

# Search for Nucleon decay in Super-Kamiokande

M.Miura

Kamioka Observatory, ICRR

Recontres de Moriond EW, 2009

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# 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:  $10^{14-16}$  GeV



Cannot be reached by Accelerators.

Lepton and baryon numbers are not conserved.

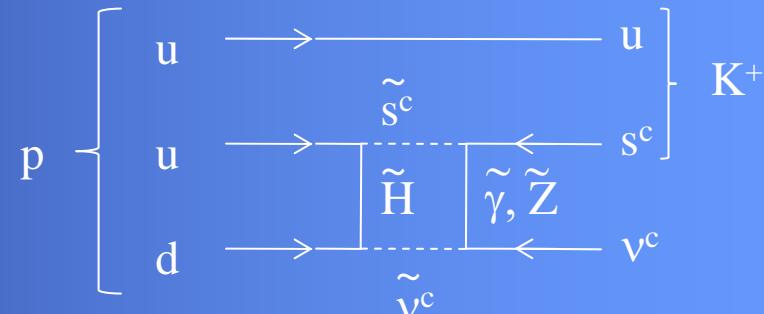
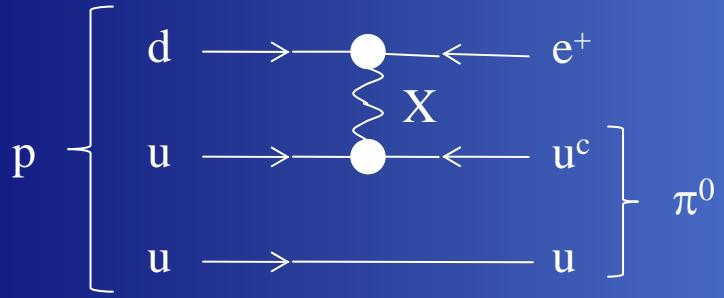


Proton decay is permitted !

Nucleon decay experiment is the direct probe for GUTs.



# Examples of proton decay model



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)	$p \rightarrow \bar{v} K^+$	$\leq 10^{30}$ [3]
SUGRA SU(5)	$p \rightarrow \bar{v} K^+$	$10^{32} \sim 10^{34}$ [4]
SUSY SO(10)	$p \rightarrow \bar{v} K^+$	$10^{32} \sim 10^{34}$ [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  
 $\Rightarrow 7 \times 10^{33}$  protons
- Run time  $\sim 6$  years (SK-1+SK2)

Some of them are reachable by Super-Kamiokande !

## 2. Super-Kamiokande Detector

**Location:** Kamioka mine, Japan. ~1000 m under ground.

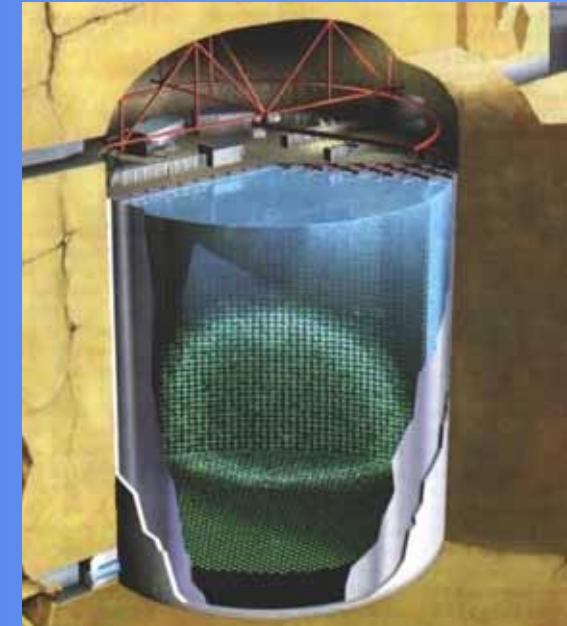
**Size:** 39 m (diameter) x 42 m (height), 50kton water.

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 for SK-1 (4.1%: SK-2).

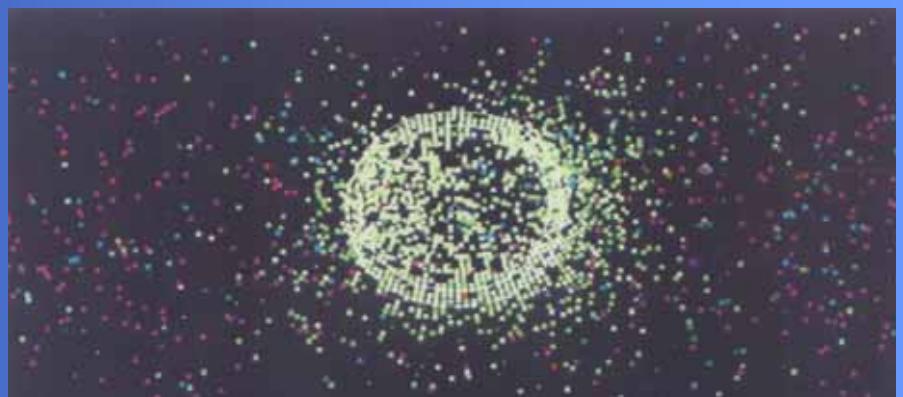
**Particle ID:** Separate into EM shower type (**e-like**) and muon type ( **$\mu$ -like**) by Cherenkov ring angle and ring pattern.



$\mu$ -like ( $\mu^\pm$ )



e-like ( $e^\pm, \gamma$ )





# *History of Super-Kamiokande*



# MC simulations

Proton decay MC  $\leq$  Efficiency

8 bounded protons in O:

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

2 free protons (H): simple two body decay.

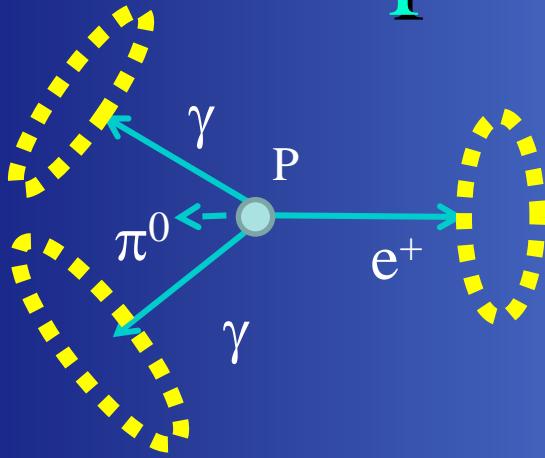
Atmospheric  $\nu$  MC  $\leq$  BKG for proton decay

Flux : Primary cosmic rays make  $\nu_\mu$  and  $\nu_e$ .

