nBHEAM 2025: Neutron Beams at High Energy: Applications and Metrology

Measurement of High-Energy Neutrons penetrating Shields from GeV protons on a Thick Copper Target

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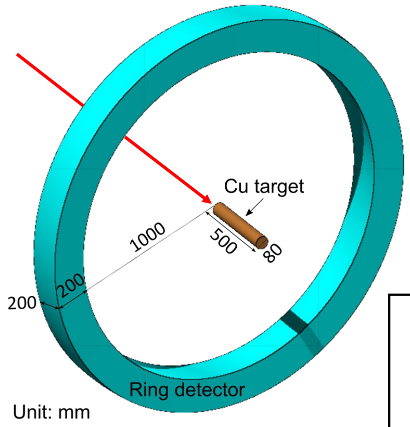
1. Background

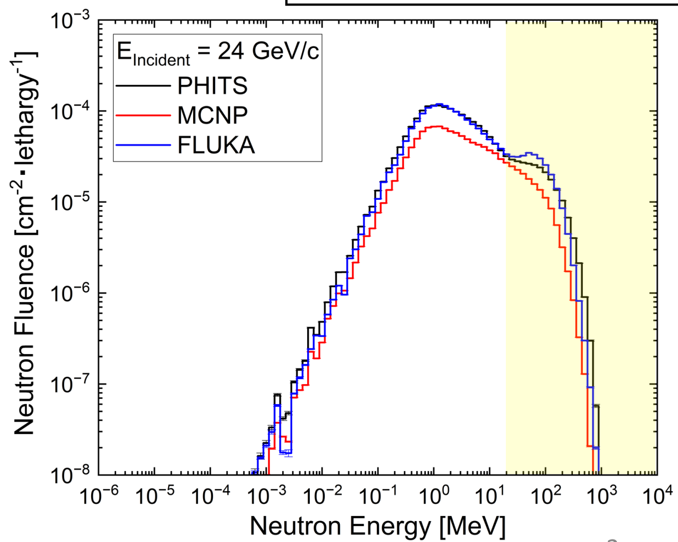
- Secondary neutrons are a significant concern in high-energy and high-intensity hadron accelerator facilities.
  - The neutrons with energies **from thermal to maximum energy** contribute to external doses behind the shields and activate materials around the beamlines.
  - **For neutrons below 20 MeV**, several techniques to measure their energy spectra and its reference field has been established.
  - **For neutrons above 20 MeV**, only a few techniques and fields are available. Thus, **Monte Carlo codes** are mainly used to obtain the energy spectra through particle production and transport.
- However, **discrepancies among calculated results** have been observed across different codes, particularly as source energy above GeV.



E_{proton} (GeV/c) = 24

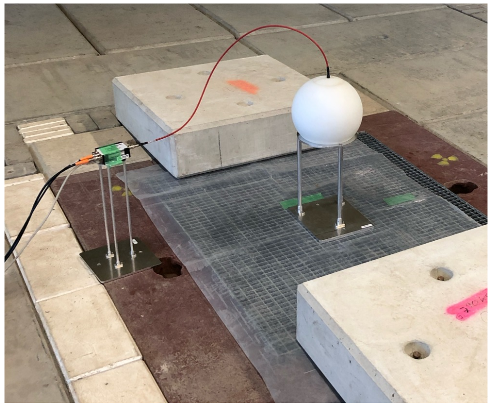
50-cm-long copper target

Energy distribution of neutrons emitted in a 90-degree direction from the target between codes



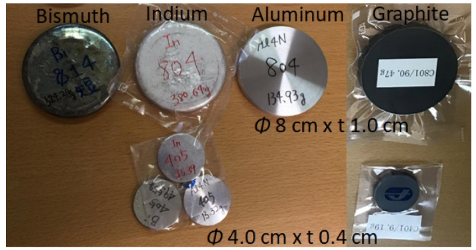
1. Background

- Technique to measure neutron energy spectra above 20 MeV is desired to obtain experimental data that enable us to validate the calculated results.



