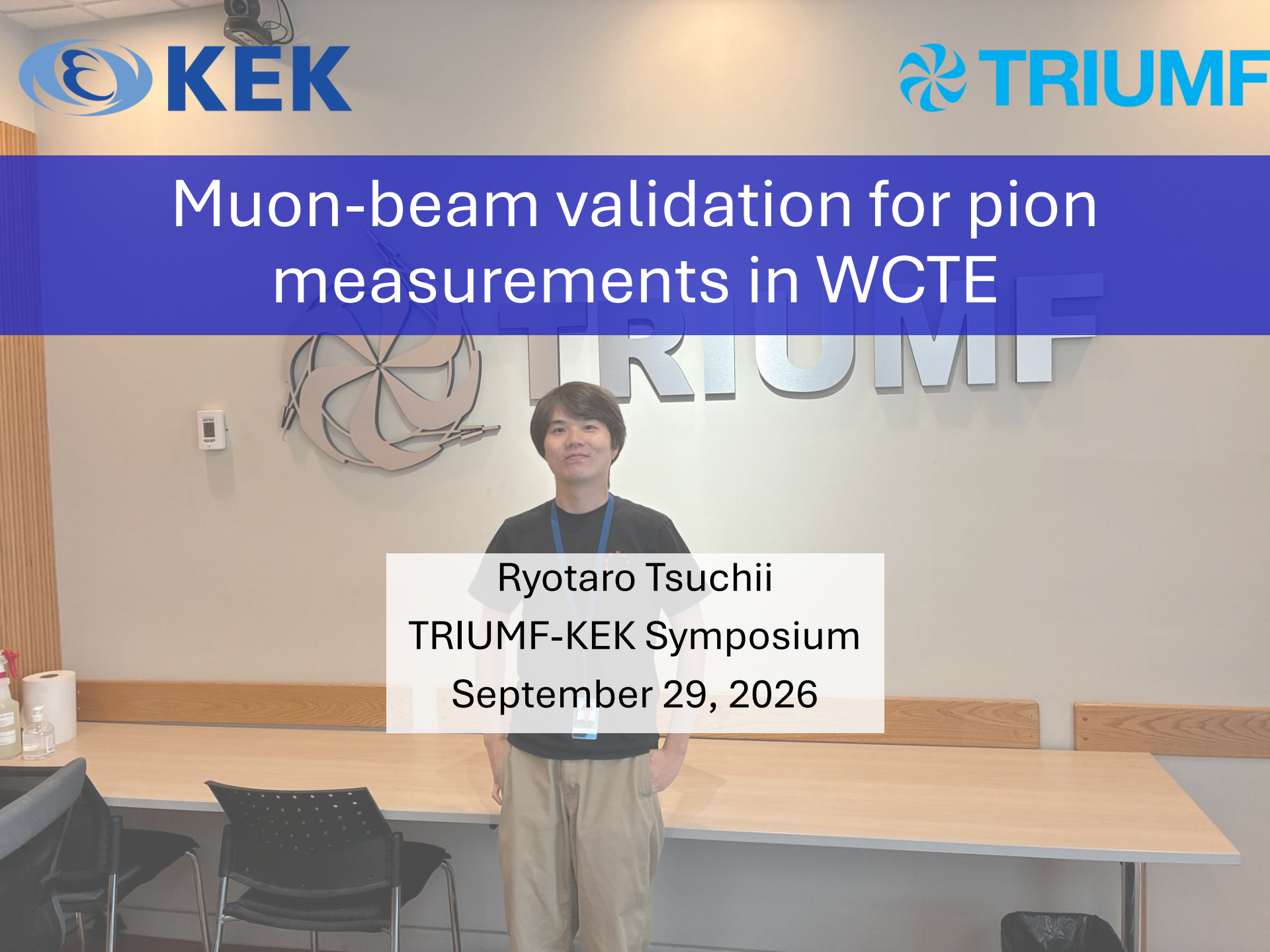


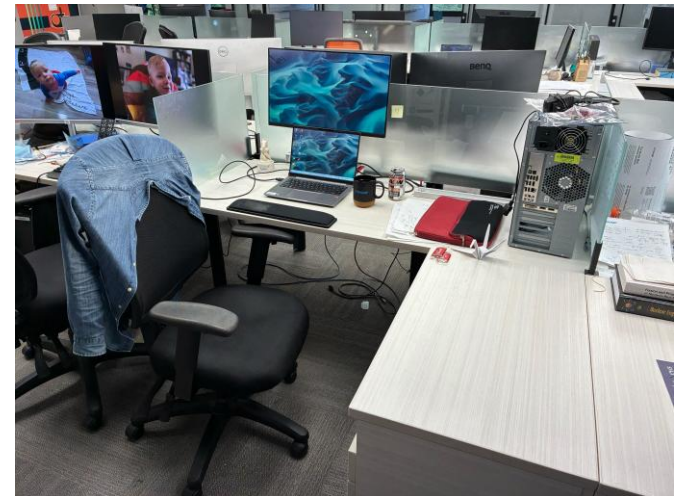
Muon-beam validation for pion measurements in WCTE



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TRIUMF-KEK Symposium
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KEK–TRIUMF exchange and my research at TRIUMF

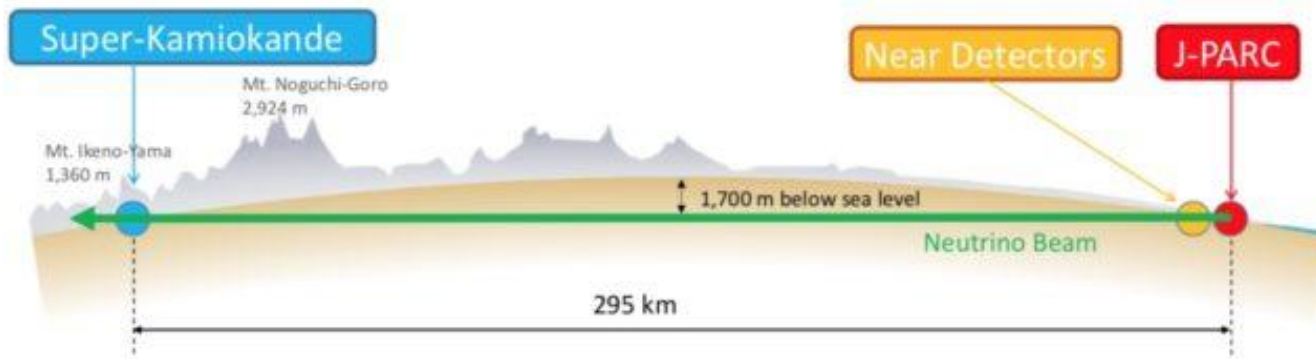
