Search for proton decay

Yoshinari Hayato

(Kamioka obs., ICRR, The Univ. of Tokyo)

New paper by Takenaka et.al. will be published soon.
https://arxiv.org/abs/2010.16098 (Accepted by PRD)

Introduction

Standard model

Successful and explains most of the results of experiments.

All the particles including Higgs have been found.

But need extensions (non-zero neutrino mass).

Remaining issues or questions

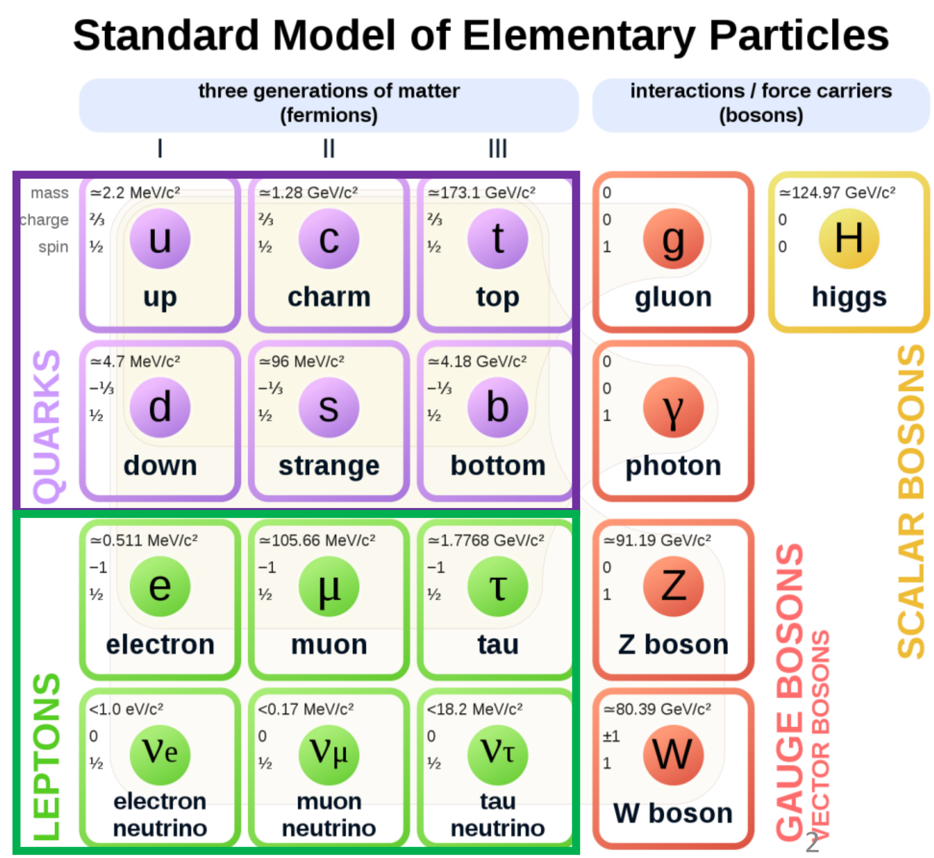
Electric charge unit

# of Generations

Too many parameters…

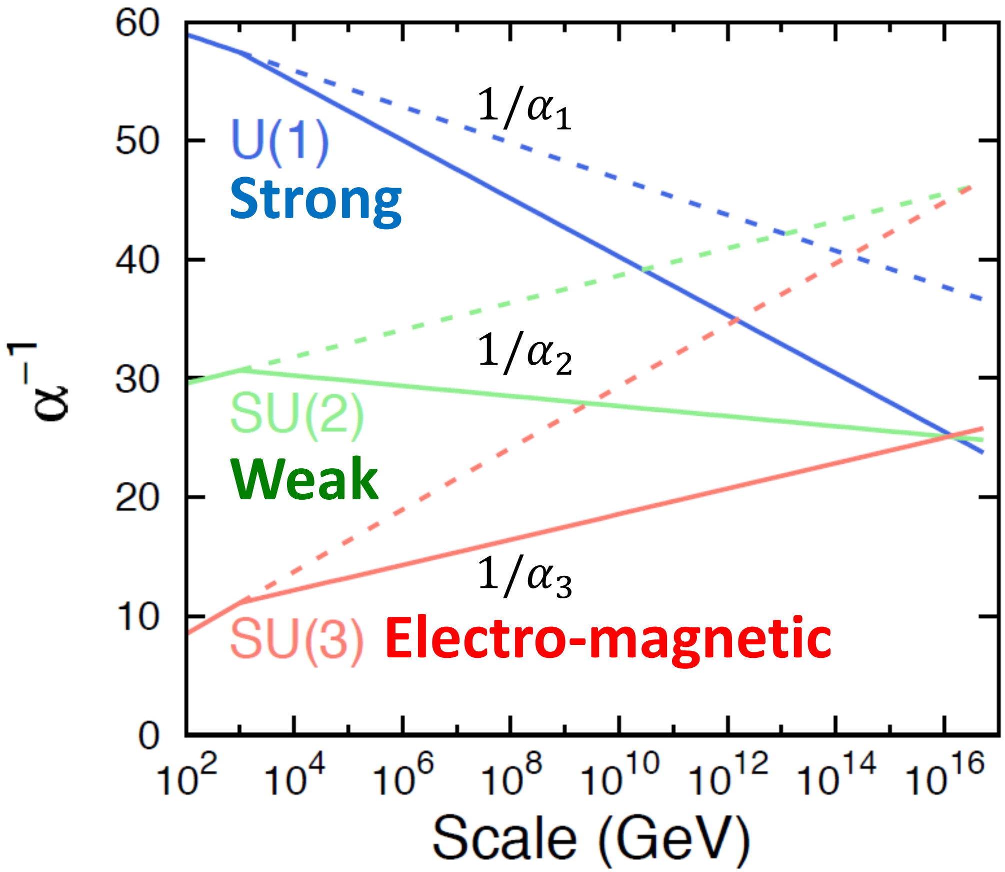
Similarity of Electroweak and Strong interactions

→ Suggesting the existence of the unified theory?



Grand Unification

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



Dashed lines Standard model
Solid lines MSSM

Unification of interactions
and
Unification of quark and lepton

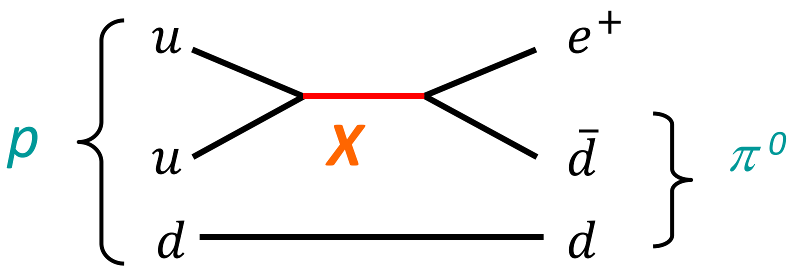
Possibility of transition
from quark to lepton

Proton decay

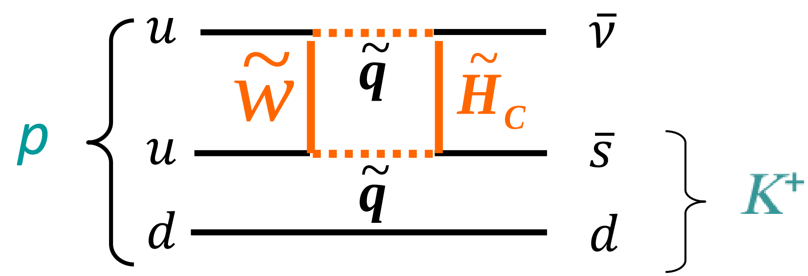
Predicted decay modes of proton

Two major decay modes

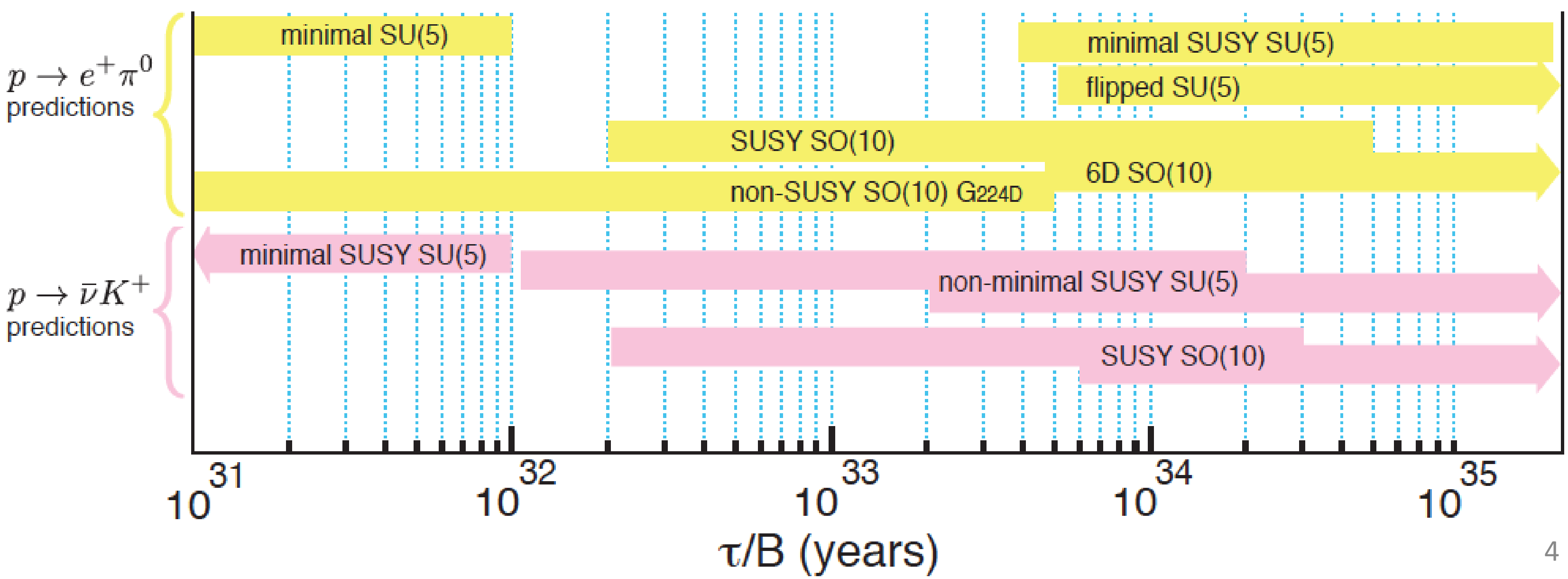
$p \rightarrow e^+\pi^0$



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



Theoretical predictions



Predicted decay modes of proton

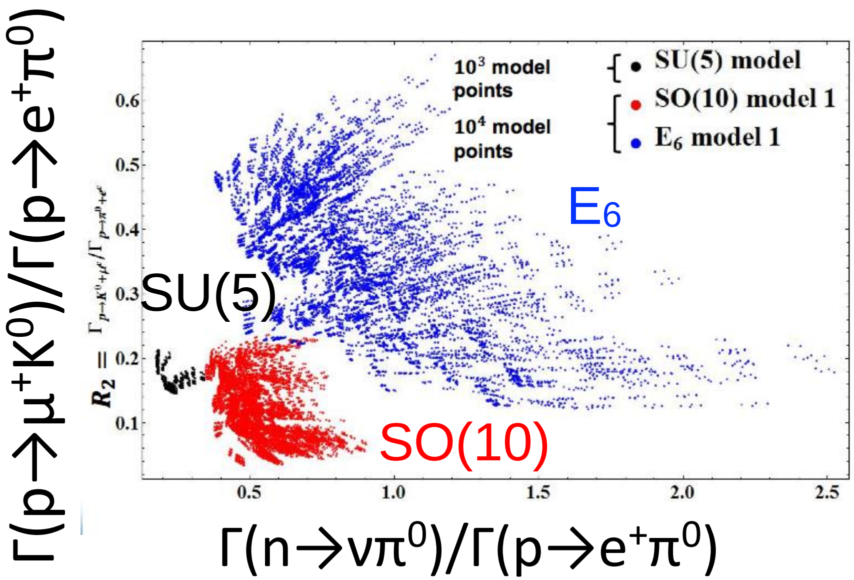
Theoretical predictions

$\Gamma(n \to \nu\pi^0)/\Gamma(p \to e^+\pi^0)$

depends on the gauge groups

SU(5), SO(10), E_6

(Y. Muramatsu)

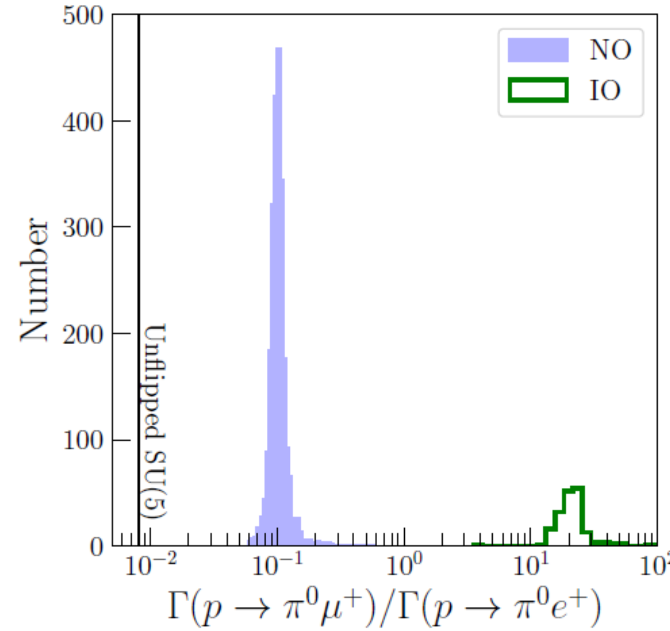


Decay branches

$\Gamma(p \to \mu^+\pi^0)/\Gamma(p \to e^+\pi^0)$

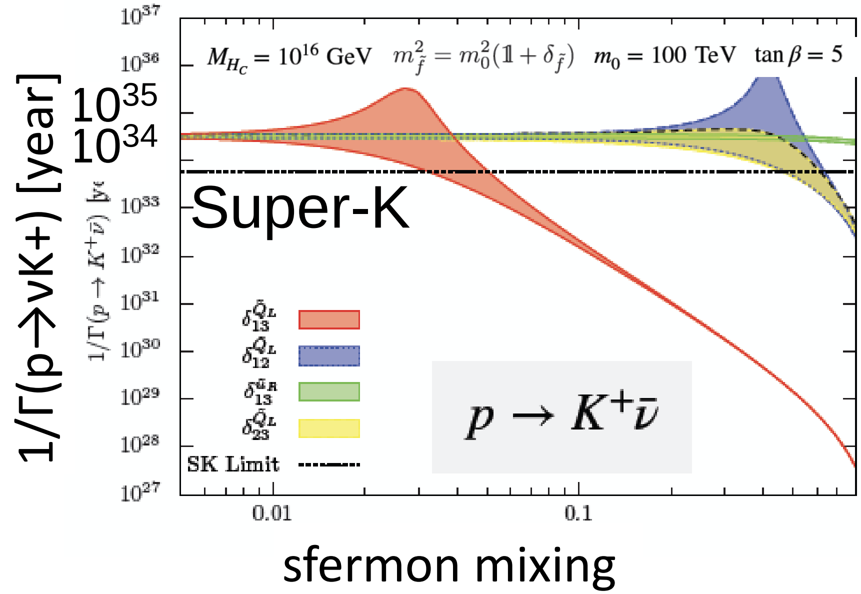
depends on the neutrino mass ordering in the flipped SU(5) GUT model.

(J. Ellis et al., JHEP05 (2020) 021)



Predicted decay modes of proton

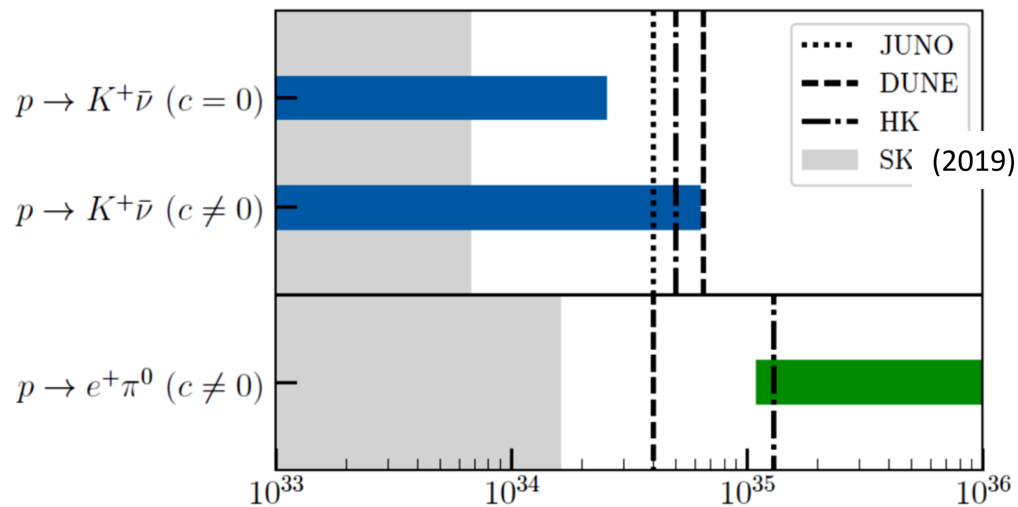
Decay branches depends on
the size of sfermion mixing.
(N.Nagata and S.Shirai,
JHEP 1403, 049 (2014))
-> Branching ratio may tell us
the flavor structure of
SUSY particles.



