

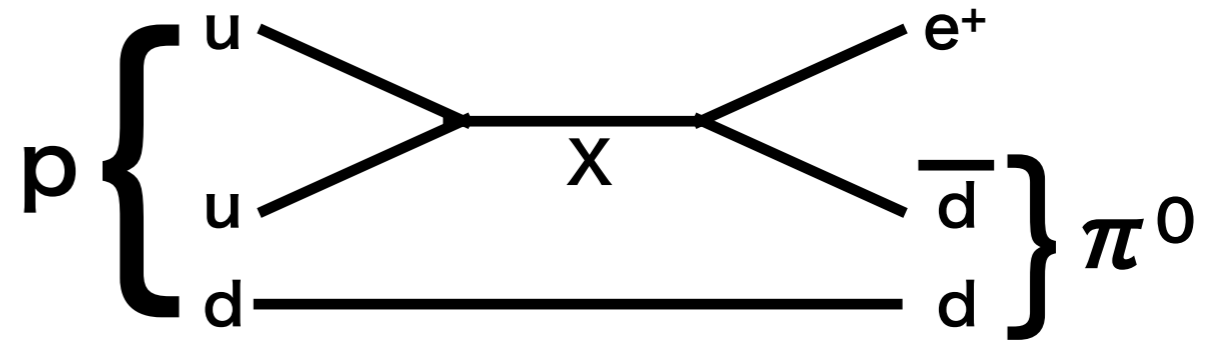
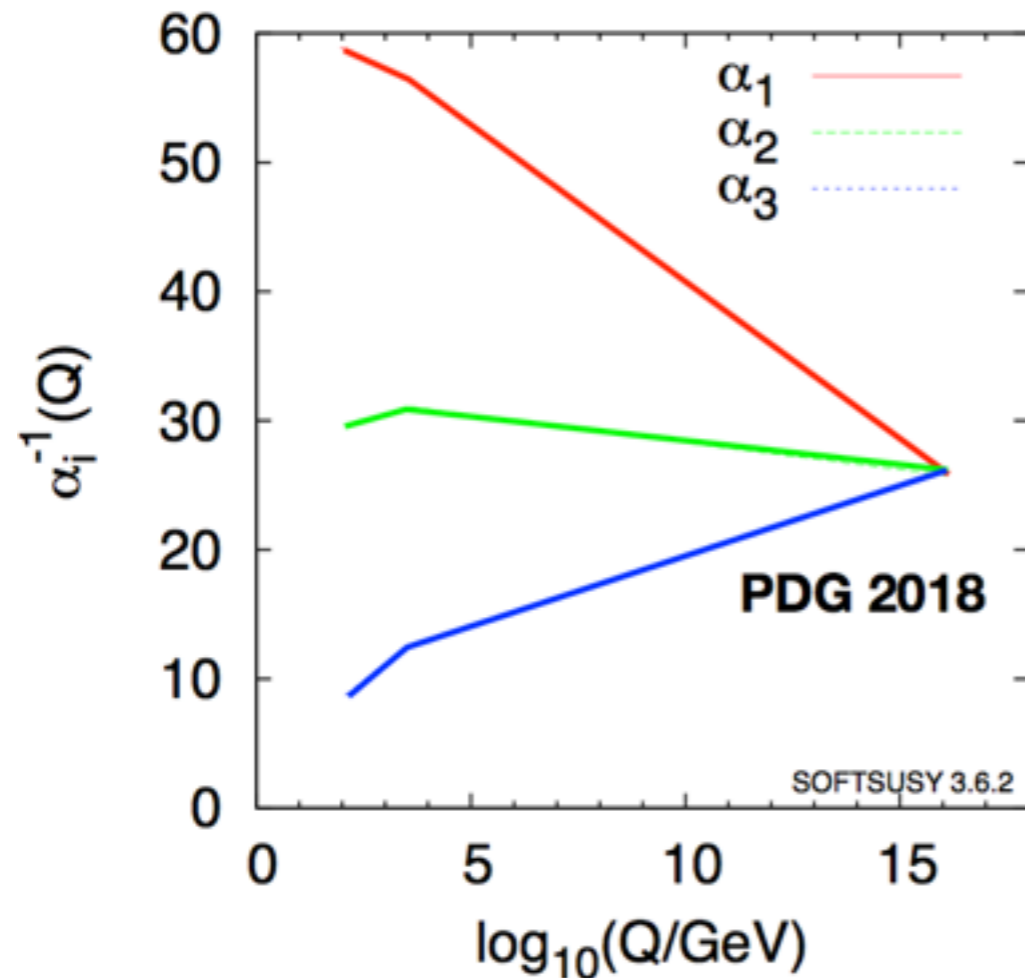


Search for Proton Decay: The Latest Results from Super-Kamiokande

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for the Super-Kamiokande Collaboration
NuPhys2019 @Cavendish Conference Centre,
London, UK

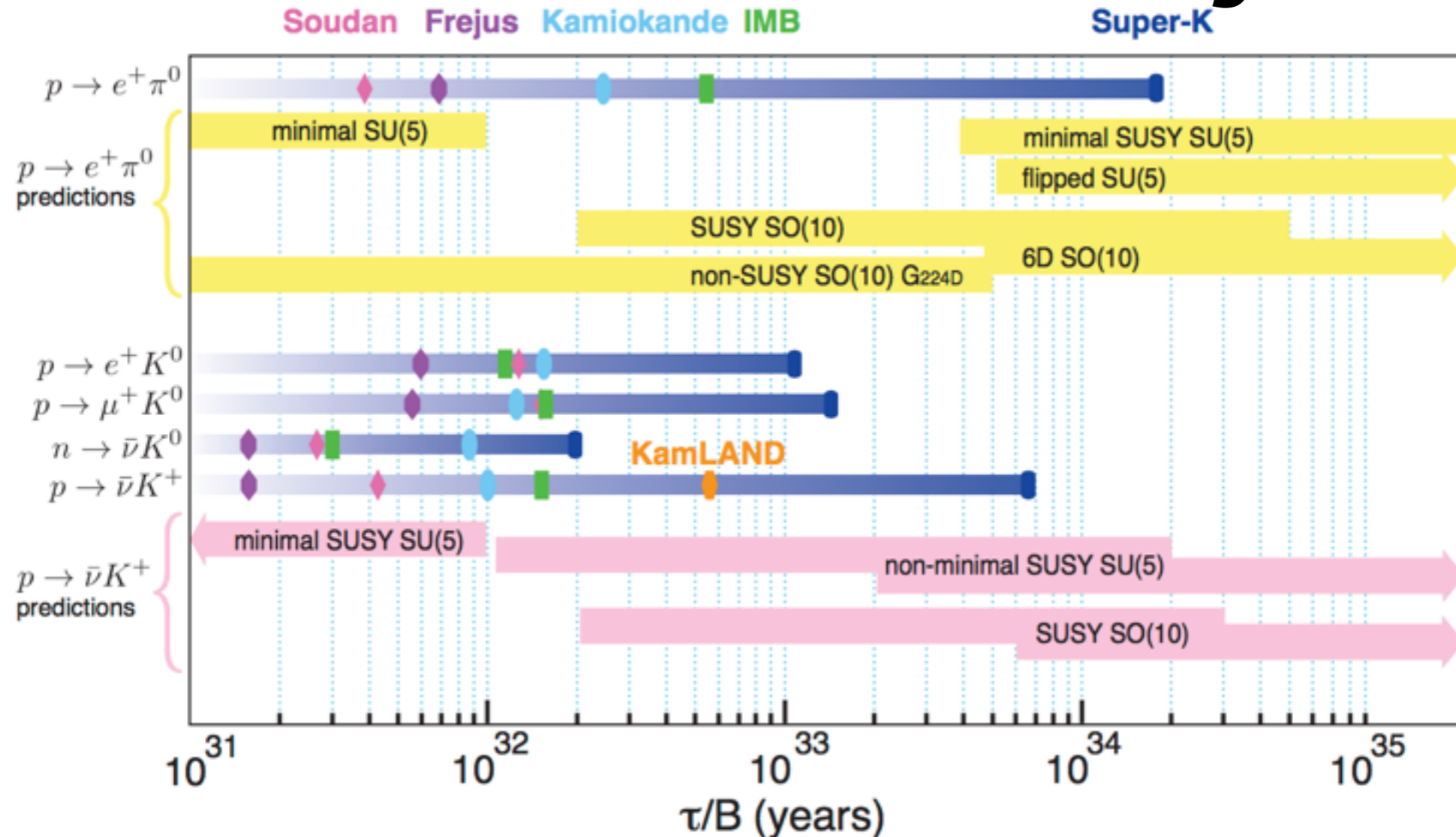
18th/Dec./2019

Proton Decay



- Grand unified theory (**GUT**) is motivated by charge quantization and coupling const. unification @ 10^{15-16} 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



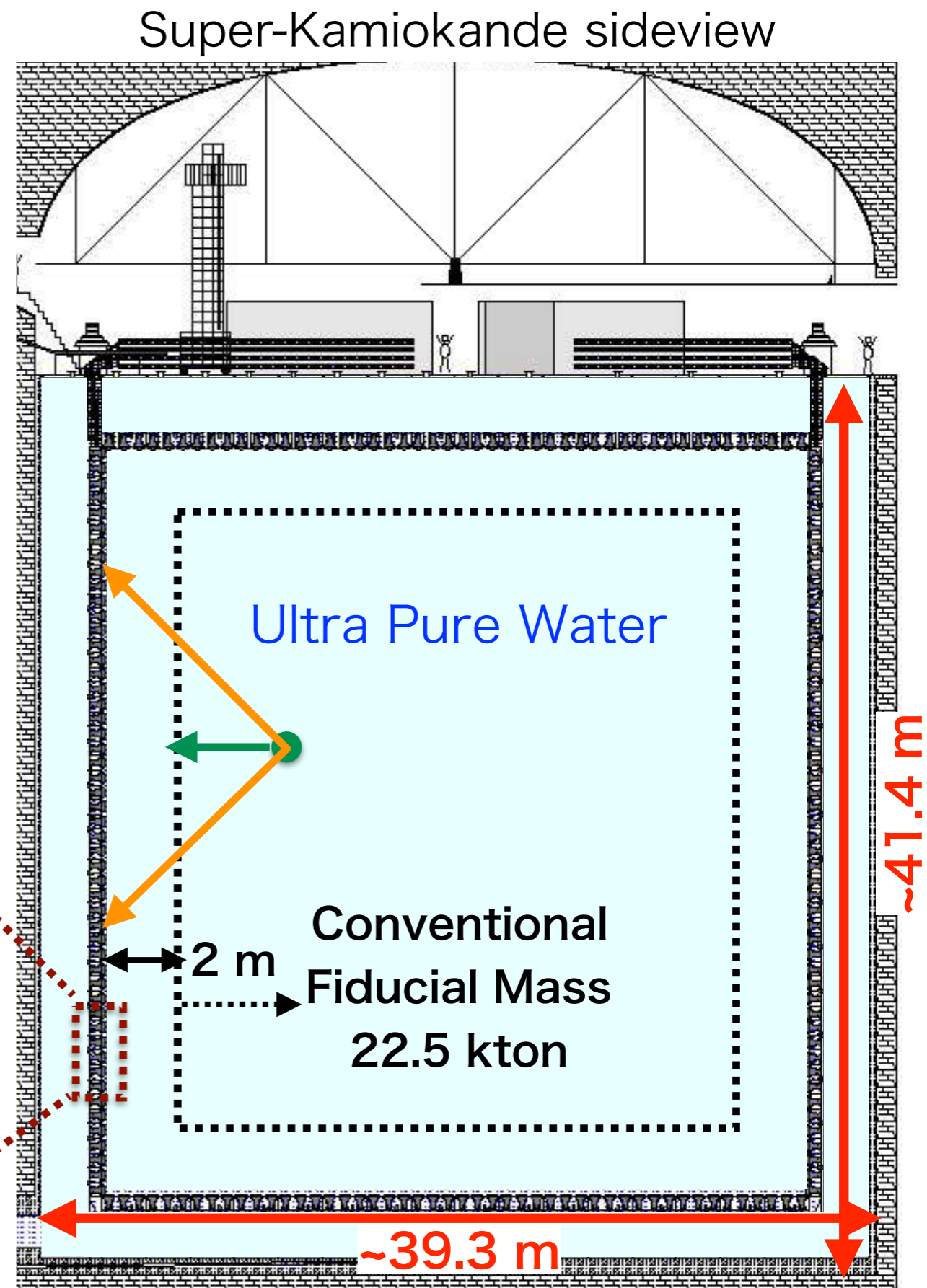
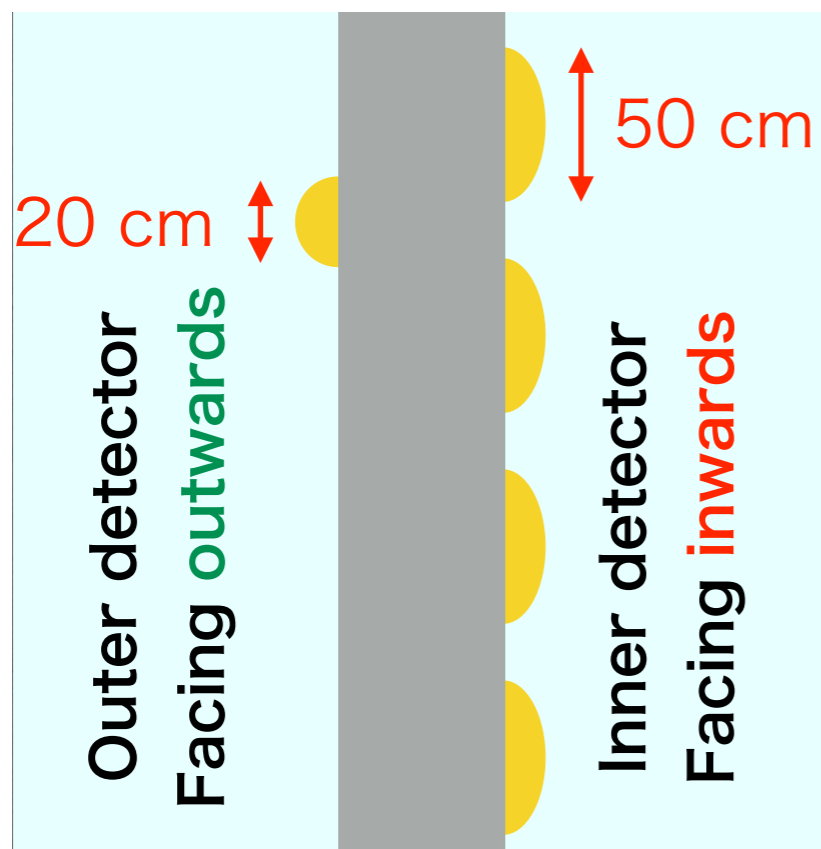
- Many GUT models are proposed, predicting proton lifetime to be **$\sim 10^{34-35}$ years**. So far, no experimental evidences...
- **Super-K** is a **world leading** experiment, reaching prediction regions with **great potential for discovery**.

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

with 306 kton*years data

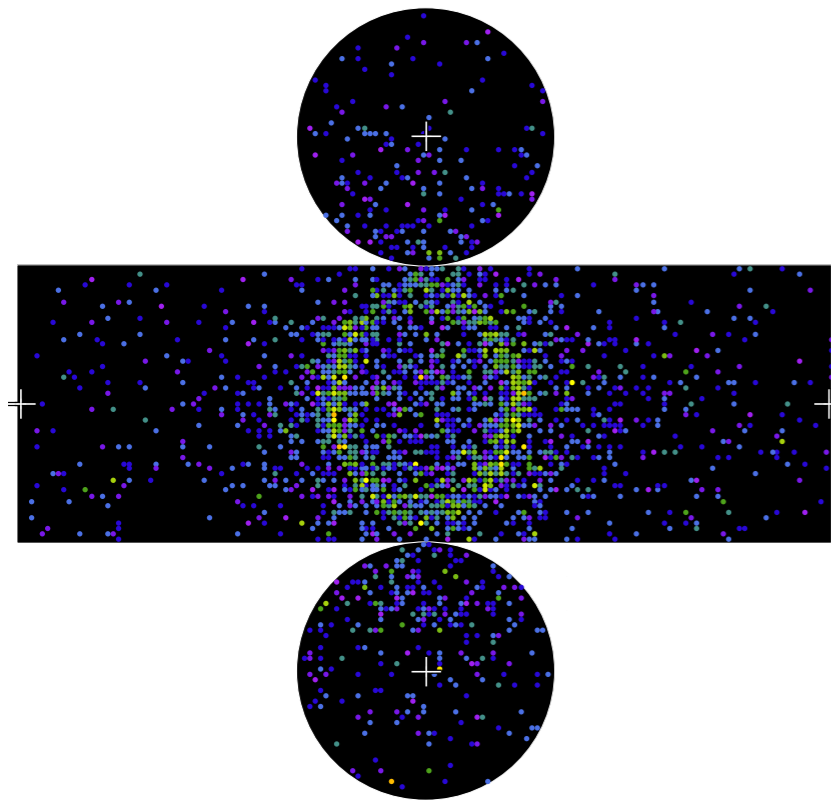
Super-Kamiokande

- 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** \times 11129
- Outer detector: **20 cm Φ PMT** \times 1885
- Mounted on **detector wall**.

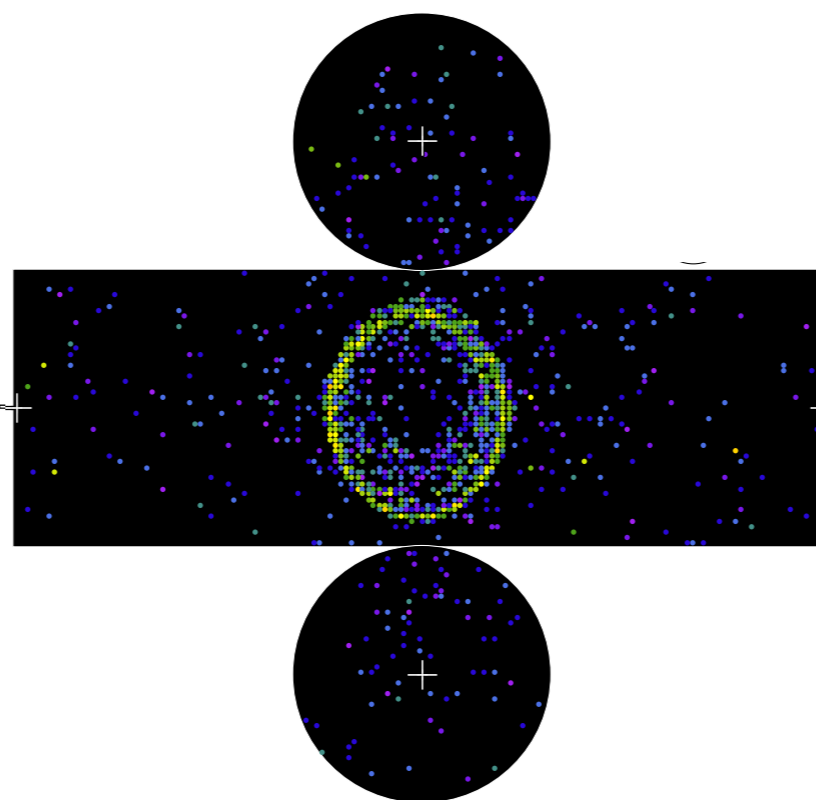


Water Cherenkov Technique

Electron (MC)

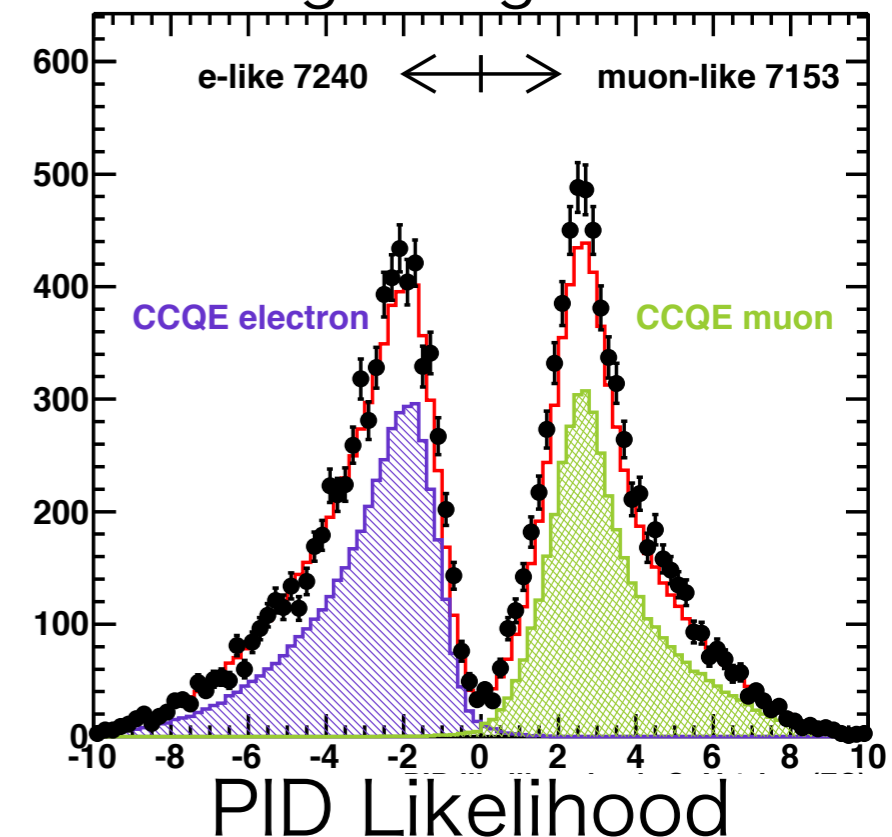


Muon (MC)



