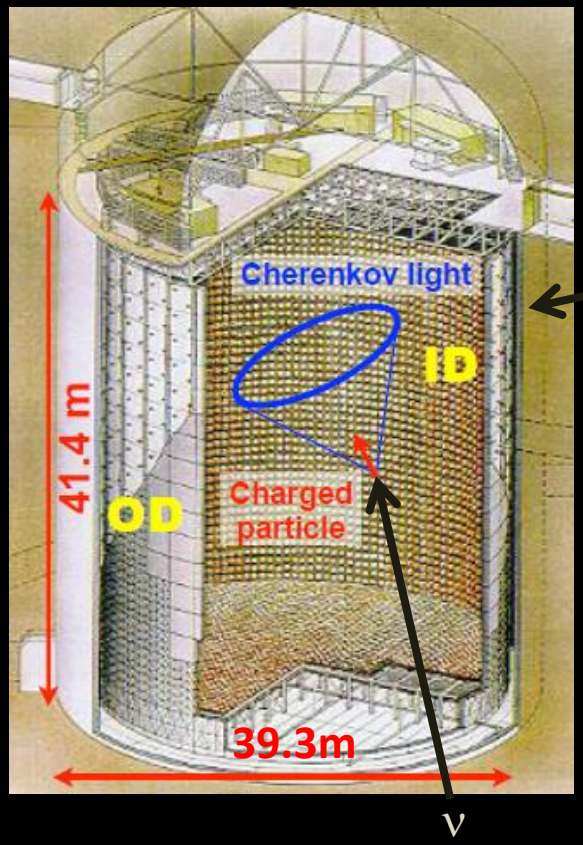
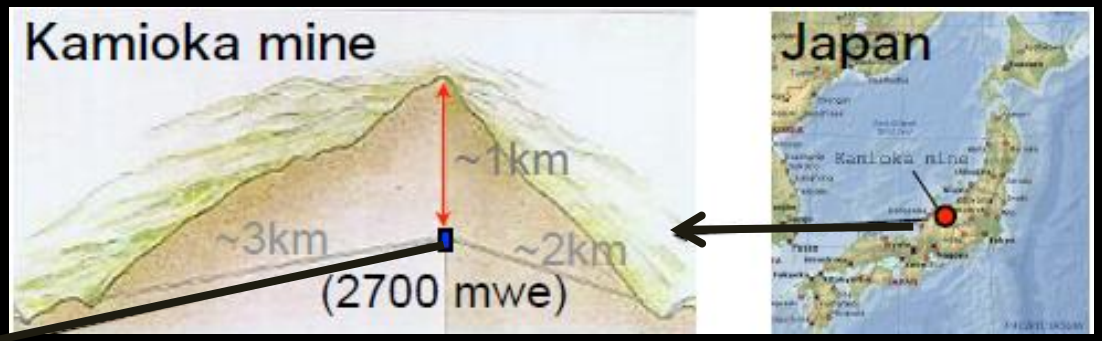
Recent nucleon decay results from Super-Kamiokande

S.Mine (University of California, Irvine)
for Super-Kamiokande collaboration

20in. PMTs by HAMAMATSU

Super-Kamiokande (Super-K, SK)





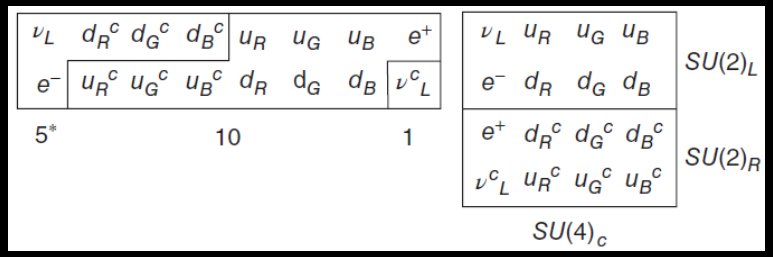
Nucl. Instr. & Meth, A 737C (2014)

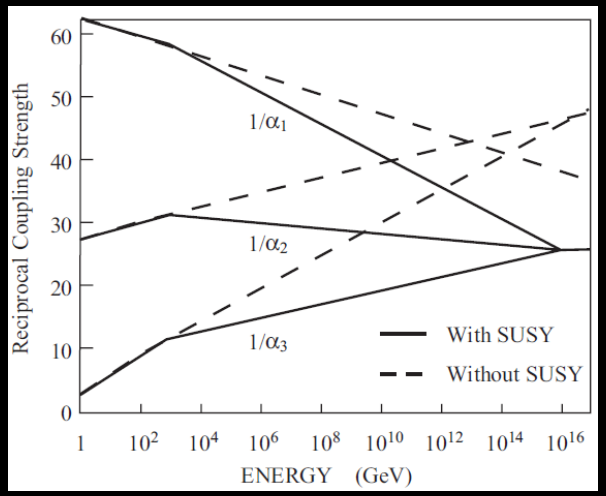
Phase		SK-I	SK-II	SK-III	SK-IV
Period	start	1996 Apr.	2002 Oct.	2006 Jul.	2008 Sep.
	end	2001 Jul.	2005 Oct.	2008 Sep.	(running)
Number of PMTs	ID (photo-coverage)	11146 (40%)	5182 (19%)	11129 (40%)	11129 (40%)
	OD	1885			
Anti-implosion container		no	yes	yes	yes
OD segmentation		no	no	yes	yes
Front-end electronics		ATM (ID) OD QTC (OD)			QBEE

- SK total ~ 20 years

Grand Unified Theory (GUT)

- Single symmetry group $G \supset SU(3)_{color} \times SU(2)_L \times U(1)_Y$
  - single coupling constant, quantization of electric charge, etc.
- Popular models:
  - SO(10) GUT
    - 15 fermions and ν_R in single rep.
  - supersymmetry(SUSY) GUT
    - 3 coupling constants meet at ~10^{16}GeV





- GUTs predict instability of nucleon:
  - two benchmark decay modes:
    - $e^+\pi^0$(non-SUSY) and νK^+(SUSY)
  - some models predict lifetime < 10^{34} years probed by SK
  - baryon asymmetry of the universe

Nucleon decay searches in SK

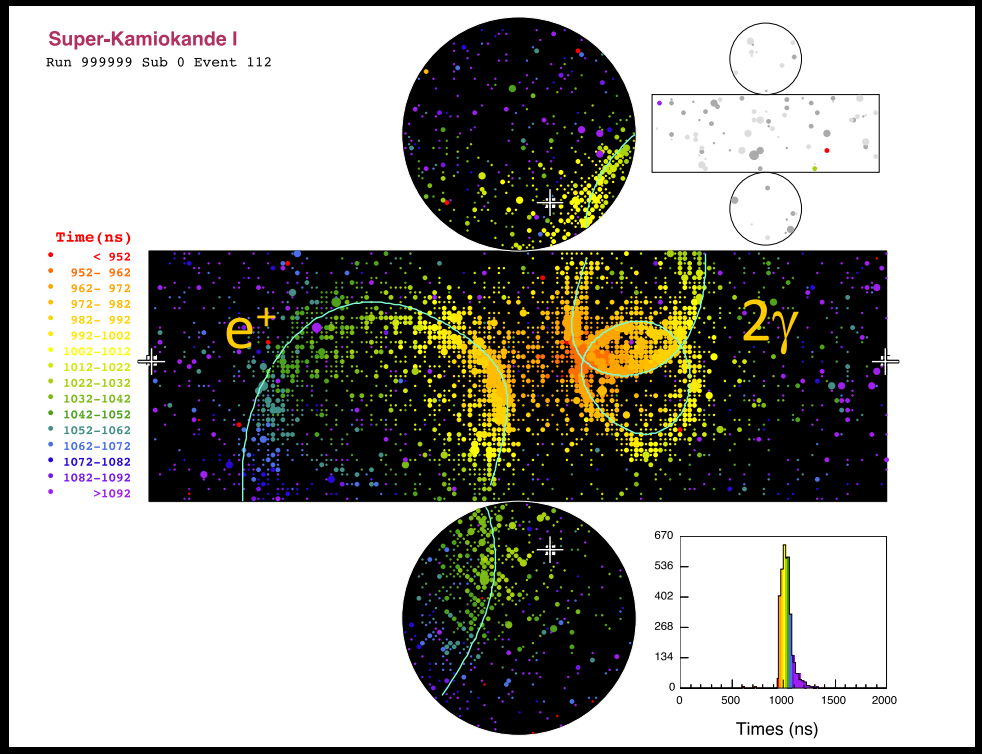
(unique way to directly probe GUTs)

- SK has the world's best sensitivities on nucleon lifetime:
  - large fiducial volume (V)
    - 22.5kt → ~7.5×10^{33} protons and ~6×10^{33} neutrons
  - excellent detector performance (ε_{sig}, #BKG)
    - ex.) Nucl. Instr. & Meth A 433 (1999)
  - long stable detector operation since 1996 (T)
- Lifetime sensitivity $\propto \begin{cases} \varepsilon_{sig} / 2.3 \cdot VT \text{ (BKG free)} \\ \varepsilon_{sig} / \sqrt{\#BKG} \cdot \sqrt{VT} \text{ (BKG dominant)} \end{cases}$
  - important to increase signal efficiency and BKG rejection
- Several new results recently
  - analysis improvements in $p \to e^+\pi^0$ and $p \to \nu K^+$ *(main in this talk)*
  - exotic searches (dinucleon decay, etc.)

