Neutrino-oxygen Neutral Current scattering measurement in the T2K Far detector (Super-Kamiokande)

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OKAYAMA UNIVERSITY

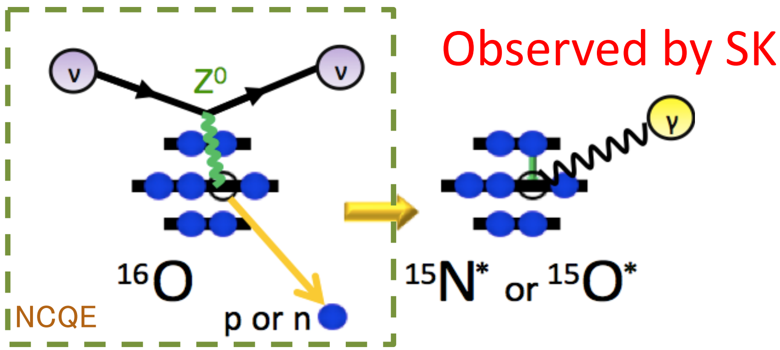
T2K

Outline

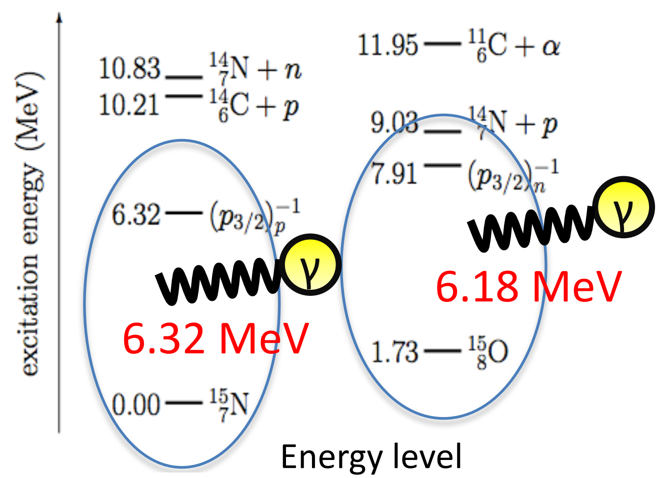
- Introduction
- Current result in NCQE cross section
- Future prospect
  - Data update
  - Neutron tagging
  - SK-Gd
- Summary

NCQE

Neutrino-oxygen Neutral Current Quasi Elastic(NCQE) interaction

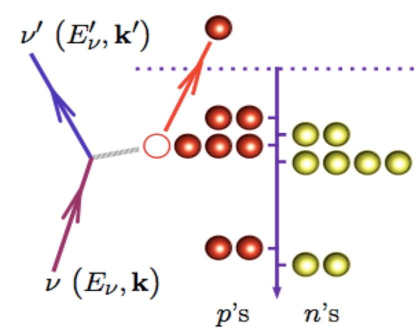


A. Ankowski et al.: Phys. Rev. Lett. 108, 052502 (2012)

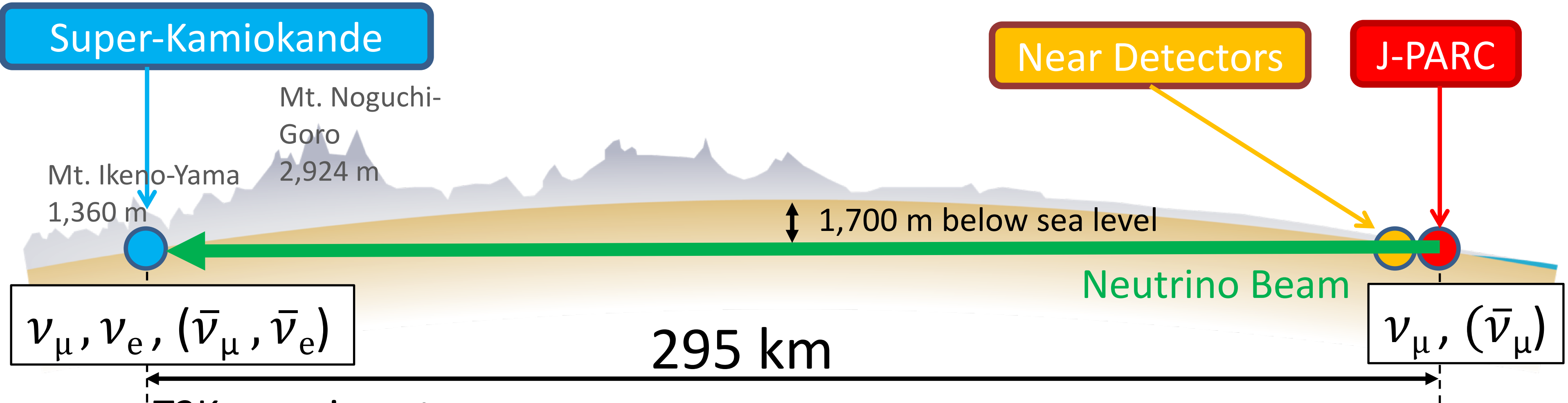


Energy level

1. Nucleon is knocked out via NCQE interaction from nucleus of Oxygen.
   - ➢ Excitation of nucleus
     - ◆ Excited state at 6.32 MeV of ^{15}N
     - ◆ Excited state at 7.91 MeV of ^{15}O
2. Nucleus emits de-excited gamma rays when the excited nucleus returns to the ground state
3. De-excited gamma rays are observed in SK.



T2K experiment

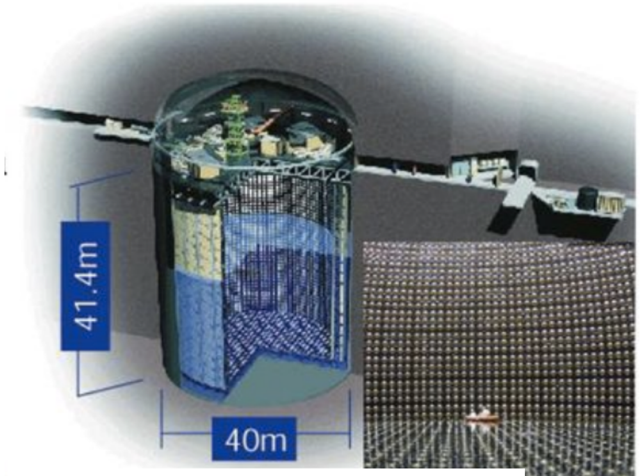


- T2K experiment
  - Neutrinos are produced at J-PARC and detected at 295km away SK
  - 2.5° Off axis beam (630 MeV peak energy)
  - Far detector is Super-Kamiokade
  - Main purpose is measurement of neutrino oscillation parameters.

- T2K experiment is good for observation of NCQE interaction.
  - T2K beam has well known beam energy and flux.
  - NC measurement does not depend on the neutrino oscillation.
  - Energy range is similar to the atmospheric neutrino.

Super-Kamiokande

- Super-Kamiokande
  - T2K far detector
  - 50kton pure water Cherenkov detector
  - Sensitive energy is low enough to see NCQE event

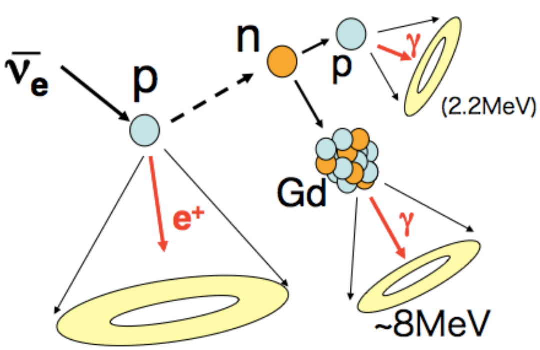


Super-Kamiokande

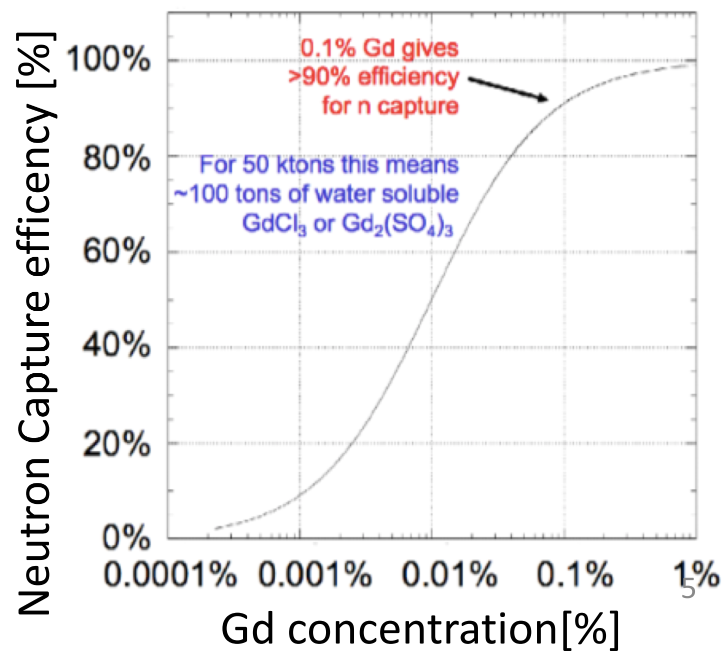
- SK-Gd (currently in upgrade process)
  - Dissolve Gadolinium($Gd_2(SO_4)_3$) into Super-K
  - Identify $\overline{\nu}_e$-p events by neutron tagging with Gd.
  - Gd and thermal neutron have very large cross section and emits total 8 MeV gamma rays.

