Neutron-Antineutron Oscillation Search at Super-Kamiokande & Prospect for SK-Gd and HK

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Motivation

- **Neutron-antineutron oscillation** is an important candidate for baryon number violating process,
  - $\boldsymbol{\Delta B = 2, \Delta L = 0}$
  - a unique probe into physics beyond the Standard Model.

- This analysis searches for $n \rightarrow \bar{n}$ oscillation by **bound neutrons in oxygen nucleus**.
  - upper limit on neutron life-time in media $T_{n\bar{n}}$
  - can be translation into transition time $\tau_{n\rightarrow\bar{n}}$ by $\tau_{n\rightarrow\bar{n}} = \sqrt{T_{n\bar{n}}/R}$, where R is the suppression factor

Super-Kamiokande Detector

Large water Cherenkov detector: 1996 ~ so far

Inner Detector Coverage: 40%

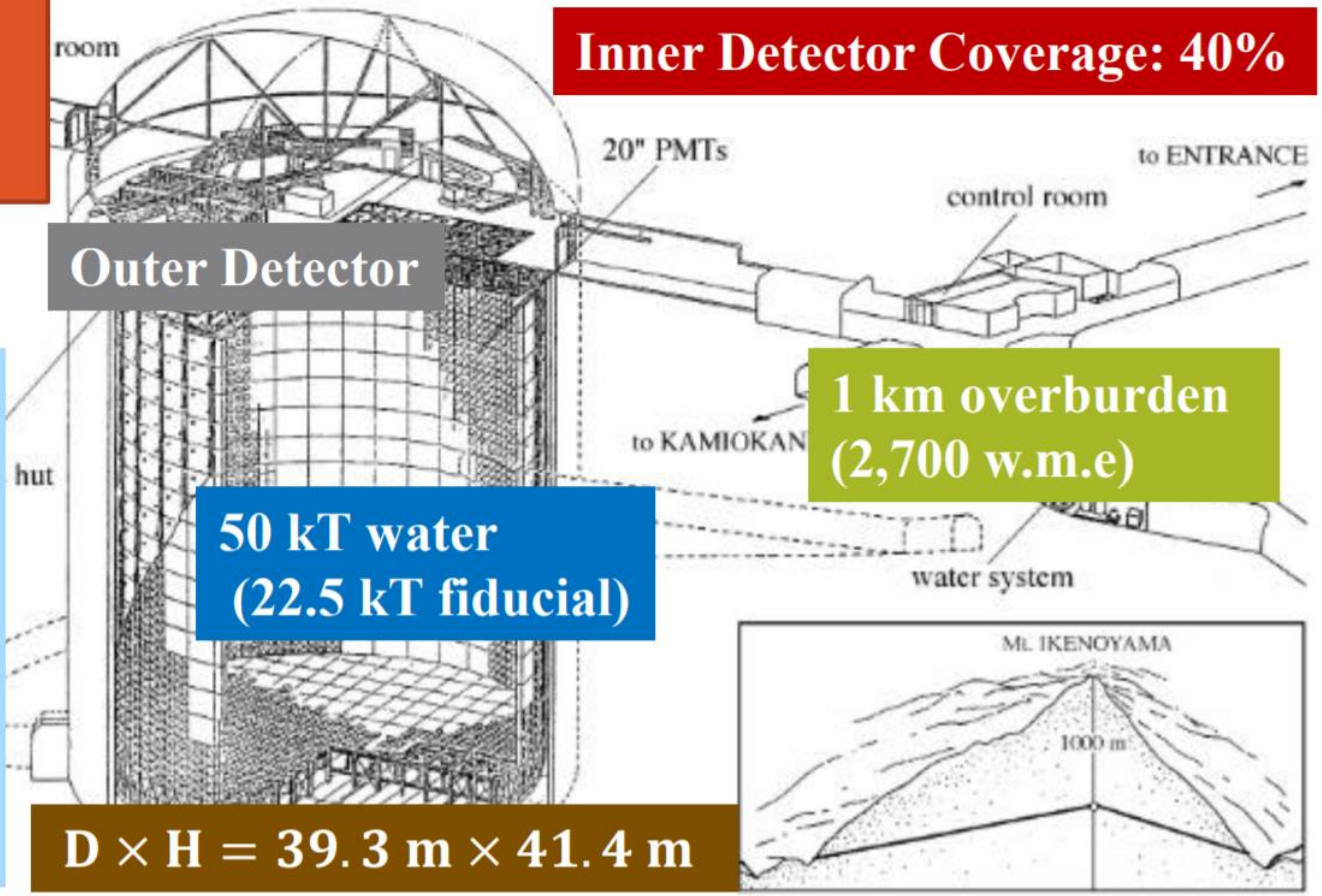
Outer Detector

In Gifu, Japan

1 km overburden (2,700 w.m.e)

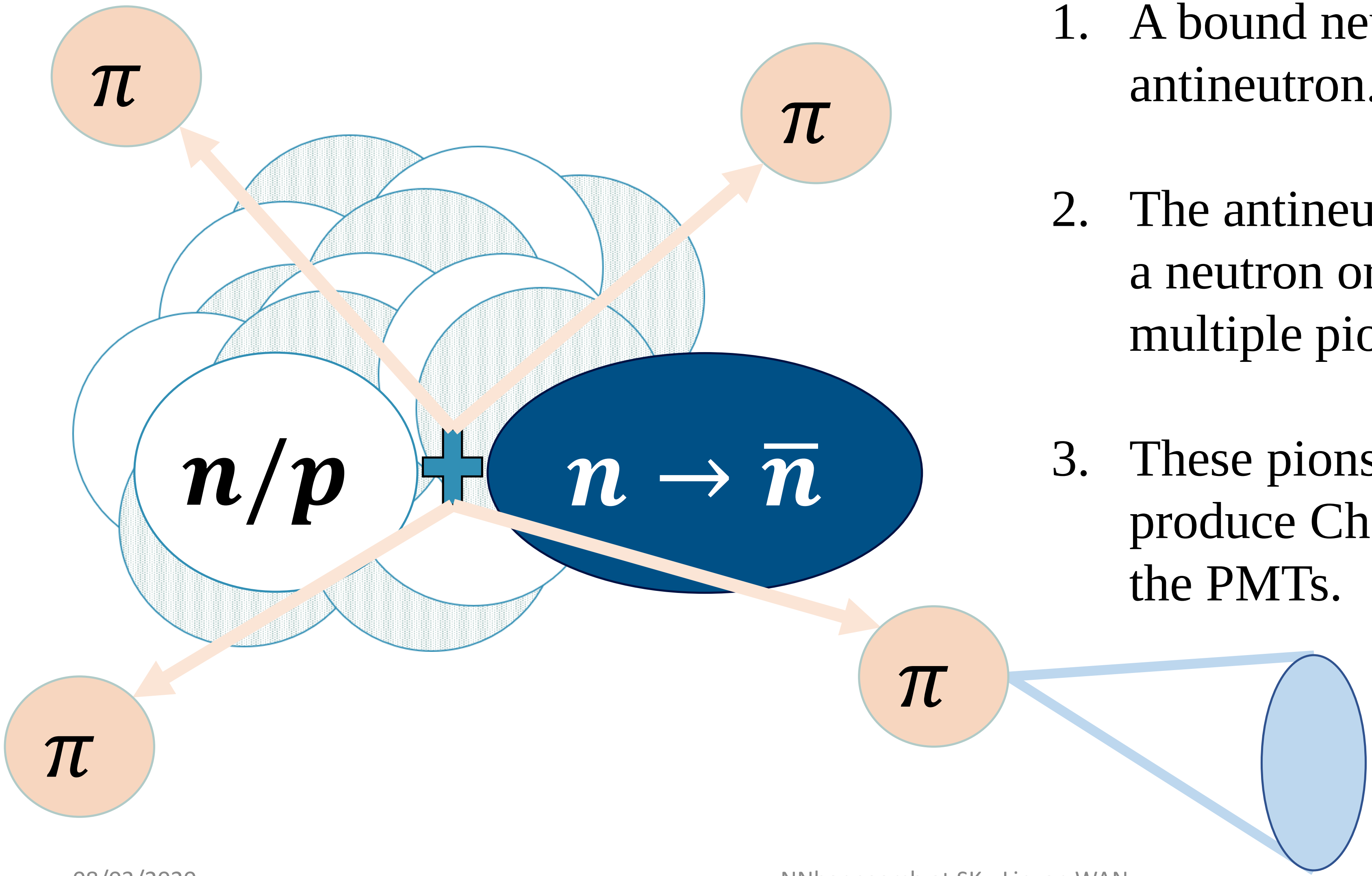
50 kT water (22.5 kT fiducial)