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

- Event selections:
  - fully contained
  - fiducial volume
  - 2 or 3 rings
  - all e-like (PID)
  - no Michel electrons
  - $85 < M_{\pi 0} < 185 MeV/c^2$ (3-ring)
  - $800 < M_p < 1050 MeV/c^2$
  - $P_{tot} < 100 MeV/c$,
    $100 \leq P_{tot} < 250 MeV/c$
  - no neutrons (SK-IV only)

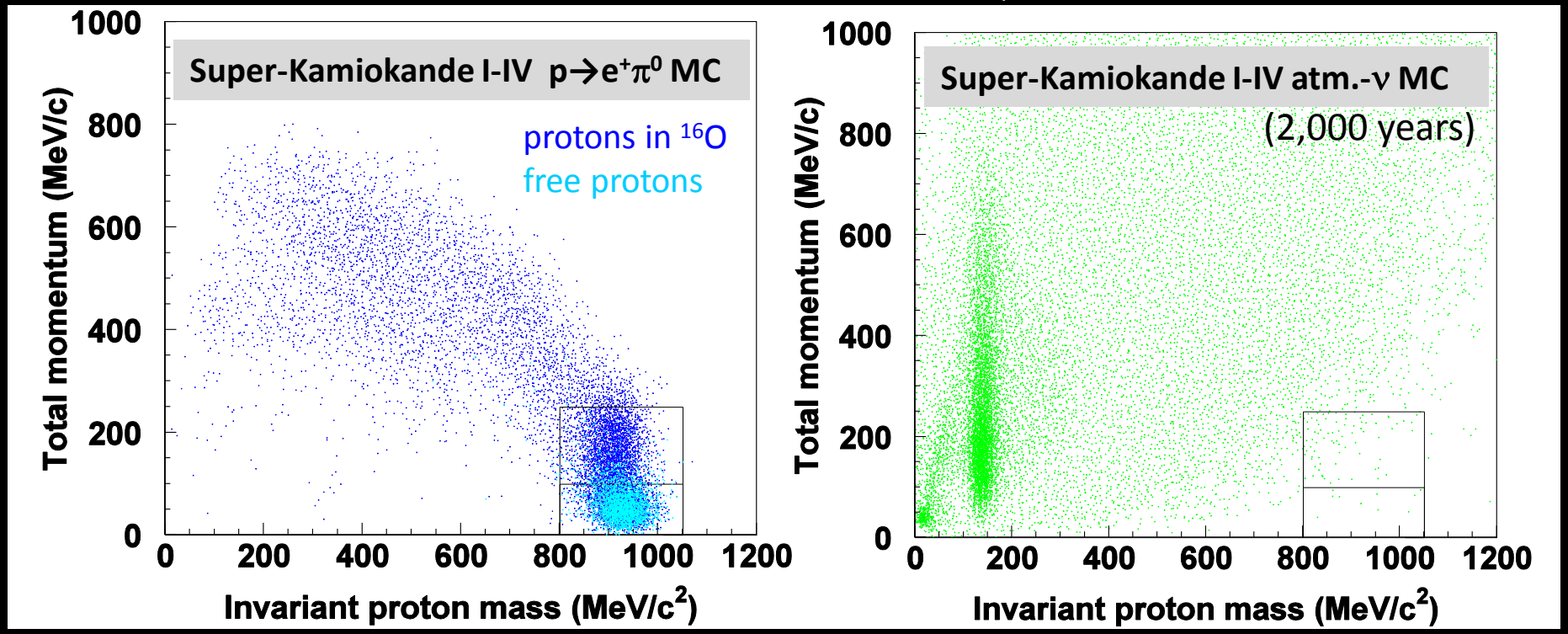
$p \rightarrow e^+\pi^0(\pi^0 \rightarrow 2\gamma)$ MC



New: P_{tot} separation into 2 regions

P_{tot}<100MeV/c, 100≤P_{tot}<250MeV/c

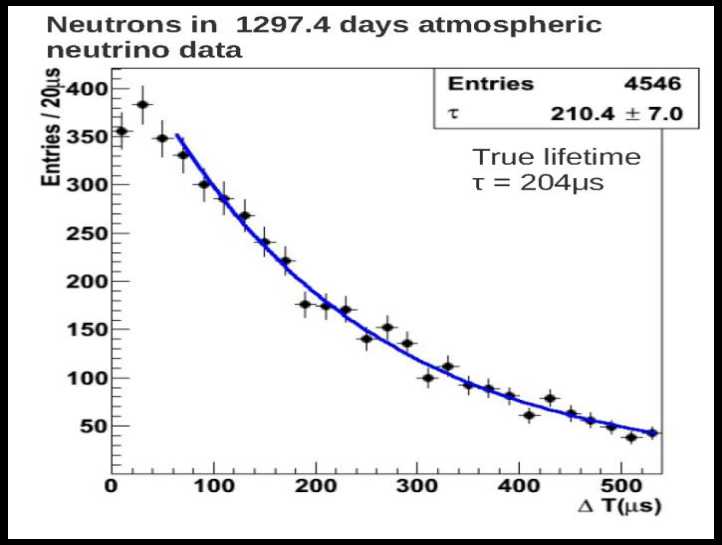
(after $p \rightarrow e\pi^0$ selections without (M_p, P_{tot}) cut)

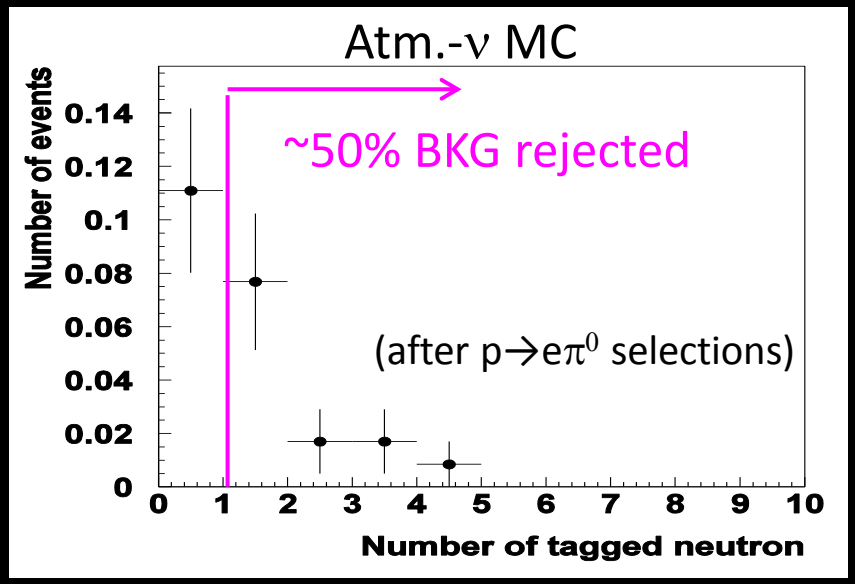


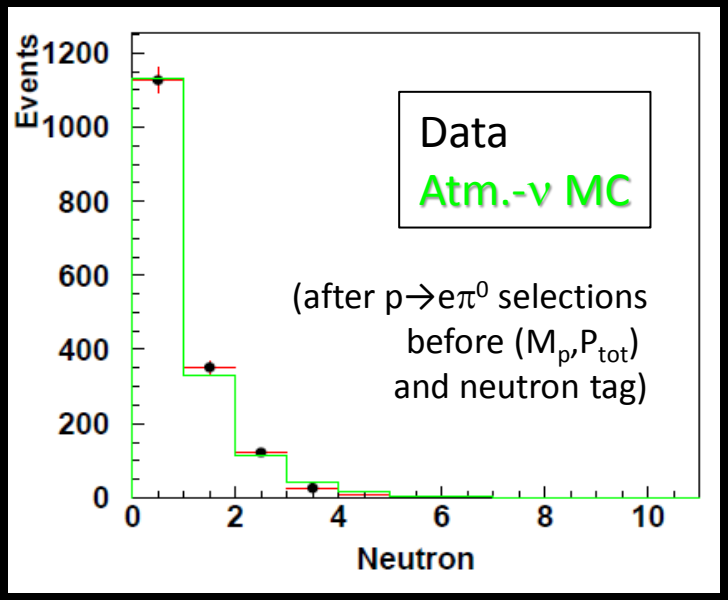
- Total(SKI-IV) expected #BKG(P_{tot}<100, 100≤P_{tot}<250): (~0.05, ~0.5)
- P_{tot}<100MeV/c: smaller systematic error on signal ε and almost BKG free → discovery potential and better sensitivity

