Search for proton decay in Super-Kamiokande

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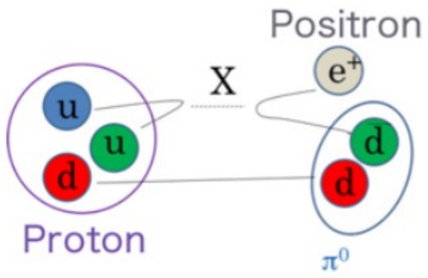
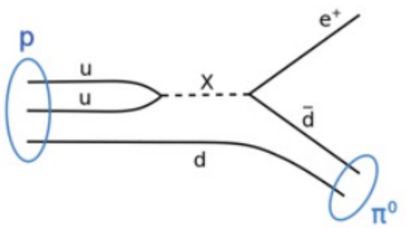
Proton decay

- Proton is a stable particle in the Standard Model
- However, in the Grand Unified Theories, proton can decay to anti-lepton and meson
  - Various GUTs predict the proton lifetime
  - Neutron also can decay!





- If I have 10^{28} protons in me and I can see the protons
- I will be waiting between 1 and 10^{11} years to see one decay

- If I have more protons, waiting time will be decreased
- And we cannot see proton by eye directly, we need a detector

Model class	References	Lifetime [years]
Minimal SU(5)	Georgi & Glashow [21]	$10^{30}-10^{31}$
Minimal SUSY SU(5)	Dimopoulos & Georgi [22]; Sakai & Yanagida [23]	$10^{28}-10^{34}$
SUGRA SU(5)	Nath, Chamseddine & Arnowitt [24]	$10^{32}-10^{34}$
SUSY (MSSM/ESSM) SO(10)/G(224)	Babu, Pati & Wilczek [25]	$2\cdot10^{34}$
SUSY (MSSM/ESSM, $d=5$) SO(10)	Lucas & Raby [26]; Pati [27]	$10^{32}-10^{35}$
SUSY SO(10) + U(1)$_{\mathrm{fl}}$	Shafi & Tavartkiladze [28]	$10^{32}-10^{35}$
SUSY ($d=5$) SU(5) – option I	Hebecker & March-Russell [29]	$10^{34}-10^{35}$
SUSY (MSSM, $d=6$) SU(5) or SO(10)	Pati [27]	$\sim10^{34.9\pm1}$
Minimal non-SUSY SU(5)	Doršner & Fileviez-Pérez [30]	$10^{31}-10^{38}$
Minimal non-SUSY SO(10)		—
SUSY (CMSSM) flipped SU(5)	Ellis, Nanopoulos & Walker [31]	$10^{35}-10^{36}$
GUT-like models from string theory	Klebanov & Witten [32]	$\sim10^{36}$
Split SUSY SU(5)	Arkani-Hamed *et al.* [33]	$10^{35}-10^{37}$
SUSY ($d=5$) SU(5) – option II	Alciati *et al.* [34]	$10^{36}-10^{39}$

https://arxiv.org/abs/2306.02401

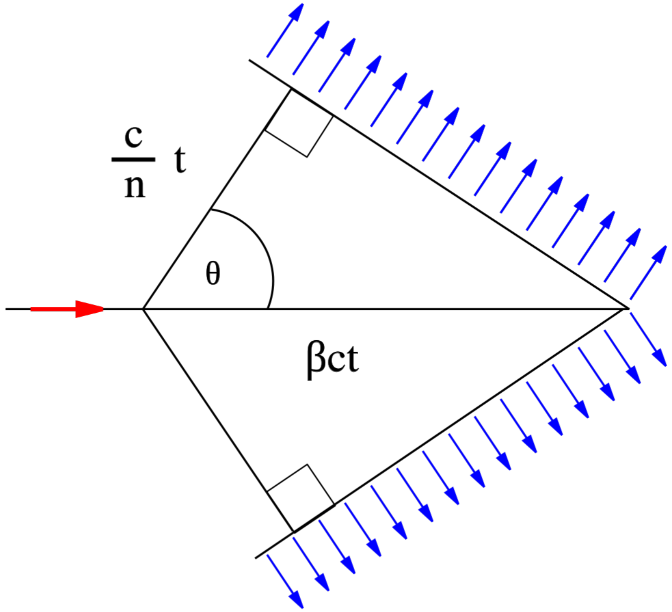
Detector for proton decay search?

- A bunch of protons
  - High exposure (at least, ton-years)
  - "Free" protons(hydrogen), ideally
- Sensitive to leptons, photons
  - Most famous decay mode $p \rightarrow e^+\pi^0$
  - Neutral pion decay into 2 gammas
  - e/mu separation
- Low backgrounds
  - Underground lab
  - Radioactive free

→ One of idea : Water Cherenkov detector

Cherenkov radiation

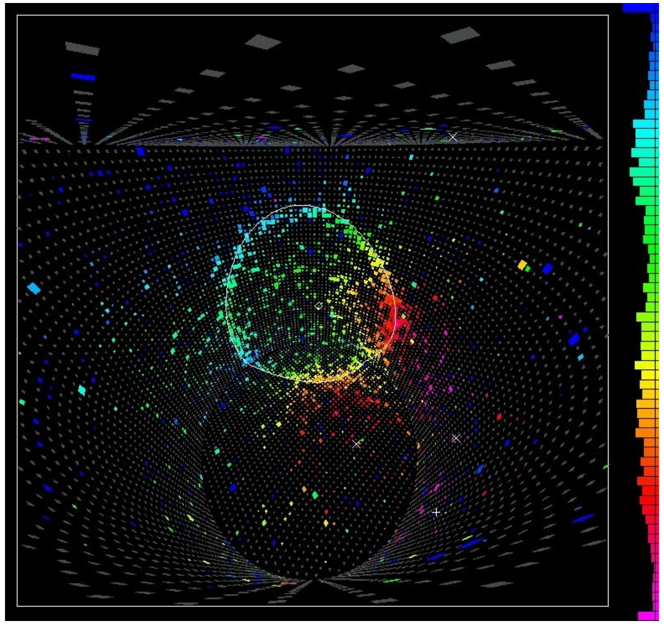
- Charged particle travel(red arrow) faster than light, $\frac{c}{n} < v_p < c$
  - n : refractive index
  - v_p : speed of the particle in a medium
  - c : speed of light in vacuum