D × H = 39. 3 m × 41. 4 m



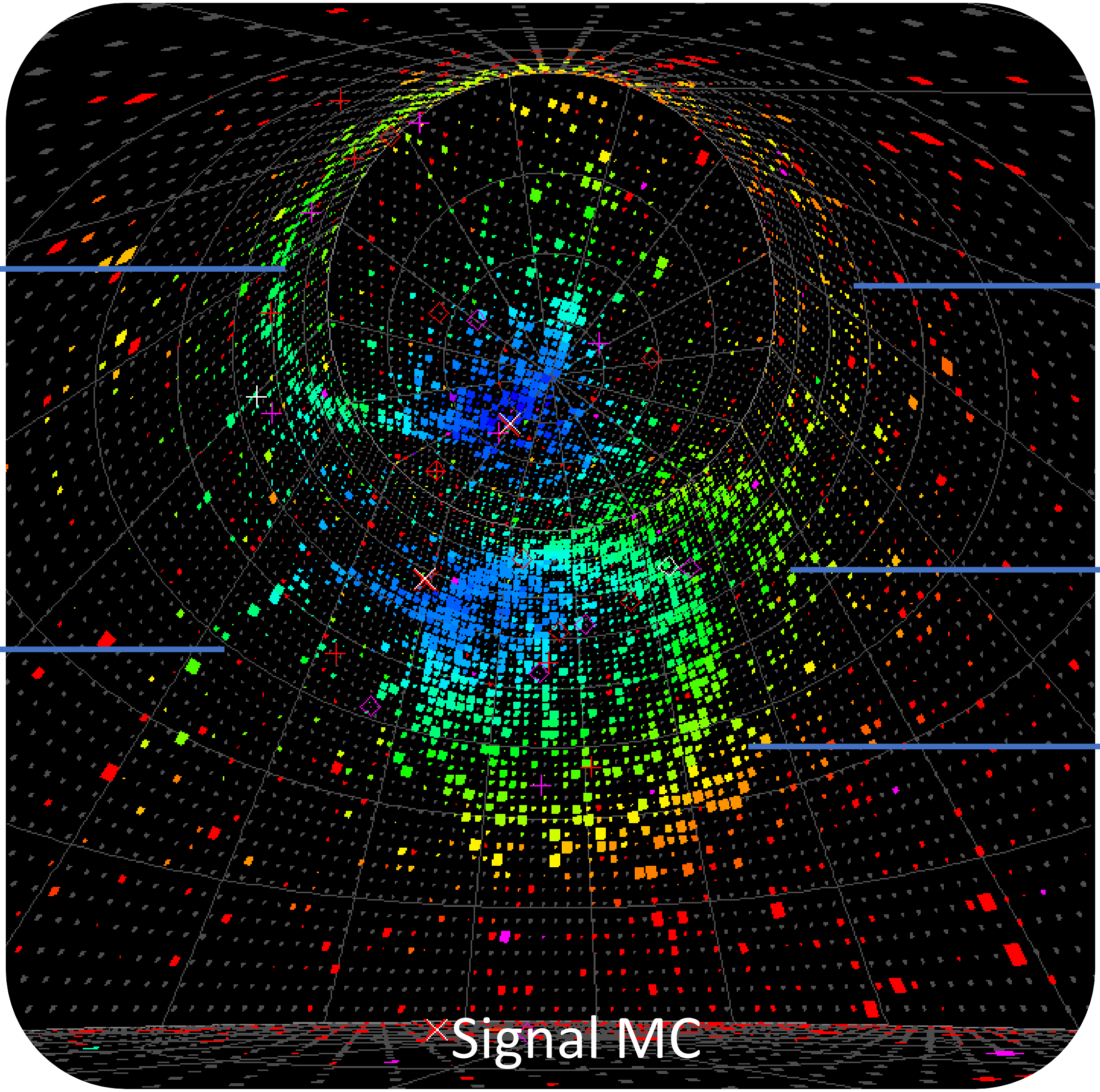
Nucl. Instr. & Meth, A 737C (2014)

Signal Mechanism



1. A bound neutron oscillates to an antineutron.
2. The antineutron then annihilates with a neutron or proton, producing multiple pions.
3. These pions or secondary particles produce Cherenkov light detected by the PMTs.

