Search for Proton Decay: The Latest Results from Super-Kamiokande

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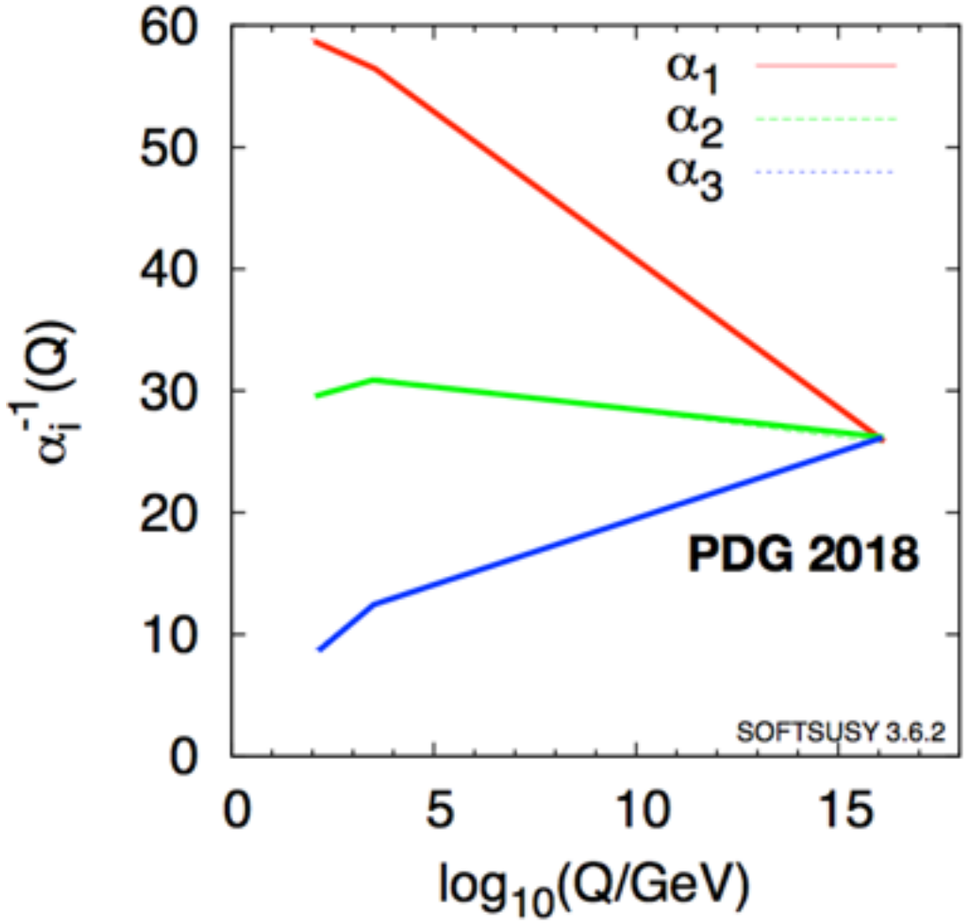
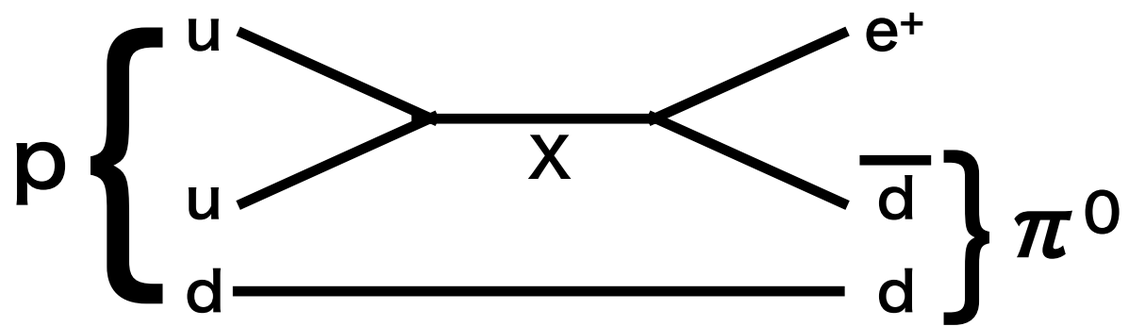
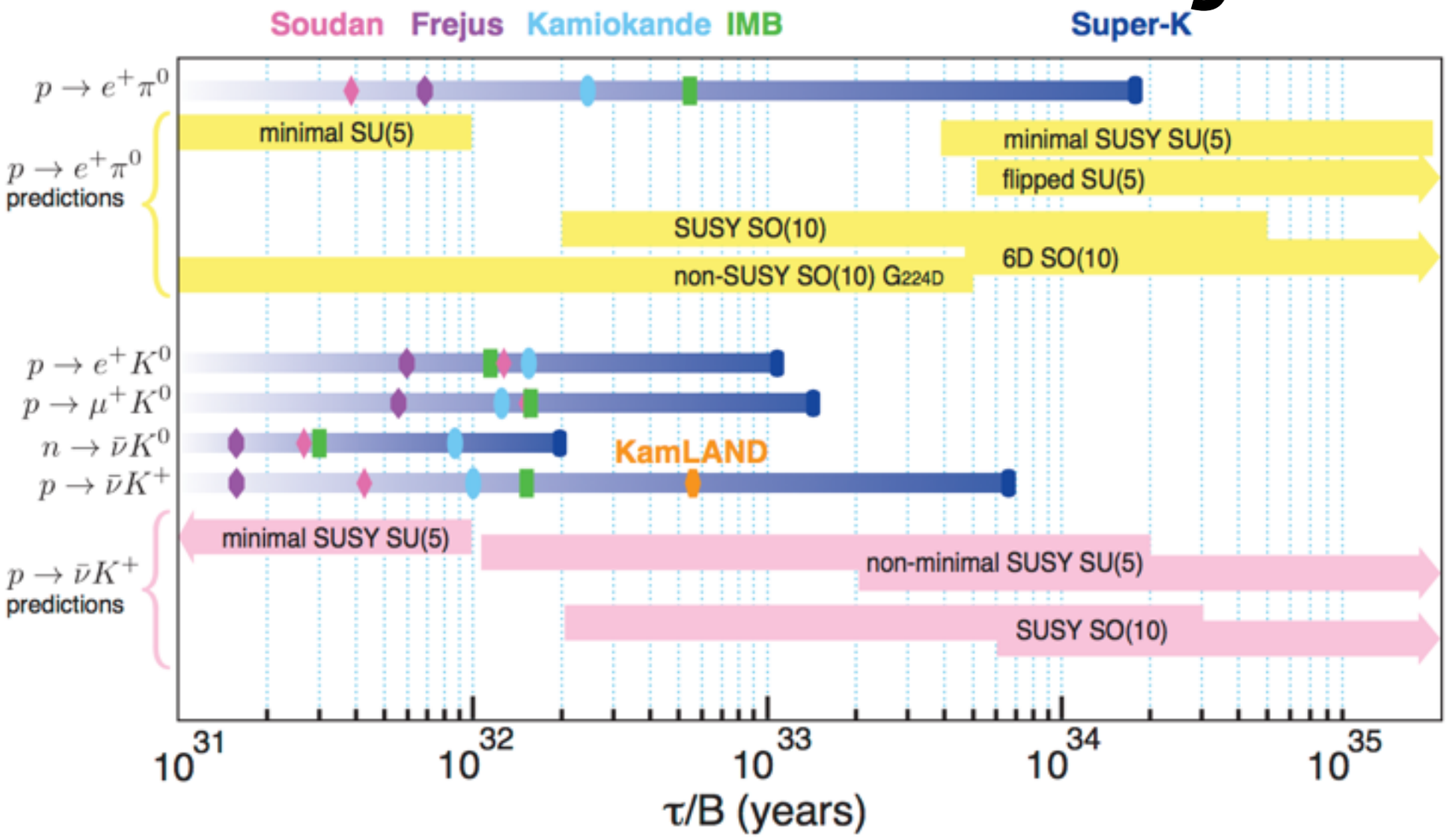
Proton Decay





- Grand unified theory (**GUT**) is motivated by charge quantization and coupling const. unification @$10^{15\sim16}$ GeV.
  - Neutrino (mass generation/CPV) physics may be related at the super high energy scale.
- **Proton decay**, direct transition between quarks and leptons, is predicted in GUT and **a unique way to prove it**.

Proton Decay



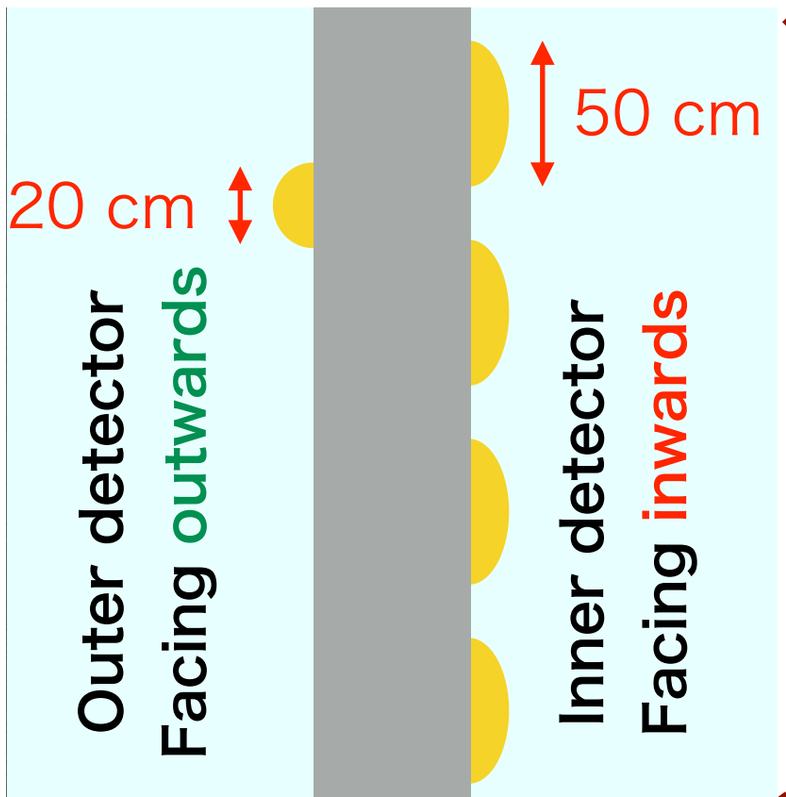
- Many GUT models are proposed, predicting proton lifetime to be **~$10^{34\text{~}35}$ years**. So far, no experimental evidences…
- **Super-K** is a **world leading** experiment, reaching prediction regions with **great potential for discovery**.

$\tau/B_{p\to e+\pi 0}$ > 1.6×10^{34} years, $\tau/B_{p\to \mu+\pi 0}$ > 7.7×10^{33} years (90% C.L.)

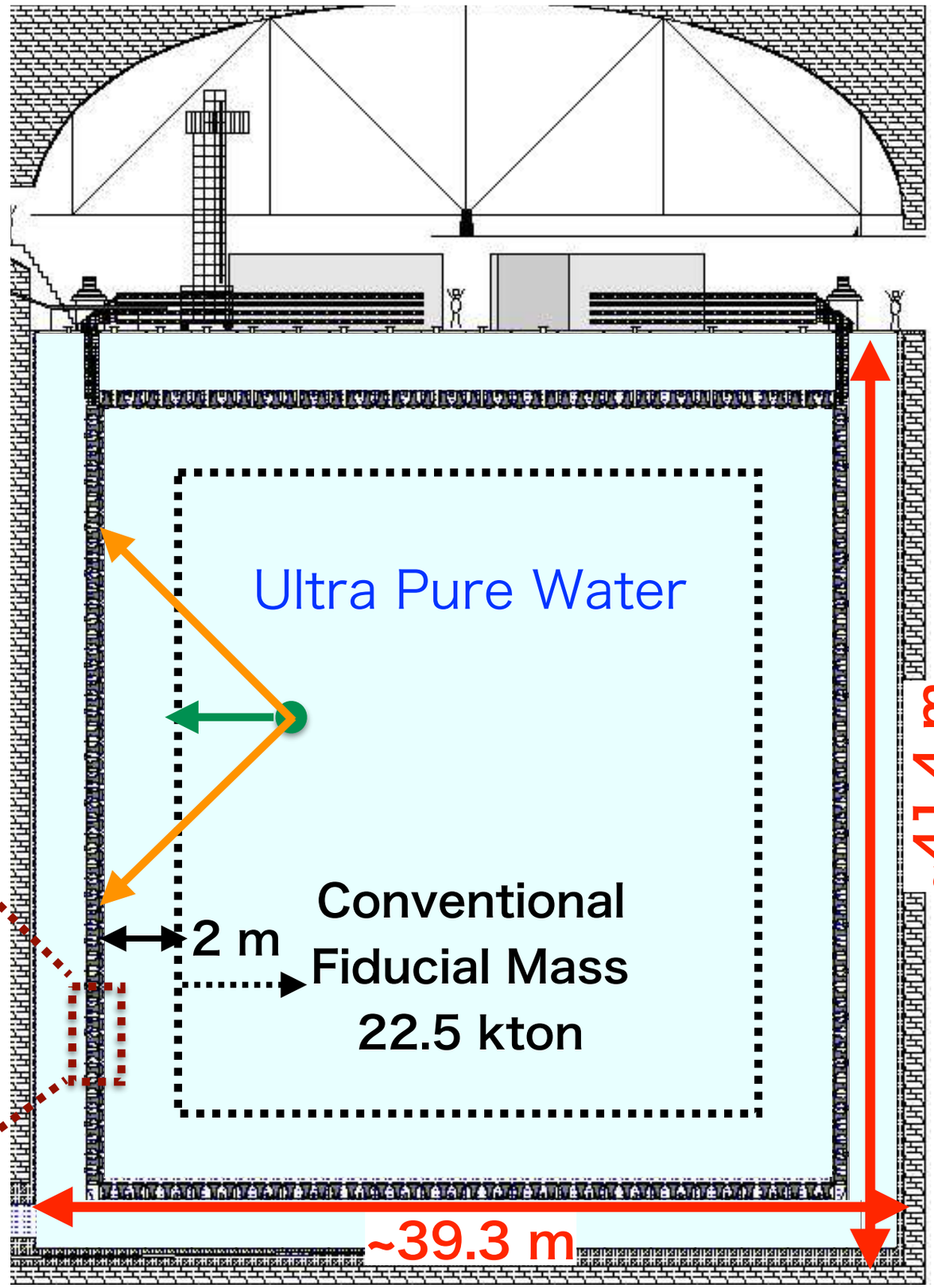
with 306 kton*years data PRD 95, 012004 (2017)

Super-Kamiokande

- **The world largest underground water Cherenkov detector.** (upright cylinder)
- ~1000 m underground @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**.

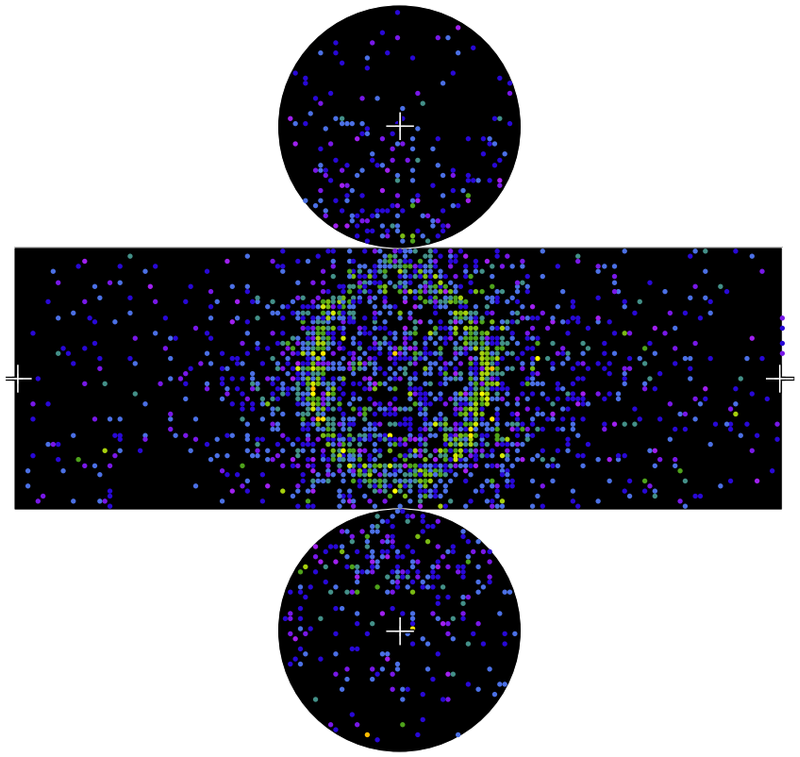


Super-Kamiokande sideview

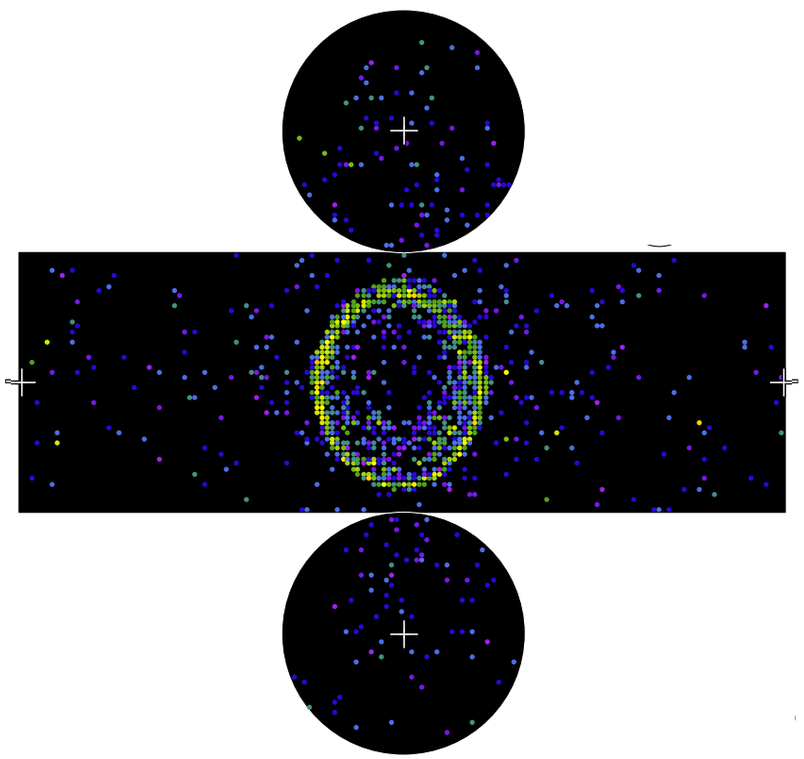


Water Cherenkov Technique

Electron (MC)

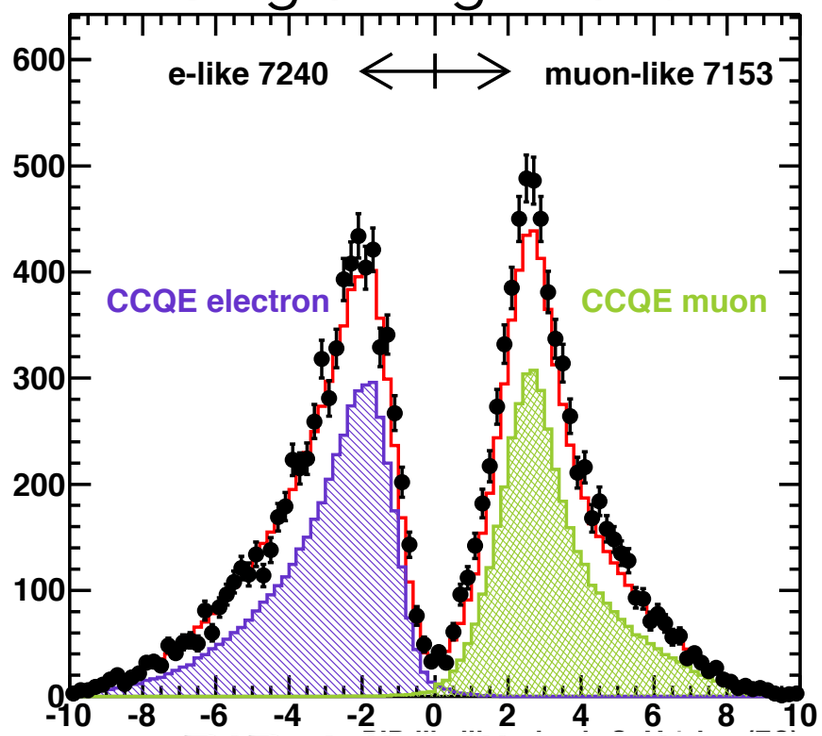


Muon (MC)



Atmospheric ν Data/MC

Single ring Event



- Well established detector technology.
  - Good particle identification (PID) capability.
    - Shower like (e, γ) and non-shower like (μ) can be identified with Cherenkov ring pattern.
    - **Mis PID rate <1% @1 GeV (1-ring)**
  - Good **momentum resolution. ~3% @1 GeV (1-ring).**
  - Energy scale uncertainty (Data/MC agreement) **~3%.**

