Proton Decay Search in Super-Kamiokande I and II

H. Nishino
(ICRR, University of Tokyo)
for the Super-Kamiokande Collaboration

September 11th, 2008 @NNN08

The Super-Kamiokande Experiment

1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008

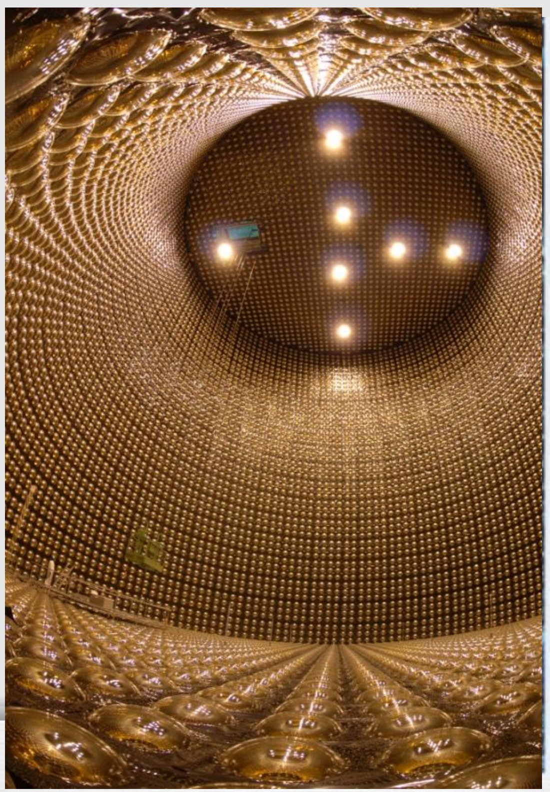
SK-I
Livetime: 1489.2 days
Exposure: 91.7 kton·yr
Photo coverage: 40 %
inner PMT: 11146

accident

SK-II
Livetime: 798.6 days
Exposure: 49.2 kton·yr
Photo coverage: 19 %
inner PMT: 5182

full reconstruction

SK-III



- Super-Kamiokande is a 50kton water Cherenkov detector located in Kamioka mine, Japan
- SK-III has just ended for electronics replacement.
- Topics except for nucleon decay searches will be covered by M.Fechner.
- **SK-I+II combined exposure: 141kton year**

➔ **The largest exposure as a proton decay search experiment.**

Nucleon Decay Searches in Super-K

- **Nucleon decay can be a direct evidence for Grand Unified Theories.**
- Recent status of nucleon decay searches in Super-K
  - $p \rightarrow e^{+}(\mu^{+})\pi^{0}$:Favored in many GUT models
    - Updated Result
  - $p \rightarrow \nu K^{+}$: Favored in SUSY GUT
    - Not updated
    - τ/B > 2.3 x 10^{33} (SK-I, Phys.Rev.D72 (2005) 052007)
  - $n \rightarrow \bar{\nu}\pi^{0}$: predicted by minimal SUSY SO(10) model with B-L violation
    - New Search Result
  - n-$\bar{n}$ oscillation: Not nucleon decay, but good test for GUT
    - Updated Result

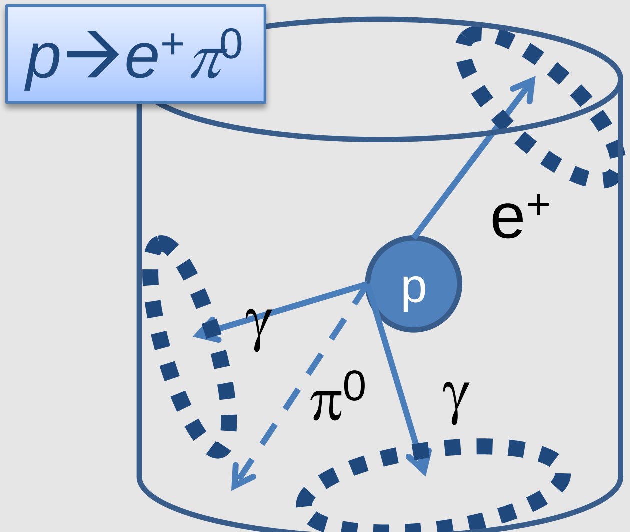
Analysis Updates

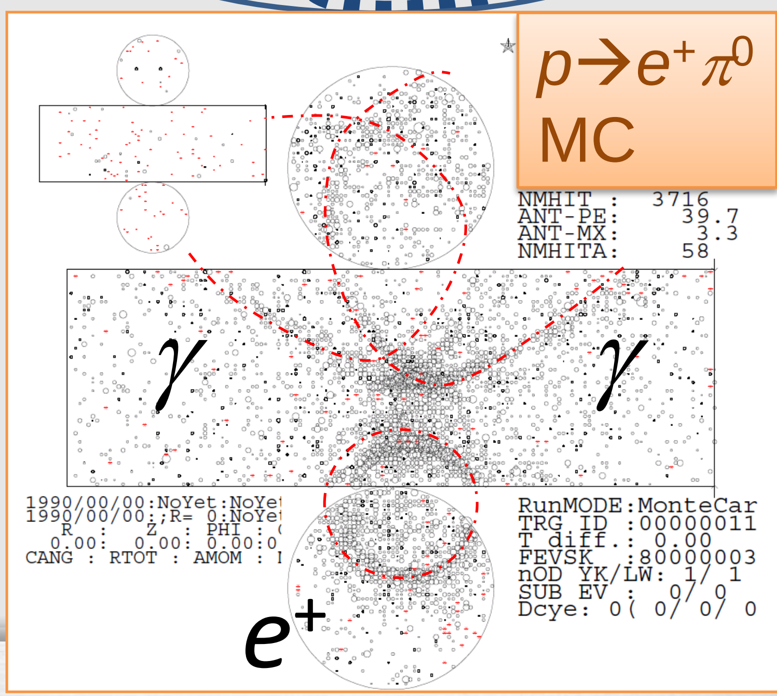
- **Improved event reconstruction algorithms**
  - ring counting
  - momentum determination (charge separation) for multi-ring events
    - PMT density is taken into account
    - better performance for total mass and momentum reconstruction, especially in SK-II
- Atmospheric neutrino background MC
  - **Increased atmospheric neutrino MC statistics**
    - 100yr → 500yr equivalent for both SK-I and SK-II

    ➔less statistical error for BG rate estimation
  - flux model: Honda06
  - Updated neutrino interaction model (NEUT)