Simulated Signal Event



gamma

gamma

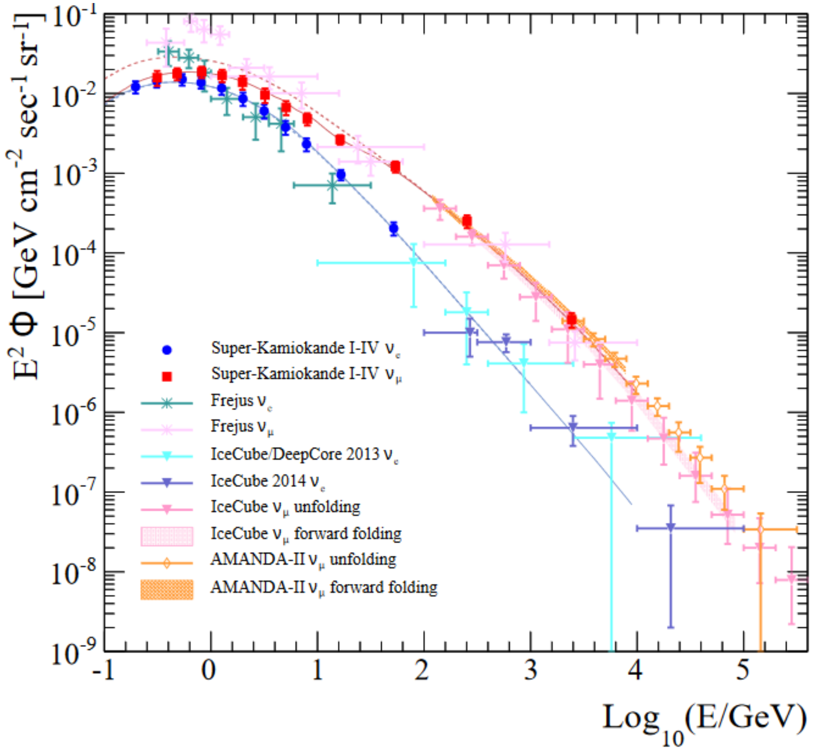
gamma

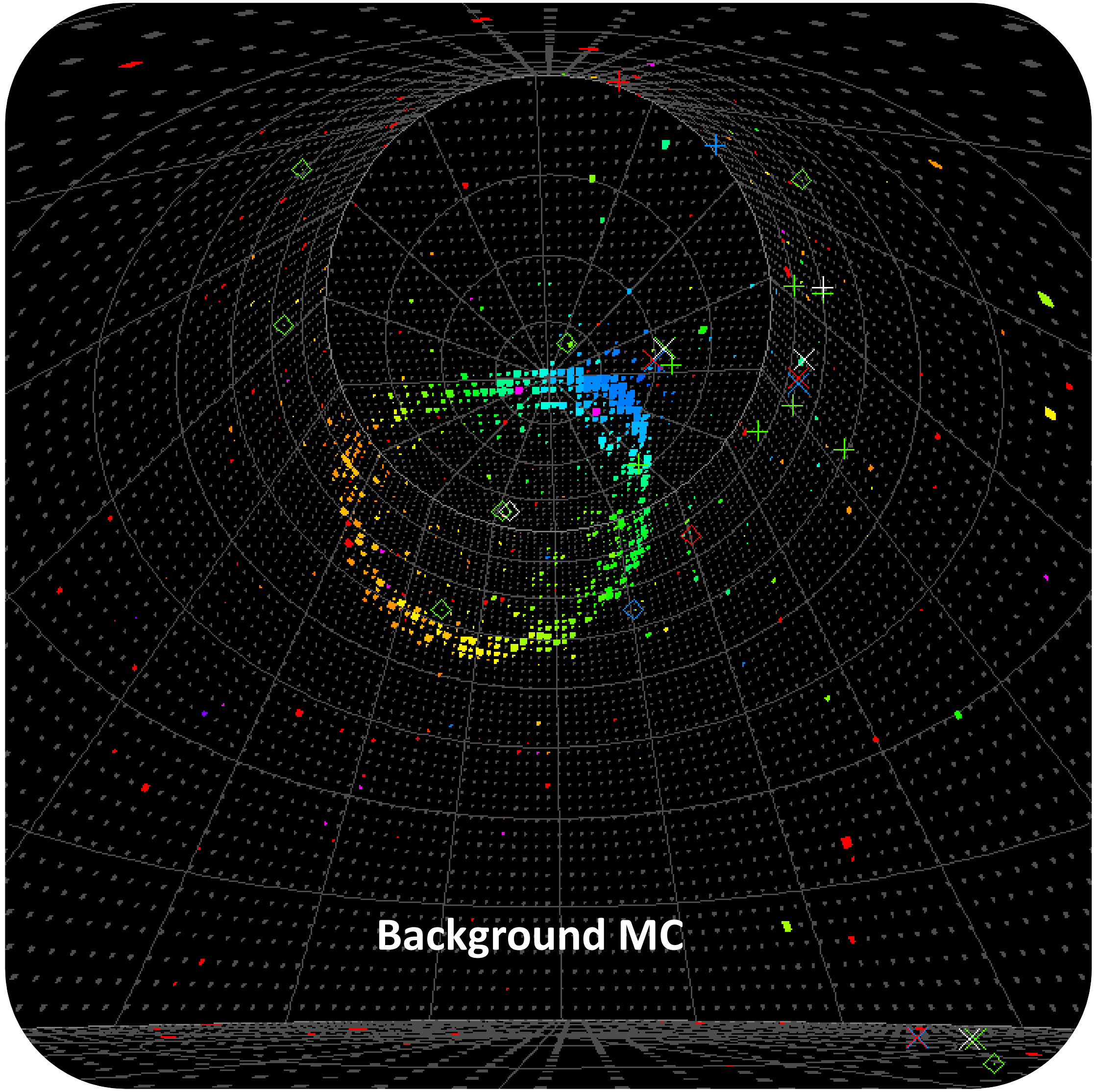
gamma

π^+

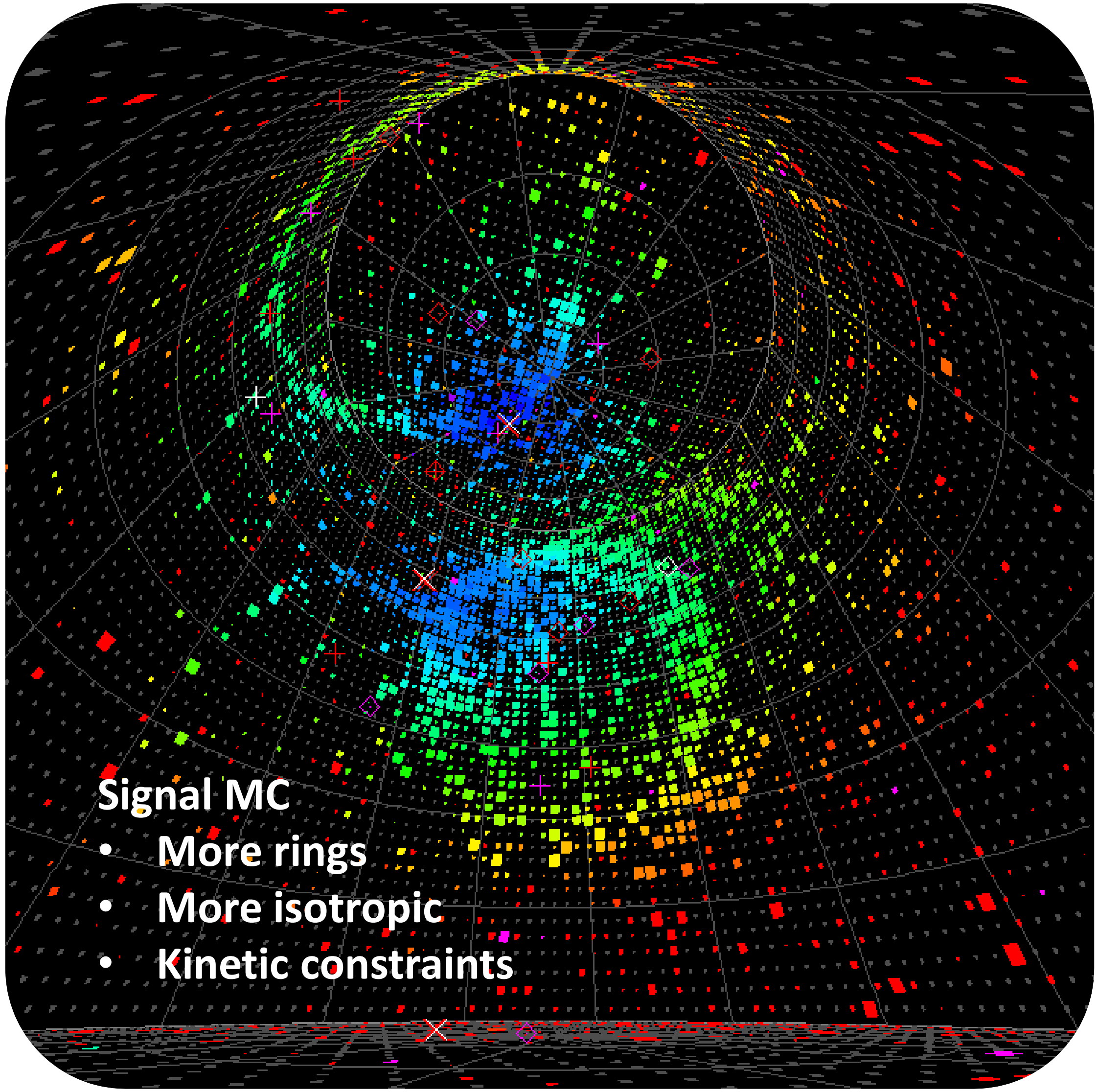
Background

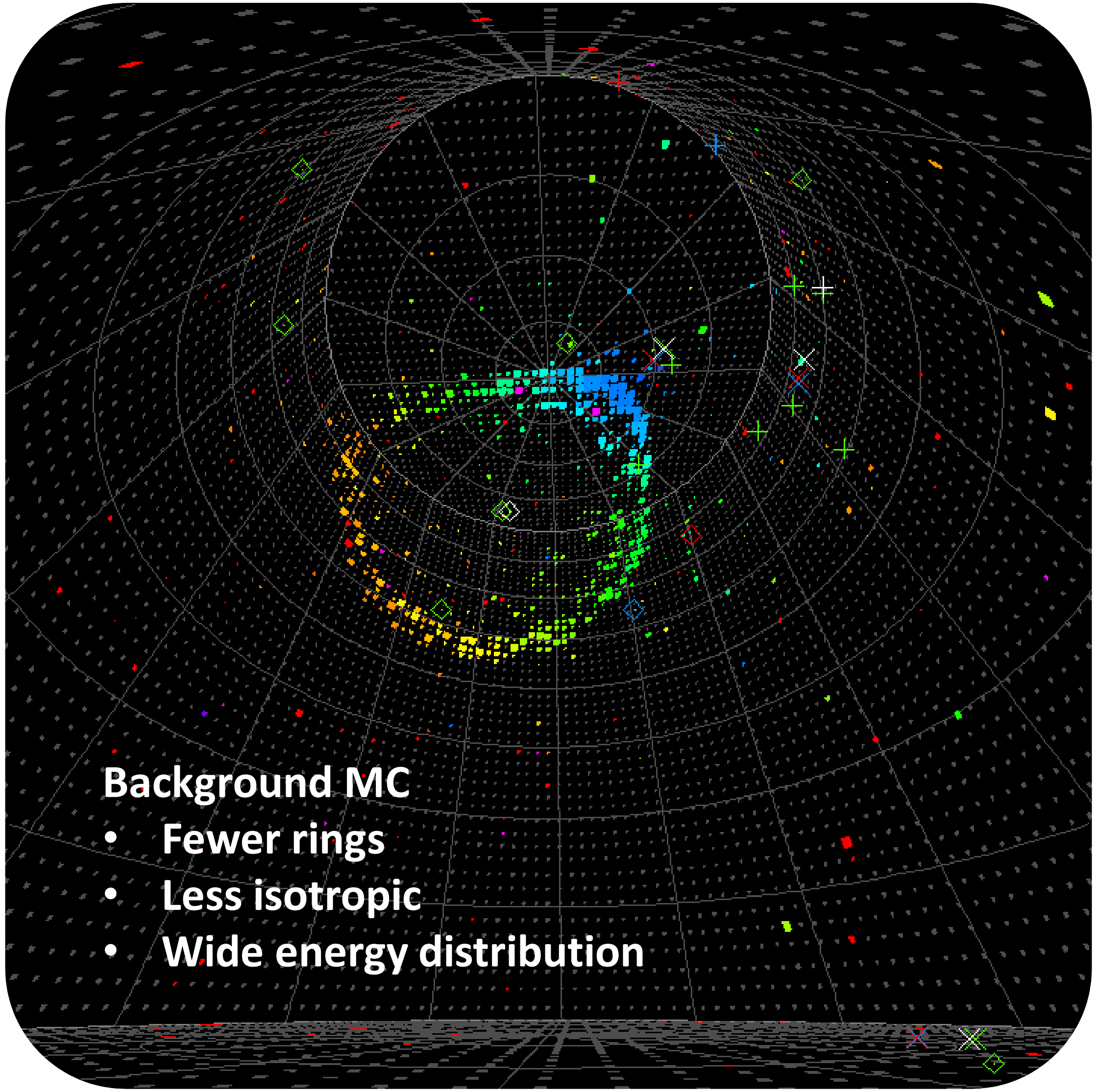
The main background for this analysis at SK is **atmospheric neutrinos**.
Pion production processes and **deep inelastic scattering** produce a similar signature to signal.