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. $\sim 3\%$ @1 GeV (1-ring).**
- Energy scale uncertainty (Data/MC agreement) **$\sim 3\%$.**

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**

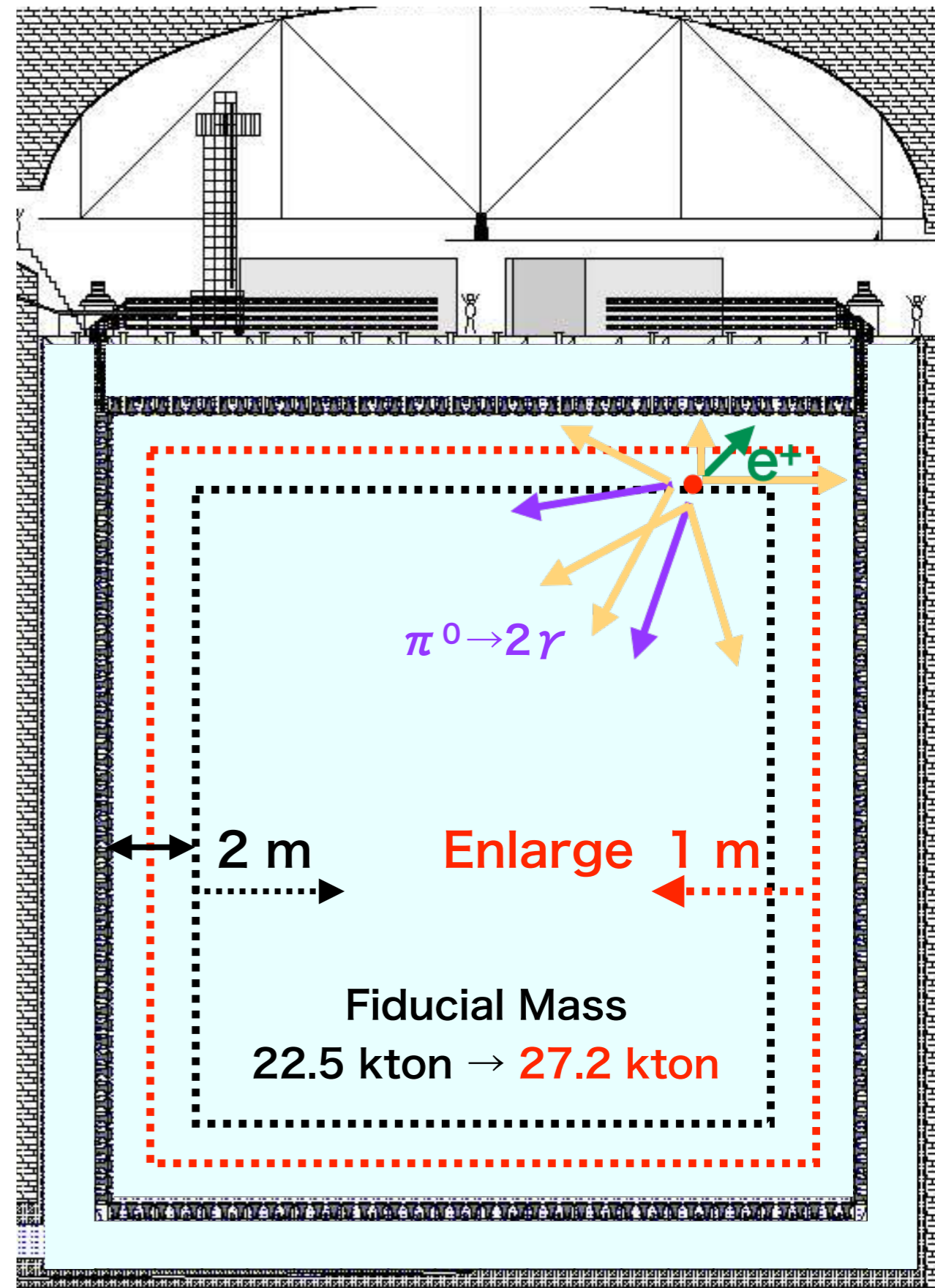
Remarkable merits

- Enables the use of **past data that has never been analyzed.**

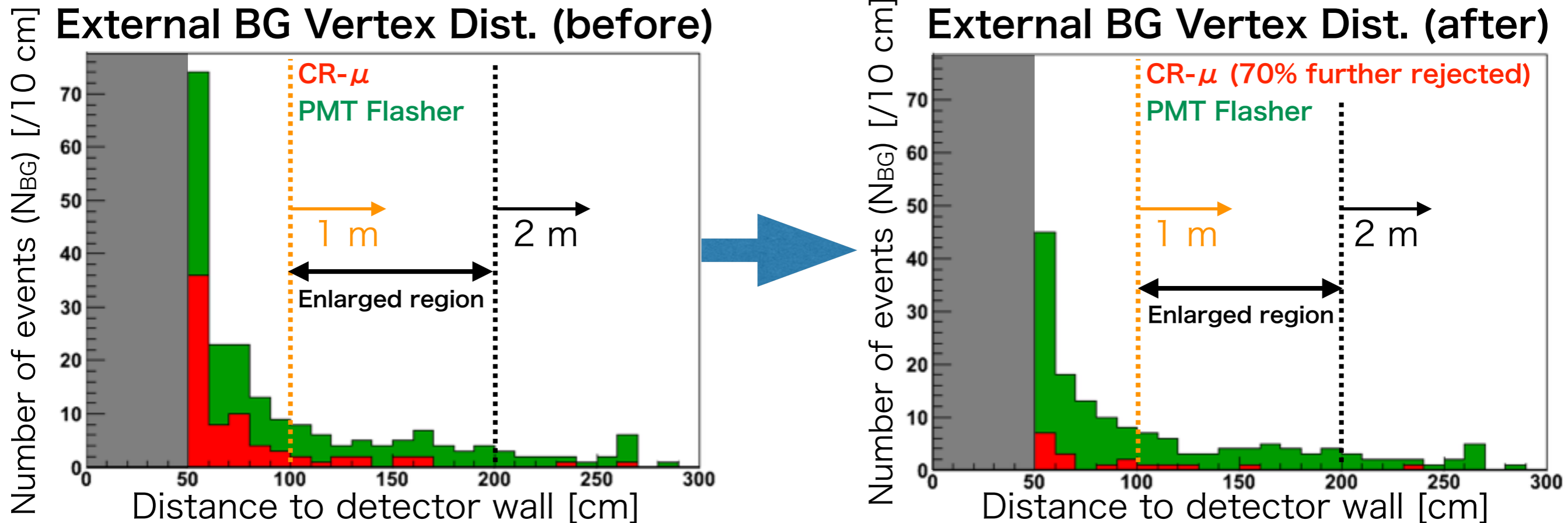
- Improves **p-decay search sensitivity for every mode** as well as the neutrino analysis.

Considerations to achieve it

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

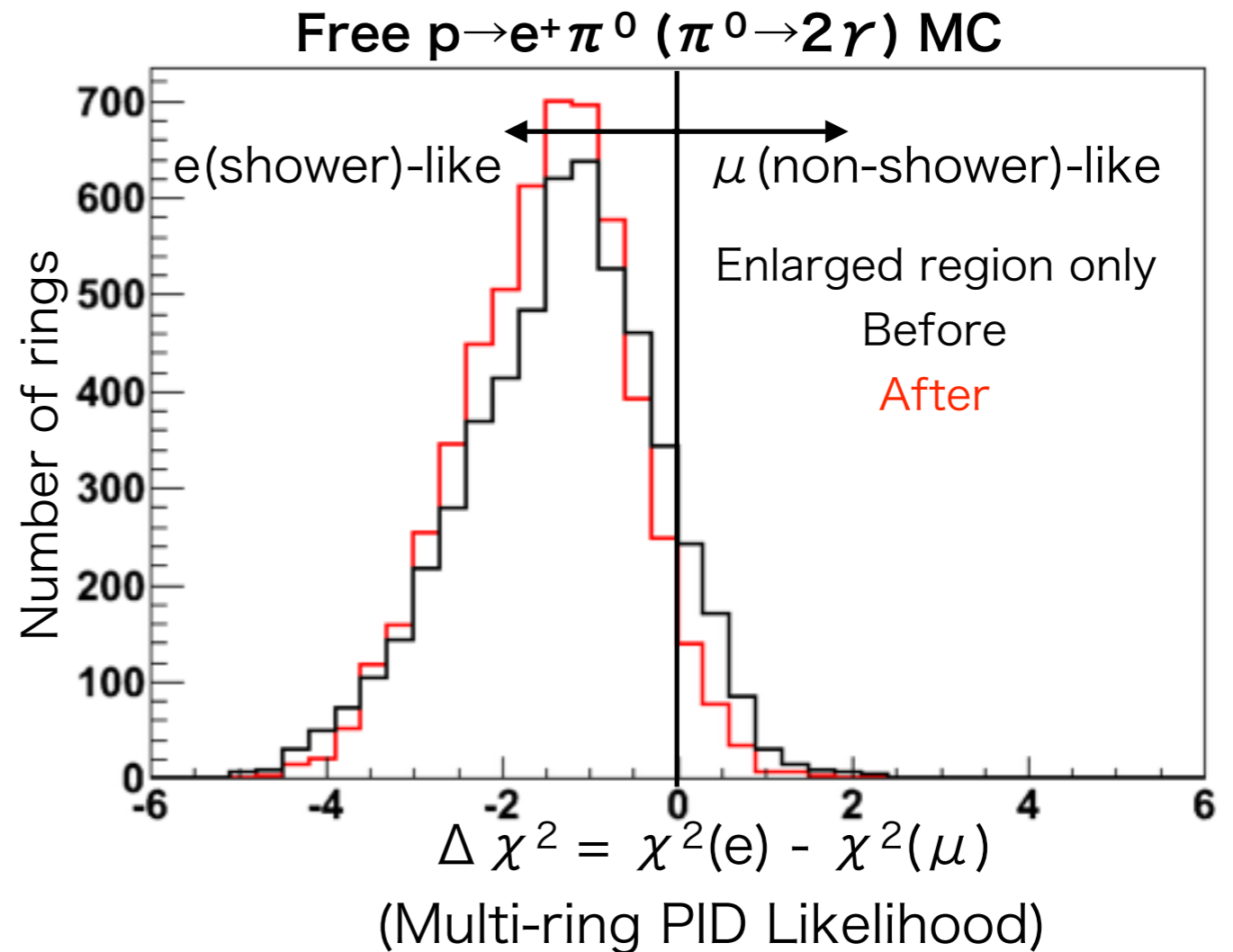
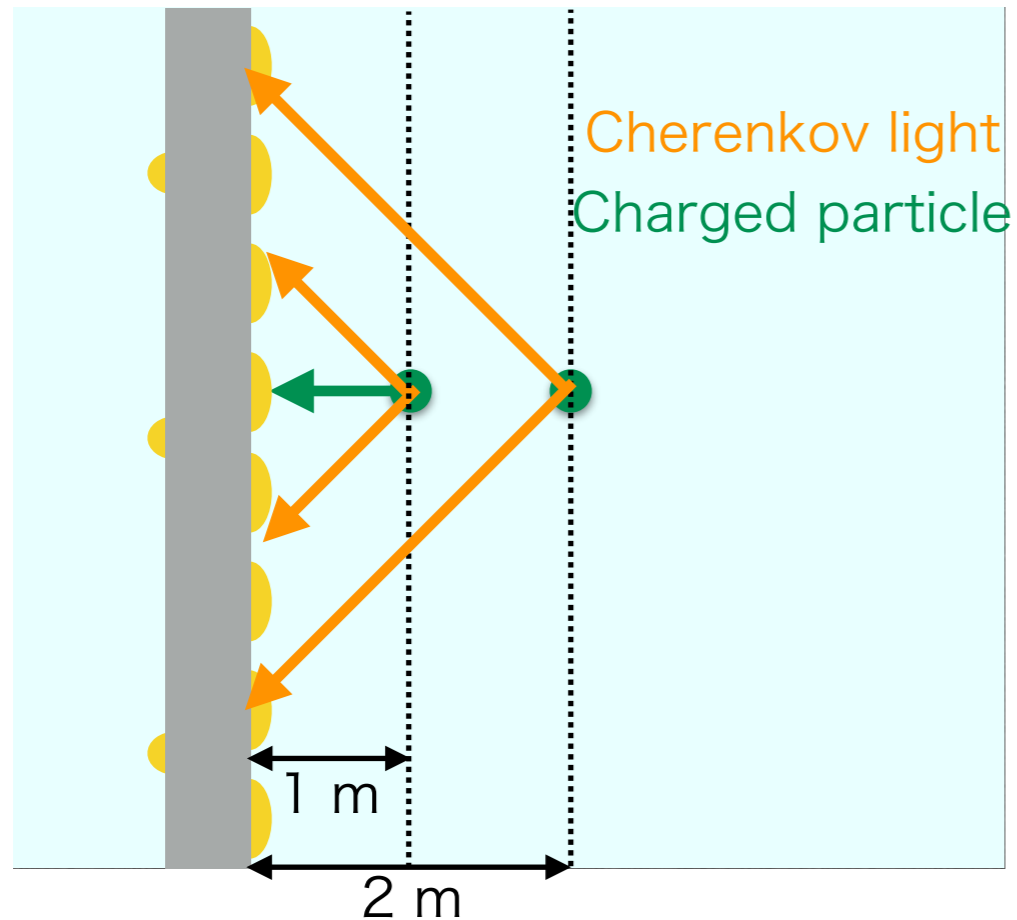


1. External Background



- 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. \rightarrow 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



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

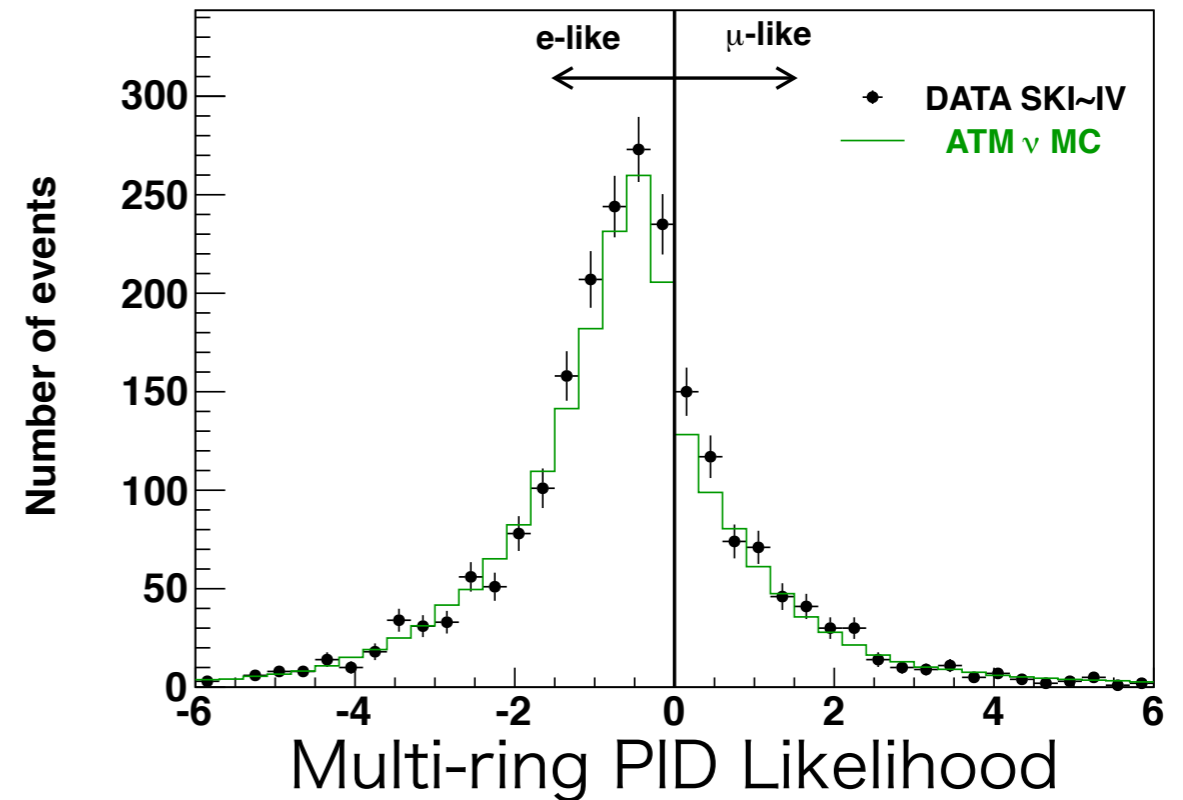
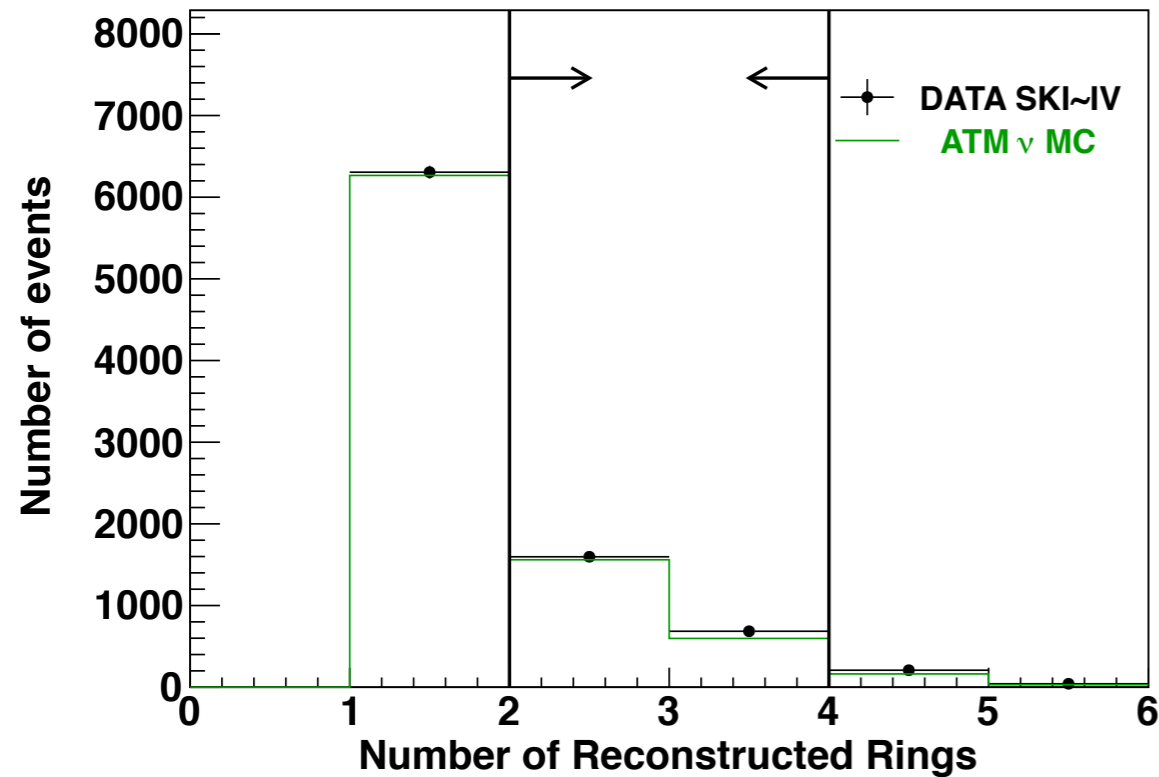
$$\chi^2(e \text{ or } \mu) \propto - \sum_{i \text{ (Hit PMT)}} \log_{10}(\text{Prob}(q_i^{obs}, q_i^{exp}(e \text{ or } \mu)))$$

- 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.

