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Super-K

# Review of Proton Decay Results

Generalities: experiments, some world limits

$e^+\pi^0$: the prototypical decay mode

$K^+\nu$: trickier techniques

Summary of Super-K limits and final comment

# Nucleon Decay Experiments

| | Fiducial Mass | |
|---|---|---|
| NUSEX (1982) | 130 t | Fe/streamer |
| KGF (1980) | 140 t | Fe/prop. tube |
| Frejus (1984) | 700 t | Fe/flash chamber |
| Soudan (1981) | 770 t | Fe/drift tube |

tracking detector

Kamiokande (1983) 1040 t

2700 mwe,
1000 50-cm pmts, 20% photocathode coverage
outer veto, solar neutrinos

IMB (1982) 3300 t

1580 mwe,
2048 20-cm PMTs, low photocathode coverage
augmented by wls plates,
pre-SK: largest, best proton decay limits

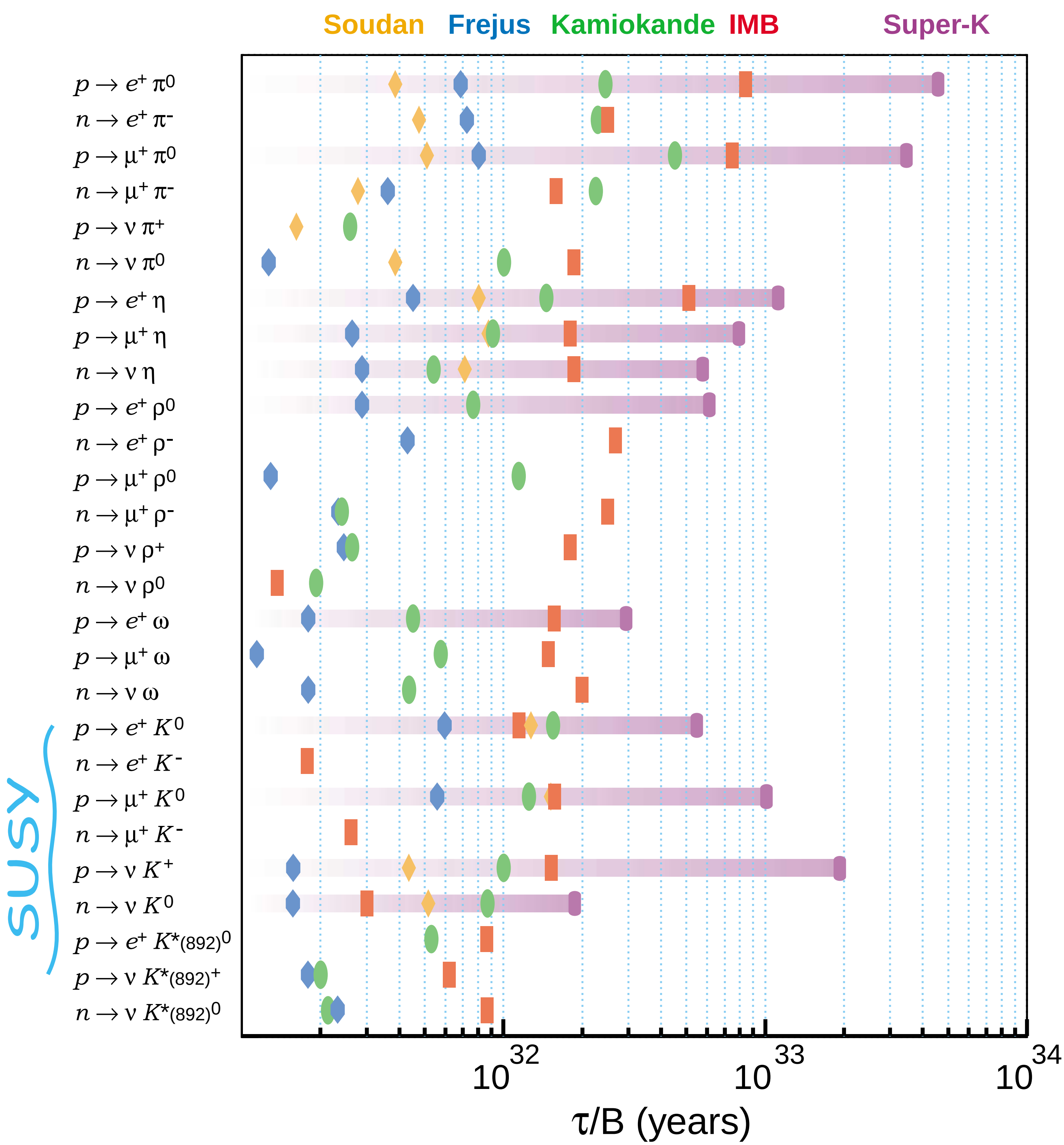
Super-K (1996) 22500 t

more on this detector shortly

water Cherenkov

# Nucleon Decay Limits

antilepton + meson

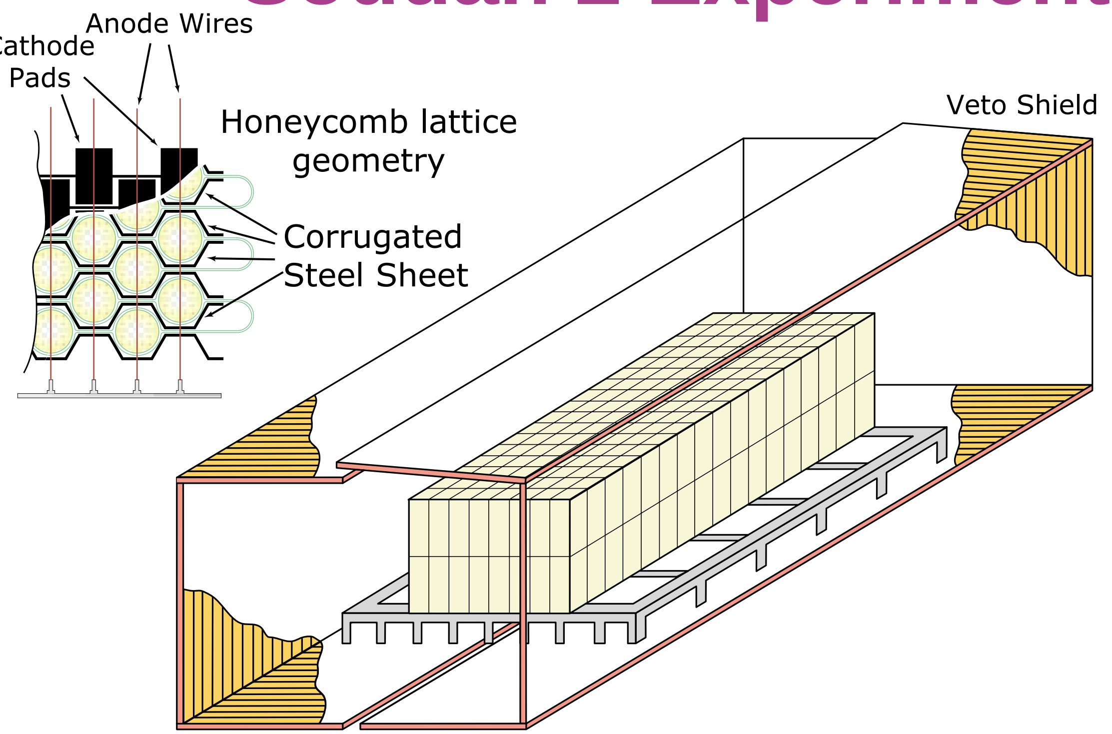


# More Nucleon Decay Limits

## non-traditional and new

| | $\tau/B$ ($10^{30}$ years) | |
|---|---|---|
| **Radiative decays:** | | |
| $p \to e^+ \gamma$ | 7300 | Super-K preliminary |
| $p \to \mu^+ \gamma$ | 6100 | Super-K preliminary |