M.Honda et .al., Phys.Rev. D75 043006(2007)

$\nu$  interaction: NEUT Y.Hayato, Nucl.Phys.Proc.Suppl. 112,171(2002)

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



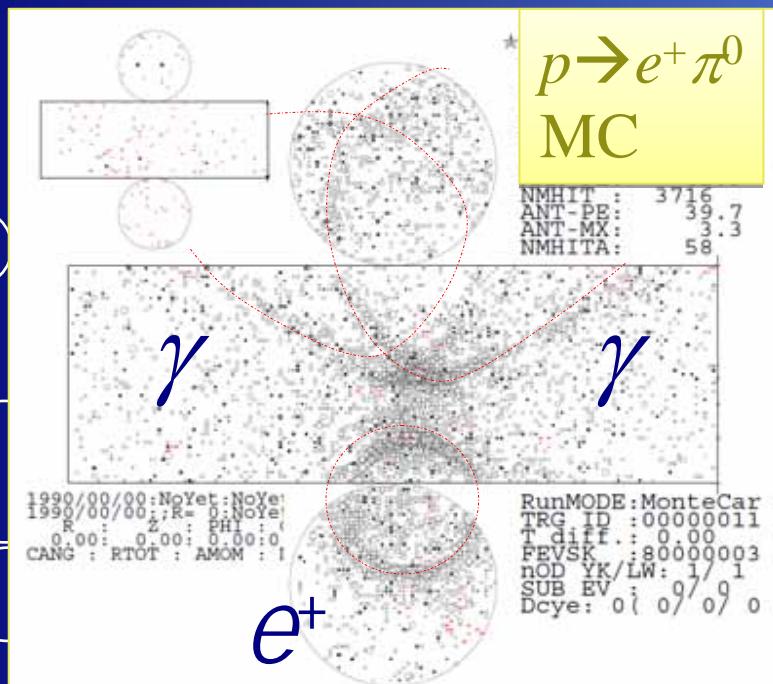
#### Event features;

- $e^+$  and  $\pi^0$  are back-to-back (459 MeV/c) in nucleon rest frame.
- $\pi^0$  decays into two  $\gamma$ s (one  $\gamma$  may be missed if direction of the other  $\gamma$  is close to  $\pi^0$ ).  
 $\Rightarrow$  **2 or 3 e-like ring** should be observed.  
 $\Rightarrow$   **$\pi^0$  mass** should be reconstructed by two ring (3-ring case).  
 $\Rightarrow$  **Proton mass** should be reconstructed by all ring and **total momentum** should be small.

#### Selection;

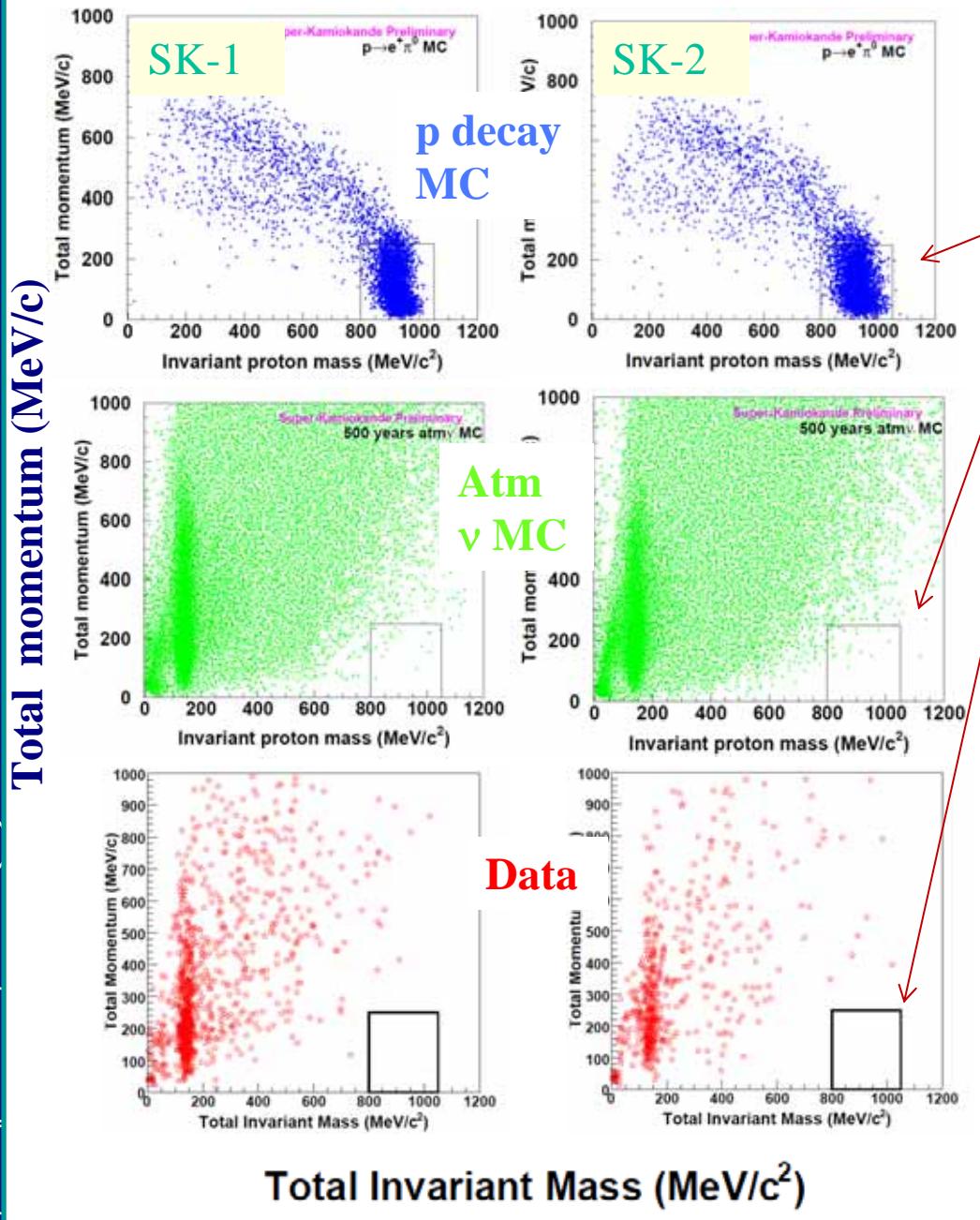
- Fully contained, VTX in fiducial volume.
- 2 or 3 ring and all e-like, w/o decay-electron.
- $85 < M_{\pi^0} < 185$  MeV (for 3-ring event).
- $800 < M_p < 1050$  MeV &  $P_{tot} < 250$  MeV/c