Enlarging Fiducial Mass

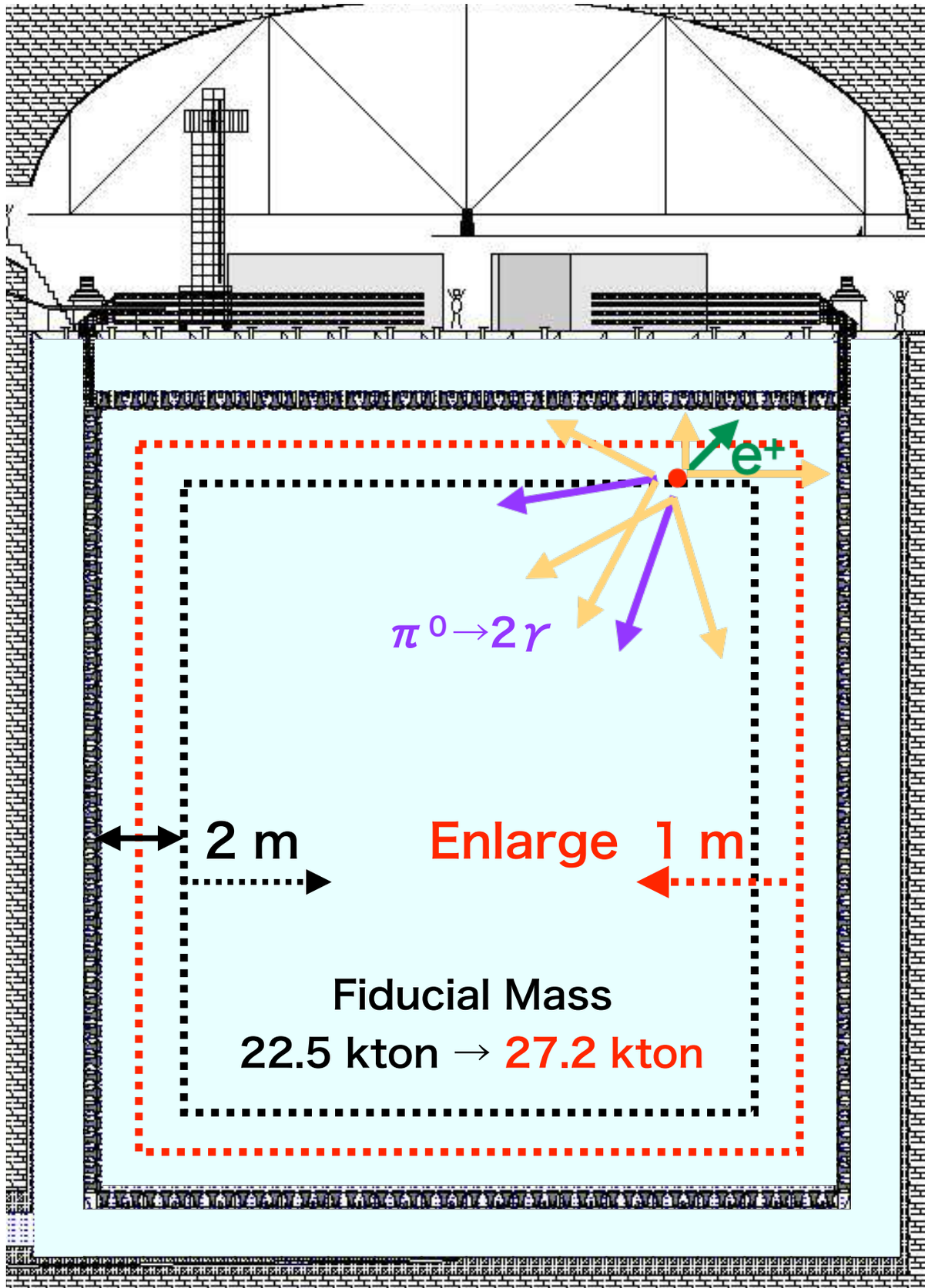
- Super-K is huge detector but its physics sensitivity is still limited by statistics…
- **Enlarge from 22.5 kton to 27.2 kton, +20%.**
  - **2 m to detector wall → 1 m**

Remarkable merits

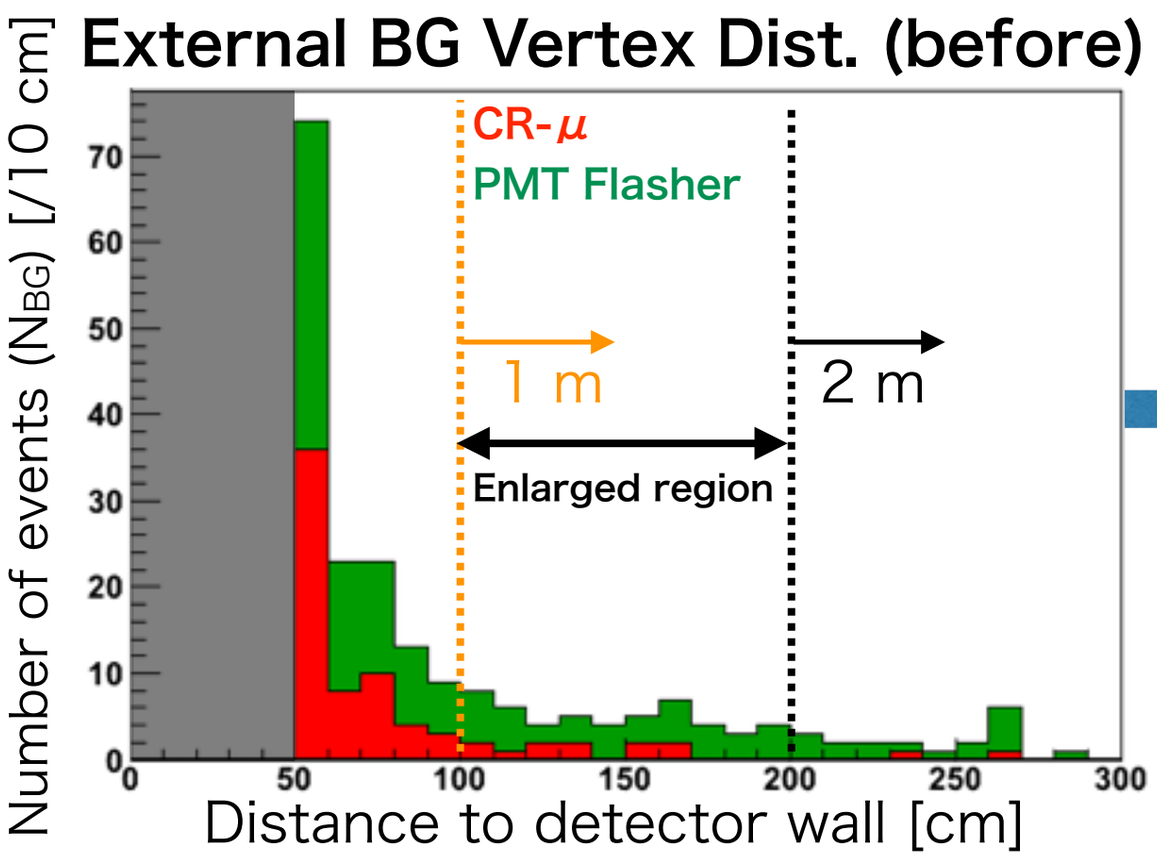
- Enables the use of **past data that has never been analyzed**.
- Improves **p-decay search sensitivity for every mode** as well as the neutrino analysis.

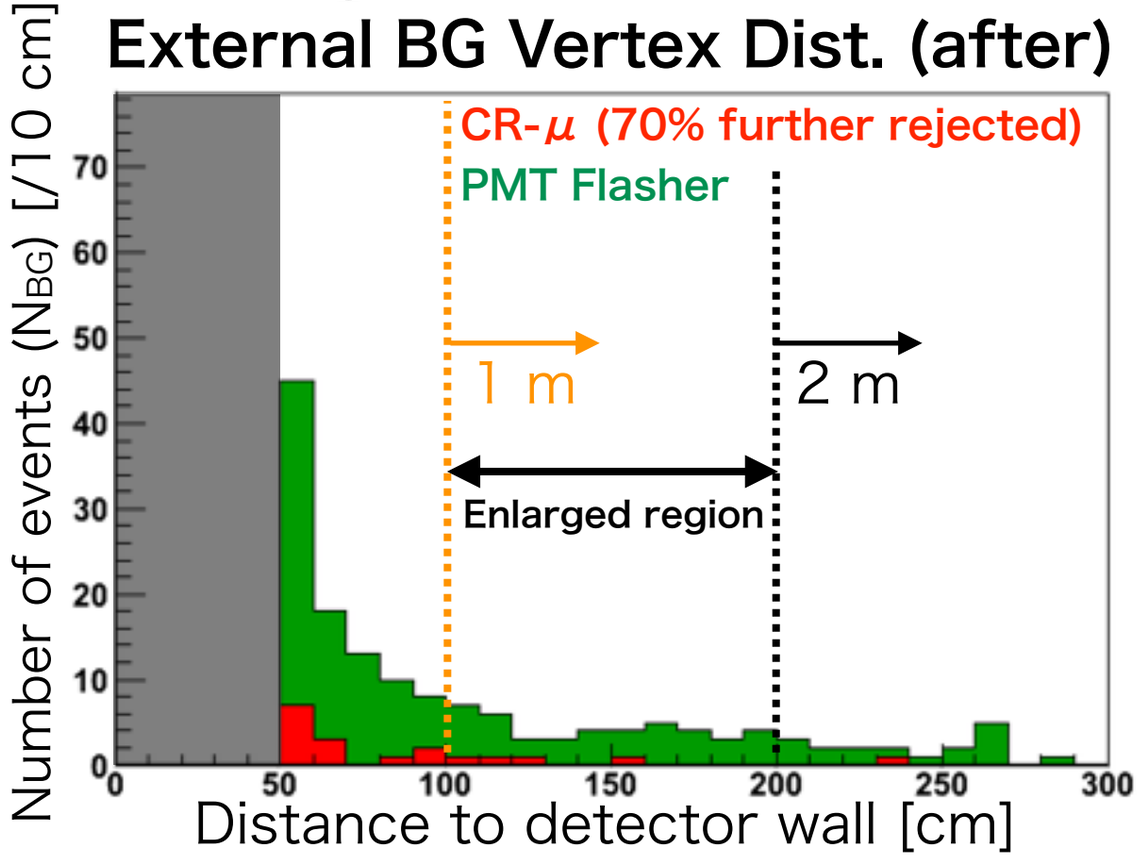
Considerations to achieve it

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



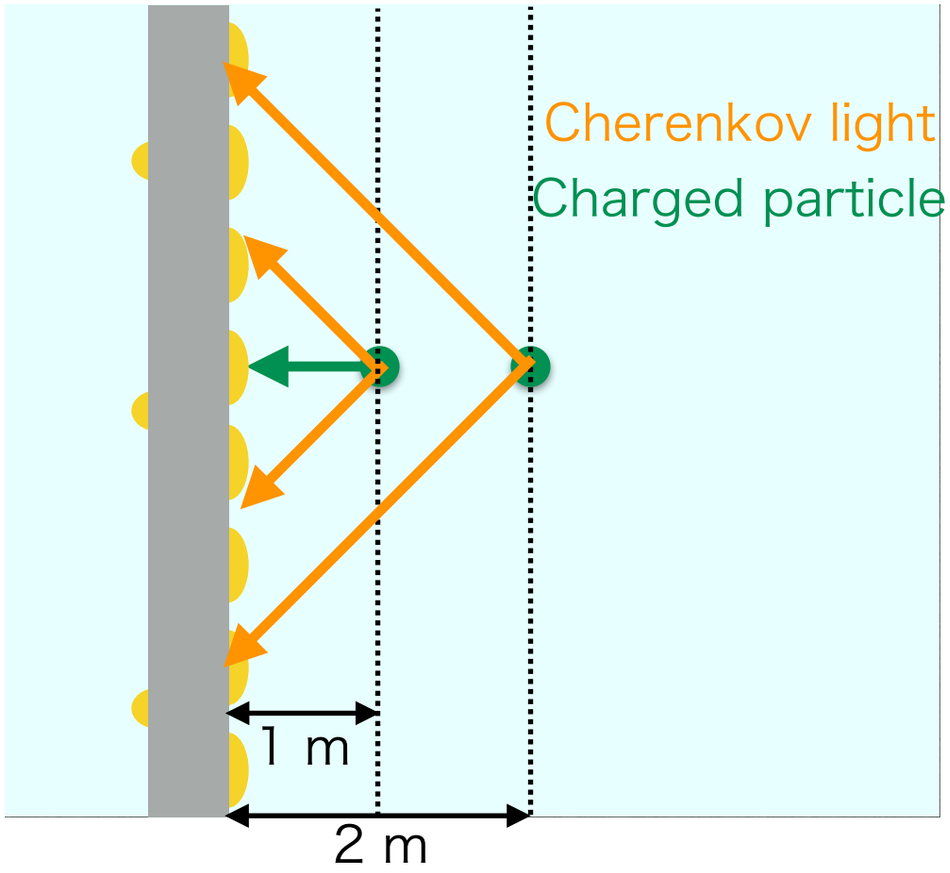
1. External Background

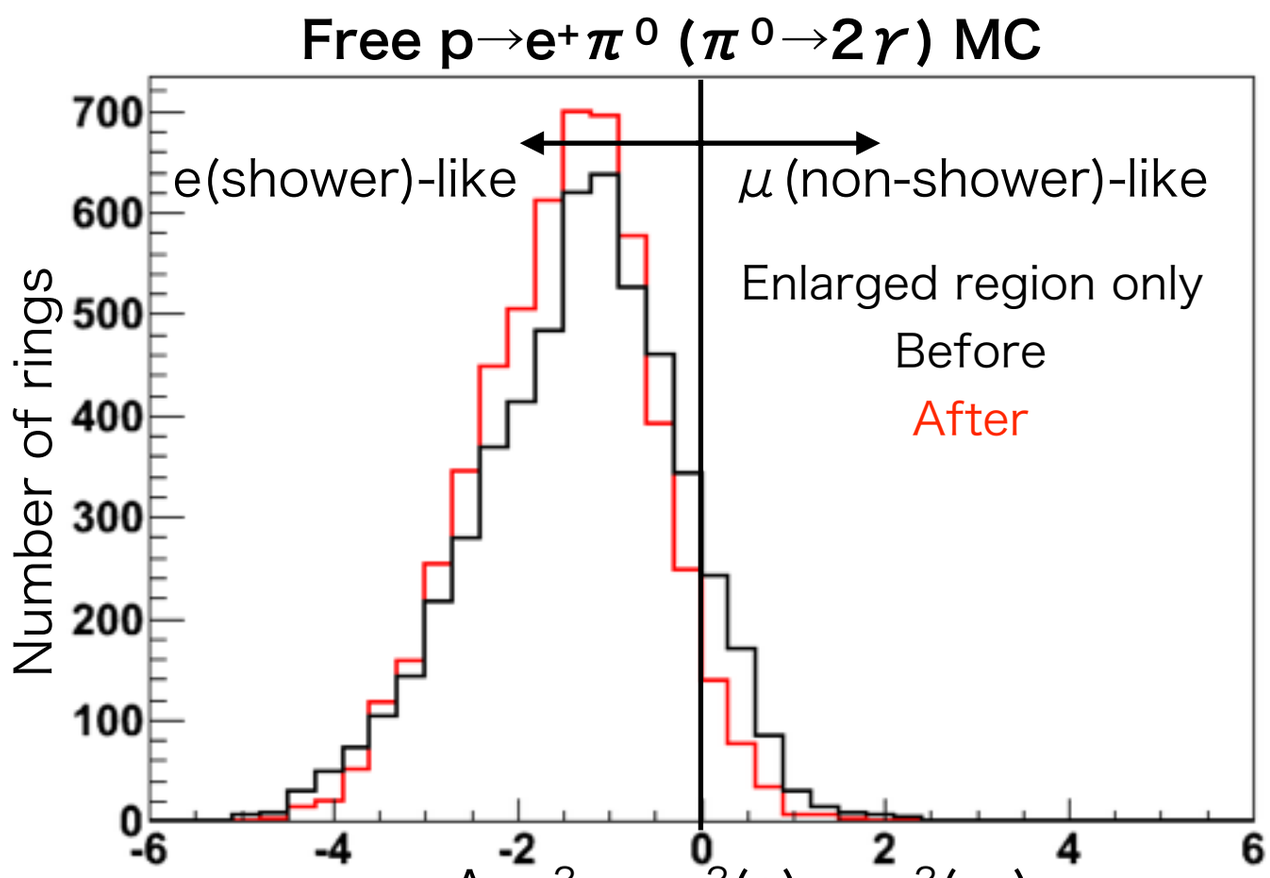




- Conducted **event scanning up to 50 cm to wall** to estimate external background (CR-μ, dummy events by PMT flashing) contamination.
  - There are less active regions in outer detector and it caused CR-μ contamination. → Newly developed tight CR-μ cut with special μ fitter and it reduces CR-μ by 70%.
- Concluded to **enlarge fiducial mass region up to 100 cm to wall** to keep background contamination rate **(N_{BG}/N_{total}) within 1%.**

2. Reconstruction Performance - PID Improvement





(Multi-ring PID Likelihood)

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

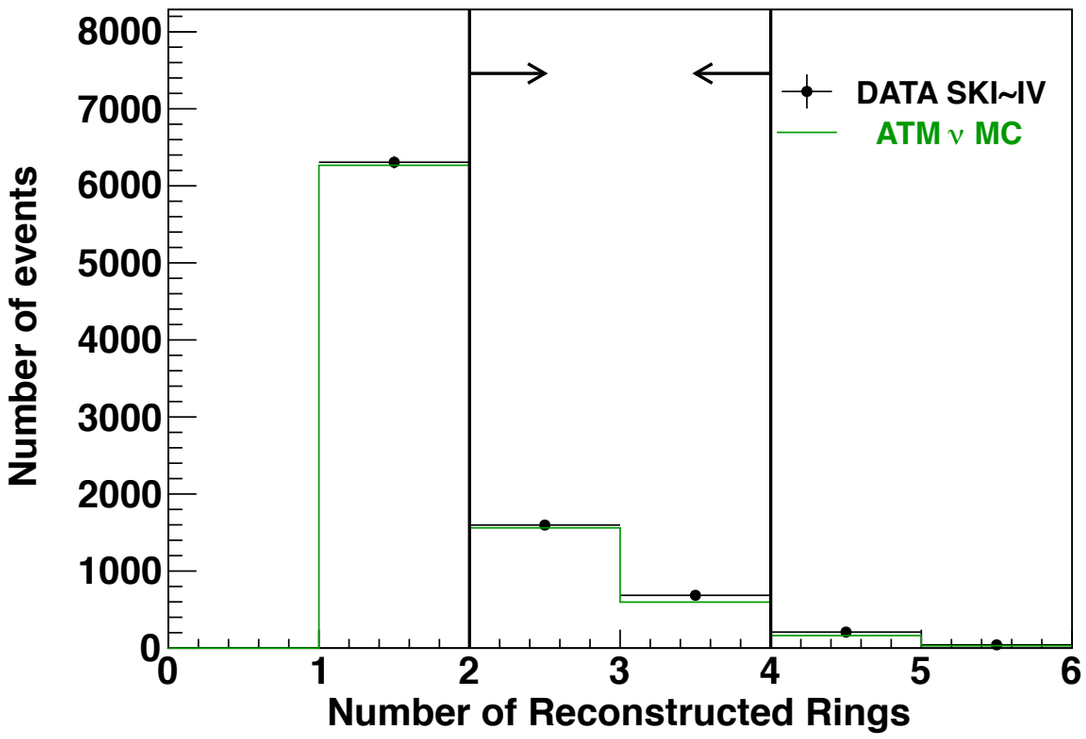
$$\chi^2(e \text{ or } \mu) \propto -\sum_{i \text{ (Hit PMT)}} \log_{10}(\mathrm{Prob}(q_i^{obs}, q_i^{exp}(e \text{ or } \mu)))$$

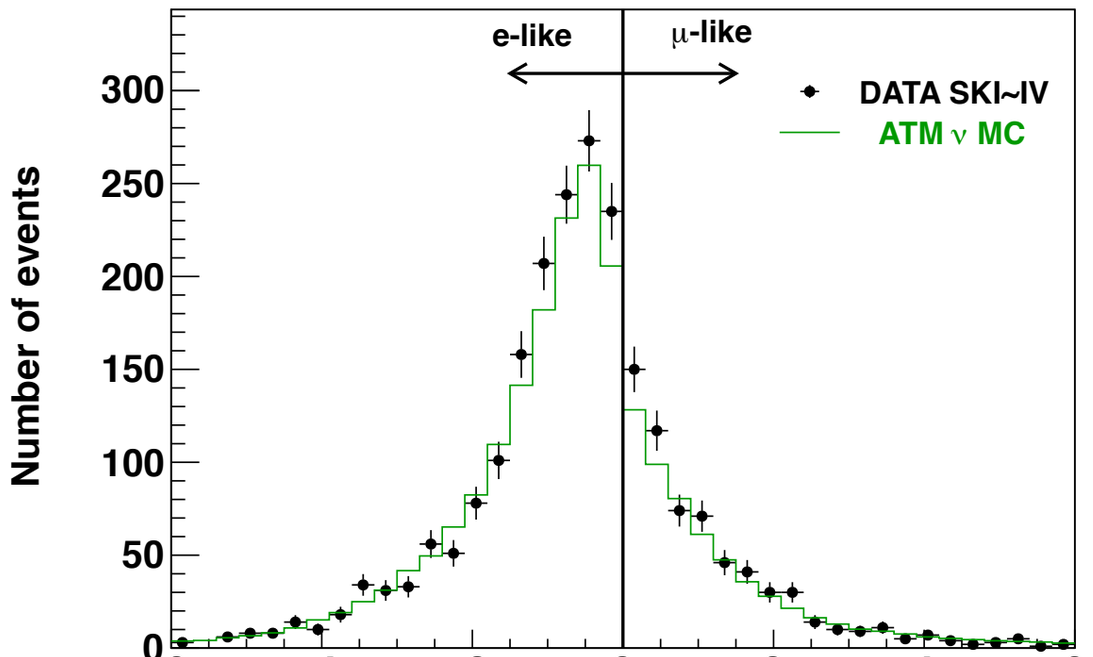
- In this situation, precise expected PMT charge (q_i^{exp}) becomes more important. → Revised expected charge table, reducing biases and **increasing p-decay signal efficiency by ~20%** in enlarged region.