| $n \to \nu \gamma$ | 39 | IMB |
| **Once suggested for atmospheric $\nu$ anomaly (Mann 1992):** | | |
| $p \to e^+ \nu \nu$ | 17 | IMB |
| **"Invisible" mode:** | | |
| $n \to \nu \nu \nu$ | .00049 | Kamiokande (use 22-35 MeV nuclear de-excitation) |
| **B-L violating modes and di-nucleon decay (Frejus limits):** | | |
| $n \to e^+ e^- \nu$ | 74 | $\Delta$(B-L)=2 $\Delta$B=1 |
| $p \to \mu^+ \pi^+ K^+$ | 5.4 | $\Delta$(B-L)=2 $\Delta$B=1 |
| $pn \to e^+ n$ | 100 | $\Delta$(B-L)=0 $\Delta$B=1 |
| $pn \to \pi^0 \pi^0$ | 3.4 | $\Delta$(B-L)=2 $\Delta$B=2 |
| $pp \to e^+ e^+$ | 5.8 | $\Delta$(B-L)=0 $\Delta$B=2 |
| **Inclusive decays:** | | |
| $p \to \mu^+\ anything$ | 12 | M.Cherry et al. (Homestake) |
| **New decay modes (Applequist, Dobrescu et al. hep-ph/0107056):** | | |
| $p \to e^- \pi^+ \pi^+ \nu \nu$ | | |
| $n \to e^- \pi^+ \nu \nu$ | ? | |
| $p \to \mu^+ e^+ \pi^- \nu \nu$ | | |

# Soudan 2 Experiment

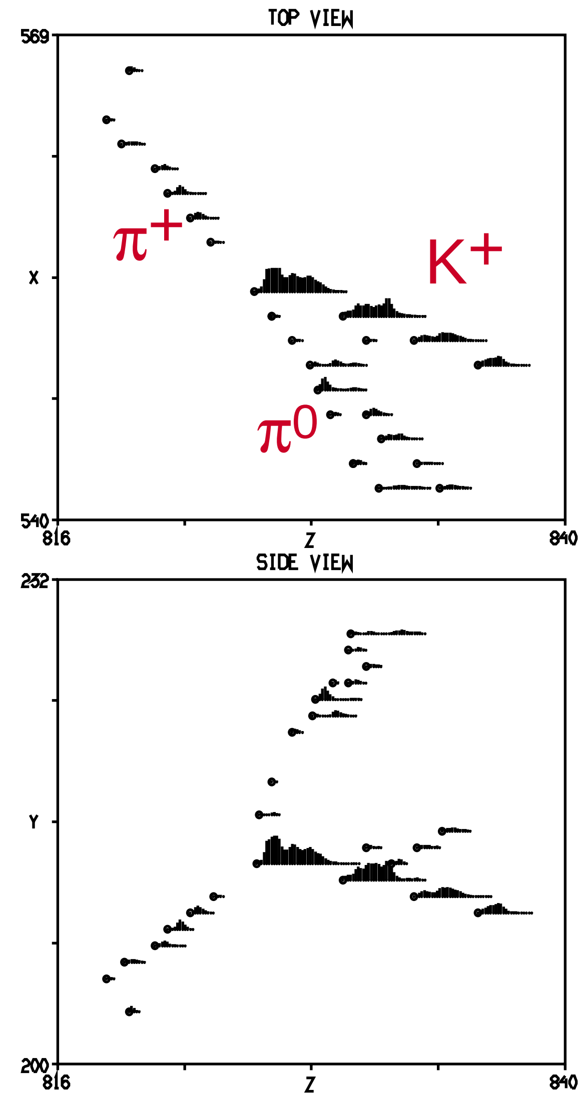



## tracking iron tracking calorimeter

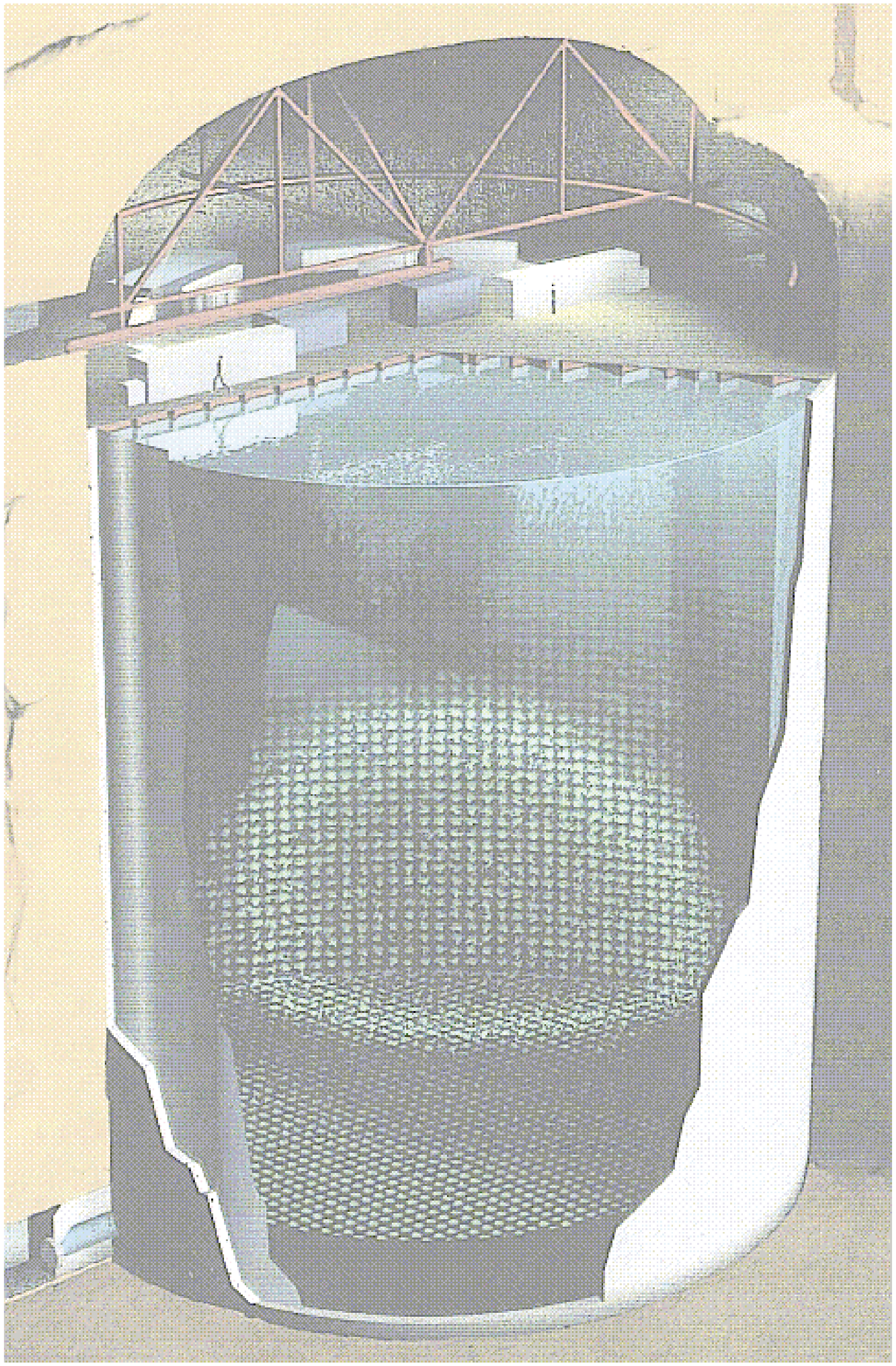
Soudan Mine (Minnesota), 2100 m.w.e., 770 ton (fiducial)
1 cm spatial resolution with dE/dx sampling

