



Mini-review on nucleon decay

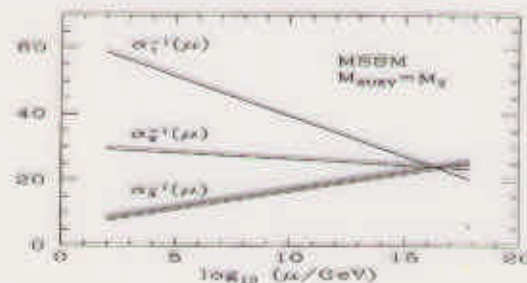
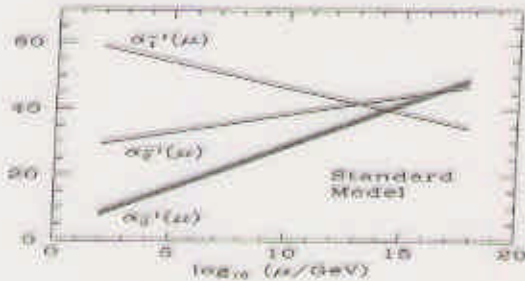
Kamioka Observatory Masato Shiozawa

- Introduction
- Experimental Results
 - Super-Kamiokande
 - Soudan 2
- Summary

Introduction

Physics motivation

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



- ν oscillations also indicate $\sim 10^{16}$ GeV

see-saw mechanism \rightarrow

$$\frac{1}{M} = \frac{m_\nu}{v^2} = \frac{\sqrt{3 \times 10^{-3} (\text{eV}^2)}}{(250 \text{ GeV})^2} = \frac{1}{1 \times 10^{15} \text{ GeV}}$$

- Beautiful unification models (GUTs)

Predicted lifetime of nucleon

- 4 fermion interactions

$$\Gamma = \frac{g^4 m_p^4}{M_X^4} : \quad \tau(p \rightarrow e^+ \pi^0) = 10^{36 \pm 1} \text{ years}$$

- 2 fermion – 2 sfermion interactions (SUSY models)

$$\Gamma = \frac{h^4 m_p^4}{M_{\text{Hx}}^4 M_X^4} : \quad \tau(p \rightarrow K^+ \bar{\nu}) = 10^{29-35} \text{ years}$$

