Nucleon decay searches - past, present, and future -

Dec.-16,17-2009 seminar@Beijing

Kamioka Observatory, Institute for Cosmic Ray Research, U of Tokyo, and
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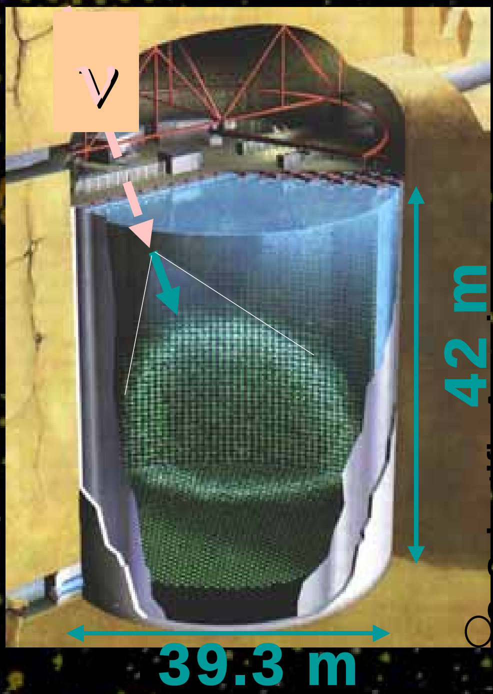
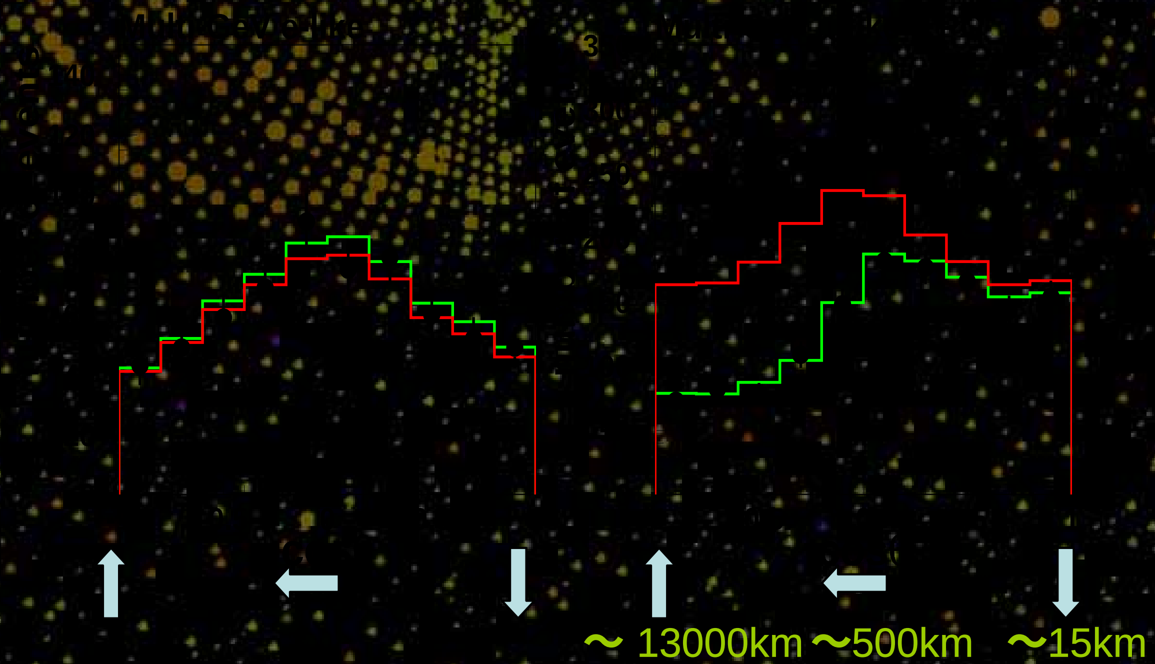
Masato Shiozawa

discovery of neutrino oscillation

- ***1998, Atmospheric neutrino observation at Super-Kamiokande***
  - ***deficit of upward going muon (neutrinos)***
  - ***electron (neutrino) as is expected***
  - ***consistent with pure $\nu\mu \rightarrow \nu\tau$***
    - ***$\sin^2\theta_{23} > 0.82$, $5\times10^{-4} < \Delta m^2_{23} < 6\times10^{-3}$ eV^2***

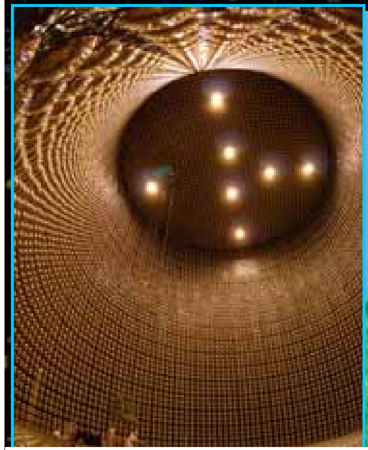


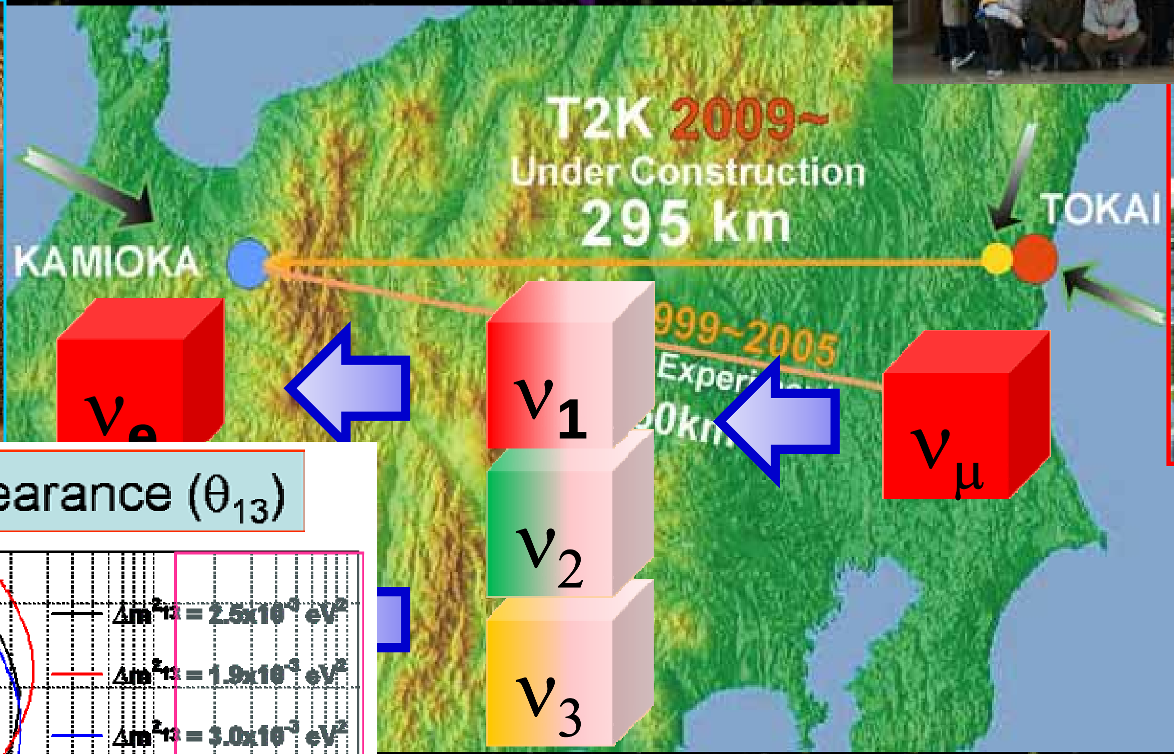


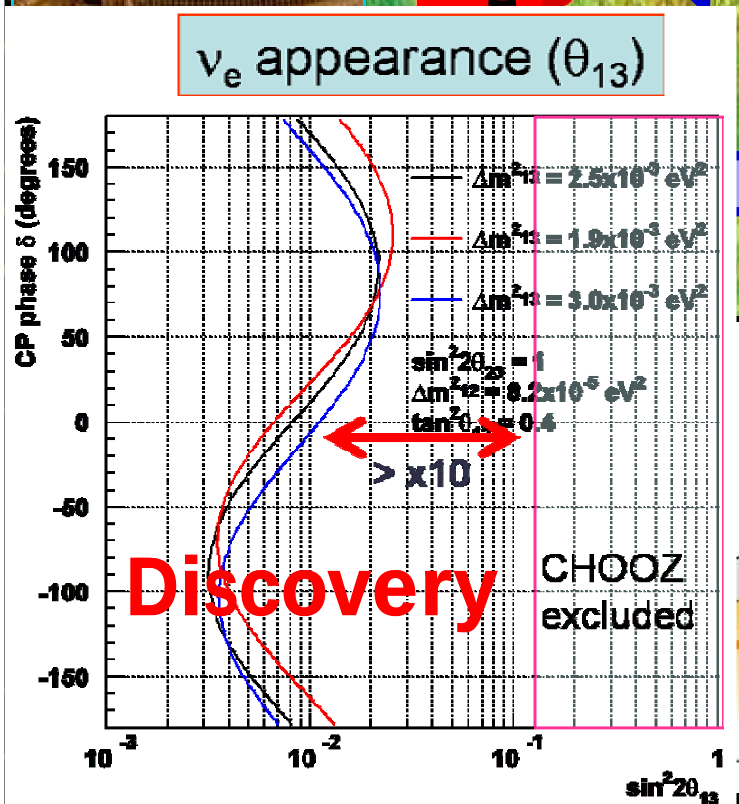
NOW: More than 28,000 events have been recorded.
Provide evidence and still provide largest statistics

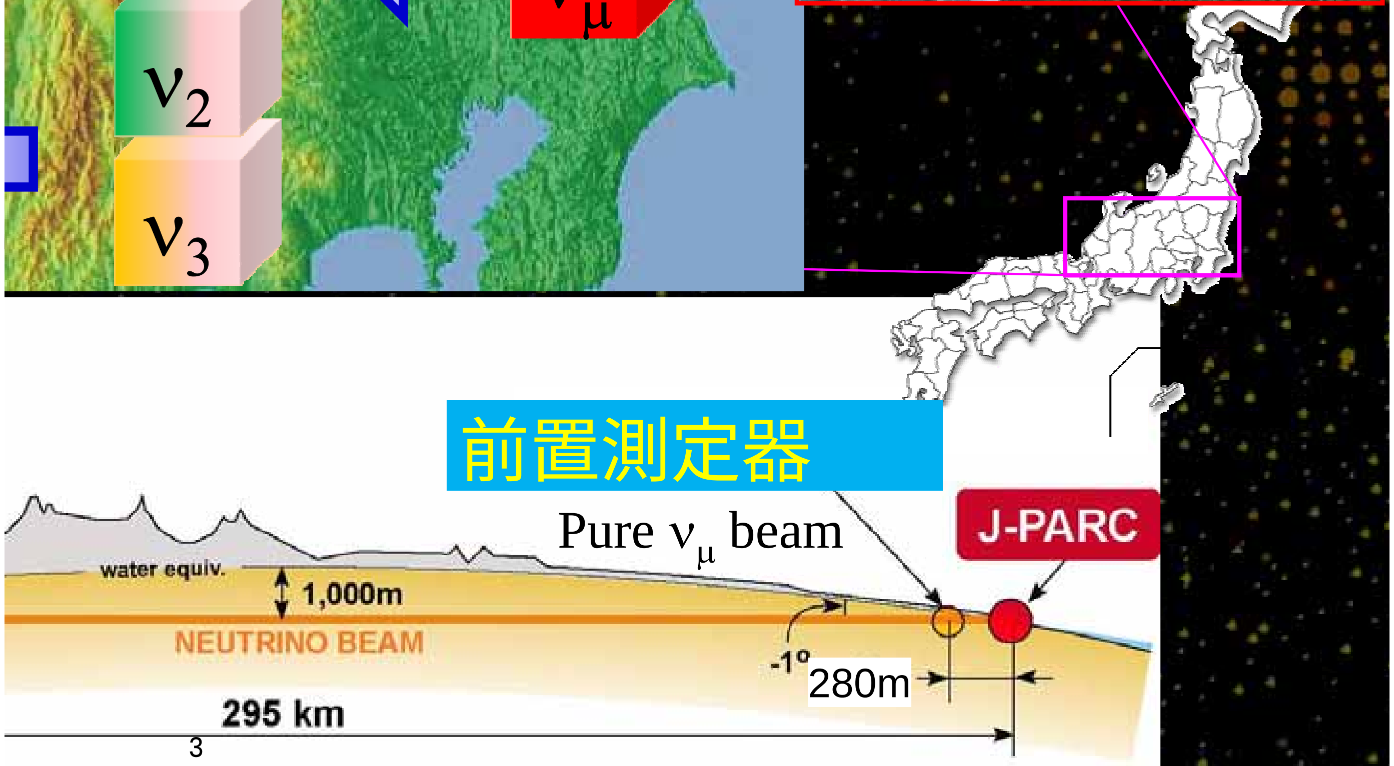
T2K: TOKAI TO(2) KAMIOKA

Physics run from January 2010
First results in 2010









Brief introduction (and apologies)

- *Ambitious theories to unify electromagnetic, weak, and strong forces (Grand Unified Theories) push up the relevant energy scale to ~10^{16} GeV which cannot be achievable by artificial accelerators.*
- *GUTs give unique predictions of baryon number violation → nucleon (proton or bound neutron) decays.*
- *I will review the experimental searches of nucleon decays in past ~10 years, present, and future. This review might be biased due to my experiences and luck of knowledge.*