Main Physics targets:

- Supernova relic neutrino (SRN)
- Neutrino/anti-neutrino discrimination

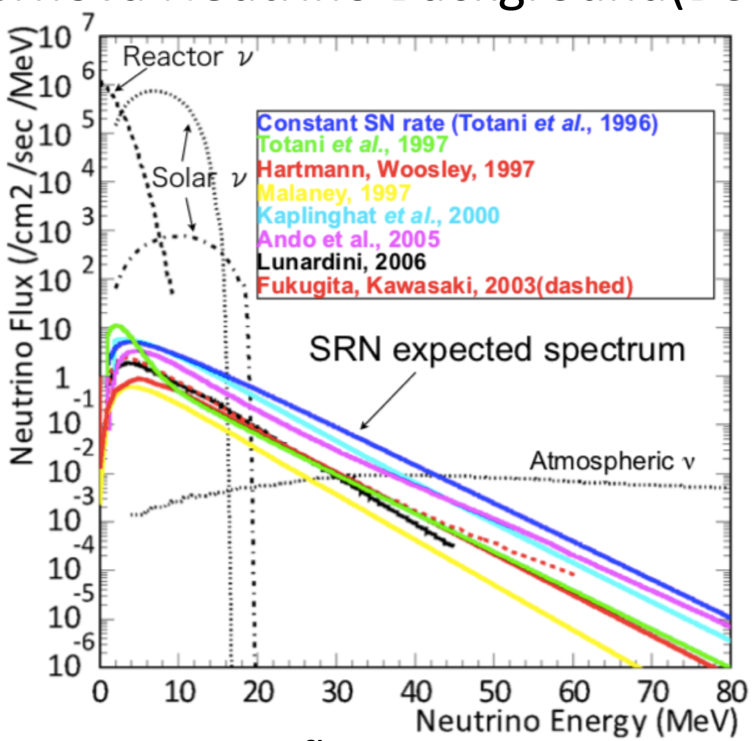


SRN at SK-Gd



Diffuse Supernova Neutrino Background

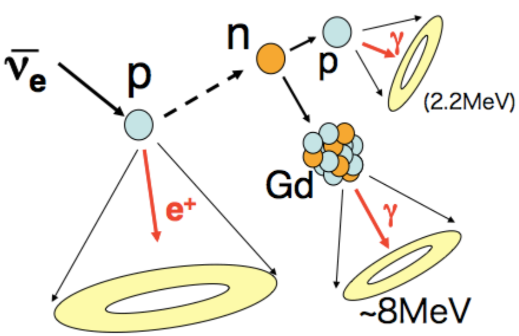
- Core collapse supernova in universe history released many supernova neutrinos. Those neutrinos are still in existence everywhere in universe.
  - Those are referred to as Supernova Relic Neutrino(SRN) or Diffuse Supernova Neutrino Background(DSNB).



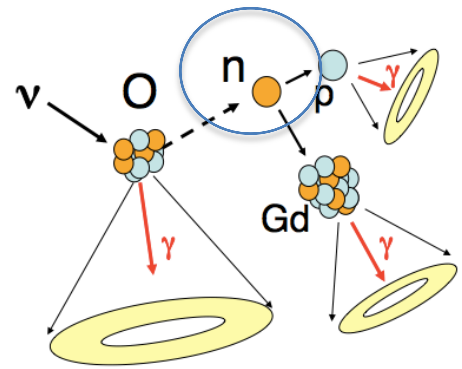
SRN flux estimation

Motivation of NCQE measurement

- NCQE interaction of atmospheric neutrino is one of the main background of SRN measurement in SK-Gd.
  - Similar to the signal



SRN (Real signal)



NCQE interaction(Background signal)
Mainly atmospheric neutrino

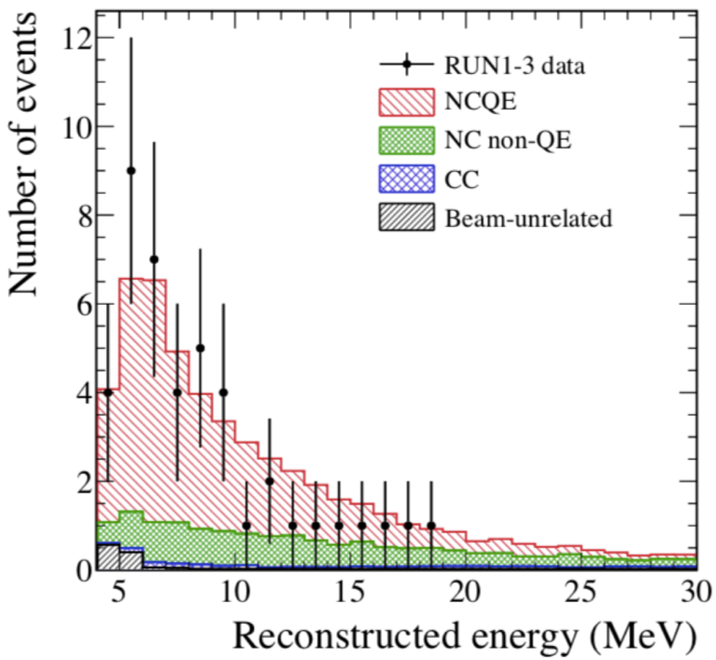
➢ Need to understand the NCQE cross section and neutron emission rate and multiplicity

➢ NCQE in T2K beam interaction is very well identify able with beam timing gate

NCQE cross section

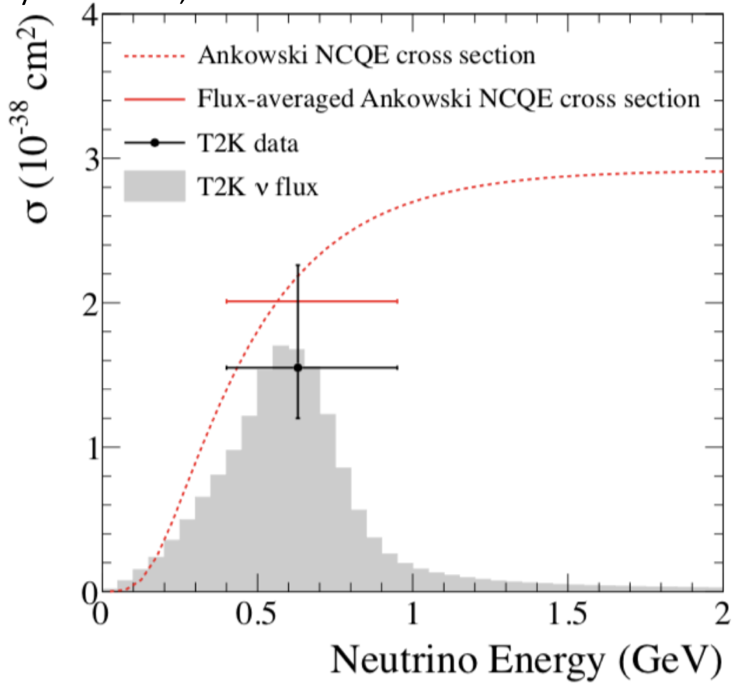
Published result

- T2K Run1~3 (~Jun, 2012, POT : 3.01×10^{20})
  - 43 de-excitation gamma's (include background)