**Clear signal and selected by simple cuts !**



# Results

Signal box

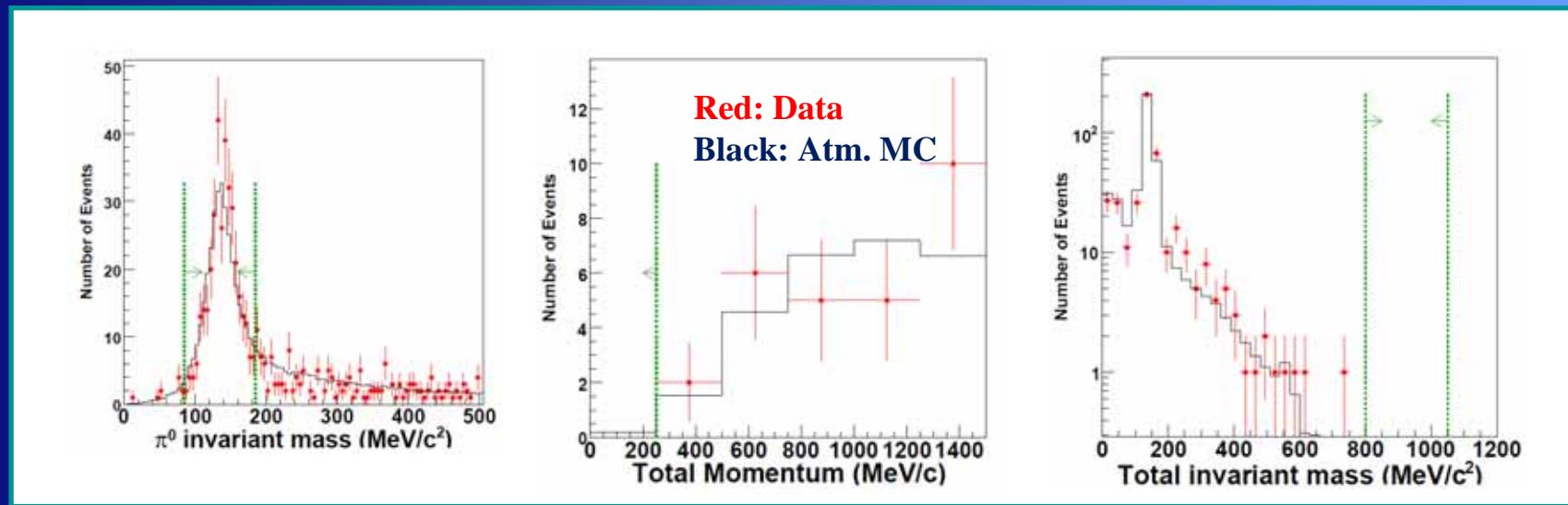


	SK-1	SK-2
Eff.(%)	$44.6 \pm 8.5$	$43.5 \pm 8.3$
BKG	0.20 evts /1489days	0.11 evnts /799days
Obs	0	0

Total BKG:  
0.31events/2288days  
=> Still low enough!



1-dim distributions: Data are consistent with Atm. v MC.



Lifetime limit (90% C.L.):  $> 8.2 \times 10^{33} \text{ yrs}$  @ 141 kton



( $= 4.7 \times 10^{34} \text{ proton} \cdot$



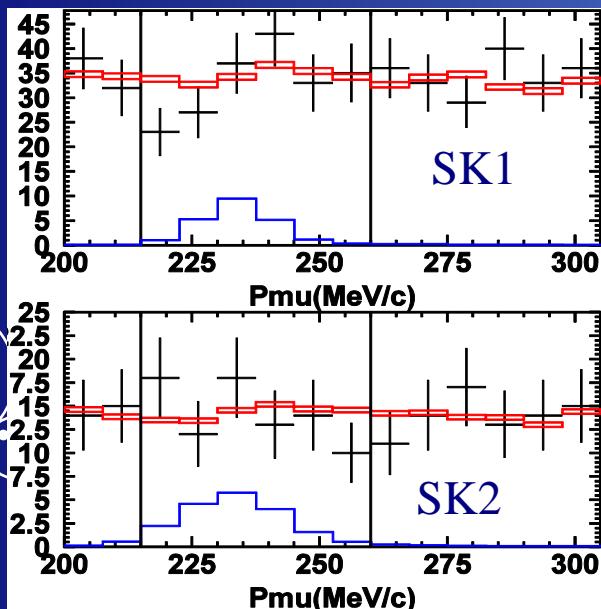
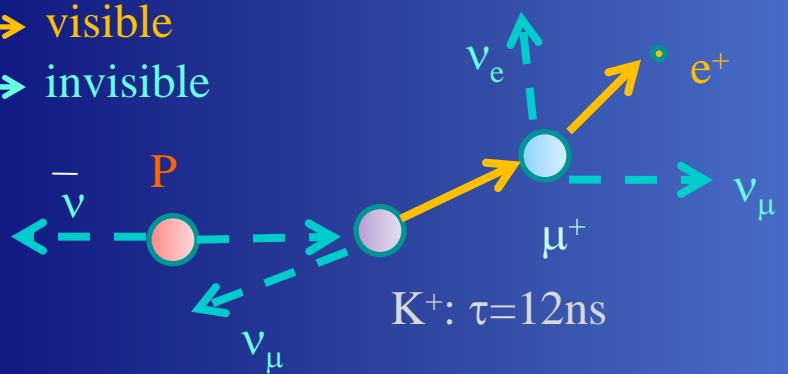
$\text{yr})$   $\Leftrightarrow > 1.6 \times 10^{33} \text{ yrs}$  @ 25.5 kton  $\cdot$  yr in prev. SK paper, 1998



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

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

→ visible  
---> invisible



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

Event features;

- Proton  $\Rightarrow K^+$ (below Č thrs.) $+\nu$ .
- $K^+$  most likely stops and decays into  $\mu^+$  (236 MeV/c) $+\nu$  (Br.64%).

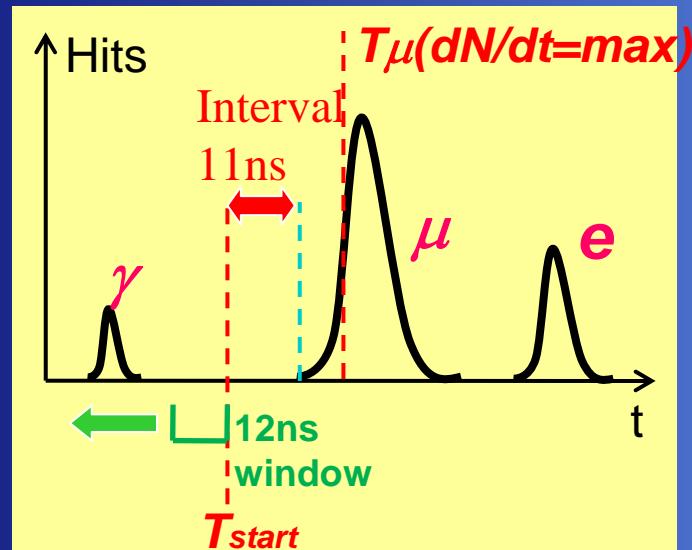
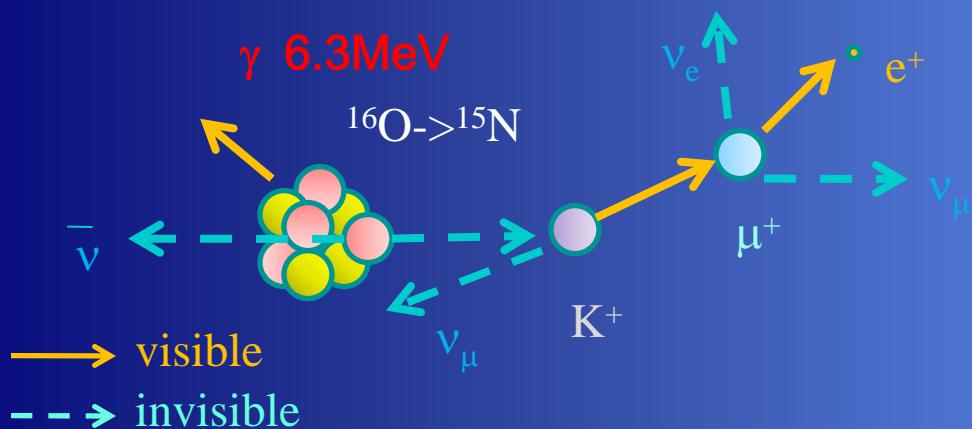
⇒ Monochromatic  $\mu$