3. Data/MC Agreement

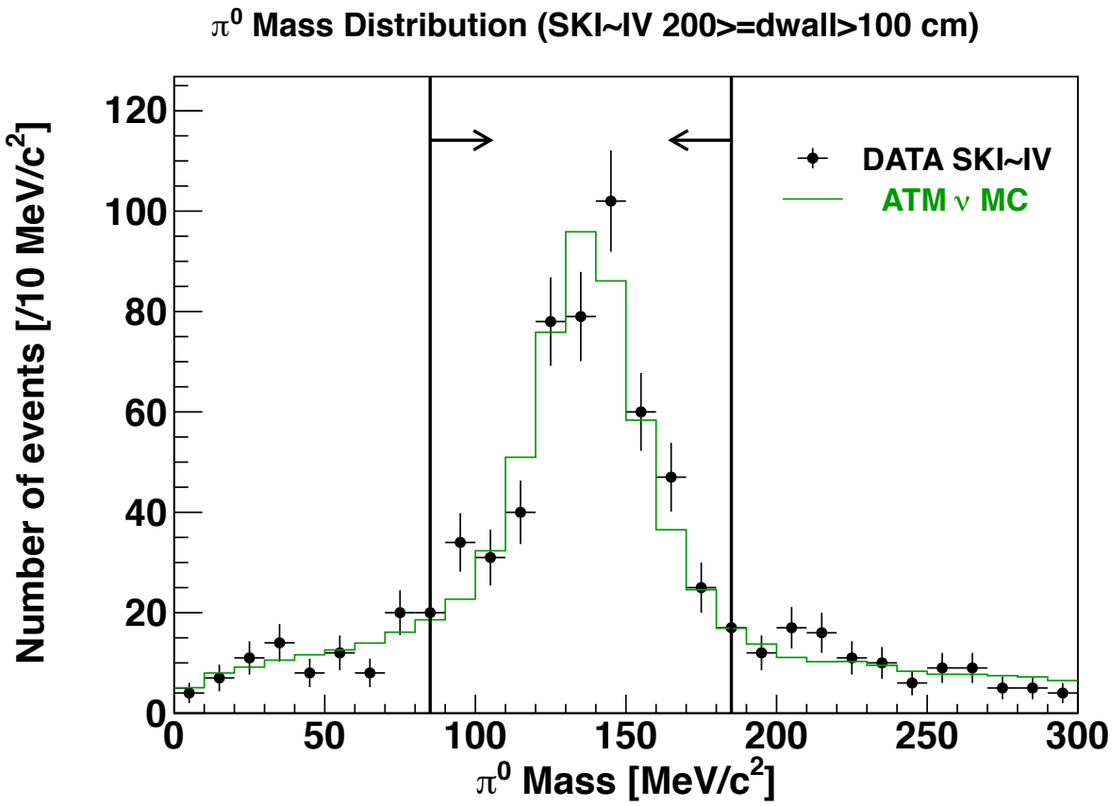
Atmospheric ν Data/MC in enlarged region only.

Distance to detector wall: 1~2 m.



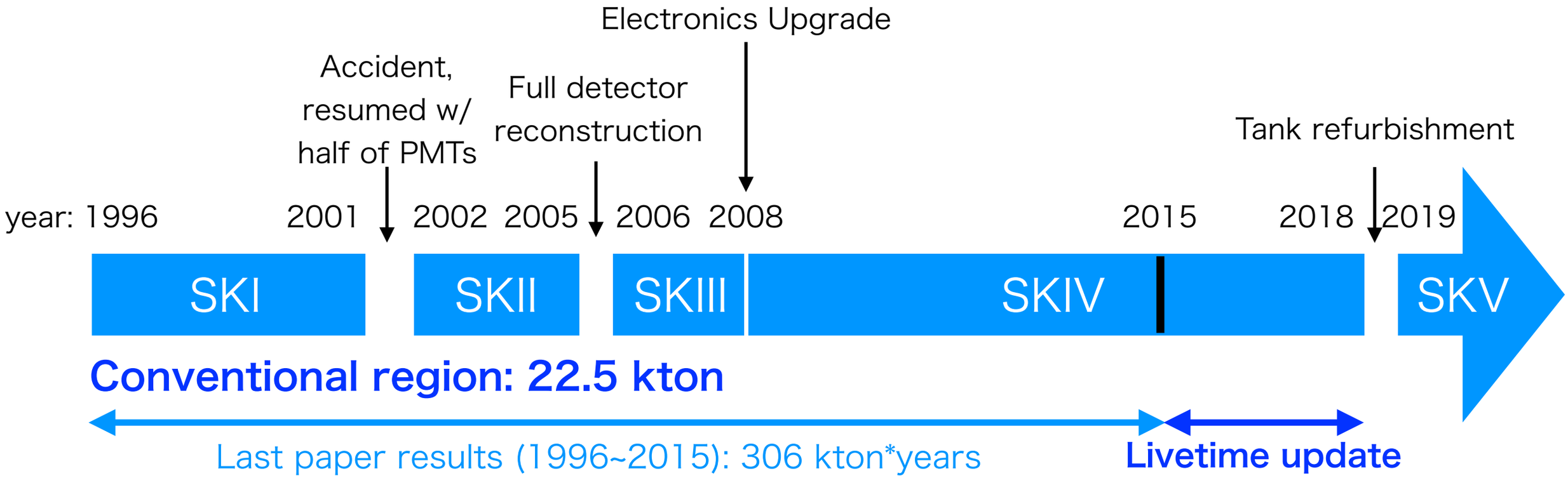


Multi-ring PID Likelihood



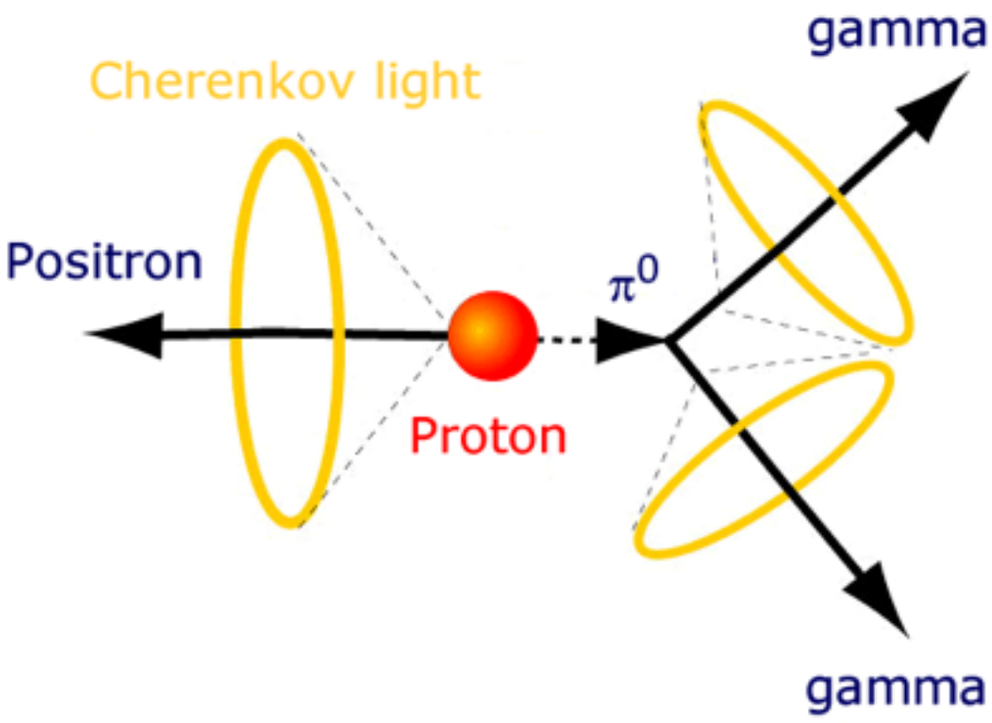
- Conducted careful data/MC comparison & systematic estimation.
- Confirmed **good Data/MC agreement and no show stoppers in enlarged region.**

Super-K History & Total Exposure

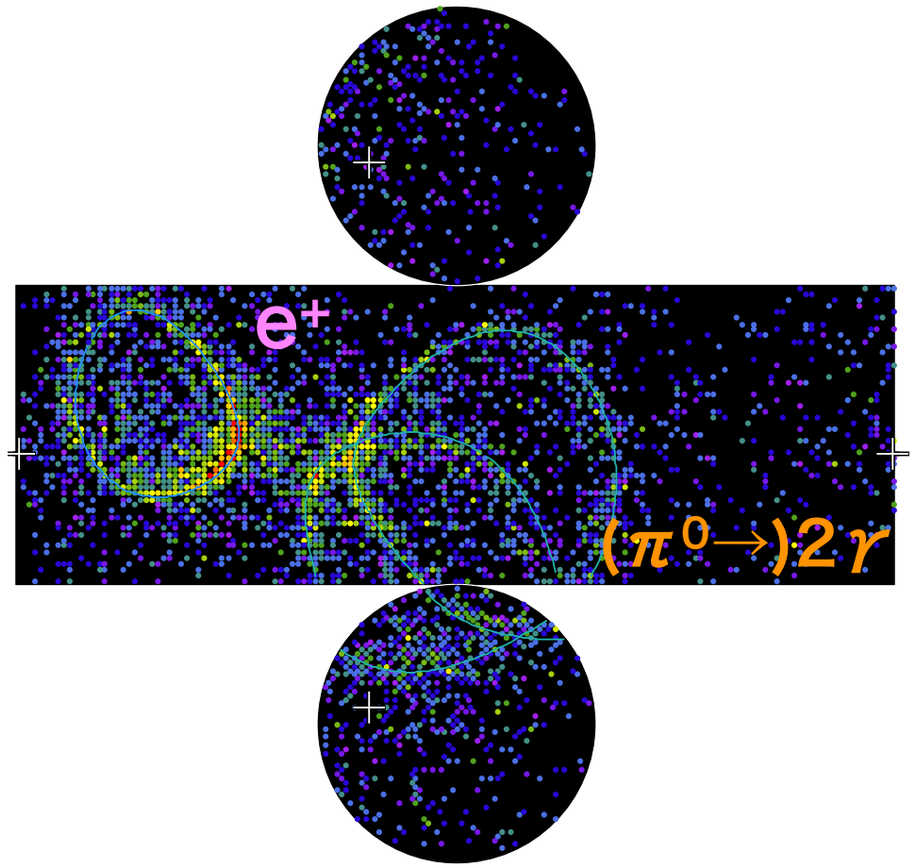


- The latest $p \to e^+ \pi^0$ & $p \to \mu^+ \pi^0$ search results with **full SKI~IV livetime (1996~2018)** & **enlarged fiducial mass** are presented in this talk.
- **Total exposure: 306+66(livetime)+78(enlarged fiducial mass) = 450 kton*years**
  - 1.5 times larger than published (306 kton*years). **PRD 95, 012004 (2017)**

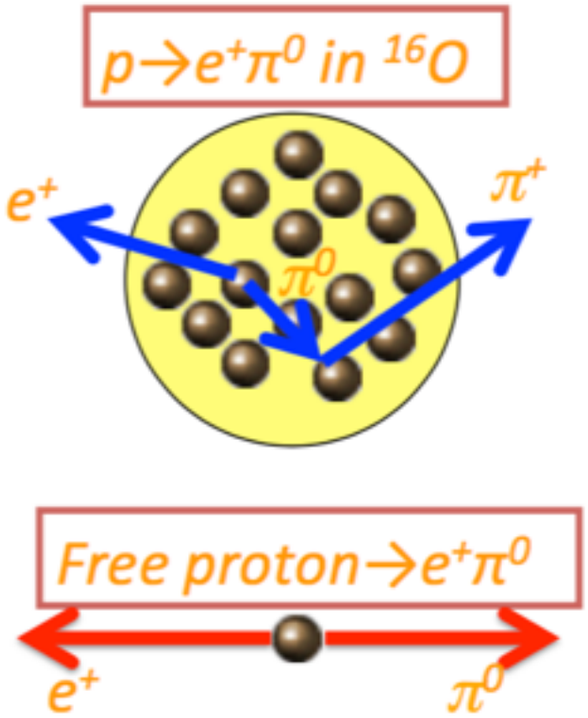
$p \to e^+ \pi^0$ Signal



$p \to e^+ \pi^0$ MC event display



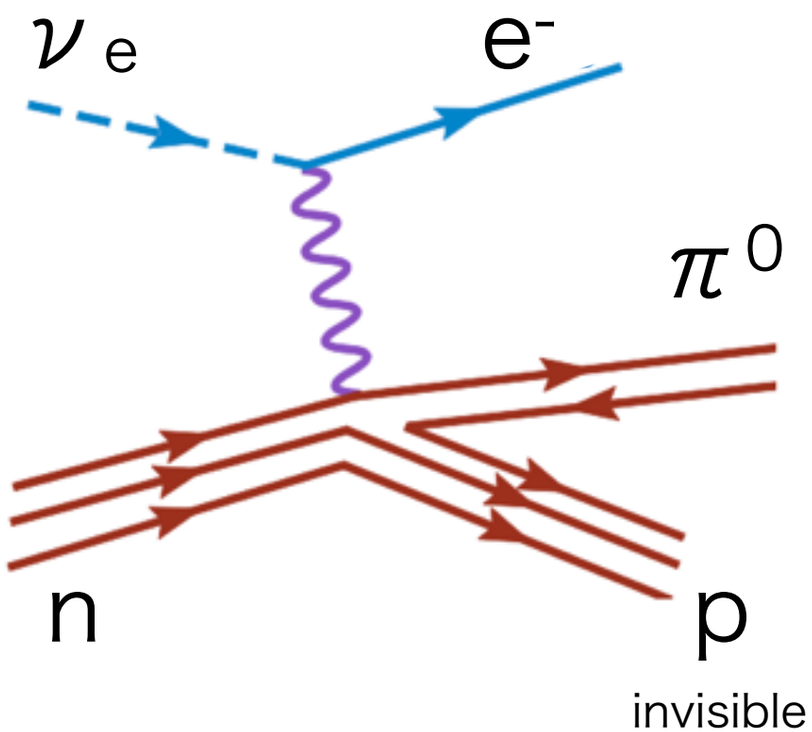
Protons in H_2O



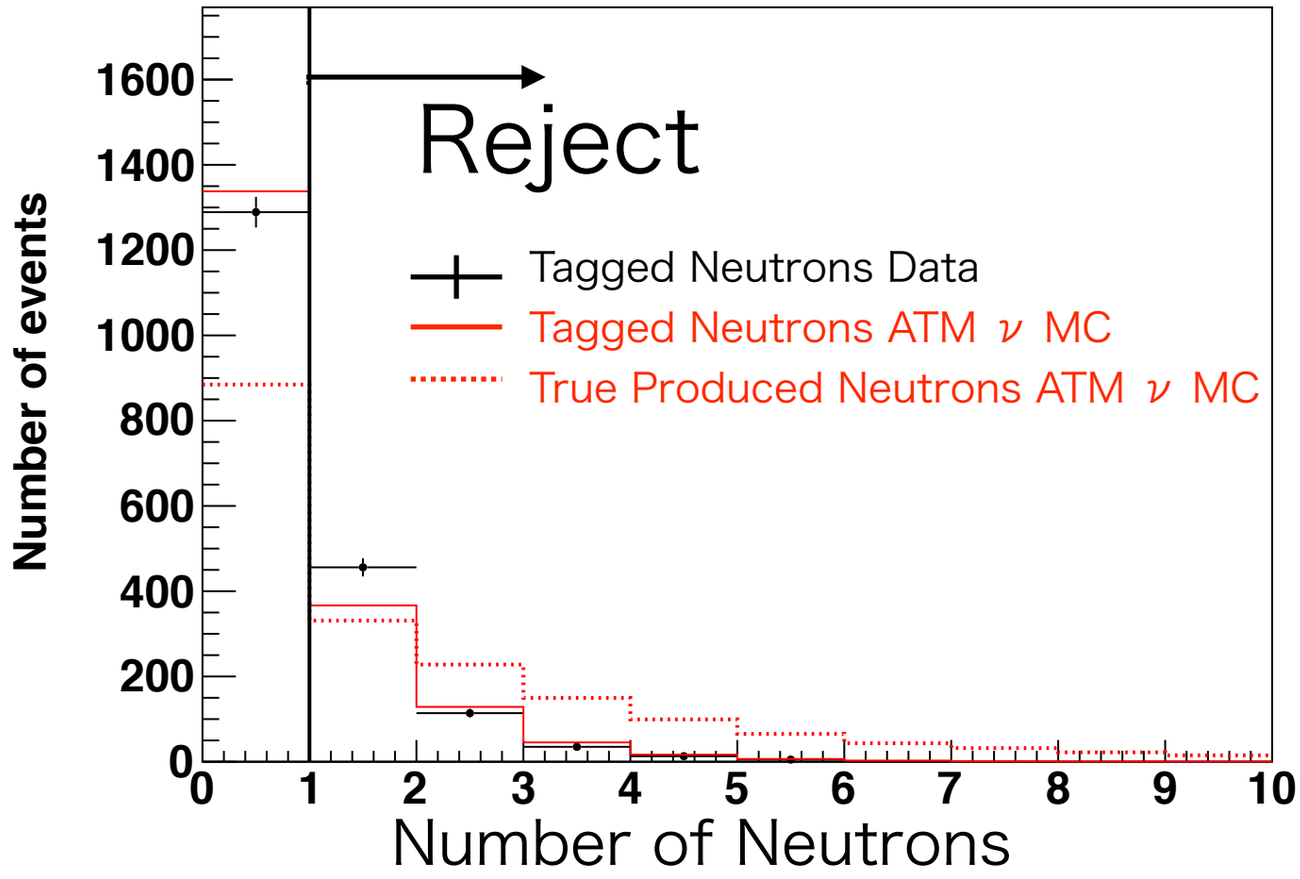
- All secondary particles (e^+, γ) can be reconstructed.
- From unique (back-to-back) event topology, **signal and background (atmospheric ν) can be clearly discriminated**.
- **Free protons (H)** are available in Super-K.
  - **Free from fermi motion and nuclear effects.**

Background & Reduction Technique

Atmospheric ν



Neutron Multiplicity



- Atmospheric (ATM) neutrino events can mimic p-decay signal.
  - ~60% of them are produced via CC pion production interaction.
  - **Often accompanied with neutrons.**
- Since SKIV (2008~2018), faint signature of **neutrons (γs) can be recorded** thanks to electronics upgrade. (n+p→d+γ (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 π^0 mass cut

