Optimization of neutron tagging for DSNB search in SK-Gd

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Abstract

For the detection of diffuse supernova neutrino background (DSNB), the SK-Gd experiment was started with a 0.01% gadolinium (Gd) concentration (SK-VI) in August 2020. The concentration was increased to 0.03% (SK-VII) in July 2022. We increased the anti-electron neutrino sensitivity by detecting the total 8MeV gamma from Gd neutron capture.

We developed a neural network (NN) that effectively selects the neutron capture events and rejects the BG events. In this study, we evaluated the neutron capture efficiency in SK-VII using the NN and obtained higher capture efficiency than the conventional method with low BG contamination. We performed the first DSNB search analysis with SK-VII data using this NN.

1. Diffuse Supernova Neutrino Background(DSNB)

◎**What is DSNB?**

Background flux of neutrinos originating from all past core-collapse supernovae in the universe.

→ The flux is low, even Super-Kamiokande, the detection rate is expected to be 0.5~5 events per year.

◎**Why do we search DSNB?**

It provides insights into the population and properties of supernovae throughout cosmic history.

The DSNB flux F(E_ν) in the Earth

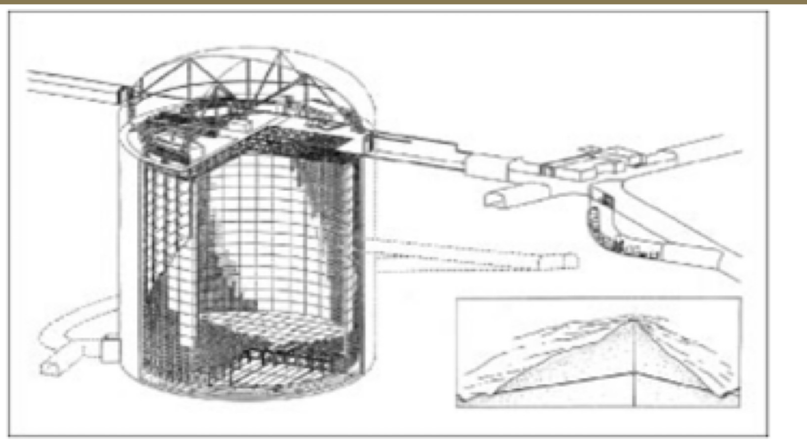
$$\frac{dF(E_\nu)}{dE_\nu} = c\int_0^{z_{max}} \frac{dz}{H_0\sqrt{\Omega_m(1+z)^3}} \times [R_{cc}(z)\int_0^{Z(max)} \psi_{ZF}(z,Z)\left\{\int_{M_{min}}^{M_{max}} \psi_{IMF}(M)\frac{dN(M,Z,E'_\nu)}{dE'_\nu}dM\right\}dZ]$$

$H_0 = 70kms^{-1}Mpc^{-1}, \Omega_m = 0.3,\ z: the\ red\ shift, E'_\nu = (1+z)E_\nu$

2. Super-Kamiokande(SK)

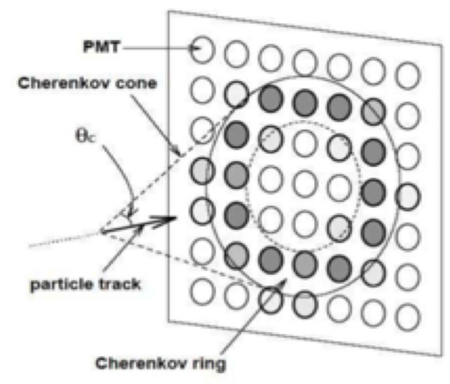
◎**What is Super-Kamiokande?**

- 50 kiloton water Cherenkov detector located 1000m underground in Japan.
- **11129 50cm PMTs in Inner Detector**
- **1885 20cm PMTs in Outer Detector**