Selection:

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

Data are consistent with Atm.  $\nu$  MC.  
From upper limit of the fit, lifetime limit can be estimated.

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



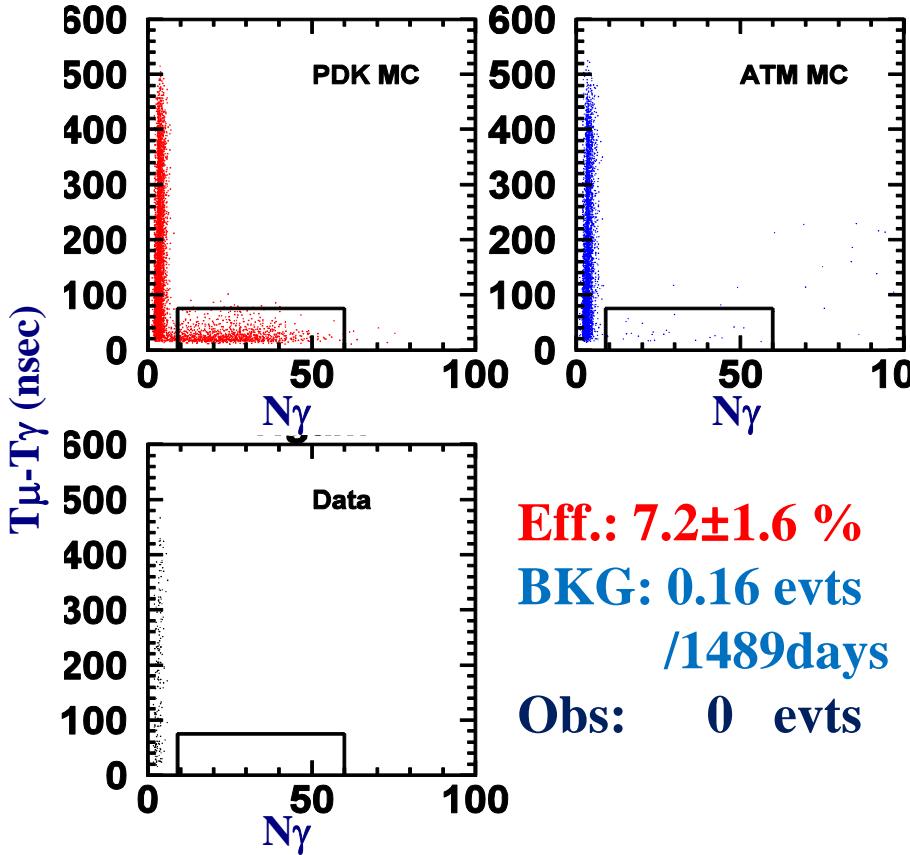
### Event features:

- Proton in  $^{16}\text{O}$  decays and excited nucleus emits 6 MeV  $\gamma$  (Prob. 41%, not clear ring).
- => Tag  $\gamma$  to eliminate BKG.

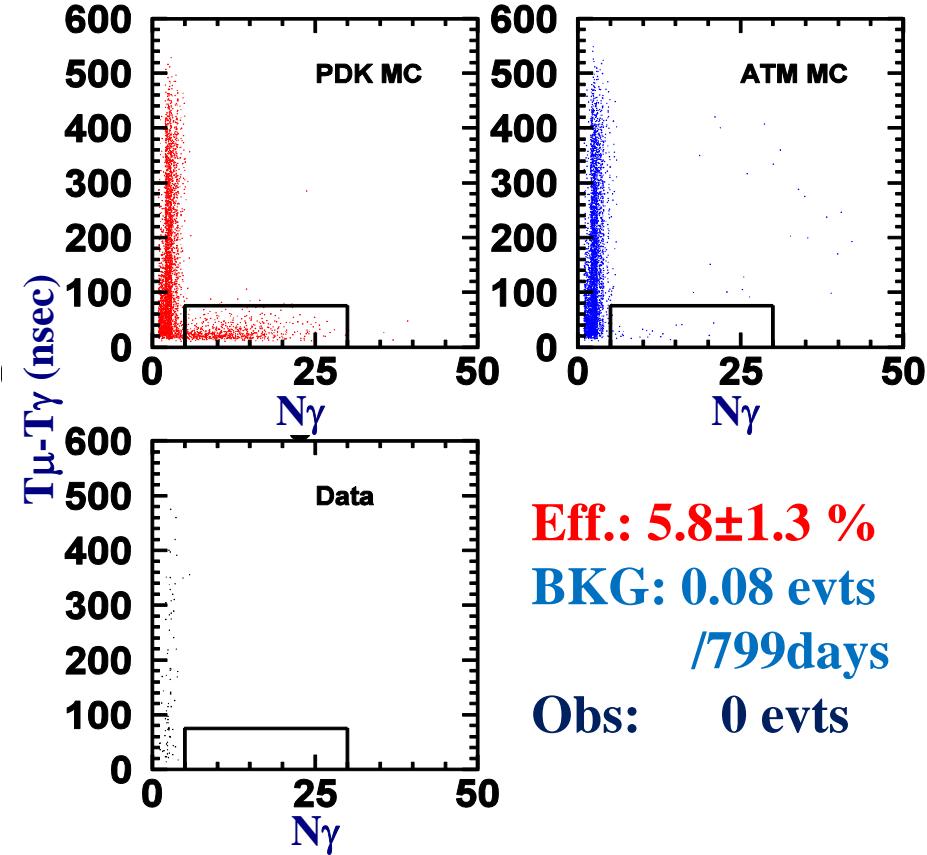
### Selection:

- 1  $\mu$ -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
  - $4 < N_\gamma < 30$  hits for SK-2
  - &
  - $T_\mu - T_\gamma < 75$  nsec

## SK-1



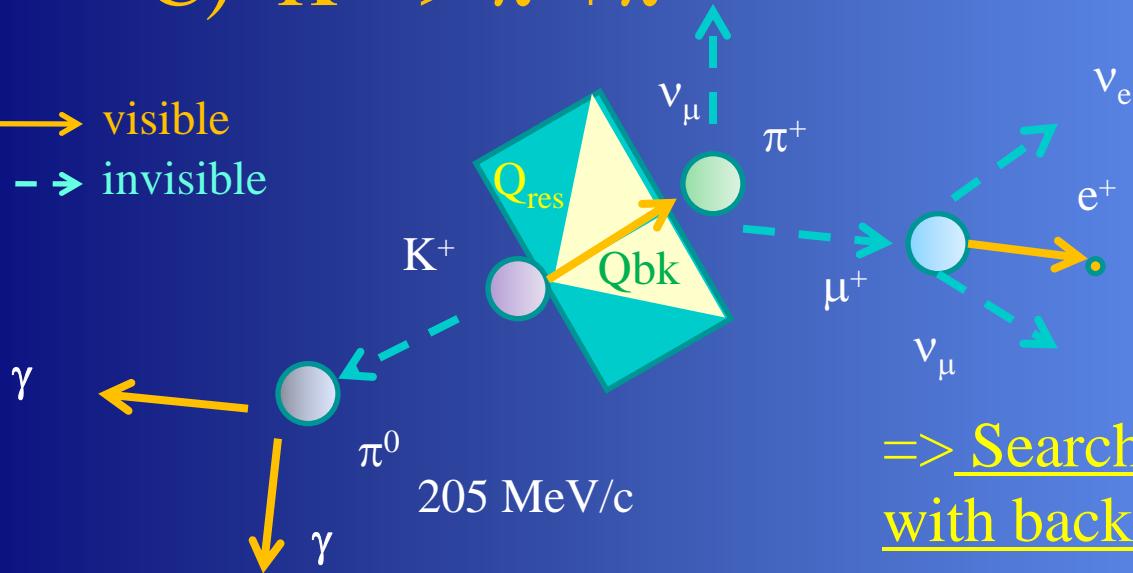
## SK-2



Even though photo coverage decreased by 50 %,  
efficiency in SK-2 keeps 80 % of SK-1.

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

—→ visible  
- - - → invisible



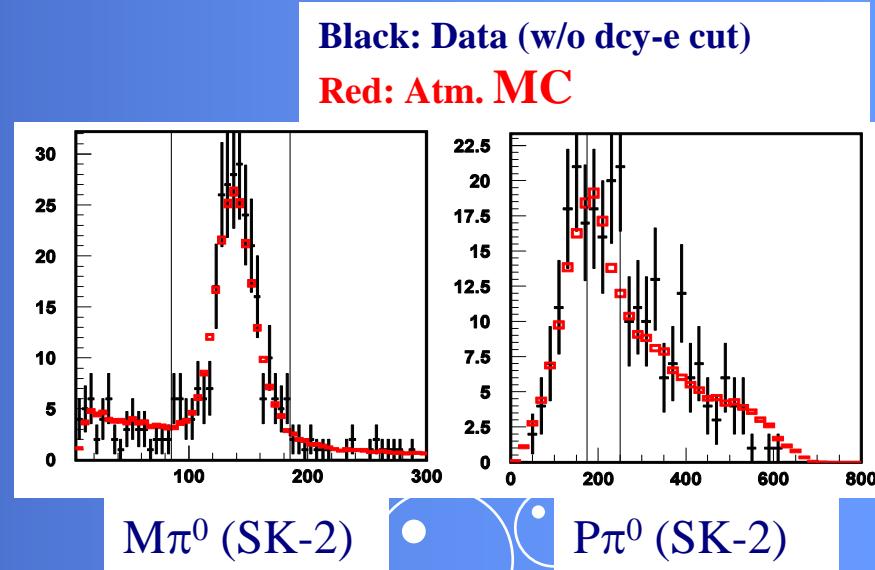
### Selection:

- 2 e-like rings with decay-e.
- $85 < M\pi^0 < 185$  MeV.
- $175 < P\pi^0 < 250$  MeV/c.
- $Q_{bk}$ : charge sum in 140-180 deg. of  $\pi^0$  dir,
- $Q_{res}$ : in 90-140 deg.
- (SK-1)  $40 < Q_{bk} < 100$  pe &  $Q_{res} < 70$  pe
- (SK-2)  $20 < Q_{bk} < 50$  pe &  $Q_{res} < 35$  pe

### Event features:

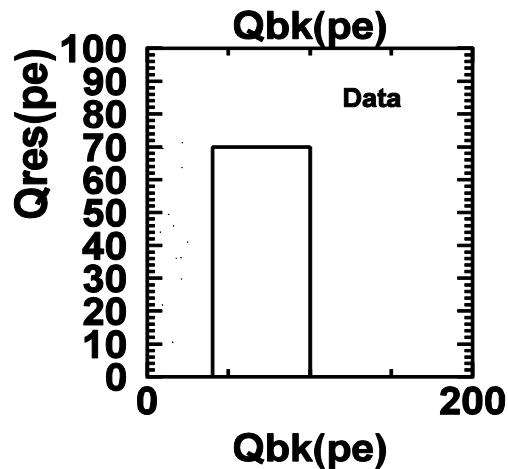
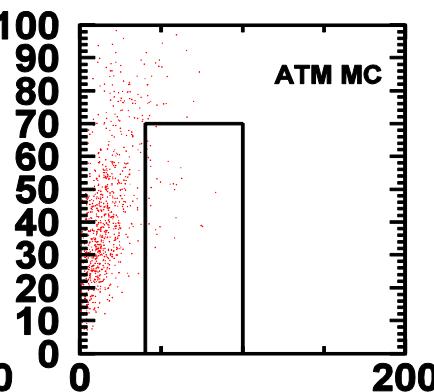
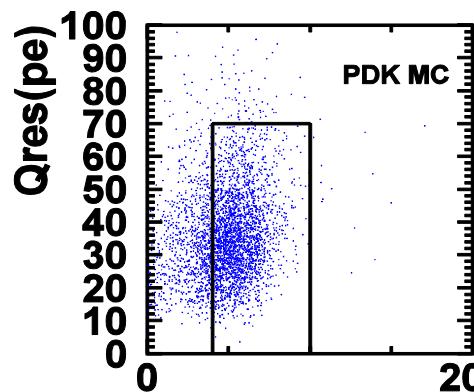
- Br. 21 %.
- $\pi^0$  and  $\pi^+$  are back-to-back and have 205 MeV/c.
- $P\pi^+$  is just above Č thres. (not clear ring).