Bonner Sphere Spectrometry

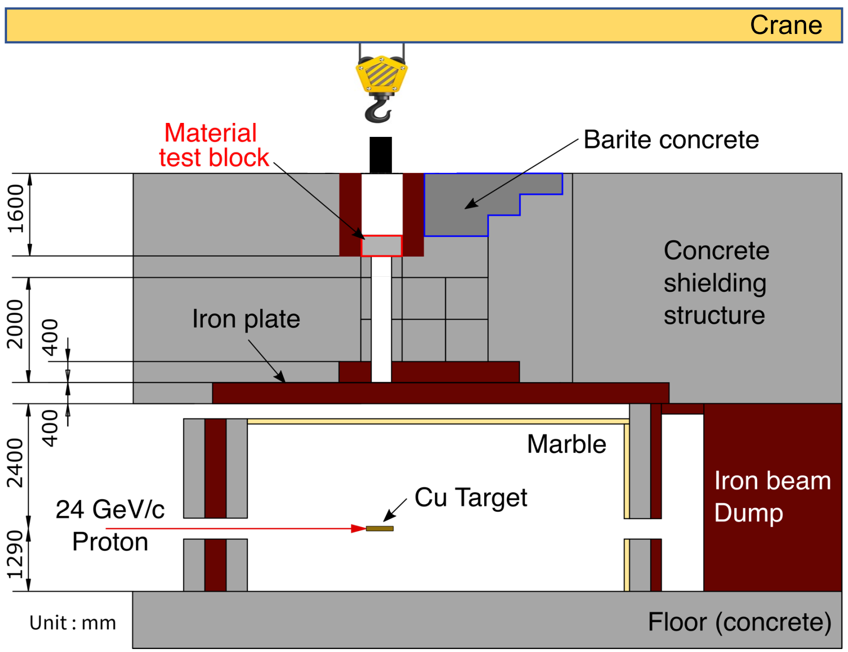
5'' Liquid Scintillator



Activation Detector

2. Shielding experiment at CHARM facility

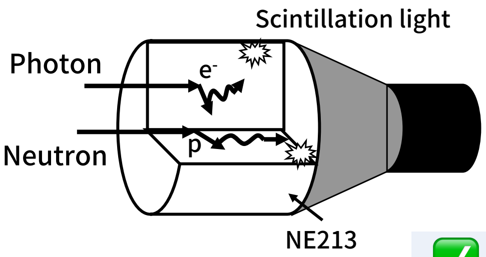
- The CHARM facility is located in the East hall of the CERN Proton Synchrotron.
- Irradiation field with energies exceeding several 10 GeV
  - 24 GeV/c Proton Beam
- Beam intensity can be reduced to 1/500
- Simple layout of beamline and surrounding shielding
- Flexible shielding configurations using a crane
  - Shielding blocks such as concrete, stainless steel are easily replaced for each measurement
  - Allows adjustment of the neutron energy distributions
  - Enables studies on the dependence of neutron spectra on shielding material and thickness
- Previous experiment for neutron measurement (2015~)
  - Neutrons after the shielding were measured using various neutron detectors. (e.g., Liquid scintillator[1-3], Bonner Sphere Spectrometer[4], Activation foils[5-7])



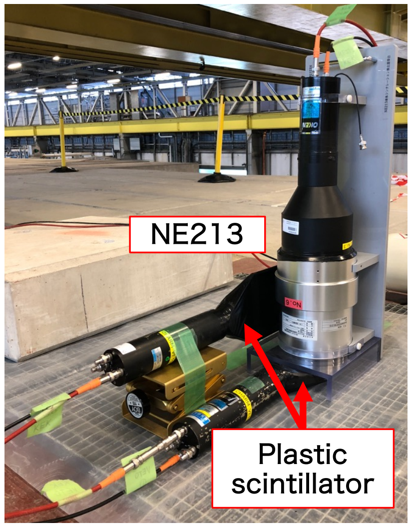
Cross-section of CHARM Beam line

[1] T. Kajimoto, et al., NIMB 429:27–33 (2018).
[2] T. Kajimoto, et al., NIMA 906:141–149 (2018).
[3] E. Lee, et al., NIMA 998:165189 (2021).
[4] T. Matsumoto, et al., JNST 61(1) 98–110 (2024).
[5] E. Iliopoulou, et al., NIMA 855: 79–85 (2018).
[6] N. Nakao, et al., JNST 57 (9) 1022–1034 (2020).
[7] N. Nakao, et al., JNST 61 (4) 429–447 (2024).

