Overview talk on proton decay searches

Current status of the nucleon decay search and some future prospects

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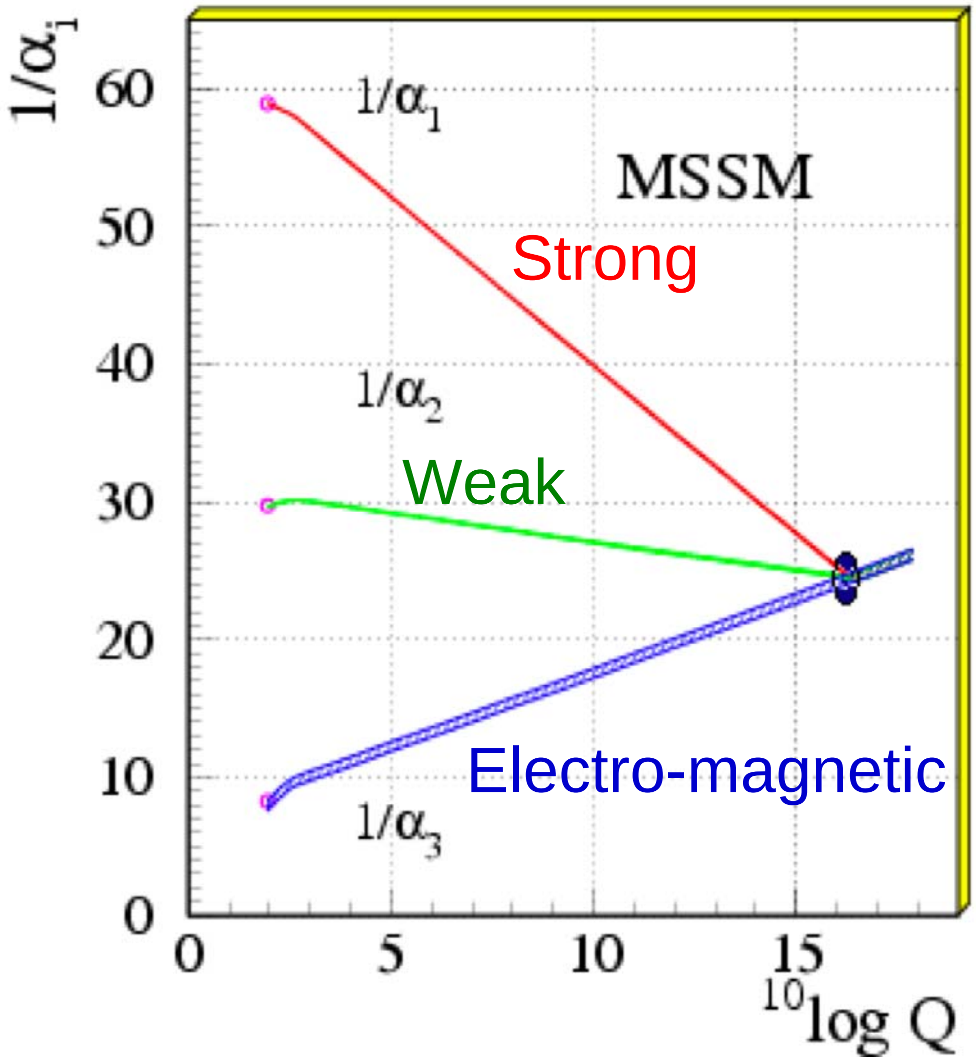
GLA2011 (June 7, 2011)

Proton decay ~ Grand Unification

Running coupling constants seem to cross at single point
(unification scale)



↓

Unification of interactions
and
Unification of quark and lepton

↓

Possibility of transition
from quark to lepton

↓

Proton decay

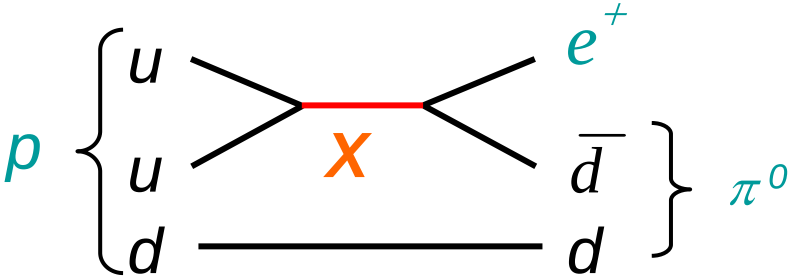
Predicted decay modes of proton

Two major decay modes

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

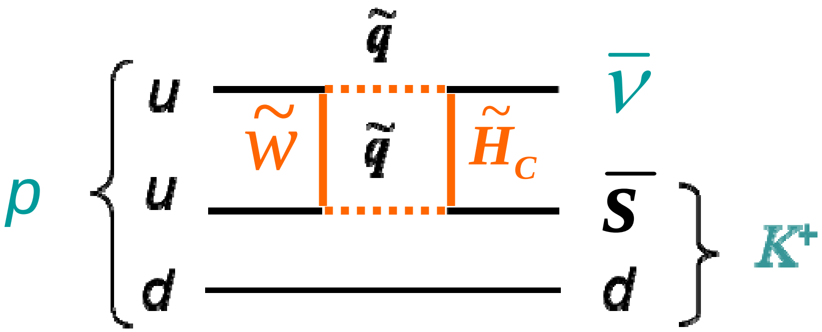
$p \rightarrow \bar{\nu} K^+$

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



X : Gauge boson $\tau_p \propto M_X^4$

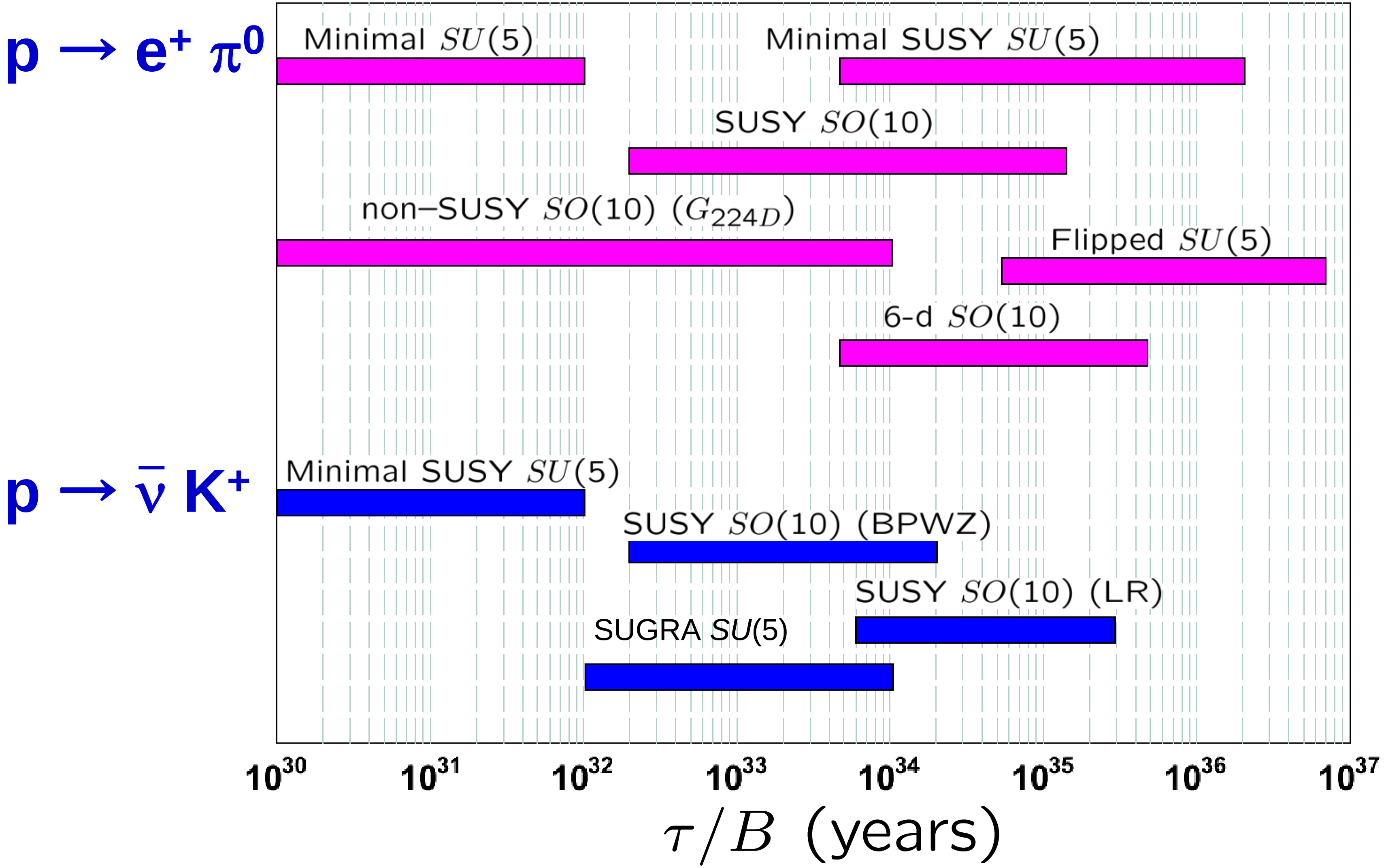
$p \rightarrow \bar{\nu} K^+$ (SUSY favored mode)



Predicted lifetime of proton for major two decay modes

$p \to e^+ \pi^0$ and $p \to \bar{\nu} K^+$

Predictions of τ / *B* ~ *10^30* ~ *10^37 years*



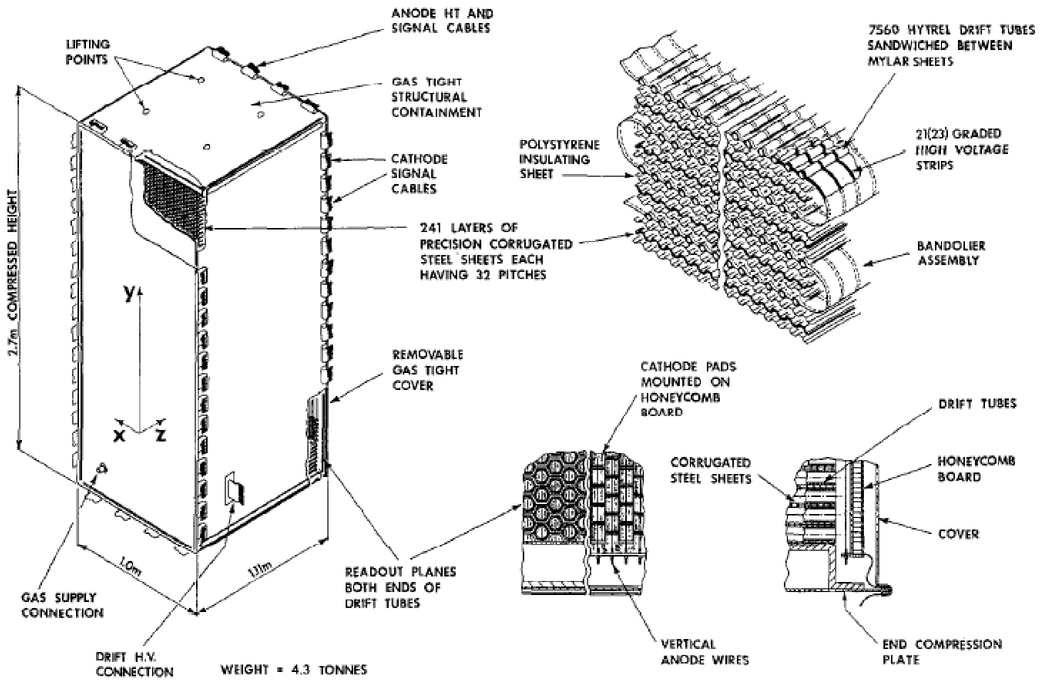
Proton decay experiments in '80s and '90s