- I stayed at TRIUMF for three months through the KEK–TRIUMF exchange program (EPECR).
- During my stay, I worked on pion-interaction analysis for the WCTE experiment.
- Today I will introduce a validation study that I developed during this stay.



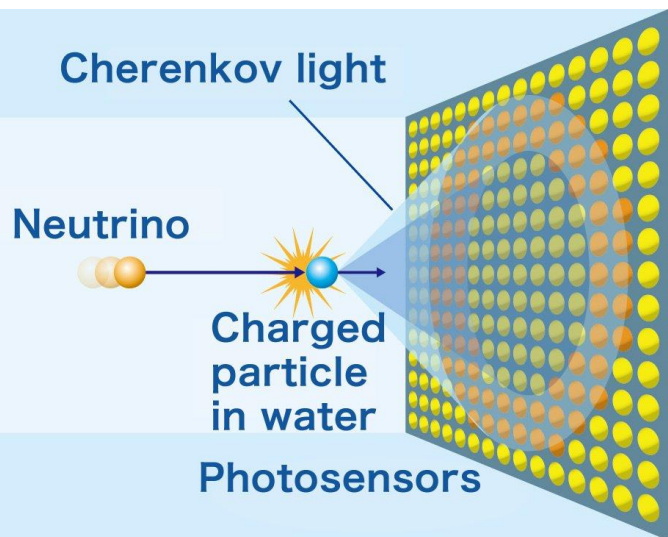
Matter-antimatter asymmetry and neutrino