◎**How to observe neutrinos**

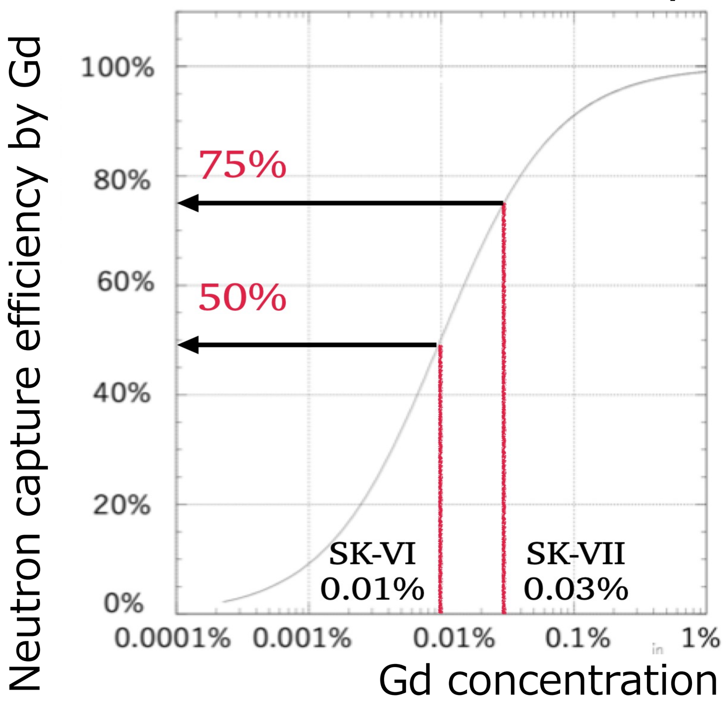
- By detecting Cherenkov light produced when neutrinos interact with water and charged particles travel in the inner detector



→We measure the vertices of the interactions and energy by reconstructing the observed charged leptons! (1MeV ~ 6hits)

3. Inversed Beta Decay(IBD) and neutron capture

- Gadolinium sulfate Octa-hydrate was loaded in SK to increase the detection efficiency of IBD.



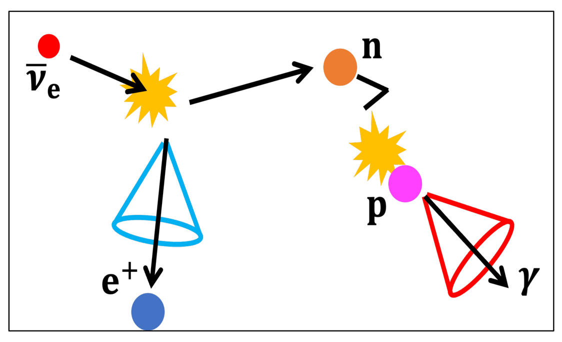
$$\overline{\nu_e} + p \rightarrow e^+(Main\ tagrget) + n$$

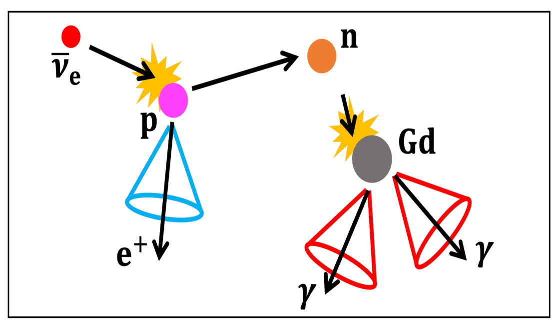
$${}^1H + n \rightarrow {}^2H + \gamma(mono\ 2.2MeV)\ \text{or}\ {}^ZGd + n \rightarrow {}^ZGd^* \rightarrow {}^ZGd + \gamma(Total\ 8MeV)$$

- To tag this interactions, **the e⁺(prompt event) and the gamma from neutron capture should be identified.**