Iron with trackers ~ 1 kton

Frejus experiment

plastic flash tubes ($25mm^2$)
with geiger tubes ($225mm^2$)

900 tons of Iron



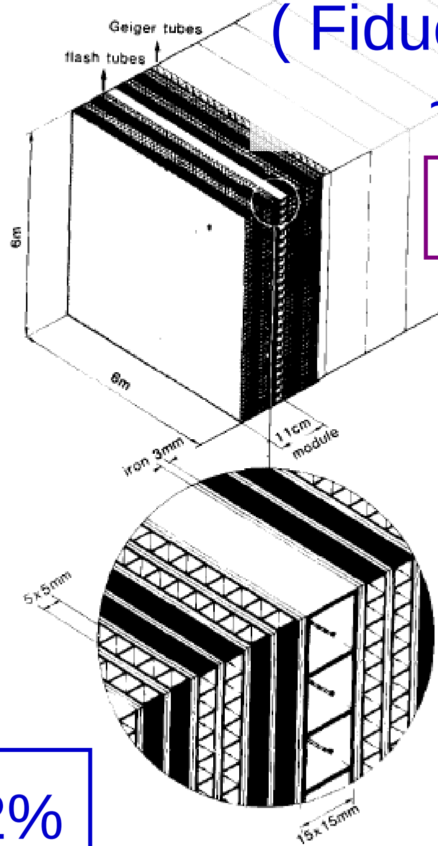
Soudan experiment

gas ionization,
time projection calorimeter

974 tons in total

(Fiducial
~ 770 tons)

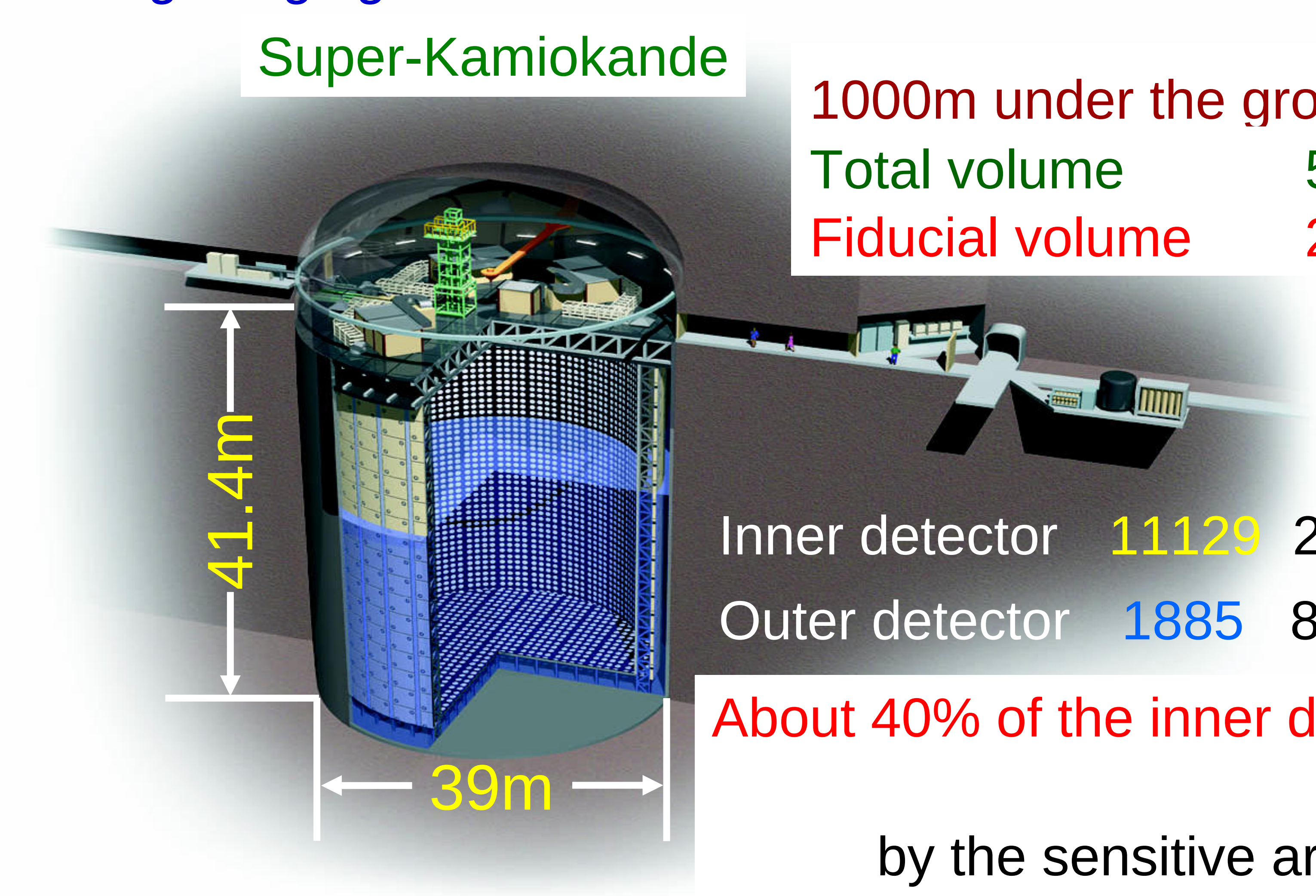
Iron ~ 85%



$\varepsilon (p \rightarrow \bar{\nu} K^+) \sim 12\%$

Proton decay experiments from 1996~

Ring imaging water Cherenkov detector ~ 22.5k ton



1000m under the ground

Total volume 50 ktons

Fiducial volume 22.5 ktons

Inner detector 11129 20” PMTs

Outer detector 1885 8” PMTs

About 40% of the inner detector is covered by the sensitive area of PMT.

Every day, ~ 20 solar and atmospheric neutrinos are observed.

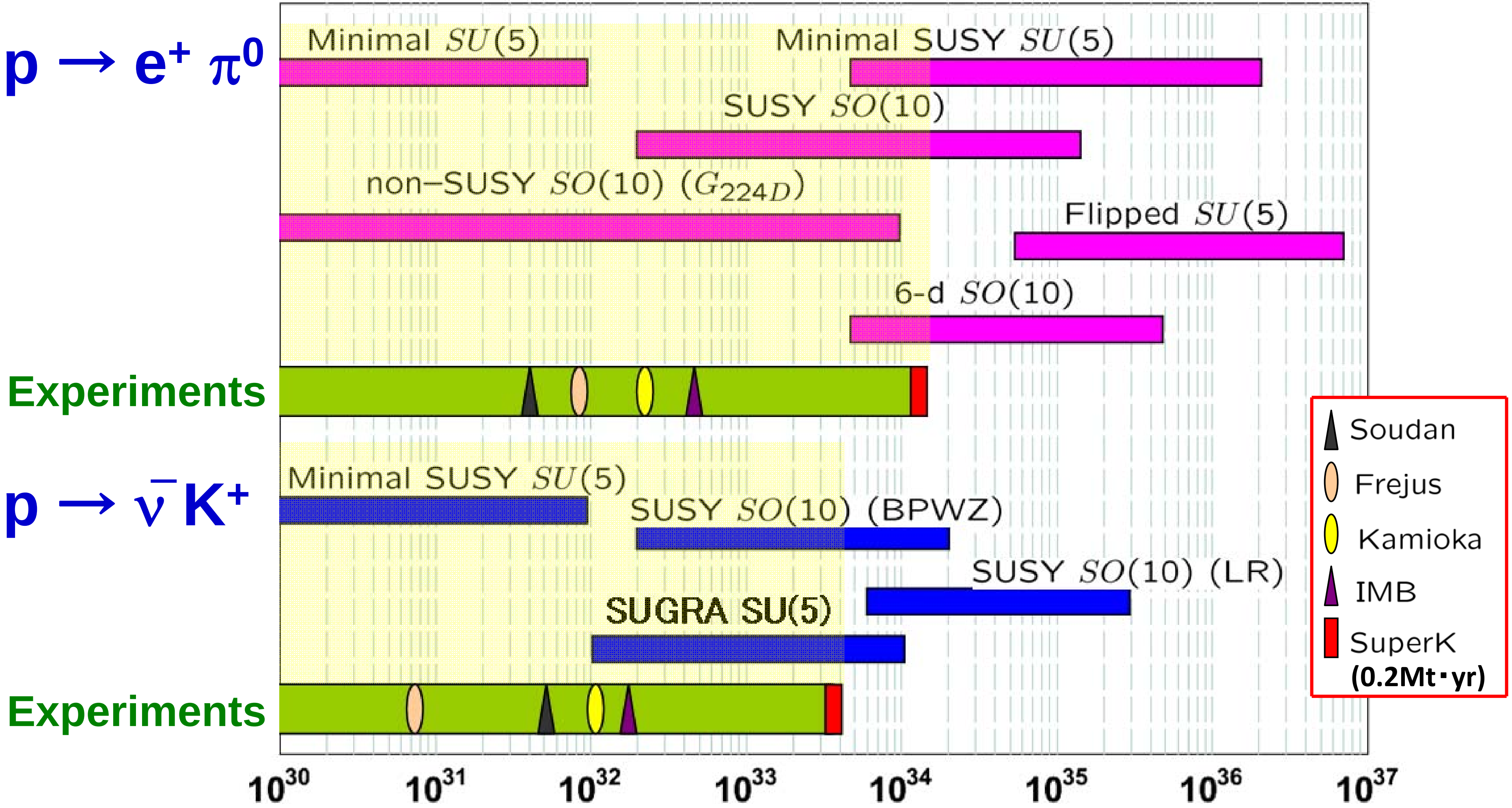
→ *Background of proton decay*

Predicted lifetime of proton for major two decay modes

$p \to e^+ \pi^0$ and $p \to \bar{\nu} K^+$

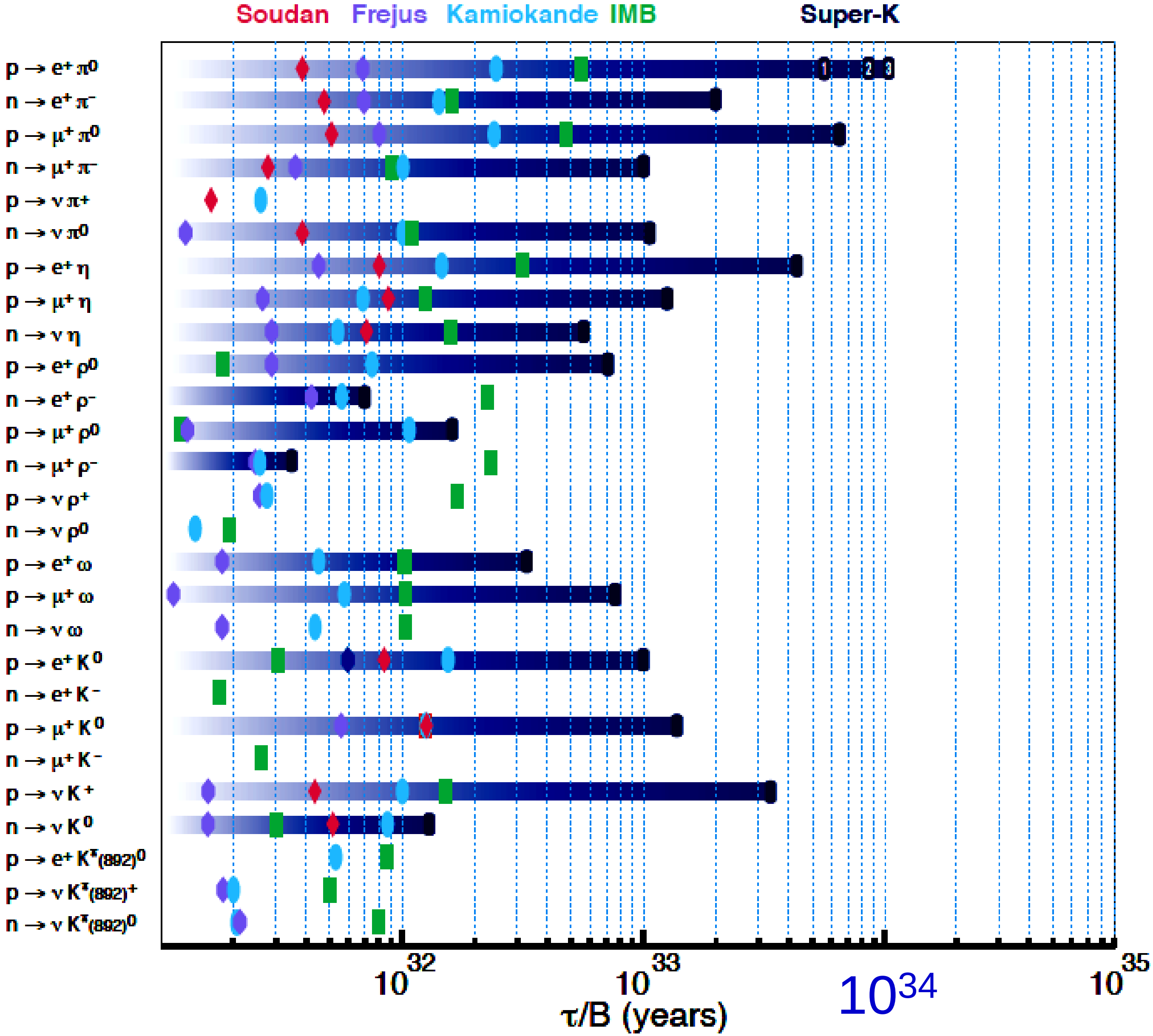
Summary of the current status

comparison with the experimental data



Nucleon decay search

Many other decay modes have been studied.