- Charged particle emitted light wave (blue arrow)
  - $speed\ of\ light\ wave = c/n$
  - $speed\ of\ particle = \beta c$, where $\beta = v_p/c$
- Emission angle (Cherenkov opening angle)

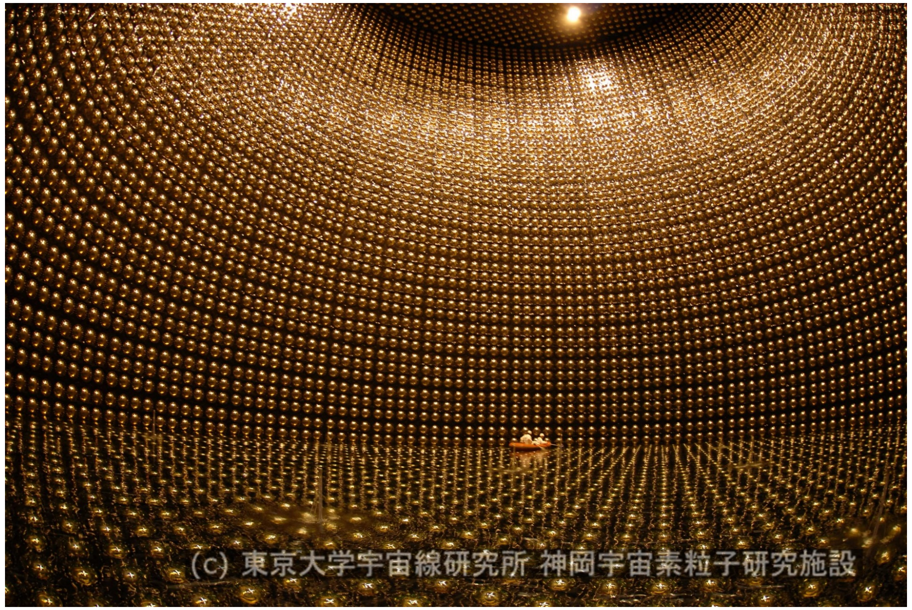
$$cos\theta = \frac{1}{n\beta}$$

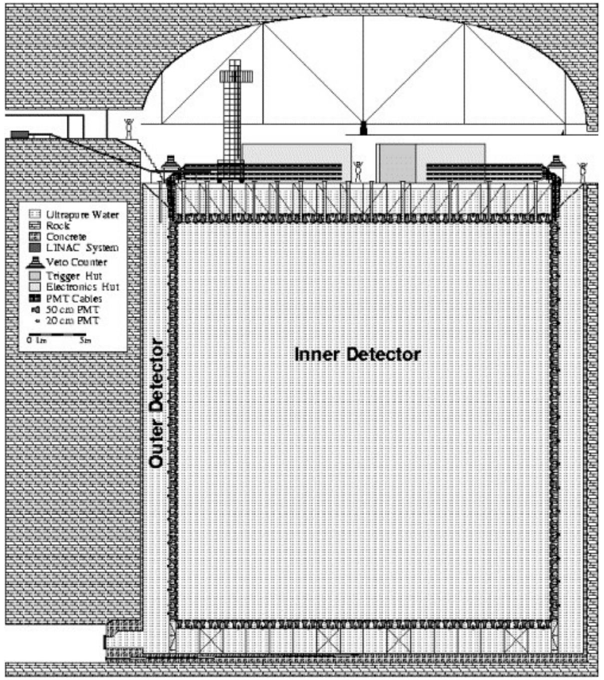
- Refractive index of water = 1.33
  - Charged particles could be faster than light in the water
  - We can observe Cherenkov ring image



Super-Kamiokande

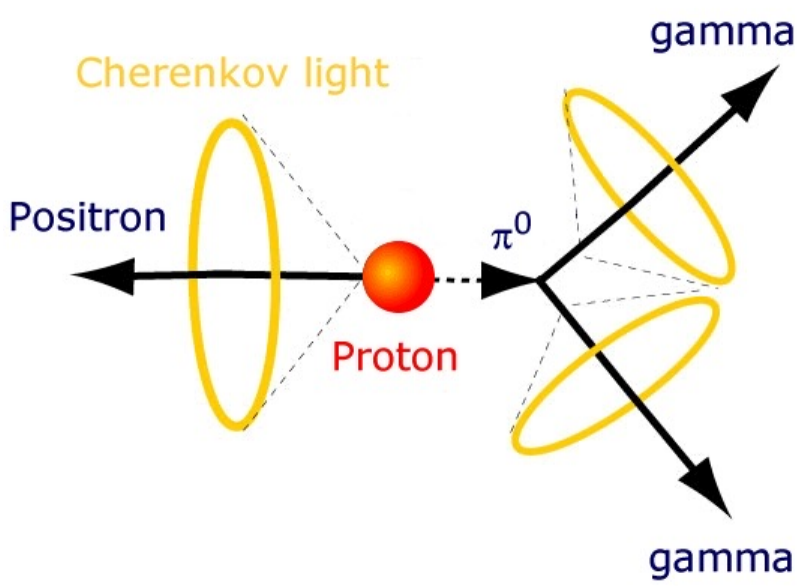
- World largest water Cherenkov detector
  - Located 1,000 m underground in the Gifu prefecture, Japan
- Upright cylindrical shape
  - Diameter 39.4 m
  - Height 41.4 m
  - Inner detector : ~11k PMTs, 20″
    (Photo coverage 40%)
  - Outer detector : ~2k PMTs, 8″
  - Filled with 50 kton of pure water
    - from 2021, filled Gd-loaded water

