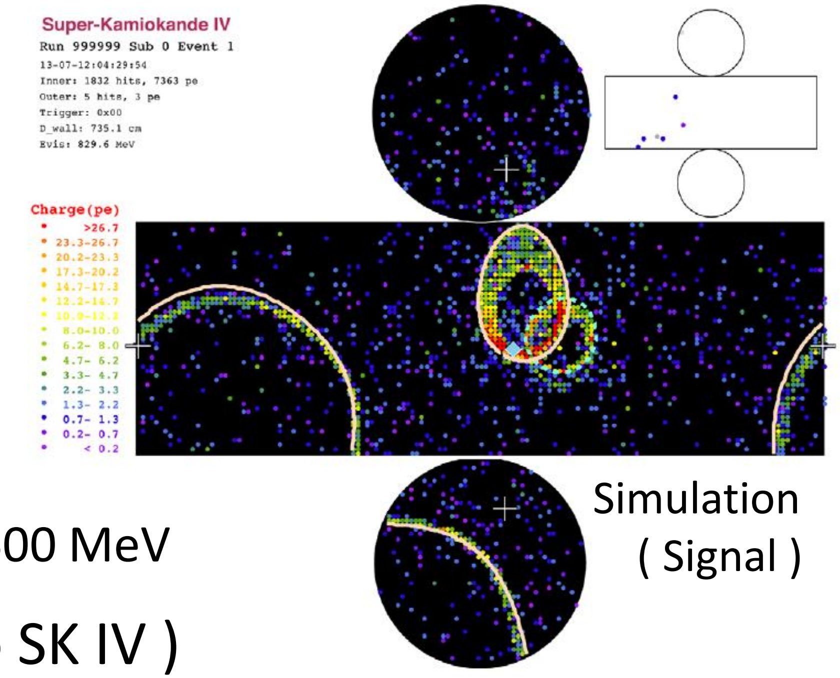
Simple cut-based analysis results in poor efficiency and poor background rejection power.

Search for dinucleon decay in Super-Kamiokande (I)

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

Pre-selection (to reduce large background of atmospheric ν)

A0) Fully contained in fiducial events
A1) More than 1 Cherenkov ring
A2) Two most energetic rings are non-showering (μ-like)
A3) Opening angle of the two most energetic rings > 120 deg.
A4) Total visible energy (electron equiv. energy) < 1600 MeV



Simulation (Signal)

Total exposure : 282.1 kt·yr (SK I to SK IV)

	SK-I	SK-II	SK-III	SK-IV
Eff. (%)	11.2 ± 0.2	10.5 ± 0.2	12.0 ± 0.2	12.1 ± 0.2
Bkg.	33 ± 0.9	17 ± 0.5	13 ± 0.4	45 ± 1.2
data	27	14	8	43

(Total number of FC atmospheric ν ~ 37700 & 70 % are 1 ring events.)

Search for dinucleon decay in Super-Kamiokande (I)

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

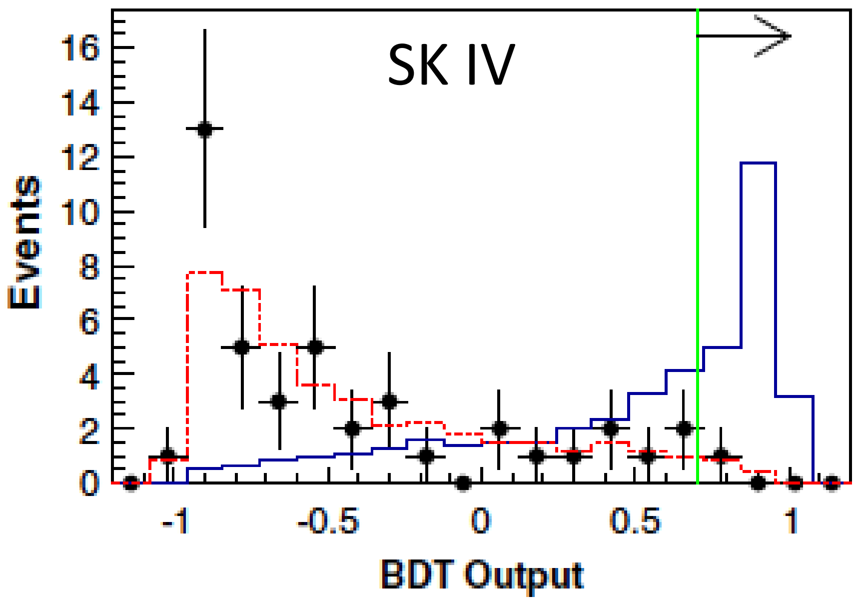
Use Boosted Decision Trees (BDT) to improve analysis

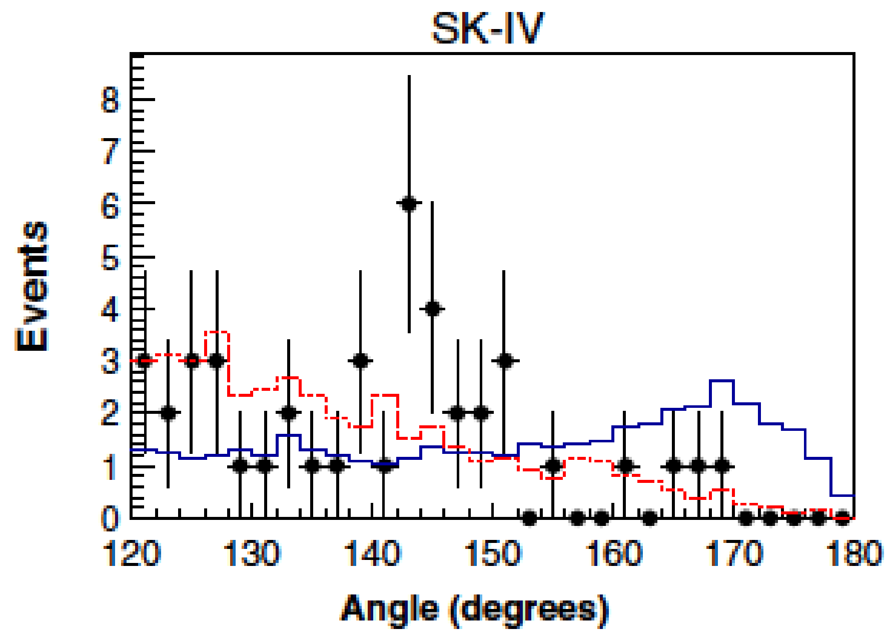
Use 9 parameters to enhance the signal selection efficiency and background rejection power.