suitable for: non-relativistic particles ($K^+$)
high final state multiplicities

however: greater intranuclear scattering than water
smaller in size due to cost and complexity




Soudan 2 proton decay M.C.



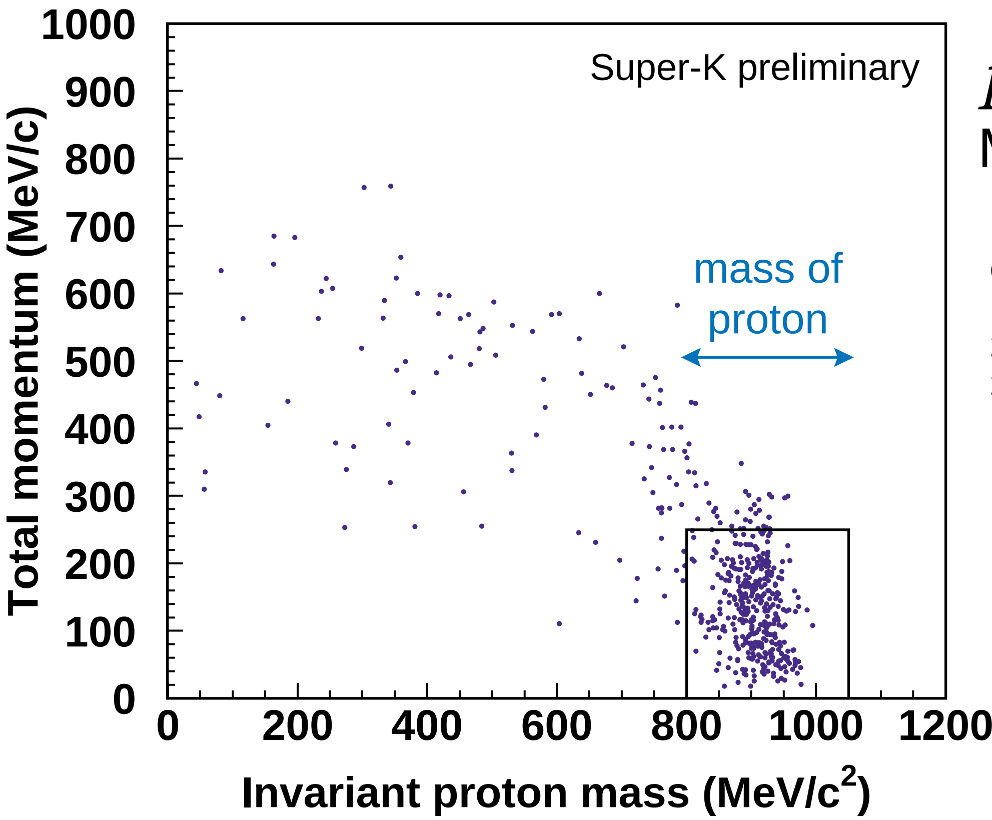
# Super-Kamiokande

water Cherenkov detector
1 km deep (2600 m.w.e.)
11000 50-cm PMTs
~2 ns timing resolution
40% photocathode coverage
outer detector veto ex-IMB
22.5 kton fiducial mass
$\Rightarrow$ 7.5 x $10^{33}$ protons
$\Rightarrow$ 6.0 x $10^{33}$ neutrons

## Proton Decay Students:

M.Earl, S.Hatakeyama, Y.Hayato
J.Kameda, M.Kirisawa, K.Kobayashi
M.Shiozawa, B.Viren