Detectors

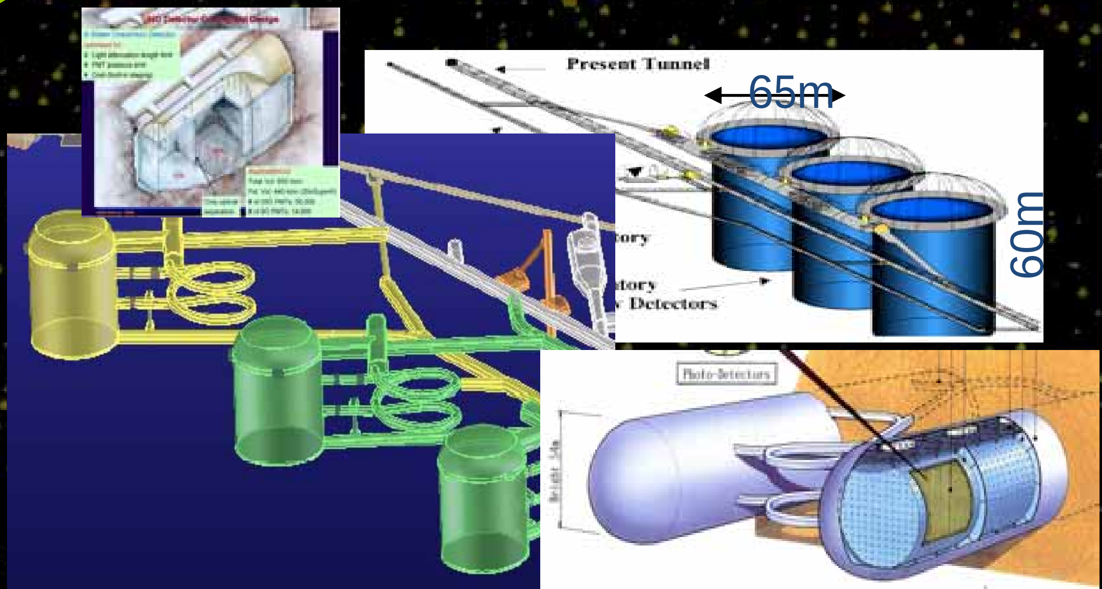
COMPLETED
~1kton

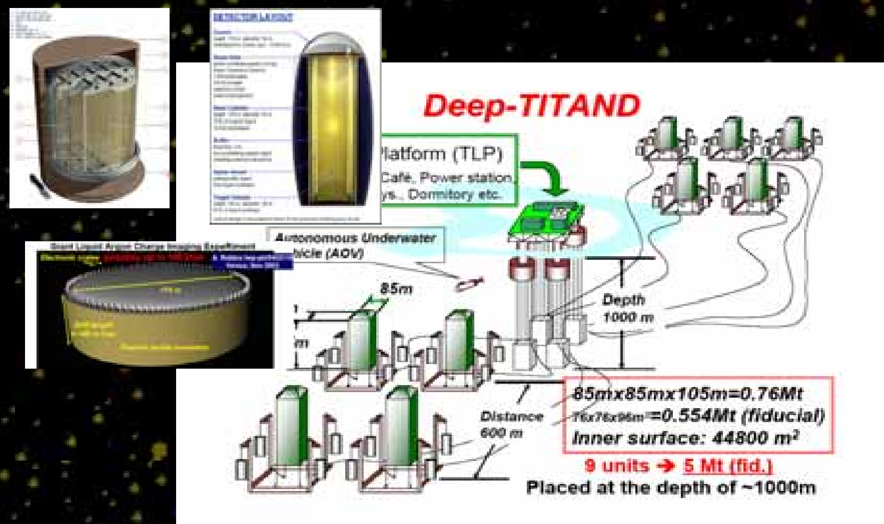
—	IMB I,II,III	WaterCh.	3.3kton
—	Frejus	Iron Cal.	0.7kton
—	Kamiokade I,II,(III)	WaterCh.	1.0kton
—	Soudan II	Iron Cal.	1.0kton

Super-K gives most stringent limits on many decay modes.
→this talk will cover
- *what has been achieved/developed in ~10yrs*
- *what will (may) happen in future*

RUNNING
Super-K 22kton

FUTURE (20??~)
- ~500kton WC
- ~100kton LAr, Liq.scinti
- ~5Mton WC





Sensitivity

$$\text{lifetime limit} \propto \frac{\varepsilon VT}{N_{\text{limit}}} = \begin{cases} \dfrac{\varepsilon}{2.3} \times VT & \text{(BKG free)} \\ \dfrac{\varepsilon VT}{\sqrt{BVT}} = \dfrac{\varepsilon}{\sqrt{B}} \times \sqrt{VT} & \text{(BKG dominant)} \end{cases}$$

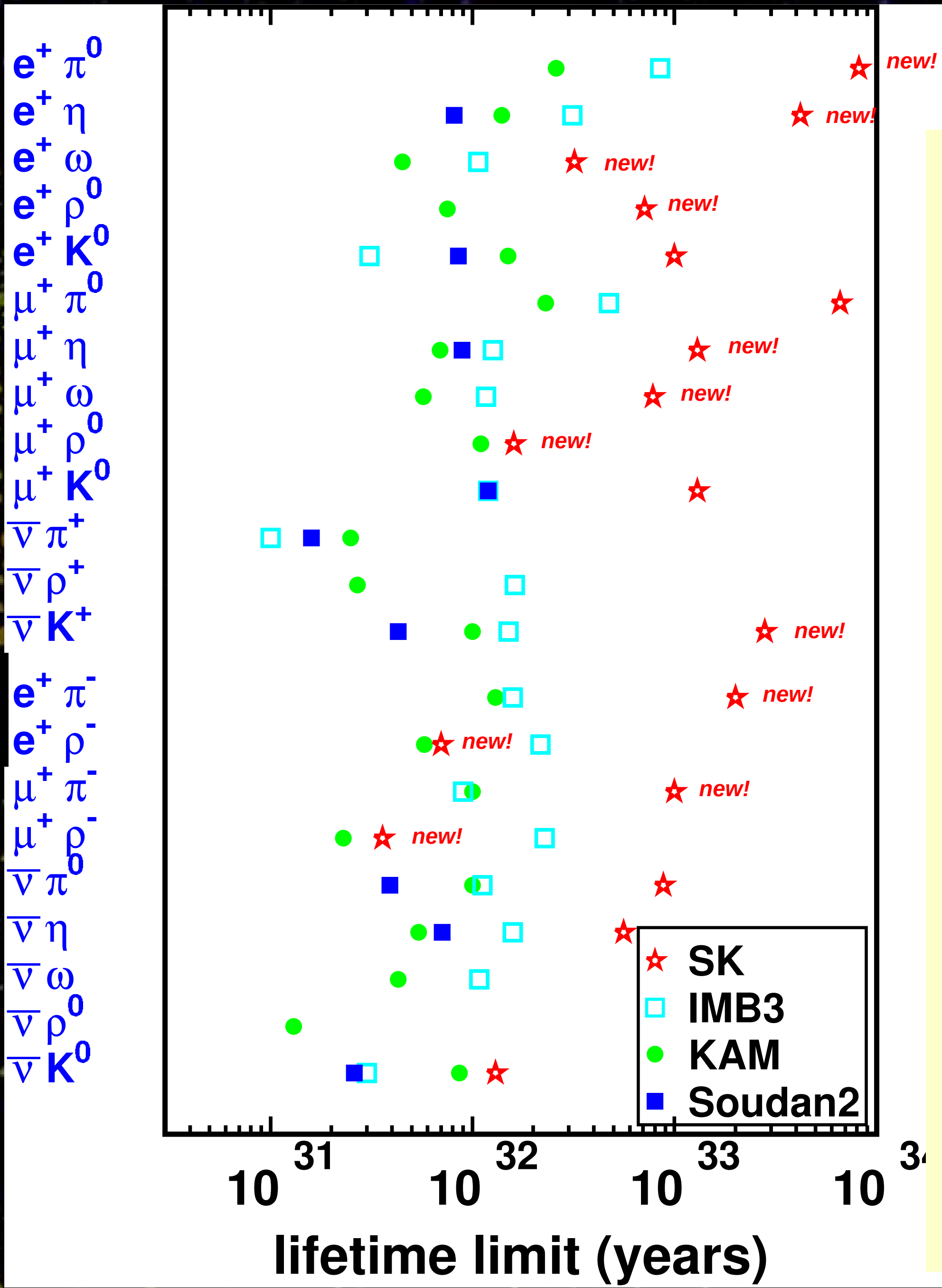
- *Background rate*
  - *Improved BKG rejection is required as size of detectors scales up (Super-K, Next generation detectors)*
  - *Improved knowledge of BKG is required to extract convincing signal (or convincing BKG subtraction in limit)*
  - *Keep signal efficiency high*

- *What has been developed in past? What can be improved in future?*

Experimental limits on proton lifetime

Proton decay

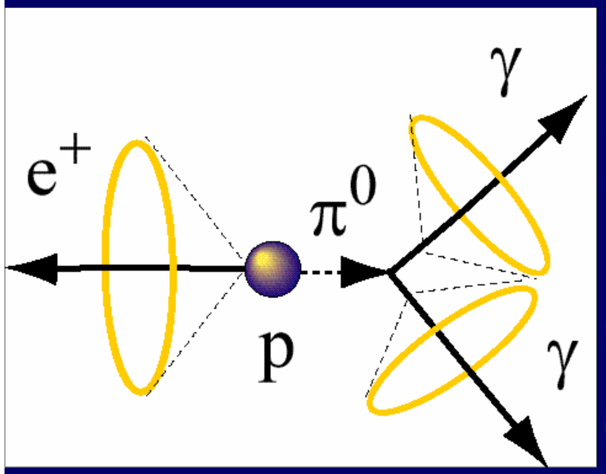
Neutron decay



analyzed 173ktyr data (SK-I+II+III)

- ***p → e+π⁰***
  - ***just reached to 10^{34} yrs***
- ***p,n → (e^+ or μ^+) + (π,η,ρ,ω)***
  - ***many modes updated***
- ***SUSY favored p → νK^+ updated***
- ***K^0 modes, $\nu\pi 0$, $\nu\pi$+ to be updated***
- ***Super-K has searched only for favored modes and got most stringent limits of O(10^{32})~O(10^{34}) years***
- ***It is important to test many decay modes***
  - ***radiative decays***
    - ***p → (e^+,μ^+)+γ***
  - ***invisible decays***
    - ***n → $\nu\nu\nu$***
  - ***neutron-antineutron oscillation***
  - ***di-nucleon decay (|ΔB|=2)***
    - ***pp → ?***
    - ***pn → ?***
    - ***nn → ?***

History of $p \to e^+ + \pi^0$ searches



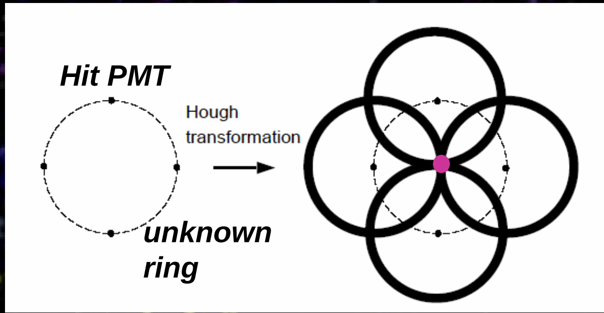
	ε x B_{meson}	BKG (/Mtonyr)	BG (/yr)
IMB3	0.48	26	0.087
KAM-I	0.53	<15	<0.015
KAM-II	0.45	<8	<0.008
Super-K	0.44	2.1	0.047

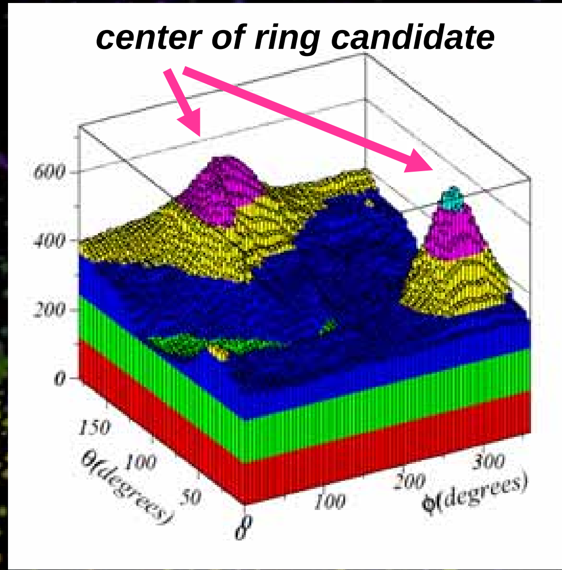
- past
  - IMB3: loose light pattern cuts, semi-automatic track fit, no particle ID, no π^0 mass cut
  - KAM-II: perform ring (track) fit but by an interactive graphic display

- Super-K
  - Full automated reconstruction has been developed
    - x_i, p_i(each ring), e or μ(each ring), muon-decays
    - full kinematics cuts: vertex, Nring, particle ID, π^0 mass, proton mass, proton momentum, muon-decays

