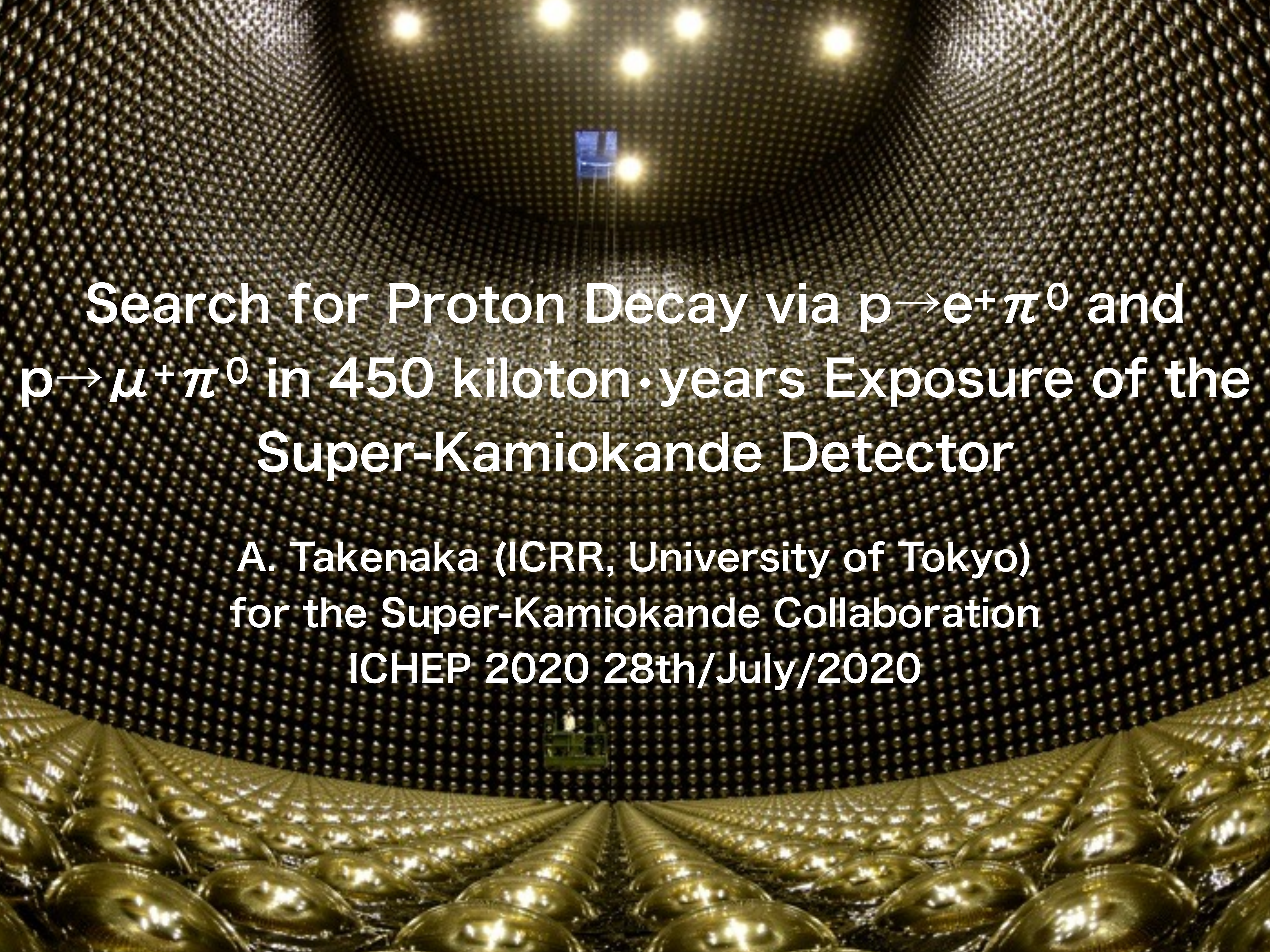
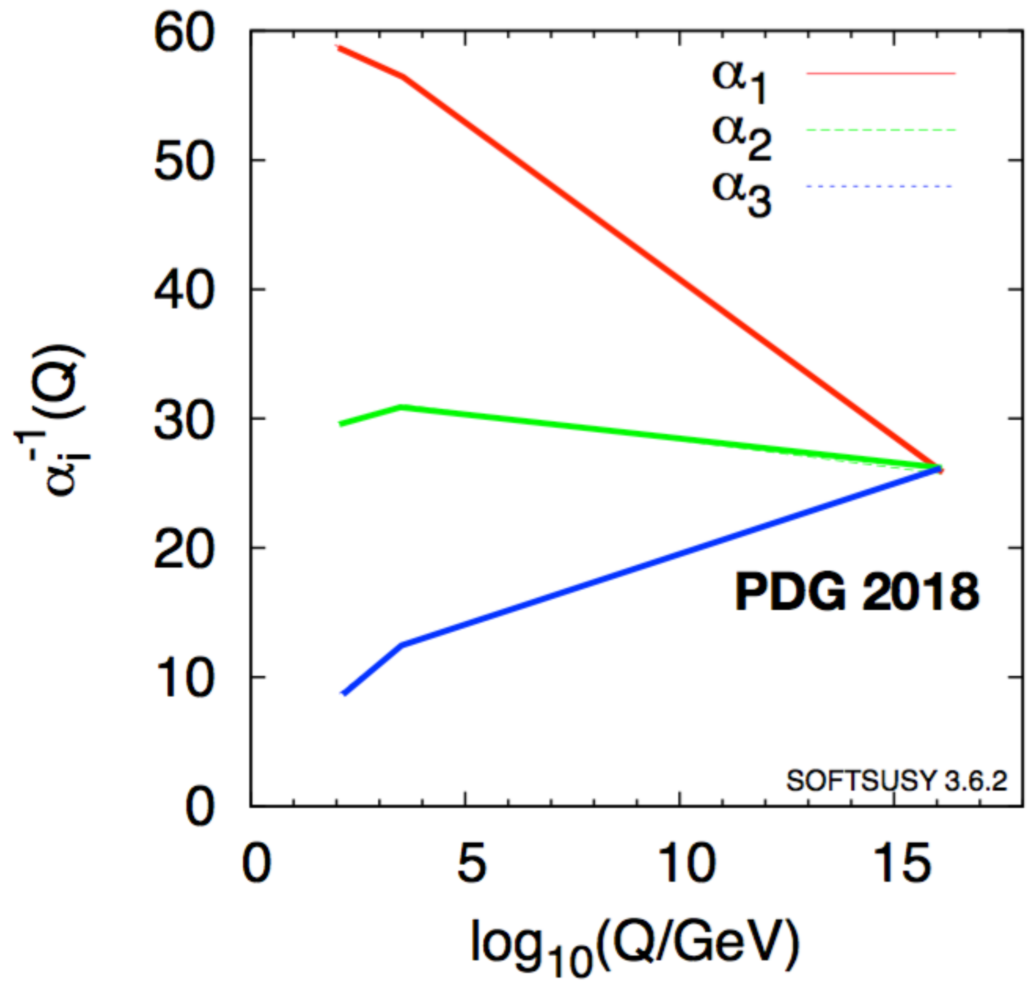


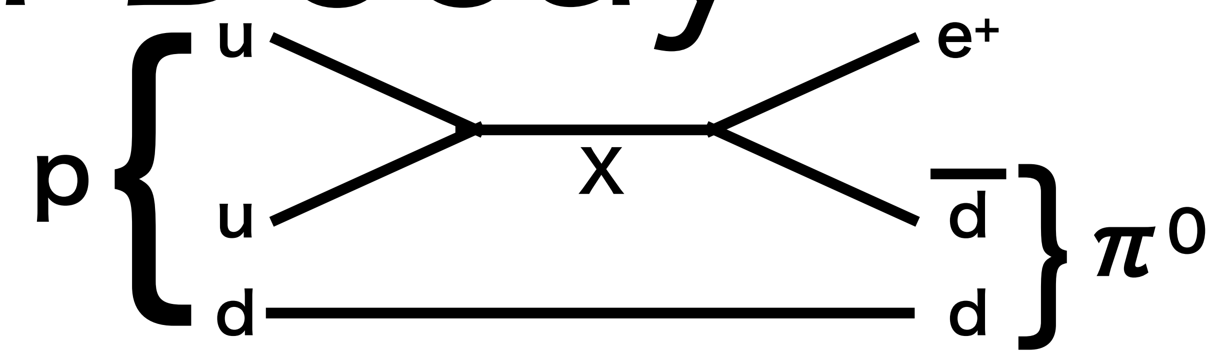
Search for Proton Decay via $p \rightarrow e^{+}\pi^{0}$ and $p \rightarrow \mu^{+}\pi^{0}$ in 450 kiloton・years Exposure of the Super-Kamiokande Detector