De-excitation gamma ray energy distribution

Phys. Rev. D **90**, 072012 – Published 31 October 2014



NCQE cross section

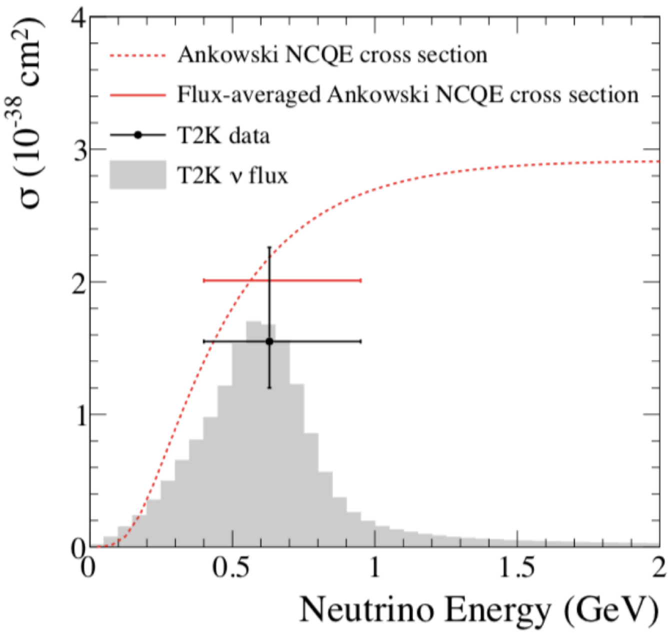
$$< \sigma^{obs}_{\nu,NCQE} > = 1.55 \times 10^{-38}\ cm^2 \pm 0.395(Stat.)\ ^{+0.65}_{-0.33}\ (sys.)$$

NCQE cross section

- How to calculate of NCQE cross section
  - Take a ratio with theory which is calculated by Ankowski
    - Ref: Phys. Rev. Lett. **108**, 173901 – Published 24 April 2012

$$< \sigma^{obs}_{\nu,NCQE} > = \frac{N^{obs} - N^{exp}_{bkg}}{N^{exp}_{total} - N^{exp}_{bkg}} < \sigma^{Theory}_{\nu,NCQE} >$$

$N^{obs} = 43$ Number of observation (include background)
$N^{exp}_{bkg} = 16.2$ Number of background by MC
$N^{exp}_{total} = 51.0$ Number of signal MC estimation
$\sigma^{Theory}_{\nu,NCQE} = 2.01 \times 10^{-38}$ Cross section theory



Result

$$< \sigma^{obs}_{\nu,NCQE} > = \frac{43 - 16.2}{51.0 - 16.2} \times 2.01 \times 10^{-38} = 1.55 \times 10^{-38}\ cm^2$$

Systematic uncertainties

- 6 types of systematic errors are considered.

Interactions	NCQE	NCother (Background)	CC (Background)	beam-unrelated
Fraction	68%	26%	4%	2%
T2K beam flux	11%	10%	12%	—
Cross-section	—	18%	24%	—
Detector response	2.2%	2.2%	2.2%	—
Oscillation parameters	—	—	10%	—
Primary γ	15%	3%	9%	—
Secondary γ	13%	13%	7.6%	—
Total Systematic error	23%	25%	31%	0.8%

$$< \sigma_{\nu,NCQE}^{obs} > = 1.55 \times 10^{-38}\ \ cm^2 \pm 0.395(Stat.)\ {}^{+0.65}_{-0.33}\ (sys.)$$

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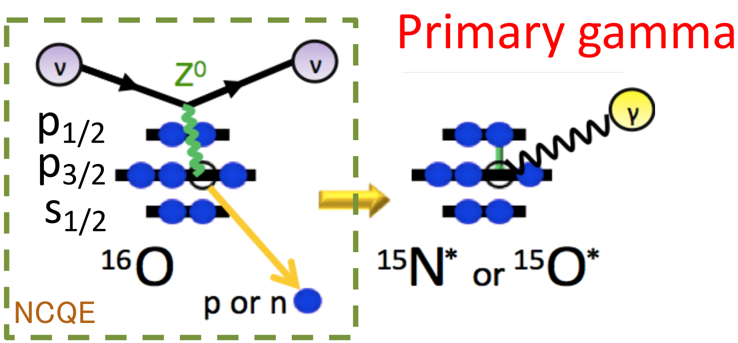
Large error

T2K beam flux error already reduced → A few %

$$< \sigma^{obs}_{\nu,NCQE} > = 1.55 \times 10^{-38} \ cm^2 \pm 0.395(Stat.)\ ^{+0.65}_{-0.33}\ (sys.)$$

Plan for reevaluation of systematic uncertainties

Primary gamma emission model



Excited states

$p_{1/2}$: no gamma emission

$p_{3/2}$: gamma emission (6.18, 6.32 MeV, etc…)

$s_{1/2}$: particle decay + gamma emission

others: higher state than s1/2, physics not known well

"others" is treated as non gamma emission in our setting.

Spectroscopic factor

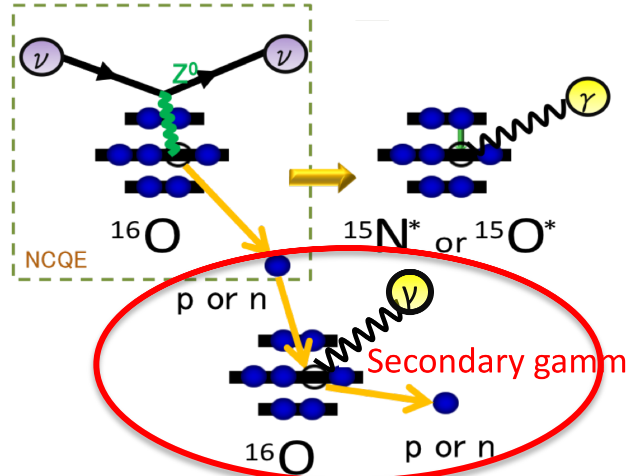
Residual nucleus		**$p_{1/2}$**	**$p_{3/2}$**	**$s_{1/2}$**	**others**
Publish Analysis	^{15}N	0.158	0.3515	0.1055	0.385
	^{16}O	0.158	0.3515	0.1055	0.385

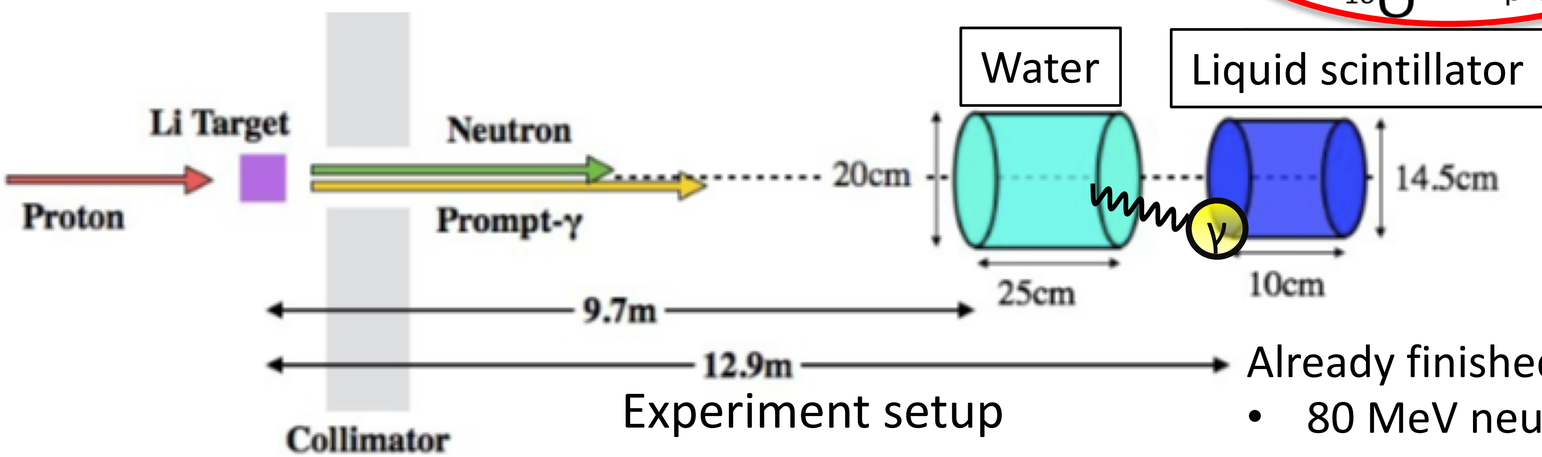
The uncertainty was calculated from the comparison between local density approximation and simple shell model, but it should be conservative, we will re-estimate it.

Primary gamma systematic error : 15% → ??%.

Secondary gamma emission rate

- Secondary gamma uncertainty mainly comes from the uncertainty of neutron interaction in water.
- Neutron beam experiment at RCNP in Osaka university
  - Precise measurements of the cross section, energy and multiplicity of γ-rays from neutron interaction for water target





Experiment setup

Already finished
- 80 MeV neutron

Future experiment
- 30 and 250 MeV

We already preformed several experiments in RCNP.
➢ The Analysis now on going.

Systematic error 13% → ??%. Not yet finished. We aim for ~5%.