Cherenkov ring fit

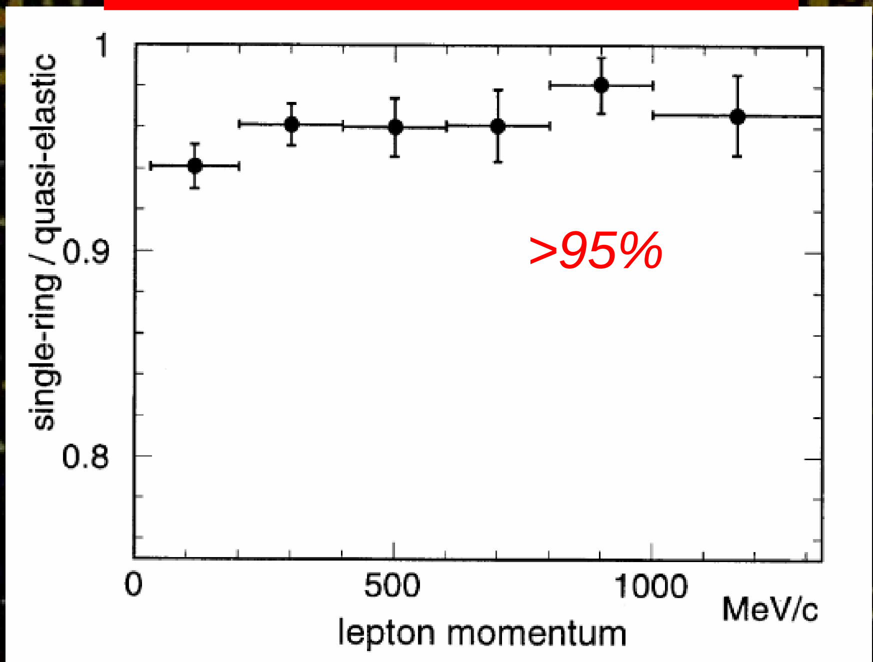
Hough transformation



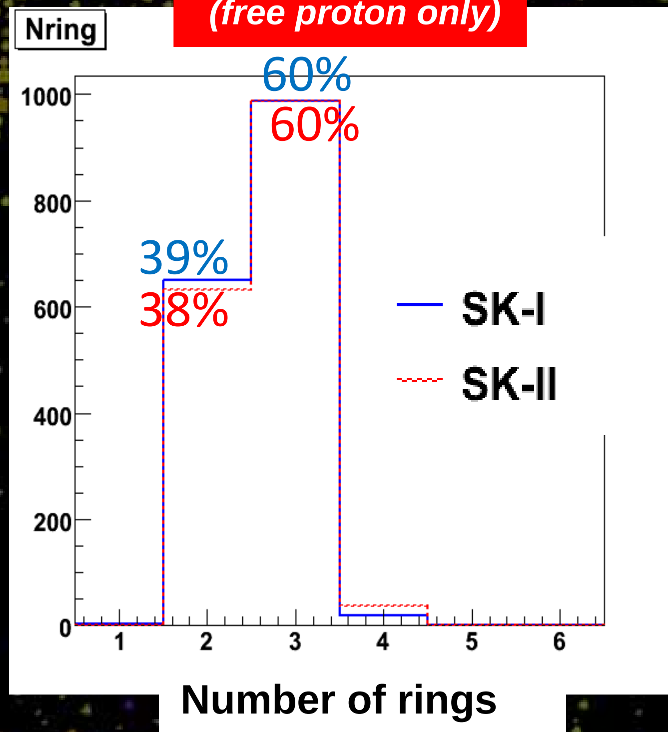


Test by likelihood method to select/reject the ring candidates

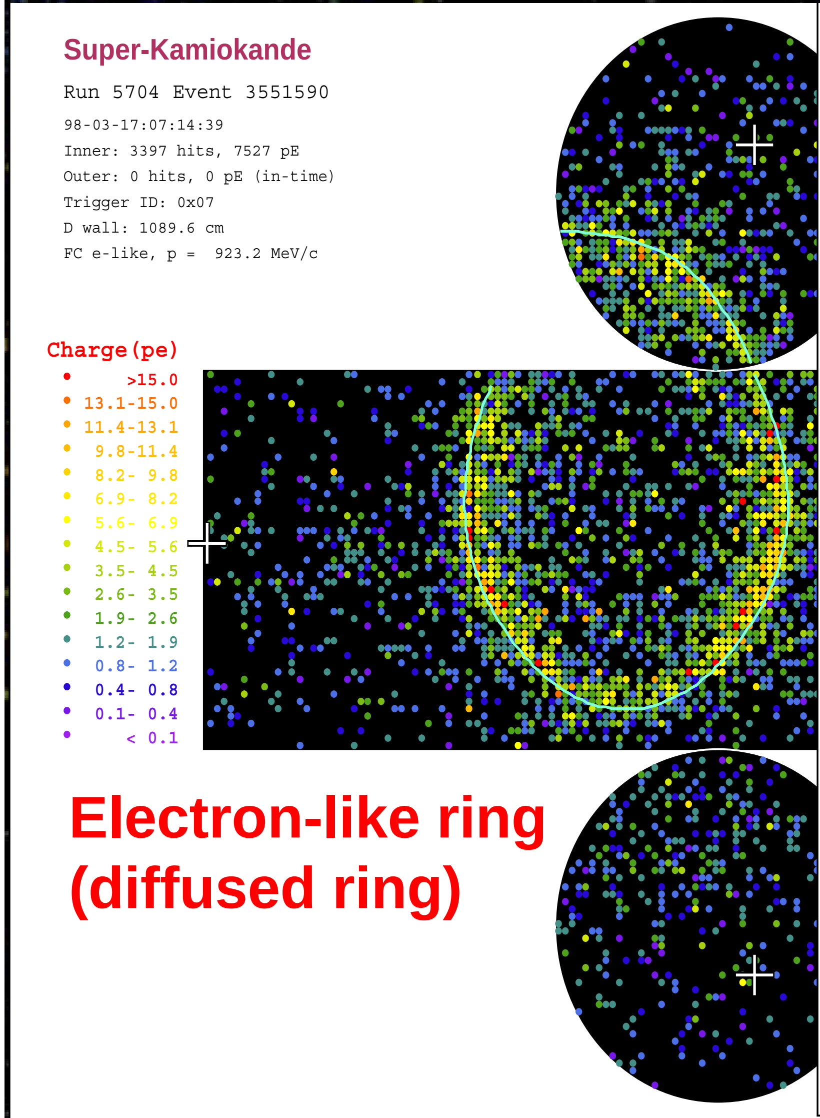
single-ring efficiency for quasi-elastic

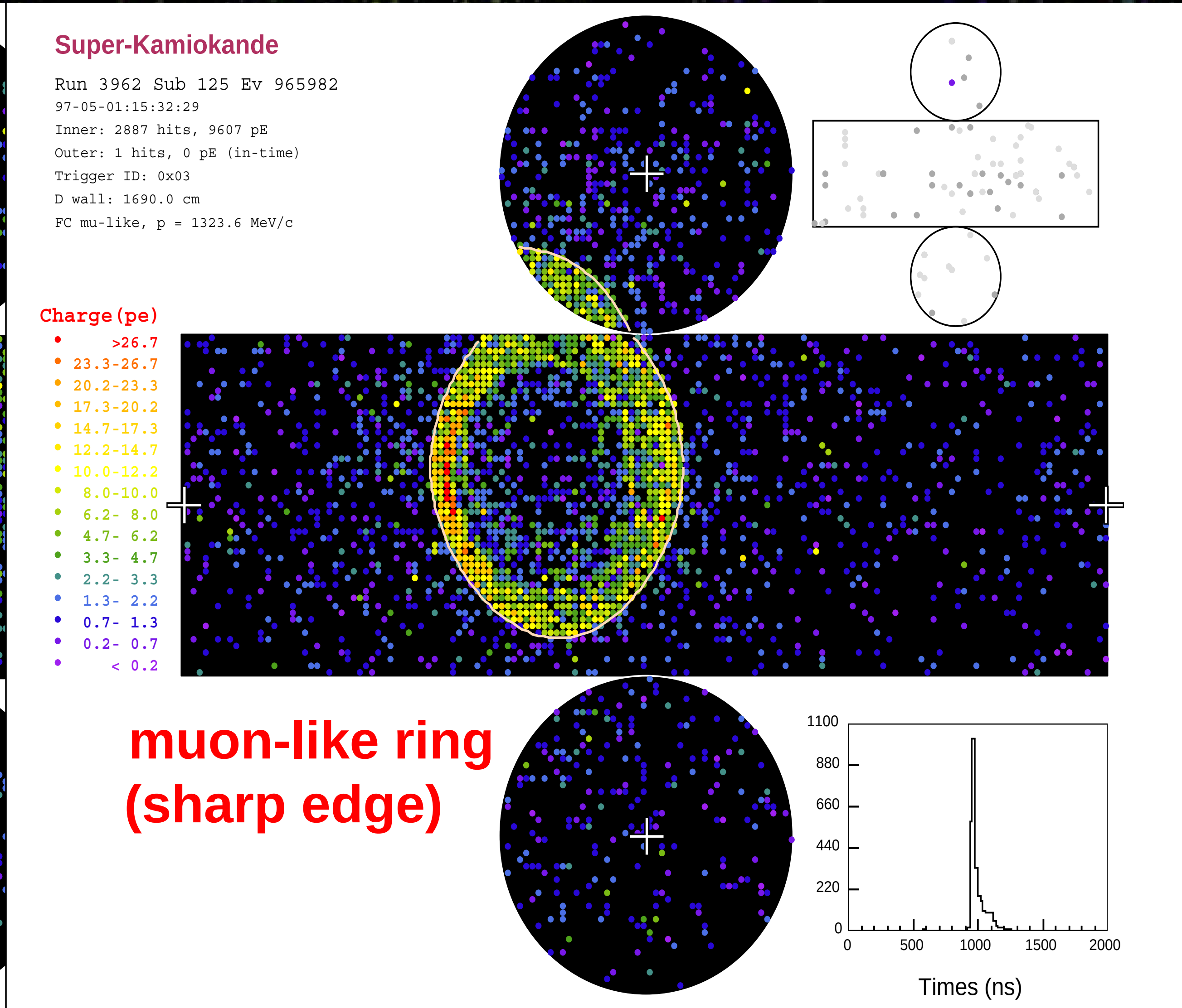


$p \rightarrow e^+ + \pi^0$ MC (free proton only)

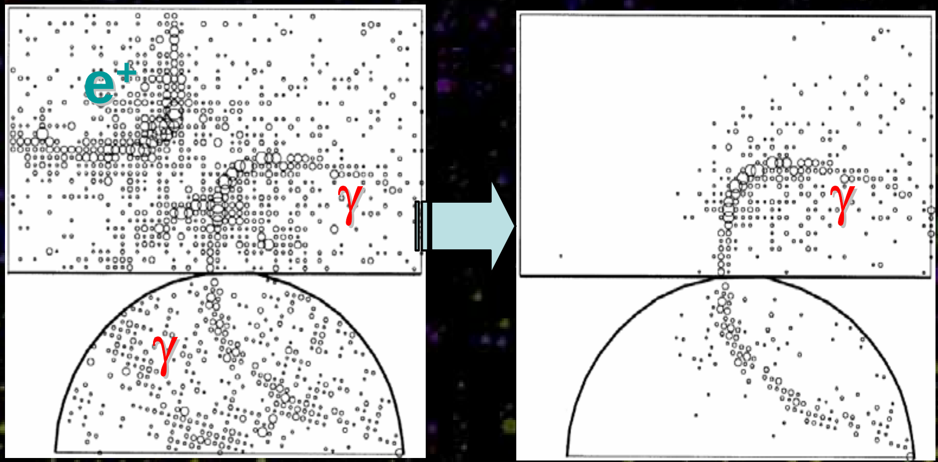


Particle ID and the number of Cherenkov rings





Charge separation



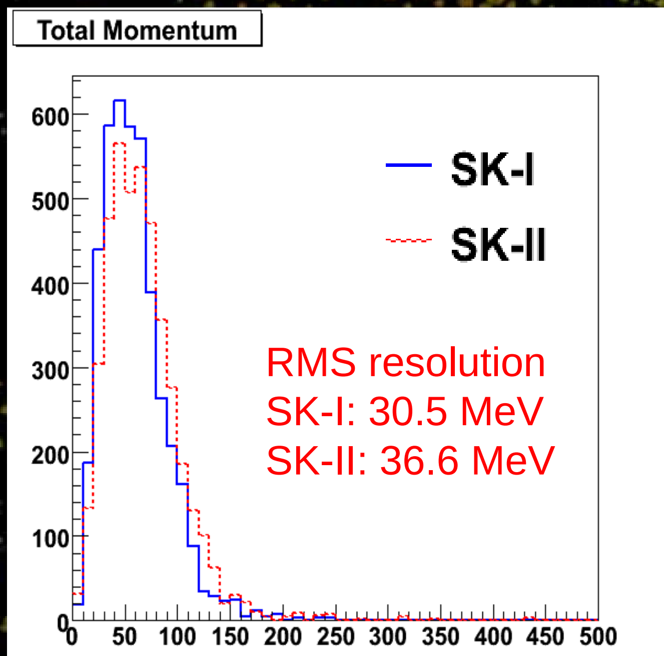
$$\text{For each PMT}, Q_{obs} = \sum_{rings} q_{ring} \qquad q_{ring} = R_{ring} \bullet Q_{obs}$$

Fraction of p.e.s in each PMT due to each ring (R_{ring}) is determined carefully by expected spatial light distribution taking into account;

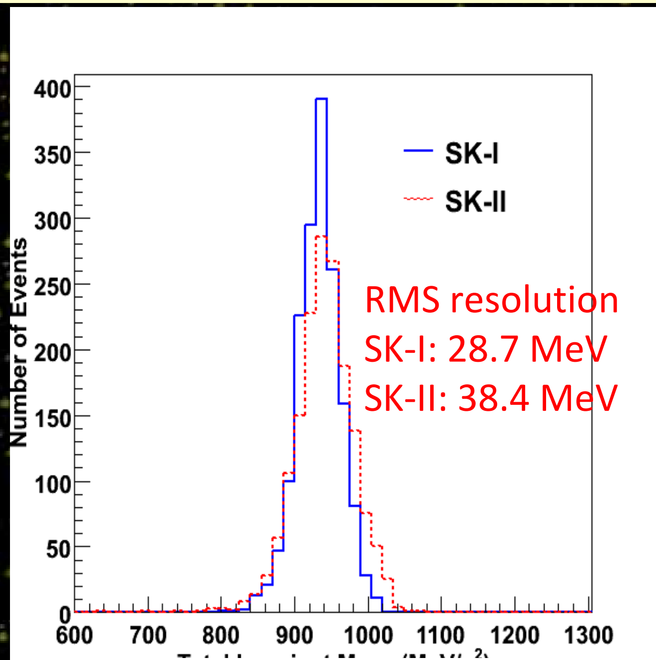
- γ's vertex position (γ's conversion length)
- Scattered light in the water
- Reflected light on the wall (differ for SK-I and II)

q_{ring} → Momentum of each ring
→ Ptot, Etot, Mtot of the event

p→e$^+$+π^0 MC
(free proton only)



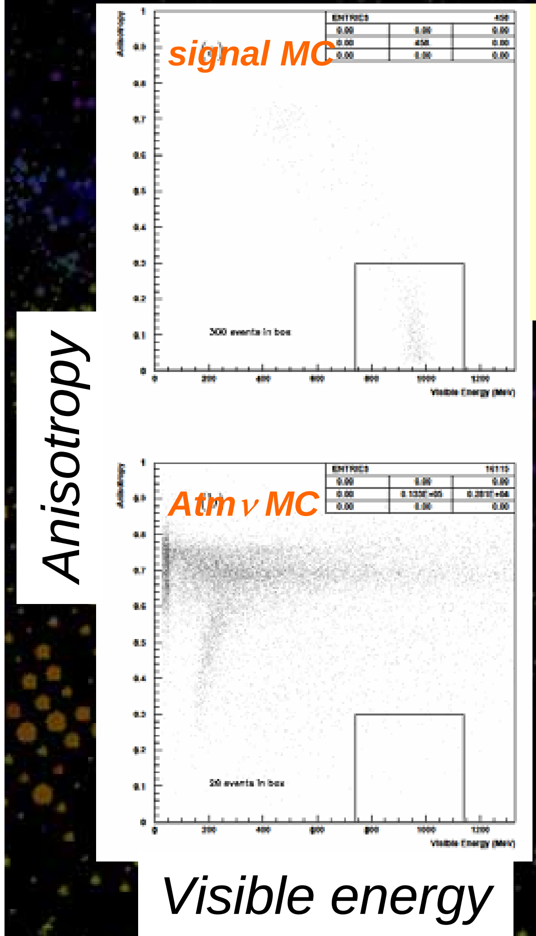
Total Momentum (MeV/c)



Invariant Mass (MeV/c^2)

First result on $p \rightarrow e^+ \pi^0$ in Super-K

PRL81,3319(1998)

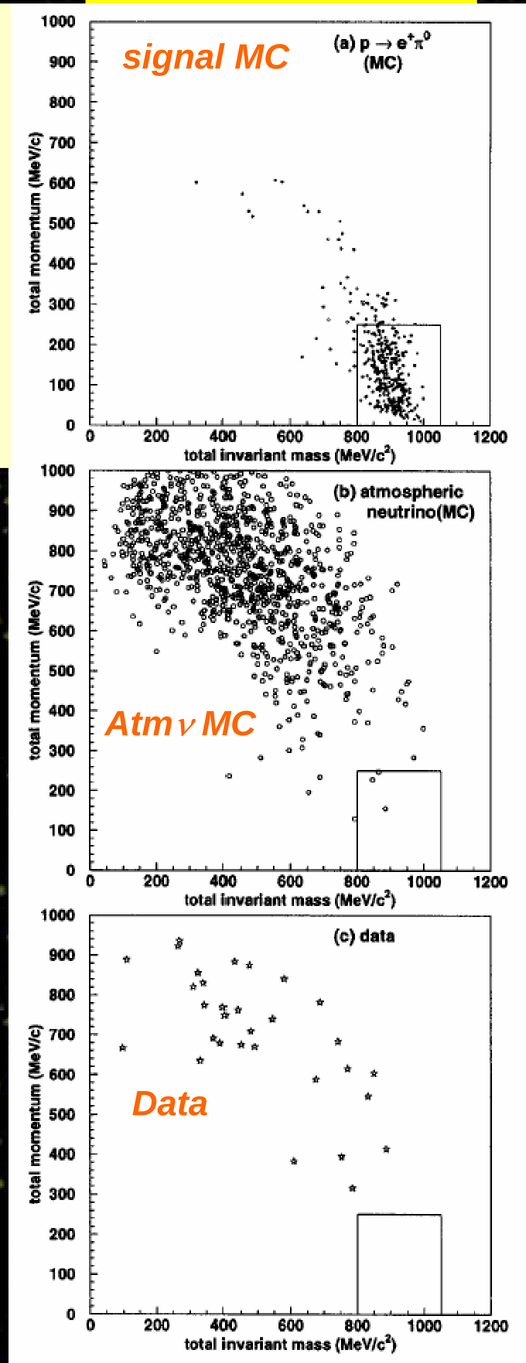


Anisotropy cut (IMB-3)