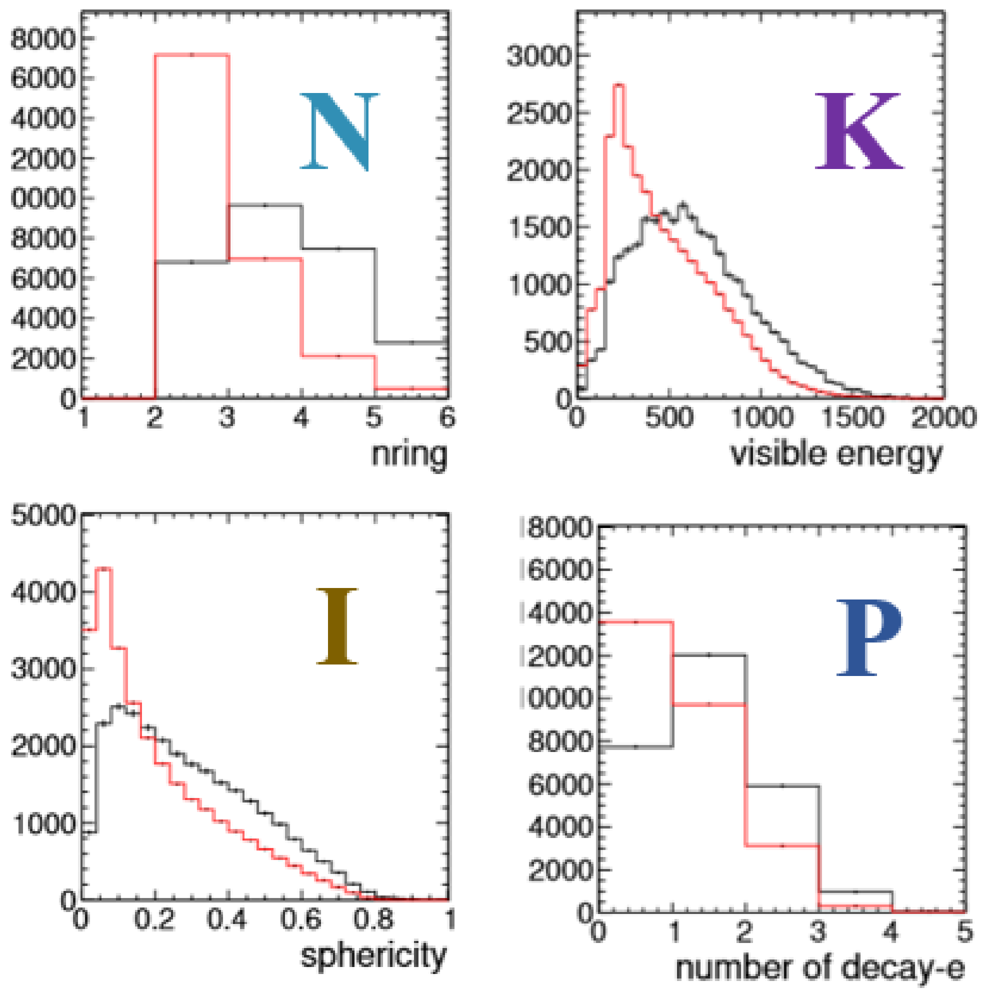
Signal / Background Comparison





Signal / Background Features

Signal v.s. Background

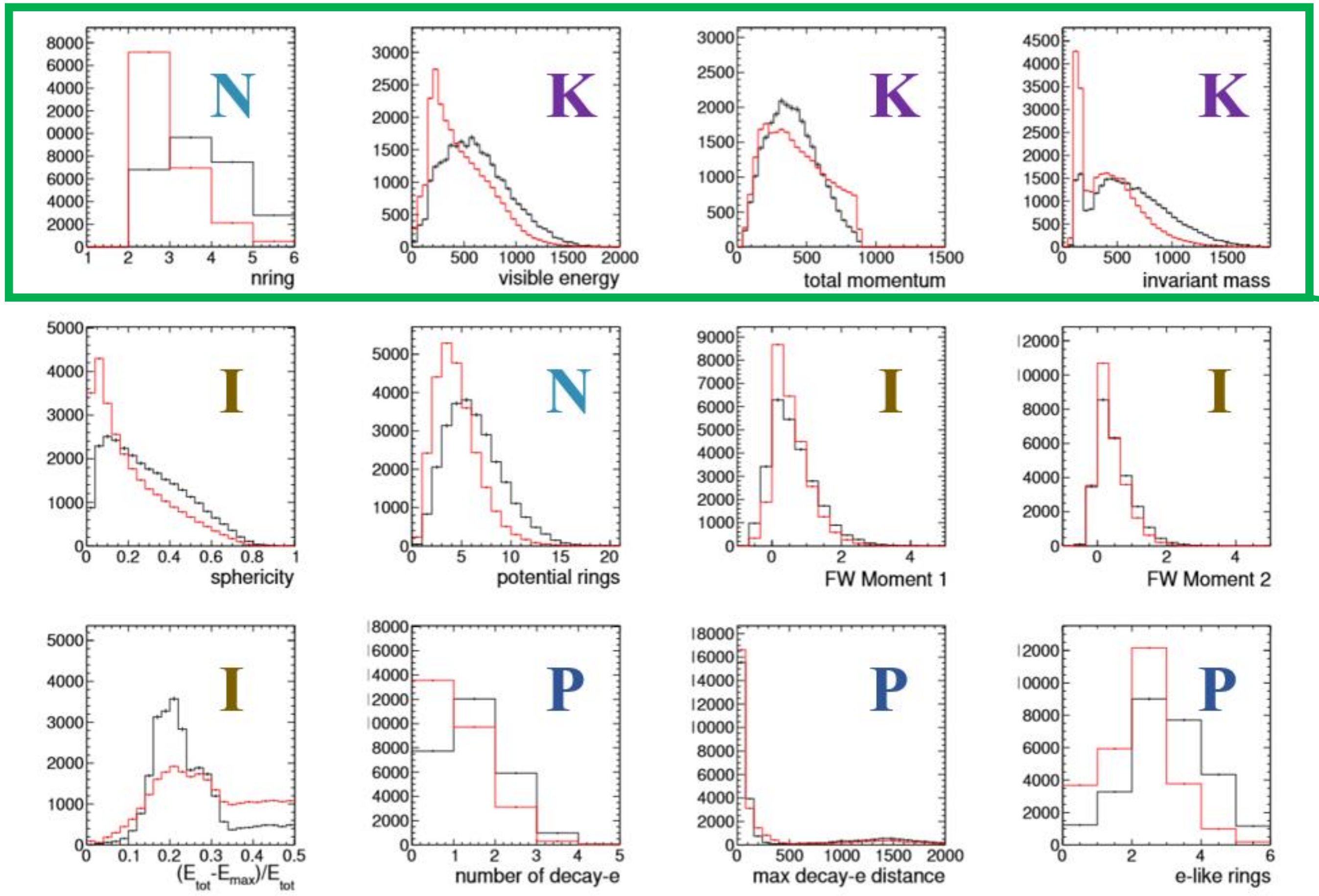


These features can be quantified by variables in four categories: **number of rings**, **kinematics**, **isotropy**, or **PID**.

Signals tend to have **more rings**, **higher visible energy** (constrained by momentum), are **more isotropic**, and have **more decay-electrons** than backgrounds.

Analysis Flow

Signal v.s. Background

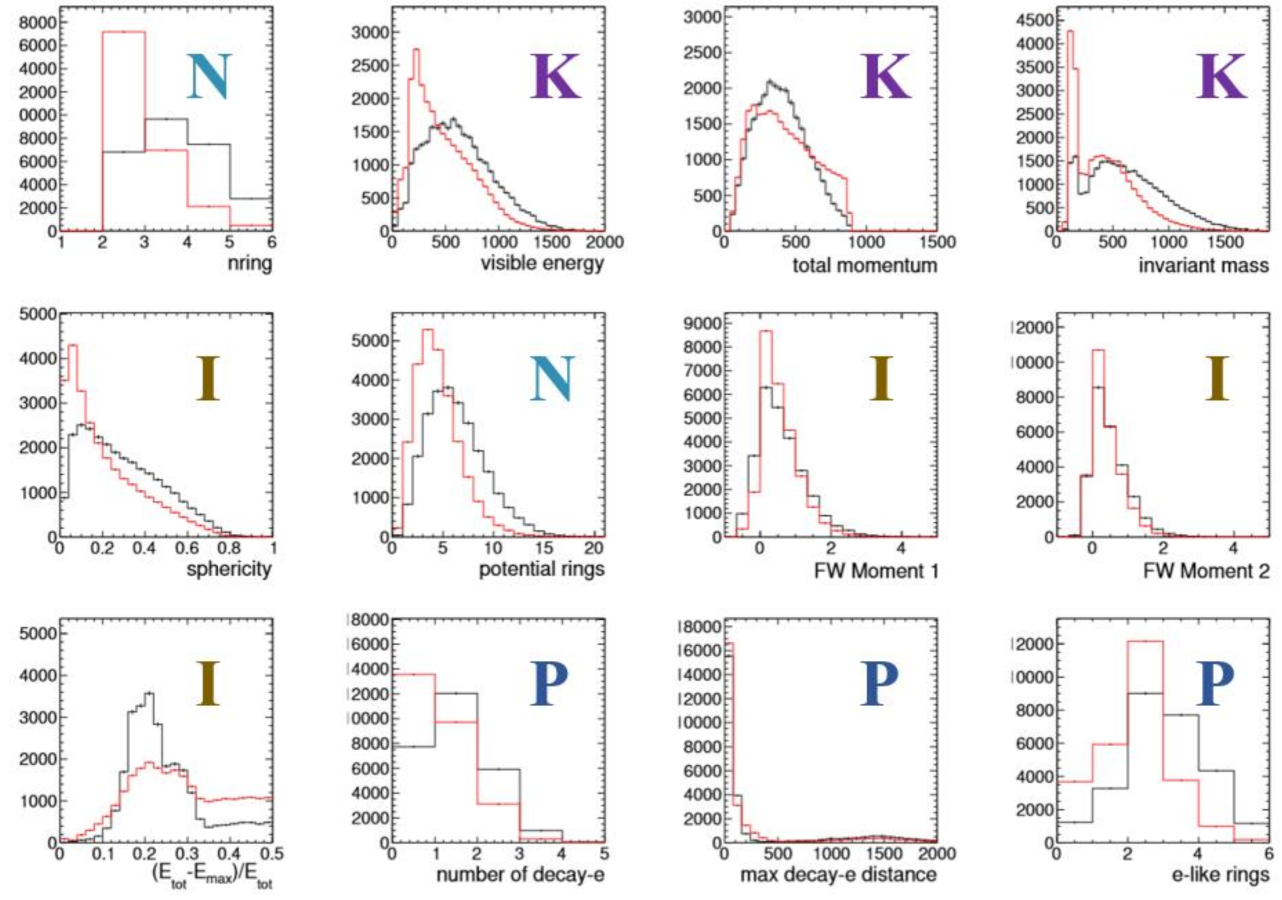


kinematics, **isotropy**, **number of rings**, or **PID**.

1. Similarly, more variables can be constructed. We quantify these features by 12 variables.
2. Among them, **4 conventional variables** (used in SK-I analysis) are selected as pre-cuts to remove non-physics events and some backgrounds at almost 100% signal efficiency.

