Search for nucleon decay in Super-Kamiokande

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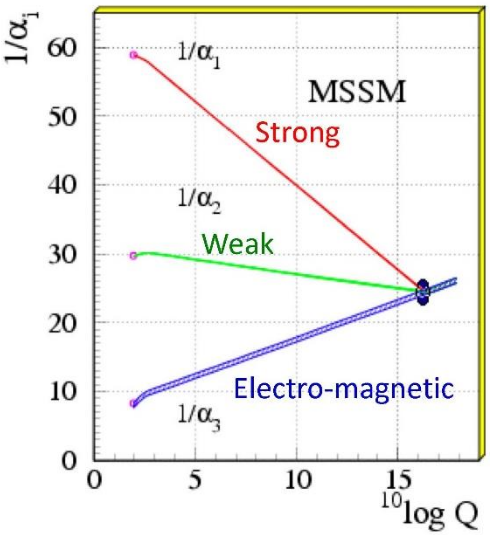
1. Introduction



The Standard Model has been successful!
… but why so many parameters?

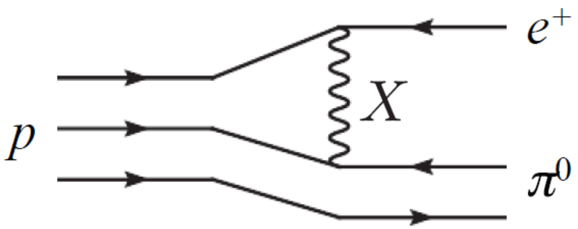
GUTs: attempt to unify Strong and Electroweak interactions.

GUTs scale: $10^{14\text{-}16}$ GeV → Cannot be reached by Accelerators.

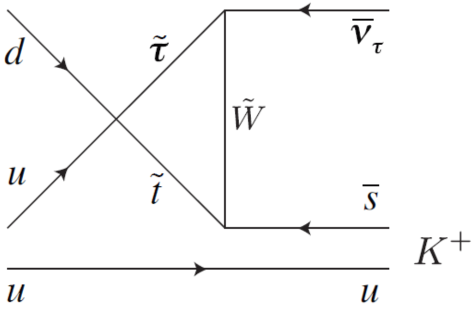
Lepton and baryon numbers are not conserved. → Proton decay is permitted !

Nucleon decay experiment is the direct probe for GUTs.

Examples of proton decay



Minimal SU(5) model



SUSY SU(5) model

Proton lifetime predictions

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)	$p \rightarrow \bar{\nu}K^+$	$\leq 10^{30}$ [3]
SUGRA SU(5)	$p \rightarrow \bar{\nu}K^+$	$10^{32} \sim 10^{34}$ [4]
SUSY SO(10)	$p \rightarrow \bar{\nu}K^+$	$10^{32} \sim 10^{34}$ [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)

$> 10^{30}$ years !

Need huge detector .

2. How to find proton decay

- Watch a proton for very long time (> 10^{30} years).
  - Age of the universe: ~ 10^{10} years
  - Obviously impossible.

OR

- Watch many protons for (relatively) short time.
  - Lifetime τ: $N(t)=N(t=0)\exp(-t/\tau)$
  - Need huge detector !

- In the late 1970s, several experiments were proposed for discovery of proton decay.
  - ➢ minimal SU(5) prediction: 10^{28} ~ 10^{32} years
  - ➢ Age of universe: ~$1.3\text{x}10^{10}$ years
  - ➢ It is impossible to continue observation one proton for such long time, but it is equivalent to study large number of proton in short time.
  - ➢ 1kt detector expected 10 ~ 10^3 decays/year.
- Like gold rash, many large detectors were build.
- Two types of detector came into fashion (the 1st generation).

Fine-grained iron calorimeter

- ➢ Excellent in track reconstruction.
- ➢ Cost per ton were expensive.
- ➢ KGF (India), Soudan I,II (Minnesota), NUSEX (Italy/France)

Water Cherenkov detector

- ➢ Good momentum resolution and PID.
- ➢ Cheaper and easier to build larger detectors.
- ➢ HPW (Harvard-Purdue-Wisconsin), IMB (Irvine, Michigan, Brookhaven), Kamiokande

Results of Water Cherenkov detector

Detector	Period	Mass (ton)	Limit ($e^+\pi^0$, 10^{30} yr)
HPW-I	1983-1984	680	1.0
Kamiokande	1983-1997	1040	260
IMB	1982-1992	3300	540

Results of Iron calorimeter

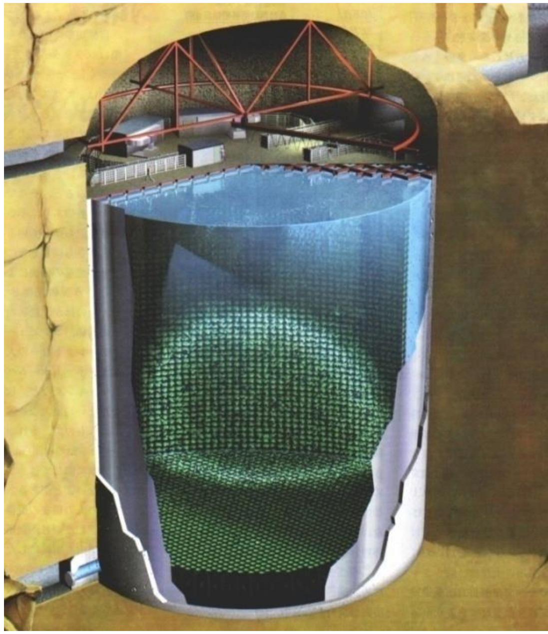
Detector	Period	Mass (ton)	Limit ($e^+\pi^0$, 10^{30} yr)
NUSEX	1982-1998	110-130	15
Frejus	1984-1988	550	70
Soudan I	1981-1990	16-24	1.3

Could not find evidence.
Need more volume !

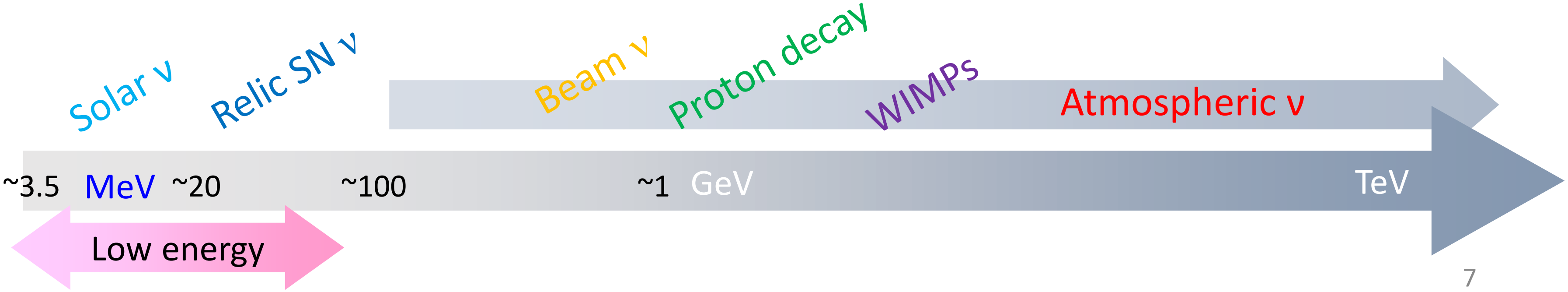
Built Super-Kamiokande !
(2nd generation)

2. History of Super-Kamiokande

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, ~1/3 comes from IMB).
Mom. resolution: 3.0 % for e 1 GeV/c (4.1%: SK-2).
Particle ID: Separate into EM shower type (e-like) and muon type (μ-like) by Cherenkov ring angle and ring pattern.



Physics targets of Super-Kamiokande

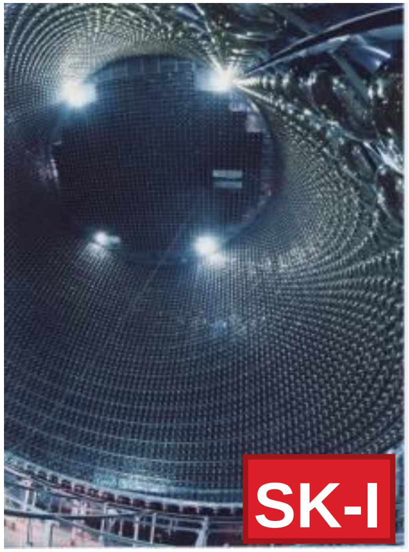


Solar ν
Relic SN ν
Beam ν
Proton decay
WIMPs
Atmospheric ν

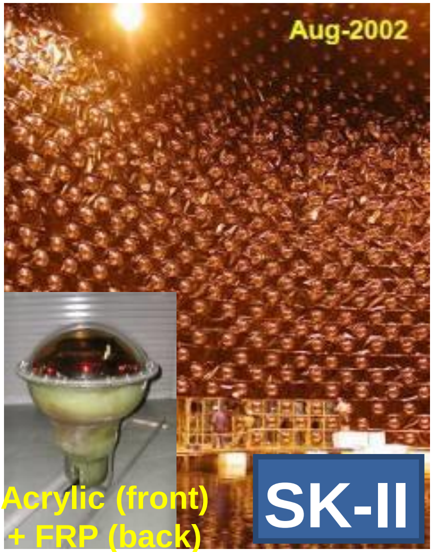
~3.5 MeV ~20 ~100 ~1 GeV TeV

Low energy

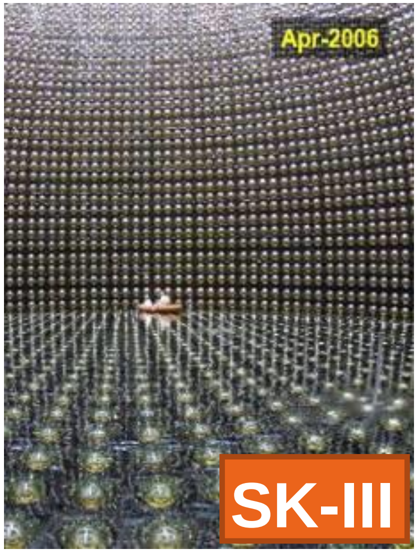
Amazingly, SK still runs stably more than 20 years.



11146 ID PMTs
(40% coverage)

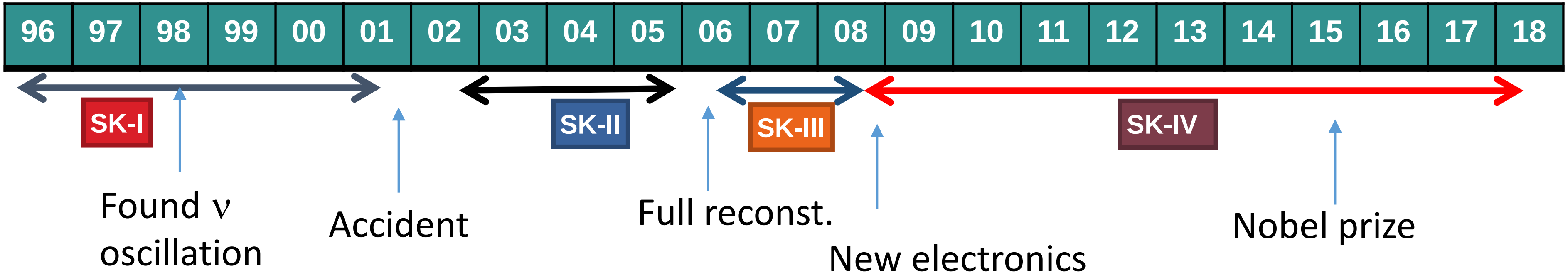


5182 ID PMTs
(19% coverage)



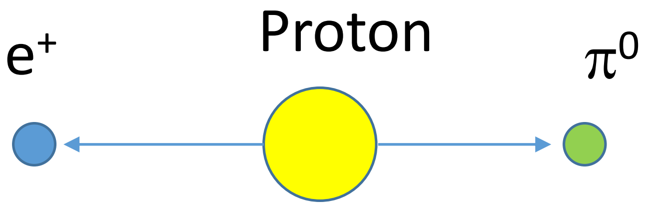
11129 ID PMTs
(40% coverage)

Electronics
Upgrade



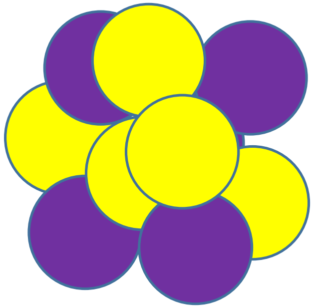
3. p→ $e^+\pi^0$ search

What's important for p→$e^+\pi^0$?



In "free" proton case, e^+ and π^0 emit in back-to-back. Energy corresponding to proton mass is fully used by decayed particles.

Nucleus

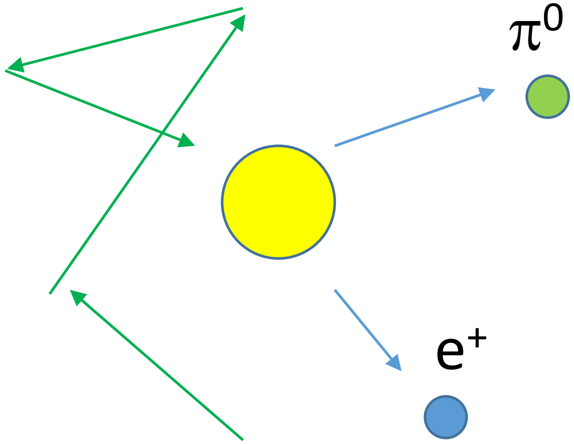


What happens if a bound proton in nucleus decays ?

Inefficiencies and uncertainties of proton decay search come from nuclear effect !

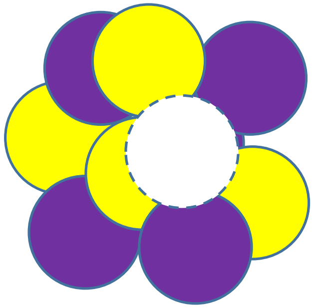
Key 1: Proton never stops in nucleus

- Protons don’t exist locally in nucleus. It is always moving in the nuclear potential (Fermi motion, $p_f \sim 225$ MeV/c).



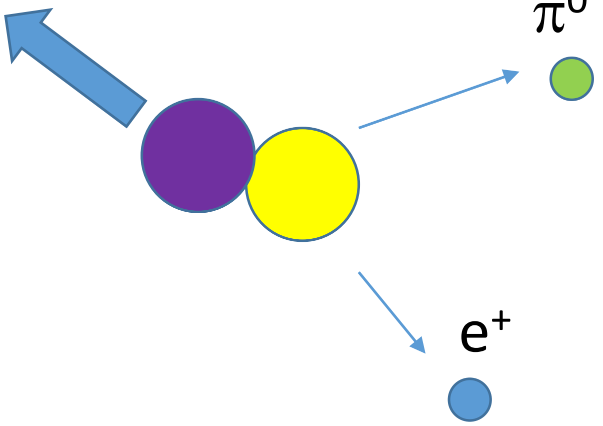
Key 2: Binding energy

- Energy corresponding proton mass should be used for compensating its binding energy (s-state: ~40 MeV, p-state:15 MeV in Oxygen).