- No decay electron
- 738 < Evis < 1138 MeV
  Anisotoropy of photons < 0.3

Super-K cut

- 2 or 3 Cherenkov rings
- All rings are showering
- $85 < M_{\pi 0} < 185 MeV/c^2$ (3-ring)
- No decay electron
- $800 < M_{proton} < 1050 MeV/c^2$
  $P_{total} < 250 MeV/c$



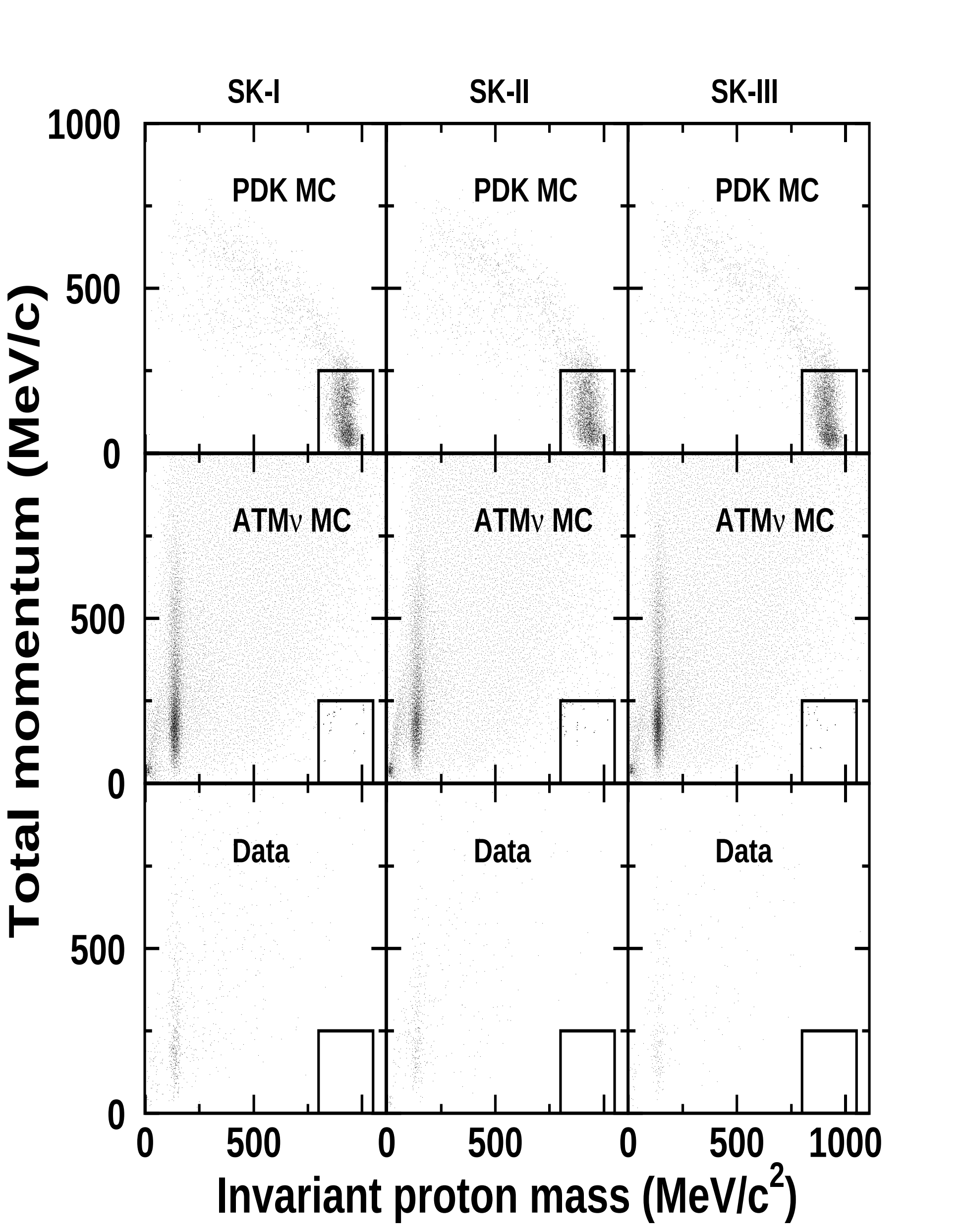
@ Super-K-I 25.5ktyr

- Anisotropy cut
  - 4 events observed
  - 3.5 / 25.5 ktyr exp'd BKG
- Super-K cut
  - No candidate
  - 0.1 / 25.5ktyr exp'd BKG
- $\tau_p / B_{p \rightarrow e+\pi 0} > 1.6 \times 10^{33}$ yrs

Kinematics cuts are powerful to reject BKG

Latest $e^+\pi^0$, $\mu^+\pi^0$ results

Updated from PRL102,141801(2009)



173kton year exposure (SK-I + II + III)

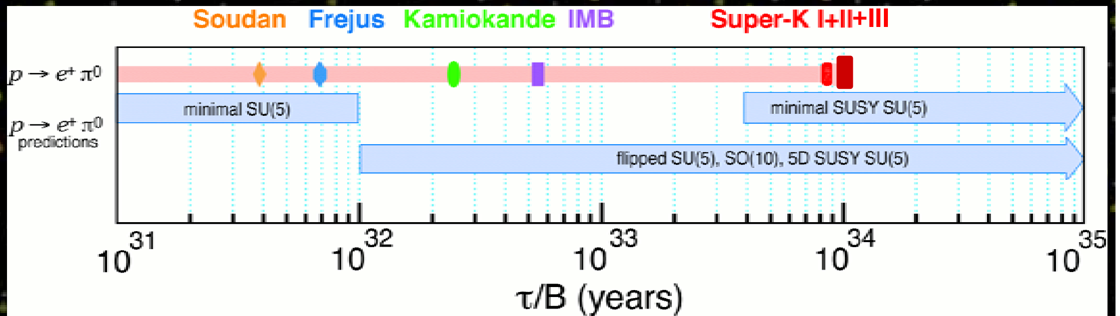
$p \rightarrow e^+\pi^0$

- **1.0 x 10^{34} years (@90%C.L.)**
  - previous limit by IMB: **8.5 x 10^{32} years**
  - previous limit by KAM: **2.6 x 10^{32} years**

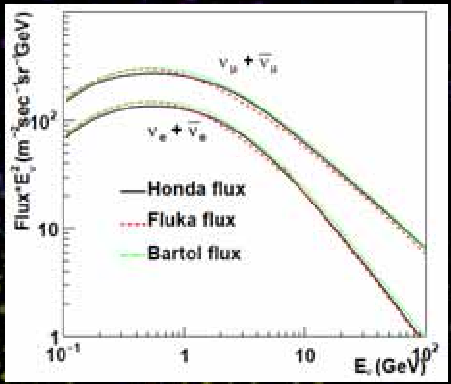
141kton year exposure (SK-I + II)

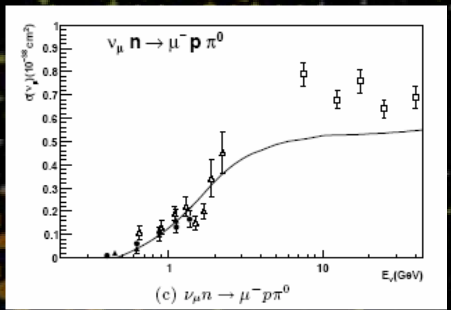
$p \rightarrow \mu^+\pi^0$

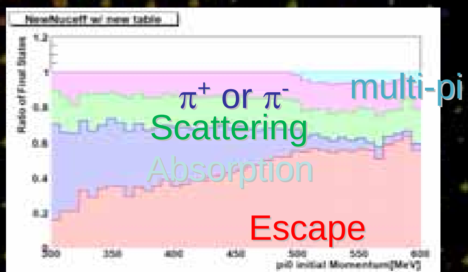
- **6.6 x 10^{33} years (@90%C.L.)**
  - previous limit by IMB: **4.7 x 10^{32} years**
  - Previous limit by KAM: **2.3 x 10^{32} years**

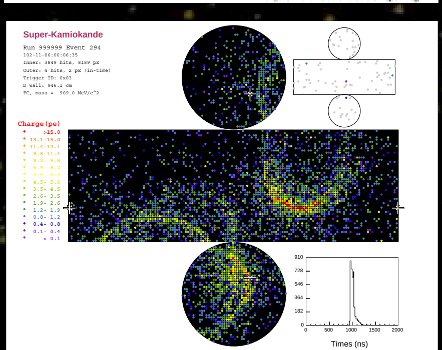


Elements of BKG estimation and their contribution to eπ^0 BKG uncertainties









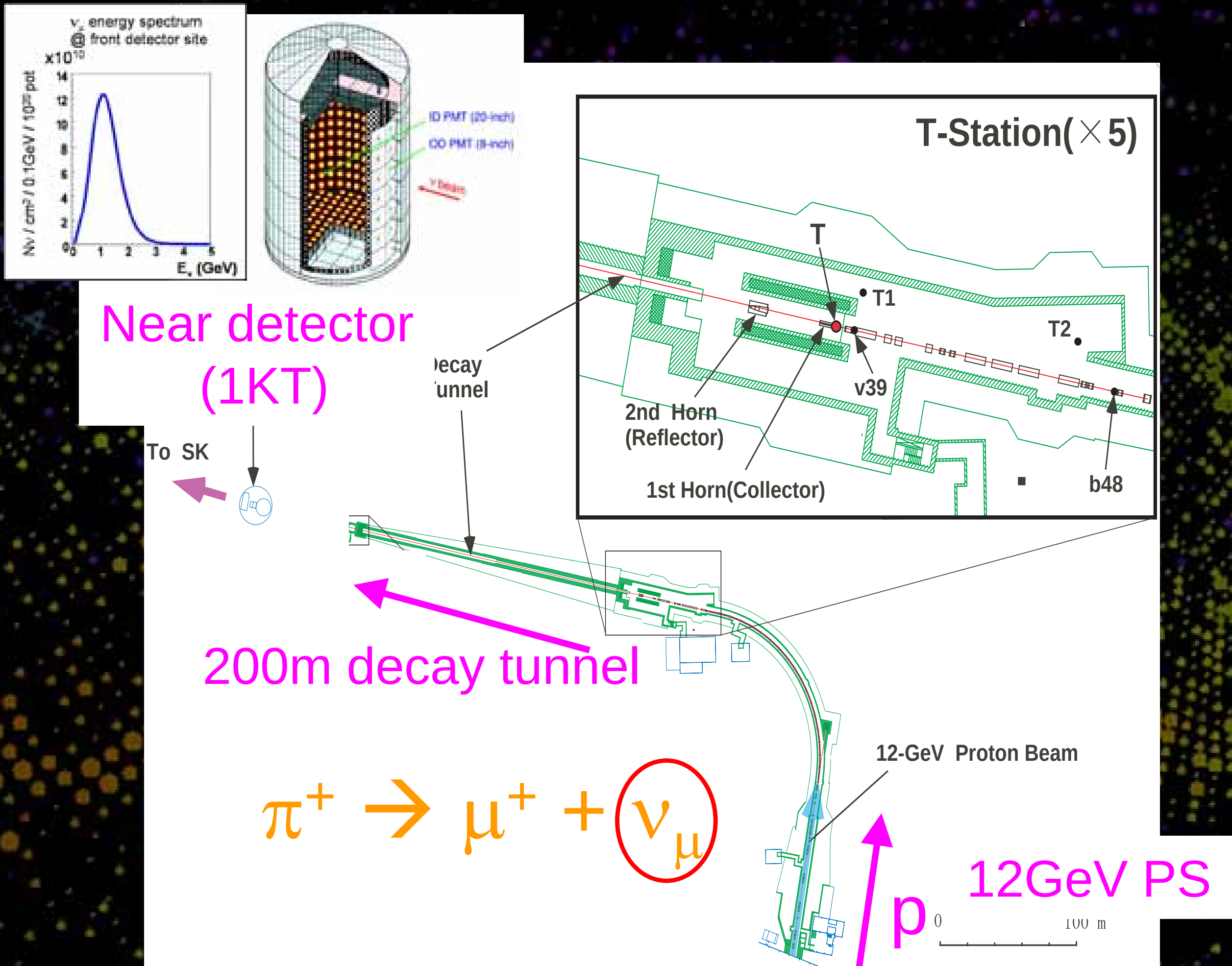
– 30% CC single π0
– 20% CC multi π prod.
– 30% CC QE + π0 by 2ndary interaction
– 20% NC

- Atmospheric ν flux calculations
  - Spectrum shape ~8%
  - Flavor ratio <1%
- Neutrino interaction simulation (NEUT)
  - CC single π^0 10%
  - CC multi pion production 7%
  - CC QE 8%
  - NC 2%
- 2ndary pion interaction in water 25%
- 2ndary nucleon interaction in water 25%
- Detector resolution 22%

$$\text{estimated BKG for } p \to e^+\pi^0$$
$$= 2.1 \pm 0.3(stat.) \pm 0.8(syst.)\,(Mtonyrs)^{-1}$$

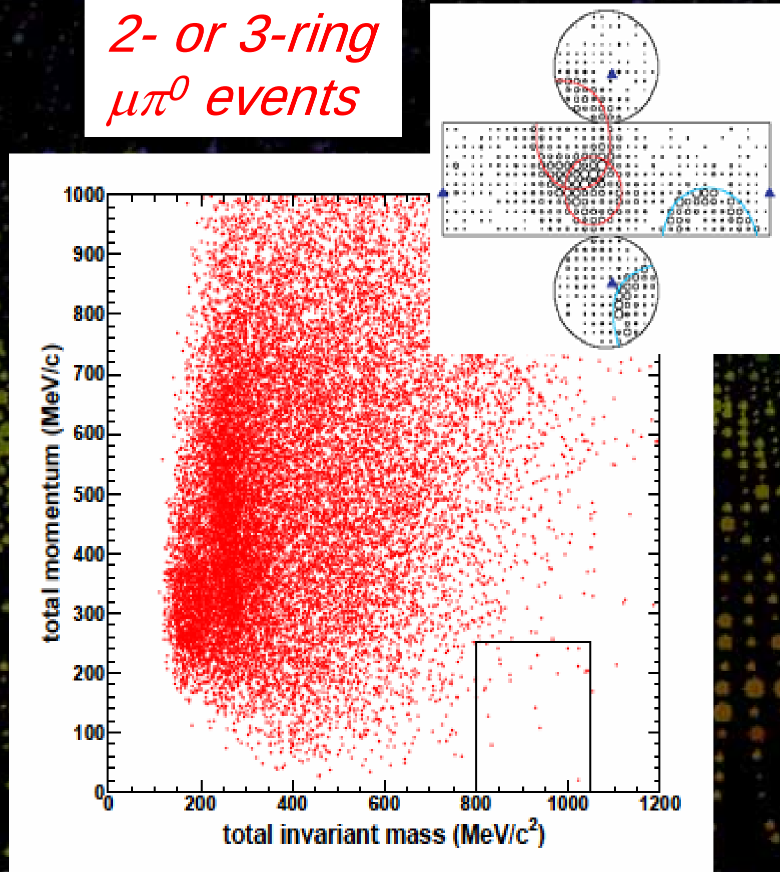
Direct BKG measurement by K2K beam

PRD77:032003,2008



$\pi^+ \rightarrow \mu^+ + \nu_\mu$

2- or 3-ring $\mu\pi^0$ events



$\mu\pi^0$ converted to $e\pi^0$ assuming lepton universality

K2K ($p \rightarrow e^+ + \pi^0$ BG by $E\nu$<3GeV)
1.63 +0.42/-0.33(stat.) +0.45/-0.51 (sys.) events/Mton-years