Analysis Flow

Signal v.s. Background



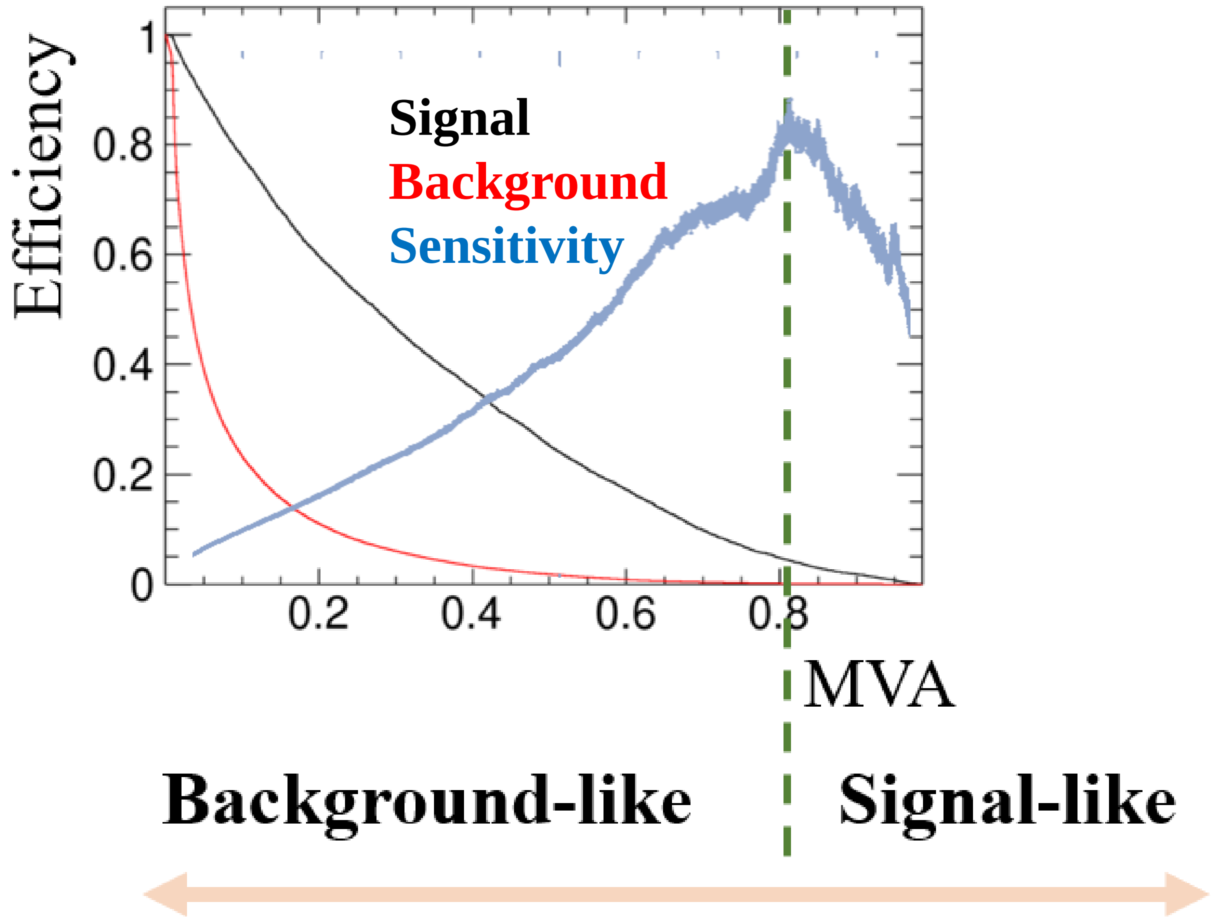
kinematics, **isotropy**, **number of rings**, or **PID**.

3. After pre-cuts, we optimized a multi-variate analysis with these 12 variables, using a multi-layer perceptron.

4. We then evaluate signal efficiency and background rate at every possible cut, and calculate the corresponding sensitivity.

5. The analysis cut is then set at the best sensitivity.

Sensitivity



The cut is optimized towards best sensitivity for 0.37 megaton × years statistics (SK I-IV) with an estimation of systematics.

Signal efficiency: 4.1%

Background rate: 0.56 / year

Sensitivity : 4.3×10^{32} years

(Rolke method)

Systematic Uncertainty

Physics	Sys. on sig. MVA	Sys. on bkg. MVA
Hadronization	4%	\
FSI	31%	\
Fermi motion	7%	\
Neutrino flux/interaction	\	24%
Detector		
E-scale	5%	11%
Non-uniformity	4%	6%
Ring counting	2%	2%
Other MVA vars	4%	7%
Total	33%	28%

Systematic uncertainty for signal efficiency is dominated by **final state interaction**, especially pion absorption within nucleus.

For background rate, it is dominated by **deep inelastic interaction** modeling and cross-section, as well as flux uncertainty.

	Efficiency	Event rate	Systematics
Signal	4.1%		33%
Background		0.56 / year	28%

Comparison with Conventional Analysis

	SK-I Paper	Box-cut method	This analysis
Data set	SK I (1489 days)	SK I-IV (6050.3 days)	
Hadron production	Bubble chamber	Crystal Barrel + Obelix + Bubble chamber	
Final state interaction	ORNL[1]	NEUT π FSI model [2]	
Analysis method	Box cut with same variables		Multi-layer perceptron
Optimization	Conventional	Towards best sensitivity	
Signal eff.	12.1%	3.7%	**4.1%**
Background rate	5.91 / year	0.90 / year	**0.56 / year**
Sensitivity	1.9×10^{32} years	2.0×10^{32} years	$\mathbf{4.3 \times 10^{32}}$ **years**

[1] ORNL-6910

[2] arXiv: 1405.3973

Branching Ratio

$\bar{n}n$ annihilation

	Branching Ratio	Relative Uncer.
$2\pi_0$	0.00065	5%
$3\pi_0$	0.0070	6%
$4\pi_0$	0.0031	6%
$5\pi_0$	0.0092	4%
$6\pi_0$	0.00012	8%
$7\pi_0$	0.0013	8%
$\pi^+\pi^-$	0.0031	4%
$\pi^+\pi^-\pi_0$	0.0154	15%
$\pi^+\pi^-2\pi_0$	0.122	15%
$\pi^+\pi^-3\pi_0$	0.1045	15%
$\pi^+\pi^-4\pi_0$	0.031	14%
$\pi^+\pi^-5\pi_0$	0.013	15%
$2\pi^+2\pi^-$	0.056	16%
$2\pi^+2\pi^-\pi_0$	0.1258	15%
$2\pi^+2\pi^-2\pi_0$	0.1458	15%
$2\pi^+2\pi^-3\pi_0$	0.006	33%
$3\pi^+3\pi^-$	0.021	15%
$3\pi^+3\pi^-\pi_0$	0.0185	15%

$\bar{n}$p annihilation

	Branching Ratio	Relative Uncer.
$\pi^+\pi_0$	0.001	32%
$\pi^+2\pi_0$	0.0068	32%
$\pi^+3\pi_0$	0.143	32%
$\pi^+4\pi_0$	0.0132	32%
$2\pi^+\pi^-$	0.019	10%
$2\pi^+\pi^-\pi_0$	0.164	10%
$2\pi^+\pi^-2\pi_0$	0.104	10%
$2\pi^+\pi^-3\pi_0$	0.291	10%
$3\pi^+2\pi^-$	0.053	10%
$3\pi^+2\pi^-\pi_0$	0.031	10%

This analysis

$\bar{n}p$		$\bar{n}n$	
$\pi^+\pi^0$	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%
$2\pi^+\pi^-\omega$	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%

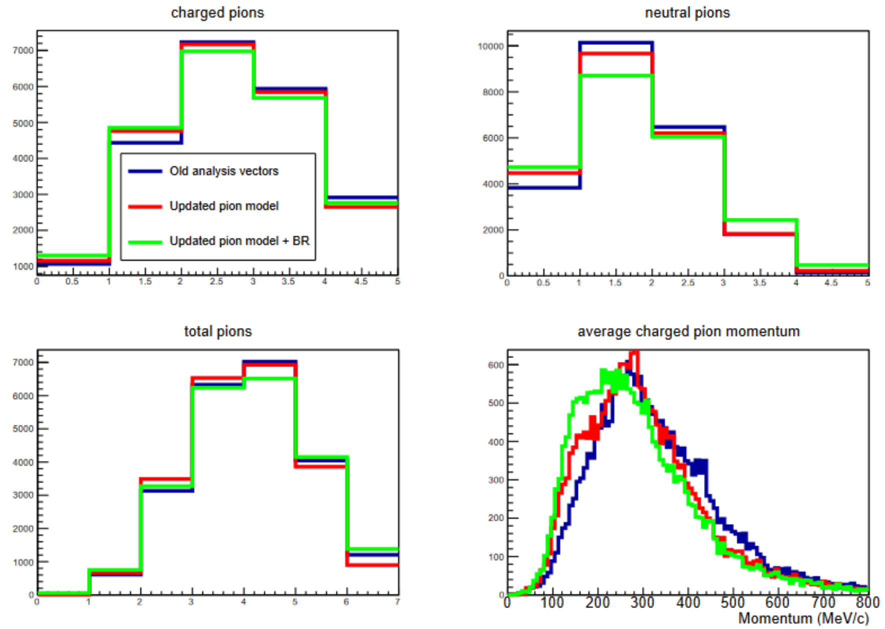
SK-I

Main difference:

- This analysis includes more recent measurement from Crystal Barrel[1] and Obelix[2]

[1] Phys. Rept. 413, 197 (2005)
[2] Phys. Rept. 383, 213 (2003)