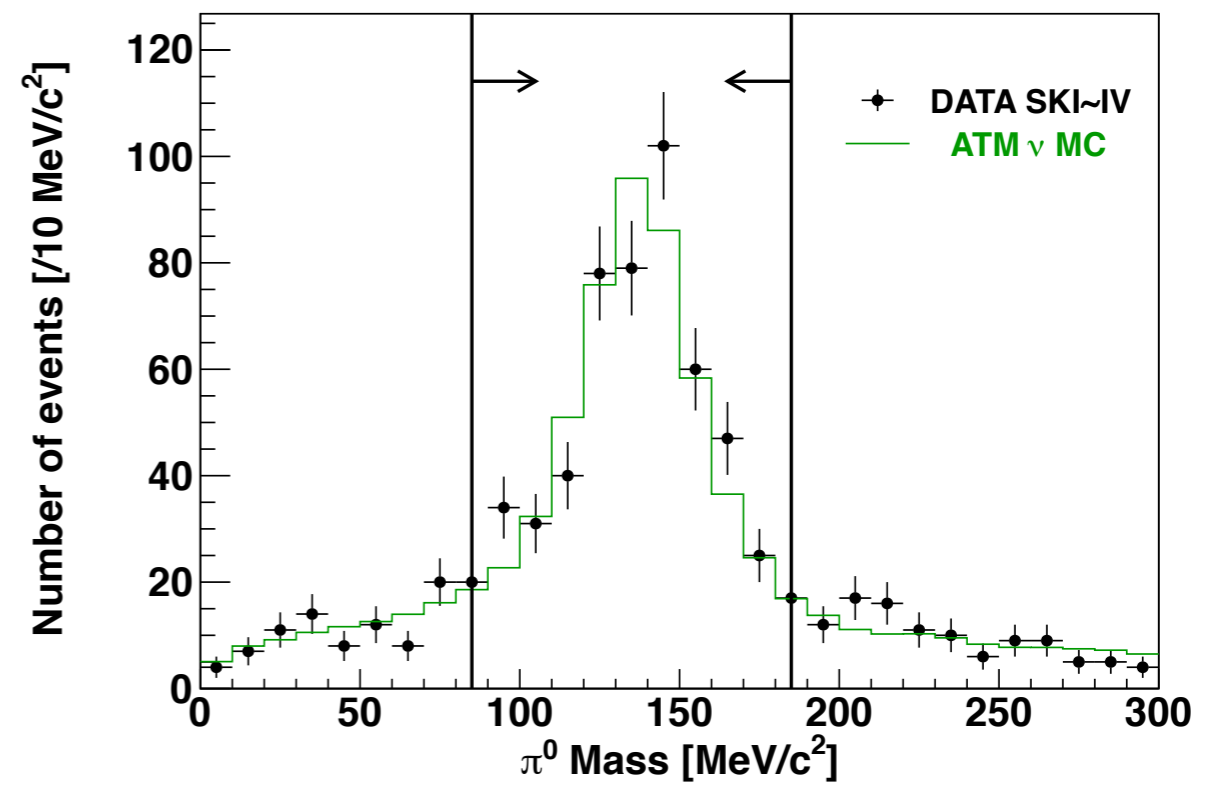
3. Data/MC Agreement

Atmospheric ν Data/MC in enlarged region only.

Distance to detector wall: 1~2 m.

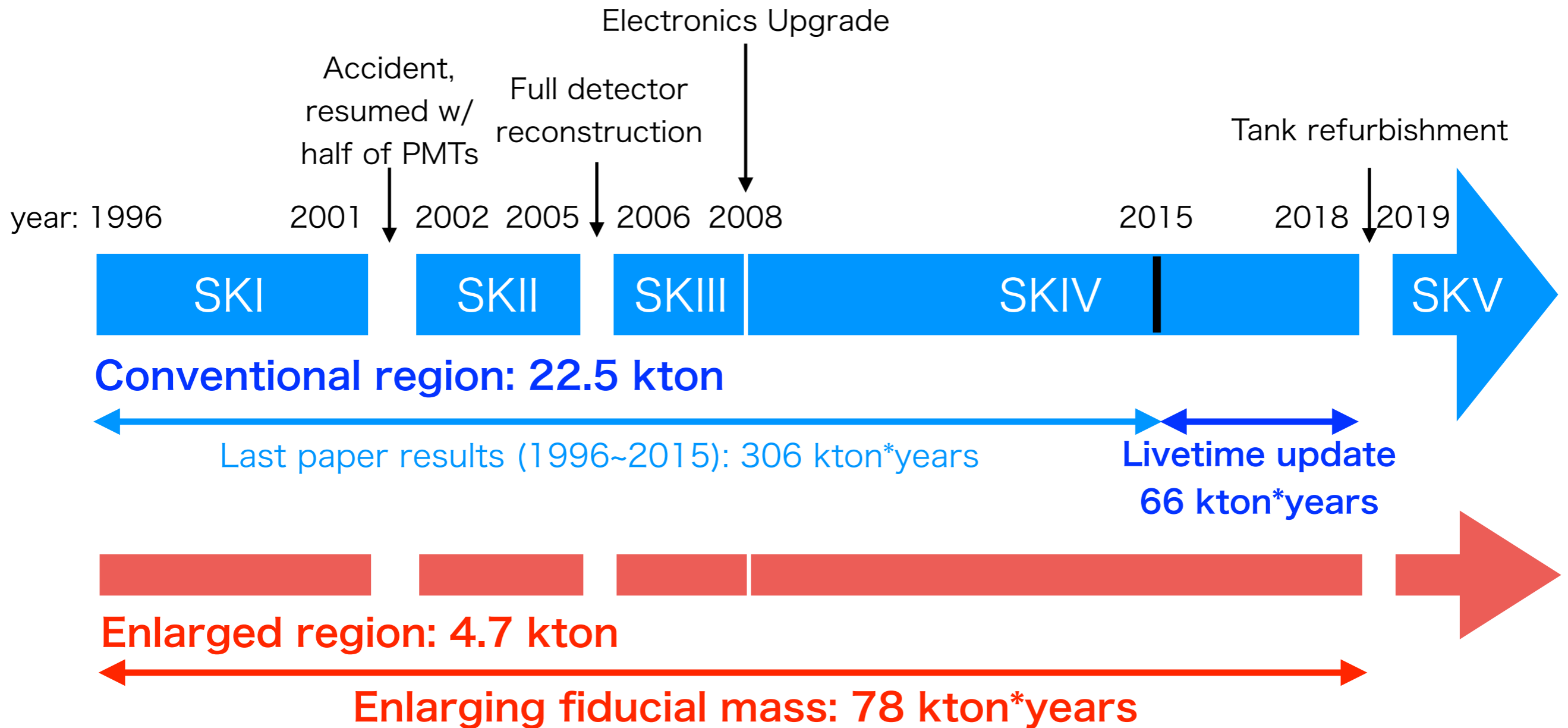


π^0 Mass Distribution (SKI-IV $200 \geq d_{\text{wall}} > 100$ cm)



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

Super-K History & Total Exposure



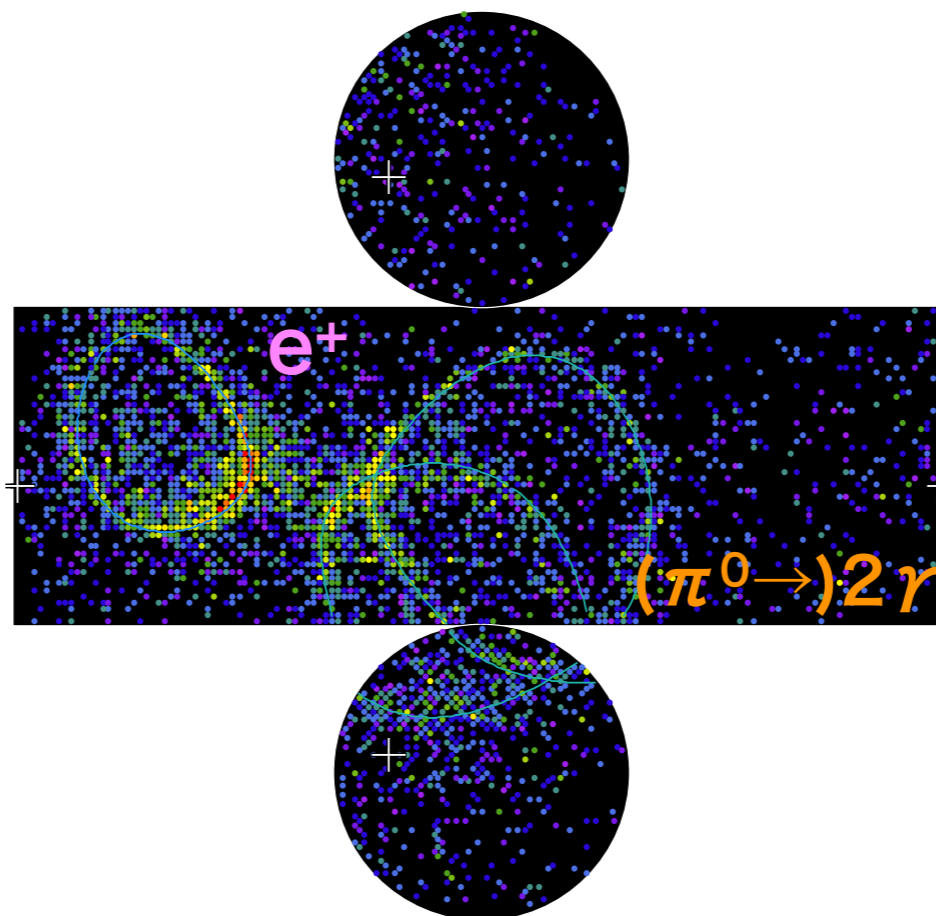
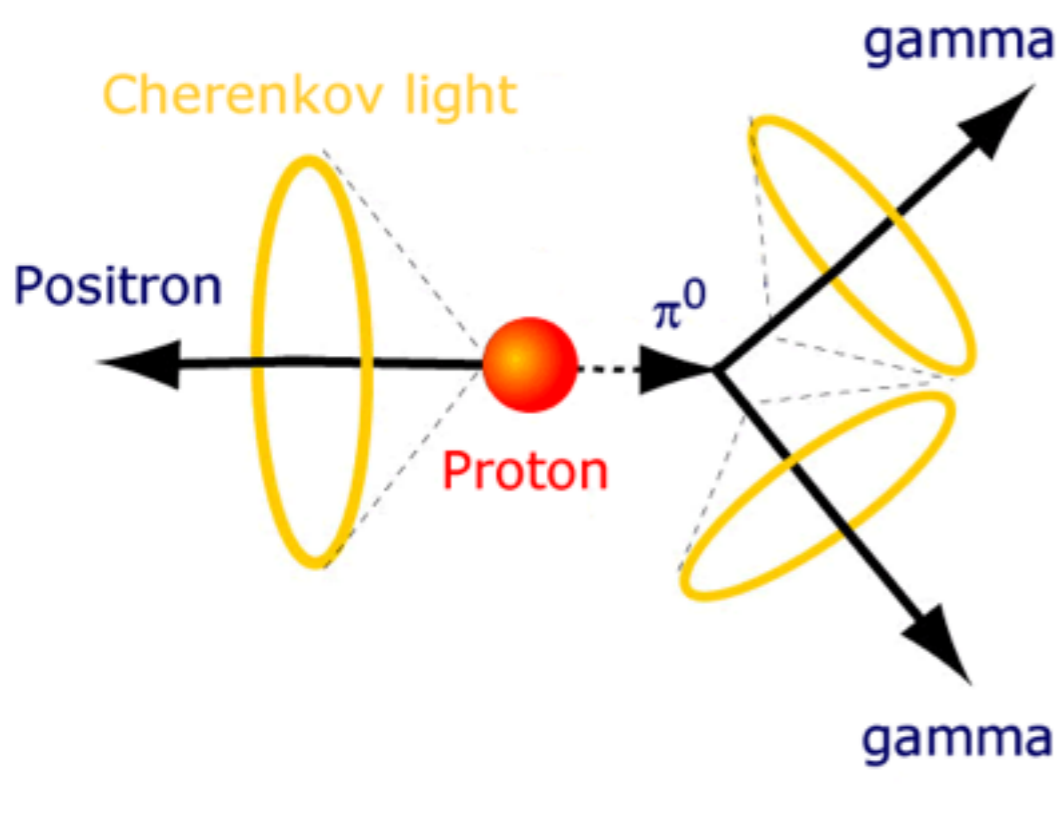
• The latest $p \rightarrow e^+ \pi^0$ & $p \rightarrow \mu^+ \pi^0$ search results with **full SKI~IV livetime (1996~2018)** & **enlarged fiducial mass** are presented in this talk.

• **Total exposure: 306+66(livetime)+78(enlarged fiducial mass) = 450 kton*years**

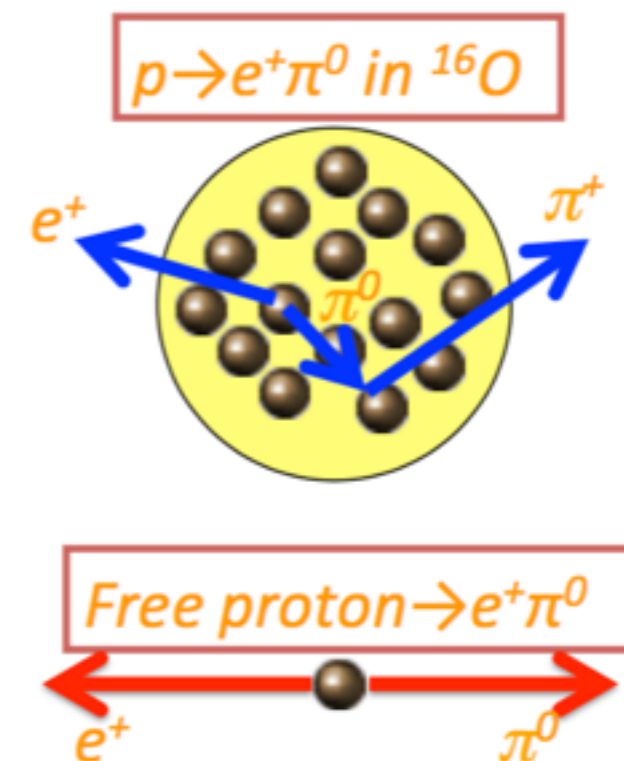
• 1.5 times larger than published (306 kton*years). PRD 95, 012004 (2017)

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

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

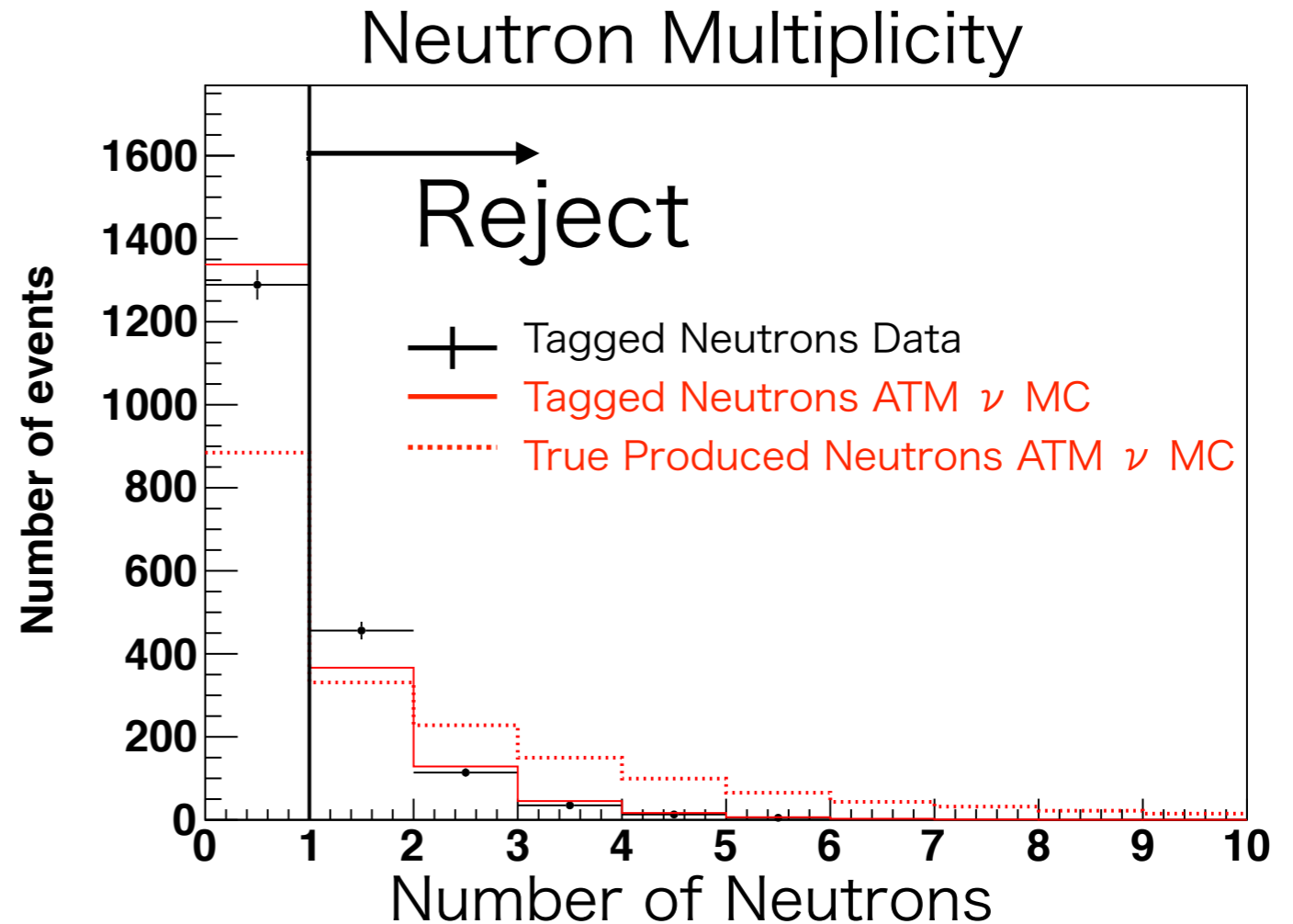
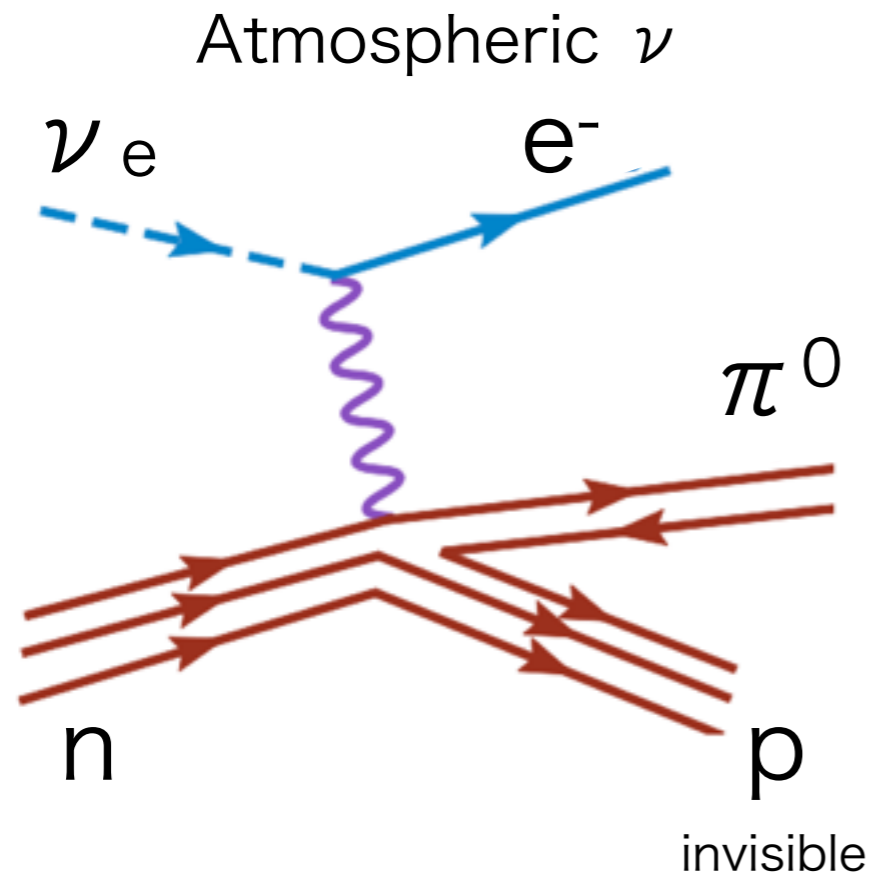