Nucleon decay search experiments

- Water Cherenkov detector

Large size with reasonable cost. \rightarrow Super-Kamiokande

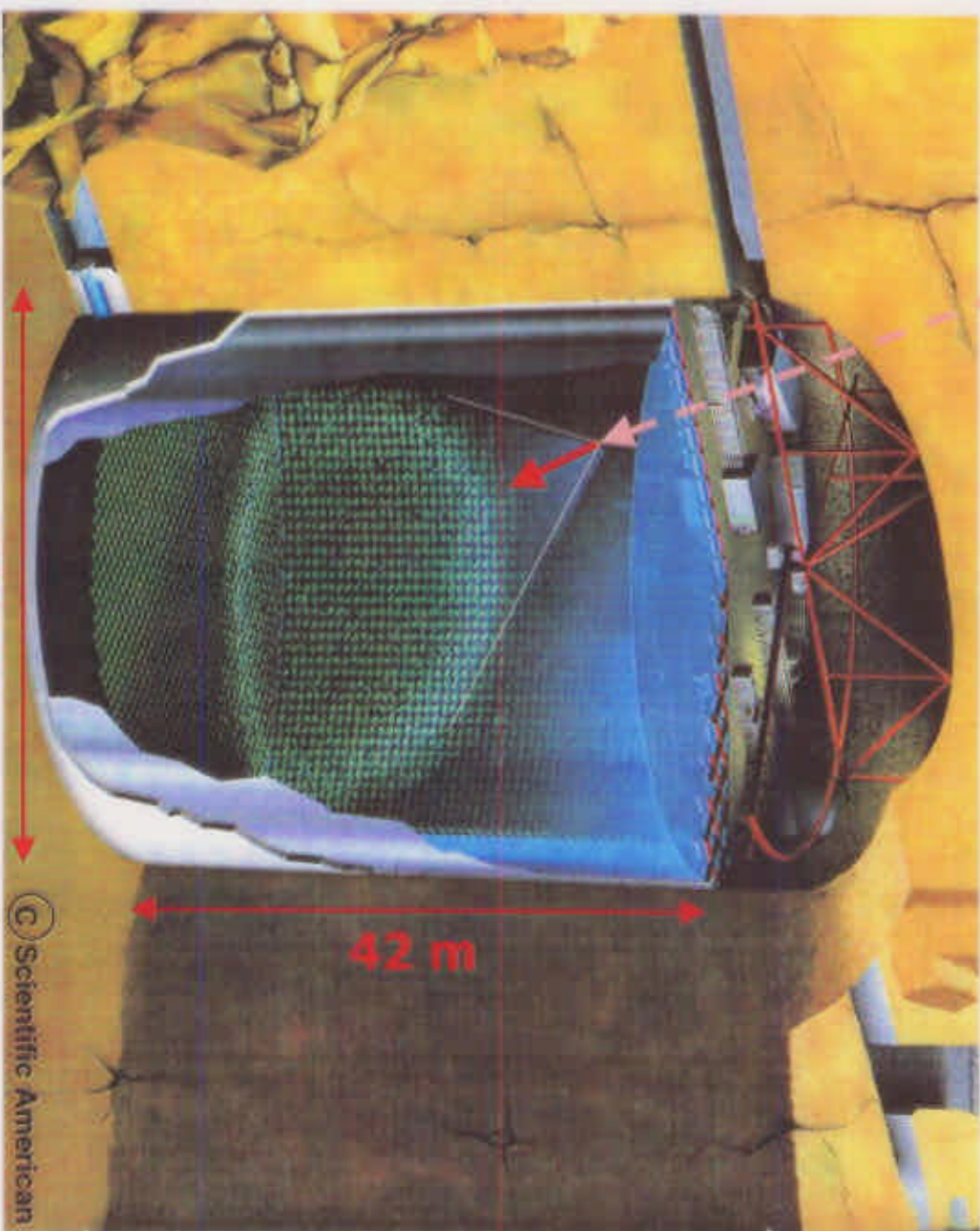
- Iron calorimeter

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



Super-Kamiokande detector

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Water Cherenkov detector

- 1000 m underground
- 50,000 ton
- 11,146 20 inch PMTs
- 1,885 anti-counter PMTs

39.3 m

42 m

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

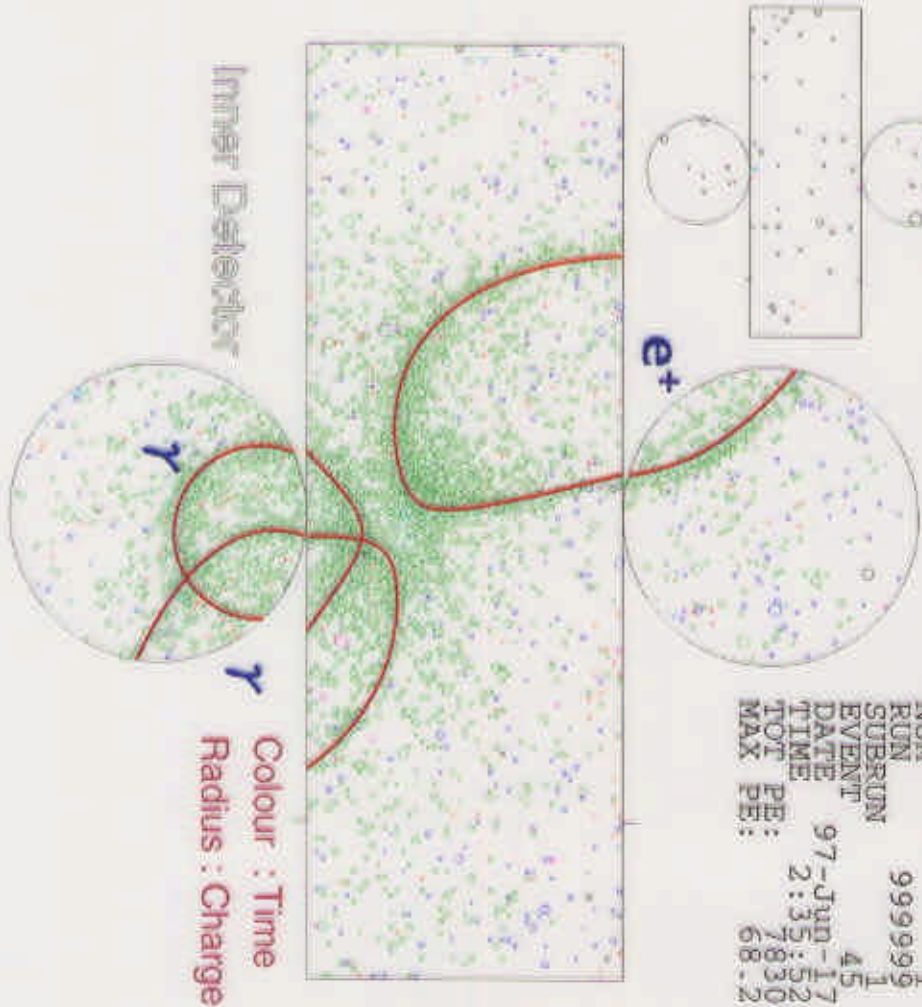


Outer Detector

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

```

★ Super-Kamiokande ★
NUM      1
RUN      9999999
SUBRUN   1
EVENT    45
DATE     97-Jul-17
TIME     2:35:52
TOT PE:  7830
MAX PE:  68.2
          9
  