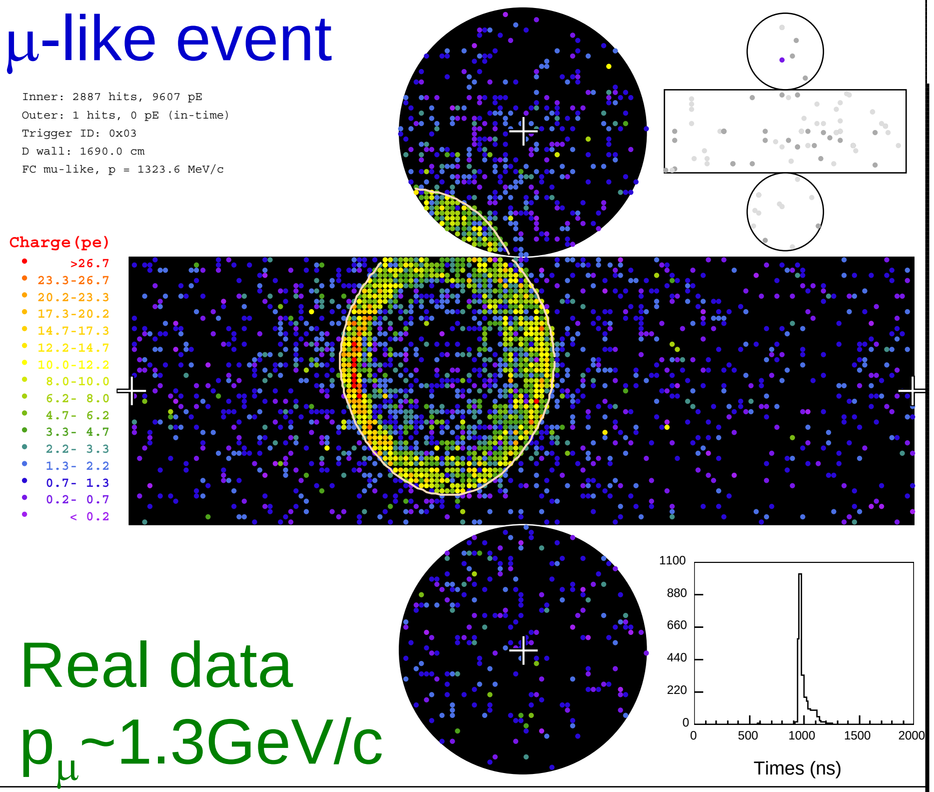
Super-Kamiokande detector

Ring imaging water Cherenkov detector

Particle types (e-like or μ-like) can be identified by the shape of the Cherenkov ring.

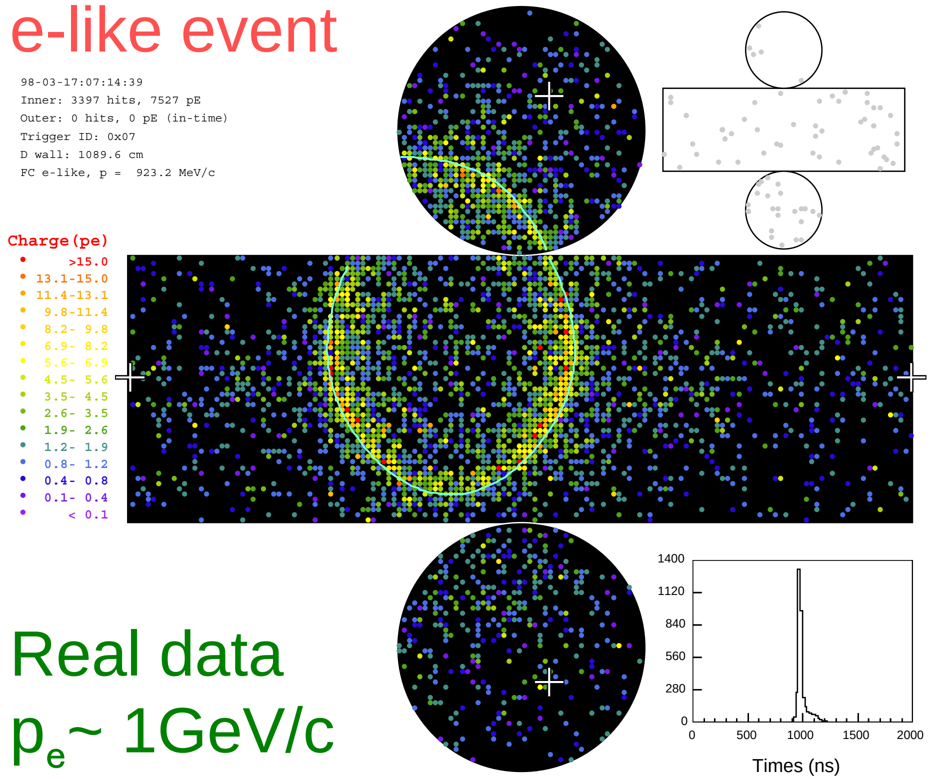
Electron (or gamma) generates electro-magnetic shower and ring is more diffused compared to the muon.

μ-like event



Real data
p_μ~1.3GeV/c

e-like event

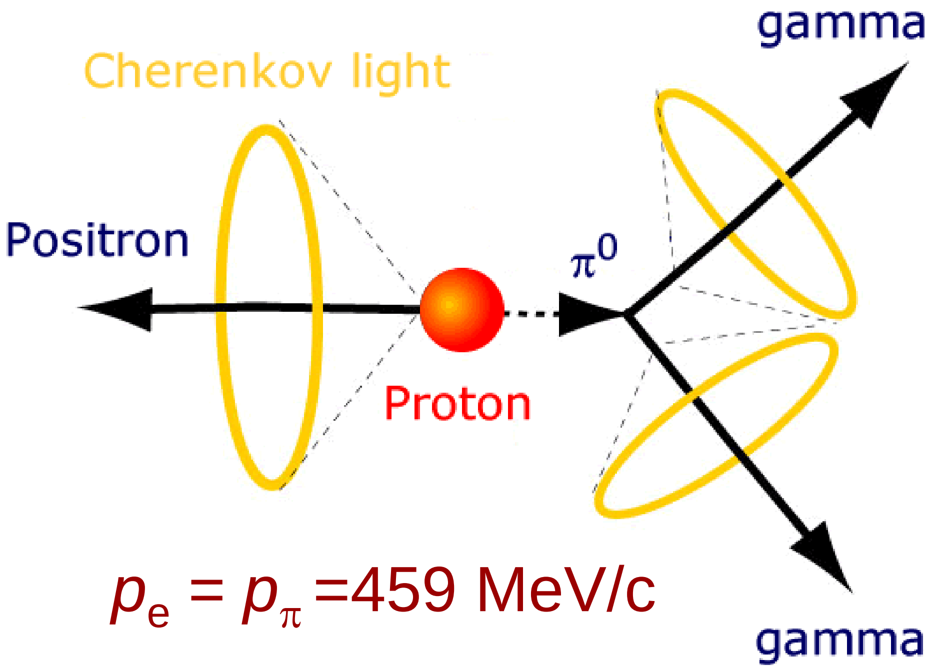


Real data
p_e~ 1GeV/c

But weak in detecting low momentum heavy particles.

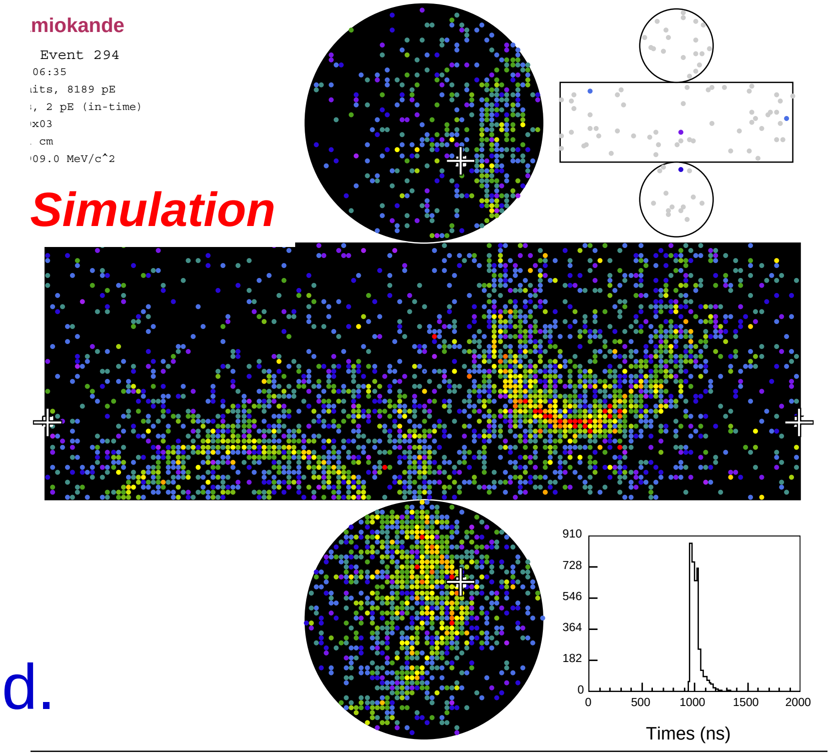
Proton decay search in SK $p \rightarrow e^+ + \pi^0$

Ring imaging water Cherenkov detectors
have very high efficiency in identifying both e^+ and π^0



$p_e = p_\pi$ =459 MeV/c

SK event display
$p \rightarrow e^+ + \pi^0$ (simulation)

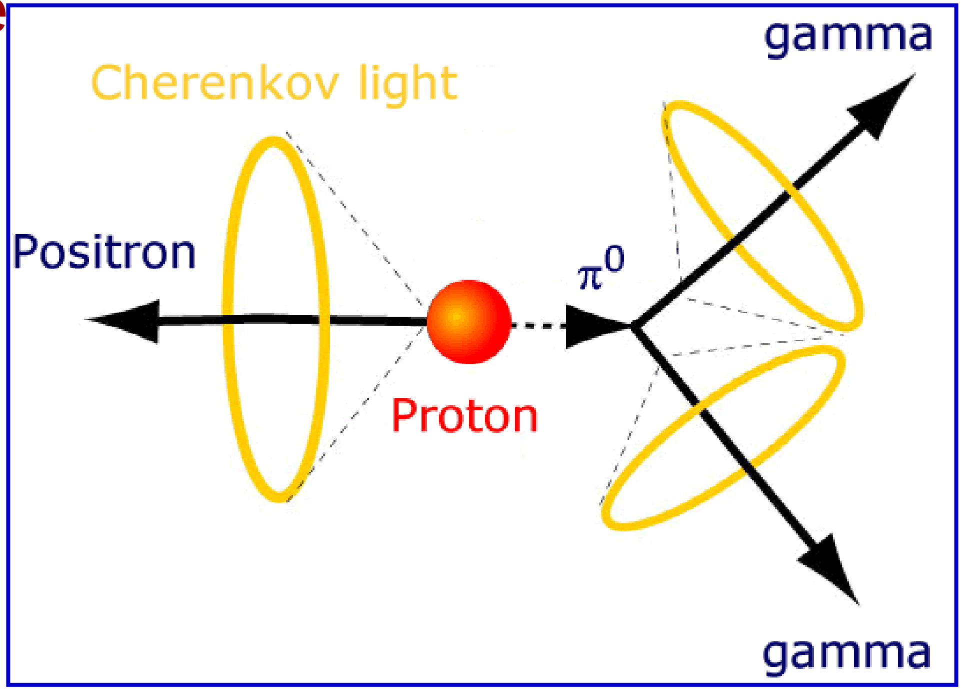


Clear 3 e-like rings
are expected to be observed.