Final State Interaction



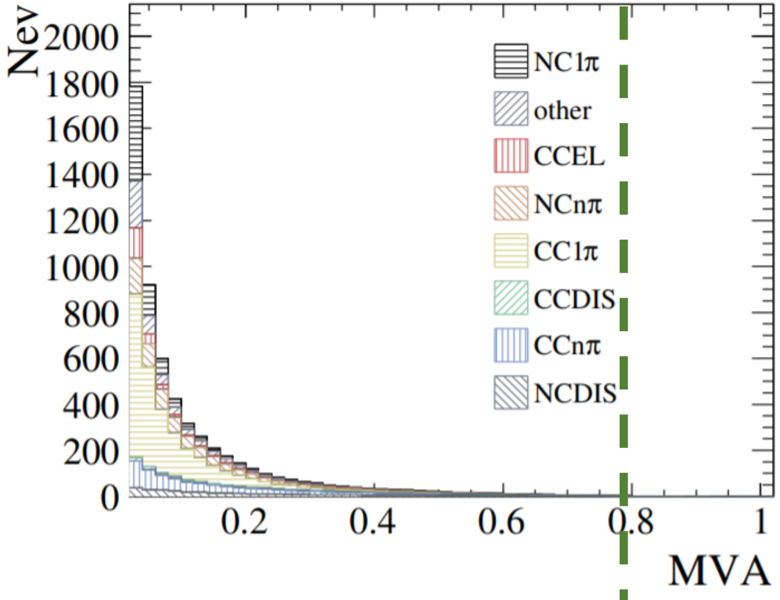
	Abs.	QE	QX	π prod.	No int.
Ref. [23] (SK-I)	24%	24%*		3%	49%
This analysis	21%	20%	23%	3%	30%

Systematic estimation for FSI:
SK-I analysis: 20%
This analysis: 31%

Main difference:

1. Pions in the new model is more interactive
2. SK-I analysis has underestimated the systematic uncertainty from FSI

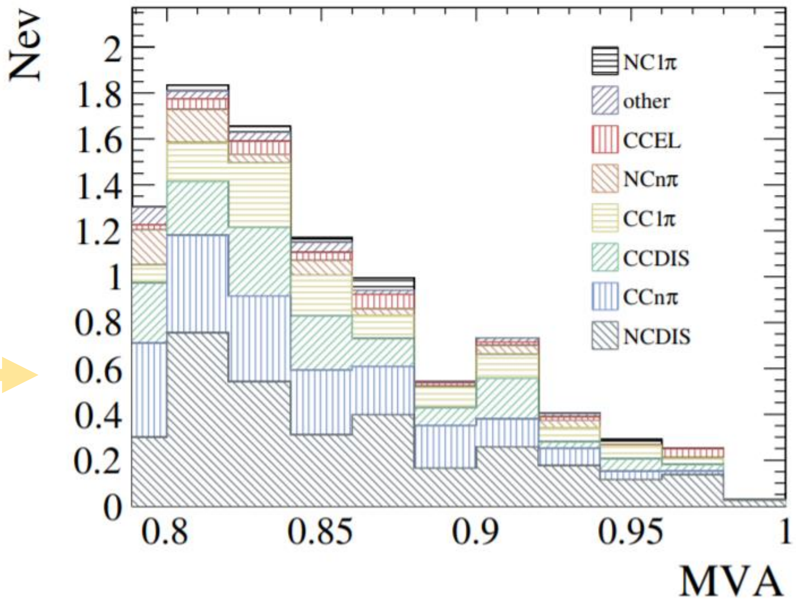
Remaining backgrounds



Before selection
Dominated by CC 1π and NC 1π process.

Signal-like

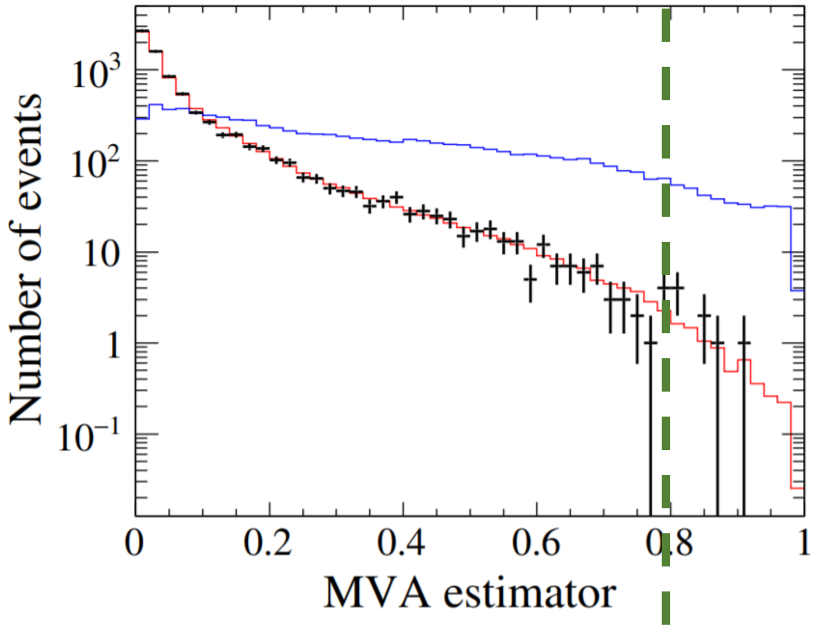
Remaining backgrounds after cuts
Dominated by deep inelastic scattering and CC pion processes.



Channel	MC Nev. (ν_μ)
NCDIS	3.2
CCnpi	2.1 (1.2)
CCDIS	1.5 (0.8)
CC1pi	1.1 (0.7)
NCnpi	0.5
CCEL	0.3 (0.1)
NC1pi	0.1
other	0.3
Total	9.3 (5.8)

= 25.1 / Megaton / year

Open Data



Before selection

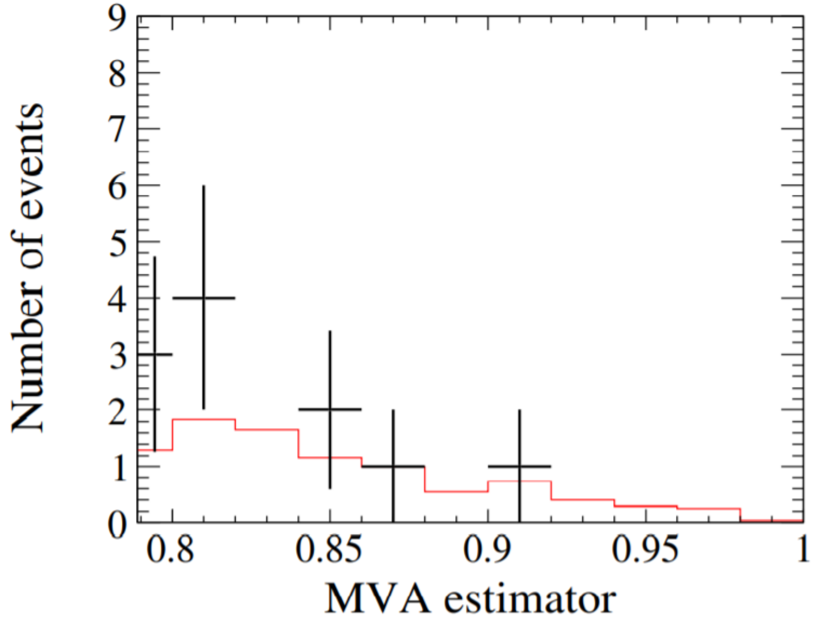
Data distribution is consistent with background MC distribution.
No excess from signal is seen.

Signal-like

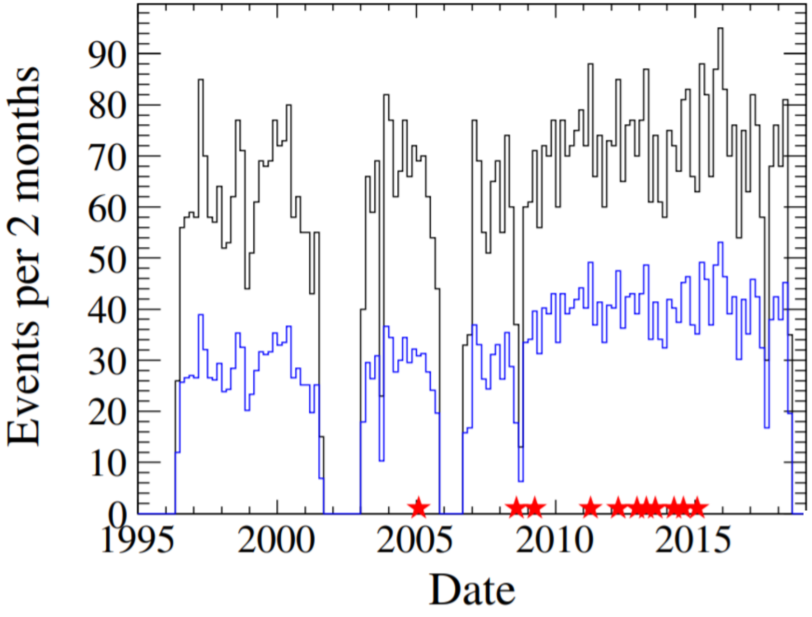
Remaining events after cut

We observed 11 events in data, compared with 9.3 events expected from background MC.

No statistically significant excess of events.