a1) Angle between two most energetic rings
a2) Ratio of charge carried by most energetic ring
a3) Total visible energy (electron equiv. energy)
a4) Maximum distance to the decay electron
a5) Maximum angle between μ-like ring and decay electron vertex
a6) Magnitude of vector sum of corrected charge (~ total momentum)
a7) Number of rings
a8) Number of decay electrons
a9) Number of non-showering rings

Search for dinucleon decay in Super-Kamiokande (I)

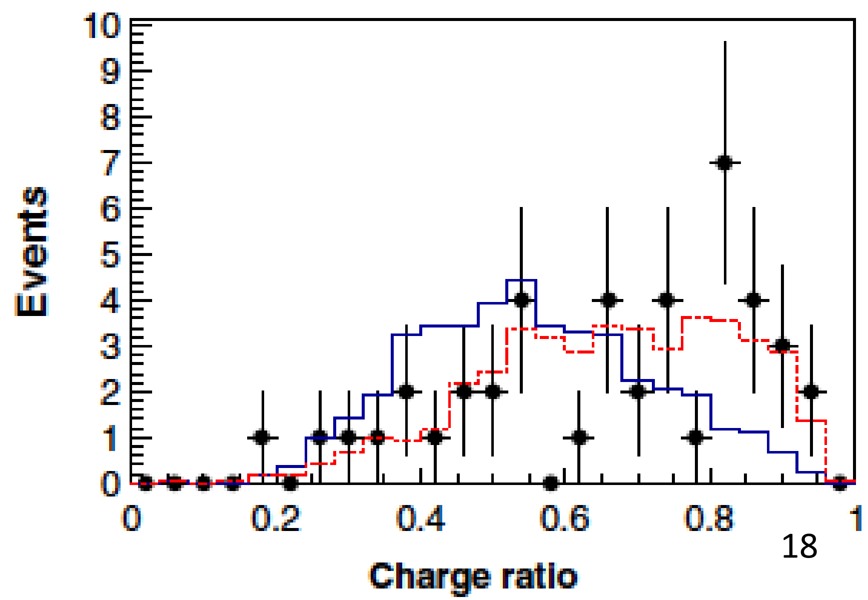
$pp \rightarrow \pi^+\pi^+$





Importance of each input

Variable	Importance
Angle between μ-like rings	0.16
Ratio of charge carried by most energetic ring	0.15
Visible energy	0.15
Max. distance to Michel vertex	0.13
Max. angle between μ-like ring and Michel vertex	0.13
Magnitude of vector sum of corrected charge	0.12
Number of rings	0.071
Number of Michel electrons	0.055
Number of μ-like rings	0.045



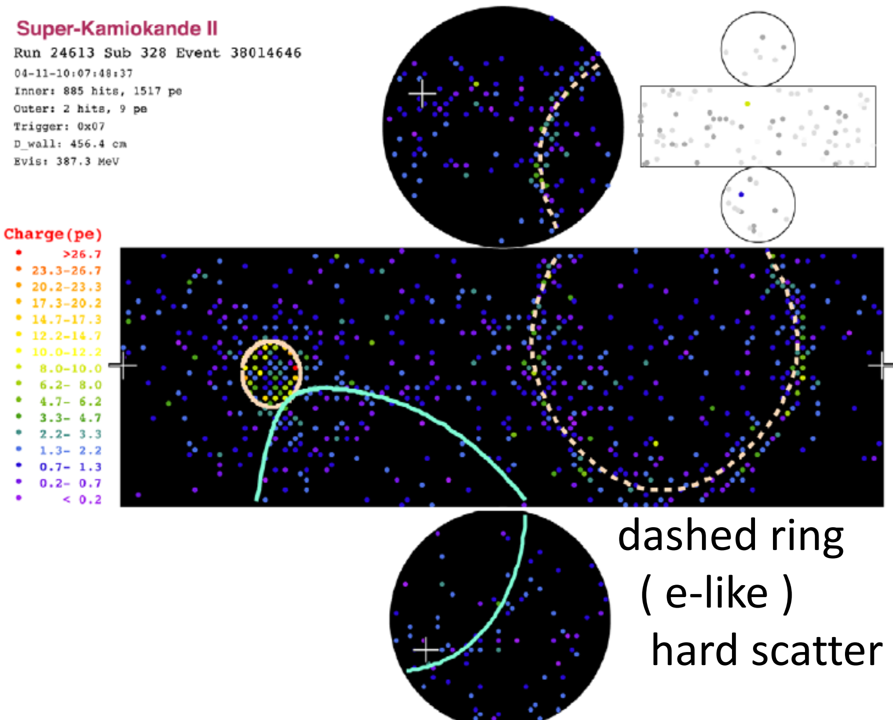
Search for dinucleon decay in Super-Kamiokande (I)

$pp \to \pi^+\pi^+$

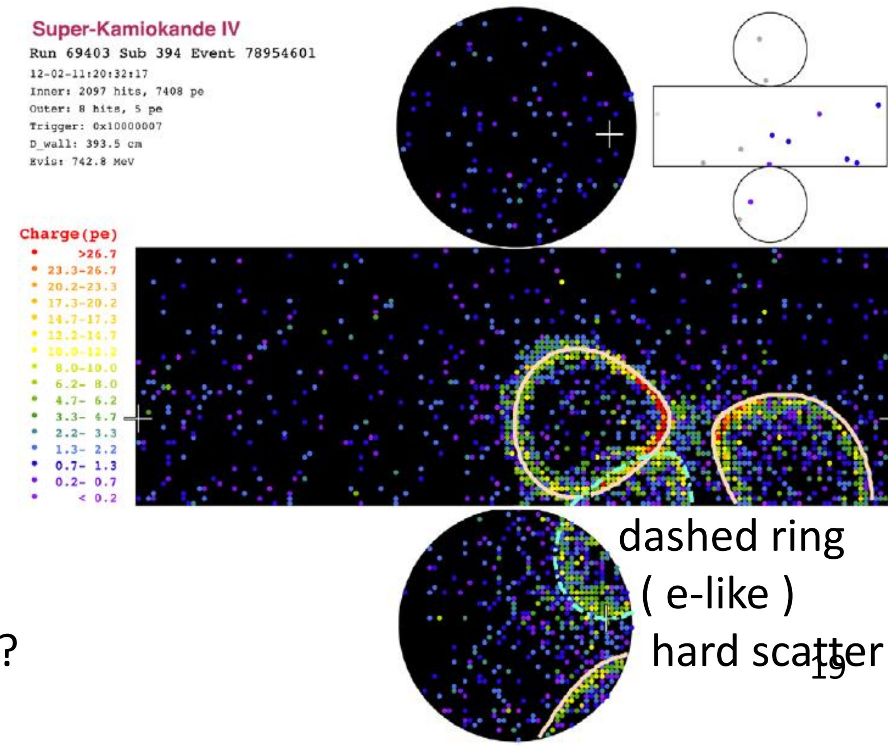
	SK-I	SK-II	SK-III	SK-IV
Eff. (%)	6.1 ± 0.2	5.3 ± 0.2	6.4 ± 0.2	5.8 ± 0.2
Bkg. (MT-yr)	17.8 ± 1.8	14.3 ± 1.6	17.4 ± 1.7	14.2 ± 1.6
Bkg. (SK live.)	1.6	0.70	0.56	1.6
Candidates	0	1	0	1