Proton decay search in SK $p \rightarrow e^+ + \pi^0$

Event selection criteria

- No activity in the outer detector
- Vertex in the fiducial volume
- No decay electron
- 2 or 3 e-like ring
  (e^+ + 1 or 2 γ)
  ~ one of the γs may overlap with e^+
- Reconstructed π^0 mass
  85 ~ 185 MeV/c^2
  (for 3 ring events)
- Reconstructed proton mass
  800 ~ 1050 MeV/c^2
- Reconstructed total (proton) momentum
  p_{tot} < 250 MeV/c

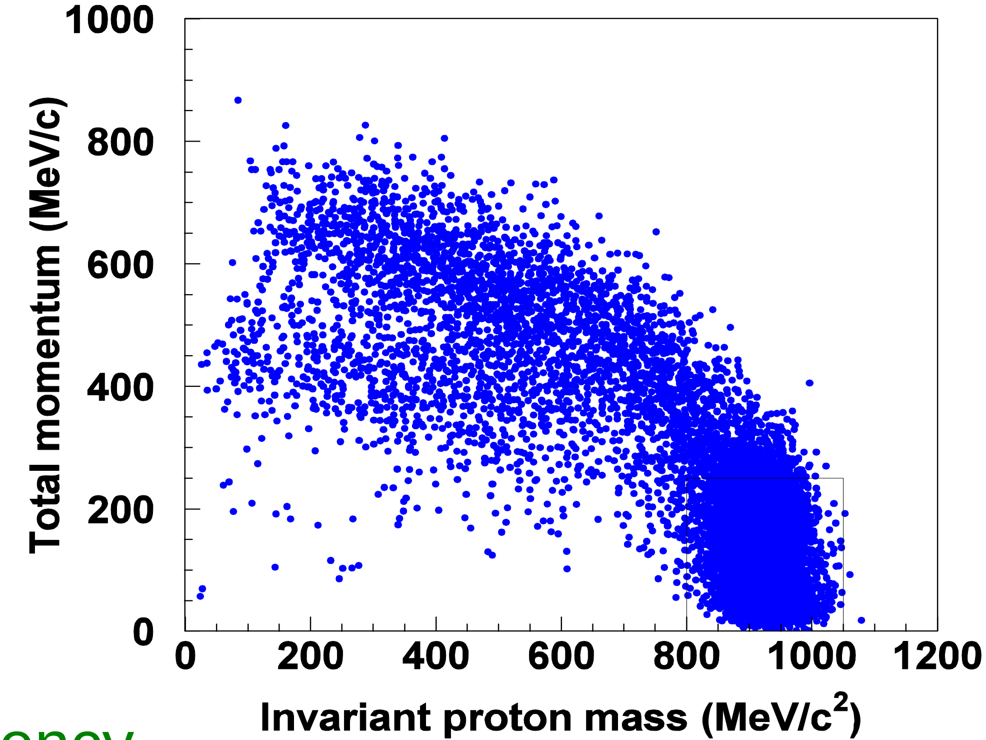


Proton decay search in SK $p \rightarrow e^{+} + \pi^{0}$

Detection efficiency

2 or 3 rings	73.7%
PID (all e-like)	65.5%
Mass of π^0	63.5%
No decay electron	62.5%
Total mass and total momentum	45.0%

→ Signal efficiency = 45%



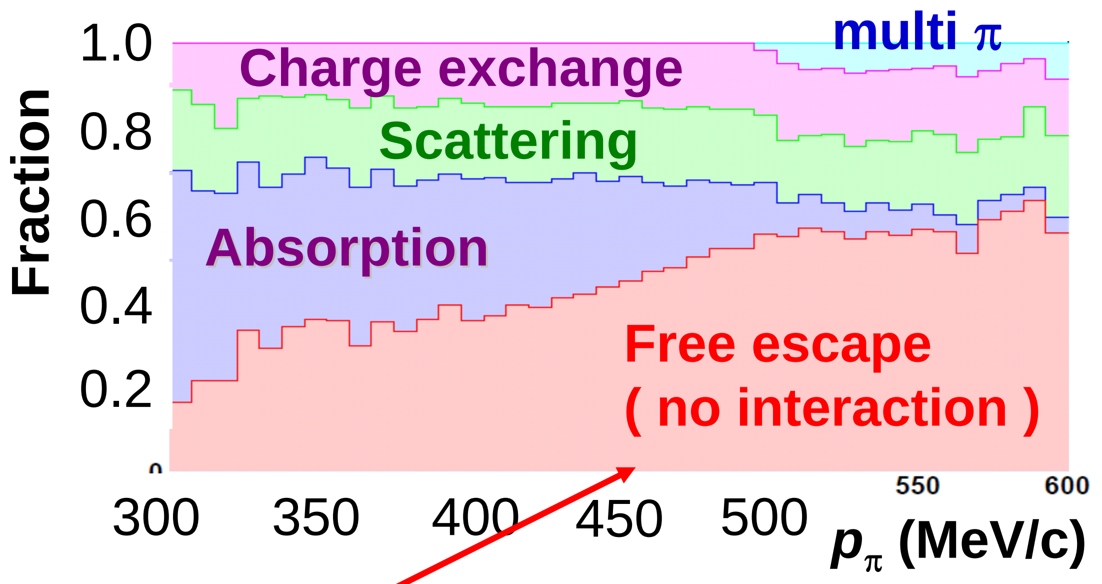
One of the major sources of inefficiency

π interaction in Oxygen (before escaping from ^{16}O)

- charge exchange ($\pi^0 \rightarrow \pi^{\pm}$)
- inelastic scattering ~ change momentum and direction of π^0

Proton decay search in SK $p \rightarrow e^+ + \pi^0$

Interaction probability of π^0 in ^{16}O (MC)



- Interaction probability of π in ^{16}O is so high.

p_π = 459MeV/c ($p \rightarrow e^+ + \pi^0$)

π^0 interactions in ^{16}O	Probability	Efficiency (SK-I)
free escape	44 %	72 %
absorption	22 %	0 %
charge exchange	15 %	0 %
other inelastic	19 %	13 %

Proton decay search in SK $p \rightarrow e^+ + \pi^0$

Source of the background events

$\rightarrow$ atmospheric ν

~ 2 events / Mt·year

30% from CC single π

(ν_e N $\rightarrow$ e N' π)

20% from CC multi π

(ν_e N $\rightarrow$ e N' mπ)

30% from CC QE

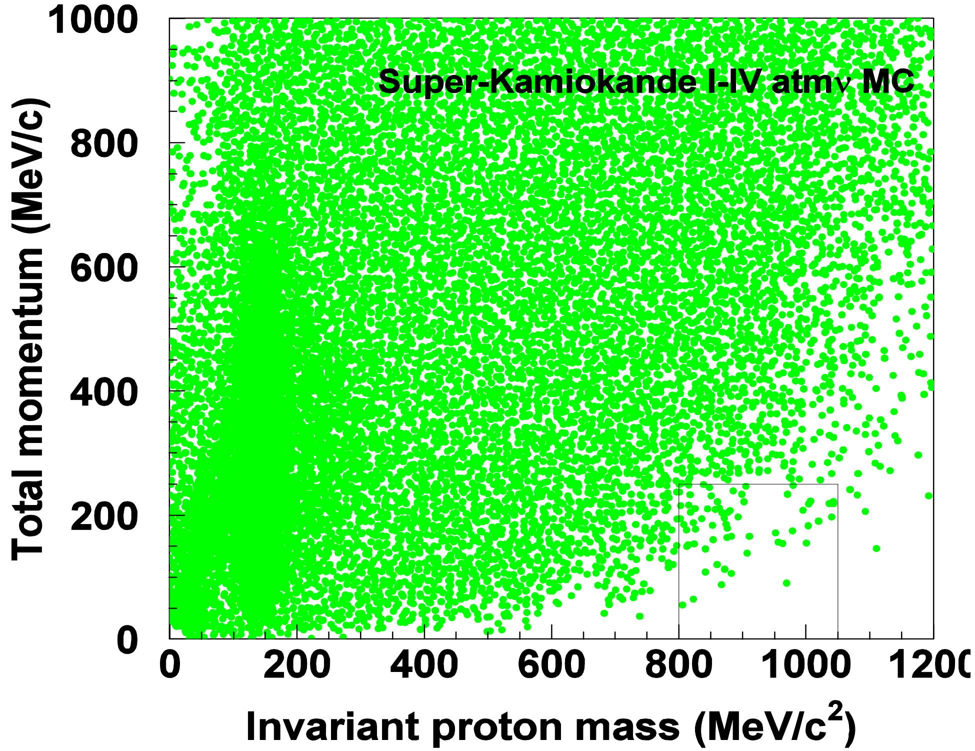
π^0 from secondary interactions of nucleon

(ν_e N $\rightarrow$ e N' + secondary π^0)

20% from NC

(ν N $\rightarrow$ ν N' X)

Total mass and total momentum
atmospheric ν MC sample



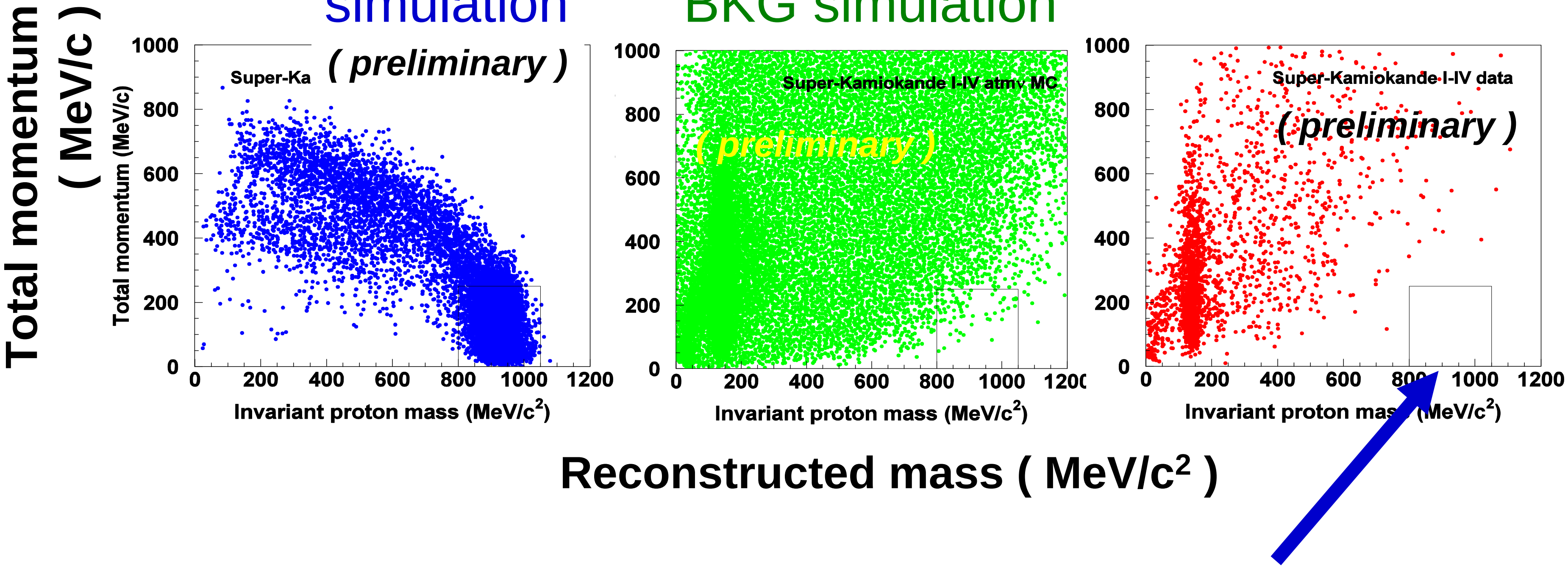
π interaction in Oxygen or in the detector changes the charge, momentum and direction of π.

