Nucleon Decay Searches (current status and future prospect)

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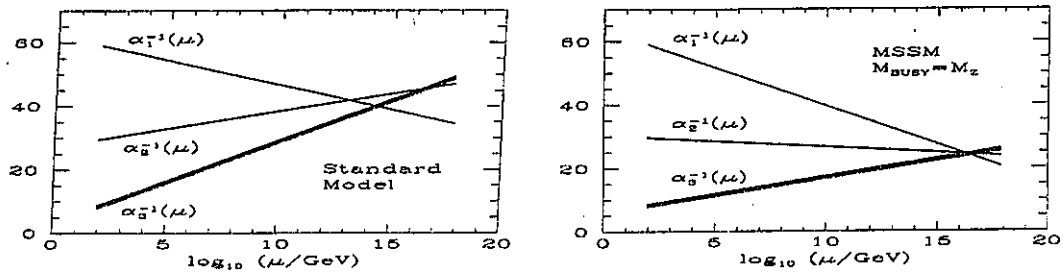
- Super-K results
  - $p \rightarrow e^+ \pi^0$
  - $p \rightarrow \nu K^+$
  - others
- Next Generation Detector
- Summary

Introduction

Physics motivation

- Indication of unification scale at 10^{16} GeV



- ν oscillations also indicate $\sim 10^{15}$ GeV

  see-saw mechanism $\rightarrow$

$$\frac{1}{M} = \frac{m_\nu}{v^2} = \frac{\sqrt{3\times10^{-3}(\mathrm{eV}^2)}}{(250\mathrm{GeV})^2} = \frac{1}{1\times10^{15}\mathrm{GeV}}$$

- Proton Decay — Only experimental access to 10^{16} GeV !

Predicted lifetime of nucleon

- 4 fermion interactions

$$\Gamma = \frac{g^4 m_p^4}{M_X^4} \quad : \quad \underline{\tau(p\rightarrow e^+\pi^0) = 10^{35\pm1}\ \text{years}}$$

- 2 fermion – 2 sfermion interactions (SUSY models)

$$\Gamma = \frac{h^4 m_p^4}{M_{H\tilde{x}}^2\ M_X^2} \quad : \quad \underline{\tau(p\rightarrow K^+\overline{\nu}) = 10^{29-35}\ \text{years}}$$

Nucleon decay search experiments

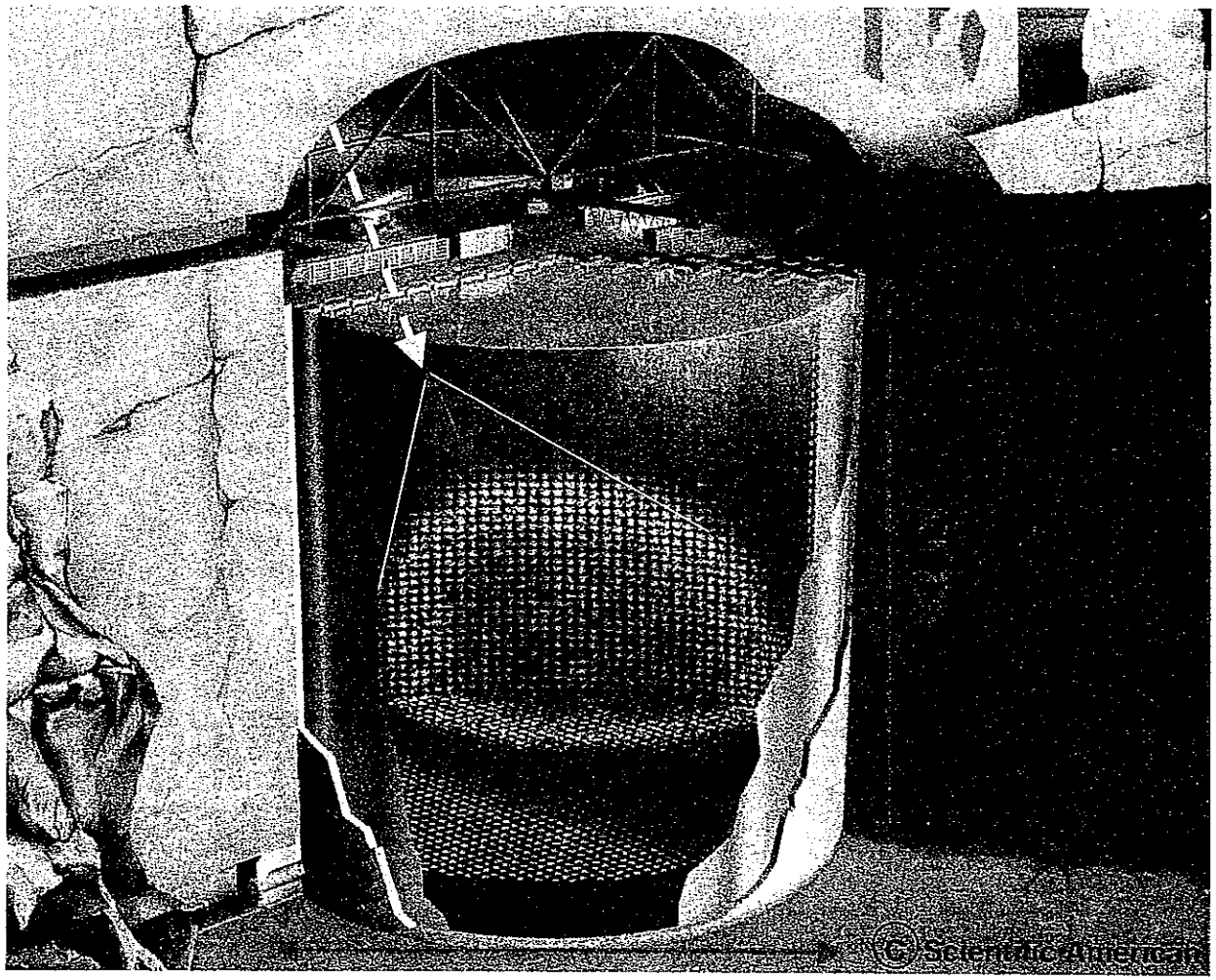
- Water Cherenkov detector

  Large size with reasonable cost. $\rightarrow$ Super—Kamiokande

- Iron calorimeter

  Good spacial resolution. Kaon is visible. $\rightarrow$ Soudan 2

Super-Kamiokande detector



39.3 m

Water Cherenkov detector

- 1000 m underground
- 50,000 ton (22,500 ton fid.)
- 11,146 20 inch PMTs
- 1,885 anti-counter PMTs

- vertex position
- each particle momentum
- each particle type (e or μ)
- # of μ decay