$85 < M_{\pi^0} < 185$ MeV/c²

6. Total Mass cut

$800 < M_{tot} < 1050$ MeV/c²

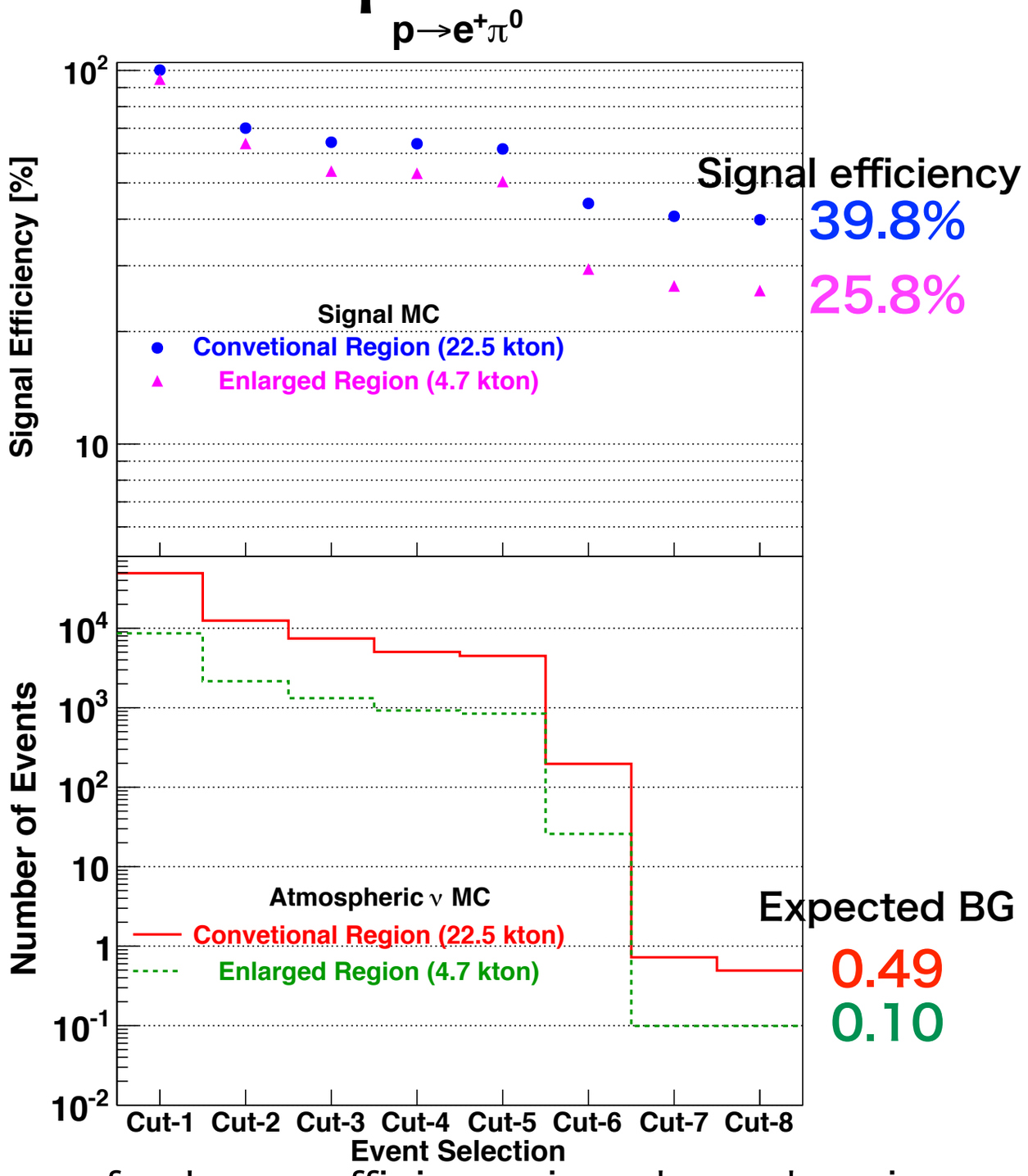
7. Total Momentum Cut

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

(Free proton rich & Low ATM ν BG)

Box2: $100 < P_{tot} < 250$ MeV/c

8. For SKIV, **no tagged neutrons**.

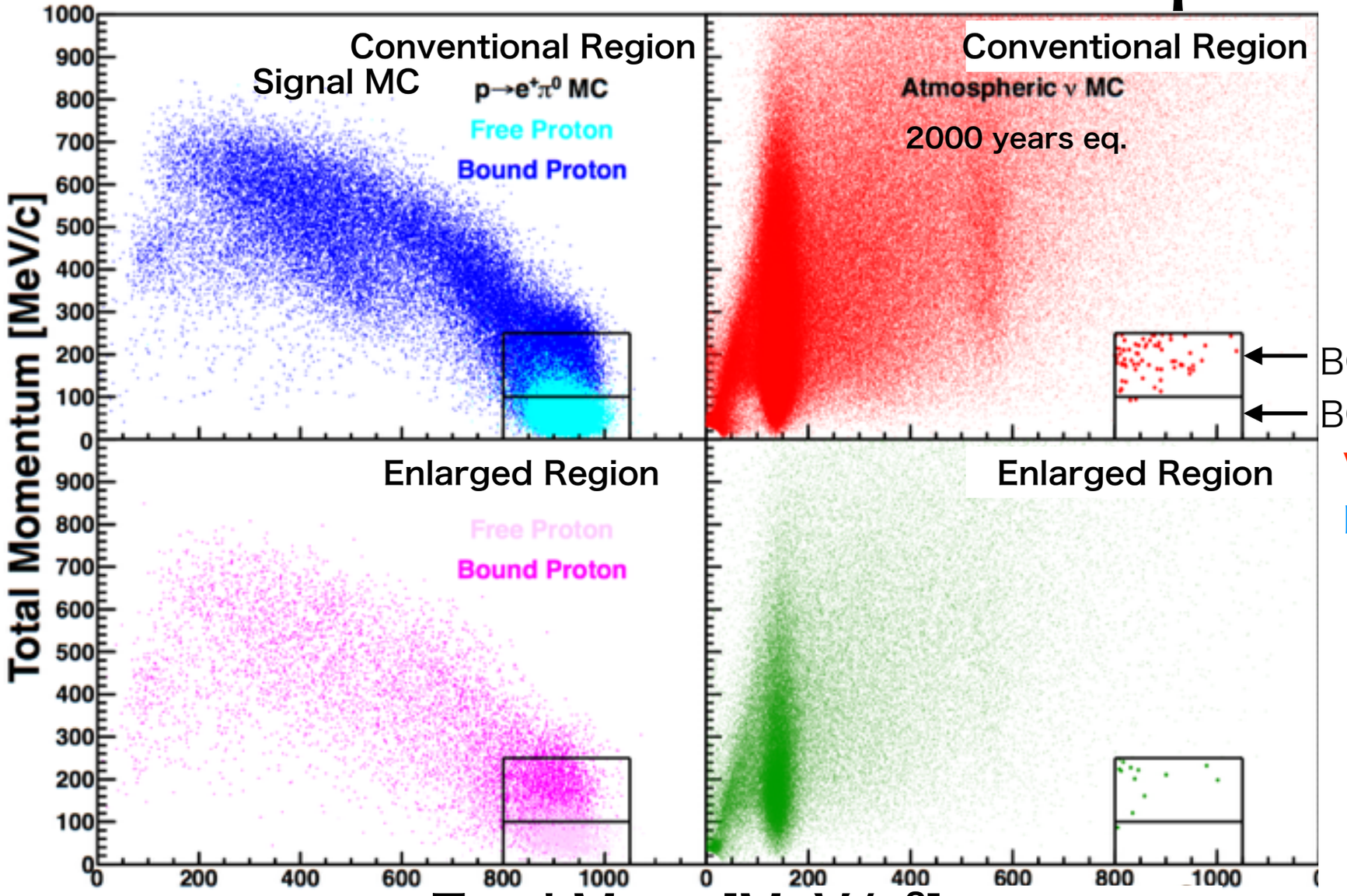


Causes for lower efficiency in enlarged region:

- Smaller number of PMT hits → difficulty in PID.
- Particle escape from detector → total energy loss.

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

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



Before M_{tot}, P_{tot} cuts

Signal Box
BOX2: $100 < P_{tot} < 250$ MeV/c
BOX1: $P_{tot} < 100$ MeV/c

Very low ATM ν BG.
Free proton rich.

	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

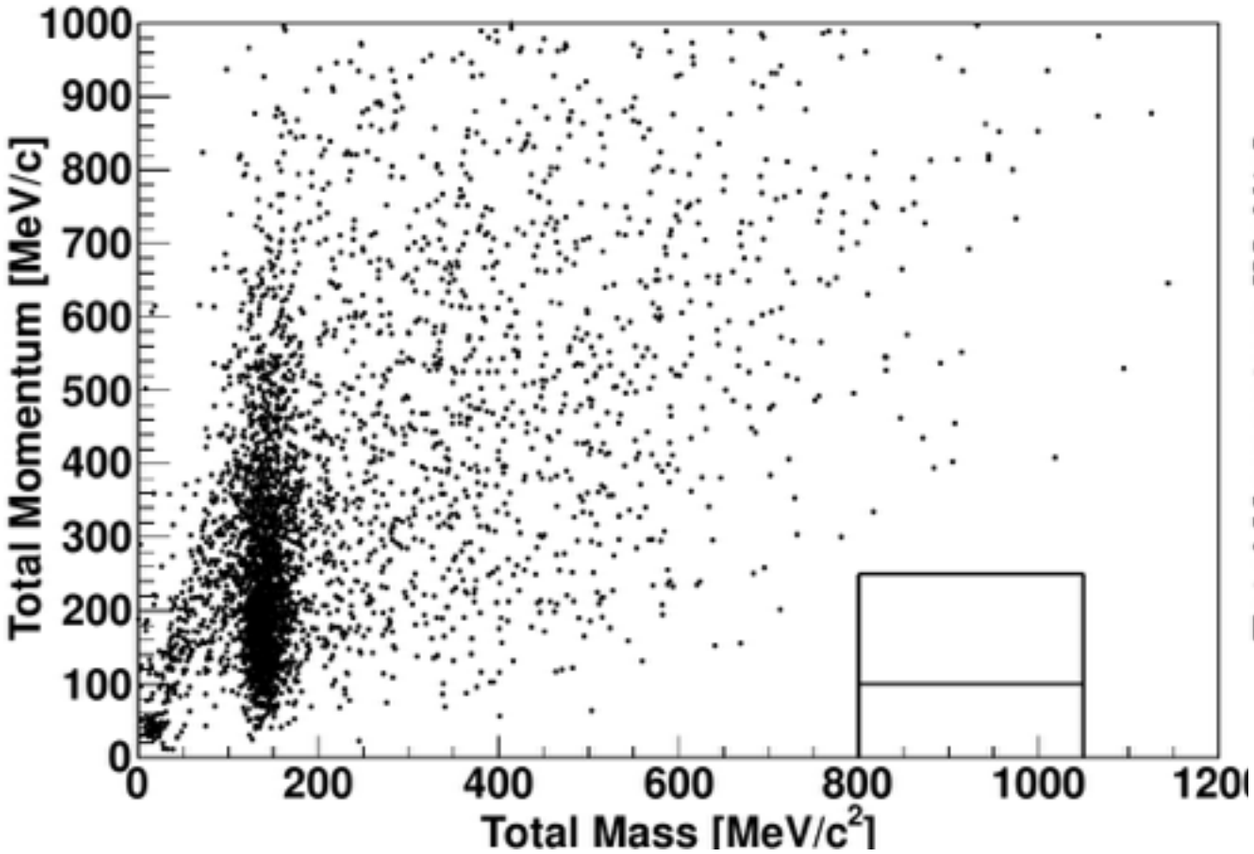
+/- denotes MC stat. & sys. uncertainties

← **Almost BG free!**

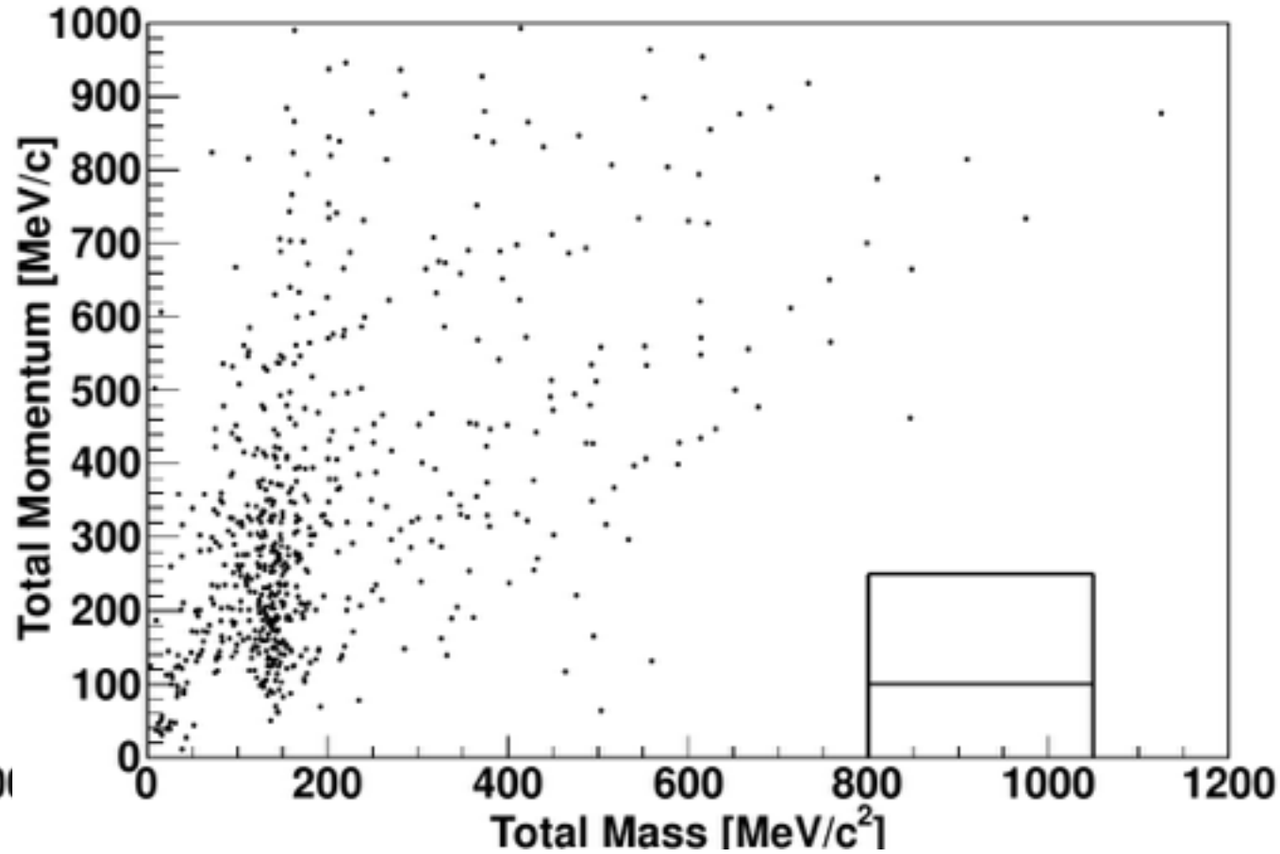
Data Result $p \to e^+ \pi^0$

Data SKI~IV 450 kton*years.

Conventional Region 372 kton*years

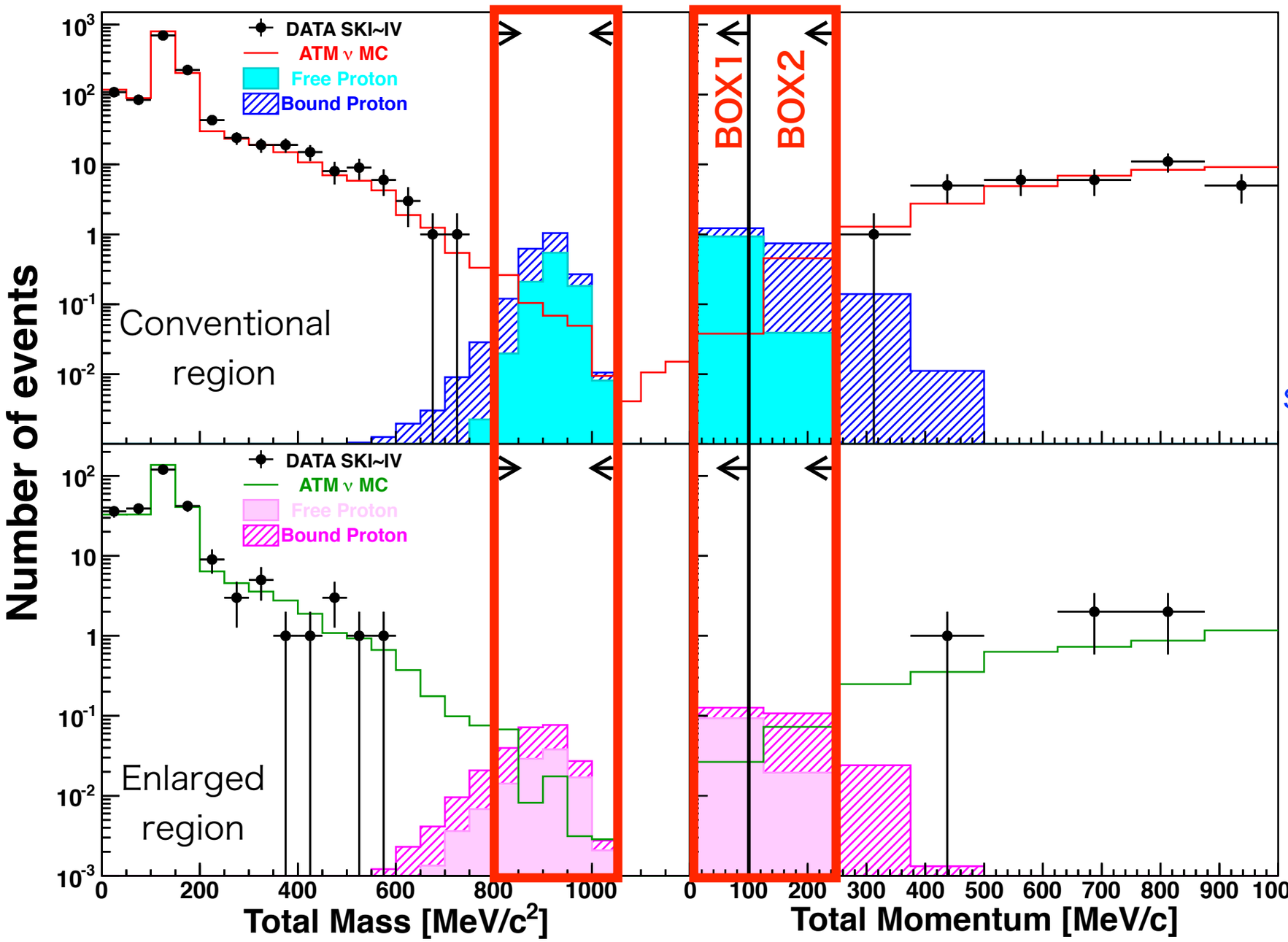


Enlarged Region 78 kton*years



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

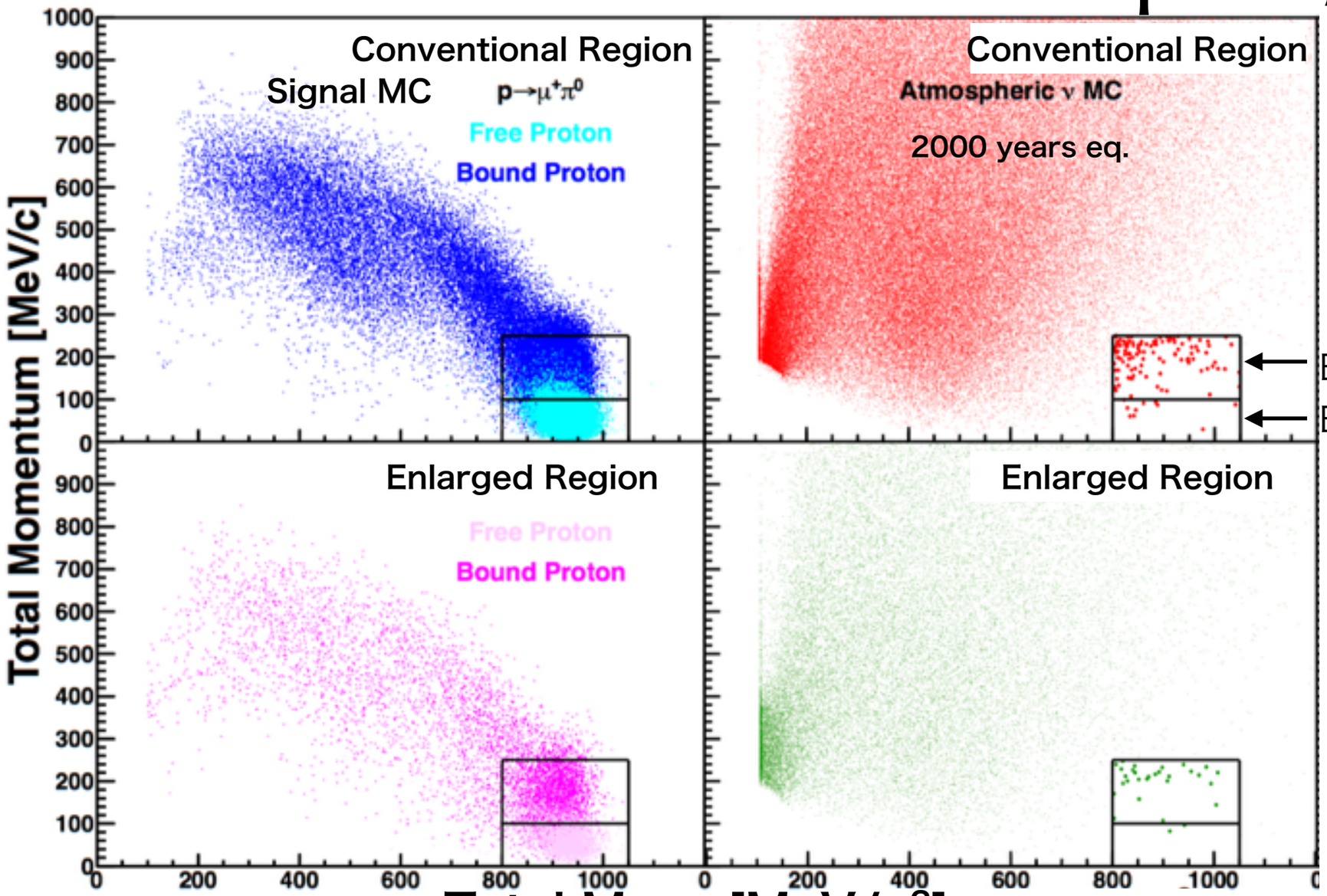
Data Result $p \to e^+ \pi^0$



Signal hist: Normalized by signal upper limit (90%C.L).