NEUT+SK simulation, Eν<3GeV
1.8 +/- 0.3(stat.) events/Mton-years

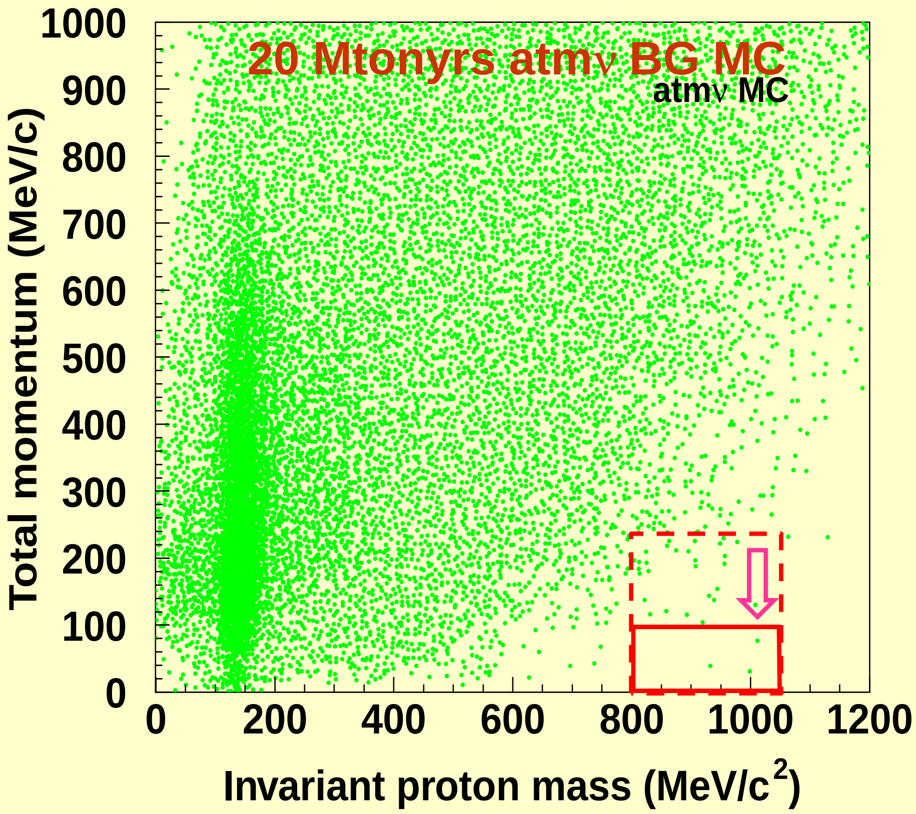
Background reduction for $p \rightarrow e^+\pi^0$ (tighter momentum cut)

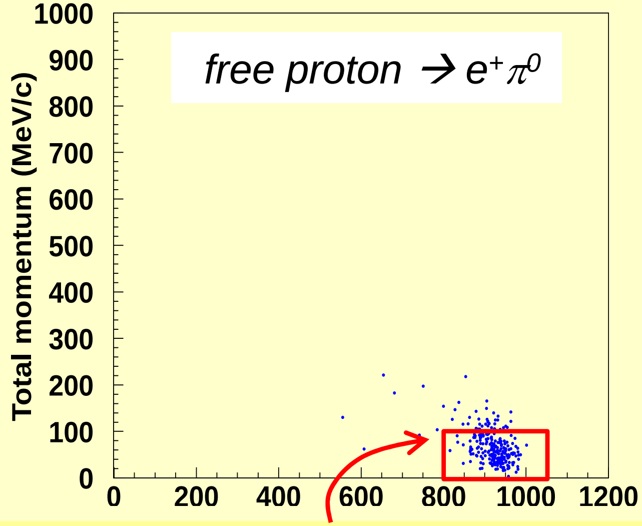
Shiozawa, talk@NNN00-Fermilab

- Ptot < 250 MeV/c (SK cut)
  BG=***2.2*** ev/Mtonyrs, eff.=***44%***

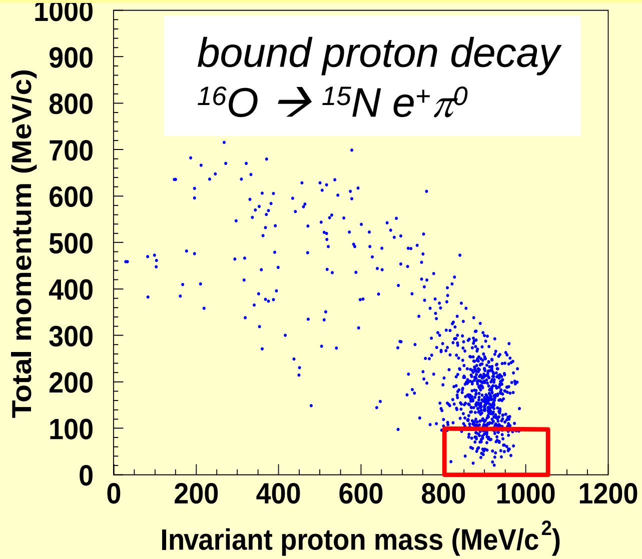
⇩ *BG reduction by ~15*

- Ptot < 100 MeV/c (tighter cut)
  BG=***0.15***ev/Mtonyrs, eff.=***17.4%***





main target is *free proton decays*



Further BG reduction by neutron?

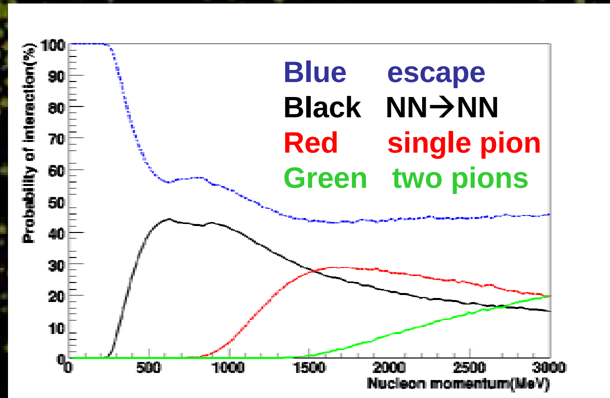
Beacom and Vagins PRL93:171101(2004)

Many BG are accompanied by neutrons

Background events for $p \to e^+ \pi^0$ (4.5Megaton years)		
	ν interactions	secondary interactions in water
1	$\nu n \to e^- p \pi^0$	Neutron production by the proton
2	$\nu p \to e^- p \pi^+$	Neutron by π^+
3	$\nu p \to e^- p (\pi^+) \pi^0$	
4	$\nu n \to \nu p \pi^- \pi^0$	
5	$\nu n \to e^- p$	Neutron by the proton
6	$\nu n \to e^- n \pi^+ \pi^-$	
7	$\nu p \to e^- p (\pi^+) \pi^0$	
8	$\nu p \to \nu p \rho$	
9	$\nu O \to e^- O \pi^+$	Neutron by π^+
10	$\nu n \to n \rho$	neutron and π^- by the neutron

More *n* should be there because

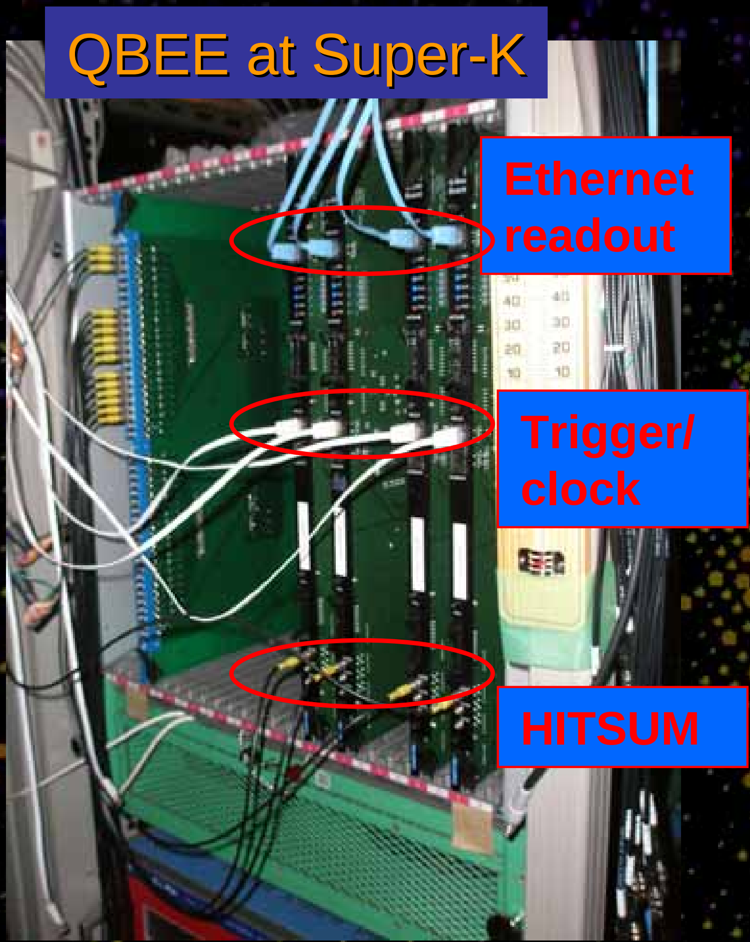
- Secondary interactions of protons in residual nucleus;
  $pp \to pp$, $pn \to pn$, $pn \to np$
  sometimes produce neutrons (not simulated)

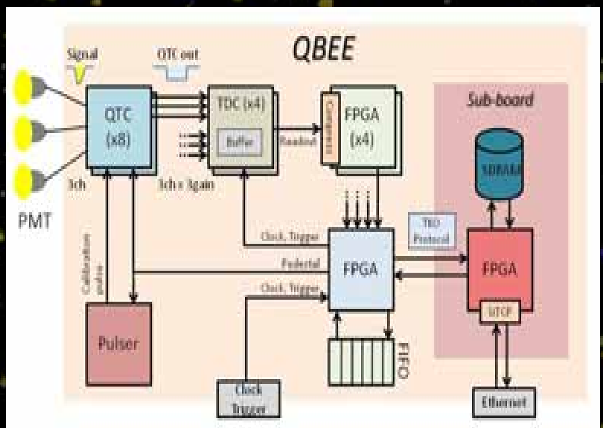


- π^+ or π^- absorbed by medium will cause particle (neutron) emission (not counted)

Further BG reduction is possible if WC detector can tag neutrons.
(need studies by experimental tests and full MC simulation)
Fraction of BG accompanied by neutron is roughly ~90%.

Neutron tagging started in SK-IV





We have replaced SK electronics with new *high speed pipelined electronics system* in 2008.

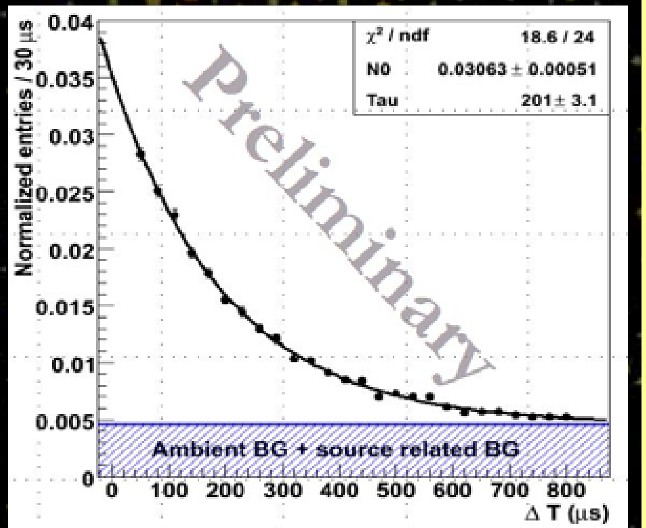
→

start recording faint neutron signature;

n+p→d+γ**(2.2MeV)**

τ~200μs

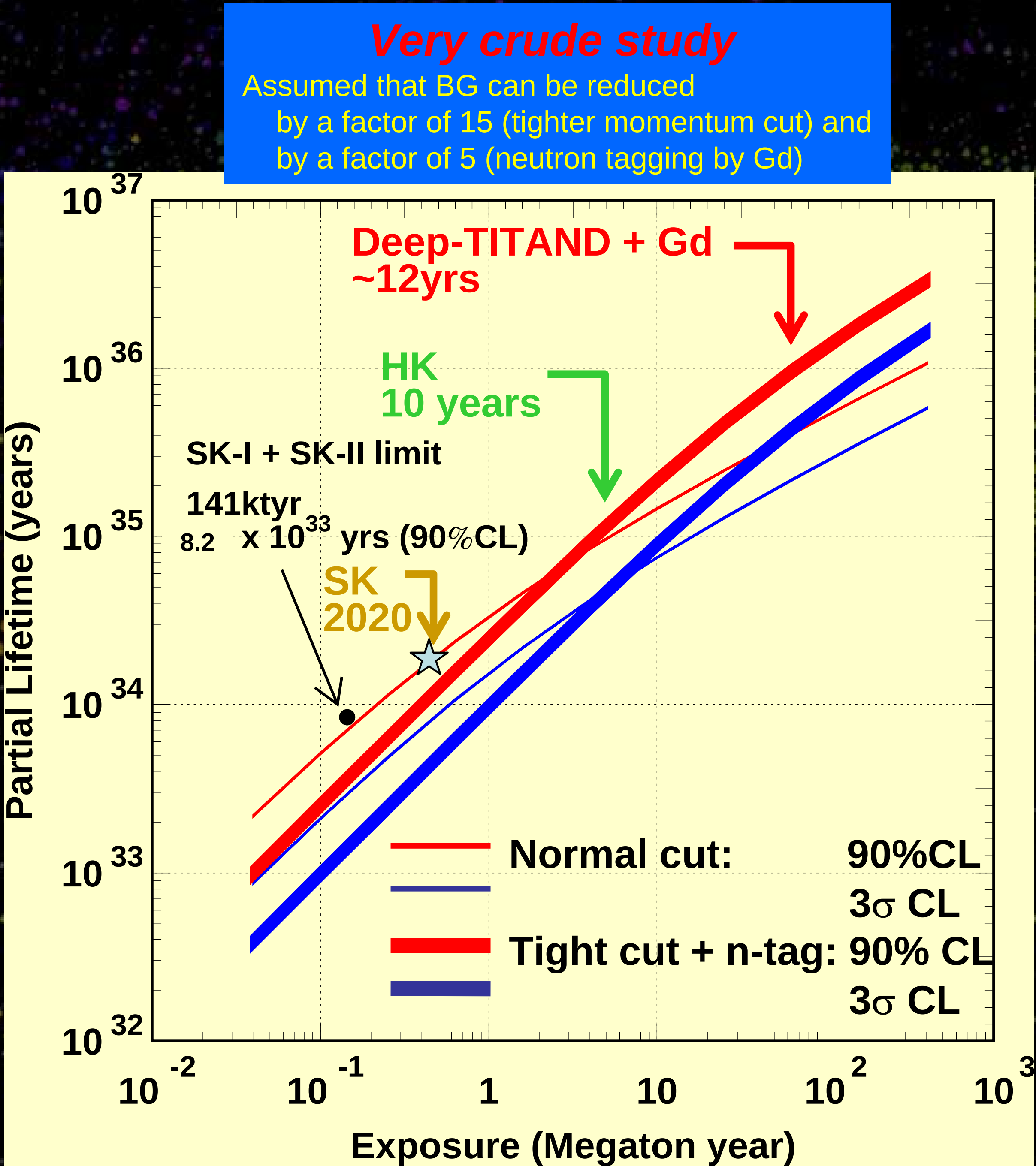
Test data @ SK-IV



Detection eff.(np→dγ) is small ~20% (measured at SK).