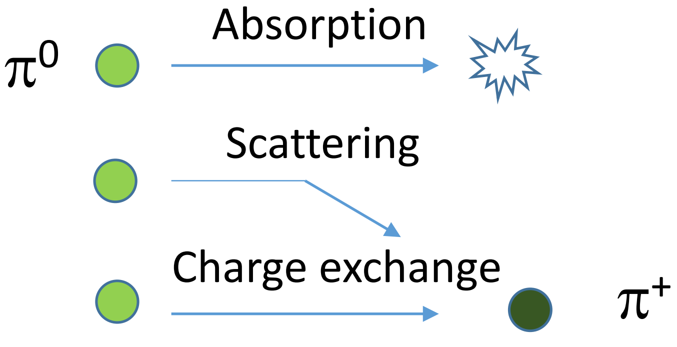
Key 3: Proton strongly binding to other nucleus

- ~ 20% protons are strongly binding to other nucleon which also bring energy when the proton decays (correlated decay)

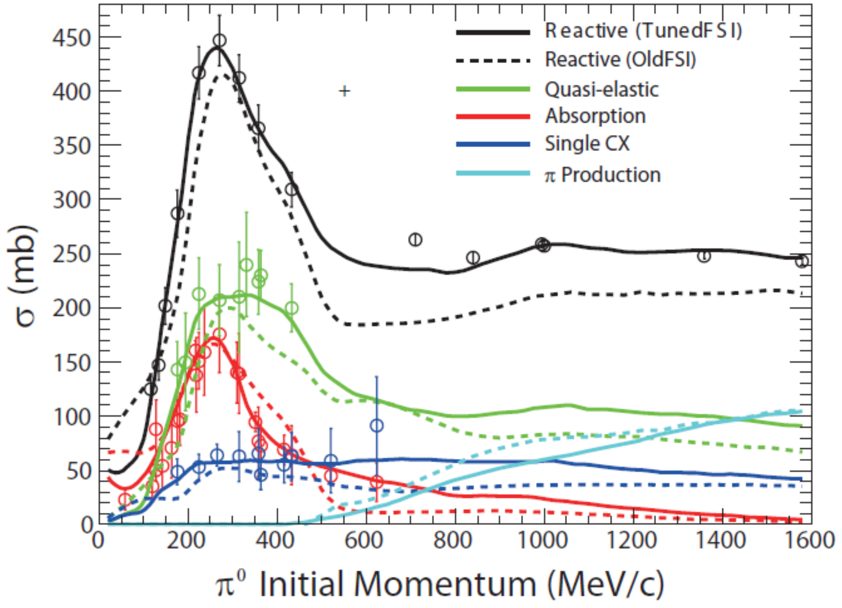


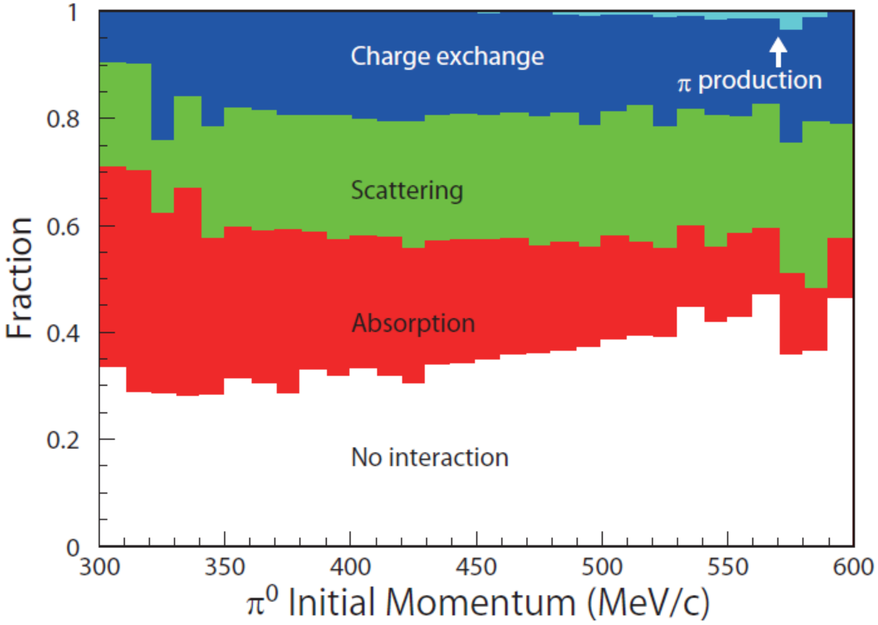
Key 4: π interacts in nucleus

- Mesons (π,K, e.t.c.) in decay products are affected in nuclear interactions before exiting nucleus.



How much pions interact in nucleus ?



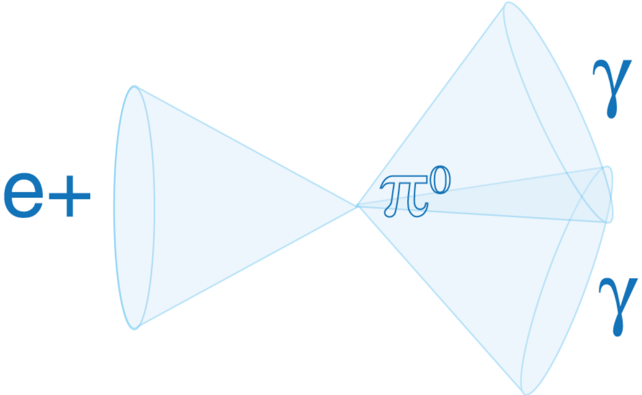


50 – 70 % of π^0 are affected by interaction before going out from Oxygen.

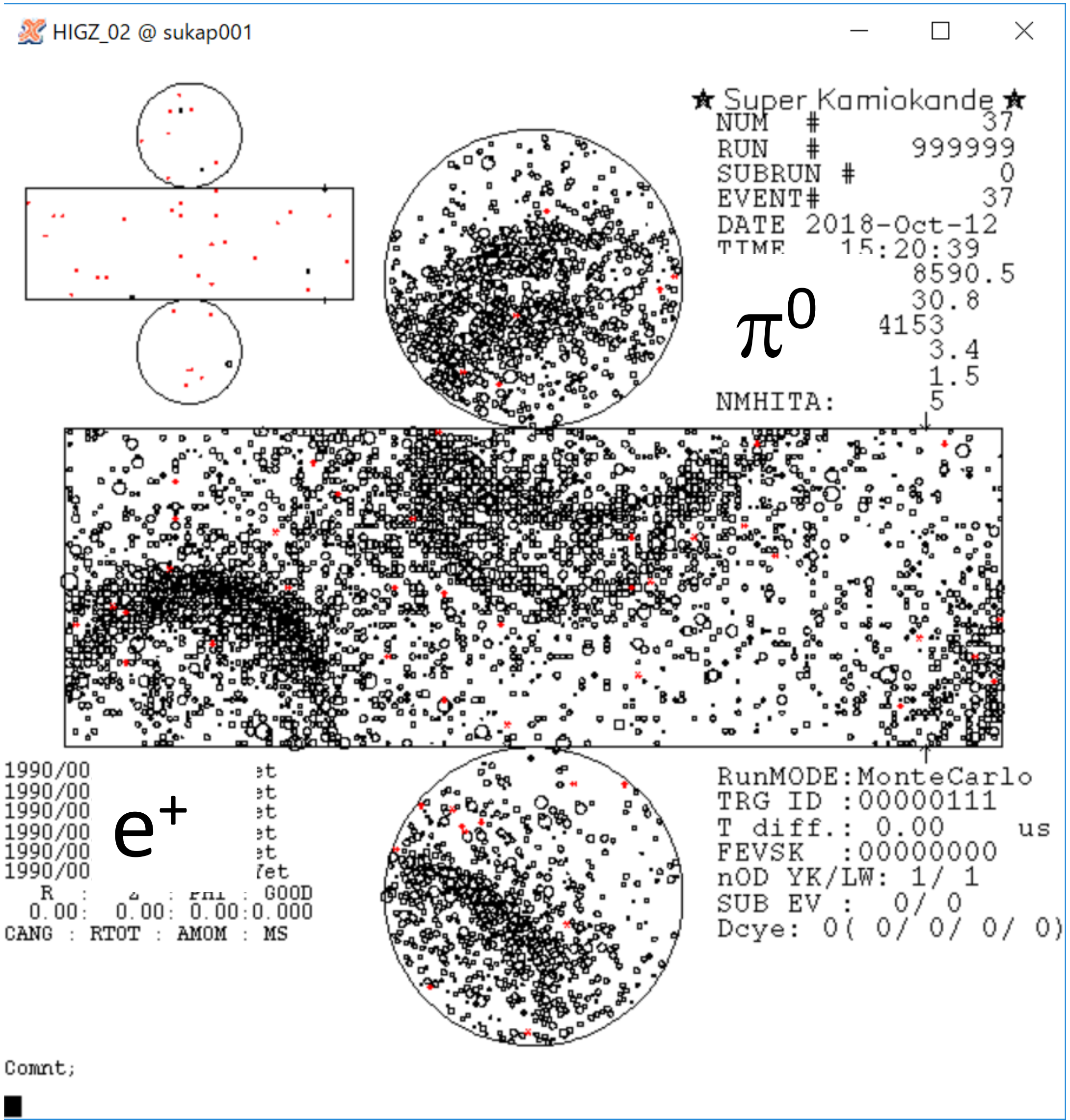
Why water is used for proton decay search ?

- Easy to construct larger detector.
  - Much cheaper than iron or gas.
  - You can find large water tank everywhere (common technology).
- High efficiency and low uncertainty.
  - H_2O has two hydrogens which are not affected by nuclear effect . They are regarded as “free” proton.
  - Free protons contribute high selection efficiency and low uncertainty.

How look like p→$e^+\pi^0$ in SK ?



Three e-like rings should be observed.



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★ Super Kamiokande ★
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SUBRUN #           0
EVENT#            37
DATE  2018-Oct-12
TIME      15:20:39
              8590.5
                30.8
          4153
                 3.4
                 1.5
NMHITA:          5
```

```
1990/00                 et
1990/00                 et
1990/00                 et
1990/00                 et
1990/00                 et
1990/00                 Vet
  R   :        :       :  GOOD
  0.00:    0.00:   0.00:0.000
CANG  : RTOT  :  AMOM  :  MS
```

```
RunMODE:MonteCarlo
TRG ID  :00000111
T diff.:  0.00      us
FEVSK   :00000000
nOD YK/LW:  1/  1
SUB EV  :   0/  0
Dcye:  0(  0/  0/  0/  0)
```

```
Comnt;
```

Stopped π^0 case

π^0

γ_1 ~~~~ ● ~~~~ γ_2

$E_1 = E_2$

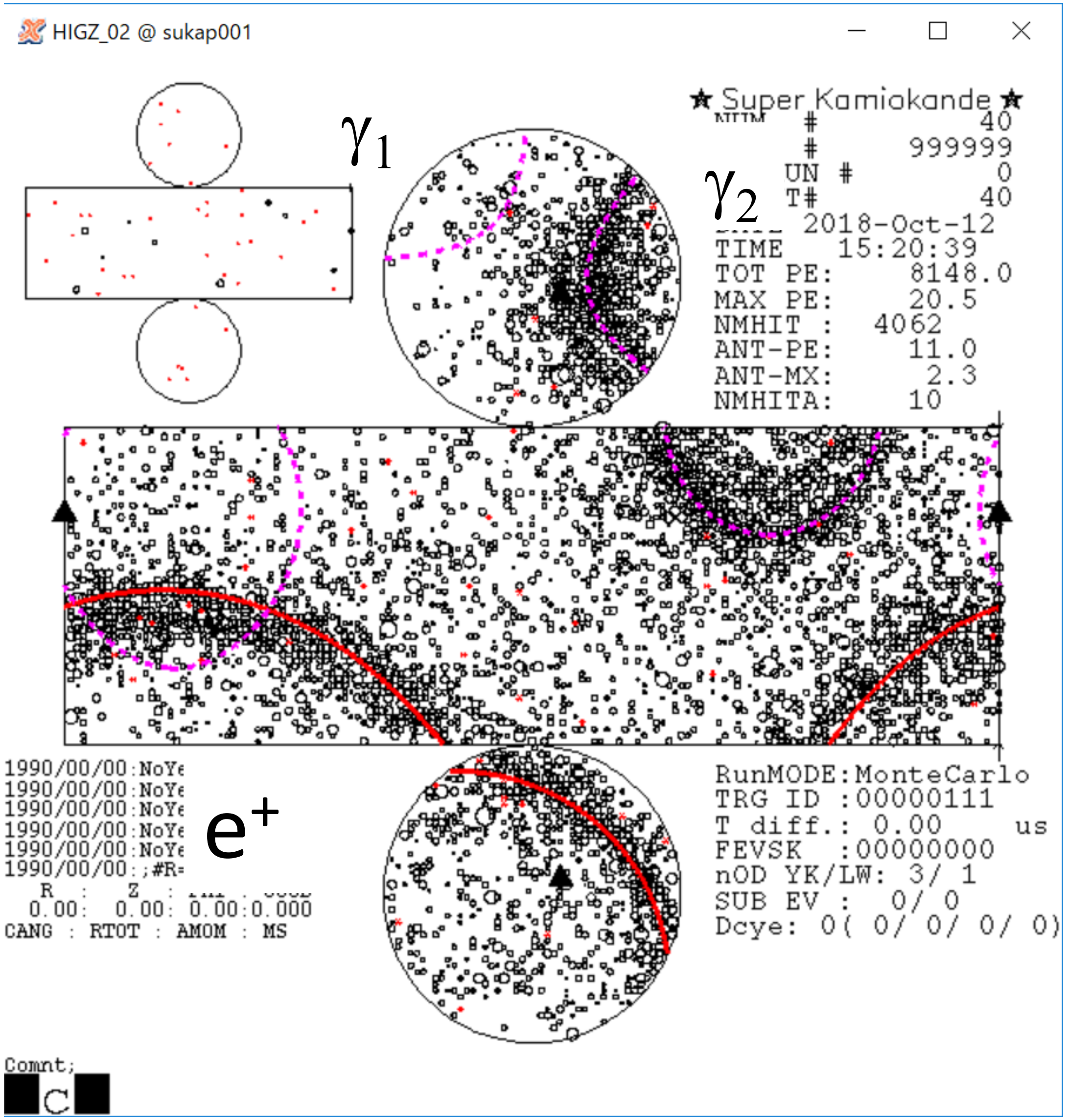
If a γ is emitted π^0 direction

π^0

γ_1 ~~ ● ➡ ~~~~ γ_2

$E_1 < E_2$

Sometimes one γ is failed to reconstruct and observed only two rings.



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      UN #             0
      T#              40
    2018-Oct-12
TIME     15:20:39
TOT PE:       8148.0
MAX PE:       20.5
NMHIT :    4062
ANT-PE:       11.0
ANT-MX:        2.3
NMHITA:       10
```

```
1990/00/00:NoYe
1990/00/00:NoYe
1990/00/00:NoYe
1990/00/00:NoYe
1990/00/00:NoYe
1990/00/00:;#R=
   R  :   Z  :
 0.00:  0.00:  0.00:0.000
CANG : RTOT : AMOM : MS
```

```
RunMODE:MonteCarlo
TRG ID :00000111
T diff.:  0.00     us
FEVSK  :00000000
nOD YK/LW:  3/ 1
SUB EV :   0/ 0
Dcye:  0(  0/  0/  0/  0)
```