$p \rightarrow e^+\pi^0$ & $p \rightarrow \mu^+\pi^0$ mode search

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





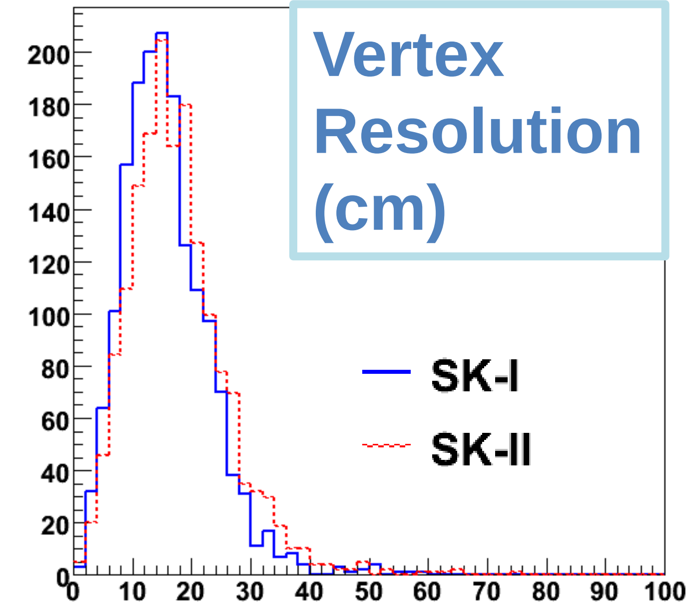
Event Selection Criteria

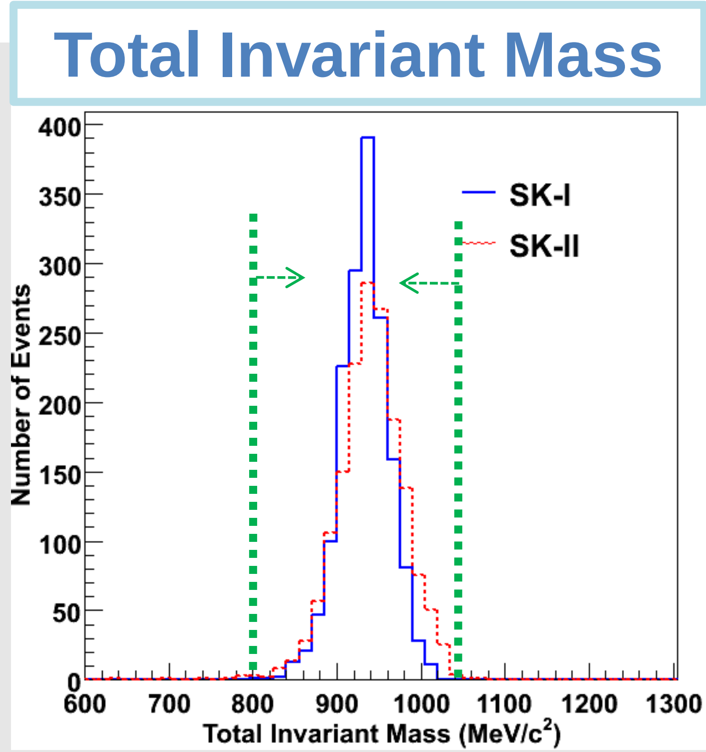
1. fully contained, fiducial volume
2. 2 or 3 Cherenkov rings
3. all *e*-like rings
4. $85 < M_\pi (MeV/c^2) < 185$ (for 3ring)
5. no decay-e
6. $800 < Mtot (MeV/c^2) < 1050$
& $Ptot (MeV/c) < 250$

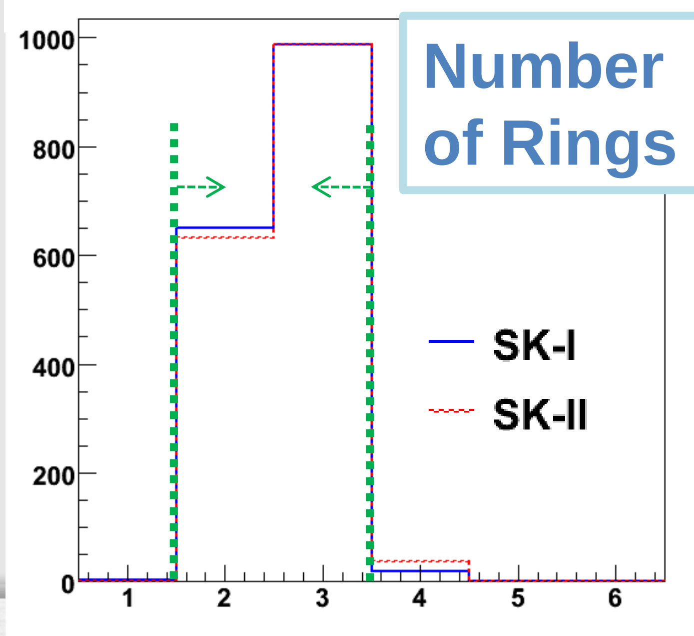
- **very clear signal**
- **simple selection criteria**
- **Efficiency for unbounded protons: 87%**

Good performance!

Proton Decay Search Performance SK-I vs. SK-II







Mis-PID Probability:

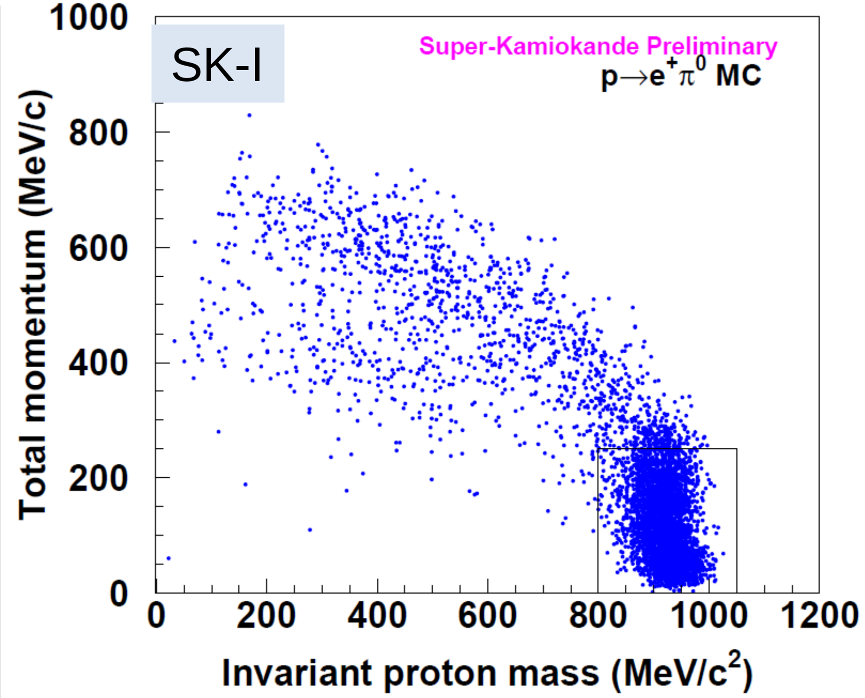
SK-I: 3.3%

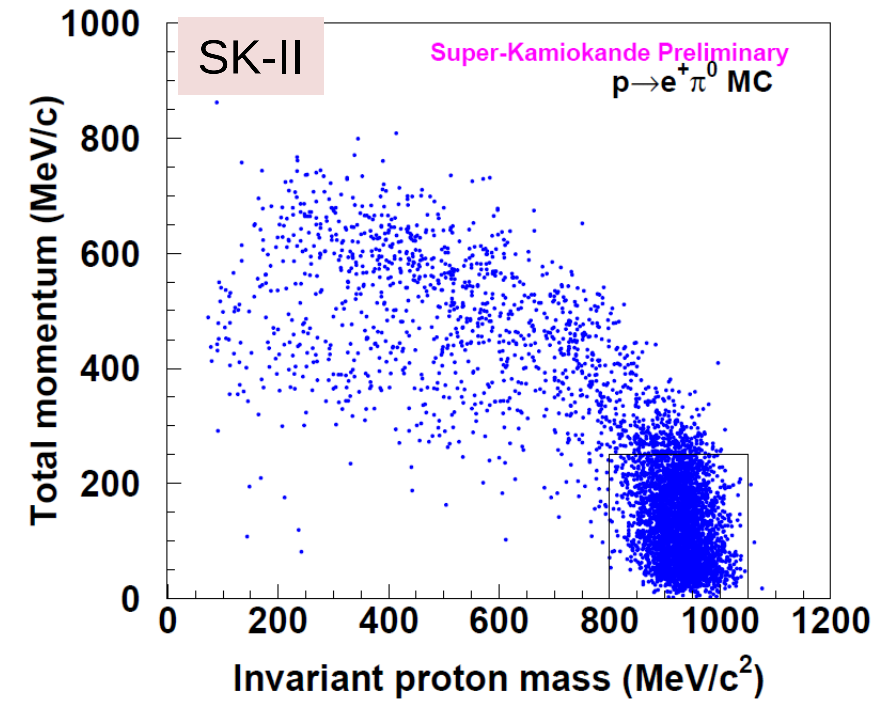
SK-II: 3.4%

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

Event reconstruction performances of SK-II is comparable to SK-I.