Neutron tag in SK-IV

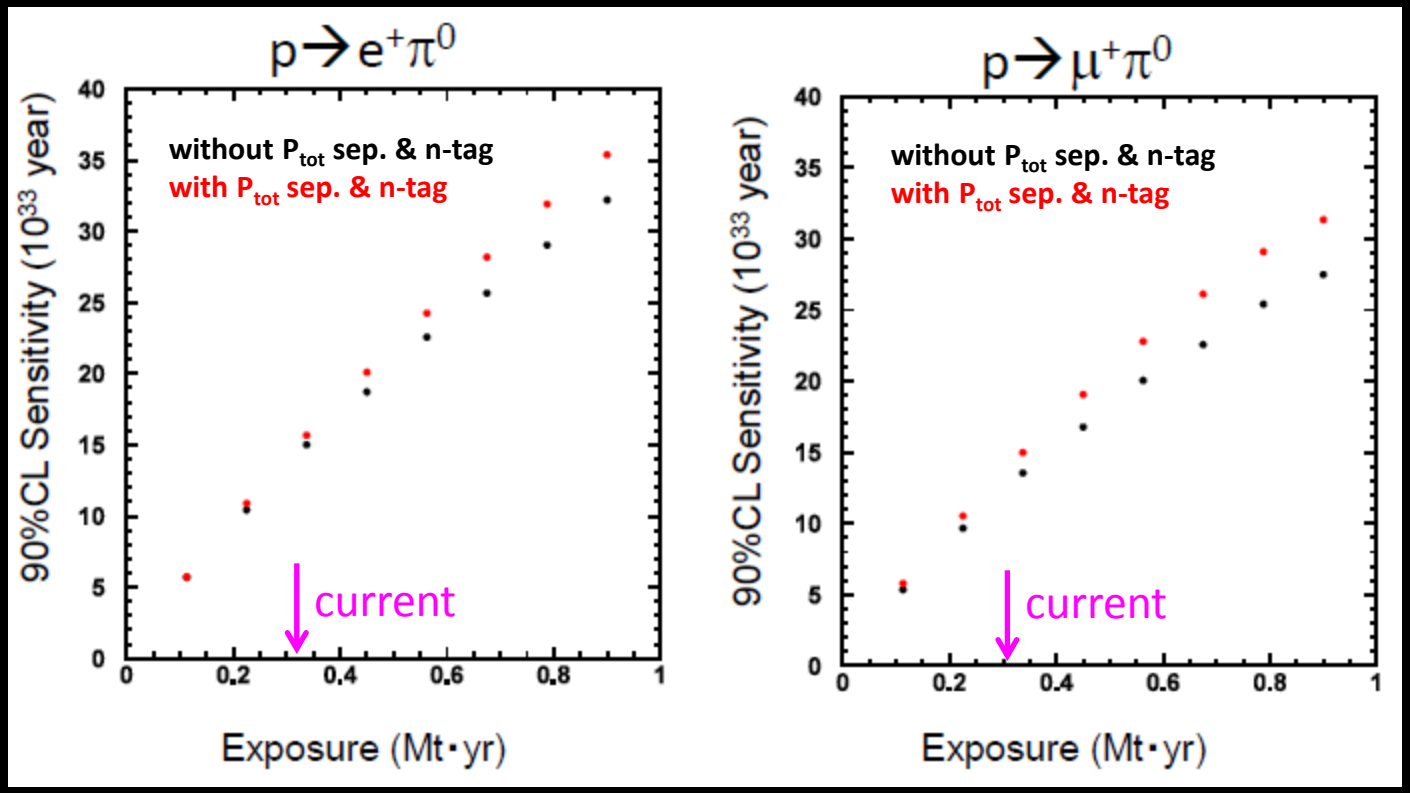
- Atm.-ν BKG frequently accompanied by neutron production
- n + p → d + γ(2.2MeV)
- Hit cluster search for γ enabled by QBEE with deadtime-less DAQ + software trigger
  - detection efficiency: 20.5%





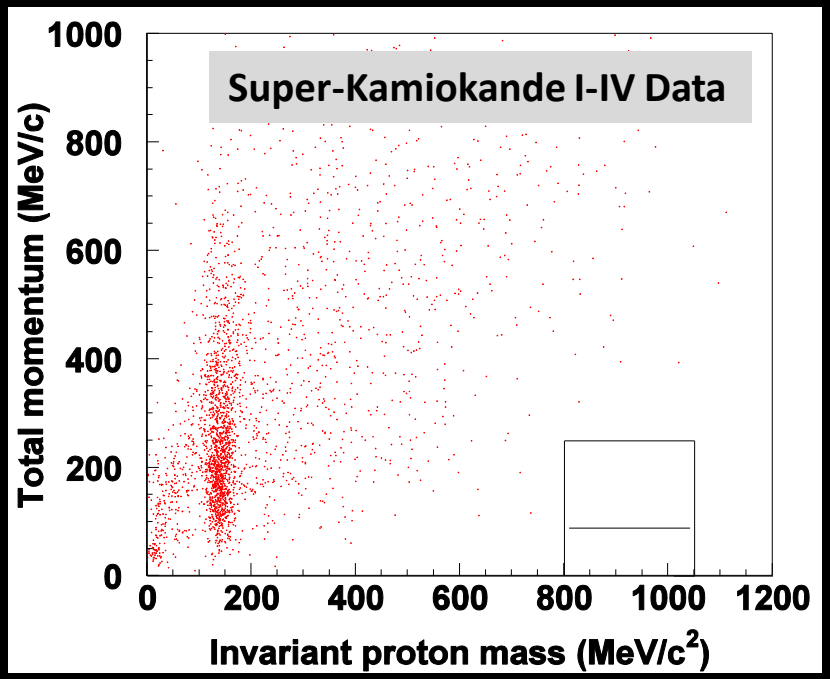


Sensitivities



- The more exposure, the more benefit.

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



		SK-I	SK-II	SK-III	SK-IV
Exp.(kton·yrs)		91.7	49.2	31.9	133.5
$p \rightarrow e^+\pi^0$					
(P_{tot}<100)	Eff.(%)	18.8±0.9	18.3±1.0	19.6±1.3	18.7±1.2
	BKG	0.03±0.01	<0.01	<0.01	0.02±0.01
	OBS	0	0	0	0
(100<P_{tot}<250)	Eff.(%)	20.4±3.1	20.2±3.1	20.5±3.2	19.4±2.9
	BKG	0.22±0.06	0.12±0.01	0.06±0.02	0.15±0.05
	OBS	0	0	0	0

- 306.3 kton·years (SKI-IV) (220kt·yrs in PRD 85, 112001 (2012))
- signal $\varepsilon(P_{tot}<250\text{MeV/c})$: ~40%
- total(SKI-IV) expected #BKG(P_{tot}<250MeV/c) < 1

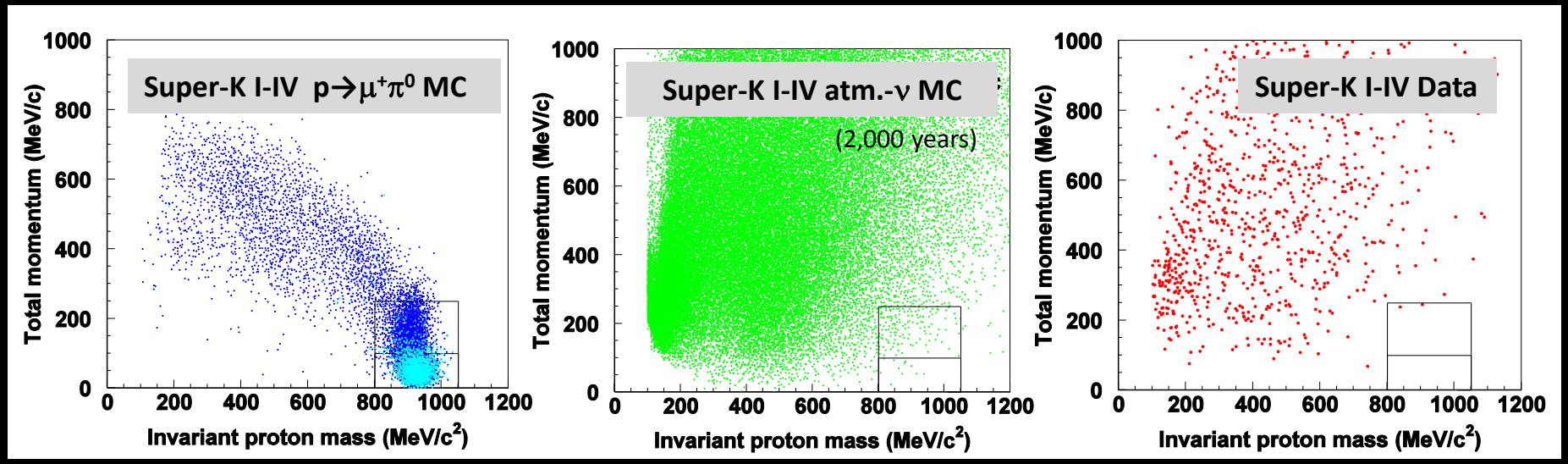
  #BKG: confirmed with K2K ν beam data PRD 77,032003(2008)
- no data candidate

  $\tau/B_{p\rightarrow e\pi 0} > 1.67 \times 10^{34}$ years (90% CL)

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

"flipped" SU(5) predicts high branching ratio

(analysis proceeds as with $e^+\pi^0$ with additional requirement of 1 Michel-e)

