NUFACT2017

(The 19th International Workshop on Neutrinos from Accelerators)

29th, Sep., 2017 @ Uppsala, Sweden

Measurement of gamma-rays from neutron-oxygen reaction for neutrino-nucleus interaction

Yosuke ASHIDA (Kyoto University)

for the RCNP-E487 Collaboration

Contents

- *Introduction*
- *Experimental Details*
- *Analysis Results*
- *Considerations*

Contents

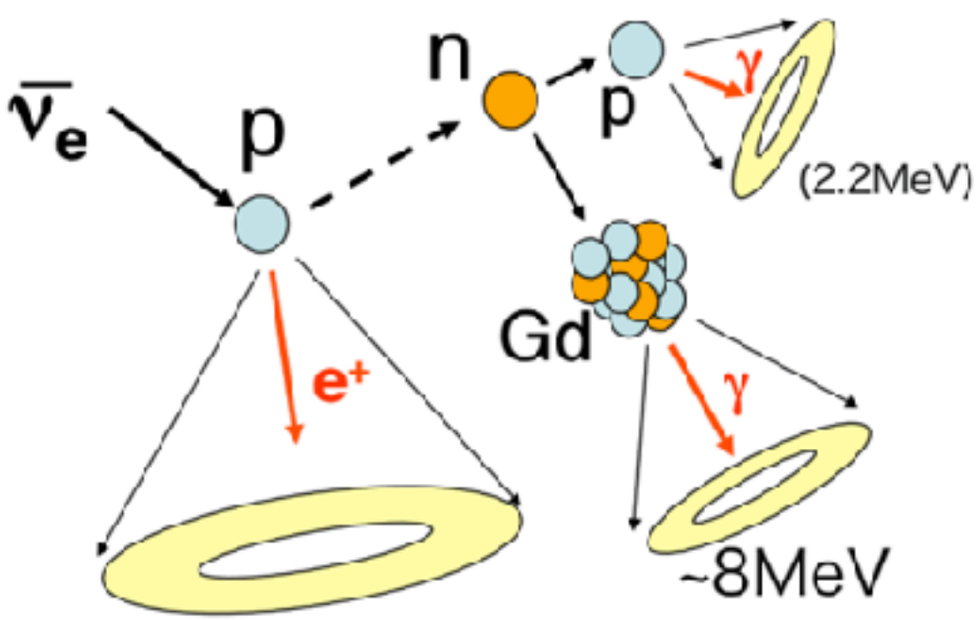
- *Introduction*
- *Experimental Details*
- *Analysis Results*
- *Considerations*

Physics Motivation on "NCQE"

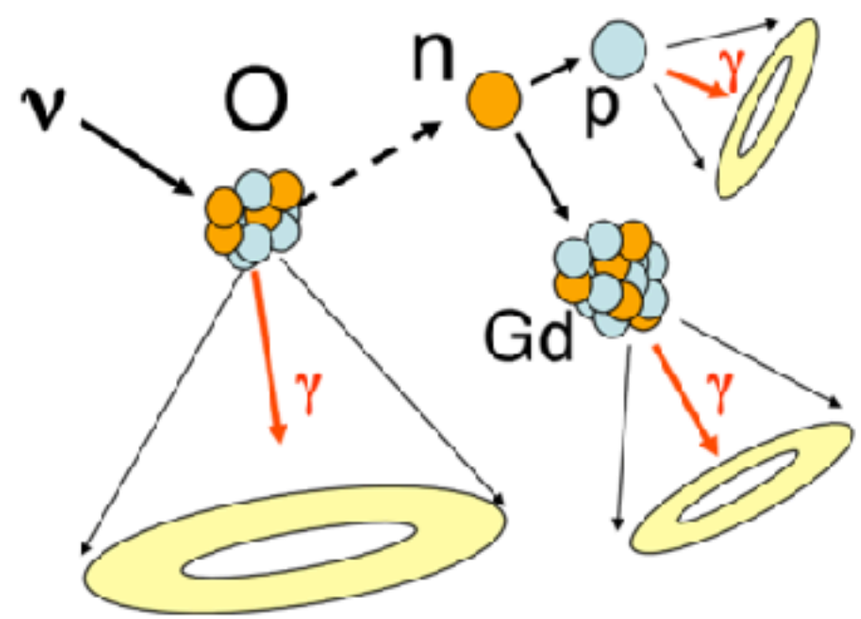
Neutrino neutral current quasielastic interaction is important for several physics searches at **T2K** and **Super-K** (also at **SK-Gd** and **Hyper-K**).

- Supernova relic neutrino
- Sterile neutrino
- Dark matter

Supernova relic neutrino (IBD)

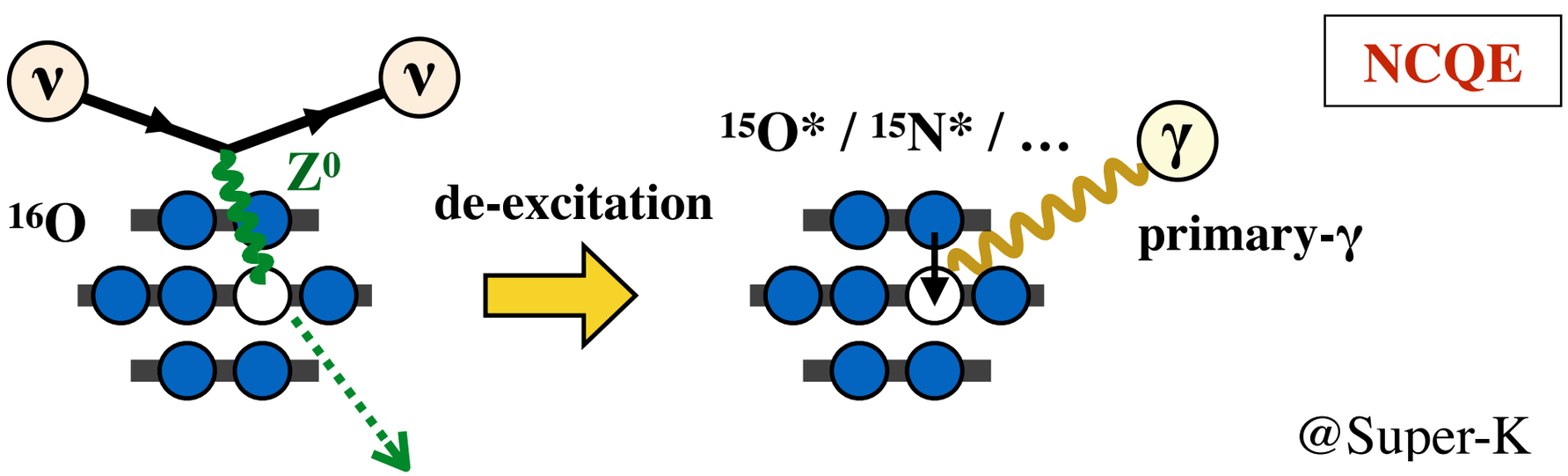


Atmospheric neutrino (NCQE)



Measurement at T2K Experiment

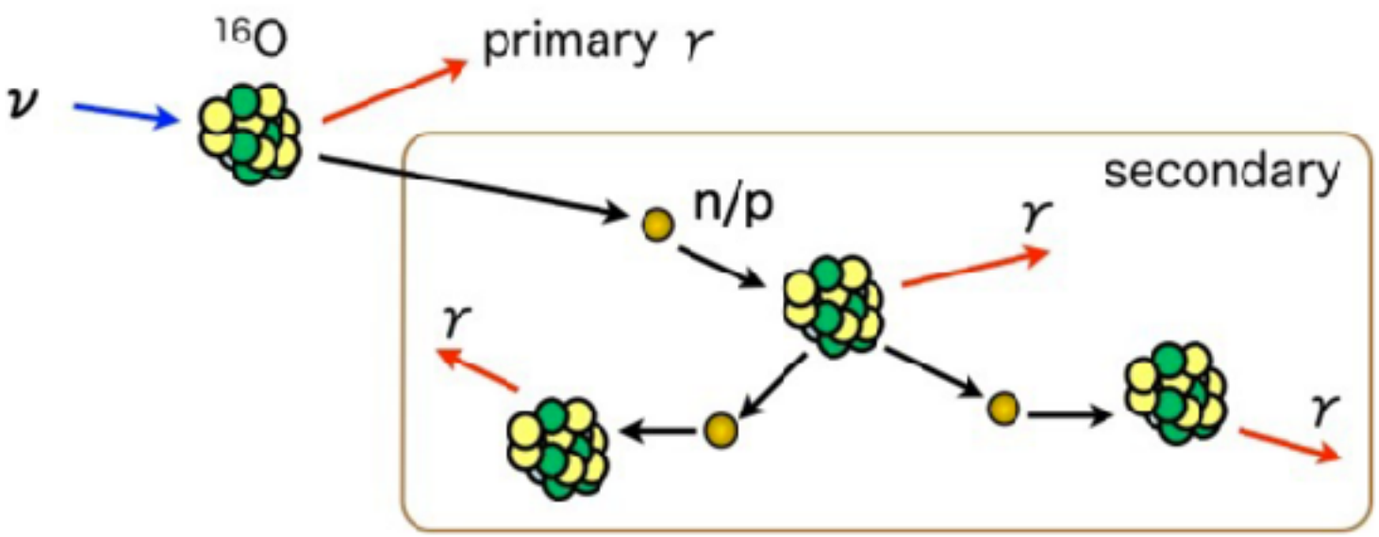
- **Gamma-ray** emitted from excited nucleus is a signal of NCQE.
- Typical energy of gamma-rays is **5 ~ 10 MeV**, and this is very low energy event at Super-K with large background.
- T2K beam is a powerful tool for measuring the NCQE cross section.
  - Background reduction with timing information
  - Similar neutrino energy to atmospheric neutrino flux peak

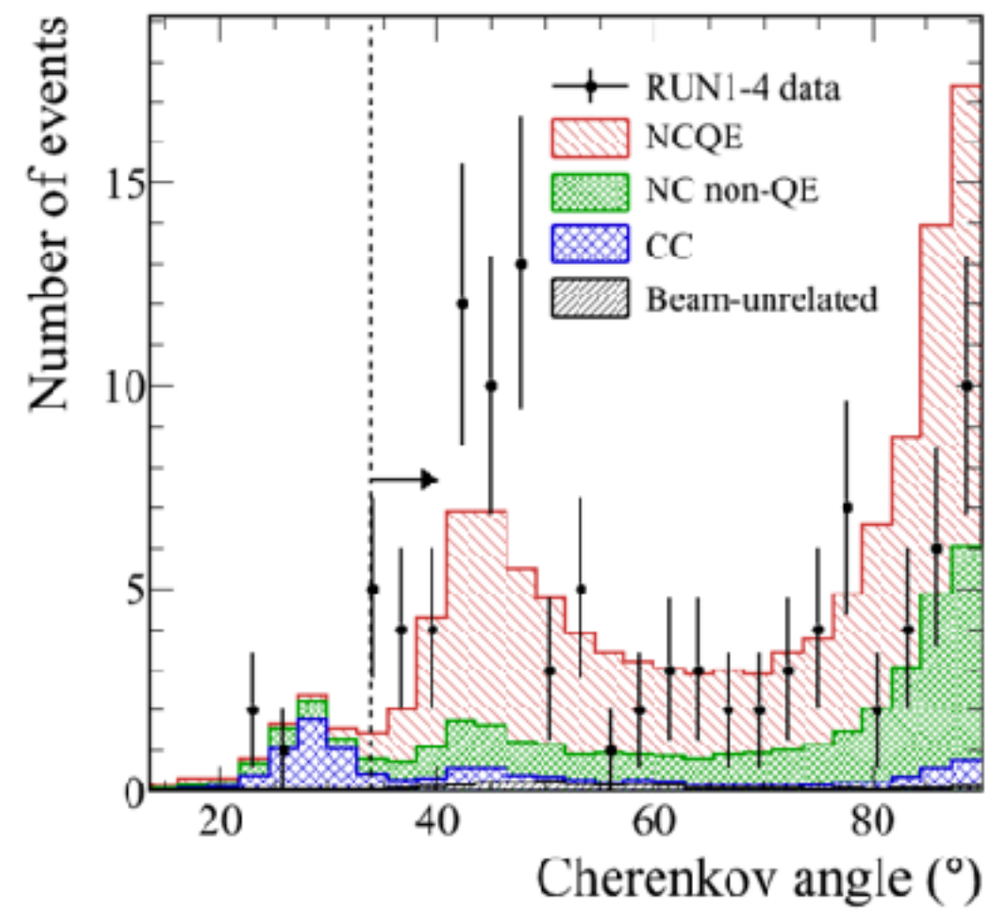


Current Problem

T2K result has large systematics due to poor nuclear reaction model.

ex.) Large gap in reconstructed Cherenkov angle between data and MC





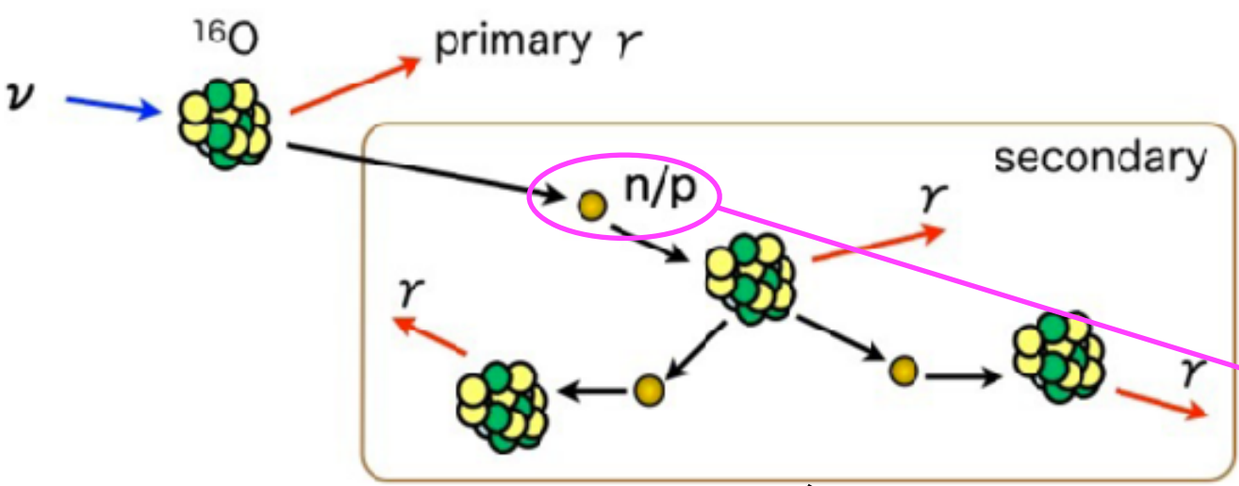
Systematics (K. Huang, Ph.D Thesis, Kyoto University (2016))

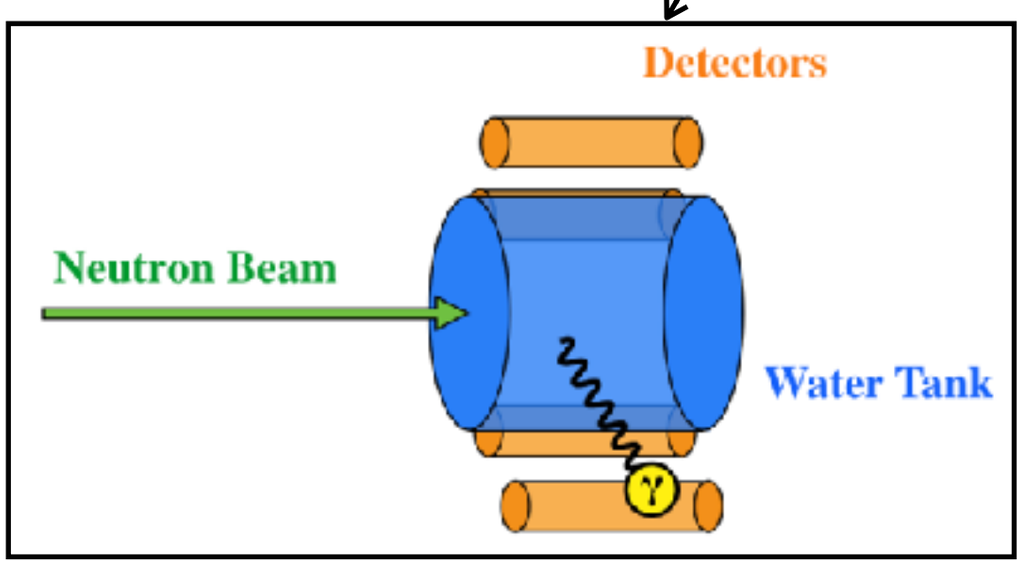
Systematic error	Signal	Background		
interactions	NCQE	NCothers	CC	beam-unrelated
fraction of events	68%	25%	4%	2%
Flux	11%	10%	12%	–
Cross-section	–	18%	24%	–
Primary γ production	10%	3%	6%	–
Secondary γ production	13%	13%	7.6%	–
Detector response	2.2%	2.2%	2.2%	–
Oscillation parameters	–	–	10%	–
Total systematic error	20%	25%	30%	0.8%

Gamma-rays from secondary nuclear processes are not well modeled!

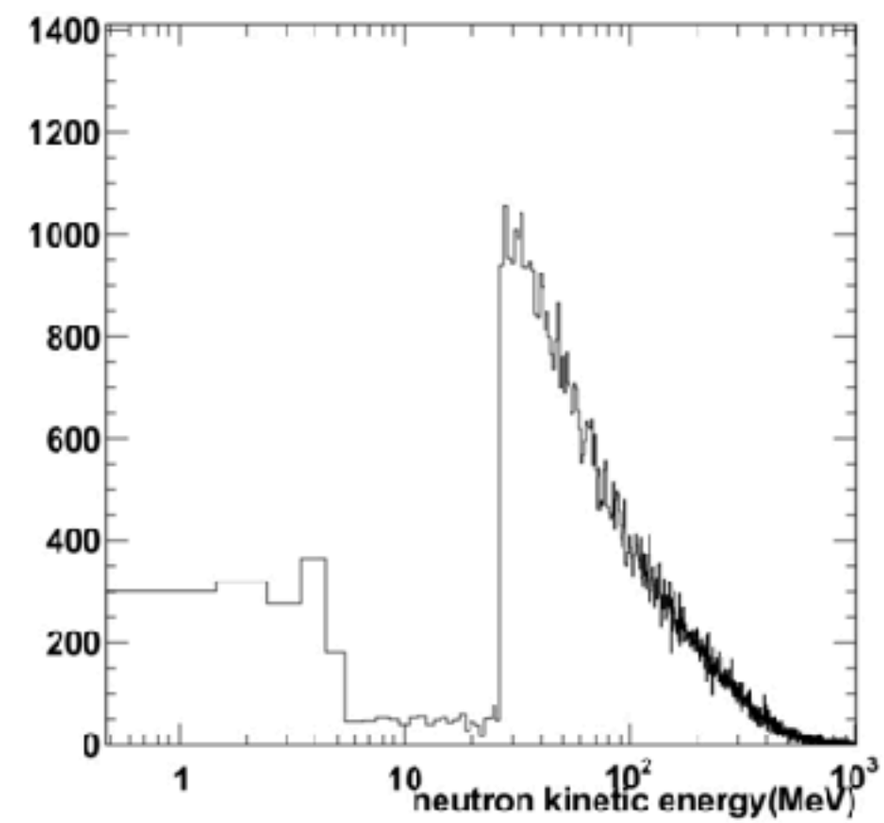
Strategy: Nuclear Physics

- No previous measurements on gamma-rays from neutron-oxygen reaction in hundred-MeV region
- Our experiment aims to measure neutron-induced gamma-rays from the secondary process only.