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' π^+ π^+ 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

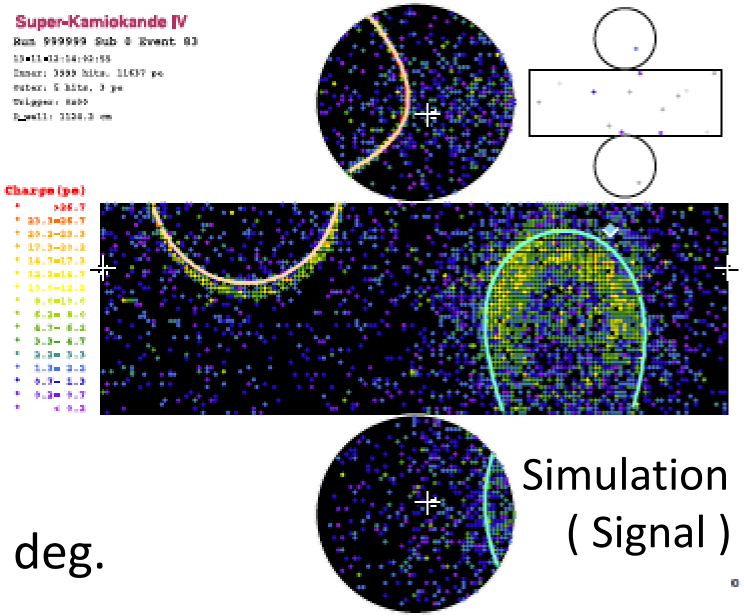
Obtained lifetime limit : $\tau_{pp \rightarrow \pi+\pi+}$ > 7.22 x 10^{31} yrs

Search for dinucleon decay in Super-Kamiokande (II)

$pn \to \pi^+\pi^0$

Pre-selection (to reduce large background of atmospheric ν)

B0) Fully contained in fiducial events
B1) More than 1 Cherenkov ring
B2) At least 1 non-showering (μ-like) and 1 showering (e-like) rings.
B3) # of decay electron is no more than 1.
B4) Total visible energy – reconstructed enegy of π^0 < 800 MeV
B5) Opening angle between π^+ and π^0 > 120 deg.



Simulation (Signal)

Total exposure : 282.1 kt·yr (SK I to SK IV)

	SK-I	SK-II	SK-III	SK-IV
Eff. (%)	21.0 ± 0.3	21.9 ± 0.3	21.6 ± 0.3	21.1 ± 0.3
Bkg.	132 ± 1.8	69 ± 1.0	48 ± 0.6	147 ± 2.0
data	136	66	45	171

(Total number of FC atmospheric ν ~ 37700 & 70 % are 1 ring events.)

Search for dinucleon decay in Super-Kamiokande (II)

pn → $\pi^+\pi^0$

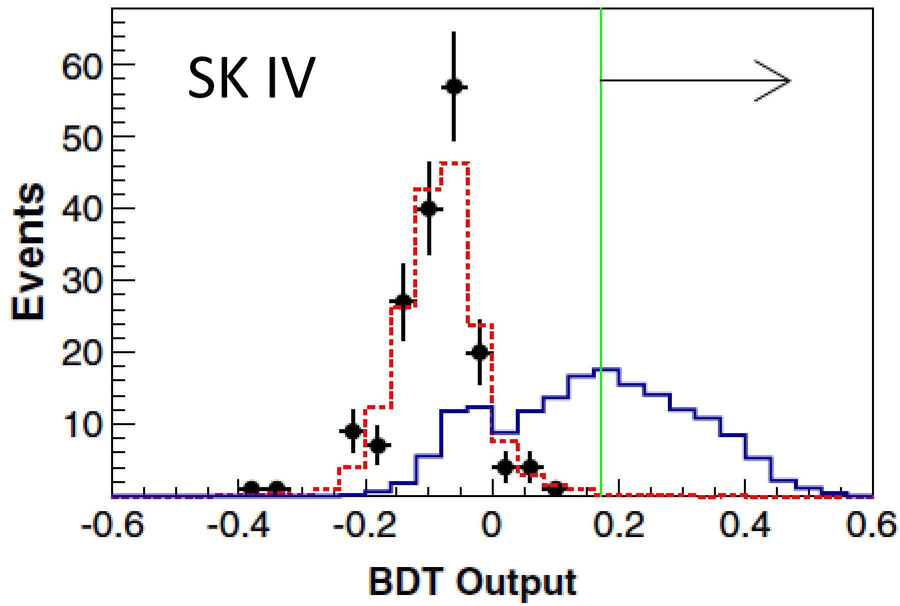
Use Boosted Decision Trees (BDT) to improve analysis

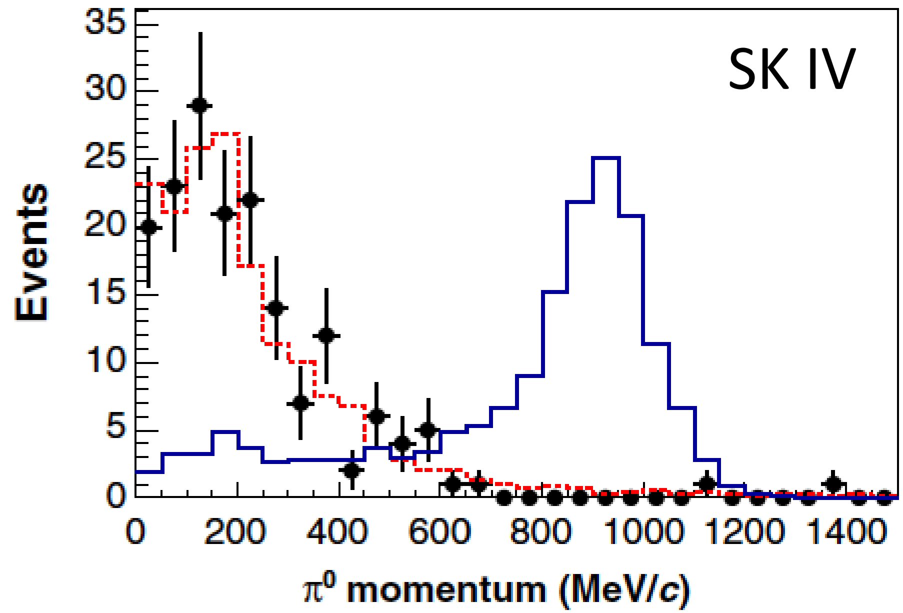
Use 9 parameters to enhance the signal selection efficiency and background rejection power.