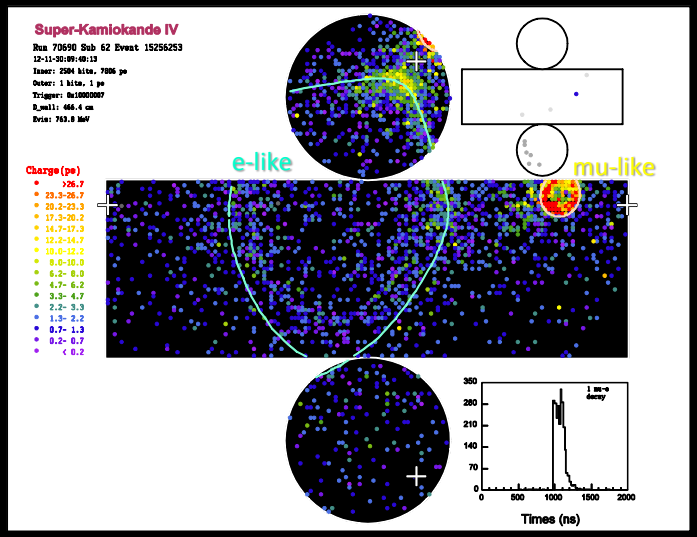


		SK-I	SK-II	SK-III	SK-IV
Exp.(kton·yrs)		91.7	49.2	31.9	133.5
$p \rightarrow \mu^+\pi^0$					
(P_{tot}<100)	Eff.(%)	16.4±0.8	16.0±0.8	16.4±1.0	20.1±1.0
	BKG	0.04±0.01	<0.01	<0.01	0.01±0.01
	OBS	0	0	0	0
(100≤P_{tot} <250)	Eff.(%)	15.3±2.5	15.3±2.6	16.5±0.8	18.2±1.1
	BKG	0.33±0.09	0.14±0.04	0.12±0.03	0.23±0.07
	OBS	0	0	0	2

next slide

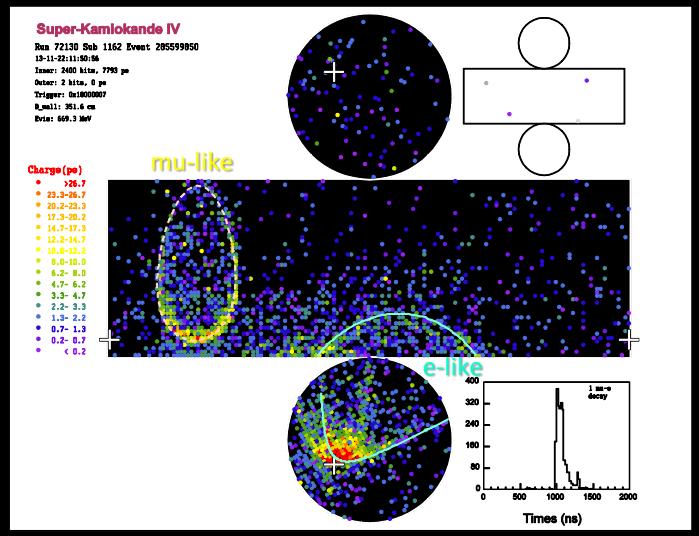
- 306.3 kton·yrs (SKI-IV) (220kt·yrs in PRD)
- signal $\varepsilon(P_{tot}<250\text{MeV/c})$: 30-40%
- total expected #BKG:
  - $P_{tot}<100$: ~0.05
  - $100 \le P_{tot} < 250$: ~0.82
- no significant data excess
  $\tau/B_{p\rightarrow\mu\pi0} > 7.78 \times 10^{33}$ years (90% CL)

Event #1



(M_p, P_{tot}) : (902.5, 248.0)MeV
Wall : 466.0cm
ring : 2
P_e: 374.9MeV/c
P_μ: 551.1MeV/c
$\theta_{e\text{-}mu}$: 157.9°

Event #2



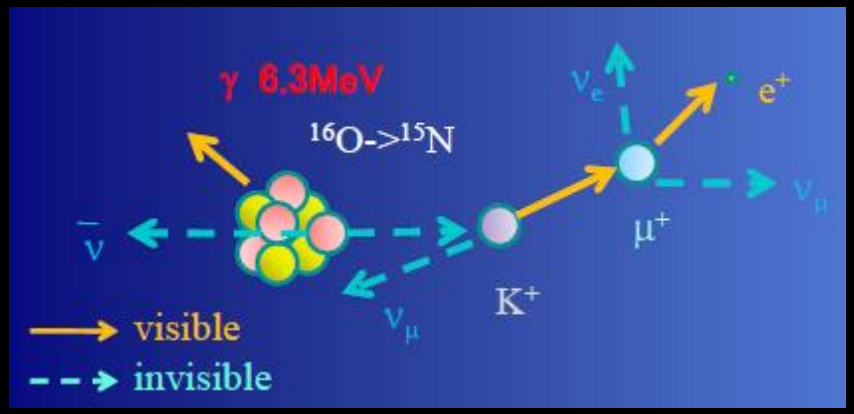
(M_p, P_{tot}) : (832.4, 237.9)MeV
Wall : 351.6cm
ring : 2
P_e: 460.5MeV/c
P_μ: 391.3MeV/c
$\theta_{e\text{-}mu}$: 148.9°

(additional ring by manual fit → $M_{\pi 0}$: 406MeV/c^2. See supplement)

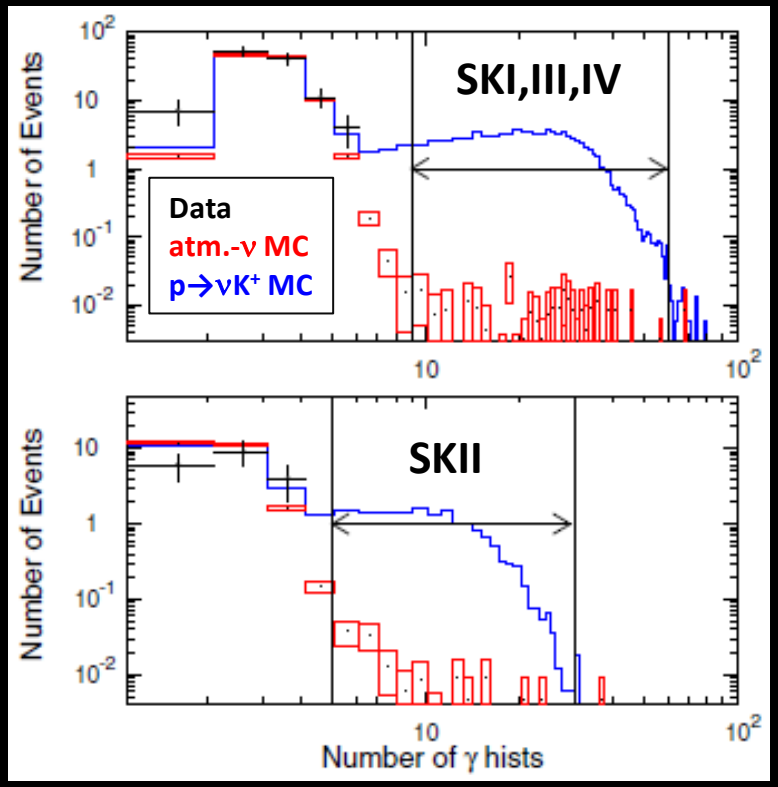
	P_{tot}<100MeV/c	100≤P_{tot}<250MeV/c
Total #BKG (SKI-IV)	~0.05	~0.82
Data(SKI-IV)	0	2

- Poisson prob. (≥2; 0.82): 19.9%

$p \rightarrow \nu K^+$ search
(prompt γ method)

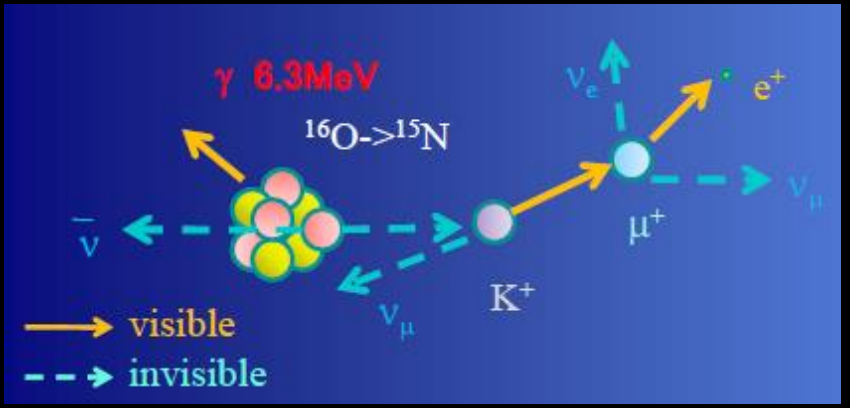


- event selections:
  - fully contained
  - fiducial volume
  - 1 μ-like (PID)
  - 1 Michel-e
  - $215<P_\mu<260$MeV/c
  - proton ring rejection
  - $8(4)<N_\gamma<60(30)$ for SK-I,III,IV(SK-II)
  - $T_\mu-T_\gamma<75$ns
  - no neutrons (SK-IV only)
- no data candidate



(plot from PRD 90, 072005 (2014))

$p \rightarrow \nu K^+$ search
(P_μ spec. method)



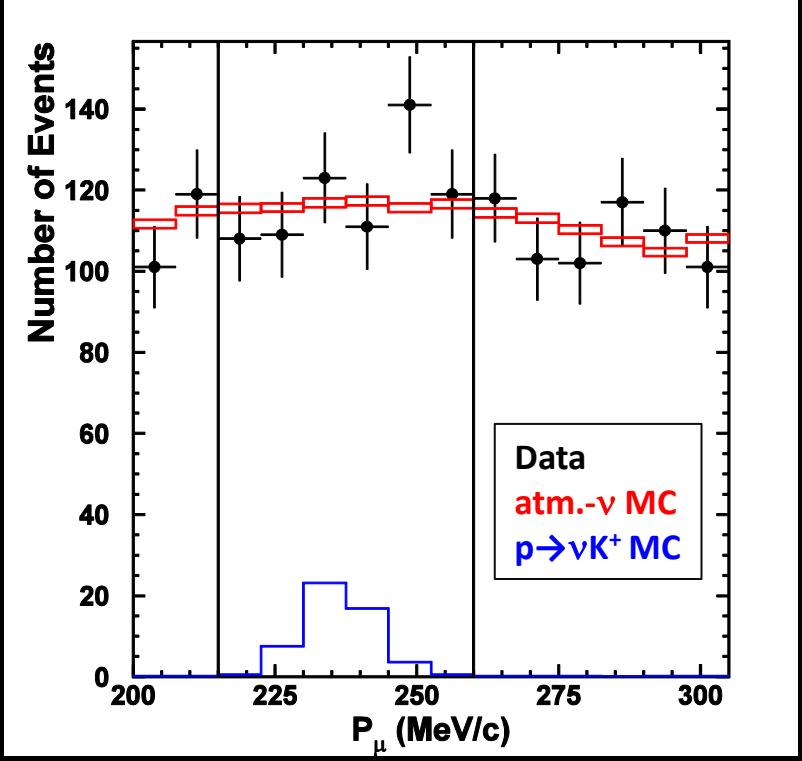
- event selections:

  same as γ meth. except:

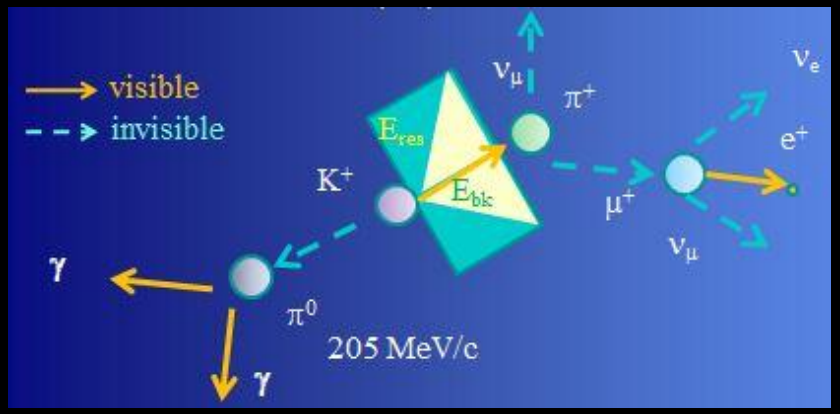
  – no prompt γ hits

  – relaxed P_μ cut

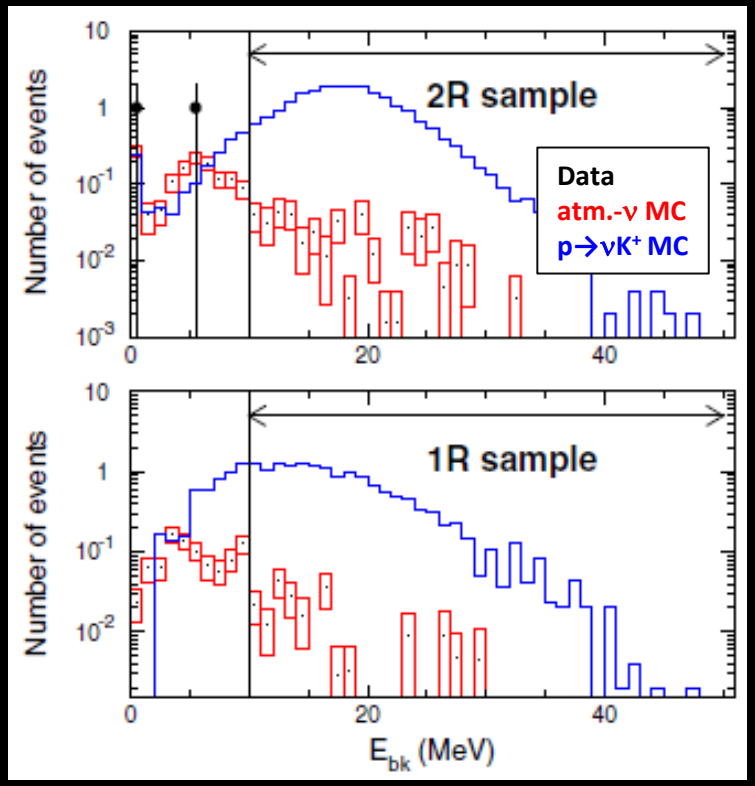
- no data excess



$p \rightarrow \nu K^+$ search
($\pi^+\pi^0$ method)



- event selections:
  - fully contained
  - fiducial volume
  - 1 or 2 e-like rings (PID)
  - 1 Michel-e
  - $85<M_{\pi0}<185 MeV/c^2$, $175<P_{\pi0}<250 MeV/c$
  - charge profile likelihood for π^+
  - $10<E_{bk}<50 MeV$
  - no neutrons (SK-IV only)
- no data candidate



(plot from PRD 90, 072005 (2014))

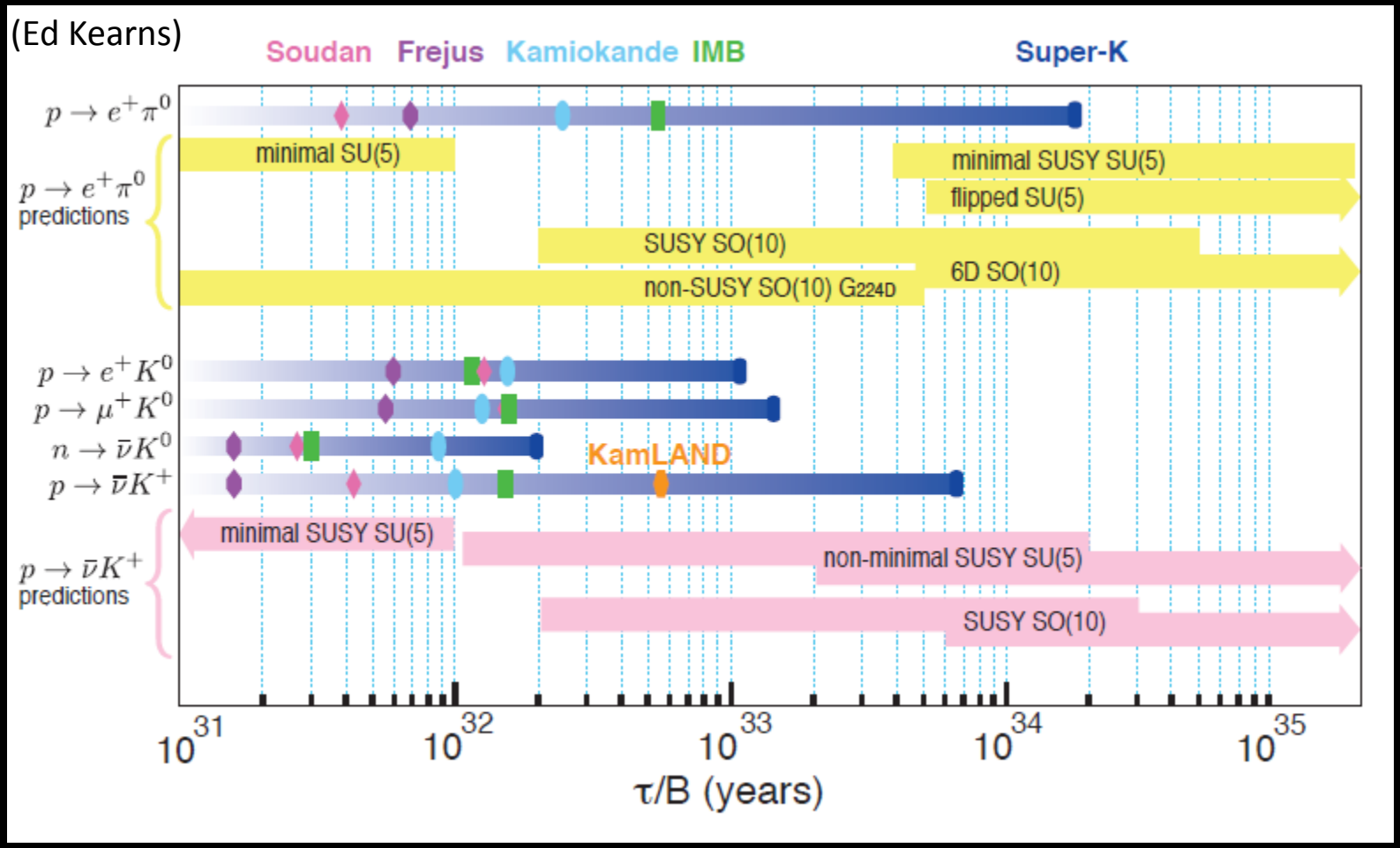
$p \to \nu K^+$ search result

		SK-I	SK-II	SK-III	SK-IV
Exp.(kt·yrs)		91.7	49.2	31.9	133.5
Prompt γ	Eff.(%)	7.9	6.3	7.7	8.5
	BKG	0.08	0.14	0.03	0.14
	OBS	0	0	0	0
$\pi^+\pi^0$	Eff.(%)	7.8	6.7	7.9	9.0
	BKG	0.18	0.17	0.09	0.12
	OBS	0	0	0	0