=> Search for monochromatic  $\pi^0$  with backward activities.

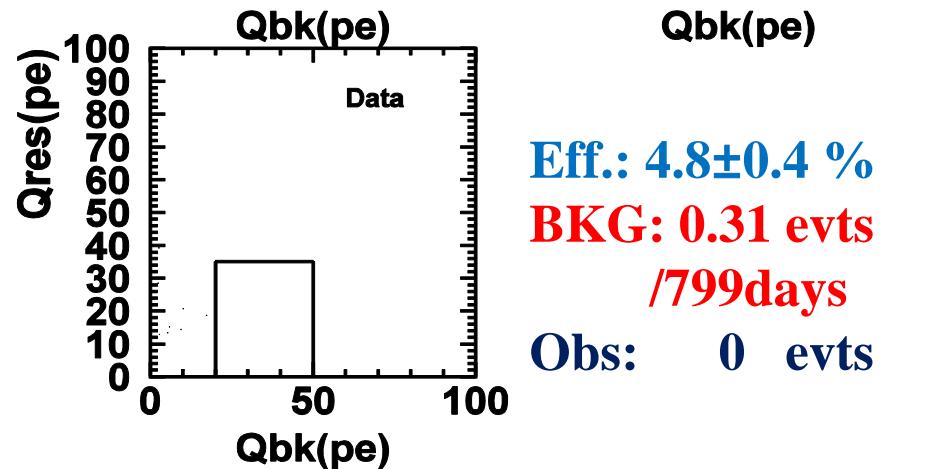
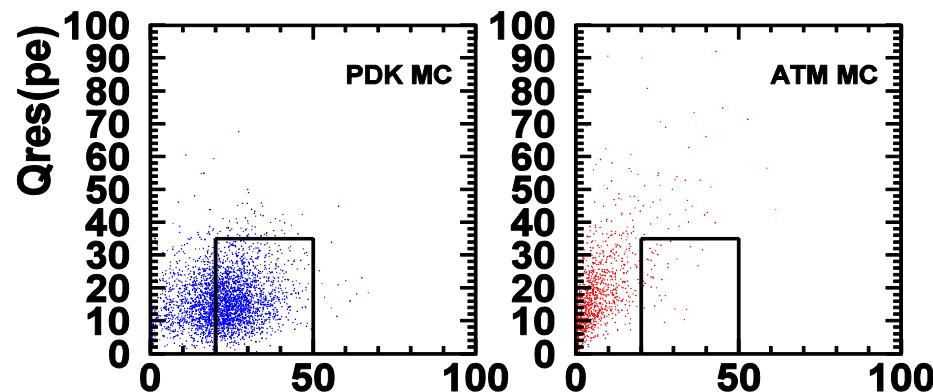


SK-1

SK-2



Eff.:  $6.2 \pm 0.5$  %  
BKG: 0.43 evts  
 $/1489$  days  
Obs: 0 evts



Data  
Eff.:  $4.8 \pm 0.4$  %  
BKG: 0.31 evts  
 $/799$  days  
Obs: 0 evts

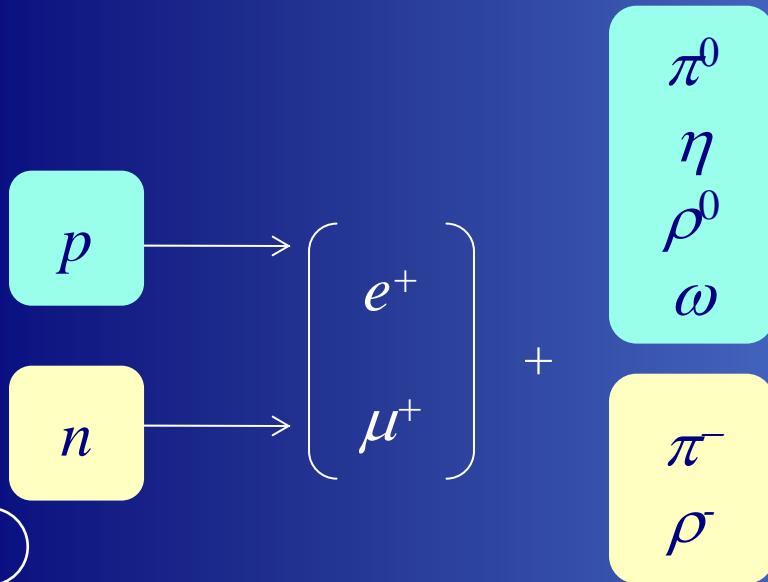
# Summary of $p \rightarrow \bar{v}K^+$

K->			Eff (%)	BKG	Obs.	
$\mu^+\nu$	P $\mu$	SK-1	$37.0 \pm 0.4$	$188.9 \pm 5.7$	$198 \pm 14.1$	
		SK-2	$35.7 \pm 0.4$	$95.5 \pm 2.0$	$85 \pm 9.2$	
	Prompt $\gamma$ tag	SK-1	$7.2 \pm 1.6$	$0.16 \pm 0.05$	0	
		SK-2	$5.8 \pm 1.3$	$0.08 \pm 0.03$	0	
$\pi^+\pi^0$		SK1	$6.2 \pm 0.5$	$0.43 \pm 0.13$	0	
		SK2	$4.8 \pm 0.4$	$0.31 \pm 0.10$	0	