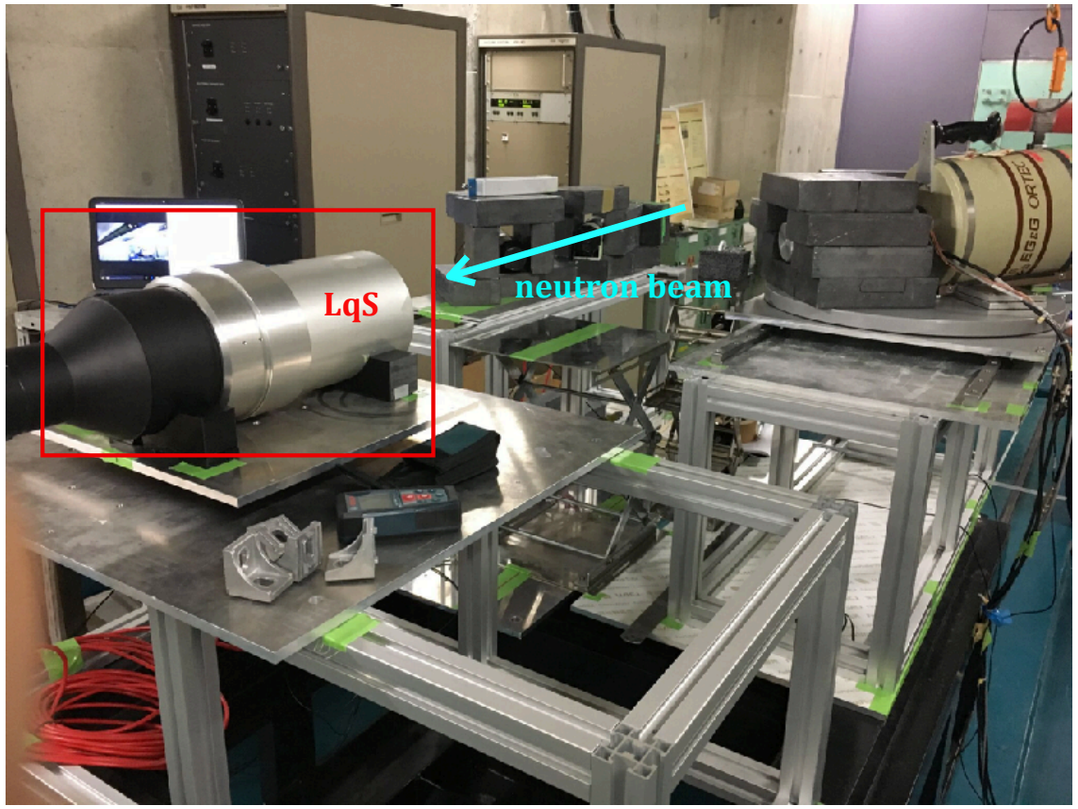


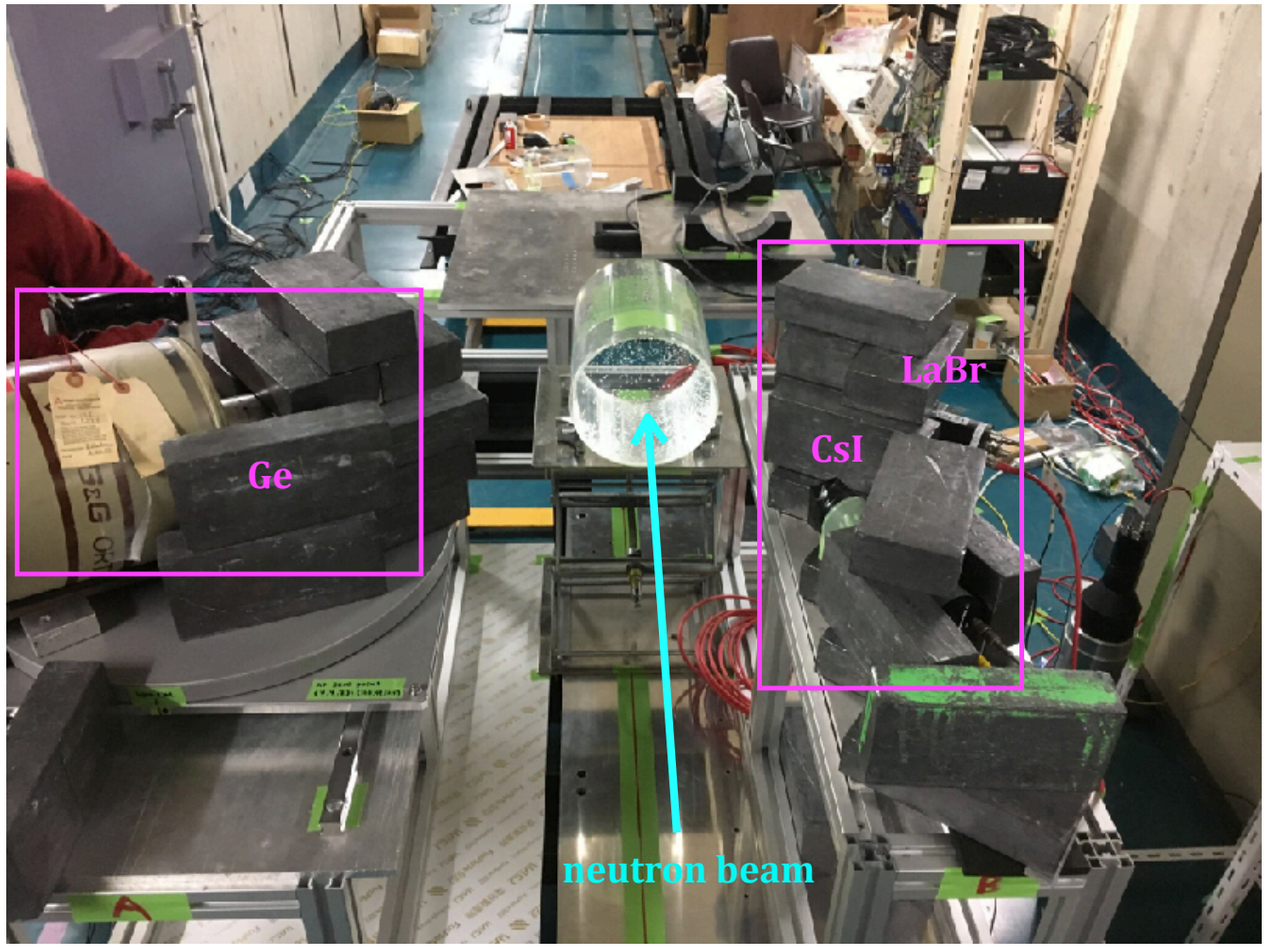
Simulated kinetic energy (Fermi gas model)



Contents

- *Introduction*
- *Experimental Details*
- *Analysis Results*
- *Considerations*

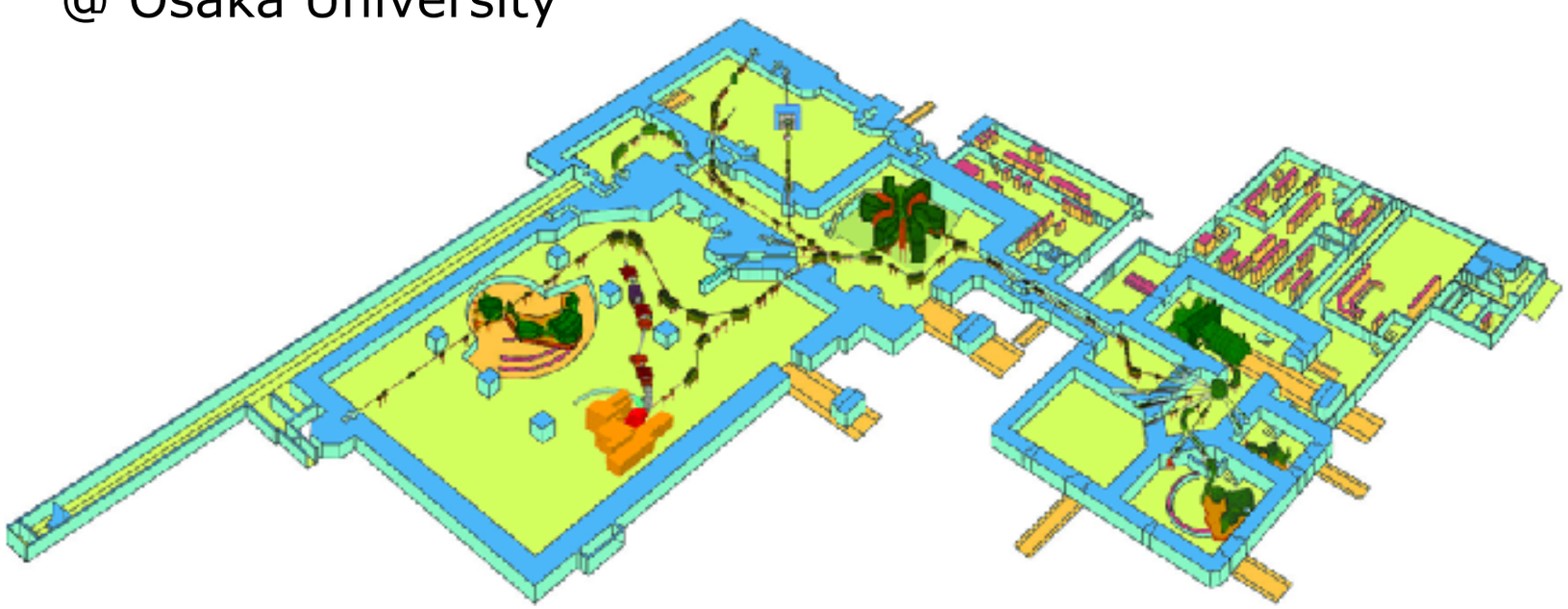


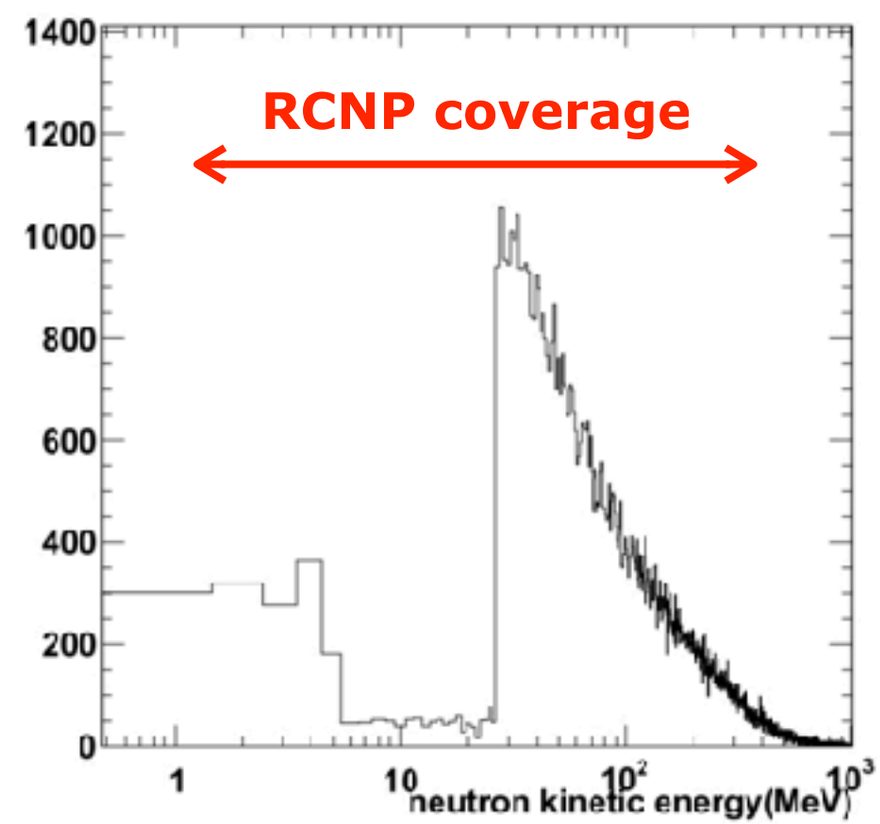


RCNP-E487 Experiment

- RCNP's wide range neutron beam is suitable for our purpose.
- We carried out the experiment using 80 MeV neutron beam (**E487**).
- Beam setting:
  - beam time : 24 hours
  - proton energy : 80.6 +/− 0.6 MeV (neutron produced by **^{7}Li(p,n)**)
  - Chopping : 1/9 (to separate peak/fast and tail/slow neutron)

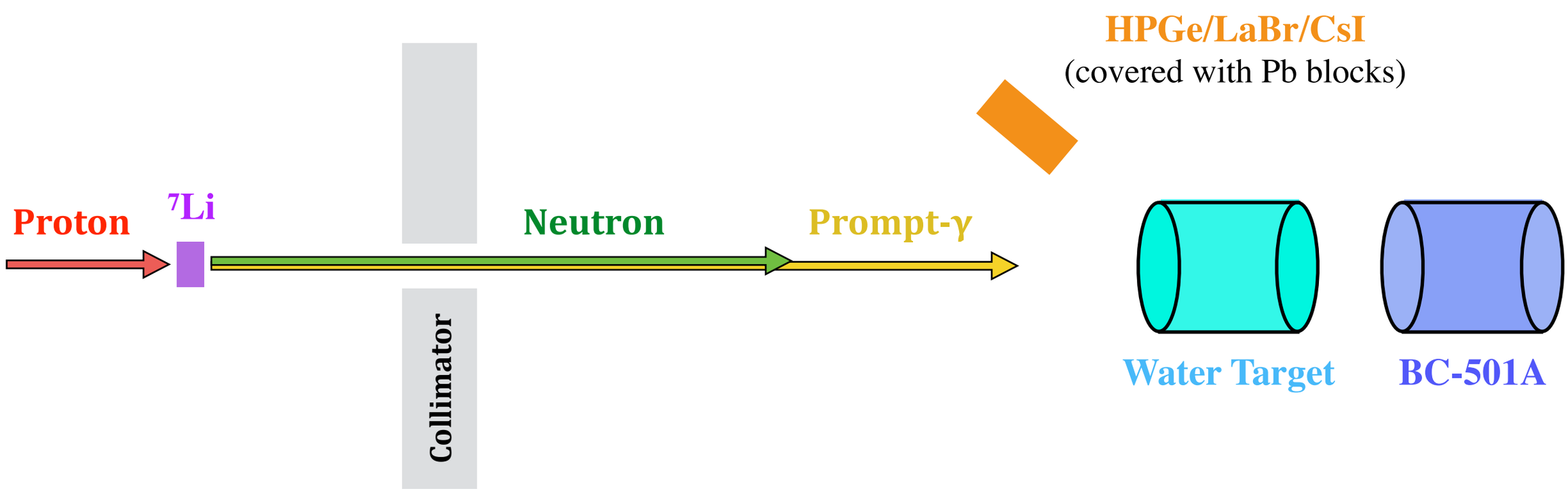
Research Center for Nuclear Physics (RCNP)
@ Osaka University





Detectors

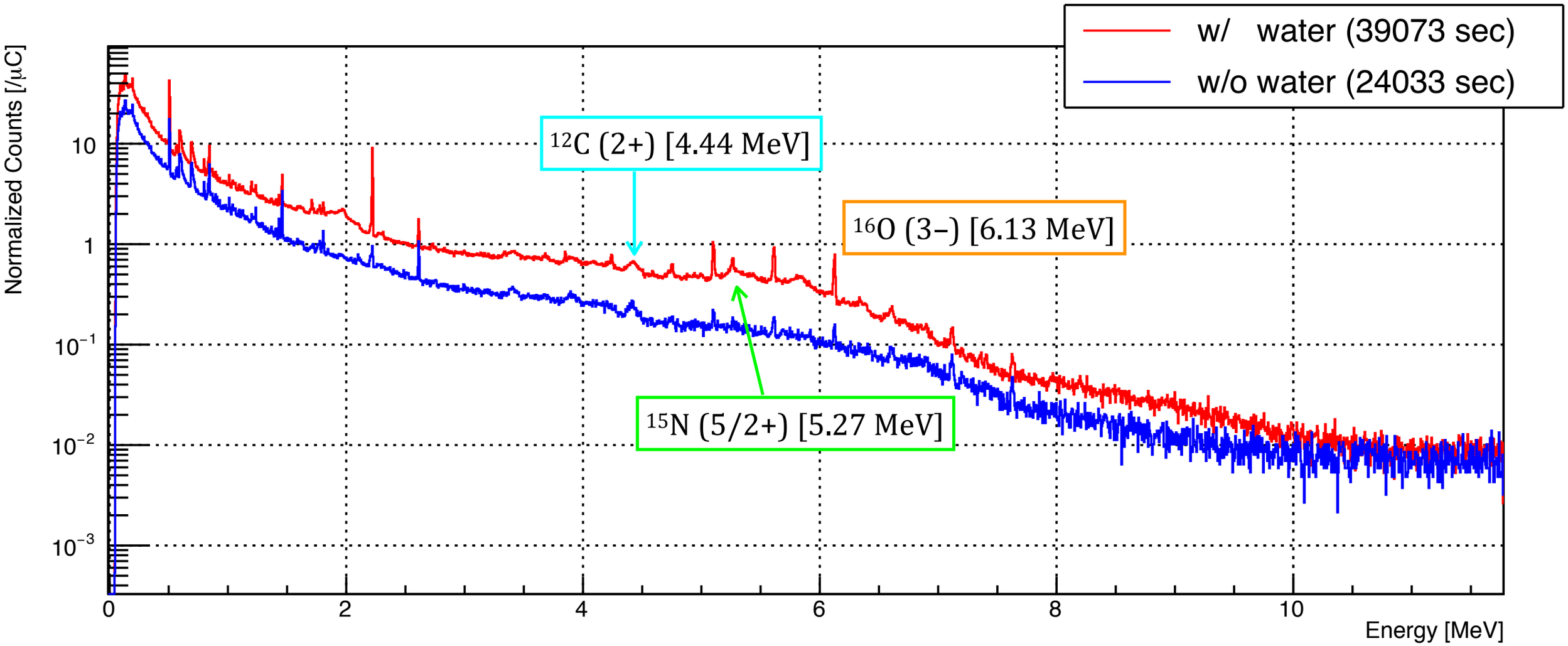
- **Gamma-ray production**: **HPGe detector** and **$LaBr_3$(Ce) scintillator**
  - Upstream to water target & Covered with Pb blocks
- **Neutron flux**: **Organic liquid scintillator (BC-501A)**
  - On-axis position & without water target
- **Scattered neutron**: **CsI(Tl) scintillator**
  - Upstream to water target & Covered with Pb blocks



Contents

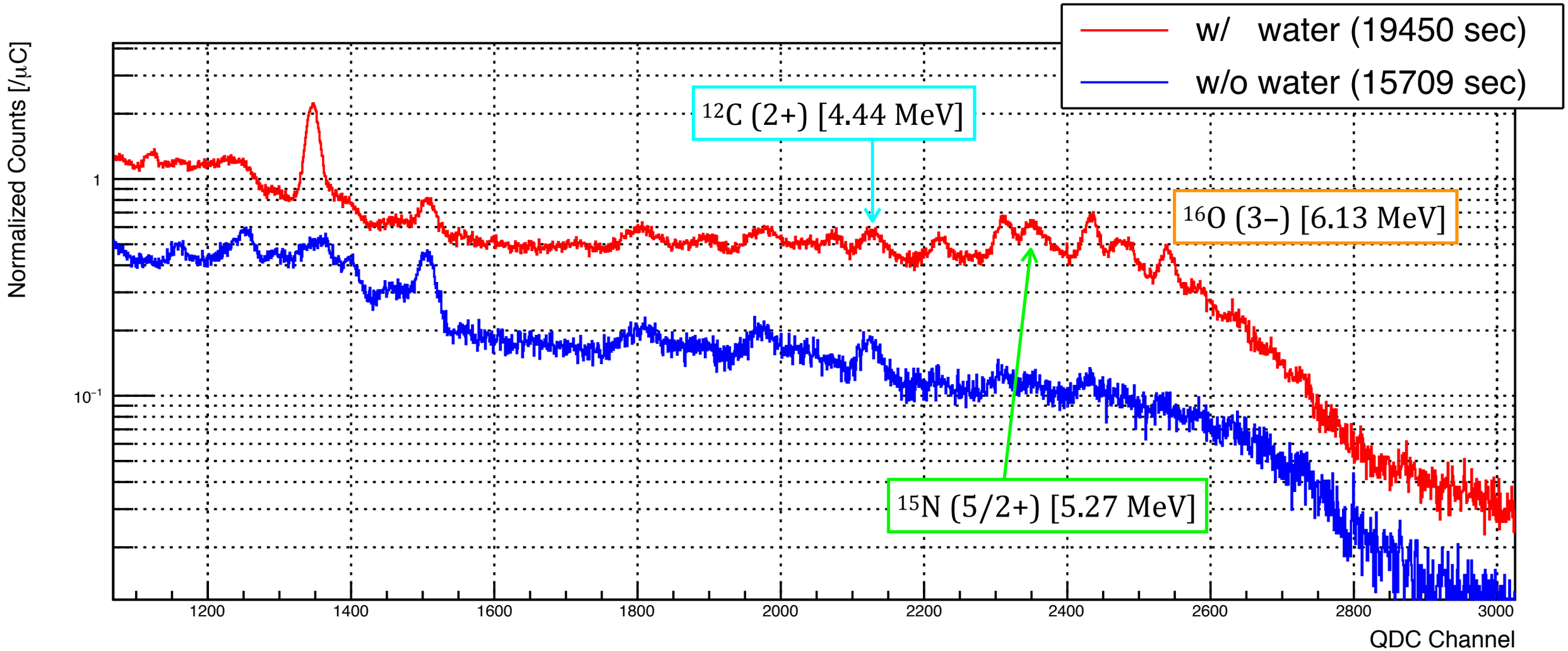
- *Introduction*
- *Experimental Details*
- *Analysis Results*
- *Considerations*

Gamma-ray Production: HPGe



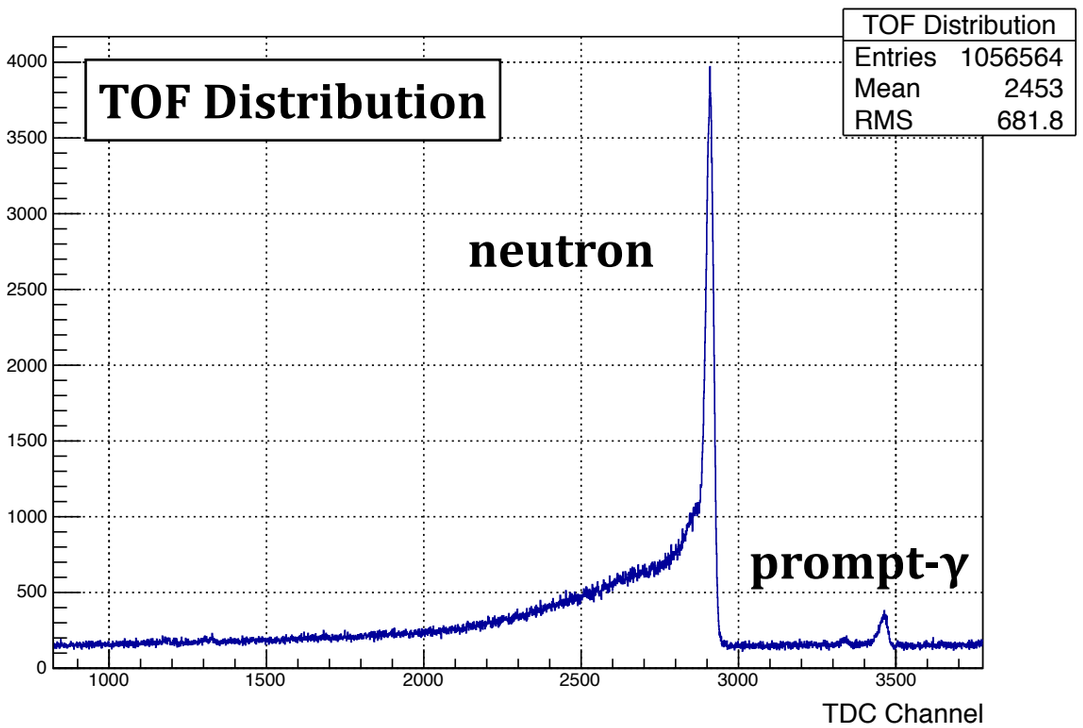
- **Observation of strong peaks** (6.13 MeV from ^{16}O, 5.27 MeV from ^{15}N)
- Observation of other peaks that are from neutron-oxygen reactions (later)
- (We also have time information with O(10 ns) accuracy.)