Detection Efficiencies for *$p \rightarrow e^+\pi^0$*



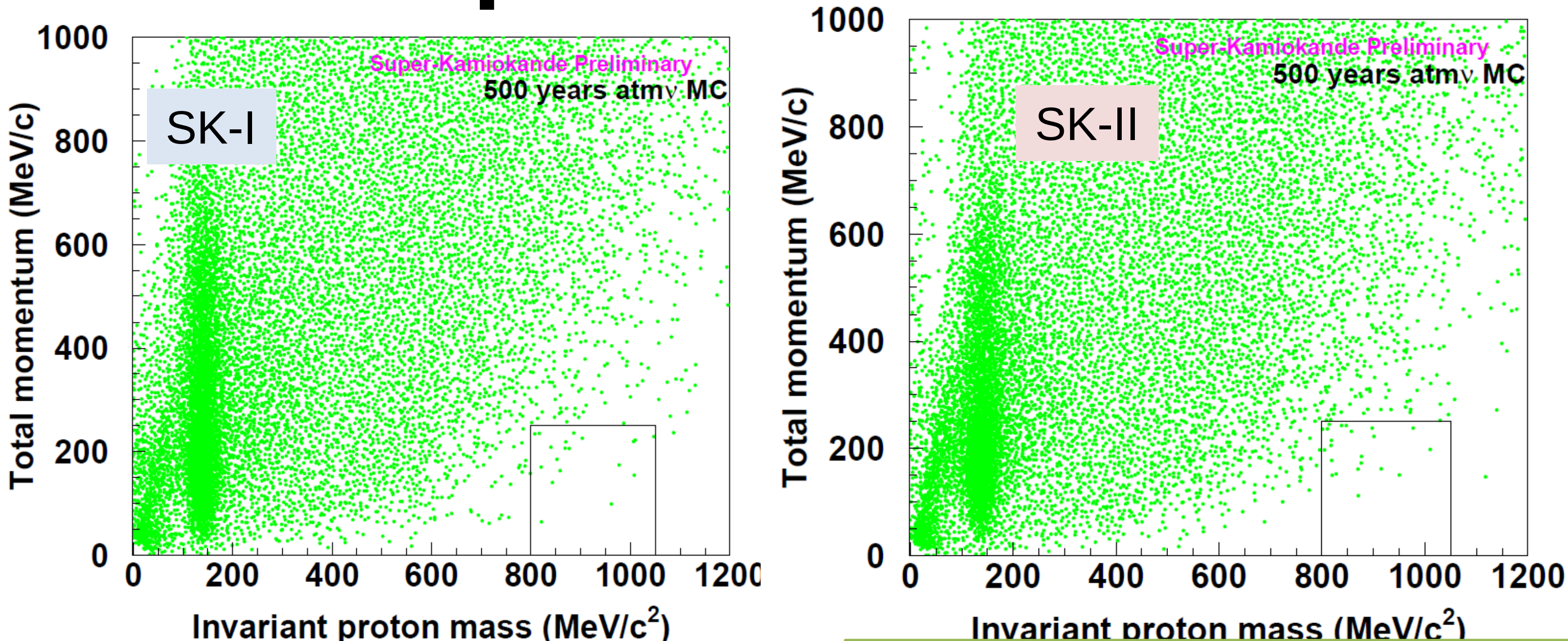


Detection Efficiency
= 44.9 ± 8.5(sys.) %

Detection Efficiency
= 43.7 ± 8.3(sys.) %

- **Detection efficiency of SK-II is also comparable to SK-I.**
- **Systematic uncertainty mostly comes from uncertainty of pion nuclear effect.**

Atmospheric neutrino BG



Expected BG (exposure: 92kt·yr)
= 0.20±0.04(MCstat.)±0.07(sys.)

Expected BG (exposure: 42kt·yr)
= 0.11±0.02(MCstat.)±0.04(sys.)

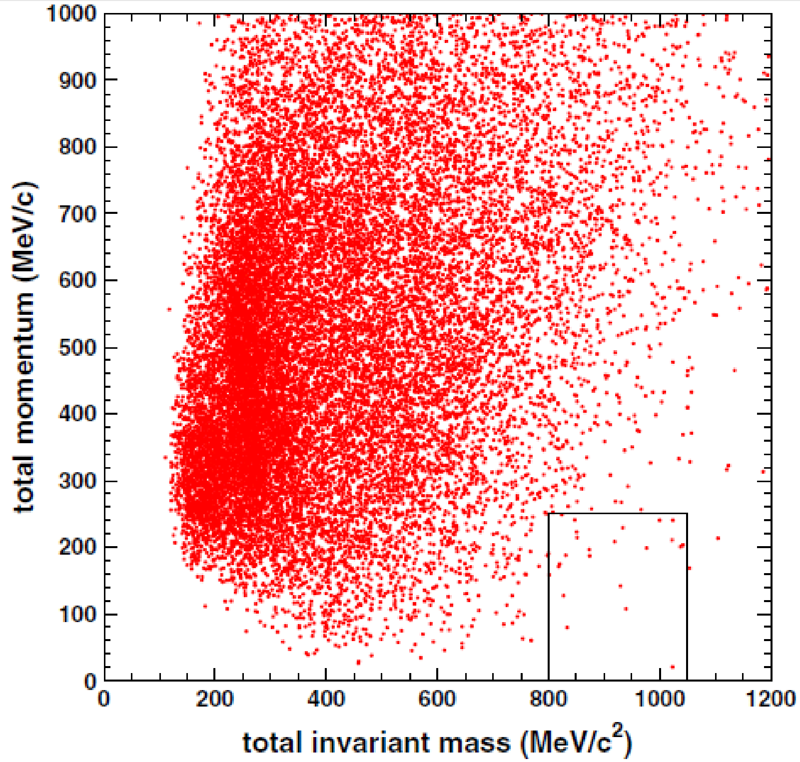
Contribution to BG	
CCQE	21%
CC single pi	38%
CC multi pi	20%
other CC	7%
NC	14%

- dominant contribution to BG:
  - CC single pi production
- systematic uncertainties of BG rate: 36.5%
  - cross sections (neutrino, hadron propagation): 29.0%
  - event reconstructions: 20.6%
  - neutrino flux: 8.2%

BG rate estimations

Experimental BG estimation by K2K ν beam and 1kT water Cherenkov detector ⇔ equivalent to atmospheric ν exposure of
- 15.9 Mton year CC
- 4.5 Mton year NC

(500yr+500yr MC ⇔ 22.6 Mton year)

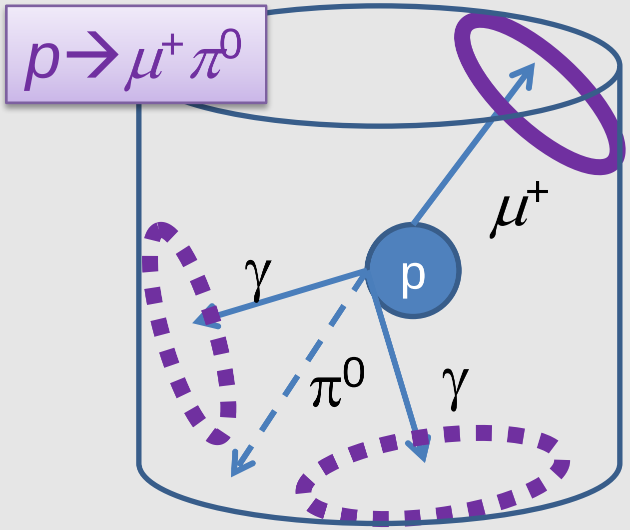


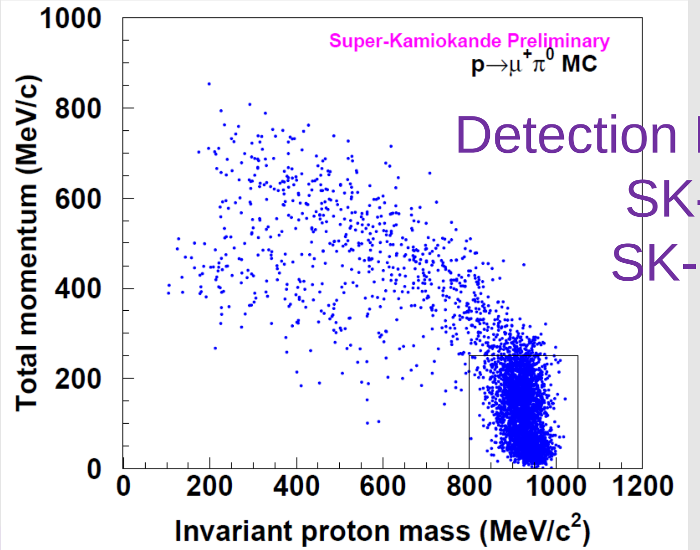
Ptot vs Mtot for $\mu^+\pi^0$ events from the K2K KT data (PRD77, 032003 (2008))

	BG rates (events/Mt year)
our estimation (NEUT)	2.1±0.3 (MCstat.) ± 0.8 (sys.)
NUANCE (different MC for ν interaction)	1.9±0.7 (MCstat.)
K2K ν beam ($E\nu$ < 3GeV)	$1.63^{+0.42}_{-0.33}$ (stat.) $^{+0.45}_{-0.51}$ (sys.)

