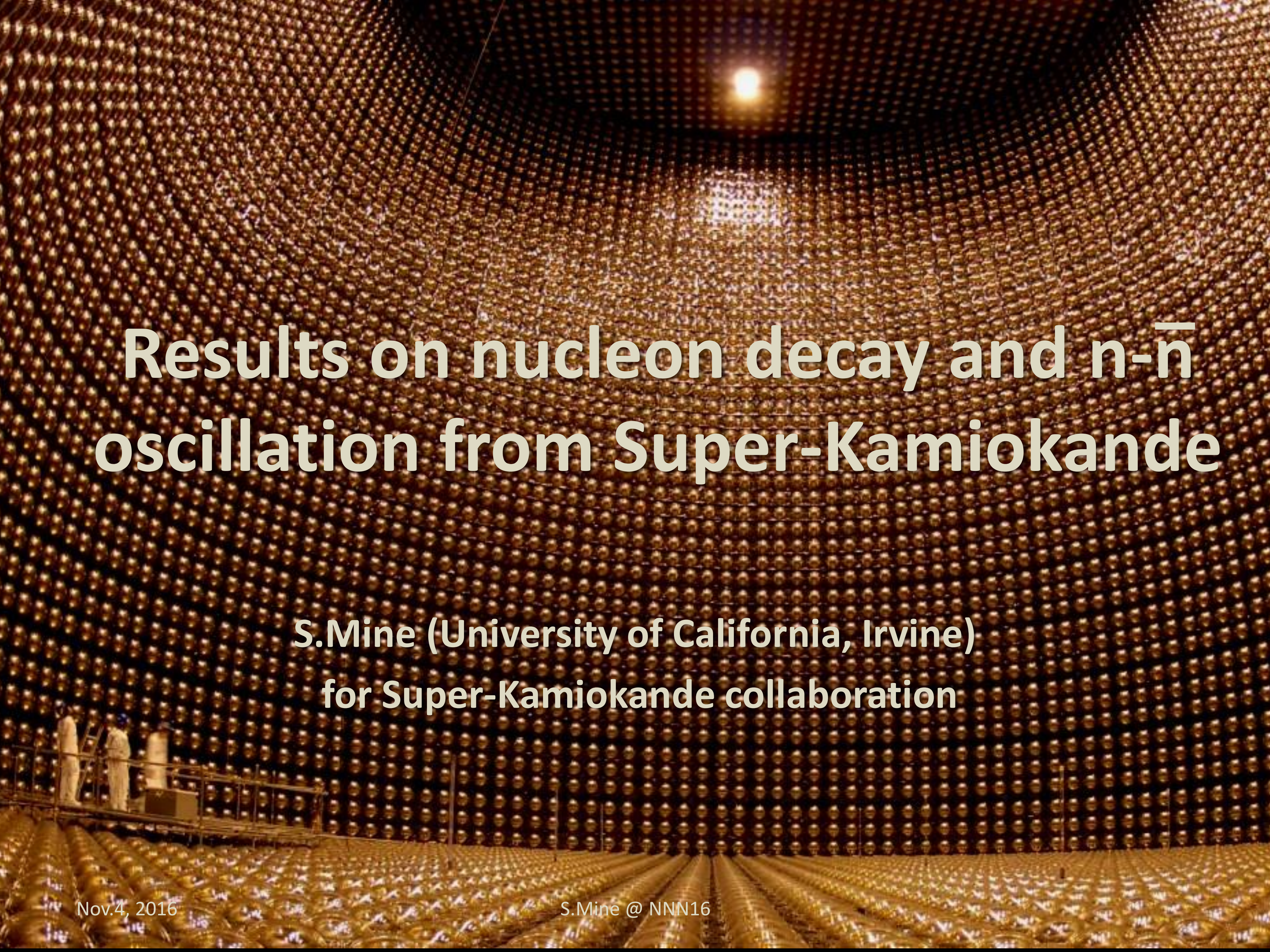
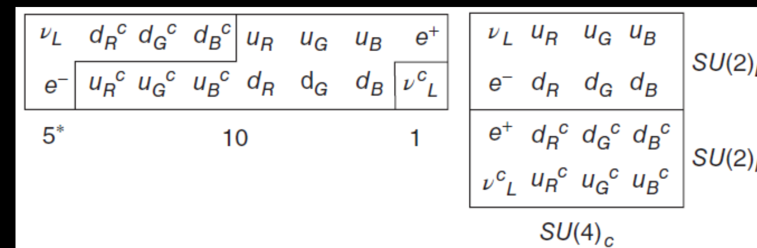


Results on nucleon decay and n-$\bar{n}$ oscillation from Super-Kamiokande

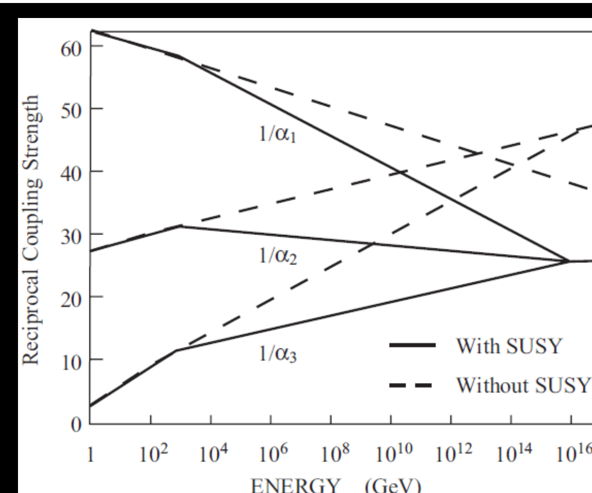
S.Mine (University of California, Irvine)
for Super-Kamiokande collaboration

Grand Unified Theory (GUT)

- Single symmetry group G ⊃ $SU(3)_{color} \times SU(2)_L \times U(1)_Y$
  - Single coupling constant, quantization of electric charge, etc.



- Numerous GUTs exist. Examples
  - 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
    - $p \rightarrow e^+\pi^0$(non-SUSY), $p \rightarrow \nu K^+$(SUSY)
  - Some models predict lifetime < 10^{34} years, can be probed by SK
  - Baryon asymmetry of the Universe

Continued…

- Numerous GUTs…
  - Δ(B-L) = 0
  - Δ(B+L) = 0
  - 3-body decay
  - dinucleon decay
  - n-$\bar{n}$ oscillation (ΔB=Δ(B-L)=2)
  - etc.
- Lifetime prediction uncertainty: $10^{2\text{-}3}$
- Should experimentally test various GUTs

	Br. (%)				
	SU(5)				(SO10)
References	[20]	[21]	[22]	[23]	[23]
$p \to e^+\pi^0$	33	37	9	35	30
$p \to e^+\eta$	12	7	3	15	13
$p \to e^+\rho^0$	17	2	21	2	2
$p \to e^+\omega$	22	18	56	17	14
others	17	35	11	31	31
τ_p/τ_n	0.8	1.0	1.3		

[20]Nucl.Phys.B550,37(1979), [21]Phys.Lett.B98,51(1981), [22]Phys.Lett.B92,99(1980), [23]Phys.Lett.B223,178(1989)

Flipped SU(5) GUT:

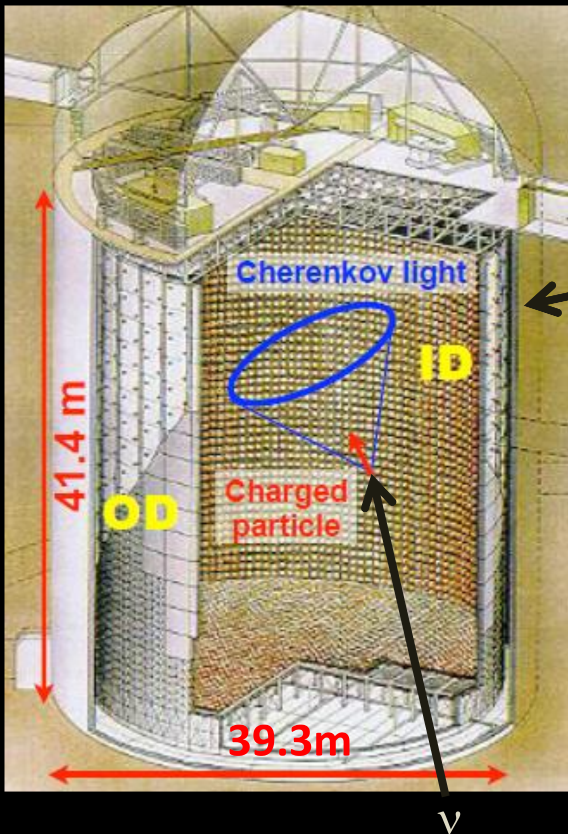
$$\frac{\Gamma\left(p \to \mu^+\pi^0\right)}{\Gamma\left(p \to e^+\pi^0\right)} = \frac{|U_{l_{12}}|^2}{|U_{l_{11}}|^2} \sim 1$$

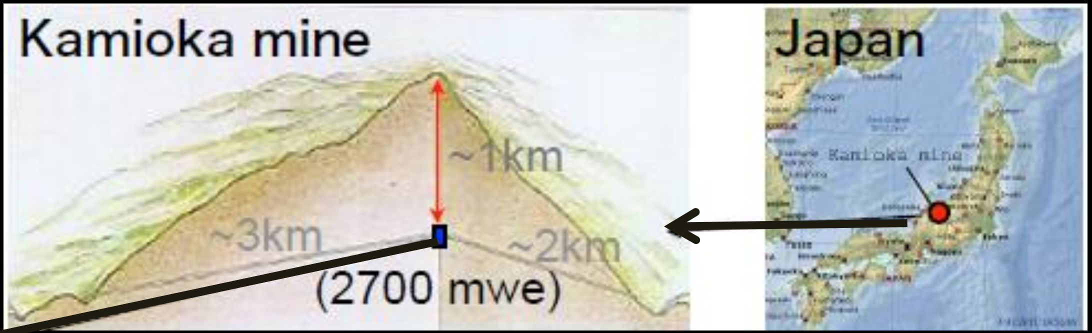
Phys.Lett.B550,99(2002)

Nucleon decay searches in SK
(unique way to directly probe GUTs)

- The world's best sensitivities on nucleon lifetime
  - large fiducial volume (V)
    - 22.5kt water → ~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
- This talk: the latest results on
  - nucleon decay to charged antilepton + meson
  - n-$\bar{n}$ oscillation (SK-I data)

Super-Kamiokande (SK)