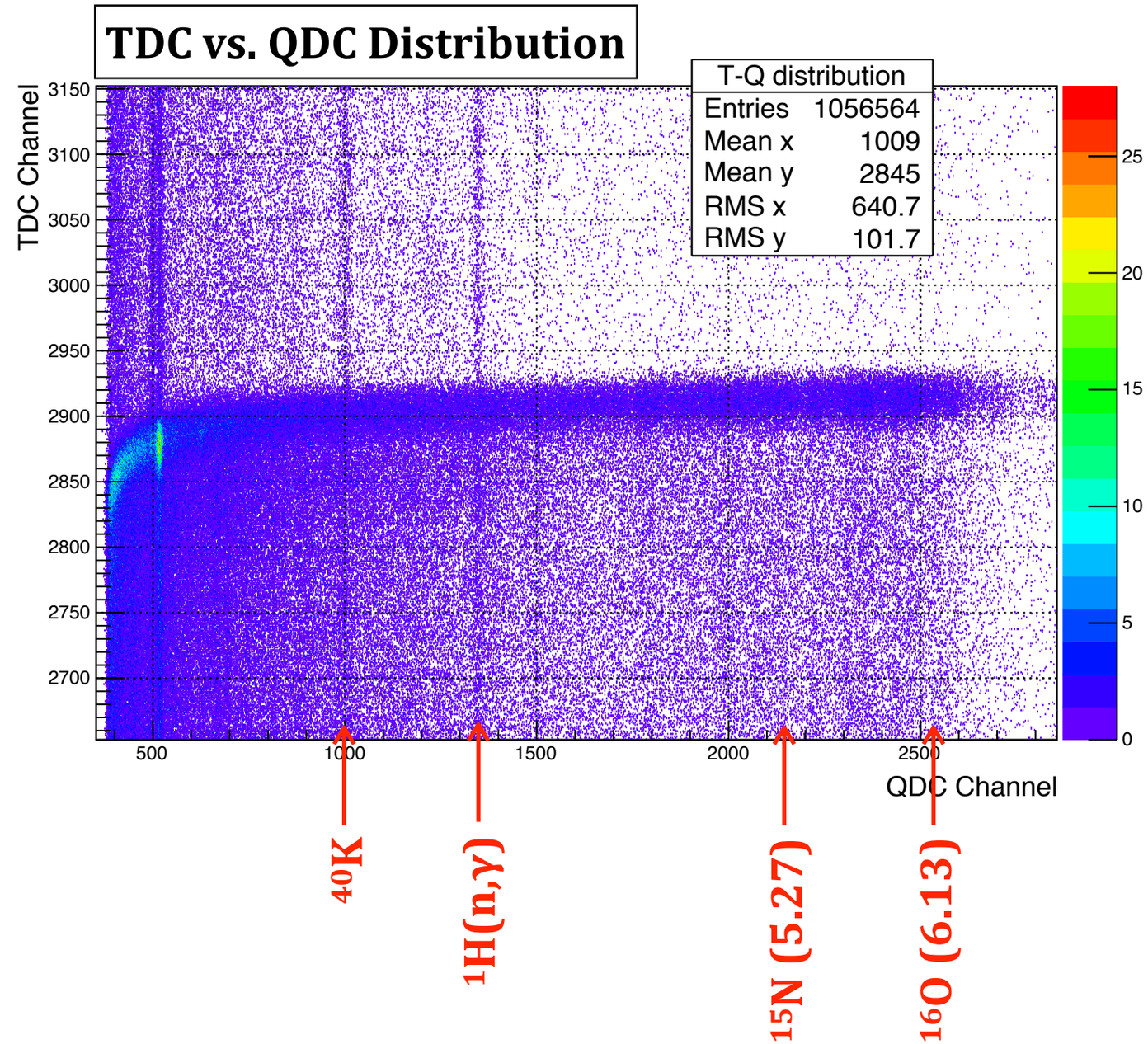
Gamma-ray Production: $LaBr_3(Ce)$



- Observation of corresponding peaks to ones by HPGe detector
- Resolution is a bit worse than HPGe.
- We have time information (Next)

Gamma-ray Production: $LaBr_3(Ce)$





- Time information is taken well.
- From the 2D distribution (TDC vs. QDC), strong gamma-ray peaks are thought to be by fast neutron reactions.

Neutron Flux: Analysis Flow

Raw data

↓ Time calibration

Time distribution (all)

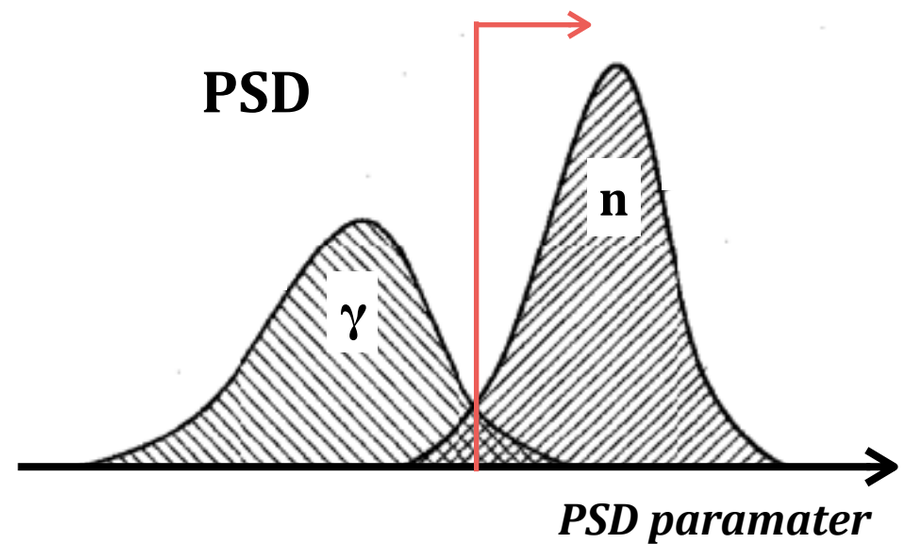
↓ Neutron selection

Time distribution (neutron)

↓ Relativity calculation $\beta = \sqrt{1 - \left(\frac{939.6}{K + 939.6}\right)^2} = \frac{v}{c}$ (neutron mass = 939.6 MeV/c²)

Kinetic energy distribution

Kinetic energy reconstruction



↓ Detection efficiency → **SCINFUL-QMD** (MC code by JAEA)

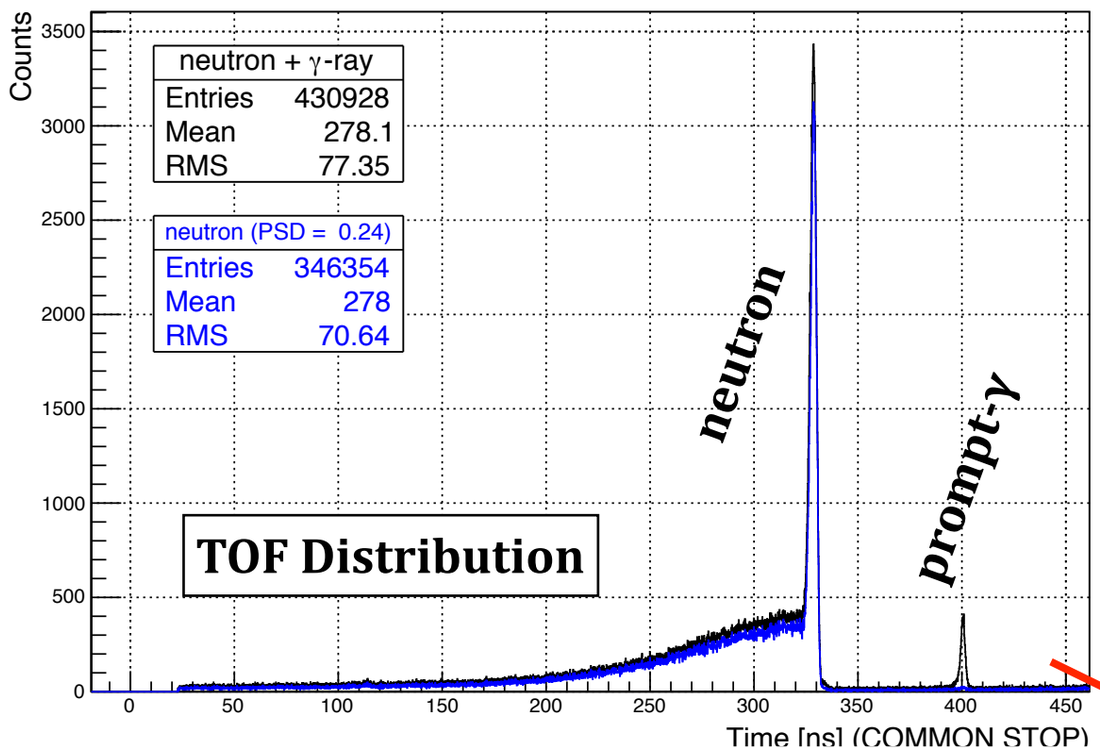
Detection efficiency calculation

inputs to simulator

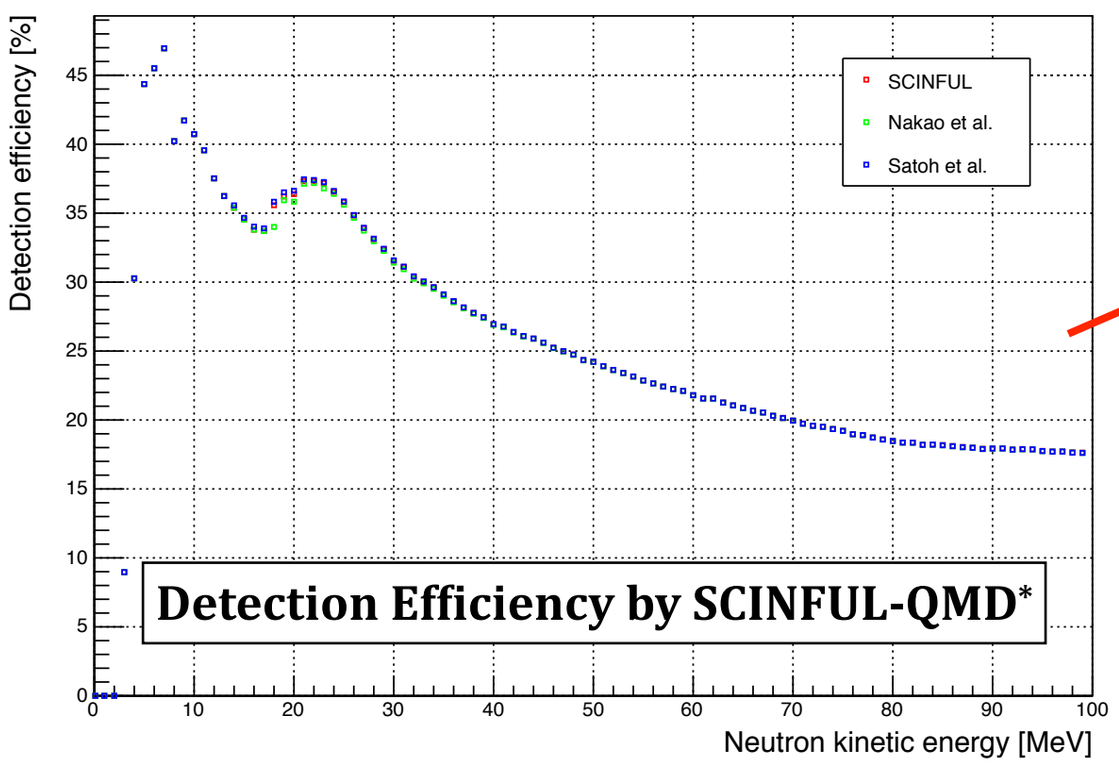
- detector position & size → well known
- light attenuation length → well known
- threshold → need energy calibration

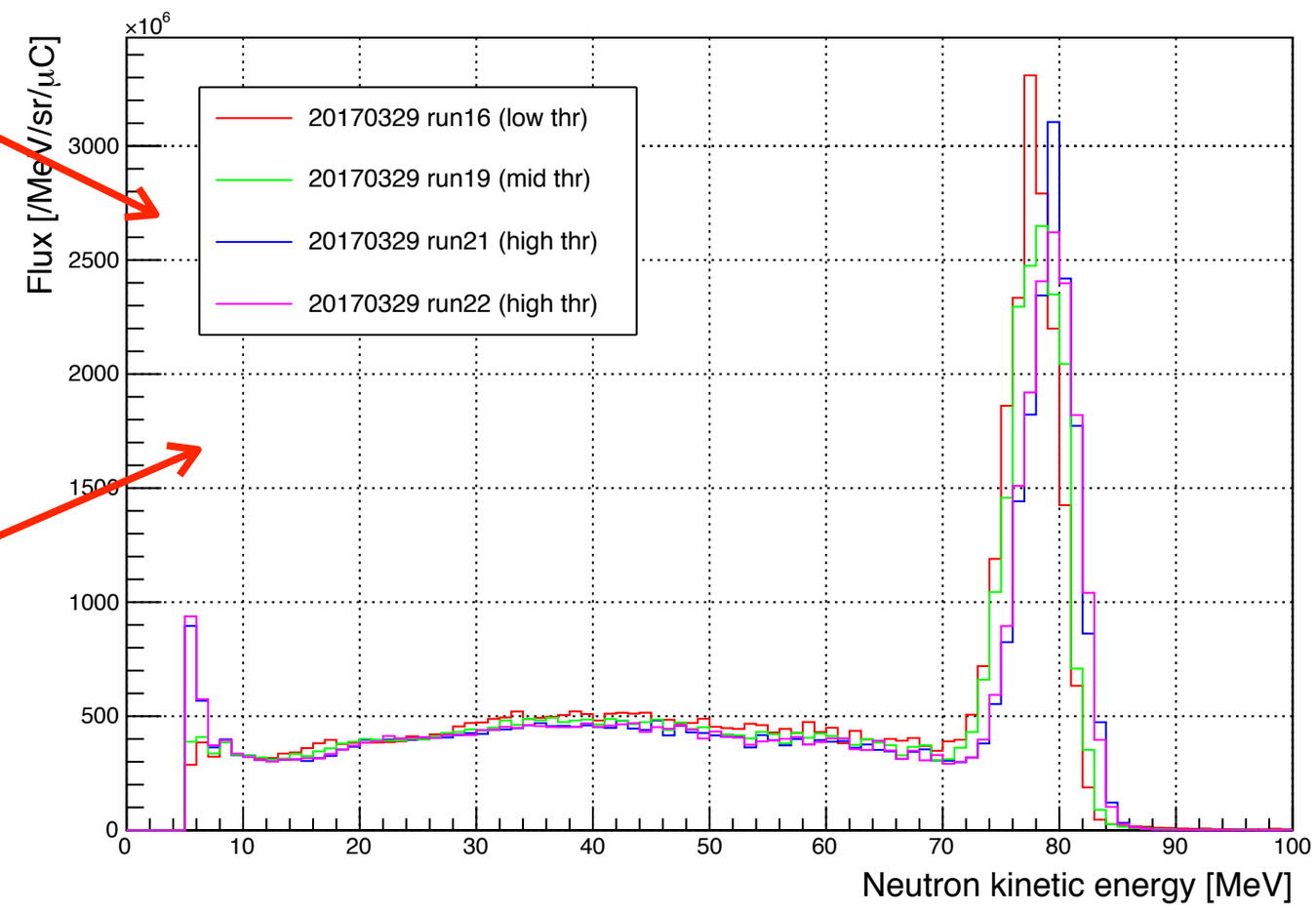
Flux

Neutron Flux: Results



- Reconstruct kinetic energy by using time information (t_0 by gamma-ray).
- Neutron selection is done by Pulse Shape Discrimination (PSD).
- Detection efficiency by MC





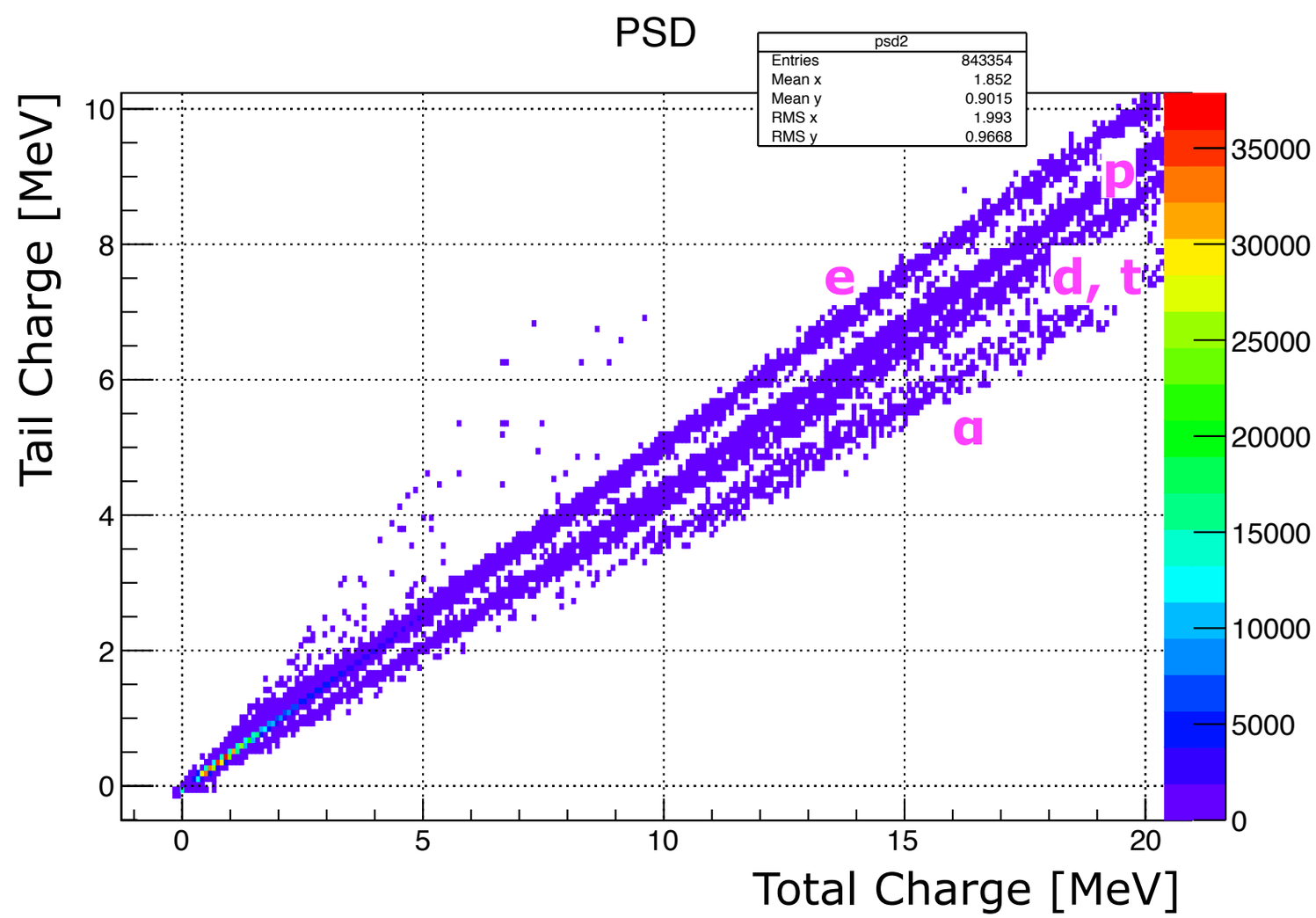
*D. Satoh *et al.*, JAEA-DATA/CODE 2006-023 (2006)

Neutron Flux: Uncertainties

Source		Error
Statistic		+/– 0.8 ~ 2.2 %
Systematic (kinetic energy)	PSD cut failure	< 0.1 % (can be ignored)
	high energy deposit γ-ray	– 0.8 %
	environmental γ-rays former bunch neutrons scattered neutrons	– 0.3 %
	charged particles	< 0.1 % (can be ignored)
Systematic (detection efficiency)	SCINFUL-QMD model (< 100 MeV)	+/– 6 %
	input threshold (energy calibration)	< 0.1 % (can be ignored)
	input light attenuation factor	< 0.1 % (can be ignored)
	input light output function	< 0.1 % (can be ignored)
	MC statistic	+/– 0.3 %
	kinetic energy reconstruction	+/– 2 %
Total		+/– 6.5 %