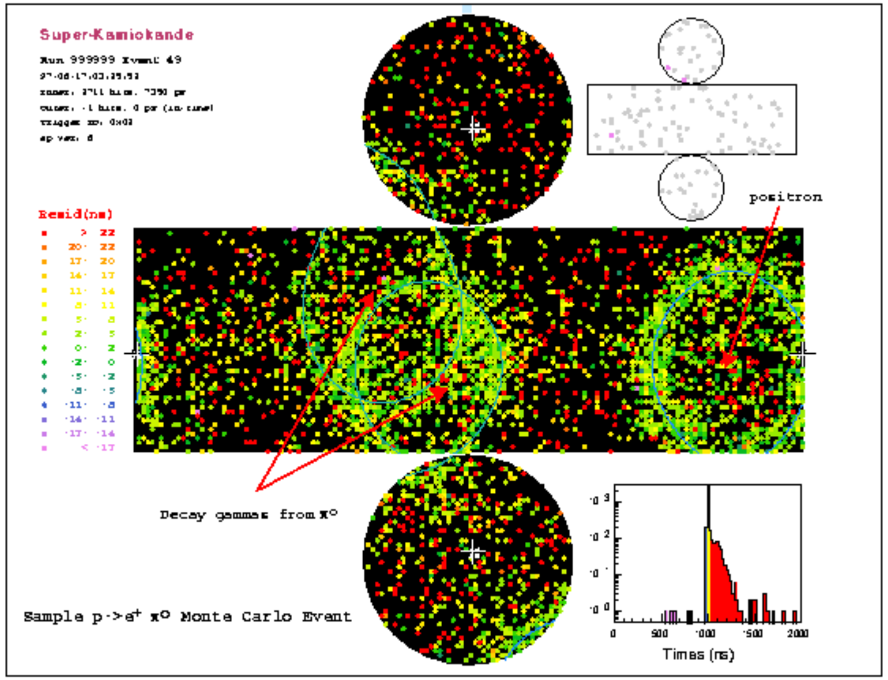




Super-Kamiokande

- Fiducial mass of Super-Kamiokande is 22.5 kton
  - A water molecule has 10 protons
    - 2 "free" protons (hydrogen) and 8 "bound" protons (oxygen)
  - corresponding to 7.5×10^{33} protons
  - Particles came from proton decay generate Cherenkov rings
  - For example, we can detect 3 rings for $p \rightarrow e^{+}\pi^{0}$ decay mode





Main background of proton decay search

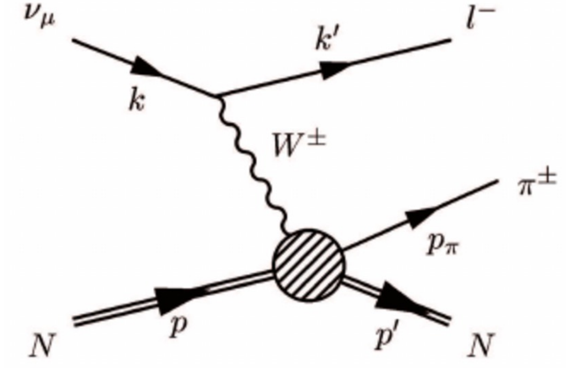
- Atmospheric neutrino
  - High energy particles (protons & helium nuclei) from space, “cosmic ray”

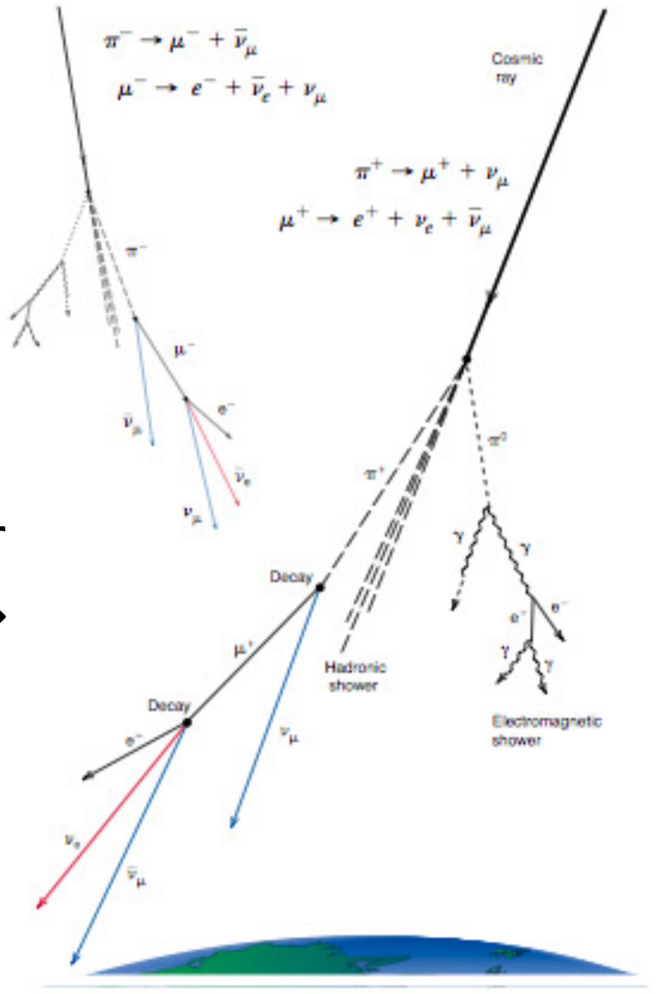
  → it collide with atoms in atmosphere and produce “shower”

  → “shower” include pion and muon → emit neutrino

  → called as “atmospheric neutrino”
  - Sub-GeV ~ multi GeV(~100GeV)

- Atm-v can mimic proton decay event in the SK detector
  - For example, CC 1pion interaction is similar as $p \rightarrow e^+\pi^0$ or $p \rightarrow \mu^+\pi^0$