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

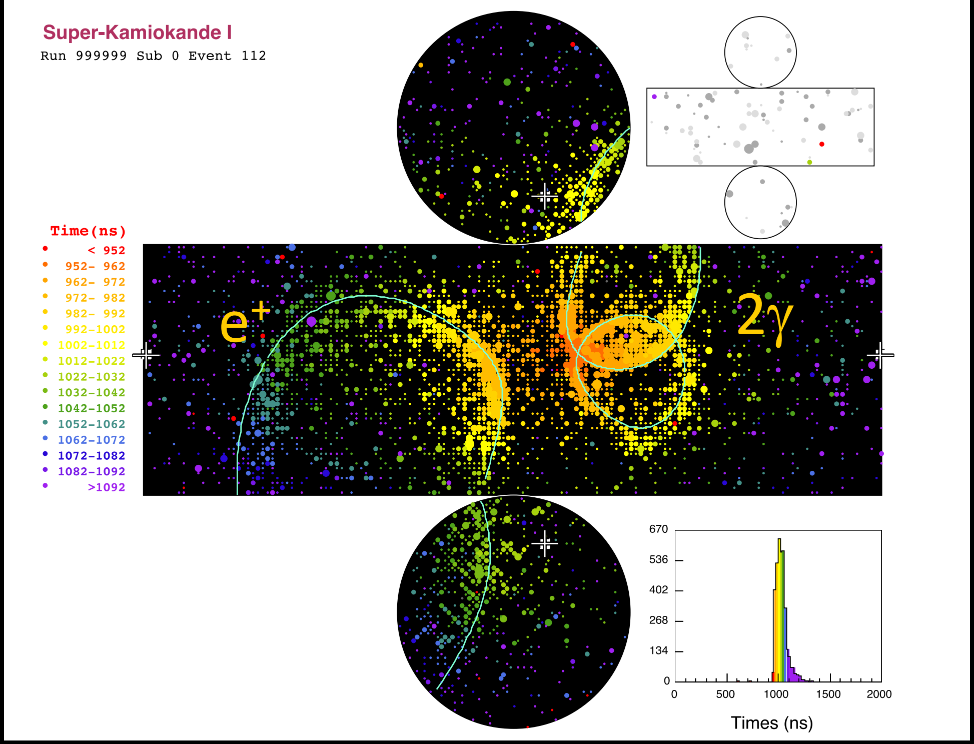
Phase		SK-I	SK-II	SK-III	SK-IV
Period	start end	1996 Apr. 2001 Jul.	2002 Oct. 2005 Oct.	2006 Jul. 2008 Sep.	2008 Sep. (running)
Number of PMTs	ID (photo-coverage)	11146 (40%)	5182 (19%)	11129 (40%)	11129 (40%)
	OD	1885			
Anti-implosion container		no	yes	yes	yes
OD segmentation		no	no	yes	yes
Front-end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

- SK total ~ 20 years

$p \rightarrow e^+\pi^0$ 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)
  - $800<M_{tot}<1050 MeV/c^2$
  - $P_{tot}<100 MeV/c$,
    $100 \leq P_{tot}<250 MeV/c$
  - no neutrons (SK-IV only)

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



New: Neutron tag in SK-IV

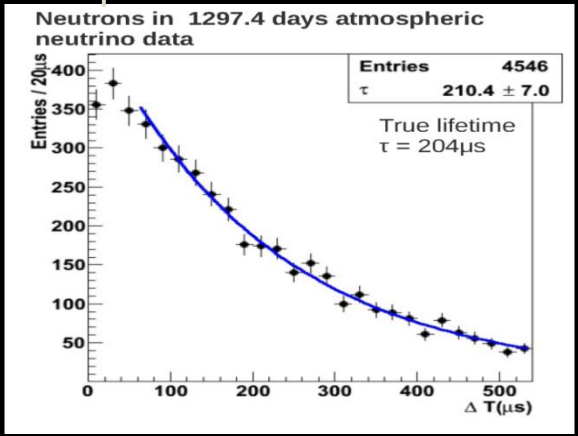
- Atm.-ν BKG frequently accompanied by neutron production
- $n + p \rightarrow d + \gamma(2.2\text{MeV})$
- γ hit search enabled by QBEE

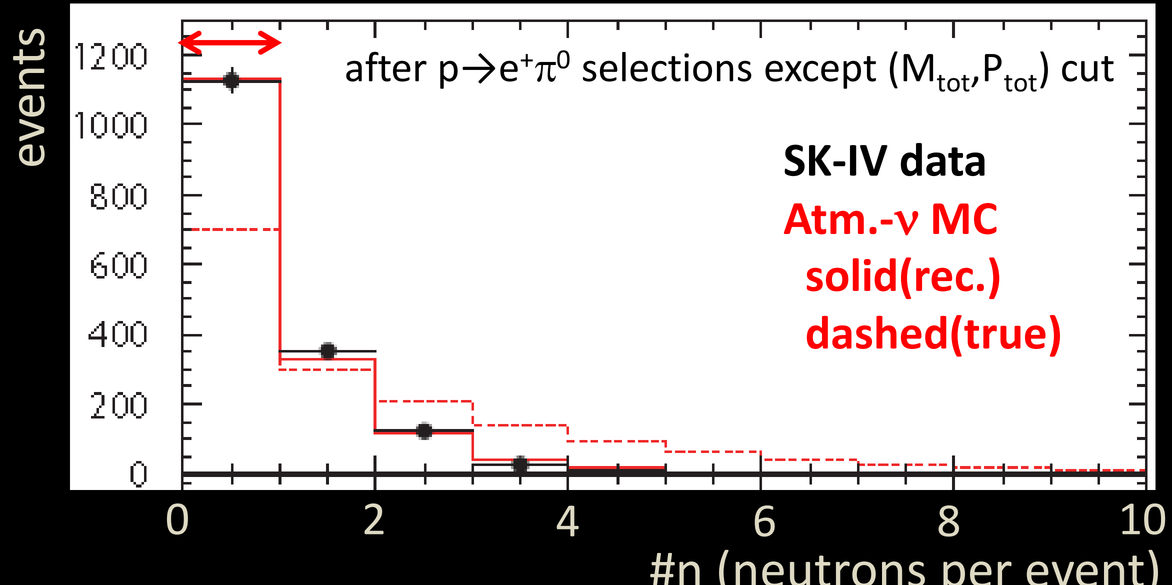
  - signal detection ε: 20.5%

    (ε: ~80% with Gd. See SK-Gd talk)

  - ~50% BKG rejected (#n=0)

n capture time

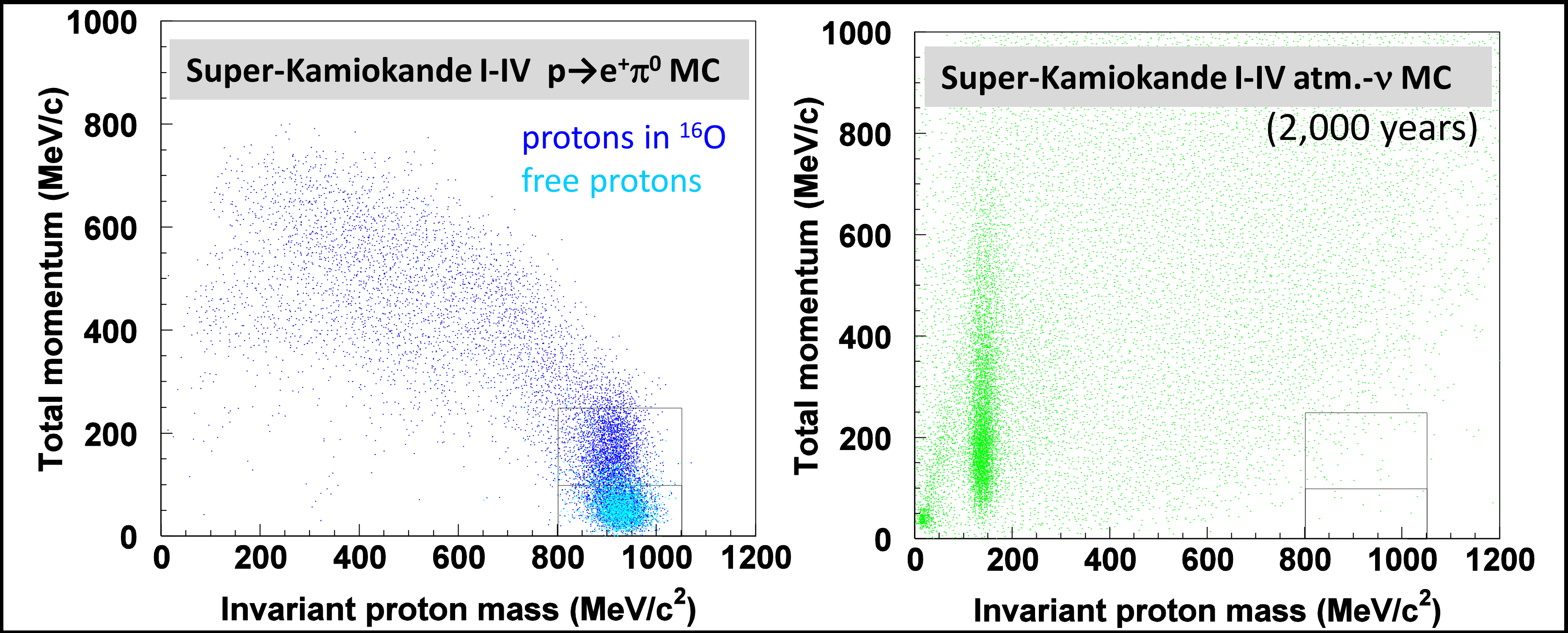




New: P_{tot} separation into 2 regions

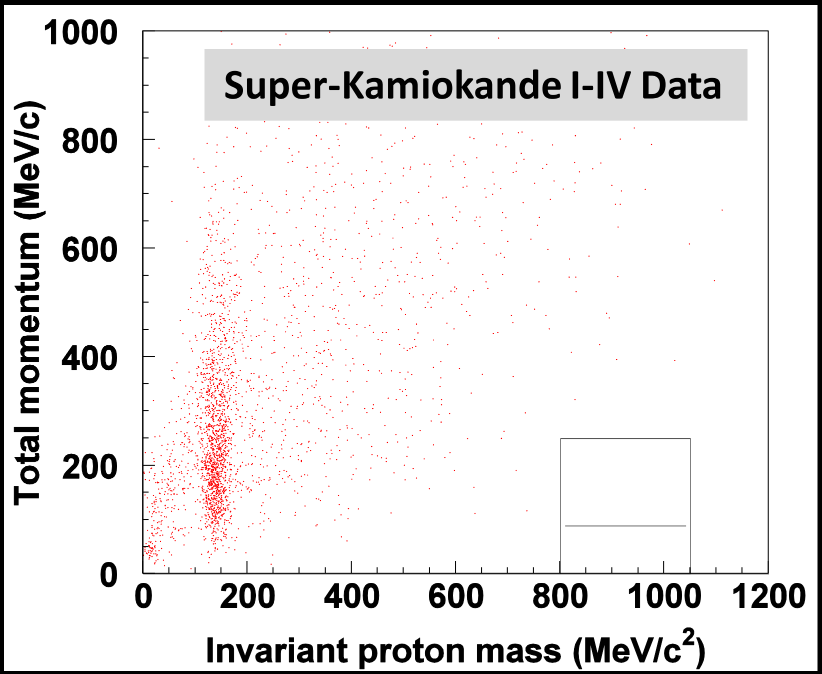
P_{tot}<100MeV/c, 100≤P_{tot}<250MeV/c

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



- Total(SK I-IV) expected #BKG(P_{tot}<100, 100≤P_{tot}<250): (~0.05, ~0.5)
- P_{tot}<100MeV/c: smaller syst. error on ε and almost BKG free
  → 3σ discovery reach in lifetime: ~13%(~21%) higher at ~0.3(1)Mt·yr

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



		SK-I	SK-II	SK-III	SK-IV
Exp.	kt·yrs	91.7	49.2	31.9	133.5
$p \rightarrow e^+\pi^0$					
(P_{tot}<100)	Eff.(%)	18.8±1.9	18.3±1.9	19.6±2.0	18.7±1.9
	BKG	$0.03^{+0.03}_{-0.02}$	<0.01	<0.01	$0.02^{+0.03}_{-0.02}$
	(/Mt·yr)	$0.36^{+0.30}_{-0.20}$	$0.26^{+0.27}_{-0.17}$	$0.09^{+0.21}_{-0.08}$	$0.18^{+0.25}_{-0.13}$
	OBS	0	0	0	0
(100<P_{tot} <250)	Eff.(%)	20.4±3.6	20.2±3.6	20.5±3.6	19.4±3.4
	BKG	0.22±0.08	0.12±0.04	0.06±0.02	0.15±0.06
	(/Mt·yr)	2.4±0.8	2.5±0.9	1.8±0.7	1.1±0.3
	OBS	0	0	0	0

- 306.3 kton·years (SKI-IV)
- signal ε(P_{tot}<250MeV/c): ~40%
- total(SKI-IV) expected #BKG(P_{tot}<250MeV/c) < 1