Details of the Super-K detector

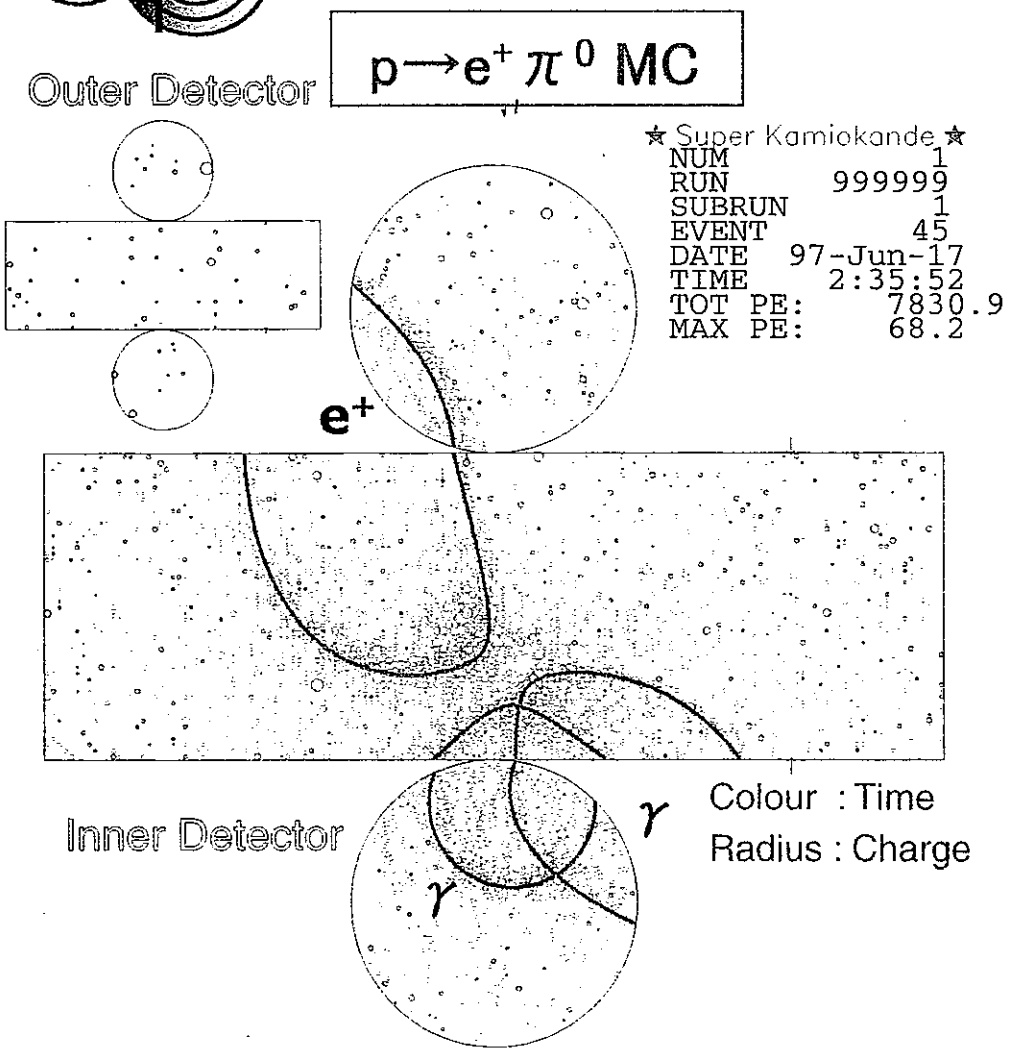
Source H_2O

- 22.5 kton →~8×10^{33} protons
- 2/10 free proton
  - →no nuclear effect
    accurate high efficiency
  - → no Fermi motion
    good momentum valance

Performance

- Vertex resolution: ~30 cm (1-ring)
  :~15 cm($p \rightarrow e^+ \pi^0$)
- Trigger threshold: ~5 MeV e
  →trigger ε =100% for
  most of nucleon decay modes
- Energy resolution:
  $\Delta E/E$ = ~3% for 1GeV e, μ
  = ~4% for 236MeV μ
- Energy stability : ±1%
- Partile ID : ~99% 1-ring μ, e
  : >97% $p \rightarrow e^+ \pi^0$, $p \rightarrow \mu^+ \pi^0$

$p \to e^+ \pi^0$, $p \to \mu^+ \pi^0$ @Super-K



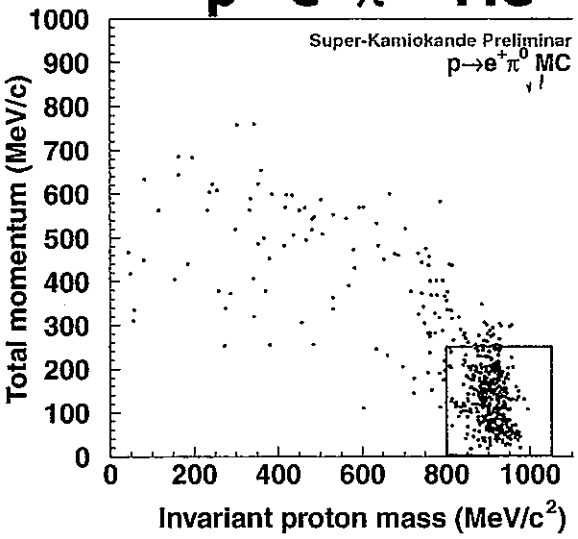
Criteria for $p \to e^+ \pi^0$ ($p \to \mu^+ \pi^0$)

- 2 or 3 Cherenkov rings
- All rings are showering
  (1 non-showering and others are showering)
- $85 < M_{\pi^0} < 185 MeV/c^2$ (3-ring)
- No decay electron
  (1 decay electron)
- $800 < M_p < 1050\ MeV/c^2$
  $P_{tot} < 250\ MeV/c$

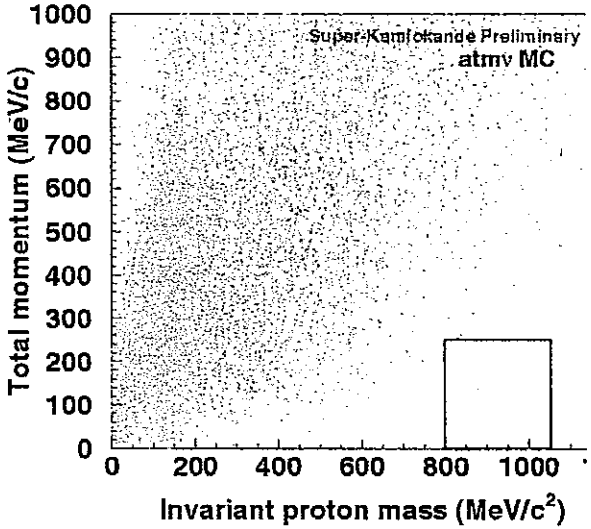
results on $p \rightarrow e^+ \pi^0$ search

1289 days (79.3 ktyr exposure)

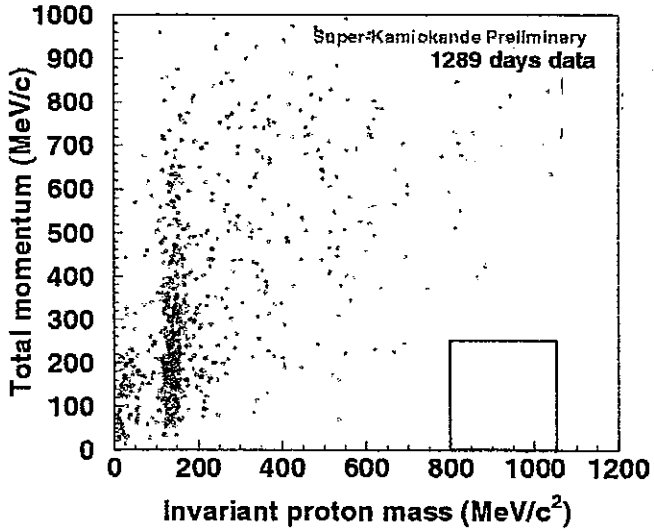
$p \rightarrow e^+ \pi^0$ MC



atm ν BG MC



data



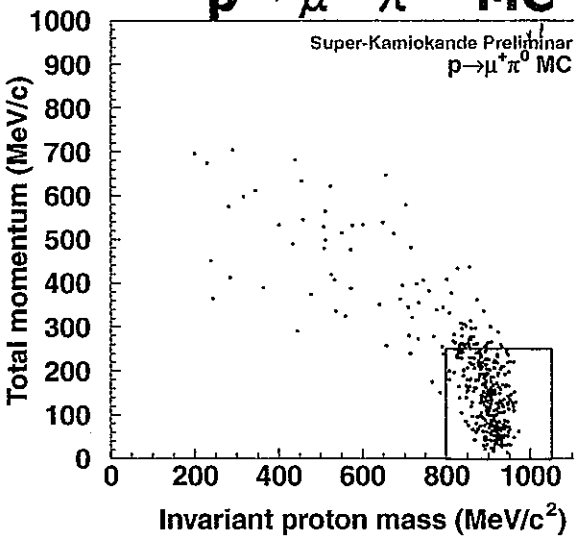
$\varepsilon = 43\ \%$ 0.2 exp'd BG 0 candidate

$$\tau_p / B(p \rightarrow e^+ \pi^0) > 5.0 \times 10^{33} \text{ years (90\% CL)}$$

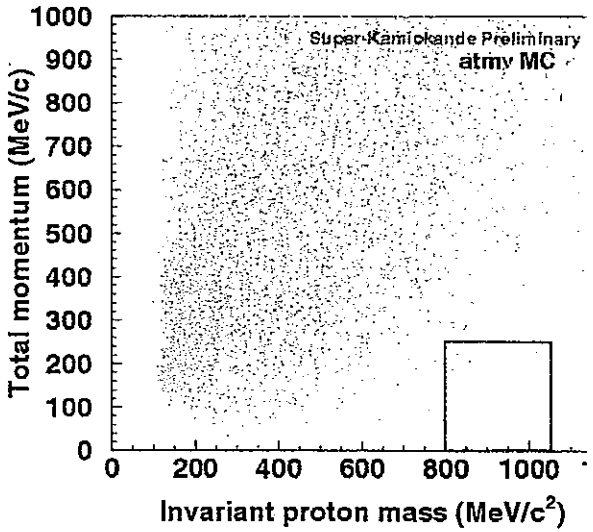
results on $p \to \mu^+ \pi^0$ search

1289 days (79.3 ktyr exposure)