Proton decay search in SK $p \rightarrow e^+ + \pi^0$

Latest result from SK

Detection efficiency	45%	(SK-IV)
Total exposure	205.7 kt·yr	(SK I ~ IV)
Estimated # of backgrounds	0.42	(SK I ~ IV)

proton decay simulation | Atmospheric ν BKG simulation | DATA

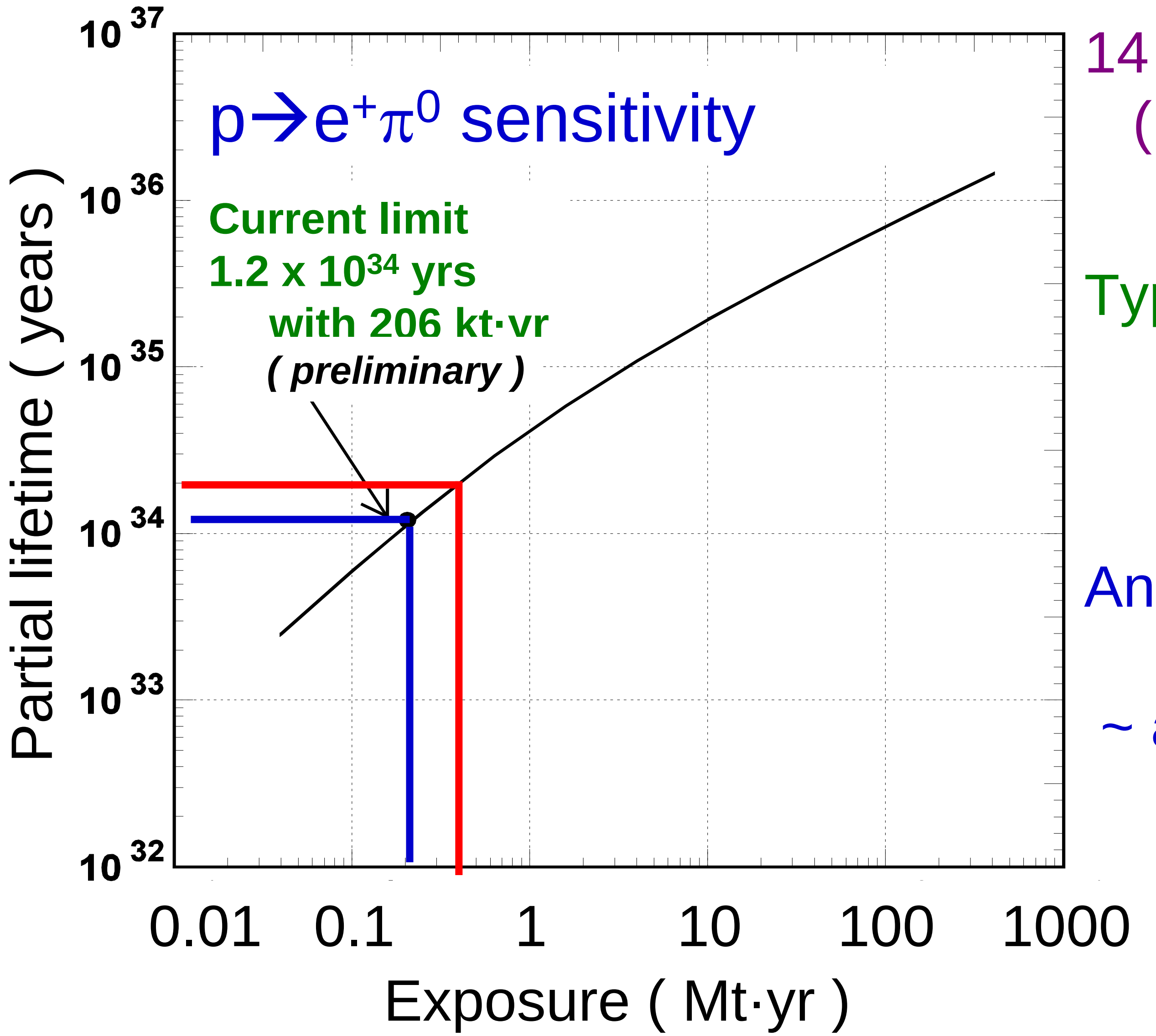


So far, no candidate events have been observed.

Partial lifetime limit = 1.2x10^{34}year ***(preliminary)***

Proton decay search in SK $p \rightarrow e^+ + \pi^0$

Future prospects



14 years of running
(with accident…)
~ 200 kt·yr

Typical live-time ratio
> 85%

Another 10 yr
of operation
~ almost doubled
exposure

Proton decay search in SK $p \rightarrow e^+ + \pi^0$

Once we have candidate events,

background evaluation becomes really important.

Uncertainties ***(background estimation)***

- Atmospheric ν flux calculations

Spectrum shape	~8%
Flavor ratio	<1%

- Neutrino interaction simulation

(incl. π interactions in ^{16}O)

CC single π	10%
CC multi π productions	7%
CC QE	8%
NC	2%

• π interactions in water	25%
• nucleon interactions in water	25%
• Detector resolutions	22%

→ Uncertainty in the hadronic interactions in / with ^{16}O nucleus and water has large contribution.

Proton decay search in SK $p \rightarrow e^+ + \pi^0$

Toward the precise estimation of the background

Data from the accelerator experiments are very useful.

For the SK analysis,

data from the 1kt water Cherenkov detector

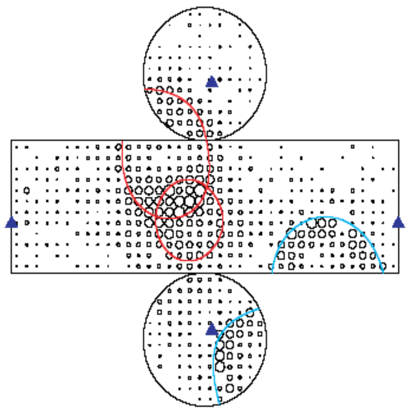
in the K2K experiment

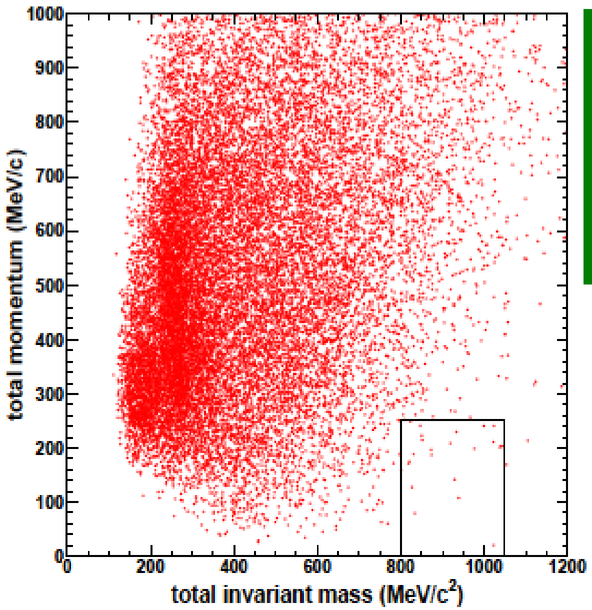
were used to check our estimations.

K2K : ν_μ beam, E_ν ~ a few hundreds of MeV ~ a few GeV.

2- or 3-ring

$\mu\pi^0$ events





K2K ($p \rightarrow e^+ + \pi^0$ BG by $E\nu$<3GeV)

1.63 +0.42/-0.33 (stat.)

+0.45/-0.51 (sys.)

events / Mt·yr

↕ Good agreement

Simulation, E_ν<3GeV

1.8 +/- 0.3(stat.)

events / Mt·yr

Data from π beam experiments are also useful.

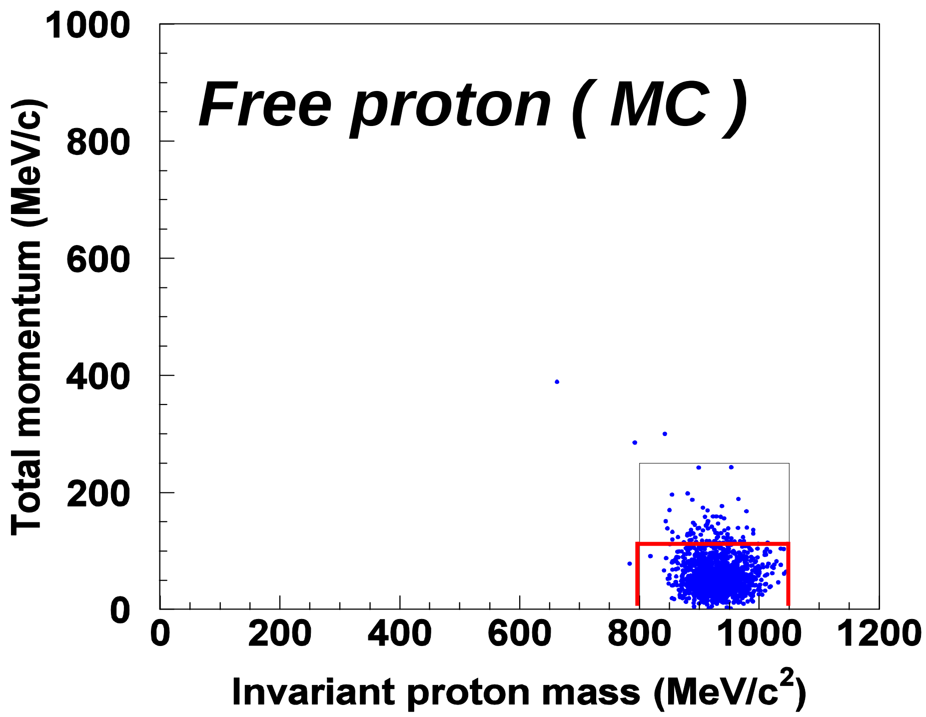
Proton decay search in SK $p \rightarrow e^+ + \pi^0$

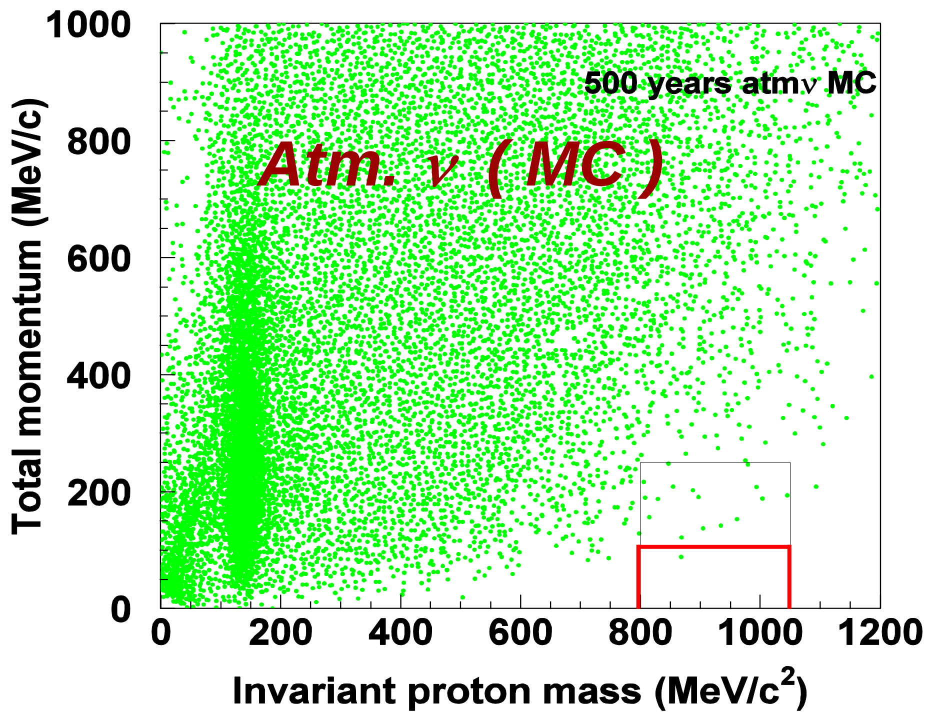
Possible way to reduce # of background

➔ Focus on the decay of free protons.