Prediction from the constrained Minimal SUSY Standard model

Traditional benchmark model

Supersymmetric Proton Decay Revisited
J. Ellis, J. L. Evans, N. Nagata,
K. A. Olive, L. Velasco-Sevilla
arXiv:1912.04888

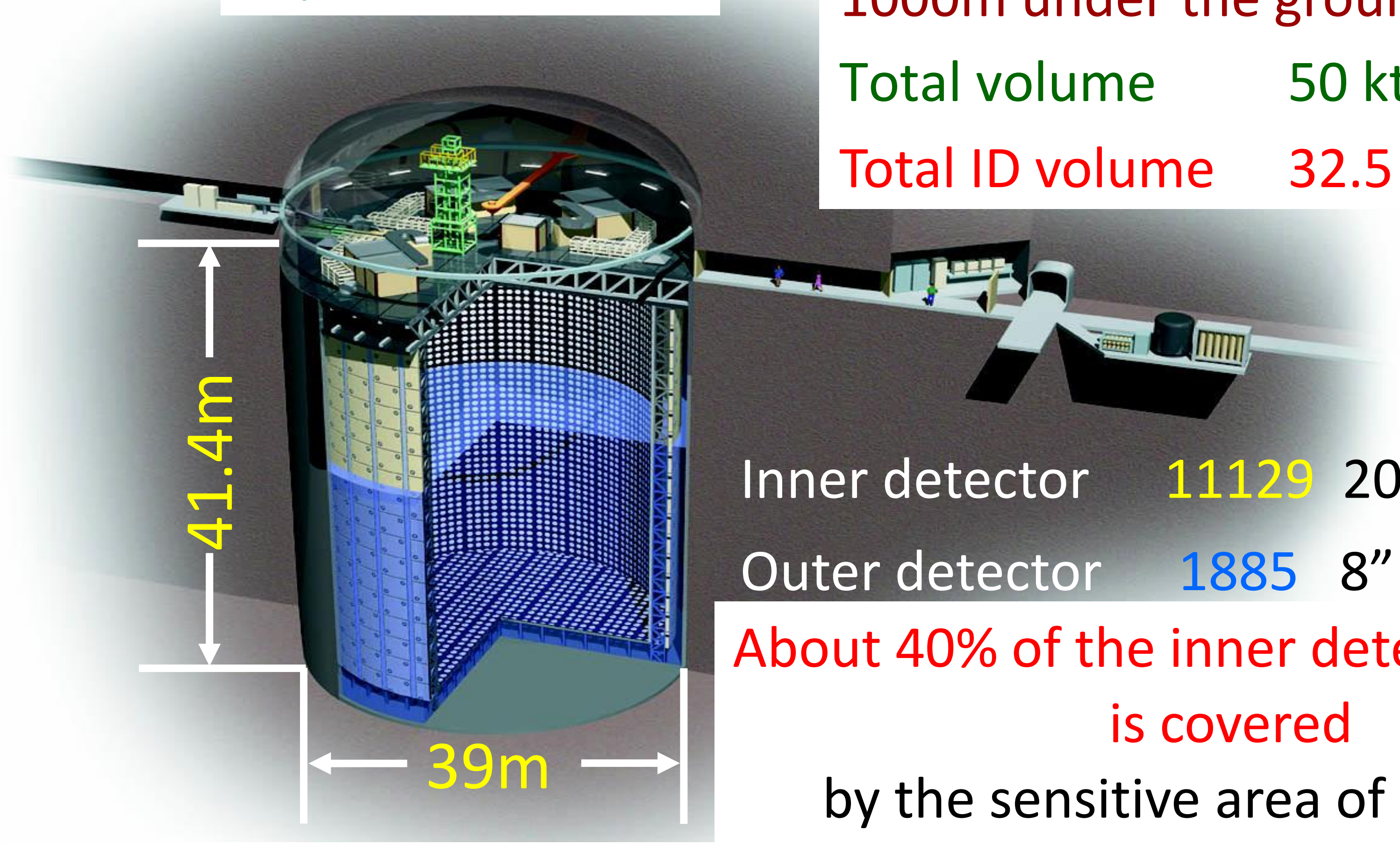


(c : dimension-five operator coupling parameter)

Super-Kamiokande detector

Ring imaging water Cherenkov detector

Super-Kamiokande



1000m under the ground

Total volume 50 ktons

Total ID volume 32.5 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.

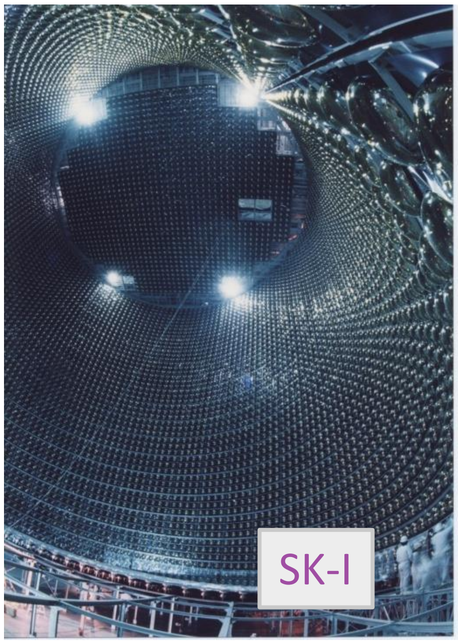
Every day, ~ 20 solar and atmospheric neutrinos are observed.

→ *Background of proton decay*

Super-Kamiokande detector

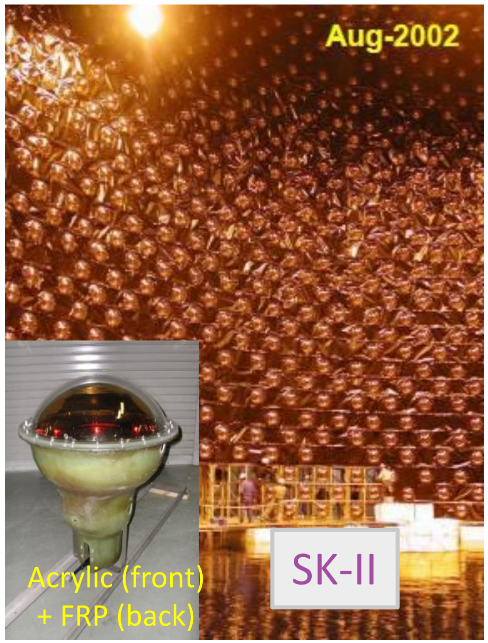
History of the SK detector

SK-I
April 1996
~ June 2001



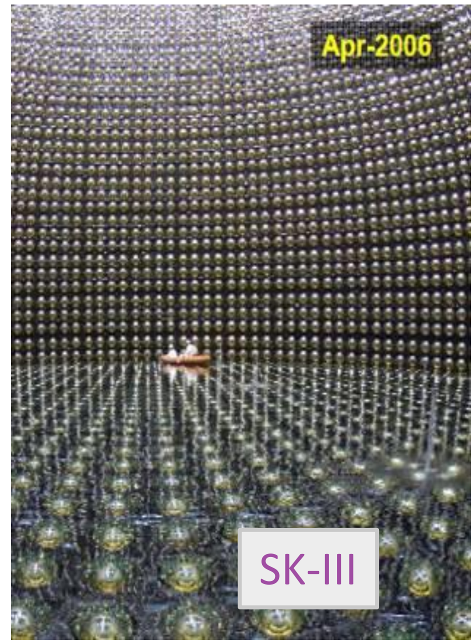
11146 ID PMTs
(40% coverage)

SK-II
October 2002
~ October 2005



5182 ID PMTs
(19% coverage)

SK-III
June 2006
~ September 2008



11129 ID PMTs
(40% coverage)

SK-IV
September 2008
~ June 2018

Electronics
Upgrade

Since August 2020, SK is running with 0.01% Gd.

Ring imaging water Cherenkov detector

Event reconstruction

Amount of the Cherenkov photons

$\propto$ Momentum of the particle

➡ Use observed # of photons

to reconstruct energy.

(For low energy electrons 1MeV ~ 6 hits)

Interaction position

~ starting point of the charged particle

➡ Use photon arrival timing.

Ring pattern is also used

for the precise reconstruction.

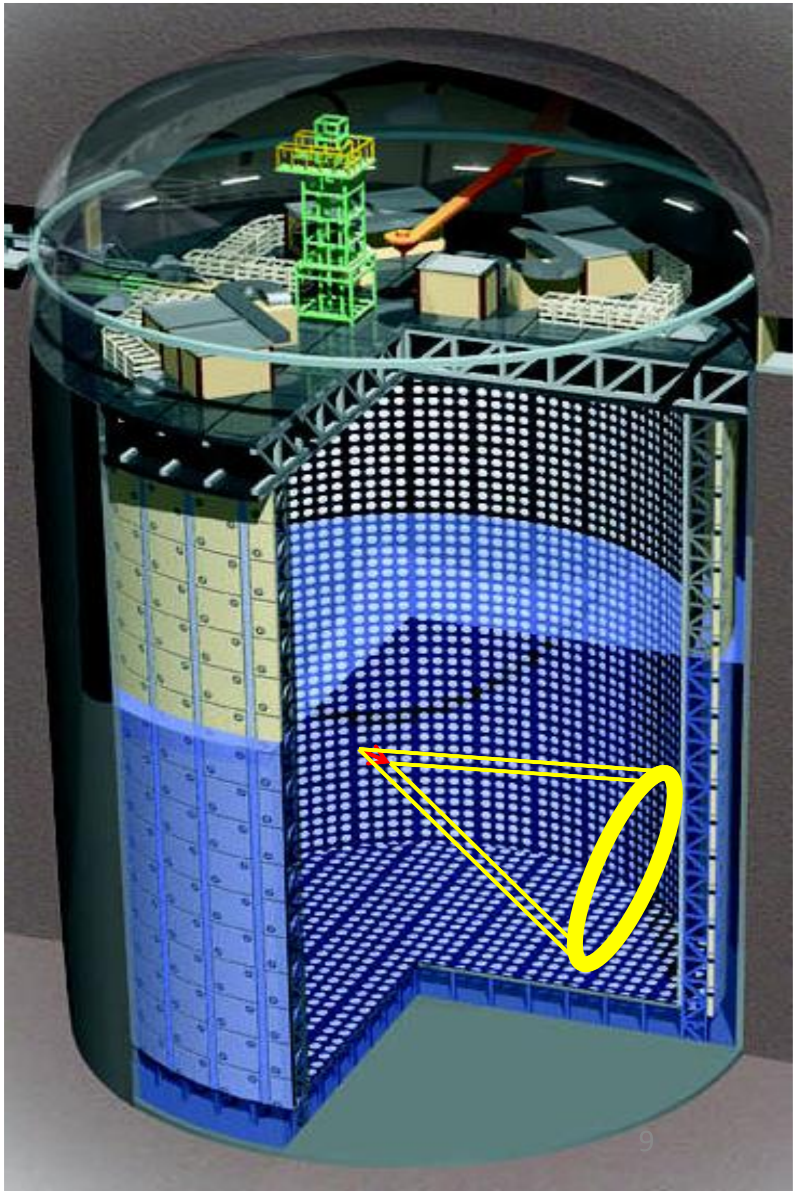
of the charged particles & γ

➡ # of the Cherenkov rings

Also, electrons generated

by the decay of μ, π etc.

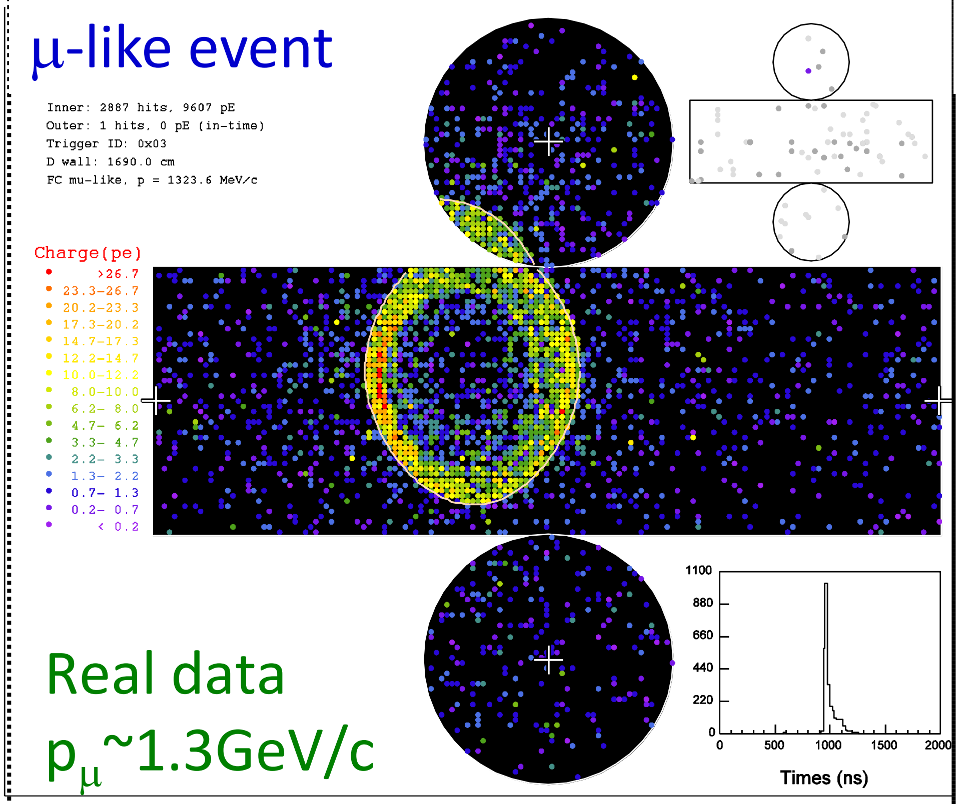
gives useful information.

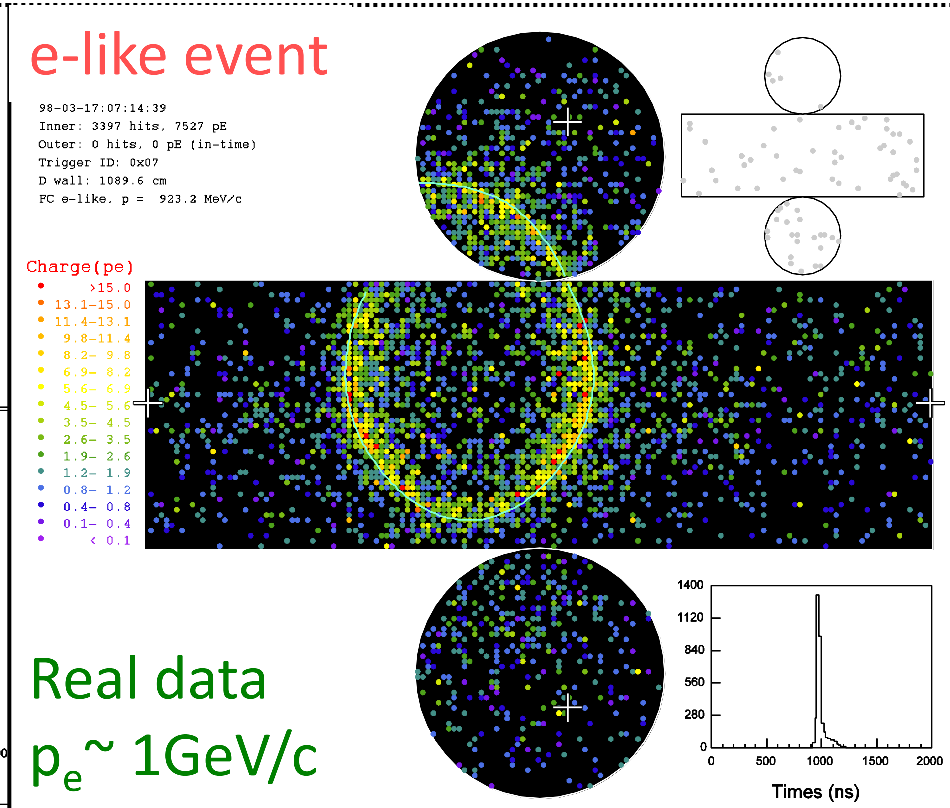


Ring imaging water Cherenkov detector

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.