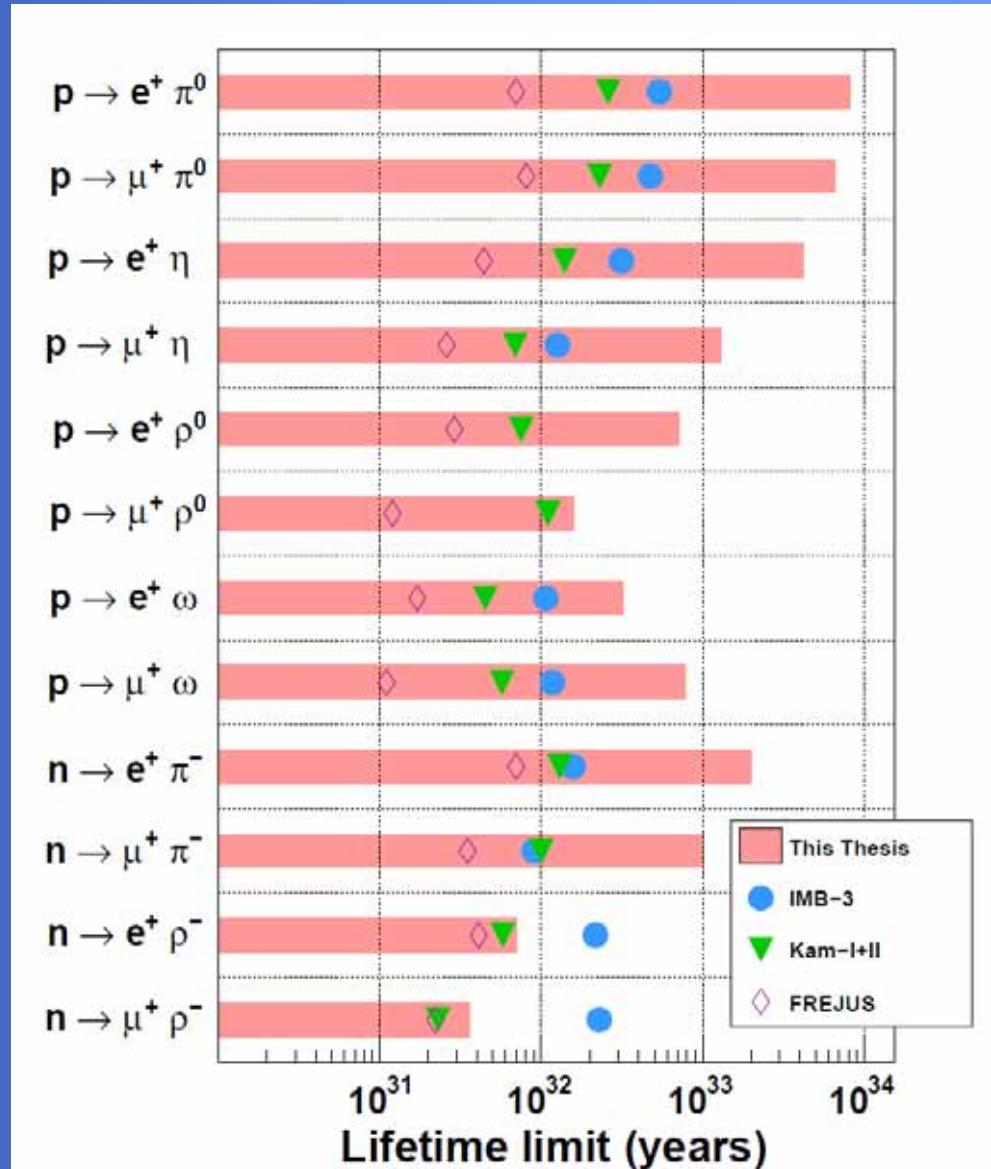
Lifetime limit:  $2.8 \times 10^{33}$  yrs @ 141 kton $\cdot$  yr  
 ⇔  $2.3 \times 10^{33}$  yrs @ 92 kton $\cdot$  yr in prev. paper (05')

# 5. Other modes

Nucleon => lepton + meson



- 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 SK-1 + SK-2 data, 141 kton· yrs in total exposure.
- We could **not find any evidences** of nucleon decay.
- We calculated nucleon lifetime limits with 90 % C.L.

$e^+\pi^0: > 8.2 \times 10^{33}$  yrs => publish soon!

$\nu K^+: > 2.8 \times 10^{33}$  yrs

Other lepton+meson :  $> 6.6 \sim 0.04 \times 10^{33}$  yrs

# Backup

# Future prospects

- BKG for  $e^+\pi^0$  :0.3 events/2288days  
 $\nu K^+$  :0.2 events (prompt  $\gamma$ )

Still low enough!

- SK-3 data will be open soon ( $\sim 560$  days).
  - At least, continue until T2K phase-I ( $> 5$  years)  
=> lifetime limit :2~3 times more.
- => Further study: Need to construct larger detector (Hyper-K).

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

Contribution to BG	
CCQE	28%
CC single $\pi$	32%
CC multi $\pi$	19%
other CC	2%
NC	19%

$\nu + N \rightarrow \text{lepton} + N^*; N^* \rightarrow N' + \text{meson}$

$\nu_e$  CC case, e and  $\pi^\pm, \pi^0$  are out-going particles.

$\nu + N \rightarrow \text{lepton} + p$

$\nu_e$  case, e and p are out-going particles and p interacts in water and make secondary  $\pi^0$ .

# Systematic error for $e^+\pi^0$ (Efficiency)

Detection Efficiency	SK-I	SK-II
<b>Total</b>	<b>19 %</b>	<b>19 %</b>
Nuclear Effect		15 %
Energy Scale	0.4 %	1.4 %
Un-uniformity of Detector Gain	0.7 %	0.5 %
PID	1.6 %	0.9 %
decay-e detection efficiency		
Fermi Momentum	8.2 %	8.7 %
Fraction of Correlated Decay	6.5 %	6.4 %
Fiducial Volume	3 %	2 %
Fitting Biases		
- Vertex	2.0 %	1.4 %
- Cherenkov Opening Angle	0.7 %	0.9 %
- Ring Counting	0.1 %	0.1 %
Exposure		
Live Time	< 1 %	



# Q. What are BKG for $\nu K^+$ mode ?

$K^+ \rightarrow \nu + \mu$

$\nu + N \rightarrow \text{lepton} + N^*; N^* \rightarrow N' + \text{meson}$ : 44%

Resonance  $N^*$  decays into  $K^+$ .

$\nu + N \rightarrow \text{charged lepton} + P$ : 17 %

Low  $P$  lepton, High  $P$  proton  
 $\Rightarrow$  VTX mis-reconstructed

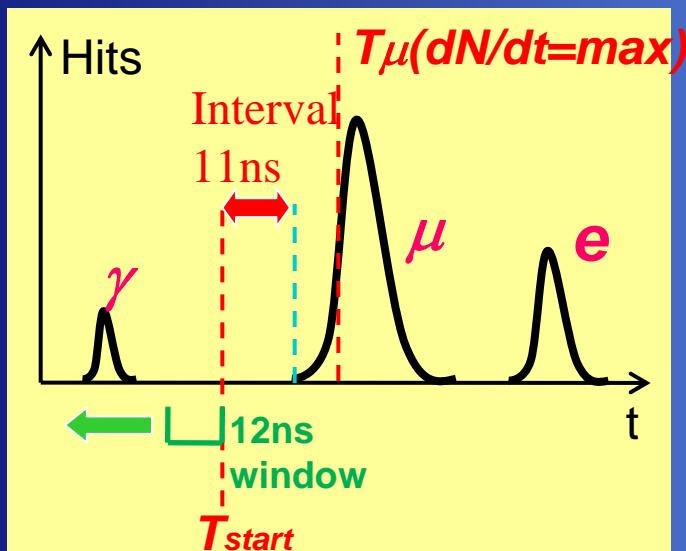
$K^+ \rightarrow \pi^+ + \pi^0$

$\nu + N \rightarrow \text{lepton} + N^*; N^* \rightarrow N' + \text{meson}$ : 63%

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

# Q. Why improvement in $\nu K^+$ mode is small ?

- Efficiency in SK2 is lower than SK-1 for  $\nu K$  mode.
- In SK-1 paper, BKG in prompt g method is 0.7.
- Selection is refined to get max S/N ratio.
- $T_{start}$  changed from 9 nsec to 11 nsec.