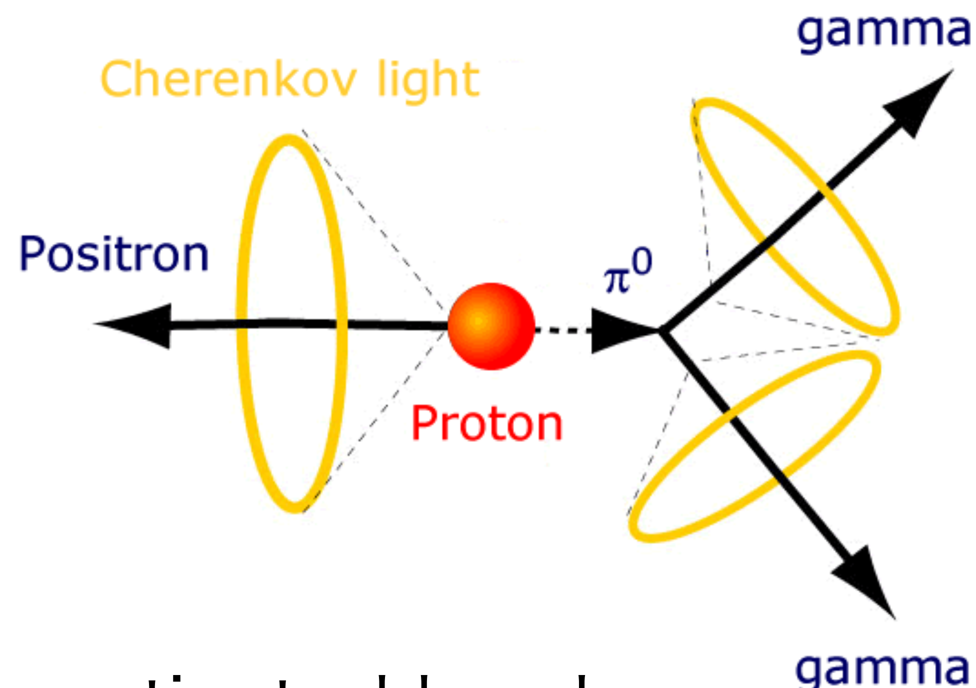
A. Takenaka (ICRR, University of Tokyo)
for the Super-Kamiokande Collaboration

ICHEP 2020 28th/July/2020

Proton Decay







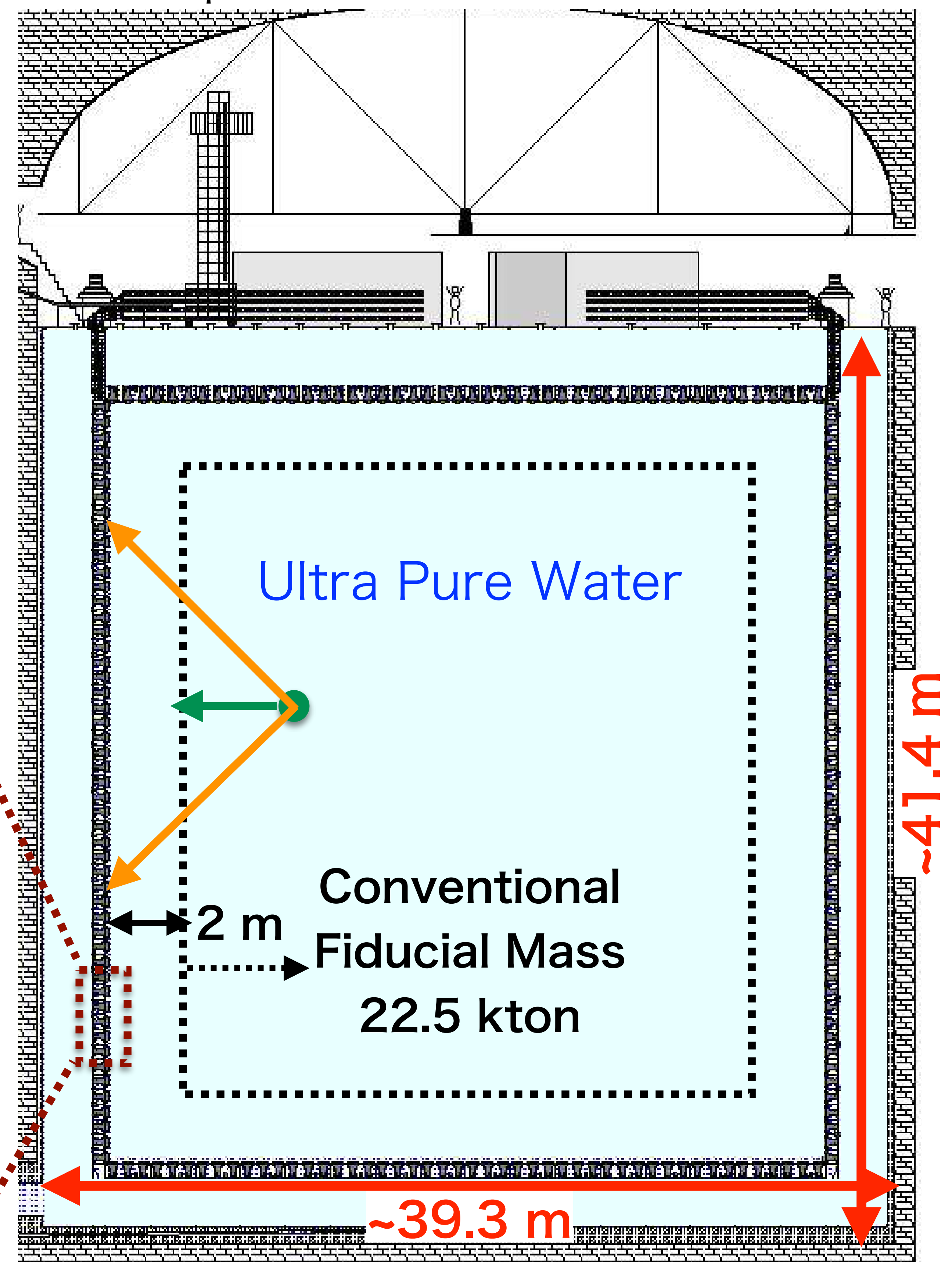
- Grand unified theory (**GUT**) is motivated by charge quantization and coupling const. unification @$10^{15\sim16}$ GeV.
- **Proton decay**, direct transition between quarks and leptons, is predicted in GUT and **gives a strong evidence**.
- Typically predicted proton lifetime is ~$10^{34\sim35}$ years. So far, no experimental evidences…
- **Super-K** is a **world leading** experiment on this search.

Previous limits: $\tau/B_{p\rightarrow e+\pi0} > 1.6\times10^{34}$ years, $\tau/B_{p\rightarrow \mu+\pi0} > 7.7\times10^{33}$ years (90% C.L.) PRD 95, 012004 (2017)

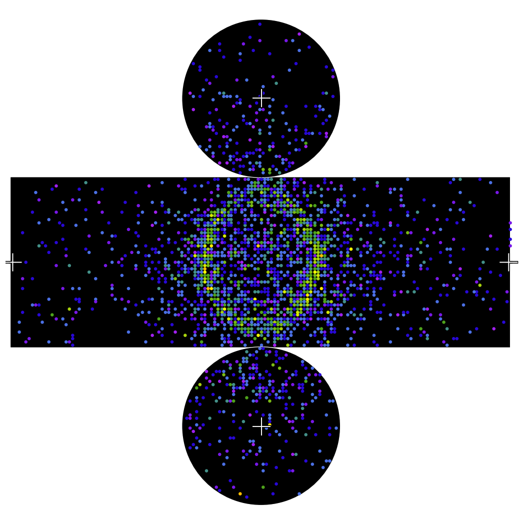
Super-Kamiokande

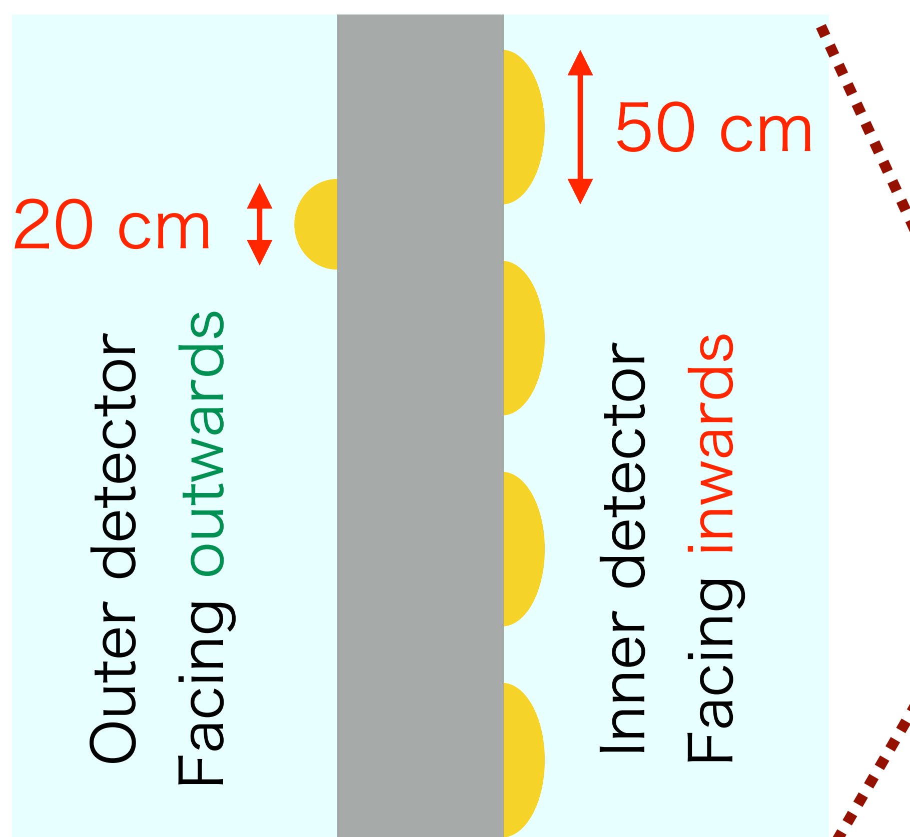
- **The world largest underground water Cherenkov detector.** (upright cylinder)
- ~1,000 m underground (2,700 m.w.e.) @Mt. Ikenoyama in Japan.
- Detects water Cherenkov light from charged particles and reconstructs events with PMT charge & timing.
- Inner detector: 50 cm Φ PMT × 11129
- Outer detector: 20 cm Φ PMT × 1885
  - Mounted on detector wall.