→ An effective algorithm to tag neutrons **must be implemented.**

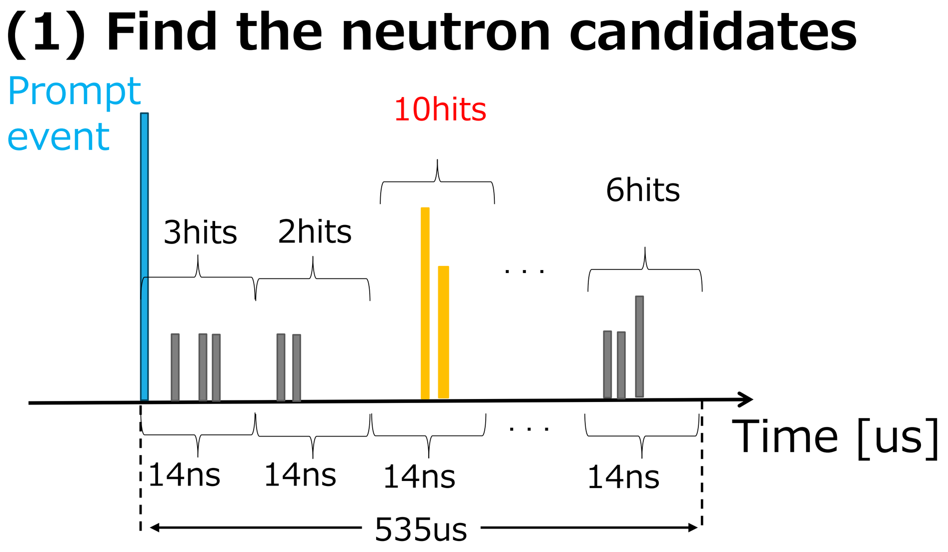
- **Neural Network, a machine-learning method, is used to evaluate performance.**





4. Neutron tagging with Neural Network(NN) through TMVA (ROOT library)

(1) Find the neutron candidates



NHits: The number of PMT hits in 14nsec.

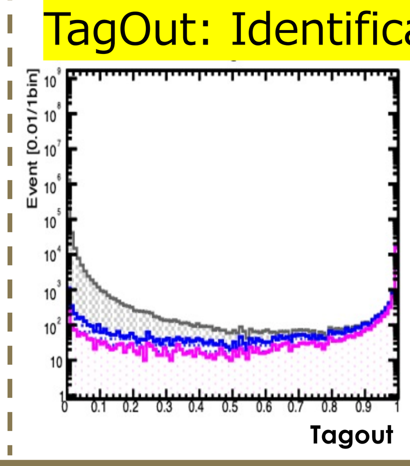
The events NHits ≥7hits within 535μs after prompt events are selected as neutron capture candidates!

(2)Prepare 12 variables

- PMT hits
- PMT hit timing
- Mean direction from SK wall
- Harmonic Beta parameters
- Hit pattern