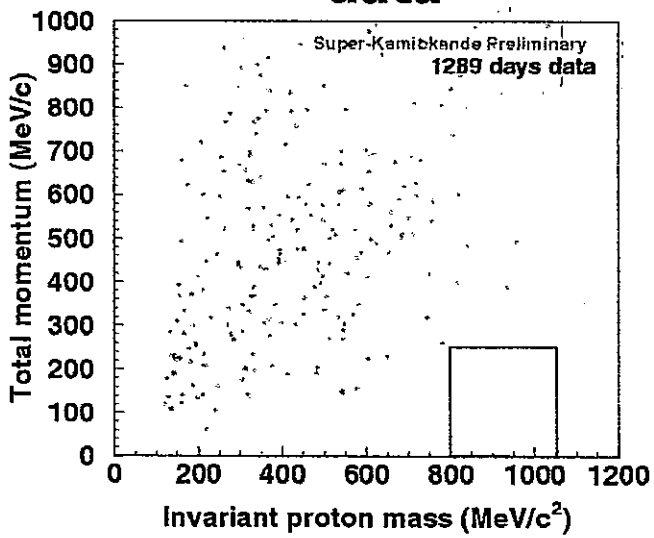
$p \to \mu^+ \pi^0$ MC



atm ν BG MC



data



ε = 32 % 0.4 exp'd BG 0 candidate

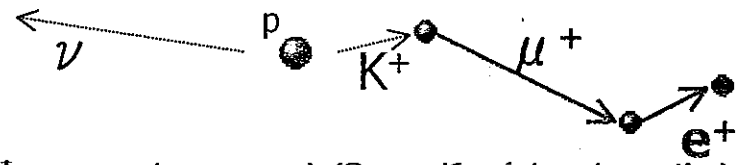
$$\tau_p / B(p \to \mu^+ \pi^0) > 3.7 \times 10^{33} \text{ years (90\% CL)}$$

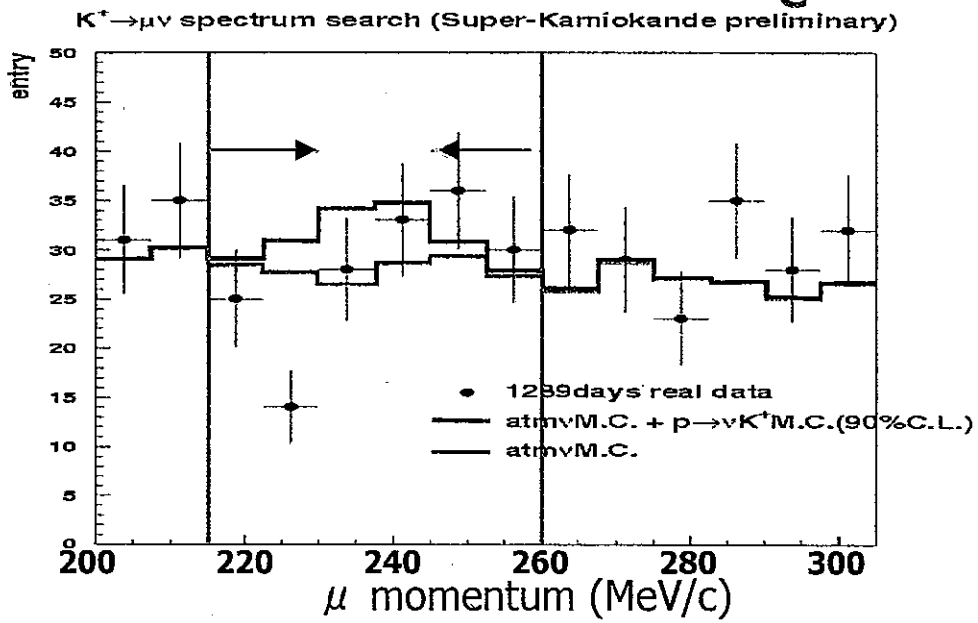
$p \rightarrow \nu K^+, K^+ \rightarrow \mu^+ \nu$ search

Br($K^+ \rightarrow \mu^+ \nu$)=63%

- 1 μ and 1 decay electron
- $215 < P_\mu < 260$ MeV/c

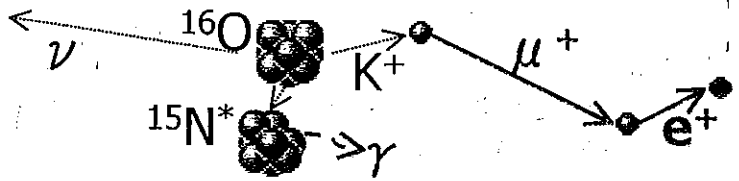
Method I (spectrum fit)

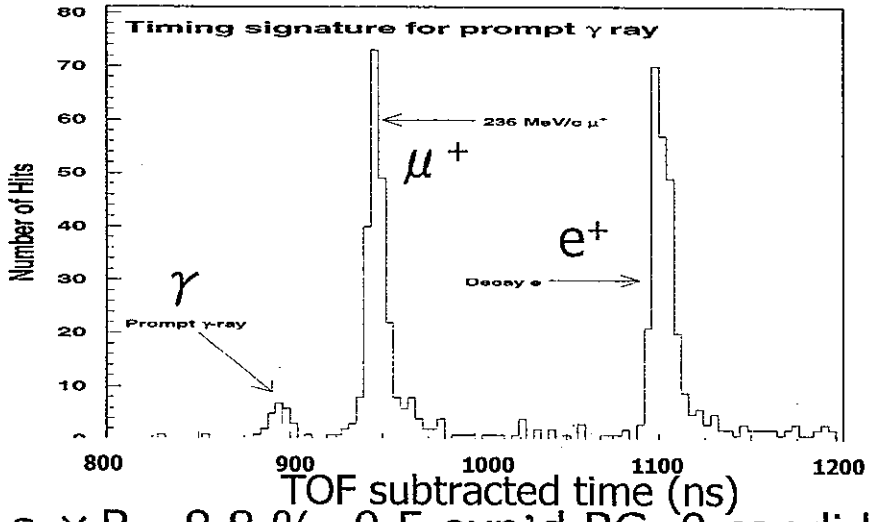




$\tau_p / B(p \rightarrow \nu K^+) >$
4.4×10^{32} years (90% CL)

Method II (prompt γ tag)





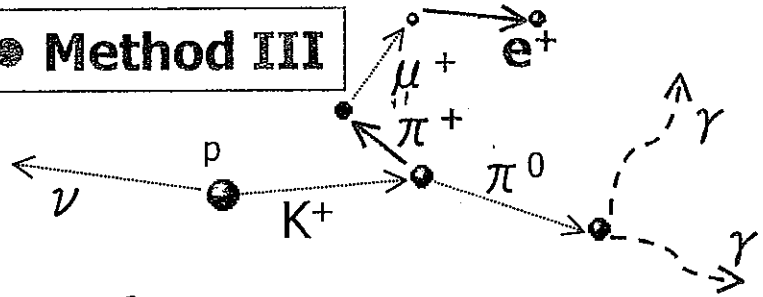
$\varepsilon \times B = 8.8$ %, 0.5 exp'd BG, 0 candidate

$\tau_p / B(p \rightarrow \nu K^+) >$
1.0×10^{33} years (90% CL)

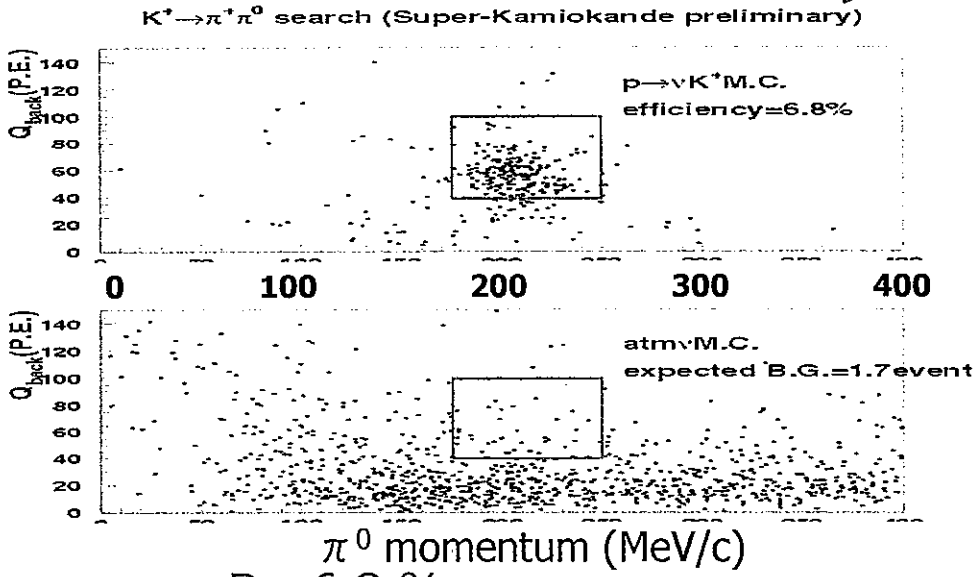
$p \rightarrow \nu K^+, K^+ \rightarrow \pi^+ \pi^0$ search