Super-Kamiokande sideview



Cherenkov Ring Image (MC)





Enlarging Fiducial Mass

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

  → **Enlarging the fiducial mass.**

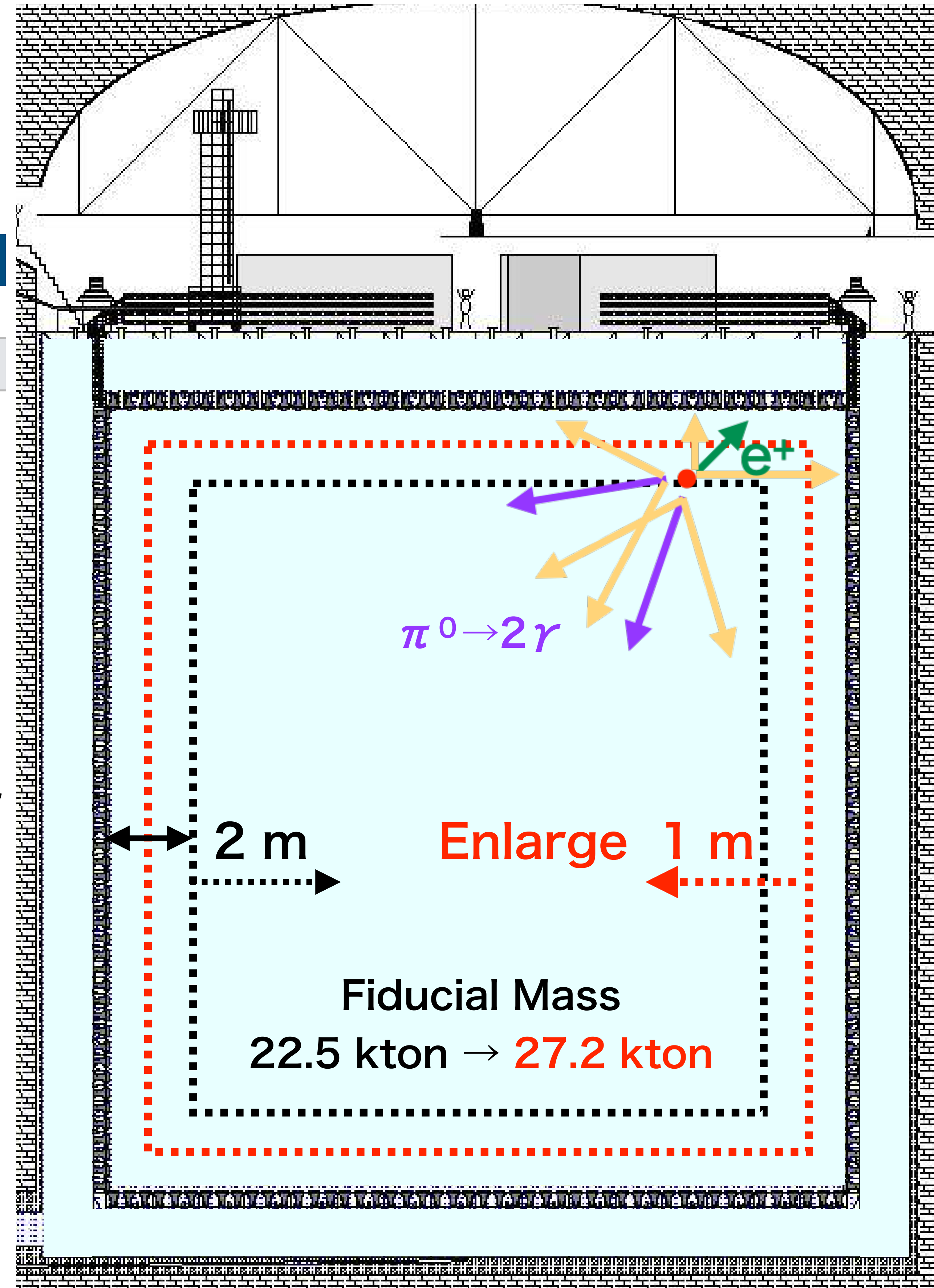
	Conventional	Enlarged
Fiducial Mass	22.5 kton	27.2 kton
Distance to wall	2 m	1 m
Exposure (1996~2018)	372 kton*years	450 kton*years

Remarkable merits

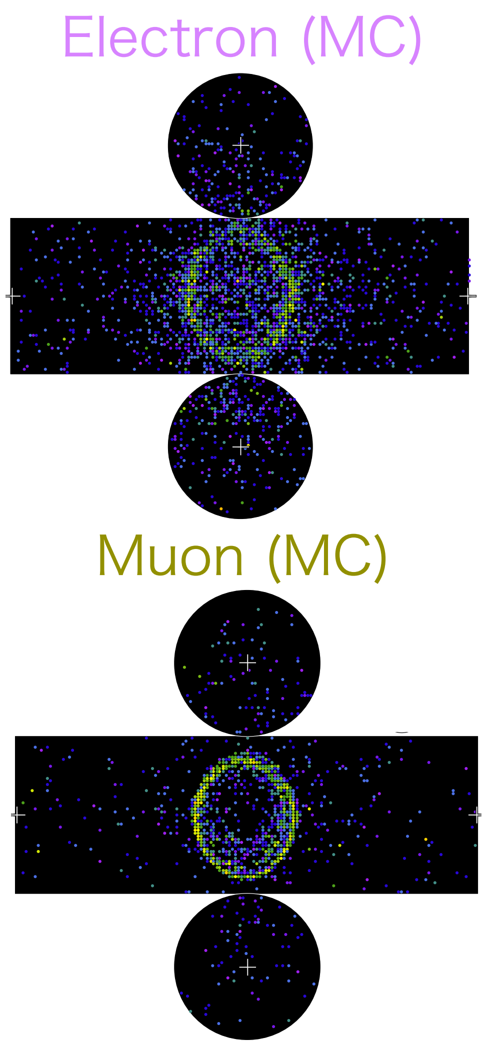
- **Enables the use of past data** that has never been analyzed.
- Improves **p-decay search sensitivity for every mode.**