- The current universe has an asymmetry between matter and antimatter.
- By measuring the difference in behavior between neutrino and anti-neutrino, the origin of the asymmetry may be clarified.
- Neutrinos are elementary particles.
 - Three types (ν_e, ν_μ, ν_τ).
 - The type changes into other types during flight (neutrino oscillation).
- The asymmetry can appear as a difference between neutrino and antineutrino oscillation probabilities.
$$P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$
- The T2K experiment measures these oscillation probabilities(→next page).

Introduction of neutrino measurement

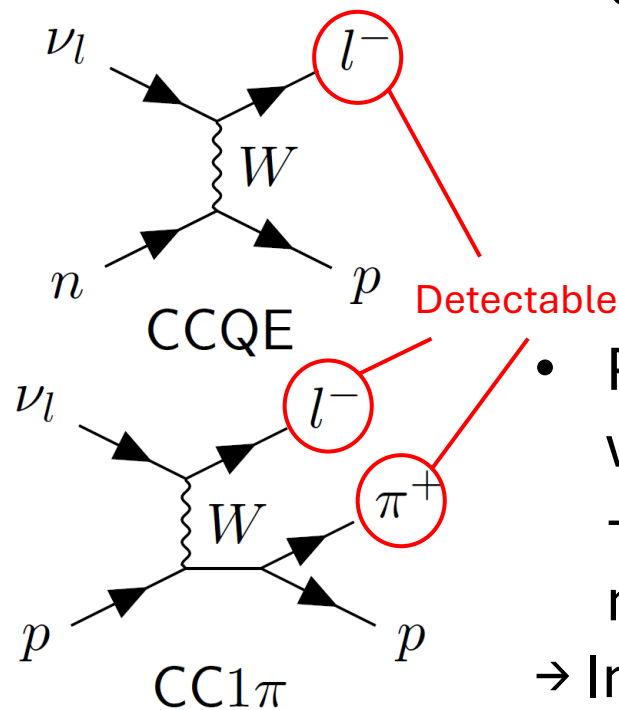


- The T2K experiment measures the neutrino oscillation probabilities using the neutrinos from the accelerator.
- Neutrino oscillations are measured by comparing the neutrino flavor at the near and far detectors.
- Neutrinos themselves are not directly observed.
→ We detect charged particles produced by neutrino interactions.
- Cherenkov light is emitted when a charged particle travels faster than the speed of light in water.
- Neutrino oscillation probabilities depend on energy, so accurate neutrino-energy reconstruction is essential.



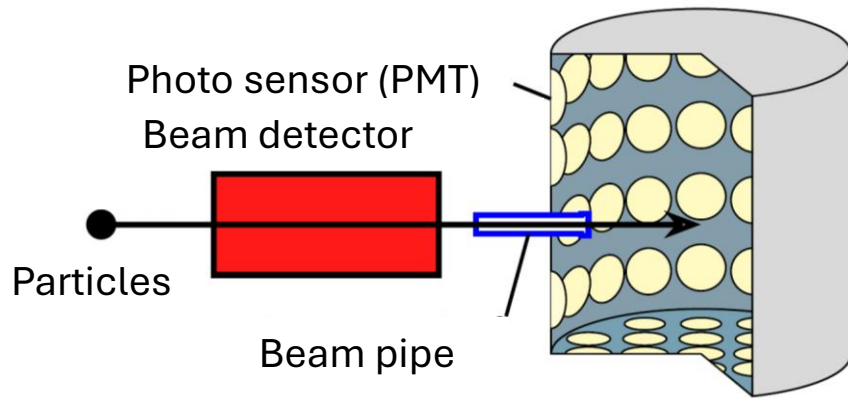
Kamioka Observatory, ICRR, The Univ. of Tokyo

Pion in neutrino measurement



- Accelerator neutrinos ($\sim 10^2$ MeV) mainly cause CCQE and CC1 π interactions in water.
 - CCQE (two-body) $\rightarrow$ can reconstruct ν energy
 - CC1 π (three-body) $\rightarrow$ cannot reconstruct $\rightarrow$ Use only CCQE events to measure the oscillation in the current analysis.
 - Pions are sometimes scattered in nucleus or water, making them difficult to detect. $\rightarrow$ Need to estimate the number of CC1 π events misidentified as CCQE.
- $\rightarrow$ Important to understand pion interaction in water.