Protons in H₂O



- 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

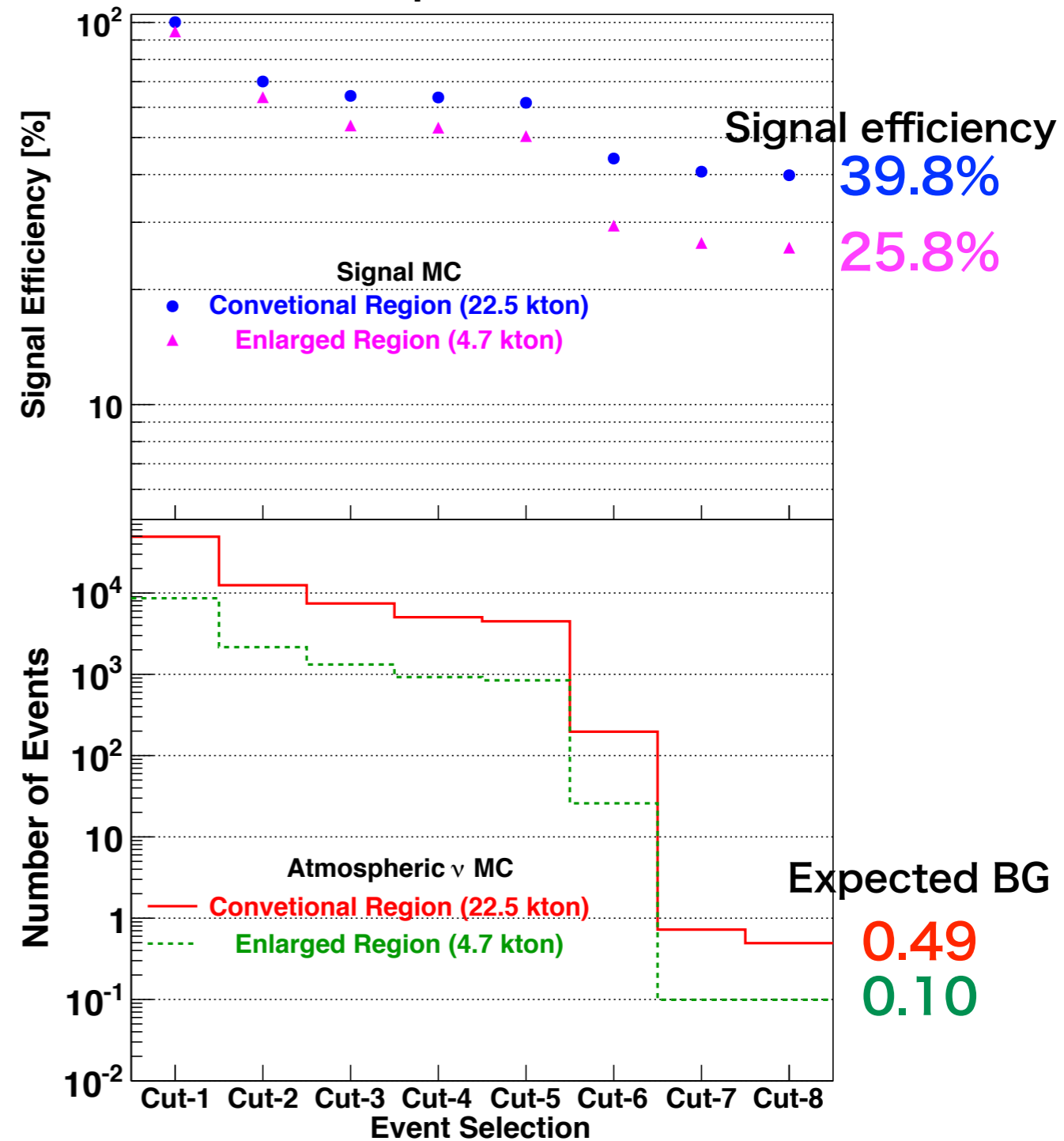


- Atmospheric (ATM) neutrino events can mimic p-decay signal.
 - ~60% of them are produced via CC pion production interaction.
 - **Often accompanied with neutrons.**
- Since SKIV (2008~2018), faint signature of **neutrons (γ s) can be recorded** thanks to electronics upgrade. ($n+p \rightarrow d + \gamma$ (2.2 MeV))
 - Neutron tagging efficiency ~25%.
 - **Requiring no tagged neutrons reduces ATM ν BG by ~50%.**

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

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

- Fully contained and **vertex in fiducial mass region.**
- Cherenkov ring = 2 or 3**
- Particle identification
all shower-like rings
- No Michel-e.
- for 3-ring π^0 mass cut
 $85 < M_{\pi^0} < 185 \text{ MeV}/c^2$
- Total Mass cut
 $800 < M_{\text{tot}} < 1050 \text{ MeV}/c^2$
- Total Momentum Cut
Box1: $0 < P_{\text{tot}} < 100 \text{ MeV}/c$
(Free proton rich & Low ATM ν BG)
Box2: $100 < P_{\text{tot}} < 250 \text{ MeV}/c$
- For SKIV, **no tagged neutrons.**

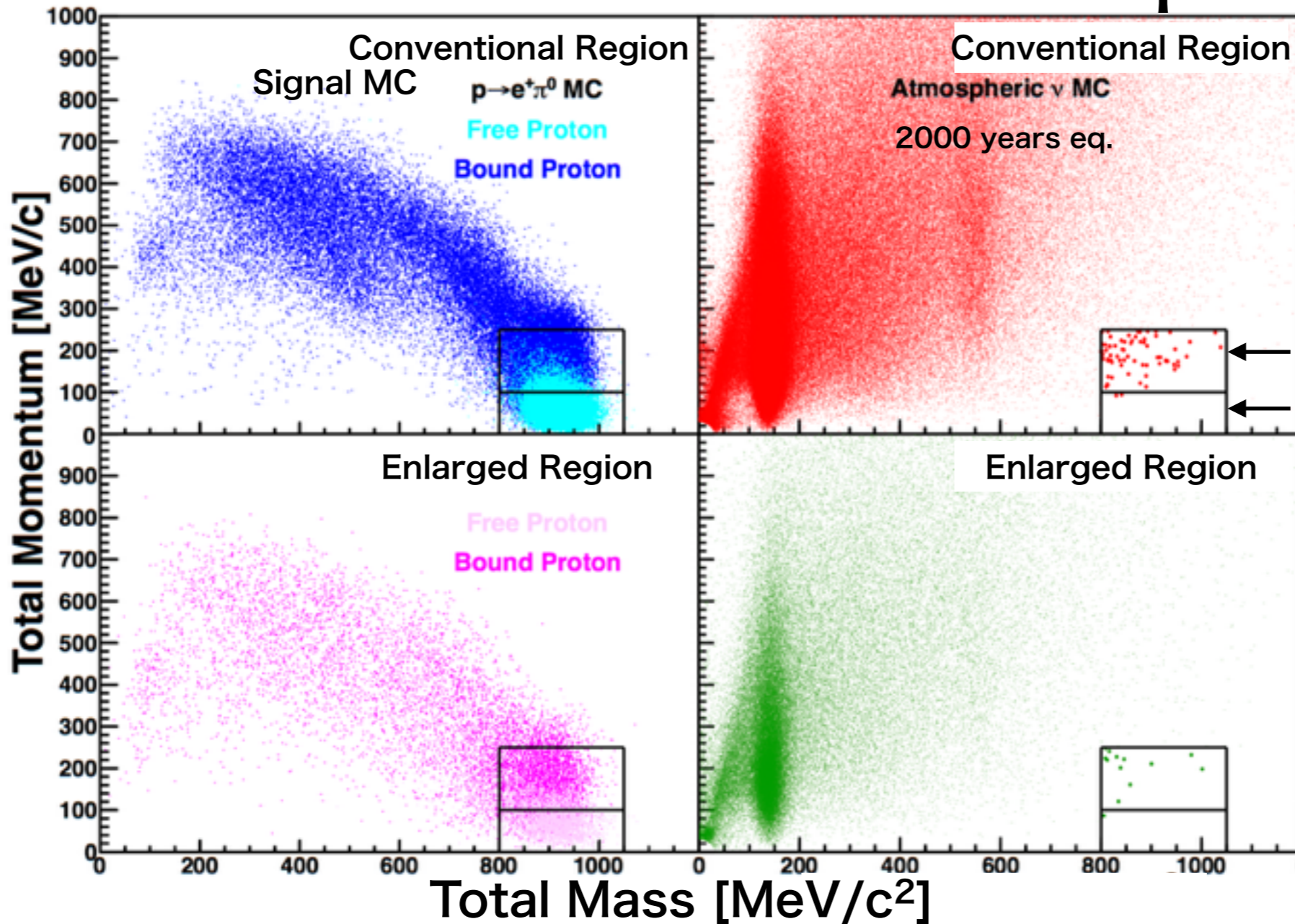


Causes for lower efficiency in enlarged region:

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

• **Enlarging fiducial mass increases p -decay search sensitivity by $\sim 12\%$.**

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



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 [./lifetime]	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

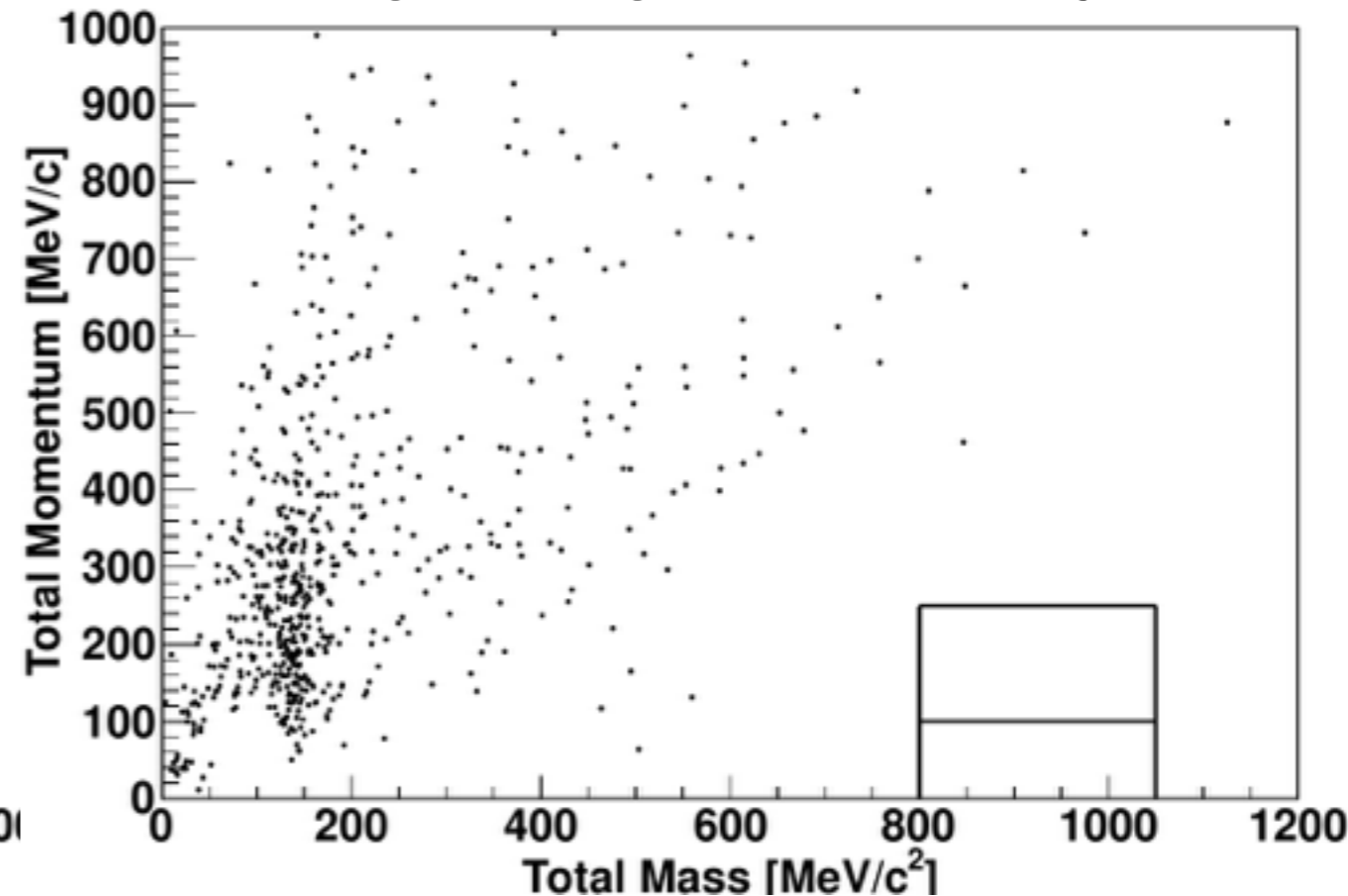
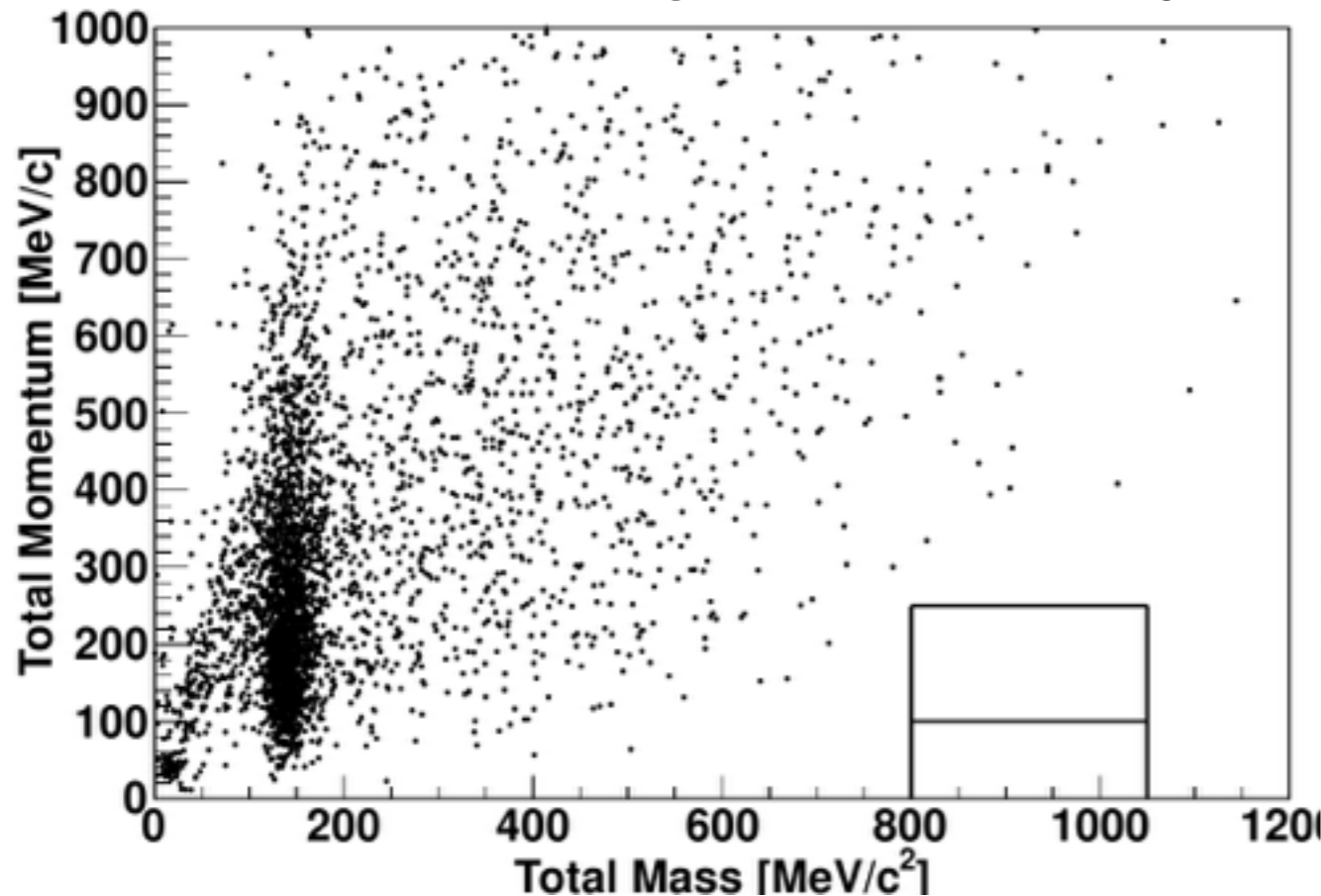
← Almost BG free!

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

Data SKI-IV 450 kton*years.

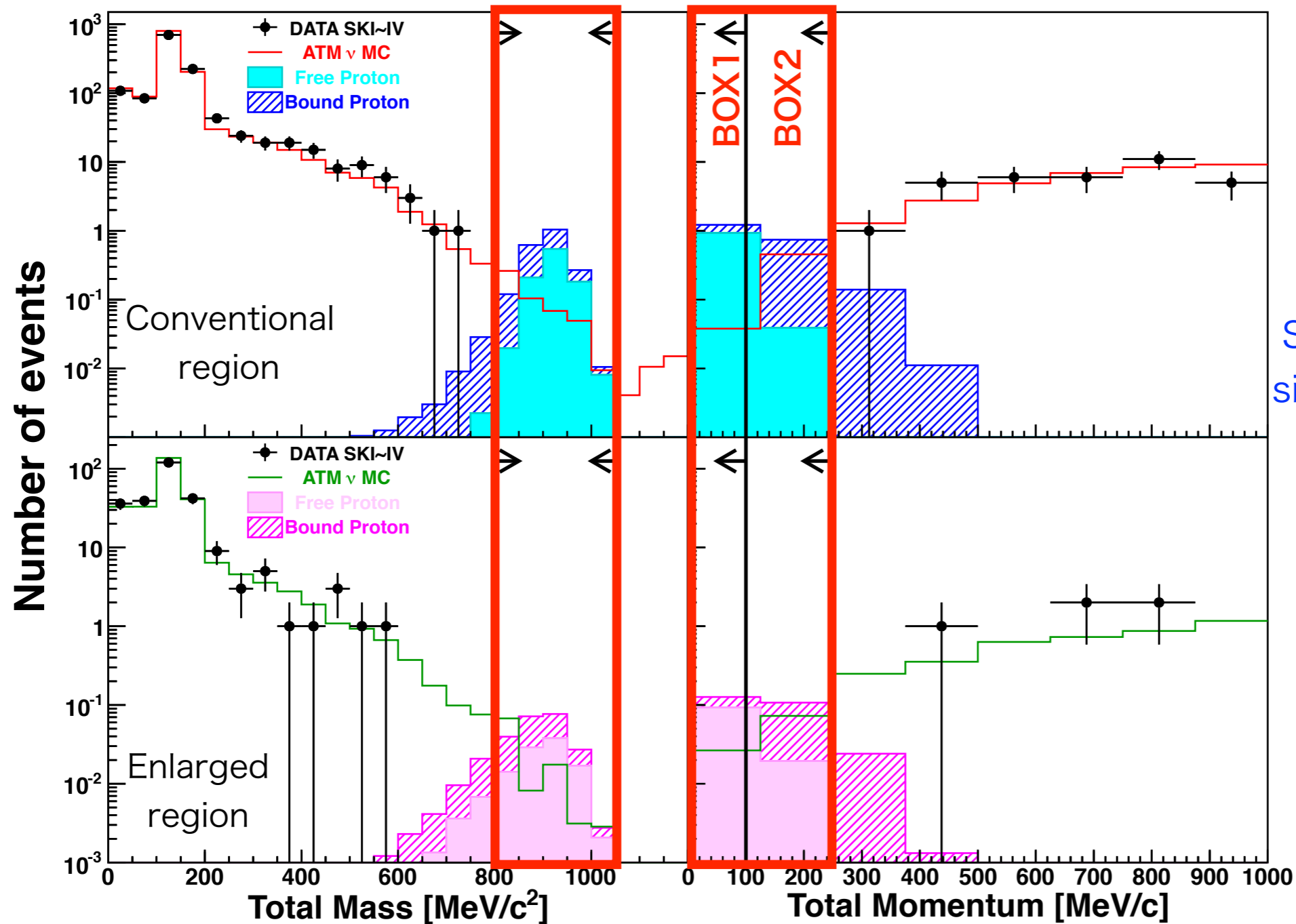
Conventional Region 372 kton*years

Enlarged Region 78 kton*years



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

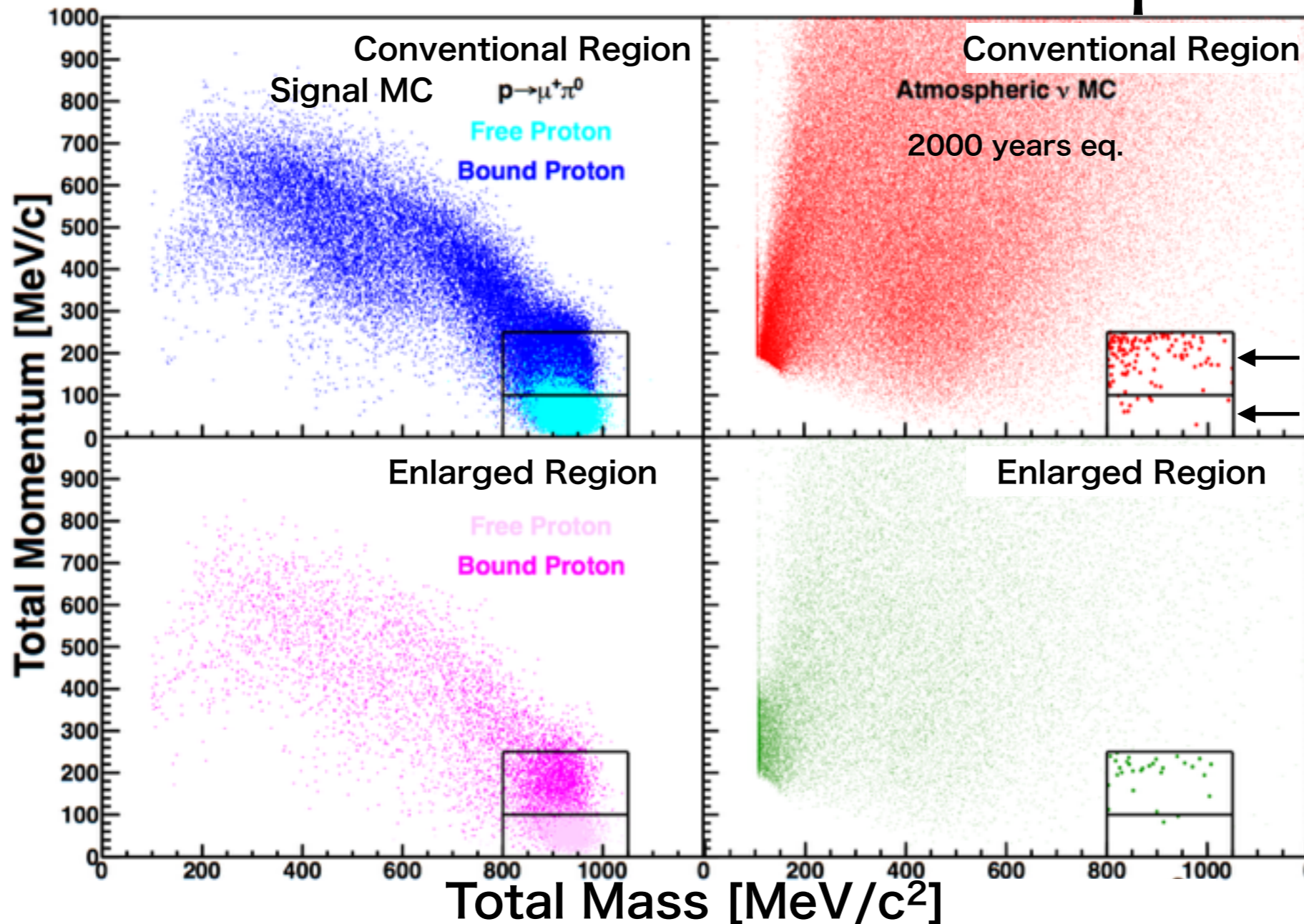
Data Result $p \rightarrow e^+ \pi^0$



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

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

Search Performance $p \rightarrow \mu^+ \pi^0$ 17



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

- 1 mu-like ring
- 1 Michel Electron

Signal Box
 BOX2: $100 < P_{\text{tot}} < 250$ MeV/c
 BOX1: $P_{\text{tot}} < 100$ 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 [//lifetime]	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