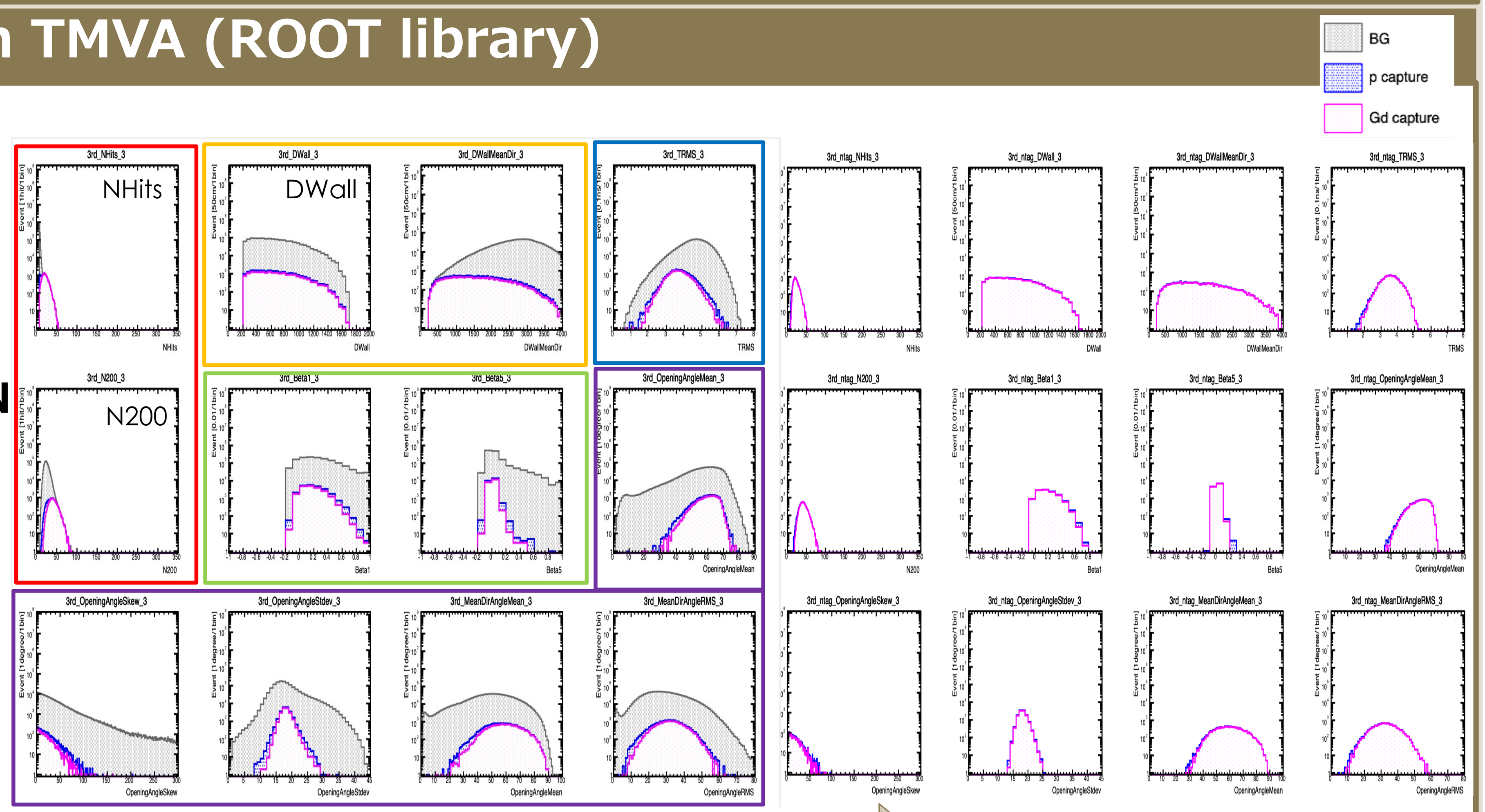
(3)Input the variables into NN and get TagOut value

TagOut: Identification value (0 to 1)



- **Set the threshold of TagOut**

→Find the best threshold within the BG contamination rate < 0.02%



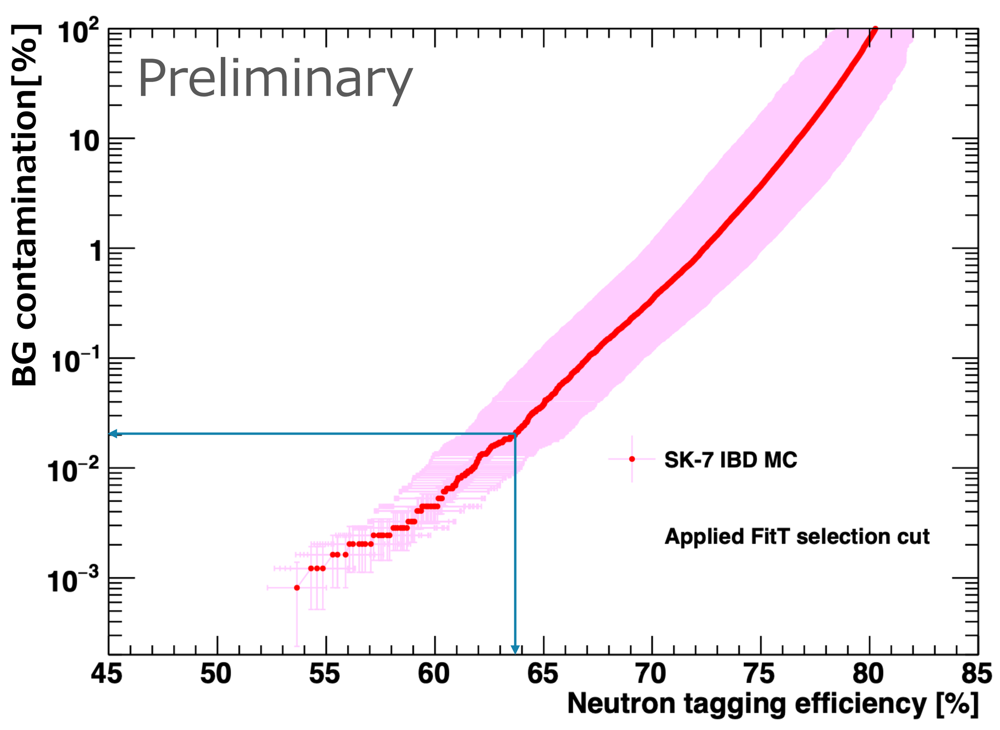
Before TagOut selection TagOut>0.98 After TagOut selection

