Search for Nucleon decays in Super-Kamiokande

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For Super-Kamiokande collaboration

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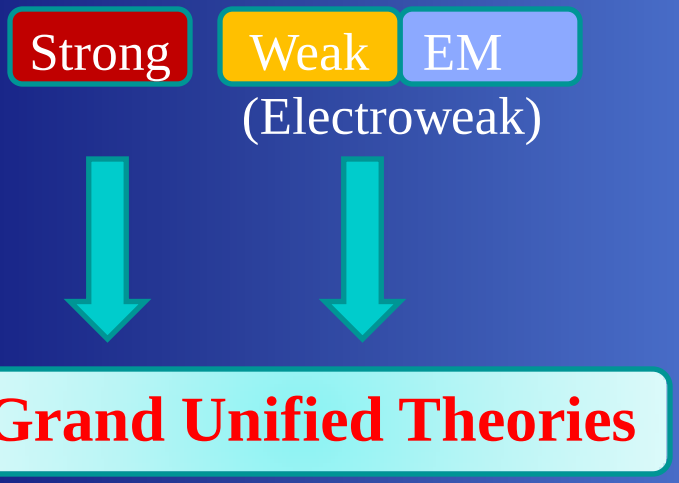
1. Introduction



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.

Major proton decay mode

Non-SUSY GUTs model: $p \rightarrow e^+\pi^0$

SUSY GUTs model: $p \rightarrow \bar{\nu}K^+$

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)

Super-Kamiokande

-Large Water Cherenkov detector

- Fiducial volume: 22.5 kton
  => 7×10^{33} protons
- Run time ~ 7 years (SK1+SK2+SK3)

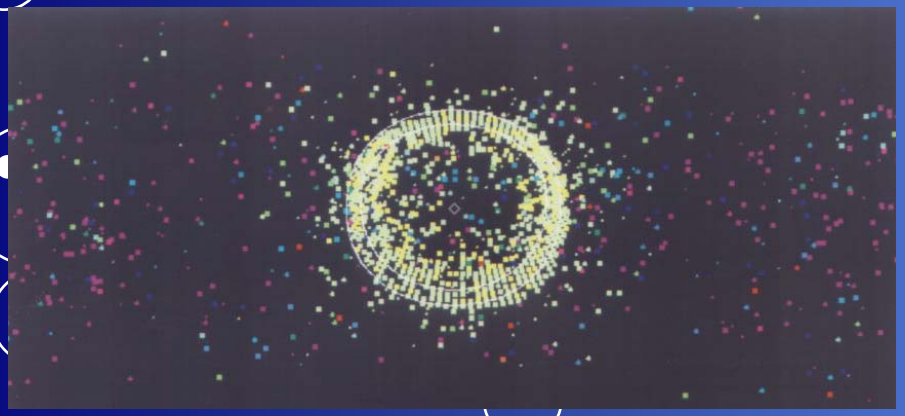
Some of them are reachable by Super-Kamiokande !

Nucleon Decay Experiment

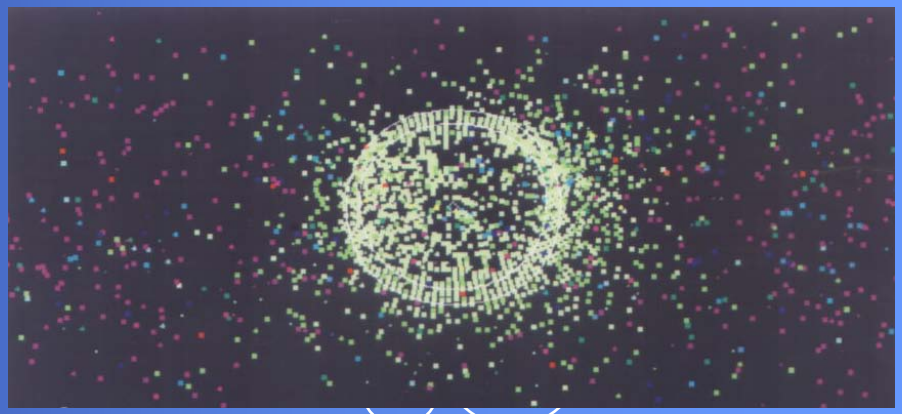
2. Super-Kamiokande Detector

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)



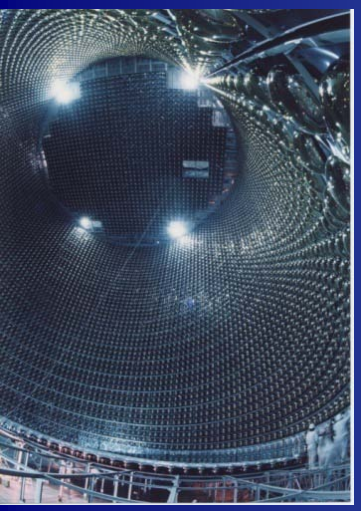
History of Super-Kamiokande

accident

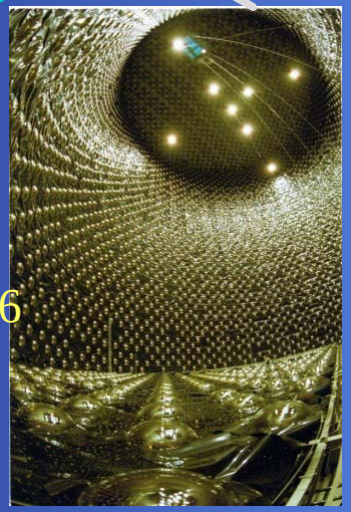
full reconstruction

electronics upgrade

1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008

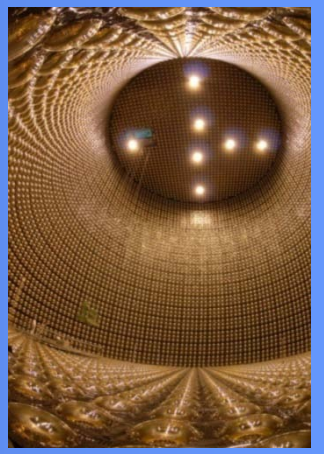


SK-1
Livetime:
- 1489.2 days
Exposure:
- 91.7 kton·yr
Inner PMT: 11146
Photo coverage:
40 %



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

SK-3



SK-4

Livetime:518.1 days
Exposure: 31.9kton·yr
Inner PMT:11146 again!