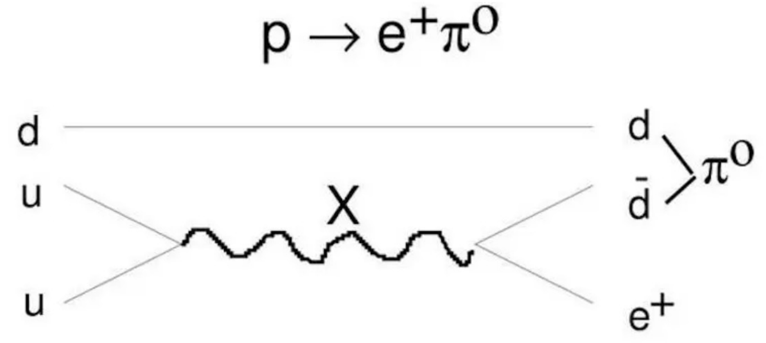


Flagship proton decay modes

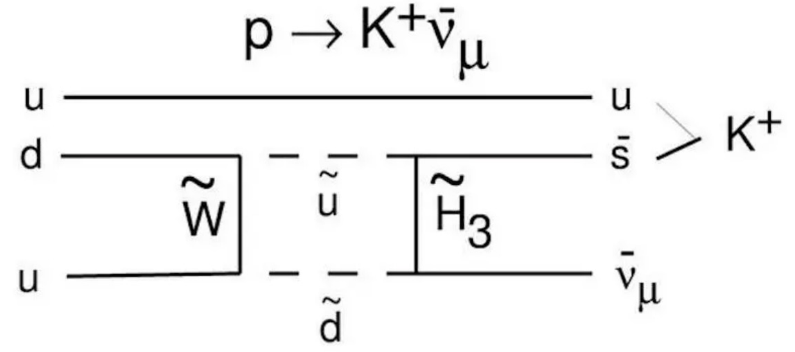
- GUT : $p \to e^+\pi^0 / \mathrm{p} \to \mu^+\pi^0$
  - anti-lepton + neutral pion mode
  - Lifetime limit (90% C.L.)

    $p \to e^+\pi^0$: $\sim 2.4\times10^{34}$ *years*

    $p \to \mu^+\pi^0$: $\sim 1.6\times10^{34}$ *years*



- SUSY GUT : $p \to \bar{\nu}K^+$
  - neutrino cannot detect
  - $\mathrm{K}^+ \to \mu^+\nu_\mu$ or $\mathrm{K}^+ \to \pi^+\pi^0$
  - Lifetime limit (90% C.L.) : $\sim 8.2\times10^{33}$ *years*



Results of proton decay searches in SK

Decay mode	SK detector	Exposure [kt-years]	Lifetime limit [years]
$p \to e^+\pi^0$	I–IV	450	2.4×10^{34}
$p \to \mu^+\pi^0$	I–IV	450	1.6×10^{34}
$p \to \nu\pi^+$	I–III	173	3.9×10^{32}
$n \to \nu\pi^0$	I–III	173	1.1×10^{33}
$p \to e^+\eta$	I–IV	373	1.4×10^{34}
$p \to \mu^+\eta$	I–IV	373	7.3×10^{33}
$p \to e^+\rho^0$	I–IV	316	7.2×10^{32}
$p \to \mu^+\rho^0$	I–IV	316	5.7×10^{32}
$p \to e^+\omega$	I–IV	316	1.6×10^{33}
$p \to \mu^+\omega$	I–IV	316	2.8×10^{33}
$n \to e^+\pi^-$	I–IV	316	5.3×10^{33}
$n \to \mu^+\pi^-$	I–IV	316	3.5×10^{33}
$n \to e^+\rho^-$	I–IV	316	3.0×10^{31}
$n \to \mu^+\rho^-$	I–IV	316	6.0×10^{31}
$p \to e^+\pi^0\pi^0$	I–V	401	7.2×10^{33}
$p \to \mu^+\pi^0\pi^0$	I–V	401	4.5×10^{33}
$p \to e^+e^+e^-$	I–IV	373	3.4×10^{34}
$p \to \mu^+e^+e^-$	I–IV	373	2.3×10^{34}
$p \to \mu^-e^+e^+$	I–IV	373	1.9×10^{34}
$p \to e^+\mu^+\mu^-$	I–IV	373	9.2×10^{33}
$p \to e^-\mu^+\mu^+$	I–IV	373	1.1×10^{34}
$p \to \mu^+\mu^+\mu^-$	I–IV	373	1.0×10^{34}
$p \to e^+\nu\nu$	I–IV	273	1.7×10^{32}
$p \to \mu^+\nu\nu$	I–IV	273	2.2×10^{32}
$p \to e^+X$	I–IV	273	7.9×10^{32}
$p \to \mu^+X$	I–IV	273	4.1×10^{32}
$n \to \nu\gamma$	I–IV	273	5.5×10^{32}
$p \to \nu K^+$	I–IV	365	8.2×10^{33}
$p \to \mu^+K^0$	I–IV	373	3.6×10^{33}
$p \to e^+K^0$	I	92	1.3×10^{33}
$p \to \mu^+K^0$	I	92	1.0×10^{33}

*This is not a full list of reported nucleon decay results by SK

SK preliminary

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

Analyzer : Seo Ji-Woong & Eunhyang Kwon (SKKU)

Motivation

- Discovery of the proton decay would provide strong evidence of GUTs

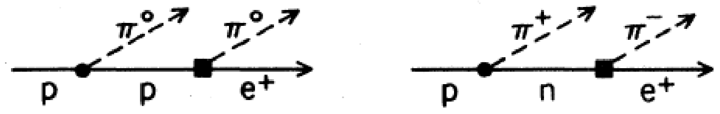


FIG. 1. Born or pole diagrams contributing to $p \to \pi\pi e^+$.