WCTE (Water Cherenkov Test Experiment)



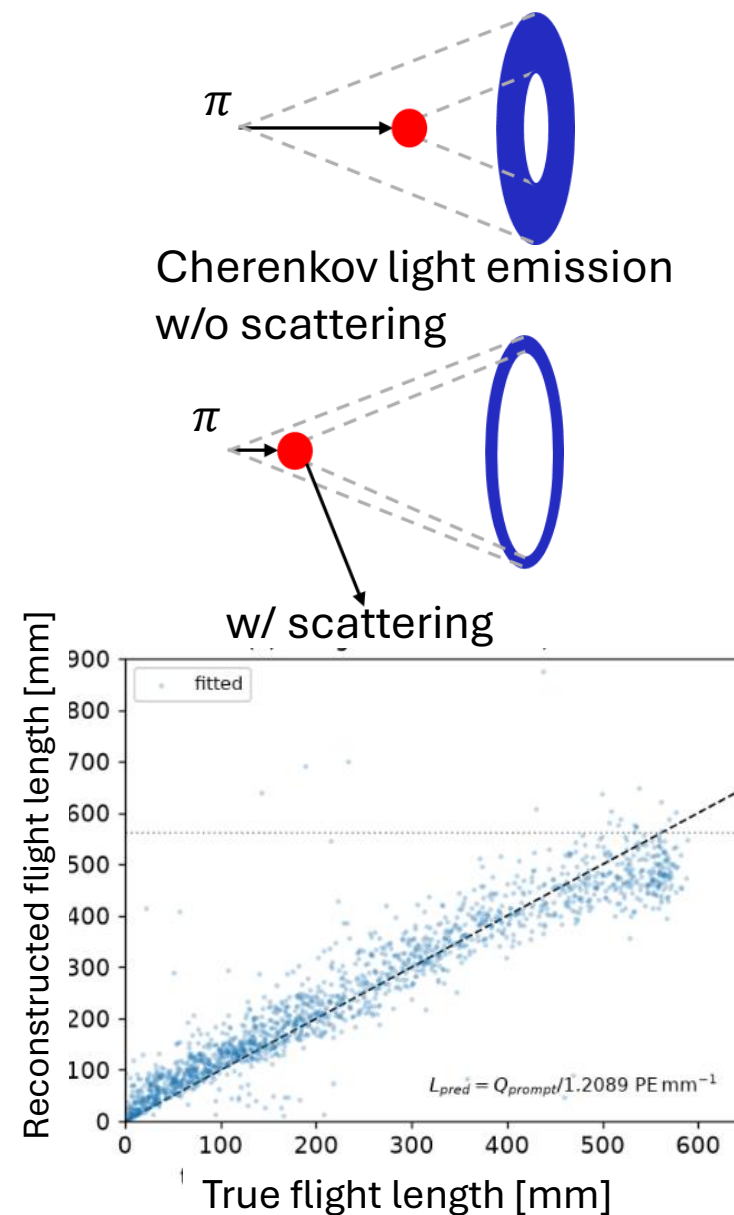
- WCTE is a test experiment for the photo-sensor used in the water Cherenkov detectors
- Particle beams (e.g. e , μ , π , p) are injected into a 4.1 m diameter water Cherenkov detector and detects them by photo sensors on the wall of the tank.
 - Momentum: 200-1000 MeV/c.
- The incoming particle is characterized event by event:
 - Momentum
 - Injection position
 - Direction
 - Particle Identification

WCTE's unique things

- WCTE can use:
 - Known particle species and momentum
 - Known and repeatable entry position and direction
 - High-statistics controlled beam samples
- Unlike neutrino interactions, the initial particle state is well controlled.
- We can precisely investigate behaviors of pions in water.