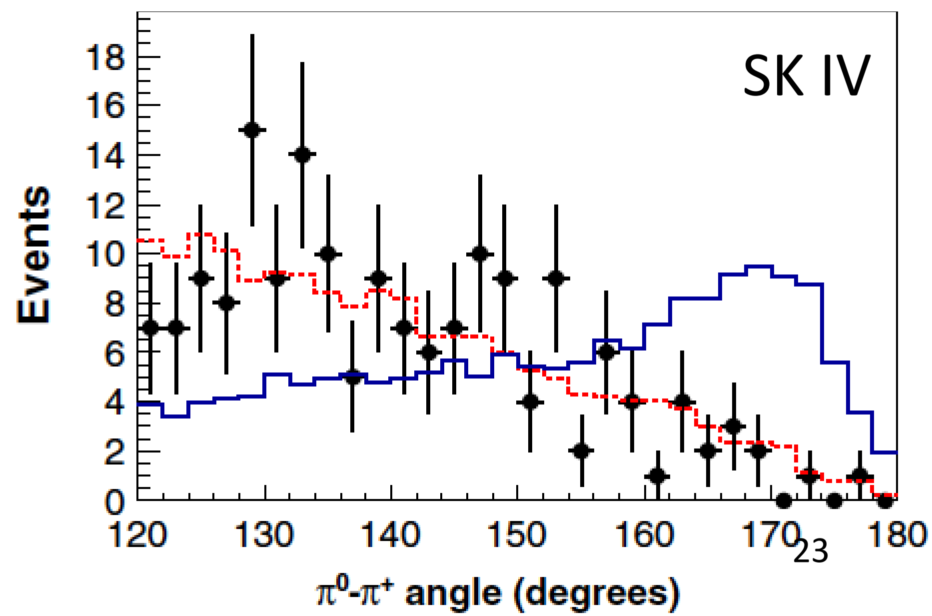
b1) Reconstructed momentum of π^0
b2) Angle between π^+ and π^0
b3) Reconstructed momentum of π^+
b4) Invariant mass of π^0
(For this, we use special π^0 reconstruction tool)
b5) Ratio of charge carried by most energetic ring
b6) Total visible energy (electron equiv. energy)
b7) Number of decay electrons

Search for dinucleon decay in Super-Kamiokande (II)

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







Importance of each input

Variable	Importance
π^0 candidate momentum	0.19
Angle between π^0 and π^+ candidates	0.17
π^+ candidate momentum	0.16
π^0 candidate invariant mass	0.15
Ratio of charge carried by most energetic ring	0.14
Visible energy	0.14
Number of Michel electrons	0.058

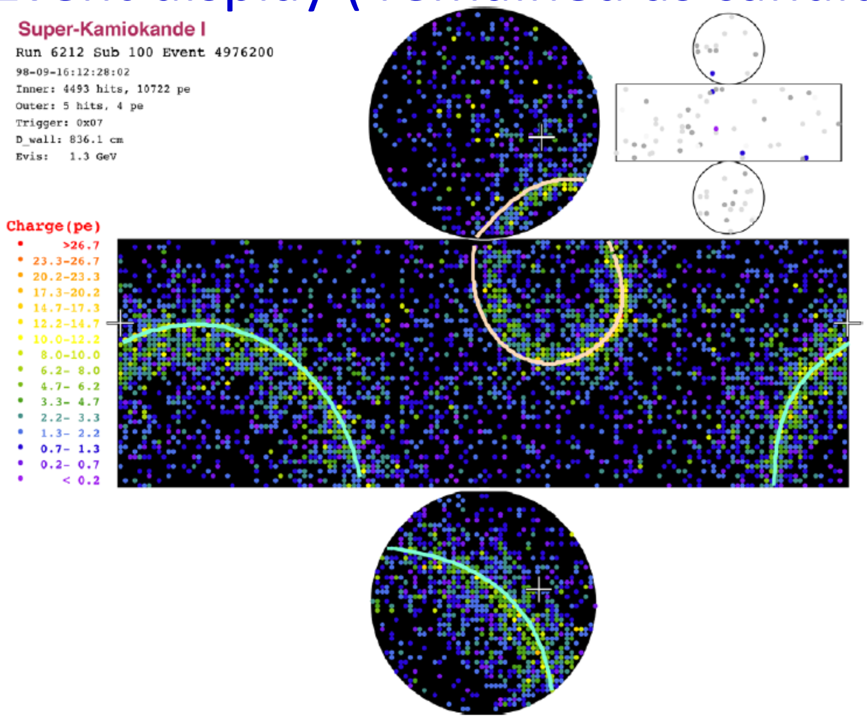
Search for dinucleon decay in Super-Kamiokande (II)

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

	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

(ν N → *l*- N' π^+ etc.)