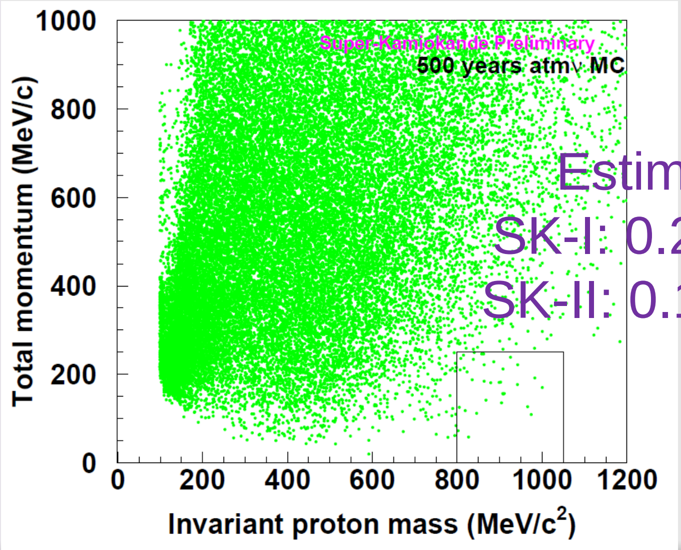
Our BG estimation is consistent with the other estimations.

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





Detection Effciency
SK-I: 35.7%
SK-II: 34.8%



Estimated BG
SK-I: 0.23events
SK-II: 0.11events

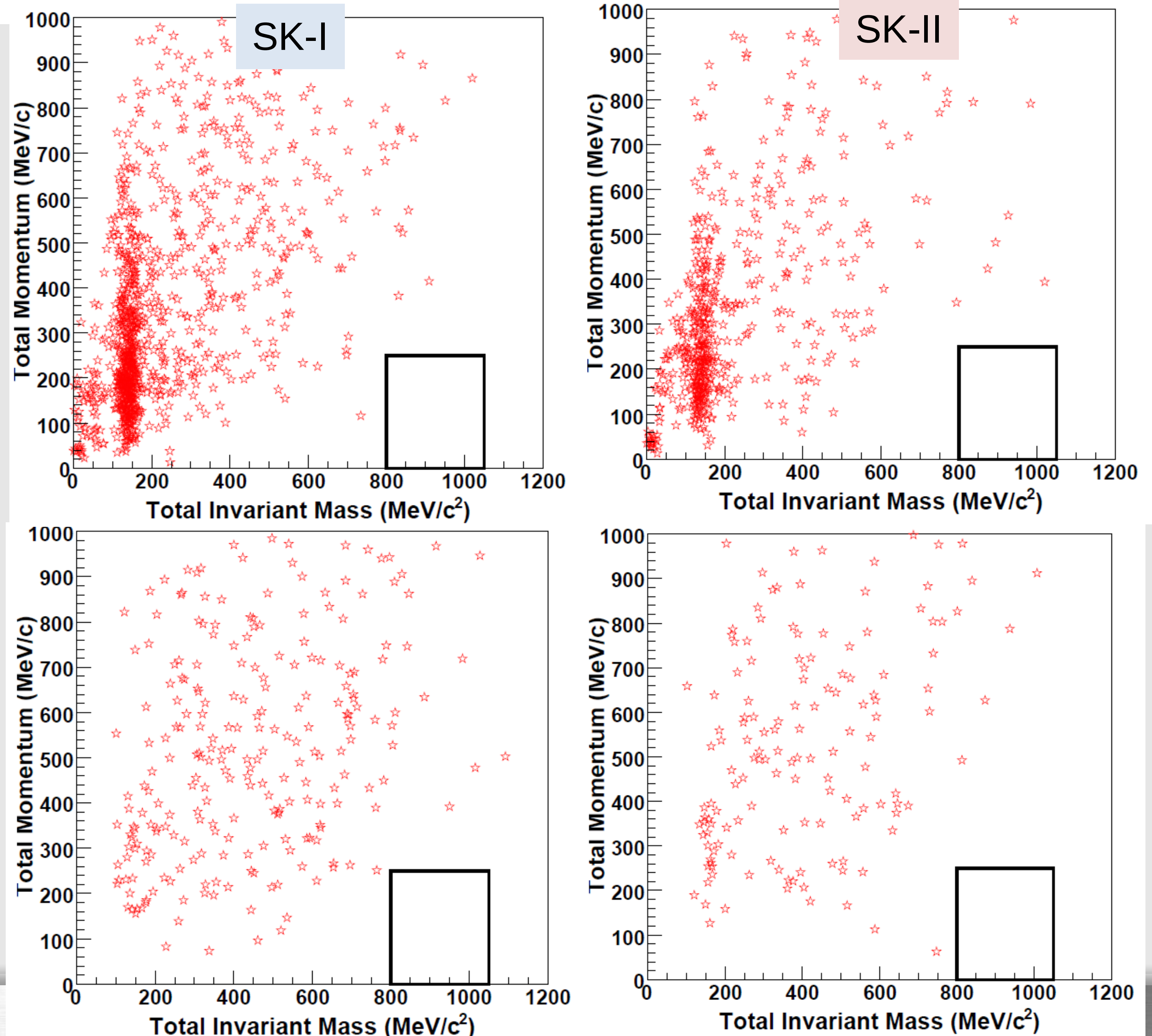
Event Selection Criteria

1. fully contained, fiducial volume
2. 2 or 3 Cherenkov rings
3. (2 or 1) e-like rings, 1-mu-like
4. 85<M_π(MeV/c^2)<185(for 3ring)
5. 1 decay-e
6. 800 < Mtot (MeV/c^2) < 1050
& Ptot (MeV/c) < 250

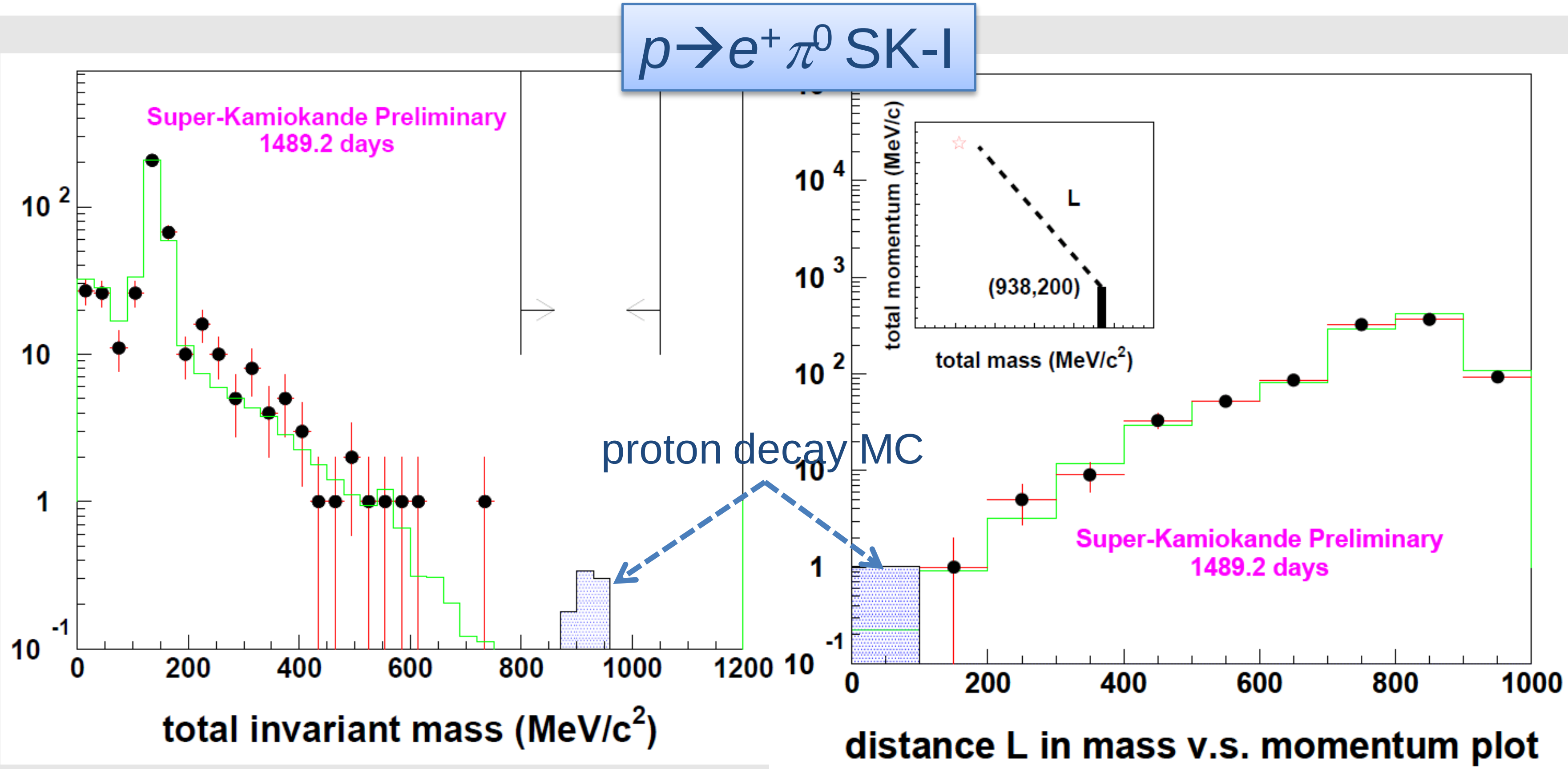
proton decay signal search in SK-I+II data