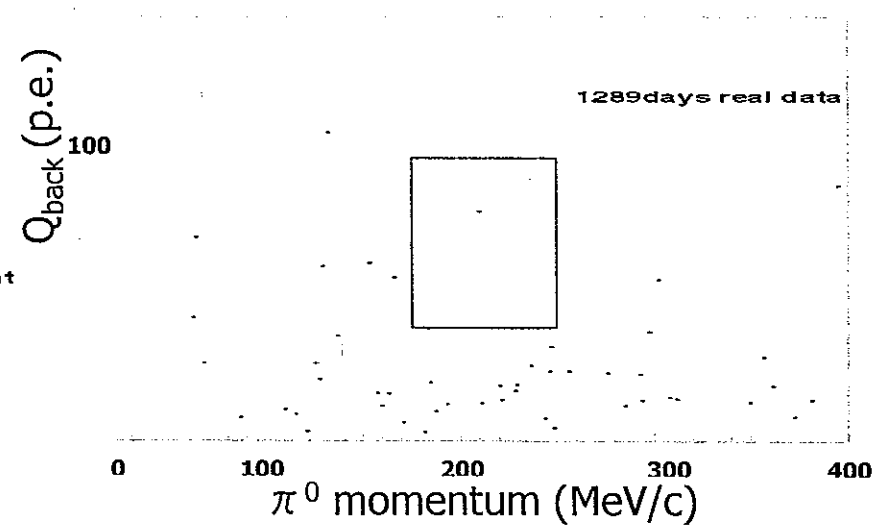
Br($K^+ \rightarrow \pi^+ \pi^0$)=21%

● Method III



- 2 showering Cherenkov rings
- 1 decay electron
- $85 < M_{\pi 0} < 185$ MeV/c^2
- $175 < P_{\pi 0} < 250$ MeV/c
- tag π^+ ($40 < Q_{back} < 100$ p.e.)





$\varepsilon \times B = 6.8$ %,

1.7 exp'd BG, 1 candidate $\tau_p / B(p \rightarrow \nu K^+) > 5.9 \times 10^{32}$ years (90% CL)

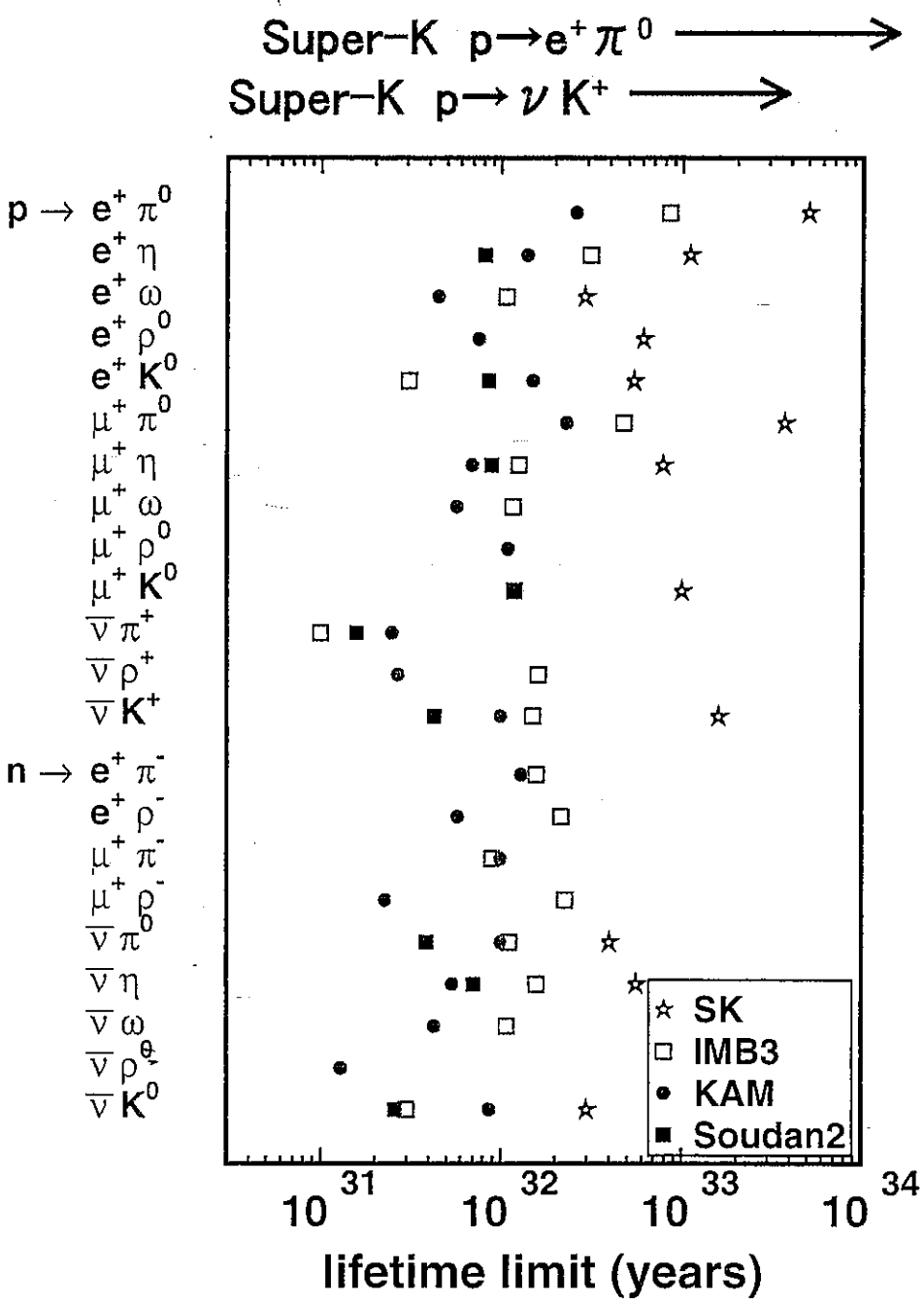
combined limit $\tau_p / B(p \rightarrow \nu K^+) > 1.6 \times 10^{33}$ years (90% CL)

Nucleon decay searches in Super-K

Summary of Nucleon Decay Searches

mode	exposure (kt• yr)	εB_m (%)	observed event	B.G.	τ/B limit (10^{32} yrs)
$p \to e^+ + \pi^0$	79	43	0	0.2	50
$p \to \mu^+ + \pi^0$	79	32	0	0.4	37
$p \to e^+ + \eta$	45	17	0	0.3	11
$p \to \mu^+ + \eta$	45	12	0	0	7.8
$n \to \overline{\nu} + \eta$	45	21	5	9	5.6
$p \to e^+ + \rho$	61	6.8	0	0.6	6.1
$p \to e^+ + \omega$	61	3.3	0	0.3	2.9
$p \to e^+ + \gamma$	70	71	0	0.1	73
$p \to \mu^+ + \gamma$	70	60	0	0.2	61
$p \to \overline{\nu} + K^+$	79				16
$K^+ \to \nu\mu^+$ (spectrum)		33	--	--	4.4
prompt $\gamma + \mu^+$		8.8	0	0.5	10
$K^+ \to \pi^+\pi^0$		6.8	0	1.7	5.9
$n \to \overline{\nu} + K^0$	79				3.0
$K^0 \to \pi^0\pi^0$		9.6	25	33.8	3.2
$K^0 \to \pi^+\pi^-$		4.6	10	6.7	1.1
$p \to e^+ + K^0$	70				5.4
$K^0 \to \pi^0\pi^0$		11.8	1	1.4	8.8
$K^0 \to \pi^+\pi^-$					
2-ring		6.2	6	1.0	1.5
3-ring		1.4	0	0.2	1.4
$p \to \mu^+ + K^0$	70				10
$K^0 \to \pi^0\pi^0$		6.1	0	1.1	6.2
$K^0 \to \pi^+\pi^-$					
2-ring		5.3	0	1.5	5.4
3-ring		2.8	1	0.2	1.8