Change allowed momentum region
*from 250 MeV/c to **100 MeV/c**.*

- High efficiency for the decay of free protons.
- Most of the background events are rejected.





Proton decay search in SK $p \rightarrow e^+ + \pi^0$

Possible way to reduce # of background

→ Focus on the decay of free protons. → *Tight momentum cut*

Signal efficiency	All	Free proton
2 or 3 rings	73.7%	98.0%
PID (all e-like)	65.5	90.9
Mass of π^0	63.5	87.3
No decay electron	62.5	87.3
Total mass and momentum	45.0	87.0
Total momentum < 100MeV/c	20.7	78.7

# of background events ~ 0.1 event / Mt·yr

(~ 20 time smaller)

Drawback : free protons / all protons = 20%

But still, efficiency is still fairly large.

(45% vs ~ 16%)

Proton decay search with Lq. Ar TPC $p \rightarrow e^+ + \pi^0$

arXiv:hep-ph/0701101v1

Lq. Ar TPC has high efficiency in detecting e+ and π^0.

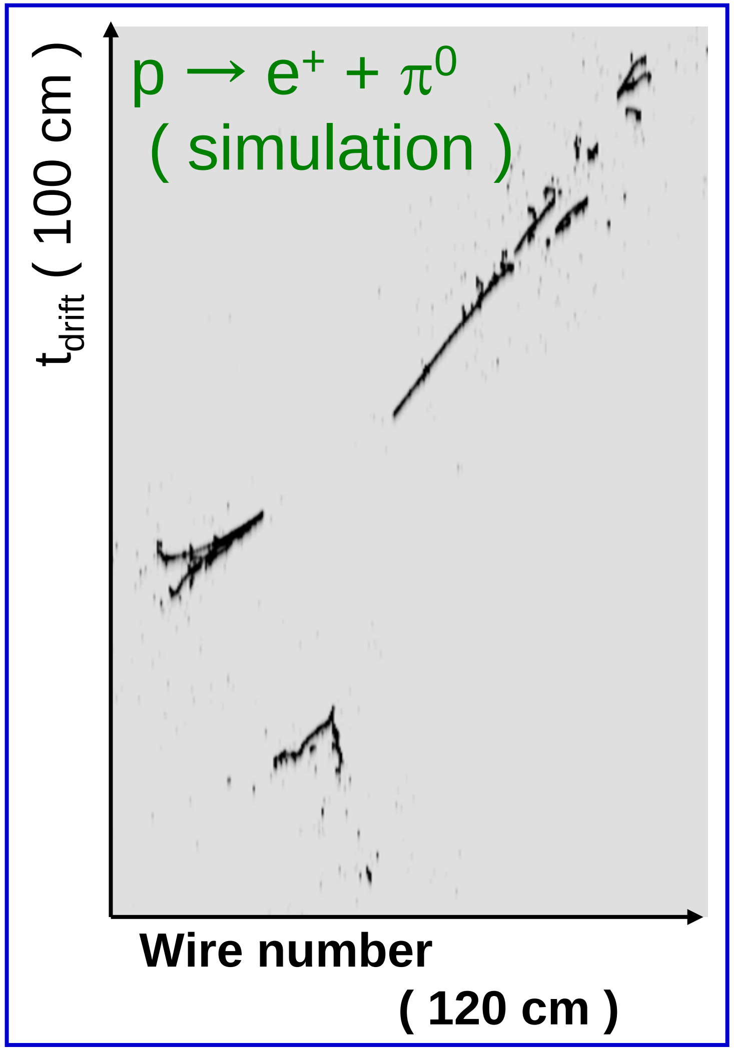
Clear e^+ and 2 γ signals.

γ identification is one advantage.

Detection efficiency ~ 45%
# of backgrounds ~ 1 event / Mt·yr

→ Almost same detection efficiency and background is estimated to be 1/2

compared with SK (Water Cherenkov detectors)



Beam data (ν, π etc.) will help to understand various systematic uncertainties.

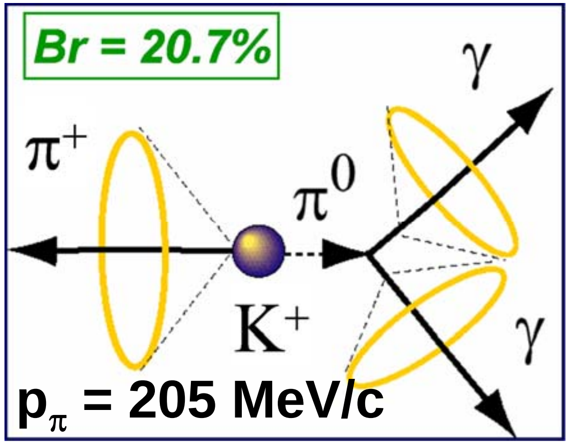
Proton decay search in SK $p \to \bar{\nu} + K^+$

Ring imaging water Cherenkov detectors
can not detect K+ from proton decay directly
due to its small momentum. ($p_K = 339$ MeV/c)

Interaction probability of low momentum K^+ is small
and most of K^+ are expected to decay at rest.

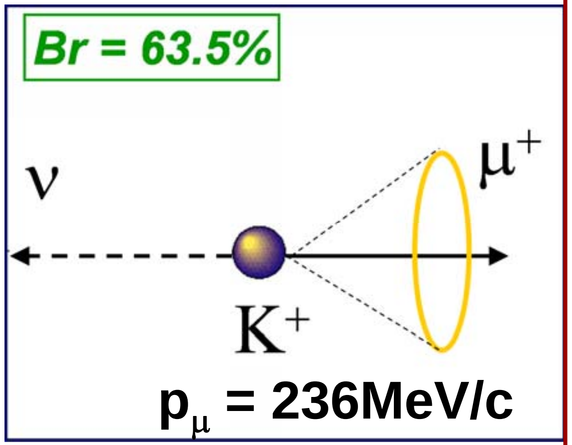
→ Use decay products of K^+
for the identification of the candidate events

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



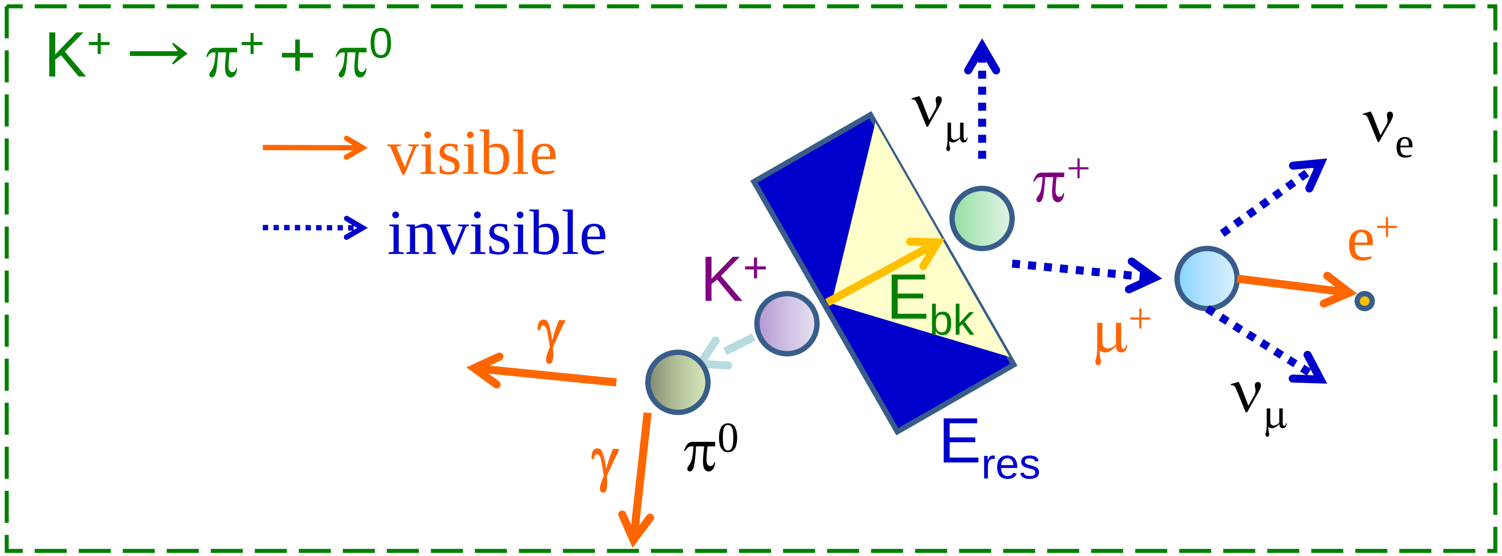
- Two e-like rings with 1 decay-e
- Small activity (from π^+) in the opposite direction of π^0

$K^+ \to \mu^+ + \bar{\nu}$



- Single μ-like ring with 1 decay electron

Proton decay search in SK $\quad p \rightarrow \bar{\nu} + K^+$



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

$\pi^0 \rightarrow \gamma + \gamma$ ← Use two γs to identify 205 MeV/c π^0

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\mu^+ \rightarrow \bar{\nu}_\mu + \bar{\nu}_e + e^+$ ← delayed e^+ from μ decay

p_π = 205 MeV/c

→ barely seen (no clear Cherenkov ring)

→ Search for the activity in the opposite side of the π^0

→ Use E_{bk} (140 ~ 180 deg. w.r.t. π^0 direction) and E_{res} (90 ~ 140 deg. w.r.t. π^0 direction)