```



Colour : Time
Radius : Charge

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

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



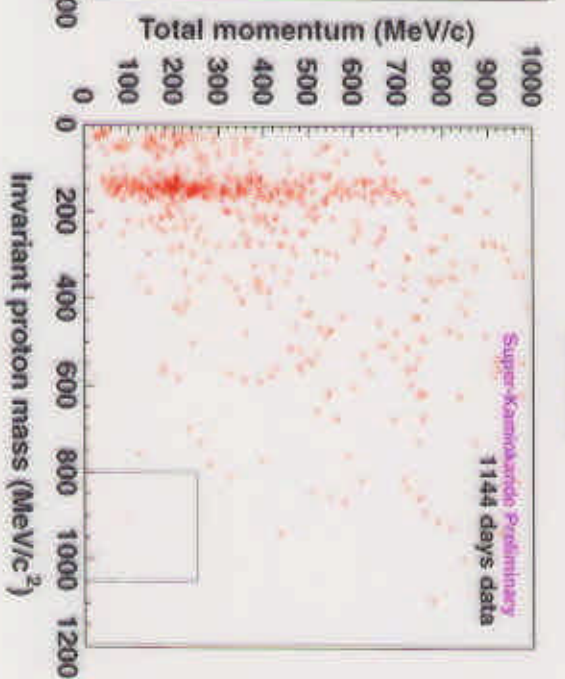
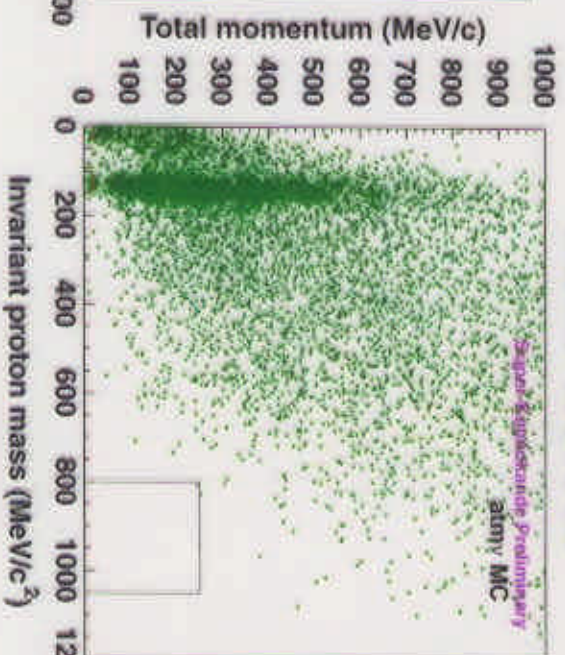
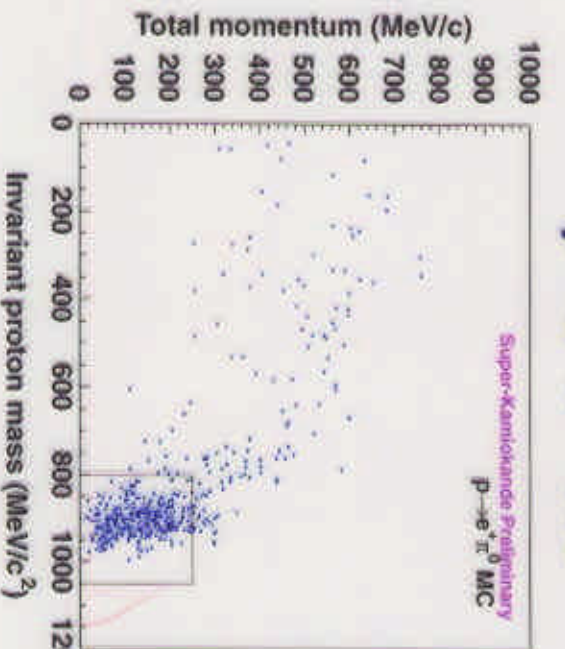
$p \rightarrow e^+ \pi^0$ @Super-K

1144 days (70.4 ktyr exposure)

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

atm ν BG MC

data



$\epsilon = 43\%$

0.1 exp'd BG

0 candidate

$$\tau_p / B(p \rightarrow e^+ \pi^0) > 4.4 \times 10^{33} \text{ years (90\% CL)}$$

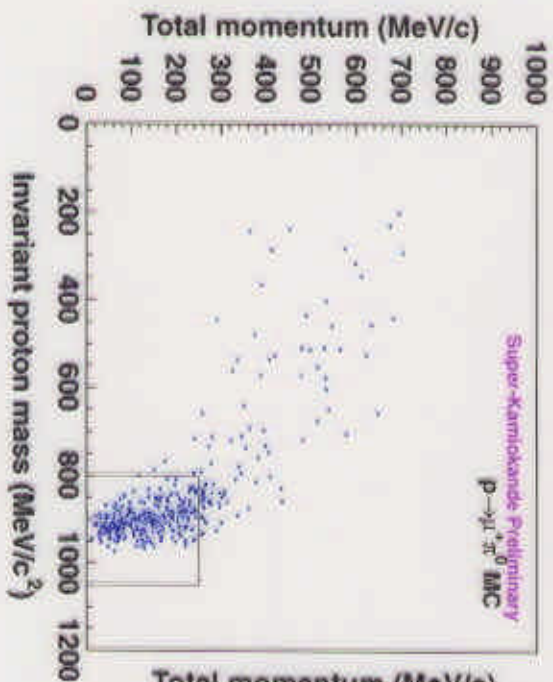


$p \rightarrow \mu + \pi^0$ @Super-K

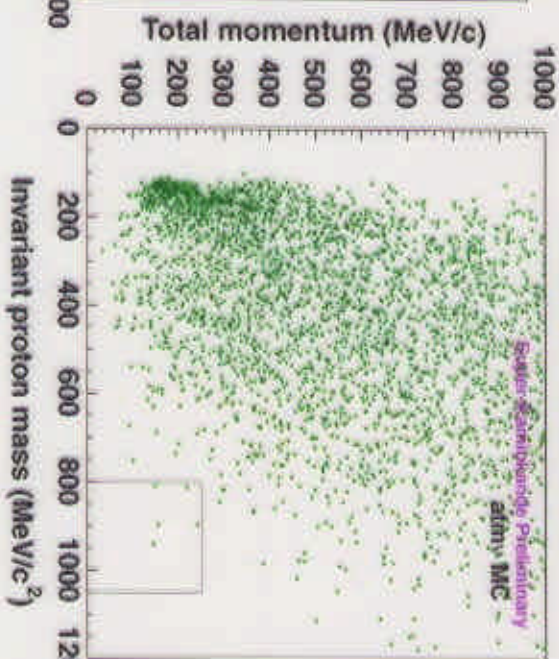
1144 days (70.4 ktyr exposure)