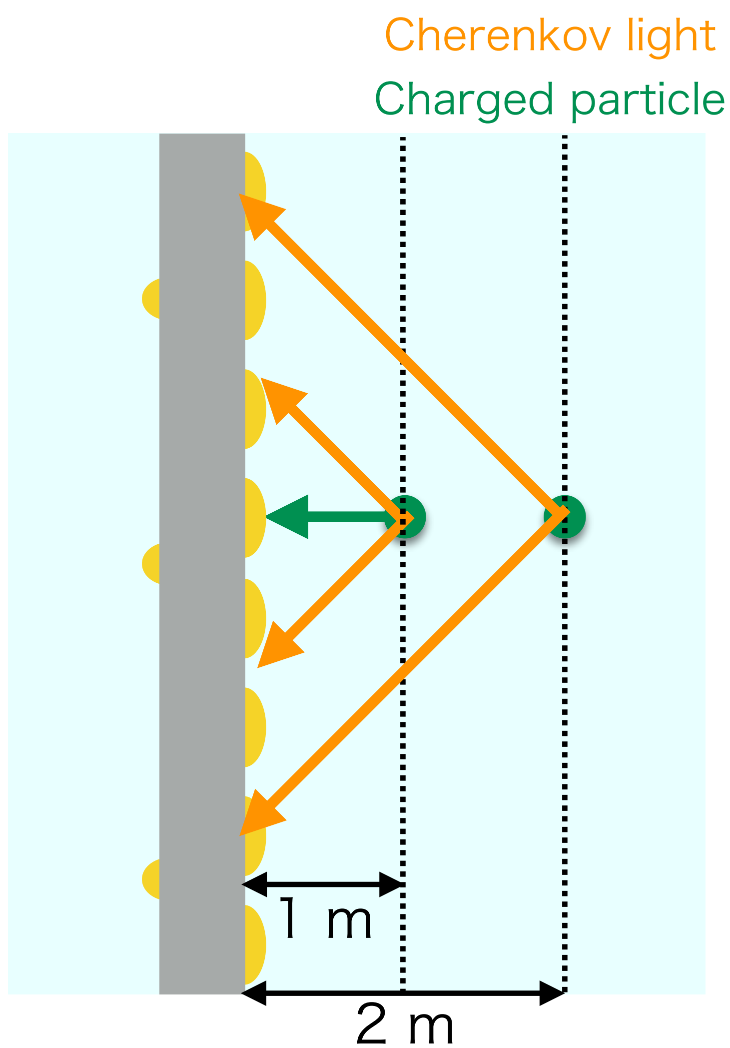
Considerations to achieve it

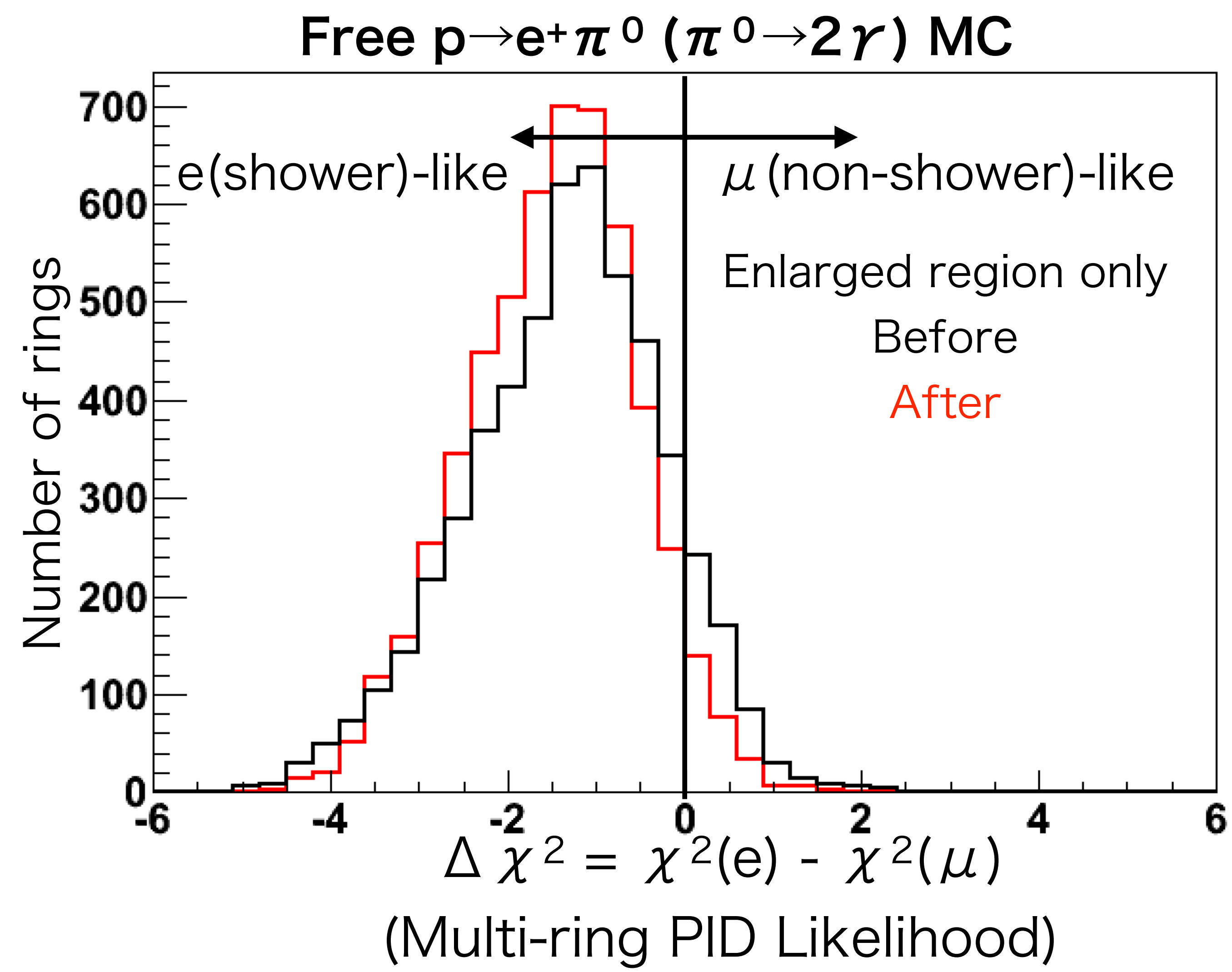
1. **Reconstruction performance**.
2. **External background** contamination.
3. **Data and MC agreement.**



1. Reconstruction Performance - PID Improvement







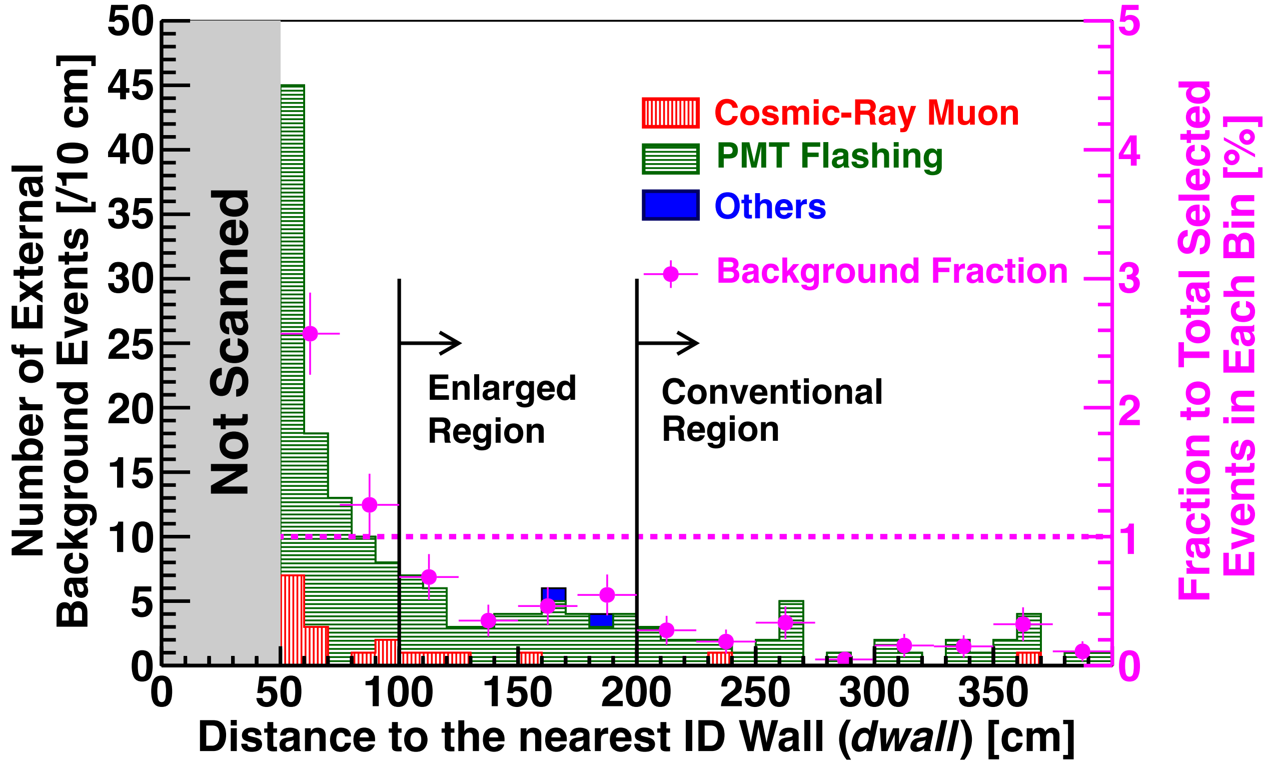
- Main issue in enlarged region: Worse **particle identification performance** due to lower number of PMT hits (unavoidable).