- One of the three-body decay modes of proton, charged lepton and two pion decay mode can be considered in a model-independent manner [1]

- IMB-3 reported the lifetime of these modes
  - **Not studied in SK yet**

[2]

$p \to e^+\pi^0\pi^0$ 1.5×10^{32} $years\ by\ IMB3$
$p \to \mu^+\pi^0\pi^0$ 1.0×10^{32} $years\ by\ IMB3$

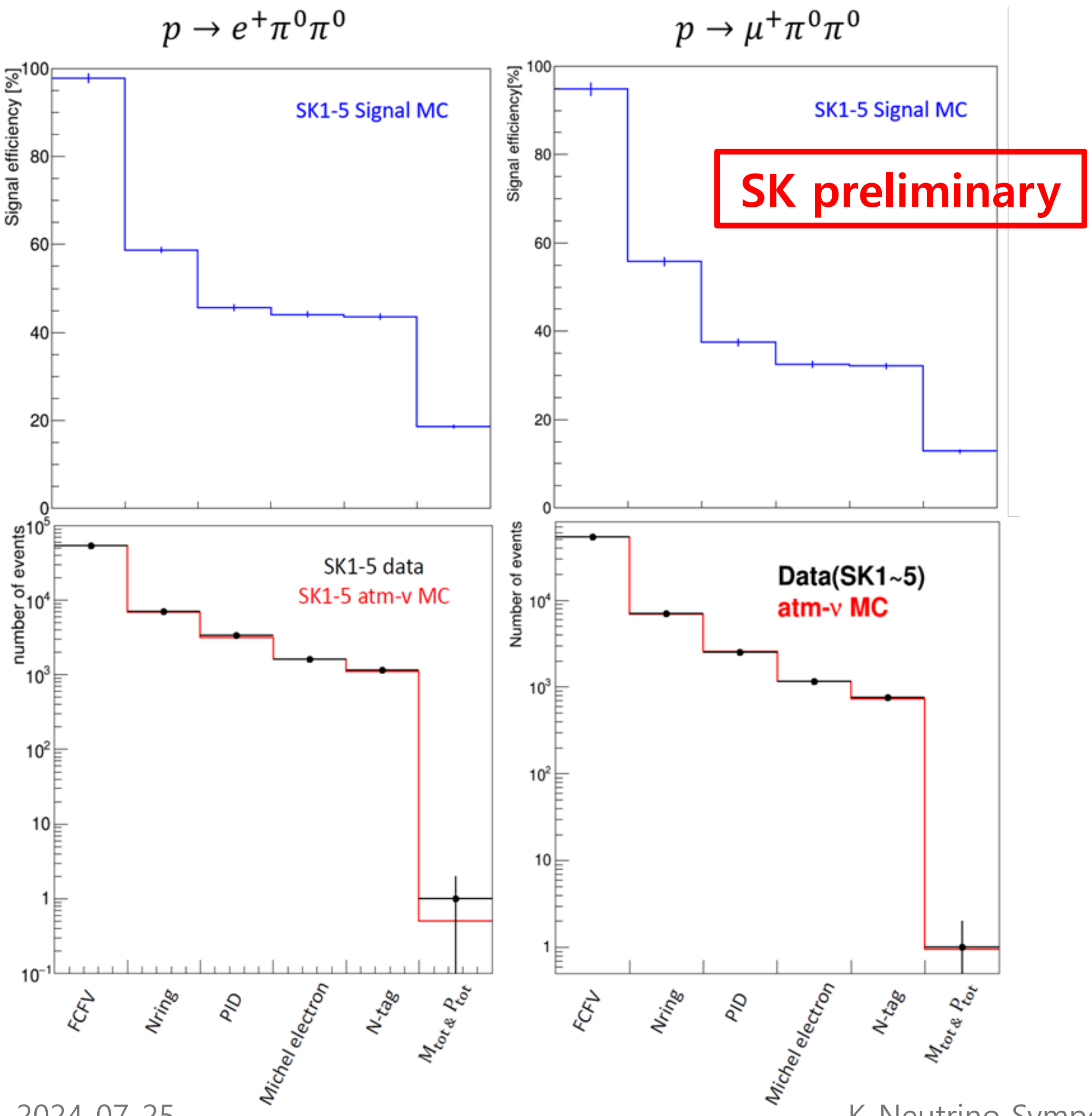
- Our analysis is $p \to e^+\pi^0\pi^0$ and $p \to \mu^+\pi^0\pi^0$
  - π^0 decay 2γ (BR = 0.988) → maximum 5 Cherenkov rings
  - Referred $p \to e^+\pi^0 (p \to \mu^+\pi^0)$ analysis

[1] ***Reference :*** Wise, Mark B., Richard Blankenbecler, and L. F. Abbott. "Three-body decays of the proton" *Physical Review D* 23.7 (1981)
[2] ***Reference :*** C. McGrew *et al.*. "Search for nucleon decay using the IMB-3 detector" *Physical Review D* 59, 052004 (1999)

Event selection

Event Selection	$p \rightarrow e^+\pi^0\pi^0$	$p \rightarrow \mu^+\pi^0\pi^0$
FCFV	Fully contained Conventional Fiducial volume (dwall > 200 cm)	
Number of rings	3,4 or 5 Cherenkov rings	
PID	All e-like ring	1 μ-like ring
Michel electron	No Michel electron	1 Michel electron
Neutron tag	No tagged neutron (for SK4 and SK5)	
Total invariant mass	$800 \leq \mathrm{M_{tot}} \leq 1050\ \mathrm{MeV/c^2}$	
Total momentum	$\mathrm{P_{tot}} \leq 200\ \mathrm{MeV/c}$	

Reduction of signal efficiency and background rate



- The event reductions along the event selections
  - Upper : signal efficiency for signal MC
  - Lower : data and atm-ν MC background
- "Nring" and "M_{tot}&P_{tot}" cuts are dominant reduction
- After applied all selections
  - signal efficiency is ~20% for $p \to e^+\pi^0\pi^0$ and ~15% for $p \to \mu^+\pi^0\pi^0$
  - Expected background event is smaller than 1
  - One data candidate is observed, respectively