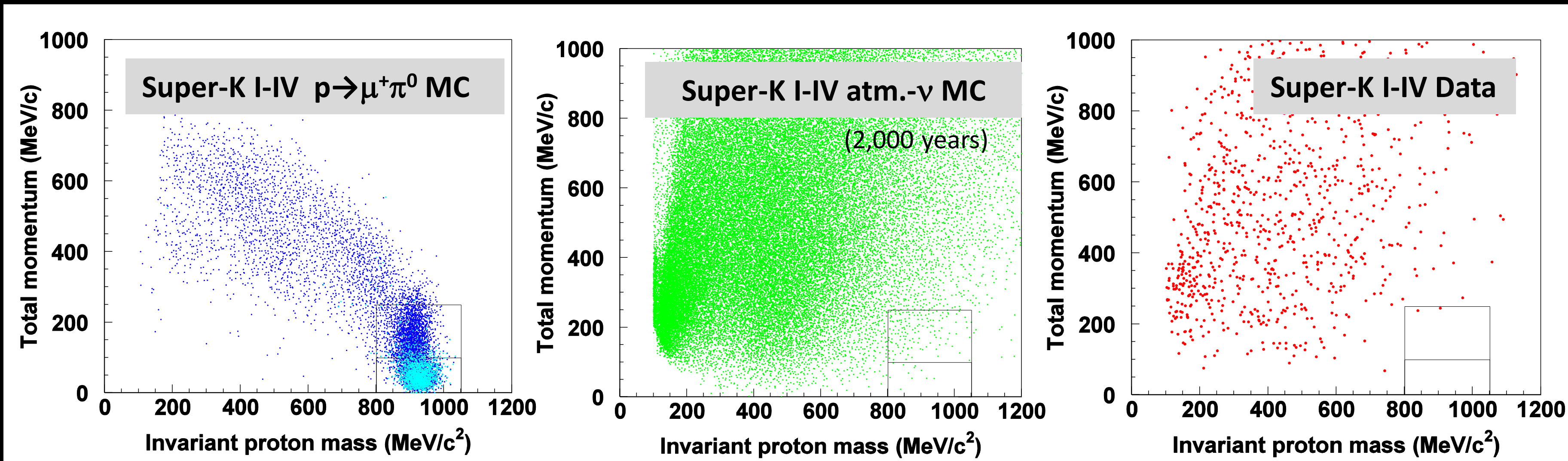
  #BKG: confirmed with K2K ν beam data [PRD 77, 032003(2008)]
- no data candidate

$$\tau/B_{p\rightarrow e\pi 0} > 1.6 \times 10^{34} \text{ years (90\% CL)}$$

arXiv:1610.03597 (submitted to PRD)

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

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



		SK-I	SK-II	SK-III	SK-IV
Exp.	kt·yrs	91.7	49.2	31.9	133.5
$p \to \mu^+\pi^0$					
(P_{tot}<100)	Eff.(%)	16.4±1.5	16.0±1.5	16.4±1.5	20.1±1.9
	BKG	$0.03^{+0.02}_{-0.02}$	<0.01	<0.01	$0.01^{+0.02}_{-0.01}$
	(/Mt·yr)	$0.31^{+0.26}_{-0.17}$	$0.10^{+0.13}_{-0.07}$	$0.22^{+0.22}_{-0.14}$	$0.09^{+0.21}_{-0.08}$
	OBS	0	0	0	0
(100≤P_{tot} <250)	Eff.(%)	15.3±2.8	15.3±2.8	16.5±3.0	18.2±3.3
	BKG	0.33±0.10	0.14±0.05	0.12±0.04	0.23±0.08
	(/Mt·yr)	3.6±1.1	2.9±0.9	3.7±1.2	1.7±0.6
	OBS	0	0	0	2

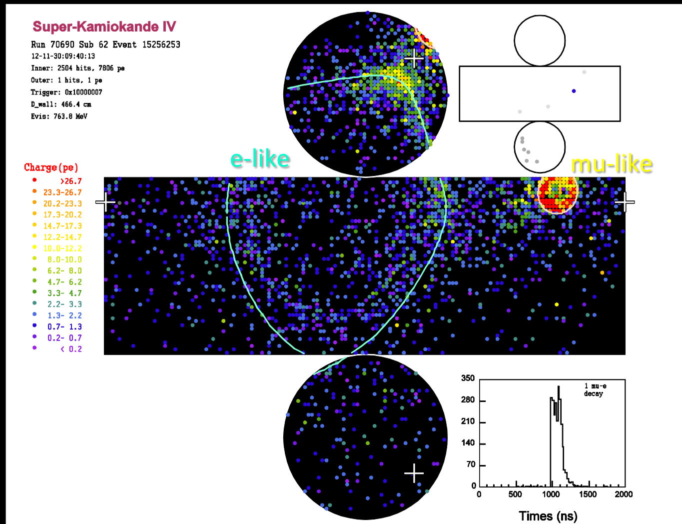
next slide

- 306.3 kton·yrs (SKI-IV)
- signal ε(P_{tot}<250MeV/c): 30-40%
- total expected #BKG:
  - P_{tot}<100: ~0.05
  - 100≤P_{tot}<250: ~0.82
- no significant data excess

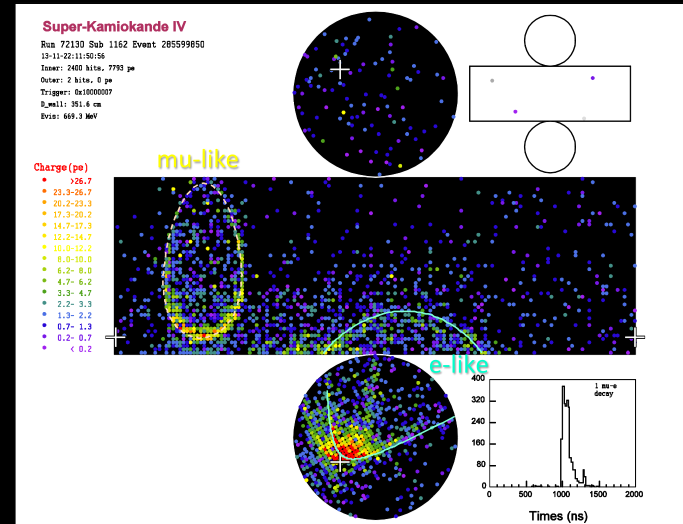
$\tau/B_{p\to\mu\pi^0} > 7.7 \times 10^{33}$ years (90% CL)

arXiv:1610.03597 (submitted to PRD)

Event #1



Event #2



Event #1

(M_{tot}, P_{tot}) : (903, 248)MeV

Wall : 466cm

ring : 2

P_e: 375MeV/c

P_μ: 551MeV/c

$\theta_{e\text{-}mu}$: 158°

Event #2

(M_{tot}, P_{tot}) : (832, 238)MeV

Wall : 352cm

ring : 2

P_e: 461MeV/c

P_μ: 391MeV/c

$\theta_{e\text{-}mu}$: 149°

If we include additional initial ring rejected by ring correction →
(M_{tot}, P_{tot}): (880, 289)MeV

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

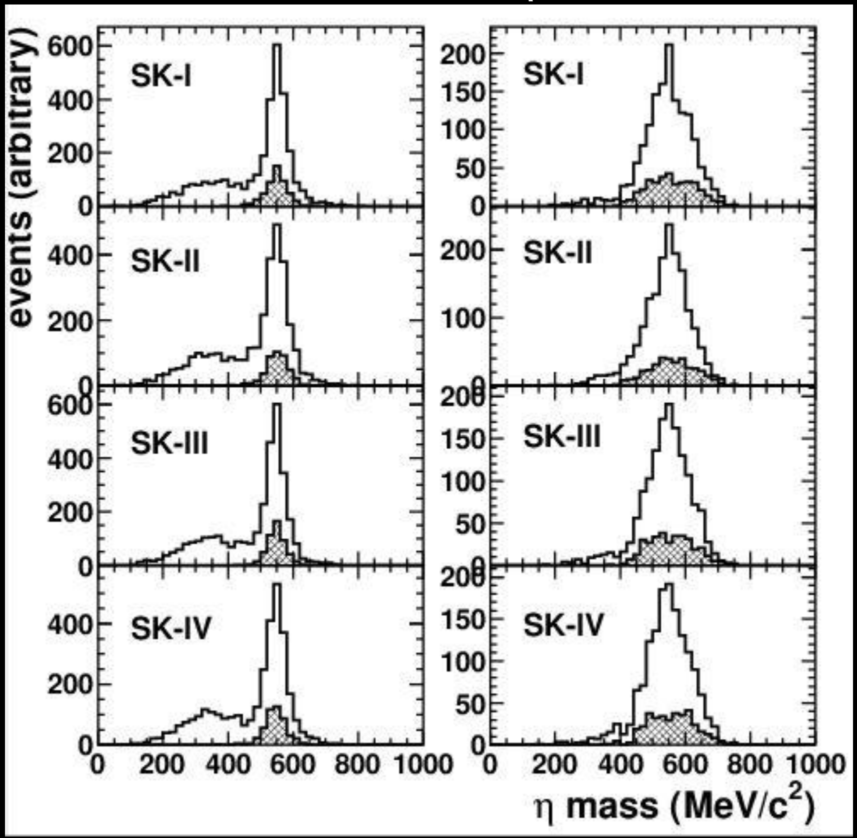
- Poisson prob. (≥2; 0.82): 19.9%

Other charged antilepton + meson searches

- $p \to (e^+, \mu^+) + (\eta^0, \rho^0, \omega^0)$,
  $n \to (e^+, \mu^+) + (\pi^-, \rho^-)$
- SK I-IV data (316kton·year)
- Several analysis improvements from previous results using SK-I,II data (PRD 85, 112001(2012))
  - 2.26 times data
  - P_{tot} separation in $p \to (e^+, \mu^+)\eta^0$, $\eta^0 \to 2\gamma$
  - n-tag in SK-IV
  - systematic error estimations
  - etc.