- 306.3 kton· years (SKI-IV) (260kt·yrs in PRD 90, 072005 (2014))
- signal ε for prompt γ and $\pi^+\pi^-$ methods: 6-9%
- total expected #BKG for prompt γ and $\pi^+\pi^0$ methods < 1
- no data excess above BKG expectation

$$\tau/B_{p\to\nu K+} > 6.61 \times 10^{33} \text{ years (90\% CL)}$$

Benchmark searches and theoretical predictions



- Huge theoretical uncertainty
- Current searches are in interesting ranges

Summary of recent nucleon decay results in SK

Decay mode	$\lvert\Delta(B-L)\rvert$	Lifetime lower limit at 90% CL (years)	Paper (previous result)
$p \to e^+\pi^0$	0	(*) 1.67×10^{34}	(PRD 85, 112001 (2012))
$p \to \nu K^+$	$0(\bar{\nu}), 2(\nu)$	6.61×10^{33}	(PRD 90, 072005 (2014))
$p \to \mu^+\pi^0$	0	(*) 7.78×10^{33}	(PRD 85, 112001 (2012))
$p \to e^+/\mu^+(\eta,\rho,\omega)$	0	$(0.04\text{-}4.2) \times 10^{33}$	PRD 85, 112001 (2012)
$p \to \mu^+K^0$	0	1.6×10^{33}	PRD 86, 012006 (2012)
$n \to \bar{\nu}\pi^0$, $p \to \bar{\nu}\pi^+$	0	1.1×10^{33}, 3.9×10^{32}	PRL 113, 121802 (2014)
$p \to e^+/\mu^+\nu\nu$	$0(\bar{\nu}\nu)$, $2(\nu\nu,\bar{\nu}\bar{\nu})$	$1.7/2.2 \times 10^{32}$	PRL 113, 101801 (2014)
$p \to e^+/\mu^+X$	?	$7.9/4.1 \times 10^{32}$	arXiv:1508.05530, accepted by PRL
$n \to \nu\gamma$	$0(\bar{\nu}), 2(\nu)$	5.5×10^{32}	arXiv:1508.05530, accepted by PRL
$pp \to K^+K^+$	2	1.7×10^{32}	PRL 112, 131803 (2014)
$pp \to \pi^+\pi^+$, $pn \to \pi^+\pi^0$, $nn \to \pi^0\pi^0$	2	7.22×10^{31}, $1,70 \times 10^{32}$, 4.04×10^{32}	PRD 91, 072009 (2015)
$np \to (e^+,\mu^+,\tau^+)\nu$	$0(\bar{\nu}), 2(\nu)$	$(0.22\text{-}5.5) \times 10^{32}$	arXiv:1508.05530, accepted by PRL
$n\text{-}\bar{n}$ oscillation	2	1.9×10^{32}	PRD 91, 072006 (2015)

(* will be published soon)

Next generation: Hyper-Kamiokande (HK)

http://www.hyperk.org/

~20 × Super-K

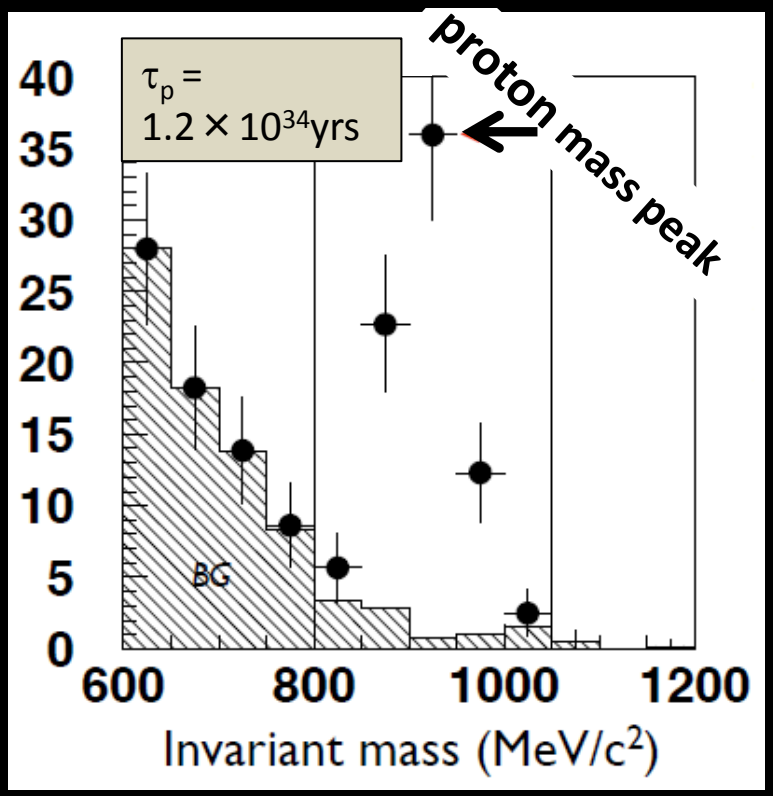
(detector design will be finalized soon)

J-PARC neutrino beam: CP-δ
Supernova to 2 Mpc
θ_{23}, mass heirarchy by atm. ν
Relic supernova neutrinos
Indirect dark matter
Nucleon decay: reach 10^{35} years

LOI: arXiv:1109.3262[hep-ex]
LBL study: PTEP 2015 (2015) 5, 053C02

Nucleon decay searches in HK

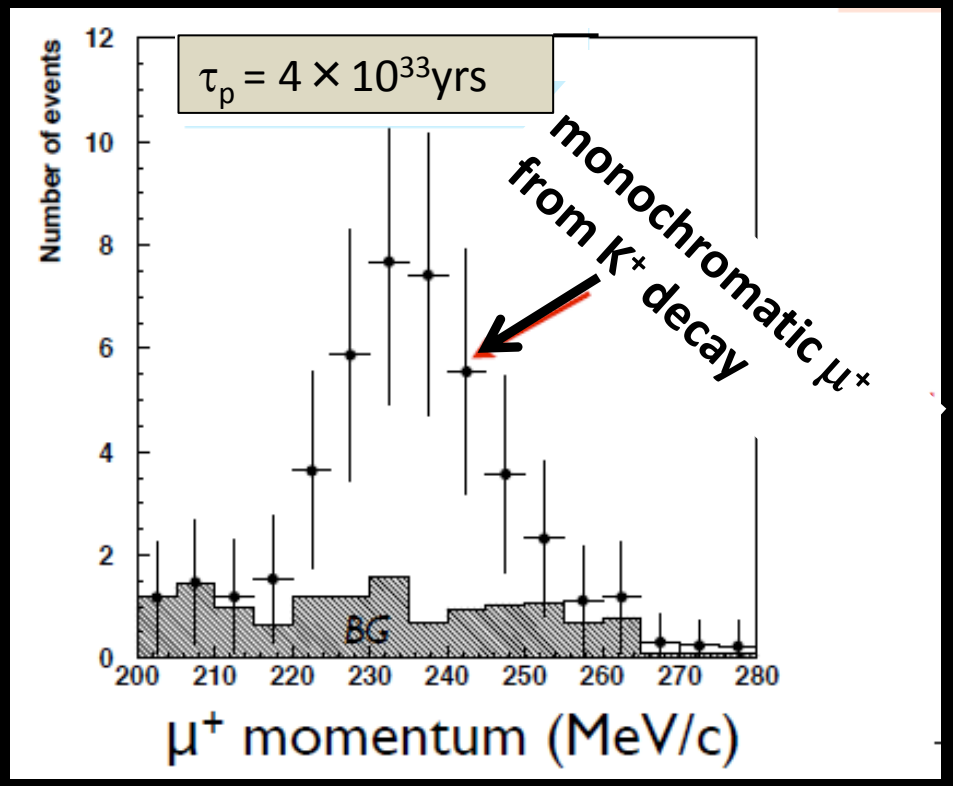
$p \rightarrow e^+\pi^0$



sensitivity (90% CL)

$\tau/B_{p\rightarrow e\pi 0} > 1 \times 10^{35}$ yrs (HK 10yrs)

$p \rightarrow \nu K^+$



sensitivity (90% CL)

$\tau/B_{p\rightarrow \nu K+} > 3 \times 10^{34}$ yrs (HK 10yrs)

Summary

- Testing baryon number violation is an essential and high priority objective of particle physics
- Nucleon decay searches in Super-Kamiokande:
  - no evidence so far → most stringent lifetime limits in the world
  - keep discovery potential and increase statistics
  - prospect of sensitivity improvements by sophisticated reconstruction algorithm, reducing systematic errors, etc.
  - search new modes
- Hyper-Kamiokande
  - http://www.hyperk.org/