- No candidates in signal box incl. enlarged region.
  - **$\tau / B_{p \to e^+ \pi^0} > 2.4 * 10^{34}$ years (90%C.L.)**
- Data is consistent with ATM ν MC prediction.

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



Almost same criteria as $p \to e^+ \pi^0$ but require

- 1 mu-like ring
- 1 Michel Electron

Signal Box

BOX2: $100 < P_{tot} < 250$ MeV/c

BOX1: $P_{tot} < 100$ MeV/c

Very low ATM ν BG.

Free proton rich.

	Fiducial Mass	22.5 kton	4.7 kton
	Exposure	372 kton*years	78 kton*years
Signal Efficiency	BOX1	18.5+/-1.7%	11.7+/-1.2%
	BOX2	17.8+/-3.3%	13.5+/-2.4%
	TOTAL	36.3%+/-3.7%	25.2+/-2.7%
Expected BG [/livetime]	BOX1	0.04+/-0.03 ev	0.01+/-0.01 ev
	BOX2	0.70+/-0.24 ev	0.19+/-0.08 ev
	TOTAL	0.74+/-0.24 ev	0.20+/-0.08 ev

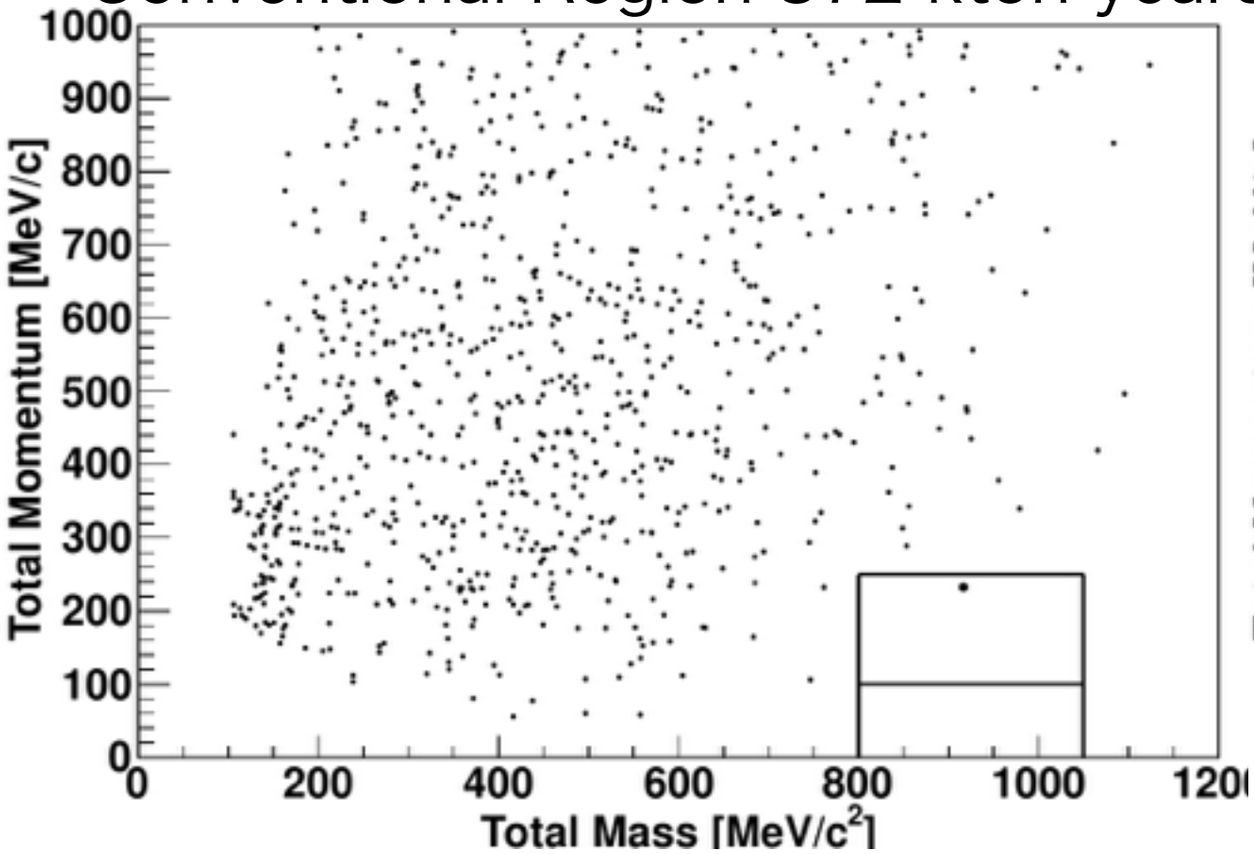
+/- denotes MC stat. & sys. uncertainties

← **Almost BG free!**

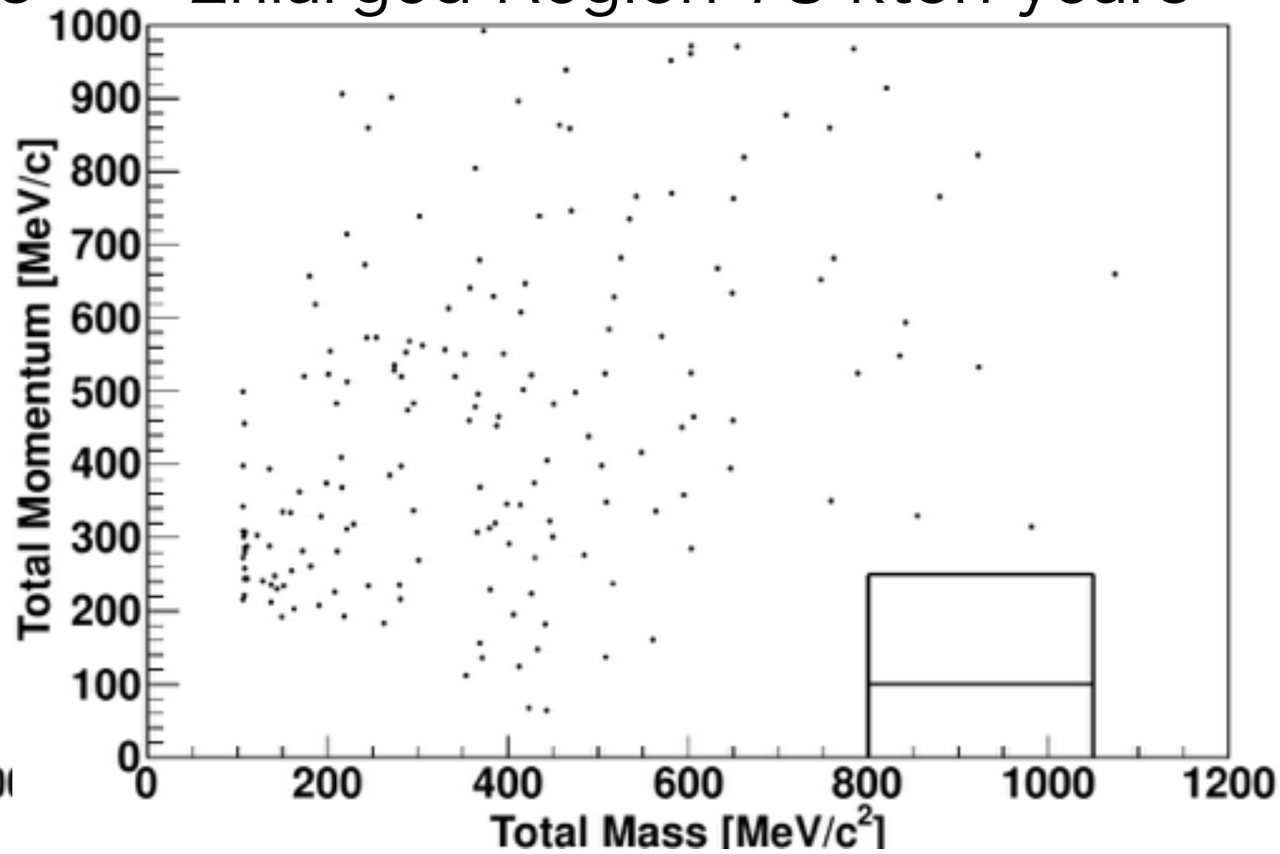
Data Result $p \to \mu^+ \pi^0$

Data SKI~IV 450 kton*years.

Conventional Region 372 kton*years



Enlarged Region 78 kton*years

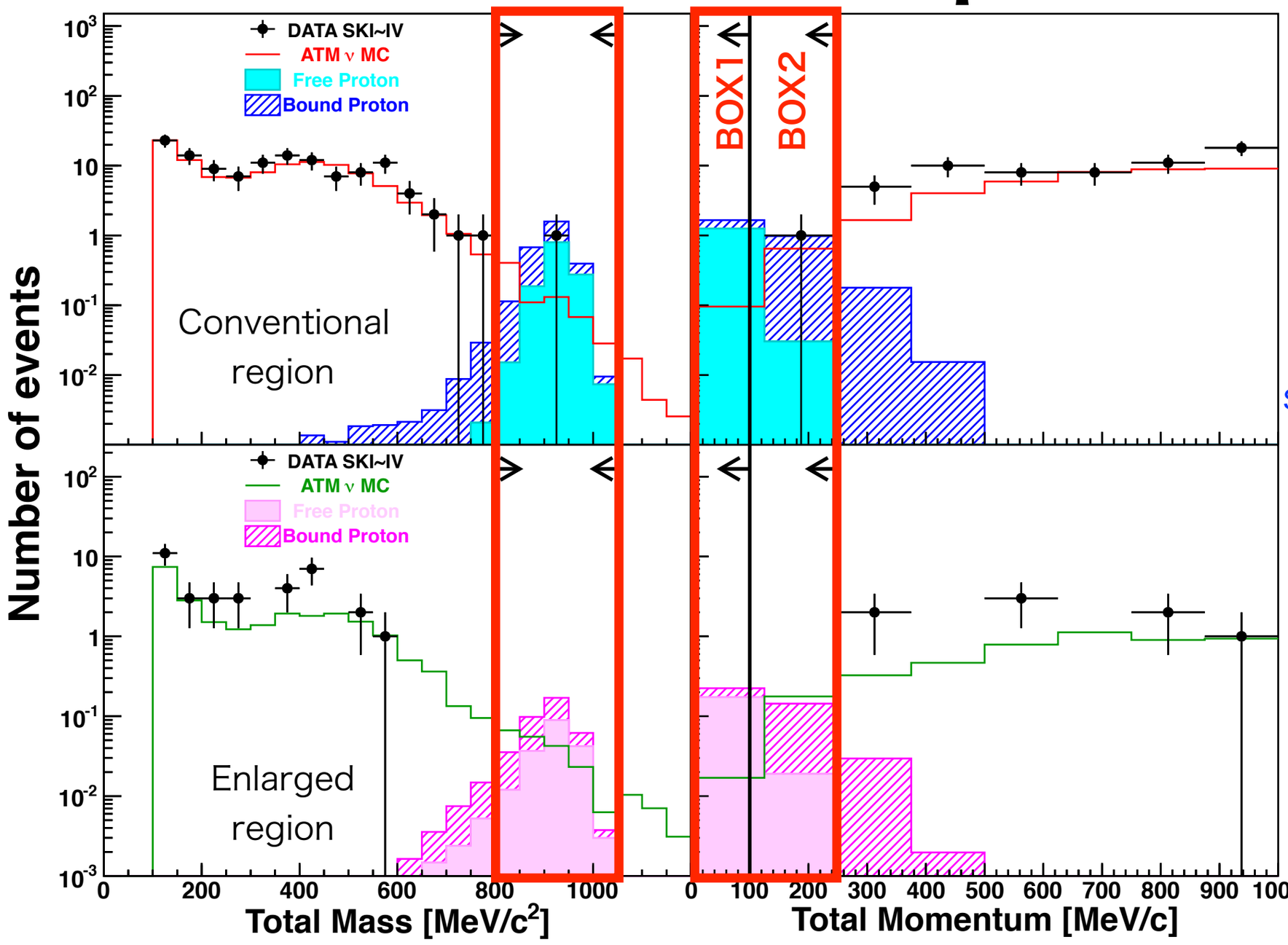


- 1 candidate in BOX2. Same event reported in the last paper.
  - Reasonable reconstruction result.

PRD 95, 012004 (2017)

- No new candidates incl. in enlarged region.
- No significant data excess compared to expected BG (0.89 in BOX2).
- Lower lifetime limit @90%C.L.
  - **$\tau / B_{p \to \mu + \pi 0} > 1.6 * 10^{34}$ years (published: $7.7 * 10^{33}$ years)**
- Most stringent constraint. **~2 times longer than published.**

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



Signal hist: Normalized by signal upper limit (90%C.L).

- 1 candidate in BOX2. (With BOX2 BG 0.89)
  - **$\tau / B_{p \to \mu + \pi 0}$ > 1.6*10³⁴ years (90%C.L.)**
- Data is consistent with ATM ν MC prediction.

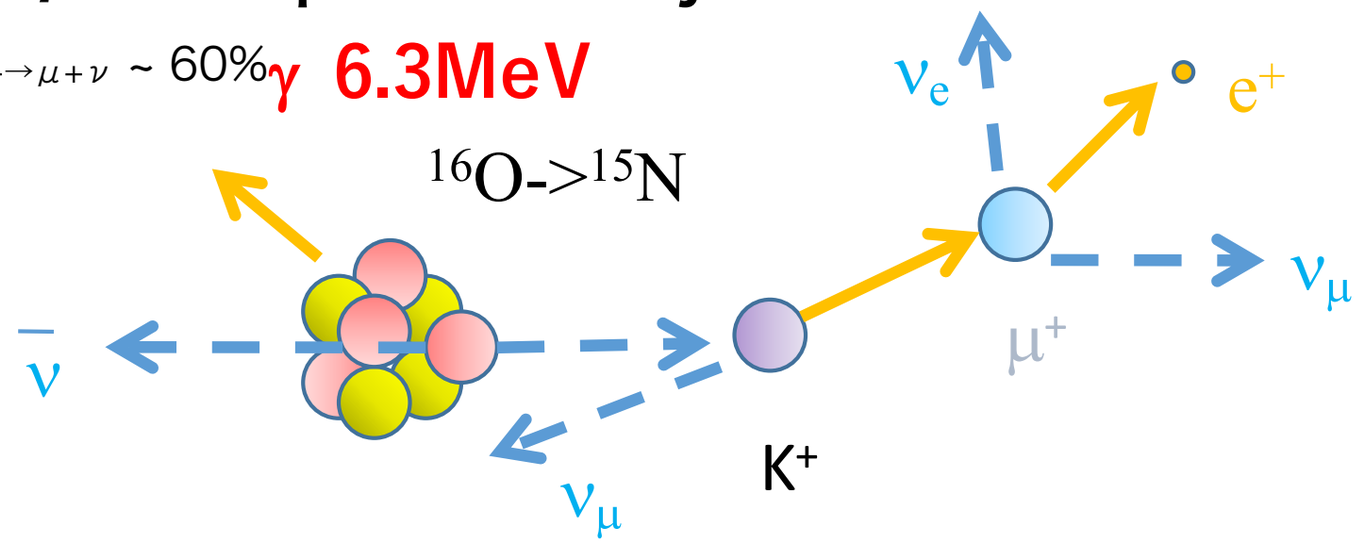
Other Decay Modes (Conventional Fiducial Mass Analysis Results)

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

Favored in SUSY.

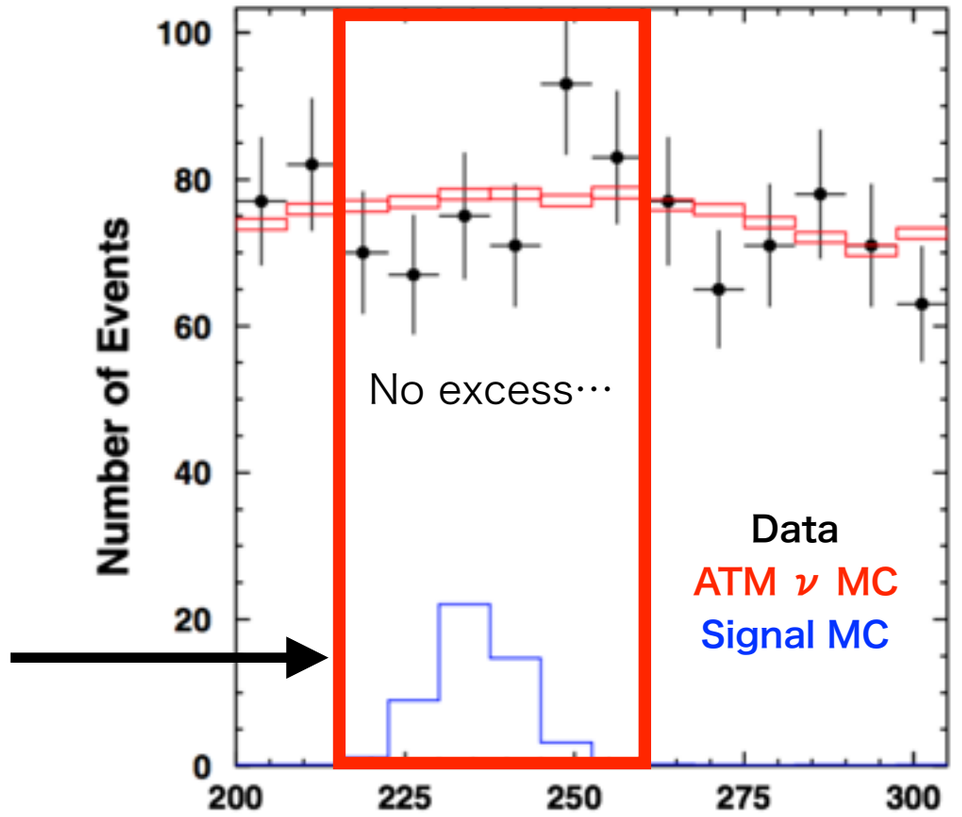
$K^+ \to \mu^+ \nu$: Leptonic decay channel

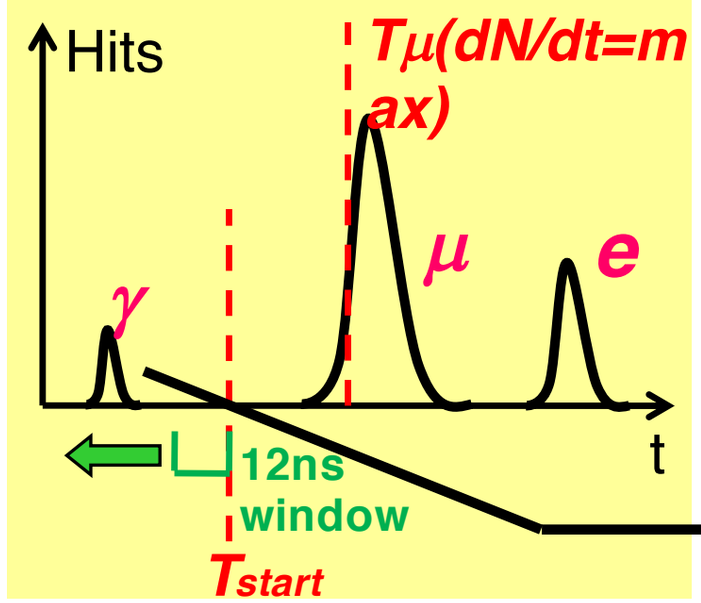
$BR_{K^+ \to \mu^+ \nu}$ ~ 60% γ **6.3MeV**

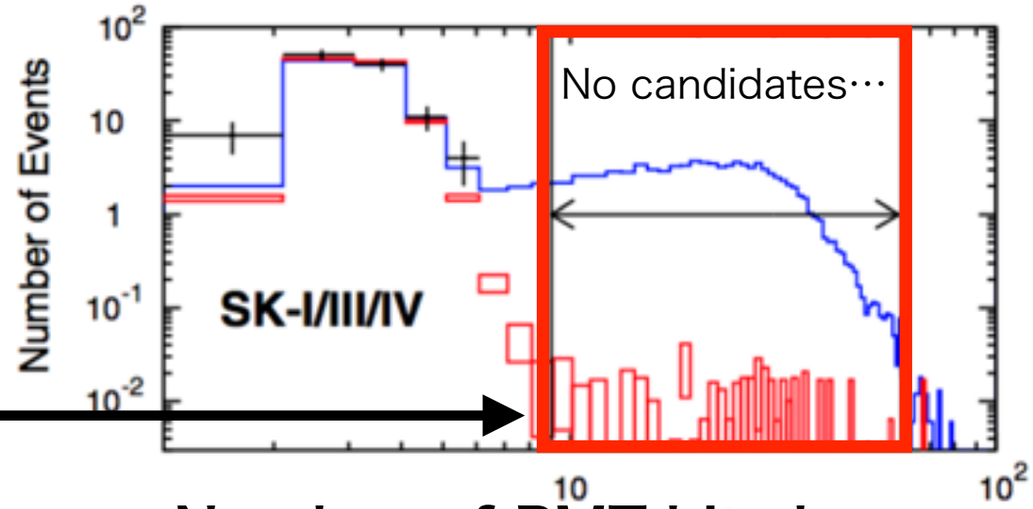


(a) Mono-energetic (236 MeV/c) μ search

· ε ~35%. No significant excess…







(b) Tag De-excitation 6.3 MeV γ and Michel-e

· Require γ, μ, and Michel-e triple coincidence.