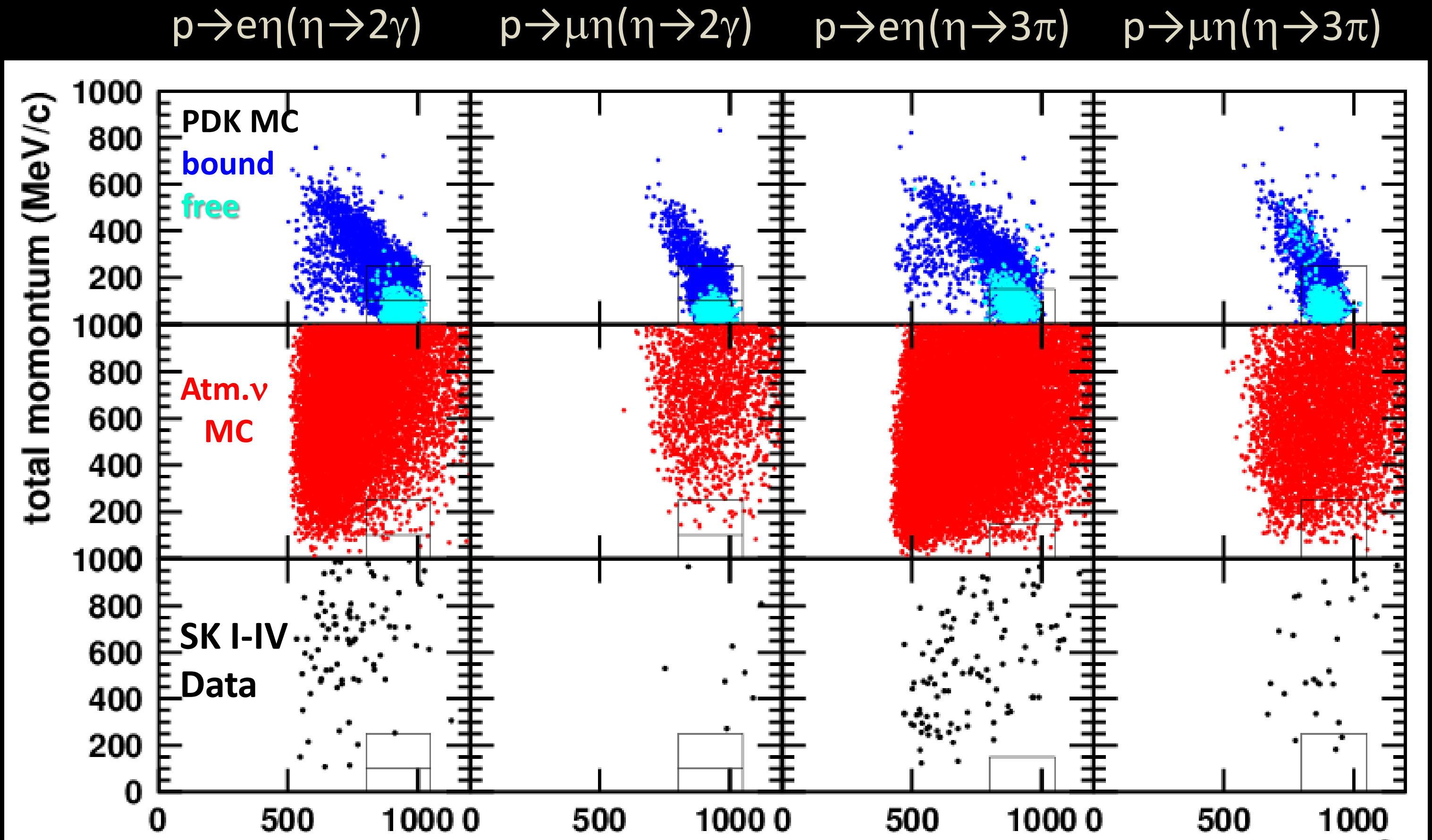
$p \to e^+\eta^0$ search

$\eta^0 \to 2\gamma$ search　　$\eta^0 \to 3\pi^0$ search



$p \to e^+\eta^0$ MC: open(hatch) for all(free) protons

$p \to (e^+, \mu^+)\eta^0$ search



after $p \to l^+\eta^0$ selections except (M_{tot}, P_{tot}) cut

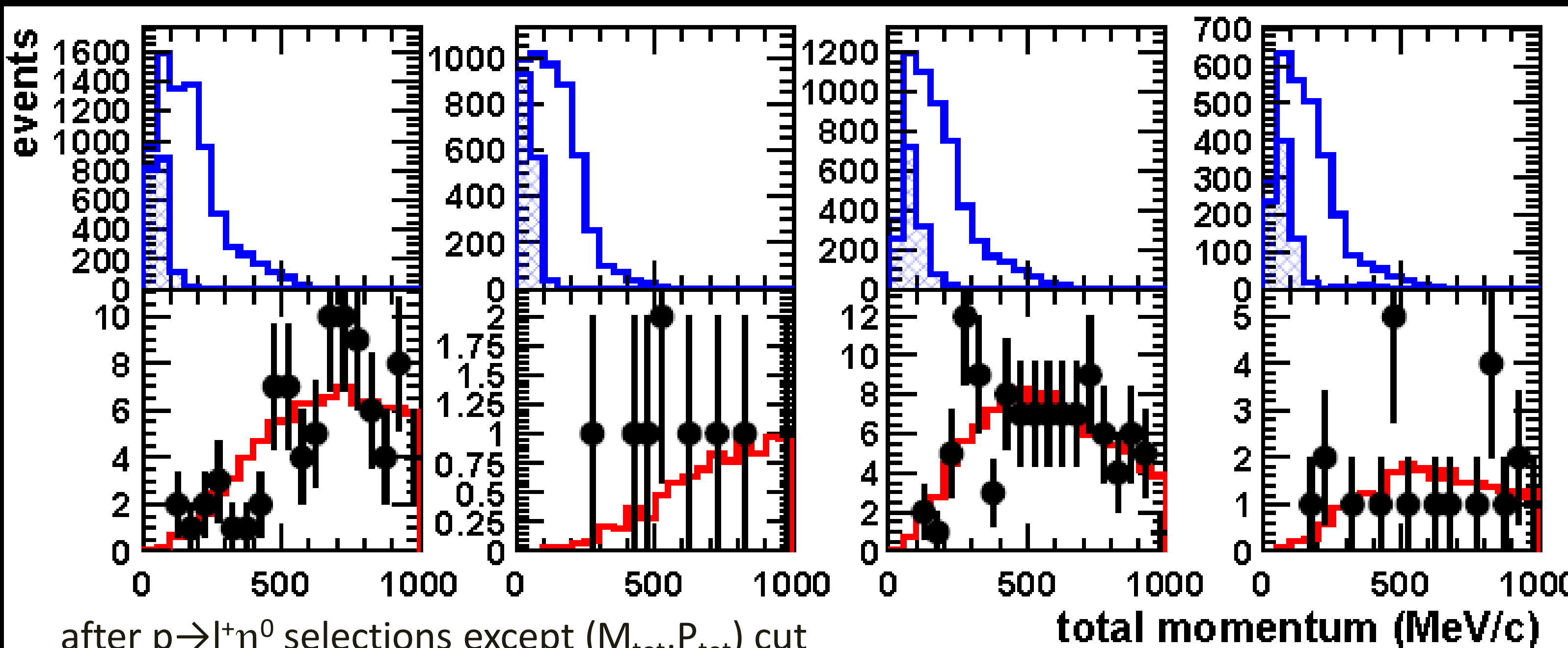
- P_{tot} separation in $\eta \to 2\gamma$ mode
  ex.) Discovery reach: ~12(~20)% higher at ~0.3(1)Mt·yr for $p \to e\eta$, $\eta \to 2\gamma$
  - ε: 10-11%($P_{tot} \geq$100MeV/c), 7-8%(P_{tot}<100MeV/c)
  - total expected #BKG: ~0.45($P_{tot} \geq$100MeV/c), ~0.03(P_{tot}<100MeV/c)
  - data candidate: 0 in both P_{tot} regions

(detail of ε, #BKG, data for all searches in supplement)

$p \rightarrow l^+ \eta^0$ MC
bound(open)
free(hatched)
Atm.ν MC
SK I-IV Data

$p \rightarrow (e^+, \mu^+)\eta^0$ search

$p \rightarrow e\eta(\eta \rightarrow 2\gamma)$ $p \rightarrow \mu\eta(\eta \rightarrow 2\gamma)$ $p \rightarrow e\eta(\eta \rightarrow 3\pi)$ $p \rightarrow \mu\eta(\eta \rightarrow 3\pi)$



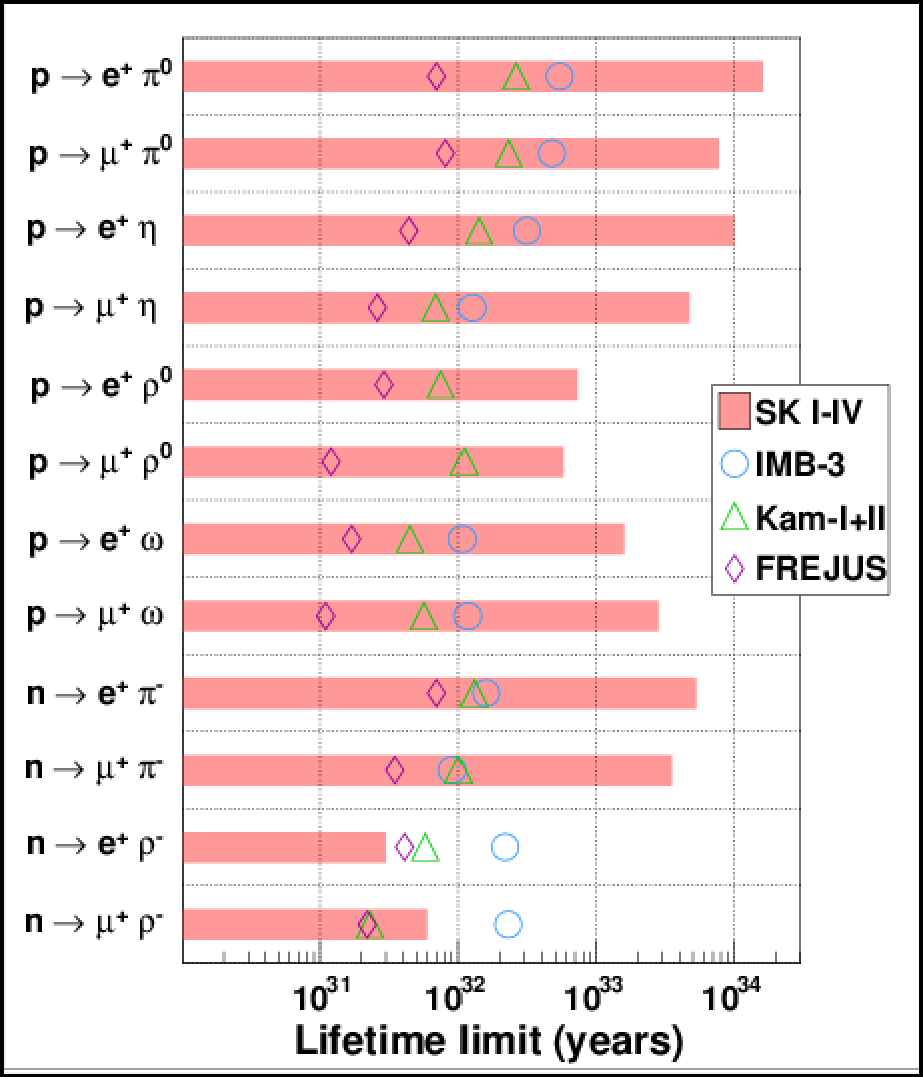
- Most free protons decay in P_{tot}<100MeV/c for $\eta \rightarrow 2\gamma$
- Data and atm.-ν MC agree well with each other

Results of other charged antilepton + meson search

Modes	Background (events)	Candidate (events)	Probability (%)	N (measurements)	Lifetime Limit ($\times 10^{33}$ years) at 90% CL
$p \to e^+\eta^0$	0.78(0.44)	0(0)	N/A	12	10.(4.2)
$p \to \mu^+\eta^0$	0.85(0.49)	2(2)	20.9	12	4.7(1.3)
$p \to e^+\rho^0$	0.64(0.35)	2(0)	13.5	4	0.72(0.71)
$p \to \mu^+\rho^0$	1.30(0.42)	1(1)	72.7	4	0.57(0.16)
$p \to e^+\omega^0$	1.35(0.53)	1(1)	74.1	4	1.6(0.32)
$p \to \mu^+\omega^0$	1.09(0.48)	0(0)	N/A	4	2.8(0.78)
$n \to e^+\pi^-$	0.41(0.27)	0(0)	N/A	4	5.3(2.0)
$n \to \mu^+\pi^-$	0.77(0.43)	1(1)	53.7	4	3.5(1.0)
$n \to e^+\rho^-$	0.87(0.38)	4(1)	1.2	4	0.03(0.07)
$n \to \mu^+\rho^-$	0.96(0.29)	1(0)	61.7	4	0.06(0.04)
total	8.6(4.1)	12(6)	15.7	N/A	N/A

- Numbers in ( ) are from previous analysis in SK-I,II
- No significant excess of data above background expectation
  - the smallest Prob.(≥cand.,#BKG) in $n \to e^+\rho^-$ search (detail in supplement)
- Limits are typically higher than previous results by factor 2-3
  - will submit to PRD