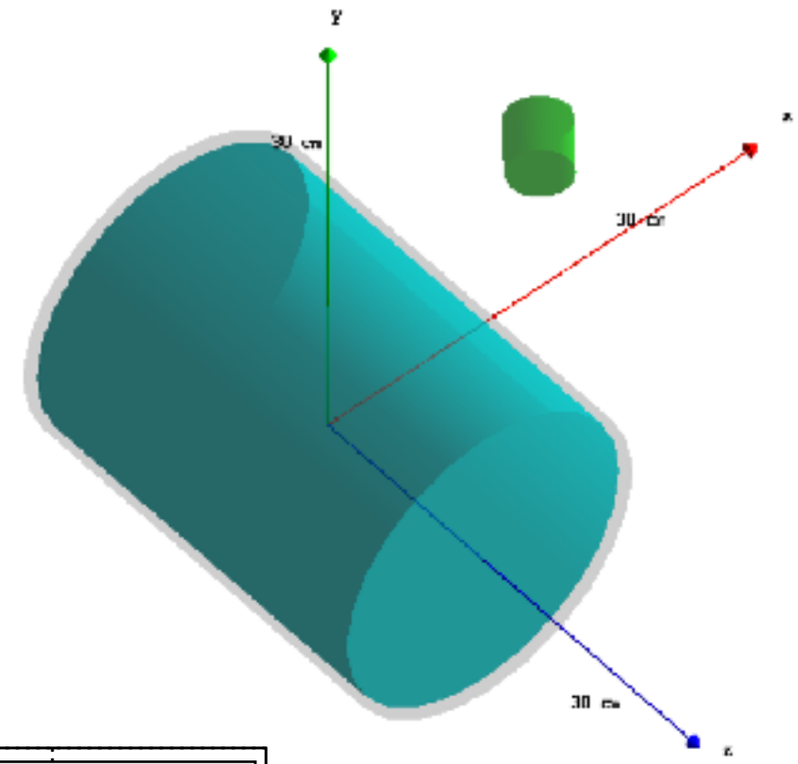
Scattered Neutron

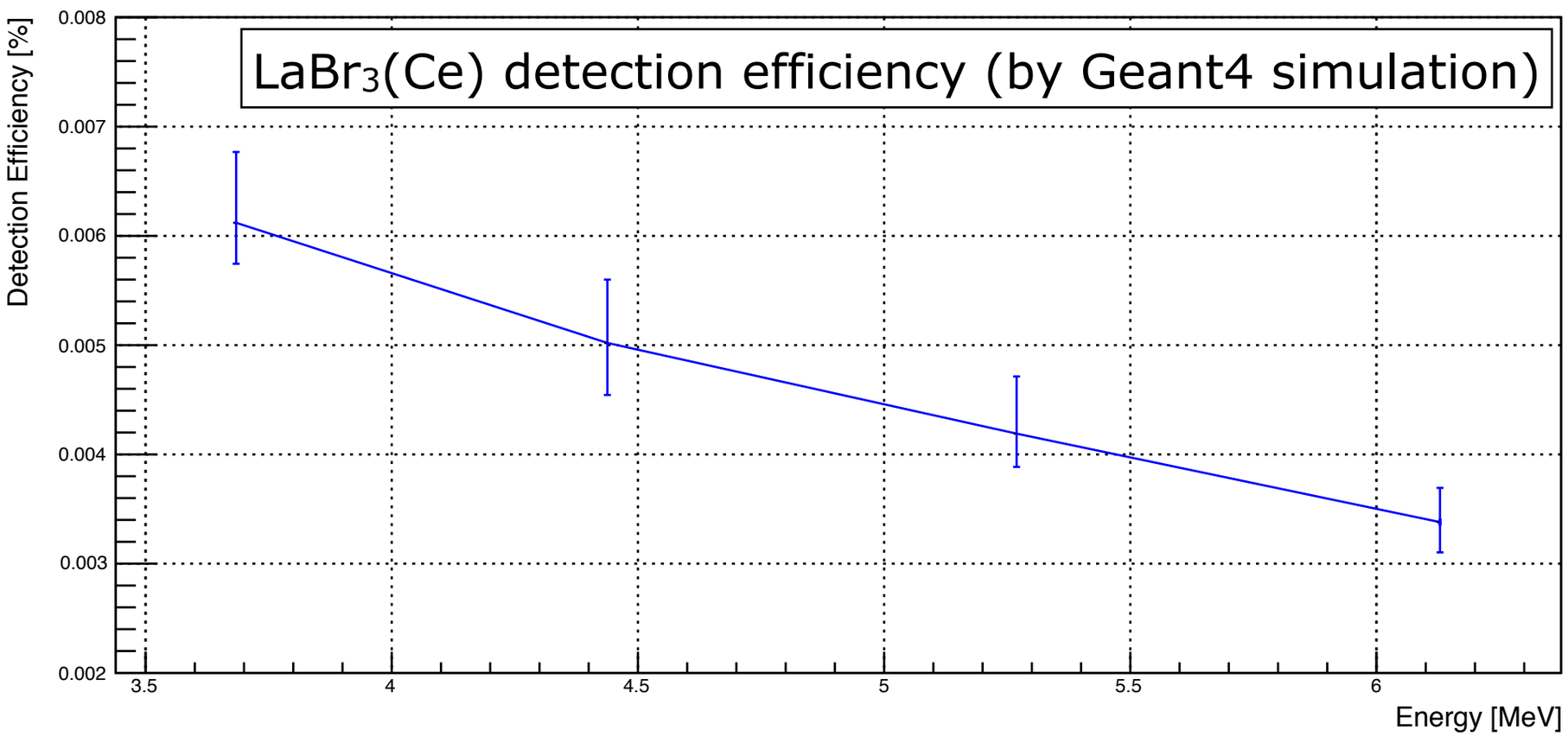
- Measure the neutron-induced background at the gamma-ray detector position using CsI(Tl) PSD.
- Neutron background in signal region for peak neutron energy is estimated to be less than **2 %** (small enough).
- Density of CsI is close to that of Ge and LaBr, so it is useful for background estimation.



Cross Section Estimation

- Detection efficiencies for peak gamma-rays are calculated using MC.
- Production cross section for 6.13 MeV
  - $\sigma \sim 5$ mb (Very preliminary!)
  - Background estimation, systematic estimation works remain.

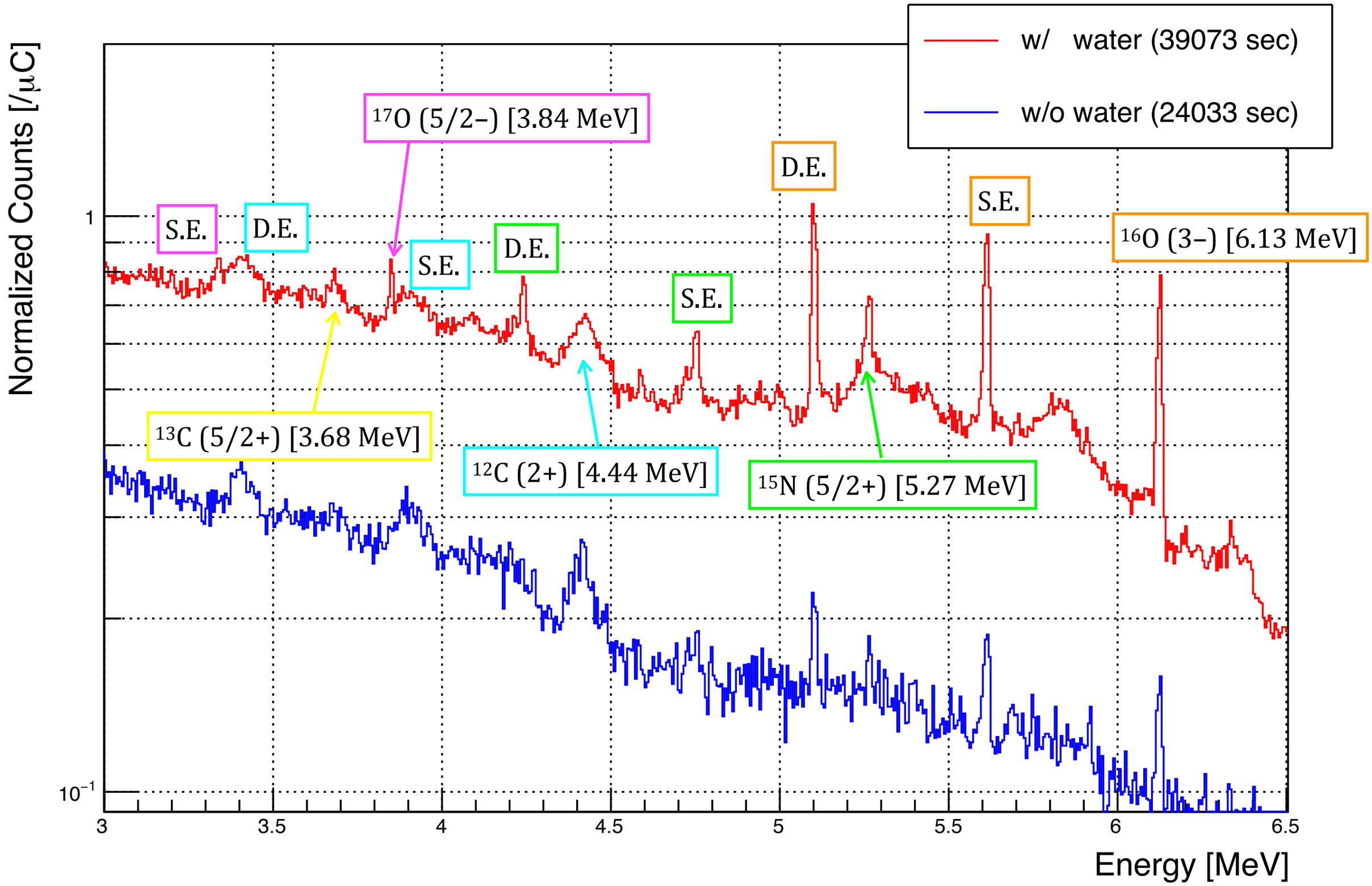




Contents

- *Introduction*
- *Experimental Details*
- *Analysis Results*
- *Considerations*

Reminder: Observed Peaks



Clues for Process Identification

- Peak width from light nucleus is larger (Doppler effect):
  - 4.44 MeV and 3.68 MeV peaks are from excited carbons.
- In the decay with particle emission, it is more probable to decay to the state with large energy gap from the original excited state or with large angular momentum:
  - In **^{16}O(3−; 6.13 MeV) → ^{12}C + α**, ^{12}C(2+; 4.44 MeV) is dominant.
  - In **^{16}O(3−; 6.13 MeV) → ^{15}N + p**, ^{15}N(5/2+; 5.27 MeV) is dominant.
  - In **^{16}O(3−; 6.13 MeV) → ^{15}O + n**, ^{15}O(5/2+; 5.24 MeV) is dominant.
  - α-threshold (7.16) < p-threshold (12.13) < n-threshold (15.66) [MeV]
  - When ^{16}O(3−; 6.13 MeV) is created, ^{15}O is unlikely to be produced compared to ^{12}C and ^{15}N.

Physics Process

(a) 6.13 MeV from $^{16}O(3-)$:

$^{16}O(n,n')^{16}O^*$, then $^{16}O^* \rightarrow {}^{16}O + \gamma$

(b) 5.27 MeV from $^{15}N(5/2+)$: (*)

$^{16}O(n,n')^{16}O^*$, then $^{16}O^* \rightarrow {}^{15}N^* + p$, then $^{15}N^* \rightarrow {}^{15}N + \gamma$ (p-emission)

(c) 4.44 MeV from $^{12}C(2+)$:

$^{16}O(n,n')^{16}O^*$, then $^{16}O^* \rightarrow {}^{12}C^* + \alpha$, then $^{12}C^* \rightarrow {}^{12}C + \gamma$ (α-emission)

(d) 3.84 MeV from $^{17}O(5/2-)$:

^{17}O creation (neutron capture by ^{16}O or inelastic scattering with ^{17}O ?),

then $^{17}O^* \rightarrow {}^{17}O + \gamma$

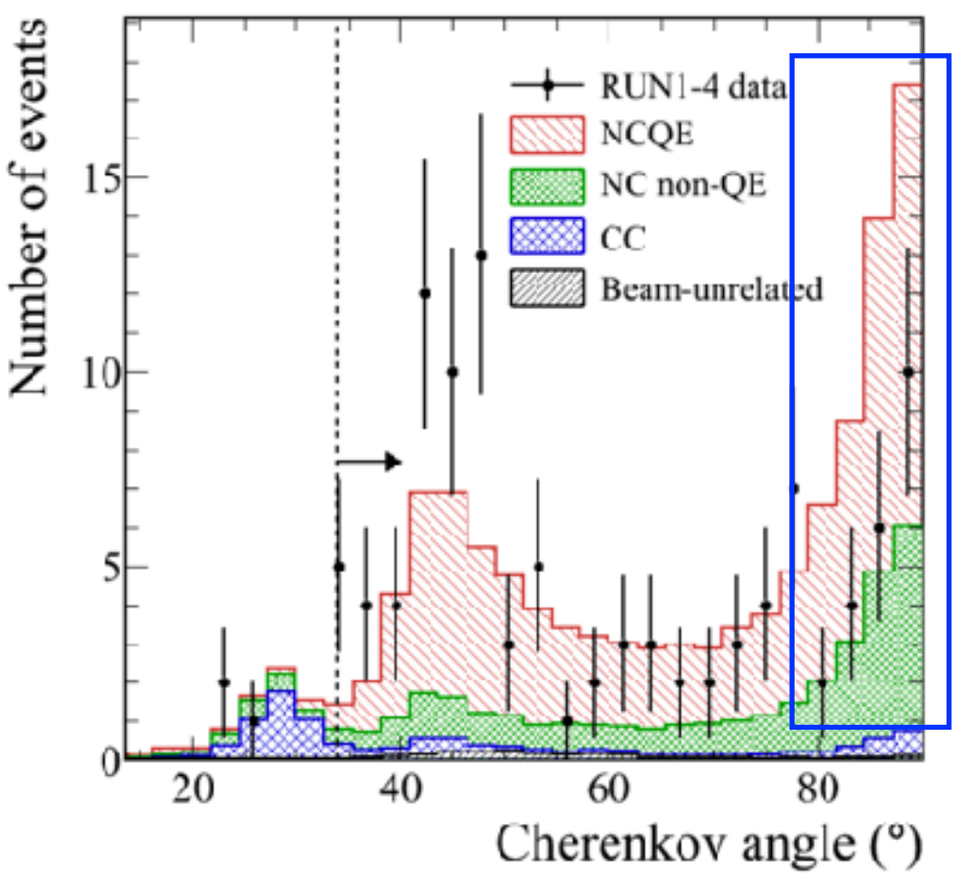
(e) 3.68 MeV from $^{13}C(5/2+)$:

$^{16}O(n,\alpha)^{13}C^*$, then $^{13}C^* \rightarrow {}^{13}C + \gamma$

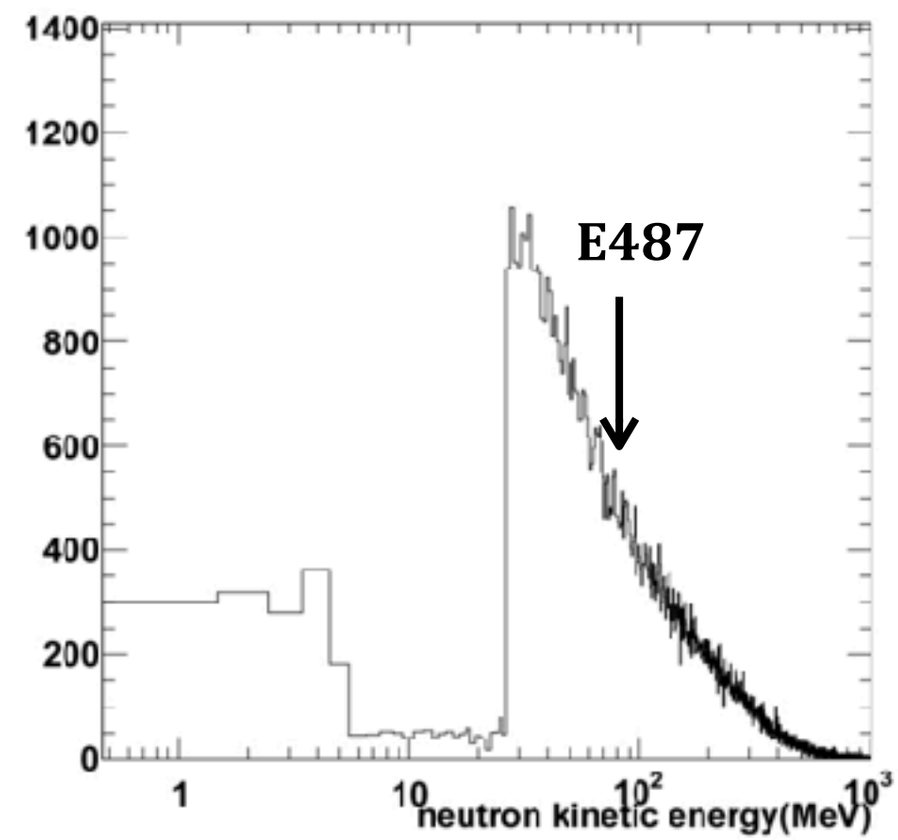
(*) In (n,np) reaction, 6.32 MeV from $^{15}N(5/2+)$ is dominant: (e,e'p), (p,2p) experiments

Consideration on T2K Results

- Main contribution to secondary processes are made by neutrons, because protons or alphas would stop very soon due to ionization (and they have kinetic energy smaller than Cherenkov threshold).
- Our results show no additional neutrons are emitted in any processes.
- E487 is with 80 MeV, and at lower energy inelastic cross section is expected to become larger, therefore the case may be more clear.



MC says many secondary-γs are emitted.



Summary

- Precise knowledge of neutrino NCQE interaction is important for several physics searches at T2K and SK.
- Largest source of systematics comes from poor nuclear physics model.
- We study the nuclear process with measurement and aim to improve the model.
- At RCNP, we made a gamma-ray measurement with 80 MeV neutron;
  - **Observed gamma-rays from neutron-oxygen reactions**
  - Measured items necessary to obtain neutron flux
  - Measured scattered neutron backgrounds
  - Estimated very preliminary cross section (analysis is on-going.)
- Physics processes behind the E487 results seem to be consistent with T2K data.

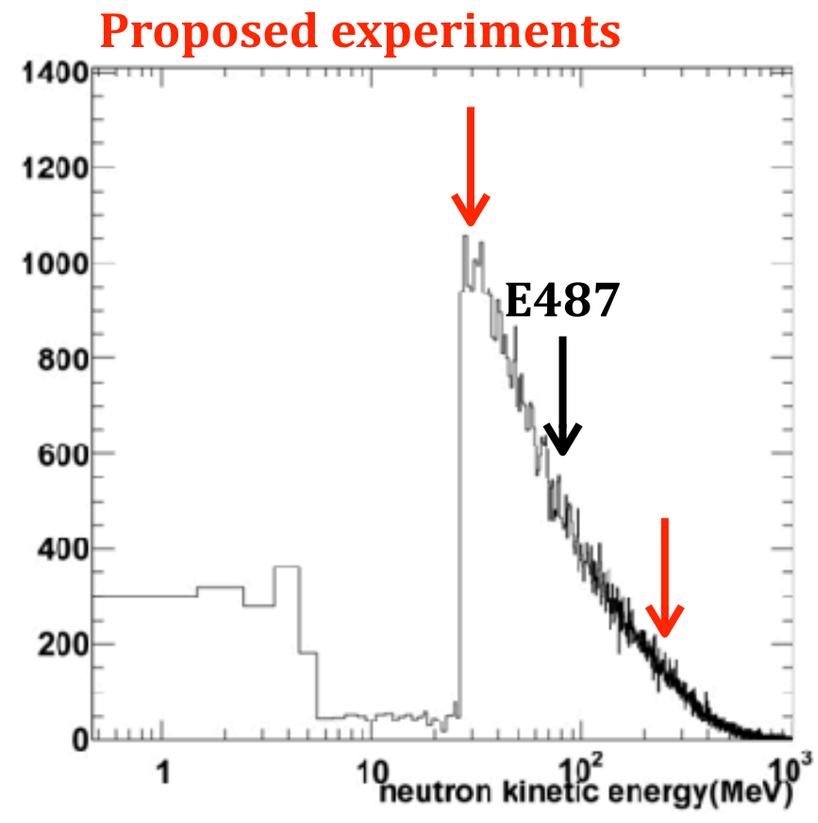
Next Plan

Additional measurements

- We are planning similar experiments to E487 with different energies.
  - 30 MeV: Flux peak, physics boundary near Fermi surface
  - 246 MeV: higher energy, below pion production threshold

T2K analysis

- Using results, we will constrain T2K model.
- Neutron-tagging method can be used for cross check (comparison of data with MC).
- Use all data taken so far (both for nu/anti-nu).



Backup Slides

Neutron Flux Analysis

1. Overflow suppression
   - CAEN V792 doesn't store data if charge integration is larger than maximum of dynamic range.
   - Even if overflow suppression is invoked, TDC stores data well.
   - PSD cannot used for these suppressed samples.

2. Sliding scale (for reduction of differential non-linearity)
   - Channel 3841 ~ 4095 of CAEN V792 are not correct.
   - PSD cannot used for samples in this region.