3. Energy spectra by NE213 liquid scintillator



- Output : **Detailed energy spectrum**
- High detection efficiency
- Pulse shape discrimination (PSD) to separate neutron and gamma-ray

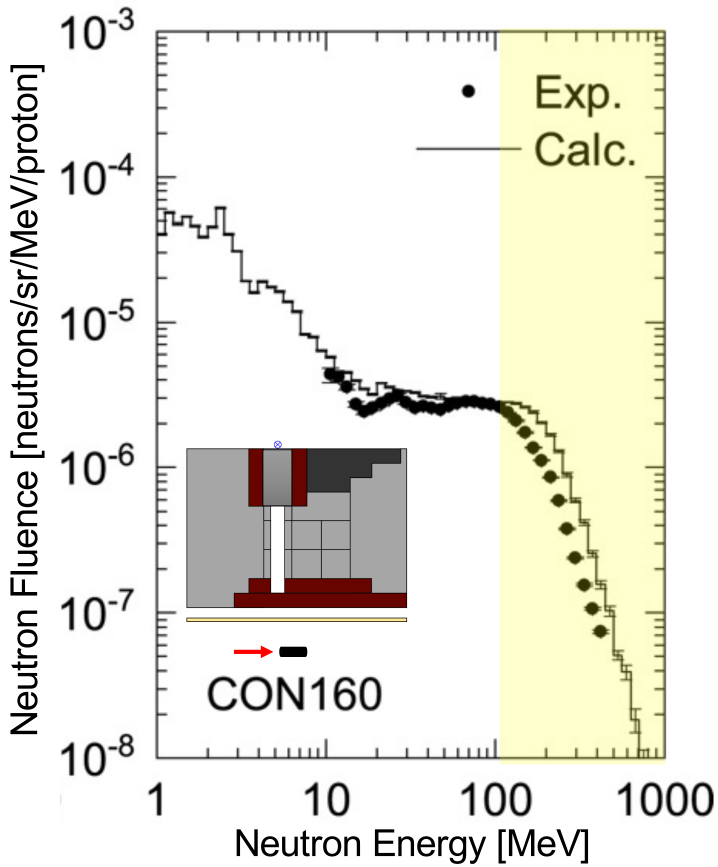


Detector set-up

✅ Measurement at CHARM facility

Result

- Derived neutron fluences by the **unfolding method using the calculated response matrix.**
- Obtained the fluences (10 ~ 400 MeV) for various thickness of the concrete (40~360 cm) and steel (20~80 cm) and their calculated results.
- Confirmed experimentally dependence on material, shielding thickness and distance from the surface of the shielding to the detector.
- The differences (C/E) were close to a factor of 1 for the energy region from 20 to 100 MeV; however, they increase above 100 MeV.
    - Because the NE213 scintillator has limited sensitivity to neutrons above 100 MeV.

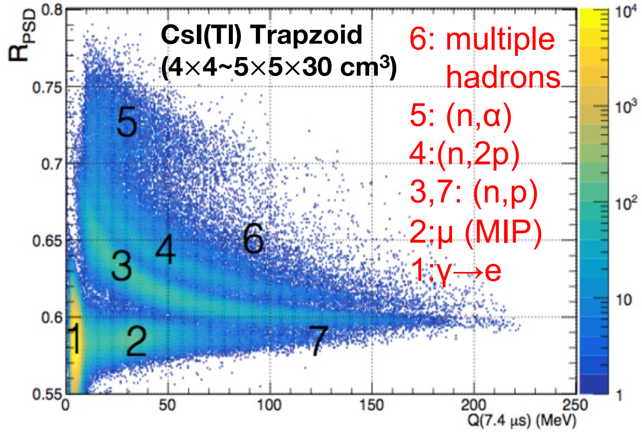


Example of neutron fluence for 160-cm-thick of concrete block

4. Objective

- **To develop a new detector system capable of measuring the yield and energy distribution of high-energy neutrons above 100 MeV.**
  - Test at the CHARM facility (well-characterized from previous experiment)
    - To confirm the synchronization between beam and detector
    - To obtain the channel-energy calibration points using energy deposition of cosmic-ray muons
    - To see neutron-induced events by removing the charged particle
  - CsI(Tl) scintillator is one of the candidates for extending the measurable neutron energy range beyond 100 MeV.
    - Easily available in large crystal
    - Capable of pulse shape discrimination (PSD)
    - References about response to high-energy neutrons

CsI(Tl) in use (5 cm × 5 cm × 30 cm)



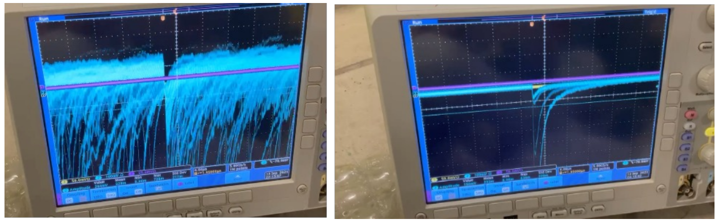
Evaluated the separation of particles from neutrons with PSD techniques in CsI(Tl) scintillators at TRIUMP.
S. Longo, et al., JINST 13, P03018 (2018).