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Comnt;
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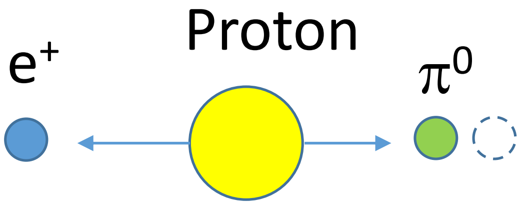
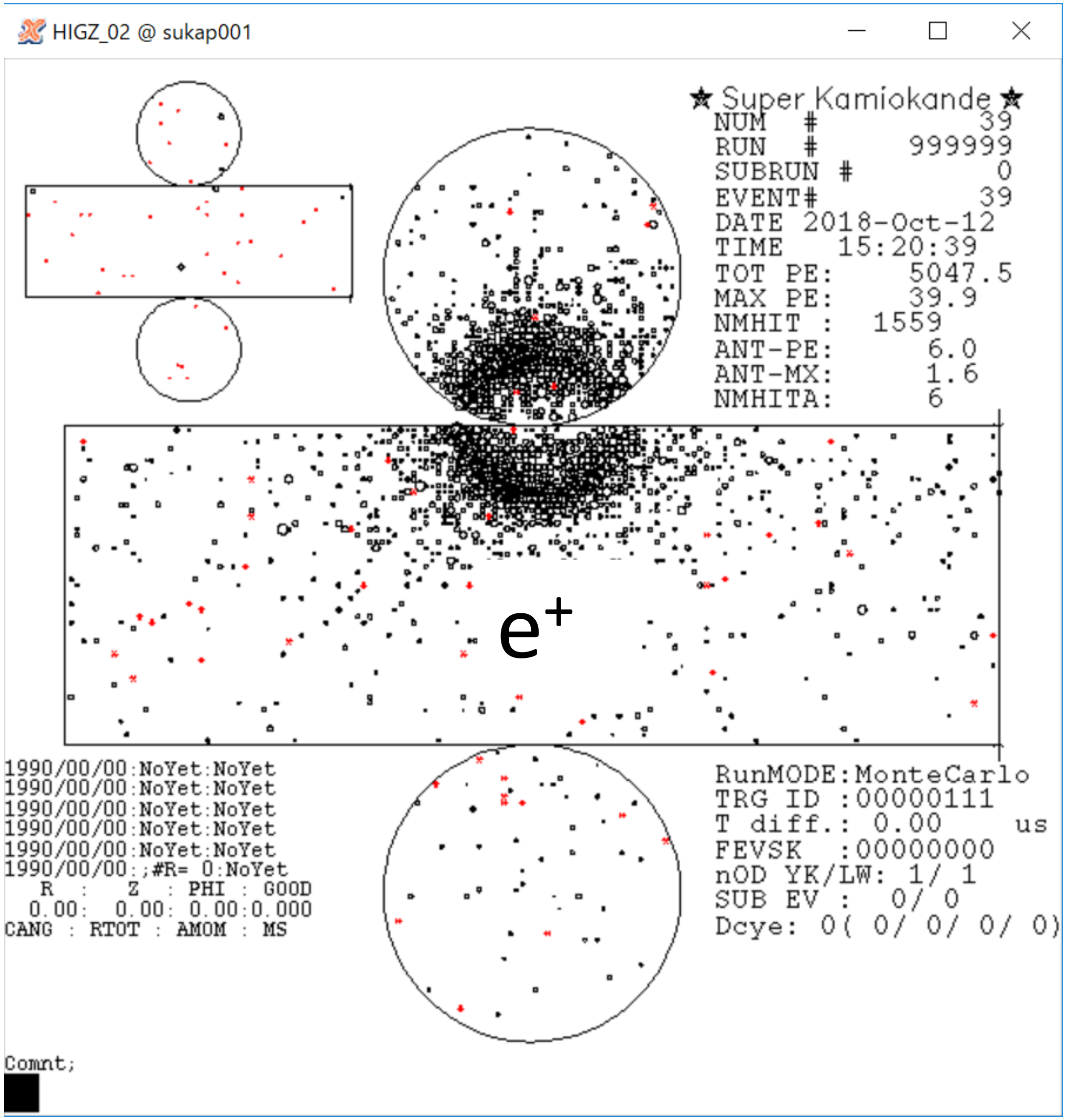