Comparison with other experiments



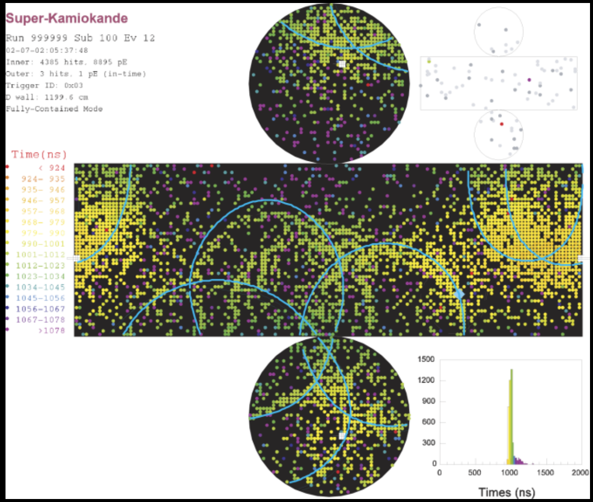
- Most SK results are better than other experiments by 1-2 orders of magnitude
  - lower for $n \rightarrow (e^+, \mu^+)\rho^-$ mainly due to lower ε, syst. errors on ε, data cand. > #BKG

n-$\bar{n}$ oscillation search

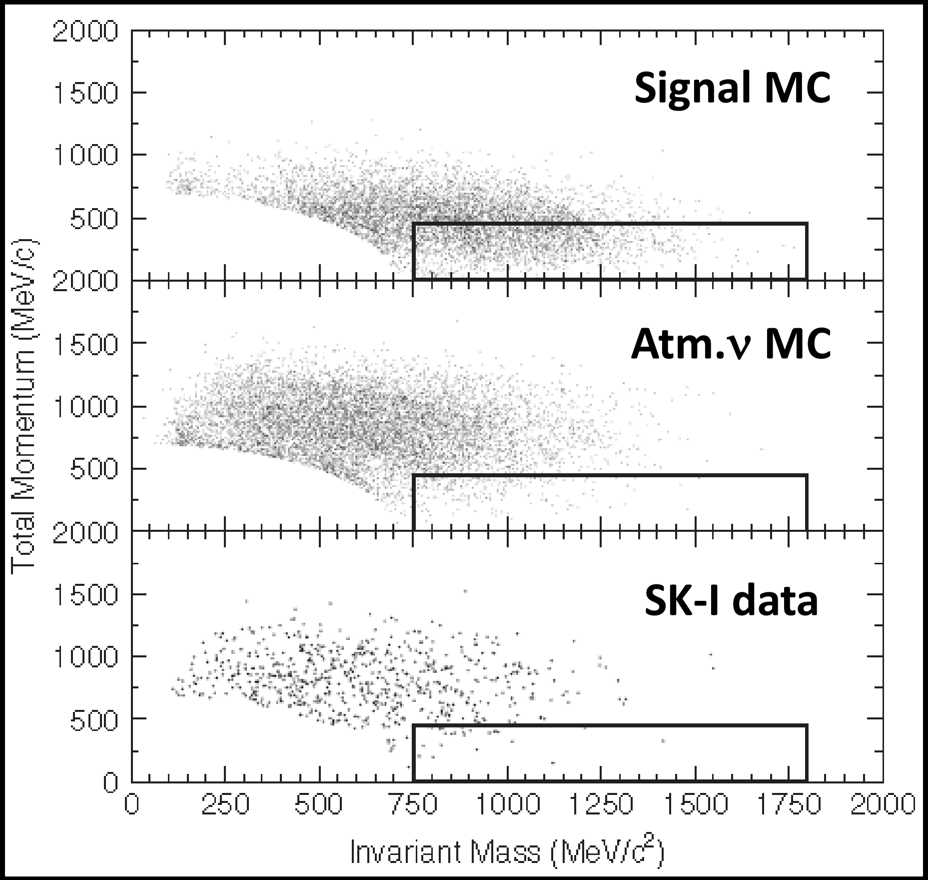
- $\Delta B = \Delta(B-L) = 2$
- PRD 91, 072006(2015)
- SK-I data only (91.5kt·yr)
  - 2.45×10^{34} neutron·year
- $\bar{n}$ annihilates with surrounding nucleon and produce mainly pions
- Event selections
  - multi rings
  - $700<E_{vis}<1300$MeV
  - $P_{tot}<450$MeV/c
  - $750<M_{tot}<1800$MeV/c^2

Branching ratios in our simulations

$\bar{n}+p$		$\bar{n}+n$	
$\pi^+\pi^0$	1%	$\pi^+\pi^-$	2%
$\pi^+2\pi^0$	8%	$2\pi^0$	1.5%
$\pi^+3\pi^0$	10%	$\pi^+\pi^-\pi^0$	6.5%
$2\pi^+\pi^-\pi^0$	22%	$\pi^+\pi^-2\pi^0$	11%
$2\pi^+\pi^-2\pi^0$	36%	$\pi^+\pi^-3\pi^0$	28%
$2\pi^+\pi^-2\omega$	16%	$2\pi^+2\pi^-$	7%
$3\pi^+2\pi^-\pi^0$	7%	$2\pi^+2\pi^-\pi^0$	24%
		$\pi^+\pi^-\omega$	10%
		$2\pi^+2\pi^-2\pi^0$	10%



Results



- ε = 12.1%
- Expected #BKG = 24.1
- 24 candidate events
- No data excess. Lifetime limit $T_{n\text{-}n} > 1.9\times10^{32}$ years (90%CL)

$$T_{n\text{-}n} = R \cdot \tau_{n\text{-}n}^{2}$$

R: nuclear suppression factor. $0.517\times10^{23}s^{-1}$ with theoretical uncertainty of 20-30%.
PRD 78, 016002(2008)

- Oscillation time $\tau_{n\text{-}n} > 2.7\times10^{8}s$
  3 times more restrictive than ILL/Grenoble reactor experiment

- On-going analysis improvements
  - SK-I to SK-IV data
  - multivariate method with a boosted decision tree
  - $\bar{n}$-nucleon annihilation branching fractions
  - pion-nucleon interaction models, and so on…

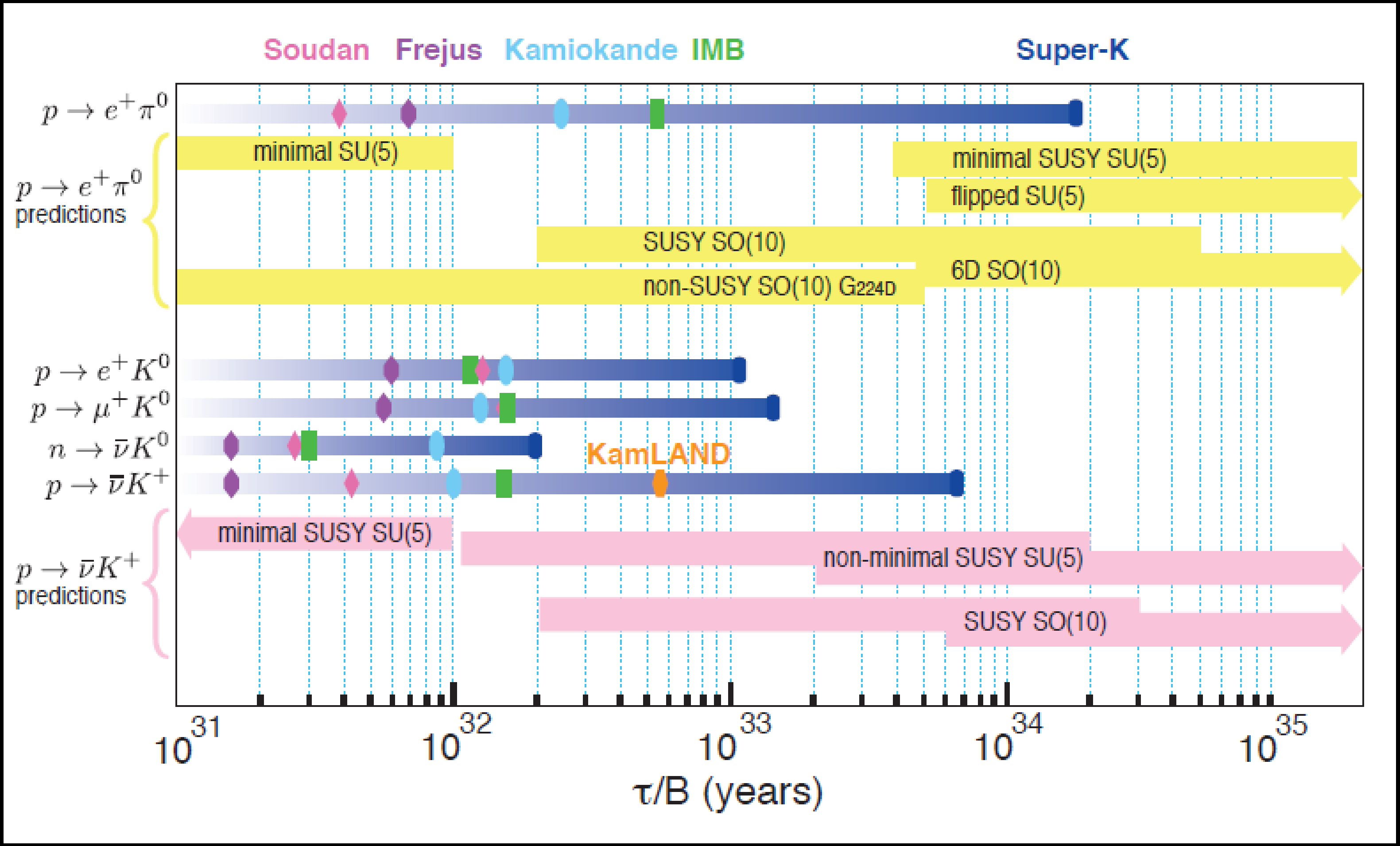
Recent nucleon decay and n-$\bar{n}$ results in SK

Decay mode	$\|\Delta(B-L)\|$	Lifetime lower limit at 90% CL (years)	Paper
$p \to e^+\pi^0$	0	1.6×10^{34}	arXiv:1610.03597 (submitted to PRD)
$p \to \nu K^+$	$0(\bar{\nu})$, $2(\nu)$	6.6×10^{33}	PRD 90, 072005 (2014)
$p \to \mu^+\pi^0$	0	7.7×10^{33}	arXiv:1610.03597 (submitted to PRD)
$p \to (e^+,\mu^+)(\eta,\rho,\omega)$, $n \to (e^+,\mu^+)(\pi,\rho)$	0	$(0.03\text{-}10)\times10^{33}$	will submit to PRD
$p \to \mu^+K^0$	0	1.6×10^{33}	PRD 86, 012006 (2012)
$\bar{n} \to \nu\pi^0$, $\bar{p} \to \nu\pi^+$	0	1.1×10^{33}, 3.9×10^{32}	PRL 113, 121802 (2014)
$p \to (e^+,\mu^+)\nu\nu$	$0(\bar{\nu}\nu)$, $2(\nu\nu,\bar{\nu}\bar{\nu})$	$1.7/2.2\times10^{32}$	PRL 113, 101801 (2014)
$p \to (e^+,\mu^+)X$	?	$7.9/4.1\times10^{32}$	PRL 115, 121803 (2015)
$n \to \nu\gamma$	$0(\bar{\nu})$, $2(\nu)$	5.5×10^{32}	PRL 115, 121803 (2015)
$pp \to K^+K^+$	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	7.2×10^{31}, $1,7\times10^{32}$, 4.0×10^{32}	PRD 91, 072009 (2015)
$np \to (e^+,\mu^+,\tau^+)\nu$	$0(\bar{\nu})$, $2(\nu)$	$(0.22\text{-}5.5)\times10^{32}$	PRL 115, 121803 (2015)
n-$\bar{n}$ oscillation	2	1.9×10^{32}	PRD 91, 072006 (2015)

- No significant excess of data above BKG expectation → lifetime limits

Benchmark searches and GUT predictions

(Ed Kearns @ 2013 Snowmass)



- Huge theoretical uncertainty (2-3 orders of magnitude)
- Current searches are in interesting ranges → SK, Hyper-K, etc.