But weak in detecting low momentum heavy particles.

Recent improvements of the event reconstruction in SK

Fiducial volume expansion

Since 1996, Super-Kamiokande proton decay analyses have been using the events at least 2m from the inner detector wall.

Improved event reconstruction software allow us to expand this to 1m from the wall for the entire period.

Previous fiducial volume

22.5kton

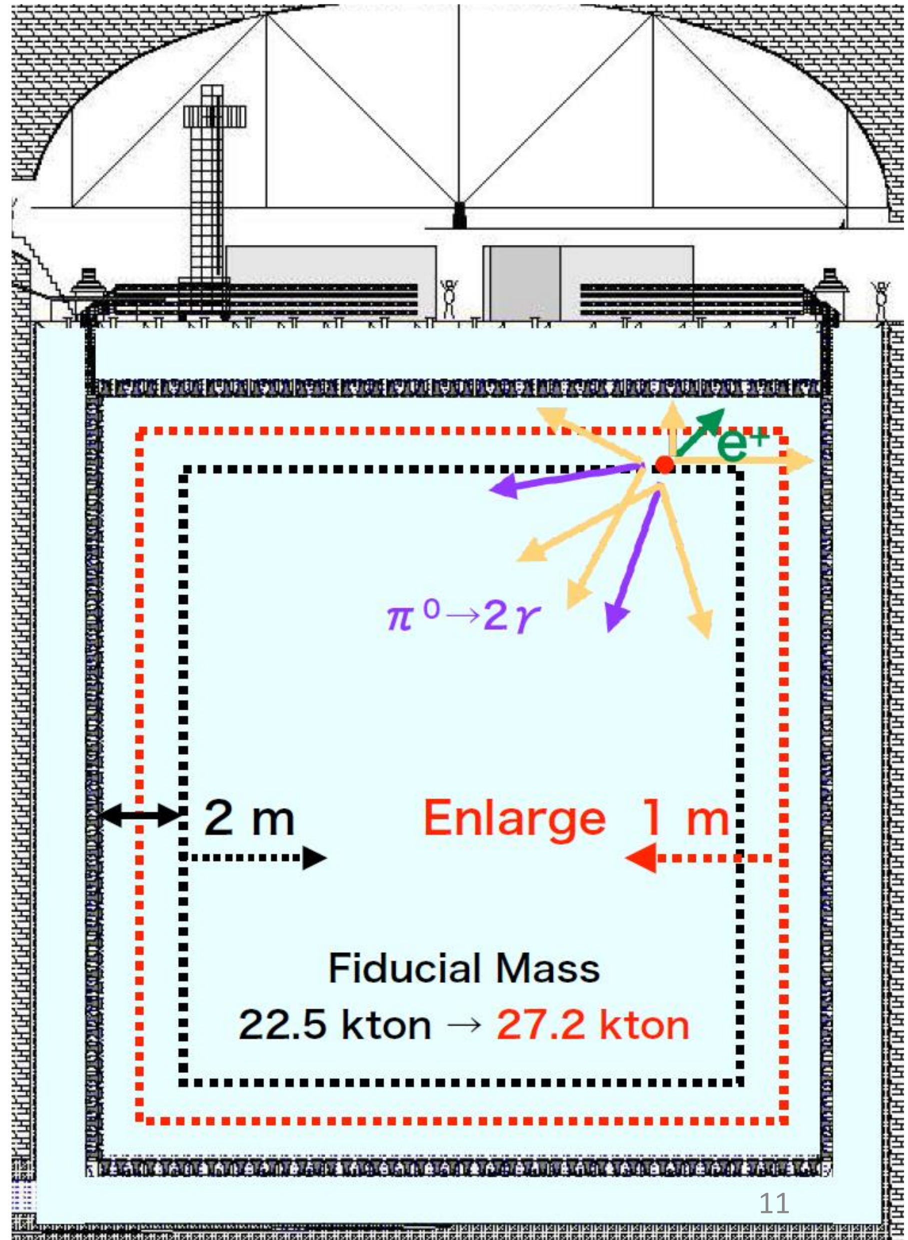
Expanded fiducial volume

27.2 kton

-> **Increased by 20%.**

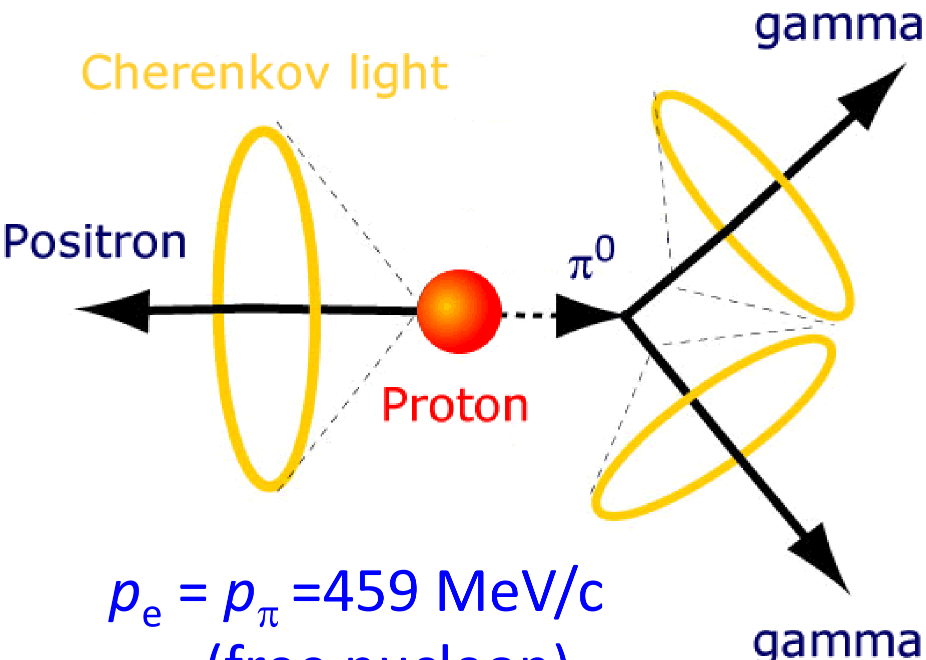
https://arxiv.org/abs/2010.16098

(Accepted by PRD)



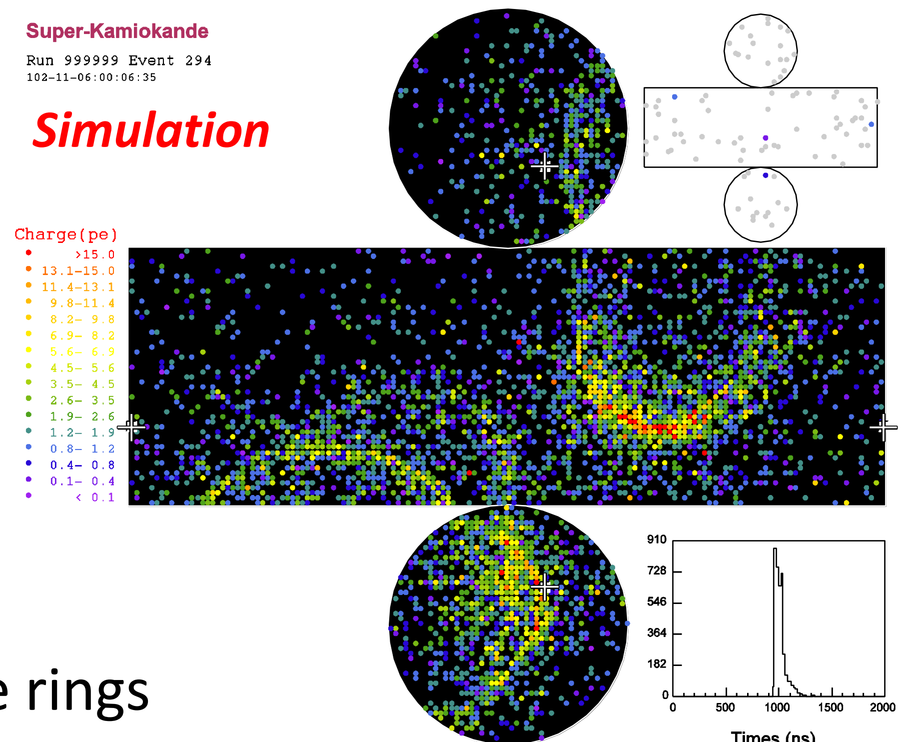
Proton decay search $p \rightarrow e^+ + \pi^0$

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



$p_e = p_\pi$ =459 MeV/c
(free nucleon)

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

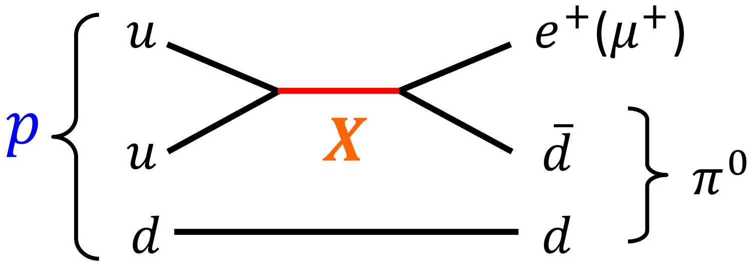


Ideally, clear 3 e-like rings
are expected to be observed.

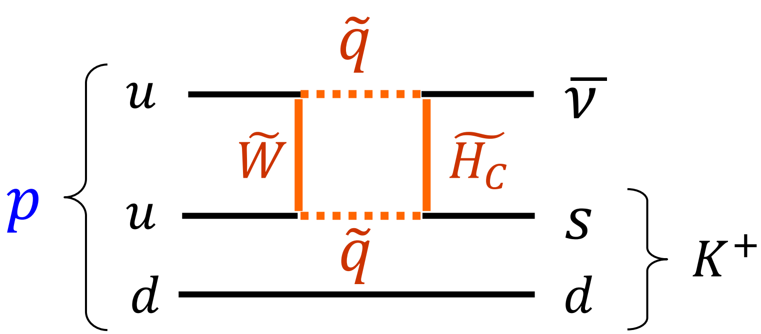
Proton decay search
Signal and background

Proton decay signal

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



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

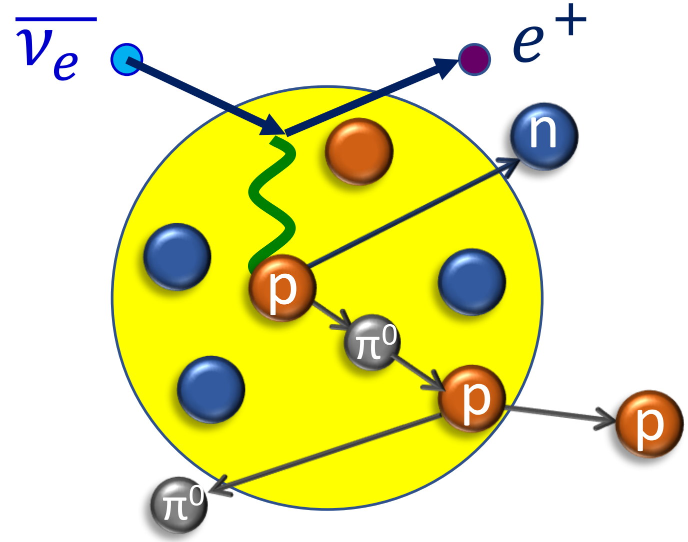


Background

neutrino-nucleus scattering

- Single π production
  + re-scattering (FSI) of π

$$\bar{\nu}_e + p \rightarrow \underline{e^{+} + \pi^{0}} + n$$



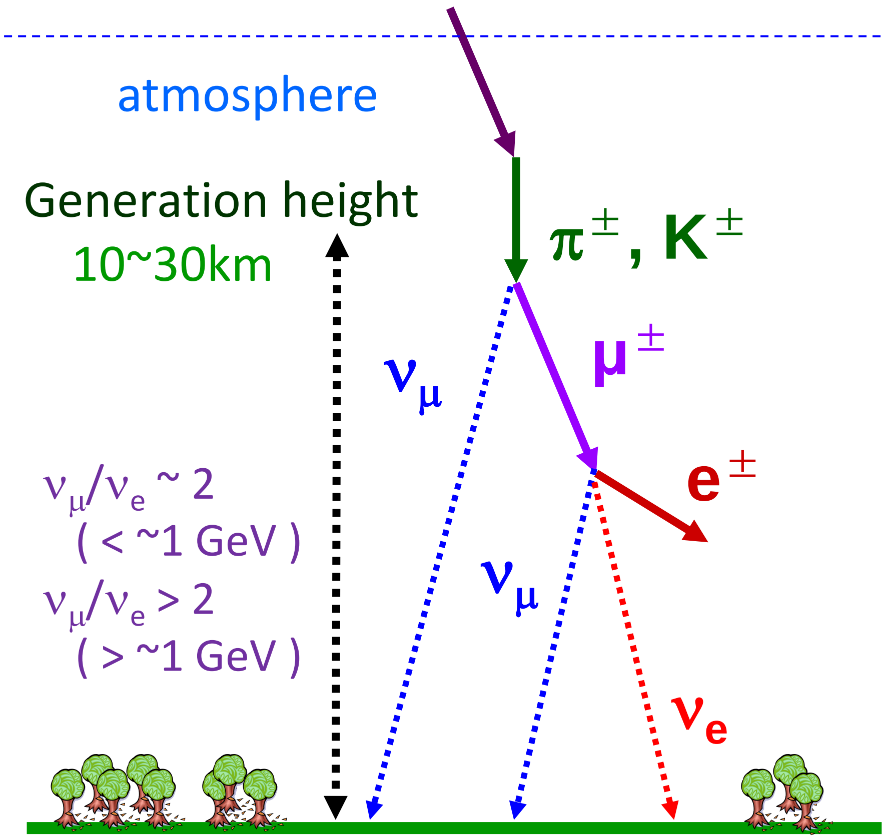
- Single Kaon production

$$\nu + N \rightarrow l^{-} + K^{+} + \Lambda$$

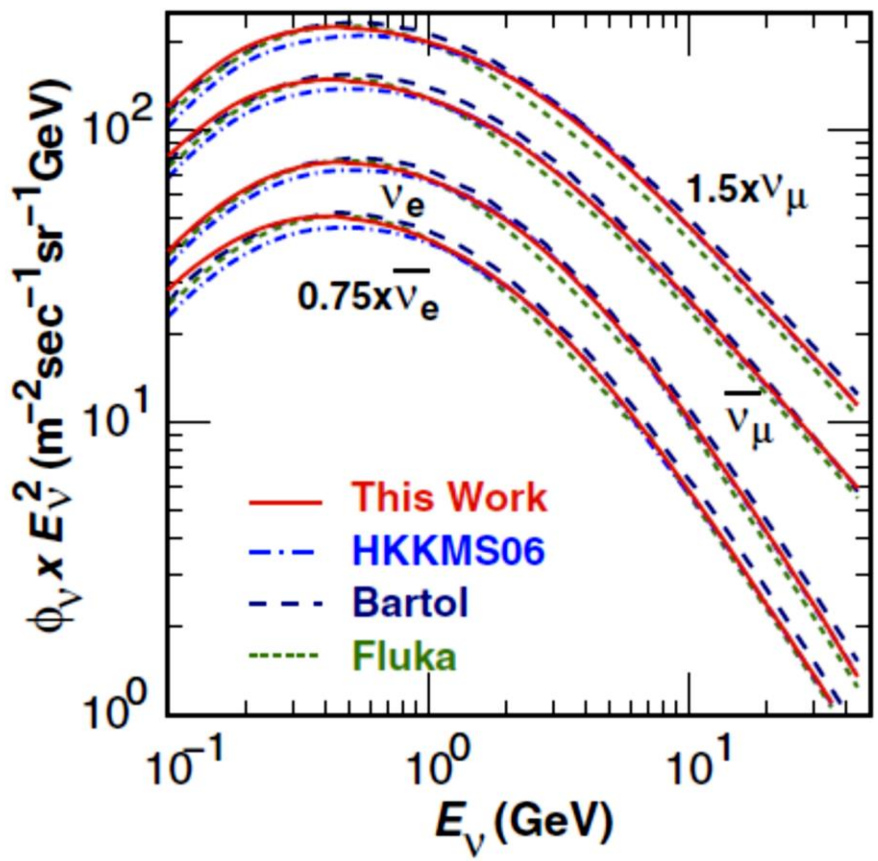
Proton decay search

Signal and background : Atmospheric neutrino

Primary cosmic ray (p, He ..)