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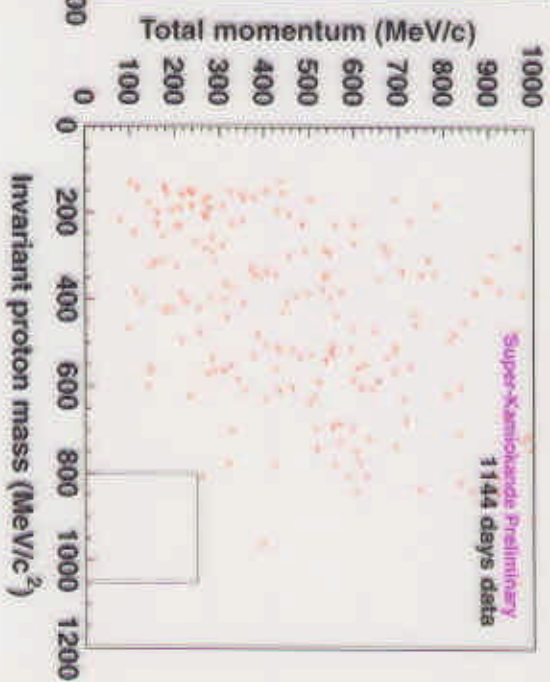
$p \rightarrow \mu + \pi^0$ MC



atm ν BG MC



data



$\epsilon = 32\%$

0.4 exp'd BG

0 candidate

$$\tau_p / B(p \rightarrow \mu + \pi^0) > 3.3 \times 10^{33} \text{ years (90\% CL)}$$

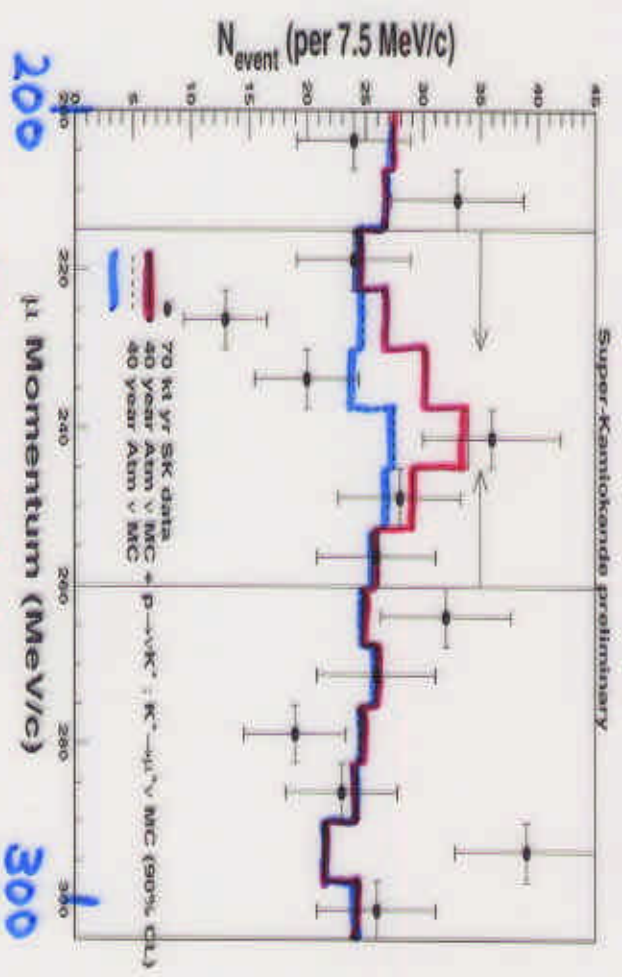


$p \rightarrow \nu K^+, K^+ \rightarrow \mu^+ \nu$ @Super-K

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

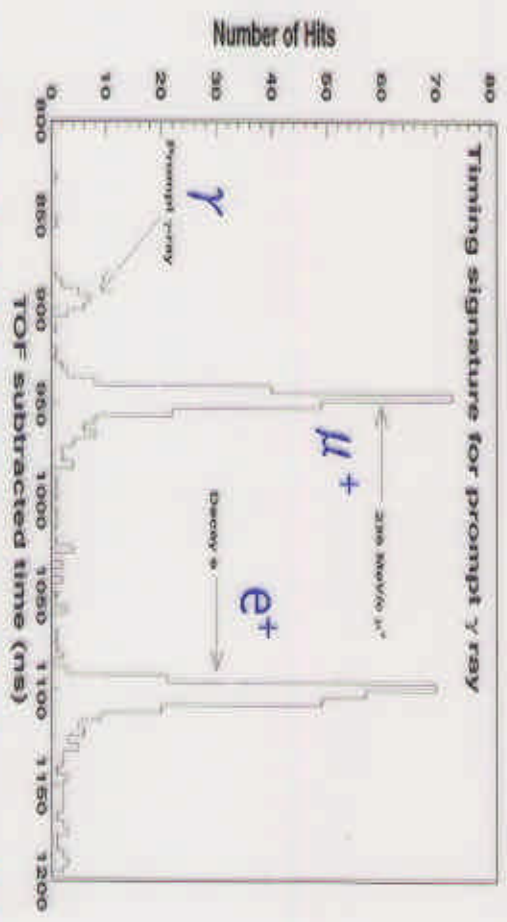
- 1 μ and 1 decay electron
- $215 < P_\mu < 260 \text{ MeV}/c$

● Method I (spectrum fit)



$T_p / B(p \rightarrow \nu K^+) >$
 4.3×10^{32} years (90% CL)

● Method II (prompt γ tag)