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
  - SK-Gd talk tomorrow
- Hyper-K/DUNE/JUNO talks in this afternoon

Supplement

p→$\mu^+\pi^0$ 2[nd] data candidate

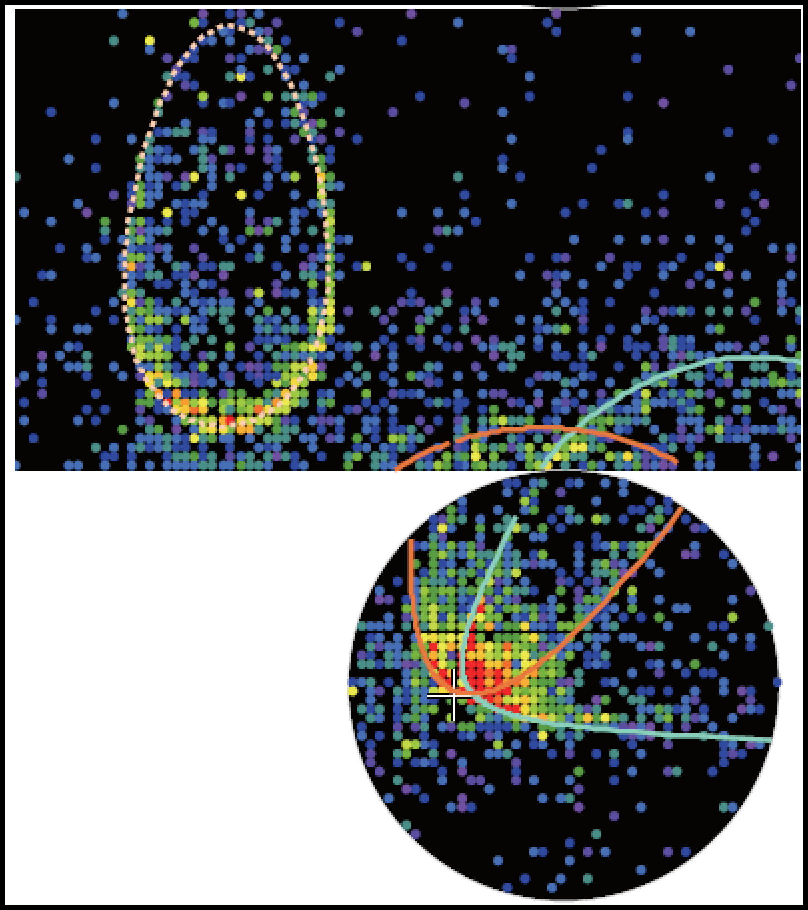


FIG. 5. (color online) Event display of the second candidate event, zoomed to the region of the rings. The blue solid line and the tan dashed line show the reconstructed e-like and μ-like ring, respectively. The dark orange solid line shows an additional e-like ring that was identified in the initial ring counting process, but it is rejected by the ring correction because it is too close in angle to the other e-like ring (blue line). As a result, this event is judged as a two-ring event.

[1] This event is judged as an 3 ring event, but leaves the signal box if we use updated PMT gain correction, introduced in 2016, which depends on PMT production year.

$p \to (e^+, \mu^+)\pi^0$ searches

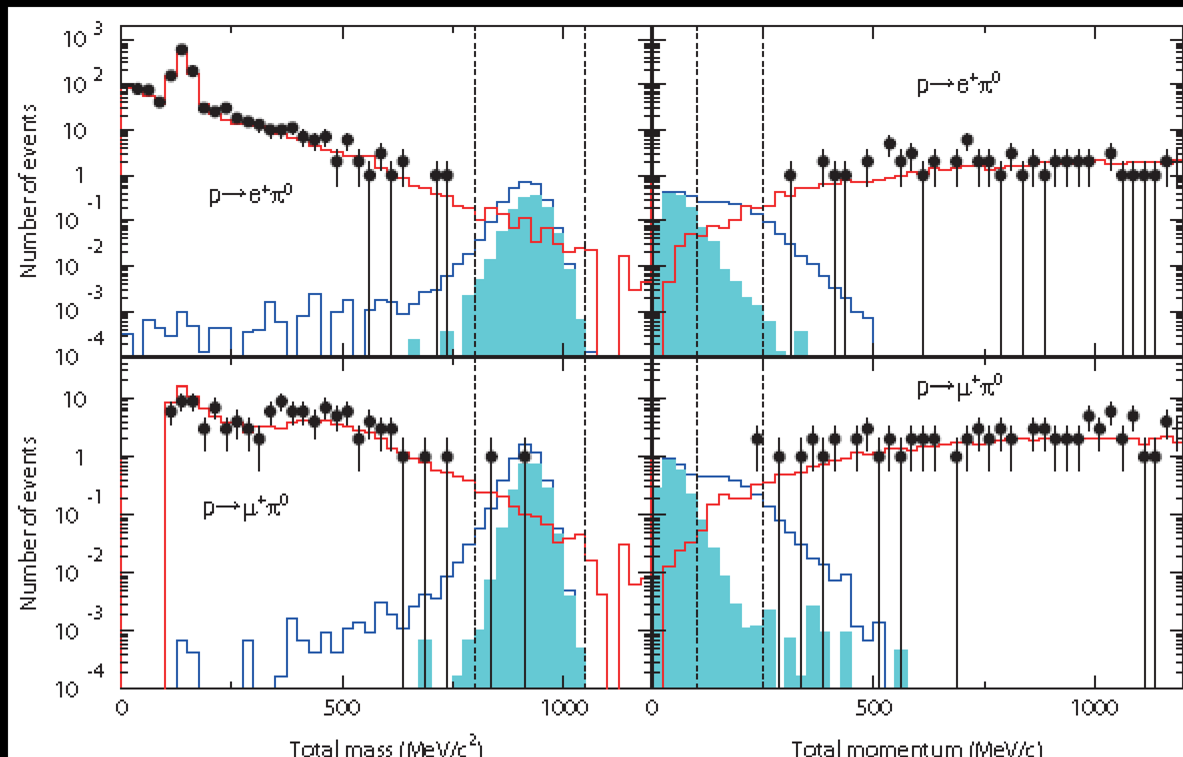
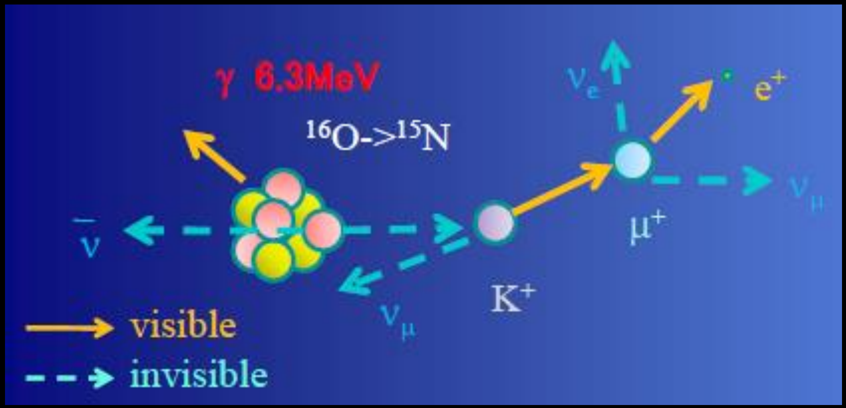
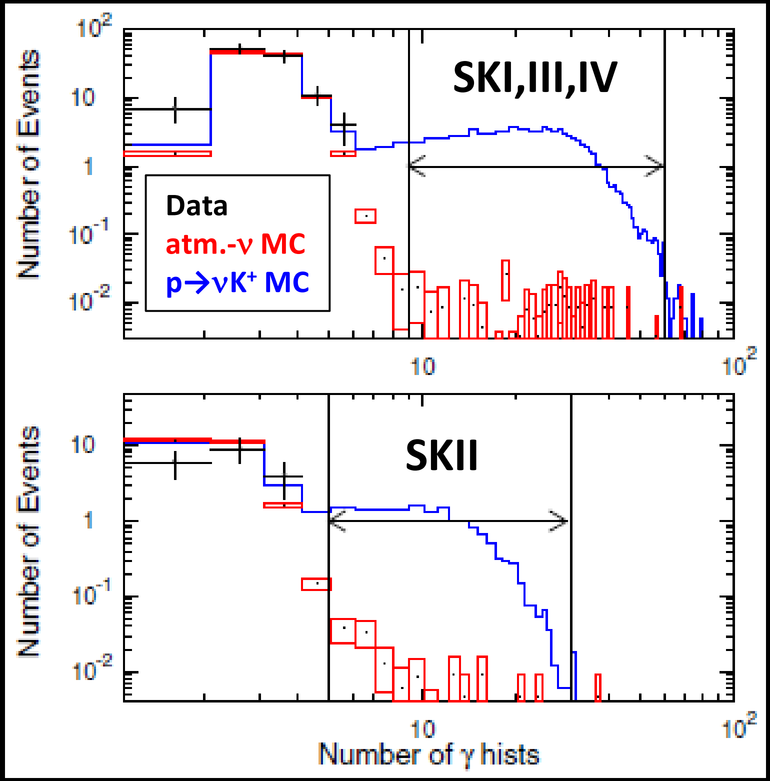


FIG. 4. (color online) Distributions of reconstructed invariant mass (left) and total momentum (right) for $p \to e^+\pi^0$ in the top panels and for $p \to \mu^+\pi^0$ in the bottom panels, after all selection cuts except cuts on the plotted variable. The dark blue histograms correspond to 90% confidence level allowed signal and the histograms filled by light blue show the portion contributed by free proton decay. The red histograms show atmospheric ν MC, and the dots are data with 0.306 Mton·years exposure. Vertical dashed lines indicate the signal regions. The peak around 150 MeV/c^2 in the total mass distribution of atmospheric ν and data in the left top panel arises from π^0 decays.

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

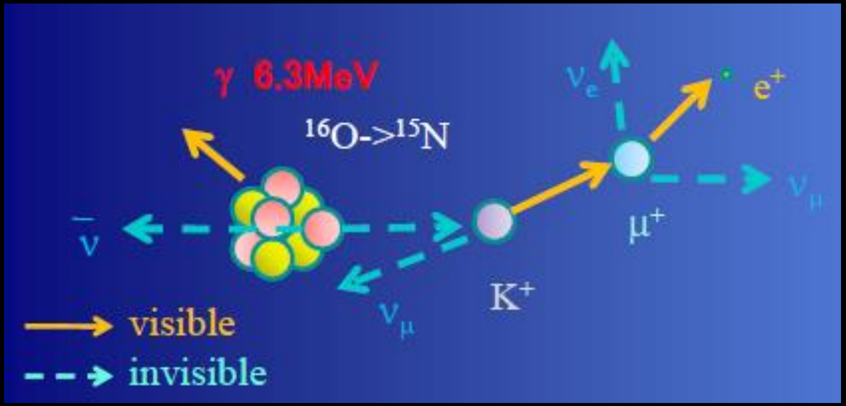


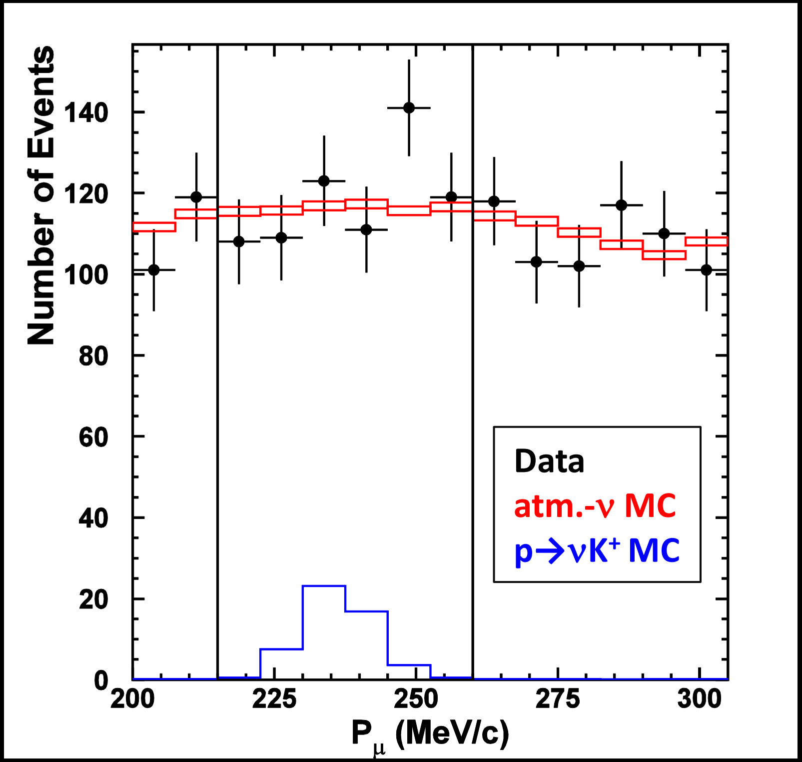
- event selections:
  - fully contained
  - fiducial volume
  - 1 μ-like (PID)
  - 1 Michel-e
  - $215 < P_{\mu} < 260$MeV/c
  - proton ring rejection
  - $8(4) < N_{\gamma} < 60(30)$ for SK-I,III,IV(SK-II)
  - T_{μ}-$T_{\gamma} < 75$ns
  - no neutrons (SK-IV only)
- no data candidate