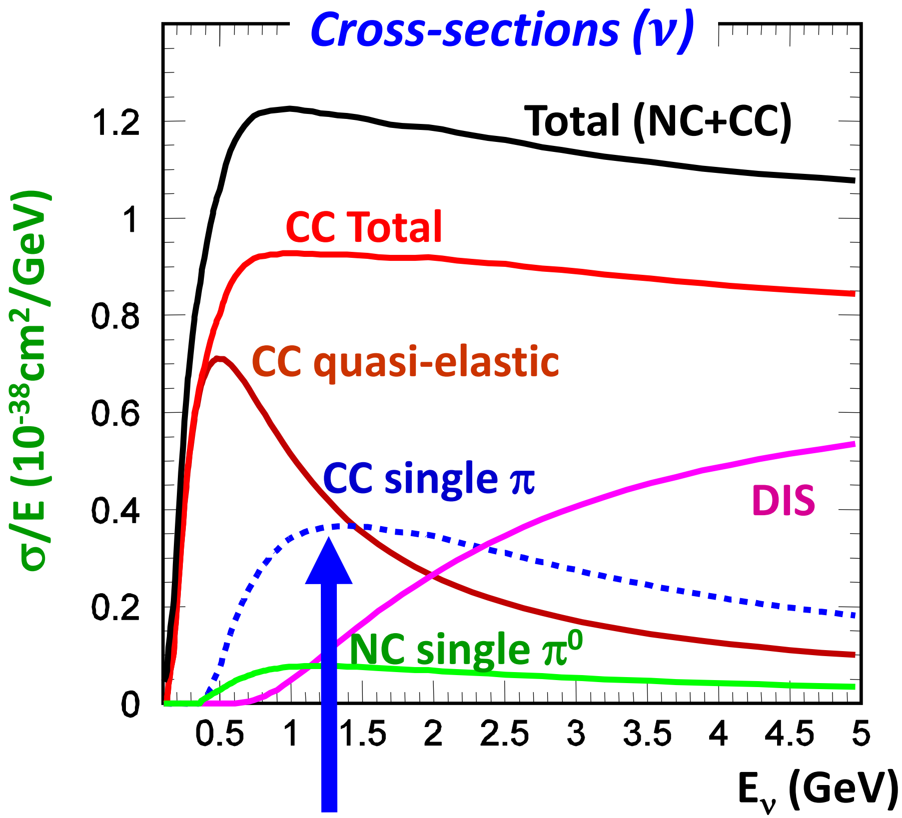
Atmospheric ν energy spectrum



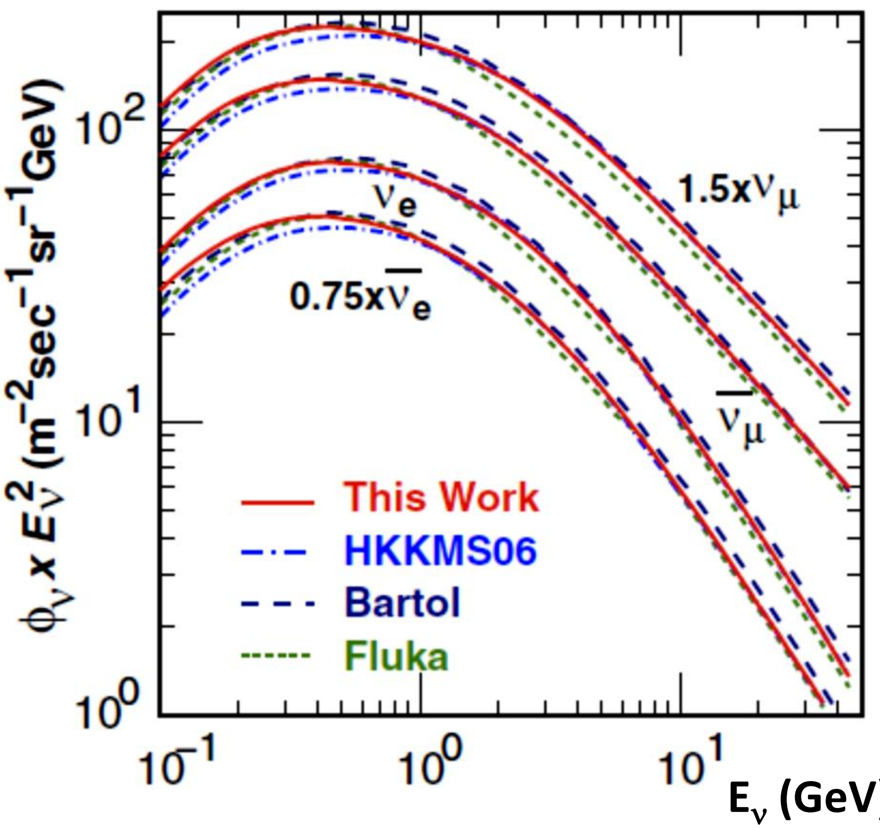
Atmospheric neutrino energy spectrum peaks around 1 GeV ~ mass of nucleon.

Proton decay search
Signal and background : Atmospheric neutrino

ν Interaction cross-sections



Atmospheric ν energy spectrum



One of the dominant interactions around 1 to a few GeV is single π production,

$$\nu(\bar{\nu}) + N \rightarrow \boldsymbol{l^-(l^+) + \pi} + N'.$$

Proton decay search
Final state interactions of pions

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

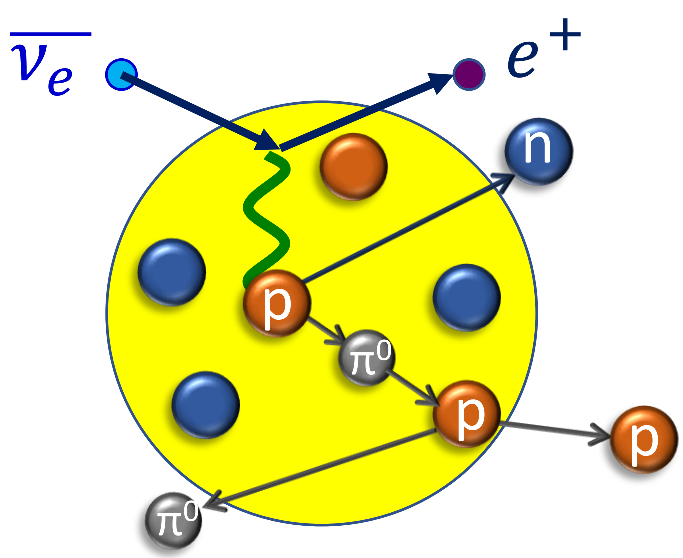
Background

neutrino-nucleus scattering

Single π production

+ re-scattering (FSI) of π

$$\bar{\nu}_e + p \rightarrow \underline{e^{+} + \pi^{0}} + n$$



π interaction in nucleus

(Final state interaction)

- Inelastic scattering
  change momentum
  and direction of π
- Charge exchange
  $(\pi^{\pm} \longleftrightarrow \pi^{0})$
  Momentum
  and direction of π
  are changed, also.
- Absorption
  Emit nucleon, gamma etc.

Final state interactions affect both signal and background.

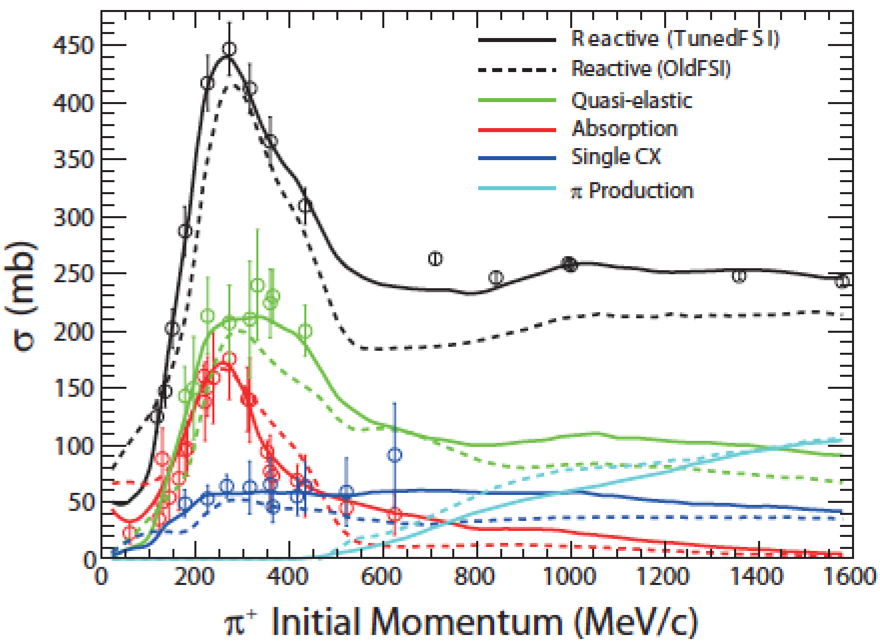
Proton decay search
Final state interactions of pions

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

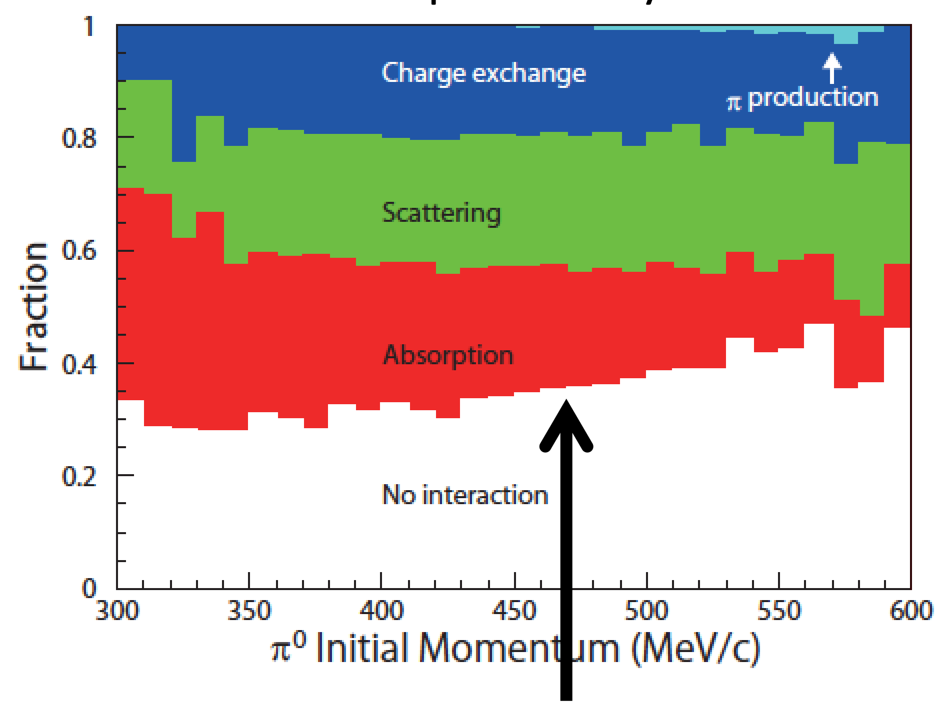
π interaction in nucleus (Final state interaction)

- Inelastic scattering — change momentum and direction of π
- Charge exchange — $(\pi^{\pm} \leftarrow\rightarrow \pi^{0})$
- Absorption — Emit nucleon, gamma etc.

π^{+} interaction cross-section on carbon



π^{0} interaction probability in ^{16}O



momentum of π^{0} from stationary proton's decay

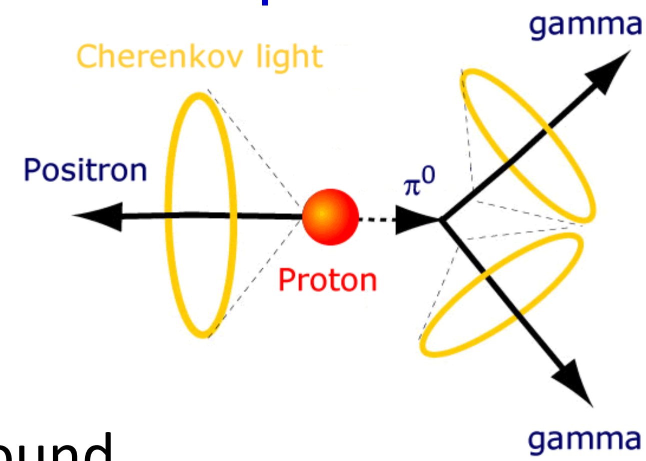
Proton decay search using ring imaging water Cherenkov detectors

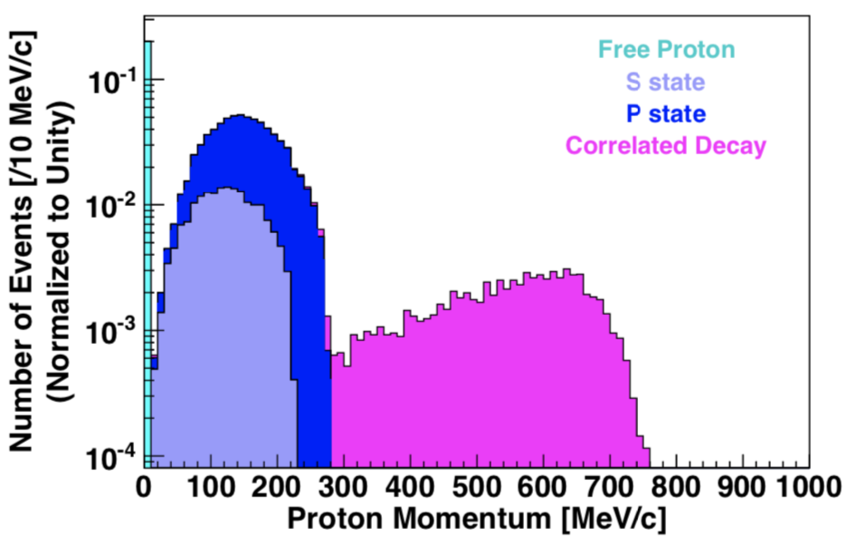
In case of water,

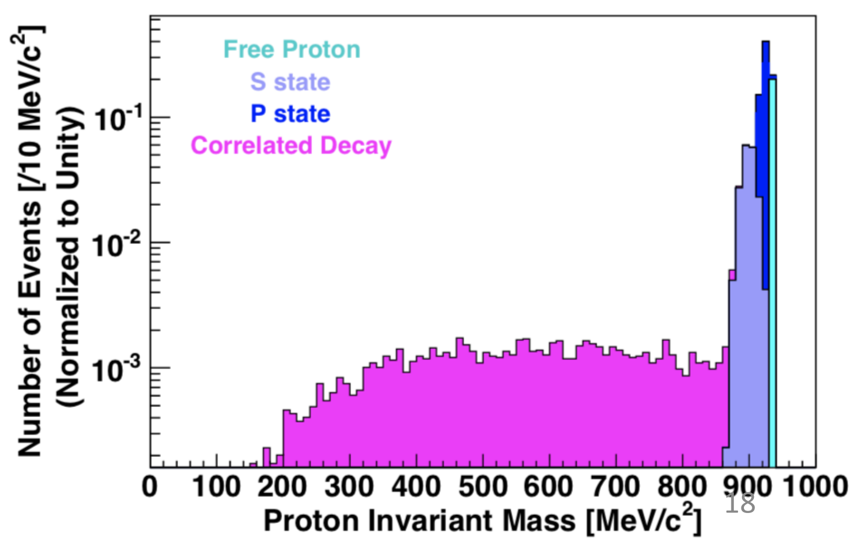
8/10 protons are bound in Oxygen.

- Nucleon inside of a nucleus is affected by the other nucleus (potential) and thus, the “observed” invariant mass is shifted from the free-nucleon mass.
- Also, nucleons are known to moving around (Fermi-motion) in the nucleus.

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





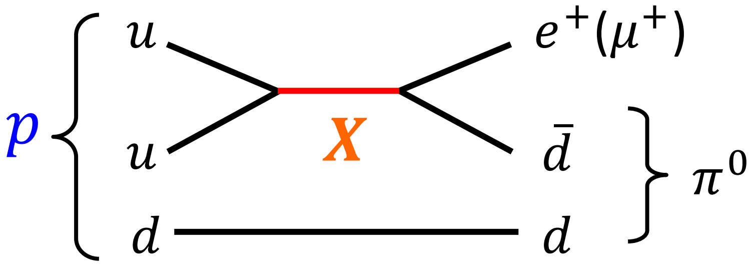


Proton decay search

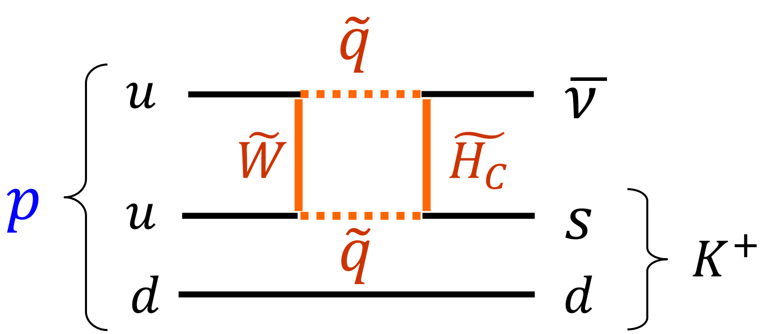
Background rejection using neutron

Proton decay signal

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



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



Background

neutrino-nucleus interactions

$$\bar{\nu}_e + p \rightarrow e^+ + \pi^0 + n$$

$$\nu + N \rightarrow l^- + K^+ + \underline{\Lambda}$$

$$\underline{\Lambda} \rightarrow N' + \pi$$

Background atmospheric neutrino events could be rejected if neutrons are tagged.