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

(ν N → *l*- N' π^+ π^+ 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 : $\tau_{pn \rightarrow \pi^+\pi^0} > 1.70 \times 10^{32}$ yrs

Search for dinucleon decay in Super-Kamiokande (III)

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

C0) Fully contained in fiducial events

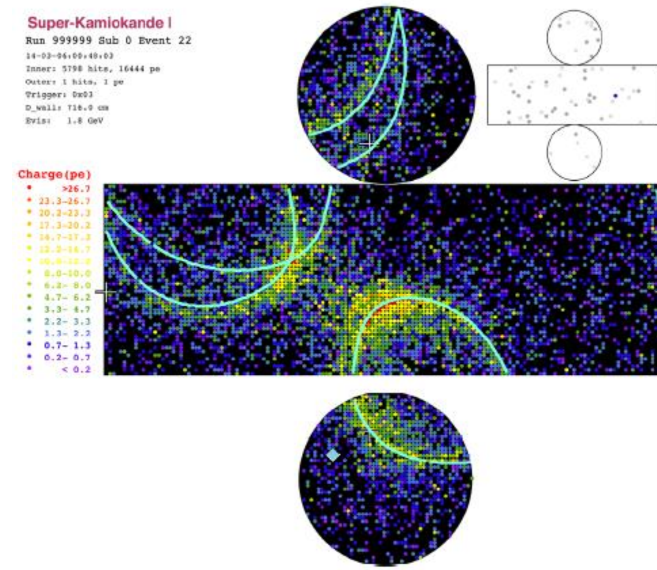
C1) Number of Cherenkov rings = 2, 3 or 4

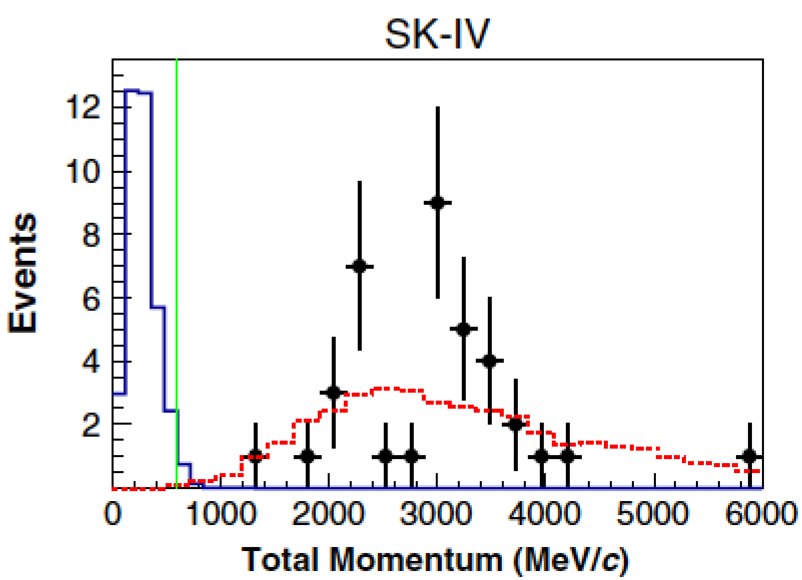
C2) All rings are identified as showering (e-like).

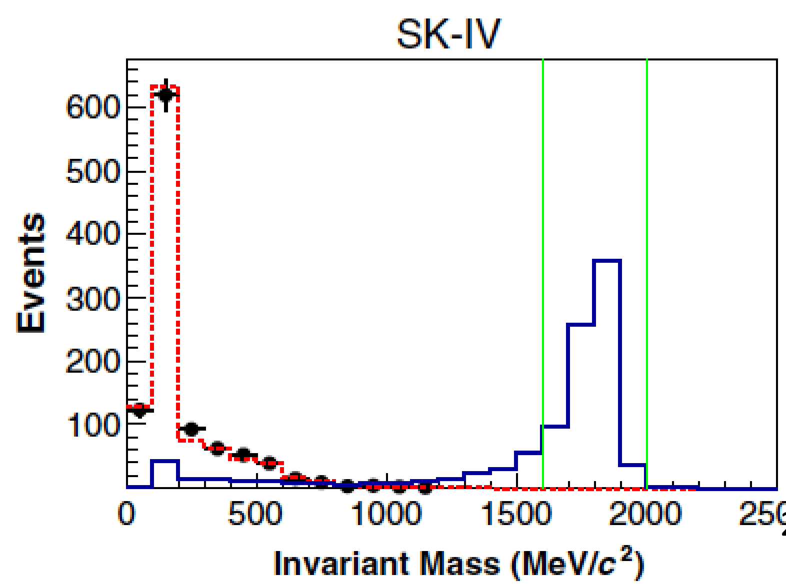
C3) No decay electrons

C4) Total momentum ≤ 600 MeV/c

C5) Reconstructed Invariant mass from 1600 MeV/c^2 to 2000 MeV/c^2



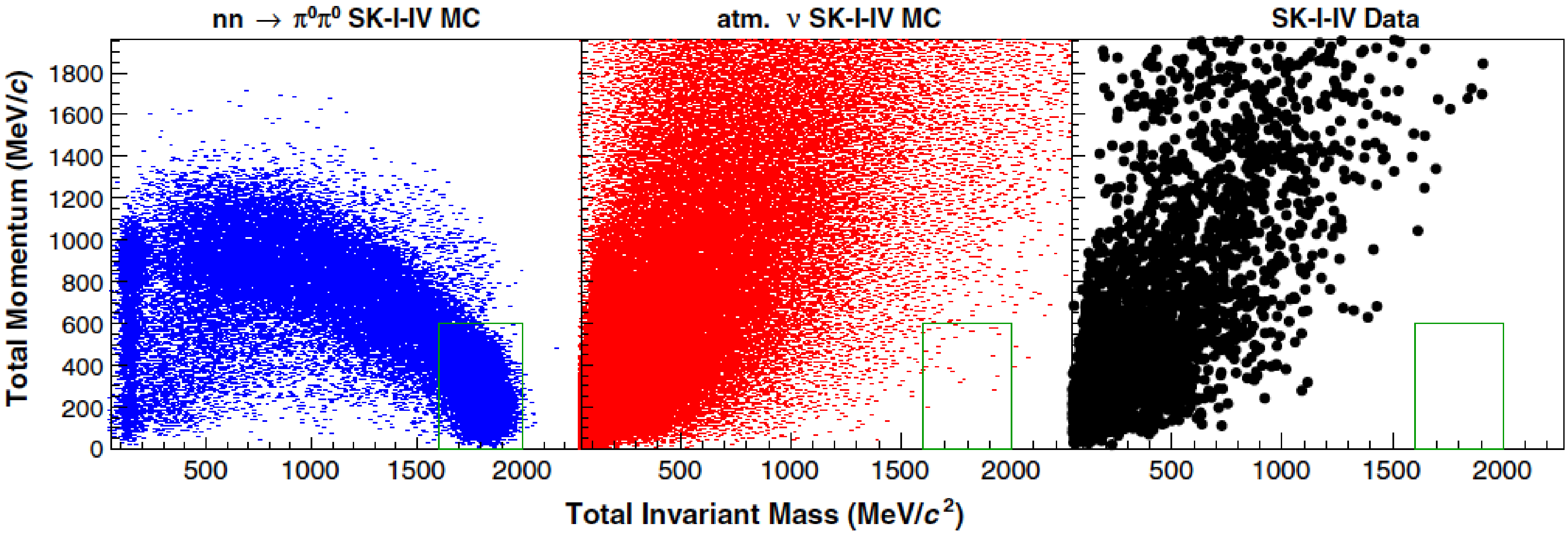




Search for dinucleon decay in Super-Kamiokande (III)

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

	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 (III)

nn → $\pi^0\pi^0$

Remaining background events

mode	SK-I	SK-II	SK-III	SK-IV
NCDIS	63±32%	30±18%	67±25%	50±50%
CCDIS	15±16%	50±22%	24±14%	0+50%
CC1π	21±15%	20±14%	9±9%	51±51%

CC 1π : Charged current single π production (ν N → *l*- N' π^+ etc.)