· ε ~9%. No candidates…

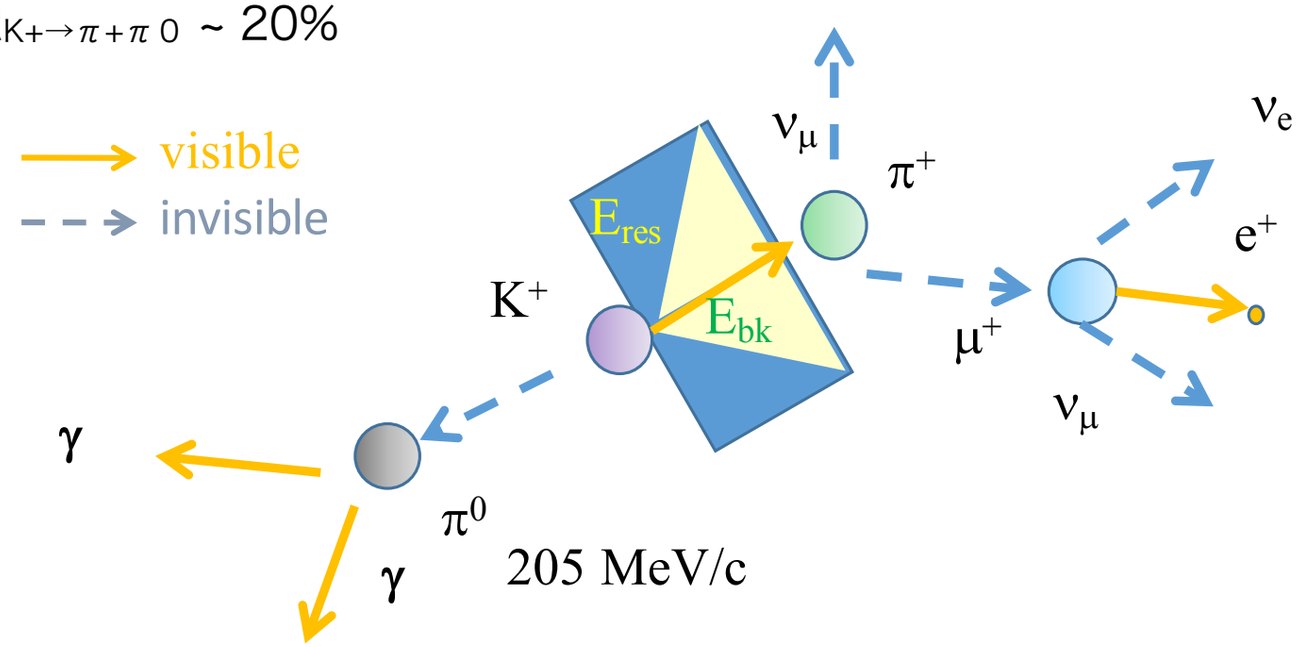
PRD 90, 072005 (2014)

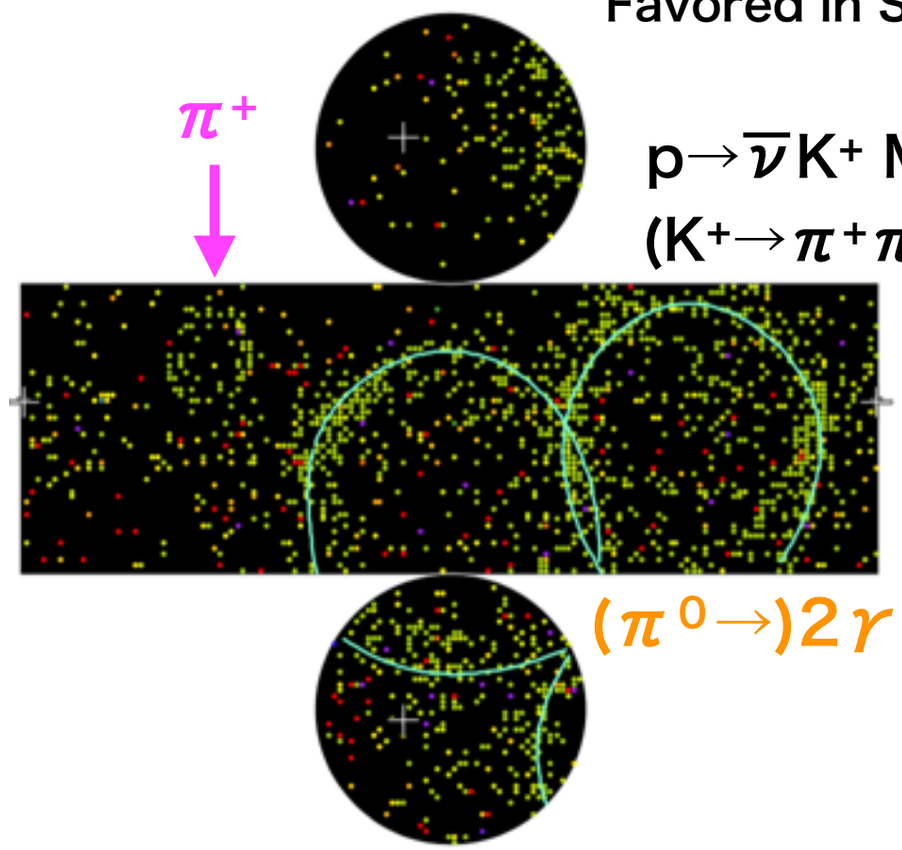
Search for $p \to \bar{\nu} K^+$

Favored in SUSY.

$K^+ \to \pi^+ \pi^0$: Hadronic decay channel

$BR_{K^+ \to \pi^+ \pi^0}$ ~ 20%





(c) Search for $\pi^+ \pi^0$ back-to-back signal

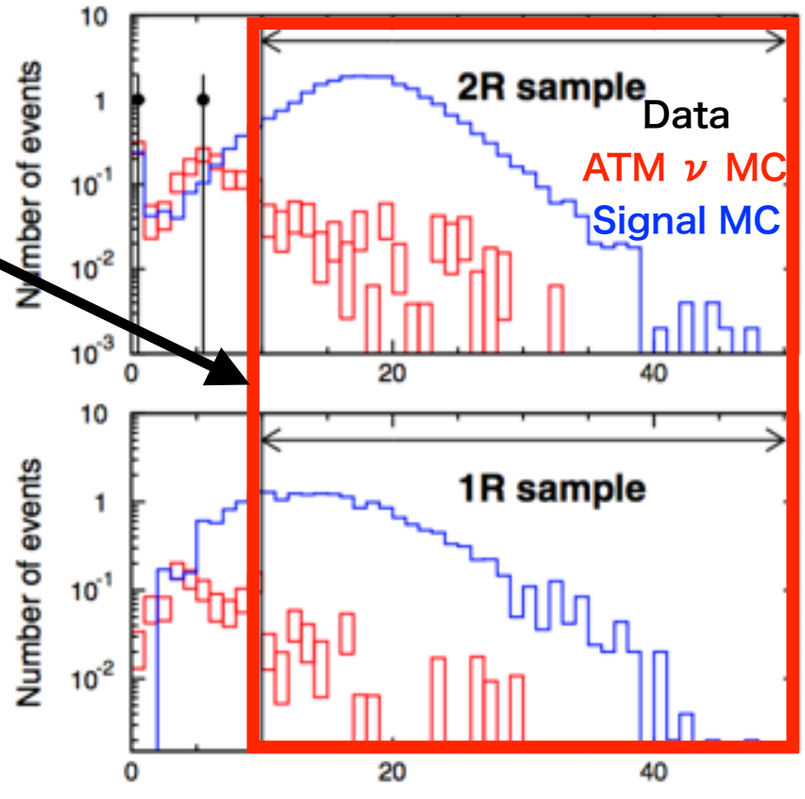
- ε ~9%. No candidates …

PRD 90, 072005 (2014)

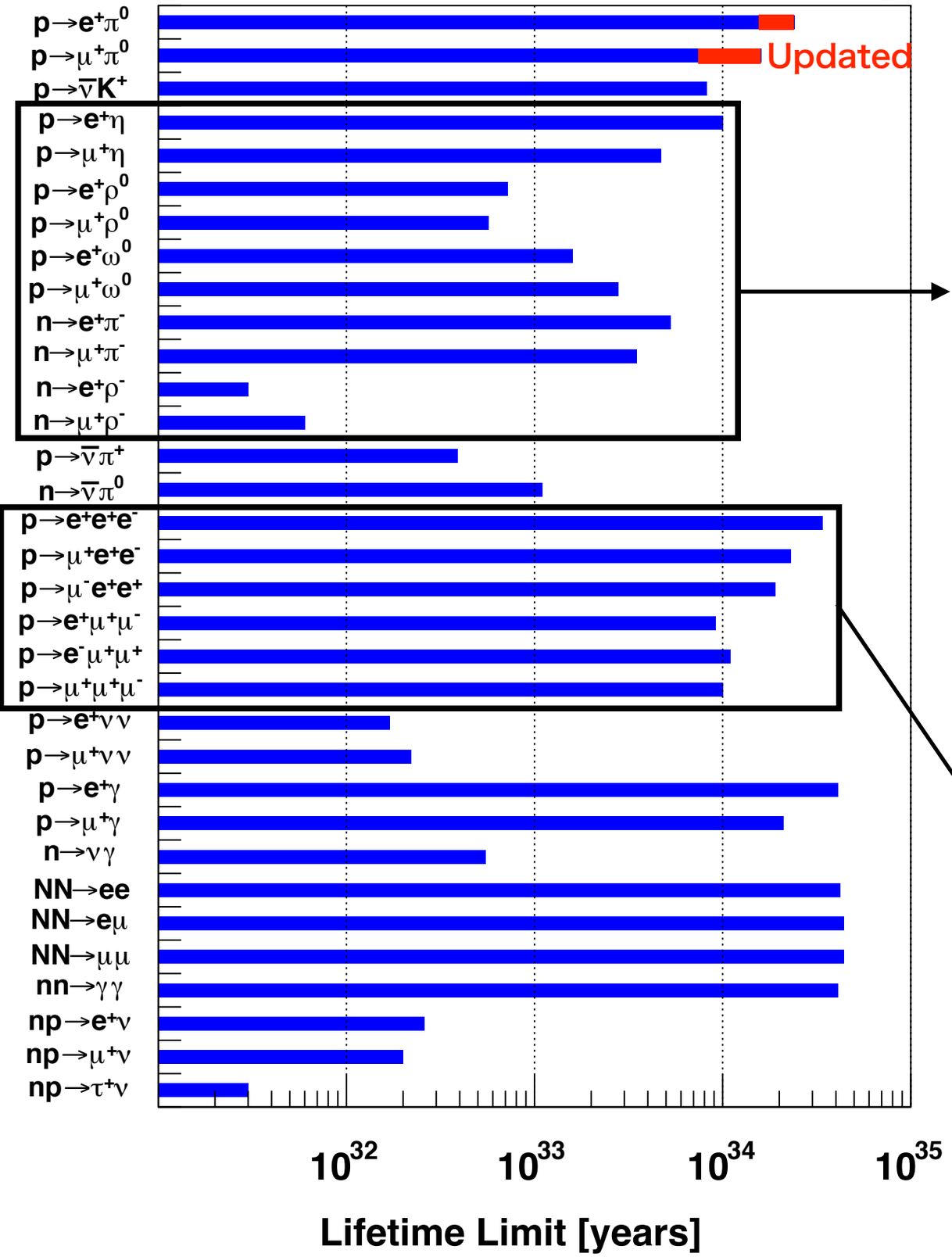
- Combining three search methods with SKI~IV data (365 kton*years)
- **$\tau / B_{p \to \nu K^+} > 8.2 * 10^{33}$ years (90%C.L.)**

[Super-K Preliminary]

- Will study feasibility of enlarging fiducial mass for this search.



Nucleon Decay Search Summary



Systematic $[e^+, \mu^+] \times [\eta, \rho, \omega, \pi]$ searches

PRD 96, 012003 (2017)

Modes	Eff (%)	Background (events)	Candidate (events)	Probability (%)	Lifetime Limit ($\times 10^{33}$ years) at 90% CL
$p \to e^+\eta$	16.0	0.78 ± 0.30	0	···	10.
$p \to \mu^+\eta$	23.3	0.85 ± 0.23	2	20.9	4.7
$p \to e^+\rho^0$	3.8	0.64 ± 0.17	2	13.5	0.72
$p \to \mu^+\rho^0$	1.9	1.30 ± 0.33	1	72.7	0.57
$p \to e^+\omega$	4.8	1.35 ± 0.43	1	74.1	1.6
$p \to \mu^+\omega$	7.9	1.09 ± 0.52	0	···	2.8
$n \to e^+\pi^-$	12.6	0.41 ± 0.13	0	···	5.3
$n \to \mu^+\pi^-$	13.4	0.77 ± 0.20	1	53.7	3.5
$n \to e^+\rho^-$	1.5	0.87 ± 0.26	4	1.2	0.03
$n \to \mu^+\rho^-$	1.2	0.96 ± 0.28	1	61.7	0.06
total		8.6	12	15.7	···

Three charged leptons searches

To be published.

Modes	Eff (%)	Background (events)	Candidate (events)	Probability (%)	Lifetime limit ($\times 10^{34}$ years) at 90% CL
$p \to e^+e^+e^-$	63.5	0.58±0.08	0	-	3.4
$p \to \mu^+e^+e^-$	47.9	0.50±0.06	0	-	2.3
$p \to \mu^-e^+e^+$	40.8	0.50±0.06	0	-	1.9
$p \to e^+\mu^+\mu^-$	32.6	0.27±0.04	1	18.4	0.92
$p \to e^-\mu^+\mu^+$	38.6	0.27±0.04	1	18.4	1.1
$p \to \mu^+\mu^+\mu^-$	32.6	0.40±0.07	1	25.8	1.0

- No evidence of N-decay so far ···. There is still room for statistic improvement (livetime & fiducial mass) except for $p \to e^+\pi^0$ & $p \to \mu^+\pi^0$.

Future Prospect

- To increase the search sensitivity, **atmospheric ν background rejection** and **larger exposure** are crucial.
- Plan to load Gd into Super-K (SK-Gd) in 2020.

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

Neutron Tagging efficiency	~25% (H capture)	~50% (Gd 0.01%)	~90% (Gd 0.1%)
ATM ν BG Reduction by Ntag	~50%	~65%	~80%

- With **Hyper-K (fiducial mass:~190 kton), sensitivity will reach $\tau/B_{p\to e+\pi 0}$~10^{35} years** for 20 years operation.
  - **Neutron tagging efficiency ~70% (w/ more sensitive PMT)**
  - Aim to start construction in 2020.

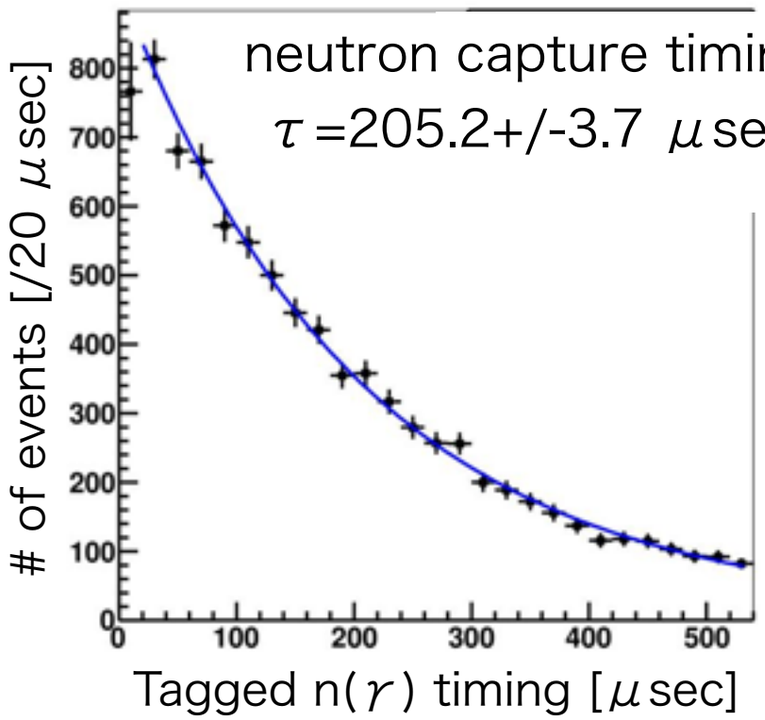
Conclusion

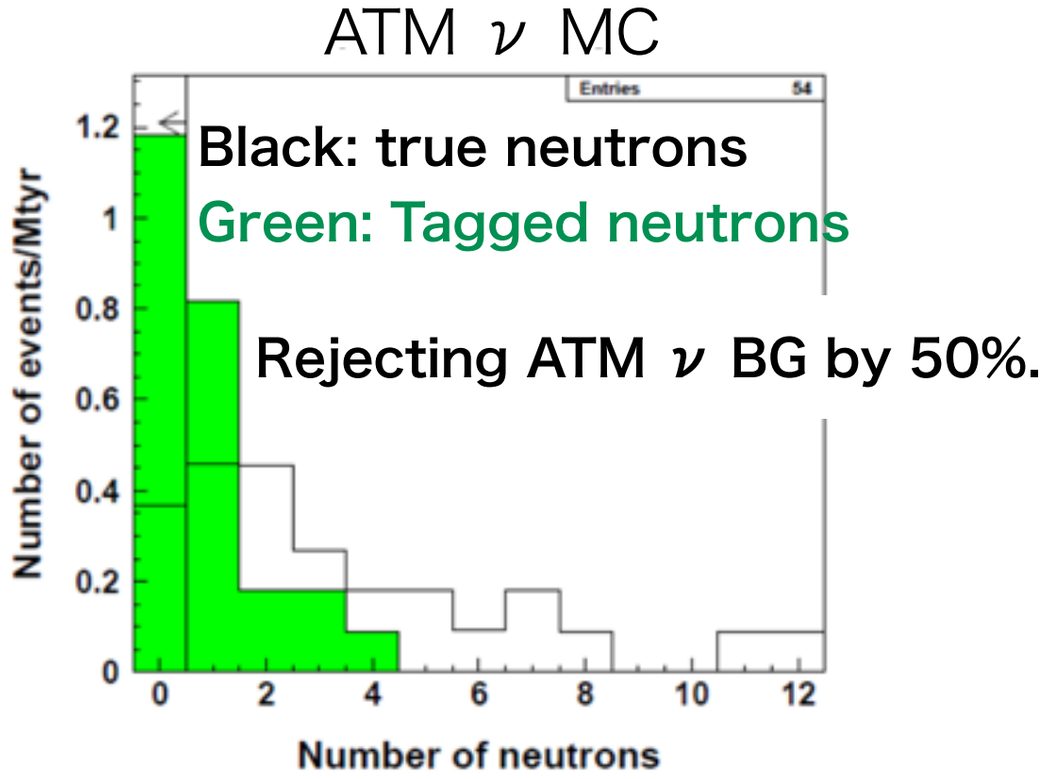
- Performed proton decay search ($p \to e^+ \pi^0$, $p \to \mu^+ \pi^0$) with enlarged fiducial mass of Super-Kamiokande detector.
  - Fiducial mass: 22.5 kton → 27.2 kton
- No evidence of proton decay…
  - **SKI~IV full livetime 450 kton*years**
  - **$\tau / B_{p \to e^+ \pi^0} > 2.4 * 10^{34}$ years (90%C.L.) (no candidates)**
  - **$\tau / B_{p \to \mu^+ \pi^0} > 1.6 * 10^{34}$ 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.