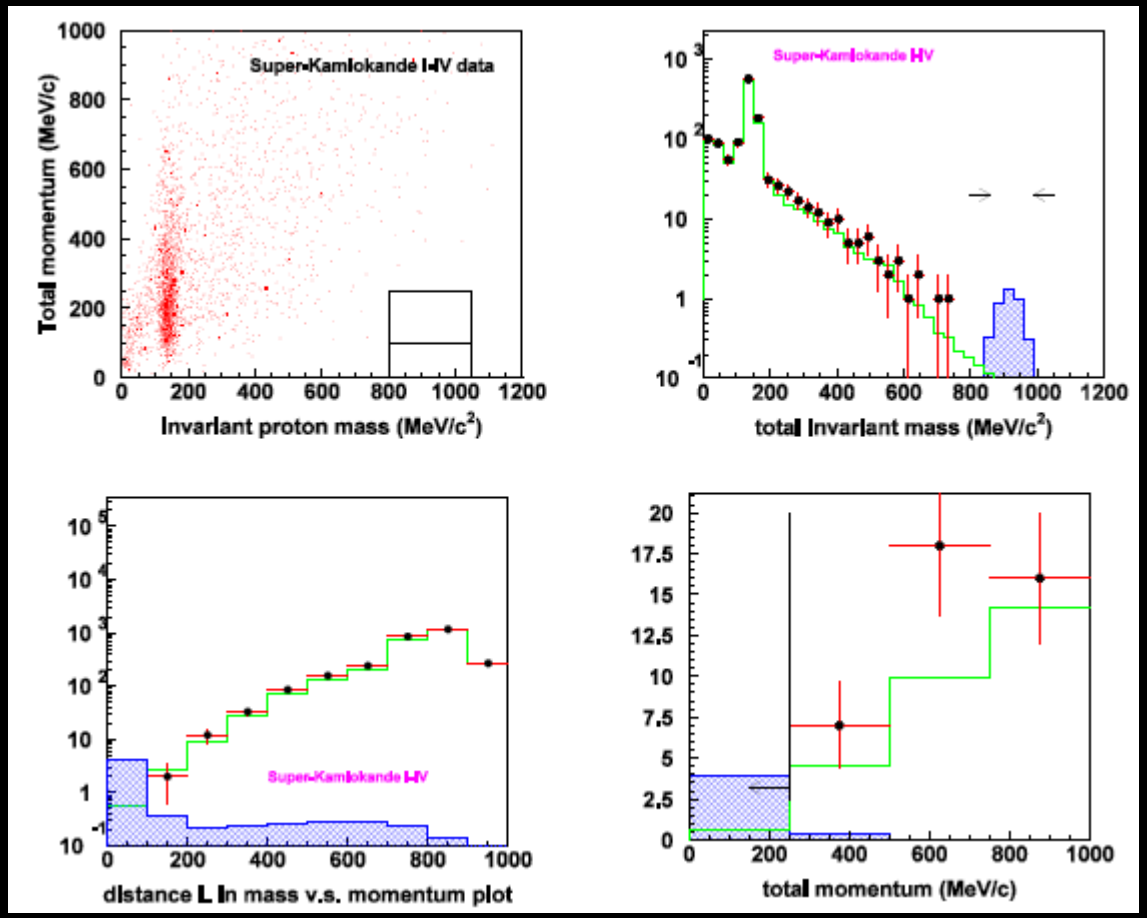
Supplement

Super-Kamiokande Collaboration

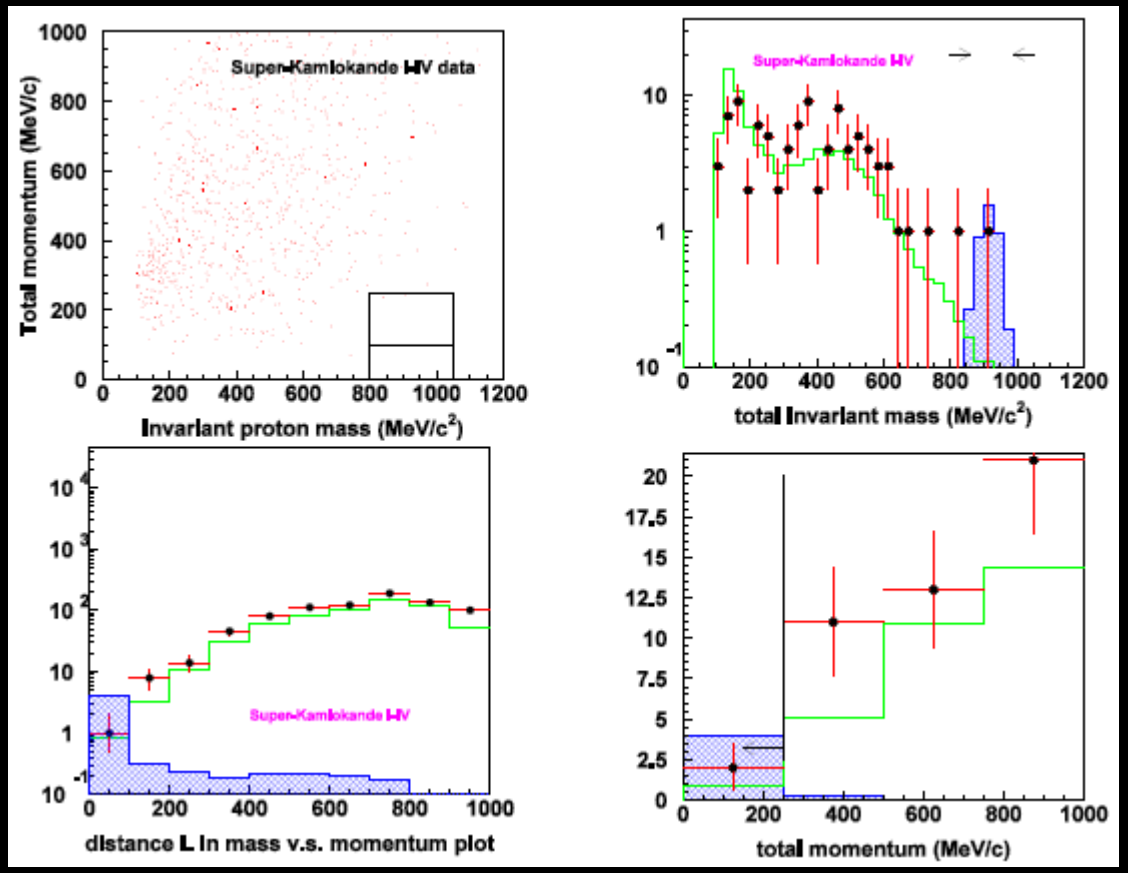
1 Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
2 RCCN, ICRResearch, Univ. of Tokyo, Japan
3 University Autonoma Madrid, Spain
4 University of British Columbia, Canada
5 Boston University, USA
6 Brookhaven National Laboratory, USA
7 University of California, Irvine, USA
8 California State University, USA
9 Chonnam National University, Korea
10 Duke University, USA
11 Fukuoka Institute of Technology, Japan
12 Gifu University, Japan
13 GIST College, Korea
14 University of Hawaii, USA
15 KEK, Japan
16 Kobe University, Japan
17 Kyoto University, Japan
18 Miyagi University of Education, Japan
19 STE, Nagoya University, Japan
20 SUNY, Stony Brook, USA
21 Okayama University, Japan
22 Osaka University, Japan
23 University of Regina, Canada
24 Seoul National University, Korea
25 Shizuoka University of Welfare, Japan
26 Sungkyunkwan University, Korea
27 Tokai University, Japan
28 University of Tokyo, Japan
29 Kavli IPMU (WPI), University of Tokyo, Japan
30 Dep. of Phys., University of Toronto, Canada
31 TRIUMF, Canada
32 Tsinghua University, China
33 University of Washington, USA
34 National Centre For Nuclear Research, Poland