CC/NC DIS : Charged/Neutral current deep inelastic scattering (ν N → *l* N' π^+ π^+ etc.)

Systematic uncertainties

	$nn \to \pi^0\pi^0$			
Signal (%)	SK-I	SK-II	SK-III	SK-IV
Simulation	31.1	34.4	37.3	33.1
Reconstruction	1.5	1.7	4.0	3.6
Total	31.2	34.4	37.6	33.3
Background (%)	SK-I	SK-II	SK-III	SK-IV
Simulation	13.6	15.5	14.5	13.9
Reconstruction	10.9	18.1	28.9	24.3
Total	17.5	24.0	32.3	28.0

Search for dinucleon decay in Super-Kamiokande

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

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

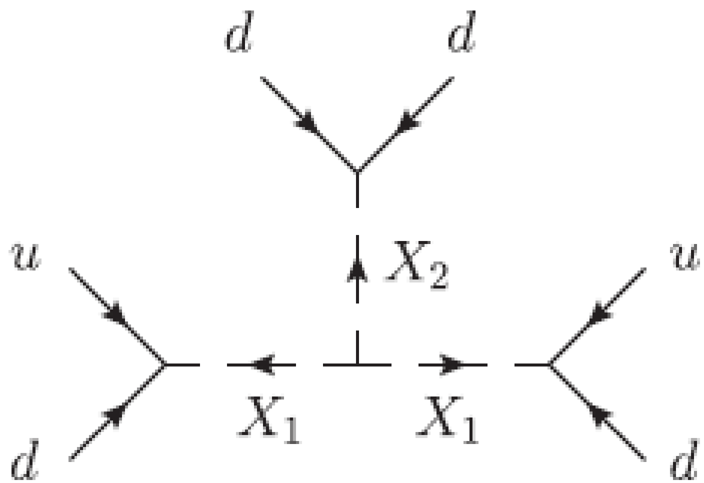
All modes are consistent with background
(atmospheric neutrino interactions)

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 – π oscillation in Super-Kamiokande

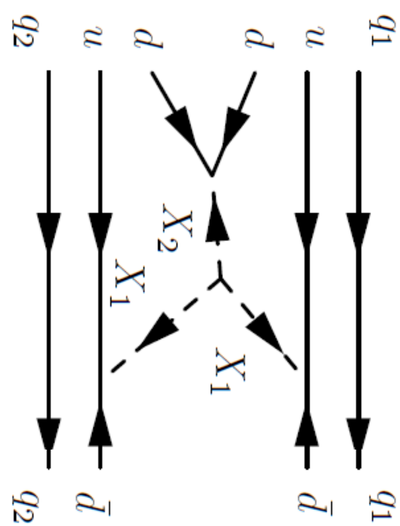
One example of Feynman diagram for dinucleon decay



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 – n̄ oscillation in Super-Kamiokande

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 p̄ p & p̄ d bubble chamber experiments)

Search for n – π oscillation in Super-Kamiokande

Used data set

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

Event selection criteria

a) Number of Cherenkov rings > 1

b) Visible energy (electron equivalent energy)

700 ~ 1300 MeV

c) Reconstructed total momentum < 450 MeV/c

d) Reconstructed invariant mass

750 ~ 1800 MeV/c^2

One of the reasons of rather wide allowed region
for visible energy and invariant mass
Among of the produced π in Oxygen,
only 49% of pions are escaped without interaction.
And 24% of pions are absorbed,
24% of pions are scattered and
3% of pions produces additional pions,
based on simulation.

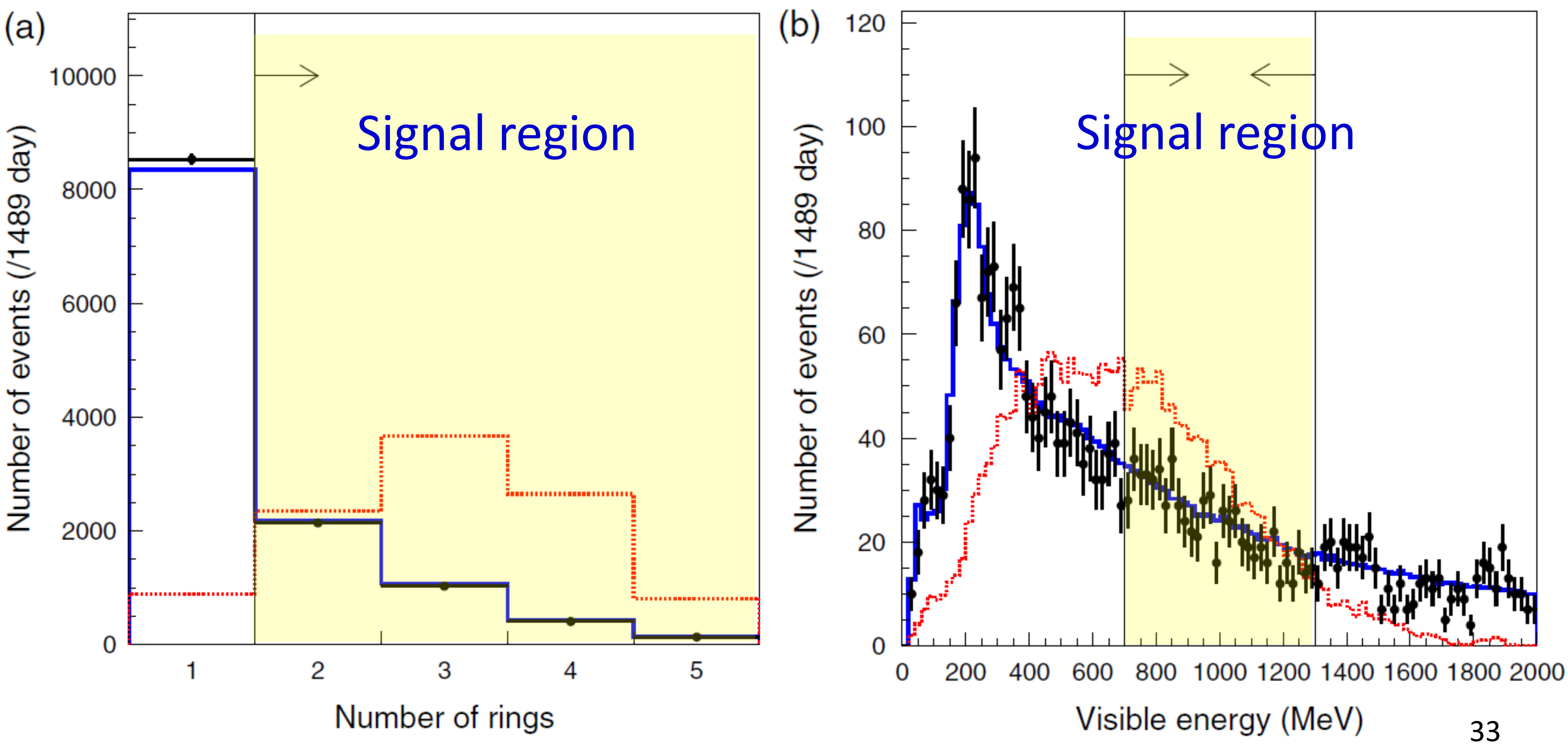
Search for n – π oscillation in Super-Kamiokande