Total invariant mass distribution

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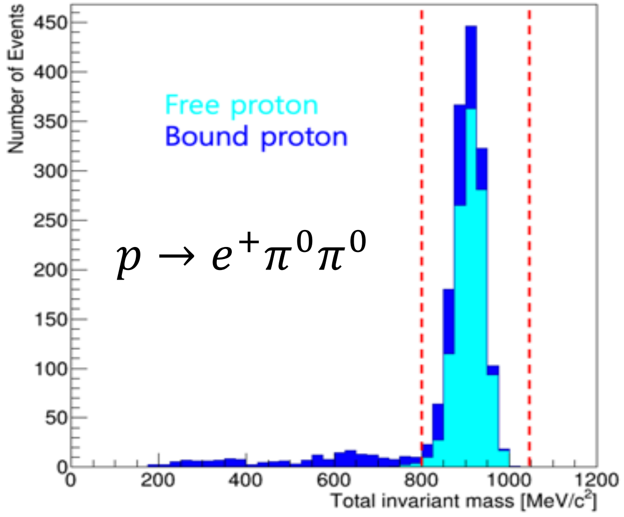
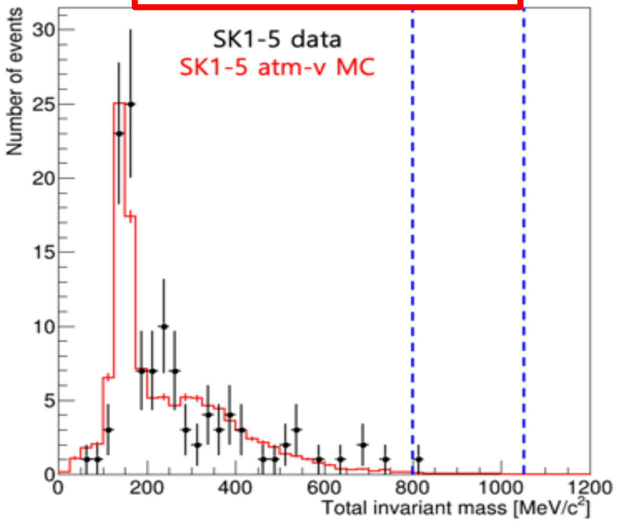
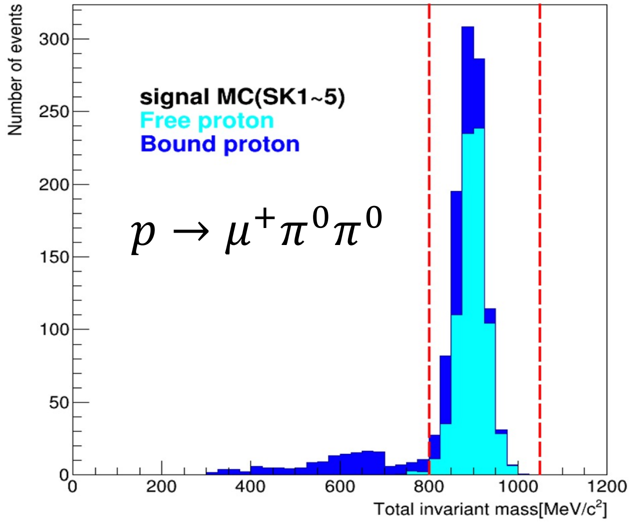
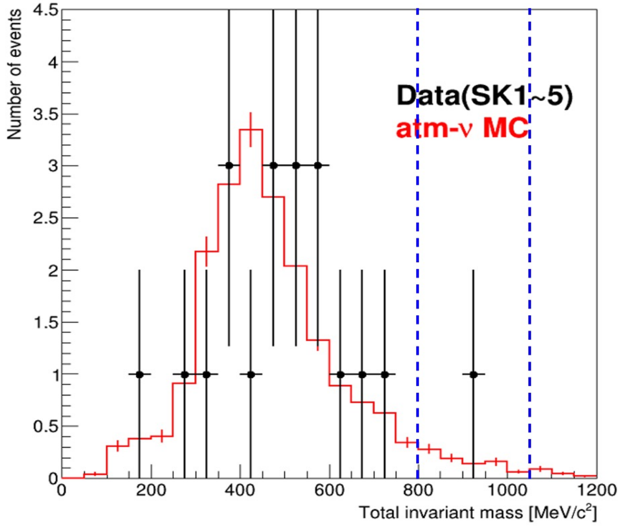