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

- 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

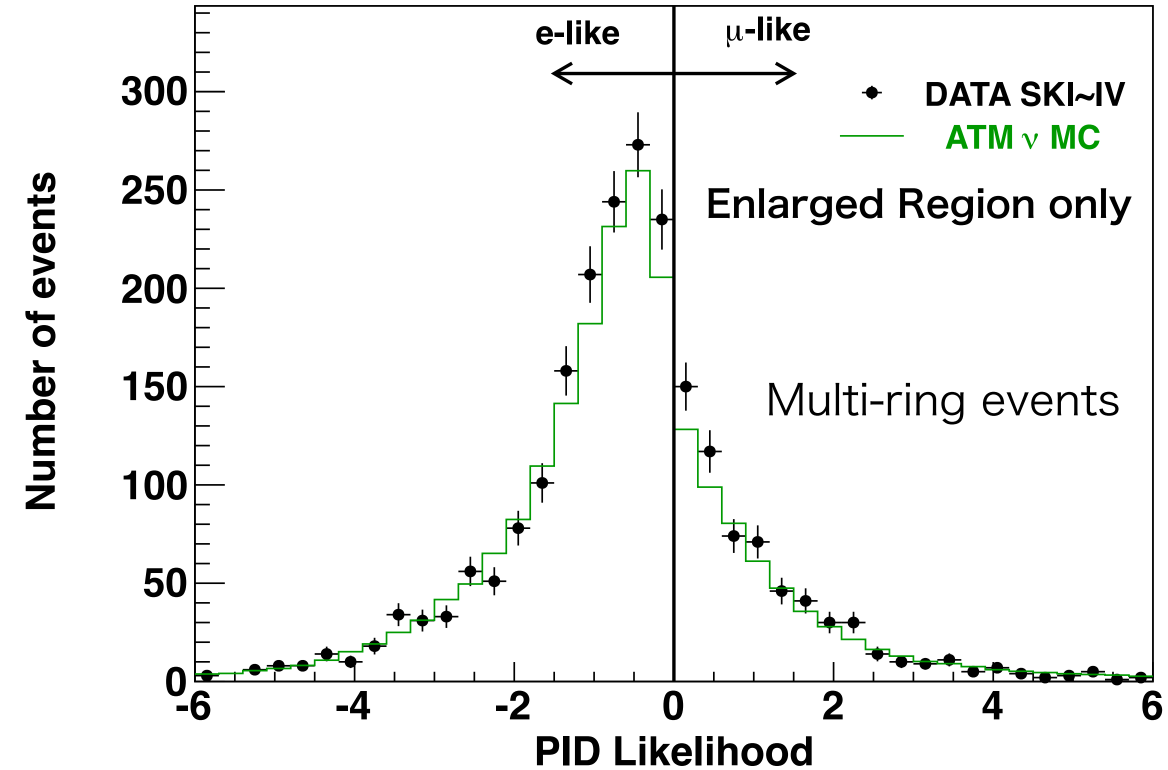
2. External Background Contamination

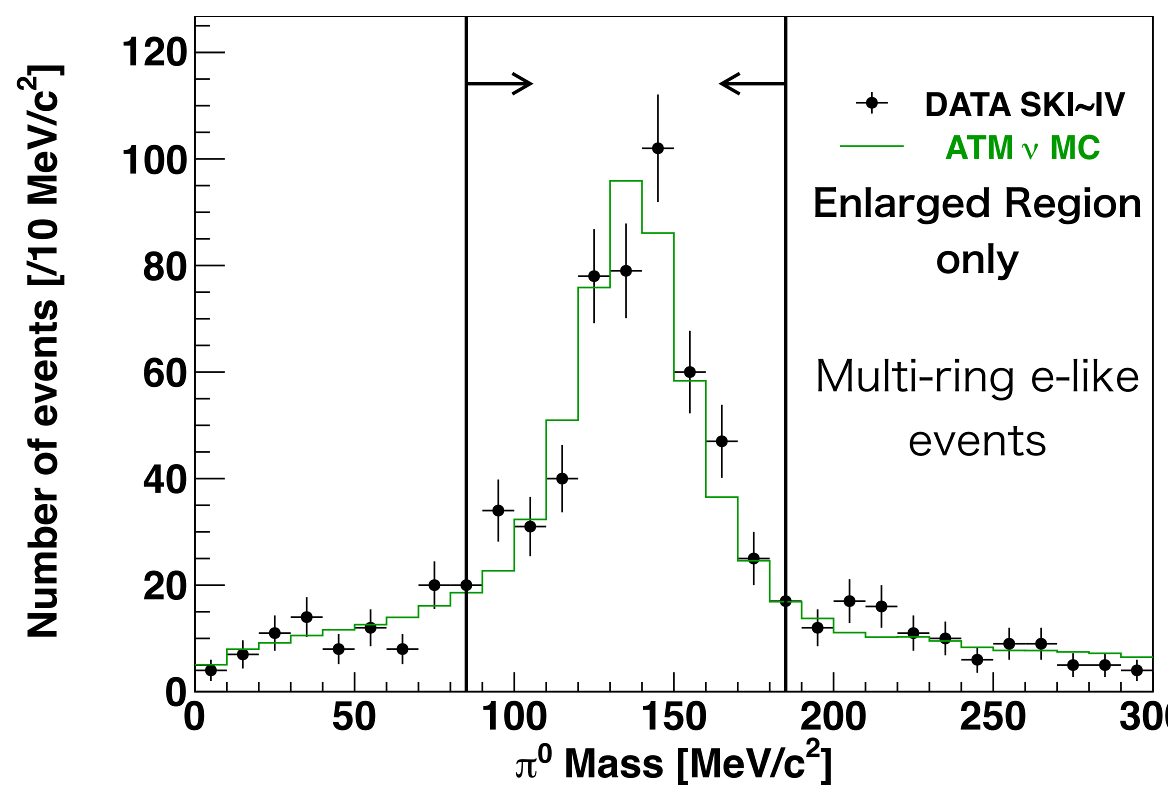


- Conducted **event scanning up to 50 cm to wall** to estimate external background contamination.
- Concluded to **enlarge fiducial mass region up to 100 cm to wall** to keep background contamination rate **(N_{BG}/N_{total}) within 1%.**
  - Most of the selected events are atmospheric neutrino events.

3. Data and MC agreement.

Demonstration using atmospheric ν

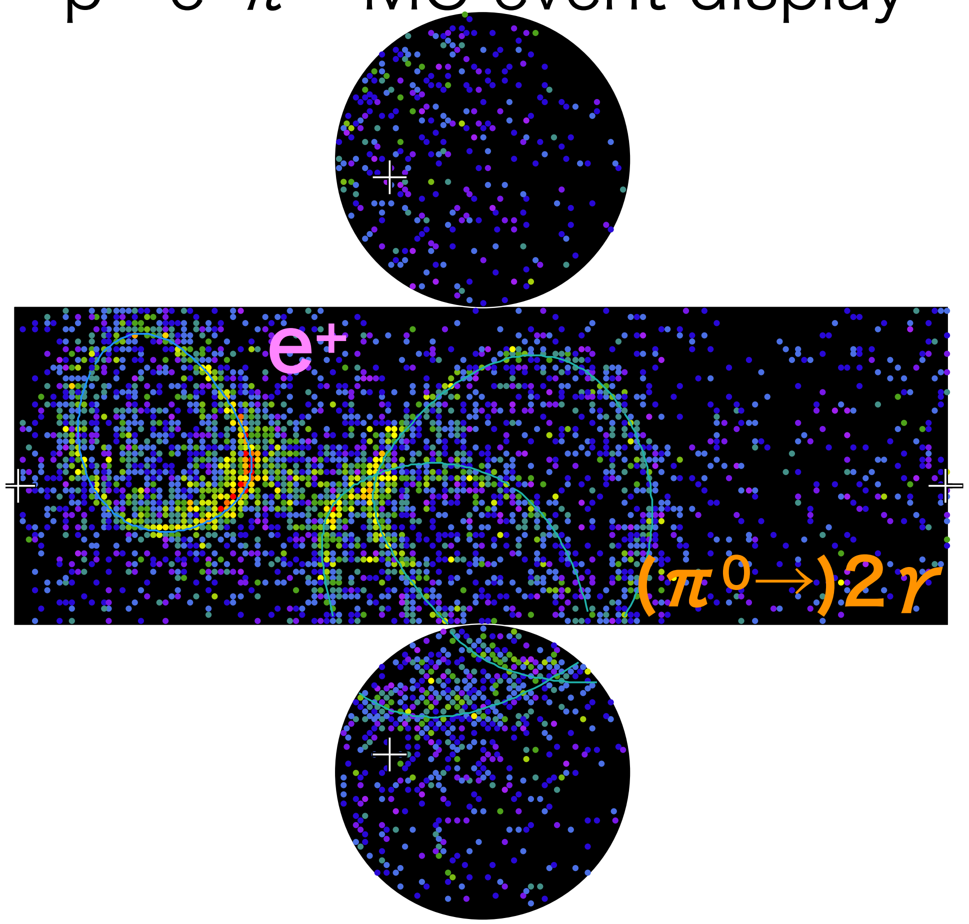


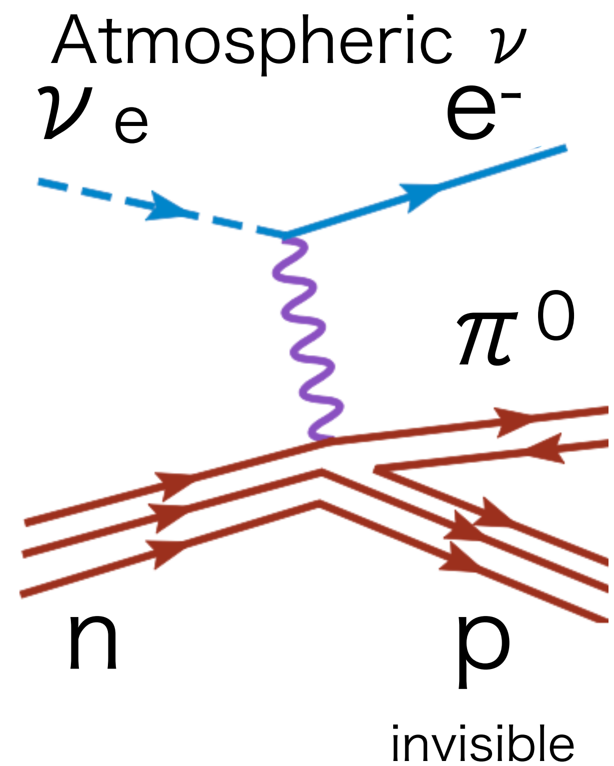


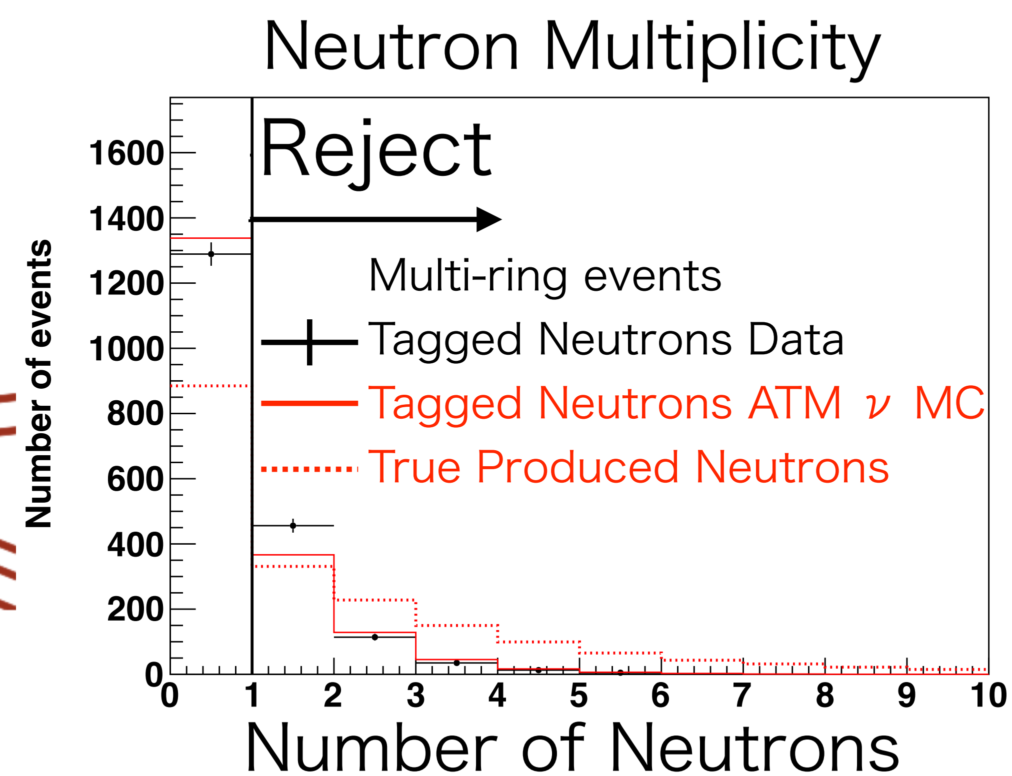
Good Data and MC agreement.