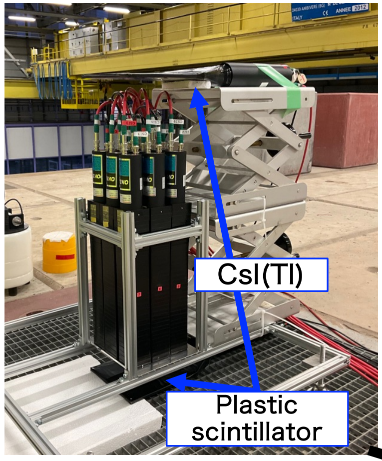
5. Experiment

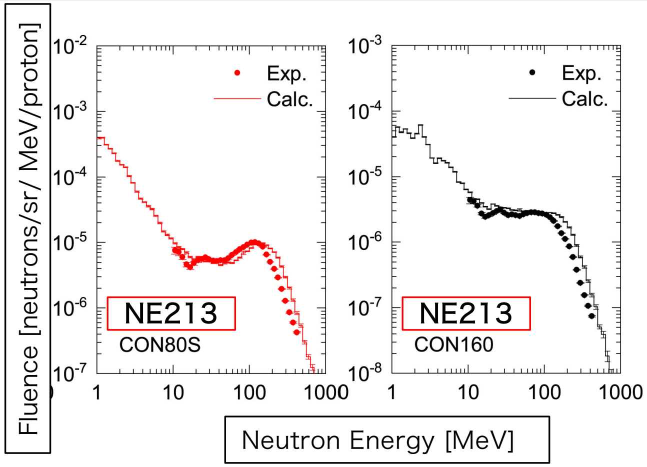
- **Detector Setup**
  - Installed detectors on the roof of CHARM (CSBF)
    - Nine CsI(Tl) crystals (3x3) with PMTs
    - Two plastic scintillators (TOP and BTM)
- **Measurement**
  - Measured neutrons penetrating through 80-cm-thick concrete and 160-cm-thick concrete shield (material test block)
    - To investigate detector response with varying neutron spectra

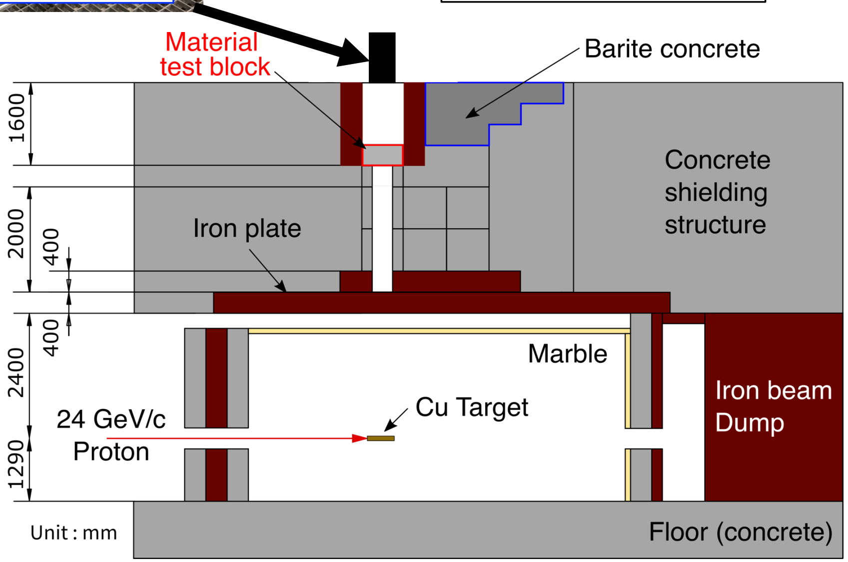
✅ **Synchronization between beam and CsI(Tl)**