# Signal and Background Monte Carlo

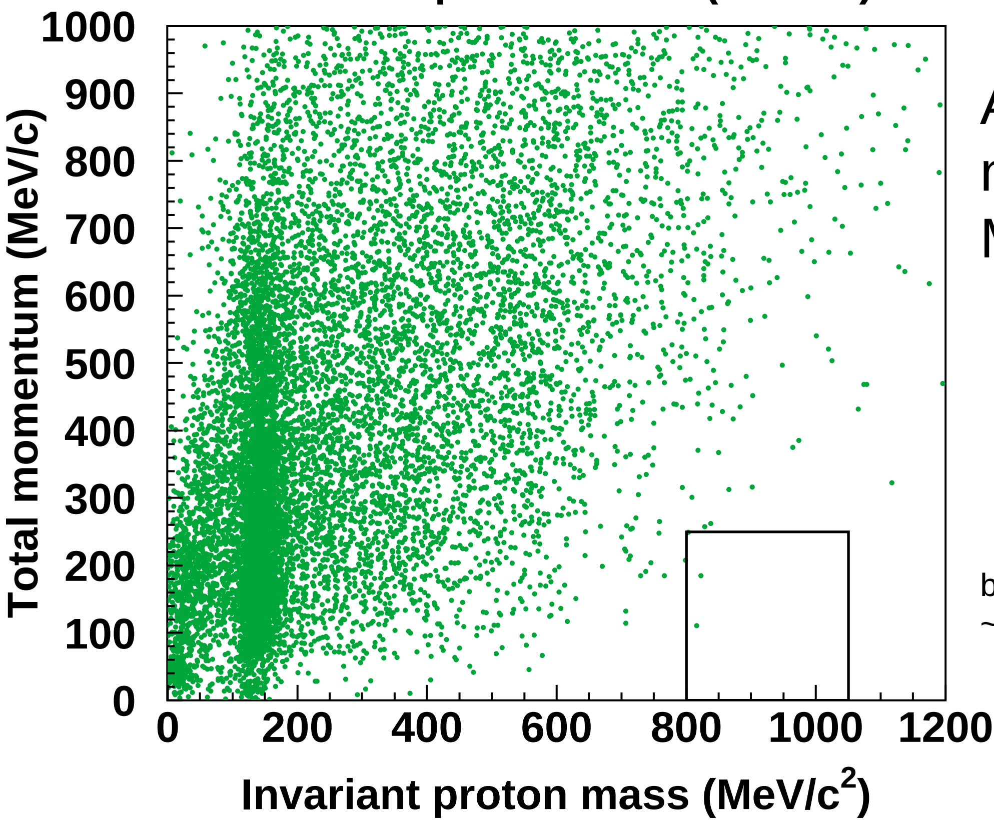



$p \rightarrow e^{+} \pi^{0}$
Monte Carlo

efficiency = 43%

20% reconstruct 2-rings
23% reconstruct 3-rings

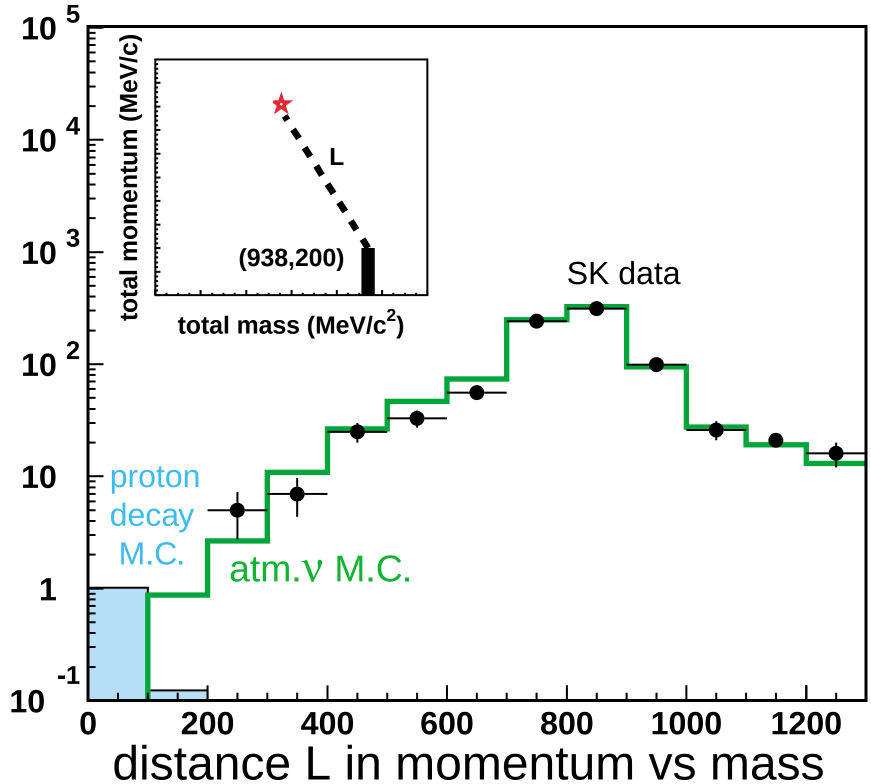
low total momentum i.e. back-to-back

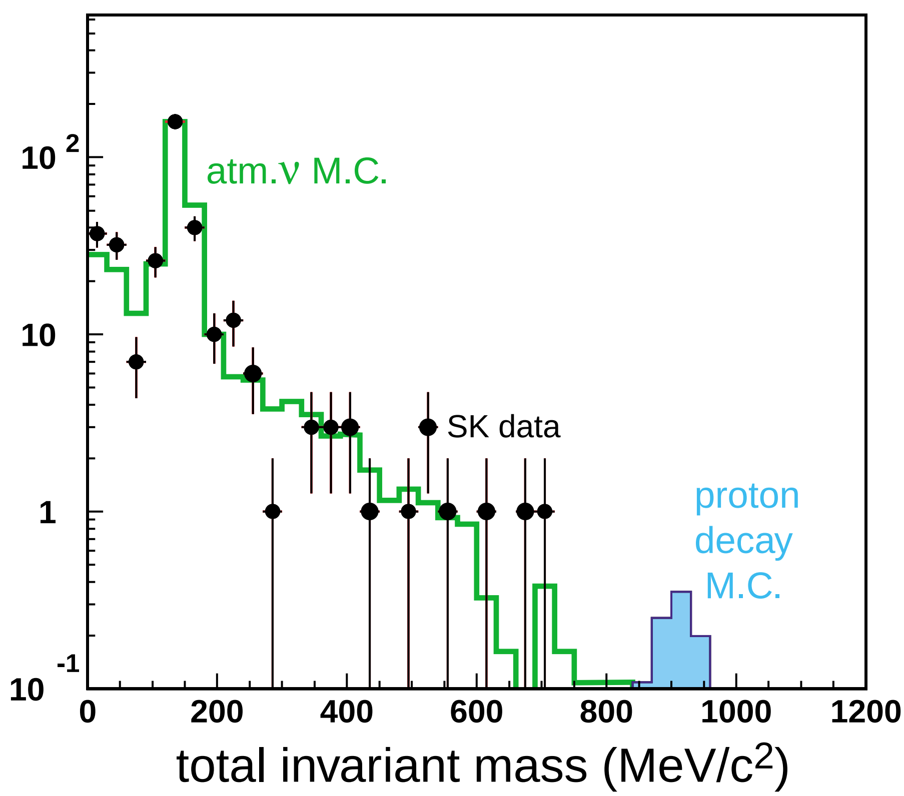



Atmospheric neutrino Monte Carlo

background estimate
~0.25 events/100 kt·yr

# Characterize Accuracy of Monte Carlo Simulation



# $p \to K^+ \nu$

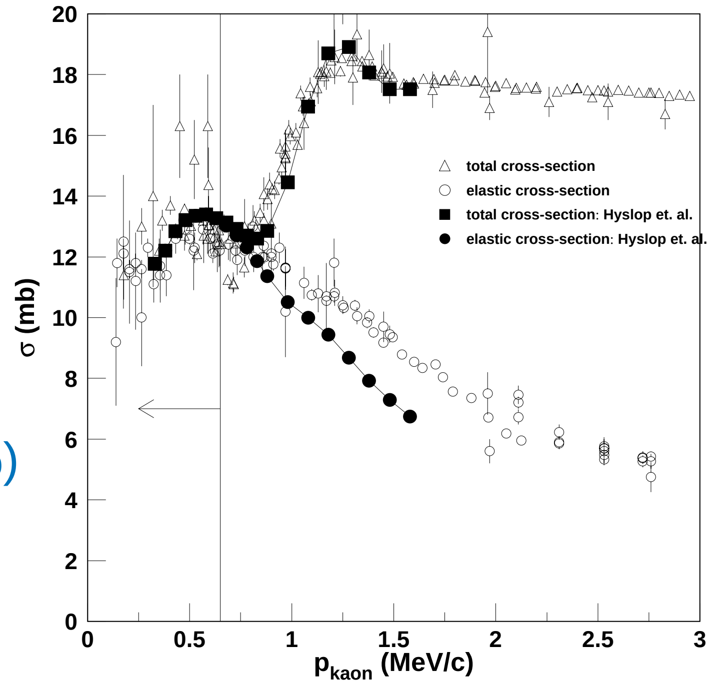
Favored SUSY decay mode

Note: Also $p \to \pi^+ \nu$ in some circumstances (Strassler and Babu, see also Goto and Nihei).
Also $\mu^+ K^0$, Babu, Pati & Wilczek

Momentum of K+ is 340 MeV/c: below Č-threshold

**Nuclear Interaction:**
cross section is small
scattering is elastic

$\Rightarrow$ K+ escapes nucleus and decays at rest (90%)