Signal and Background

$p \rightarrow e^{+}\pi^{0}$ MC event display







- All secondary particles (e^{+}, γ) can be reconstructed.
- Unique event topology (back-to-back).
- **Free protons (H)** are available in Super-K.
  - Free from Fermi motion and nuclear effects.

- Atmospheric (ATM) neutrino events can mimic p-decay signal.
- Often accompanied with neutrons.
- Since 2008, electronics upgrade enables to tag faint signature of **neutrons (γs)**. ($n+p \rightarrow d+\gamma$ (2.2 MeV))
  - Neutron tagging efficiency ~25%.
  - **Requiring no tagged neutrons reduces ATM ν BG by ~50%.**

Search Performance $p \to e^+ \pi^0$

$p \to e^+ \pi^0$ signal selection

1. Fully contained and **vertex in fiducial mass region**.
2. **Cherenkov ring** = **2** or **3**
3. Particle identification

   all shower-like rings
4. No Michel-e.
5. for 3-ring events, π^0 mass cut

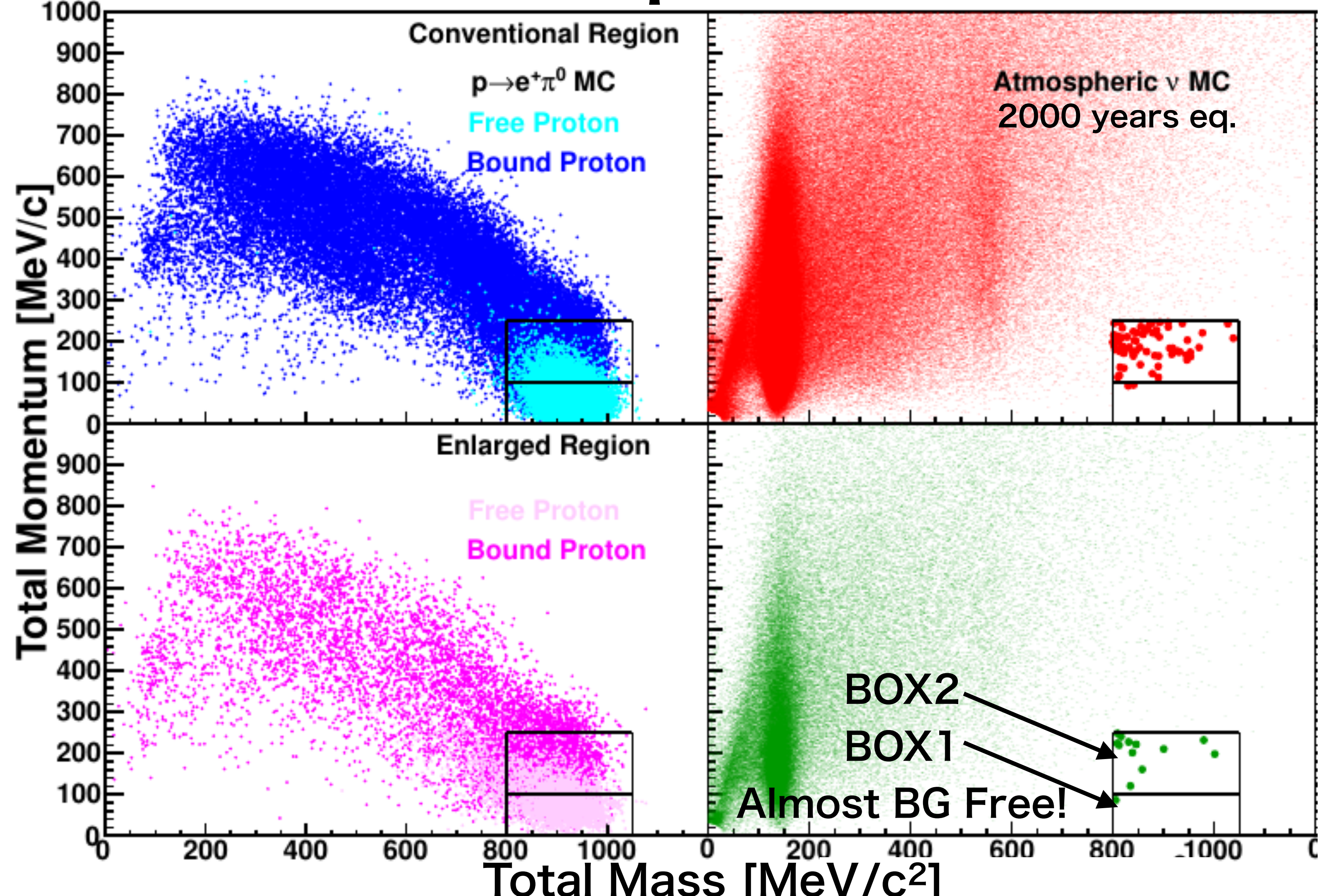
   $85 < M_{\pi^0} < 185$ MeV/c²
6. Total Mass cut

   $800 < M_{tot} < 1050$ MeV/c²
7. Total Momentum Cut

   Box1: $0 < P_{tot} < 100$ MeV/c

   (Free proton rich & Low ν BG)

   Box2: $100 < P_{tot} < 250$ MeV/c
8. For data since 2008, **no tagged neutrons**.



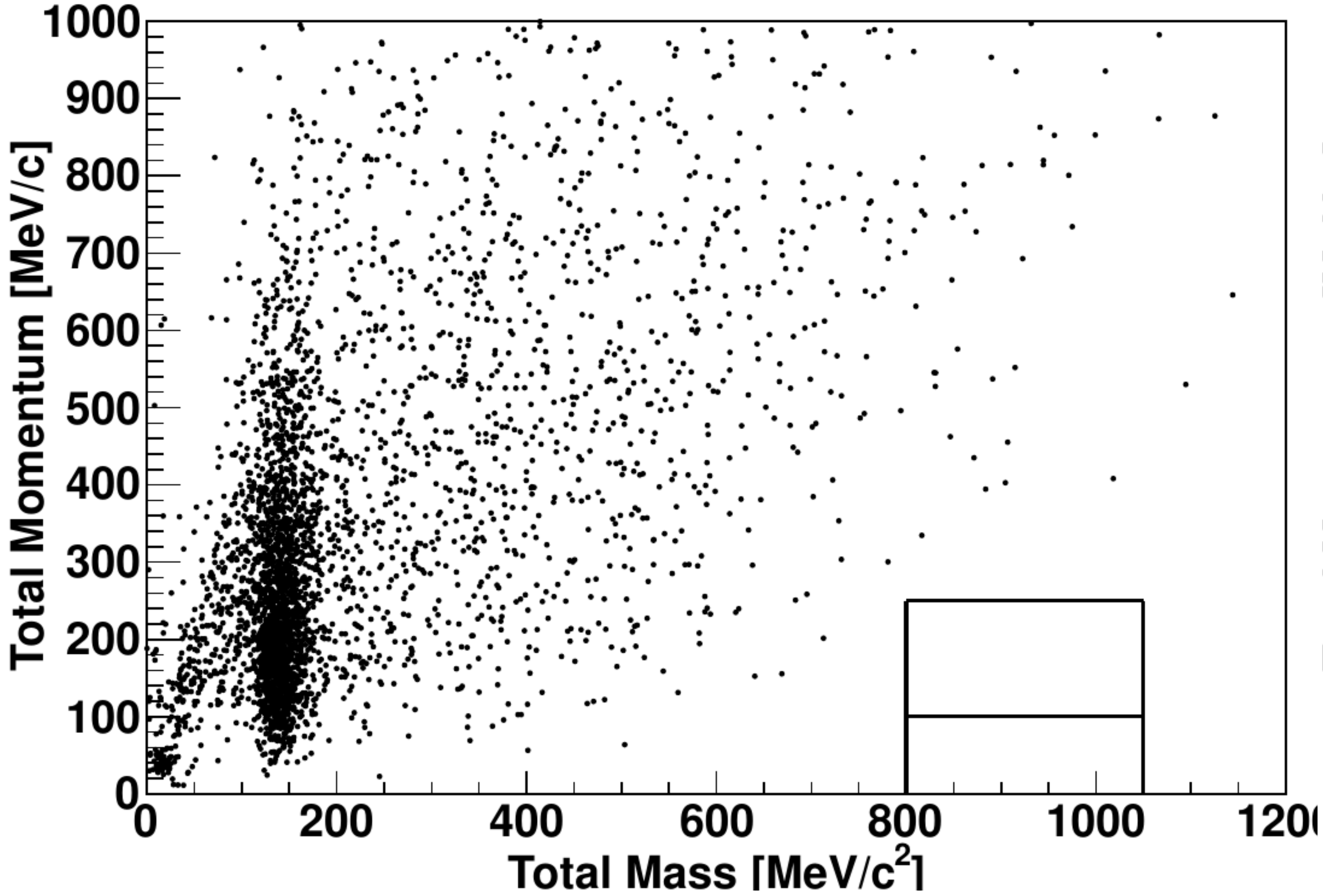
		Conventional	Enlarged
	Fiducial Mass	22.5 kton	4.7 kton
	Exposure	372 kton*years	78 kton*years
Signal Efficiency	BOX1	19.5+/-1.7%	10.3+/-1.4%
	BOX2	20.3+/-3.3%	15.5+/-2.6%
	TOTAL	39.8%+/-3.7%	25.8+/-3.0%
Expected BG [/livetime]	BOX1	0.01+/-0.01 ev	0.01+/-0.01 ev
	BOX2	0.48+/-0.21 ev	0.09+/-0.05 ev
	TOTAL	0.49+/-0.21 ev	0.10+/-0.05 ev

- Enlarging fiducial mass increases p-decay search sensitivity by ~12%.