If π^0 is absorbed before exiting nucleus, only e$^+$ is observed (one ring).



```
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SUBRUN #         0
EVENT#          39
DATE 2018-Oct-12
TIME   15:20:39
TOT PE:     5047.5
MAX PE:       39.9
NMHIT :   1559
ANT-PE:        6.0
ANT-MX:        1.6
NMHITA:      6
```

```
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1990/00/00:NoYet:NoYet
1990/00/00:NoYet:NoYet
1990/00/00:NoYet:NoYet
1990/00/00:NoYet:NoYet
1990/00/00:;#R= 0:NoYet
   R   :    Z   : PHI  : GOOD
  0.00:   0.00: 0.00:0.000
CANG : RTOT : AMOM : MS
```

```
RunMODE:MonteCarlo
TRG ID :00000111
T diff.: 0.00      us
FEVSK  :00000000
nOD YK/LW: 1/ 1
SUB EV  :  0/ 0
Dcye: 0( 0/ 0/ 0/ 0)
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Comnt;
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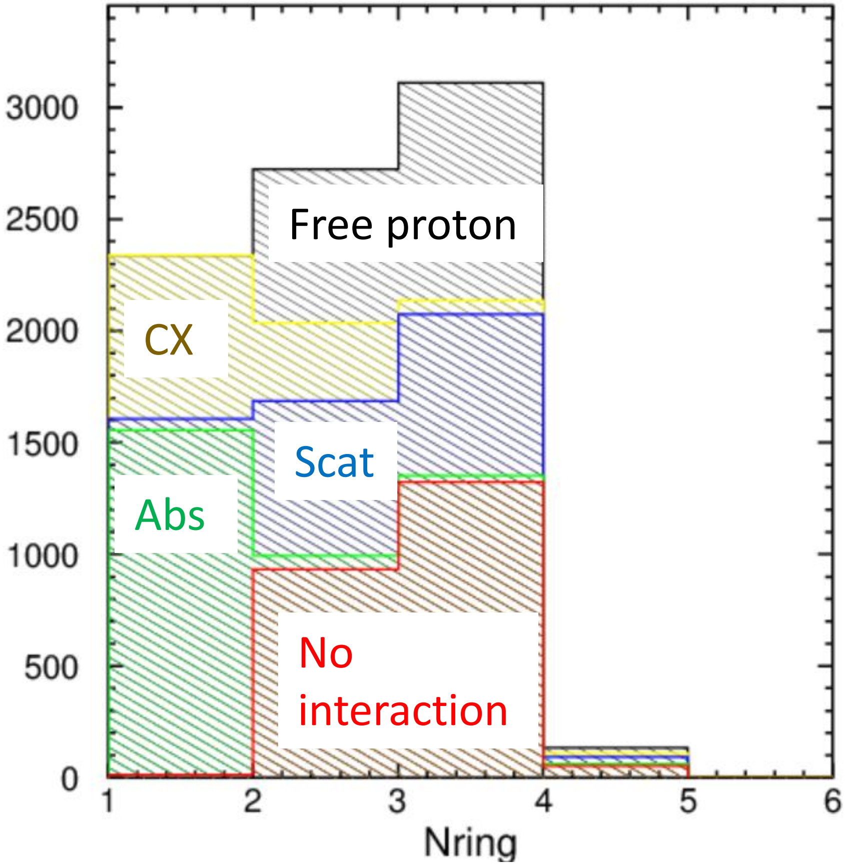
Observed number of ring for p→$e^+\pi^0$



Free proton: H in H_2O

No interaction in Nucleus

Abs: π^0 absorption in Nucleus

Scat: scattered

CX: charge exchange

($\pi^0 \rightarrow \pi^{\pm}$, below threshold)

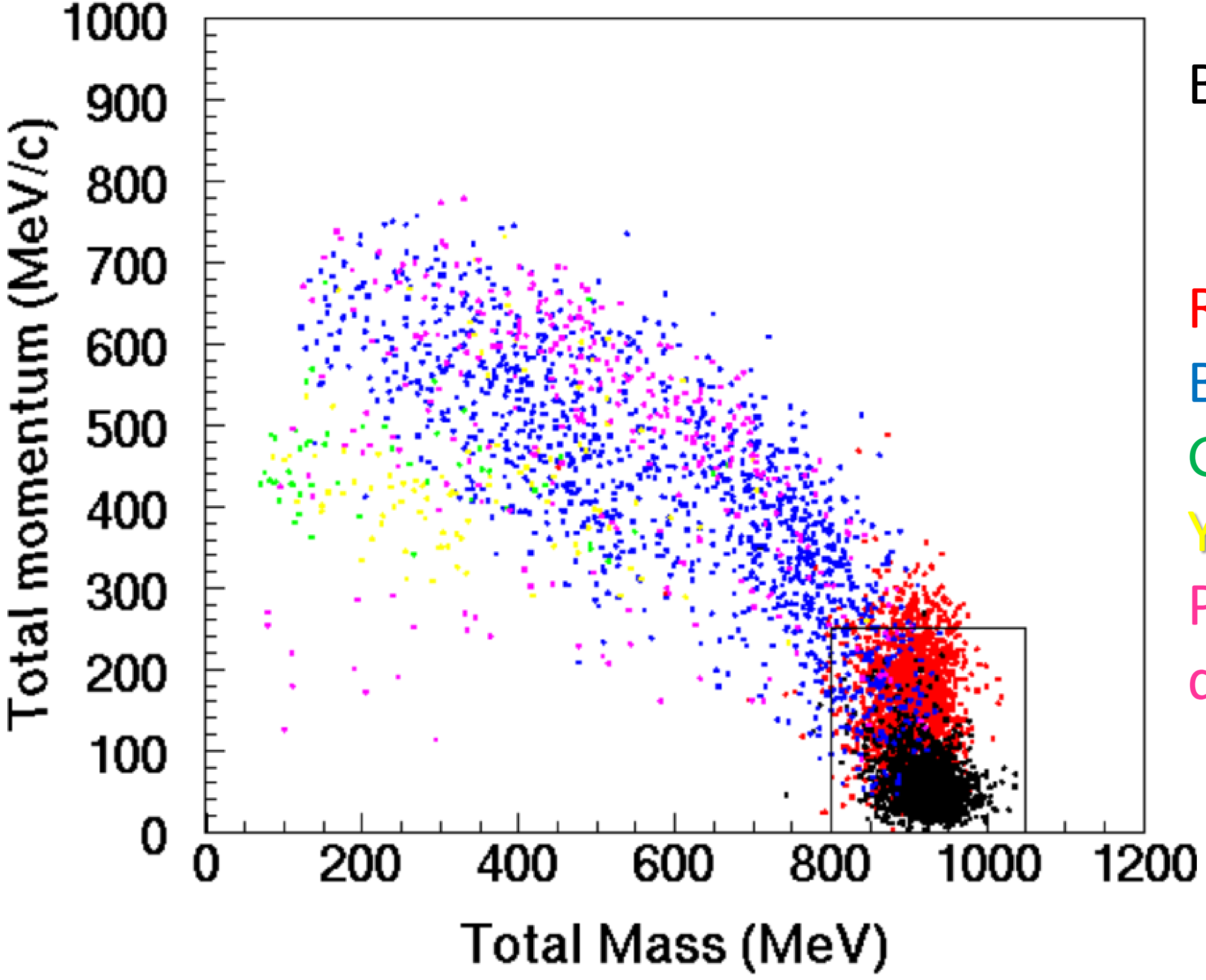
Choose 2 or 3 rings.

Selection criteria for $p \rightarrow e^+\pi^0$

1. Event vertex should be located 2 m inward from the tank wall (fiducial volume cut, 22.5kton).
2. 2 or 3 ring event.
3. All ring should be e-like.
4. No Michel electrons.
5. Reconstruct π^0 mass for 3 ring events. It should be $85 < M\pi^0 < 185$ MeV/c^2
6. Reconstruct total mass and momentum should be $800 < M_{tot} < 1050$ MeV/c^2, $P_{tot} < 250$ MeV/c.

Total mass vs Total momentum for p→$e^+\pi^0$

- Selection efficiency ~ 40 %
- Inefficiency is dominated by unavoidable physics processes.



Black: Free proton

Bound proton

Red: No π interaction

Blue: π scatter

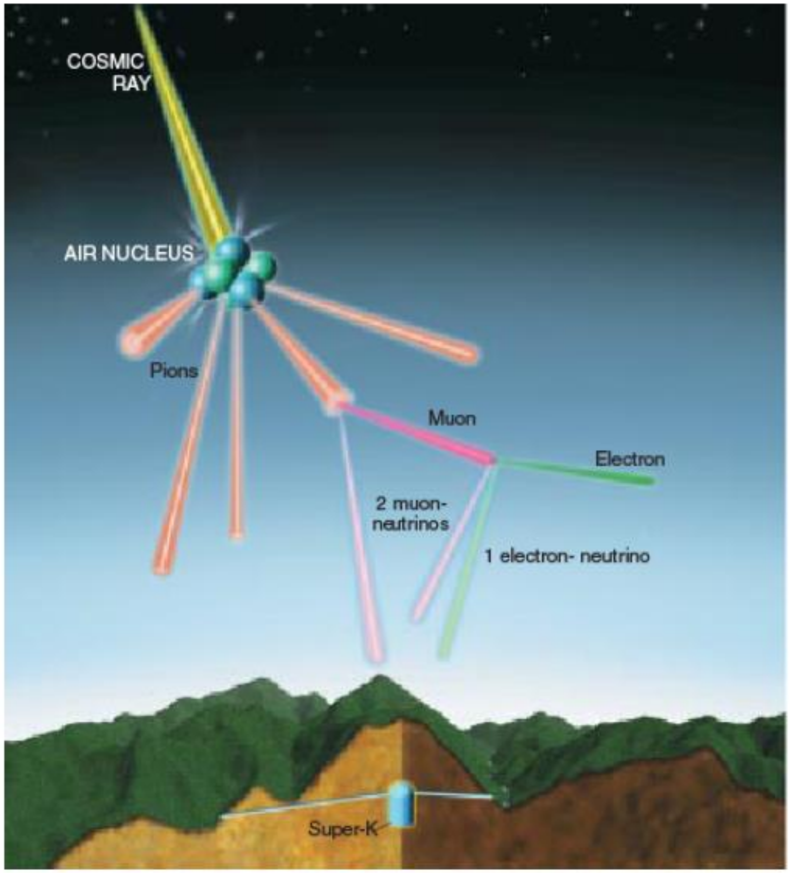
Green: π absorption

Yellow: π CX

Purple: Correlated decay

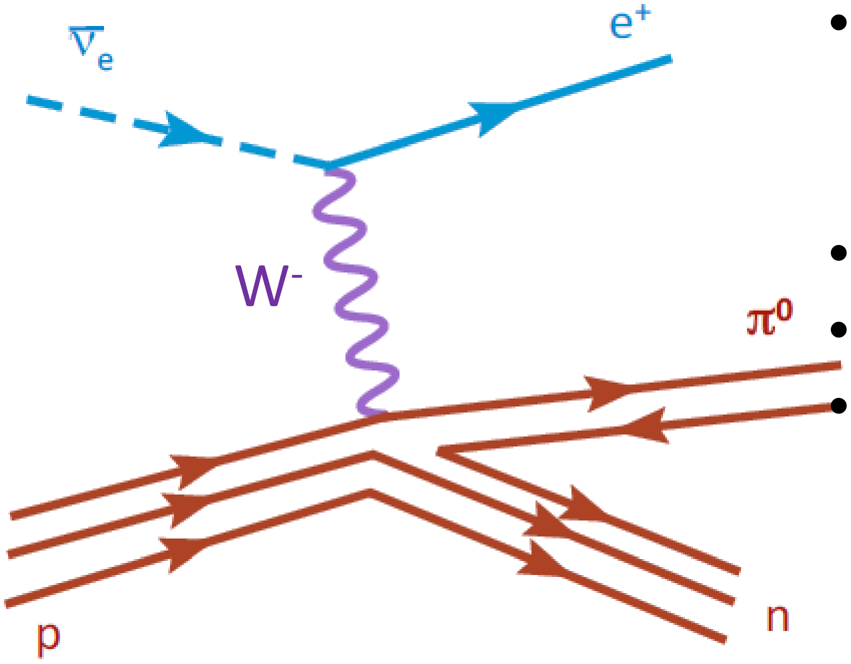
2-2. What's Background events for proton decay searches ?

- Atmospheric neutrino is dominant backgrounds for proton decay searches.
  - ➢ Visible energy ~ 1 GeV.
  - ➢ Solar or SN ν is too low energy.
  - ➢ Cosmic ray μ are rejected by outer detector.



Typical background for $p \rightarrow e^+\pi^0$

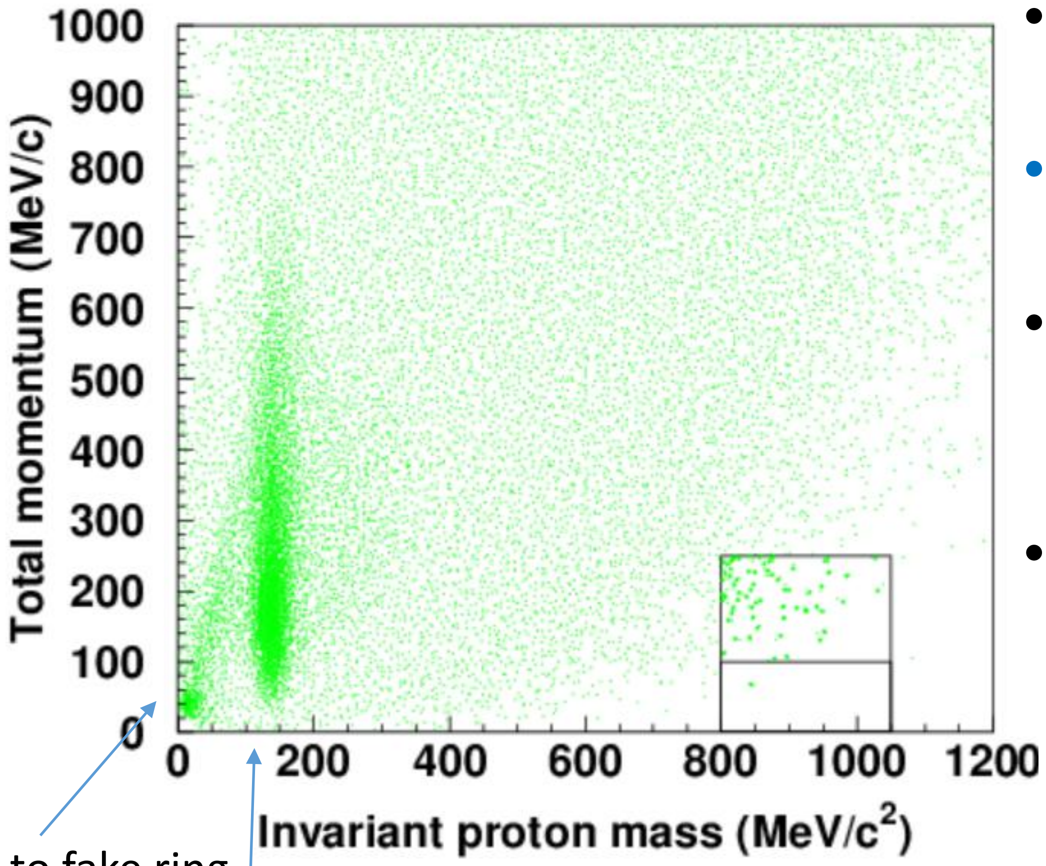
Charged current π^0 production



- Exchange W boson between ν and proton (charged current interaction).
- ν changes to e^+.
- π^0 and neutron are produced.
- Because neutron doesn't emit Chrenkov light, visible particles after the reaction are same as $p \rightarrow e^+\pi^0$

Total mass vs Total momentum for atmospheric ν background MC

(After all cuts except for total mass and momentum)

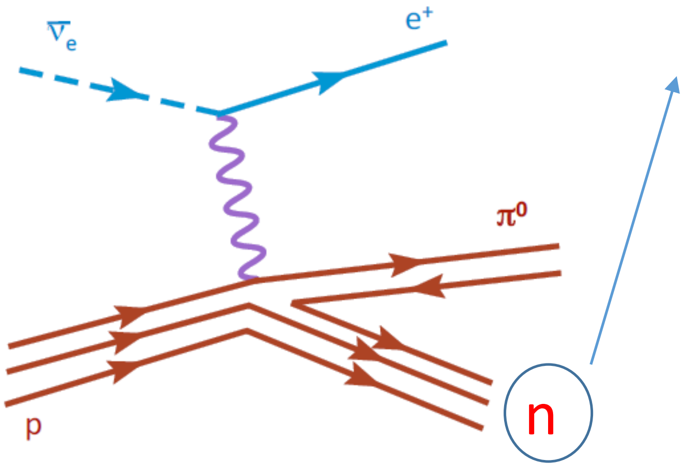


Due to fake ring

π^0 due to 2Re+e is allowed.

- Generate huge atm.ν MC, 2000 year of SK!
- Expected BG:
  ~1.3 ev/Mton*yr
- Neutrino events tend to have higher total momentum.
- Almost background free in lower momentum region (<100 MeV/c).
  - The region corresponds to free proton decay.