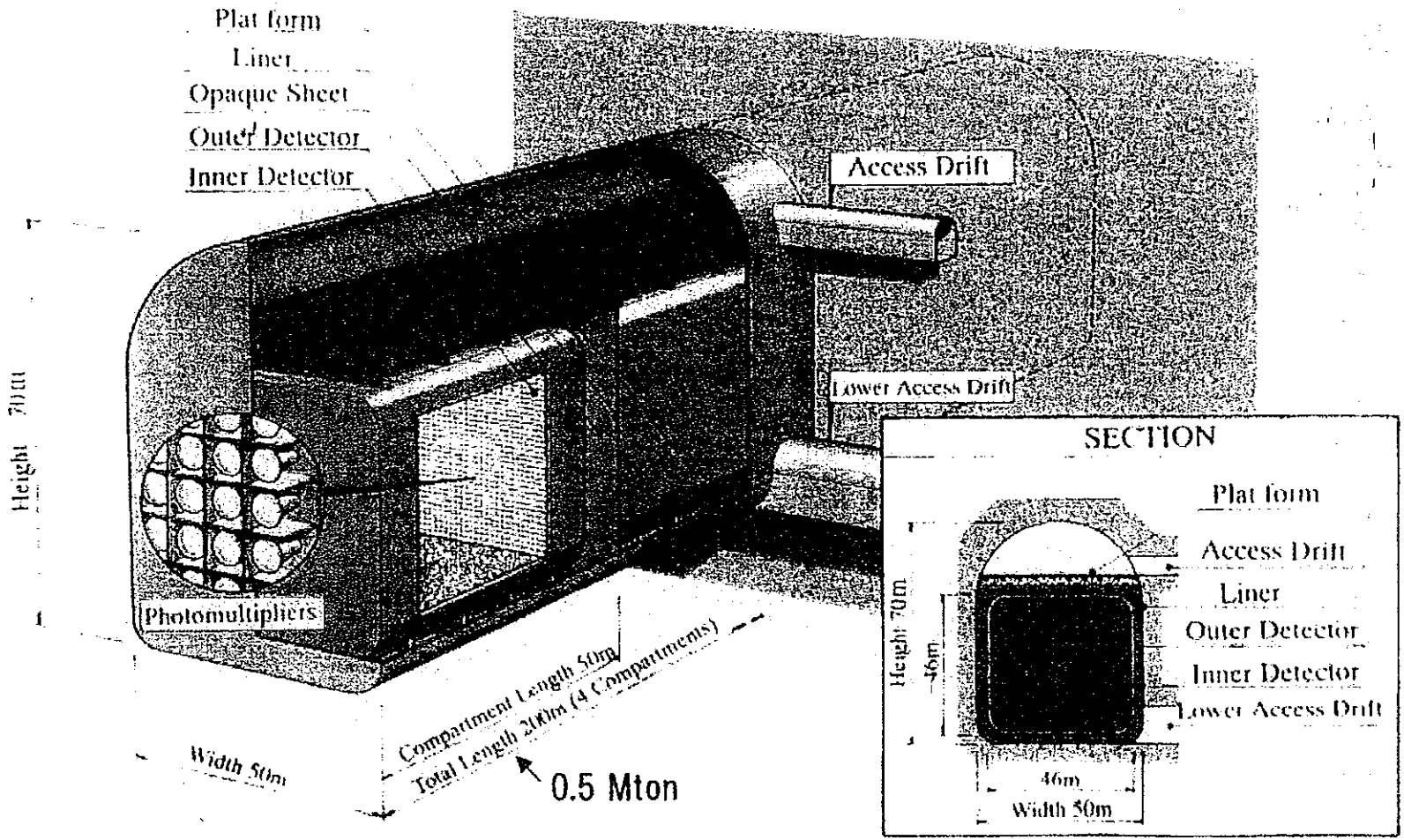
Summary of nucleon lifetime limit



No evidence for nucleon decay so far

Need to keep watching nucleons
Start to consider next generation detector

Linear Hyper-Kamiokande



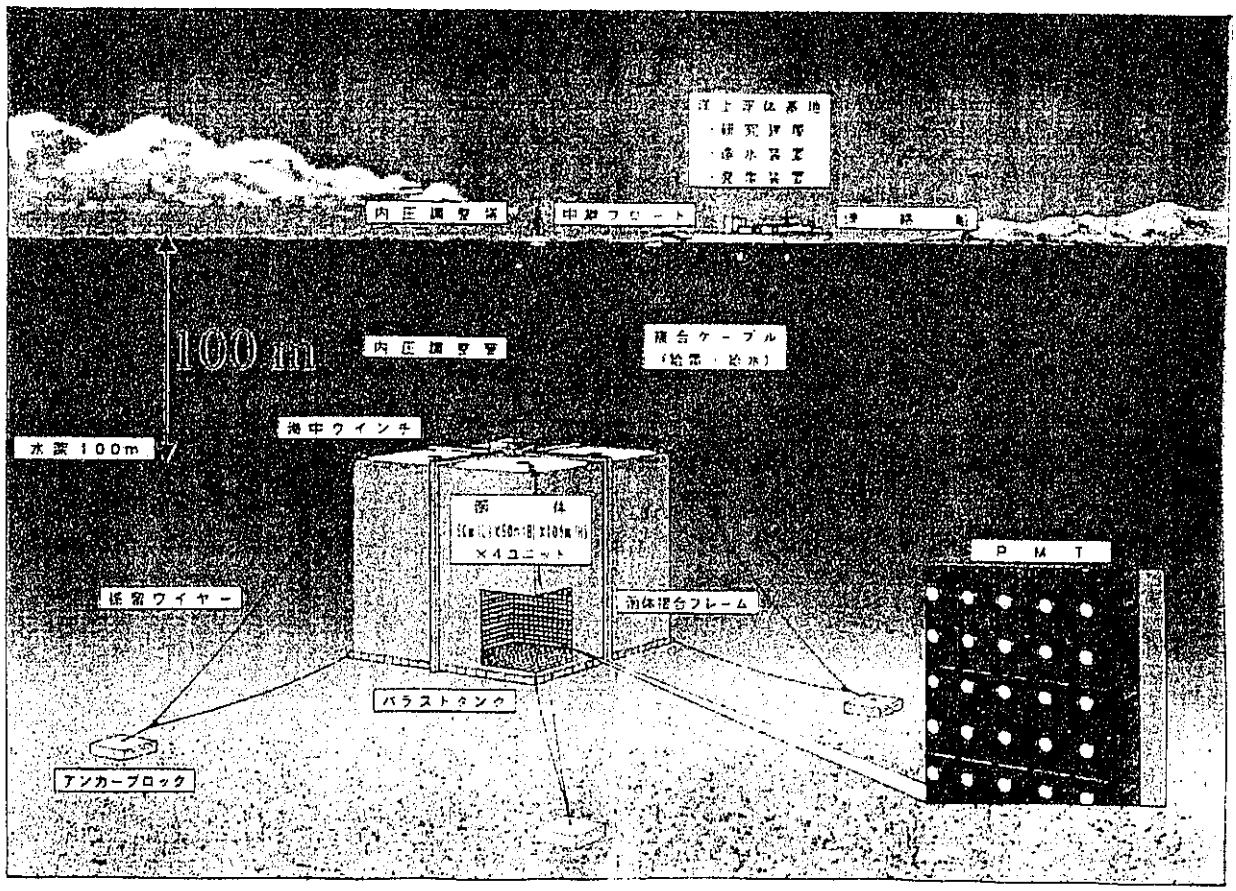
1 Mton: Total Length 400m (8 Compartments)

(STRAIGHT TYPE)

Detector

1) 50m x 50m x 100m x 4 units = 1.0 Mton
(0.813 Mton fiducial : SK x 36)

2) 70m x 70m x 100m x 4 units = 1.96 Mton
(1.673 Mton fiducial : SK x 74)
→ close to the maximum size
→ add one more module → ~ 4Mton