BEAM ON BEAM OFF

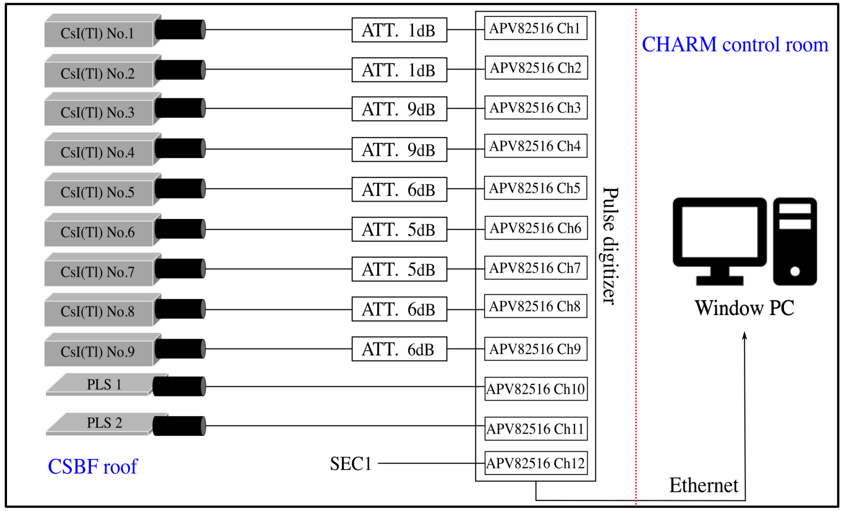


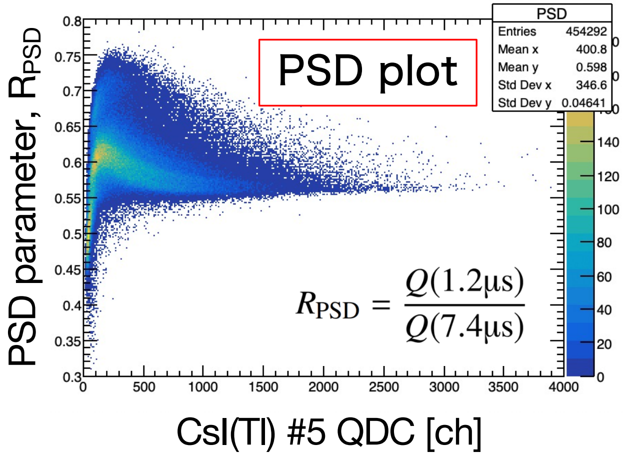


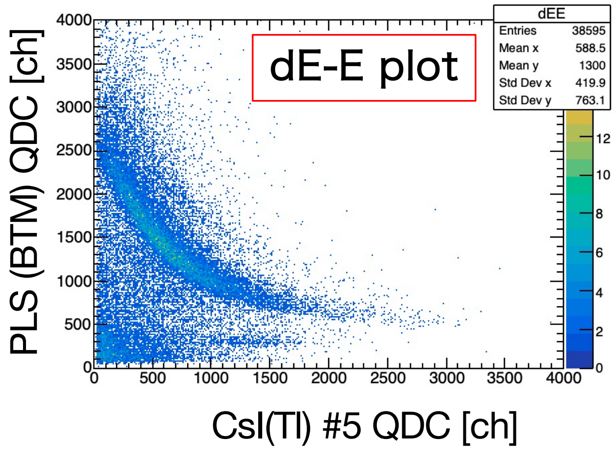




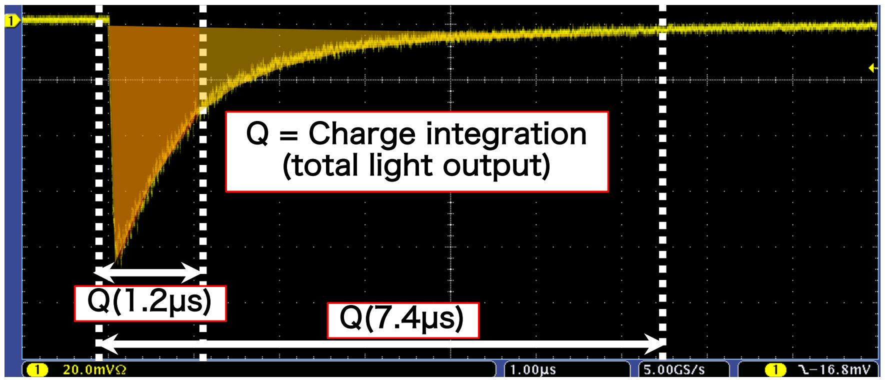
6. Data acquisition and analysis (PSD & dE-E plots)