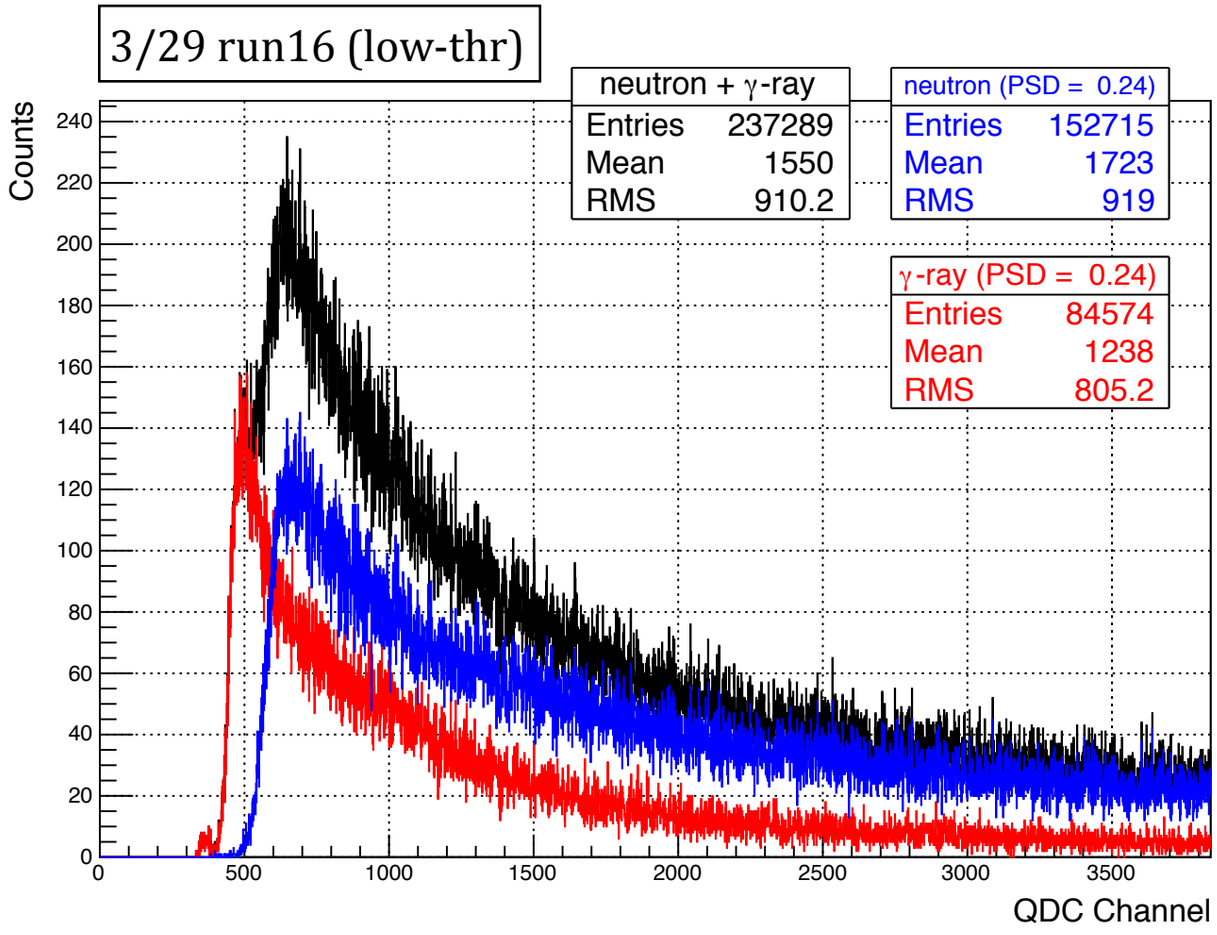
[Summary]

- **QDC channel > 3840 : assume all are neutrons (see next page)**
- **QDC channel ≤ 3840 : use PSD to extract neutrons**

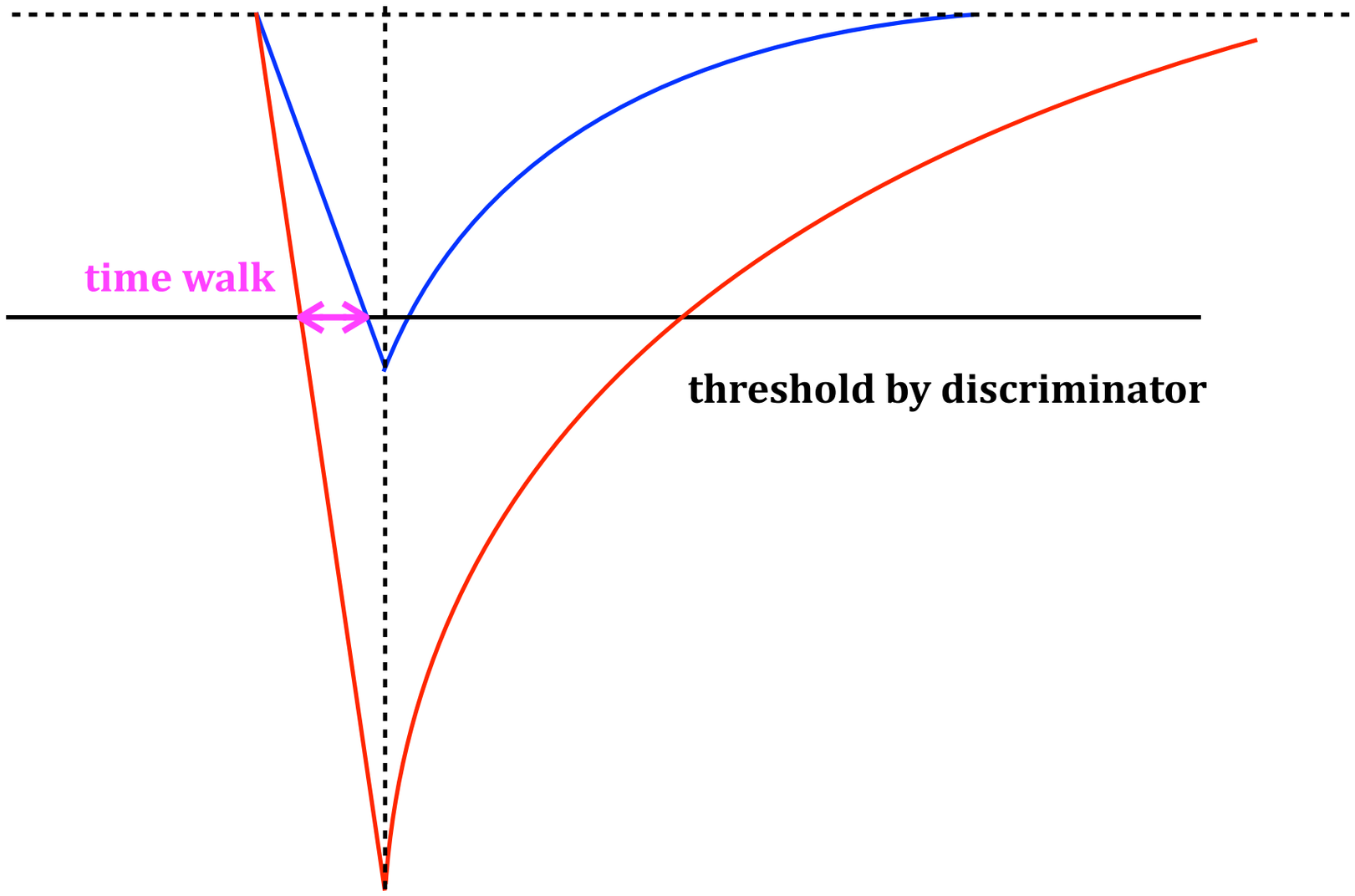
Neutron Flux Analysis

- Most events in higher energy region are thought to be due to neutrons.
  - Proton energy is ~ 80 MeV, so there's no pion productions (> 140 MeV).

    → no high energy gamma-rays (main is from excited state ~ 10 MeV).
  - Seeing energy spectra, gamma-ray contribution is getting smaller.
- Gamma-ray contamination is explained later.

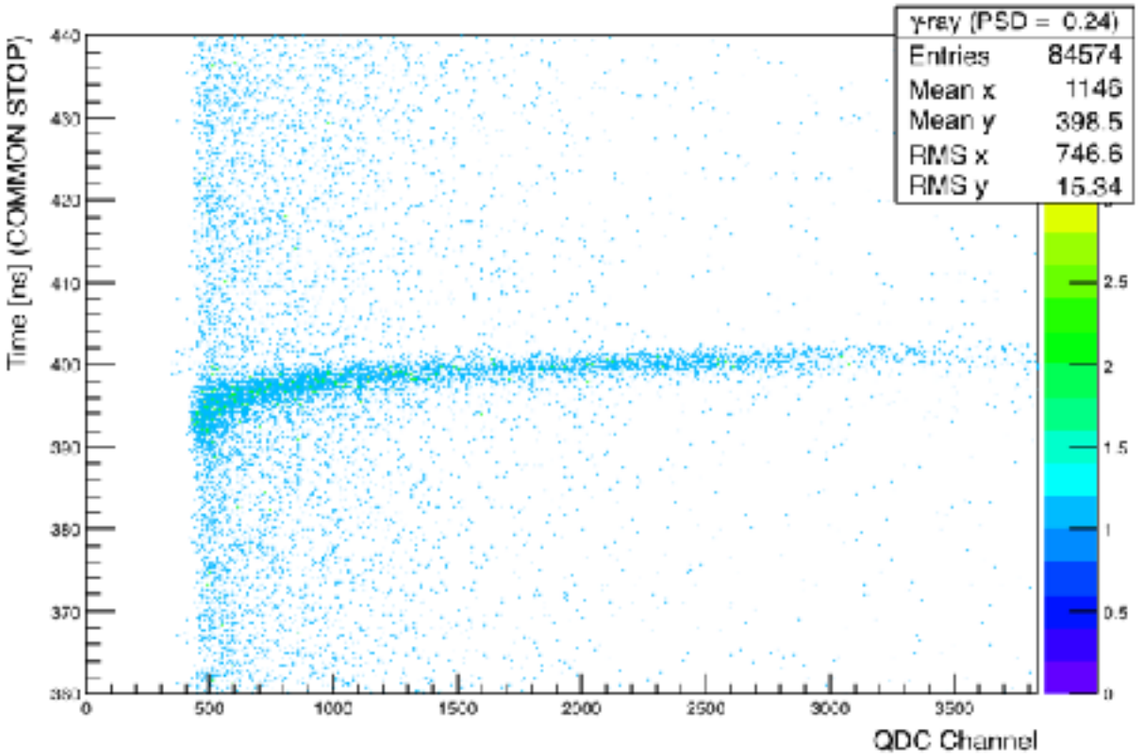


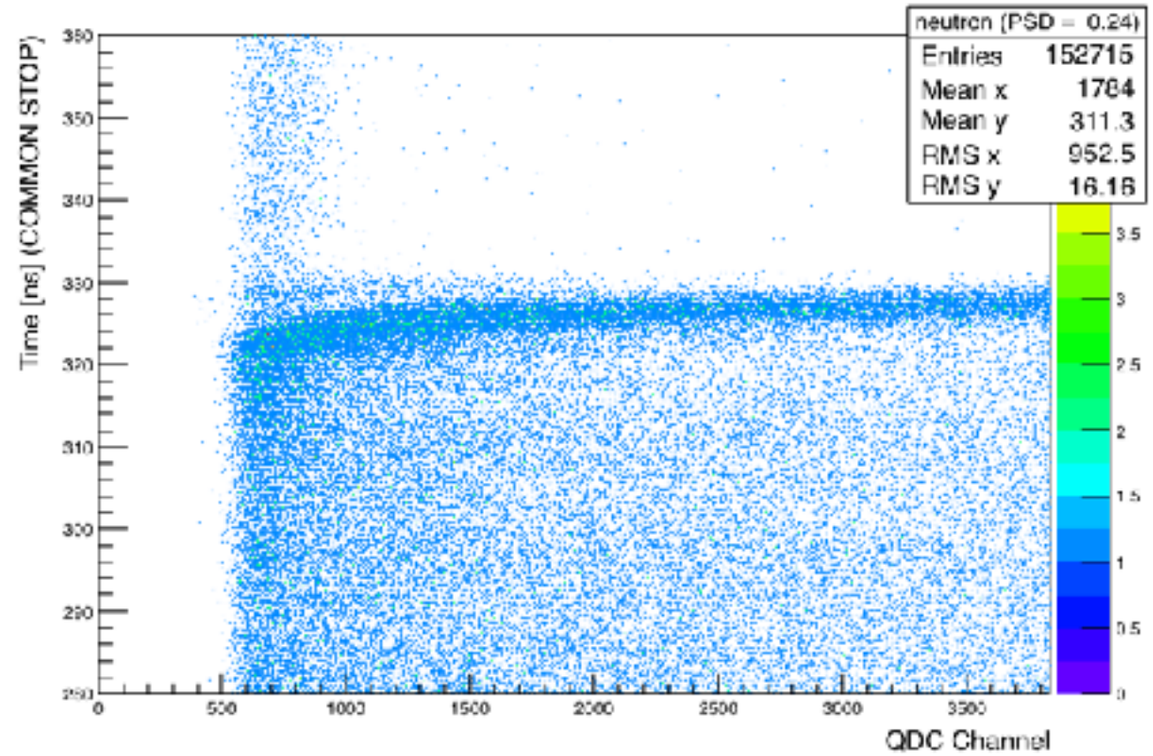
Neutron Flux Analysis

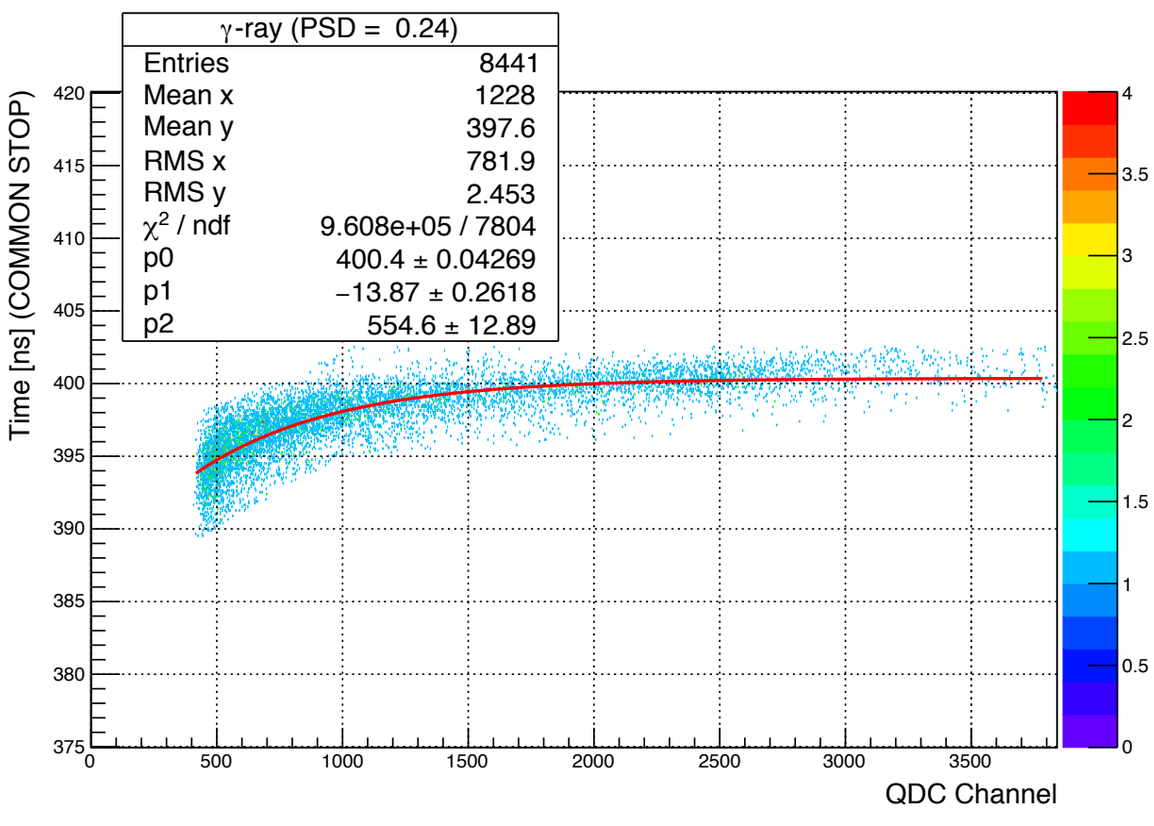


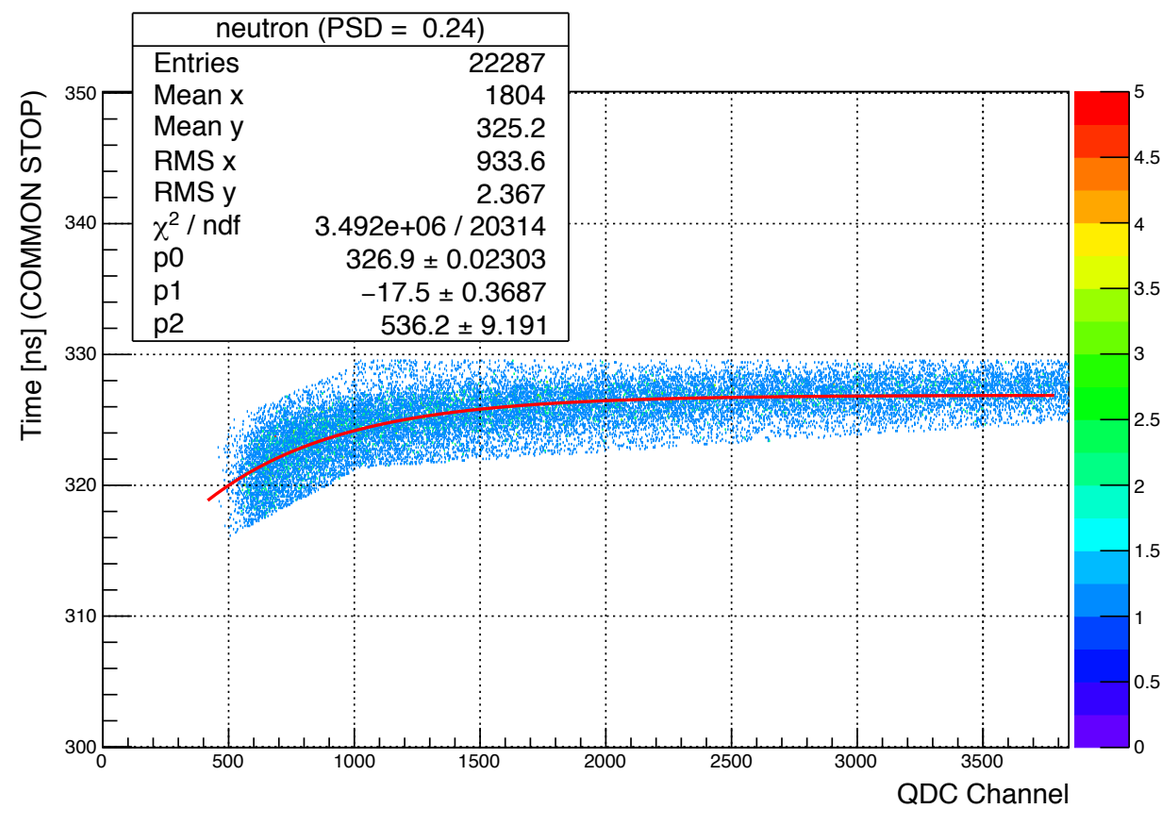
- This should affect time reconstruction and then kinetic energy distribution.
- The time walk effect should be corrected.