*(plot from **PRD 90, 072005 (2014)**)*

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





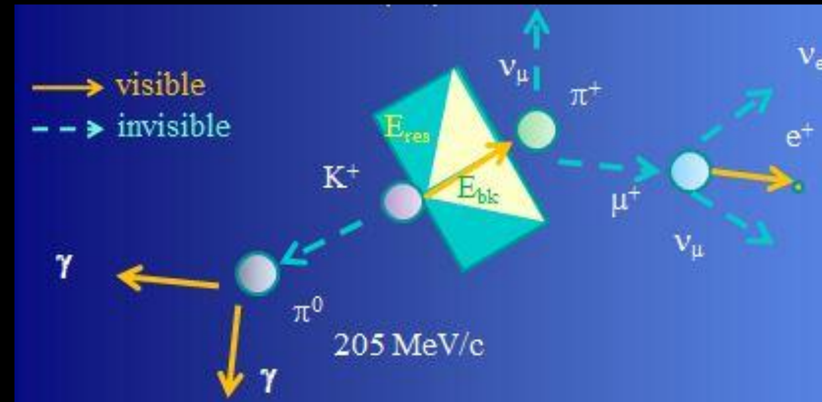
- event selections:

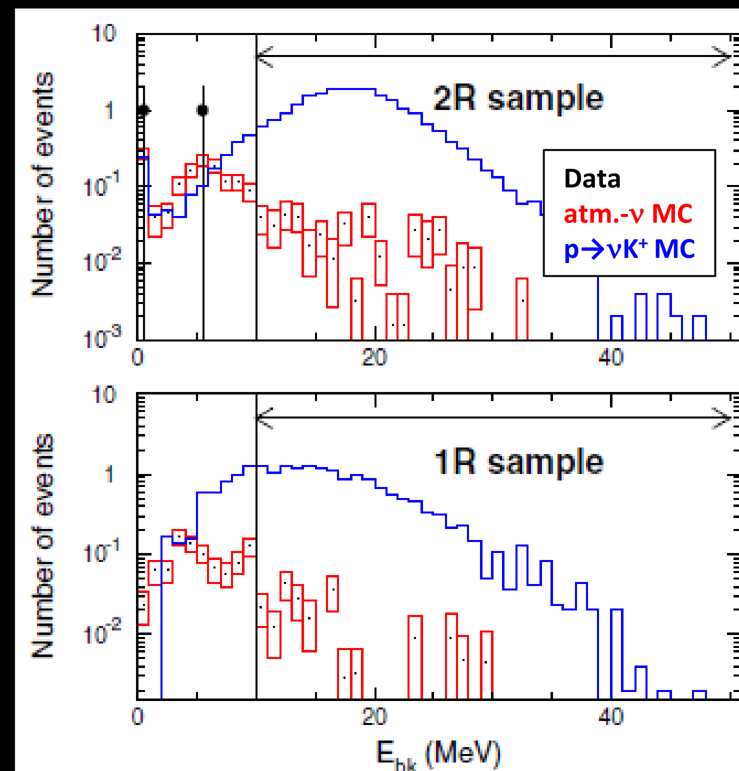
  same as γ meth. except:
  - no prompt γ hits
  - relaxed P_μ cut
- no data excess

$p \rightarrow \nu K^+$ search

($\pi^+\pi^0$ method)

- event selections:
  - fully contained
  - fiducial volume
  - 1 or 2 e-like rings (PID)
  - 1 Michel-e
  - $85 < M_{\pi 0} < 185 MeV/c^2$, $175 < P_{\pi 0} < 250 MeV/c$
  - charge profile likelihood for π^+
  - $10 < E_{bk} < 50 MeV$
  - no neutrons (SK-IV only)
- no data candidate





*(plot from **PRD 90, 072005 (2014)**)*

$p \rightarrow \nu K^+$ 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)
- 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

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

(91.5, 49.1, 31.8, 143.8 kton·year for SK-I, II, III, IV)

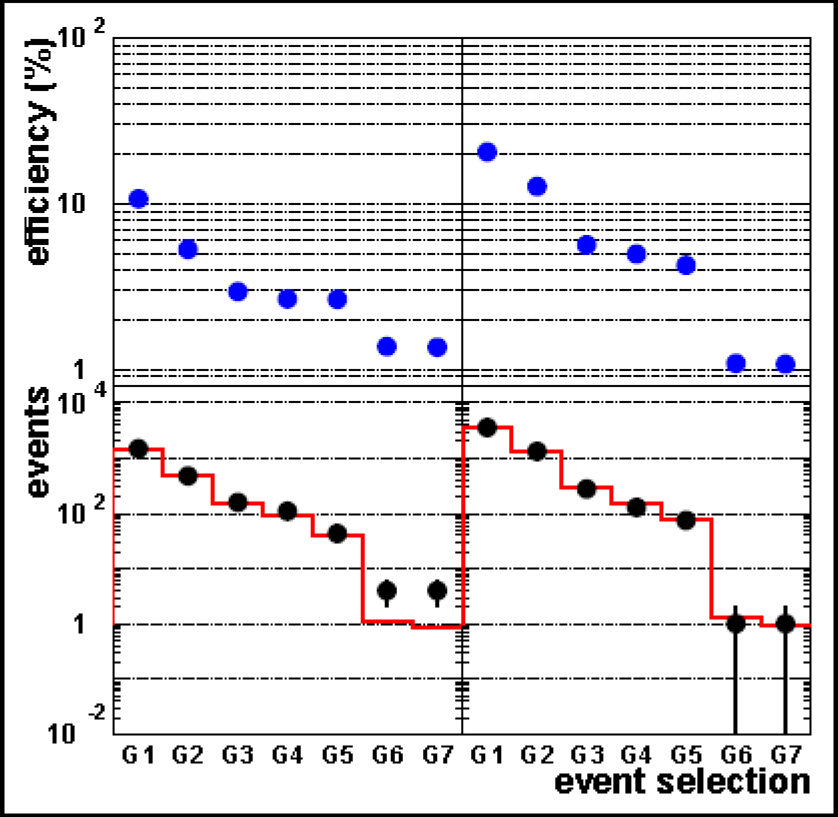
	Efficiency (%)				Background (events)				Candidate (events)			
Modes	SK-I	SK-II	SK-III	SK-IV	SK-I	SK-II	SK-III	SK-IV	SK-I	SK-II	SK-III	SK-IV
$p \rightarrow e^+\eta^0$												
(2γ, total)	18.9(18.8)	17.6(18.2)	18.9	17.3	0.17±0.04(0.19)	0.11±0.02(0.09)	0.05±0.01	0.15±0.04	0(0)	0(0)	0	0
(2γ, upper)	11.0	10.9	10.7	9.8	0.17±0.04	0.10±0.02	0.05±0.01	0.13±0.04	0	0	0	0
(2γ, lower)	7.9	6.7	8.2	7.5	0.01±0.01	0.01±0.01	<0.01	0.01±0.01	0	0	0	0
($3\pi^0$)	8.0(8.1)	8.2(7.6)	7.6	7.7	0.15±0.03(0.08)	0.06±0.02(0.08)	0.06±0.01	0.03±0.02	0(0)	0(0)	0	0
$p \rightarrow \mu^+\eta^0$												
(2γ, total)	13.1(12.4)	12.1(12.4)	13.1	15.5	0.05±0.02(0.03)	0.02±0.01(0.01)	0.01±0.01	0.03±0.01	0(0)	0(0)	0	0
(2γ, upper)	7.3	6.5	7.2	8.4	0.05±0.02	0.02±0.01	0.01±0.01	0.03±0.01	0	0	0	0
(2γ, lower)	5.8	5.6	6.0	7.0	<0.01	<0.01	<0.01	<0.01	0	0	0	0
($3\pi^0$)	6.9(6.1)	6.2(6.1)	6.9	7.9	0.34±0.05(0.30)	0.13±0.02(0.15)	0.12±0.02	0.16±0.04	0(0)	1(2)	0	1
$p \rightarrow e^+\rho^0$	3.8(4.9)	3.3(4.2)	3.6	3.8	0.29±0.05(0.23)	0.13±0.02(0.12)	0.05±0.01	0.17±0.04	0(0)	0(0)	0	2
$p \rightarrow \mu^+\rho^0$	1.9(1.8)	1.3(1.5)	2.2	1.9	0.41±0.05(0.30)	0.21±0.03(0.12)	0.13±0.02	0.55±0.07	1(1)	0(0)	0	0
$p \rightarrow e^+\omega^0$												
($\pi^0\gamma$)	2.3(2.4)	2.5(2.2)	2.3	2.1	0.16±0.04(0.10)	0.08±0.02(0.04)	0.06±0.01	0.05±0.03	0(0)	0(0)	0	0
($\pi^+\pi^-\pi^0$)	2.7(2.3)	2.2(2.3)	2.6	2.7	0.44±0.06(0.26)	0.17±0.03(0.13)	0.12±0.02	0.27±0.06	1(1)	0(0)	0	0
$p \rightarrow \mu^+\omega^0$												
($\pi^0\gamma$)	2.6(2.8)	3.0(2.8)	3.1	3.3	0.18±0.04(0.24)	0.10±0.02(0.07)	0.08±0.01	0.07±0.03	0(0)	0(0)	0	0
($\pi^+\pi^-\pi^0$)	3.1(2.7)	2.6(2.4)	3.2	4.6	0.19±0.03(0.10)	0.10±0.02(0.07)	0.08±0.01	0.29±0.05	0(0)	0(0)	0	0
$n \rightarrow e^+\pi^-$	12.7(19.4)	12.2(19.3)	13.5	12.6	0.17±0.04(0.16)	0.05±0.01(0.11)	0.07±0.01	0.12±0.04	0(0)	0(0)	0	0
$n \rightarrow \mu^+\pi^-$	11.3(16.7)	10.7(15.6)	11.5	13.4	0.29±0.04(0.30)	0.15±0.02(0.13)	0.09±0.01	0.24±0.05	0(1)	0(0)	1	0
$n \rightarrow e^+\rho^-$	1.4(1.8)	1.1(1.6)	1.4	1.5	0.36±0.05(0.25)	0.13±0.02(0.13)	0.14±0.02	0.24±0.06	1(1)	1(0)	2	0
$n \rightarrow \mu^+\rho^-$	1.0(1.1)	1.0(0.9)	1.1	1.2	0.34±0.04(0.19)	0.14±0.02(0.10)	0.14±0.02	0.34±0.06	0(0)	1(0)	0	0