Used data set

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

Number of Cherenkov rings > 1

Visible energy 700 ~ 1300 MeV



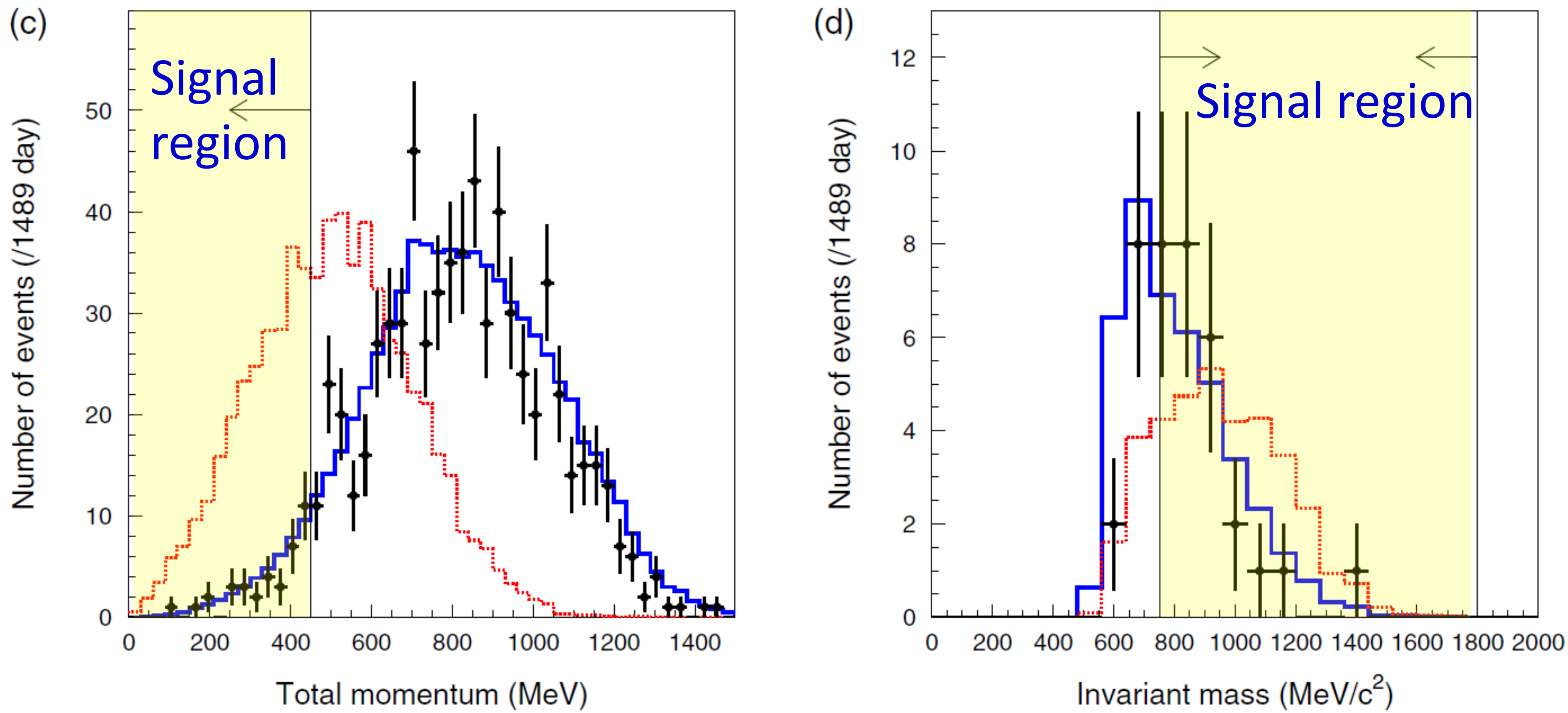
Search for n – n̄ oscillation in Super-Kamiokande