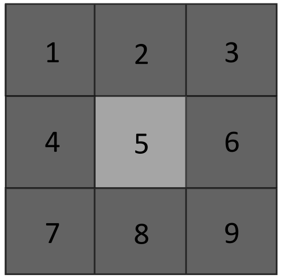




- PMT anode output was fed through the attenuator into the digital pulse processor. (APV82516)
- Data acquisition based on self-triggering
- Recorded total light output (QDC), and waveform (8ns x 1000 pts) along with timestamps
  - The data were analyzed using PSD and dE–E plots

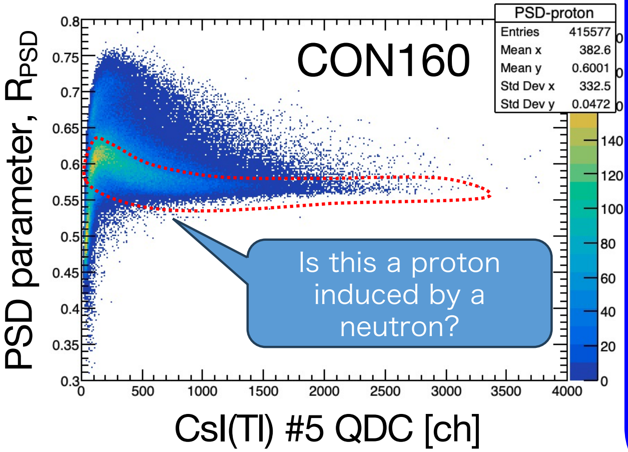


7. Identification of particles

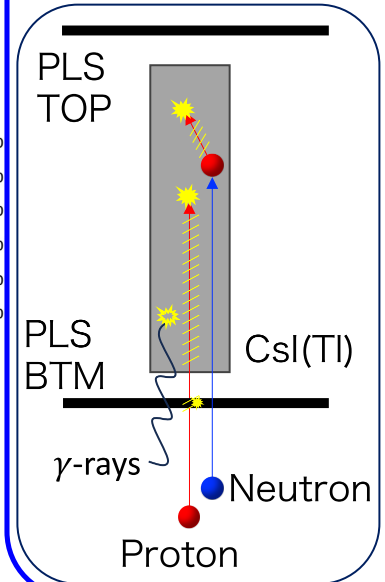


- To identify the particle types of the events obtained by CsI(Tl) #5.
  - CsI(Tl)s of #1~3, 4, 6, 7~9 block external events that do not originate from the direction perpendicular to the beam. (Anti-coincidence with timestamp data)
  - The signals of plastic scintillators were utilized to remove the charged particles.

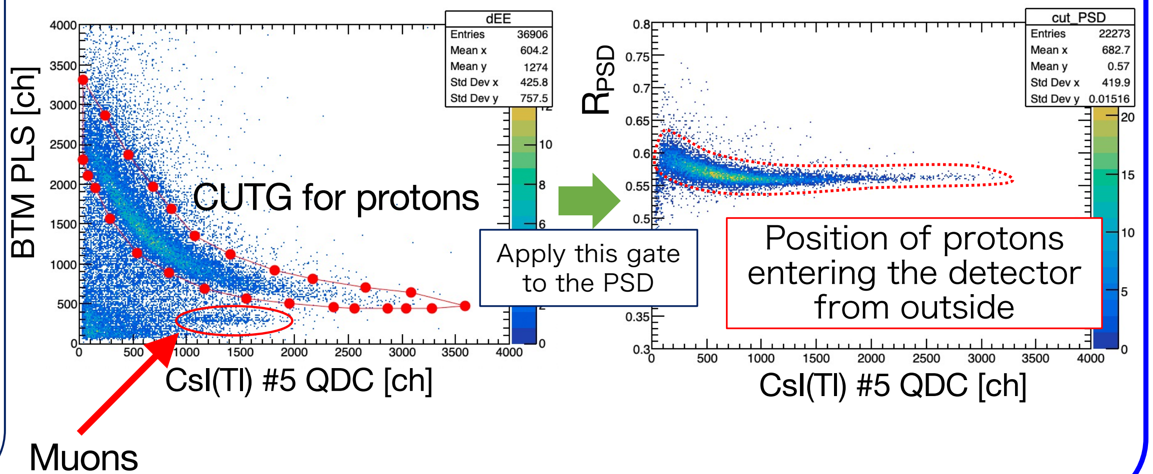
Wait,… How can we know it was generated from neutron?