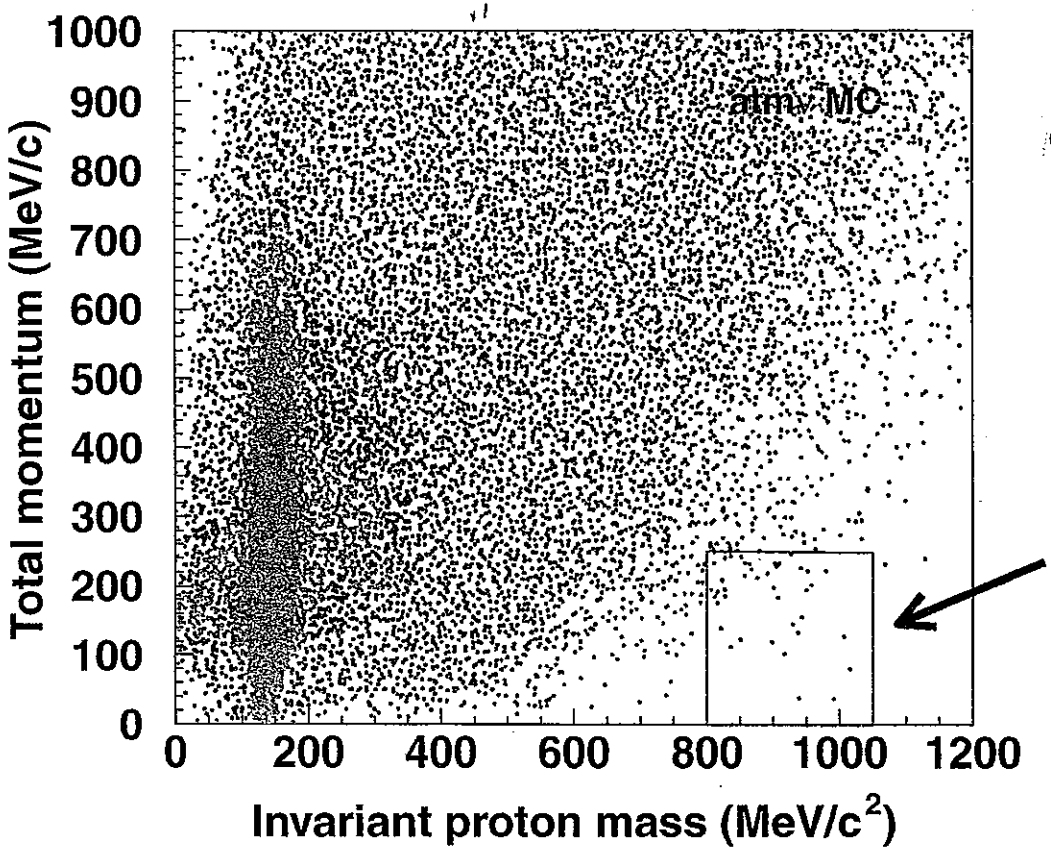


浮沈式陽子崩壊実験装置イメージ図

For 1 Mton module
Steel + epoxy lining
29,000 tons
4 units

→ **Balance to the buoyancy force**

Background sample for $p \rightarrow e^+ \pi^0$



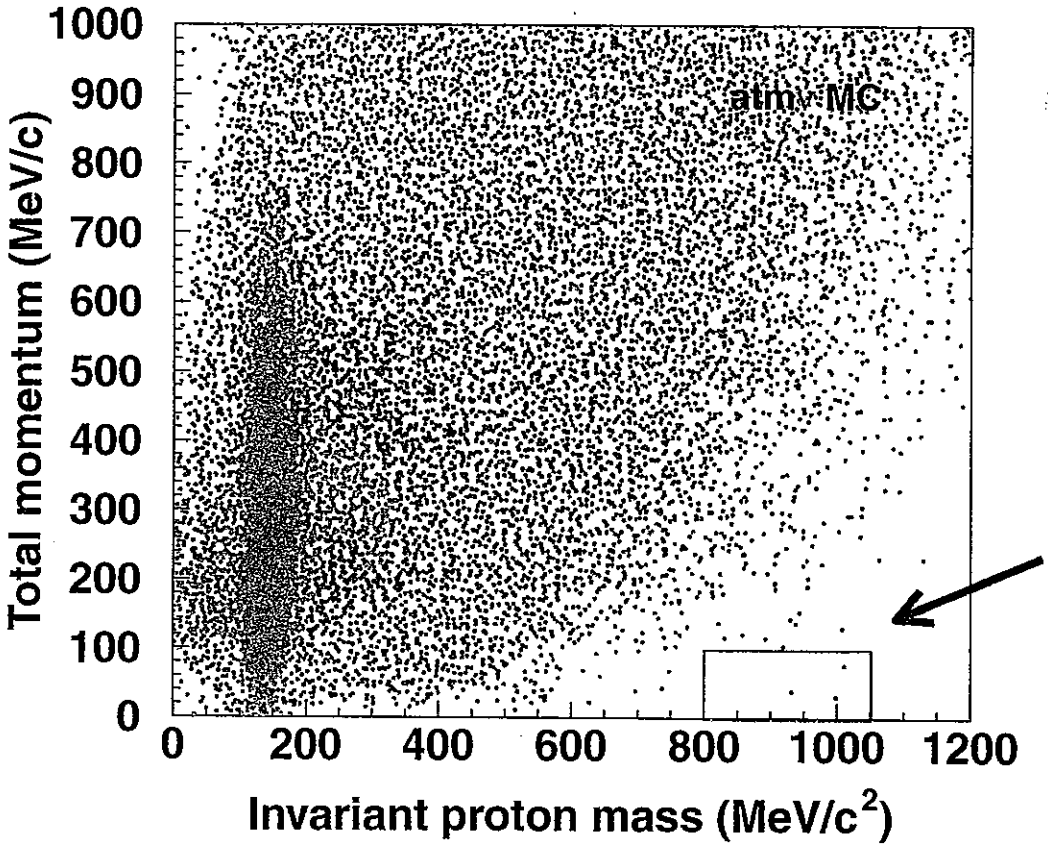
- Use established tools
  - neut (ν interaction simulator)
  - SK detector simulator
- pre-reductions
  - CC quasi-elastic
  - ν_μ CC
    - μ PID rejection $\varepsilon \sim 98\%$
    - decay electron $\varepsilon \sim 70\%$

BG events in signal box
45 events/20 Mton·yr

~2.2 events/Mton·yr

Analysis for discovery of $p \rightarrow e^+ \pi^0$

1 Tight momentum cut to reduce BG



- $P_{tot} < 250$ MeV/c
- ↓
- $P_{tot} < 100$ MeV/c

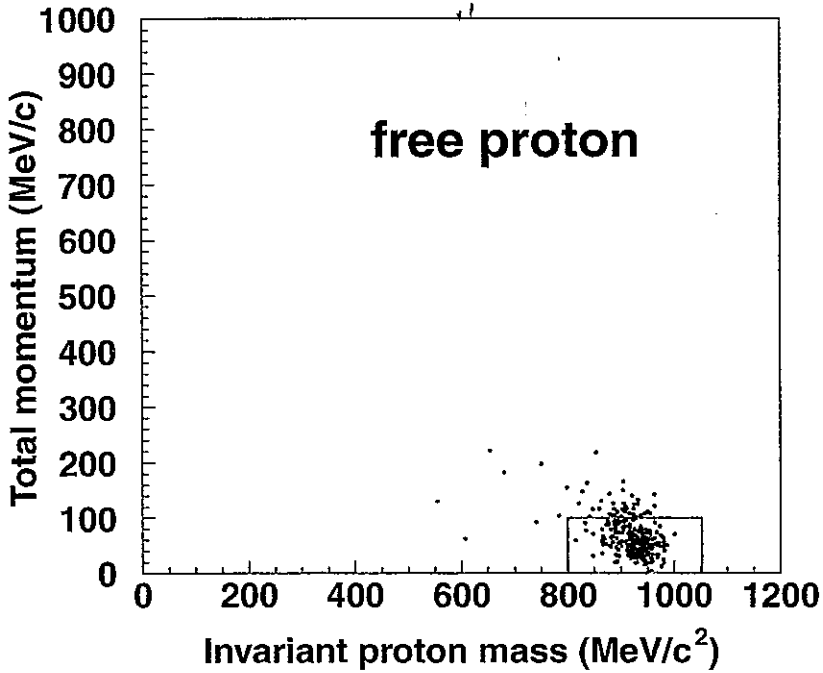
BG events in signal box
3 events/20 Mton·yr