In the water, neutron is captured by hydrogen (~ 200 μs) and emit 2.2 MeV γ ray.

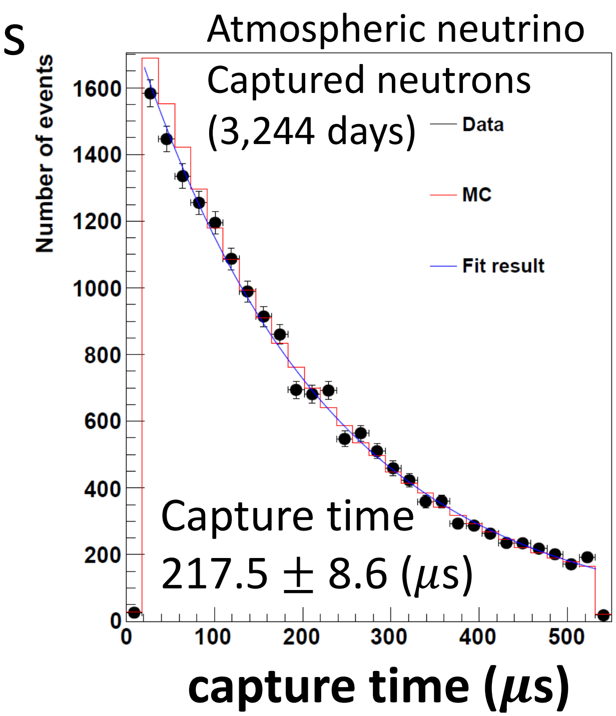
$$n + p \rightarrow d + \boldsymbol{\gamma}$$

Proton decay search
Background rejection using neutron

New electronics and DAQ system for Super-K IV allows us to store all the PMT hit information for > 500 μs after the atmospheric ν or proton decay candidate events.

→ Possible to search for 2.2 MeV γ from $n + p \rightarrow d + \gamma$ which gives about 10 PMT hits

Search for hit cluster (# of hits in 10 ns ≥ 5) after prompt event and select candidates using neural network.



Detection efficiency 25.9%

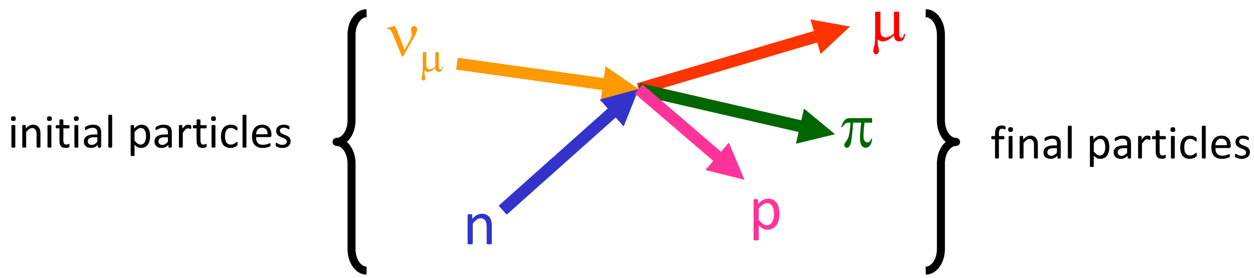
(mis-tag 0.016 per neutrino event)

About half of the background events could be rejected by requiring no neutron candidates.

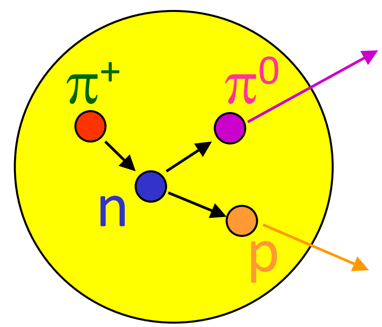
Procedure of the event simulation (for SK)

Two steps for the interaction in the nucleus

1. Primary interaction
   a. Proton decay (in the nucleus)
   b. Neutrino-nucleon interaction (in the nucleus)



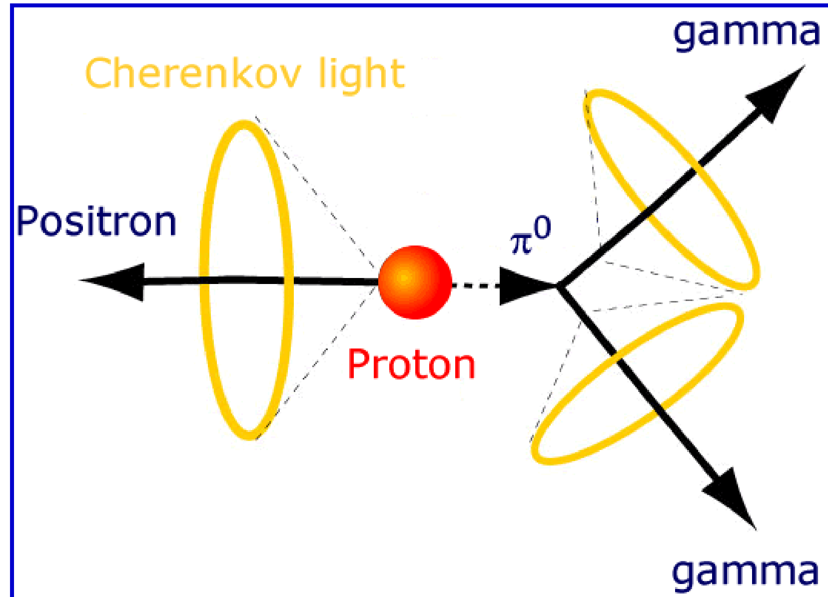
2. Re-scattering (final state interactions) in the nucleus
   Leptons are ejected without further re-interactions.
   Re-scattering of hadrons are simulated
   using the custom cascade models.



De-excitation gammas are simulated for Oxygen.
Strength of the states and the energy spectrum
are taken from theoretical calculations.

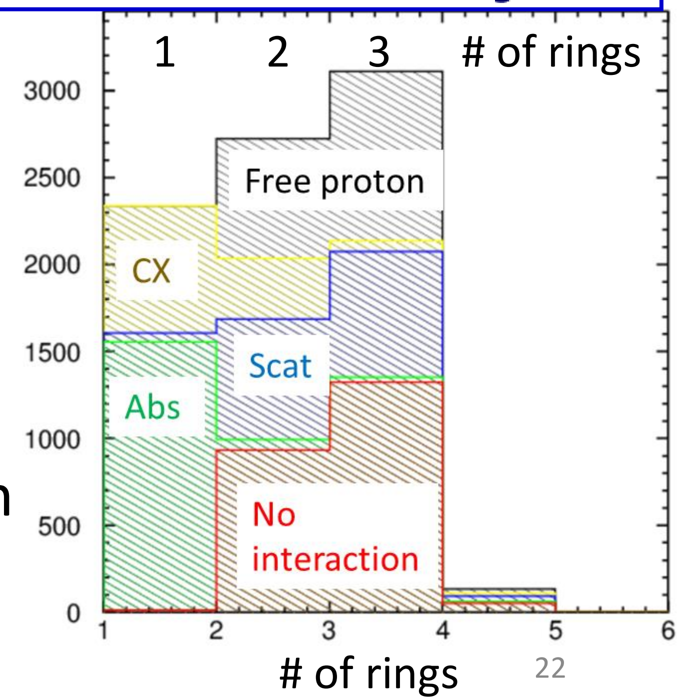
Proton decay search in SK

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



Event selection criteria

- No activity in the outer detector
- Vertex in the fiducial volume
- 2 or 3 e-like ring
  (e^+ + 1 or 2 γ)
  ~ one of the γs may have low energy or overlap with the other rings
- No decay electron
- 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
- No tagged neutron (only for SK4)

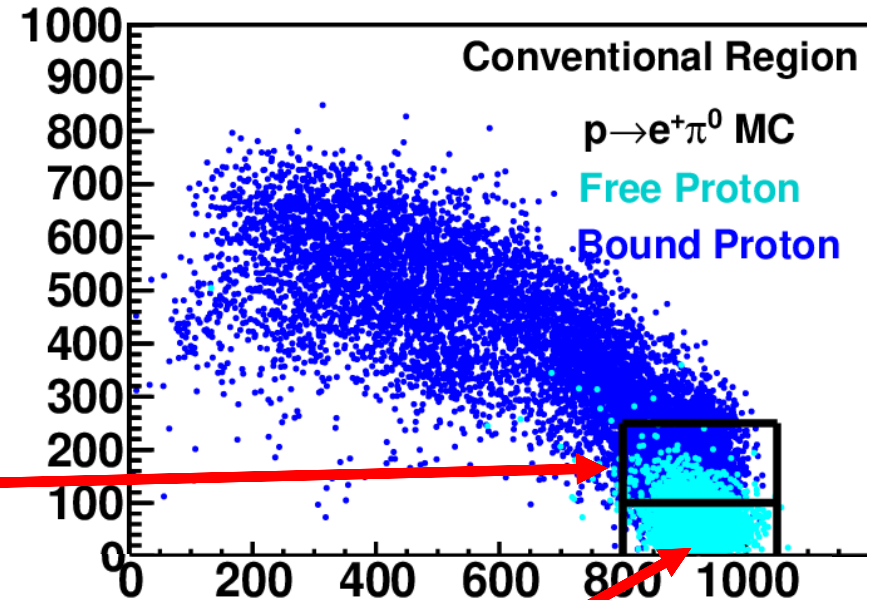


Proton decay search $p \rightarrow e^+ + \pi^0$

Source of inefficiency & backgrounds

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

- Inelastic scattering
- Charge exchange ($p^0 \rightarrow p^\pm$)
- Absorption



Reconstructed mass (MeV/c^2)

Cyan : Free proton
Blue : Bound proton

Divide the sample into two.

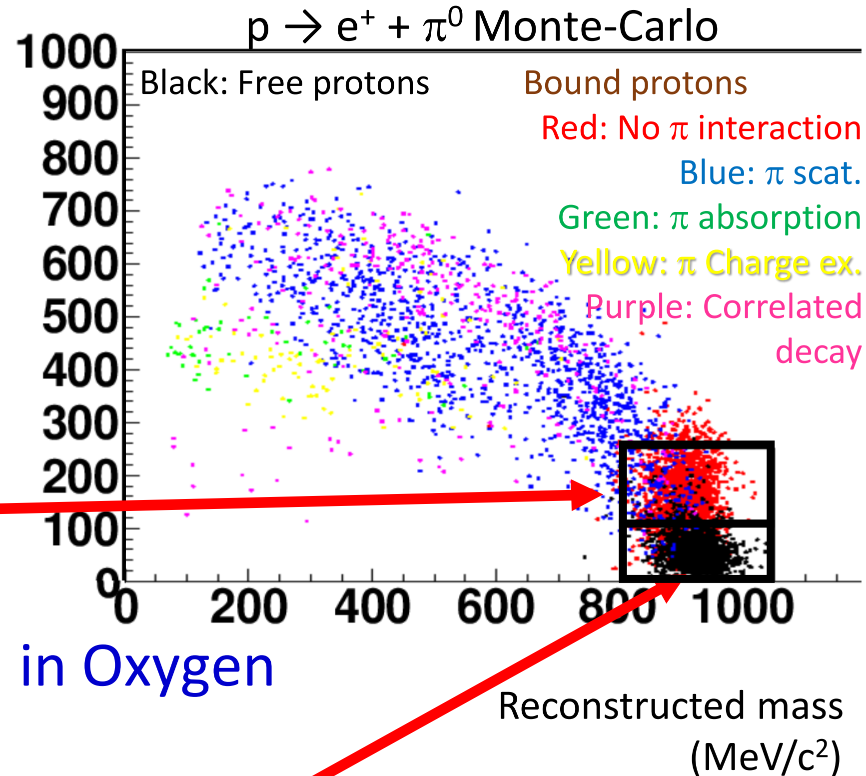
- High momentum sample
  (100 < p < 250 MeV/c)
  to search for the decay of proton in Oxygen
  Larger # of backgrounds
- Low momentum sample (p < 100MeV/c)
  to search for the decay of Hydrogen
  Smaller # of backgrounds

Proton decay search $p \to e^+ + \pi^0$

Source of inefficiency & backgrounds

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

- Inelastic scattering
- Charge exchange ($p^0 \to p^{\pm}$)
- Absorption



Divide the sample into two.

- High momentum sample
  (100 < p < 250 MeV/c)
  to search for the decay of proton in Oxygen
  Larger # of backgrounds
- Low momentum sample (p < 100MeV/c)
  to search for the decay of Hydrogen
  Smaller # of backgrounds

Cyan : Free proton
Blue : Bound proton

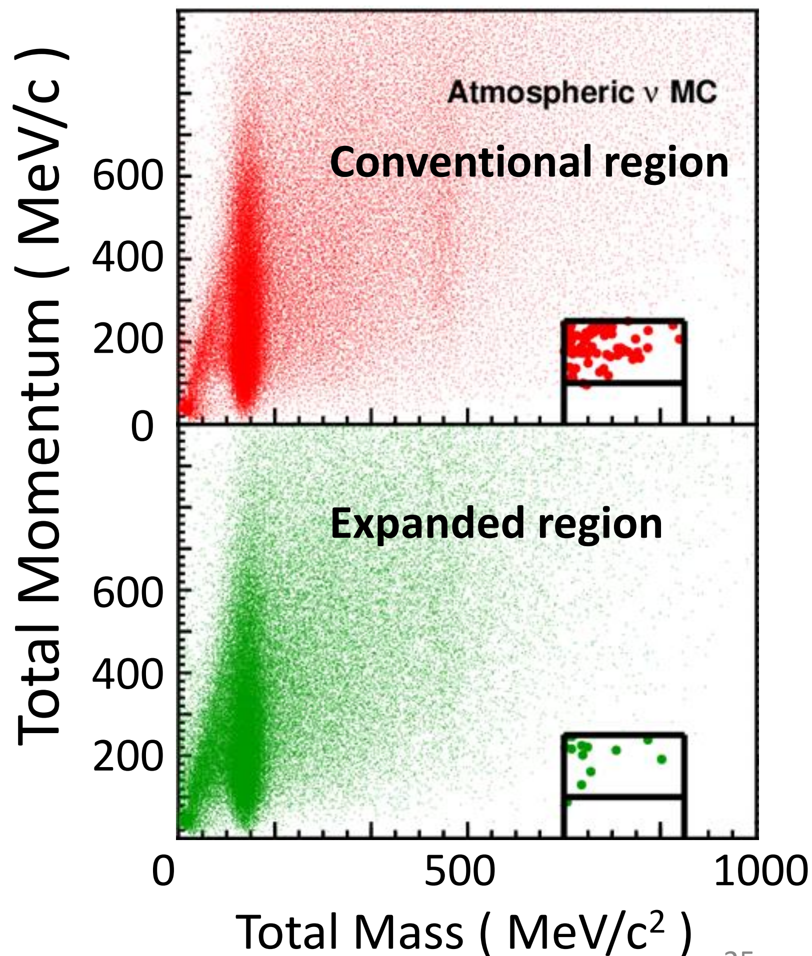
Proton decay search $p \rightarrow e^+ + \pi^0$

Source of the background events (atmospheric ν)

~ 1.0 events / Mt·year

~60 % from CC single π
(ν_e N → e N' π)
10 ~ 15 % from CC multi π
(ν_e N → e N' mπ)
~20 % from CC QE
π^0 from secondary interactions of nucleon
(ν_e N → e N' + secondary π^0)
5 ~ 10 % from NC
(ν N → ν N' X)

Reconstructed total mass and total momentum
atmospheric ν MC sample



Proton decay search $p \to e^+ + \pi^0$

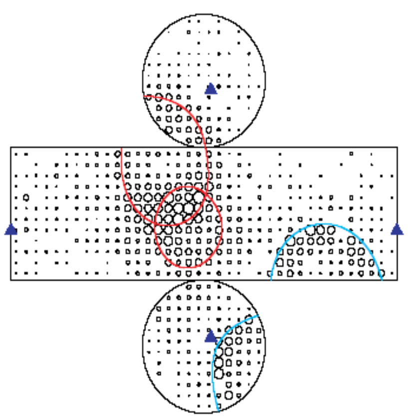
Validation of the background estimation

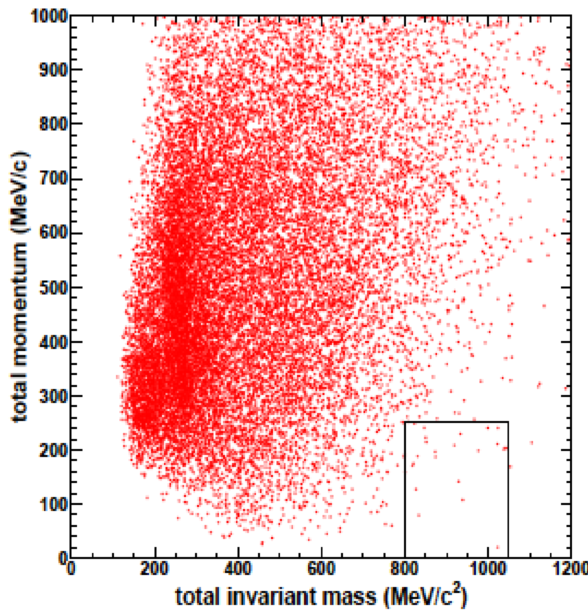
Use data from the accelerator experiments.