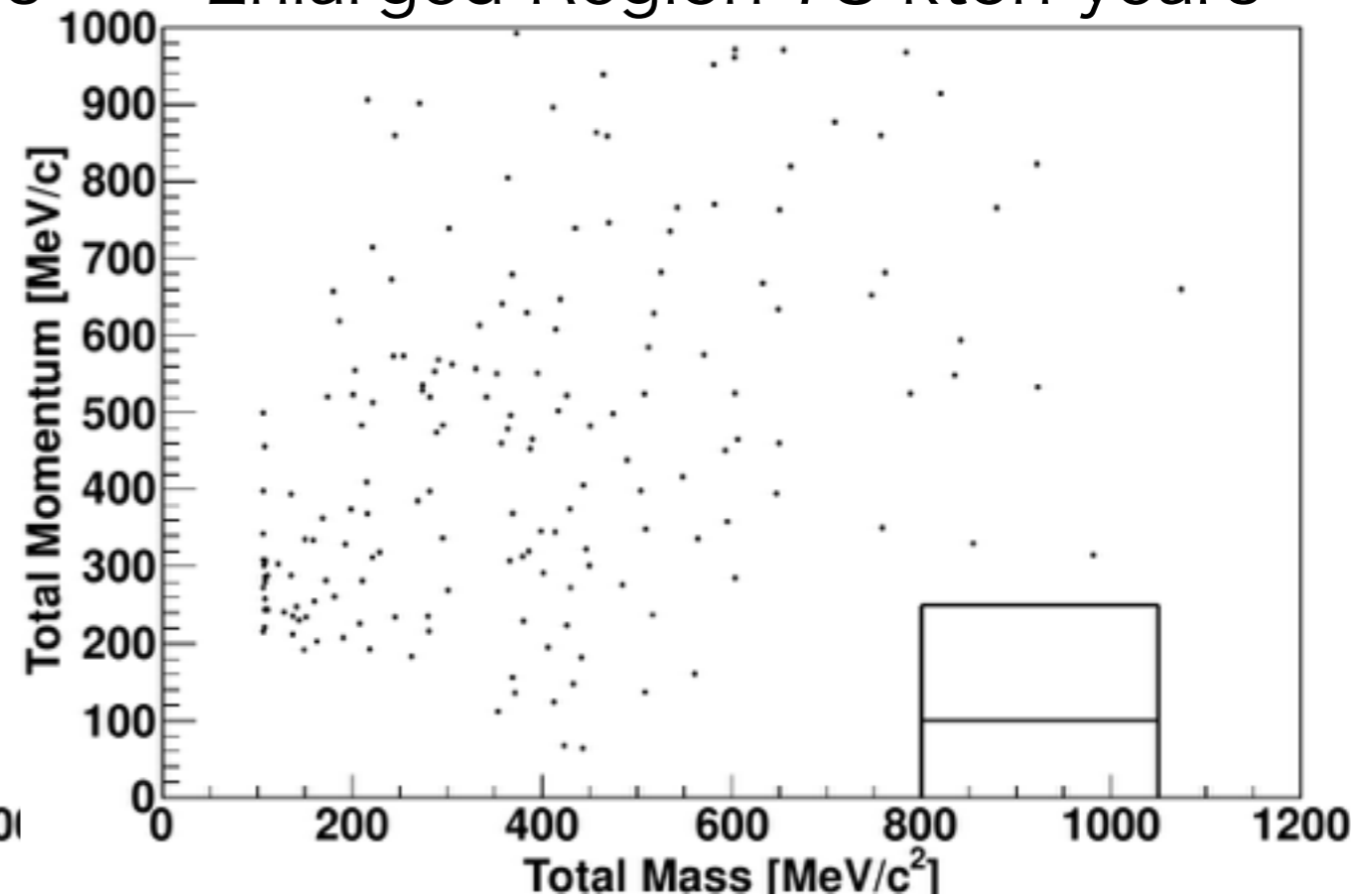
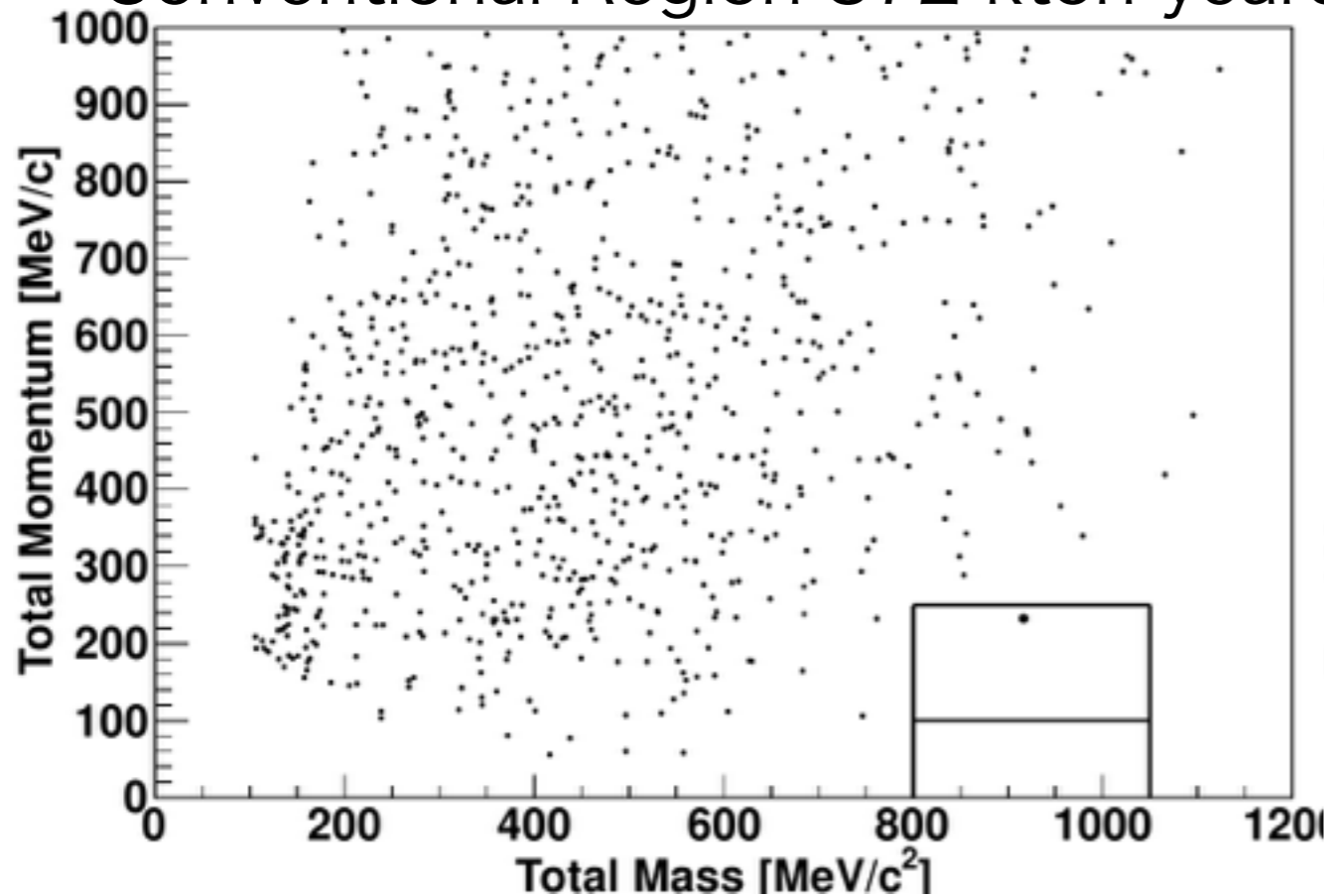
← **Almost BG free!**

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

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.

PRD 95, 012004 (2017)

- Reasonable reconstruction result.

- No new candidates incl. in enlarged region.

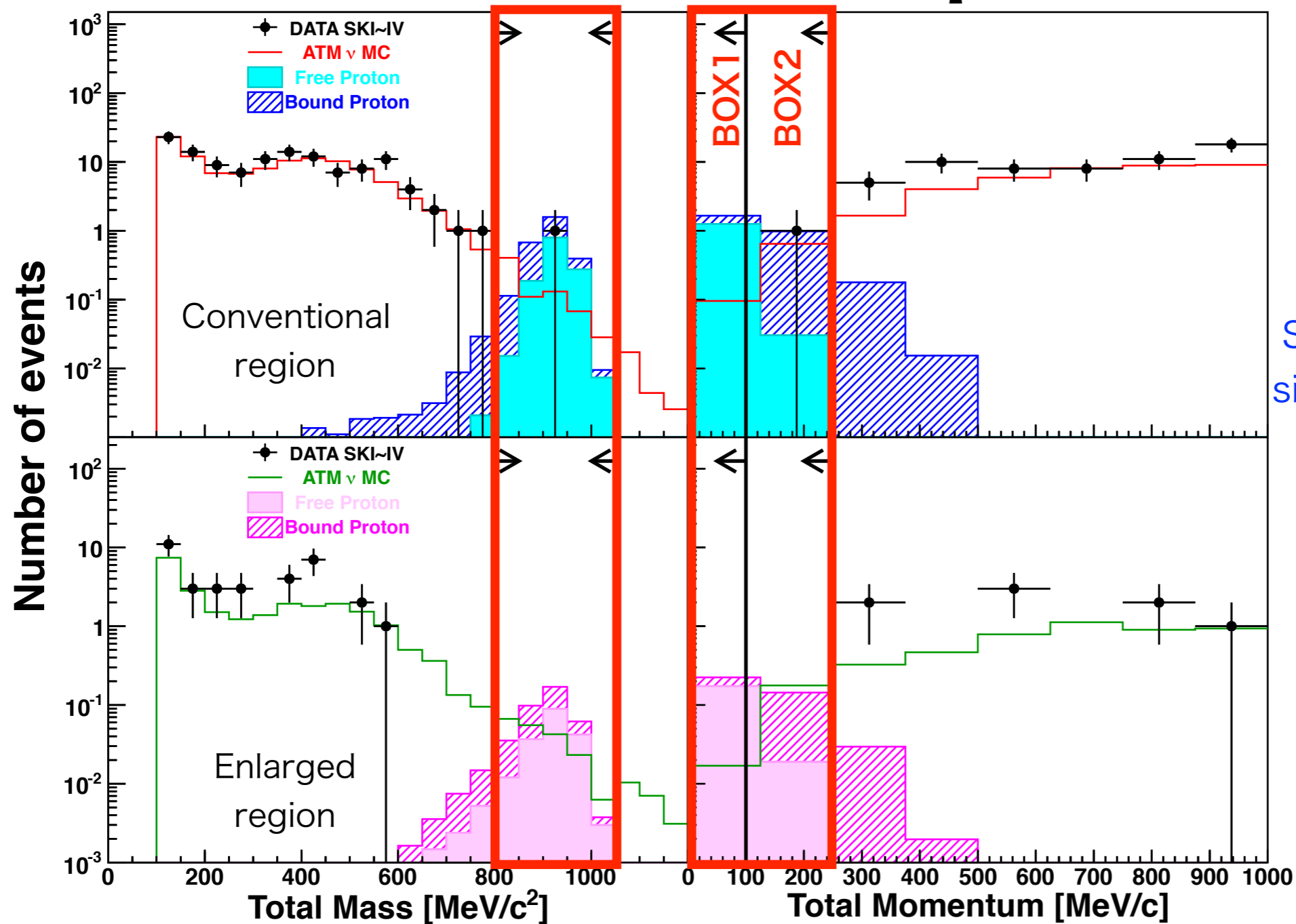
- No significant data excess compared to expected BG (0.89 in BOX2).

- Lower lifetime limit @90%C.L.

- $\tau / B_{p \rightarrow \mu^+ \pi^0} > 1.6 \cdot 10^{34}$ years (published: $7.7 \cdot 10^{34}$ years)

- Most stringent constraint. ~2 times longer than published.

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



- 1 candidate in BOX2. (With BOX2 BG 0.89)
- $\tau / \mathcal{B}_{p \rightarrow \mu^+ \pi^0} > 1.6 \cdot 10^{34}$ years (90%C.L.)
- Data is consistent with ATM ν MC prediction.

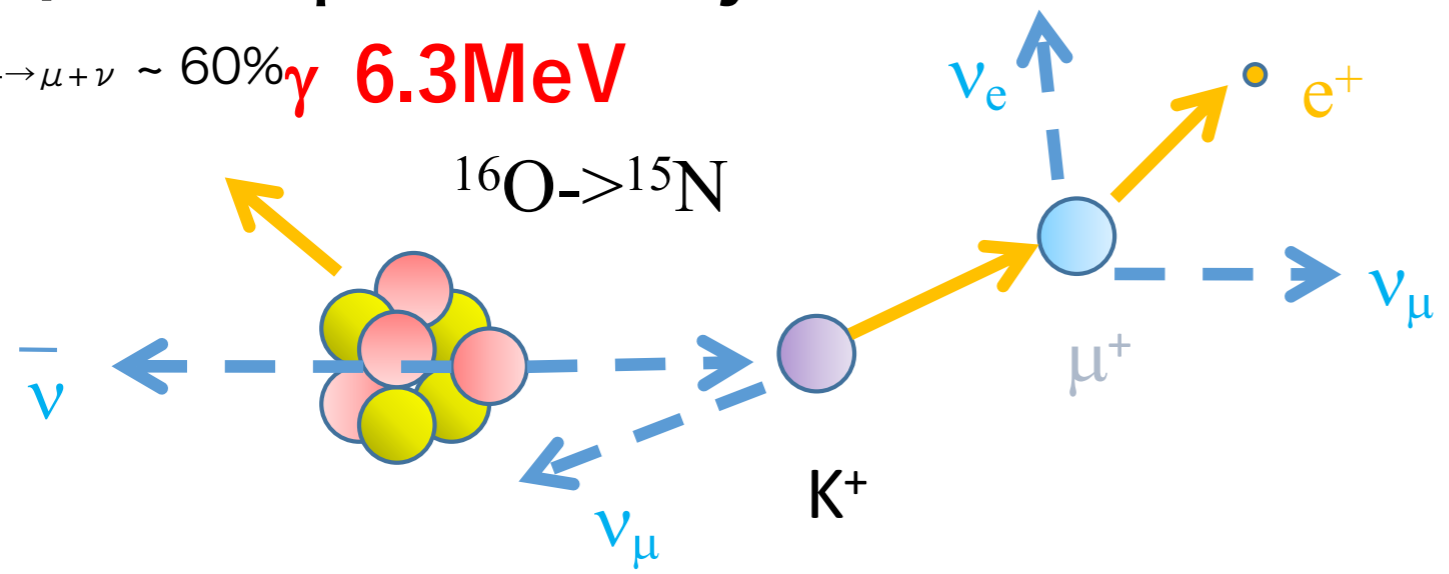
Other Decay Modes (Conventional Fiducial Mass Analysis Results)

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

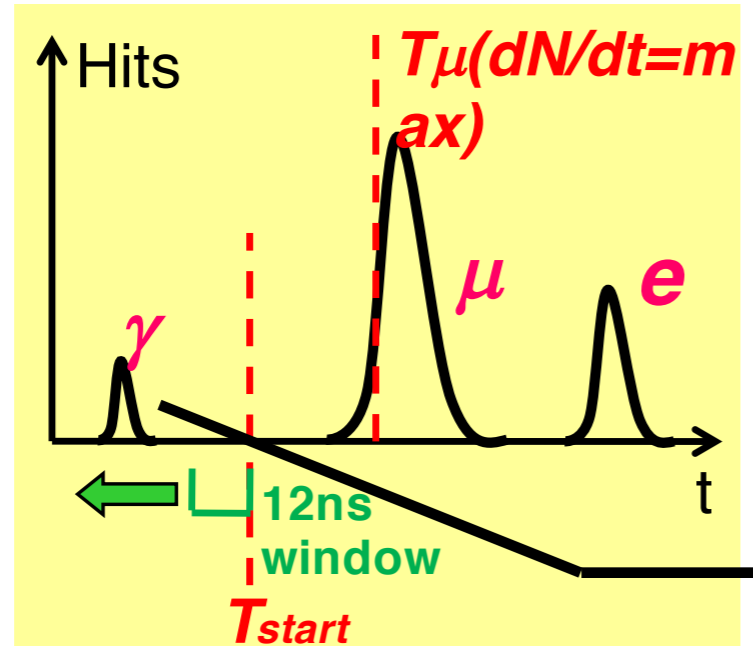
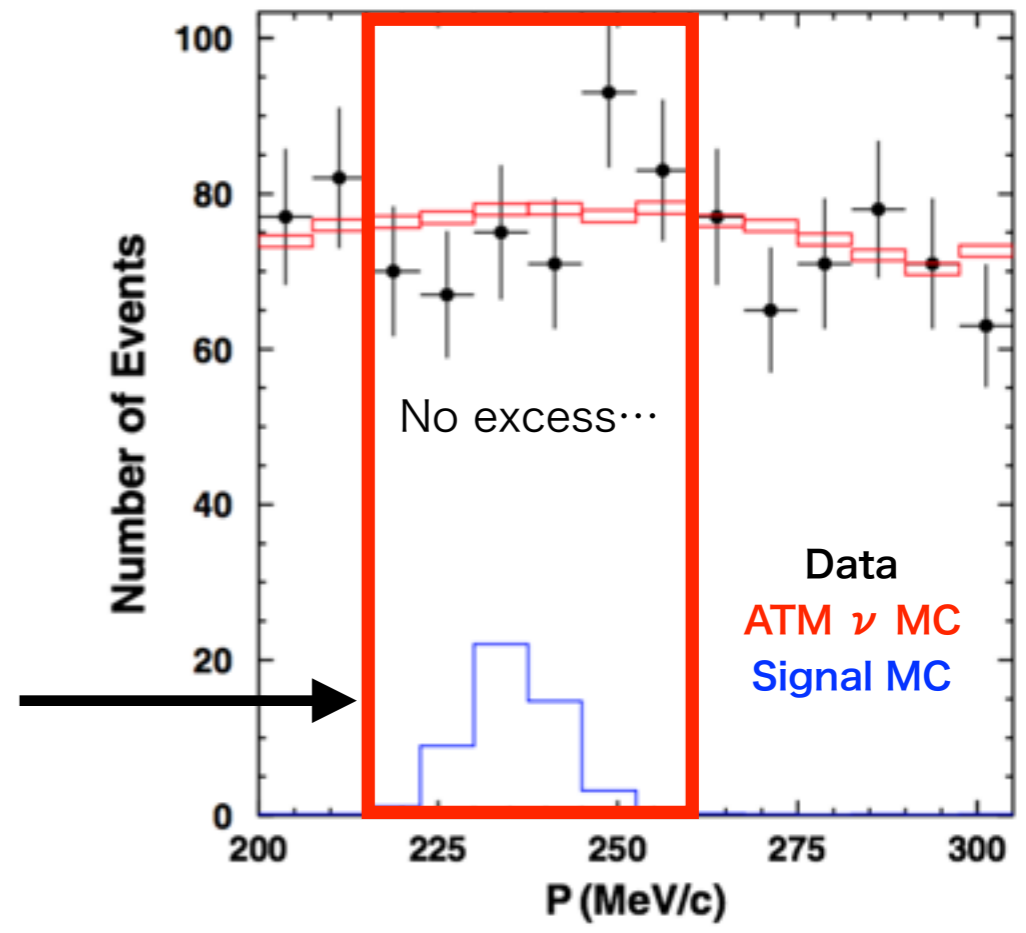
Favored in SUSY.