Future Analysis plan

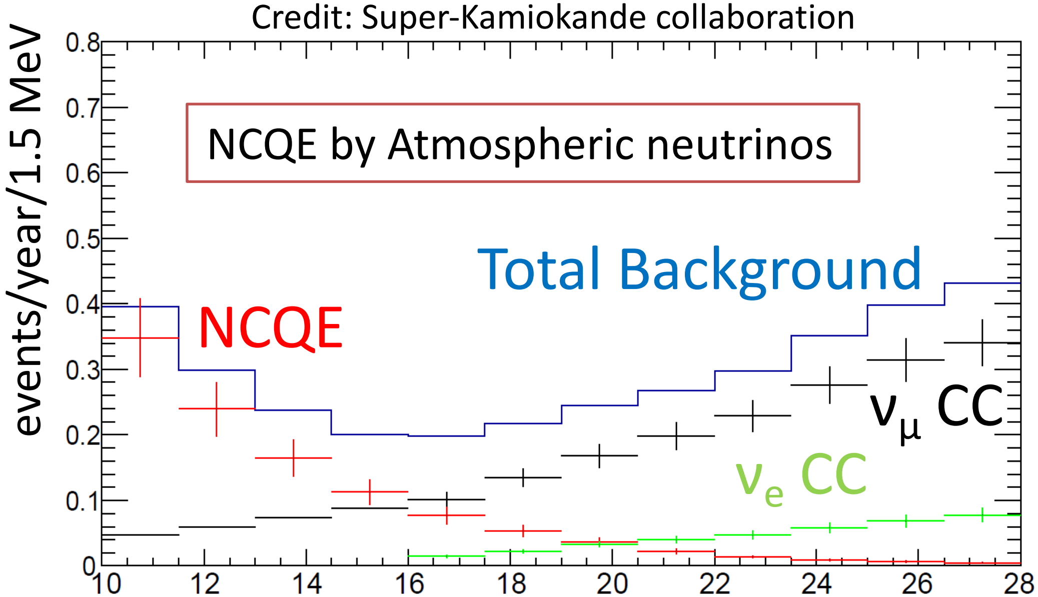
- Data
  - Analysis T2K-Run1-9
    - 3.01×10^{20}POT → 14.9×10^{20}POT (Neutrino mode)
    - 0 POT → 16.5×10^{20}POT (Antineutrino mode)
- MC update(NEUT5.1.4.2→5.3.3)
  - Main difference
    - Add 2p2h interaction
- Update of systematic error calculation
- Neutron tagging study (Next page)

Neutron tagging

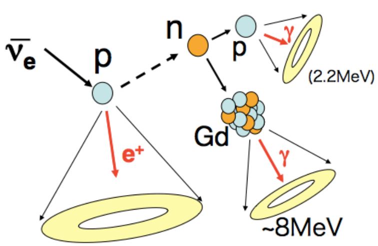
Motivation

- Main target at SK-Gd is search for SRN
  - NCQE interaction of atmospheric neutrinos with single neutron will be background.
  - Neutron tagging(its multiplicity) in atmospheric neutrino energy region is important.

Credit: Super-Kamiokande collaboration

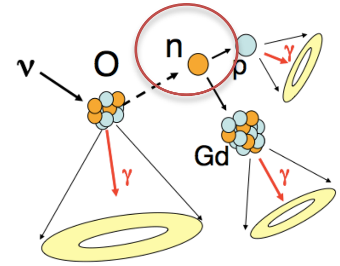


SK-Gd background types estimation



SRN

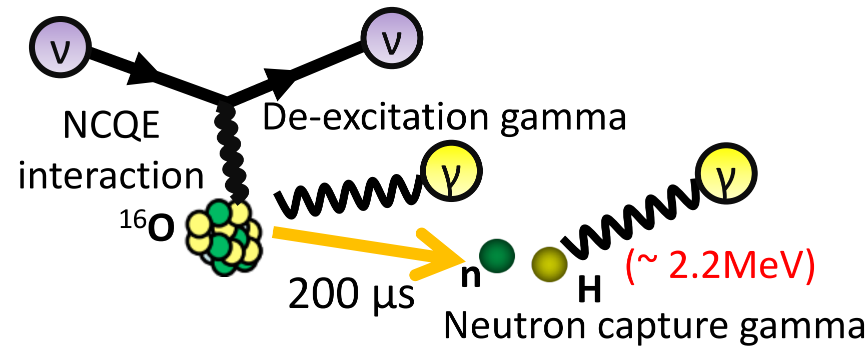
Single neutron



NCQE interaction by atmospheric neutrinos

Neutron tagging method in SK

- In the water, neutron is captured by proton after 200μs from primary gamma.
  - $n + p \rightarrow d + \gamma$ (2.2 MeV)



2.2MeV gamma-ray is hard to make an event reconstruction because of low energy. So, cannot observe by normal analysis.

- Try neural network method (TMVA), which should have enhanced sensitivity.

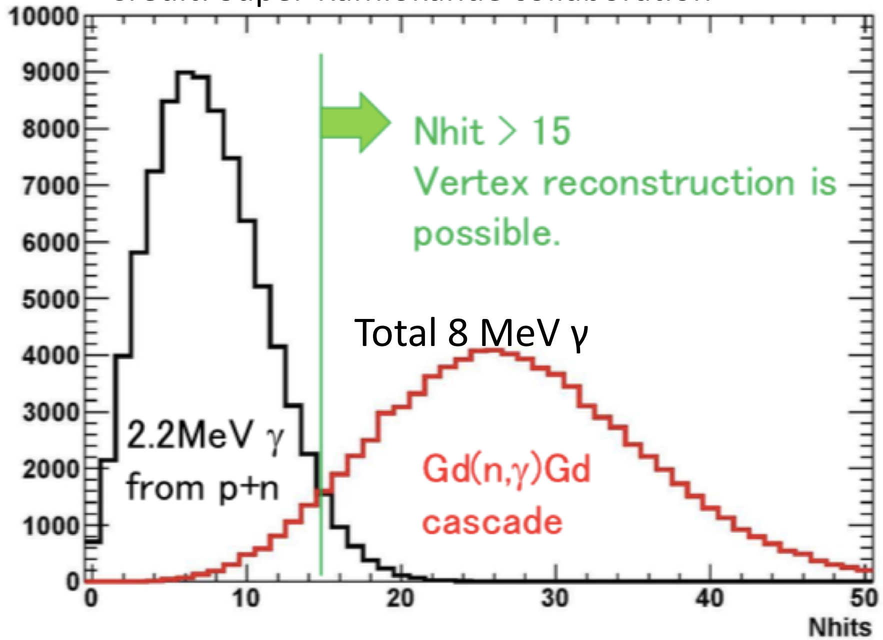
As a results, Neutron detection efficiency is about 20%.

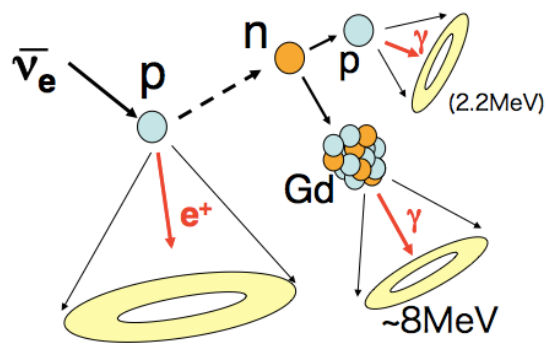
(0.02 background signal event / 1 NCQE event) → fake probability 2%

Neutron tagging in SK-Gd

- More than 90% neutron in the SK-Gd will emit total ~8 MeV gamma.
  - SK-Gd neutron capture efficiency :: > 80% (fake probability ~0.2%)
  - SK(2.2 MeV) neutron capture efficiency :: ~ 20% (fake probability 2%)

Credit: Super-Kamiokande collaboration





In the SK-Gd, further accurate measurement of the number of neutrons generated can be expected.