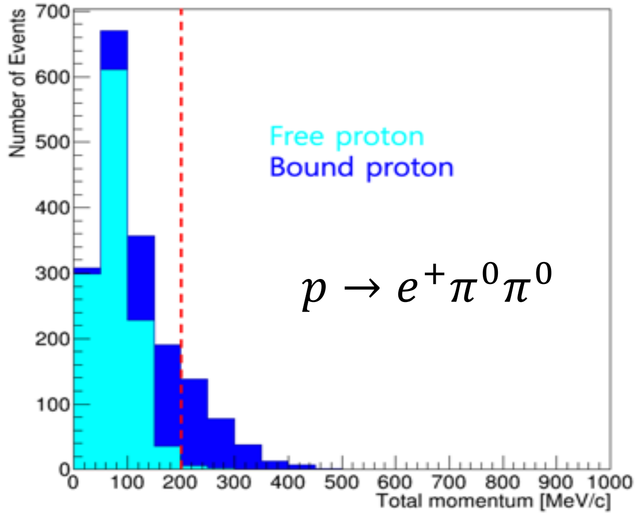


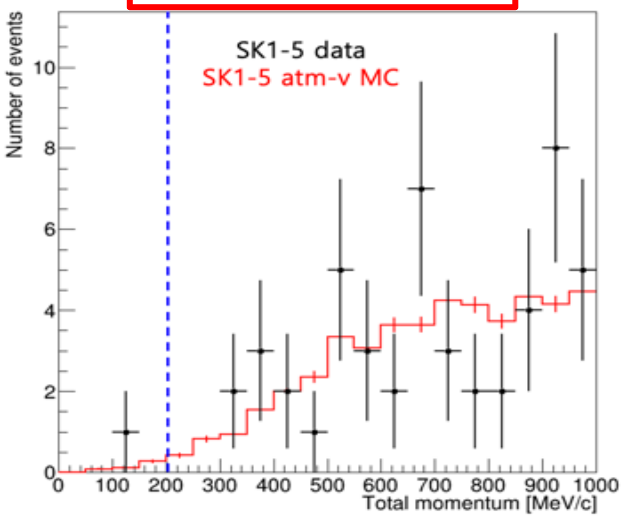


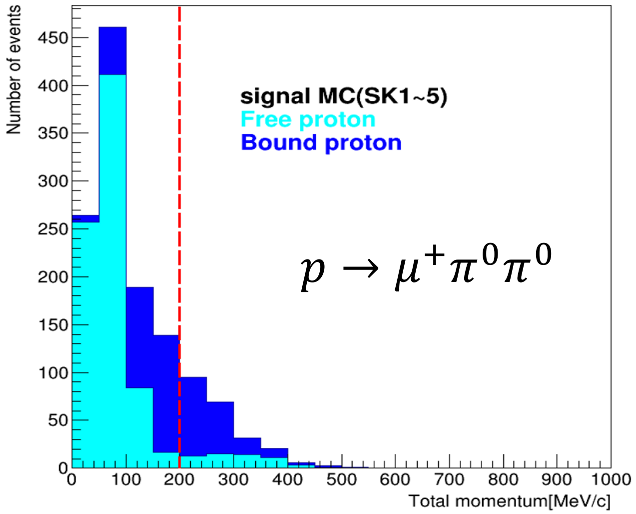
- The reconstructed total invariant mass distribution after applied all selections except itself
  - Left : signal MC
  - Right : data and atm-ν MC
- In the signal MC plots, proton mass peak is observed
  - Protons are well reconstructed
- In the right plot, atm-ν MC and data agree well
- One data candidate is shown, respectively

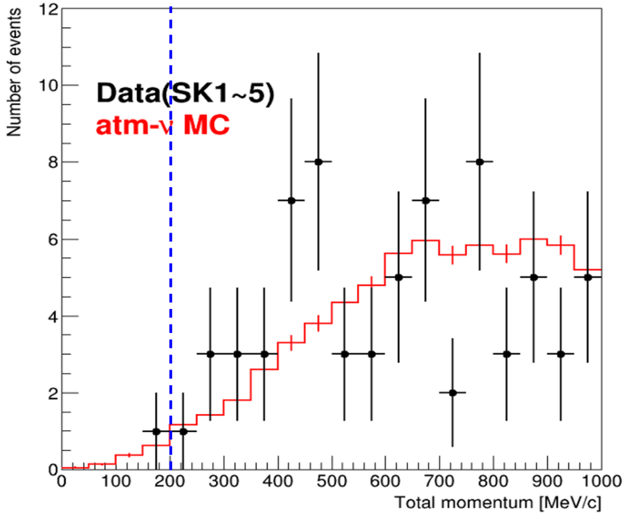
Total momentum distribution

SK preliminary









- The reconstructed momentum distribution after applied all selections except itself
  - Left : signal MC
  - Right : data and atm-ν MC
- In the signal MC plots, reconstructed total momentum of free proton represents near 0 MeV/c
  - Free proton of $p \to \mu^+\pi^0\pi^0$ has tail
    → mis-identified muons
- In the right plots, atm-ν MC and data agree well
- One data candidate is shown, respectively

Mass vs. momentum 2D distribution

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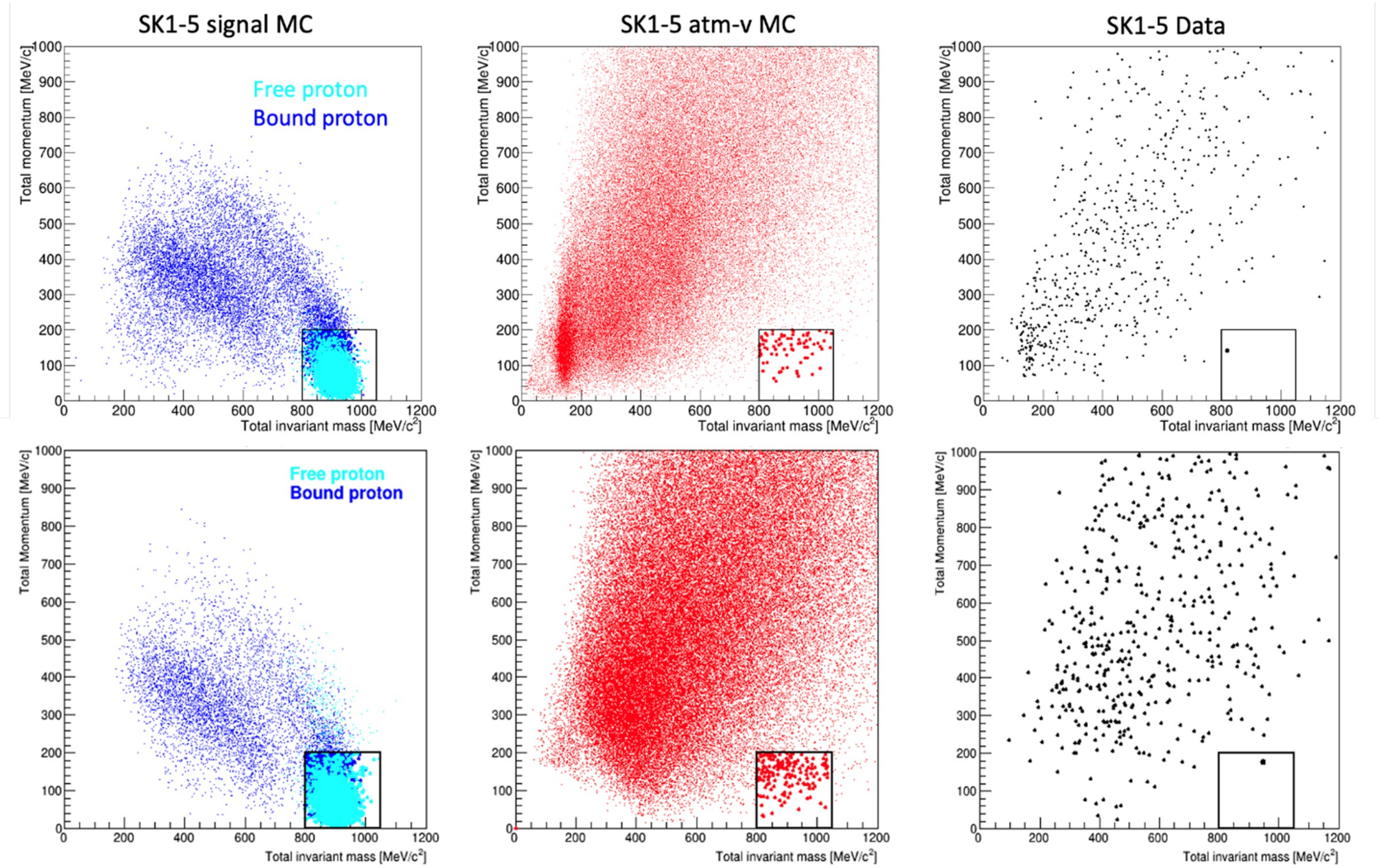
$p \rightarrow e^+\pi^0\pi^0$