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

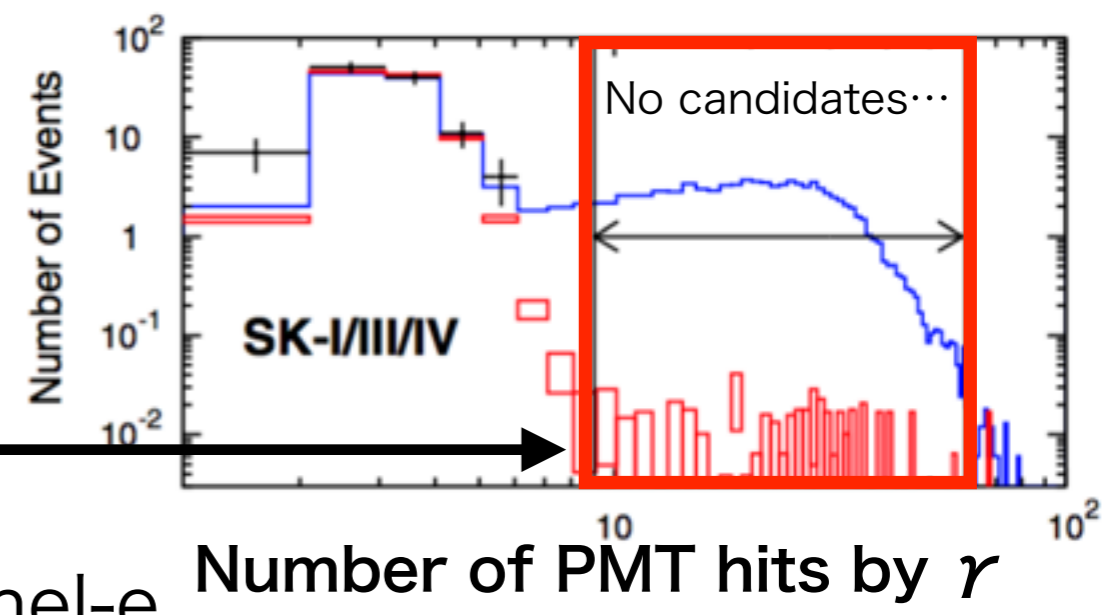
$BR_{K^+ \rightarrow \mu^+ \nu} \sim 60\%$ γ 6.3 MeV



(a) Mono-energetic (236 MeV/c) μ search
 • $\epsilon \sim 35\%$. No significant excess...



(b) Tag De-excitation 6.3 MeV γ and Michel-e
 • Require γ , μ , and Michel-e triple coincidence.
 • $\epsilon \sim 9\%$. No candidates...

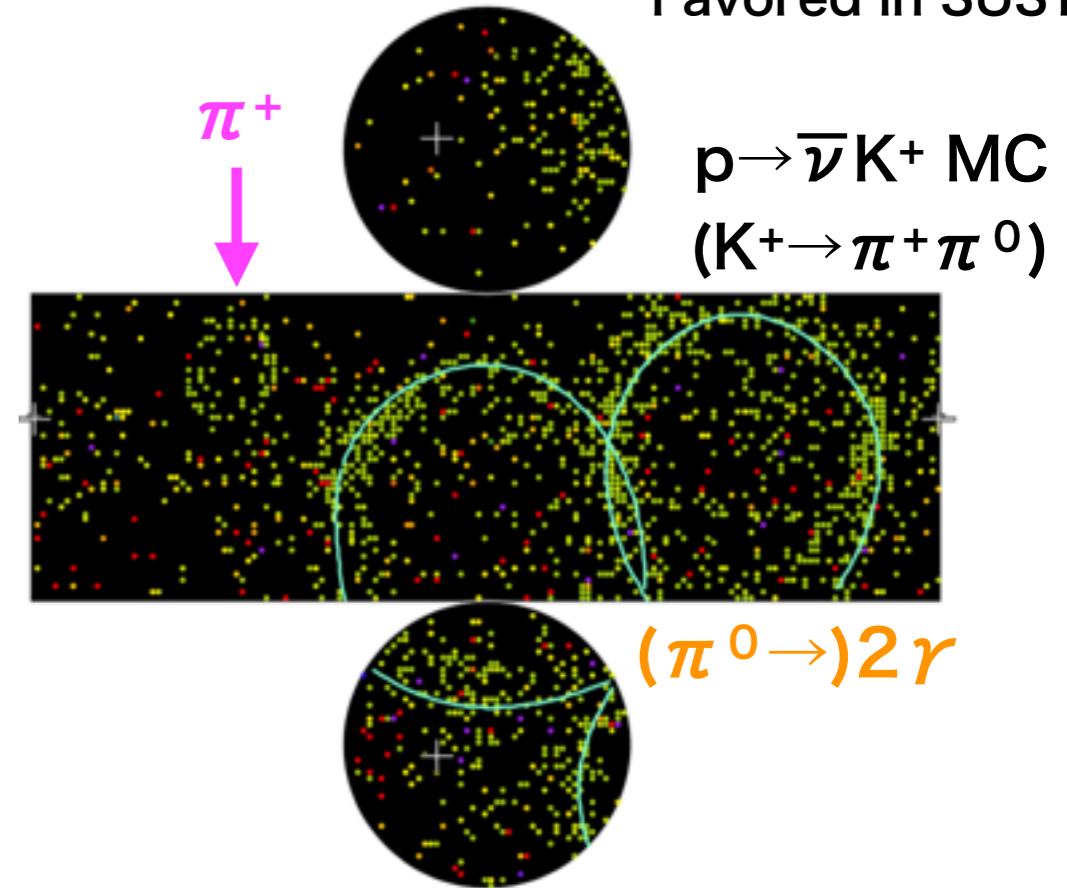
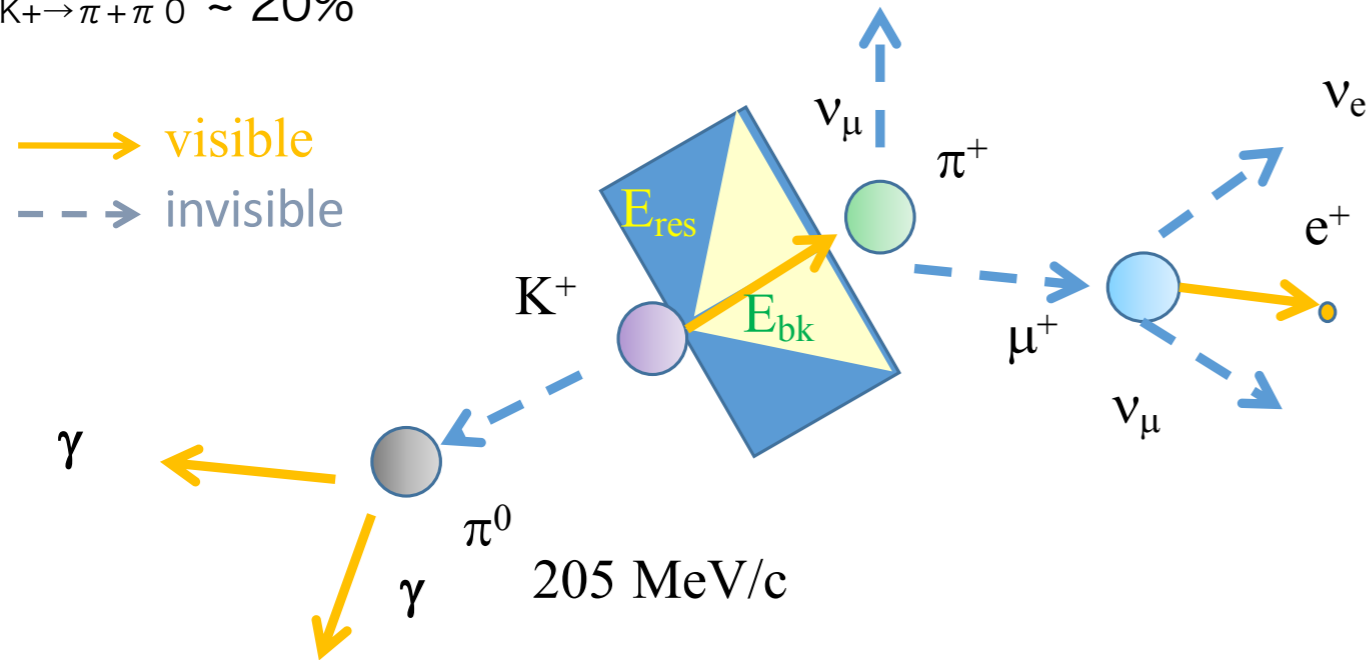


Search for $p \rightarrow \bar{\nu} K^+$

Favored in SUSY.

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

$BR_{K^+ \rightarrow \pi^+ \pi^0} \sim 20\%$



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

- $\epsilon \sim 9\%$. No candidates ...

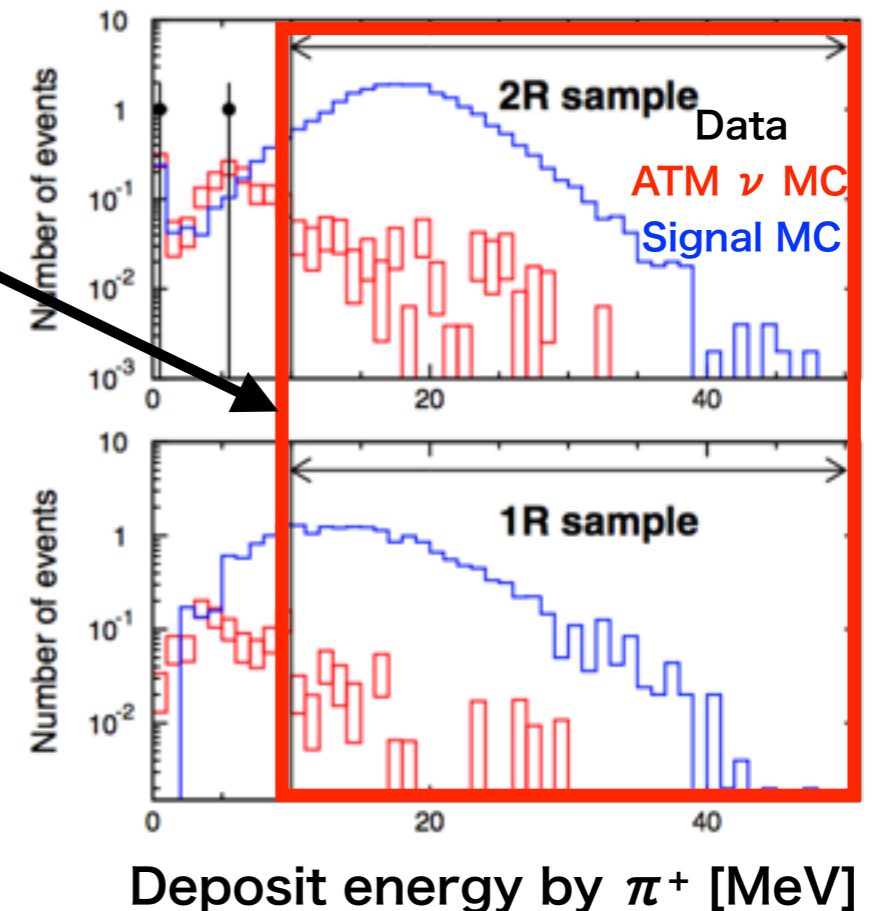
PRD 90, 072005 (2014)

- Combining three search methods with SKI-IV data (365 kton*years)

- $\tau / B_{p \rightarrow \nu K^+} > 8.2 \cdot 10^{33} \text{ years (90\% C.L.)}$

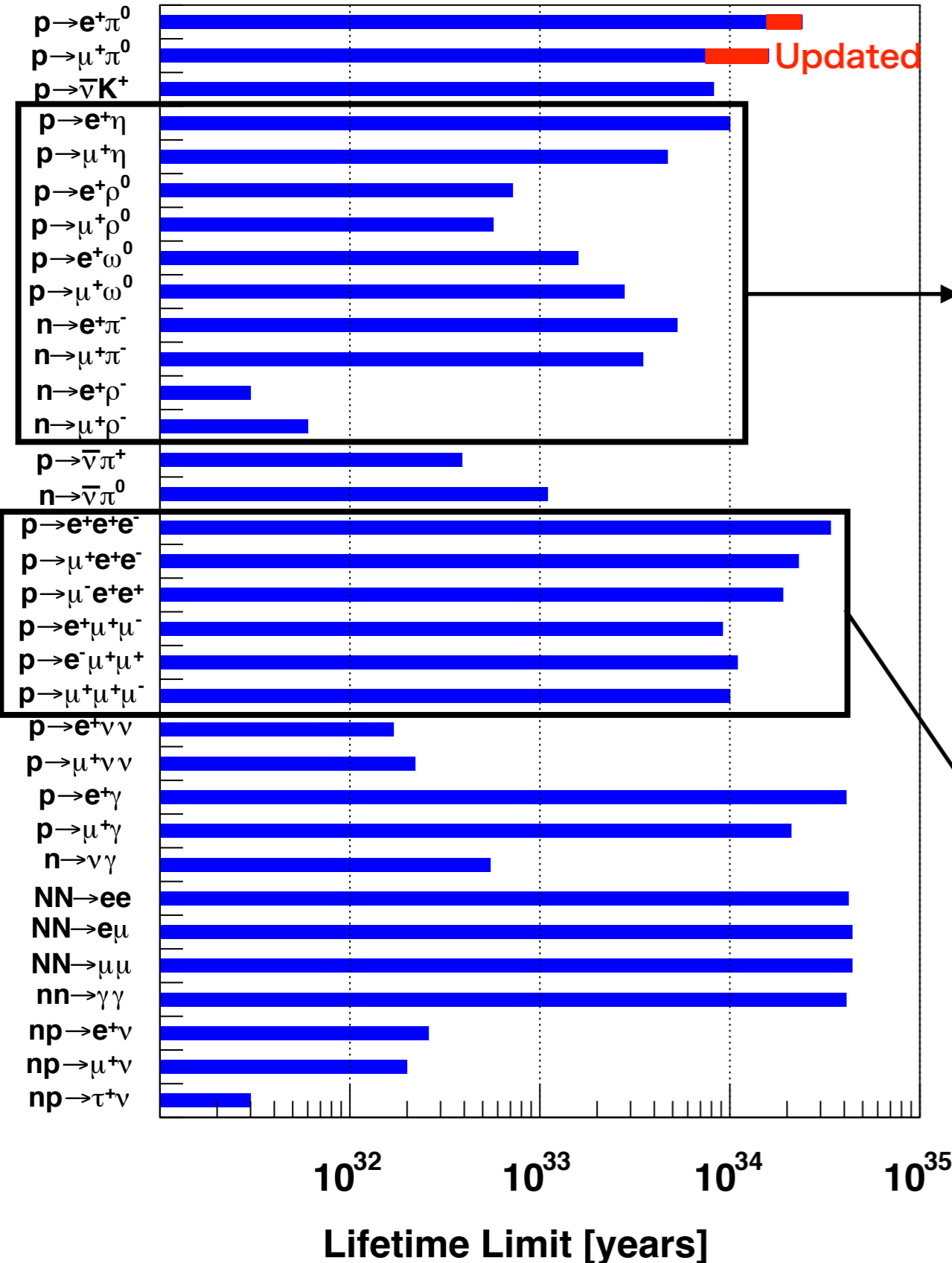
[Super-K Preliminary]

- 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
$p \rightarrow e^+ \eta$	16.0	0.78 ± 0.30	0	...	10.
$p \rightarrow \mu^+ \eta$	23.3	0.85 ± 0.23	2	20.9	4.7
$p \rightarrow e^+ \rho^0$	3.8	0.64 ± 0.17	2	13.5	0.72
$p \rightarrow \mu^+ \rho^0$	1.9	1.30 ± 0.33	1	72.7	0.57
$p \rightarrow e^+ \omega$	4.8	1.35 ± 0.43	1	74.1	1.6
$p \rightarrow \mu^+ \omega$	7.9	1.09 ± 0.52	0	...	2.8
$n \rightarrow e^+ \pi^-$	12.6	0.41 ± 0.13	0	...	5.3
$n \rightarrow \mu^+ \pi^-$	13.4	0.77 ± 0.20	1	53.7	3.5
$n \rightarrow e^+ \rho^-$	1.5	0.87 ± 0.26	4	1.2	0.03
$n \rightarrow \mu^+ \rho^-$	1.2	0.96 ± 0.28	1	61.7	0.06
total		8.6	12	15.7	...

Three charged leptons searches

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

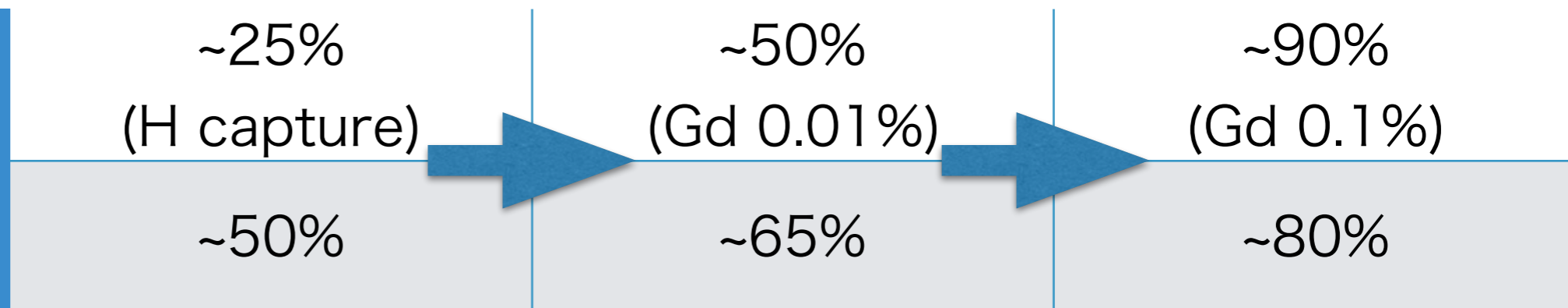
- No evidence of N-decay so far ... There is still room for statistic improvement (livetime & fiducial mass) except for $p \rightarrow e^+ \pi^0$ & $p \rightarrow \mu^+ \pi^0$.