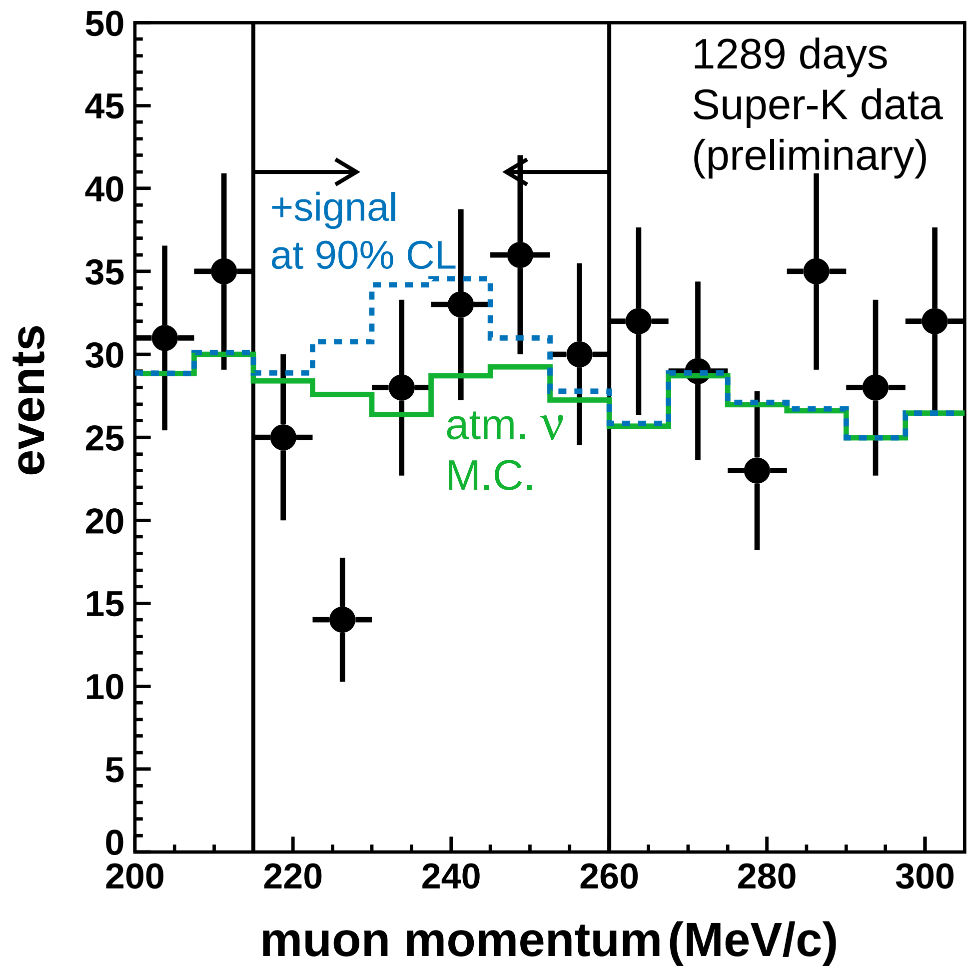

Branching ratios:

$K^+ \to \mu^+ \nu_\mu$ 65%

$K^+ \to \pi^+ \pi^0$ 21%

# $K^+ \rightarrow \mu^+$(236 MeV/c) $\nu$ search

1 $\mu$-like ring
1 decay electron
$215 < p_\mu < 260$ MeV/c
B.R. x efficiency = 33%




from joint fit to background + signal:

$\tau/B(p \rightarrow \nu K^+) > 4.4 \times 10^{32}$ yr

# Gamma Tag for $p \rightarrow \nu\ K^{+}$

Nuclear Shell Model:
$^{16}O\ (p_{3/2}) \rightarrow\ ^{15}N^{*}$ + proton hole
de-excites by 6.3 MeV gamma

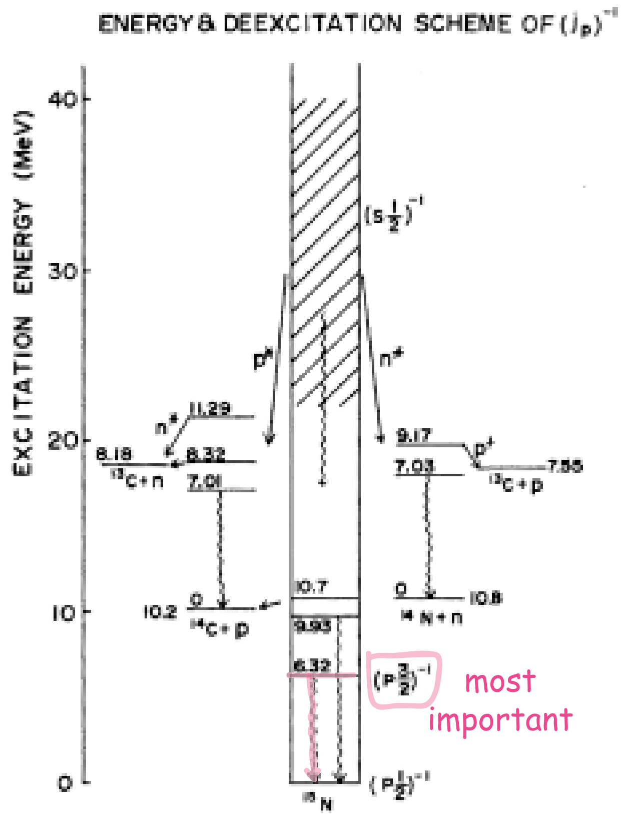
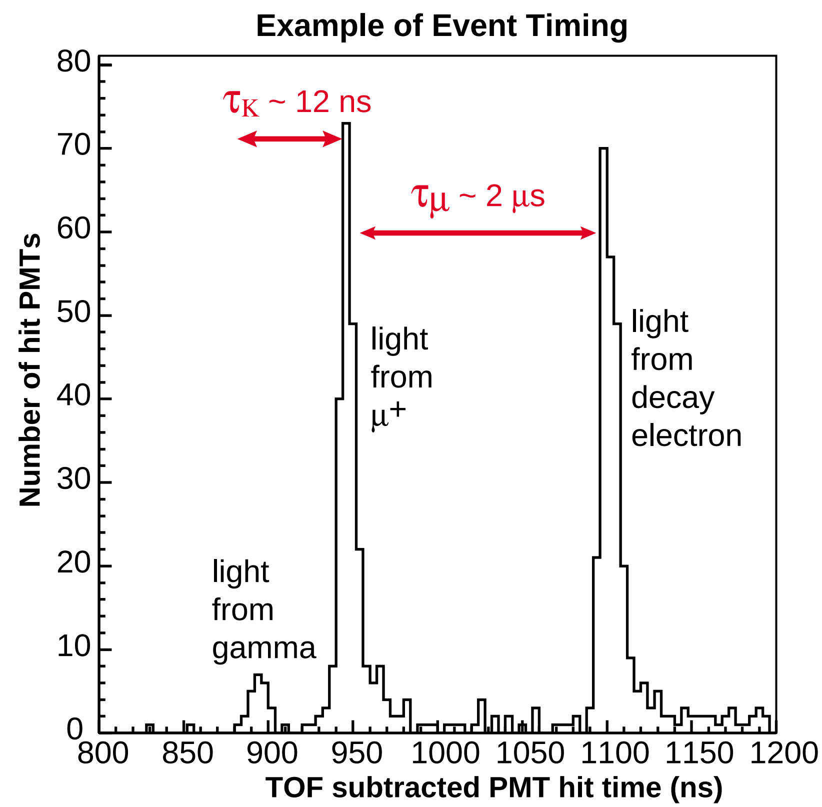



FIG. 2. Level scheme of proton-hole states in $^{15}N$ and their deexcitation modes. Energies are given in units of MeV. $p^{*}$ and $n^{*}$ are the protons and neutrons emitted from the continuum (unbound) region, respectively.