Further background reduction



- Neutron doesn’t emit Chrenkov light.
- However, neutron is thermalized in water and finally captured by hydrogen (~200 μs);

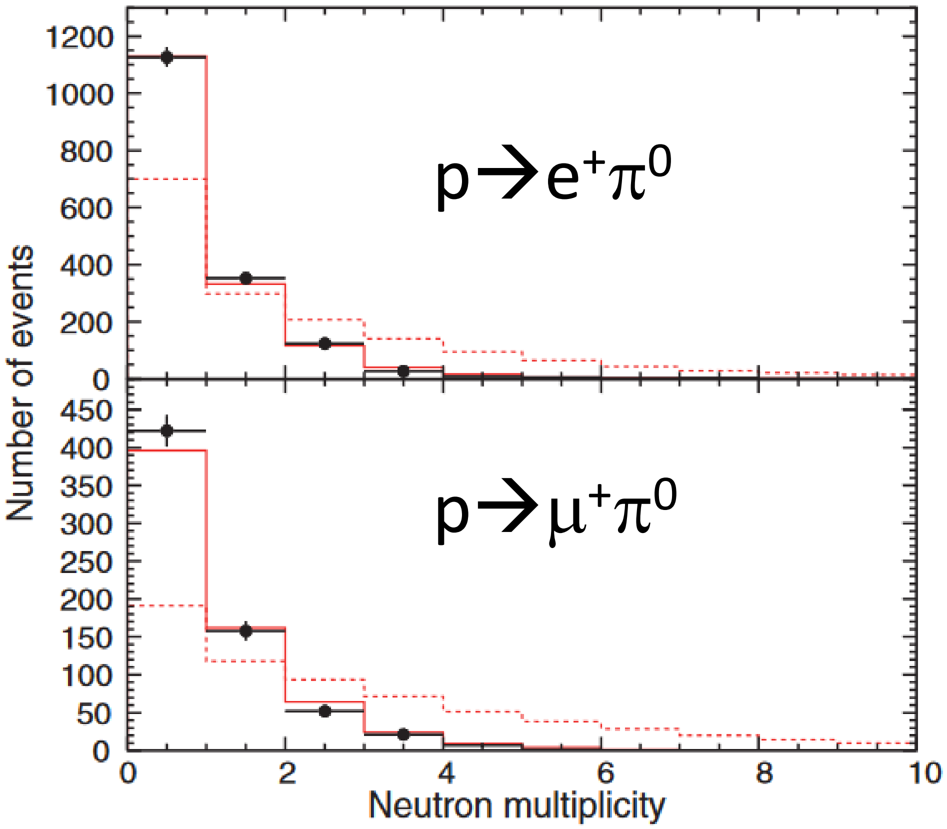
$$n + p \rightarrow d + \gamma \ (2.2\ \mathrm{MeV})$$

- If we can detect delayed 2.2 MeV γ ray, we can reduce background more.
- Neutron capture is also important for SN Relic ν and separate ν and ν-bar interactions in atmospheric ν oscillation analysis.

How to find 2.2 MeV γ

- After Time-of-Flight subtraction, search for 7 hits in 10 nsec time window. → candidates of γ.
- Make 16 variables related to space and time information of each hits (RMS of phi, theta, hit time, e.t.c.)
- Put them into Neural Network to judge γ or not.
- Neutron tagging efficiency: 21 % (mis-tagging: 1.8 %)

How powerful to reject background



- Sample: out of signal box in M_{tot} vs P_{tot} plot.
  - Dot: data,
  - Histogram: Atm.ν MC
    (solid: reconstructed, dash: true)
- ~ 50 % background events are rejected with neutron=0.
- On the other hand, ~ 7.5 % of $p \rightarrow e^+\pi^0$ are accompanied with neutron from deexcitation of nucleus. Neutron tagging reduces a few % in selection efficiency.

Enlarging Fiducial Mass

- Super-K is huge detector but its physics sensitivity is still limited by statistics…

→ **Enlarging the fiducial mass.**

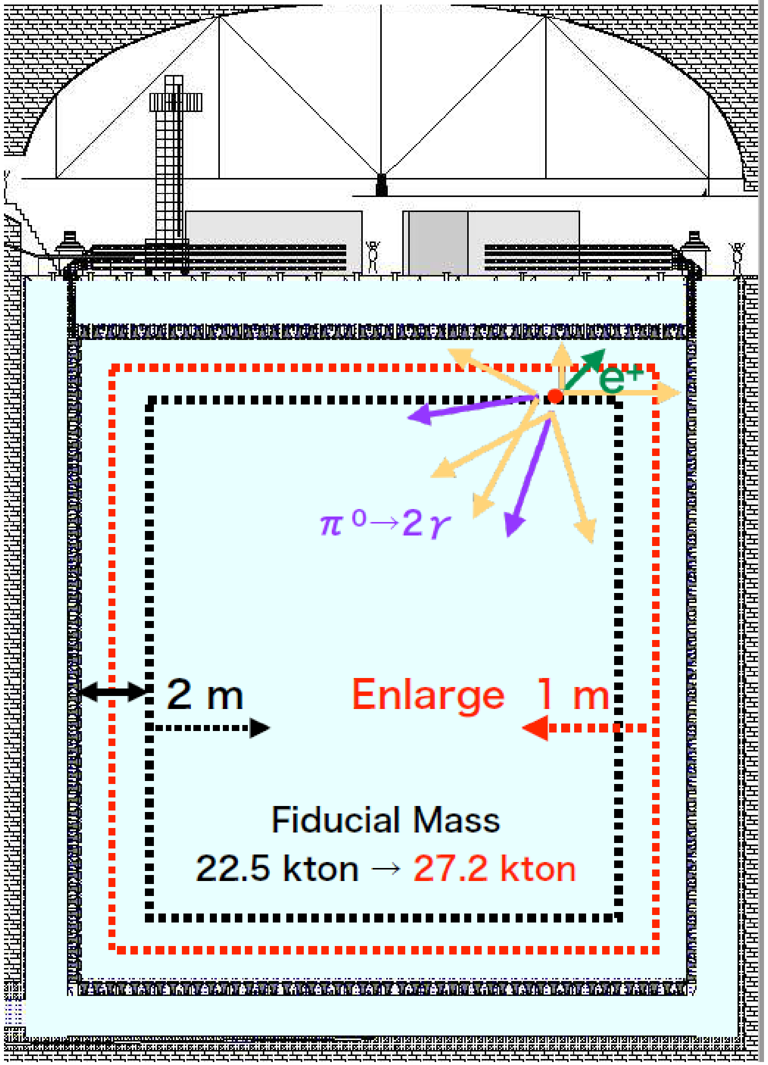
	Conventional	Enlarged
Fiducial Mass	22.5 kton	27.2 kton
Distance to wall	2 m	1 m
Exposure (1996~2018)	372 kton*years	450 kton*years

Remarkable merits

- **Enables the use of past data** that has never been analyzed.
- Improves **p-decay search sensitivity for every mode.**

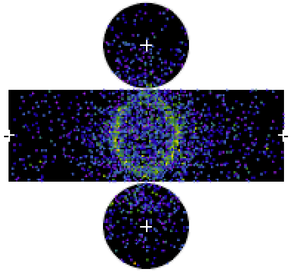
Considerations to achieve it

1. **Reconstruction performance.**
2. **External background** contamination.
3. **Data and MC agreement.**

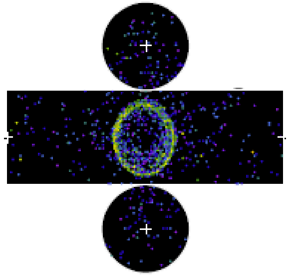


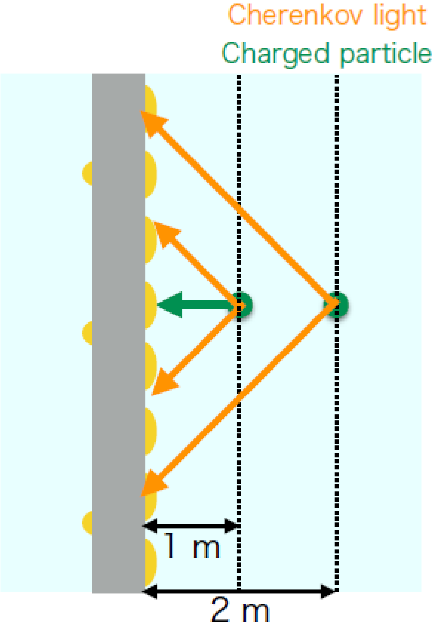
1. Reconstruction Performance - PID Improvement

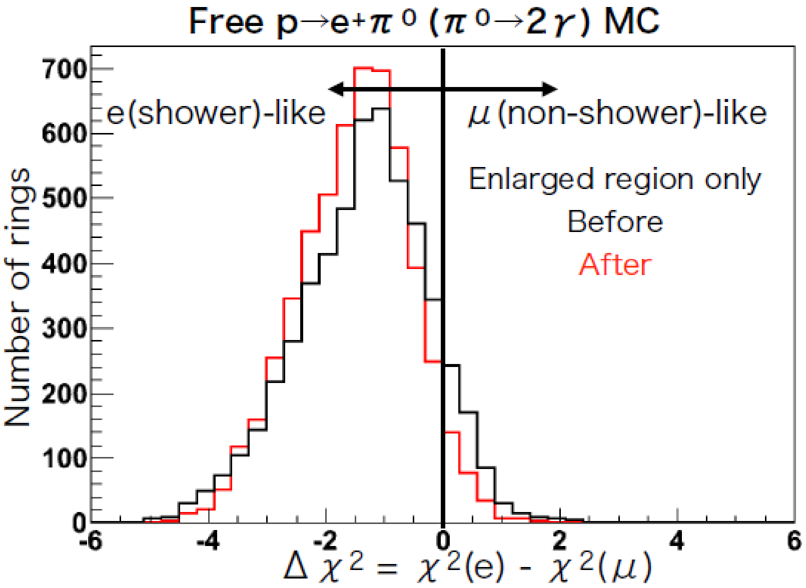
Electron (MC)



Muon (MC)







(Multi-ring PID Likelihood)

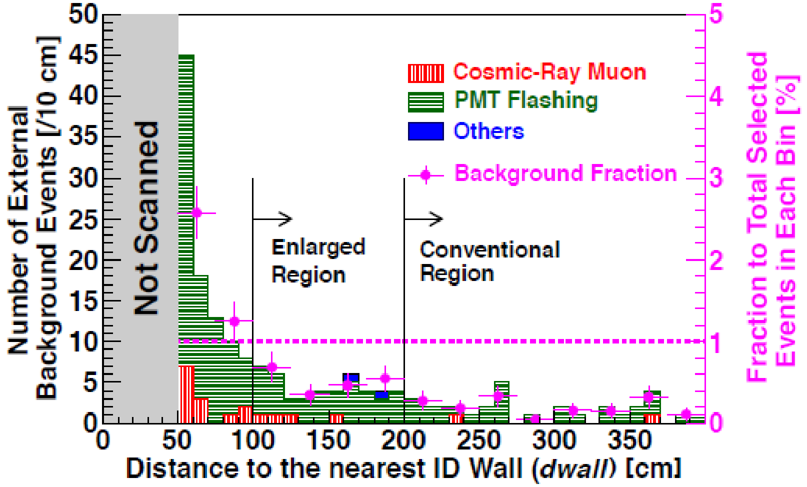
- Main issue in enlarged region: Worse **particle identification performance** due to lower number of PMT hits (unavoidable).

$$\chi^2(e \text{ or } \mu) \propto -\sum_{i\ (\text{Hit PMT})} \log_{10}(\text{Prob}(q_i^{obs}, q_i^{exp}(e \text{ or } \mu)))$$

- In this situation, accurate expected PMT charge (q_i^{exp}) becomes more important. → Revised expected charge table to reproduce real Cherenkov ring image more accurately, reducing biases and **increasing p-decay signal efficiency by ~20%** in enlarged region.

Data and MC Quality

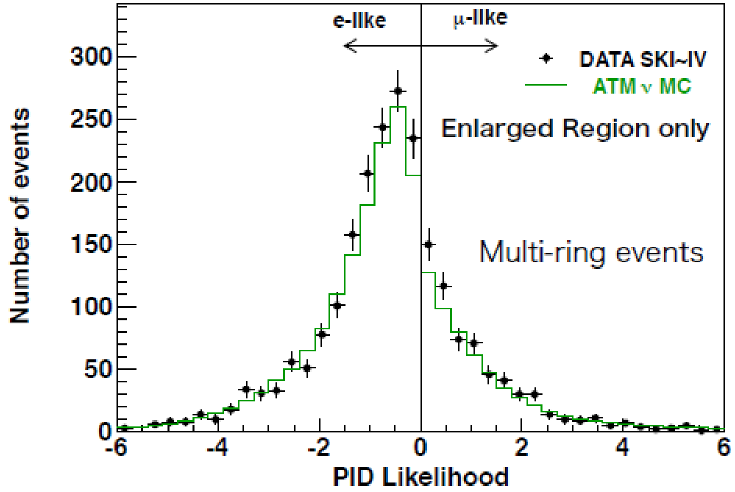
2. External Background Contamination

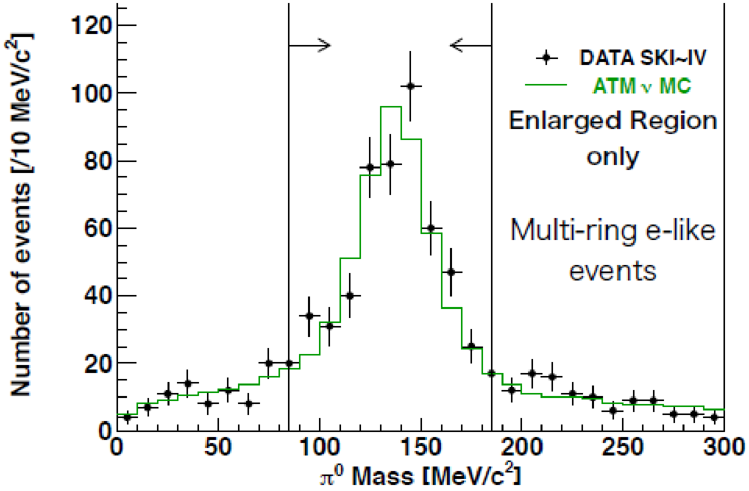


- Conducted **event scanning up to 50 cm to wall** to estimate external background contamination.