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



The black box in each panel represents the signal region

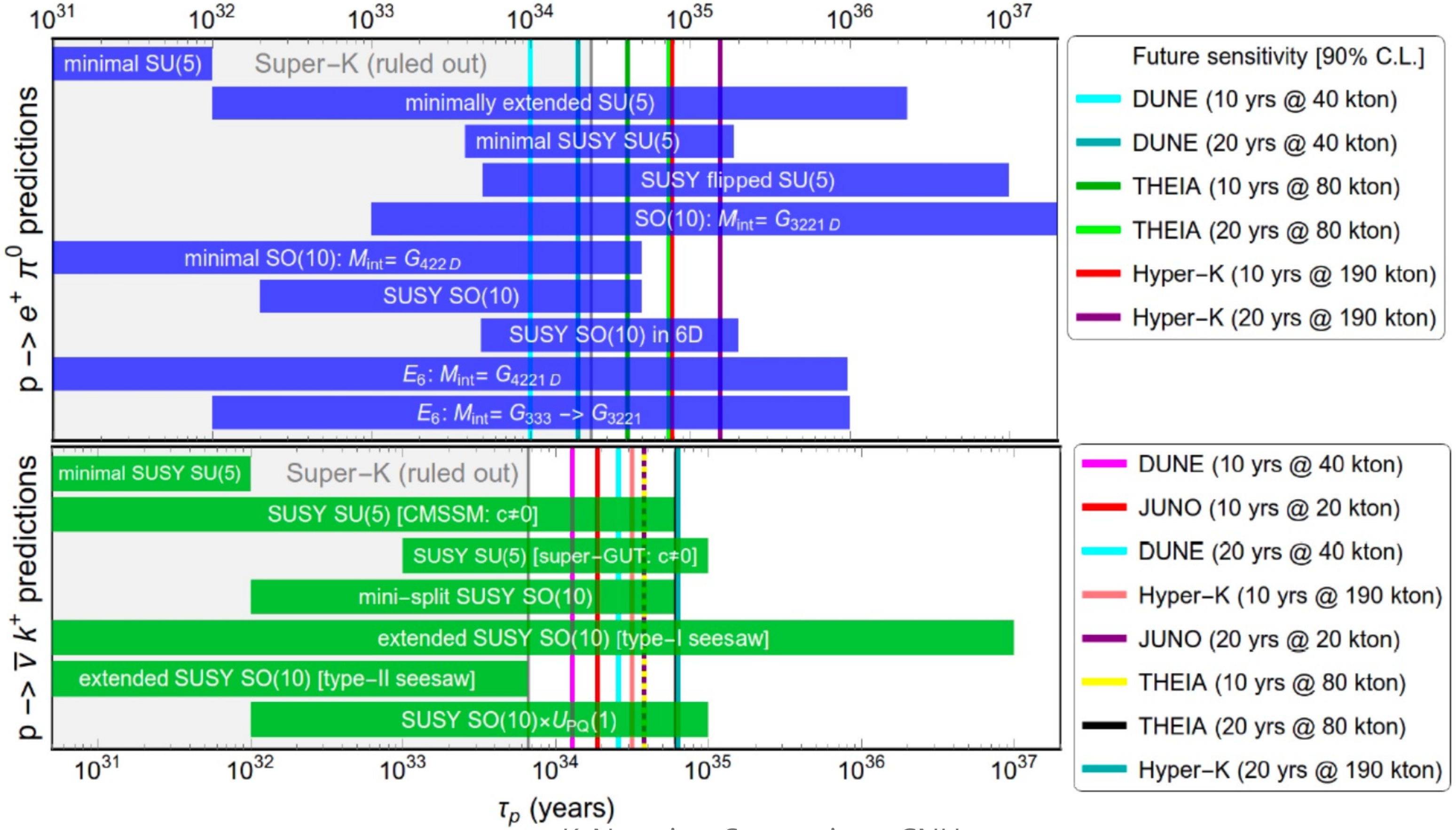
Lifetime limit

	$p \to e^{+}\pi^{0}\pi^{0}$	$p \to \mu^{+}\pi^{0}\pi^{0}$
Livetime [days]	6511.3	
# of candidates	1	1
Signal eff. [%]	18.5	12.8
Signal syst. err [%]	10.3	12.4
Bkg. rate [exposure]	0.5	0.9
Bkg. syst. Err [%]	45.2	28.1
Lifetime limit	7.2×10^{33} years (90% C.L.)	4.5×10^{33} years (90% C.L.)

- Observed event of both modes is consistent with the atm-v background MC
- No significant excess was observed in each decay mode, lower limit on the proton lifetime of each mode was calculated using Bayesian method
- These limits are ~50 times larger for both modes in comparison to the previous experiment (IMB-3)

Summary

- GUTs predict proton decay, and its lifetime is between 10^{28} and 10^{39} years
- Super-Kamiokande have been searched various proton decays
  - Lower lifetime limit of proton $\sim 10^{34}$ years
- Expected sensitivity of the future experiments



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Event display of data candidate

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