H.Ejiri Phys. Rev. C48 (1993) 1442

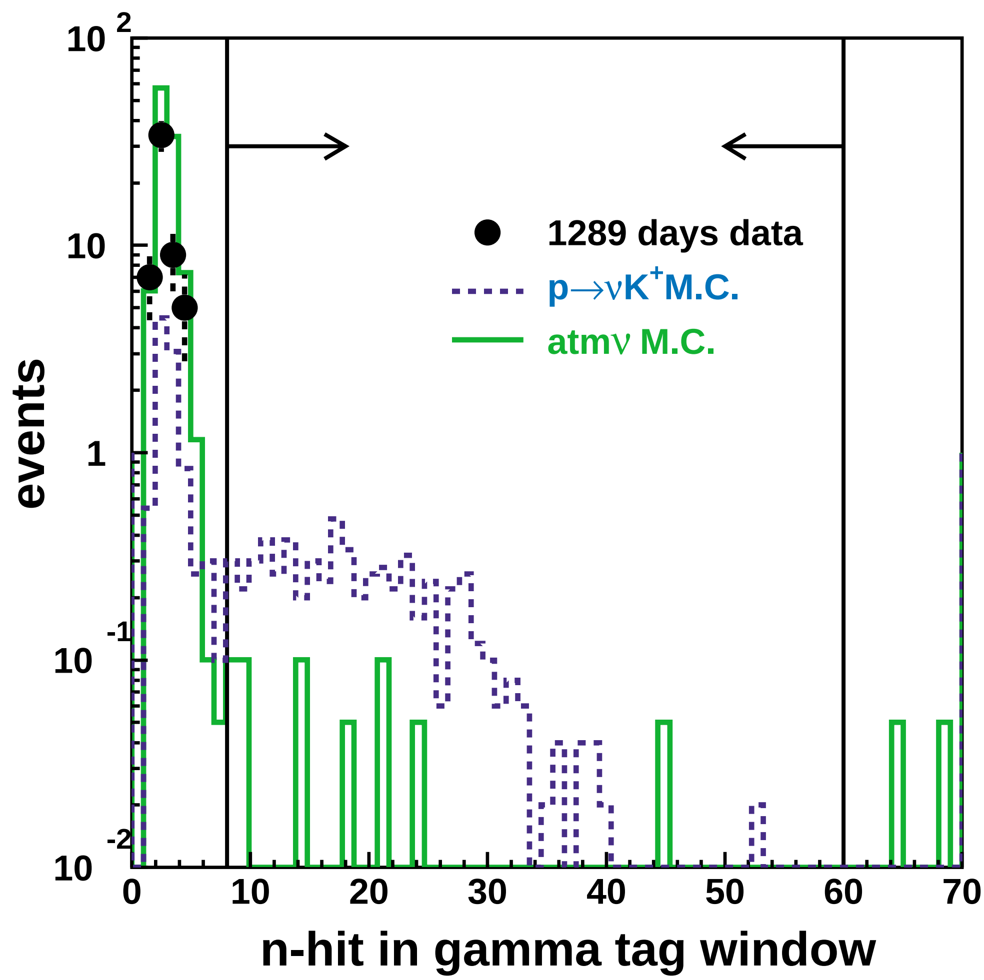
Coincidence signature:
proton decay to $K^{+}n$ accompanied by prompt $\gamma$
$K^{+}$ is below Cherenkov threshold: no light
followed by $K^{+}$ decay to $\mu^{+}\nu$ ~12 ns later
followed by muon decay to electron ~ 2 ms later



# $K^+ \rightarrow \mu^+$(236 MeV/c) $\nu$ search with gamma tag

count PMT hits
in 12-ns sliding window
*preceding* light from muon

B.R. x efficiency = 8.8%




0 events detected, background = 0.5 events:

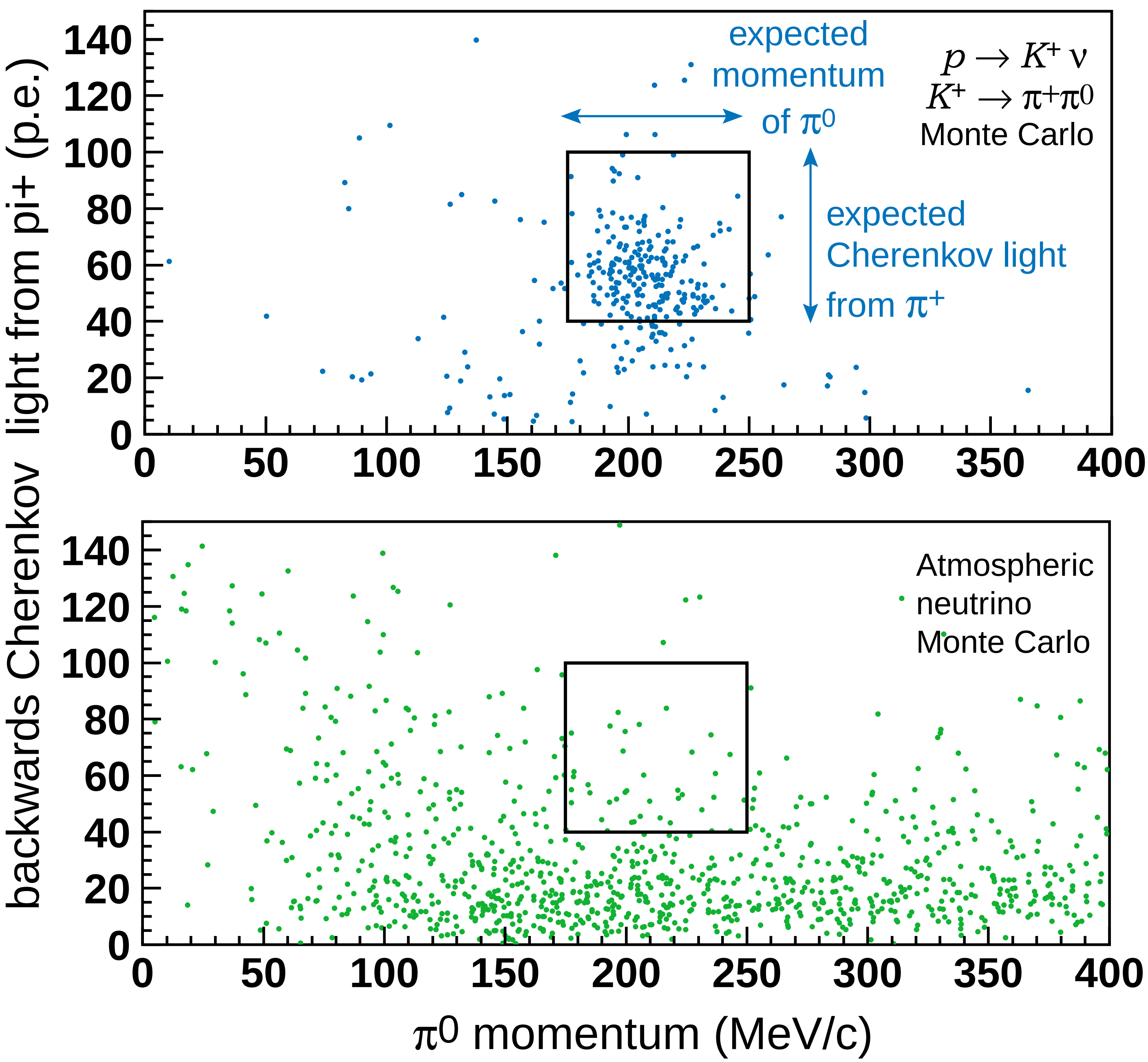
$\tau/B(p \rightarrow \nu K^+) > 10 \times 10^{32}$ yr