$p \Rightarrow e^{+}\pi^{0}$ paper (09')

$p \Rightarrow \nu K^{+}$ paper (05')

Newly analyzed (this talk).

MC simulations

Proton decay MC <= Efficiency

8 bounded protons in O:

Fermi momentum, binding energy, various nuclear effects are taken into account.

2 free protons: simple two body decay.

Atmospheric ν MC <= **BKG for proton decay**

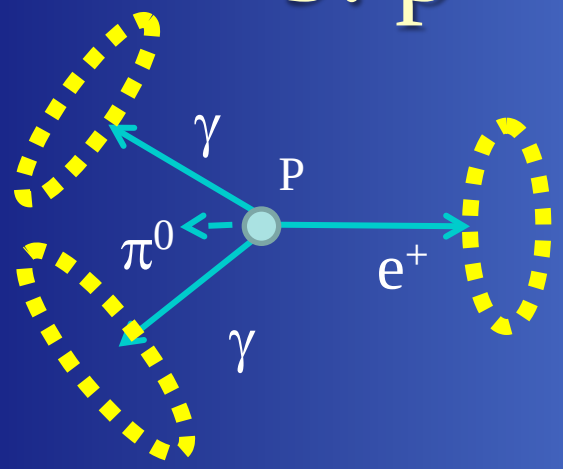
Flux : Primary cosmic rays make ν_μ and ν_e.

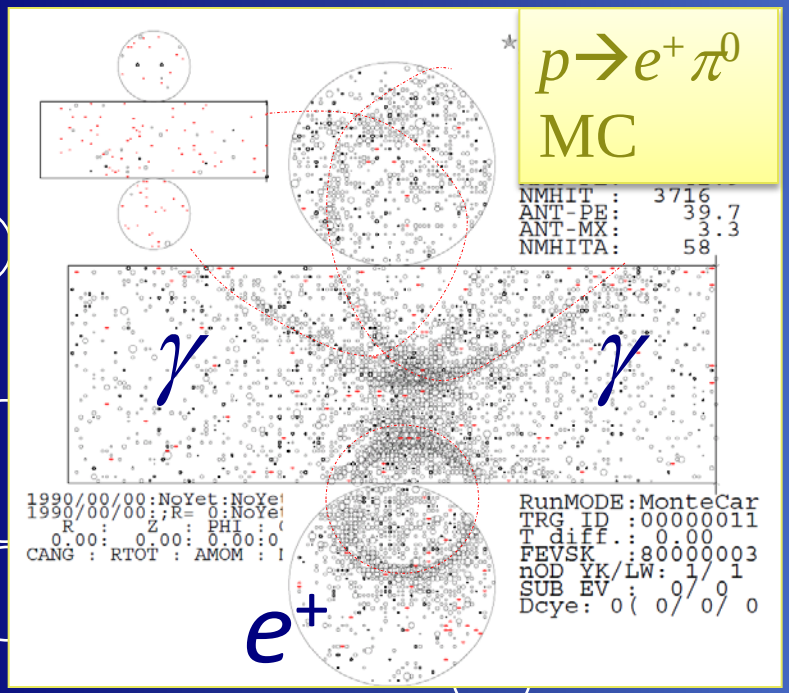
M.Honda et .al., Phys.Rev. D**75** 043006(2007)

ν interaction: NEUT Y.Hayato, Nucl.Phys.Proc.Suppl. **112**,171(2002)

Generate 500 years equivalent for each period(SK-1,2,3).

3. p->e^++π^0 mode





Event features;

- e^+ and π^0 are back-to-back (459 MeV/c) in nucleon rest frame.
- π^0 decays into two γ s (one γ may be missed if direction of the other γ is close to π^0).

=>2 or 3 e-like ring should be observed.

⇒ π^0 mass should be reconstructed by two ring (3-ring case).