backup

Neutron Tagging

- Major background for proton decay search is ATM ν events (often accompanied with neutrons).
- Since SKIV, can record faint signature of neutrons (γ s) thanks to electronics upgrade. (n+p→d+γ (2.2 MeV))
- By requiring no tagged neutrons.
  - efficiency loss: <4%,
  - **ATM ν BG reduction by ~50%.**





Systematic Uncertainty epi0

Systematics on signal Efficiency [%]

Item	dwall>200 cm		100<dwall<=200 cm		dwall>100 cm	
	Lower Box	Higher Box	Lower Box	Higher Box	Lower Box	Higher Box
Recon. Total	3.5	2.8	10.3	10.0	3.6	3.2
Correlated Decay	1.7	9.0	2.7	8.4	1.9	8.9
Fermi Momentum	7.2	6.7	7.8	1.0	7.2	5.7
π FSI	2.8	11.9	3.8	10.6	2.9	11.7
Physiscs Total	7.9	16.4	9.1	13.5	8.0	15.8
Total	8.6	16.6	13.7	16.8	**8.8**	**16.1**

Systematics on ATM ν BG [%]

Item	dwall>200 cm	100<dwall<=200 cm	dwall>100 cm
	Total Box	Total Box	Total Box
Recon. Total	21.3	25.2	20.5
ν Flux	7.3	7.2	7.3
ν Interaction	21.2	17.3	19.8
π FSI	12.8	13.9	12.7
Physiscs Total	25.8	23.3	24.6
Total	33.5	34.3	**32.0**

Systematic Uncertainty mupi0

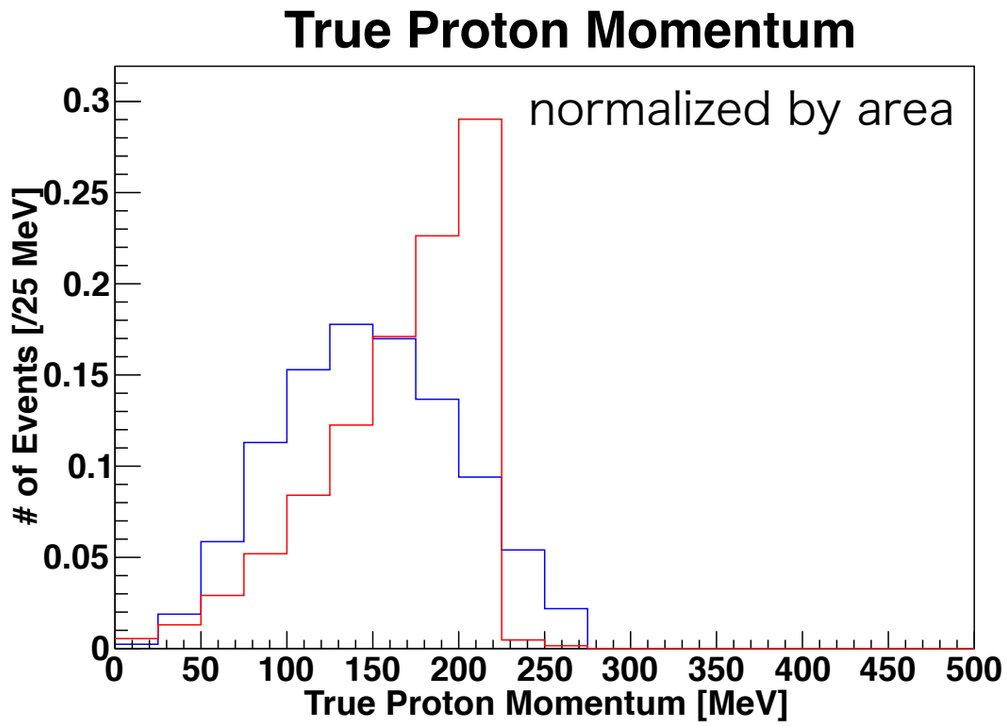
Systematics on signal Efficiency [%]

Item	dwall>200 cm		100<dwall<=200 cm		dwall>100 cm	
	Lower Box	Higher Box	Lower Box	Higher Box	Lower Box	Higher Box
Recon. Total	4.5	4.0	7.1	9.5	4.8	4.5
Correlated Decay	1.9	9.3	2.0	8.4	1.9	9.2
Fermi Momentum	7.3	8.3	6.8	4.0	7.2	7.7
π FSI	2.7	13.3	2.9	11.3	2.7	13.0
Physiscs Total	8.0	18.2	7.7	14.7	8.0	17.7
Total	9.2	18.7	10.4	17.5	**9.3**	**18.2**

Systematics on ATM ν BG [%]

Item	dwall>200 cm	100<dwall<=200 cm	dwall>100 cm
	Total Box	Total Box	Total Box
Recon. Total	16.5	21.4	15.6
ν Flux	7.2	7.3	7.3
ν Interaction	19.0	16.8	18.3
π FSI	9.3	11.3	8.0
Physiscs Total	22.4	21.5	21.2
Total	27.8	30.3	**26.3**

Fermi Motion



epi0

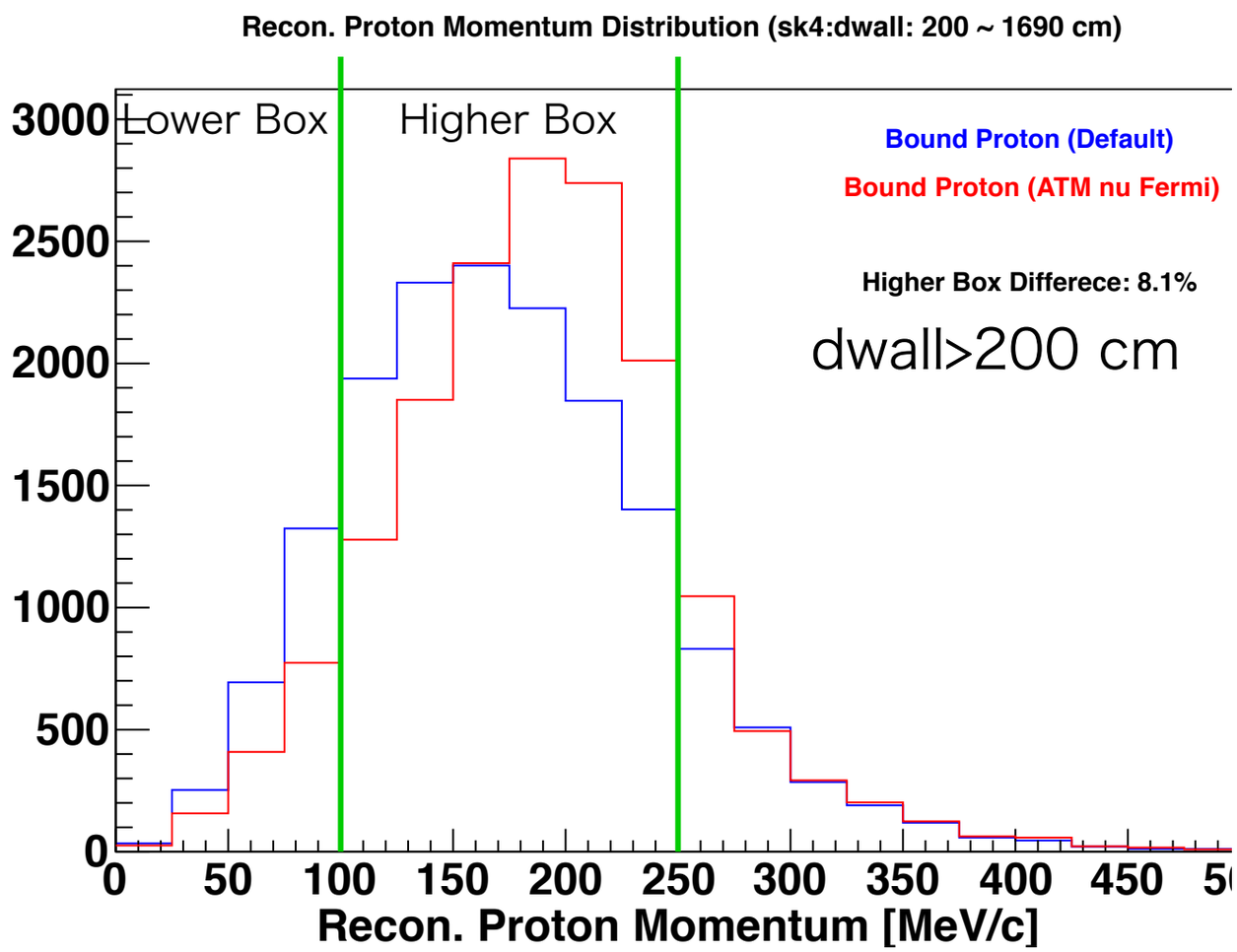
Blue: Signal MC

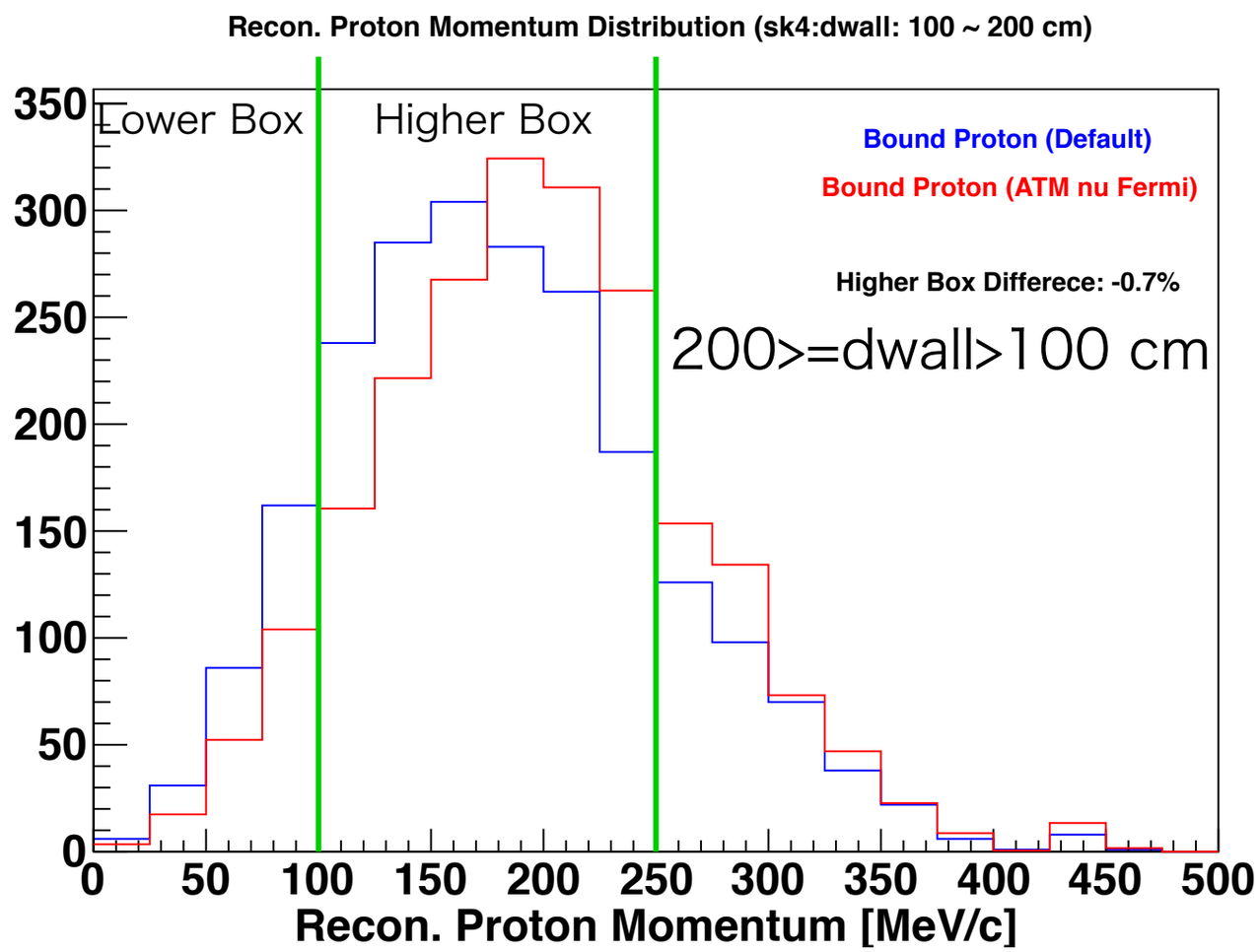
(Based on experimental result)

Red: ATM ν MC

Fermi Model

Estimate uncertainty by re-weighting from Blue to Red.





Limit Calculation epi0

Search Performance (dwall>100 cm:450 kton*yrs)

Box	SK1 (111.4 kton*yrs)		SK2 (59.4 kton*yrs)		SK3 (38.5 kton*yrs)		SK4 (241.3 kton*yrs)	
	Low Box	High Box	Low Box	High Box	Low Box	High Box	Low Box	High Box
Efficiency [%]	18.3+/-1.7	20.0+/-3.3	16.6+/-1.7	19.4+/-3.0	18.7+/-1.7	20.3+/-3.3	18.2+/-1.5	19.2+/-3.1
ATM ν BG [/livetime]	0.01+/-0.01	0.15+/-0.06	0.01+/-0.01	0.11+/-0.04	<0.01	0.07+/-0.03	<0.01	0.25+/-0.11
ATM ν BG [/Mt*yr]	0.07+/-0.08	1.32+/-0.52	0.14+/-0.11	1.85+/-0.70	<0.01	1.73+/-0.66	<0.01	1.04+/-0.44
OBS	0	0	0	0	0	0	0	0

+/- XX is quadratic sum of MC stat & sys. uncertainties.

Sys. for signal eff [%]

Item	dwall>100 cm	
	Lower Box	Higher Box
Recon. Total	3.6	3.2
Correlated Decay	1.9	8.9
Fermi Momentum	7.2	5.7
π FSI	2.9	11.7
Physiscs Total	8.0	15.8
Total	8.8	16.1

Sys. for ATM ν BG [%]

Item	dwall>100 cm
	Total Box
Recon. Total	20.5
ν Flux	7.3
ν Interaction	19.8
π FSI	12.9
Physiscs Total	24.6
Total	32.0

- Lifetime limit is calculated with dwall>100 cm inclusive performance (above) numbers.
- **$\tau_{p\to e+\pi^0}$ (dwall>1 m: 450 kton*yrs) > $2.4*10^{34}$ yrs (90%C.L.)**

Limit Calculation mupi0

Search Performance (dwall>100 cm:450 kton*yrs)

Box	SK1 (111.4 kton*yrs) Low Box	SK1 (111.4 kton*yrs) High Box	SK2 (59.4 kton*yrs) Low Box	SK2 (59.4 kton*yrs) High Box	SK3 (38.5 kton*yrs) Low Box	SK3 (38.5 kton*yrs) High Box	SK4 (241.3 kton*yrs) Low Box	SK4 (241.3 kton*yrs) High Box
Efficiency [%]	16.0+/-1.5	16.0+/-2.9	14.9+/-1.4	15.8+/-2.7	16.4+/-1.5	16.1+/-2.9	18.7+/-1.7	18.2+/-3.4
ATM ν BG [/livetime]	0.03+/-0.02	0.21+/-0.07	0.01+/-0.01	0.14+/-0.04	0.01+/-0.01	0.08+/-0.03	<0.01	0.46+/-0.15
ATM ν BG [/Mt*yr]	0.25+/-0.15	1.91+/-0.61	0.13+/-0.10	2.27+/-0.71	0.26+/-0.15	2.05+/-0.66	0.02+/-0.01	1.90+/-0.62
OBS	0	0	0	0	0	0	0	1

+/- XX is quadratic sum of MC stat & sys. uncertainties.

Sys. for signal eff [%]

Item	dwall>100 cm Lower Box	dwall>100 cm Higher Box
Recon. Total	4.8	4.5
Correlated Decay	2.0	9.2
Fermi Momentum	7.2	7.7
π FSI	2.7	13.0
Physiscs Total	8.0	17.7
Total	9.3	18.2

Sys. for ATM ν BG [%]

Item	dwall>100 cm Total Box
Recon. Total	15.6
ν Flux	7.3
ν Interaction	18.3
π FSI	7.7
Physiscs Total	21.2
Total	26.3

- Lifetime limit is calculated with dwall>100 cm inclusive performance (above) numbers.
- **$\tau_{p\to\mu+\pi^0}$(dwall>1 m: 450 kton*yrs) > 1.6*10^{34} yrs (90%C.L.)**

Discovery Potential

Improvement by Expanding FV

- Calculated expected lifetime limit for both conventional FV case and larger FV case.

epi0 Search Performance

epi0	372 kton*yrs (dwall>200 cm)		450 kton*yrs (dwall>100 cm)	
	Signal Efficiency	ATM ν BG	Signal Efficiency	ATM ν BG
Lower Box	19.5+/-1.7%	0.01+/-0.01 ev	18.1+/-1.6%	0.02+/-0.02 ev
Higher Box	20.3+/-3.3%	0.48+/-0.21 ev	19.5+/-3.1%	0.57+/-0.23 ev

+/- includes MC stat. & sys (later in slides).

- $\tau_{p\to e+\pi^0}$(exp.): $1.7*10^{34}$ yrs → $1.9*10^{34}$ yrs.

mupi0 Search Performance

mupi0	372 kton*yrs (dwall>200 cm)		450 kton*yrs (dwall>100 cm)	
	Signal Efficiency	ATM ν BG	Signal Efficiency	ATM ν BG
Lower Box	18.5+/-1.7%	0.04+/-0.03 ev	17.4+/-1.7%	0.05+/-0.03 ev
Higher Box	17.8+/-3.2%	0.70+/-0.24 ev	17.1+/-3.2%	0.89+/-0.29 ev

- $\tau_{p\to\mu+\pi^0}$(exp.): $1.4*10^{34}$ yrs → $1.6*10^{34}$ yrs.