But we can study neutron production probability in atmospheric ν interactions.

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



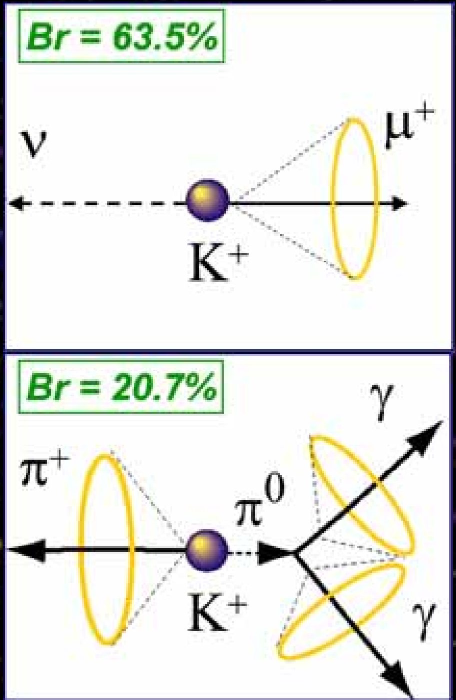
SK(0.022 Mt):2009
→
1.0×10^{34} yrs @ 90% CL

SK(0.022 Mt):2020
→
2×10^{34} yrs @ 90% CL

HK(0.5 Mt):10years
→
~10^{35} yrs @ 90% CL

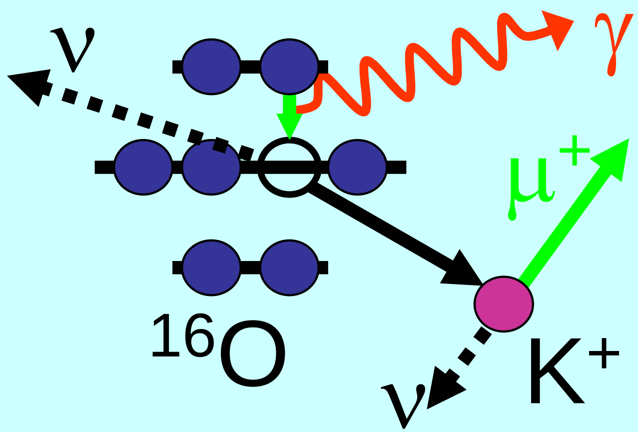
10^{36} yrs @ 90% CL
→
Deep-TITAND(5 Mt) + Gd :~12years

History of $p \rightarrow \nu + K^+$ searches

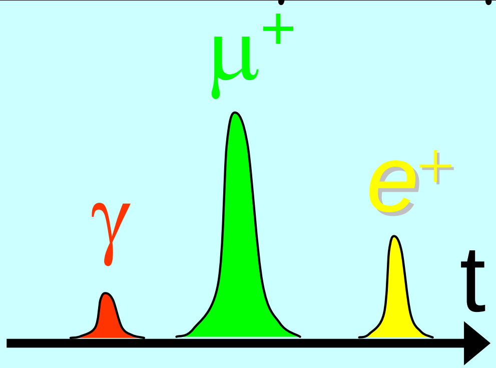


	ε x Bmeson	BKG (/Mtonyr)	BG (/yr)
IMB3	0.41	2820	9.29
KAM-I			
$K \rightarrow \mu\nu$	0.41	1500	1.5
$K \rightarrow \pi\pi$	0.10	310	0.3
KAM-II			
$K \rightarrow \mu\nu$	0.51	1800	1.8
$K \rightarrow \pi\pi$	0.10	200	0.2
Super-K			
$K \rightarrow \mu\nu$	0.36	2000	45
$K \rightarrow \mu\nu$ +pγ	0.072	1.7	0.038
$K \rightarrow \pi\pi$	0.062	4.7	0.11

NEW technique



$^{16}O \rightarrow \nu K^{+15}N\gamma$, $K^+ \rightarrow \mu^+\nu$



history of gamma tagging

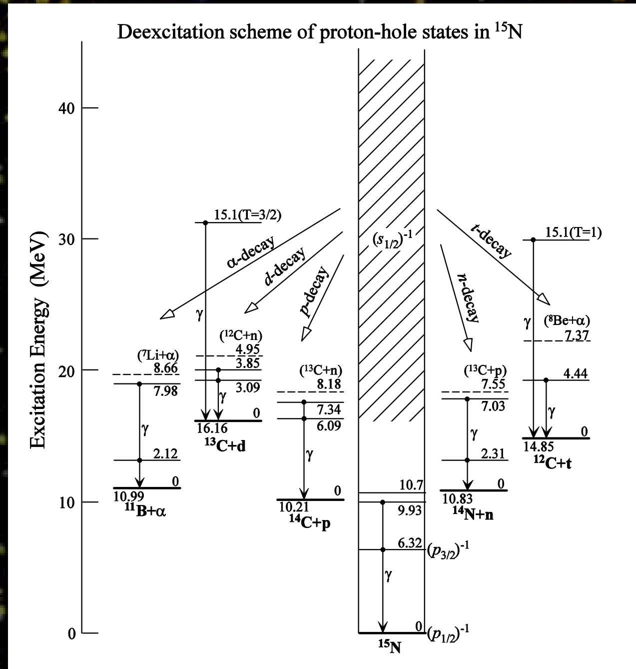
First discussion by Prof. Totsuka in 7th Workshop on Grand Unification '86

parent vertex. How does one get the parent vertex position for νK_L^0 reactions? If a nucleon in ^{16}O nuclei decays, half of the remaining ^{15}O or ^{15}N are left in the excited states which rapidly decay and produce ~ 6MeV γ rays. This 6MeV γ defines the parent vertex (see Fig.6).

We use a similar trick for νK^+. Instead of a spatial gap, a time gap between K^+ decay signal (τ=12ns) and the 6MeV γ will be used to uniquely identify K^+.

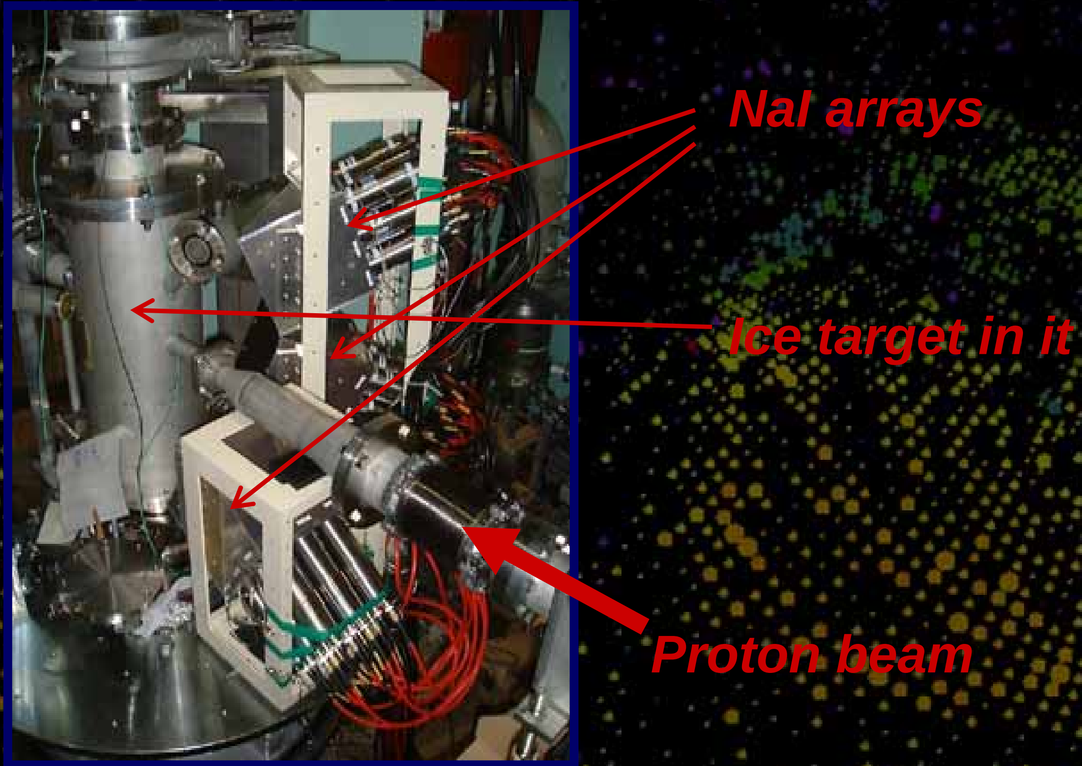
Ejiri estimated de-excitation processes in detail (PRC48,1442,'93)

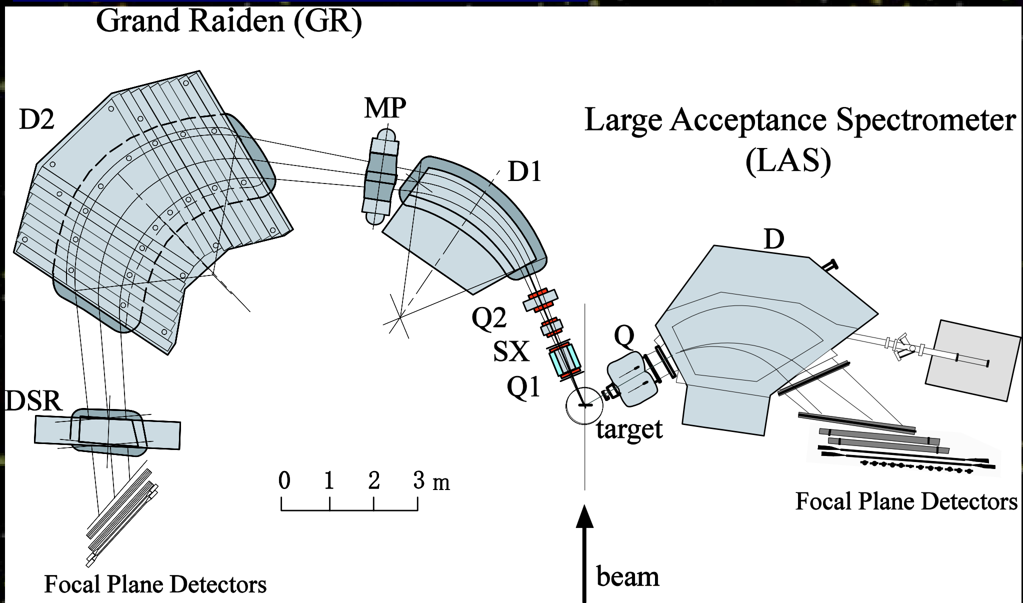
E_x (MeV)	J^π	spectroscopic factor (branching ratio) by Ejiri paper	spectroscopic factor (branching ratio) by (e,ep) reation (M.Leuschner *et al.)*
0(g.s.)	1/2	2 (0.25)	1.26 (0.158)
5.27	3/2	---	0.11 (0.014)
6.32	3/2	3.3(0.41)	2.35 (0.294)
9.93	3/2	0.26(0.03)	0.13 (0.016)



(e,ep) experiment suggests more protons in s-state.
→ Need to measure γ emission from s-state excitation

Direct measurement of de-excitation γ (RCNP E148 in Osaka)





$^{16}O(p,2p)^{15}N^*$ reaction

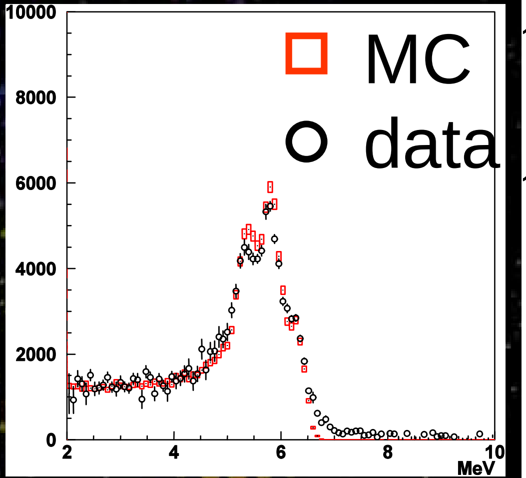
- 392MeV proton beam
- ice target

- 2 secondary protons measured by dual magnetic spectrometer system
- NaI as a γ detector
  - 51x51x151 each
  - Three 3x3-arrays (total 27)
  - 1.3 sr (10%)
  - $\Delta E/E$~2.2%@5.8MeV