💡 If proton events from outside the CsI(Tl) can be identified, it becomes possible to identify neutron-induced protons.



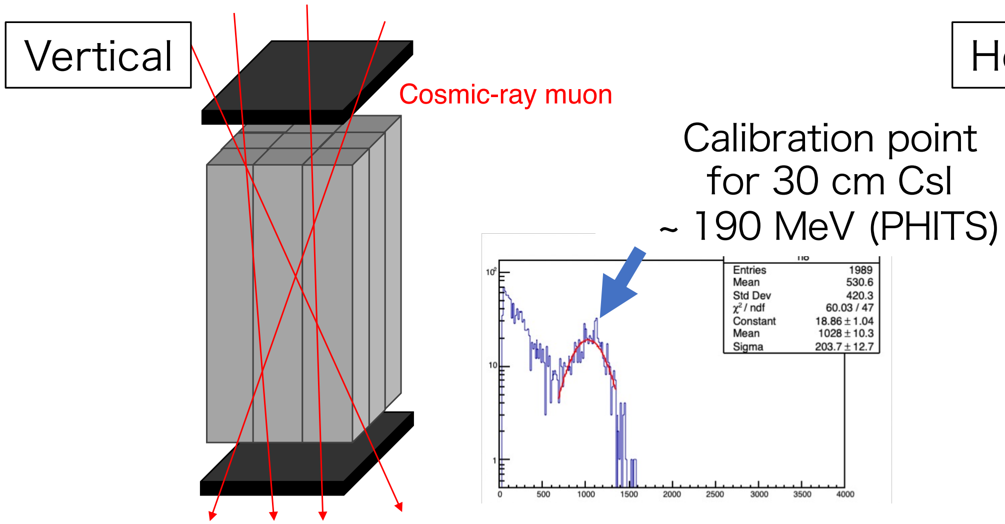
Proton identification using the dE–E plot