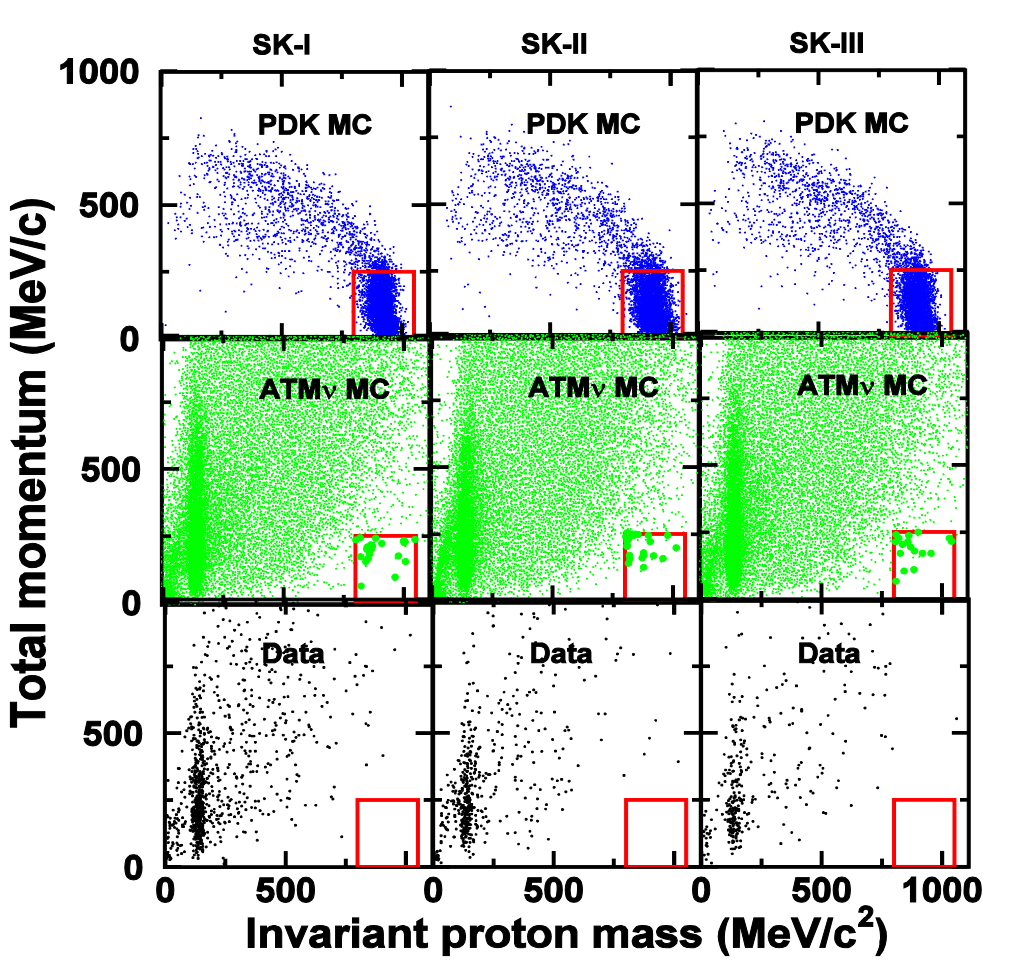
=>Proton mass should be reconstructed by all ring and total momentum should be small.

Selection;

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

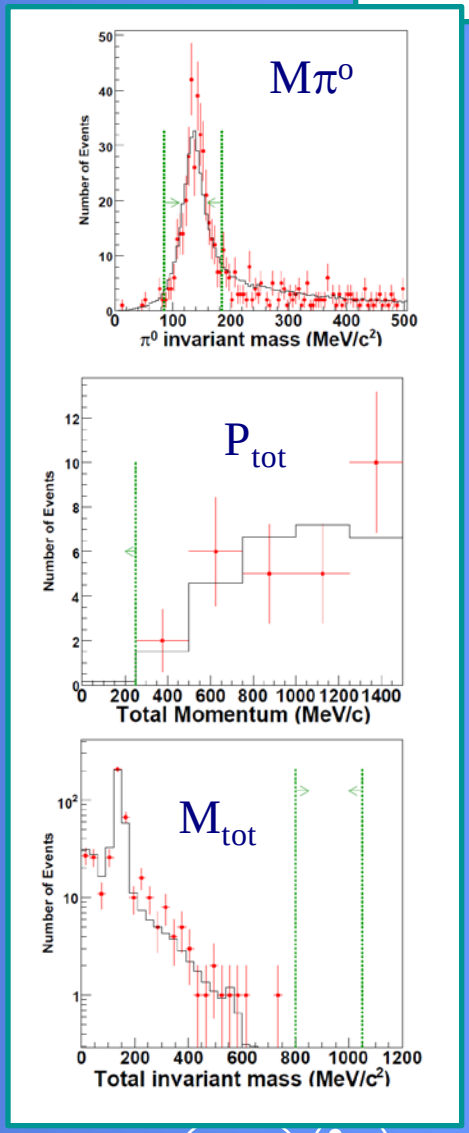
Clear signal and selected by simple cuts !

Open data !



No candidate observed.

Red: Data
Black: Atm. MC



Consistent with Atmospheric ν BKG !

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

	SK-1	SK-2	SK-3
Eff.(%)	44.6±8.5	43.5±8.3	45.2±8.6
BKG	0.20 evts /1489days	0.11 evnts /799days	0.06 evnts /518days
Obs	0	0	0

Lifetime limit (90% C.L):

$> 1.0 \times 10^{34}$ yrs@172.8kton·year

-Super-Kamiokande has reached to 10^{34} years !

-Total BKG is 0.37 events (still low enough).

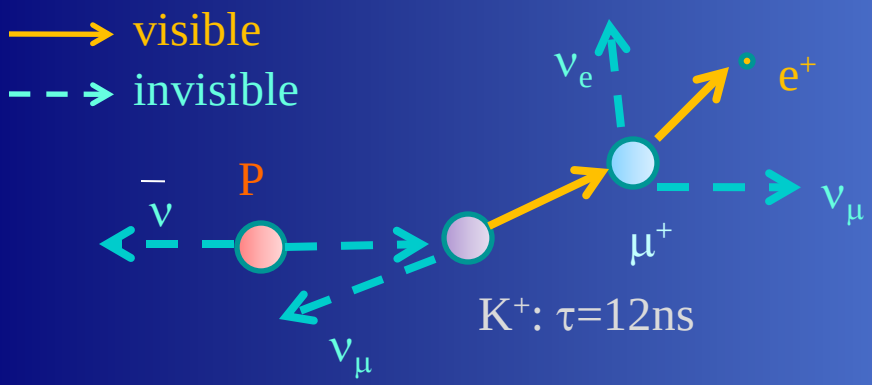
- SK-2 has almost same efficiency even though with a half PMT density.