Neutron Flux Analysis





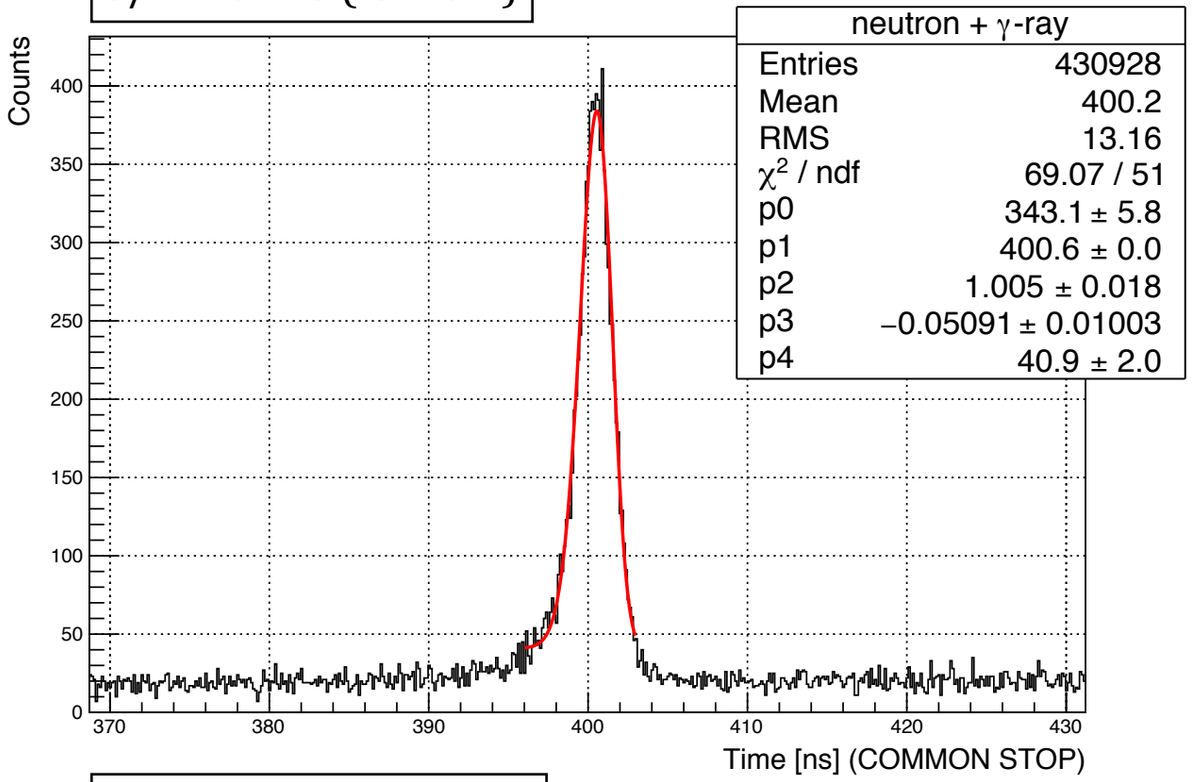




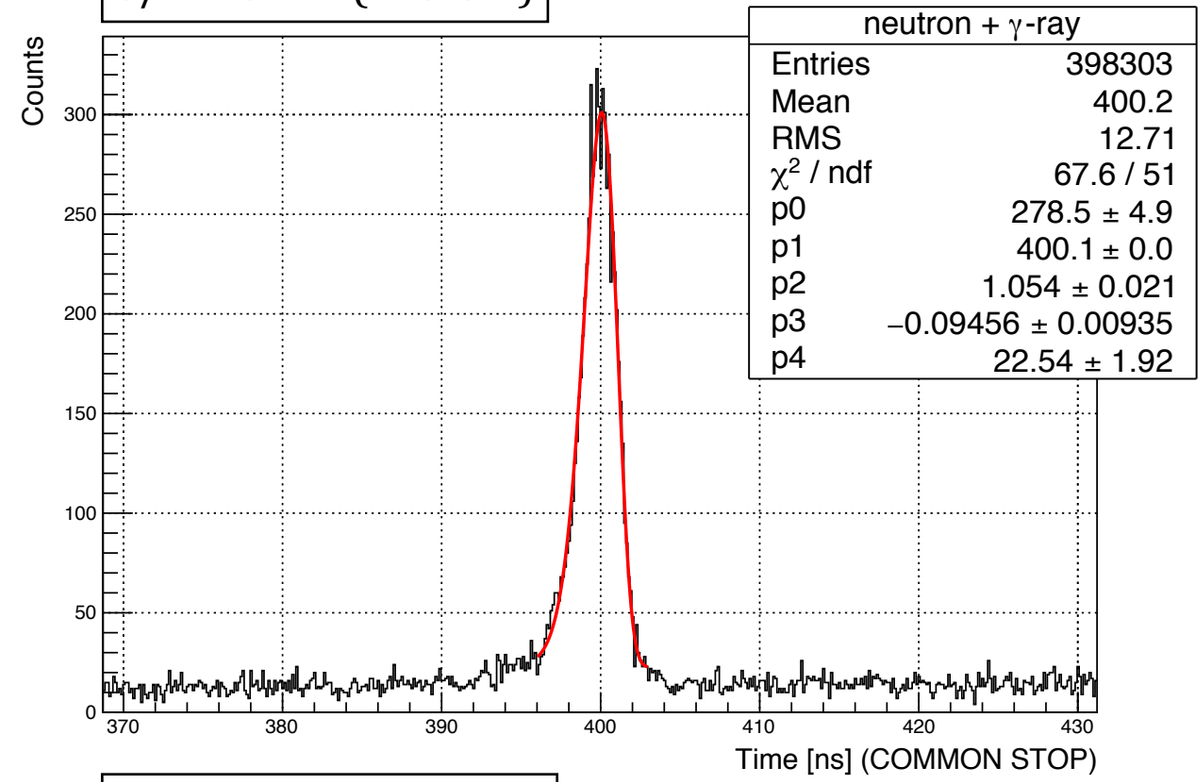
Neutron Flux Analysis

w/ time-walk correction

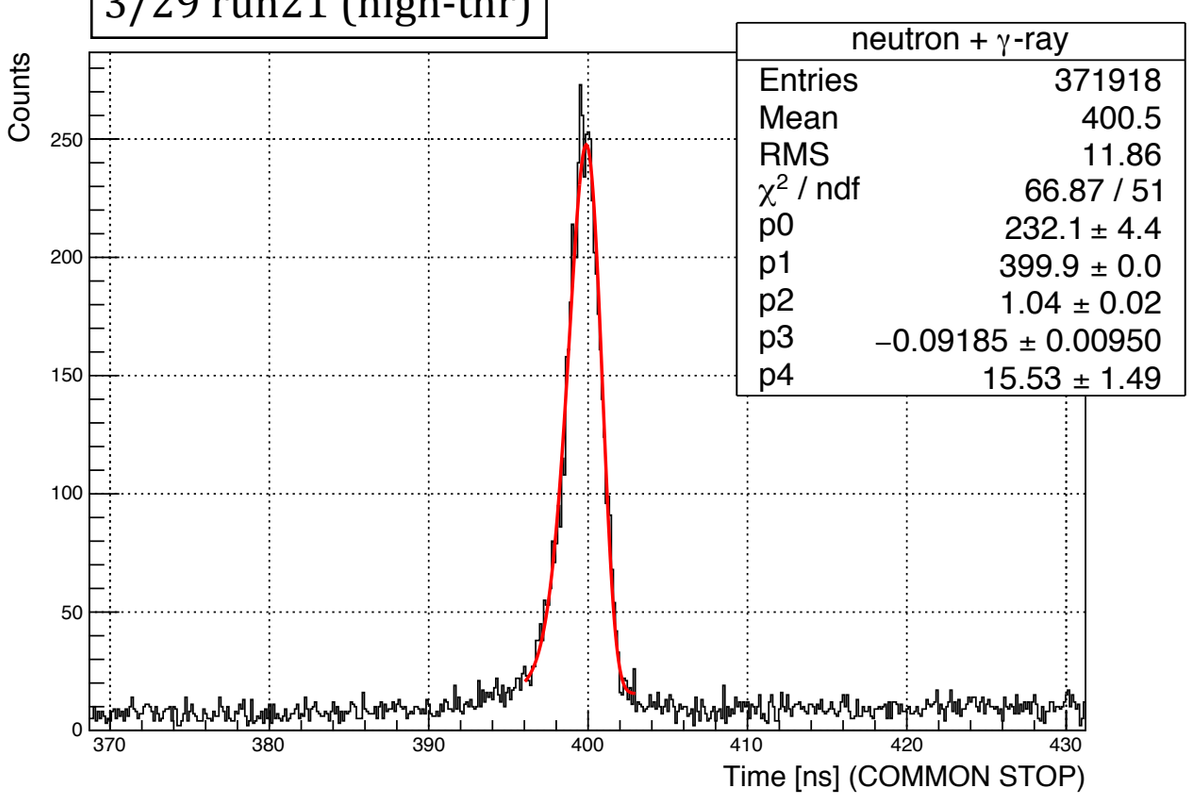
3/29 run16 (low-thr)



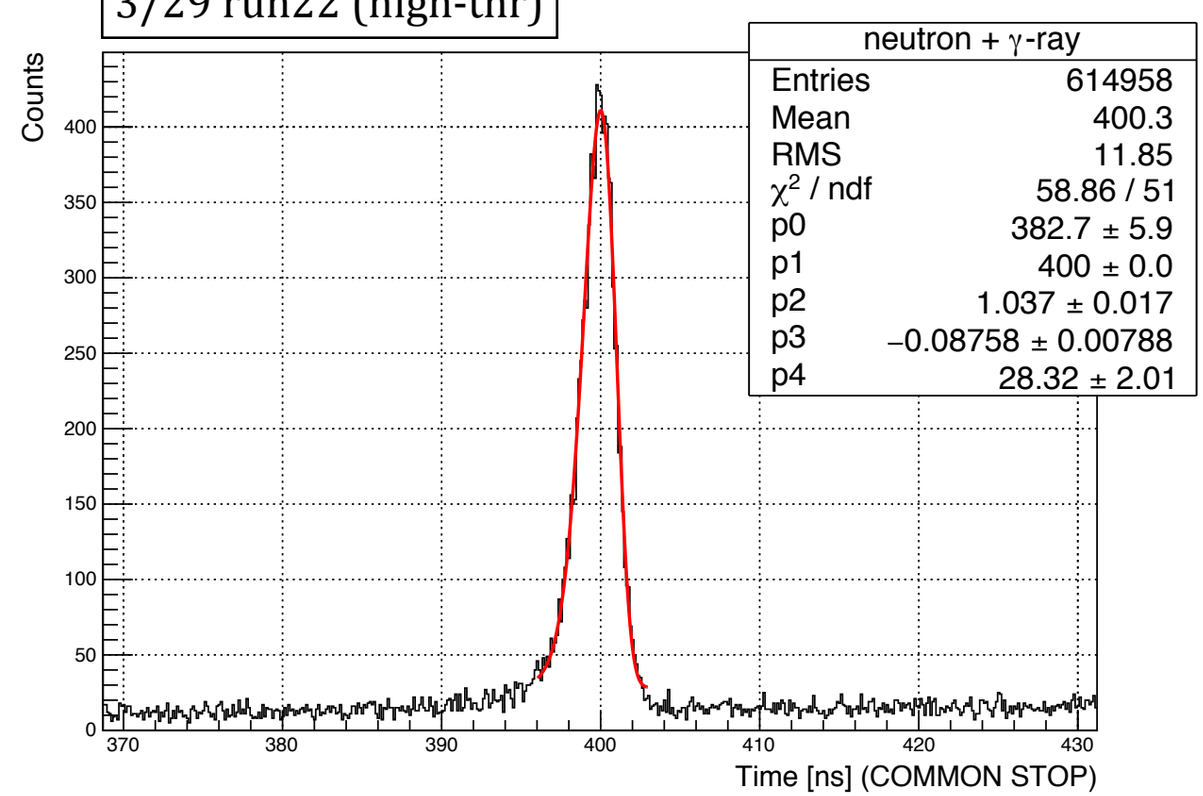
3/29 run19 (mid-thr)



3/29 run21 (high-thr)



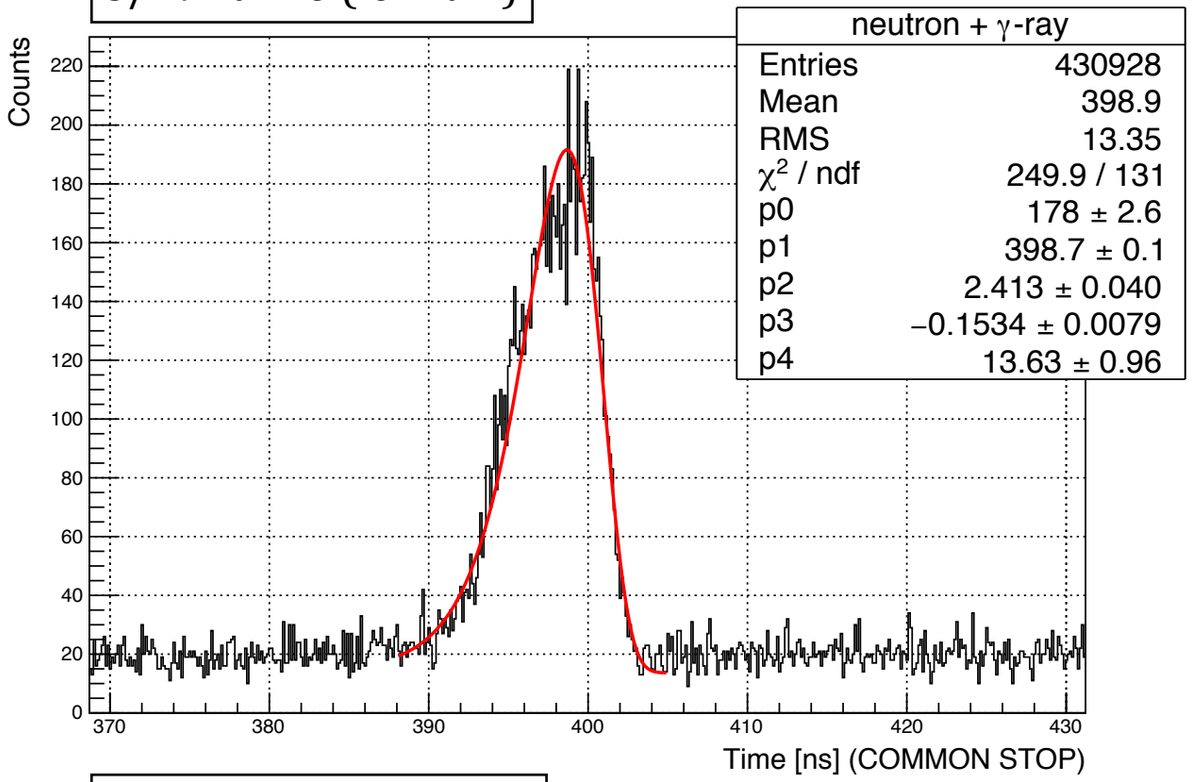
3/29 run22 (high-thr)



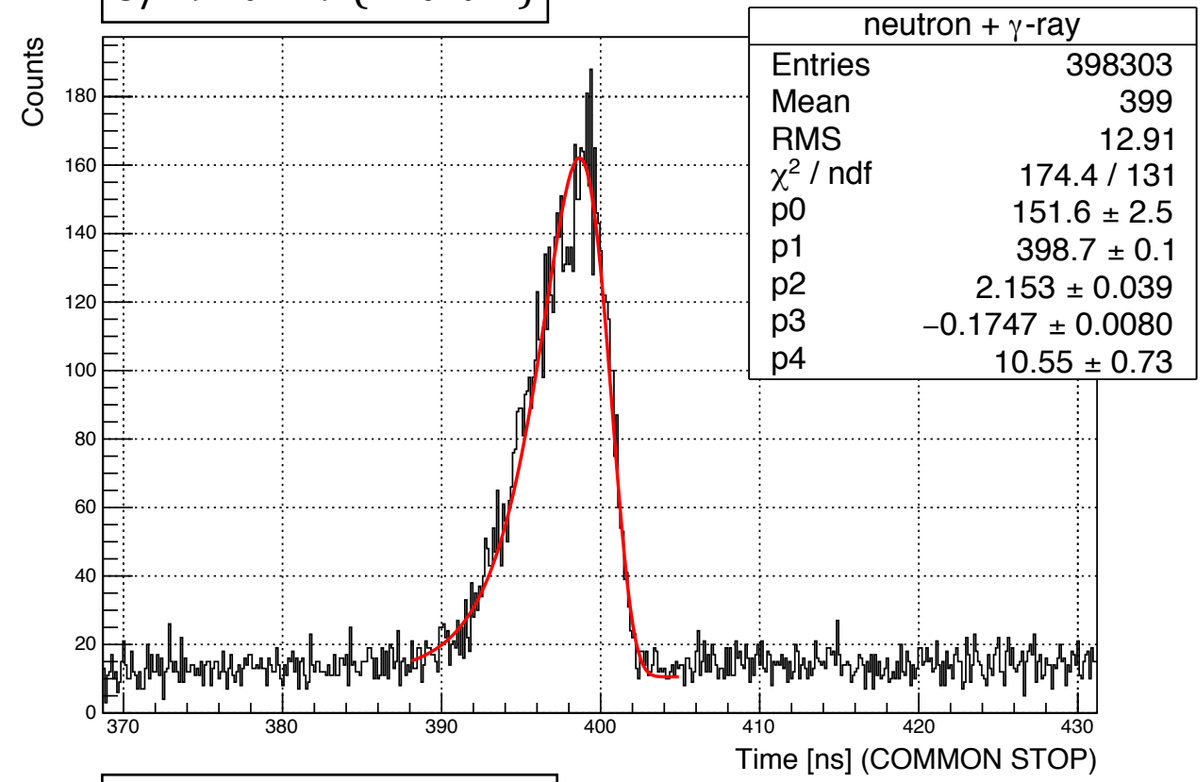
Neutron Flux Analysis

w/o time-walk correction

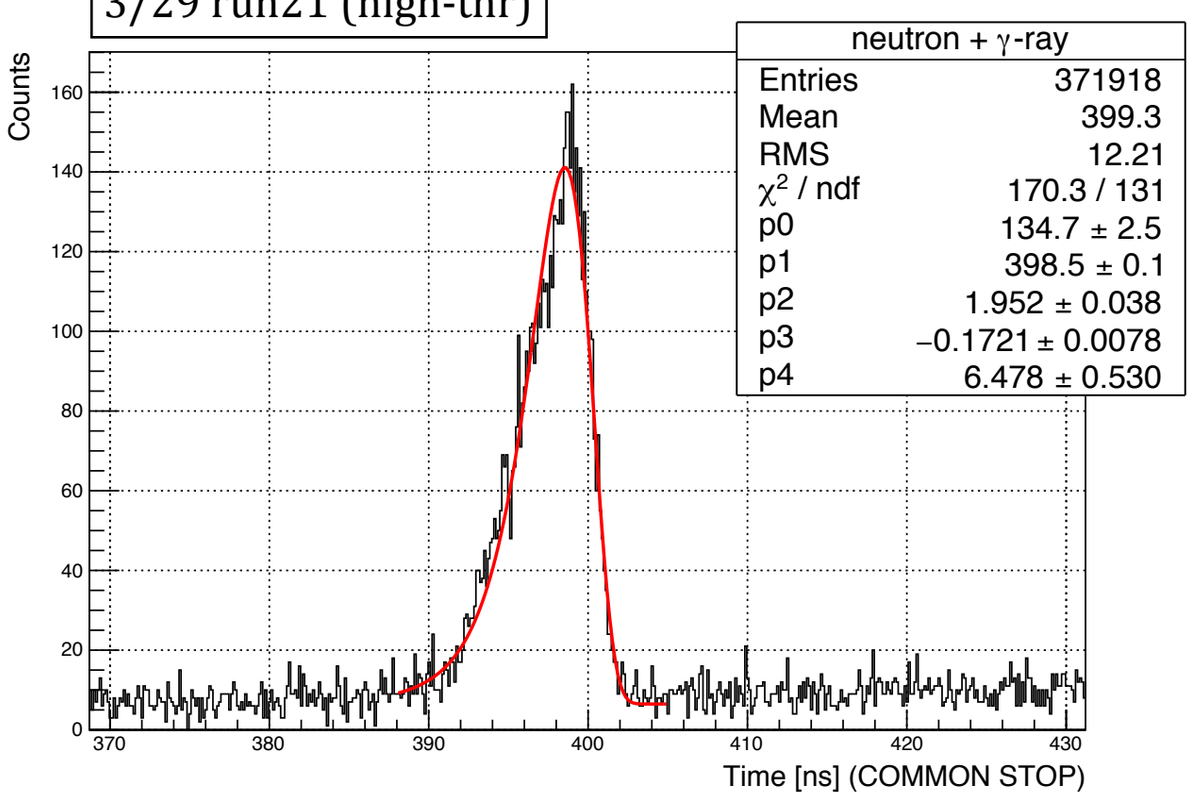
3/29 run16 (low-thr)



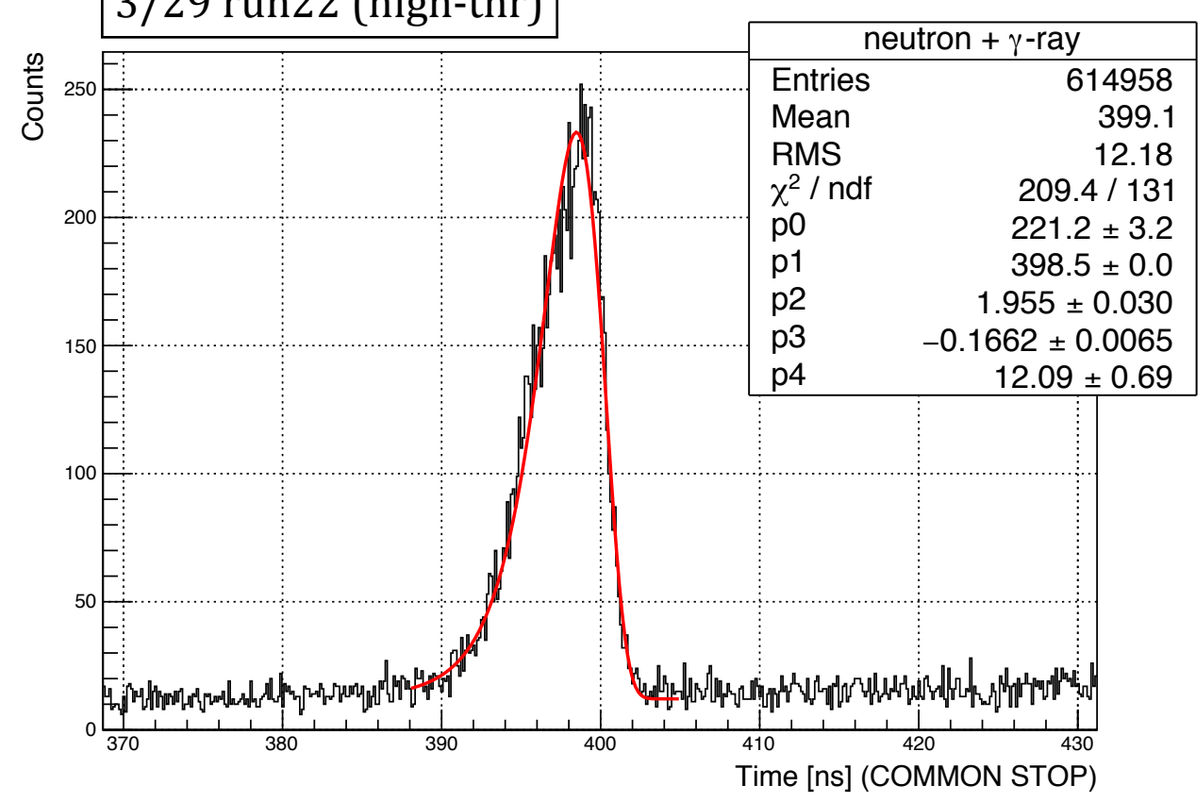
3/29 run19 (mid-thr)