Data from the 1kt water Cherenkov detector in the K2K experiment

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

2- or 3-ring $\mu\pi^0$ events





K2K ($p \to e^+ + \pi^0$ 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

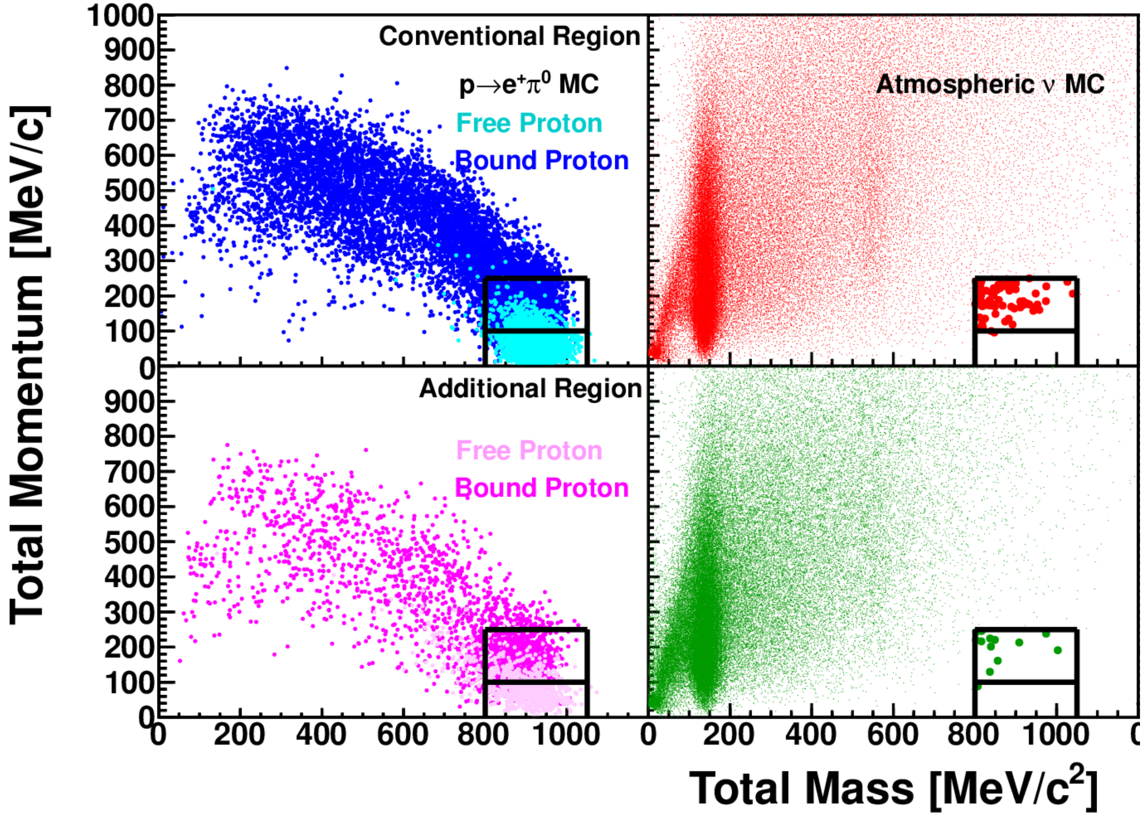
1.8 +/- 0.3(stat.) events / Mt·yr

(Without neutron rejection)

Data from π beam experiments are also used

to tune and validate the π interactions in nucleus.

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



Conventional
22.5 kton
(2m from the wall)

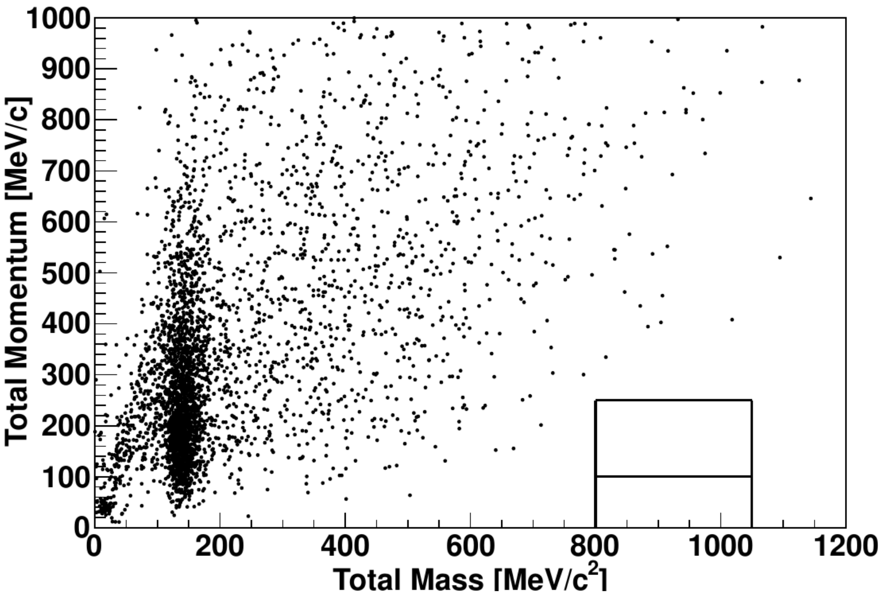
Enlarged
4.7 kton
(1m to 2m from the wall)

	Low P_{tot}		High P_{tot}	
Volume	Conventional	Enlarged	Conventional	Enlarged
Efficiency (%)	19.5 ± 1.7	10.3 ± 1.4	20.3 ± 3.3	15.5 ± 2.6
Background (/livetime)	0.01 ± 0.01	0.01 ± 0.01	0.48 ± 0.21	0.09 ± 0.05

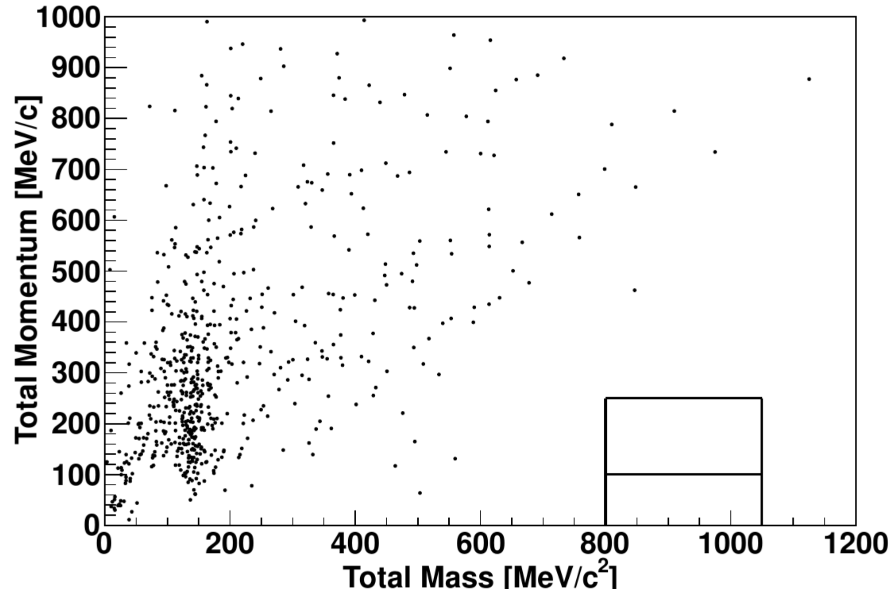
Proton decay search $p \rightarrow e^+ + \pi^0$

Super-Kamiokande 1996 ~ 2018 (450 kton·years)

Conventional region (372 kton·years)



Enlarged region (78 kton·years)



https://arxiv.org/abs/2010.16098

(Accepted by PRD)

So far, no candidate events have been observed.

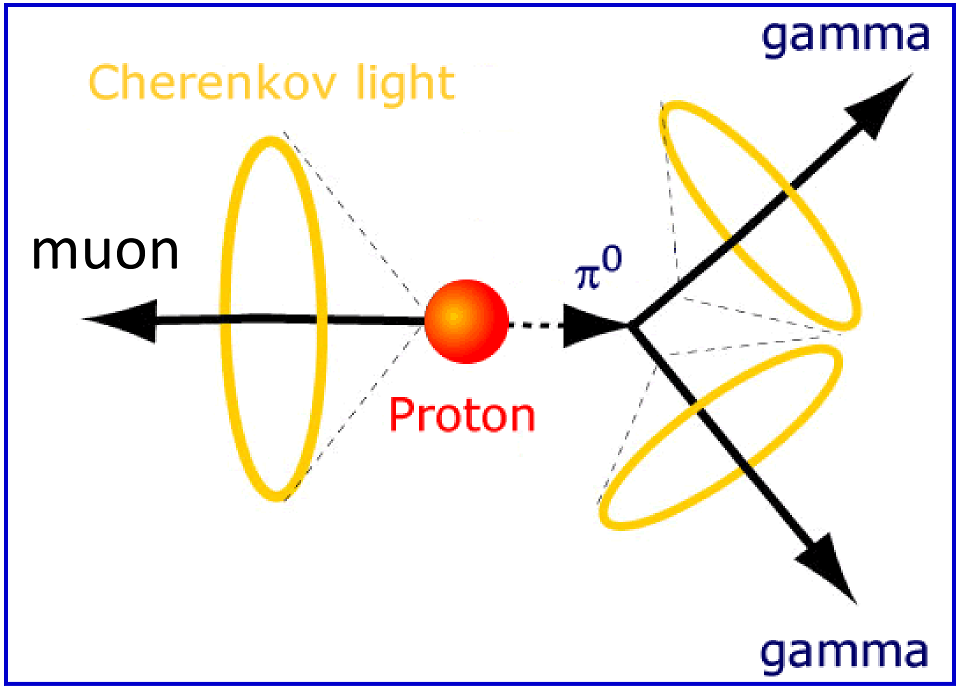
Partial lifetime limit = 2.4x10^{34}year

Proton decay search in SK

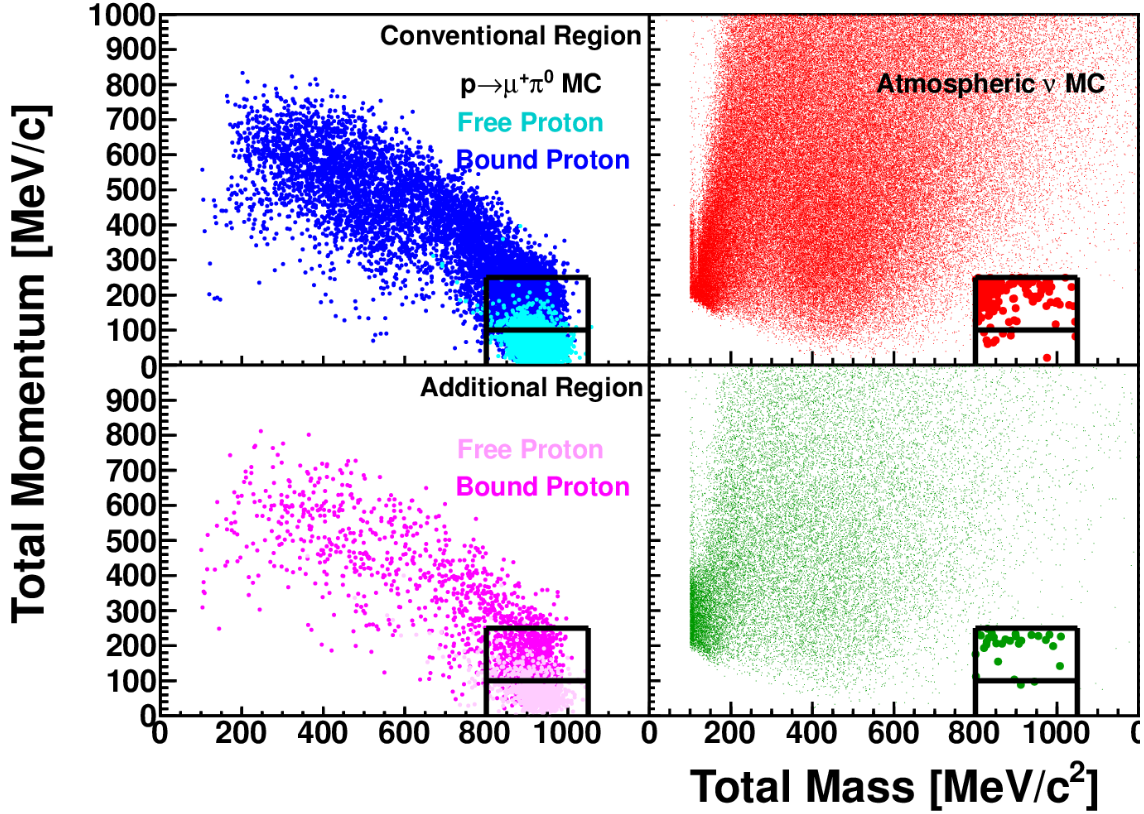
$$p \to \mu^+ + \pi^0$$

Event selection criteria

- No activity in the outer detector
- Vertex in the fiducial volume
- 2 or 3 rings and only 1 μ-like
  (μ^+ + 1 or 2 γ)
  ~ one of the γs may have low energy or overlap with the other rings
- 1 decay electron
- 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
- No tagged neutron (only for SK4)



Proton decay search in SK $p \to \mu^+ + \pi^0$



Conventional
22.5 kton
(2m from the wall)

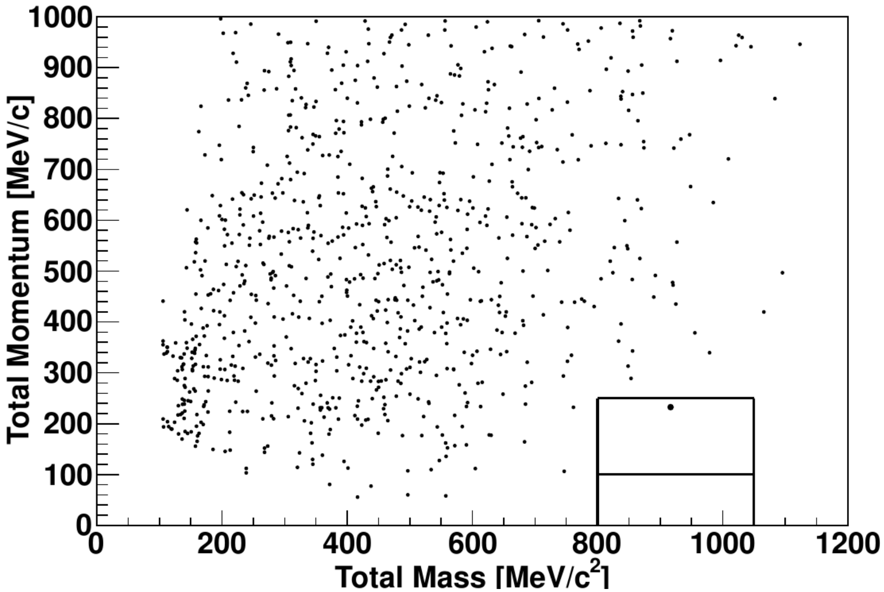
Enlarged
4.7 kton
(1m to 2m from the wall)

	Low P_{tot}		High P_{tot}	
Volume	Conventional	Enlarged	Conventional	Enlarged
Efficiency (%)	18.5 ± 1.7	11.7 ± 1.2	17.8 ± 3.3	13.5 ± 2.4
Backgrounds (/livetime)	0.04 ± 0.03	0.01 ± 0.01	0.70 ± 0.24	0.19 ± 0.08

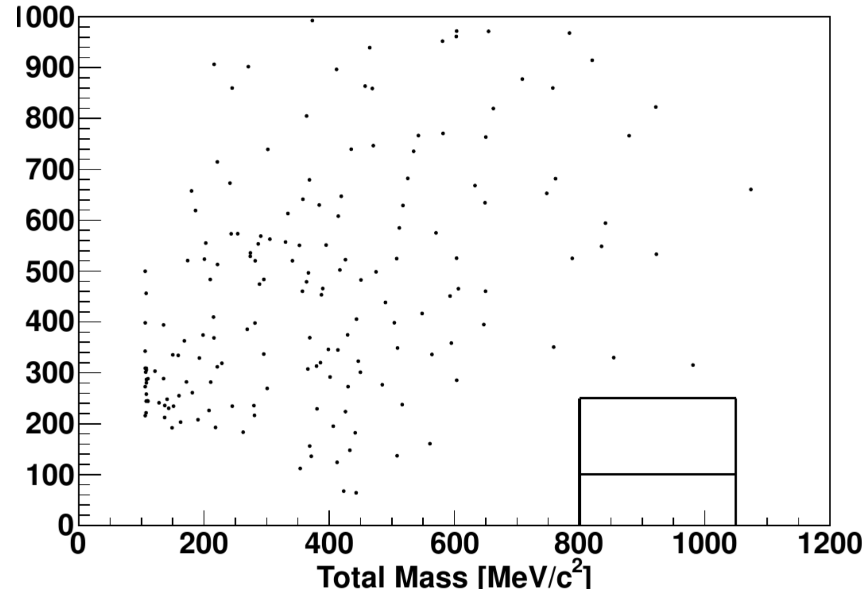
Proton decay search in SK $p \rightarrow \mu^+ + \pi^0$

Super-Kamiokande 1996 ~ 2018 (450 kton·years)

Conventional region (372 kton·years)



Enlarged region (78 kton·years)



https://arxiv.org/abs/2010.16098

(Accepted by PRD)

1 candidate found in the high P_{tot} box.