~120 collaborators
34 institutions
7 countries

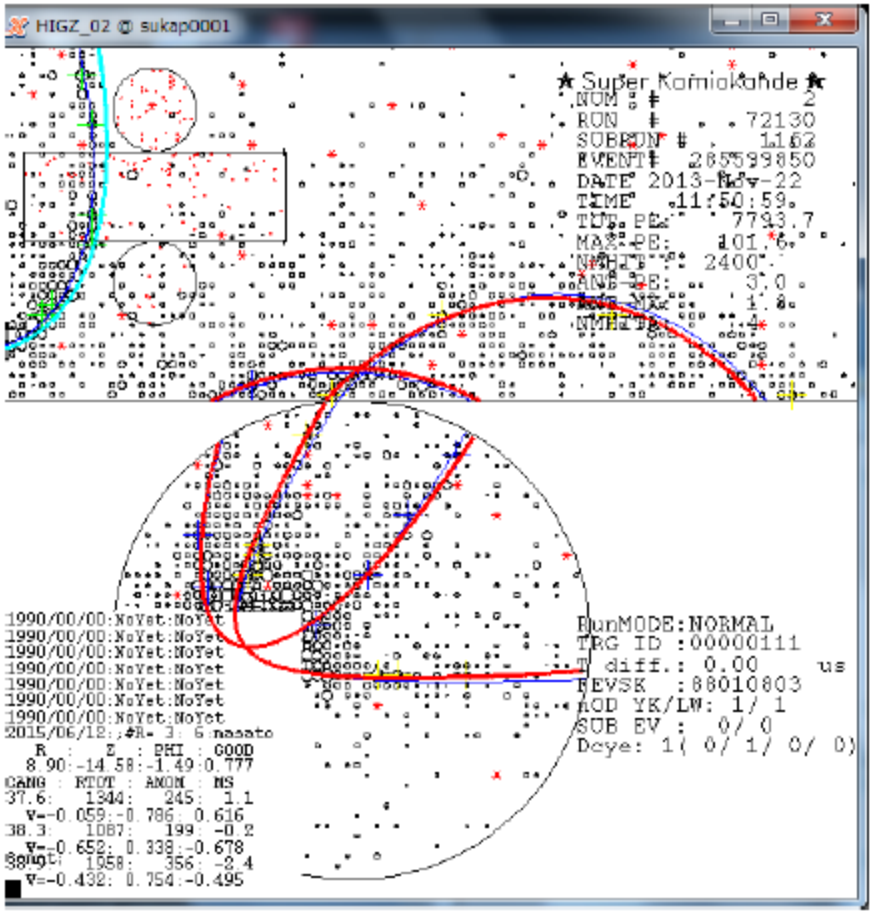
$p \rightarrow e^{+}\pi^{0}$ search



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



Manual fit on $\mu^+\pi^0$ candidate Event #2



Take 3 rings

μ: 418 MeV/c

e: 159 MeV/c

e: 338 MeV/c

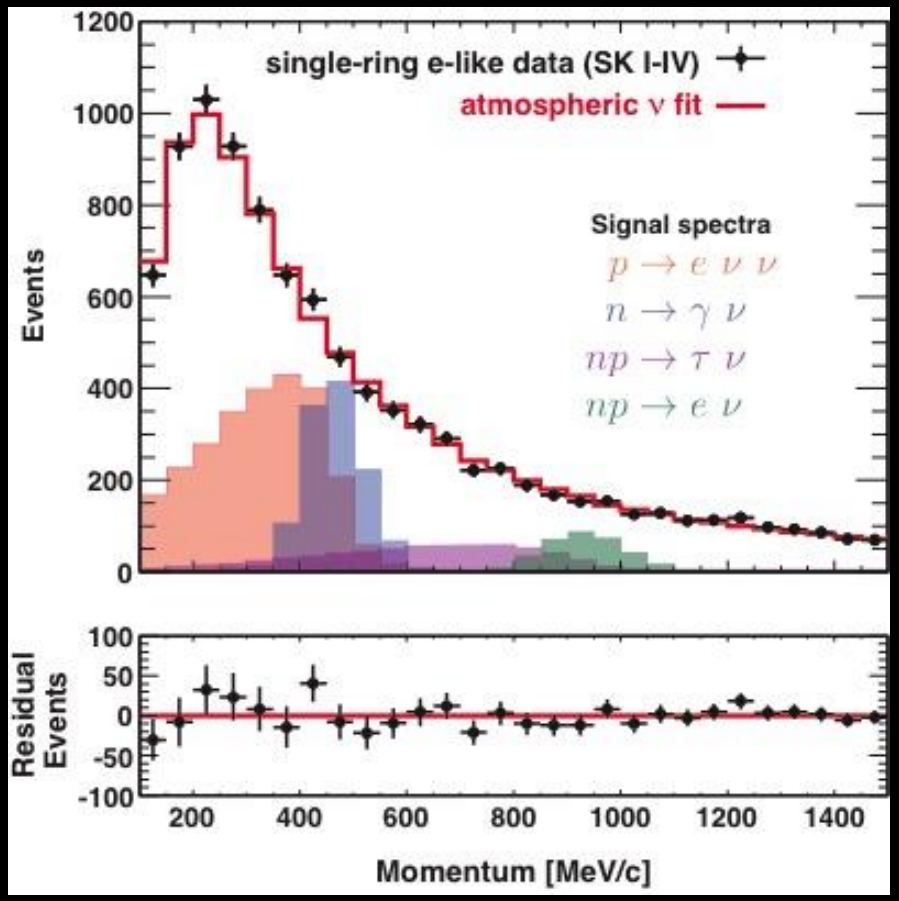
Ptot: 294 MeV/c

Mtot: 880 MeV

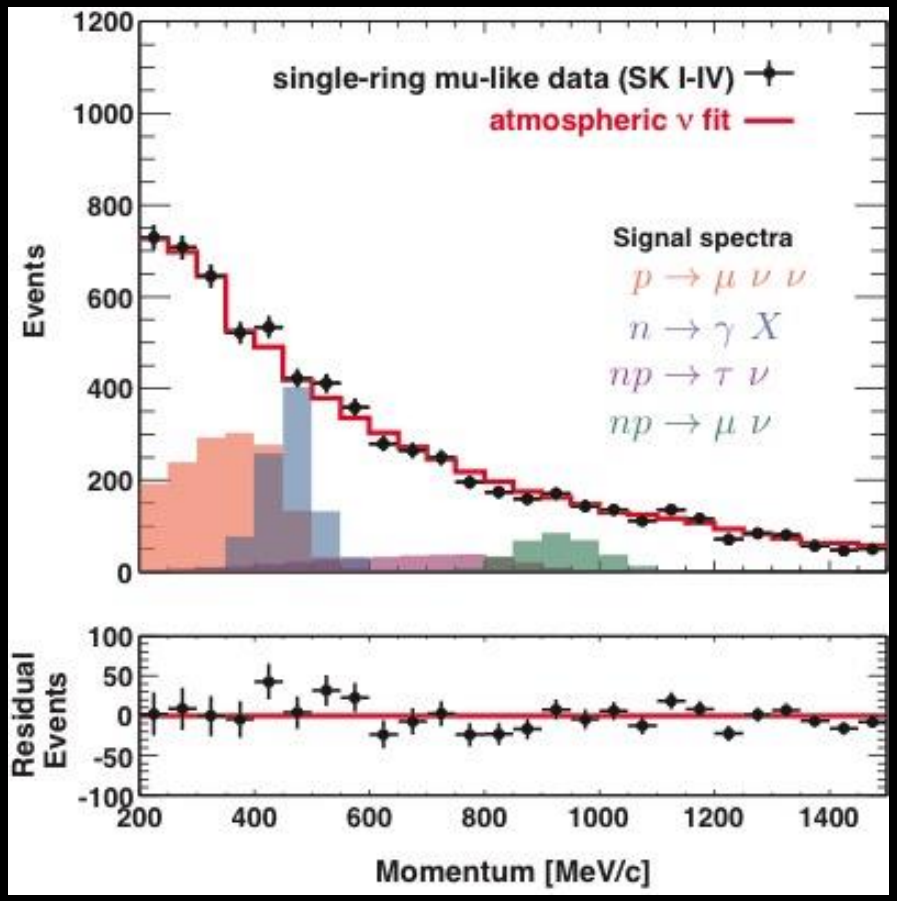
$M_{\gamma\gamma}$=406 MeV

Spectral Search for Baryon Number Violation

single e-like rings



single mu-like rings

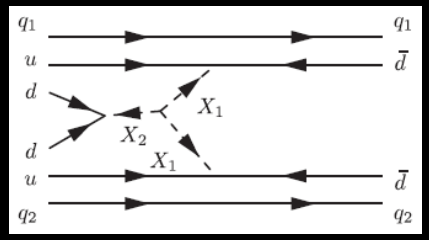


Momentum distribution of single rings is well modeled by atmospheric neutrinos

Lifetime limits(90%CL): 2×10^{31} to 8×10^{32} years

(some are novel. 1-2 orders of magnitude improvement over previous results)

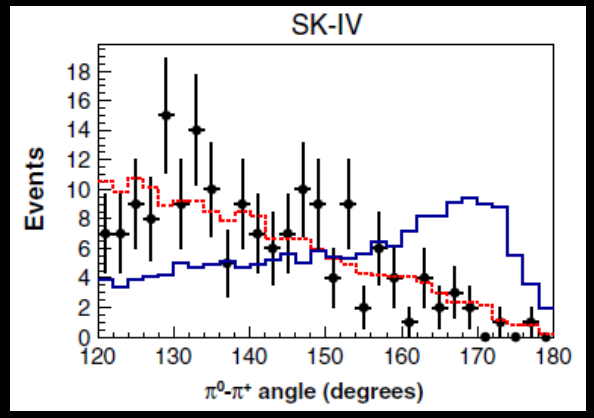
PRL 113, 101801 (2014) arXiv:1508.05530

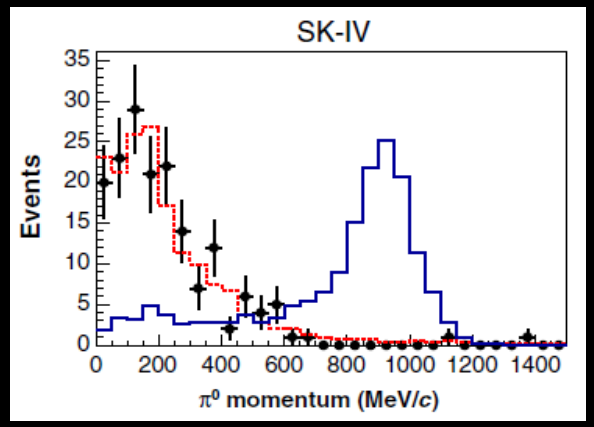


Dinucleon decay $\Delta B = |\Delta(B-L)| = 2$

(plots for pn→$\pi^+\pi^0$ in SK-IV as example)

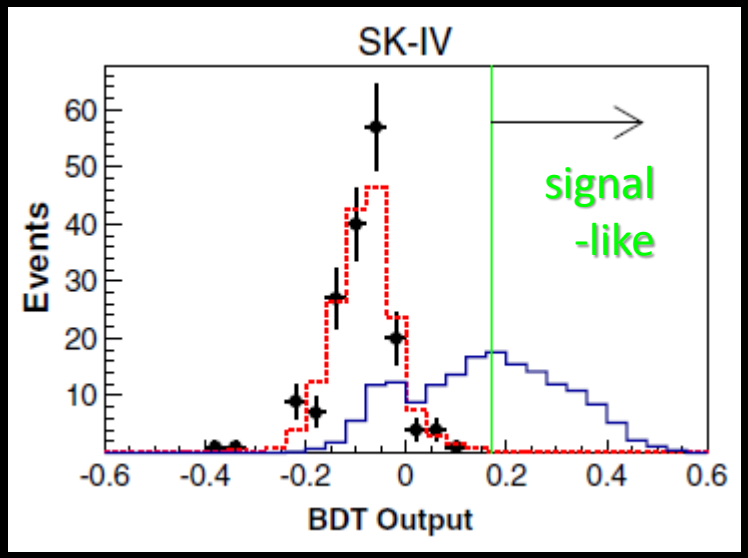
Input variables





DNDK MC
Atm.-ν MC
Data

Boosted Decision Tree Output



Mode	Frejus limit (^{56}Fe)	This analysis (^{16}O)
$pp \to \pi^+\pi^+$	7.0×10^{29} yrs	7.22×10^{31} yrs
$pn \to \pi^+\pi^0$	2.0×10^{30} yrs	1.70×10^{32} yrs
$nn \to \pi^0\pi^0$	3.4×10^{30} yrs	4.04×10^{32} yrs

PRD 91, 072009 (2015)