- **Expanding FV increases search sensitivity by ~12%.**
- **Confirmed FV expansion feasibility.**

Efficiency & Number of Events v.s. Selection Cut

Event Selection Cut

1. FCFV Cut
   (nhitac<16&&evis>30 MeV
   &&dwall>100 cm)
2. nring cut

(# of rings = 2 or 3)

3. PID cut

(ALL e-like rings)

4. No Michel Electron
5. For 3-ring events, pi0 mas
   cut

   (85 < Mpi0 < 185 MeV/c^2)
6. Total mass cut

   (800 < Mtot < 1050 MeV/c^2
7. Total momentum cut

Higher Box:

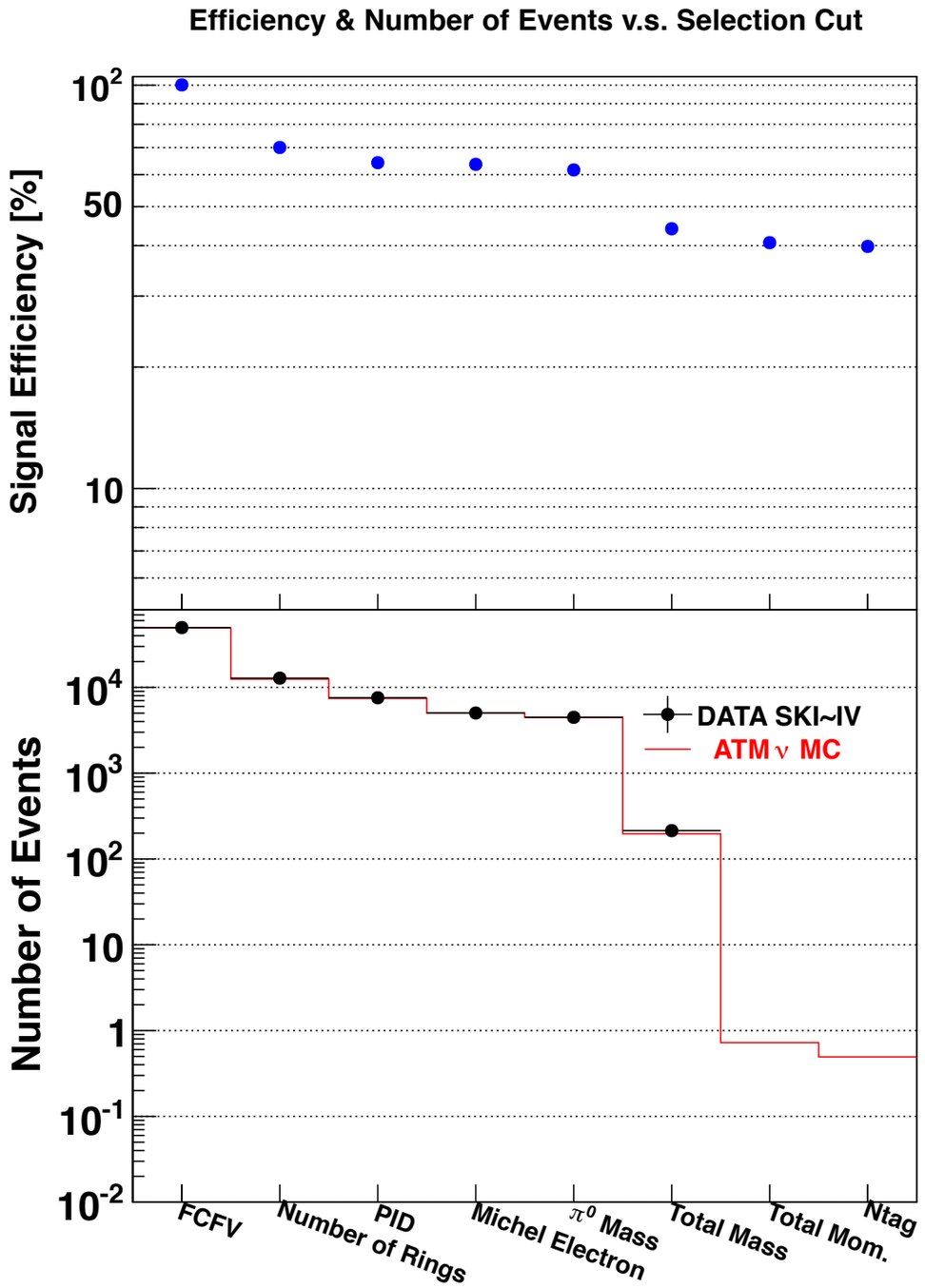
(100 <= Ptot < 250 MeV/c)

Lower Box:

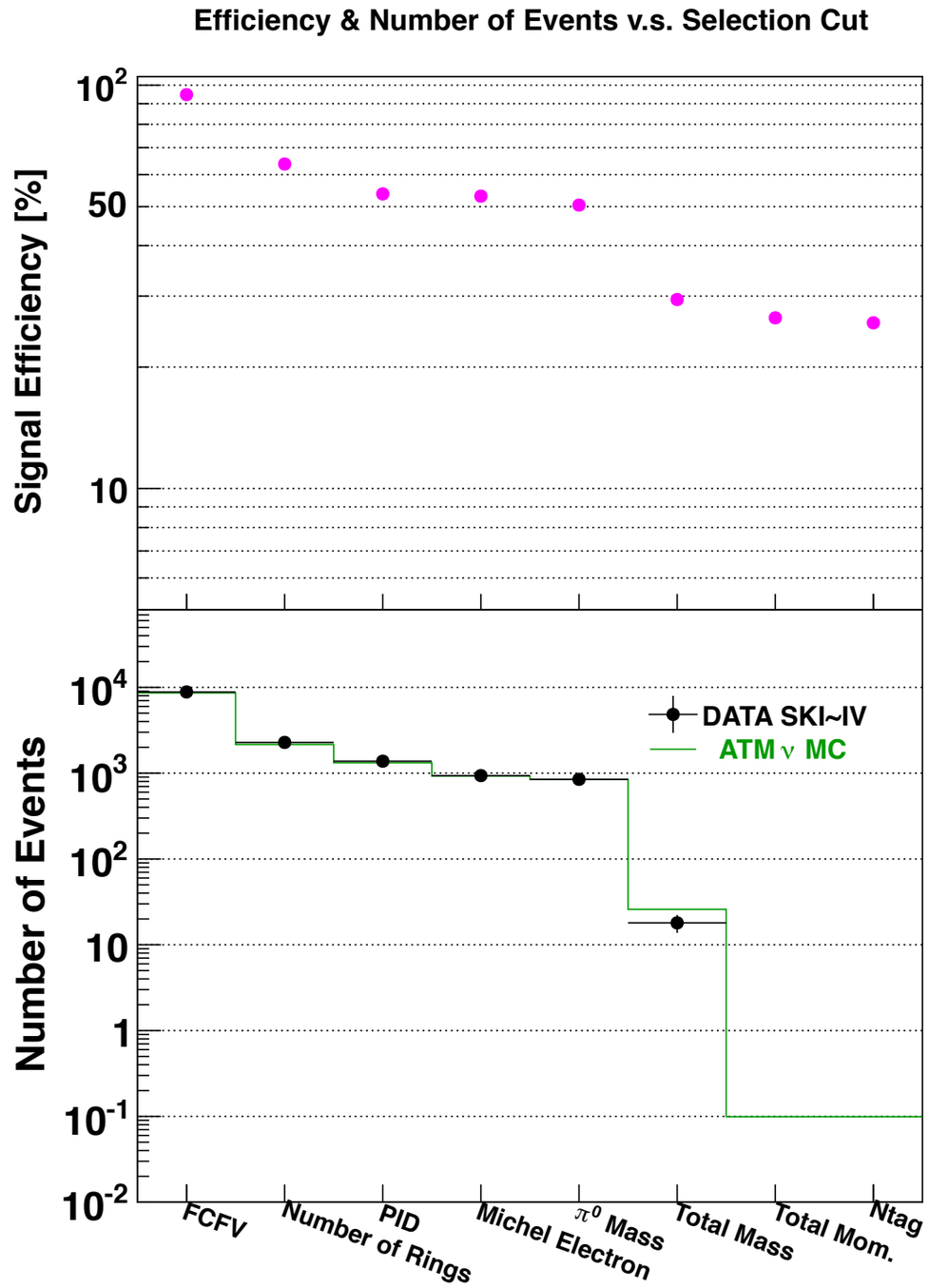
(Ptot < 100 MeV/c)

8. For SKIV, no neutron.

dwall>200 cm



200>=dwall>100 cm



ATM ν MC is normalized by livetime & 3 flavor oscillation parameters.

Efficiency & Number of Events v.s. Selection Cut

Event Selection Cut

1. FCFV Cut
   (nhitac<16&&evis>30 MeV
   &&dwall>100 cm)
2. nring cut
(# of rings = 2 or 3)
3. PID cut
(1 mu-like and 1 or 2 e-like ring
4. 1 Michel Electron
5. For 3-ring events, pi0 mass cut
   (85 < Mpi0 < 185 MeV/c^2)
6. Total mass cut
   (800 < Mtot < 1050 MeV/c^2)
7. Total momentum cut

Higher Box:

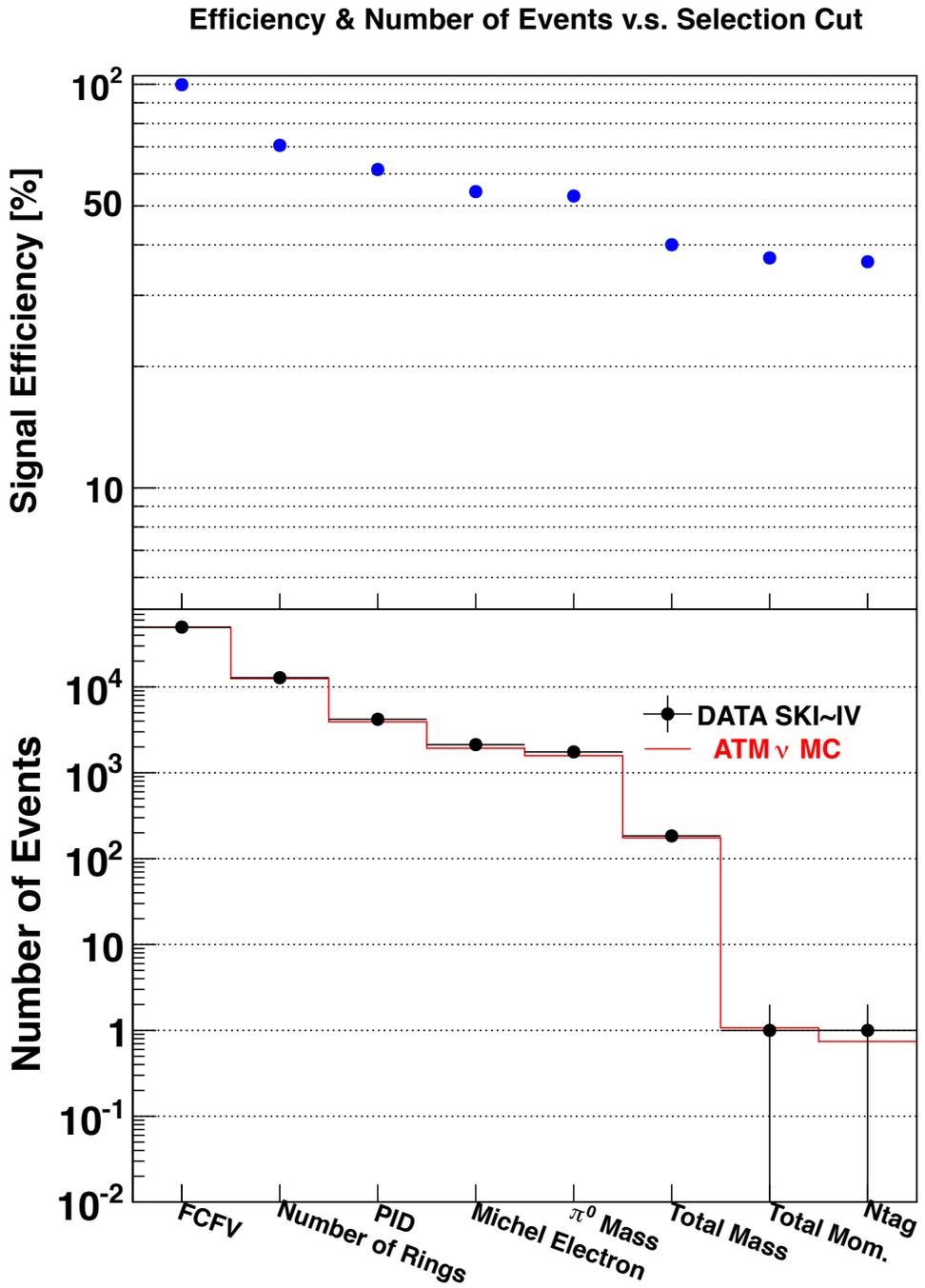
(100 <= Ptot < 250 MeV/c)

Lower Box:

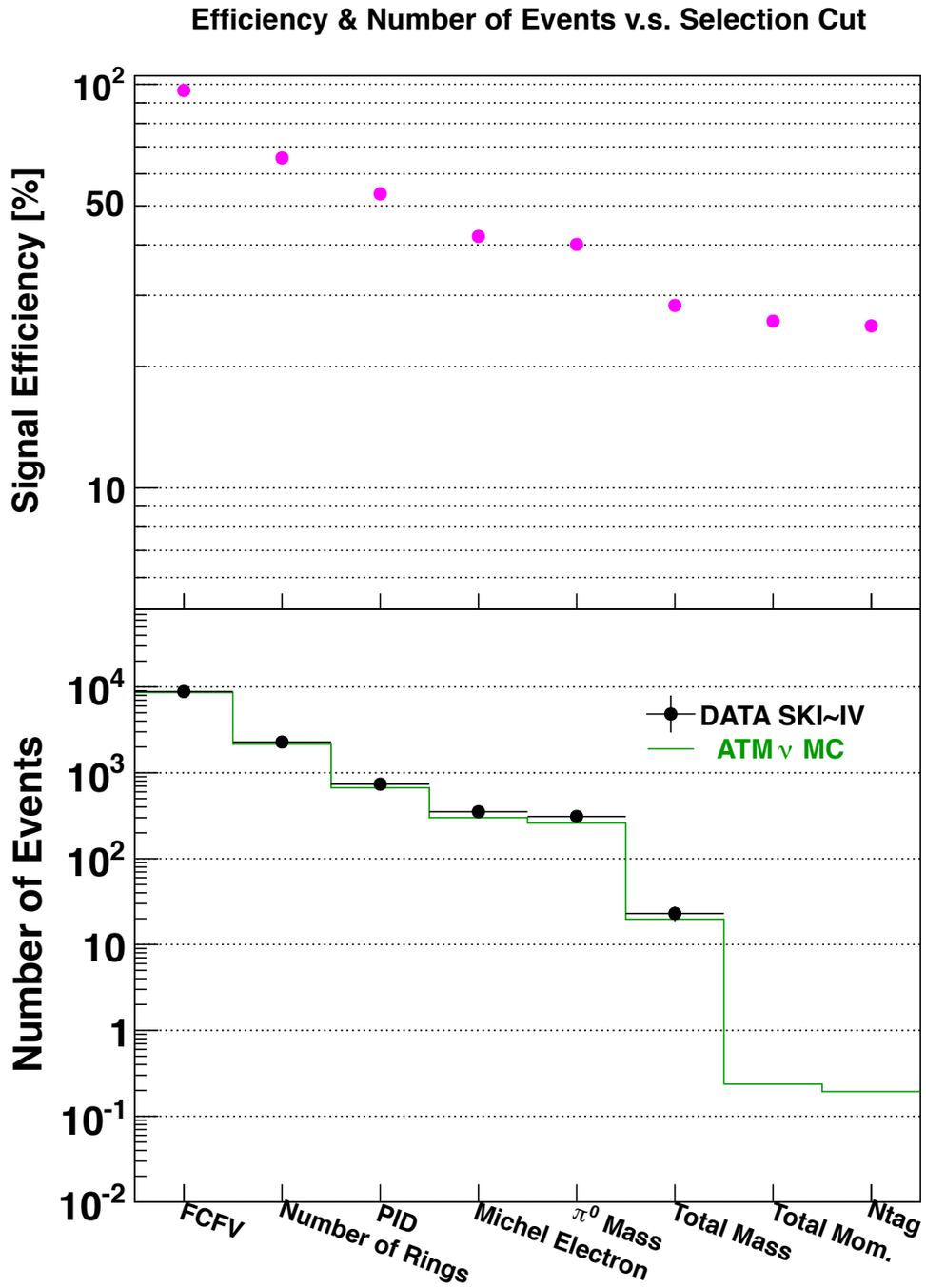
(Ptot < 100 MeV/c)

8. For SKIV, no neutron.

dwall>200 cm

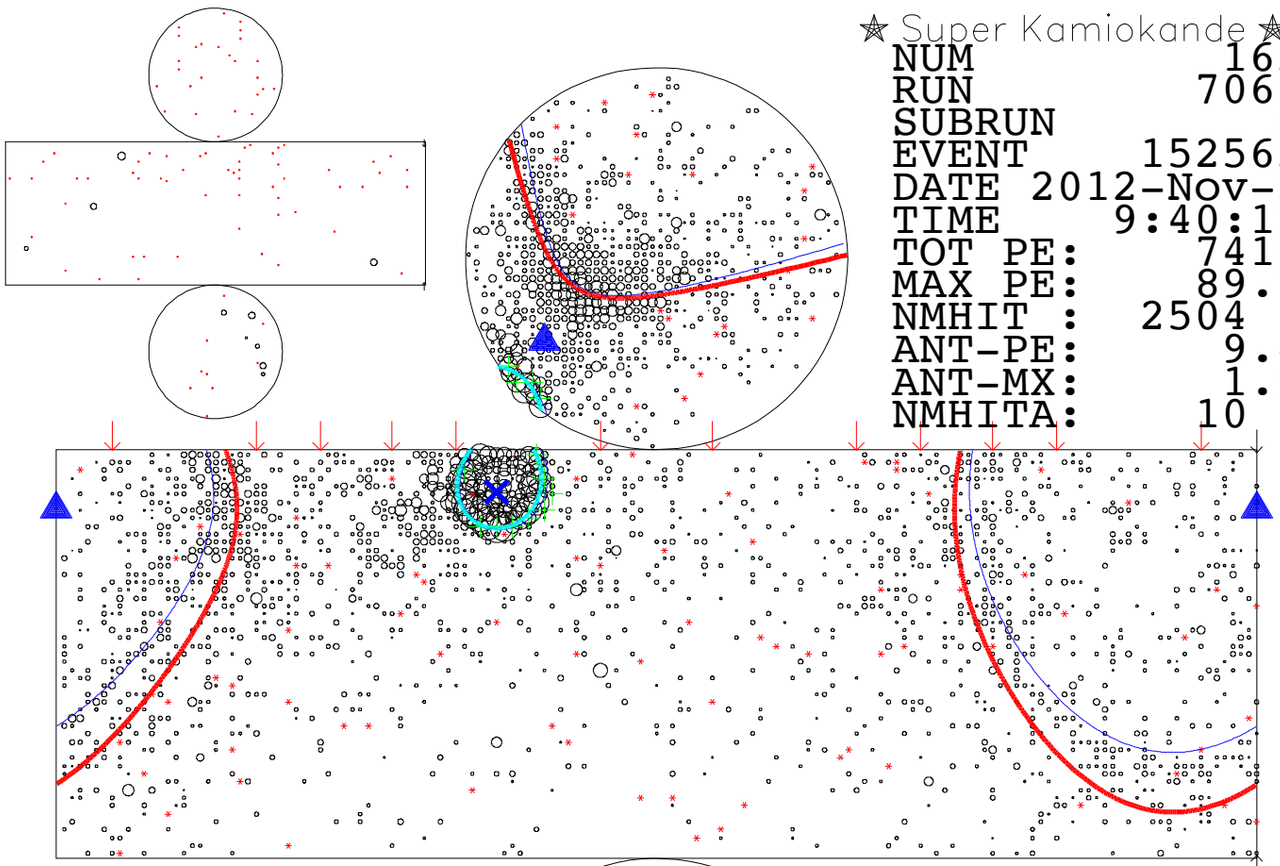


200>=dwall>100 cm

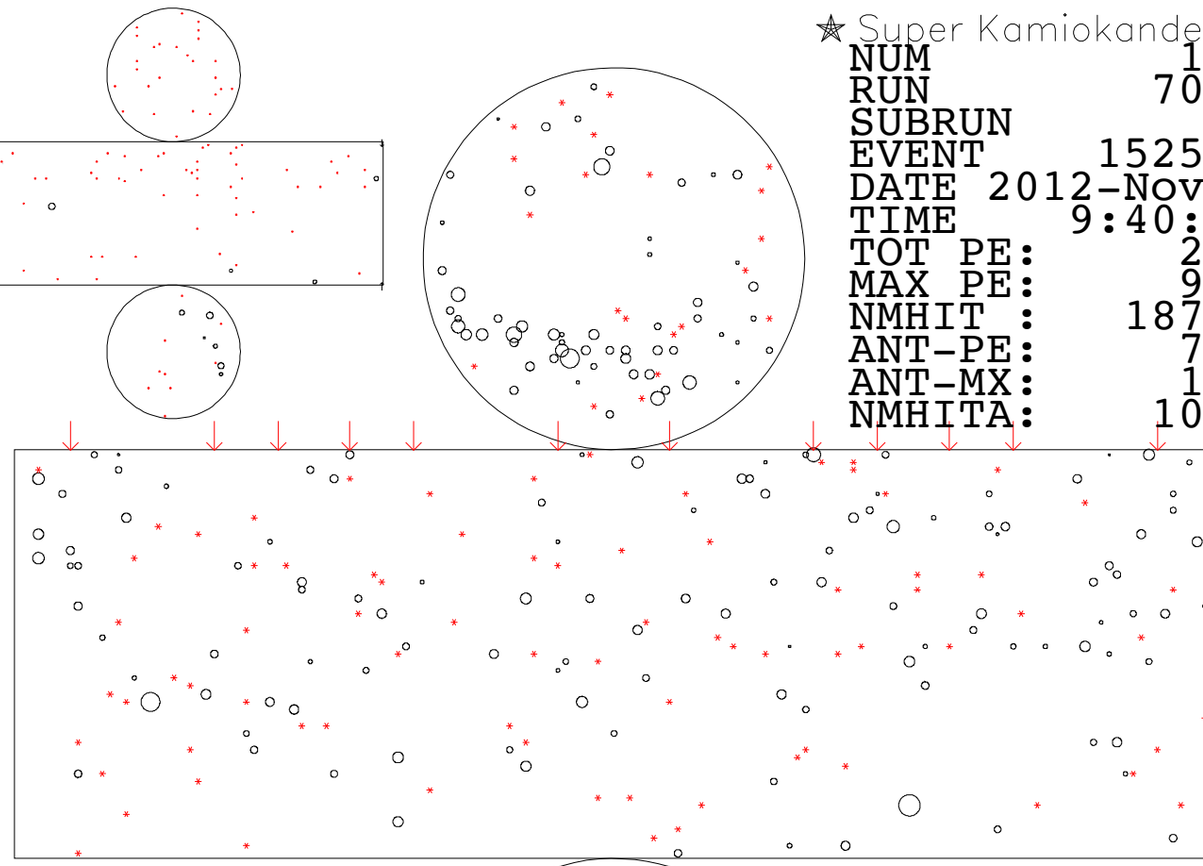


ATM ν MC is normalized by livetime & 3 flavor oscillation parameters.

Main



Michel-e



dwall = 458 cm, nring = 2, M_{tot} = 917 MeV/c^2, Ptot = 233 MeV/c

1st ring - μlike, mom 559 MeV/c, Oang 37.2 degree

2nd ring - elike, mom 377 MeV/c, Oang 43.8 degree

1 decay-e 0.834 μsec