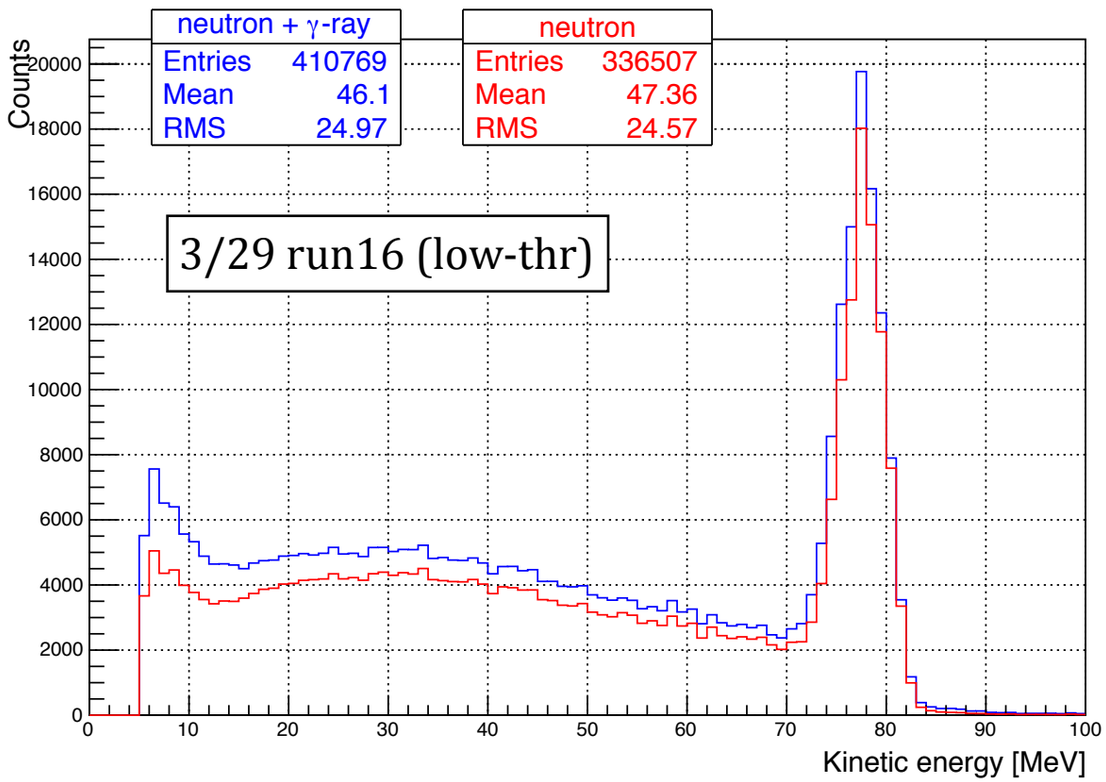
3/29 run21 (high-thr)

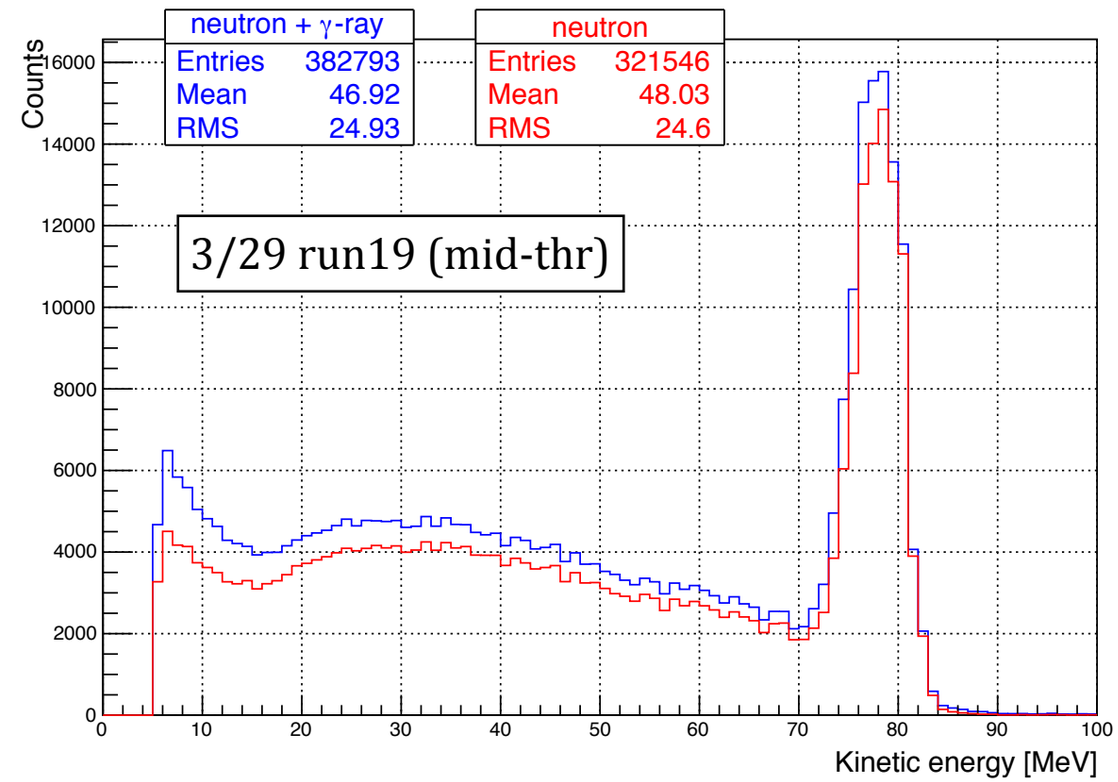


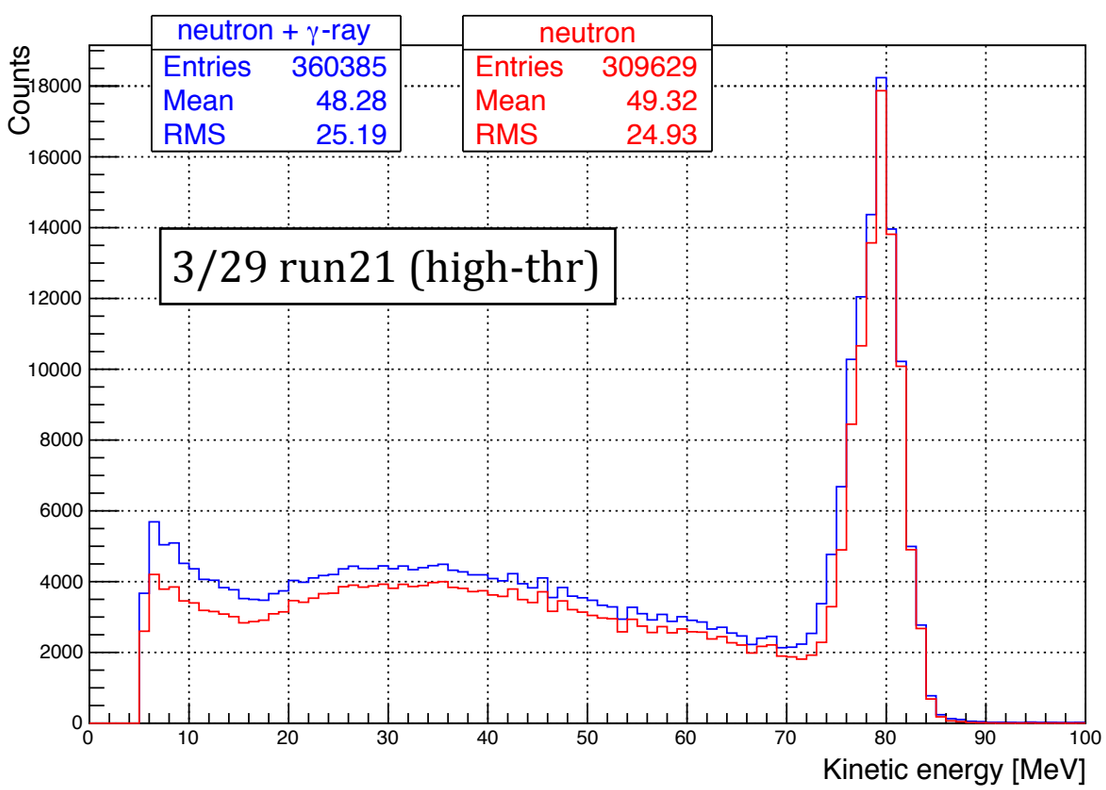
3/29 run22 (high-thr)

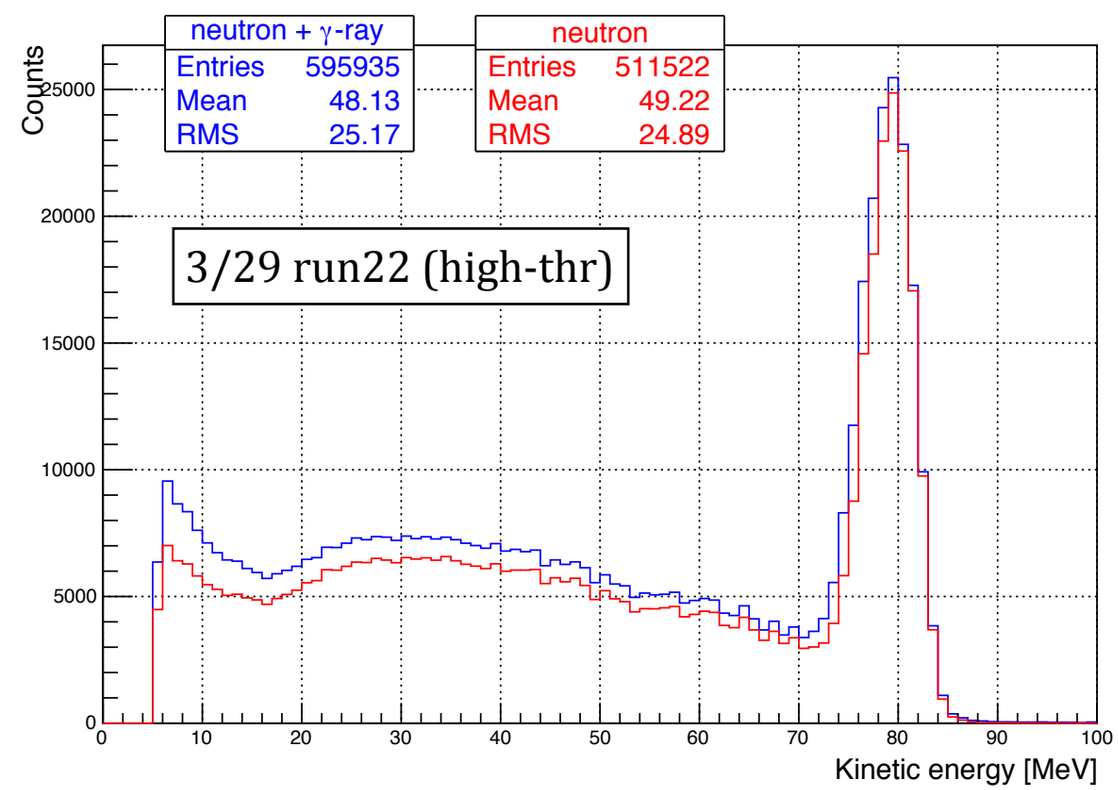


Neutron Flux Analysis



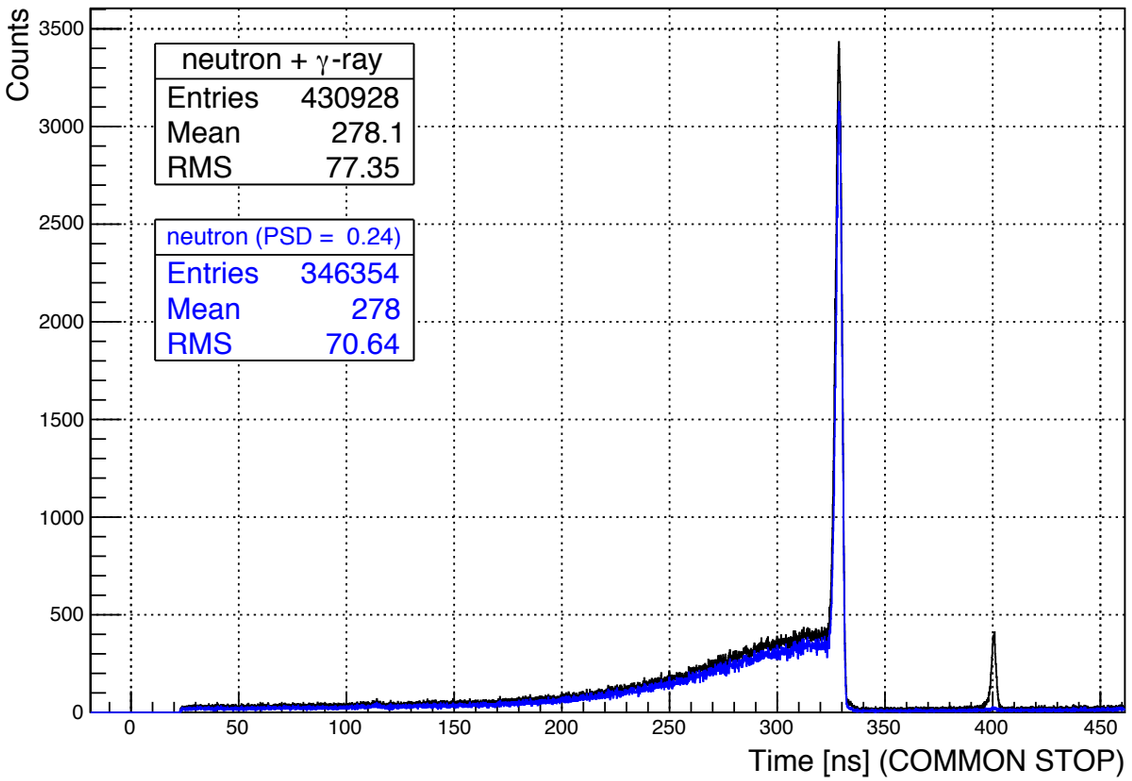


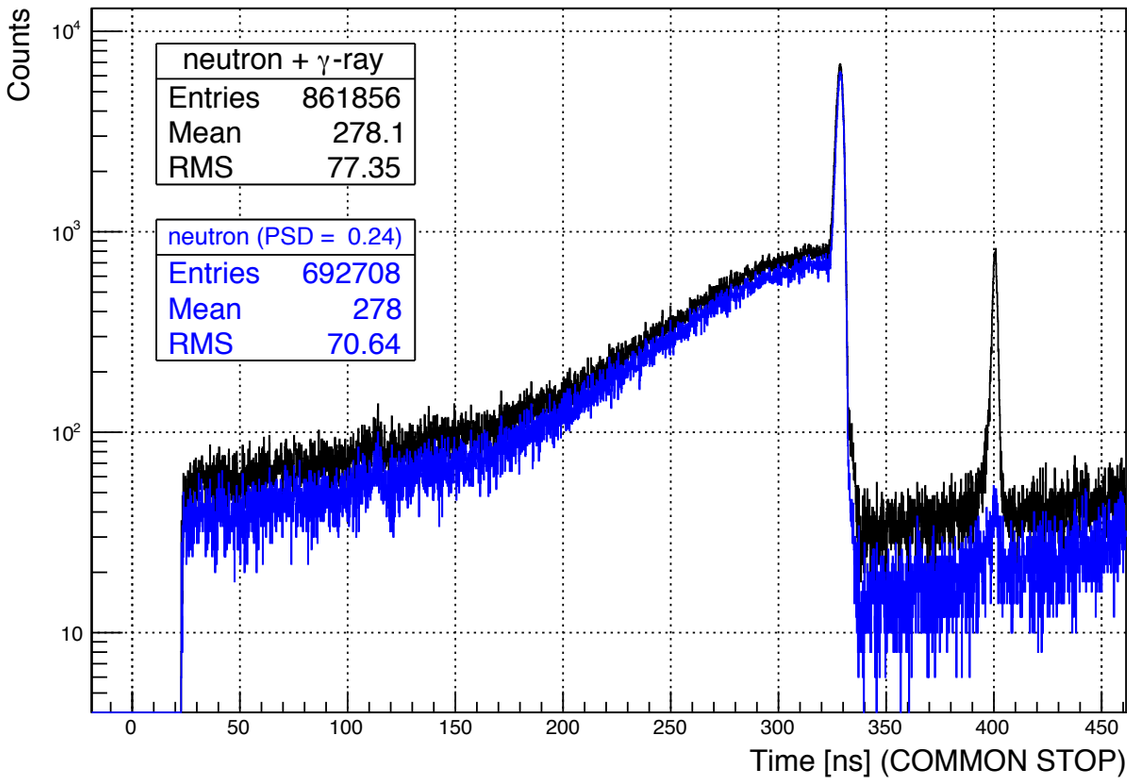




PSD Cut Failure

3/29 run16 (low-thr)

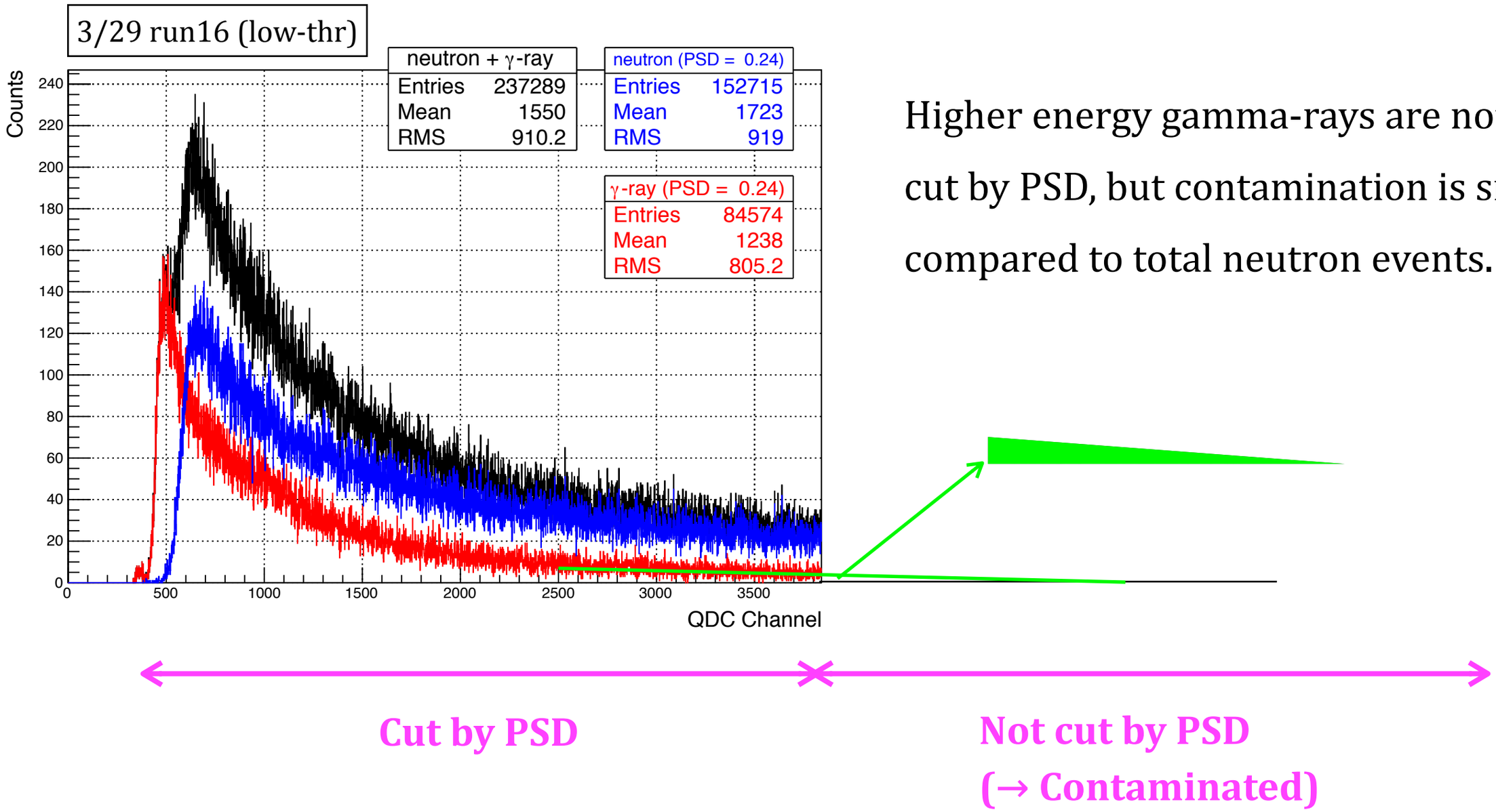




Contaminated gamma-rays that are not cut by PSD can be estimated by seeing prompt-gamma peak (background level subtracted).

4.5 % of gamma-rays are detected as neutrons
→ In peak region almost no low energy deposit gamma-ray, so such effect can be ignored.

High Energy Deposit Gamma-ray



Higher energy gamma-rays are not cut by PSD, but contamination is small compared to total neutron events.