	Prev.	Now
Eff.(SK1)	8.6 %	7.2 %
BKG	0.7	0.16
BKG largely reduced but loose efficiency and limit became worse (2.3->2.0x10 <sup>33</sup> yrs for SK-1).		

# Contributions of 3 methods in vK<sup>+</sup> mode

Lifetime limit by single  
method ( $10^{33}$ yrs)

Spectrum fit : 0.6

Prompt  $\gamma$  : 1.2

$\pi^+\pi^0$  : 1.1

# Systematic error for $\nu K^+$ (Efficiency)

$\mu + \nu$ , prompt  $\gamma$  tag

	SK1	SK2
$\gamma$ -emission prob.	20.0	20.0
Energy scale	2.3	1.2
Tstart	7.6	8.2
PID	0.4	0.6
Ring count	1.5	1.1
Water parameter	3.0	2.6
Fiducial volume	3.0	3.0
Total	22.0	22.0

$\pi^+ \pi^0$

	SK1	SK2
$\pi$ -N crs in water	5.0	5.0
Energy scale	4.1	2.9
PID	2.0	3.0
Ring count	3.6	4.8
Water parameter	2.4	2.1
Fiducial volume	3.0	3.0
Total	8.6	8.9

# Lifetime limit calculation; Bayesian method

SK-1

SK-2

$$\mathbf{P}(\Gamma | n_1, n_2) = \frac{1}{A} \int \int \int \frac{e^{-(\Gamma \lambda_1 \epsilon_1 + b_1)} (\Gamma \lambda_1 \epsilon_1 + b_1)^{n_1}}{n_1!} \frac{e^{-(\Gamma \lambda_2 \epsilon_2 + b_2)} (\Gamma \lambda_2 \epsilon_2 + b_2)^{n_2}}{n_2!} \times \mathbf{P}(\Gamma) \mathbf{P}(\delta_\epsilon) \mathbf{P}(\delta_\lambda) \mathbf{P}(\delta_b) d\delta_\epsilon d\delta_\lambda d\delta_b.$$

$$CL(0.9) = \int_0^{\Gamma_{limit}} P(\Gamma | n_1, n_2) d\Gamma$$

$\Gamma$ : decay rate ( $=1/\tau$ )

$\lambda$ : exposure

$\epsilon$ : detection efficiency

b: number of BG events

n: candidate

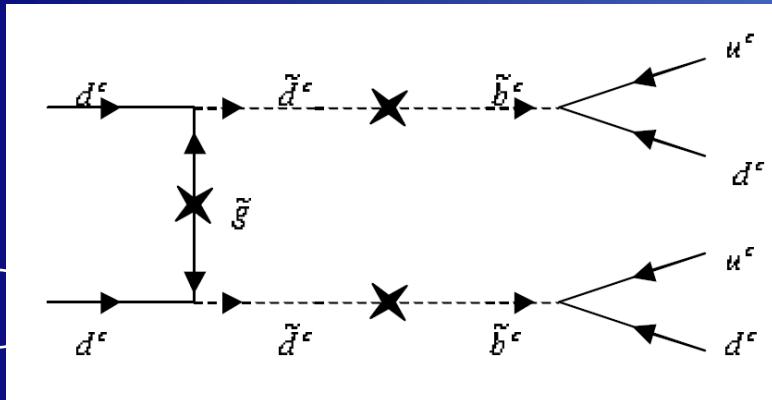
Assuming Eff, BKG, exposure are gaussian.

# neutron anti-neutron oscillation

- motivation

- Several types of (B-L)-violating Gauge theories predicts that neutron spontaneously converts to anti-neutron, and vice versa

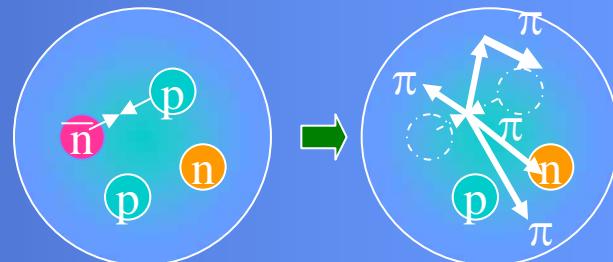
$\Leftrightarrow n - \bar{n}$  oscillation



Branching ratio derived from  
Bubble Chamber p + d  $\bar{d}$  data

- expected signal

- anti-neutron annihilates with  $n$  or  $p$ .



- pions are emitted isotropically with high multiplicity ( $>\sim 4\pi$ )

$\bar{n} + p$

$\bar{n} + n$

$\pi^+ \pi^0$	1%
$\pi^+ \pi^0 \pi^0$	8%
$\pi^+ \pi^0 \pi^0 \pi^0$	10%
$\pi^+ \pi^+ \pi^- \pi^0$	22%
$2\pi^+ \pi^- 2\pi^0$	36%
$2\pi^+ \pi^- \omega$	16%
$3\pi^+ 2\pi^- \pi^0$	7%

$\pi^+ \pi^-$	2%
$\pi^0 \pi^0$	1.52%
$\pi^+ \pi^- \pi^0$	6.48%
$\pi^+ \pi^- \pi^0 \pi^0$	11%
$\pi^+ \pi^- \pi^0 \pi^0 \pi^0$	28%
$2\pi^+ 2\pi^-$	7%
$2\pi^+ 2\pi^- \pi^0$	24%
$\pi^+ \pi^- \omega$	10%
$2\pi^+ 2\pi^- \pi^0 \pi^0$	10%



# $n - \bar{n}$ search result

$n \rightarrow \bar{n}$  transition probability ,  $P(\Gamma|n)$  is calculated by Bayesian statistics and Bayesian theorem.

$$T_{\text{bound}} = \frac{1}{\Gamma_{\text{limit}}}$$

**$> 1.97 \times 10^{32} \text{ yrs (90\% CL) (SK-I)}$**

(preliminary)



Bound neutron lifetime can be interpreted to the oscillation time of the free neutron by

$$T_{\text{bound}} = R \times (\tau_{\text{free}})^2$$

$$\tau_{\text{free}} > 2.49 \times 10^8 \text{ sec}$$

(preliminary)

used the suppression factor  $R$   
calculated by Dover et al.  
Phys. Rev. D27 (1983) 1090

## Previous limits

Kamiokande:

$$\tau_{\text{free}} > 1.2 \times 10^8 \text{ sec}$$

IMB:

$$\tau_{\text{free}} > 0.88 \times 10^8 \text{ sec}$$

ILL Beam experiment:  $\tau_{\text{free}} > 0.86 \times 10^8 \text{ sec}$

**Theoretical upper limit  $< 10^9 \sim 10^{10} \text{ sec (K.S.Babu et al., Phys.Lett.B 518(2002)269)}$**