Proton decay search in SK $p \to \bar{\nu} + K^+$

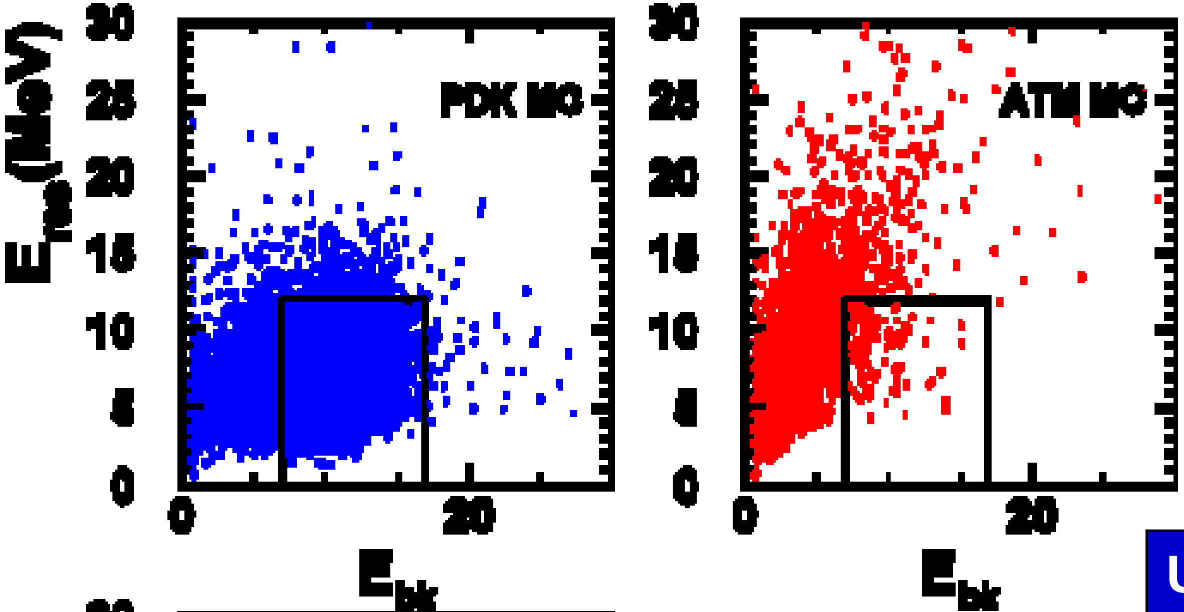
Event selection criteria for $p \to \bar{\nu} + K^+$, $K^+ \to \pi^+ + \pi^0$	**Efficiency (%) (SK 4)**	**Exp. # of Backgrounds (SK4 535.2d)**
2 rings both e-like	16.78	339.0
With 1 decay electron	13.16	63.8
Reconstructed mass of π^0 85 ~ 185 MeV/c^2	12.37	17.87
Reconstructed momentum of π^0 175 ~ 250 MeV/c	10.47	5.01
E_{res} < 12 MeV	10.19	3.68
E_{bk} 7 ~ 17MeV	7.91	0.22

E_{bk} (140 ~ 180 deg. w.r.t. π^0 direction)
E_{res} (90 ~ 140 deg. w.r.t. π^0 direction)

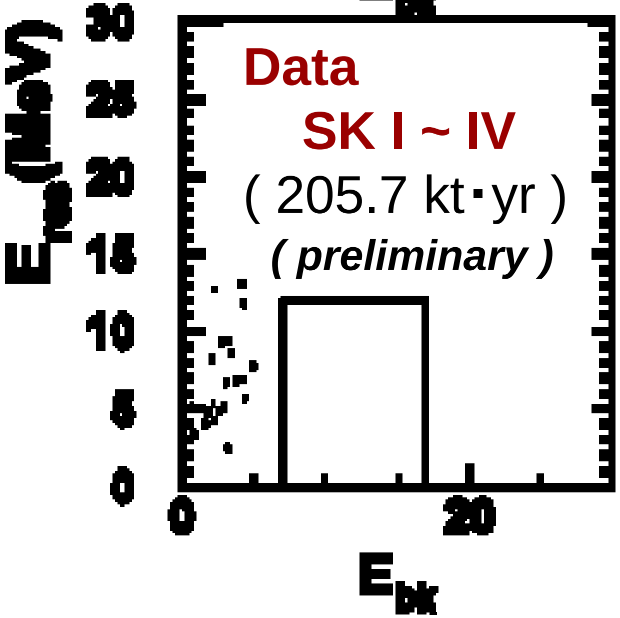
E_{bk} and E_{res} are evaluated using "electron equivalent" energy

Proton decay search in SK $p \rightarrow \bar{\nu} + K^+$

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



Expected #
of background
in SK I ~ IV
(205.7 kt·yr)
1.15 events

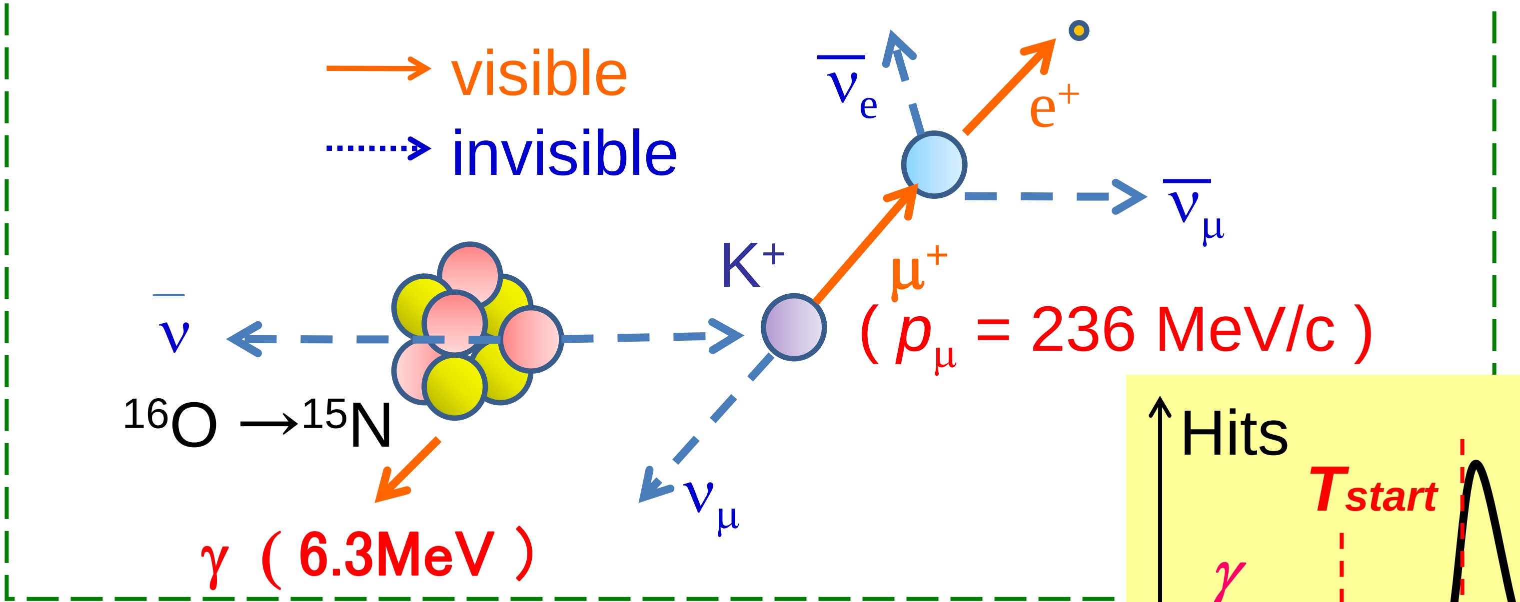


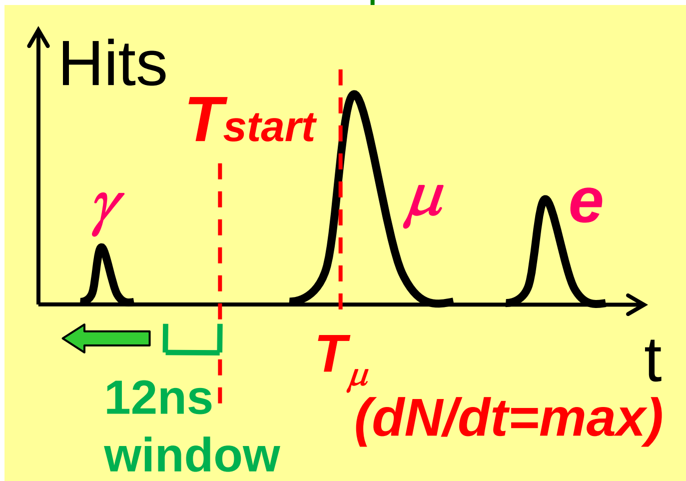
No candidates

Uncertainties	%
π-N σ in water	5.0
Energy scale	0.6
PID	2.6
Ring counting	4.1
Water parameter	1.1
Fiducial volume	3.0
Total	7.7

Proton decay search in SK $p \rightarrow \overline{\nu} + K^+$

$K^+ \rightarrow \mu^+ + \overline{\nu}$ with prompt γ tag.





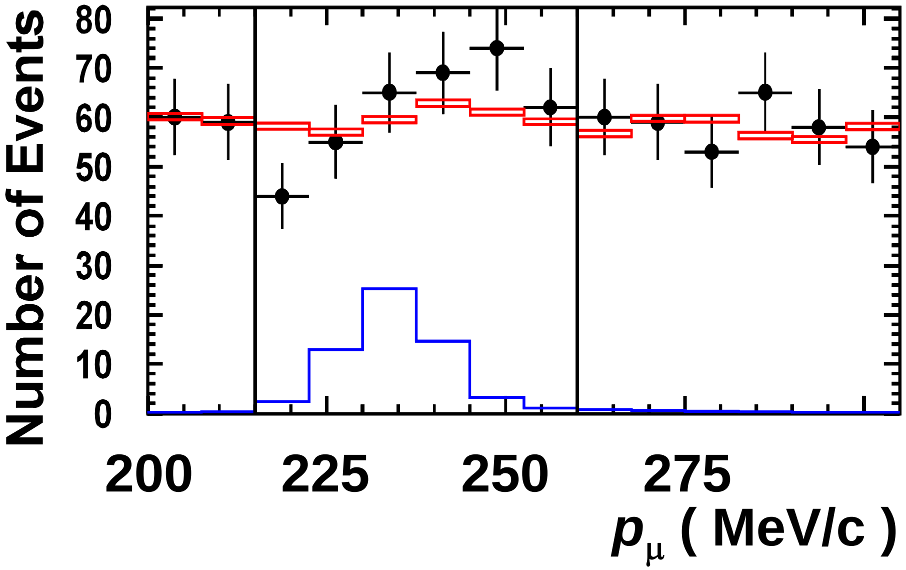
When a proton in oxygen decays,
6.3MeV de-excitation γ is also emitted
with probability of ~ 40 %.

- Search for 1 ring μ-like events with p_μ ~ 236 MeV/c
  with 1 decay electron
- Additionally, search for the pre-activity
  from prompt de-excitation 6.3 MeV γ

Proton decay search in SK $p \rightarrow \bar{\nu} + K^+$

$K^+ \rightarrow \mu^+ + \bar{\nu}$ with prompt γ tag.