- Higher ε for nucleon decay mode with μ in SK-IV thanks to QBEE
- Expected background rates are comparable between SK-I and SK-IV with n-tag
- Numbers in ( ) are from previous analysis in SK-I,II

NDK MC
Atm.ν MC
SK I-IV Data

$n \rightarrow (e^+, \mu^+)\rho^-$ search

$n \rightarrow e^+\rho^-$ $n \rightarrow \mu^+\rho^-$



(G1) the number of Cherenkov rings is four (three) for $n \rightarrow e^+\rho^-$ ($n \rightarrow \mu^+\rho^-$),

(G2) one of the rings is a no-shower type ring,

(G3) the ρ^- mass is in between 600 and 900 MeV/c^2,

(G4) the π^0 mass is in between 85 and 185 MeV/c^2,

(G5) the number of Michel electrons is 0 (1) for $n \rightarrow e^+\rho^-$ ($n \rightarrow \mu^+\rho^-$),

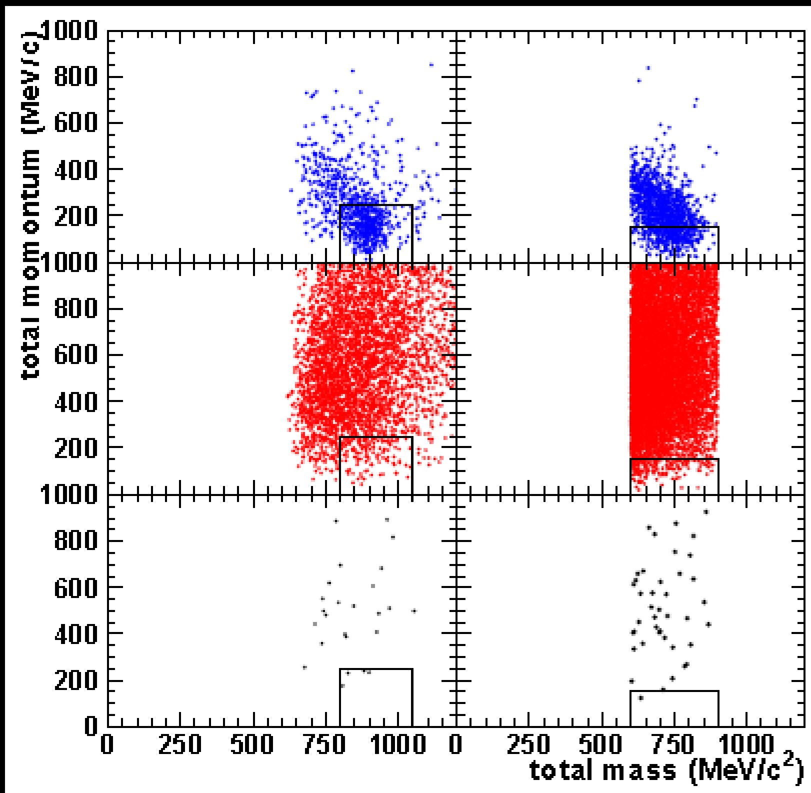
(G6) the total momentum is less than 250 (150) MeV/c for $n \rightarrow e^+\rho^-$ ($n \rightarrow \mu^+\rho^-$), and the total invariant mass is in between 800 and1050 for $n \rightarrow e^+\rho^-$,

(G7) the number of neutron is 0 in SK-IV.

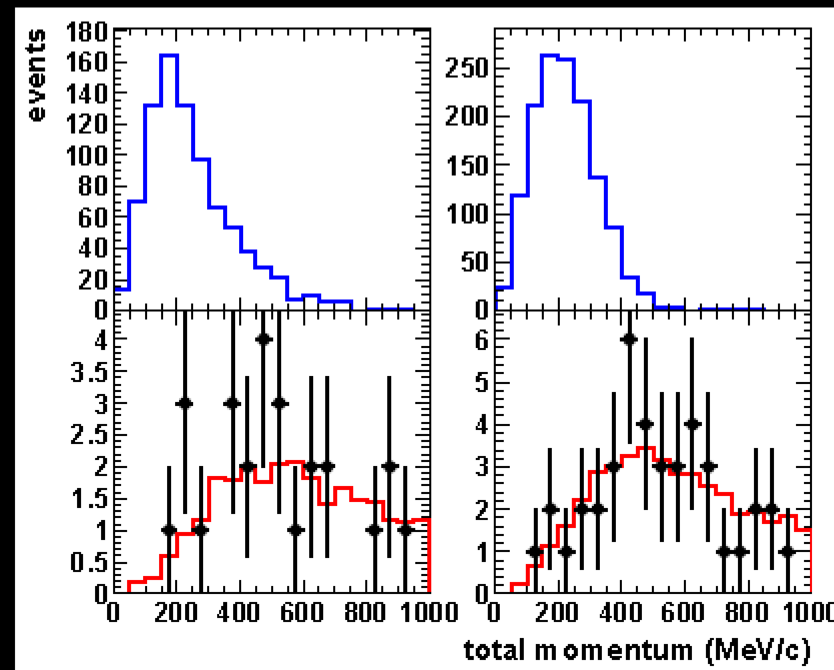
NDK MC
Atm.ν MC
SK I-IV Data

$n \to (e^+,\mu^+)\rho^-$ search

$n \to e^+\rho^-$ $n \to \mu^+\rho^-$

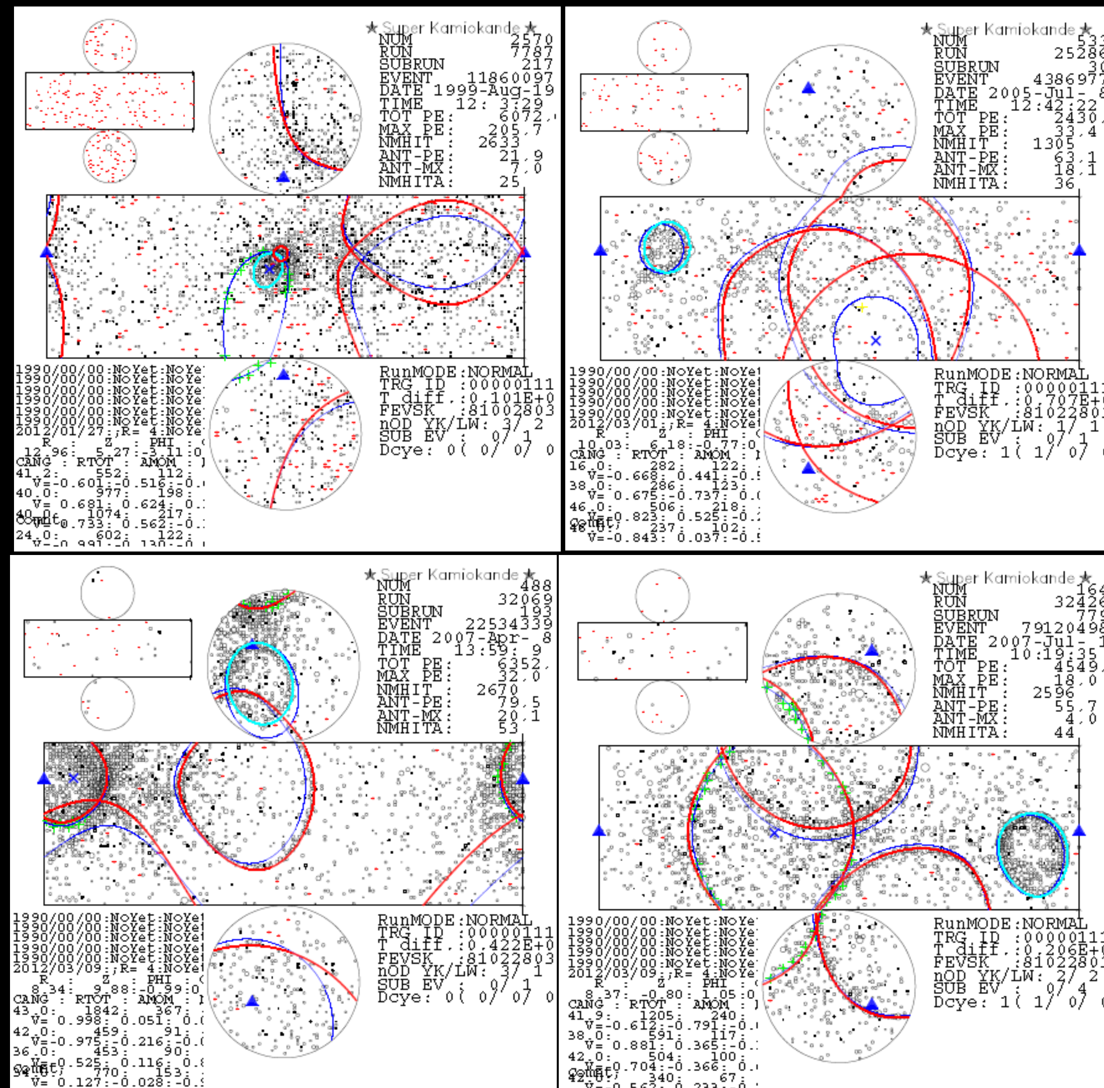


$n \to e^+\rho^-$ $n \to \mu^+\rho^-$



- All selections applied except (M_{tot},P_{tot}) cut

Data candidates in n→$e^{+}\rho^{-}$ search



Comparison with other experiments

(H.Nishino, PhD Thesis, Univ. of Tokyo, Feb. 2009)

	SK-I+II				IMB-3				KAM-I+II			
	eff. (%)	BG (/141)	N_c	τ	eff. (%)	BG (/7.6)	N_c	τ	eff. (%)	BG (/3.8)	N_c	τ
$p \to e^+\pi^0$	44.6	0.31	0	8.2	48	0.2	0	0.54	45	<0.04	0	0.26
$p \to \mu^+\pi^0$	35.5	0.34	0	6.6	42	0.6	0	0.47	43	<0.2	0	0.23
$p \to e^+\eta$	26.9	0.44	0	4.2	28	0.2	0	0.31	24	<0.04	0	0.14
$p \to \mu^+\eta$	18.5	0.49	2	1.3	23	2.8	3	0.13	21	<0.08	1	0.07
$p \to e^+\rho^0$	4.9	0.35	0	0.71	-	-	-	-	24	2.7	2	0.08
$p \to \mu^+\rho^0$	1.8	0.42	1	0.16	-	-	-	-	22	1.7	0	0.11
$p \to e^+\omega$	4.9	0.53	1	0.32	21	10.8	7	0.11	11	1.45	2	0.05
$p \to \mu^+\omega$	5.5	0.48	0	0.78	33	12.1	11	0.12	13	1.9	2	0.06
$n \to e^+\pi^-$	19.4	0.27	0	2.0	30	5.0	3	0.16	28	<0.2	0	0.13
$n \to \mu^+\pi^-$	16.7	0.43	1	1.0	14	1.9	1	0.09	23	<0.2	0	0.10
$n \to e^+\rho^-$	1.8	0.38	1	0.07	49	4.8	4	0.22	15	1.9	0	0.06
$n \to e^+\rho^-$	1.1	0.29	0	0.04	36	9.5	3	0.23	6	1.8	1	0.02
Total		4.7	6			47.9	32			11.5	9	

Table 10.1: The comparison of efficiencies, background estimations, candidates and lifetime limits between SK, IMB and KAMIOKANDE. 'BG' is the background estimation for SK, IMB and KAMIOKANDE in 141, 7.6 and 3.79 kiloton·year exposure, respectively. 'N_c' is the number of candidate. 'τ' is the partial lifetime limit in 10^{33} years. The efficiencies for SK and KAMIOKANDE are those in SK-I and KAMIOKANDE-II, respectively.