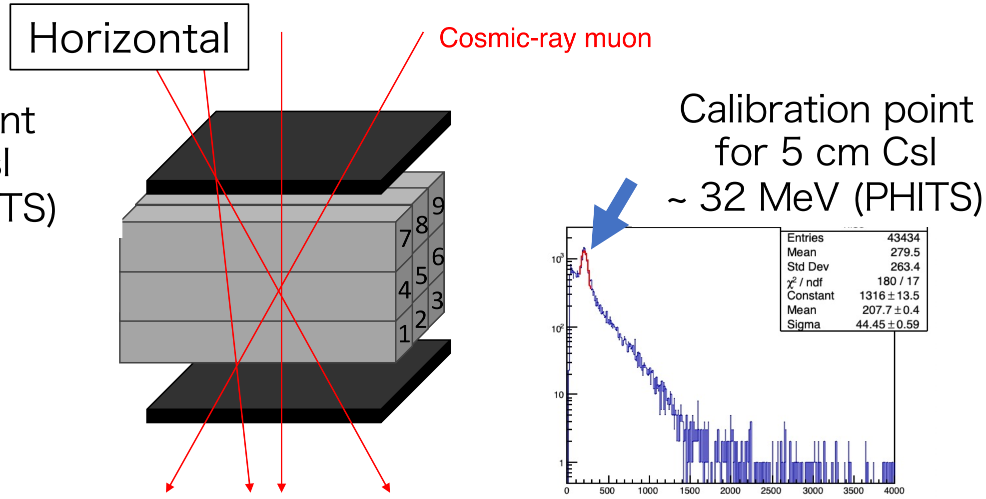


8. Channel-Energy Calibration

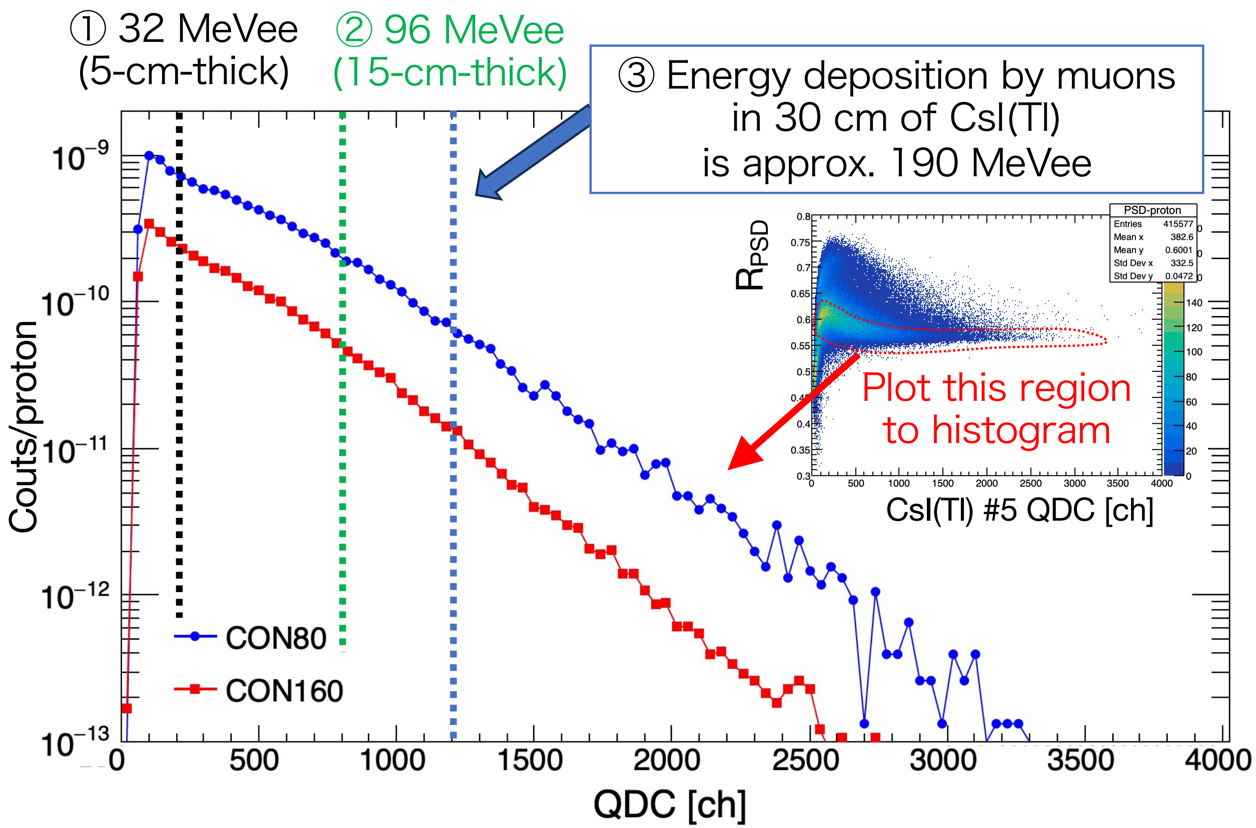
- As the measurement focuses on high-energy neutrons up to 400 MeV, gamma-ray peaks from standard radiation sources (a few MeV) are no longer visible.
- Two plastic scintillators were used in coincidence with CsI(Tl) to identify the energy deposition peaks of cosmic ray muons as calibration references.
- By changing the detector layout from vertical to horizontal, the muon path length in the CsI(Tl) crystal is varied, leading to a measurable shift in the energy deposition peak.

* **Note: These values correspond to the energy equivalent of the light output by muons.**





9. Neutron-induced proton events and their energy range



- Neutron-induced proton events with energies above 190 MeVee were observed.
  - A test measurement of high-energy neutrons using CsI(Tl) was successfully conducted at the CHARM facility.
- The difference by a factor of 3~4 in neutron counts below 1500 ch between CON80 and CON160 shielding configuration was clearly observed.
  - This factor is consistent with the result obtained using the NE213 scintillator.
  - Neutron attenuation was observed dependent on the thickness of the concrete shield.

10. Wrap-up

- Summary of Findings
  - CsI(Tl) signals synchronized with the beam were successfully observed.
  - Using the dE–E plot, the position of protons entering from outside the detector was identified.
    - Based on this, the position of protons generated by neutron-induced nuclear reactions inside the CsI(Tl) crystal was identified.
  - Cosmic-ray muon events were also identified.
  - **The sensitivity and applicability of CsI(Tl) detector system to high-energy neutrons have been experimentally confirmed, supporting its use in future measurements.**
- Future Work
  - Plan to conduct experiments with different shielding configurations
    → To investigate neutron attenuation and changes in energy distribution.
  - Plan to measure with the detector placed horizontally
    → To obtain additional energy calibration points using different muon path lengths.

We're planning an experiment this year.

I sincerely appreciate your thoughtful and constructive feedback. 😊