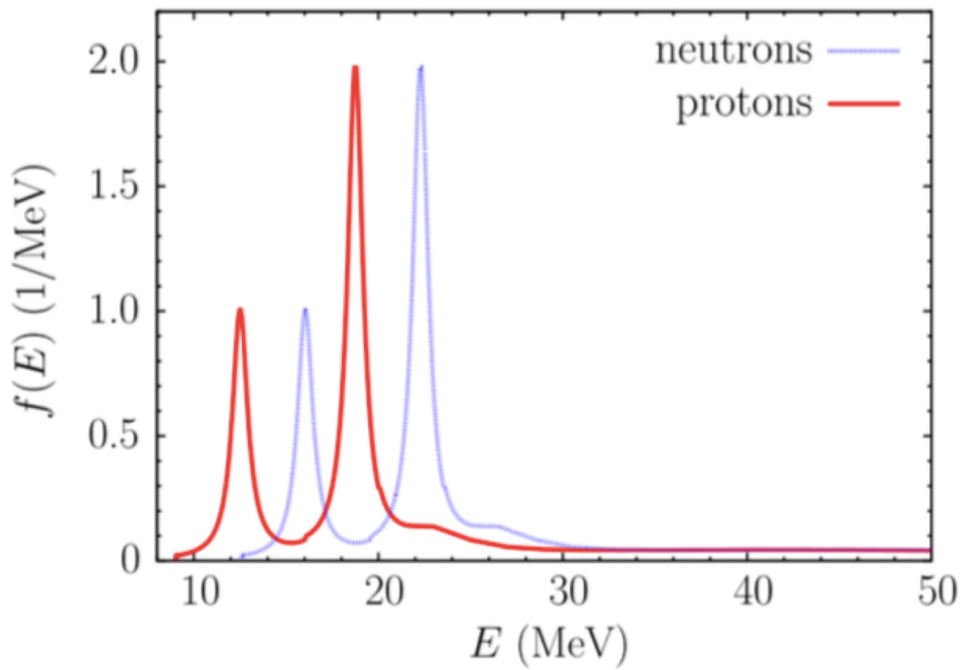
Summary

- Neutrino-oxygen NCQE interaction was measured by T2K data.
- Systematic error is still large. We try to reduced it.
- Only 1/4 data compared to the full data set was analyzed, we are now preparing to open data.
- NCQE interaction by atmospheric neutrino is main background of search for SRN in SK-Gd.
  - Neutron tagging is important.

Back up

Spectroscopic factor

- Spectroscopic factor is calculated integral the spectral function
- $11.0 \leq E \leq 14.0$ MeV → (p1/2)
- $17.25 \leq E \leq 22.75$ MeV → (p3/2)
- $22.75 \leq E \leq 62.25$ MeV → (s1/2)



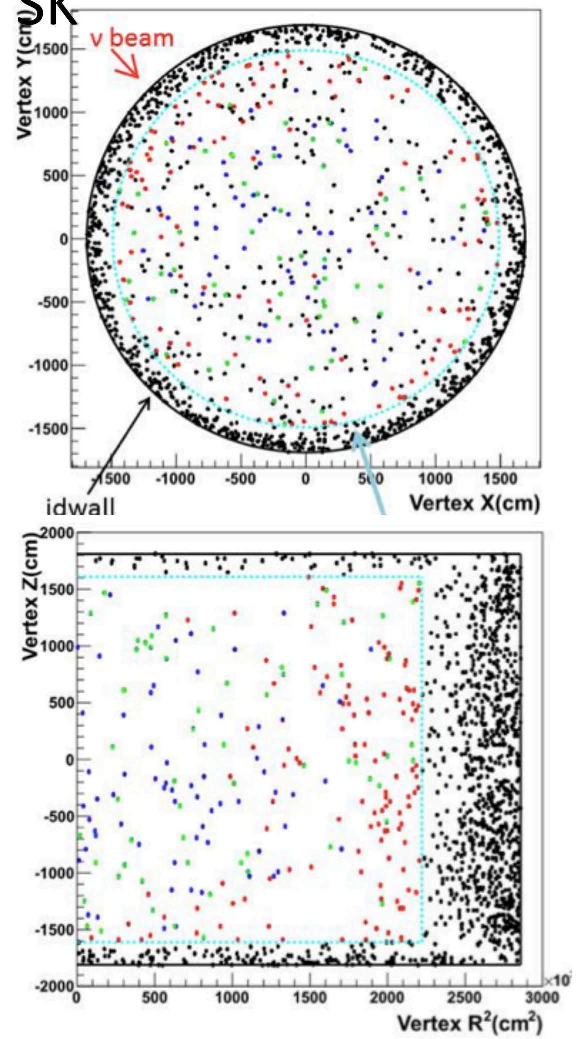
Event selection

- Radioactive b.g. cut
  - Black: after bunch time cut (GPS)
  - Red: after dwall cut
  - Blue: after effwall cut
  - Green: after ovaQ cut

NCQE event is observed as low energy event at SK
- About 6MeV

Cut criteria

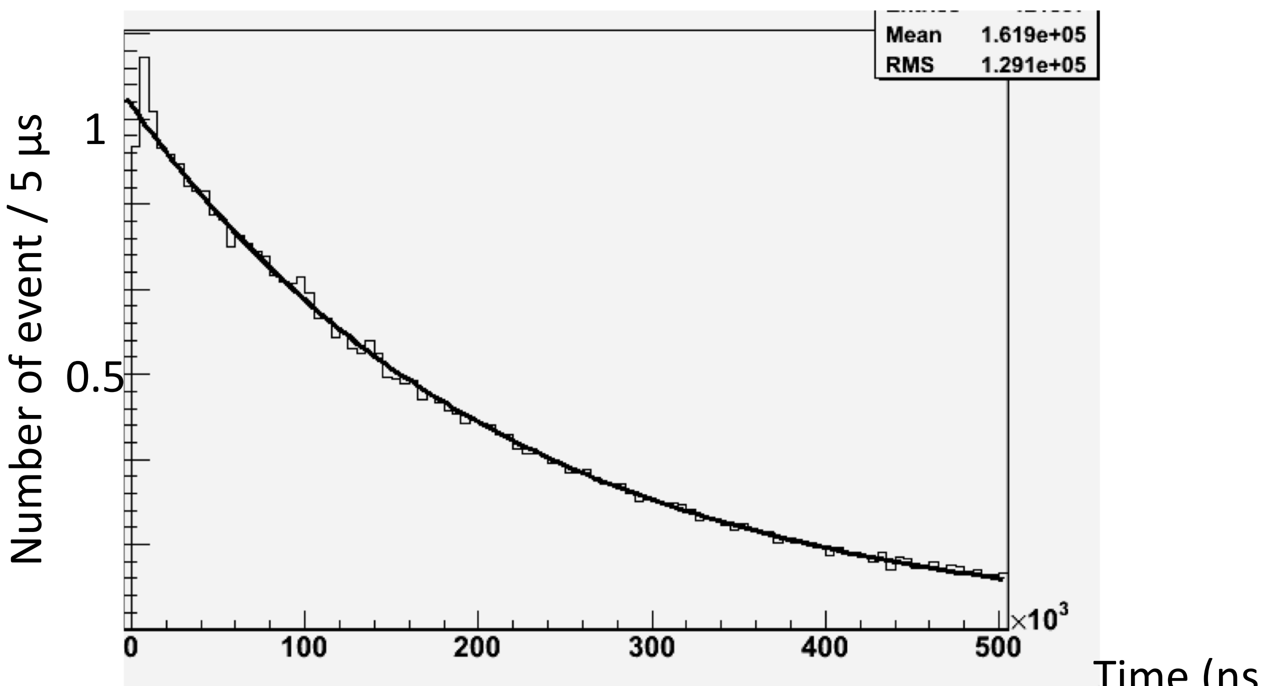
- Timing cut
  - Sync of T2K beam
- Energy cut
  - 4 MeV < Reconstruction energy < 30 MeV
- Reconstruct vertex cut
  - Vertex within Fiducial volume
- Reconstruct quality cut
  - OvaQ cut
- Pre-activity cut
  - Cut of back ground event forexample Cosmic ray muon
- Cherenkov angle cut
  - Cherenkov angle > 34°



Vertex Cut

Neutron tagging by MC

- Training result apply to MC
  - Only NCQE interaction MC result



Lifetime 205µs

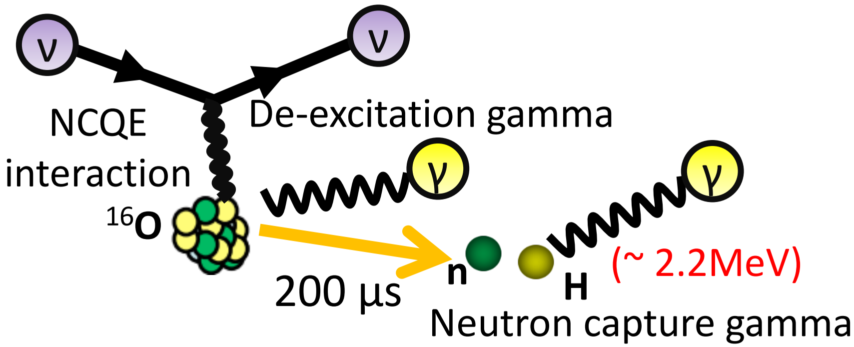
Neutron capture time at MC(Scaling 102 event)

Number of expected neutrino in T2K Run 1-4 is estimated to be 46 event.