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

momentum of $\pi^+$ is only 205 MeV/c:
barely above Cherenkov threshold

require 1 decay electron, $\pi^0$ mass

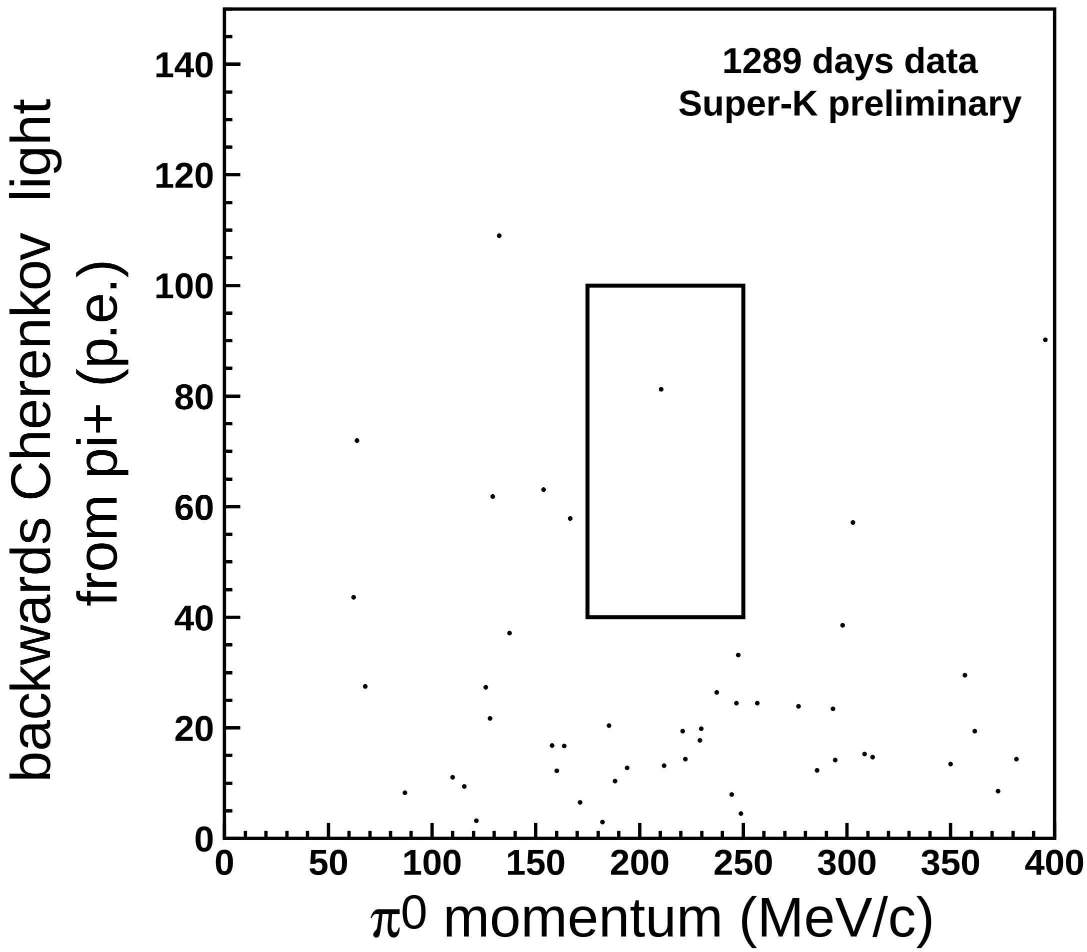
BR x efficiency = 6.8%




background estimate
~2.3 events/100 kt·yr

# Super-K Data: $p \rightarrow K^{+} \nu$

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




result for 79.3 kt·yr (Super-K preliminary):