Used data set

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

Reconstructed total momentum < 450 MeV/c

Reconstructed invariant mass 750 ~ 1800 MeV/c^2



Search for n – π oscillation in Super-Kamiokande

Used data set

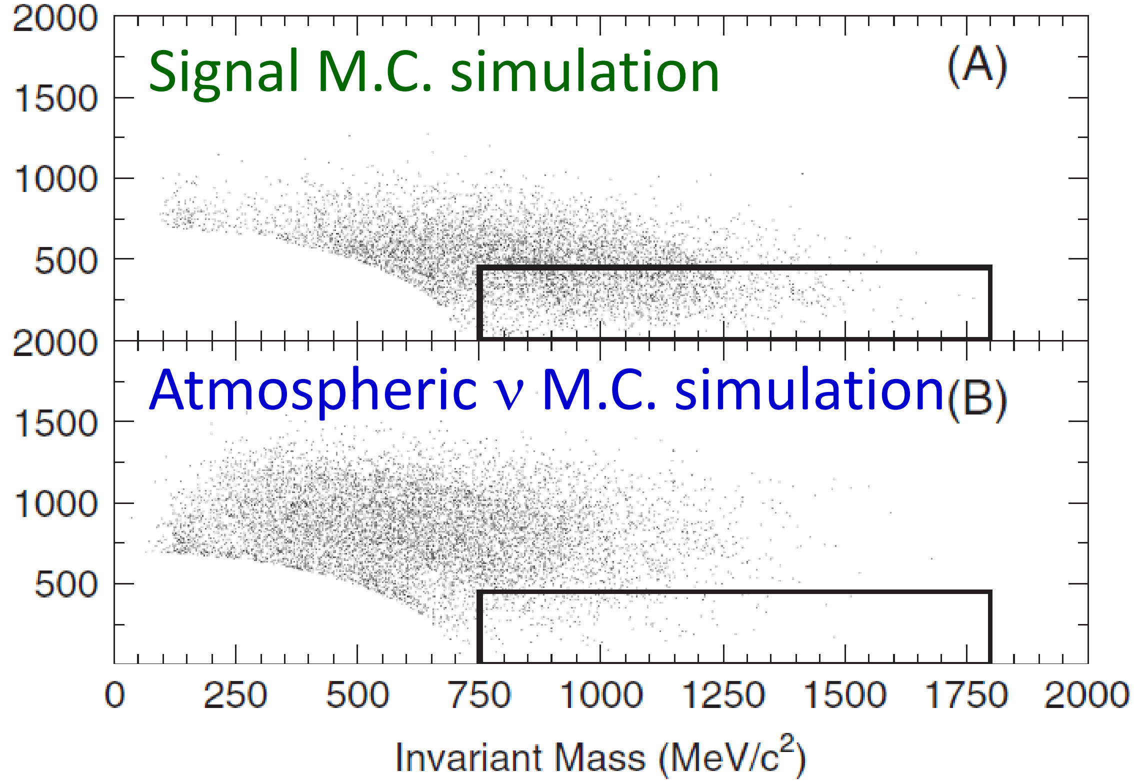
SK 1 (1489 days) 92 kt·yr = 2.45 x 10^{34} neutron·year

Signal efficiency

12.1 %

Expected # of background events

24.1



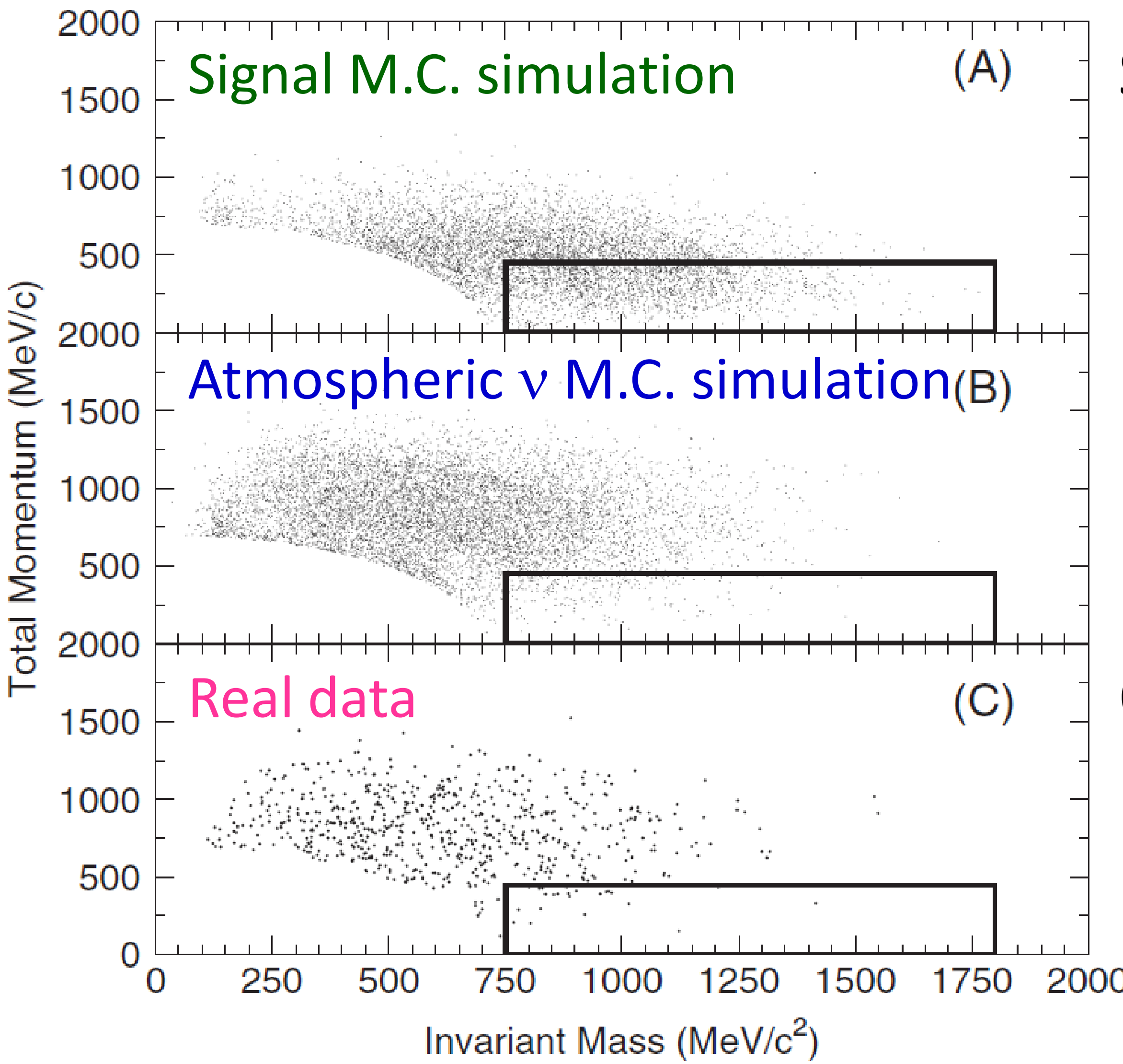
Systematic errors

Signal	22.9% (Dominant	π interactions in nucleus)
Exposure	3.0%	
Background	23.7% (Dominant	ν interaction (DIS) , ring finding efficiency)

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 – π 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 : $R = 0.571 \times 10^{23}$ sec^{-1}

$T_{n\text{-}\bar{n}} > 1.9 \times 10^{32}$ years

$\Rightarrow \tau_{n\text{-}\bar{n}} > 2.7 \times 10^{8}$ 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

fin.