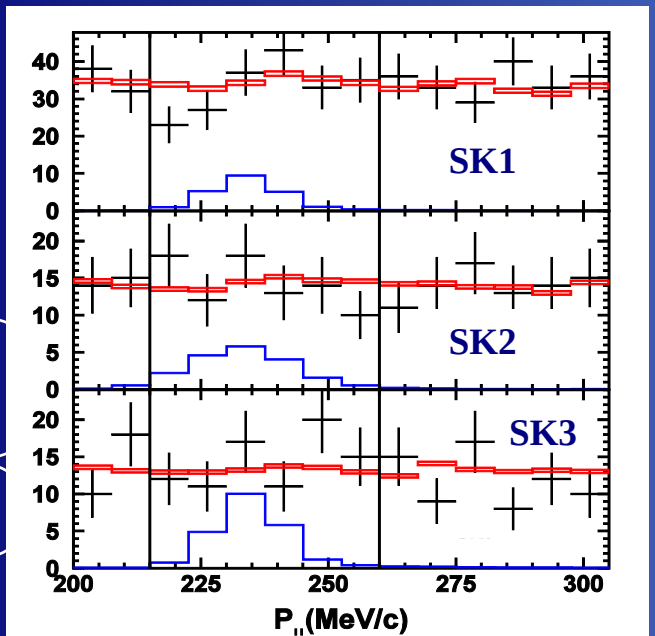
Systematic errors

Detection Efficiency	SK-I	SK-II	SK-III
Total	19 %		
π nuclear effect	15 %		
Energy Scale	0.4 %	1.4 %	1.5%
Un-uniformity of Detector Gain	0.7 %	0.5 %	0.8%
PID	1.6 %	0.9 %	2.7%
Fermi Momentum	8.2 %	8.7 %	8.2%
Fraction of Correlated Decay	6.5 %	6.4 %	6.5%
Fiducial Volume	3 %	2 %	3%
Vertex	2.0 %	1.4 %	2.0%
Cherenkov Opening Angle	0.7 %	0.9 %	0.7%
Ring Counting	0.1 %	0.1 %	0.1%
Live Time	< 1 %		

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

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





Black: Data
Red: Atm. MC
Blue: PDK MC

Event features;

- Proton => K^+(below Č thrs.)+ν.
- K^+ mostly stops and decays into μ^+ (236 MeV/c)+ν (Br.64%).

=> Monochromatic μ

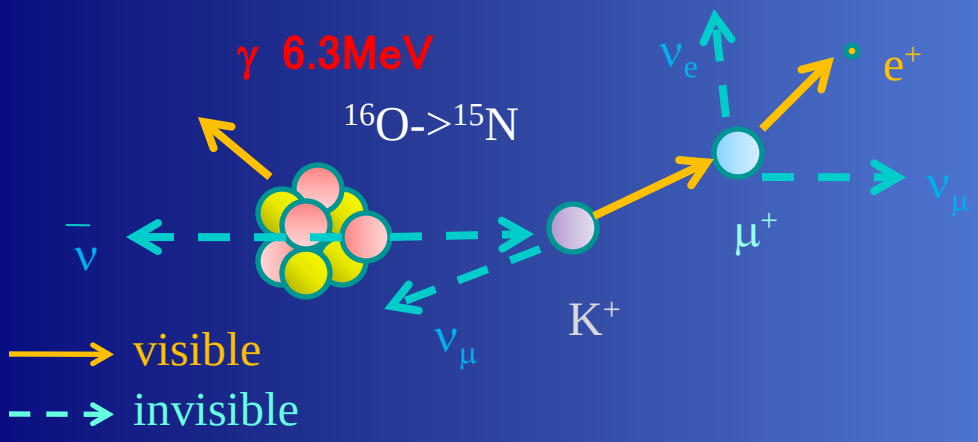
Selection:

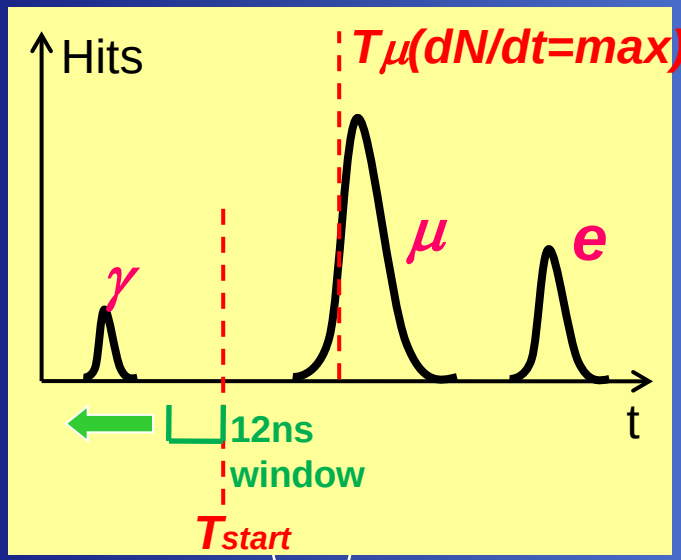
- 1 μ-like ring with decay-e (except method-B in next page).
- Fit P_μ of data by PDK and Atm MC.

Data are consistent with Atm. ν MC.

From upper limit of the fit, lifetime limit can be estimated.