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
ATM ν BG
Reduction by Ntag



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

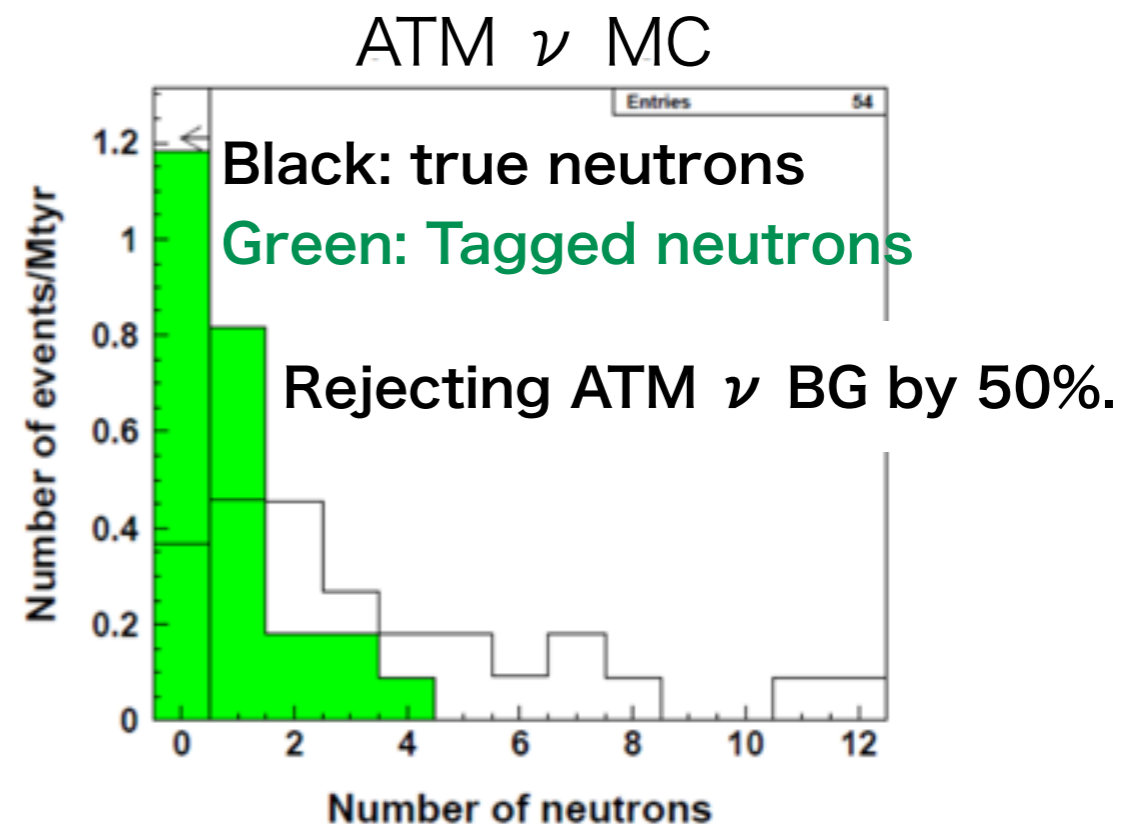
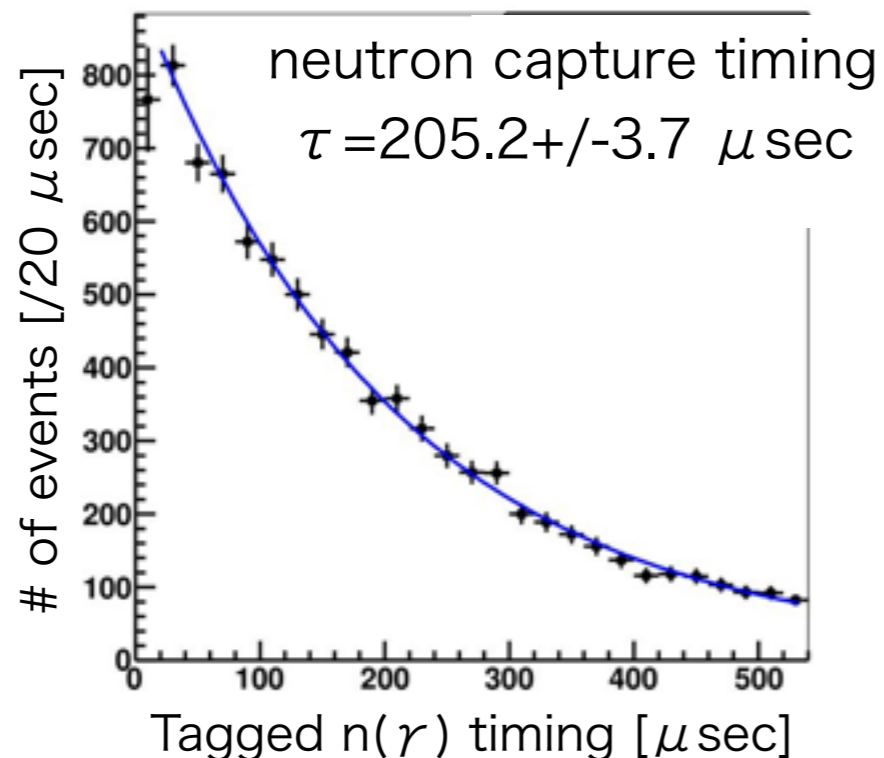
Conclusion

- Performed proton decay search ($p \rightarrow e^+ \pi^0$, $p \rightarrow \mu^+ \pi^0$) with enlarged fiducial mass of Super-Kamiokande detector.
 - Fiducial mass: 22.5 kton \rightarrow 27.2 kton
- No evidence of proton decay...
 - **SKI-IV full livetime 450 kton*years**
 - $\tau / B_{p \rightarrow e^+ \pi^0} > 2.4 * 10^{34}$ years (90%C.L.) (no candidates)
 - $\tau / B_{p \rightarrow \mu^+ \pi^0} > 1.6 * 10^{34}$ 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. ($n+p \rightarrow d + \gamma$ (2.2 MeV))
- By requiring no tagged neutrons.
 - efficiency loss: $<4\%$,
 - **ATM ν BG reduction by $\sim 50\%$.**



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
Physics 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
Physics Total	25.8	23.3	24.6
Total	33.5	34.3	32.0

Systematic Uncertainty mupi0

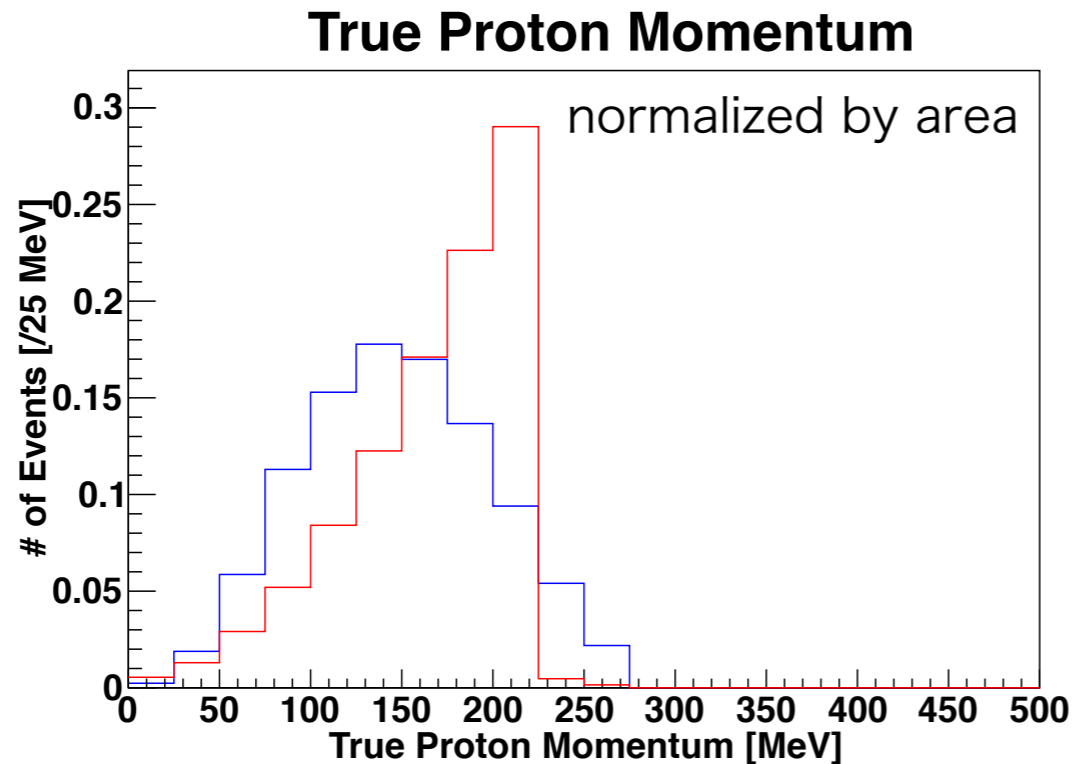
Systematics on signal Efficiency [%]

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
Physics 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
Physics Total	22.4	21.5	21.2
Total	27.8	30.3	26.3

Fermi Motion



epi0

Blue: Signal MC

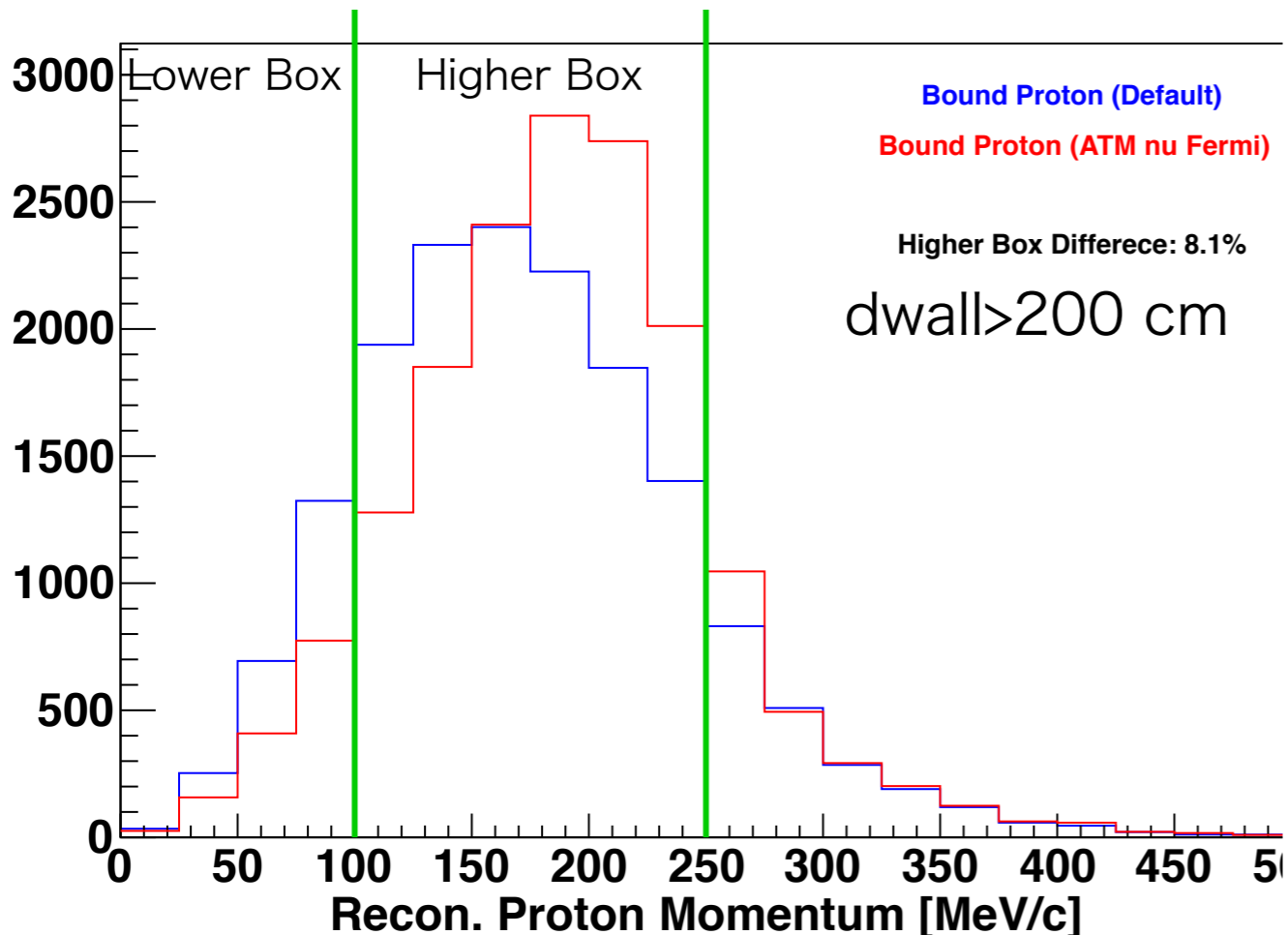
(Based on experimental result)

Red: ATM ν MC

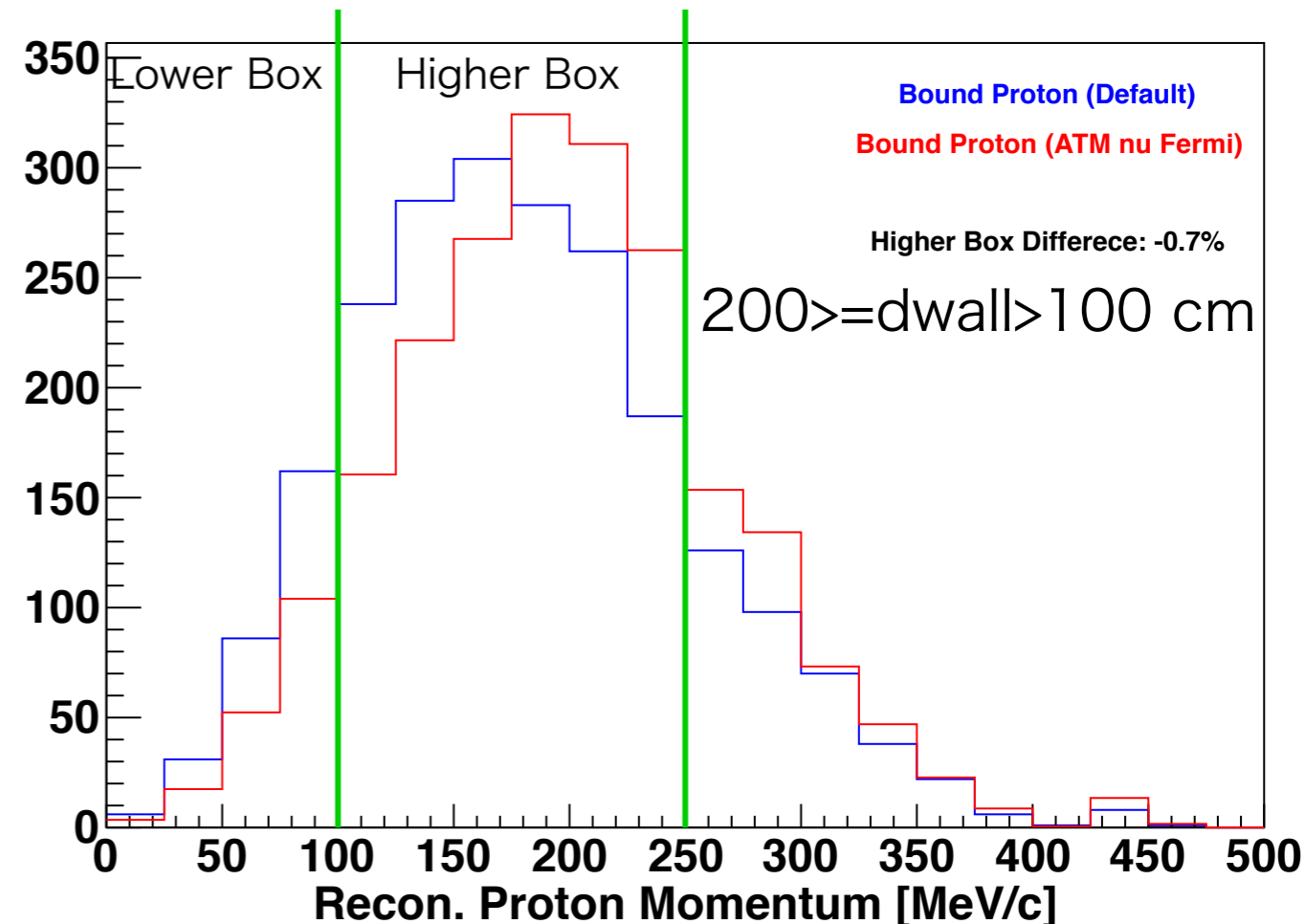
Fermi Model

Estimate uncertainty by re-weighting
from Blue to Red.

Recon. Proton Momentum Distribution (sk4:dwall: 200 ~ 1690 cm)



Recon. Proton Momentum Distribution (sk4:dwall: 100 ~ 200 cm)



Limit Calculation epi0

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

Box	SK1 (111.4 kton*yr)		SK2 (59.4 kton*yr)		SK3 (38.5 kton*yr)		SK4 (241.3 kton*yr)	
	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 [/lifetime]	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
Physics 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	
Physics Total	24.6	
Total	32.0	

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

Limit Calculation mupi0

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

Box	SK1 (111.4 kton*yr)		SK2 (59.4 kton*yr)		SK3 (38.5 kton*yr)		SK4 (241.3 kton*yr)	
	Low Box	High Box	Low Box	High Box	Low Box	High Box	Low Box	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 [/lifetime]	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	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
Physics 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	
Physics Total	21.2	
Total	26.3	

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

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*yr (dwall>200 cm)		450 kton*yr (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).

- $\tau_{p \rightarrow e + \pi^0}(\text{exp.}): 1.7 \cdot 10^{34} \text{ yrs} \rightarrow 1.9 \cdot 10^{34} \text{ yrs.}$

mupi0 Search Performance

mupi0	372 kton*yr (dwall>200 cm)		450 kton*yr (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

- $\tau_{p \rightarrow \mu + \pi^0}(\text{exp.}): 1.4 \cdot 10^{34} \text{ yrs} \rightarrow 1.6 \cdot 10^{34} \text{ yrs.}$

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

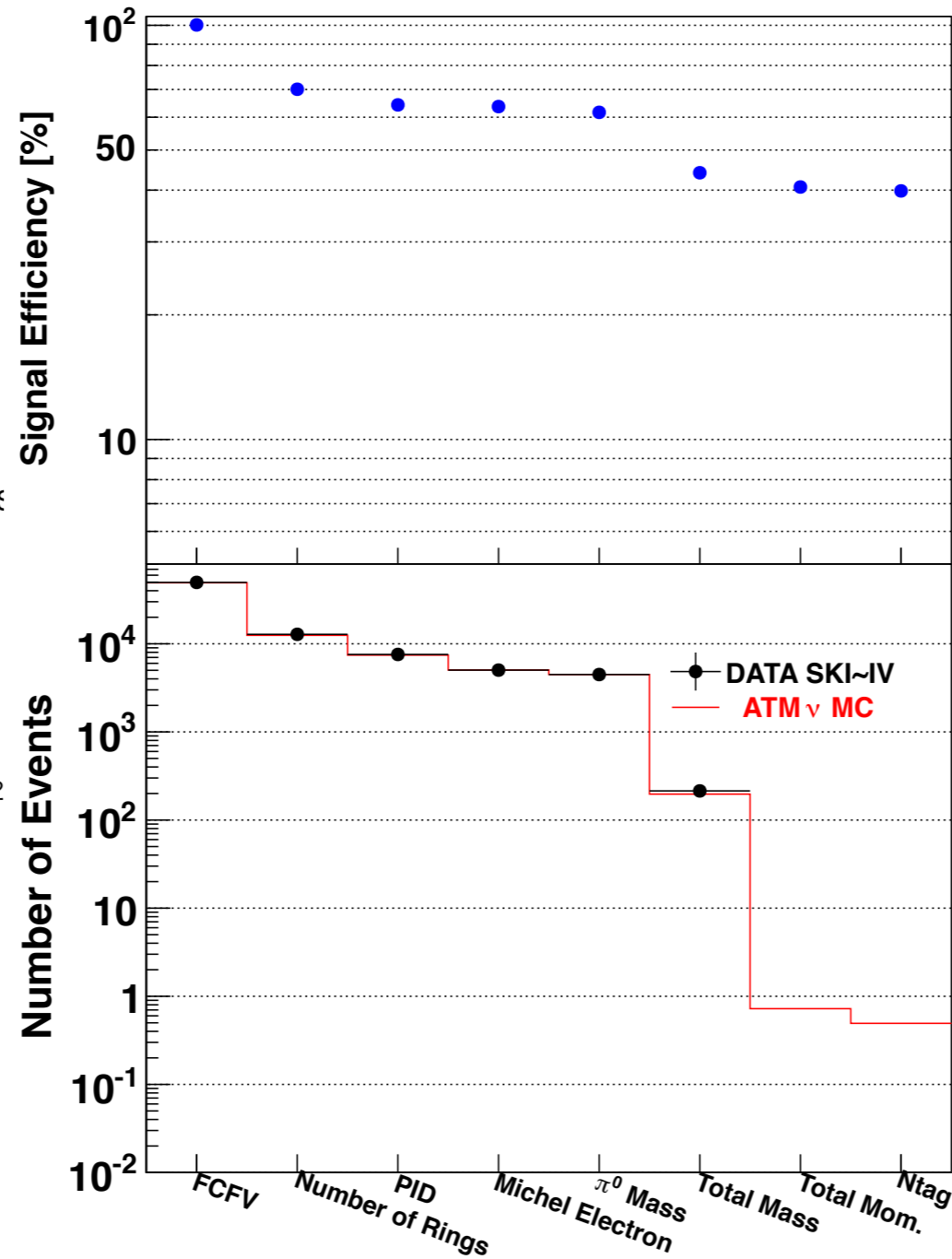
Efficiency & Number of Events v.s. Selection Cut

Event Selection Cut

- FCFV Cut
($n_{hitac} < 16$ & $e_{vis} > 30$ MeV
& $d_{wall} > 100$ cm)
- ring cut
(# of rings = 2 or 3)
- PID cut
(ALL e-like rings)
- No Michel Electron
- For 3-ring events, π^0 mass cut
($85 < M_{\pi^0} < 185$ MeV/ c^2)
- Total mass cut
($800 < M_{tot} < 1050$ MeV/ c^2)
- Total momentum cut
Higher Box:
($100 \leq P_{tot} < 250$ MeV/ c)
Lower Box:
($P_{tot} < 100$ MeV/ c)
- For SKIV, no neutron.