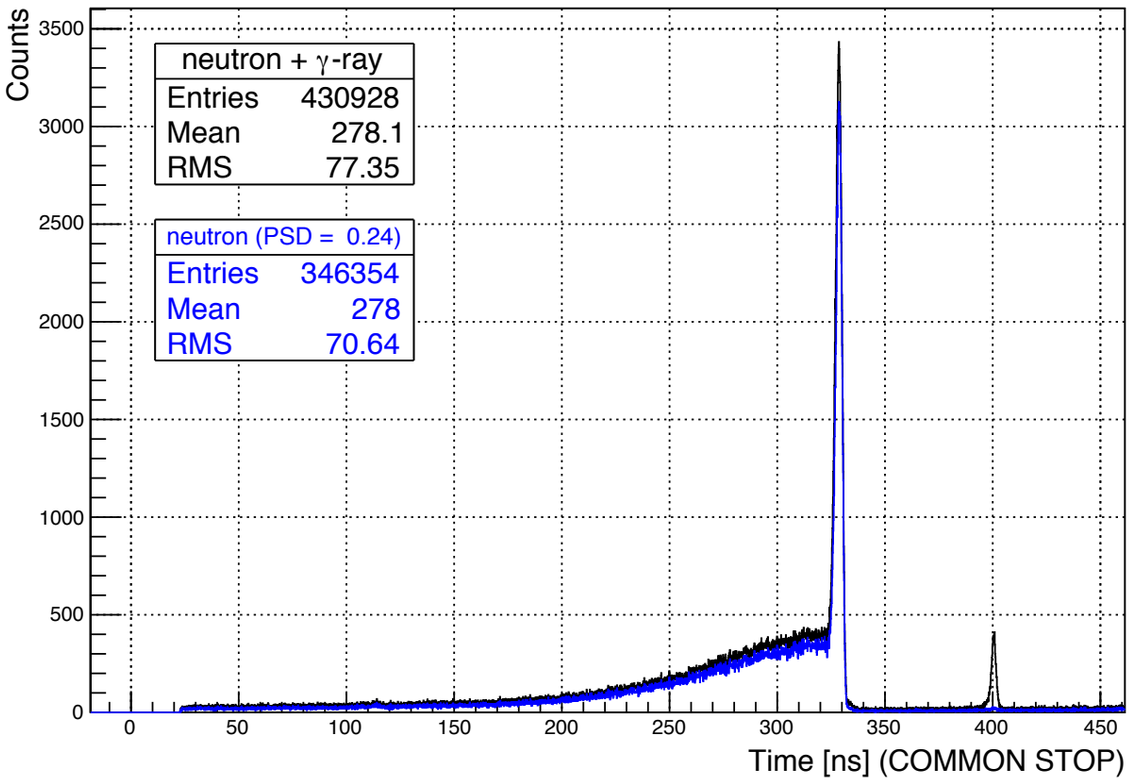
linear fit (p0 = 16.0 +/− 0.5, p1 = − 0.0034 +/− 0.0002)

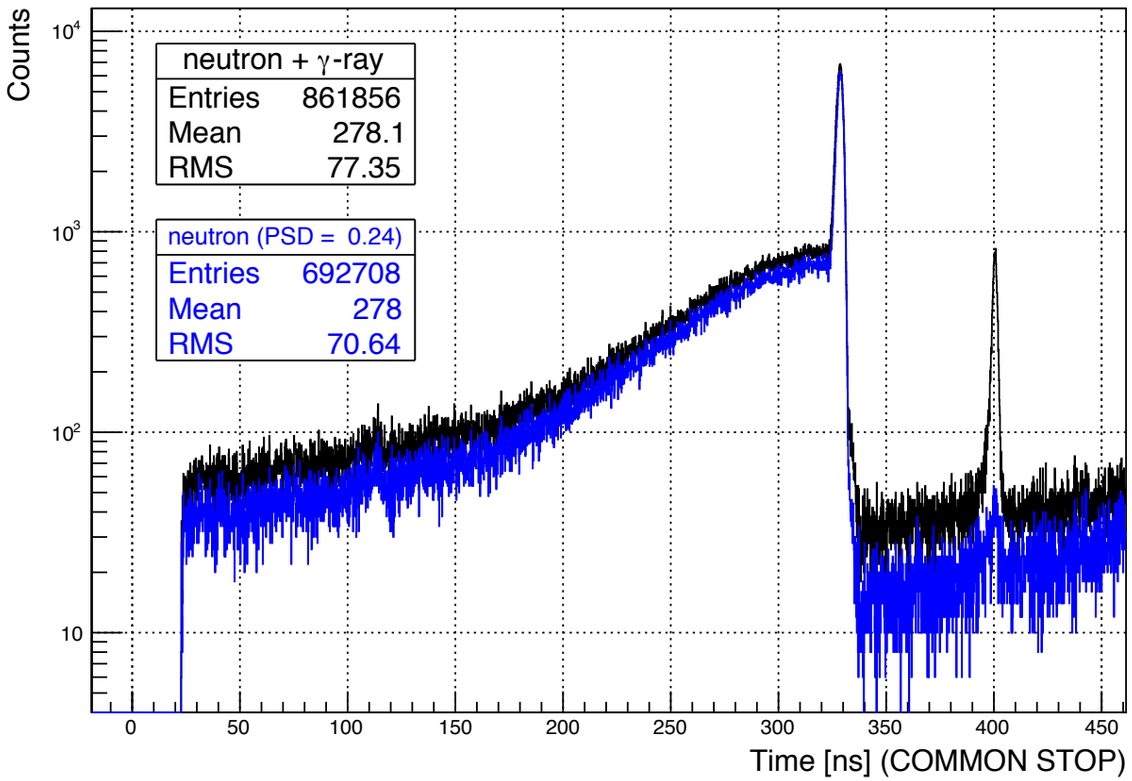
→ event number in triangle can be calculated as ~ 2784, Total neutron number = 346354

→ contamination level is 0.8 %.

Former Bunch Neutron

3/29 run16 (low-thr)

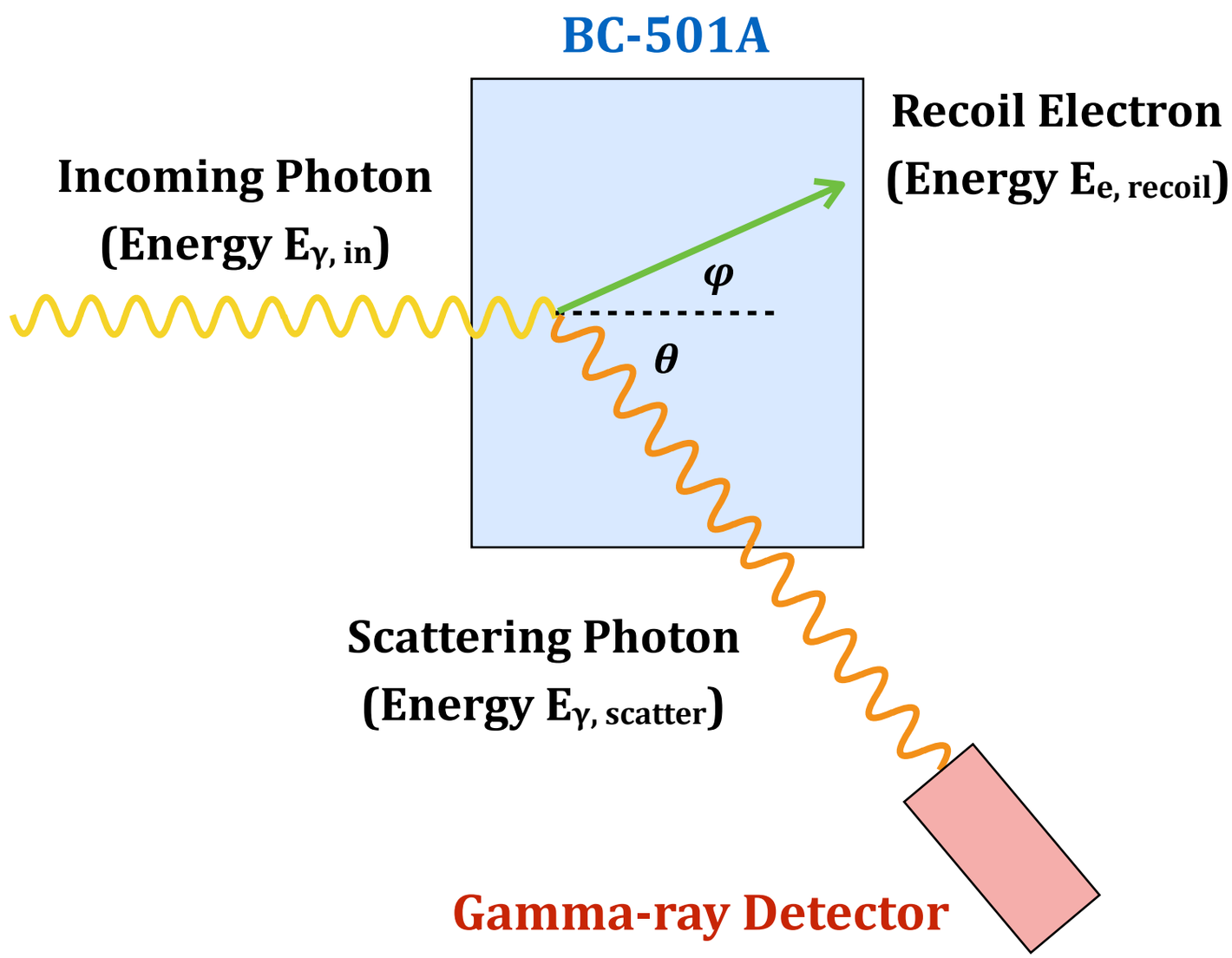




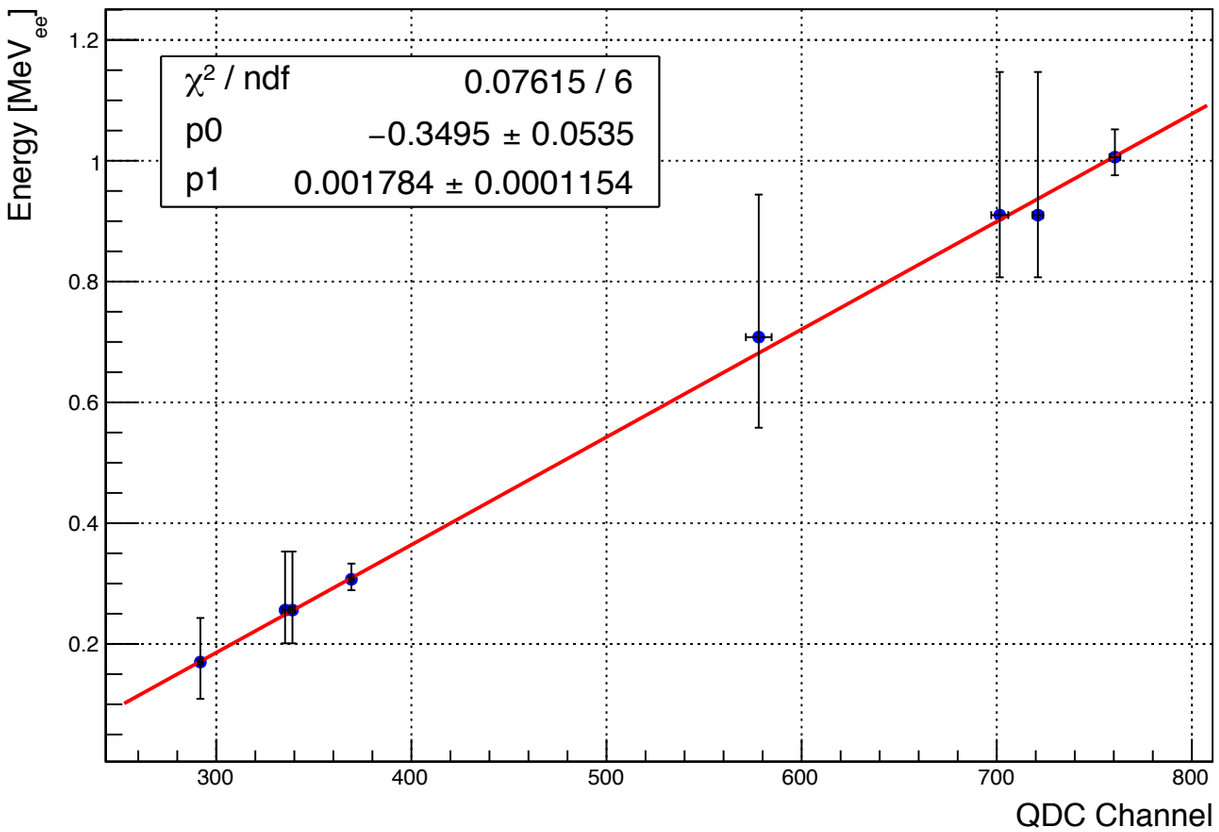
Former bunch neutrons can be estimated by seeing just before fastest neutron peak (environmental gamma-rays & former bunch neutrons inclusive).

0.3 % contamination level in peak region

LqS Calibration

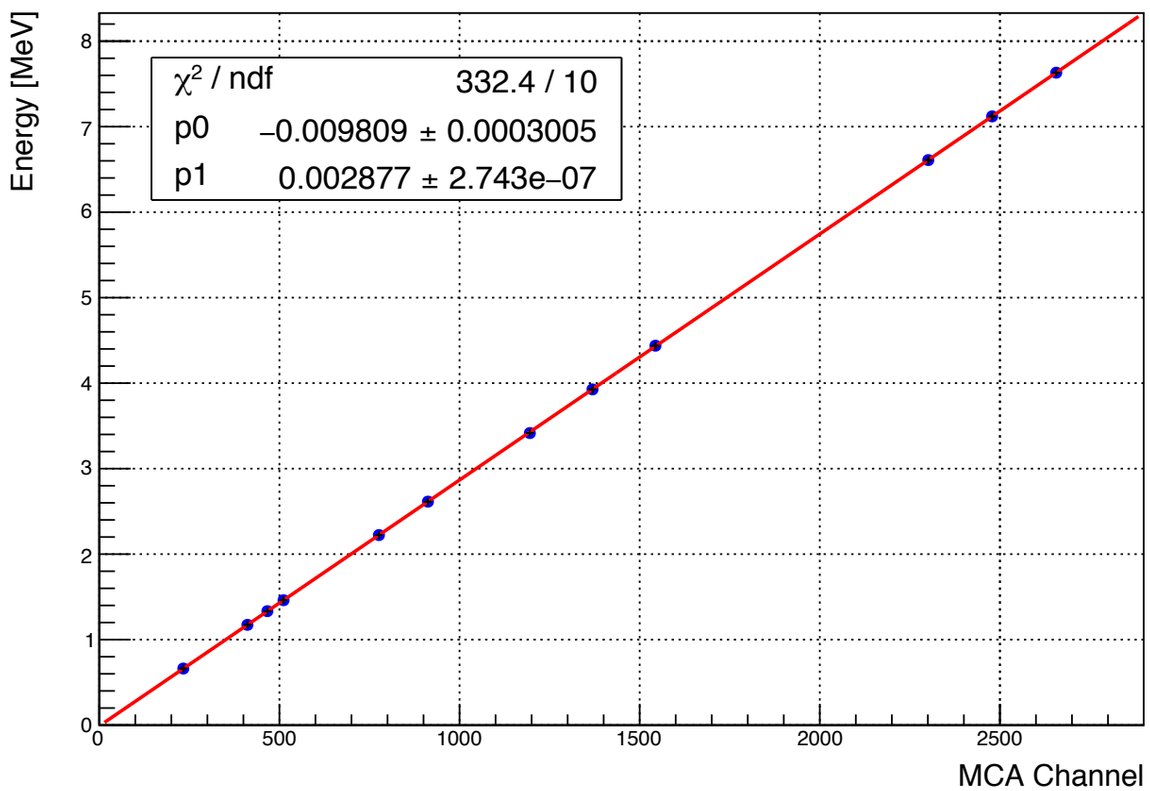


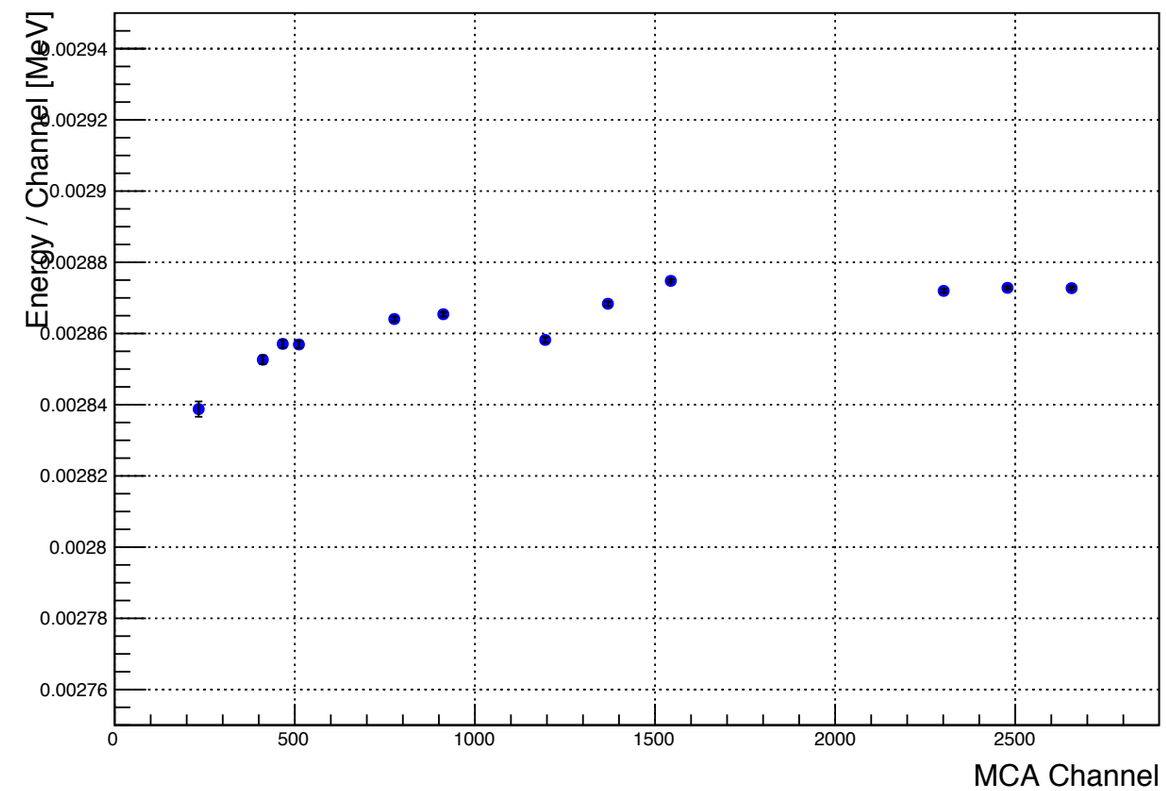
LqS Calibration



$E_{\gamma,\,in}$ [MeV]	θ [deg]	$E_{e,\,recoil}$ [MeV]
1.275	120	1.006 + 0.046 / – 0.030
	90	0.910 + 0.237 / – 0.103
	60	0.708 + 0.236 / – 0.150
0.511	120	0.307 + 0.026 / – 0.018
	90	0.256 + 0.097 / – 0.055
	60	0.170 + 0.073 / – 0.061

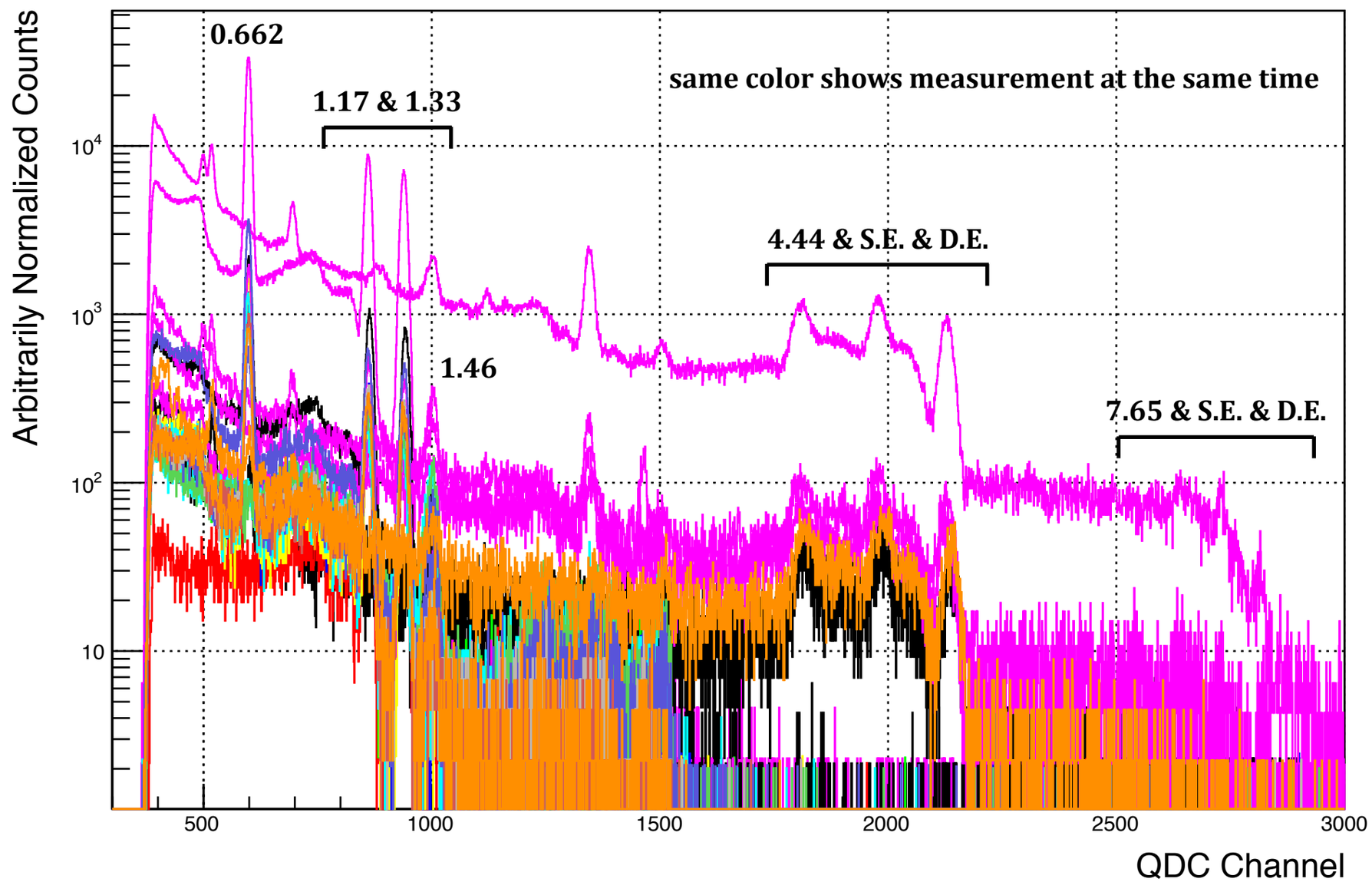
HPGe Calibration





- Linearity is achieved within ± 0.7%.
- χ^2/ndf seems not good? (I think some fitting problem in ROOT.)

LaBr Calibration



- Gain shift is < 0.5% during whole beam time.
- This is small enough considering resolution.