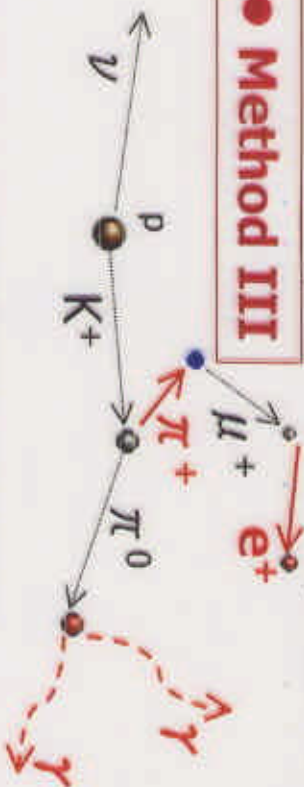


$\epsilon \times B = 9.3\%$, 1.1 exp'd BG, 0 candidate
 $T_p / B(p \rightarrow \nu K^+) >$
 9.5×10^{32} years (90% CL)

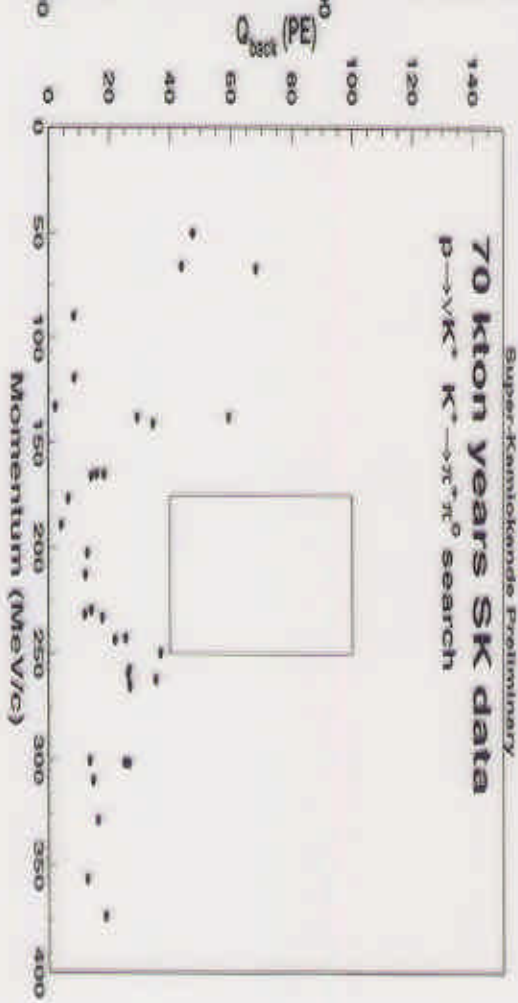
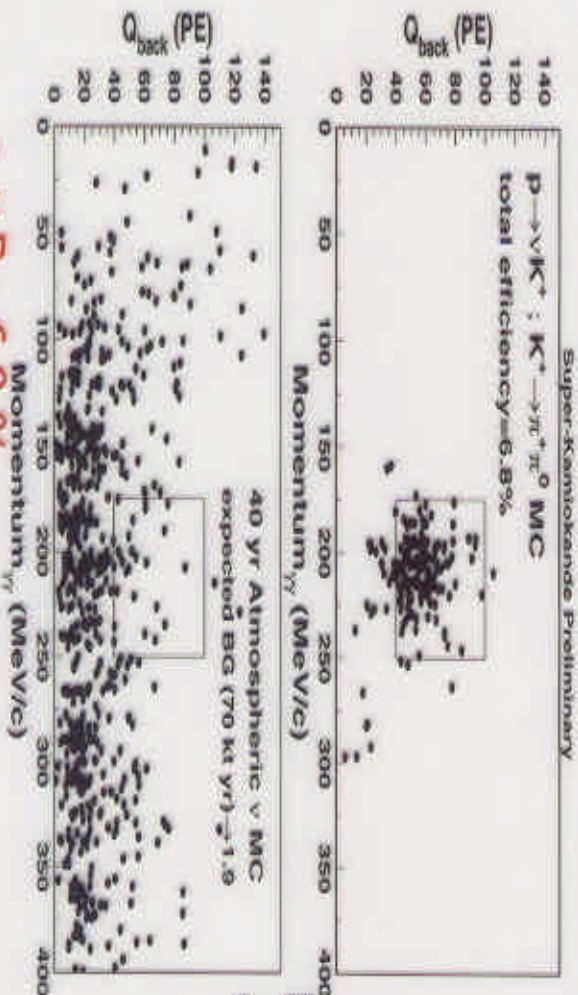
$p \rightarrow \nu K^+, K^+ \rightarrow \pi^+ \pi^0$ @Super-K