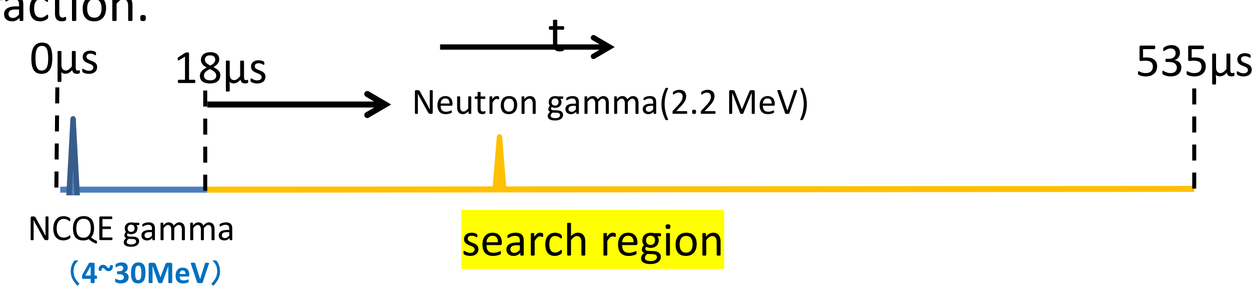
I'm now calculating using the final MC sample, (inc. other interaction modes)

Neutron tagging method in SK

- In the water, neutron is captured by proton after 200μs from primary gamma.
  - ➢ n + p → d + γ (2.2 MeV)



- Search for 2.2 MeV gamma produced by proton capture until 535 μs from NCQE interaction.



N10	Hit counts of 10ns window
Nc	Positon relation of hit PMT
Nlow	Number of low probability hitting PMT
N300	Hit counts within ±150ns at N10
Trms	Minimum of N10 Timing RMS
ϕ	Phi-root mean square of hits
Θ	Theta mean of hits
nn back	N10 – No. hits in backward direction
nn highQ	Check HighQ event
nn lowtheta	Check HighQ event
dqrms	N10 Qrms
dqmean	N10 Qmean
dthetarms	Θ rms
Mintrms6	Minimum T-rms of clusters of 6 hits out of N10.
Mintrms3	Minimum T-rms of clusters of 3 hits out of N10.
fpdist	Difference between parent particle and N10 vertex
fwall	Reconstructed dwall using Neut fit
trmsdiff	trmsold - trms
n10d	hits in 10ns after using min-trms vertex – N10
bfdist	N/A (Neutron Bonsai vertex, not used)

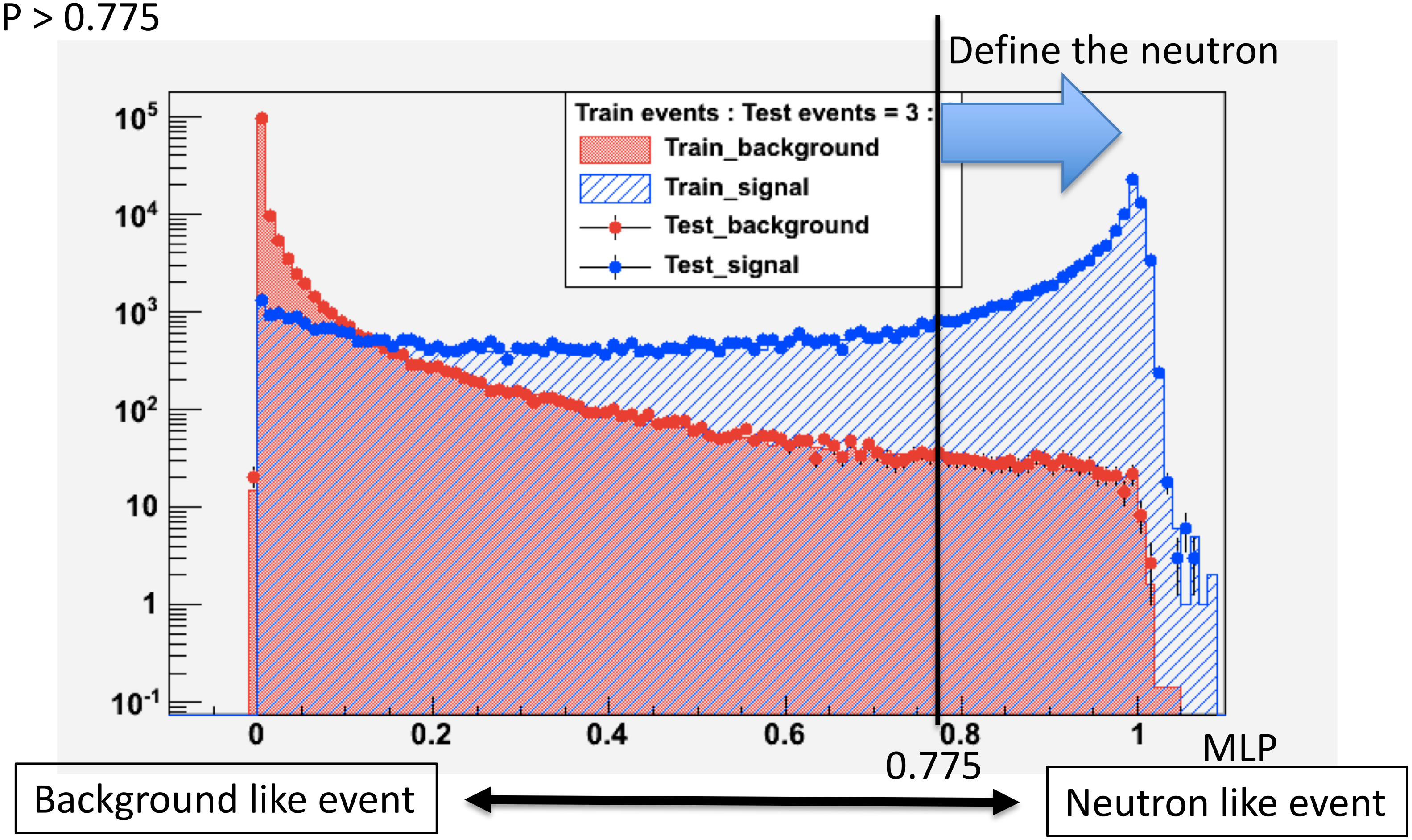
How to judgment of truth or false

- Judgment of truth
  - When N10 timing and MC true timing coincide (absolute difference value within ±150 ns), it event is decided true signal. Otherwise event is decided back ground.

Training result

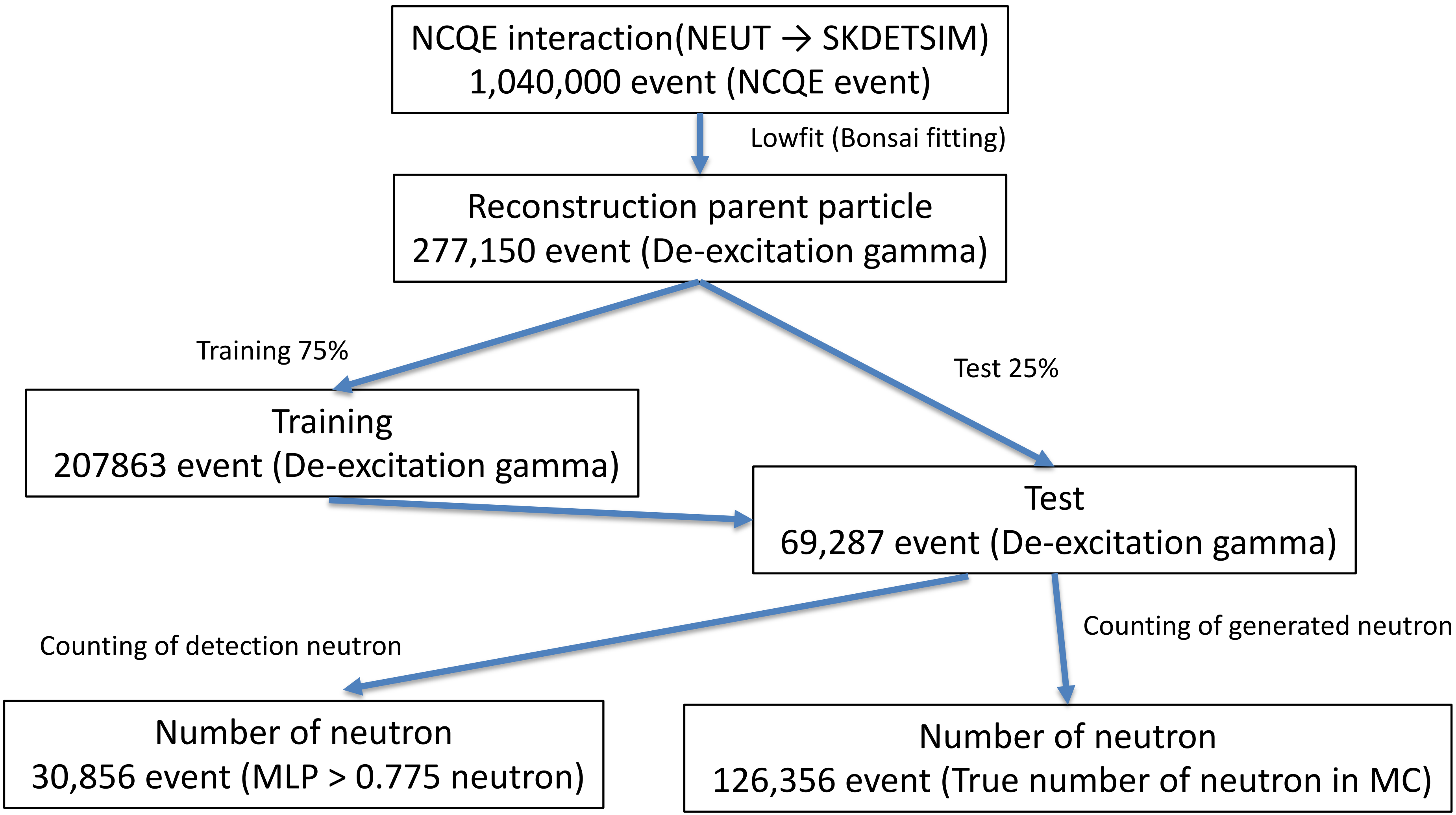
Threshold : 0.02 background signal event / 1 NCQE event