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

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



Data is consistent with BG MC



Fully contained data are well predicted by atmospheric neutrino MC.

Lifetime limits

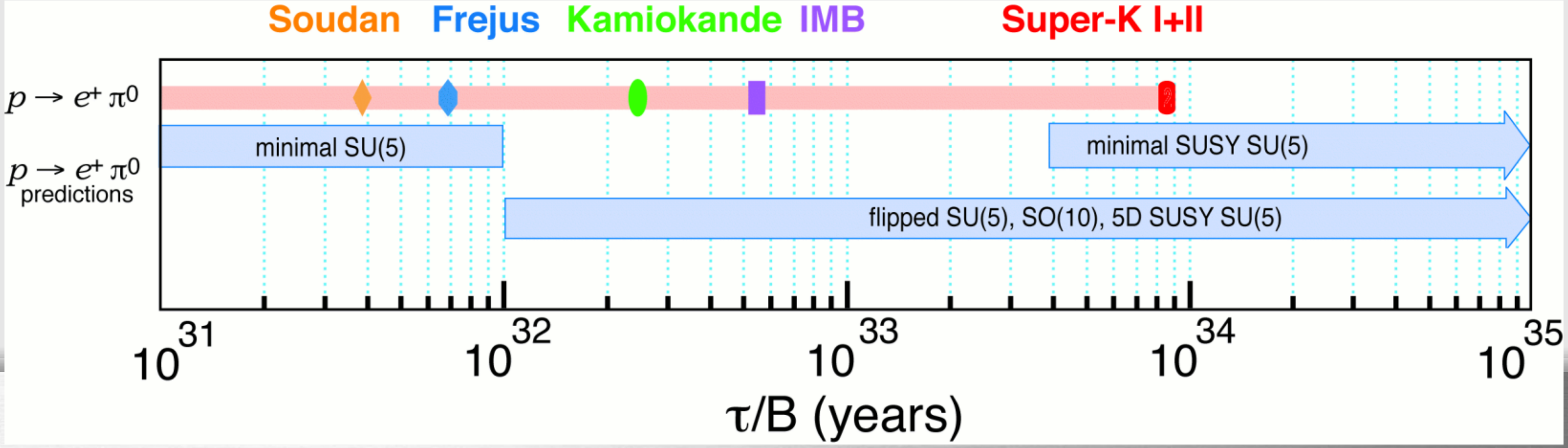
Lifetime limits by 141kton year exposure calculated by Bayesian method.

$p \rightarrow e^+ \pi^0$ (preliminary)

- **SK-I+II Combined limit: 8.2 x 10^{33} years (@90%C.L.)**
  - previous limit by SK (25.5kton year): **1.6 x 10^{33} years**

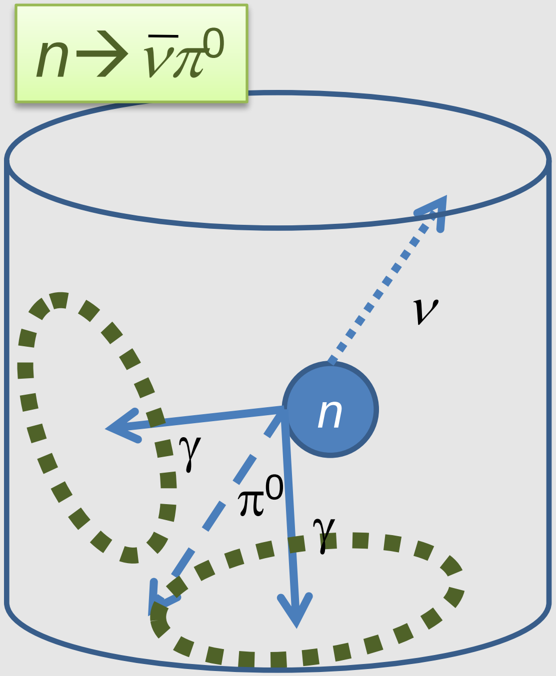
$p \rightarrow \mu^+ \pi^0$ (preliminary)

- **SK-I+II Combined limit: 6.6 x 10^{33} years (@90%C.L.)**
  - previous limit by IMB (7.6kton year): **4.7 x 10^{32} years**



$n \to \bar{\nu}\,\pi^0$ search

$n \rightarrow \bar{\nu}\,\pi^0$ mode search



- predicted by minimal SUSY SO(10) model with (B-L) violation
- we can only see $\pi^0 \rightarrow 2\gamma$

➔ **inevitably large background!**

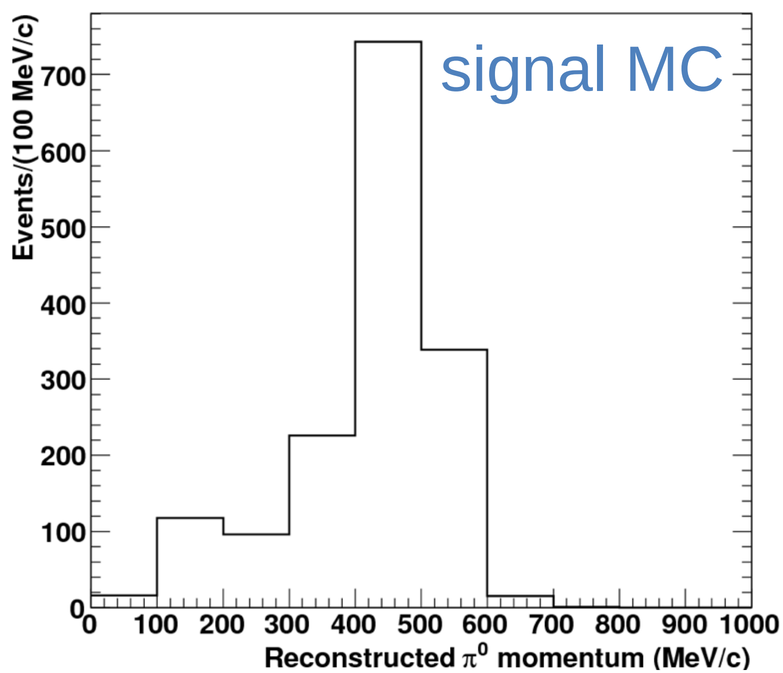
➔ **look for excess in π^0 momentum distribution above atmospheric neutrino BG**