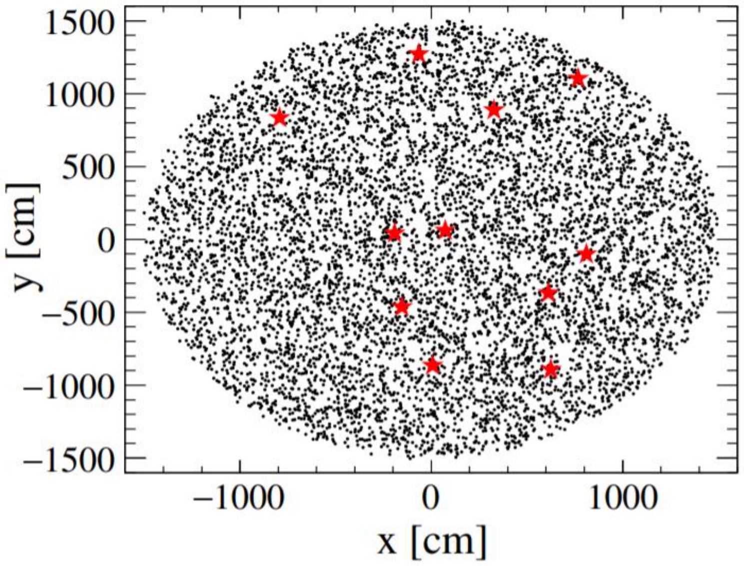
Uniformity Check

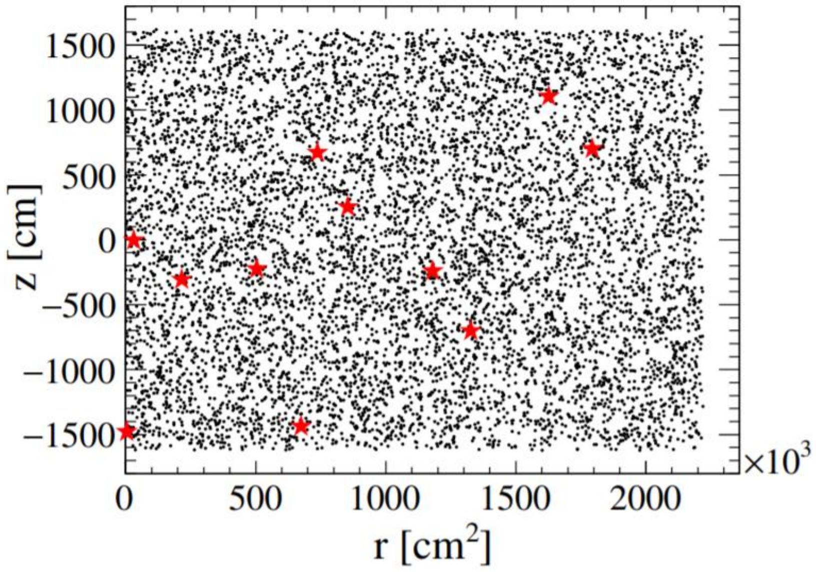


	SK-1	SK-2	SK-3	SK-4
Sig. Eff	3.7%	3.3%	3.7%	4.4%
Bkg. (per year)	0.49	0.47	0.52	0.62
Bkg. (SK-live)	1.98	1.03	0.74	5.50
Data	0	1	1	9

KS test prob=0.14

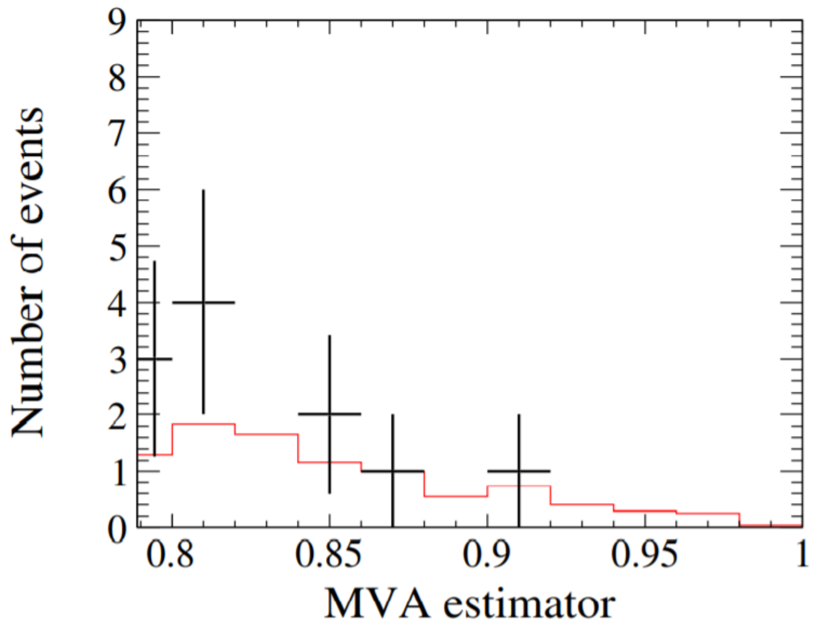
- Time distribution of the observed event (red stars) are consistent with background distribution (blue histogram scaled by 500).
- Spatial observation is consistent with uniform distribution for observed events (red stars) and events after precut (black points).





Result

	Nev	$T_{n\bar{n}}$ (10^{32} yrs)	$\tau_{n\to\bar{n}}$ (10^8 s)
MC	9.3	4.3	5.1
Data	11	3.6	4.7



No statistically significant excess of events has been observed.

The observation limit is set at $\mathbf{3.6 \times 10^{32}}$ **years** at 90% C.L..

Taking R=0.517 × 10^{23} / s, this corresponds to $\boldsymbol{\tau_{n\to\bar{n}} > 4.7 \times 10^{8}}$ **s**

R from Phys. Rev. D78, 016002 (2008)

Comparison with Other Experiments

For better comparison and easier conversion, in this table $\tau_{n\to\bar{n}}$ is presented as $\sqrt{T_{n\bar{n}}/R}$ using the most recent R, regardless of the reported $\tau_{n\to\bar{n}}$ in corresponding paper.

		$T_{n\bar{n}}(10^{32}$ years)	R (10^{23}/s)	$\tau_{n\to\bar{n}}(10^{8}$ s)
^{16}O	SK-I-IV (this study)	3.6	0.517	4.7
^{16}O	SK-I [8] (2015)	1.9	0.517	3.4
^{16}O	Kamiokande [11] (1986)	0.4	0.517	1.6
^{2}H	SNO [9] (2017)	0.1	0.25	1.4
^{56}Fe	Soudan II [10] (2002)	0.7	1.4	1.3
^{56}Fe	Frejus [38] (1990)	0.7	1.4	1.2
^{16}O	IMB [12] (1984)	0.2	0.517	1.2
Free neutron	Grenoble [7] (1994)	-	-	0.9

*SK-I paper considered uncertainty in theoretical prediction of R. Reported $2.7 \times 10^{8} \to 3.4 \times 10^{8}$ in the table

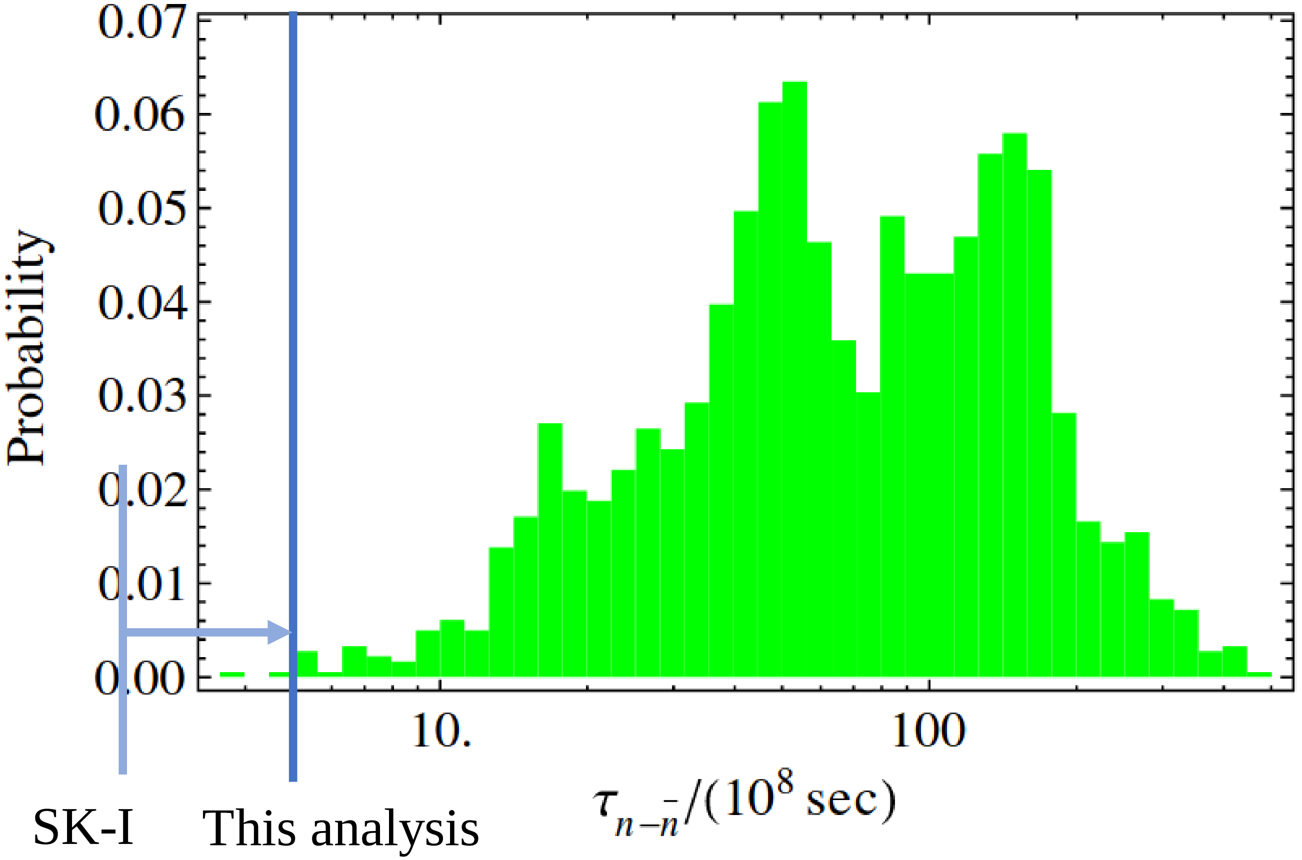
*Old papers before 2000 typically report $\tau_{n\to\bar{n}}$ with R=1. In this table $\tau_{n\to\bar{n}}$ is scaled by $\sqrt{1/R}$.