B) $K^+ \rightarrow \mu^+ + \nu_\mu$ with prompt γ





Event features;

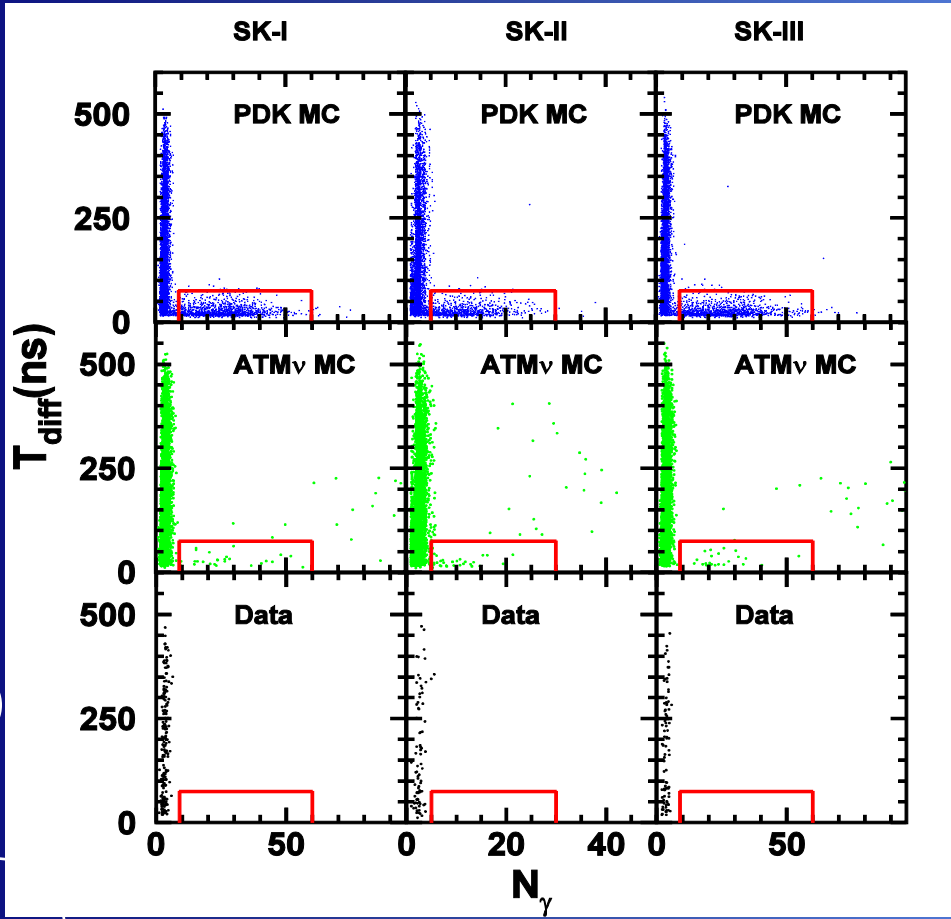
- Proton in ^{16}O decays and excited nucleus emits 6 MeV γ (Prob. 41%, not clear ring).

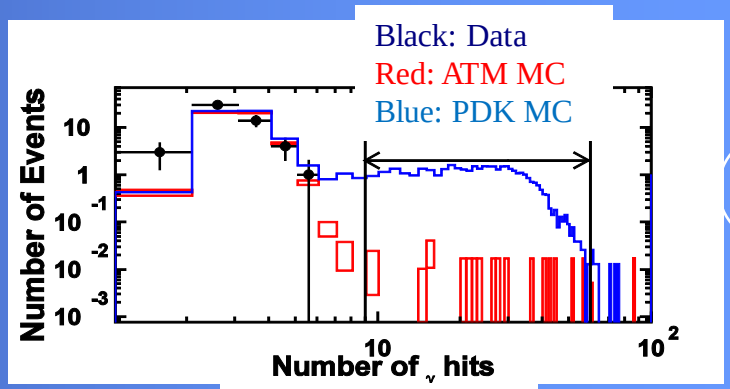
=> Tag γ to eliminate BKG.

Selection:

- 1 μ-like ring with decay-e.
- $215 < P\mu < 260$ MeV/c
- Search Max hit cluster by sliding time window (12ns width);
  - $8 < N\gamma < 60$ hits for SK-1&SK-3
  - $4 < N\gamma < 30$ hits for SK-2
  - &
  - $T_\mu - T_\gamma < 75$ nsec

Results





(1-D histogram)

Data is consistent with ATM ν MC.

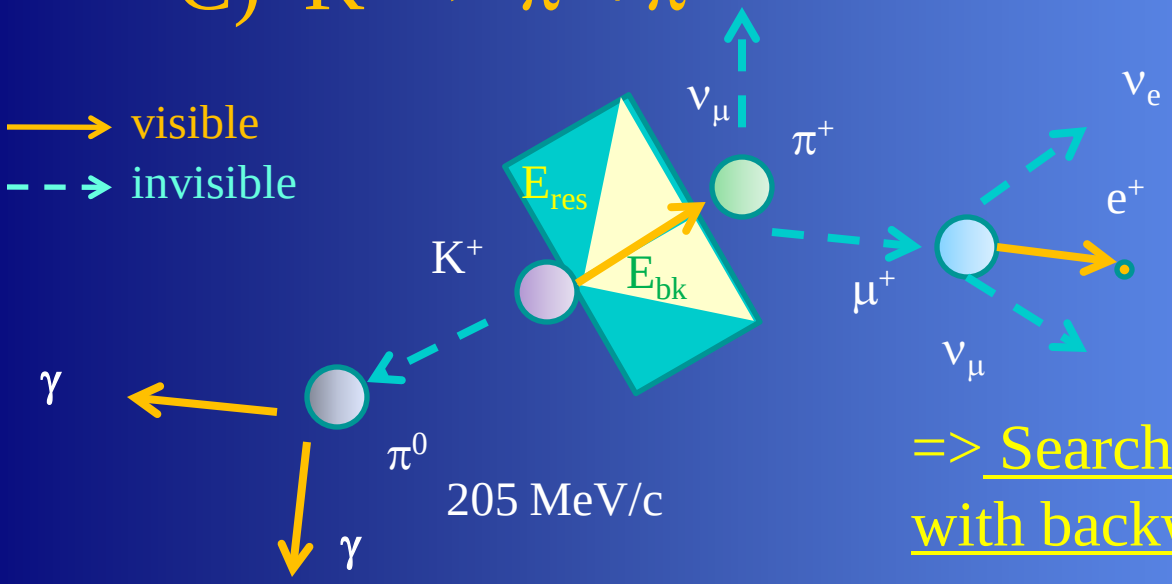
	SK-1	SK-2	SK-3
Eff.(%)	7.2±1.6	5.8±1.3	7.3±1.6
BKG	0.16 evts /1489days	0.08 evnts /799days	0.03 evnts /518days
Obs	0	0	0

No candidates.