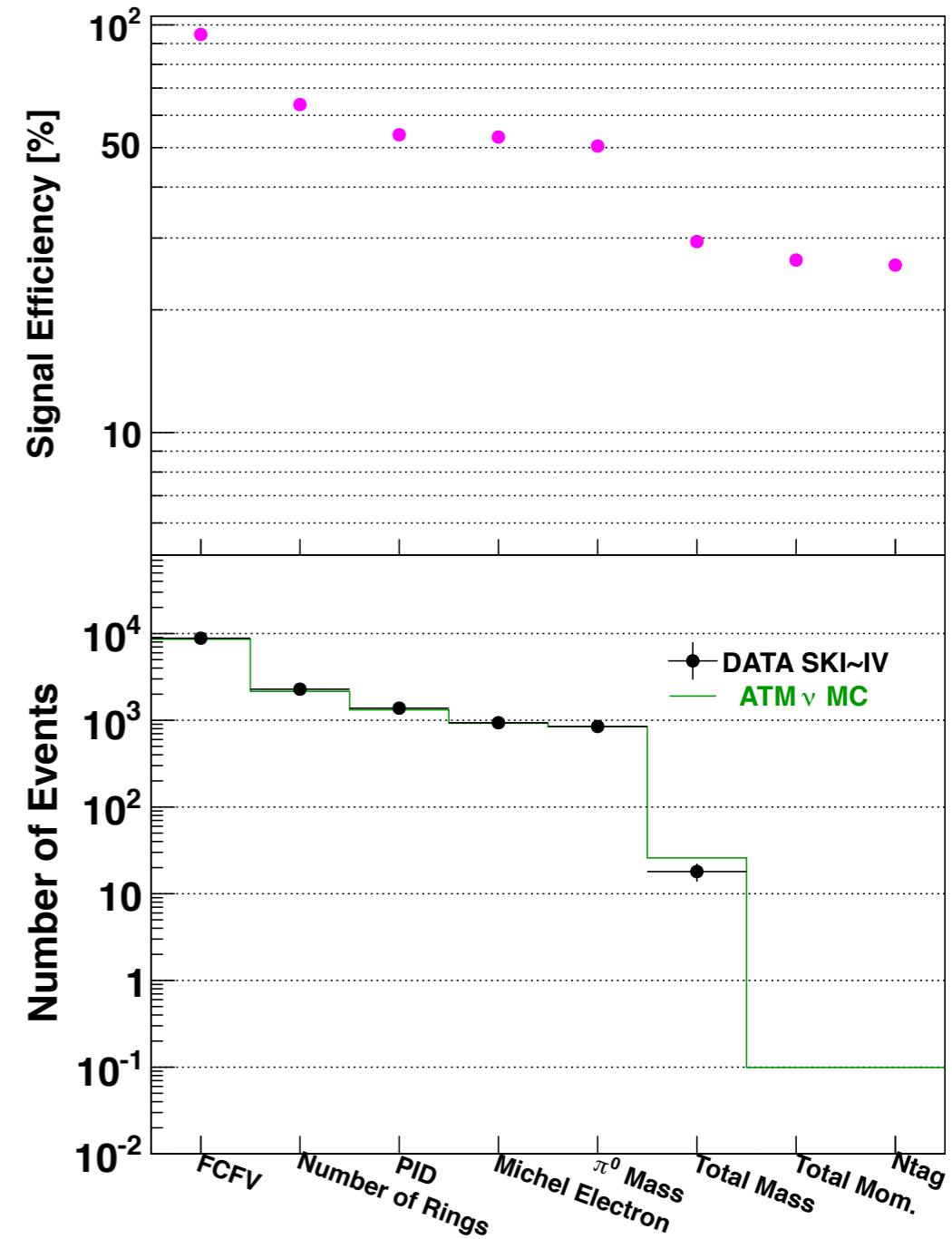
$d_{wall} > 200$ cm

Efficiency & Number of Events v.s. Selection Cut



$200 \geq d_{wall} > 100$ cm

Efficiency & Number of Events v.s. Selection Cut

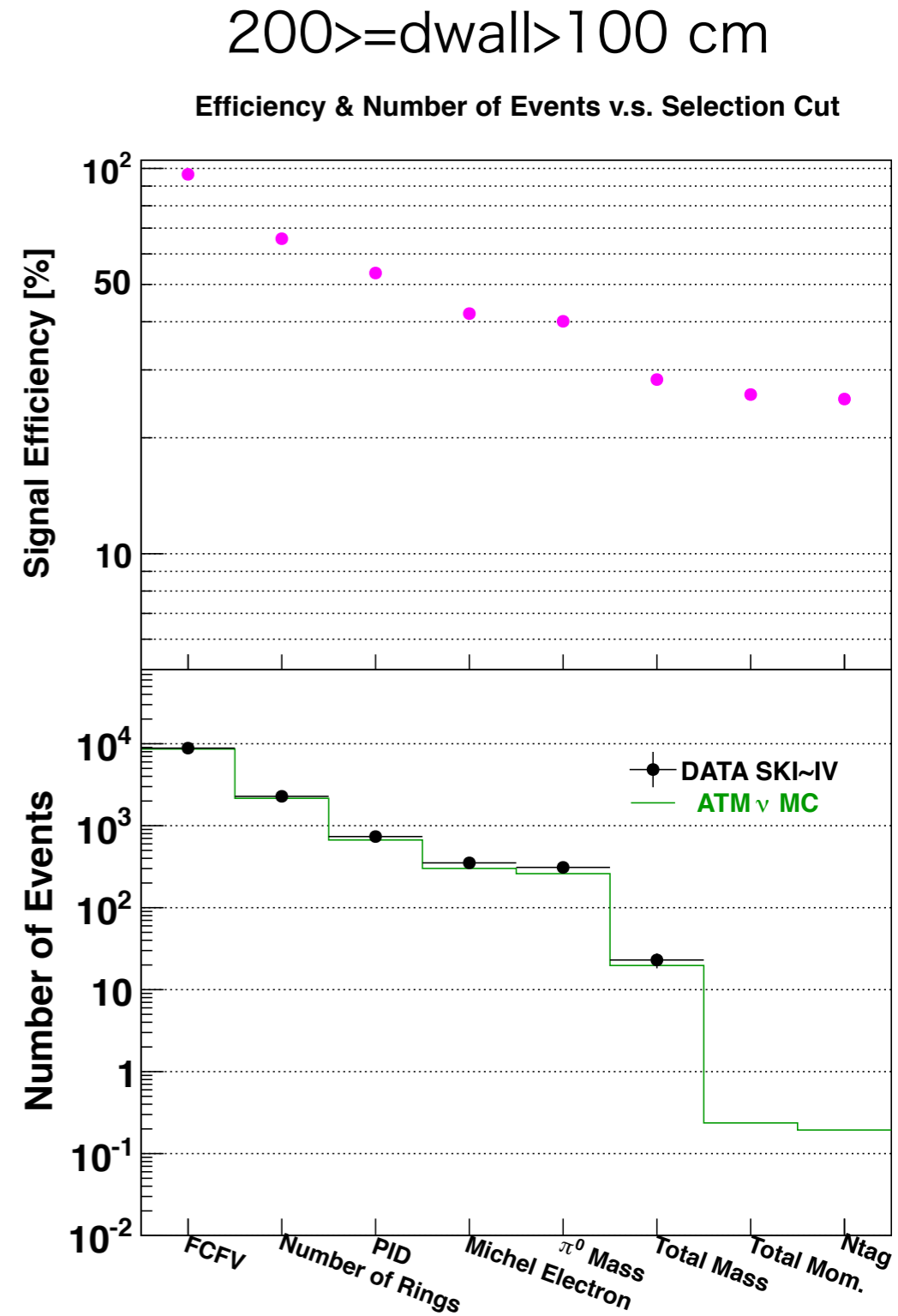
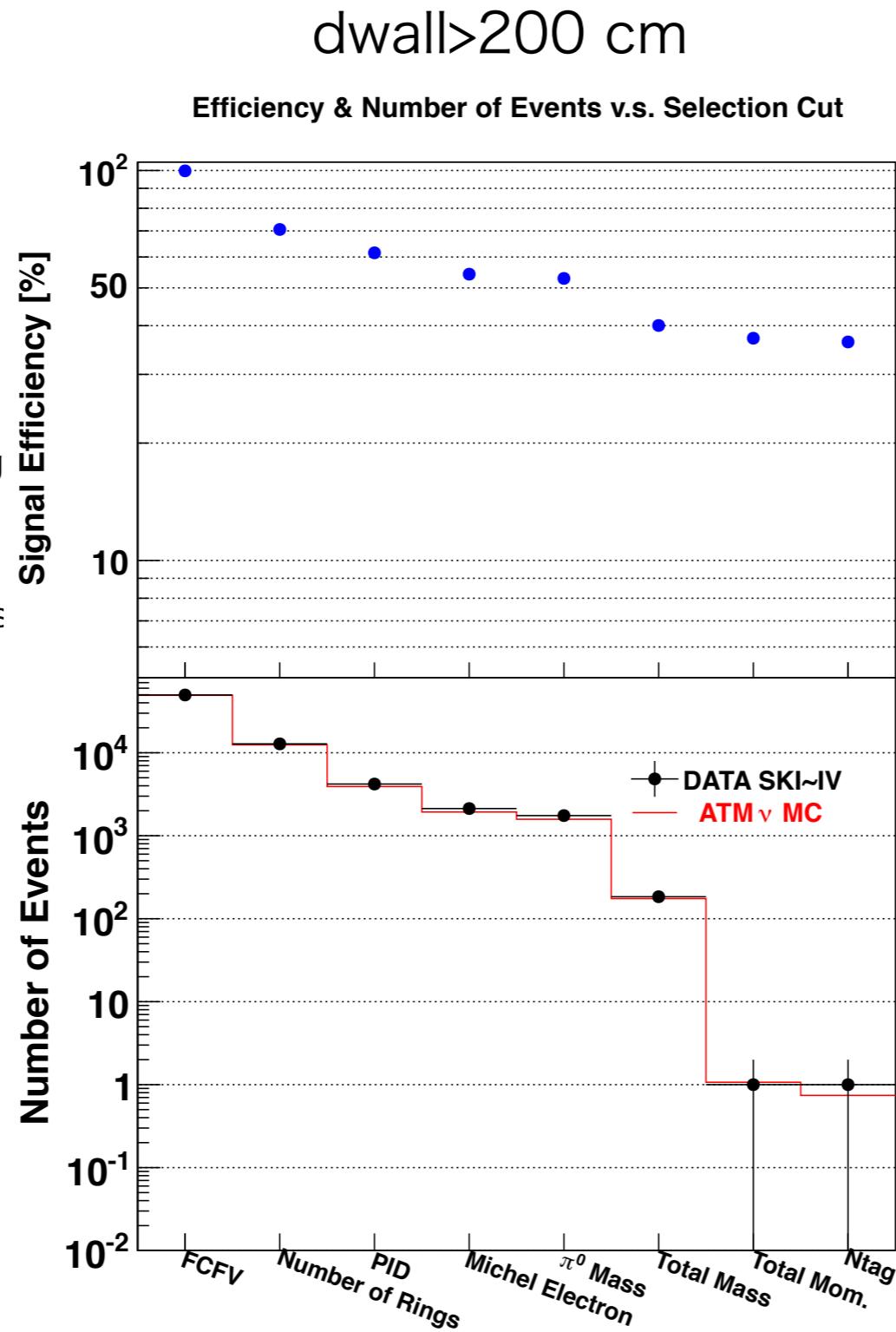


ATM ν MC is normalized by livetime & 3 flavor oscillation parameters.

Efficiency & Number of Events v.s. Selection Cut

Event Selection Cut

1. FCFV Cut
($n_{hitac} < 16$ & $e_{vis} > 30$ MeV
& $d_{wall} > 100$ 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, 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
Higher Box:
($100 \leq P_{tot} < 250$ MeV/c)
Lower Box:
($P_{tot} < 100$ MeV/c)
8. For SKIV, no neutron.



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

Main

Michel-e

★ Super Kamiokande ★

```

NUM          1629
RUN          70690
SUBRUN       62
EVENT        1525625
DATE 2012-Nov-30
TIME        9:40:17
TOT PE:     7418.
MAX PE:     89.7
NMHIT       2504
ANT-PE:     9.4
ANT-MX:     1.9
NMHITA      10

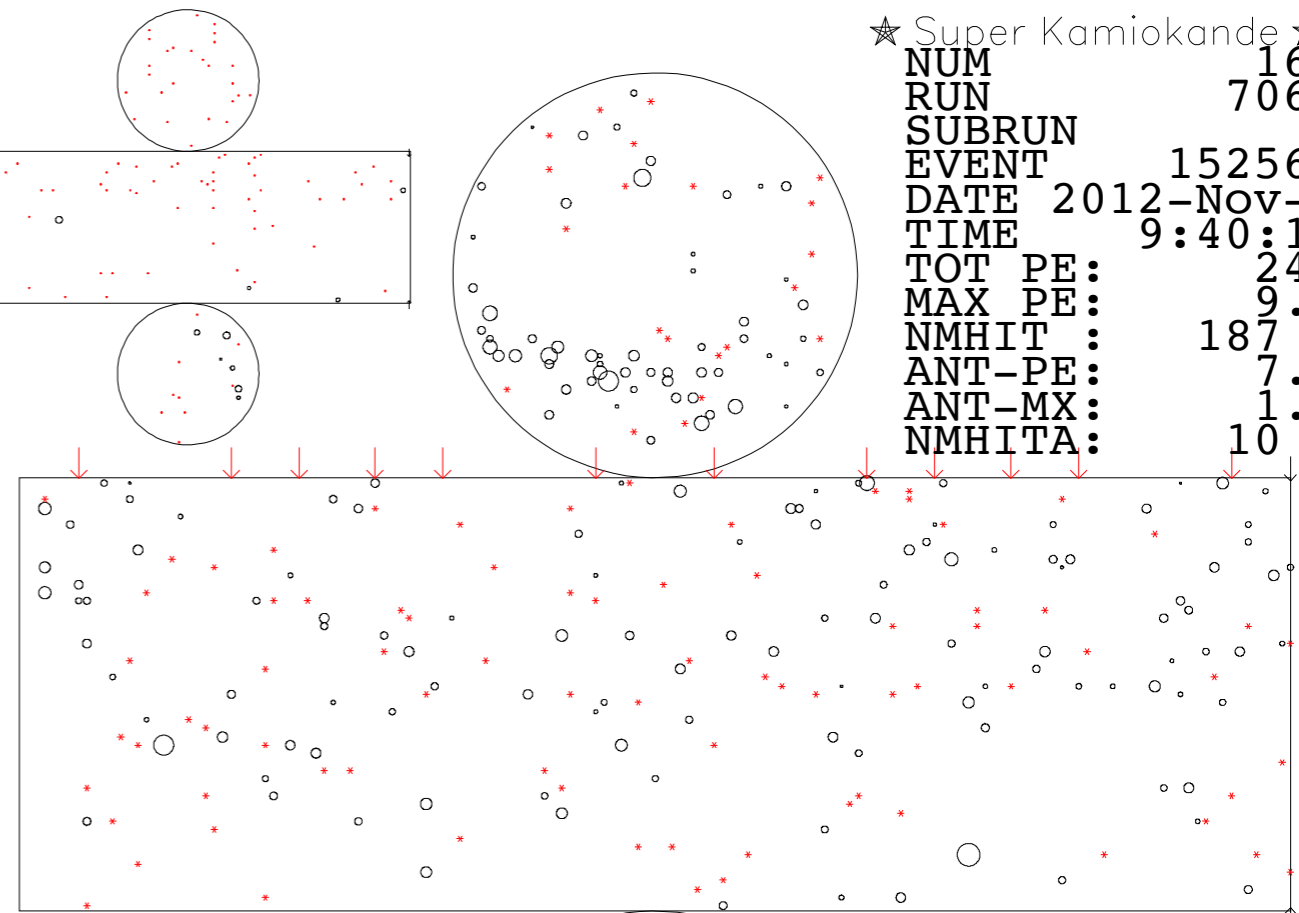
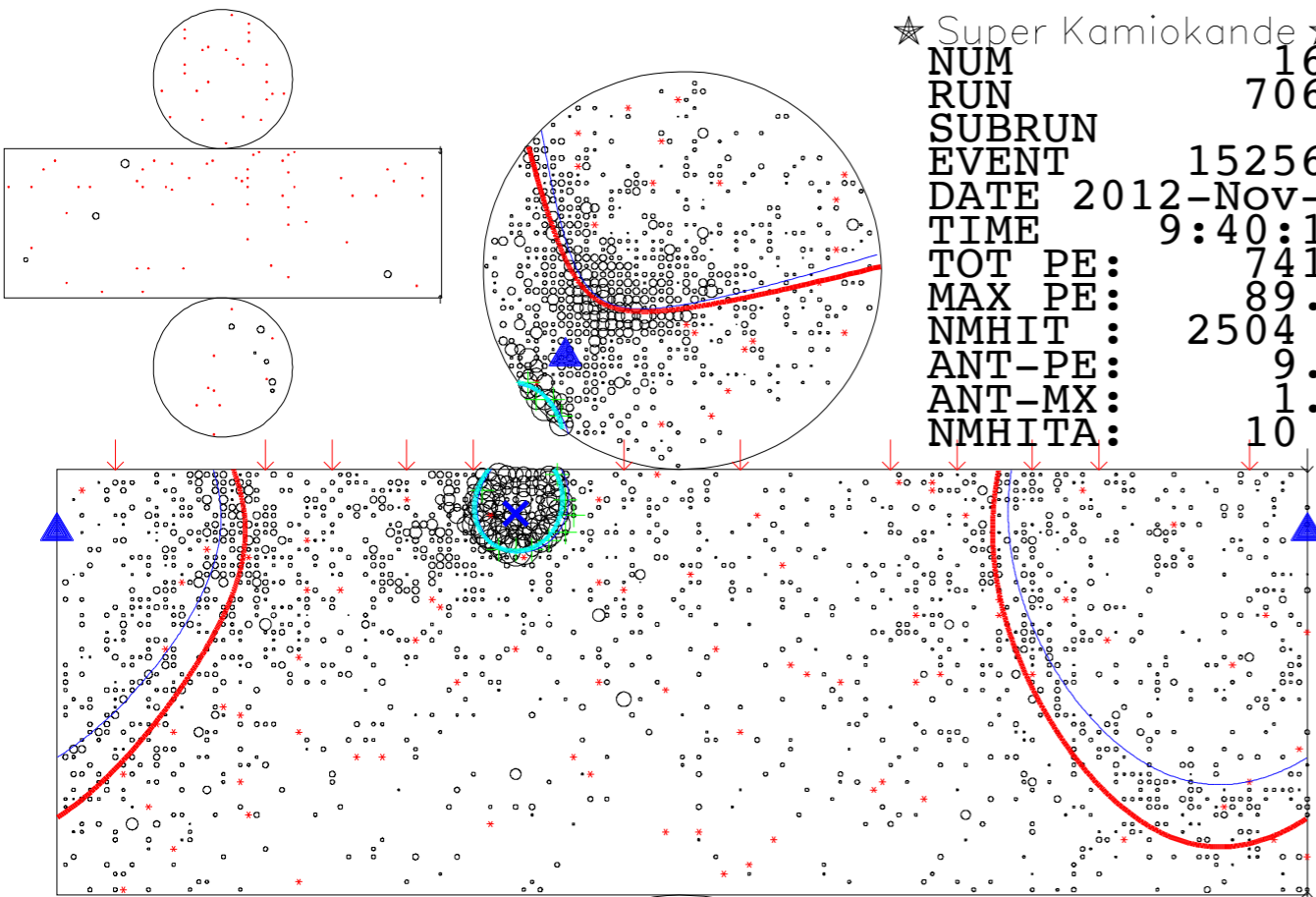
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★ Super Kamiokande ★

```

NUM          1629
RUN          70690
SUBRUN       62
EVENT        1525625
DATE 2012-Nov-30
TIME        9:40:17
TOT PE:     2418.
MAX PE:     9.7
NMHIT       187
ANT-PE:     7.4
ANT-MX:     1.9
NMHITA      10

```



```

1990/00/00:NoYet:NoYe
1990/00/00:NoYet:NoYe
1990/00/00:NoYet:NoYe
1990/00/00:NoYet:NoYe
1990/00/00:NoYet:NoYe
2019/03/19:;R= 2:NoYe
R      Z      PHI
12.32: 12.85:-2.20:0
CANG : RTOT : AMOM : 1
37.6: 1991: 362:
V=-0.801:-0.521:0.
40.0: 2274: 414:
V= 0.843: 0.537: 0.

```

```

RunMODE: NORMAI
TRG_ID  : 000001
T_diff  : 0.00
FEVSK   : 880108
nOD_YK/LW: 1/
SUB_EV  : 0/
Dcye   : 1( 1/ 0/
Dcȳ T: 0.834
Dcȳ T: 0.00

```

```

1990/00/00:NoYet:NoYe
1990/00/00:NoYet:NoYe
1990/00/00:NoYet:NoYe
1990/00/00:NoYet:NoYe
1990/00/00:NoYet:NoYe
1990/00/00:NoYet:NoYe
R      Z      PHI
0.00: 0.00: 0.00:0
CANG : RTOT : AMOM : 1

```

```

RunMODE: NORMAI
TRG_ID  : 000001
T_diff  : 0.00
FEVSK   : 880108
nOD_YK/LW: 4/
SUB_EV  : 0/
Dcye   : 0( 0/ 0/
Dcȳ T: 0.834
Dcȳ T: 0.00

```

Comnt;

Comnt;

$d_{wall} = 458 \text{ cm}$, $n_{ring} = 2$, $M_{tot} = 917 \text{ MeV}/c^2$, $P_{tot} = 233 \text{ MeV}/c$
 1st ring - μ like, mom $559 \text{ MeV}/c$, $\theta_{ang} 37.2 \text{ degree}$
 2nd ring - elike, mom $377 \text{ MeV}/c$, $\theta_{ang} 43.8 \text{ degree}$
 1 decay-e $0.834 \mu\text{sec}$