- MLP > 0.775



When the neutron capture gamma ray is selected as neutron candidate events (N10 ≧ 7), 72% neutron can be correctly distinguished.

Current efficiency



Efficiency of detecting neutrons is 24% (30,856 / 126,756)

- 0.02 background signal event / 1 NCQE event

Neutron search method

- This searches method is besed on Haibing's (Linyan) SK2p2MeV class.
- N10 was searched by parent particles vertex information.

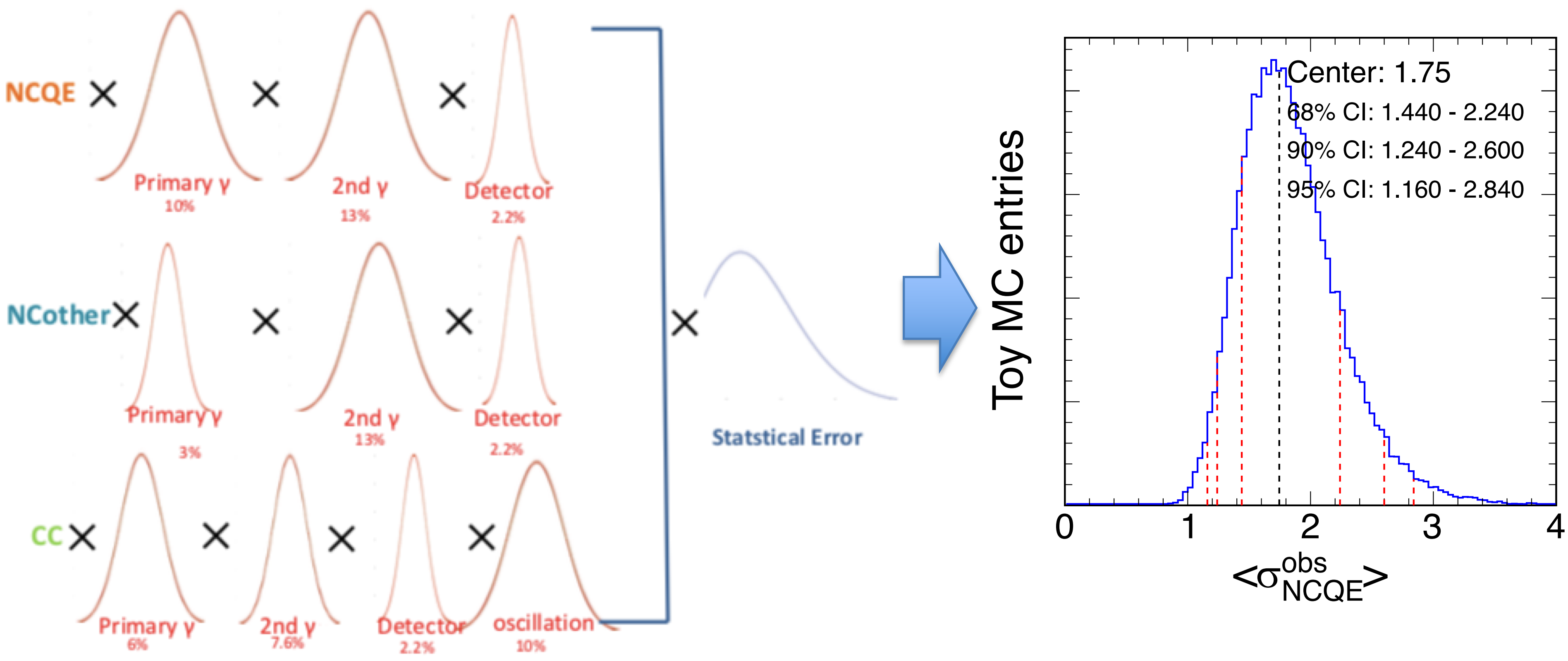
- Neural network is using MLP method of TMVA application.

Current typical neural network input value

NCQE vertex	Bonsai Fit	NCQE vertex information
First reduction	N_{10}	Hit counts of 10ns window
Hit information	N_{300}	Hit counts within ±150ns at N10
	Nc	Position relation of hit PMT
	Nlow	Number of low probability hitting PMT
	Φrms	Hit angle information
	Θmean	Hit angle information
	Trms	Minimum of N10 Timing RMS
	Neut fit	Neutron fit is fitter, using N10 information

20 parameter etc…

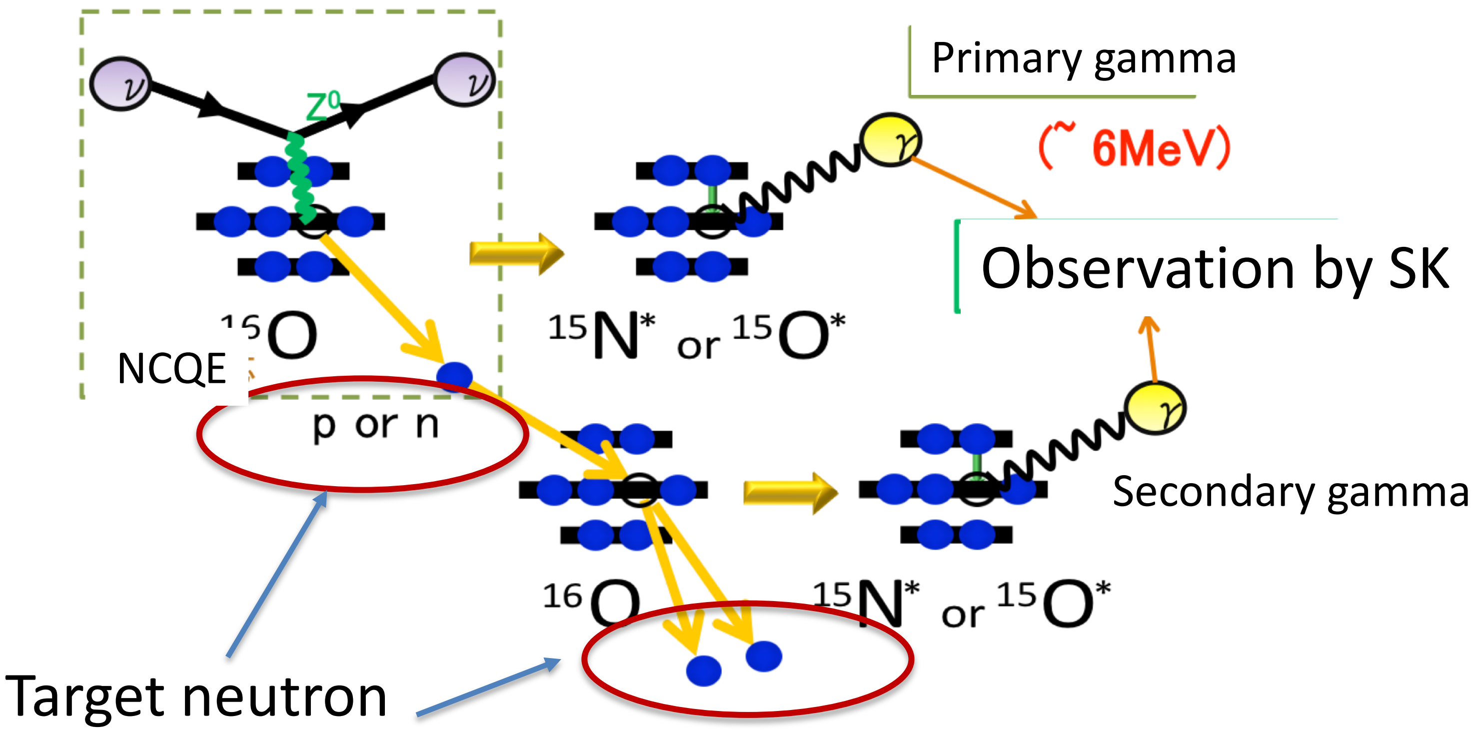
Calculate of NCQE cross section (error)



$$< \sigma_{\nu,NCQE}^{obs,RUN1\sim4} >= 1.75 \times 10^{-38} cm^2 \pm 0.27(stat.)^{+0.70}_{-0.31}(sys.)$$