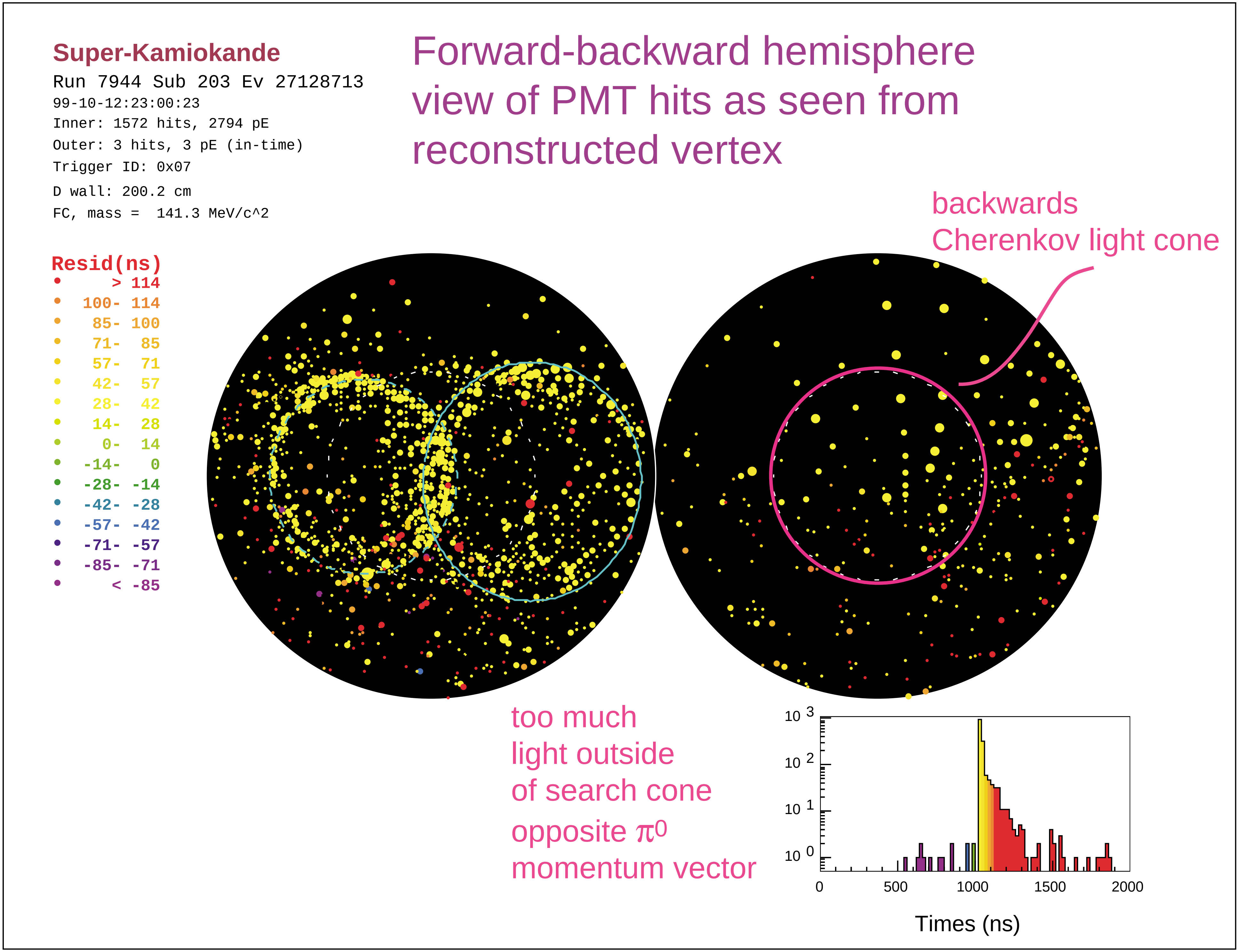
1 candidates

6.8% efficiency

1.7 events background

$\tau/B\ (p \rightarrow K^{+} \nu) > 5.9 \times 10^{32}$ yr    (90% C.L.)

**For final limit: combine all three results (they are independent)**

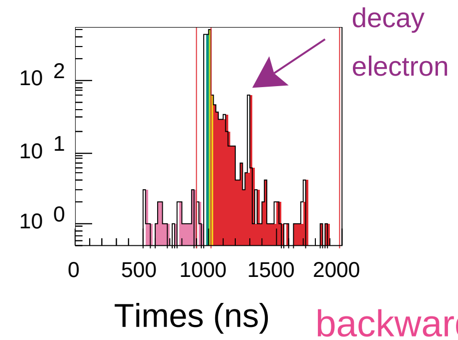


Super-Kamiokande
Run 7944 Sub 203 Ev 27128713
99-10-12:23:00:23
Inner: 1572 hits, 2794 pE
Outer: 3 hits, 3 pE (in-time)
Trigger ID: 0x07
D wall: 200.2 cm
FC, mass = 141.3 MeV/c^2
Resid(ns)
> 114
100- 114
85- 100
71- 85
57- 71
42- 57
28- 42
14- 28
0- 14
-14- 0
-28- -14
-42- -28
-57- -42
-71- -57
-85- -71
< -85
Forward-backward hemisphere view of PMT hits as seen from reconstructed vertex
backwards Cherenkov light cone
too much light outside of search cone opposite $\pi^0$ momentum vector
$10^3$
$10^2$
$10^1$
$10^0$
0
500
1000
1500
2000
Times (ns)

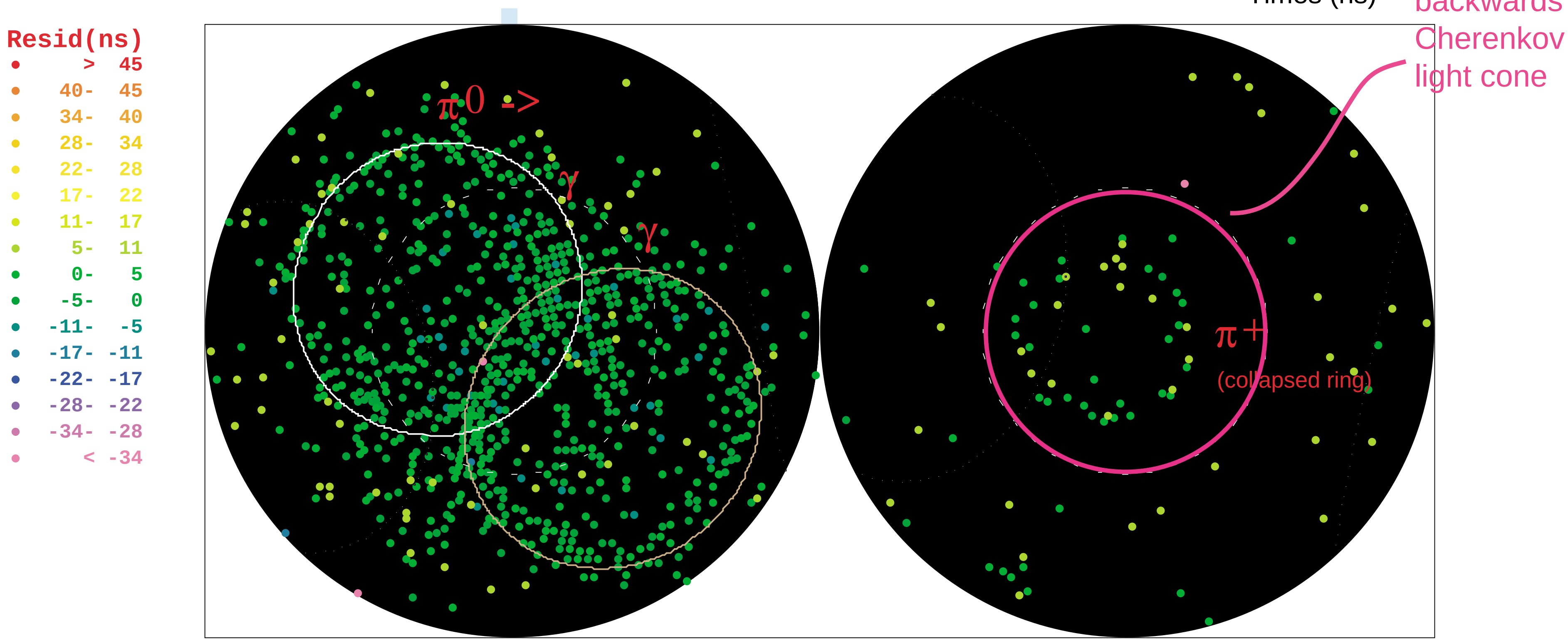
**Super-Kamiokande**

Run 1000000 Event 474
1997-06-25:12:59:29
Time to prev. event: 0.0us
Inner: 1395 hits, 2128 pE
Outer: 16 hits, 9 pE (in-time)
Trigger ID: 0x03

# Forward-backward hemisphere view of Monte Carlo event




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




(only hits in time window drawn)

expect only small
amount of light
outside backwards cone

# Summary of Super-K Limits

| mode | exposure (kt• yr) | $\varepsilon B_m$ (%) | observed event | B.G. | $\tau/B$ 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 | 1 | 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 |

# Final Comments:

Proton decay searches have been negative so far ... it's a good thing that supernova, neutrino oscillations, etc. helped us pass the time.

Past experiments and Super-K have set severe constraints on viable GUTs. Minimal SU(5), minimal SUSY SU(5) are dead. New models must struggle with these limits.

Unfortunately, there is **no experimental hint of any sort** for which decay modes the next generation experiments should concentrate on. So far.

Super-K has set strong limits on the most "popular" modes. But there is a lot of work to comprehensively test the conservation of baryon number.