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

visible

invisible



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:

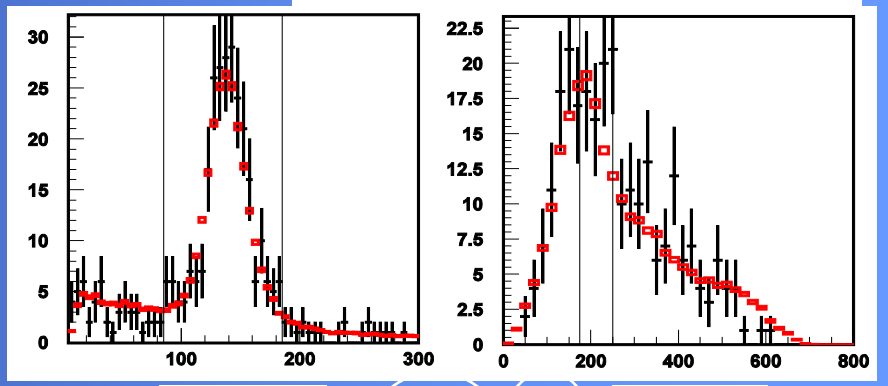
- 2 e-like rings with decay-e.
- $85 < M\pi^0 < 185$ MeV.
- $175 < P\pi^0 < 250$ MeV/c.
- E_{bk}: visible energy sum in 140-180 deg. of π^0 dir,

E_{res}: in 90-140 deg.

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

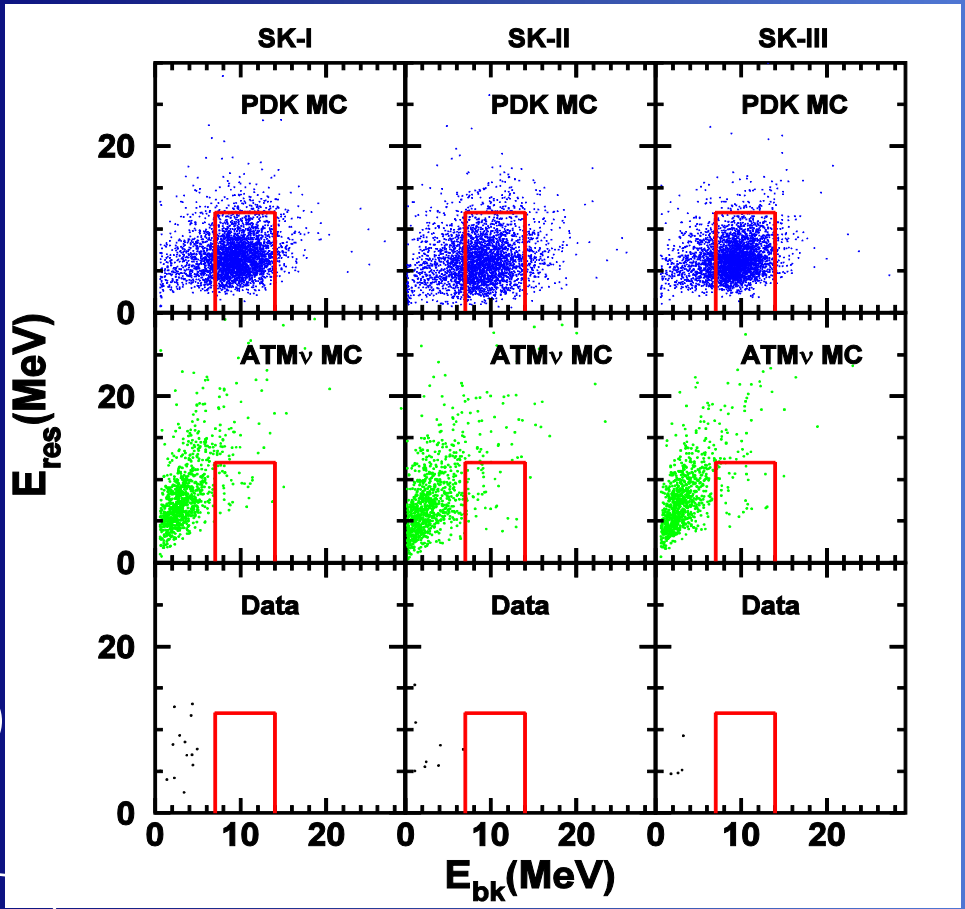
Black: Data (w/o dcy-e cut)