No significant data excess compared to the expected B.G.

Partial lifetime limit = 1.6x10^{34}year

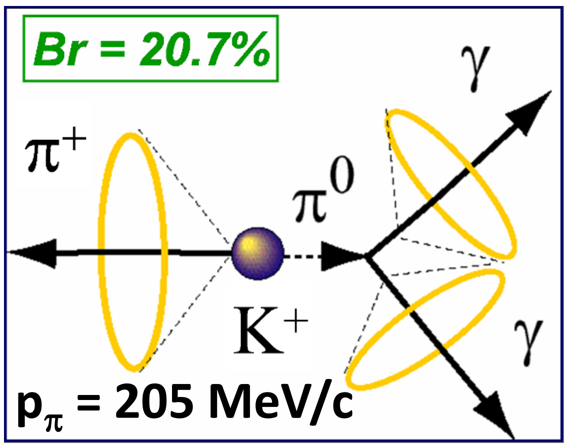
Proton decay search in SK $p \to \bar{\nu} + K^+$

SK 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.

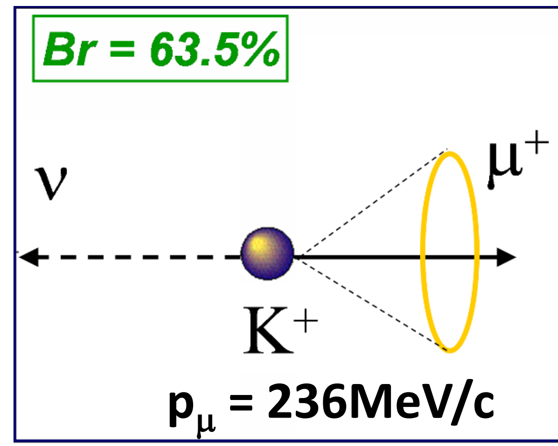
→ Use decay products of K^+
for the identification of the candidate events

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



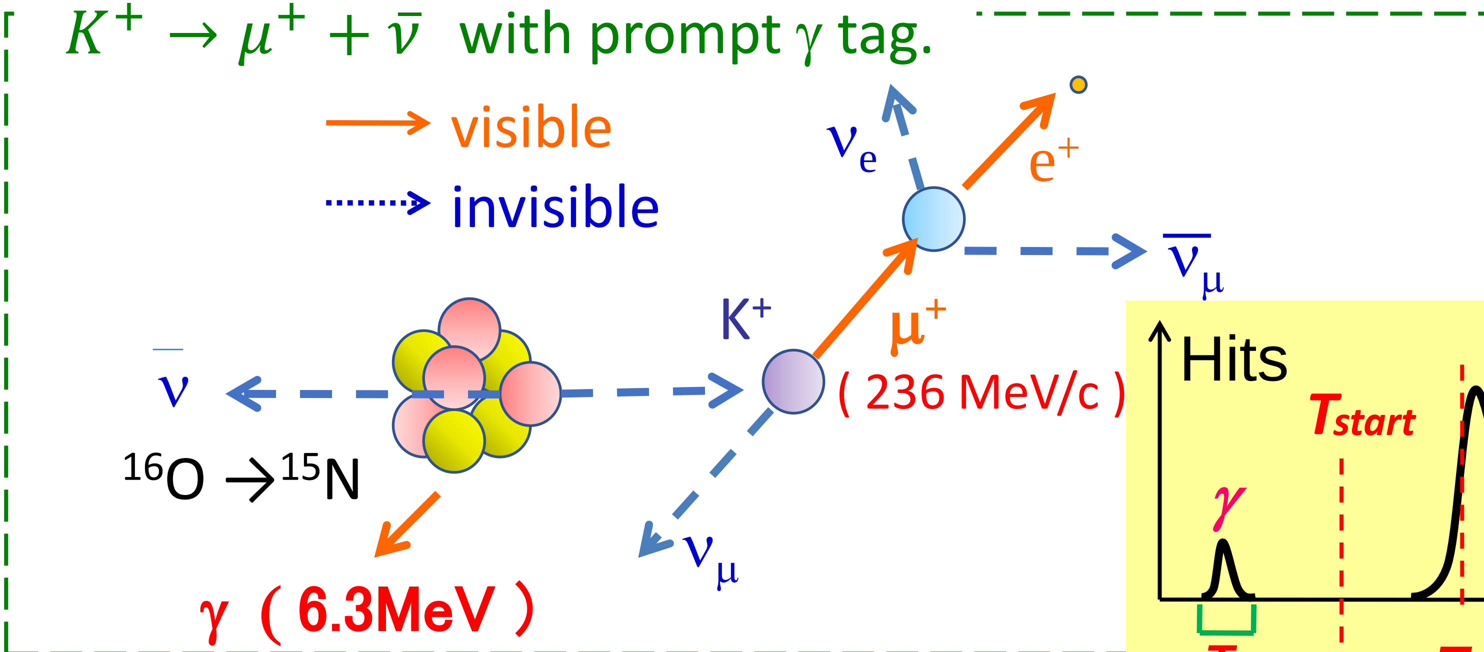
- Two e-like rings with 1 decay-e
- Small activity (from π^+) in the opposite direction of π^0

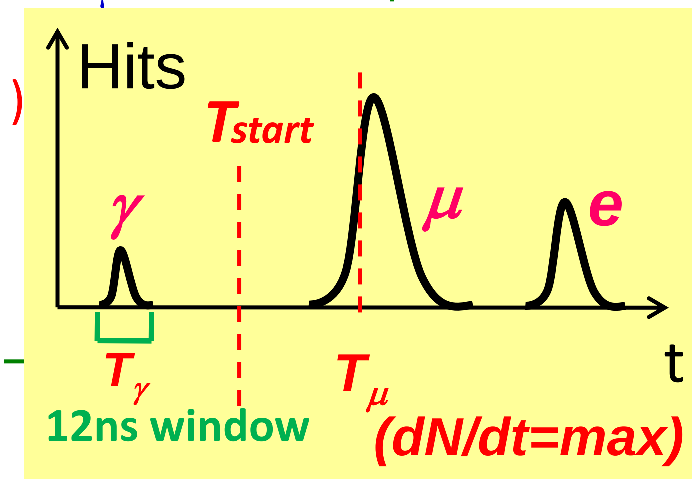
$K^+ \to \mu^+ + \bar{\nu}$



- Single μ-like ring with 1 decay electron

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



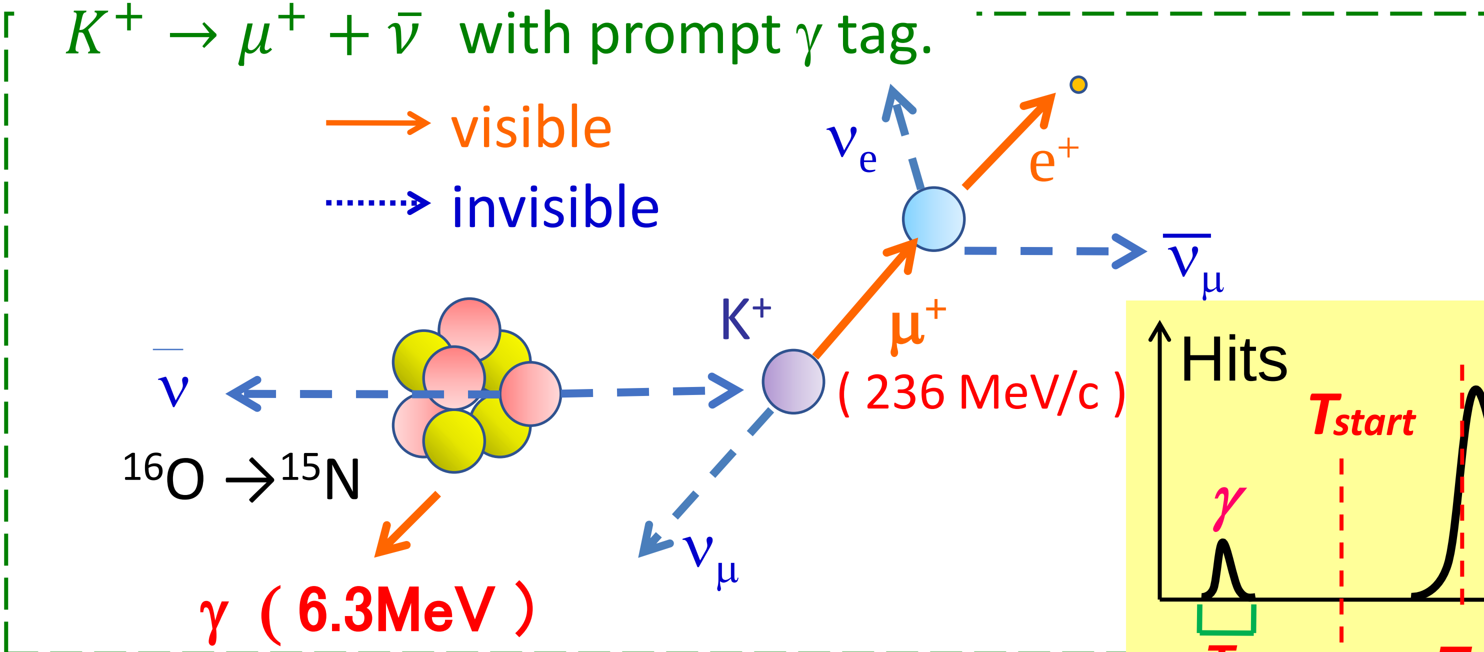


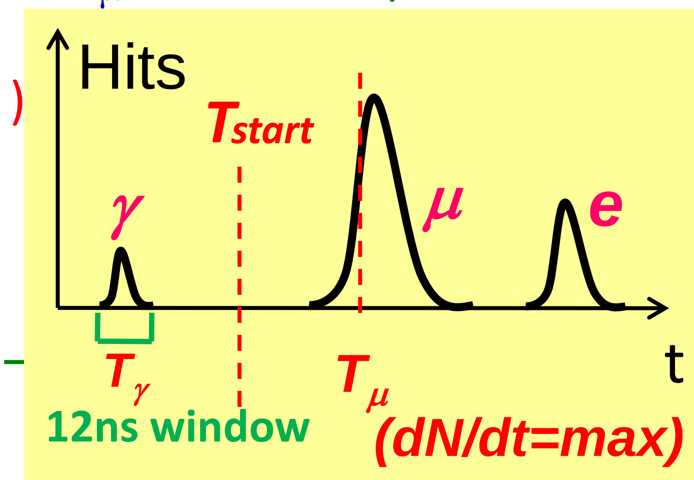
When a proton in oxygen decays,
6.3MeV de-excitation γ is also emitted
with probability of ~ 40 %.

- 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

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





Event selection criteria

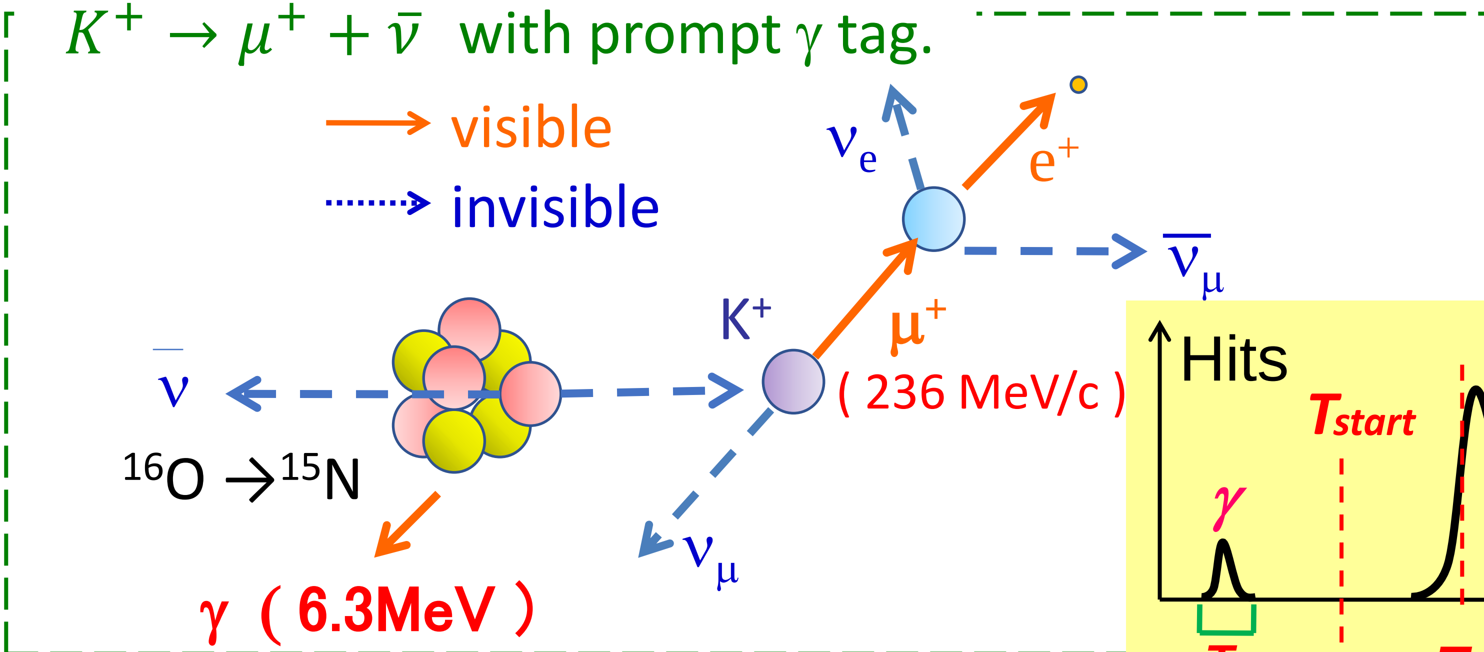
- No activity in the outer detector
- Vertex in the fiducial volume
- 1 decay electron
- 1 μ-like ring
- No tagged neutron (only for SK4)
- Maximum # of hit cluster in 12ns after prior to the μ signal (N_{12})

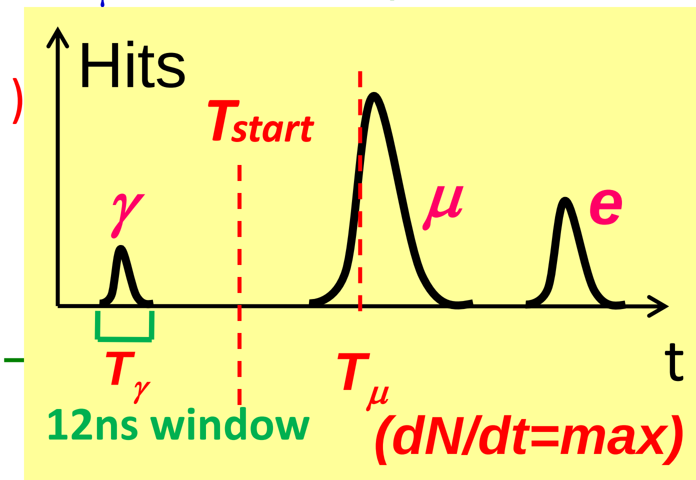
  $8 < N_{12} < 60$ (SK1,3,4)

  $4 < N_{12} < 30$ (SK2)