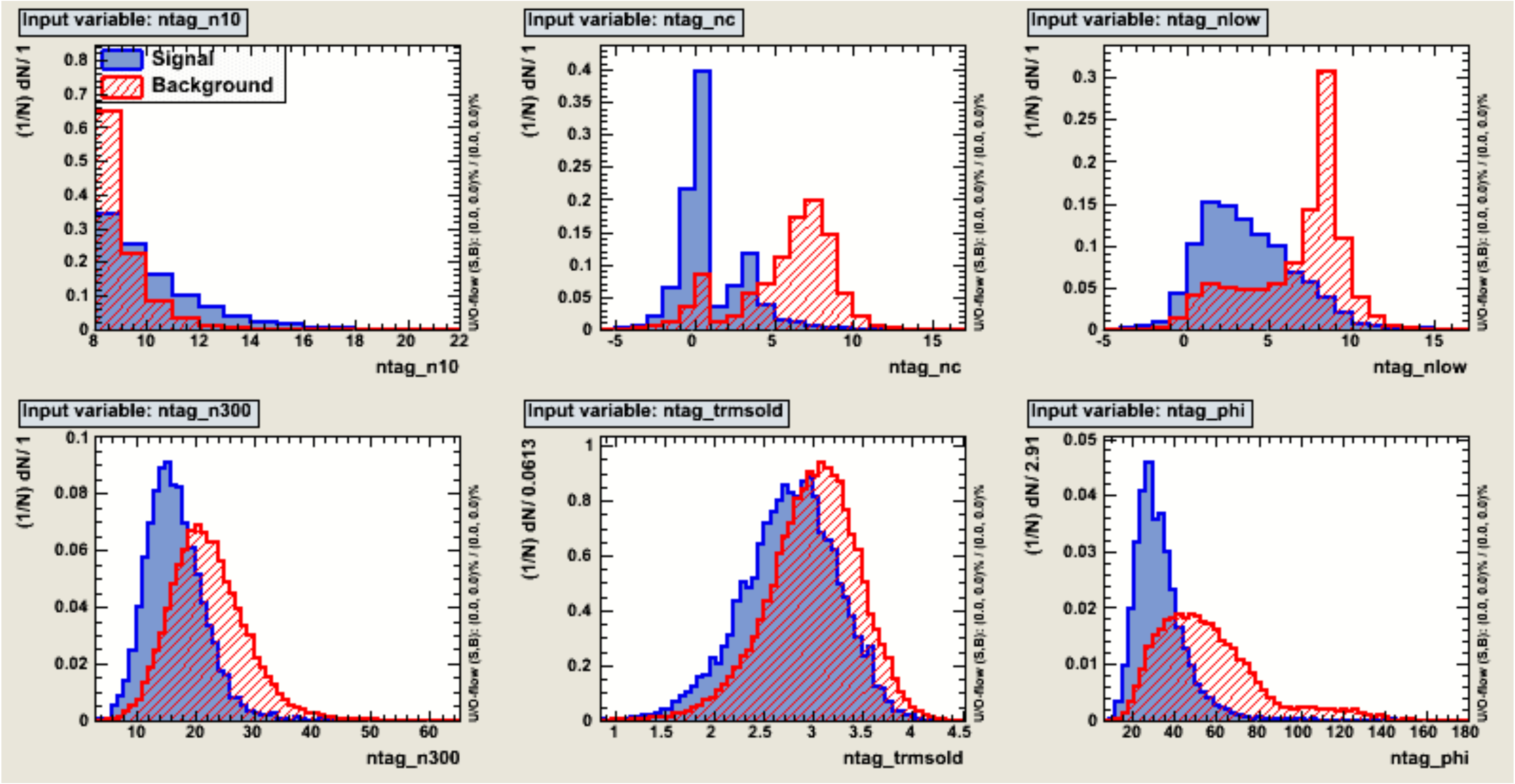
NCQE

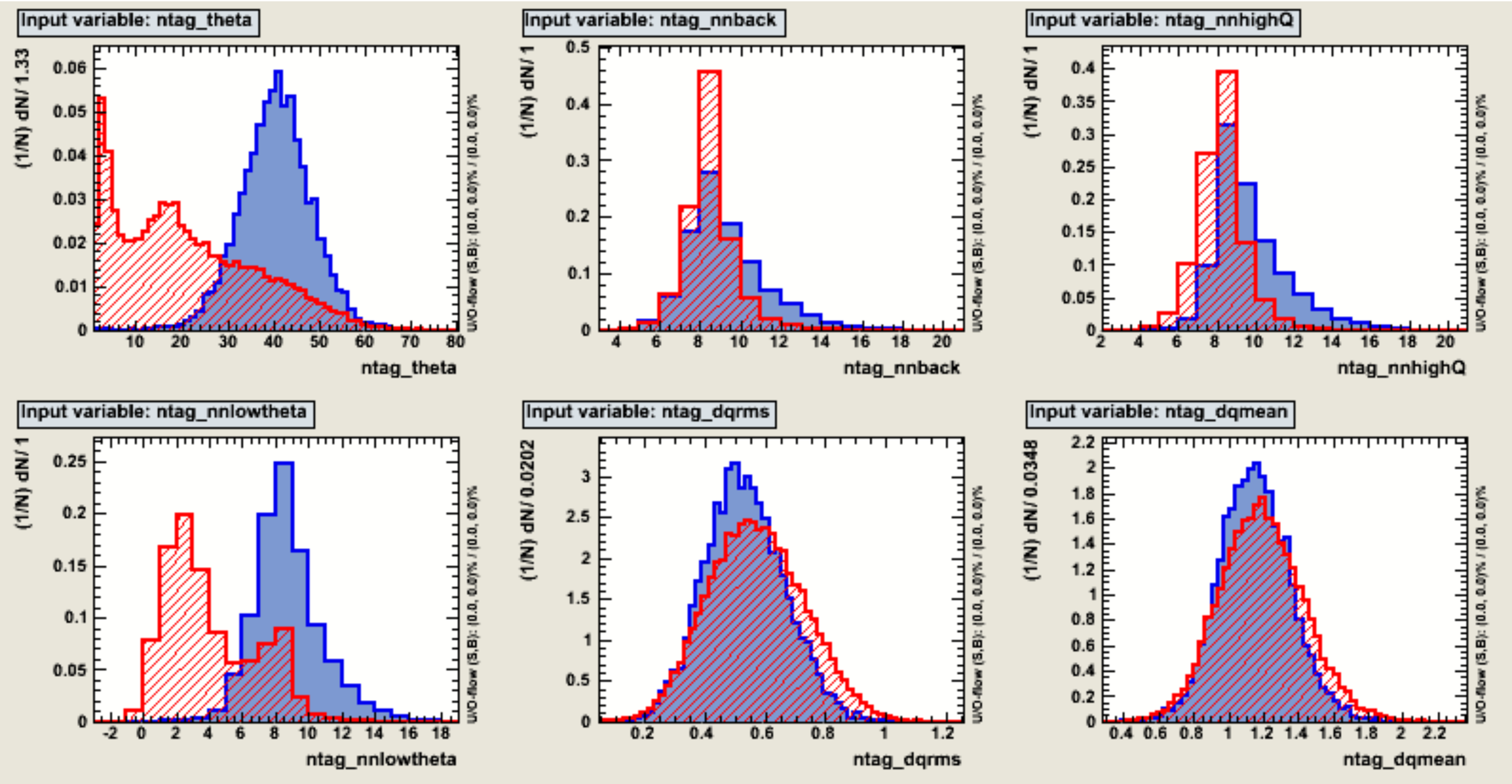
- Neutrons are often produced via NCQE interaction.
  - We will try to tag neutrons in SK



Typical value difference

- There are large difference values is more important.




Input variable: ntag_theta
(1/N) dN/ 1.33
ntag_theta
Input variable: ntag_nnback
(1/N) dN/ 1
ntag_nnback
Input variable: ntag_nnhighQ
(1/N) dN/ 1
ntag_nnhighQ
Input variable: ntag_nnlowtheta
(1/N) dN/ 1
ntag_nnlowtheta
Input variable: ntag_dqrms
(1/N) dN/ 0.0202
ntag_dqrms
Input variable: ntag_dqmean
(1/N) dN/ 0.0348
ntag_dqmean