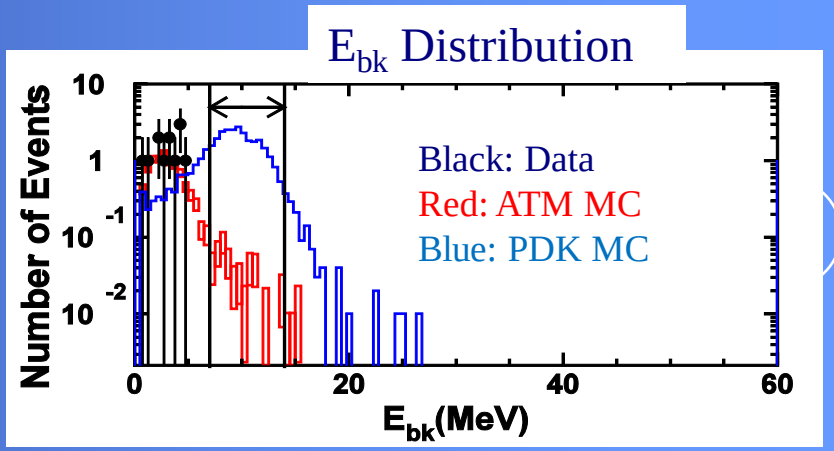
Red: Atm. MC



$M\pi^0$ $P\pi^0$

Results





Data is consistent with ATM ν MC.

	SK-1	SK-2	SK-3
Eff.(%)	6.5±0.6	5.3±0.5	6.6±0.6
BKG	0.46 evts /1489days	0.33 evnts /799days	0.14 evnts /518days
Obs	0	0	0

No candidates.

Summary of p -> $\bar{\nu}K^+$ mode

K->	Method	Period	Eff (%)	BKG	Obs.
$\mu^+\nu$	Pμ	SK-1	37.0±0.4	188.9±5.7	198±14.1
		SK-2	35.7±0.4	95.5±2.0	85± 9.2
		SK-3	37.5±0.4	79.4±2.1	86±9.3
	Prompt γ tag	SK-1	7.2±1.6	0.16±0.05	0
		SK-2	5.8±1.3	0.08±0.03	0
		SK-3	7.3±1.6	0.03±0.01	0
$\pi^+\pi^0$		SK-1	6.5±0.6	0.43±0.13	0
		SK-2	5.3±0.5	0.31±0.10	0
		SK-3	6.6±0.6	0.14±0.04	0

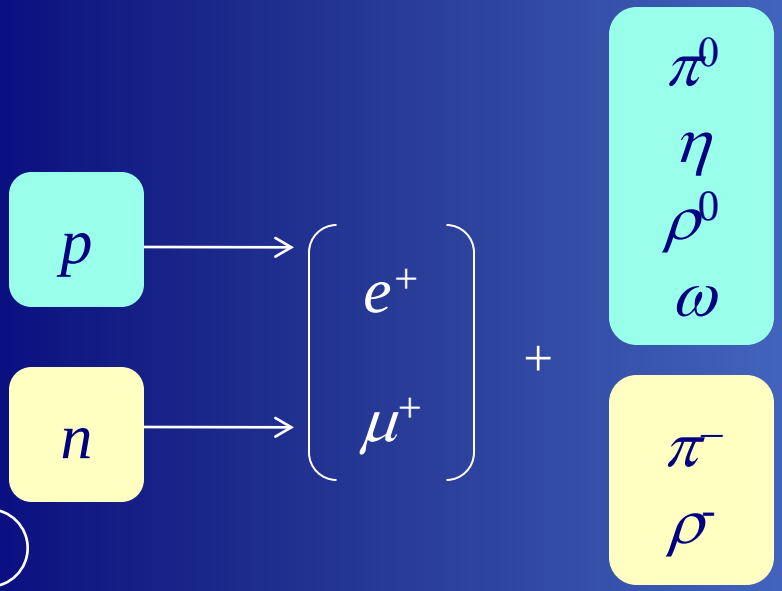
Lifetime limit (90% CL):

> 3.3×10^{33} yrs @172.8 ktont·yr

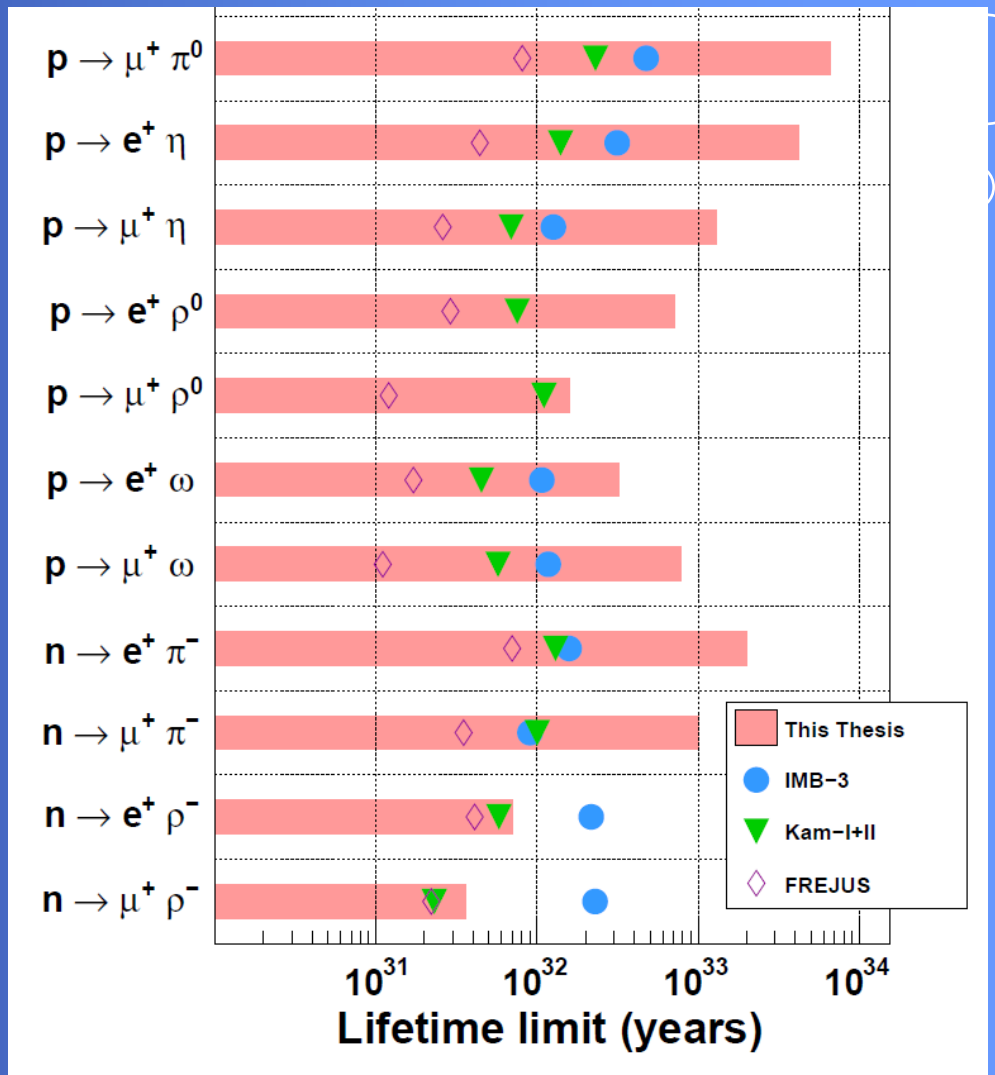
Note: Efficiencies in SK2 (half PMT density) are ~80 % of SK1 (full density).