gamma-ray from s-hole and p3/2

Nucl-ex/0604006

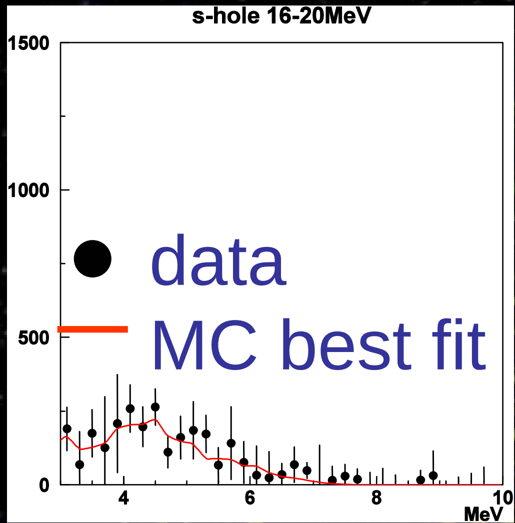
P3/2 state
4.8<Ex<6.8MeV



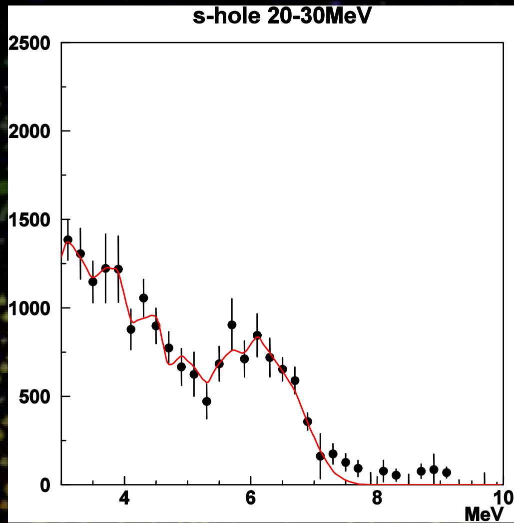
Br(γ)~100%

S-hole

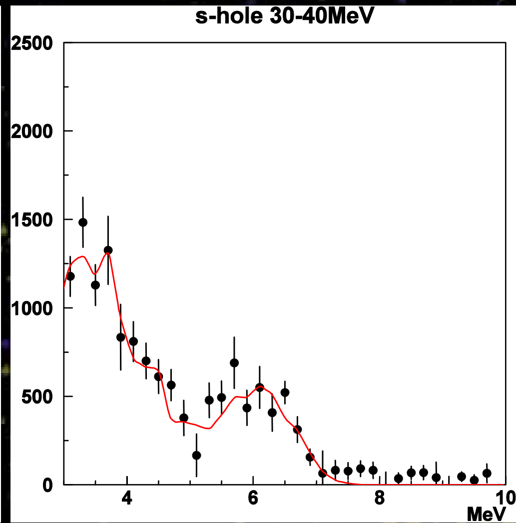
A:16<Ex<20MeV

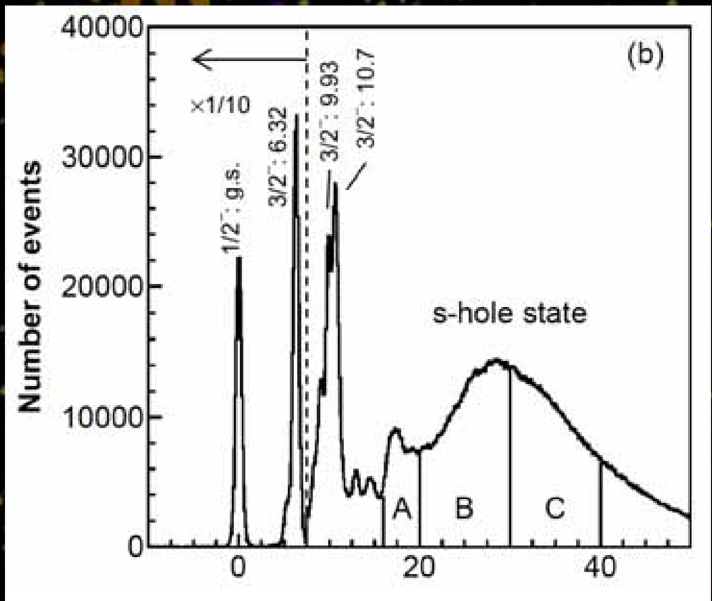


B:20<Ex<30MeV



C:30<Ex<40MeV



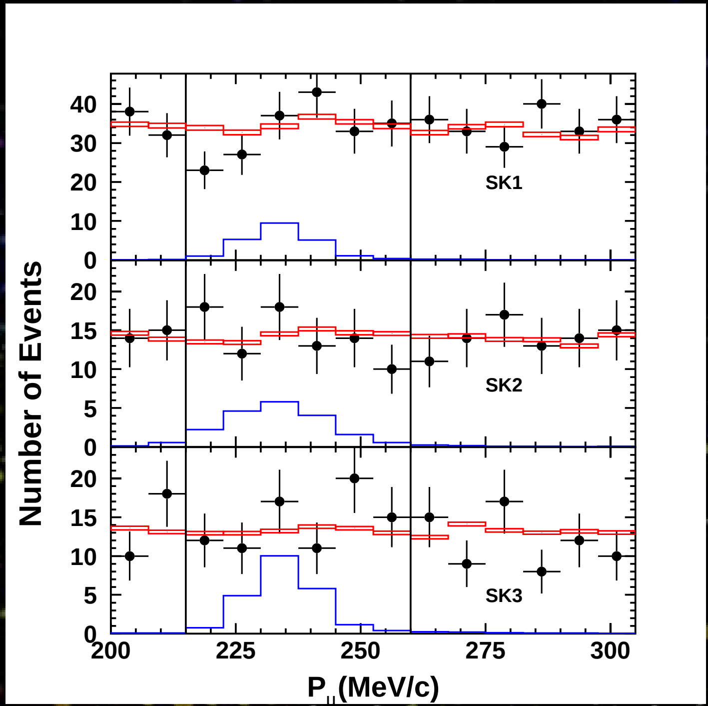


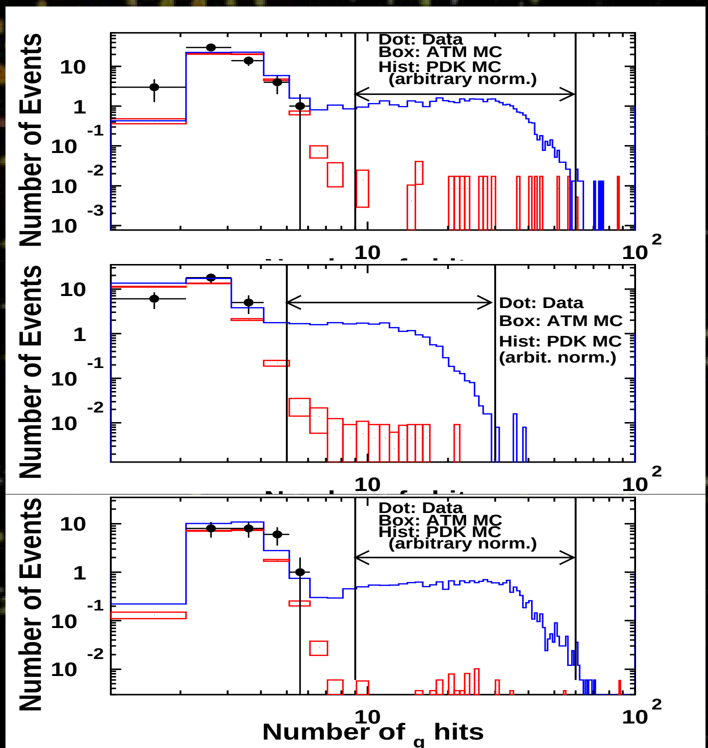
^{15}N Excitation Energy (MeV)

γ emission from s-hole state		
	Br(γ)	*P(γ)*
3<Eγ<6MeV	*27.9+-1.5+3.4/-2.6%*	*5.6%*
6MeV<Eγ	*15.6+-1.3+0.6/-0.1%*	*3.1%*

- *first measurement of γ from s-hole state*
  - *Br(γ) is as high as ~50% for s-hole state*
- *Br(γ) of Ex=6.32MeV is ~100% as is expected*

Latest $p \rightarrow \nu K^+$ result (SK-I+II+III)





173kton year exposure (SK-I + II + III)

- ***Prompt γ tagging***

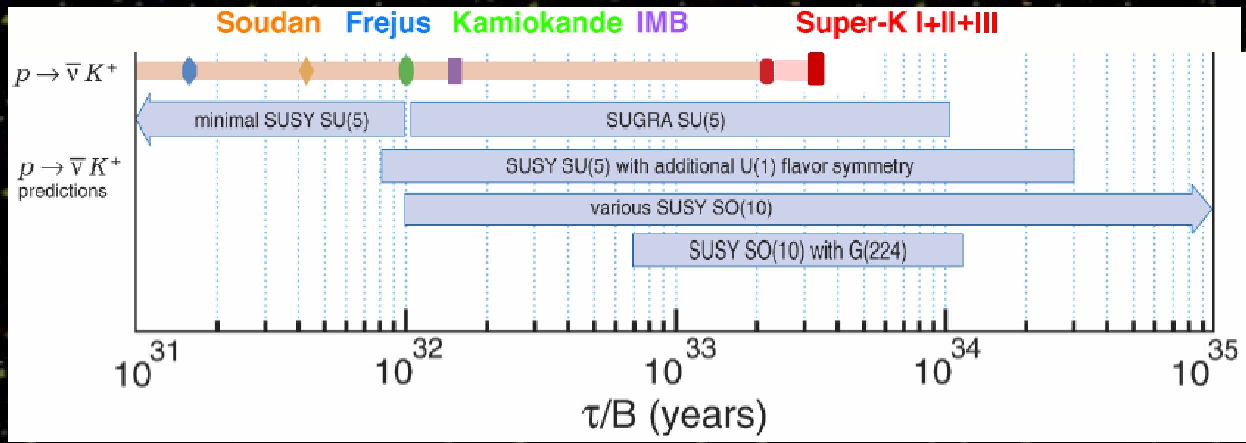
	SK-I	*SK-II (Half PMT density)*
• criteria	8 < Number of γHIT < 60	4 < Number of γHIT < 30
• efficiency	7.2%	5.8%
• background	1.7+-0.4 events / Mton-years	1.7+-0.3 events / Mton-years

- ***backward light ($K^+ \rightarrow \pi^+ \pi^0$)***

	SK-I	*SK-II (Half PMT density)*
• criteria	40 p.e. < Qback < 100 p.e.	20 p.e. < Qback < 50 p.e.
• efficiency	6.2%	4.8%
• background	4.7+-0.6 events / Mton-years	6.3+-0.7 events / Mton-years

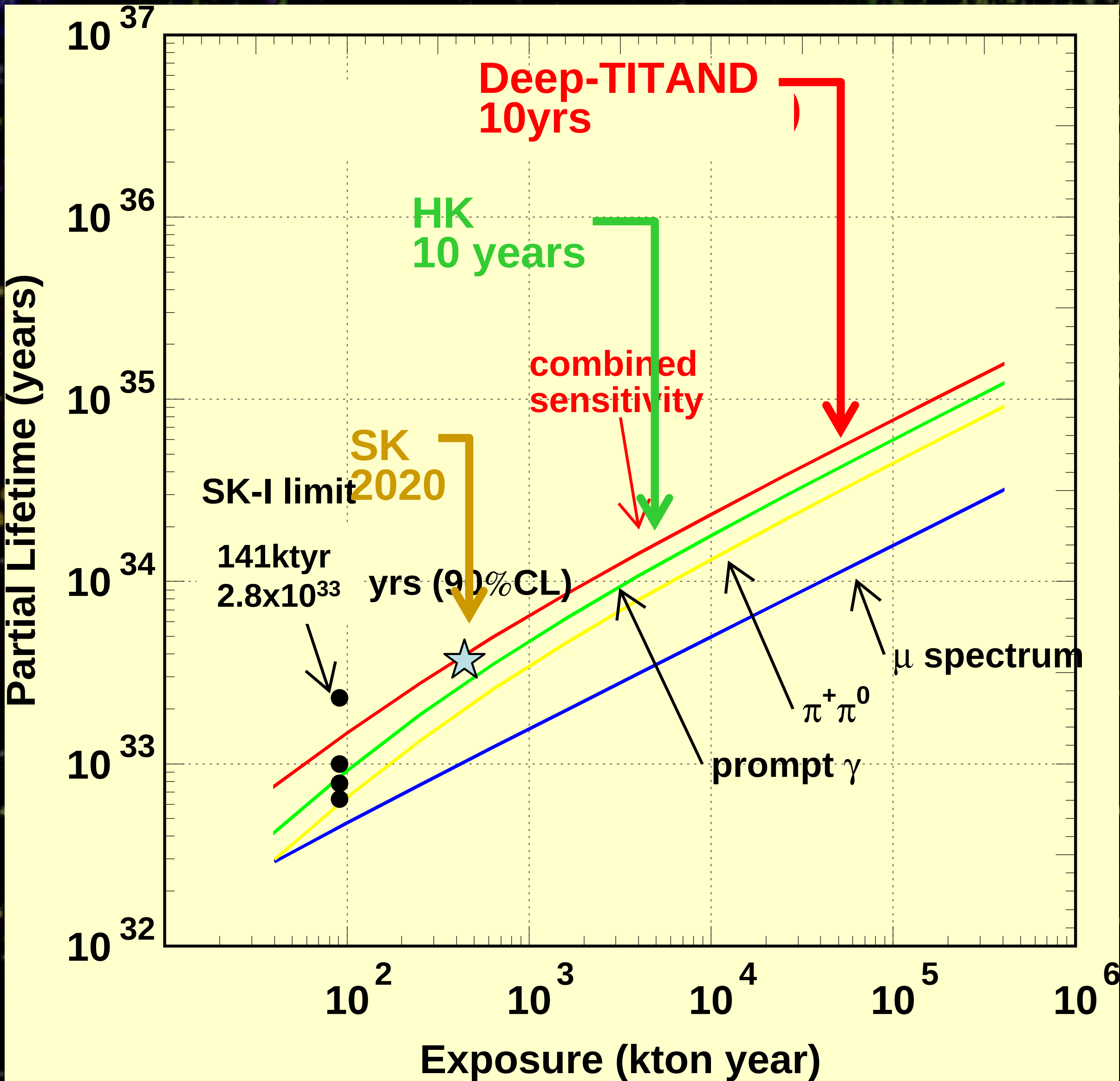
$p \rightarrow \nu K^+$

- **3.3×10^{33} years (@90%C.L.)**
  - previous limit by IMB: **1.5×10^{32} years**
  - previous limit by KAM: **1.0×10^{32} years**



$p \rightarrow \nu K^+$ sensitivity

Assume 40% PMT coverage (SK efficiency and BG rate)



SK(0.022 Mt):2009
→
3.3×10^{33} yrs @ 90% CL

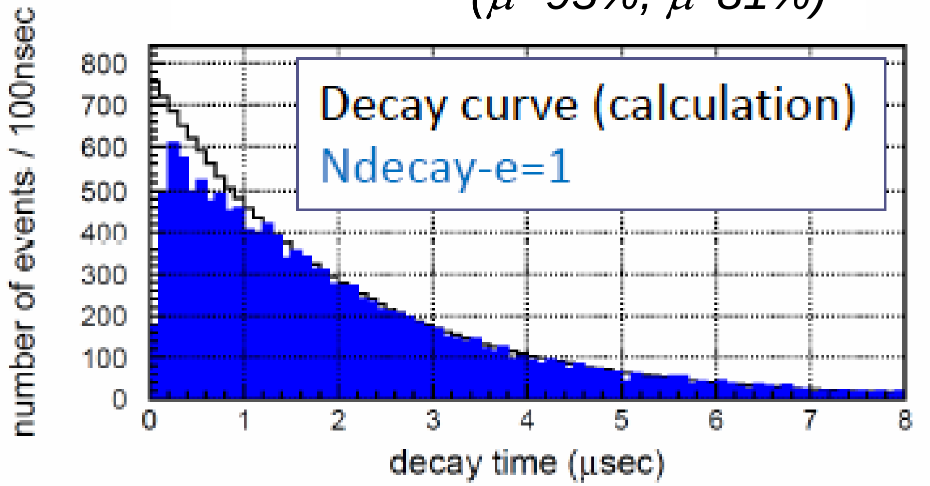
SK(0.022 Mt):2020
→
~3 $\times10^{33}$ yrs @ 90% CL