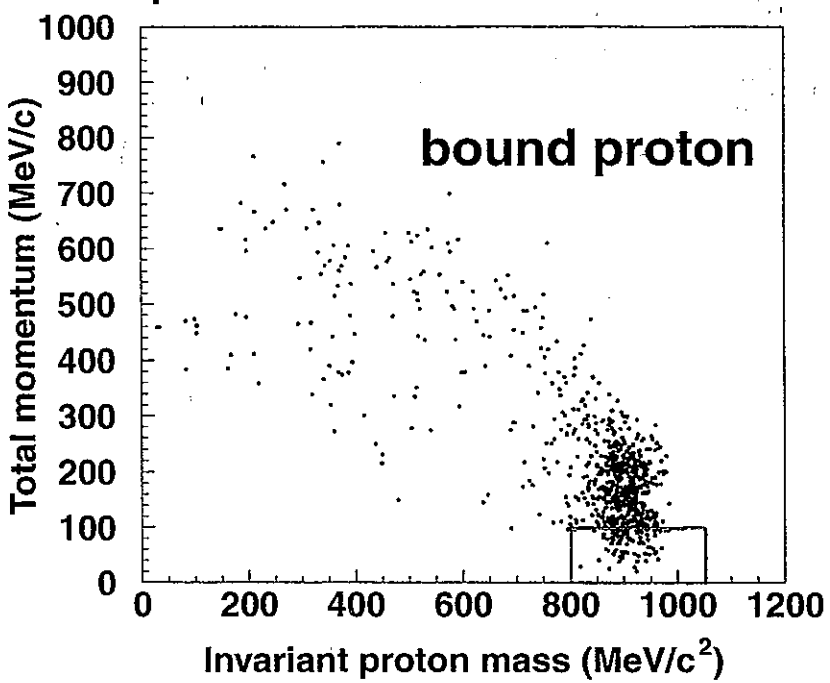
~0.15 events/Mton·yr

Analysis for discovery of $p \rightarrow e^+ \pi^0$

Tight momentum cut to reduce BG

⇒ target is mainly free protons



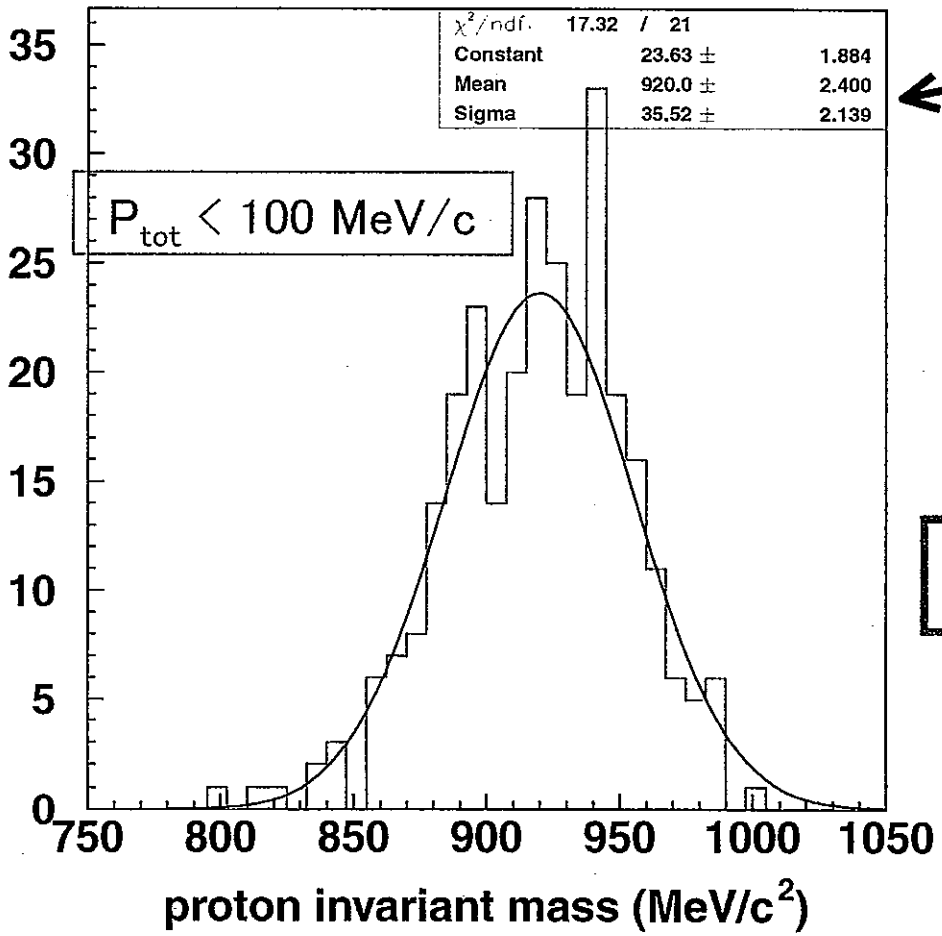


No Fermi momentum
No binding energy
No nuclear effect

⇒ Small systematic uncertainty of detection efficiency perfectly known proton mass and momentum

Analysis for discovery of $p \rightarrow e^+ \pi^0$

2 peak of invariant proton mass

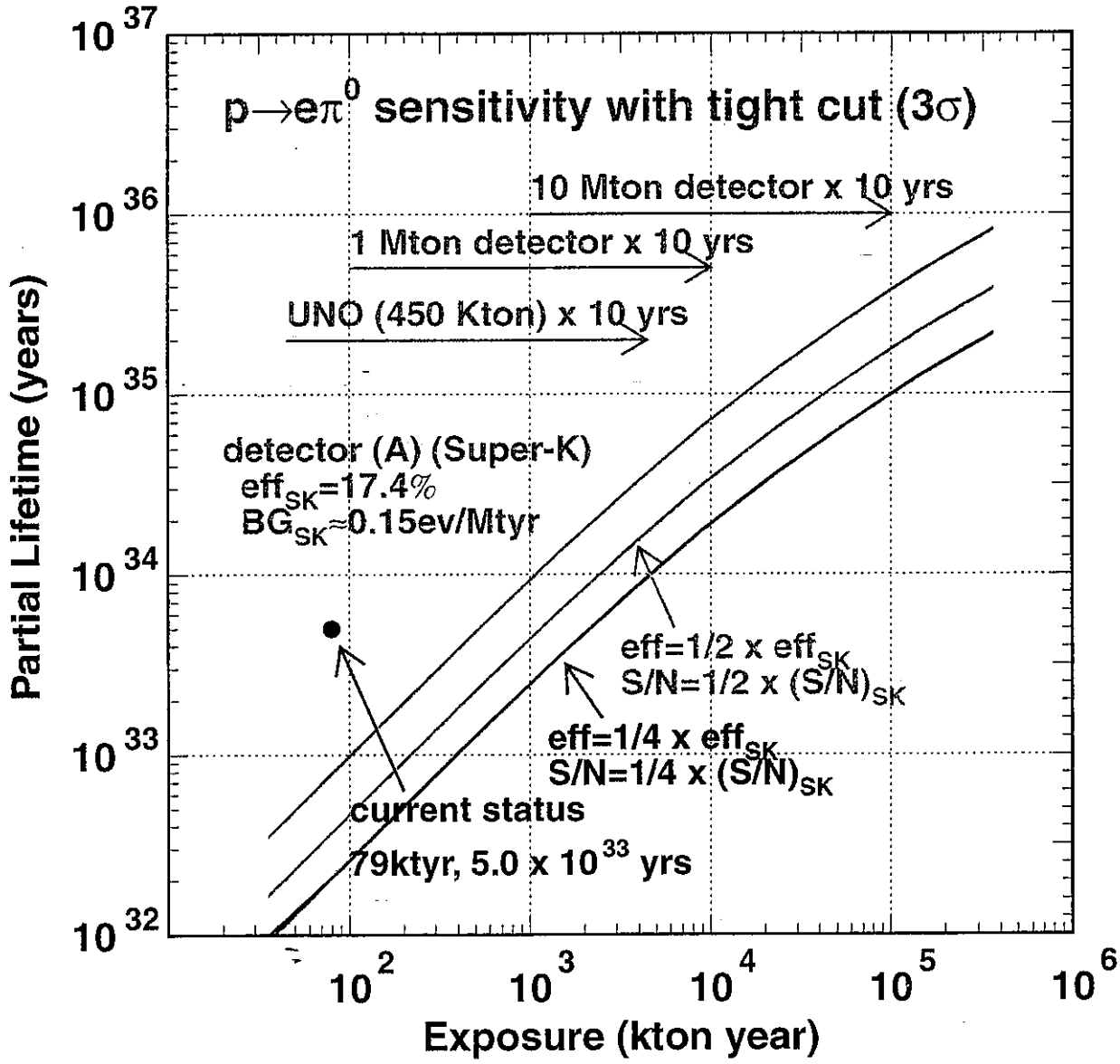


Good mass resolution
$\Delta M/M = 4\%$

Observing mass peak at M_p

Evidence of proton decay!