- Concluded to **enlarge fiducial mass region up to 100 cm to wall** to keep background contamination rate **(N_{BG}/N_{total}) within 1%.**
    - Most of the selected events are atmospheric neutrino events.

3. Data and MC agreement.

Demonstration using atmospheric ν

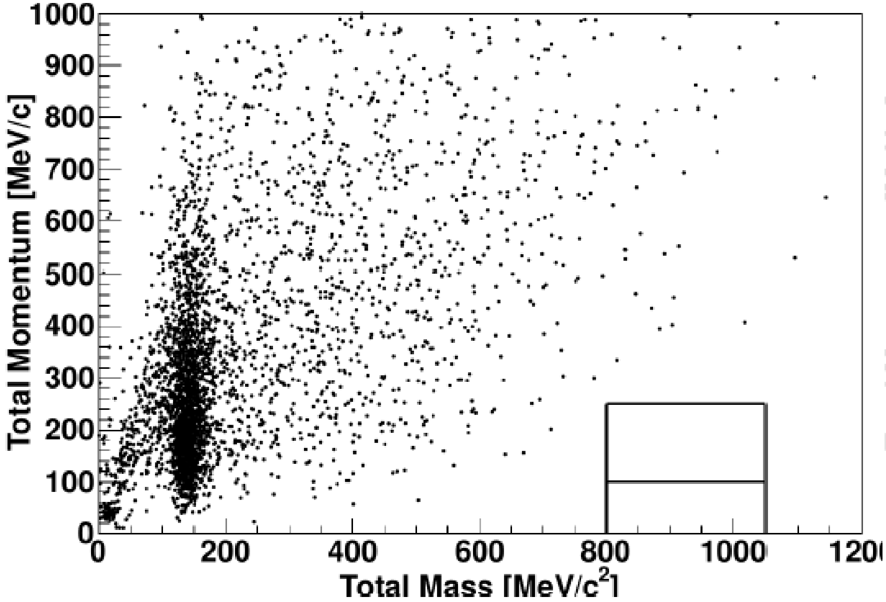


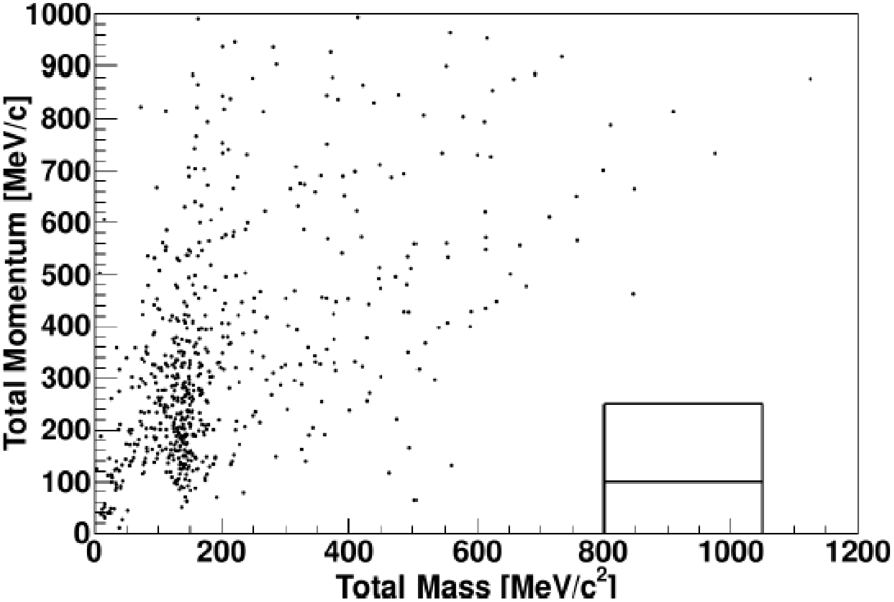


Good Data and MC agreement.

Data Result $p \rightarrow e^{+} \pi^{0}$

Data: Super-K Full Livetime, 1996~2018, 450 kton*years.

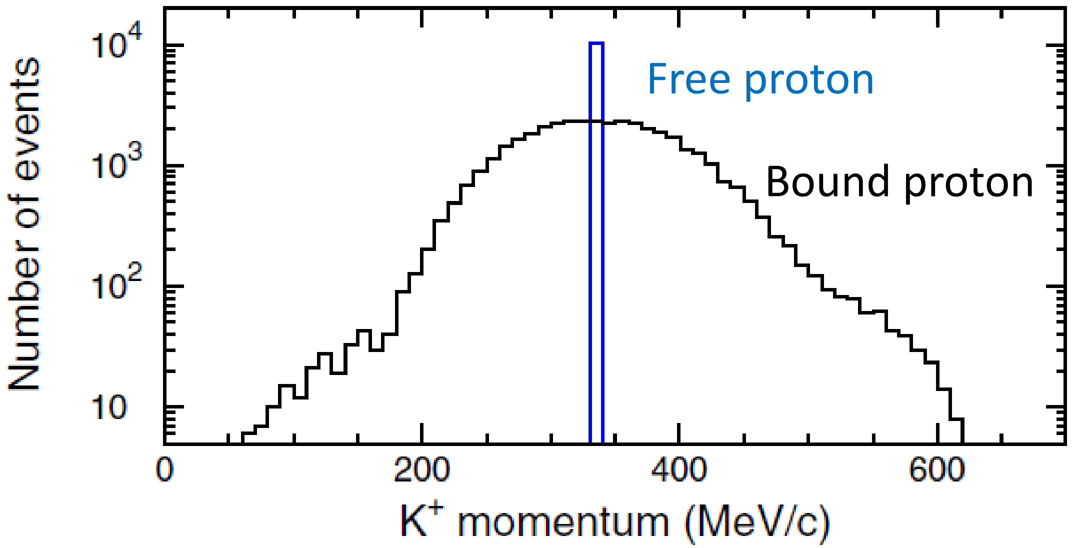

Conventional Region 372 kton*years


Enlarged Region 78 kton*years

- No candidates in signal box incl. enlarged region.
- Lower lifetime limit @90%C.L.
  - **$\tau / B_{p \rightarrow e+\pi 0} > 2.4 \times 10^{34}$ years** (published: 1.6×10^{34} years, 306 kton*years)
- Most stringent constraint. **~1.5 times longer than published.**

4. p$\rightarrow\nu K^+$ search

Difficulty of p→νK$^+$

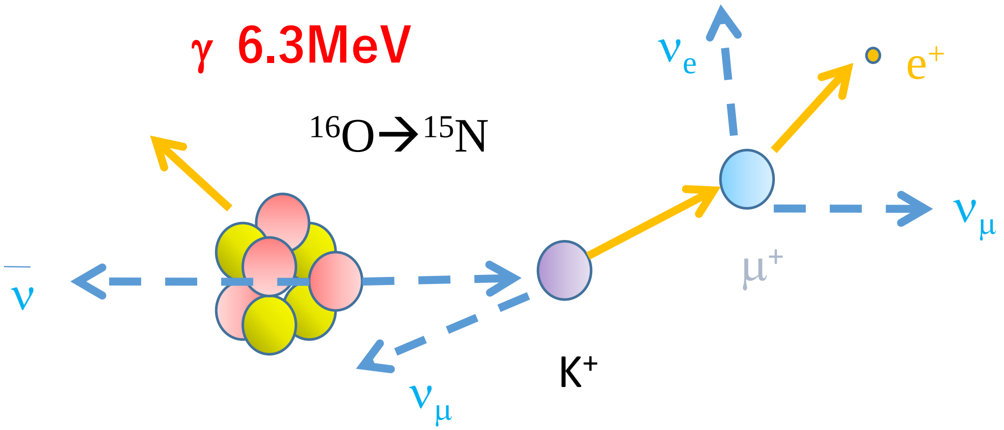


- K$^+$ mass: 494 MeV, relatively heavy.
- Cherenkov threshold: 560 MeV/c.
- Most of K$^+$ can not emit Cherenkov light.

4-1 How to find $p \rightarrow \nu K^+$ in Water Cherenkov detector

- K^+ has low momentum, most of them stop in water and decay with 12 nsec lifetime.
- Major K^+ decay mode
  - $K^+ \rightarrow \nu\mu^+$: 64 %
  - $K^+ \rightarrow \pi^+\pi^0$: 21 %
- "Stopping K^+" means two body decay products of K^+ should have monochromatic momentum.
  - $K^+ \rightarrow \nu\mu^+$: 236 MeV/c
  - $K^+ \rightarrow \pi^+\pi^0$: 206 MeV/c
- Using this property, Water Cherenkov detector can search for $p \rightarrow \nu K^+$.

4-2. Search for p→νK⁺, K⁺→νμ⁺

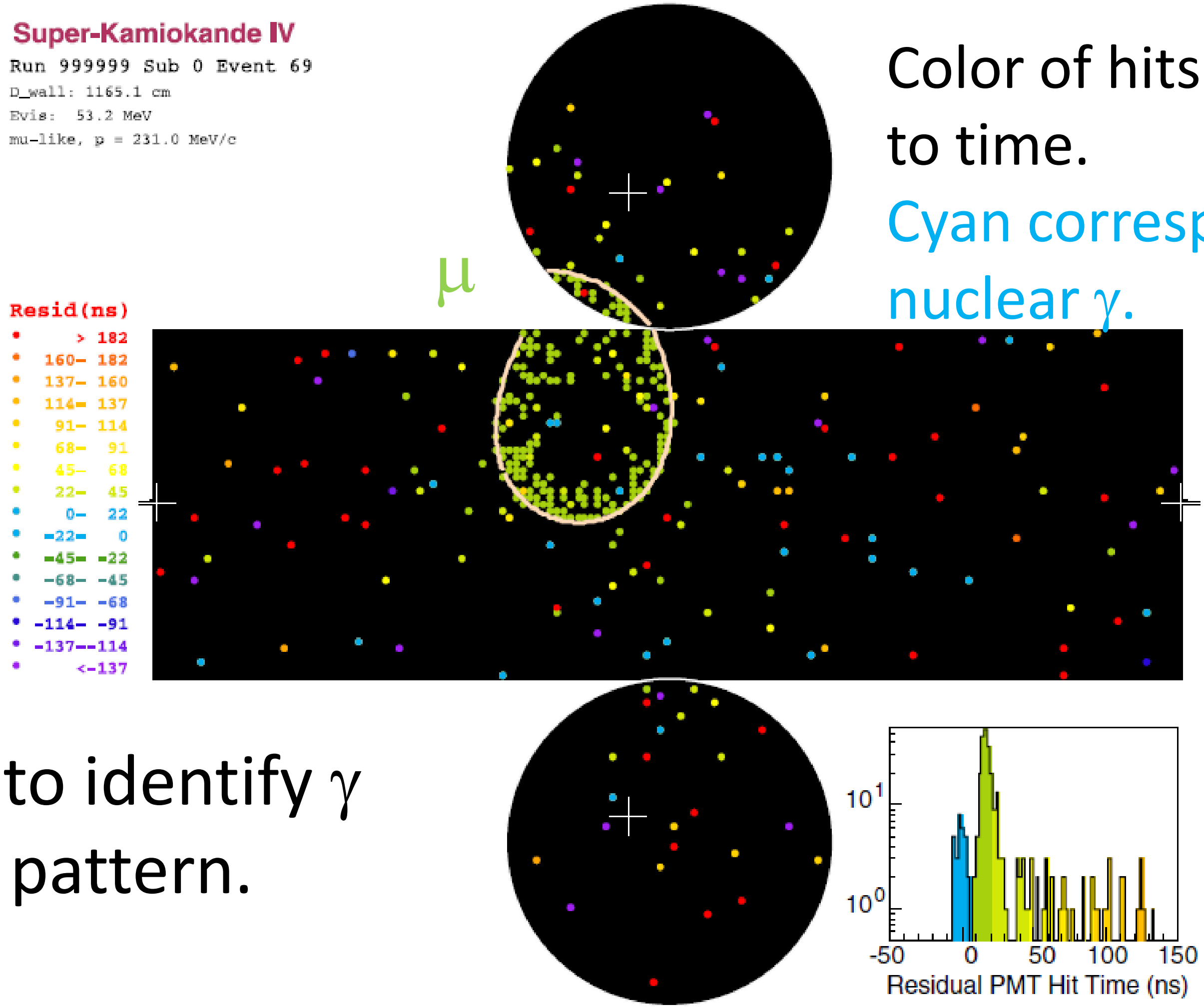


- Visible particle is only μ^+ with Michel electron.
- Search for data excess around 236 MeV/c of μ comparing with atmospheric ν MC.
- After proton decay, 40 % of remaining nucleus emits 6 MeV γ for deexcitation. It is useful to reduce background.

Example of $p \rightarrow \nu K^+$, $K^+ \rightarrow \nu \mu^+$ with γ

Color of hits corresponds to time.

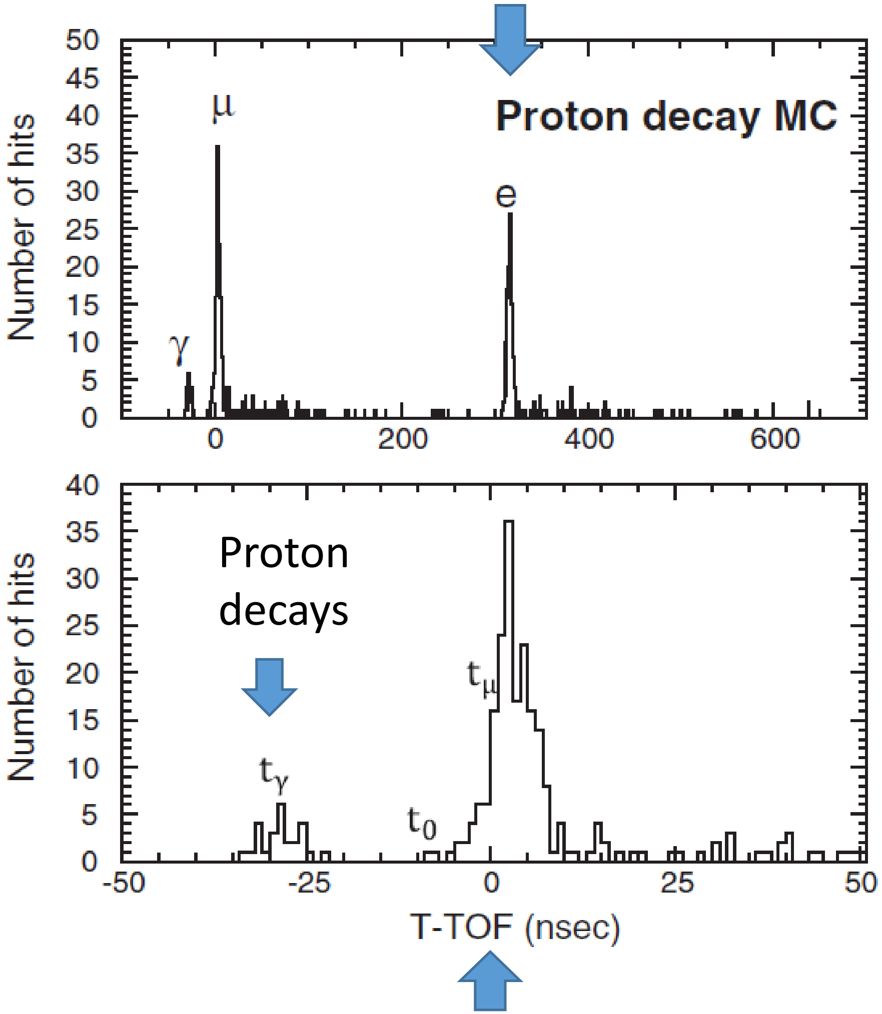
Cyan corresponds to nuclear γ.



Difficult to identify γ from hit pattern.

Time structure with nuclear γ

μ decays



Proton decays

K^+ decays

- 3 hit clusters in time should be observed in case of signal.
- The event is triggered by μ hits.
- γ signal is much smaller than μ and easily hidden by tail of μ hits.
- Make 12 nsec time window and slide it toward left from t_0 (end of μ tail) to search for maximum hit cluster.

Selection criteria for $p \rightarrow \nu K^+$, $K^+ \rightarrow \nu \mu^+$

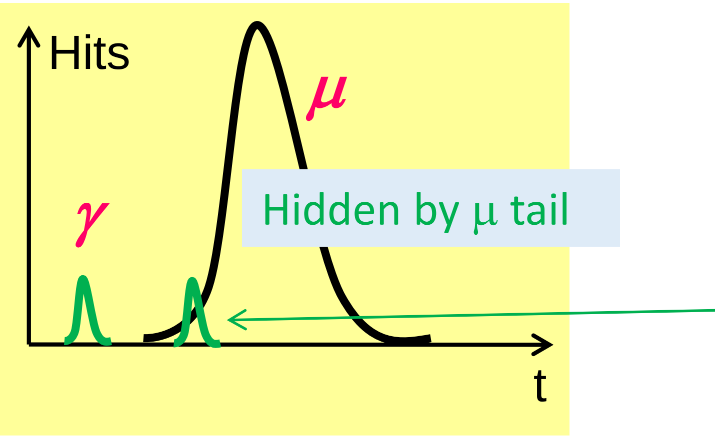
- 1 μ-like ring with Michel electron
- $215 < P\mu < 260$ MeV/c
- Proton rejection cuts
- Search Max hit cluster by sliding time window (12ns width);
  - $4 < N\gamma < 30$ hits
  - $T_\mu - T_\gamma < 75$ nsec

Reduce background by 5×10^{-4} !

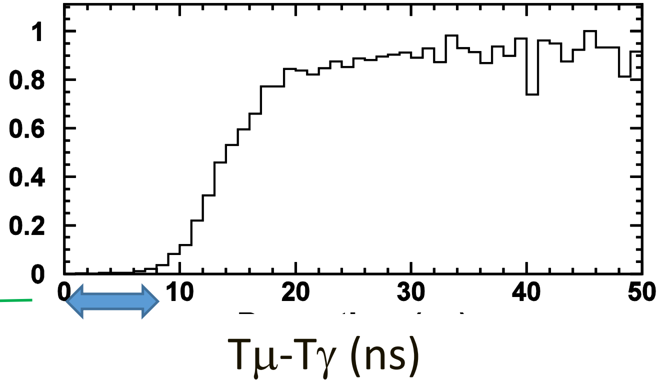
- No neutron
- Selection efficiency = (selected events)/(proton decay in fiducial volume): 9 %