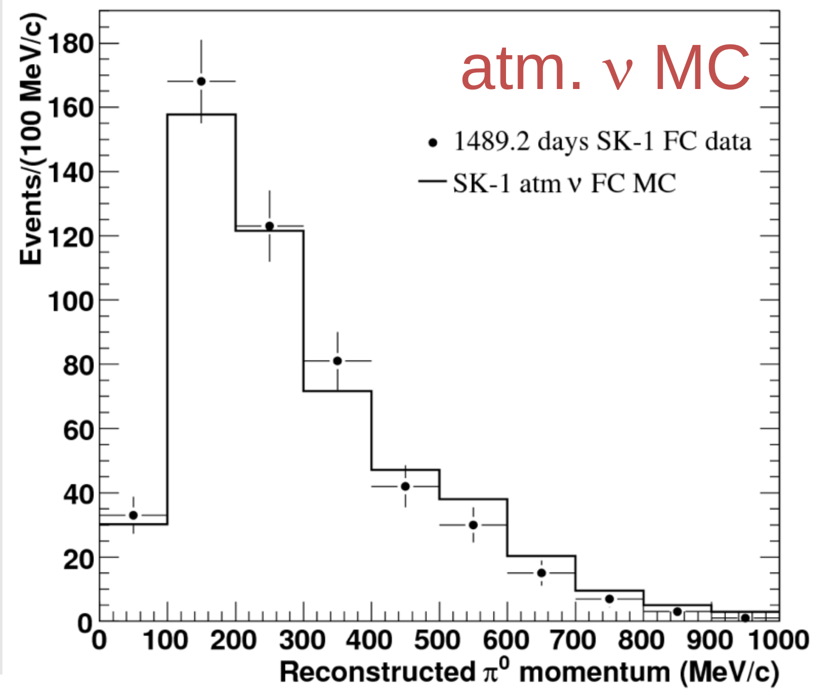
Event Selection Criteria

1. fully contained, fiducial volume
2. 2 *e*-like rings
3. $85 < M_\pi(\mathrm{MeV}/c^2) < 185$
4. no decay-e

Detection Efficiency
SK-I: 48.5%
SK-II: 44.0%

$n \rightarrow \bar{\nu}\,\pi^0$ mode search





$$\chi^2 = \sum_{i=1}^{nbins} \frac{\left(N_i^{obs} - N_i^{exp}\left(1 + \sum_{j=1}^{N_{syserr}} f_j^i \cdot \varepsilon_j\right)\right)}{\sigma_i^2} + \sum_{j=1}^{N_{syserr}} \left(\frac{\varepsilon_j}{\sigma_j}\right)^2$$

where $N_i^{exp} = \alpha \cdot N_i^{\nu} + \beta \cdot N_i^{NDK}$

Minimize χ^2 to find best fit parameters, with systematic terms

$n \rightarrow \bar{\nu}\,\pi^0$ Result

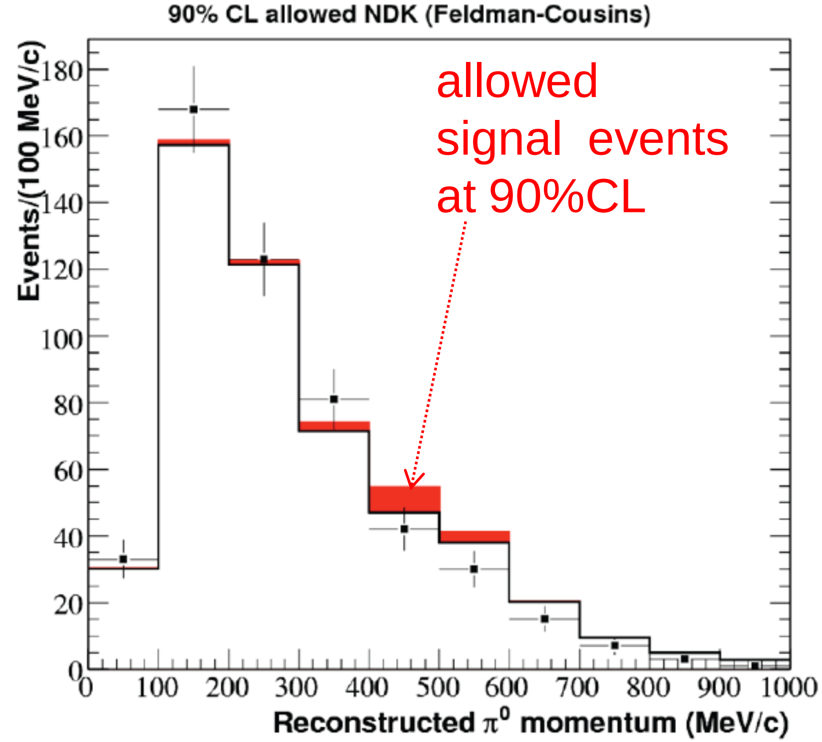
$$\frac{\tau}{B_{n\rightarrow\nu\pi^0}} = \frac{\Delta t \varepsilon N_{nucleons}}{N_{90CL}}$$

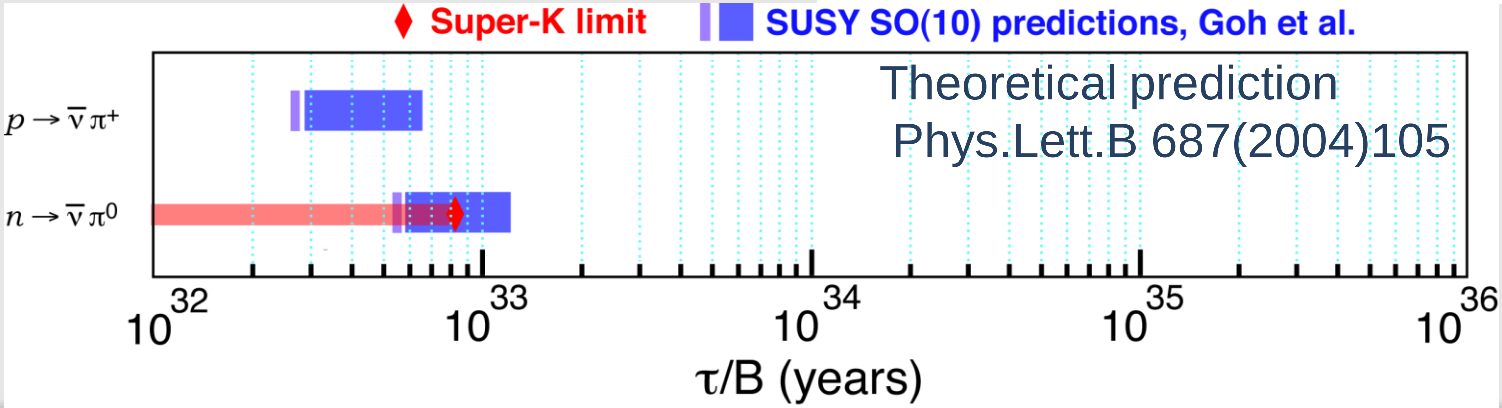
	N_{90CL}	90% CL Limit
SK-I+II combined	20.2	> 8.8 x 10^{32} yrs

(preliminary)

N_{90CL} :Number of signal events allowed at 90% CL from best fit parameters

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



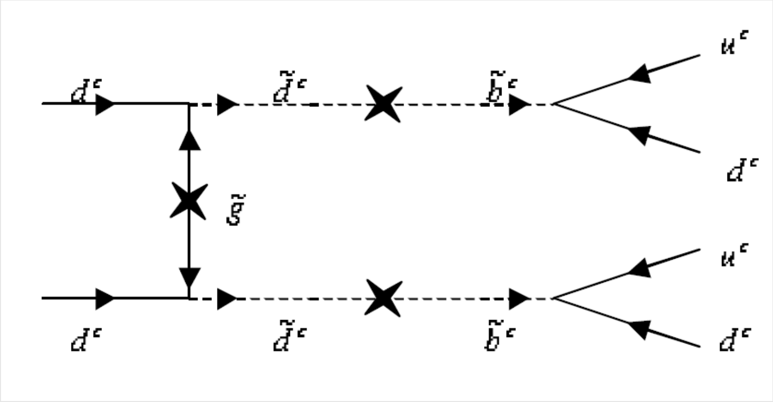


n-$\bar{n}$ oscillation search in SK-I

neutron anti-neutron oscillation

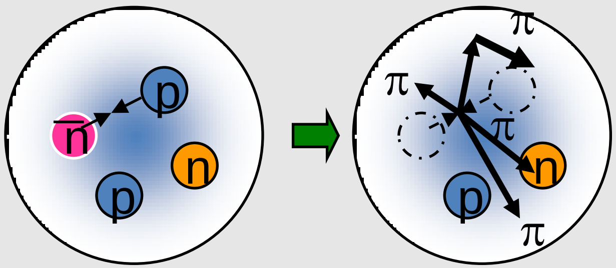
- motivation
  - Several types of (B-L)-violating Gauge theories predicts that neutron spontaneously converts to anti-neutron, and vise versa

⇔ $n - \bar{n}$ oscillation



- expected signal

1. anti-neutron annihilates with n or p.