Lifetime sensitivity with tight cut

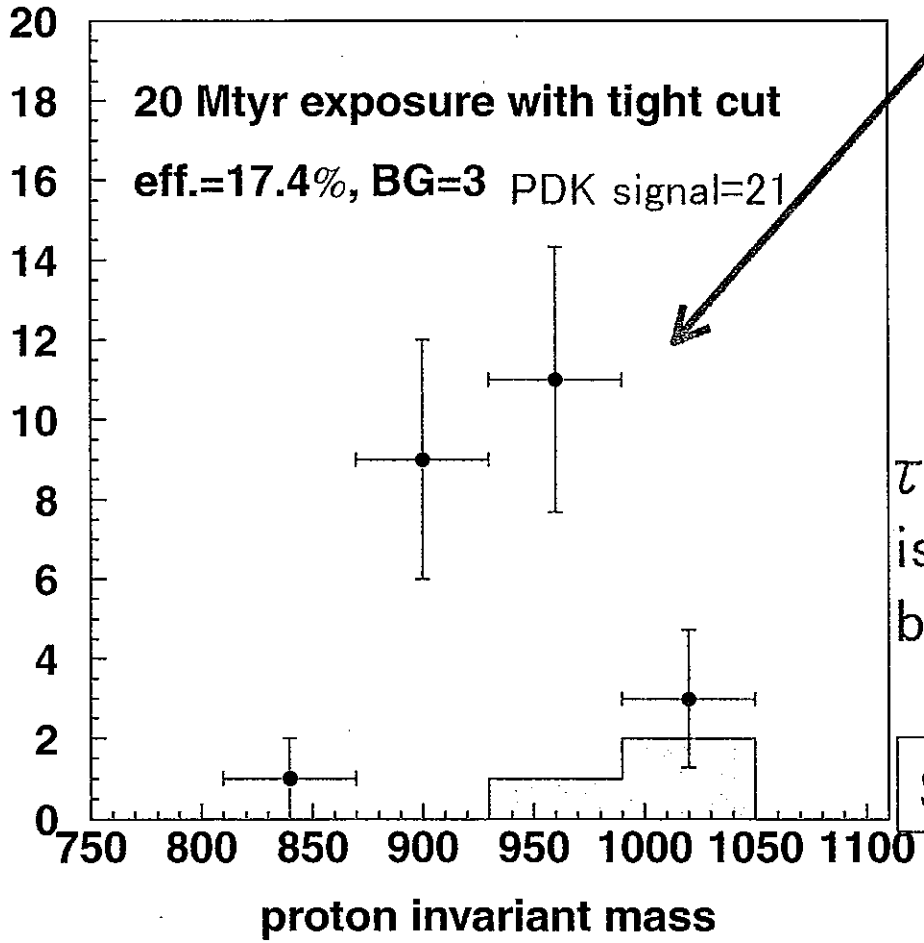


With 3σ (99.73%) level

- 1Mton $\times$10 years $\rightarrow$ $\sim 7 \times 10^{34}$ years lifetime
- 10Mton $\times$10 years $\rightarrow$ $\sim 4 \times 10^{35}$ years lifetime

How the signal looks like

$\tau_p/B(p\rightarrow e^+\pi^0) = 1\times10^{35}$ years



Proton mass peak can be observed !

S/N = 7 for 1×10^{35} years

↓

S/N = 1 for 7×10^{35} years

$\tau_p/B(p\rightarrow e^+\pi^0)$ = several $\times10^{35}$ yrs is reachable by water Cherenkov detector

Several Mton detector is needed.

Backgrounds in p→ ν K^+ searches

K.Kobayashi

1. prompt γ ~6 events/Mtyr ➡ most are misfitted vertex events
   μ spectram 2100 events/Mtyr (single-ring μ, π, proton)
   $\pi^+\pi^0$ ~22 events/Mtyr

   ⬇

   we should reject them by improved vertex fitter

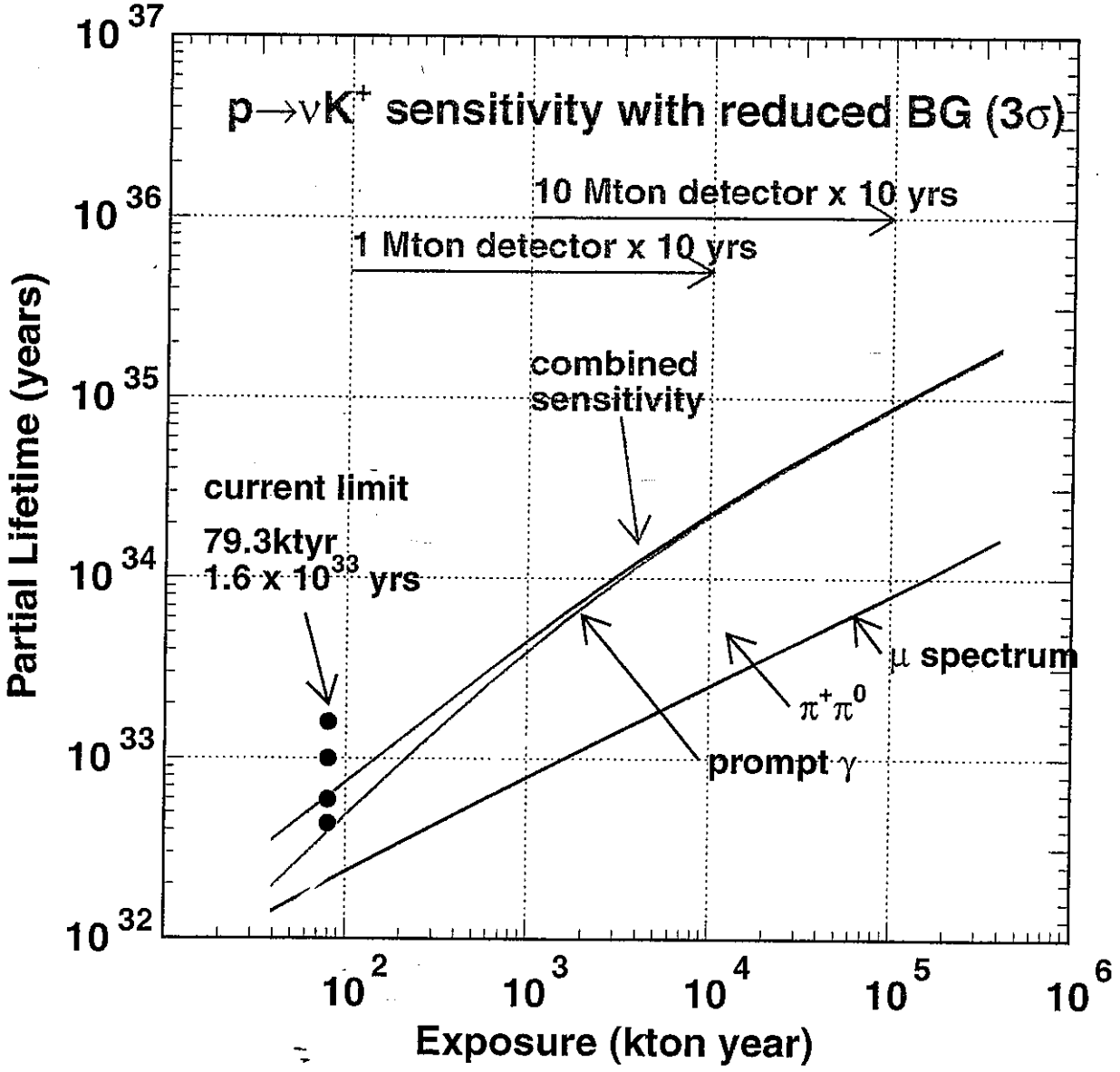
2. K^+ production by atm ν

   $\nu N \rightarrow \nu N^* \rightarrow \Lambda K^+$

   ~1 events/Mtyr (after pdecay cut) ➡ **very serious backgrounds if both Λ and K^+ are invisible**

3. other unknown background?

Lifetime sensitivity with reduced BG



Prompt γ tagging is essential

With 3σ (99.73%) level

- 1Mton ×10 years → ~2×10^{34} years lifetime
- 10Mton×10 years → ~8×10^{34} years lifetime

Summary

- No evidence for nucleon decays so far
  - $\tau_p/B(p \rightarrow e^+ \pi^0) > 5.0 \times 10^{33}$ years (90% CL)
  - $\tau_p/B(p \rightarrow \nu K^+) > 1.6 \times 10^{33}$ years (90% CL)
- We have chance to observe unequivocal evidence for $p \rightarrow e^+ \pi^0$
  - Target is the decay of free protons with ~0.15 BG/Mtyr
  - multi-Mton volume is desired for over 10^{35} years lifetime
- 10^{34} years lifetime can be tested for $p \rightarrow \nu K^+$
  - serious background would appear over 10^{34} years