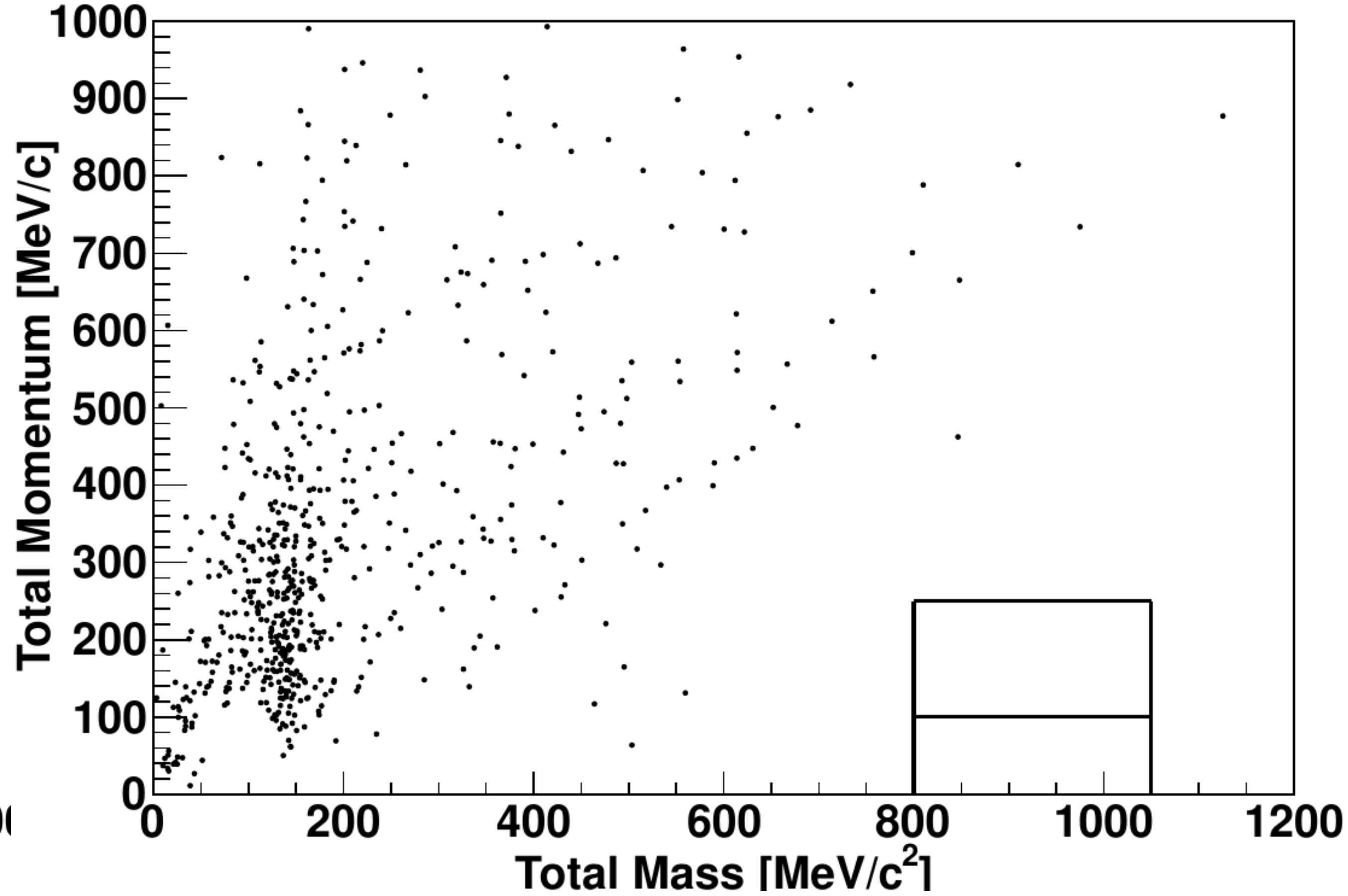
Data Result $p \to e^+ \pi^0$

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

Conventional Region 372 kton*years



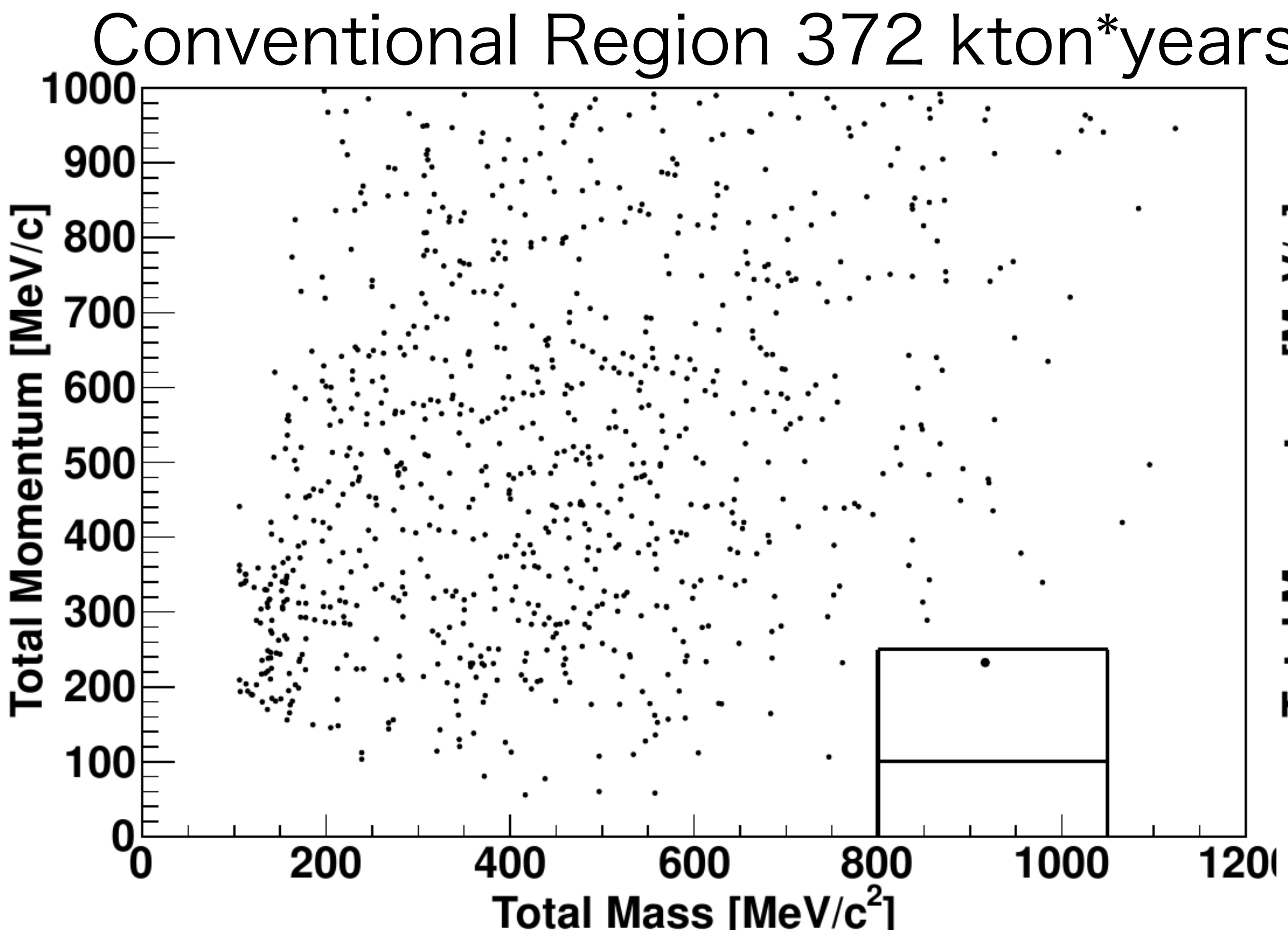
Enlarged Region 78 kton*years

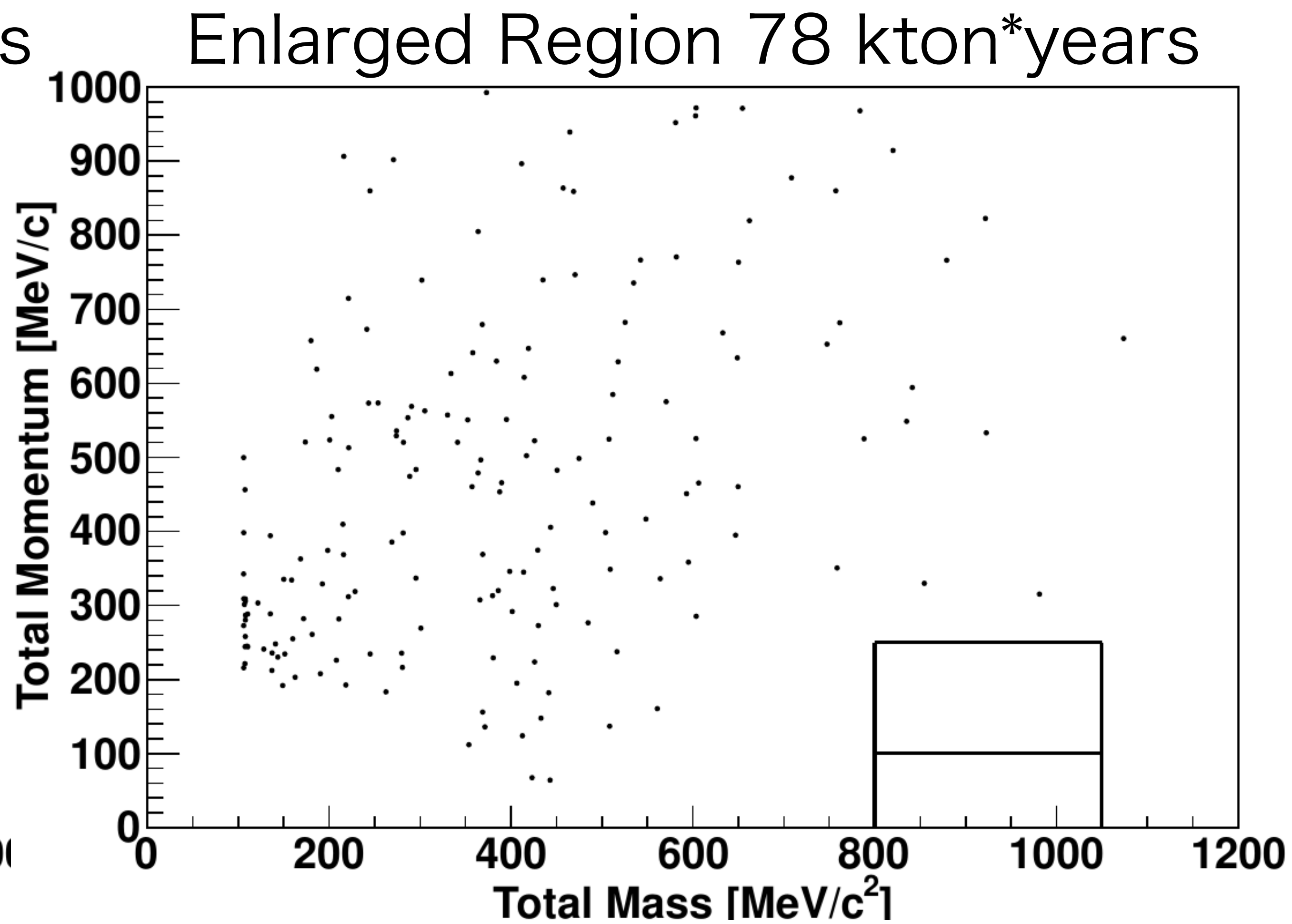


- No candidates in signal box incl. enlarged region.
- Lower lifetime limit @90%C.L.
  - **$\tau / B_{p \to e^+ \pi^0} > 2.4 \times 10^{34}$ years** (published: 1.6×10^{34} years, 306 kton*years)
- Most stringent constraint. **~1.5 times longer than published.**

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

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





- Almost same criteria except 1 μ ring and 1 Michel electron (required).
- 1 candidate in BOX2. Same event reported in the last paper.

PRD 95, 012004 (2017)

- No new candidates incl. in enlarged region.
- No significant data excess compared to the expected BG (0.94 in total).
- Lower lifetime limit @90%C.L.
  - $\tau / B_{p \to \mu + \pi 0} > 1.6 \times 10^{34}$ **years** (published: 7.7×10^{33} years, 306 kton*years)
- Most stringent constraint. **~2 times longer than published.**

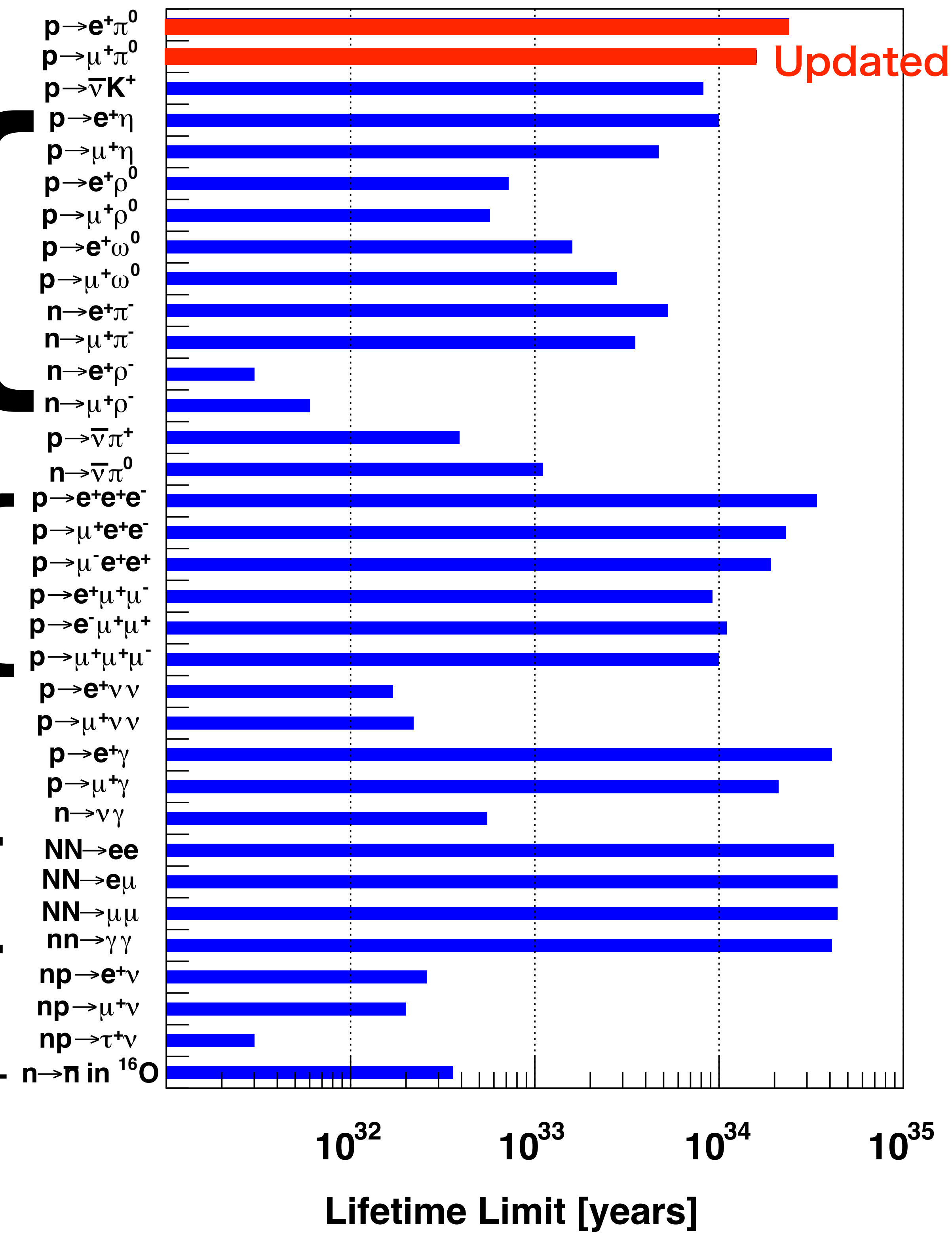
Other BNV Searches in Super-K

Systematic anti-lepton + meson mode searches
PRD 96, 012003 (2017)

Recent Results: p-decays to anti-lepton mode searches
PRD 101, 052011 (2020)

Dinucleon Decay searches
arXiv:1811.12430 (2018)

New Result: Neutron Anti-neutron Oscillation Search
$\tau_{n\to\bar{n}} > 4.7\times10^8$ seconds for free neutrons
Poster @Neutrino 2020



- No evidence of BNV process so far …. There is still room for statistic improvement (other than $p\to e^+\pi^0$ and $p\to\mu^+\pi^0$, convetional fiducial mass results).

Future Prospect

- To increase the search sensitivity, atmospheric ν background rejection and larger exposure are crucial.