  - $Br(K^+ \rightarrow \nu \mu^+) = 64$ %, only 40 % emits nuclear γ → 26 % even if detector is perfect.

Remark for this analysis

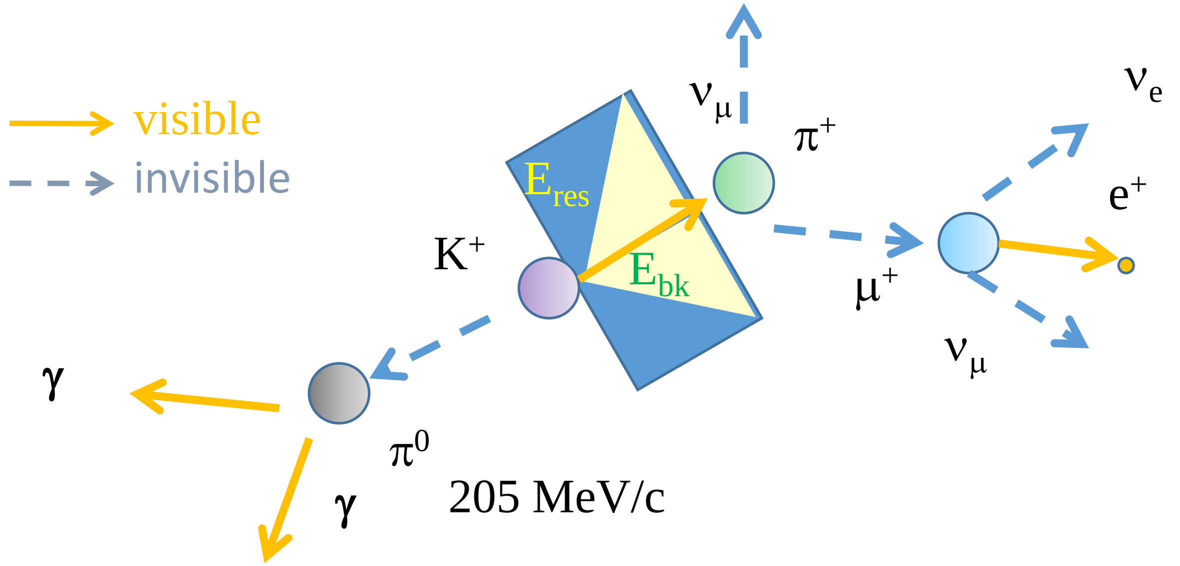
- This analysis is limited by time resolution of PMTs.
  - ➢ If γ is close to μ, γ peak is hidden by μ hits.
  - ➢ Time resolution of SK PMT is 2.2 nsec at 1 photoelectron.
  - ➢ If μ peak becomes sharper, the selection efficiency will be improved.



γ tagging efficiency

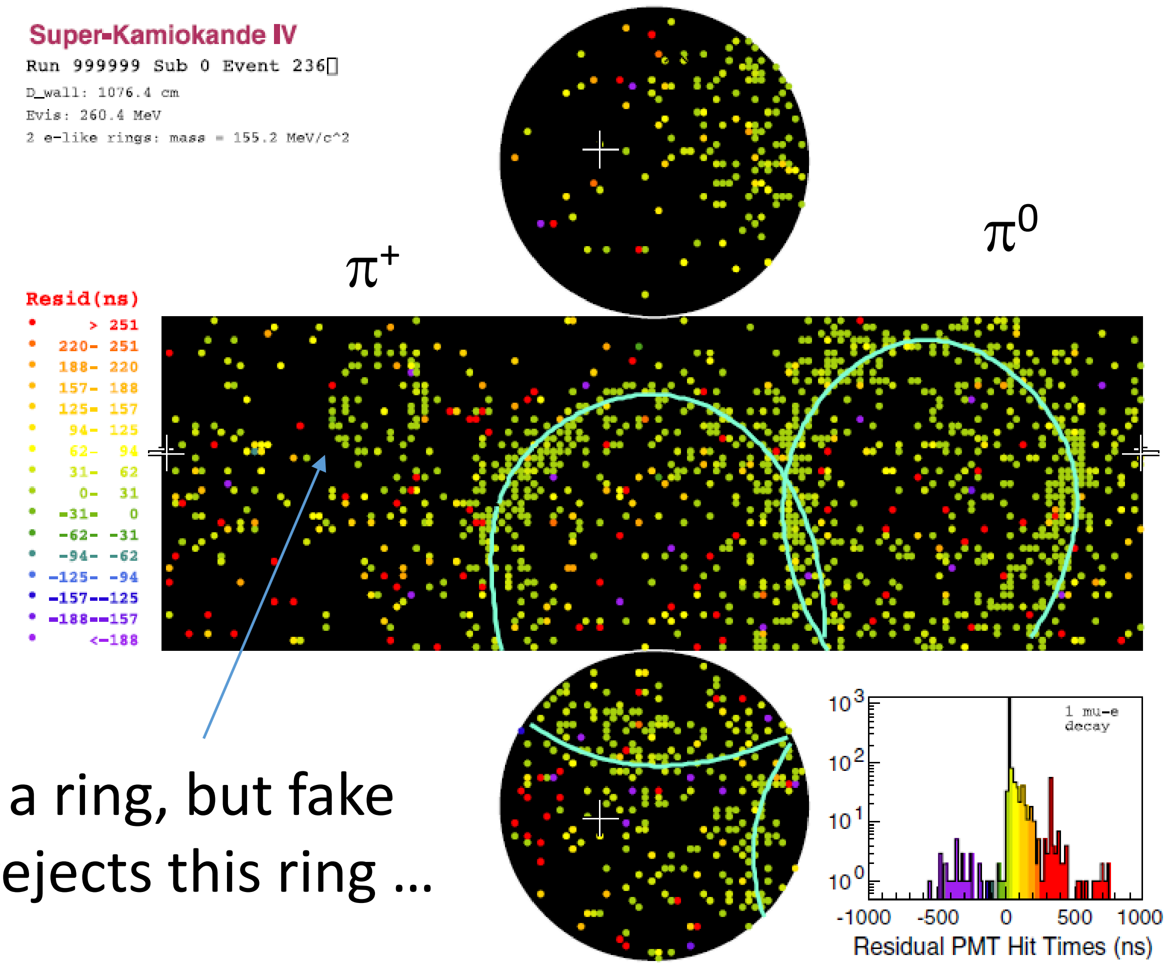


4-3. Search for $p \rightarrow \nu K^+$, $K^+ \rightarrow \pi^+\pi^0$



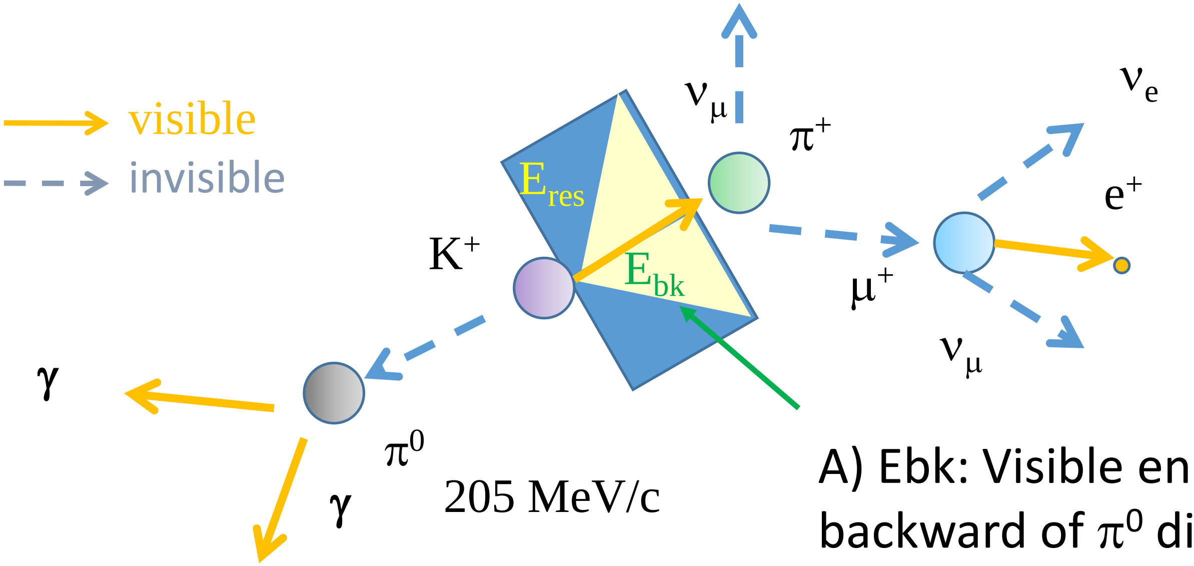
- Both π^+ and π^0 has 205 MeV/c in momentum. This is just above Cherenkov threshold for π^+, thus it is not identified as a ring in most of case.
- π^+ decays into μ (invisible) and ν, μ decays into $e\nu_e\nu_\mu$.
- π^0 decays into 2 γs.
- Search for 206 MeV/c π^0 with Michel electron.

Example of p→νK^+, K^+→$\pi^+\pi^0$



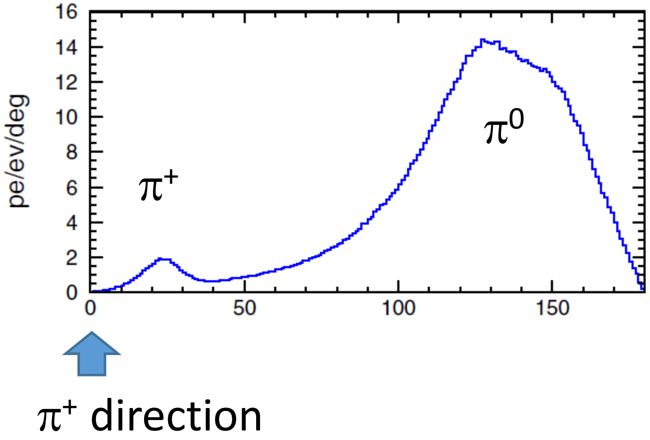
Look like a ring, but fake ring cut rejects this ring …

Use π^+ information to select events



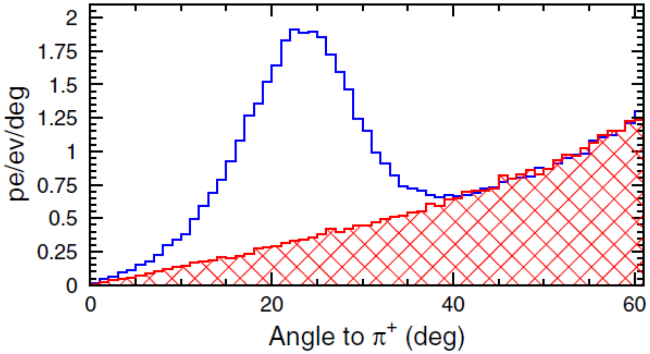
A) Ebk: Visible energy sum in backward of π^0 direction (140°-180°)

Charge distribution



Zoom

B) Make likelihood for hit pattern.



Selection criteria for $p \rightarrow \nu K^+$, $K^+ \rightarrow \pi^+\pi^0$

- 1 or 2 e-like rings with decay-e.
- $85 < M\pi^0 < 185$ MeV.
- $175 < P\pi^0 < 250$ MeV/c.
- E_{bk}: visible energy sum in 140-180 deg. of π^0 dir,

  E_{res}: in 90-140 deg,

  L_{shape}: Likelihood based on charge profile

  $10 < E_{bk} < 50$ MeV

  $E_{res} < 12$ MeV (20 MeV for 1ring)

  $L_{shape} > 2.0$ (3.0 for 1ring)
- No neutrons
- Selection efficiency: 10 % ($Br(K^+ \rightarrow \pi^+\pi^0) = 21$ %)

Background for $p \rightarrow \nu K^+$

- Dominant background is K^+ production by neutrino interactions.
  - $\nu p \rightarrow \nu \Lambda K^+$, $\Lambda \rightarrow p \pi^-$ (BR:64 %, mostly invisible in WCD)
  - Emit nuclear γ as same as the signal.
- It is also rare interaction and we had poor information from very old bubble chamber. Large uncertainty.
- Recently MINERvA measures K^+ production. It is very useful information for this analysis.

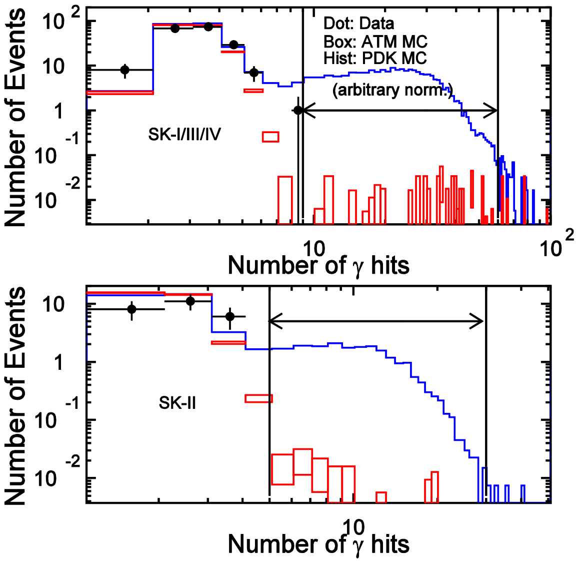
4-4. SK results (So far)

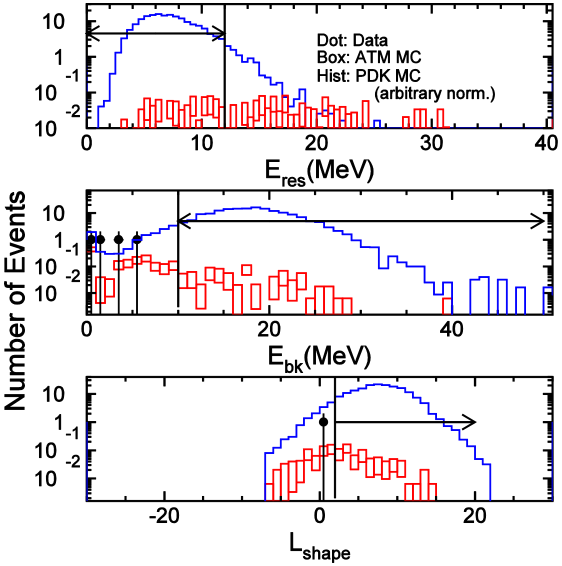
- Exposure: 365 kton・year
- Expected background: 0.3 events for $K^+ \rightarrow \nu\mu$ with nuclear γ, 0.6 events for $K^+ \rightarrow \pi^+\pi^0$.
- No candidates observed and no excess in momentum distribution.
- Lower lifetime limit: > 0.8×10^{34} year

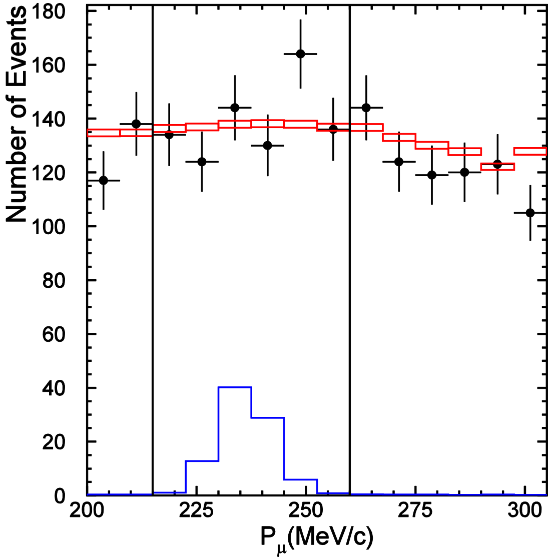
Black: Data

Red: Atm.n MC

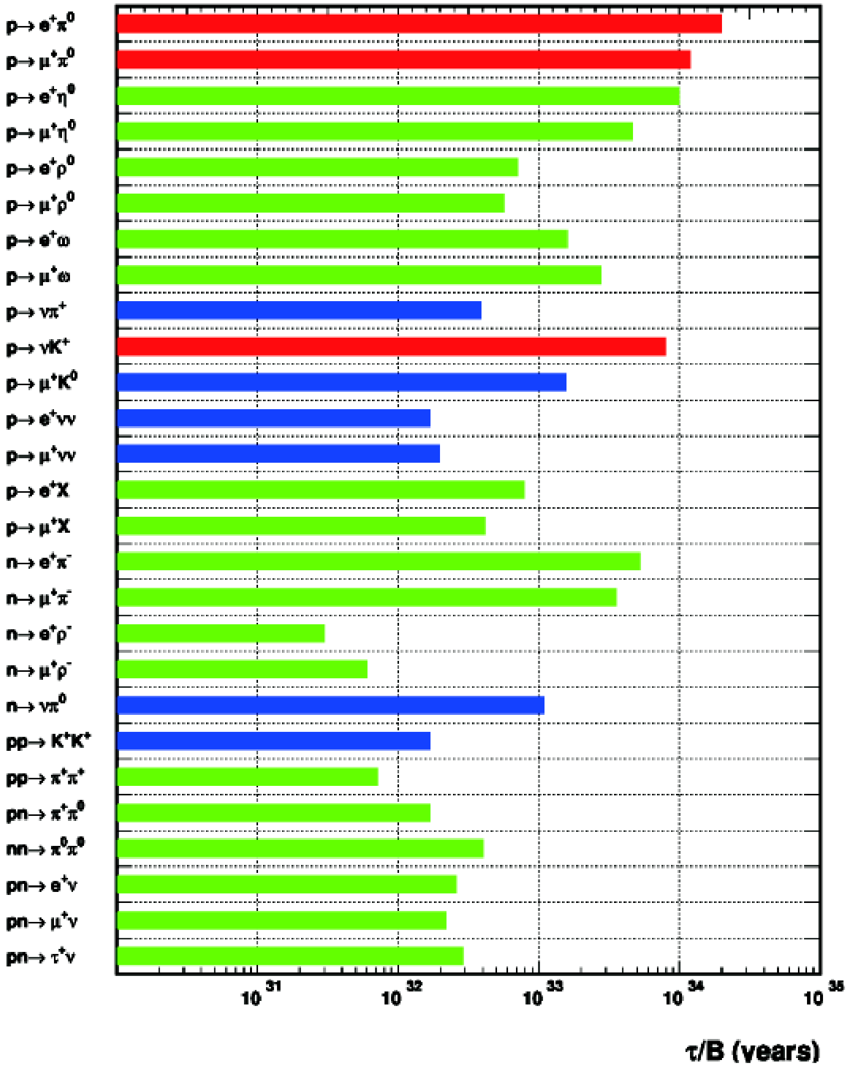
Blue: Signal MC







5. Summary of SK results



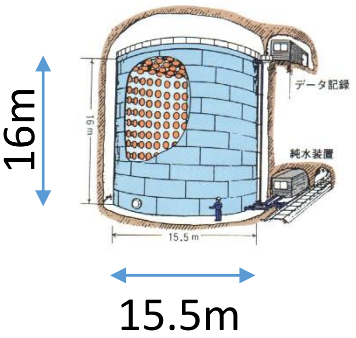
- Most of modes have been investigated with > 0.3 Mton・year exposure (red and green in the left figure).
- Super-Kamiokande can cover large number of decay modes.
- Many of them are the most stringent limits on nucleon lifetime.