5. Other modes

Nucleon => lepton + meson
(using SK-1&SK-2 data)



- Consistent with BKG for all modes.
- Most of them give the most stringent limits in the world.



6. Summary

- We performed nucleon decay search with data from SK-1 to SK-3, 173 kton･yrs in total.
- We could not find any evidences of nucleon decay.
- We calculated nucleon lifetime limits with 90 % C.L.

$e^+\pi^0$: > 1.0×10^{34} yrs

$\bar{\nu}K^+$: > 3.3×10^{33} yrs

Other lepton+meson : > 6.6 ~0.04×10^{33} yrs

(SK-1&SK-2 data,141 kton･yrs)

Remarks & Future prospects

- BKG for $e^+\pi^0$: 0.37 events/2806days

  νK^+ : 0.27events (prompt γ)

  Still low enough!
- SK-4 data will be open soon (~450 days).
- Even PMT density became half in SK-2, the detection efficiencies were almost same as SK-1. => Good information for design larger detectors in future.

Backup

Q. What are BKG for $e^+\pi^0$ mode ?

Contribution to BG	
CCQE	28%
CC single π	32%
CC multi π	19%
other CC	2%
NC	19%

ν+N -> lepton+N*; N*->N'+meson

ν_e CC case, e and $\pi^{\pm}$, π^0 are out-going particles.

ν+N -> lepton+P

ν_e case, e and P are out-going particles and P interacts in water and make secondary π^0.

Q. What are BKG for νK^+ mode ?

$K^+ \to \nu + \mu$

$\nu + N \to$ lepton$+N^*$; $N^* \to N' +$meson: 44%

Resonance N^* decays into K^+.

$\nu + N \to$ charged lepton$+P$: 17 %

Low P lepton, High P proton
=> VTX mis-reconstructed

$K^+ \to \pi^+ + \pi^0$

$\nu + N \to$ lepton$+N^*$; $N^* \to N' +$meson: 63%

-Resonance N^* decays into K^+.
- N^* decays into π^0 and charged lepton goes backward of π^0.

Systematic error for νK^+ (Efficiency)

$\mu+\nu$, prompt γ tag

	SK1	SK2	SK3
γ-emission prob.	20.0	20.0	20.0
Energy scale	2.3	1.2	2.7
Tstart	7.6	8.2	8.3
PID	0.4	0.6	0.6
Ring count	1.5	1.1	1.4
Water parameter	3.0	2.6	1.9
Fiducial volume	3.0	3.0	3.0
Total	22.0	22.0	22.2

$\pi^+\pi^0$

	SK1	SK2	SK3
$\sigma(\pi$-N) in water	5.0	5.0	5.0
Energy scale	4.1	2.9	2.5
PID	2.0	3.0	2.1
Ring count	3.6	4.8	4.0
Water parameter	2.4	2.1	2.8
Fiducial volume	3.0	3.0	3.0
Total	8.6	8.9	8.3

Lifetime limit calculation; Bayesian method

SK-1 SK-2 SK-3

$$P(\Gamma \mid n_1 \cdot n_2 \cdot n_3) = \frac{1}{A}\iiint \frac{e^{-(\Gamma\lambda_1\varepsilon_1+b_1)}(\Gamma\lambda_1\varepsilon_1+b_1)^{n_1}}{n_1!}\frac{e^{-(\Gamma\lambda_2\varepsilon_2+b_2)}(\Gamma\lambda_2\varepsilon_2+b_2)^{n_2}}{n_2!}\frac{e^{-(\Gamma\lambda_3\varepsilon_3+b_3)}(\Gamma\lambda_3\varepsilon_3+b_3)^{n_3}}{n_3!}$$
$$\times P(\Gamma)P(\delta_\varepsilon)P(\delta_\lambda)P(\delta_b)d\delta_\varepsilon d\delta_\lambda d\delta_b$$

$$CL(0.9) = \int_0^{\Gamma_{\max}} P(\Gamma \mid n_1 \cdot n_2 \cdot n_3)d\Gamma$$

Assuming Eff, BKG, exposure are gaussian.

Γ: decay rate (=1/τ)
λ: exposure
ε: detection efficiency
b: number of BG events
n: candidate