Momentum distribution of 1 ring μ

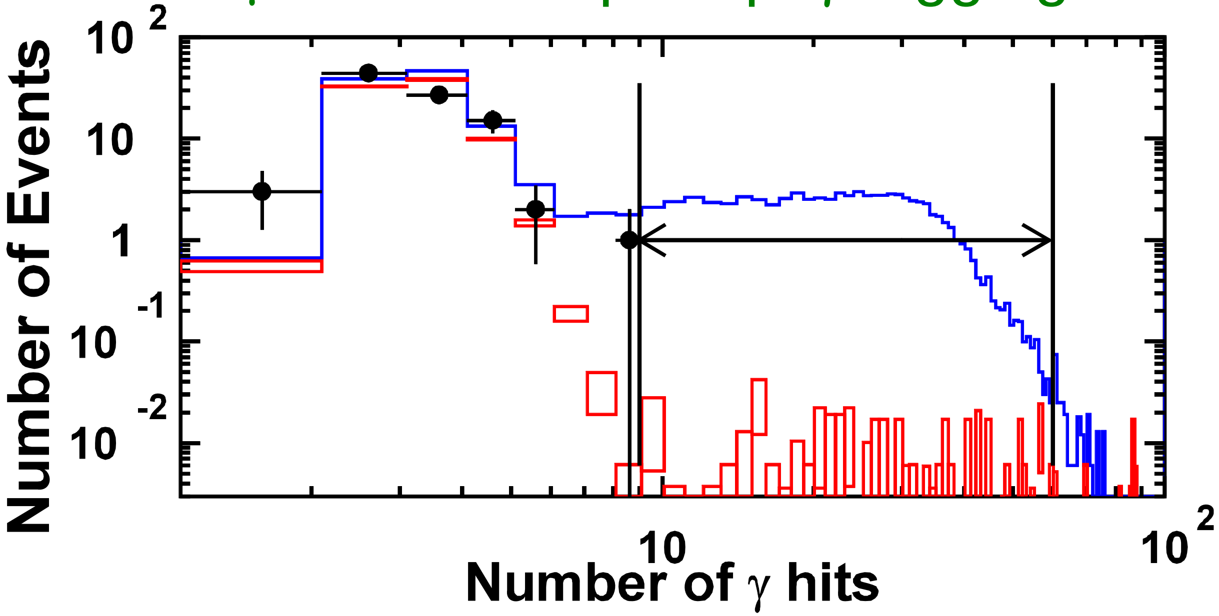


- Reject proton and π^+ events
- Search prompt γ hit cluster
  (12 ns sliding time window)
  $8 < N_\gamma < 60$
  $4 < N_\gamma < 30$ (SK 2)
- $T_\mu - T_\gamma < 100$ nsec

	Sig. eff. (%)	BKG in 535.2 days
FC1R μ	57.2	1122.6
1 decay-e	56.8	884.6
$215 < p_\mu < 260$ (MeV/c)	52.9	84.7
Distance btw. μ stop point and decay e vertex	51.8	83.4
Proton rejection	50.6	81.4
# of prompt hits	8.28	0.07
Tdiff < 100ns	8.23	0.06
π rejection ($T_{good} - m_{good} < 0.1$)	8.21	0.05 **1.5 / Mt·yr**

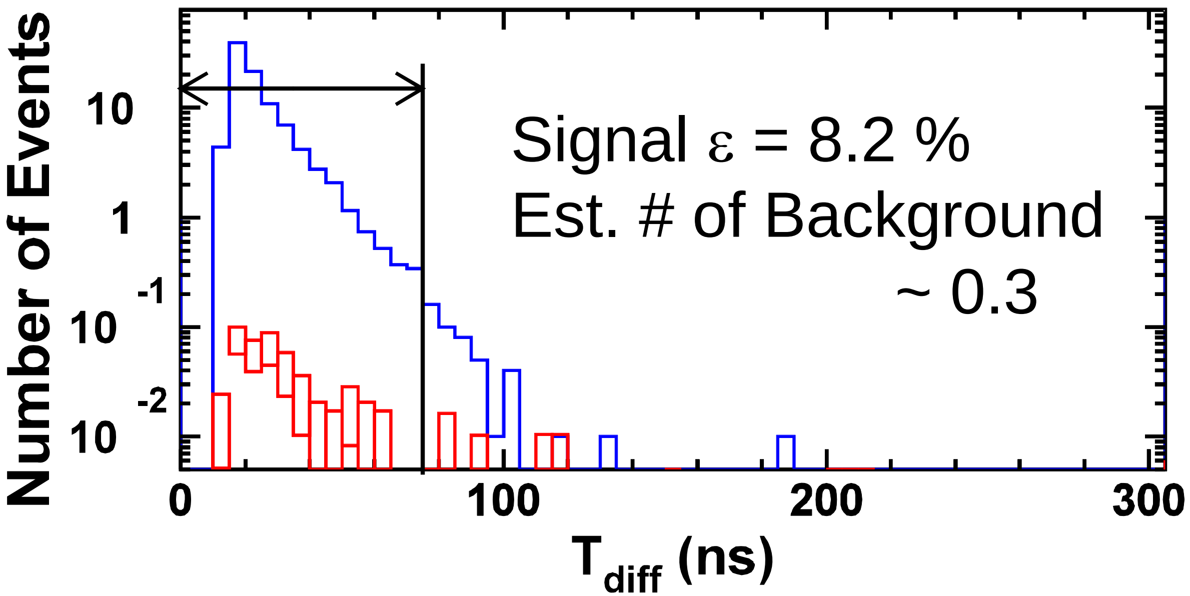
Proton decay search in SK $p \rightarrow \bar{\nu} + K^+$

$K^+ \rightarrow \mu^+ + \bar{\nu}$ with prompt γ tagging



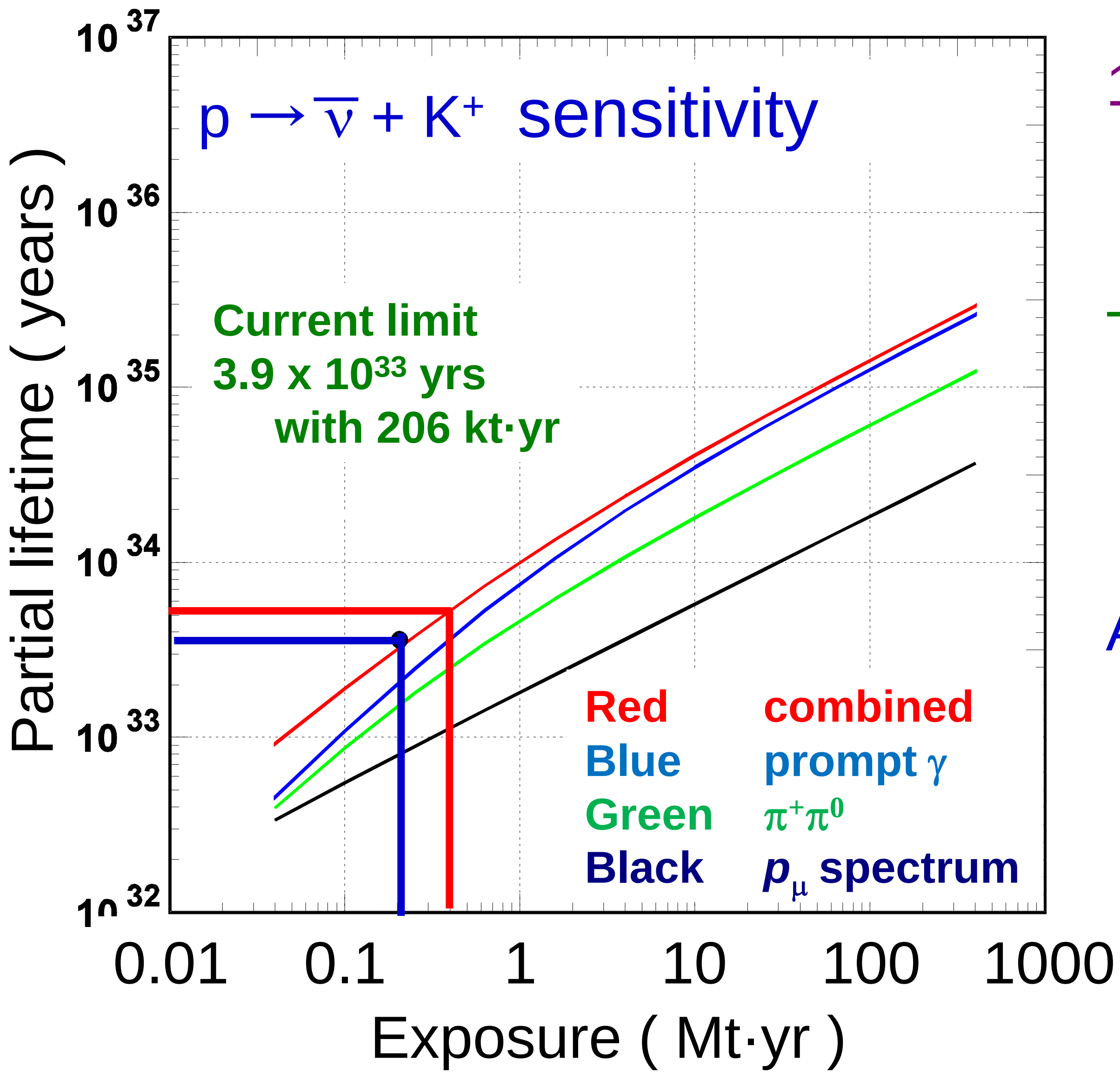
Box Atm. ν MC
Histo. Signal MC
Dot Data
(SKI ~ IV)

No candidates



Partial lifetime
($\pi^+\pi^0$ & μ^+ combined)
> 3.9×10^{33} year

Proton decay search in SK $p \rightarrow \bar{\nu} + K^+$



14 years of running
(with accident…)
~ 200 kt·yr

Typical live-time ratio
> 85%

↓

Another 10 yr
of operation
~ almost doubled
exposure

Proton decay search with Lq. Ar TPC $p \rightarrow \bar{\nu} + K^+$

Lq. Ar TPC can detect K^+ from proton decay.

Also, it is possible to detect the decay products of K^+.

Event selection can be simple.

- Detection efficiency

1 kaon	96.8 %
No other charged tracks No π^0	96.8 %
Visible energy < 0.8 GeV	96.8 %

(c.f. SK efficiency ~ 8%)

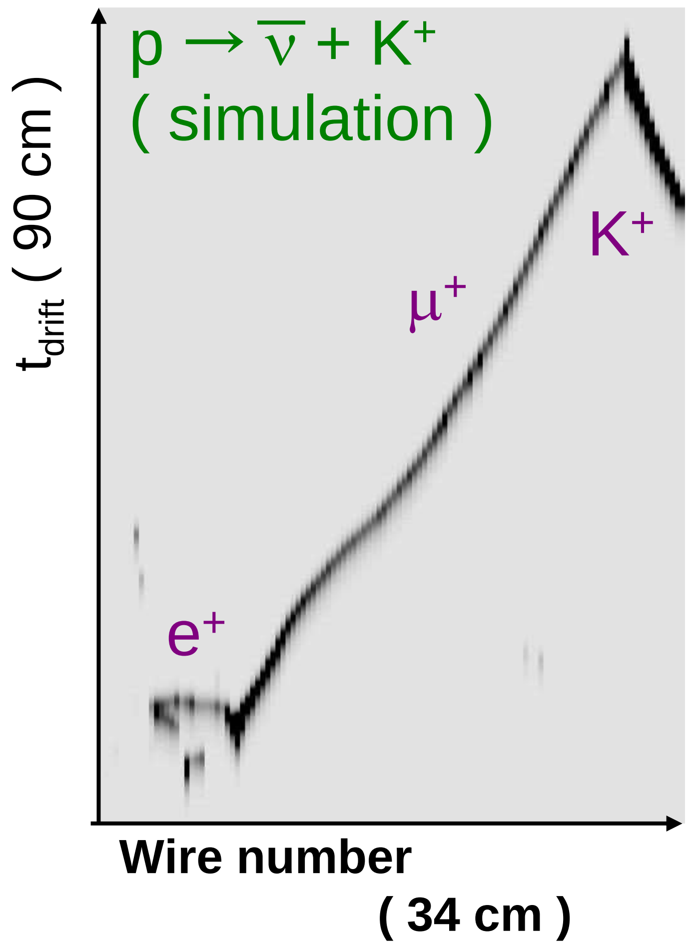
- Estimated # of backgrounds

  1 event Mt·yr

→ Expected to reach at

$\tau/B = 1\text{x}10^{34}$ yr with ~ 0.1 Mt·yr

$\tau/B = 5\text{x}10^{34}$ yr with ~ 1.0 Mt·yr



arXiv:hep-ph/0701101v1

Summary

- Current lifetime limits of proton decay

$p \rightarrow e^{+} \pi^{0}$ $\tau/B = 1.2 \times 10^{34}$ yr

$p \rightarrow \bar{\nu} K^{+}$ $\tau/B = 3.9 \times 10^{33}$ yr

Already excluded simple models like
minimal SU(5), minimal SUSY-SU(5) etc..

→ SO(10) prediction ~ 1×10^{35} yr

- Future proton decay experiments
  - Huge fiducial volume (# of protons)
  - High efficiency
  - Small # of background events

Already, # of background events in SK ~ O(1)

Precise understanding and estimation
of the background events

Neutrino and hadron interactions in the detector
Use existing neutrino and hadron beams.