HK(0.5 Mt):10years
→
~2 $\times10^{34}$ yrs @ 90% CL

Deep-TITAND(5 Mt):
10yrs
→
7 $\times$ 10^{34} yrs @ 90%CL

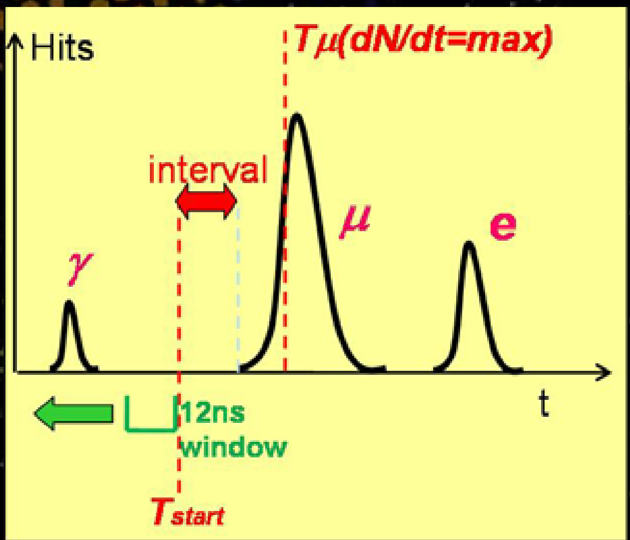
On-going improvements

SK-IV *Muon decay efficiency = 88.7%*
(μ^+ 95%, μ^- 81%)

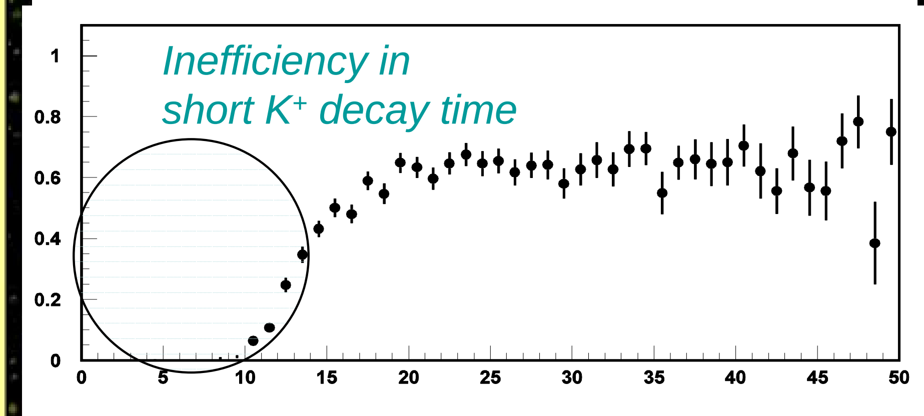


μ+ decay efficiency
~80%(SK-I,II,III) → 95% (SK-IV)

$\varepsilon(K^+ \rightarrow \nu\mu^+)$ to be increased by 20%



($K^+ \rightarrow \nu\mu^+$ + tagged γ) / (signal with γ)



K^+ decay time (nsec)

Improved vertex fitter will improve γ tagging efficiency

$\varepsilon(K^+ \rightarrow \nu\mu^+ + \gamma)$ to be increased by 10%

Other SUSY modes (SK-I)

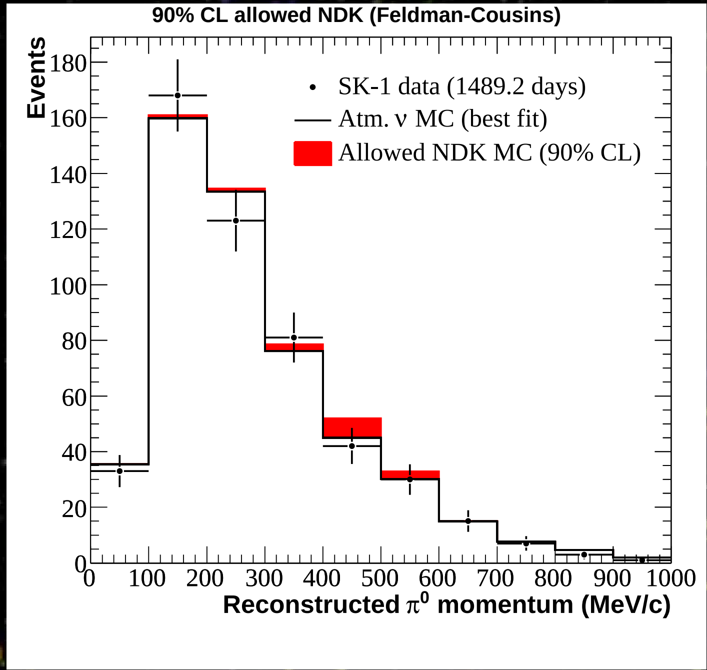
Decay mode	kton-yrs	eff.	Cand.	BG	limit ($\times 10^{32}$ yrs)
$n \to \bar{\nu} + K^0$	92				1.3
$K^0 \to \pi^0\pi^0$		6.9	14	19.2	1.3
$K^0 \to \pi^+\pi^-$		5.5	20	11.2	0.69
$p \to e^+ + K^0$	92				10
$K^0 \to \pi^0\pi^0$		9.2	1	1.1	8.4
$K^0 \to \pi^+\pi^-$					
2-ring		7.9	5	3.6	3.5
3-ring		1.3	0	0.04	1.6
$p \to \mu^+ + K^0$	92				13
$K^0 \to \pi^0\pi^0$		5.4	0	0.4	7.0
$K^0 \to \pi^+\pi^-$					
2-ring		7.0	3	3.2	4.4
3-ring		2.8	0	0.3	3.6

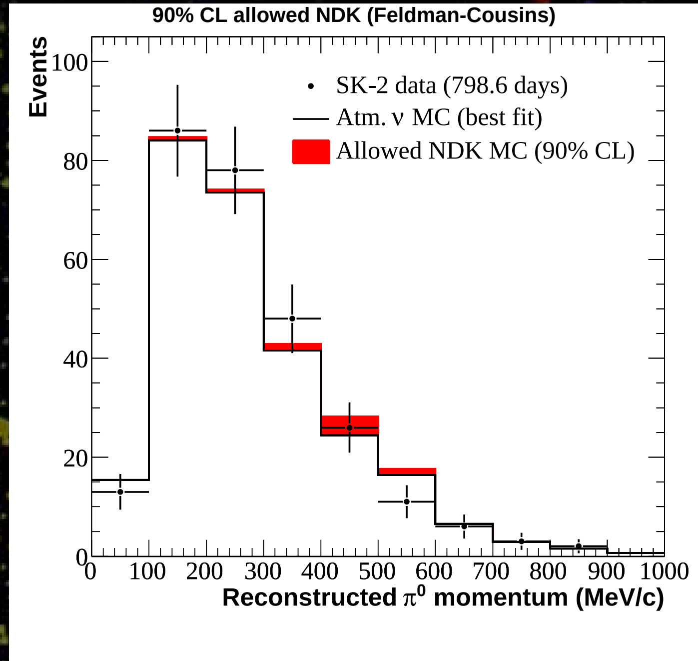
– *only Ks has been looked for so far.*
– *K_{Long} search technique has been developed.*
– *to be updated soon (add SK-II)*

$n \rightarrow \nu + \pi^0$

Predicted by minimal SUSY SU(10) model with (B-L) violation (Mohapatra, PLB587 (2004) p105)
Look for excess of 460MeV/c π^0 over atmν BGs

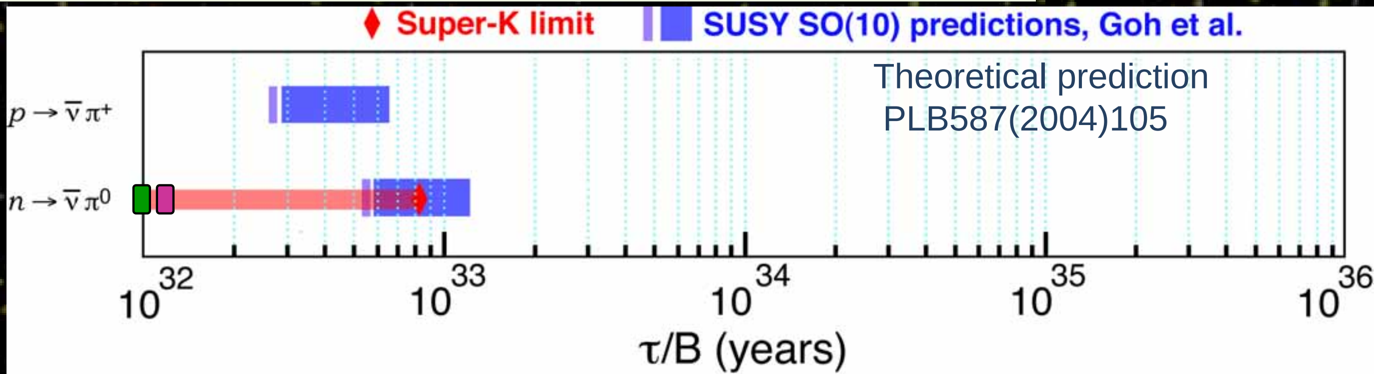
Selection Criteria
- 2 e-like rings
- no decay electrons
- $M\pi^0$ 85 ~ 185 MeV/c^2



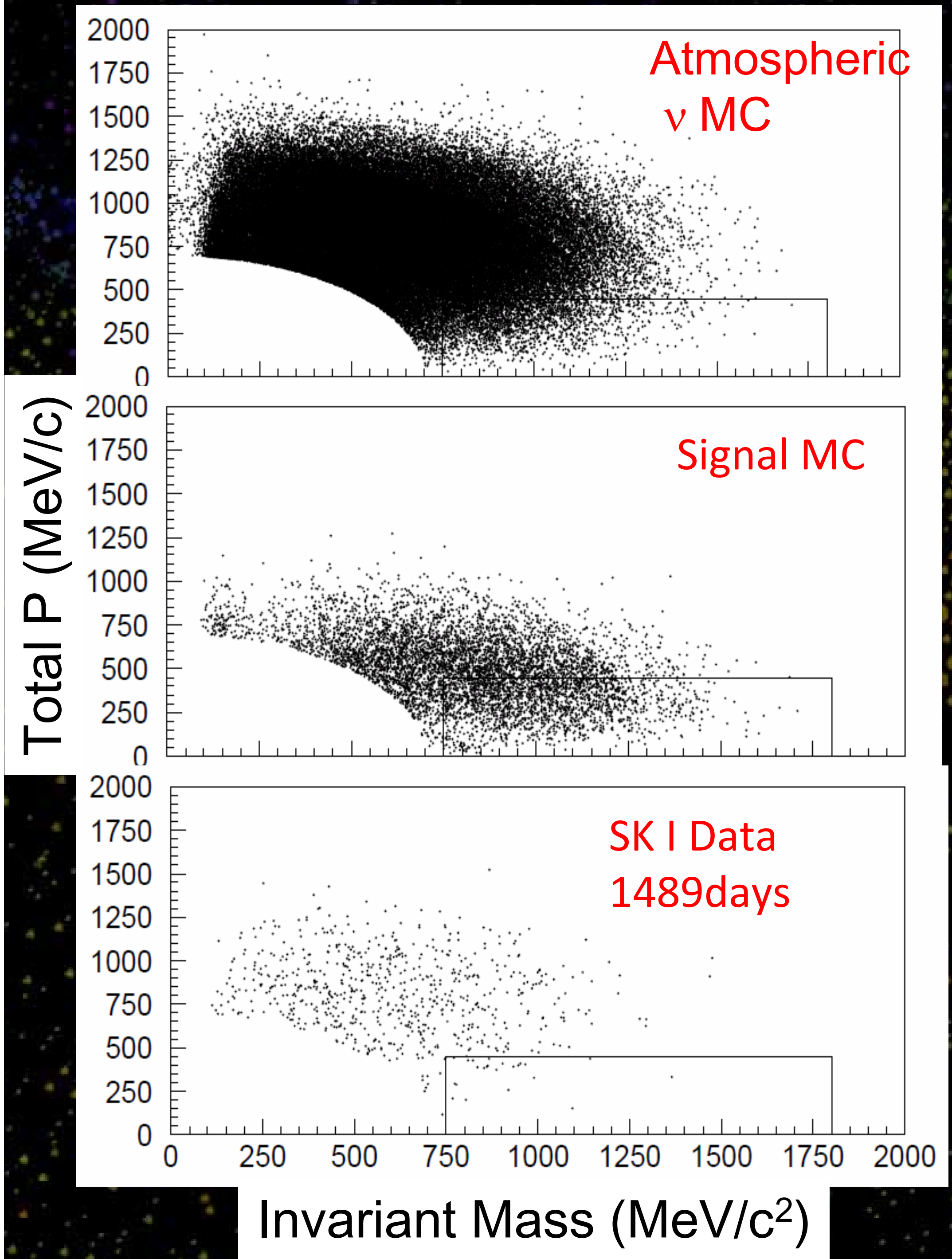


τ/BR > 8.8 x 10^{32} years (90% CL, Feldman-cousins)

previous limit: > 1.12 x 10^{32} yrs by IMB



Results on n-nbar oscillation



Estimated B.G. events 24event
w/ 23.7% sys. error

Detection efficiency 12.0%
w/ 22.9% sys. error

Candidates 23events

Limit on the inverse of event rate;

$$T_{bound} = \frac{1}{\Gamma_{limit}} = 1.99\times10^{32}\,years\,(90\%CL)$$

Oscillation time of free neutron;

$$\sqrt{T_{bound}/(R=1.0\times10^{23}\,\sec^{-1})} = \tau_{free} = 2.49\times10^{8}\,\sec$$

$$cf\ \text{ILL Reactor Experiment};\ \tau_{free} = 0.86\times10^{8}\,\sec$$

Invisible decays

PRB311(93),p357

PRB563(03),p23

PRL92:102004,'04

- $\tau_{neutron} > 4.9 \times 10^{26}$ years (KAM)

- $\tau_{neutron} > 1.8 \times 10^{25}$ years (Borexino CTF)
- $\tau_{proton} > 1.1 \times 10^{26}$ years (Borexino CTF)
- $\tau_{2neutron} > 4.9 \times 10^{25}$ years (Borexino CTF)
- $\tau_{2proton} > 5.0 \times 10^{25}$ years (Borexino CTF)
- $\tau_{neutron} > 1.9 \times 10^{29}$ years (SNO)
- $\tau_{proton} > 2.1 \times 10^{29}$ years (SNO)

Summary

We have to improve BKG rejection and accuracy of its estimation

- *Past*
  - *Full automatic reconstruction algorithms,*
  - *BG measurement with accelerator ν beam,*
  - *Establish de-excitation γ tagging,*
    - *Experimental measurement of s-hole state γ.*
- *Future*
  - *K_{Long} search technique*
  - *Improving γ tagging and decay electron tagging efficiencies,*
  - *Tighter kinematics cuts,*
  - *Neutron tagging may become an important technique,*
  - *Proton tagging in WC? Capable in LAr and Lscintillator,*
  - *π^+ and π^- tagging? → Indirect tagging by neutron and muon decays,*
  - *Other idea?*