  $T_\mu - T_\gamma < 75$ns

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





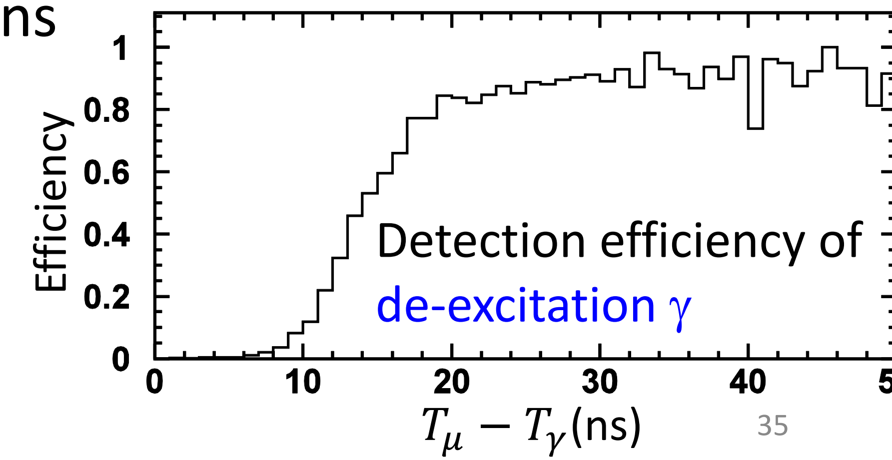
Criteria to search for the de-excitation γ

Maximum # of hit cluster in 12ns after prior to the μ signal (N_{12})

$8 < N_{12} < 60$ (SK1,3,4)

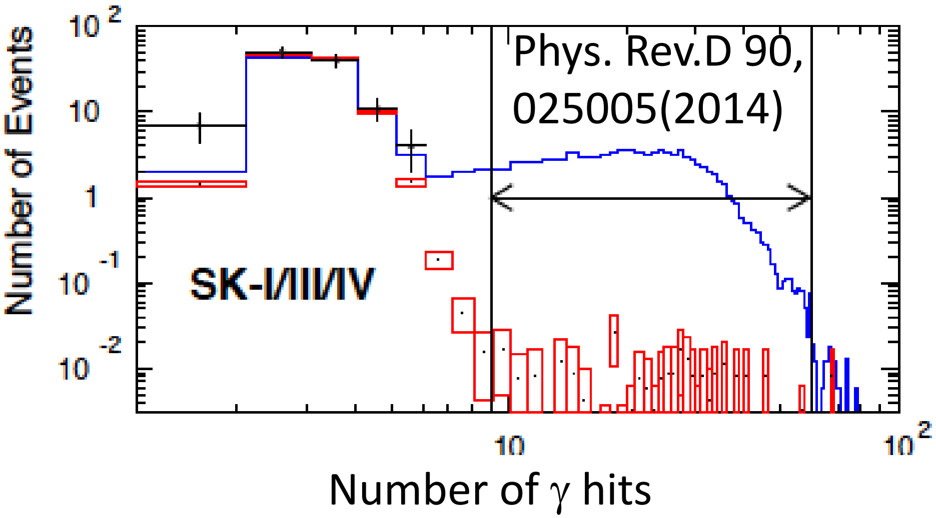
$4 < N_{12} < 30$ (SK2)

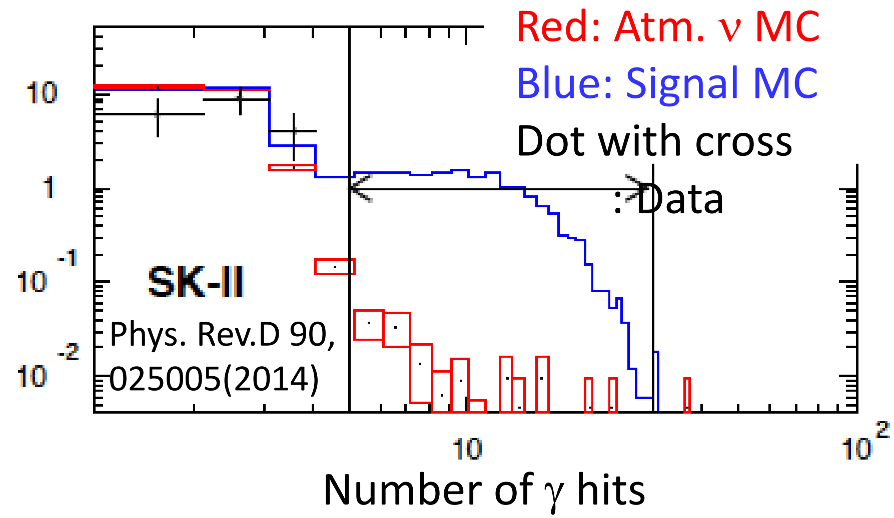
$T_\mu - T_\gamma < 75$ns



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

$K^+ \rightarrow \mu^+ + \bar{\nu}$ with prompt γ tag. *(Fiducial volume : 2m from the wall)*



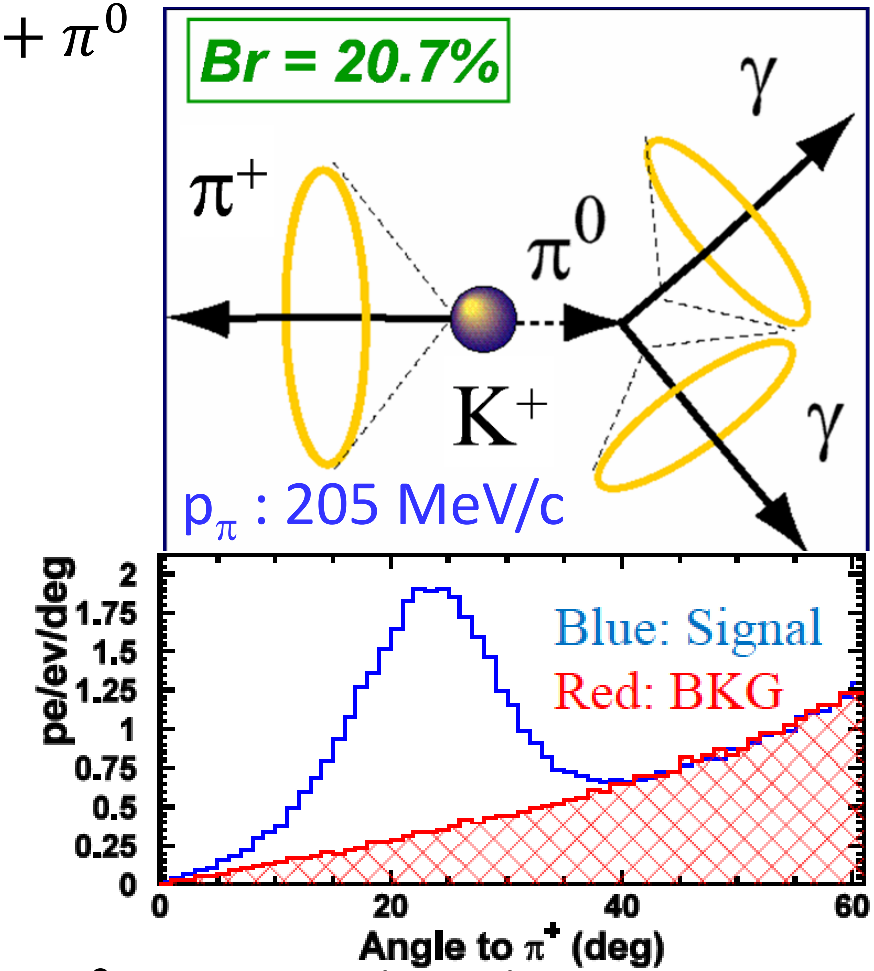


2017 Preliminary	Exposure (kt.yr)	Efficiency (%)	Expected # of backgrounds	Data
SK1	91.7	7.9 ± 0.1	0.08	0
SK2	49.2	6.5 ± 0.1	0.08	0
SK3	31.9	7.5 ± 0.1	0.02	0
SK4	192.2	9.4 ± 0.1	0.12	0
Total	365.0		0.30	0

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

Event selection criteria $K \rightarrow \pi^+ + \pi^0$

- No activity in the outer detector
- Vertex in the fiducial volume
- 1 decay electron
- 1 or 2 e-like rings (from π^0)
- Reconstructed π^0 mass
  85 ~ 185 MeV/c^2
- Reconstructed π^0 momentum
  175 ~ 250 MeV/c
- Visible energy sum in 140~180° from π^0 direction (E_{bk})
  $10 < E_{bk} < 50$ MeV



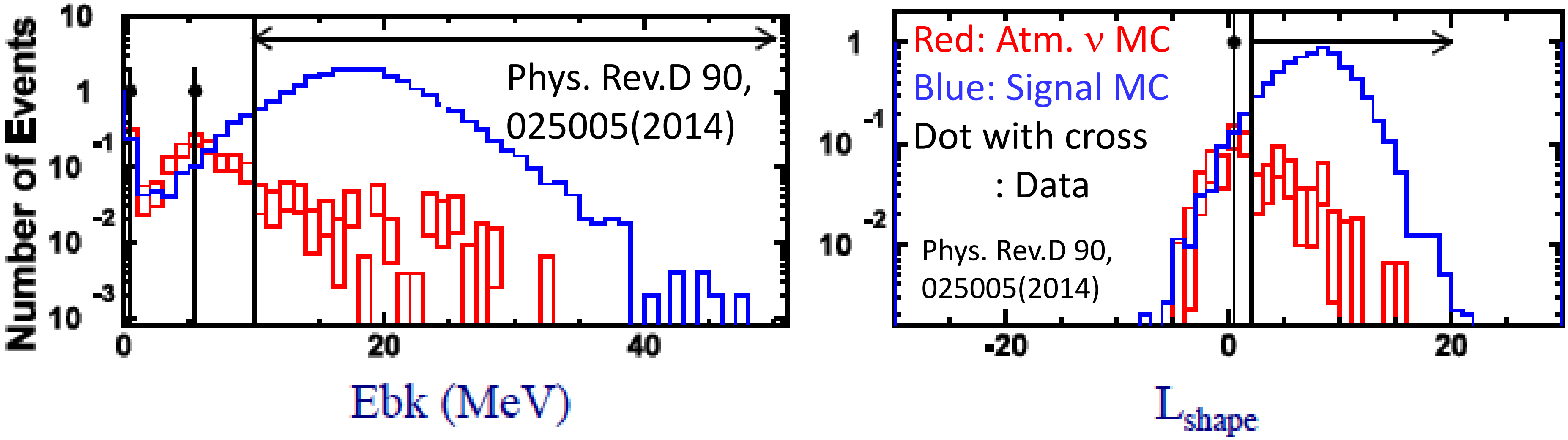
- Visible energy sum in 90~140° from π^0 direction (E_{res})
  E_{res} < 12 MeV (2 rings), 20 MeV (1 ring)
- Charge distribution likelihood cut
- No tagged neutron (only for SK4)

Proton decay search in SK

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

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

(Fiducial volume : 2m from the wall)



2017 Preliminary	Exposure (kt.yr)	Efficiency (%)	Expected # of backgrounds	Data
SK1	91.7	7.9±0.1	0.21	0
SK2	49.2	6.5±0.1	0.19	0
SK3	31.9	8.3±0.1	0.07	0
SK4	192.2	9.4±0.1	0.14	0
Total	365.0		0.61	0

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

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

	Exposure (kt.yr)	Efficiency (%)	Backgrounds	Data
SK1	91.7	7.9±0.1	0.08	0
SK2	49.2	6.5±0.1	0.08	0
SK3	31.9	7.5±0.1	0.02	0
SK4	192.2	9.4±0.1	0.12	0
Total	365.0		0.30	0

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

	Exposure (kt.yr)	Efficiency (%)	Backgrounds	Data
SK1	91.7	7.9±0.1	0.21	0
SK2	49.2	6.5±0.1	0.19	0
SK3	31.9	8.3±0.1	0.07	0
SK4	192.2	9.4±0.1	0.14	0
Total	365.0		0.61	0

Preliminary

Partial lifetime limit (combined) = 8.2×10^{33} year @ 364.96 kt·yr

Preliminary result and the fiducial volume is 2m from the wall.

Summary

Various proton decay modes have been studied in SK.

Fiducial volume has been expanded by 20% for two decay modes.

However, no signature of nucleon decay was observed.

Obtained partial lifetime limits:

$p \rightarrow e^{+} + \pi^{0}$ 2.4x10^{34} year

$p \rightarrow \mu^{+} + \pi^{0}$ 1.6x10^{34} year

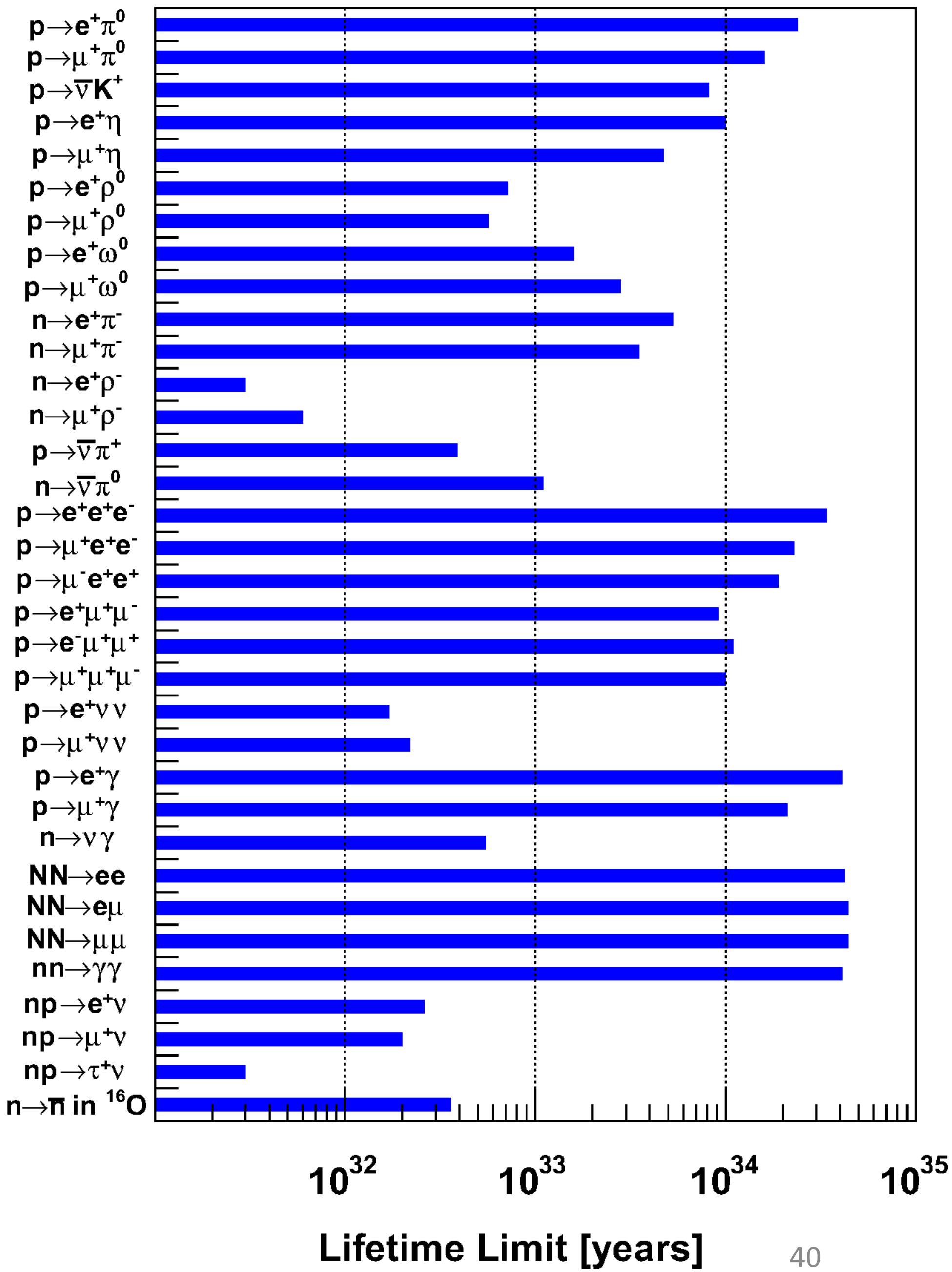
(450 kt·yr)

https://arxiv.org/abs/2010.16098

(Accepted by PRD)

$p \rightarrow \bar{\nu} + K^{+}$ 8.2 x10^{33} year

(365 kt·yr, Preliminary)



Future prospect

We are now analyzing the data to search for $p \rightarrow \overline{\nu} + K^+$ using the expanded fiducial volume.

Now Gd is loaded and SK-Gd has been started.

Neutron detection efficiency will be improved.

Possible to reject backgrounds more efficiently.

Neutron Tagging efficiency	~25% (H capture)	~50% (0.1% $Gd_2(SO_4)_3$)	~90% (0.2% $Gd_2(SO_4)_3$)
ATM ν BG reduction by neutron tagging	~50%	~65%	~80%

Hyper-Kamiokande is expected to start in 2027.

Sensitivity of $p \rightarrow e^+ + \pi^0$ will reach 10^{35} years.