2. pions are emitted isotropically with high multiplicity (>~4π)

$\bar{n}+p$

$\pi^+\pi^0$	1%
$\pi^+\pi^0\pi^0$	8%
$\pi^+\pi^0\pi^0\pi^0$	10%
$\pi^+\pi^+\pi^-\pi^0$	22%
$2\pi^+\pi^-2\pi^0$	36%
$2\pi^+\pi^-\omega$	16%
$3\pi^+2\pi^-\pi^0$	7%

$\bar{n}+n$

$\pi^+\pi^-$	2%
$\pi^0\pi^0$	1.52%
$\pi^+\pi^-\pi^0$	6.48%
$\pi^+\pi^-\pi^0\pi^0$	11%
$\pi^+\pi^-\pi^0\pi^0\pi^0$	28%
$2\pi^+2\pi^-$	7%
$2\pi^+2\pi^-\pi^0$	24%
$\pi^+\pi^-\omega$	10%
$2\pi^+2\pi^-\pi^0\pi^0$	10%

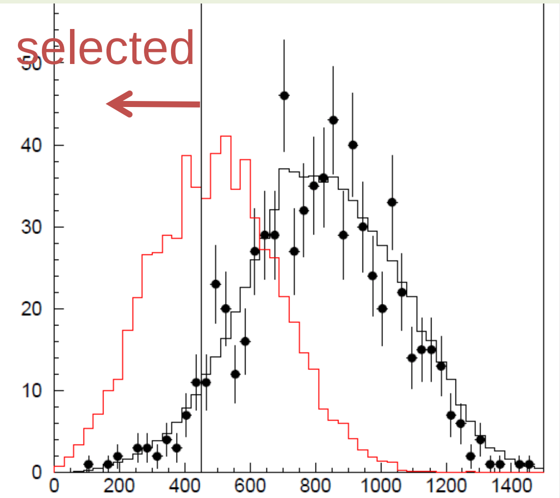
Branching ratio derived from Bubble Chamber p + $\bar{d}$ data

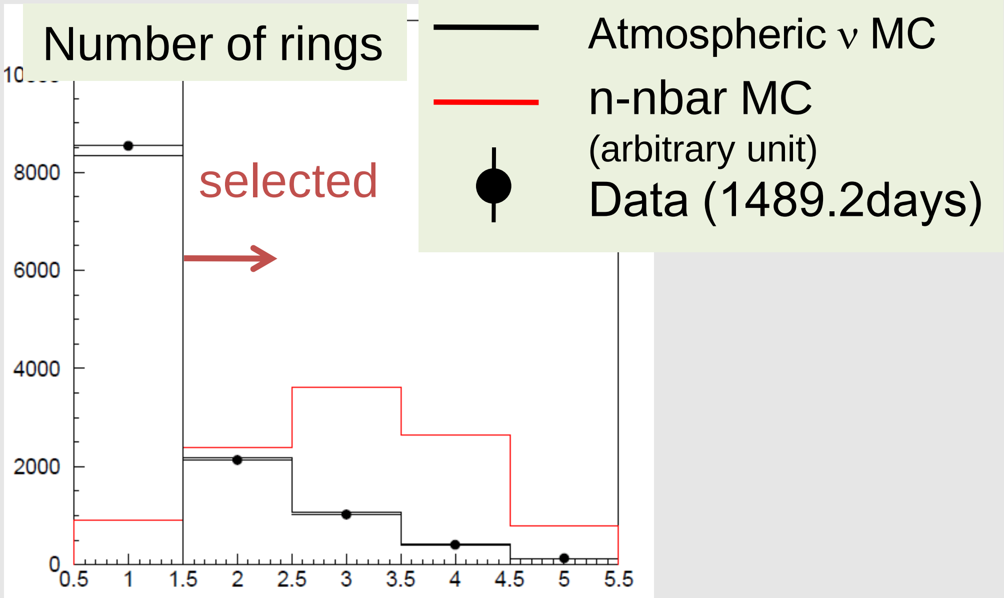
Event Selection Criteria

Event Selection Criteria

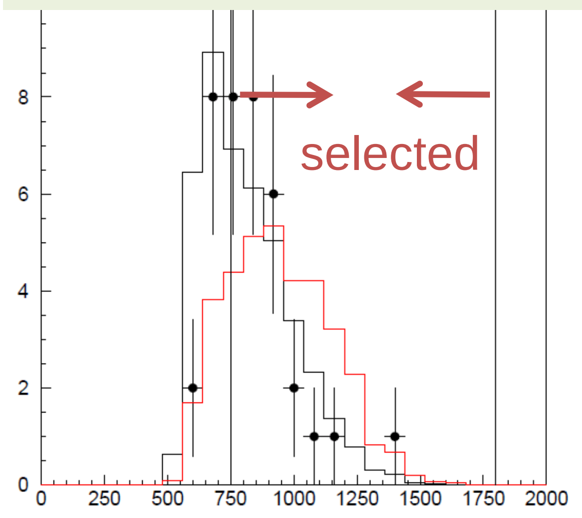
1. fully contained, fiducial volume
2. Number of rings > 1
3. 700<visible energy<1300 (MeV)
4. Ptot < 450 MeV/c
4. 750 < Mtot < 1800 (MeV/c^2)

Total Momentum (MeV/c)