- We observed some candidates, but still consistent with expected backgrounds and no evidence of nucleon decay has been observed.

Future prospects

- Still no evidence has been found. Major decay modes are explored up to around 10^{34} years.
- Proton lives longer, ~10^{35} years ?
  - ➢ Run SK 10 times more (~200 years)? → Impossible.
- Absolutely, we need larger detector !

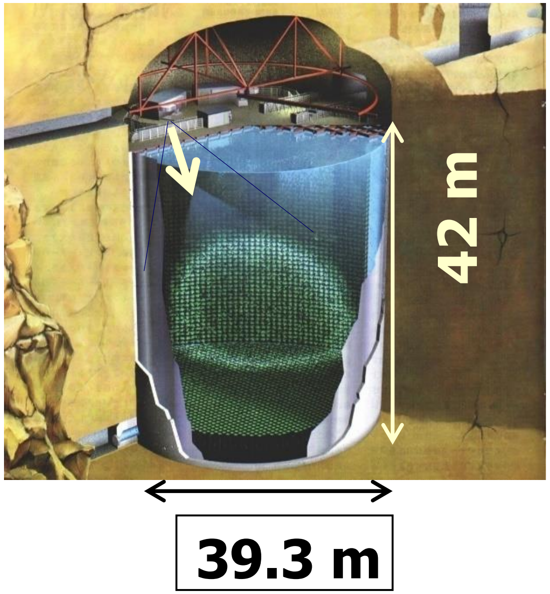
5. Hyper-Kamiokande project

SN Neutrino



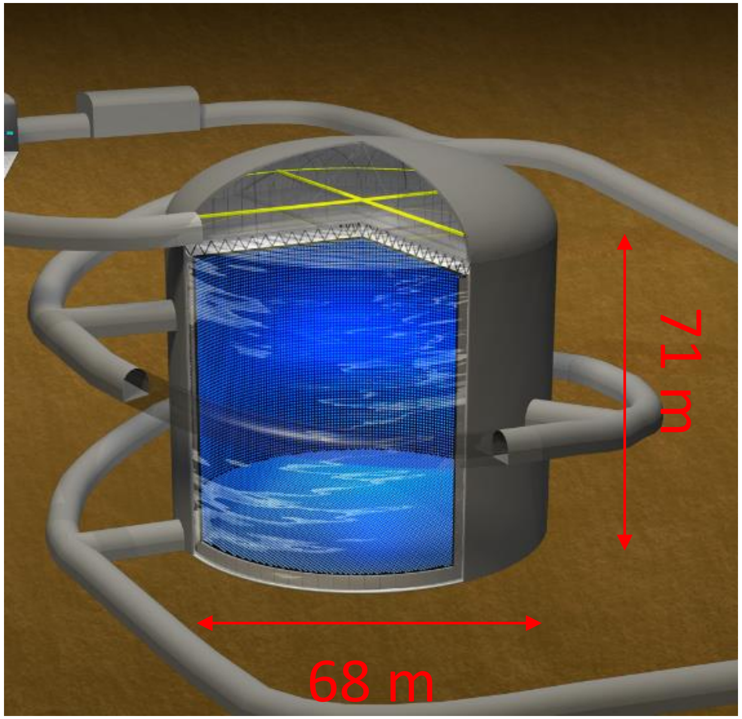
Kamiokande
3kton

Neutrino oscillation



Super-Kamiokande
50kton

Proton decay ?

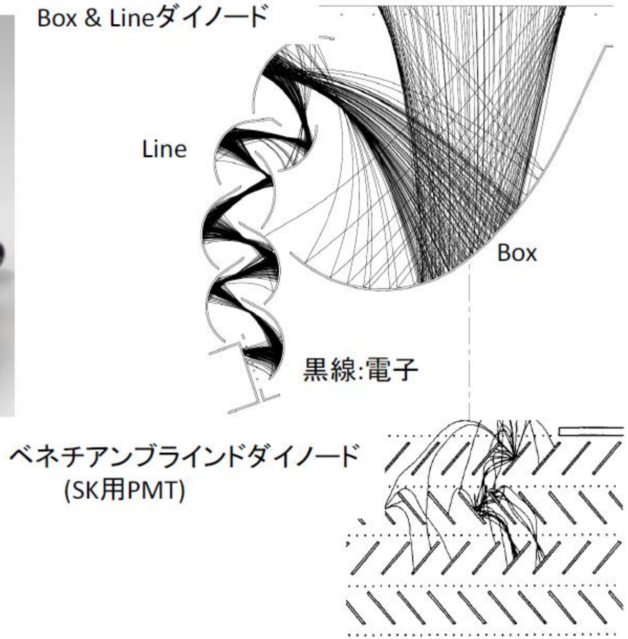


Hyper-Kamiokande
260kton

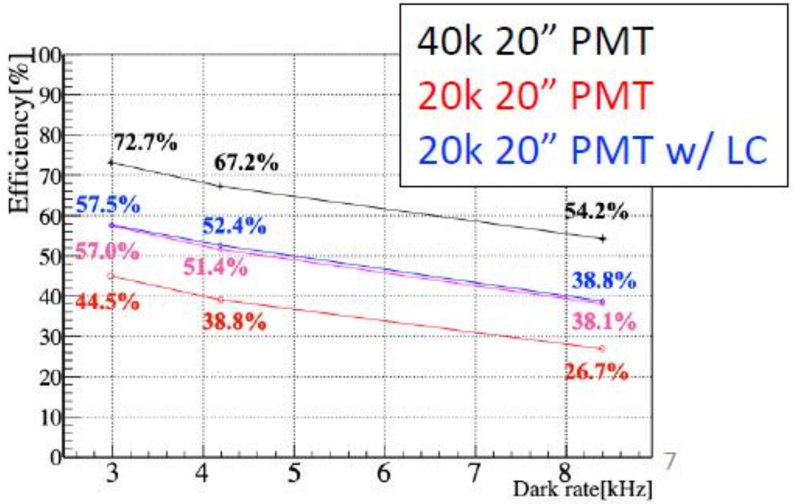
Enhance proton decay search with HK

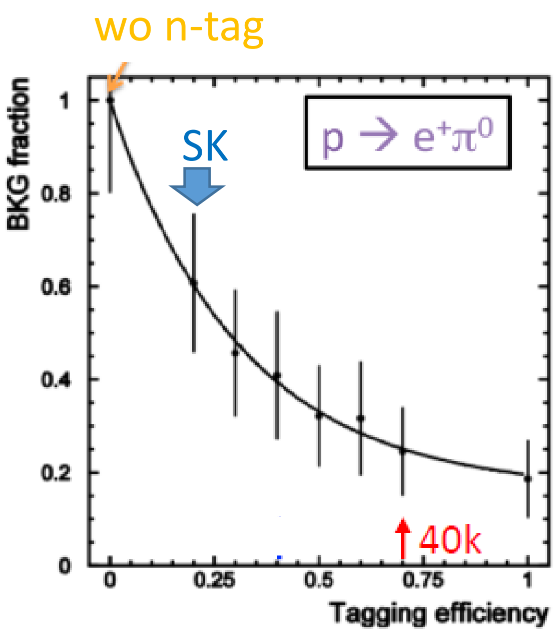
- Fiducial volume: 22.5kton (SK) → 190kton (HK)
- New photo sensor: Box&Line PMT
  - 2 times better photon counting performance
  - a half time resolution

Box&Line PMT



Better photon counting contributes neutron tagging

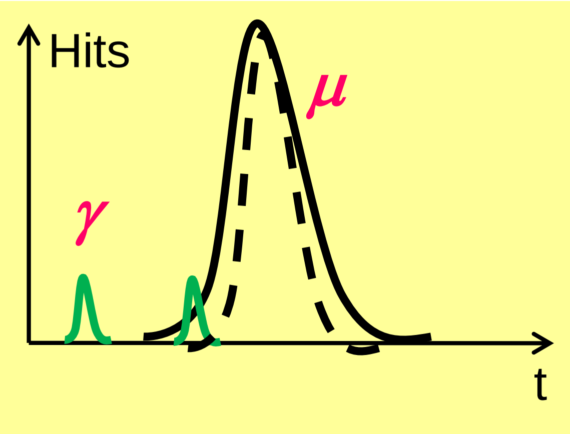




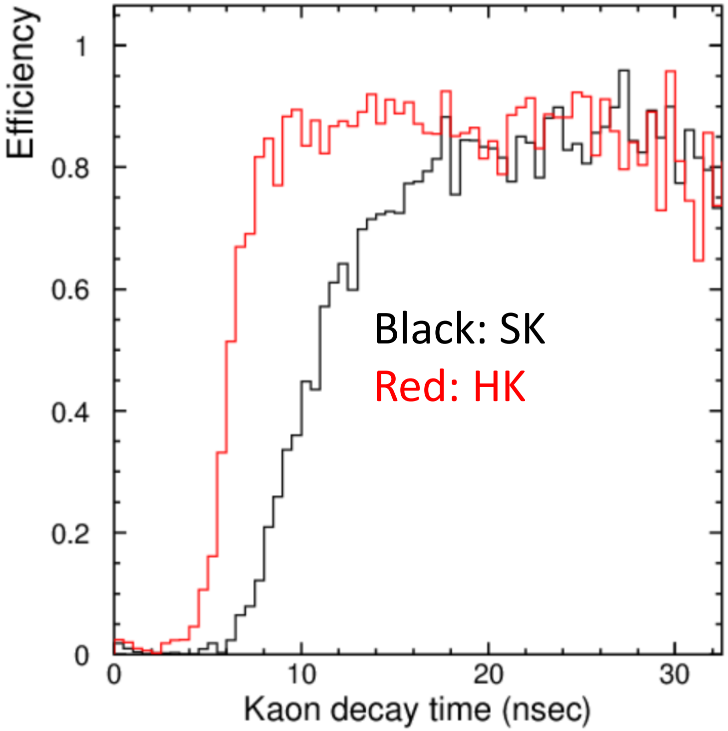
- Neutron tagging efficiency study with several detector set up.
- Efficiency depends on dark rate.
- Achive ~ 70% in the current baseline design (black) with ~ 4kHz dark rate.

- p→e+p0 background reduction vs. Neutron tagging efficiency
- Background of HK becomes a half of SK !

Faster PMT response improves nuclear γ tagging in $p \rightarrow \nu K^+$



γ tagging efficiency

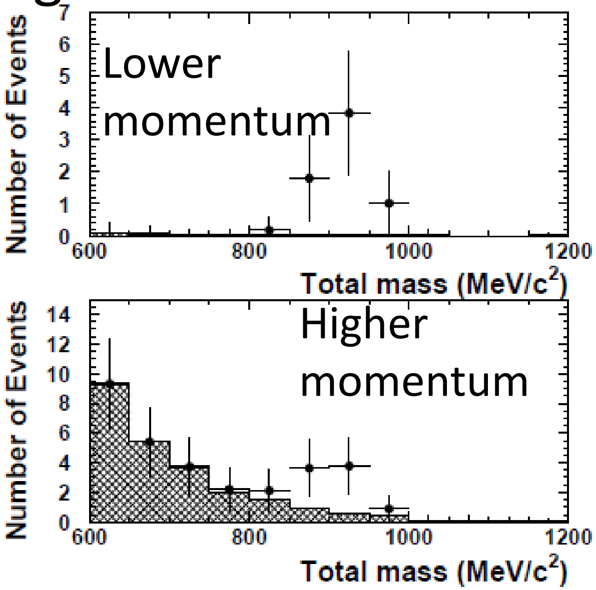


- Time resolution: 2.2nsec (SK) →1.1 nsec (HK).
- Sharper time distribution of μ → γ close to μ cab be identified !

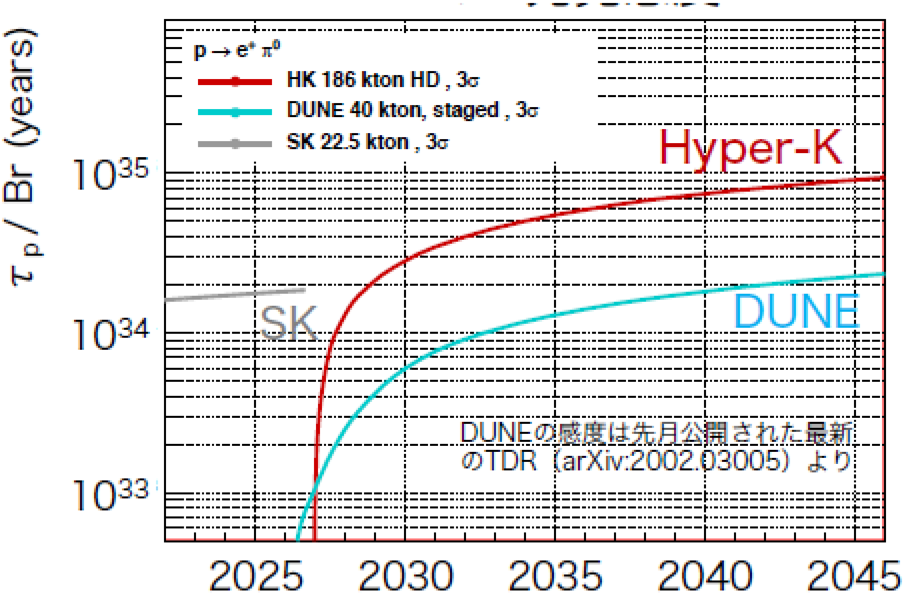
(Better photon counting also contributes improvement)

Sensitivity for $p \rightarrow e^{+}\pi^{0}$

Expected signal after 10 years run assuming the current lifetime limit



3σ discovery potential



DUNEの感度は先月公開された最新のTDR（arXiv:2002.03005）より

$0 < p_{tot} < 100$ MeV/c		$100 < p_{tot} < 250$ MeV/c	
ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]
18.7 ± 1.2	0.06 ± 0.02	19.4 ± 2.9	0.62 ± 0.20

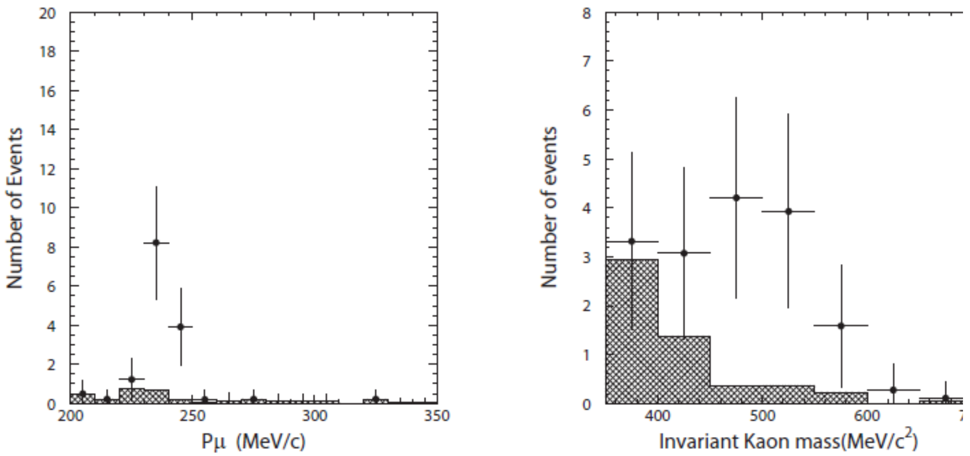
(SK: 0.18)

(SK: 1.1)

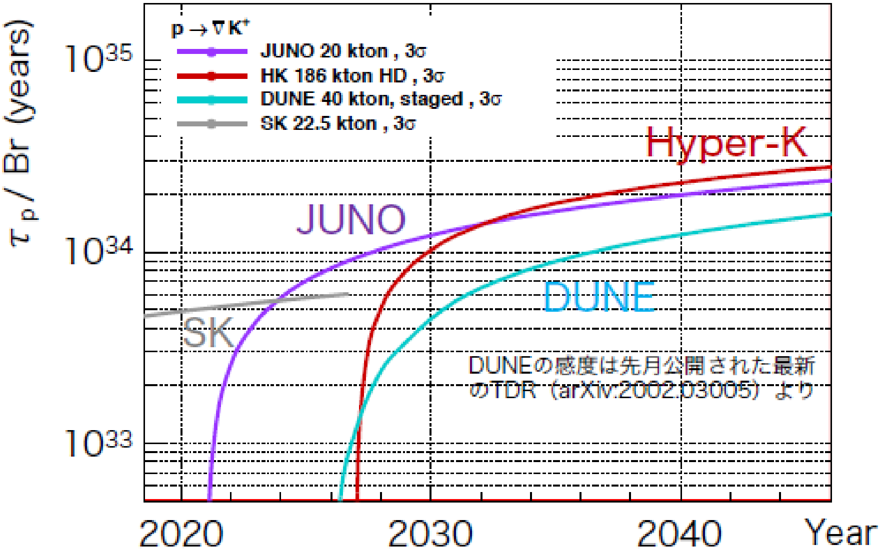
Reach to 10^{35} years !

Sensitivity for p→νK$^+$

Expected signal after 10 years run assuming the current lifetime limit



3σ discovery potential



DUNEの感度は先月公開された最新のTDR（arXiv:2002.03005）より

Prompt γ		$\pi^+\pi^0$		p_μ Spectrum		
ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]	σ_{fit} [%]
12.7 ± 2.4	0.9 ± 0.2	10.8 ± 1.1	0.7 ± 0.2	31.0	1916.0	8.0

Better sensitivity than other detectors !.

6. Summary

- Proton decay is a key phenomena of Grand Unified Theories beyond the Standard Model.
- Super-Kamiokande is the leading detector to hunt proton decays and have searched for it for more than 20 years.
- However, no evidence has been observed and the current proton lifetime limits are around 10^{34} years.
- It may be around the corner ! Hope three times lucky in Hyper-Kamiokande.