Comparison with Theoretical Prediction

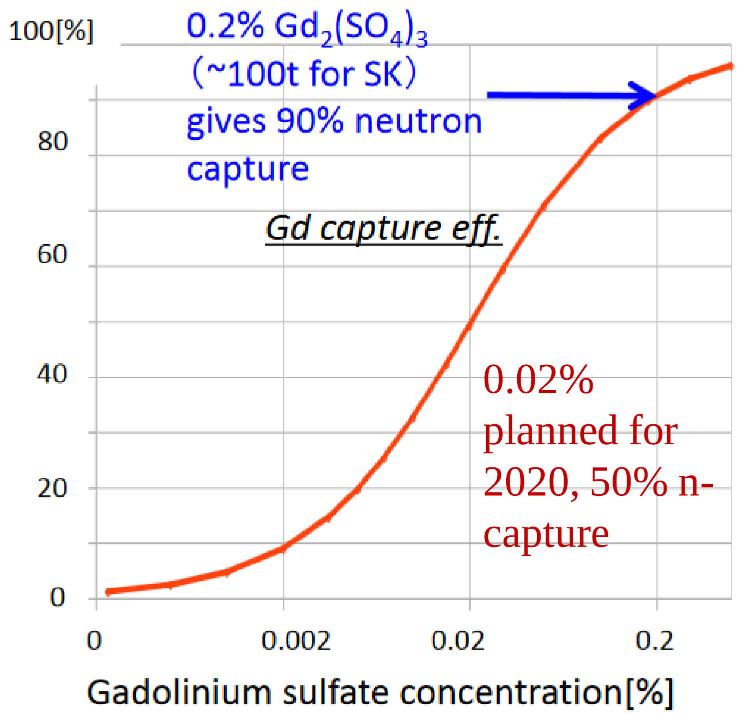
Reaching the range of theoretical prediction

Green from PSB model
PRD 87 115019 (2013)

Blue from this analysis



NNbar Future at SK-Gd: neutron multiplicity!

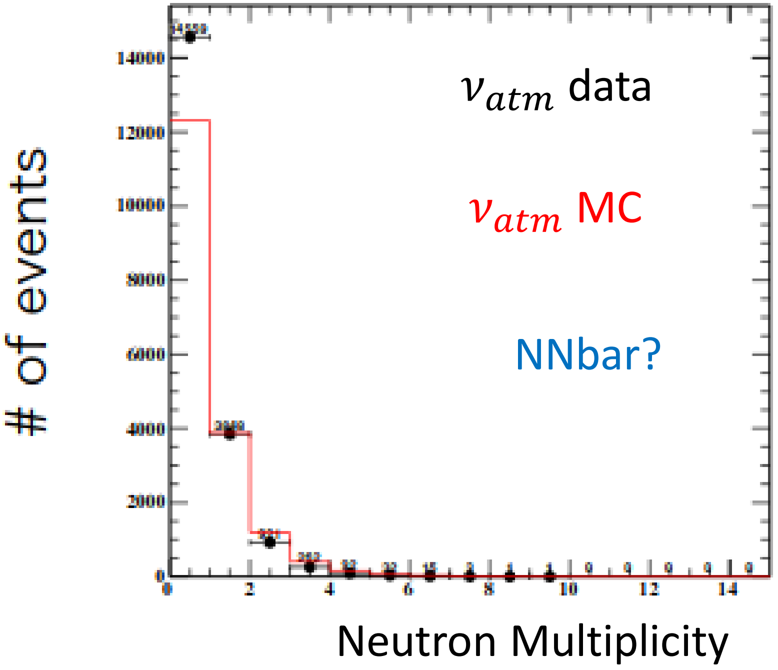


SK I-V: pure water	SK-Gd: Gd-loaded water

1996 ⟶ 2020 ⟶

- Expect better rejection of background when **nnbar neutron multiplicity** is understood

- Gd loading in operation
- Neutron tagging efficiency will be increased from 25% to 90%.

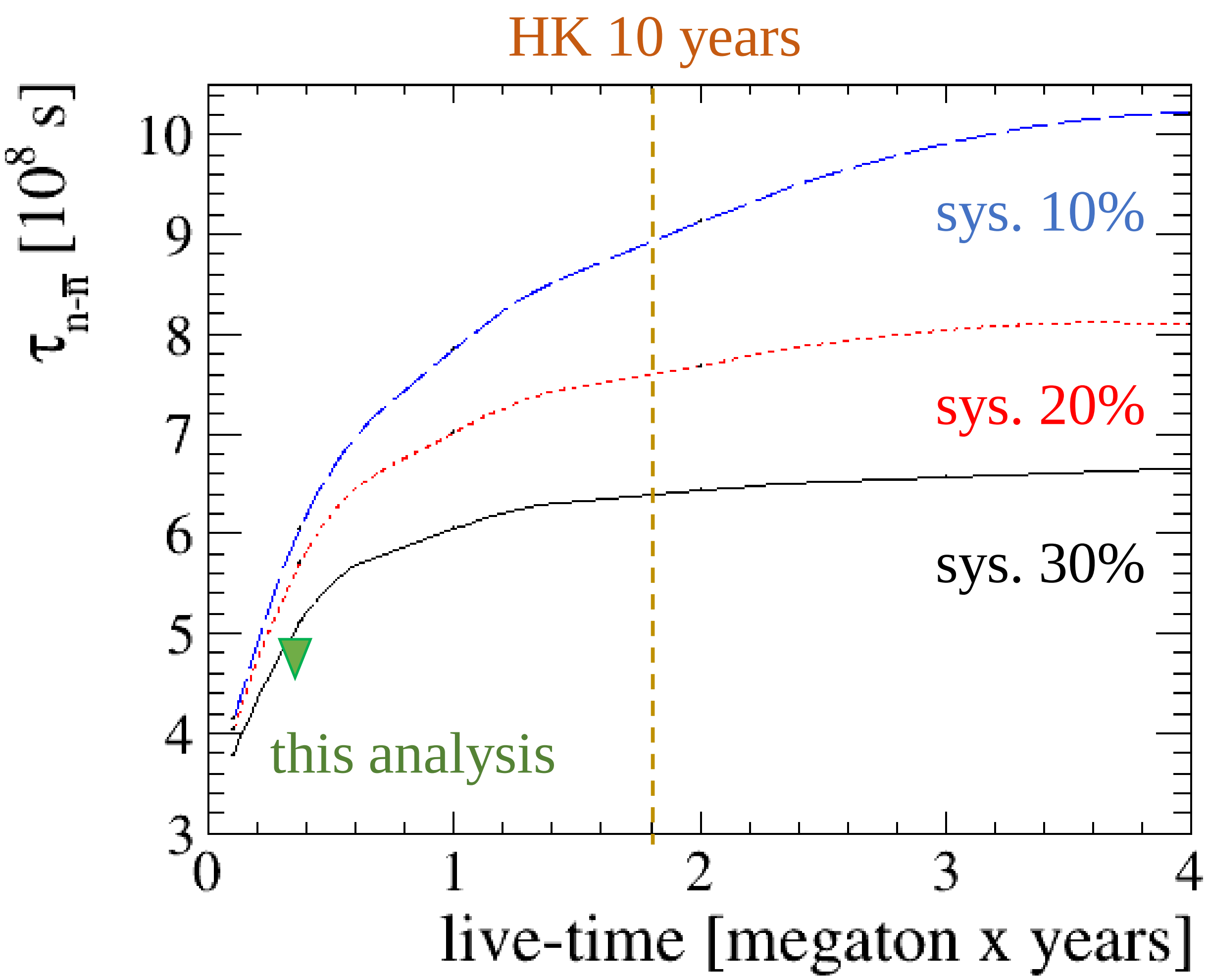


NNbar Future at HK: tackle systematics!

Assuming the same signal efficiency and background rate, we show the sensitivity curves with present **sys. uncer. (~30%), 20%, and** 10% for both signal and bkg.

This analysis: SK I-IV, 0.37 Mton × yrs
HyperK: 0.18 Mton × 10 yrs, (1 module)

Soon this search will be **systematically constrained**. Calling for further study on final state interaction and neutrino bkg…



*This is NOT from HyperK collaboration.

Conclusion

- SK obtained the strongest constraints for $n - \bar{n}$ oscillation so far at neutron lifetime $\mathbf{3.6 \times 10^{32}}$ **years**, corresponding to neutron oscillation time at $\mathbf{4.7 \times 10^{8}}$ **s**.
  - Large exposure (SK I-IV, 0.37 megaton × years)
  - Multi-variate analysis
  - Updated final state interaction and hadron production simulation

- In future, water Cherenkov experiment is expected to push forward the limit for bound neutron oscillation search
  - SK-Gd: better background rejection
  - HK: larger FV of 0.18 megaton

Thank you for your attention!

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