- **We are loading Gd into Super-K (SK-Gd) NOW** to obtain higher neutron tagging efficiency.

Talk 30th/July 10:45~
By Lluis @ν session

Relation b/w Neutron tagging efficiency and ATM ν BG rejection power

Neutron Tagging efficiency	~25% (H capture)	~50% ($Gd_2(SO_4)_3$ 0.02%)	~90% ($Gd_2(SO_4)_3$ 0.2%)
ATM ν BG Reduction by Ntag	~50%	~65%	~80%

- With **Hyper-K (fiducial mass:~190 kton), sensitivity will reach $\tau/B_{p\rightarrow e^{+}\pi^{0}}$~$10^{35}$ years** for 20 years operation.
  - Neutron tagging efficiency ~70% (w/ more sensitive PMT)
  - **The detector construction is ongoing. (Operation 2027~)**

Conclusion

- Performed proton decay search ($p \rightarrow e^+ \pi^0$, $p \rightarrow \mu^+ \pi^0$) with enlarged fiducial mass of Super-Kamiokande detector.
  - Fiducial mass: 22.5 kton → 27.2 kton
- No evidence of proton decay…
  - **Using all available data (1996~2018, 450 kton*years),**
  - **$\tau / B_{p \rightarrow e+\pi 0} > 2.4 \times 10^{34}$ years (90%C.L.) (no candidates)**
  - **$\tau / B_{p \rightarrow \mu+\pi 0} > 1.6 \times 10^{34}$ years (90%C.L.) (1 candidate)**
  - **1.5~2 times longer than published and most stringent constraints on proton lifetime for these modes.**
- Keep pursuing with improved analysis technique.
  - **Further background reduction** in SK-Gd.
  - **Enlarging fiducial mass** for other decay modes.
  - Develop more **sophisticated reconstruction** tools.

Other Super-K talks

200. The diffuse supernova neutrino background in Super-Kamiokande, Sonia El Hedri, 30th/July 10:00
210. Spallation background in the Super-Kamiokande experiment, Laura Bernard, 29th/July 18:30
444. Status of the SK-Gd project, Lluis Marti-Magro, 30th/July 10:15
827. Atmospheric Neutrino Oscillation with Super-Kamiokande, Volodymyr Takhistov, 30th/July 9:45