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

Method III



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



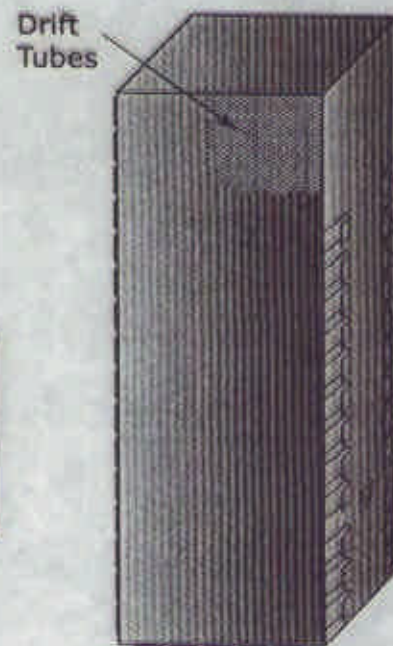
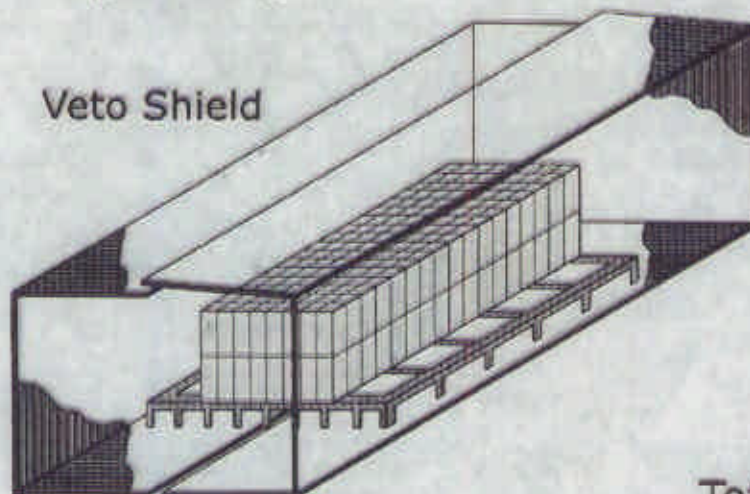
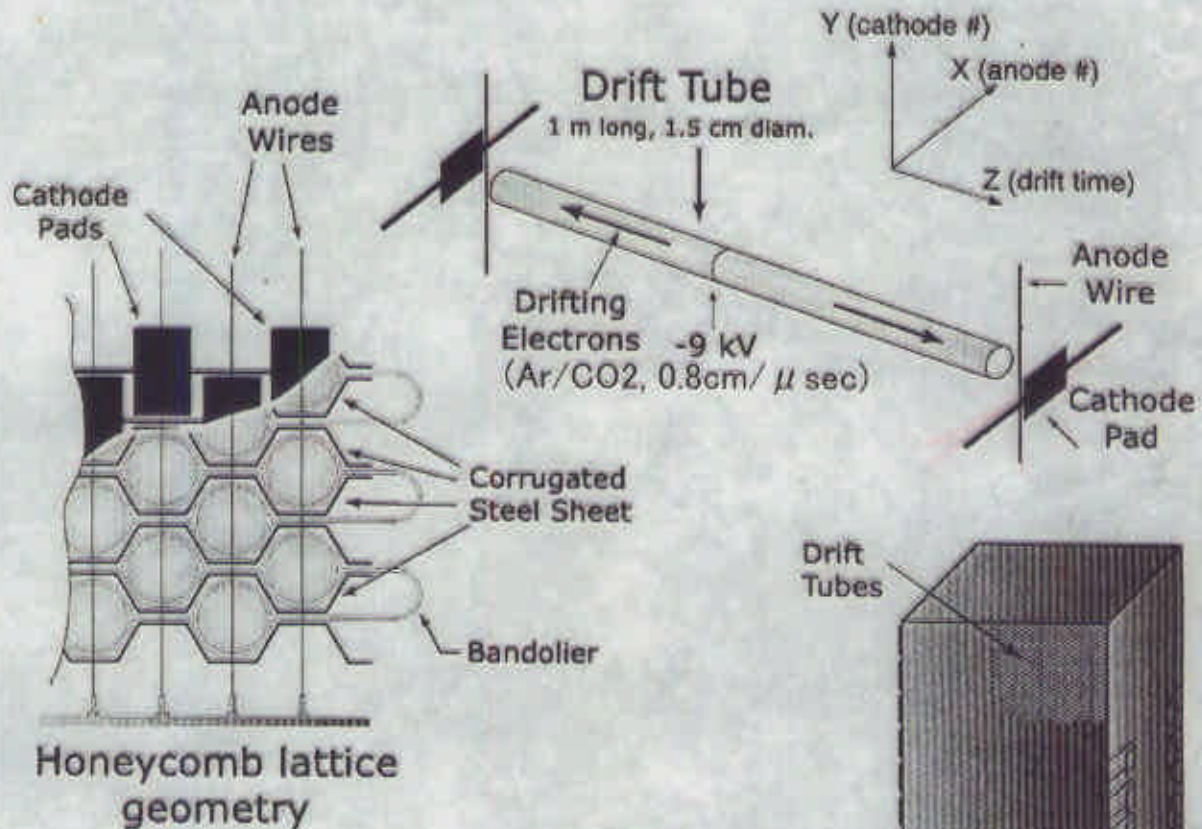
$\epsilon \times B = 6.8\%$,

1.9 exp'd BG, 0 candidate $\tau_p/B(p \rightarrow \nu K^+) > 6.9 \times 10^{32}$ years (90% CL)

combined limit $\tau_p/B(p \rightarrow \nu K^+) > 1.9 \times 10^{33}$ years (90% CL)

The Soudan 2 Detector:

Slow-drift time projection chamber



4.3 ton Module
× 224

Total mass: 963 tons

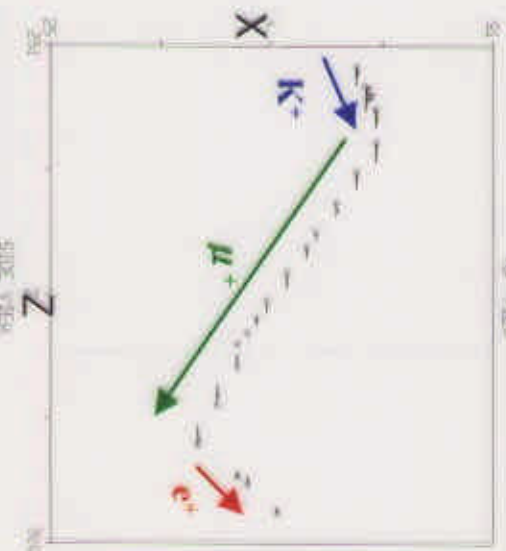
Fiducial mass: 770 tons



$p \rightarrow \nu K^+, K^+ \rightarrow \mu^+ \nu$ @Soudan2

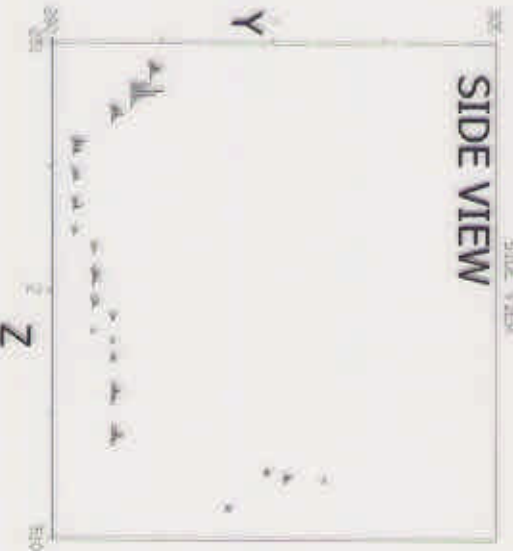
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TOP VIEW
TOP VIEW

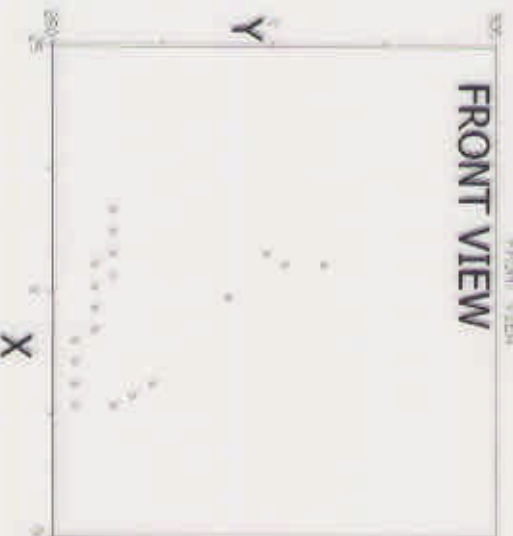


MC Simulation
P-Jan 11 58:79 E-Mail 1:785
CO-Proc-11889 16:30-27:53

SIDE VIEW
SIDE VIEW



FRONT VIEW
FRONT VIEW



- 2 charged tracks (no proton)
- K range < 50 cm
- 28 < μ range < 58 cm
- decay electron ($\epsilon \sim 60\%$)

$$\underline{\epsilon \times B(K^+ \rightarrow \mu^+ \nu) = 9.0\%}$$

3.56 kt·yr exposure

observed candidate = 1 event

exp'd BG

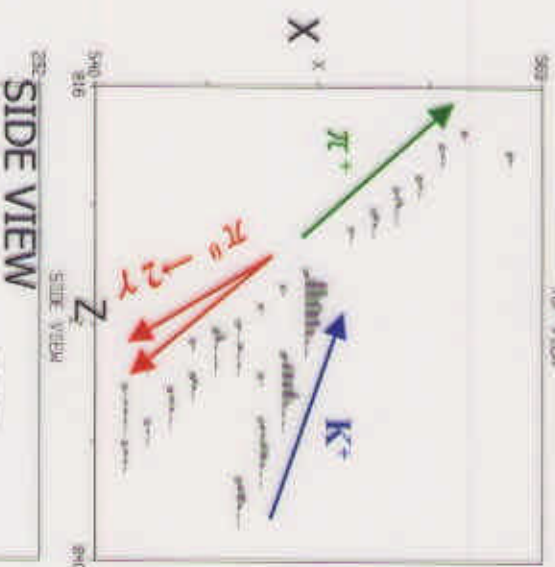
$$= 0.21 (\text{atm } \nu) + 0.19 (\text{rock})$$



$p \rightarrow \nu K^+, K^+ \rightarrow \pi^+ \pi^0$ @Soudan2

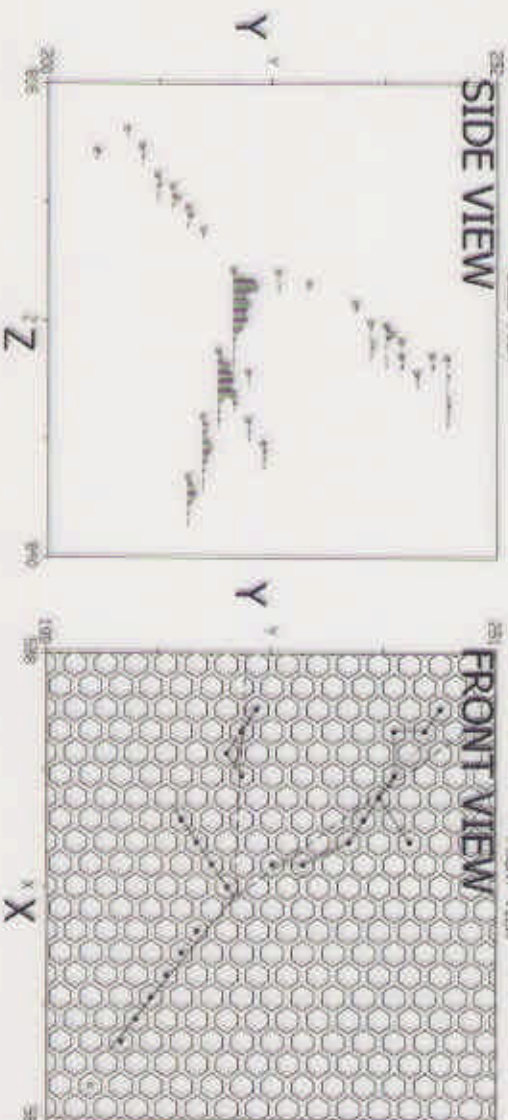
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TOP VIEW