5.Optimization of TagOut threshold with IBD MC

- **The used MC: e⁺ (0~90MeV) and neutrons are emitted uniformly in SK with Gd**
- **Evaluated the neutron tagging efficiency and BG contamination defined as follows and summarized them in the ROC curve.**

$$\text{Neutron tagging efficiency[\%]} = \frac{\text{Total number of tagged Gd and proton events}}{\text{Total number of prompt events}}$$

$$\text{BG contamination[\%]} = \frac{\text{Total number of tagged BG events}}{\text{Total number of prompt events}}$$

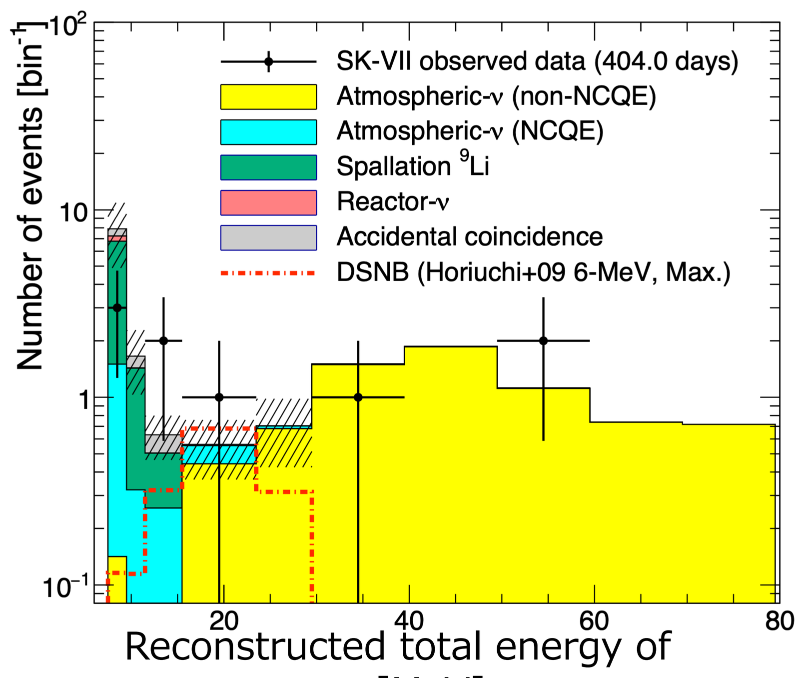


Tagg. efficiency: 63.3±2.2%
when BG contami. = 0.018±0.003%
(TagOut > 0.98)

※ Breakdown of systematic errors of NN

Summary table	Absolute sys err
Time variation	0.6%
Position dependence	0.5%
Discrepancy between Data and MC	~3.4%

6. Energy spectrum of tagged events in SK-VII



Reconstructed total energy of prompt event[MeV]

- Among various DSNB models, **Horiuchi+09 model is shown as DSNB signal** Phys. Rev. D 79, 083017 (2009)
- Background events could be
  - **Atmospheric neutrinos**
    - Decay electrons from muons or pions
    - CCQE or NCQE interactions
  - **Radioisotope decay with neutrons from Muon spallation and Litium-9**
  - **Reactor $\overline{\nu_e}$**

→Low BG level is achieved. More statistics are needed to see DSNB

7. Summary and Prospects

- DSNB search has been conducted for 404 days of SK-VII data with Neural Network, in which the performance of selecting neutron capture events has been improved from the conventional method.
- For the next, the upper limit to the DSNB flux will be derived.