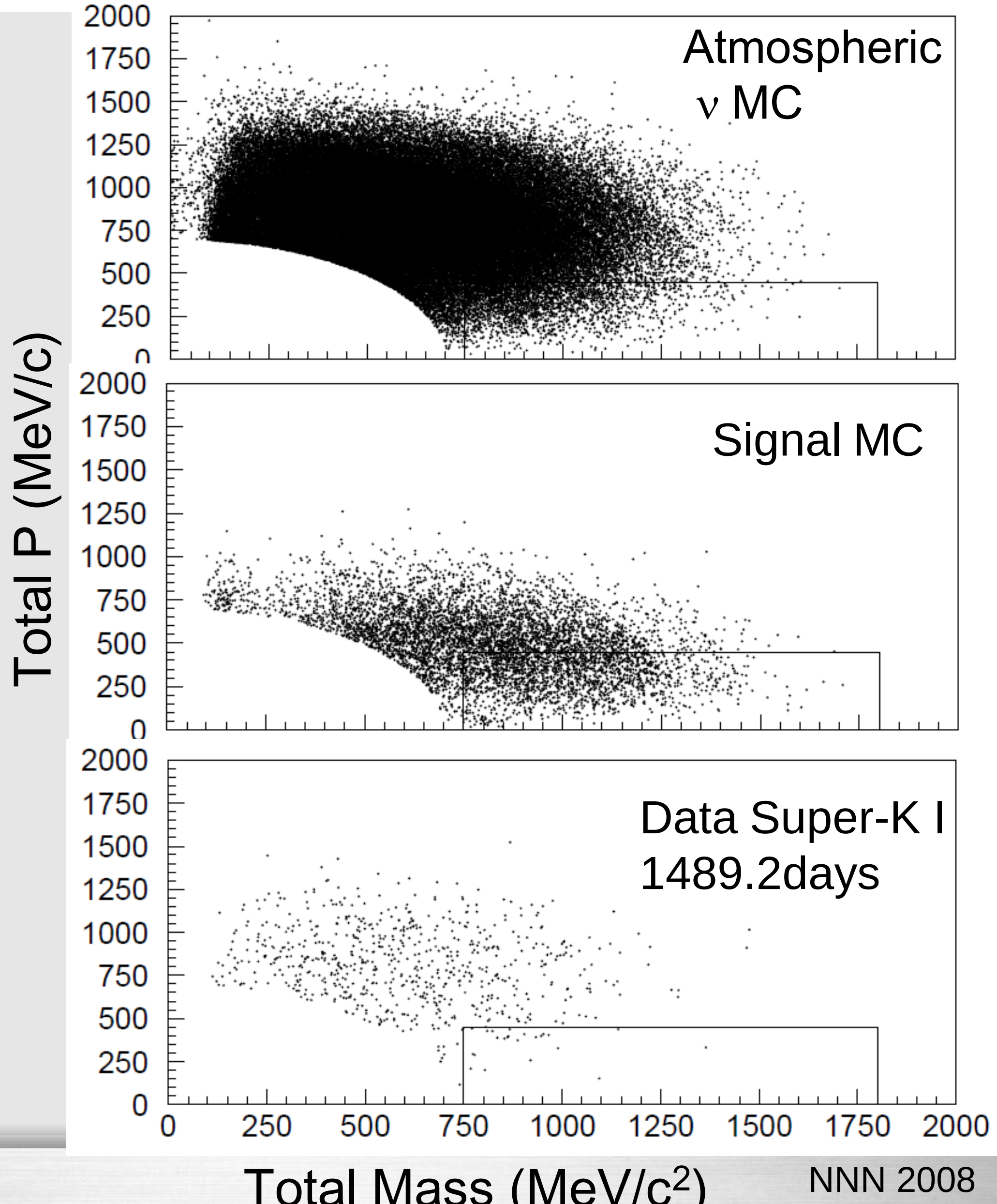




Total Mass (MeV/c)



n-$\bar{n}$ search in SK-I



NNN 2008

Estimated Backgrounds:

23.99 events

sys. uncertainty: 23.7%

(dominant: cross sections of neutrino interaction and event reconstruction)

Detection Efficiency:

12.0%

sys. uncertainty: 22.9%

(dominant: pion nuclear effect)

Candidates:

23 events

No significant excess above atmospheric neutrino BG

n-$\bar{n}$ search result

$n \rightarrow \bar{n}$ transition probability , $P(\Gamma|n)$ is calculated by Bayesian statistics and Bayesian theorem.

$$T_{bound} = \frac{1}{\Gamma_{limit}} > 1.97 \times 10^{32} \text{ yrs (90\% CL) (SK-I)}$$

(preliminary)

Bound neutron lifetime can be interpreted to the oscillation time of the free neutron by

$$T_{bound} = R \times (\tau_{free})^2$$

$$\tau_{free} > 2.49 \times 10^{8} \text{ sec}$$

(preliminary)

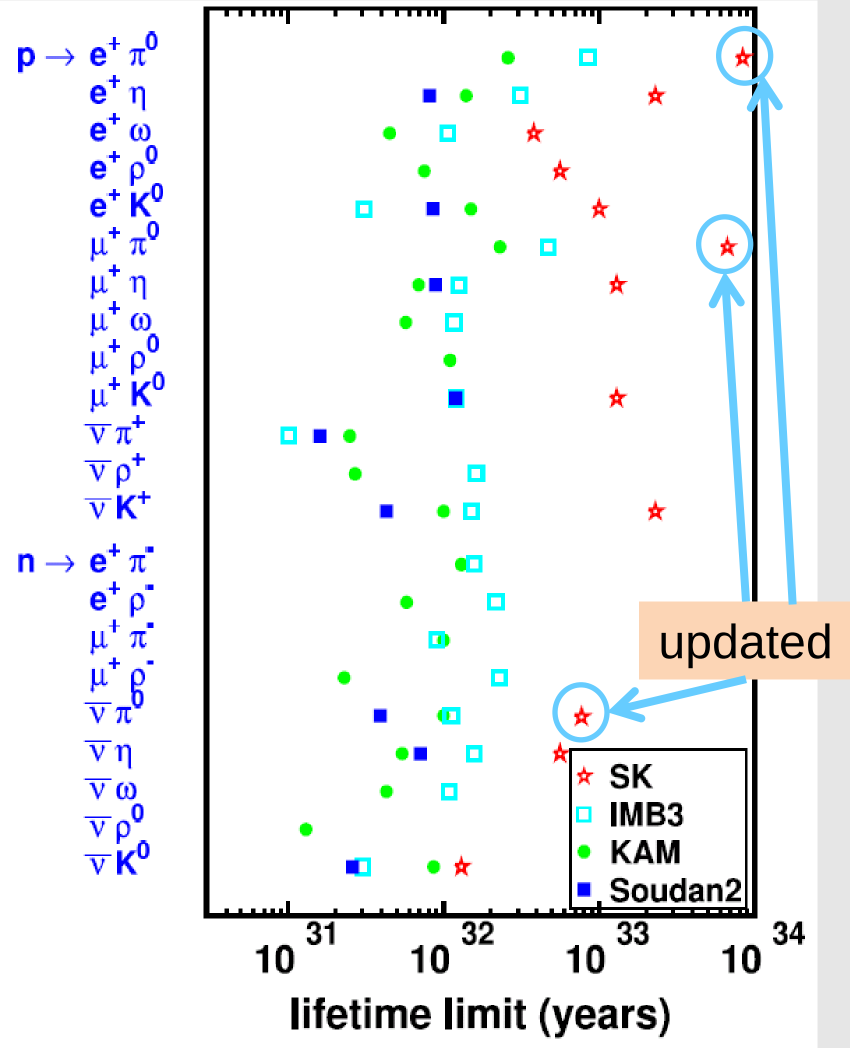
used the suppression factor R calculated by Dover et al. Phys. Rev. D27 (1983) 1090

Previous limits

Kamiokande:	$\tau_{free} > 1.2 \times 10^8$ sec
IMB:	$\tau_{free} > 0.88 \times 10^8$ sec
ILL Beam experiment:	$\tau_{free} > 0.86 \times 10^8$ sec

Theoretical upper limit $< 10^9 \sim 10^{10}$ sec
(K.S.Babu et al., Phys.Lett.B 518(200)269)

Future Prospects



- **Sensitivity for $p \rightarrow e^+\pi^0$ will reach to $\tau/Br \sim 10^{34}$ yrs in near future.**
- **Super-K has published some favored modes** ($p \rightarrow e^+\pi^0$, $p \rightarrow \nu K^+$…)
  - ➔ IMB still has the best limits in many modes (in PDG)
- **Recently many efforts are devoted to cover unsearched modes.**
  - – ($p \rightarrow \nu K^+$ in SK-II)
  - – systematical study for (charged-lepton+meson) mode
    - $N \rightarrow (e^+, \mu^+) + (\pi, \eta, \rho, \omega)$
  - – $p \rightarrow \mu^+ K^0_L$
  - – $pp \rightarrow K^+ K^+$
  - – $p \rightarrow \nu \pi^+$
  - – etc…

Coming Soon!

Summary

- **Detection efficiencies for proton decay signals in SK-II are comparable to that in SK-I.**
- **Updated the results of nucleon decay searches via $p \rightarrow e^{+}\pi^{0}$, $p \rightarrow \mu^{+}\pi^{0}$ and $n \rightarrow \bar{\nu}\pi^{0}$ and n-$\bar{n}$ oscillation.**
  - No positive signals were found.
  - Updated the lifetime limits
    - $p \rightarrow e^{+}\pi^{0}$: $\tau/B > 8.2 \times 10^{33}$ years
    - $p \rightarrow \mu^{+}\pi^{0}$: $\tau/B > 6.6 \times 10^{33}$ years
    - n-$\bar{n}$ oscillation: $\tau_{free} > 2.49 \times 10^{8}$ sec
    - $n \rightarrow \bar{\nu}\pi^{0}$: $\tau/B > 8.8 \times 10^{32}$ years
- **Super-K will continue to be the largest proton decay experiment until NNN starts.**
  - We will continue to keep searching for proton decay signals.
  - We are now trying to cover unsearched decay modes.