MC Soudan2 Data
Run 56872 Event 999
30-Oct-1994 16:05:14.52

FRONT VIEW



- 2 tracks and 2 showers
- K range < 50 cm
- $100 < M_K < 660 \text{ MeV}/c^2$
- $80 < P_{\pi^+} < 400 \text{ MeV}/c$
- $40 < P_{\pi^0} < 390 \text{ MeV}/c$
- $10 < M_{\pi^0} < 290 \text{ MeV}/c^2$

$$\epsilon \times B(K^+ \rightarrow \pi^+ \pi^0) = 5.5\%$$

3.56 kt·yr exposure

observed candidate = 0 event
exp'd BG

$$= 1.05 \text{ (atm } \nu) + 0.09 \text{ (rock)}$$

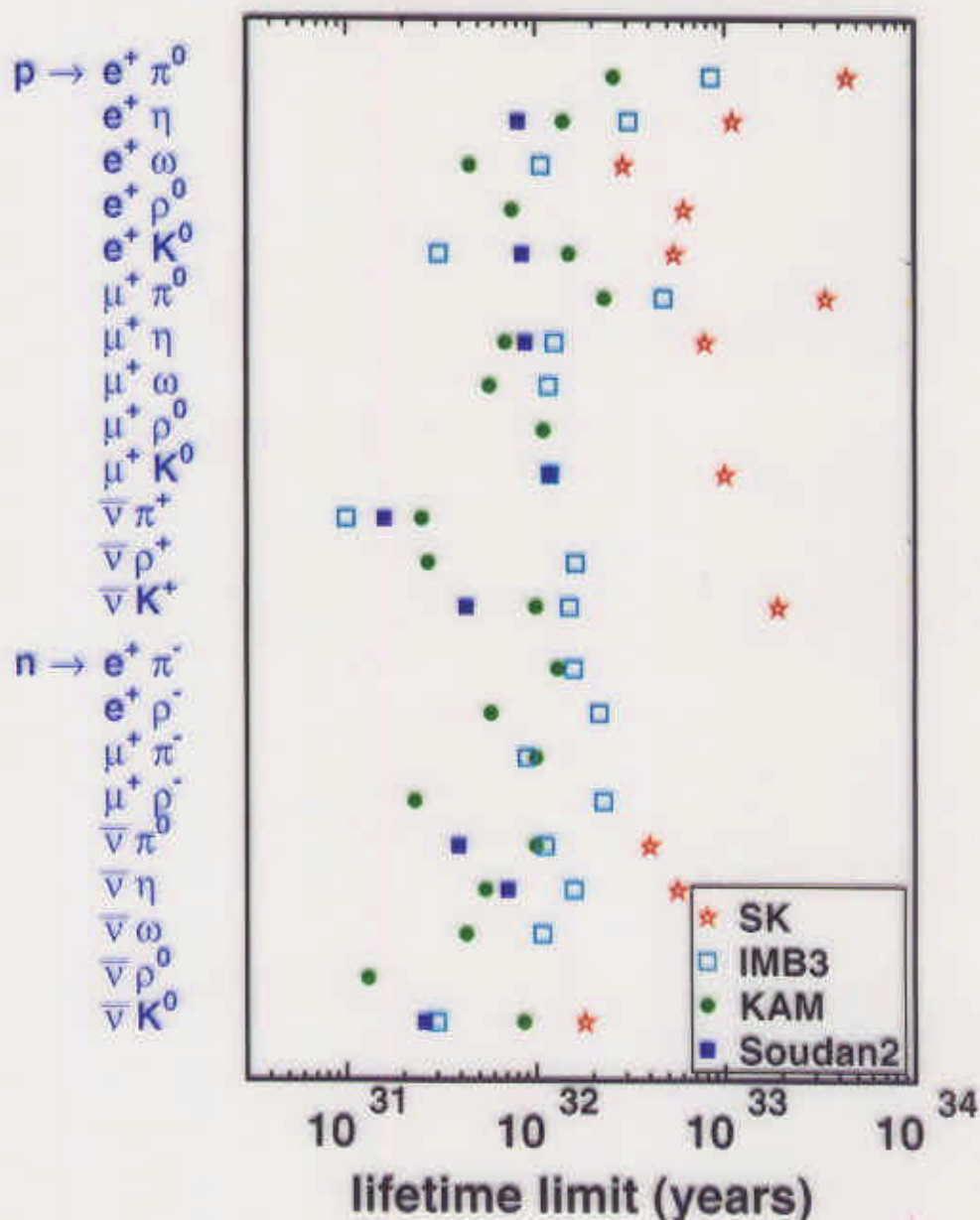
combined limit

$$\tau_p / B(p \rightarrow \nu K^+) >$$

$$4.3 \times 10^{31} \text{ years (90\% CL)}$$

Summary of nucleon decay searches

Super-K $p \rightarrow e^+ \pi^0$ \longrightarrow
 Super-K $p \rightarrow \nu K^+$ \longrightarrow



No evidence for nucleon decay so far



Need to keep watching nucleons