Pion-water cross section measurement in WCTE

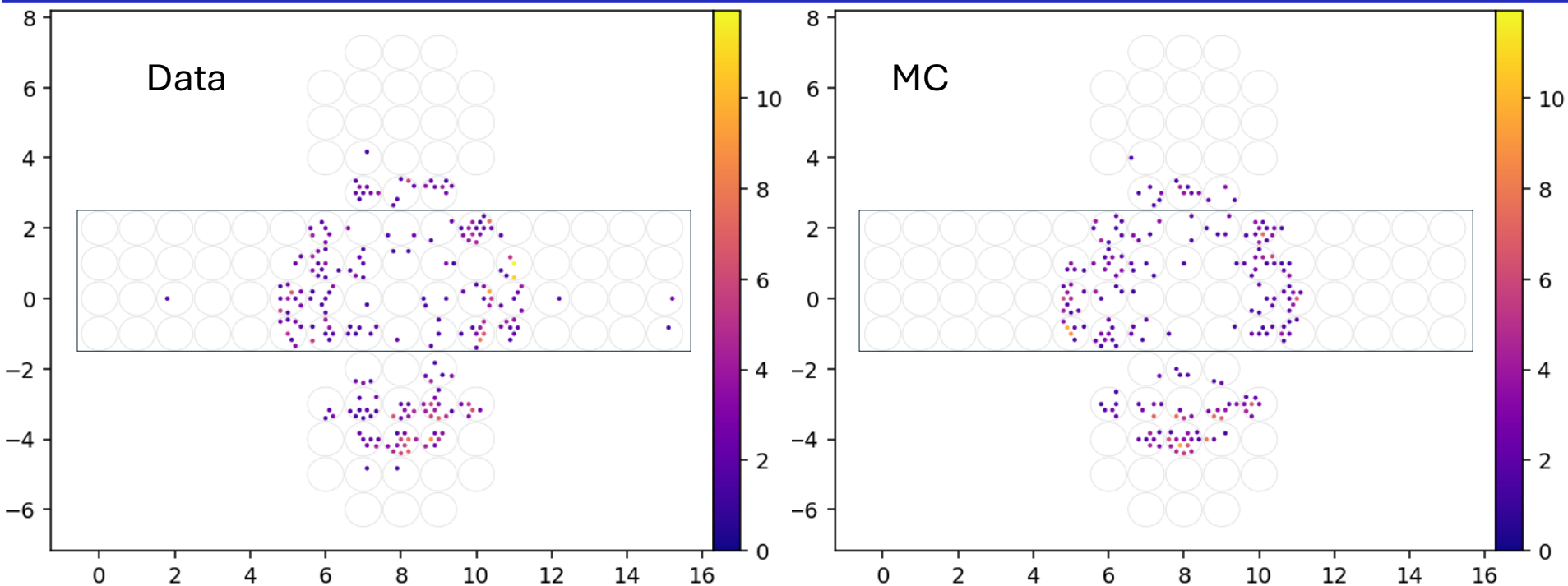
- The pion cross sections can be extracted by measuring the distributions of the pion interaction points in the water tank.
- Pion interactions stop the development of Cherenkov rings and create thin rings.
- The interaction point can be estimated from the charge pattern of the partially developed Cherenkov ring.
→ This requires an accurate understanding of the PMT response around the Cherenkov ring.



Muon data as control sample

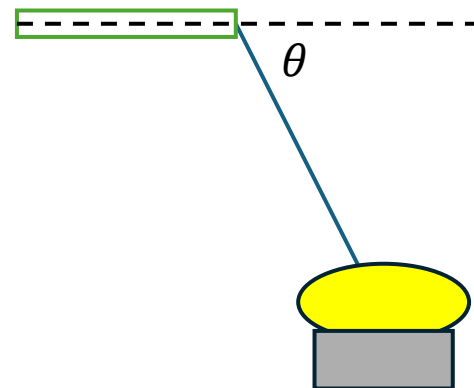
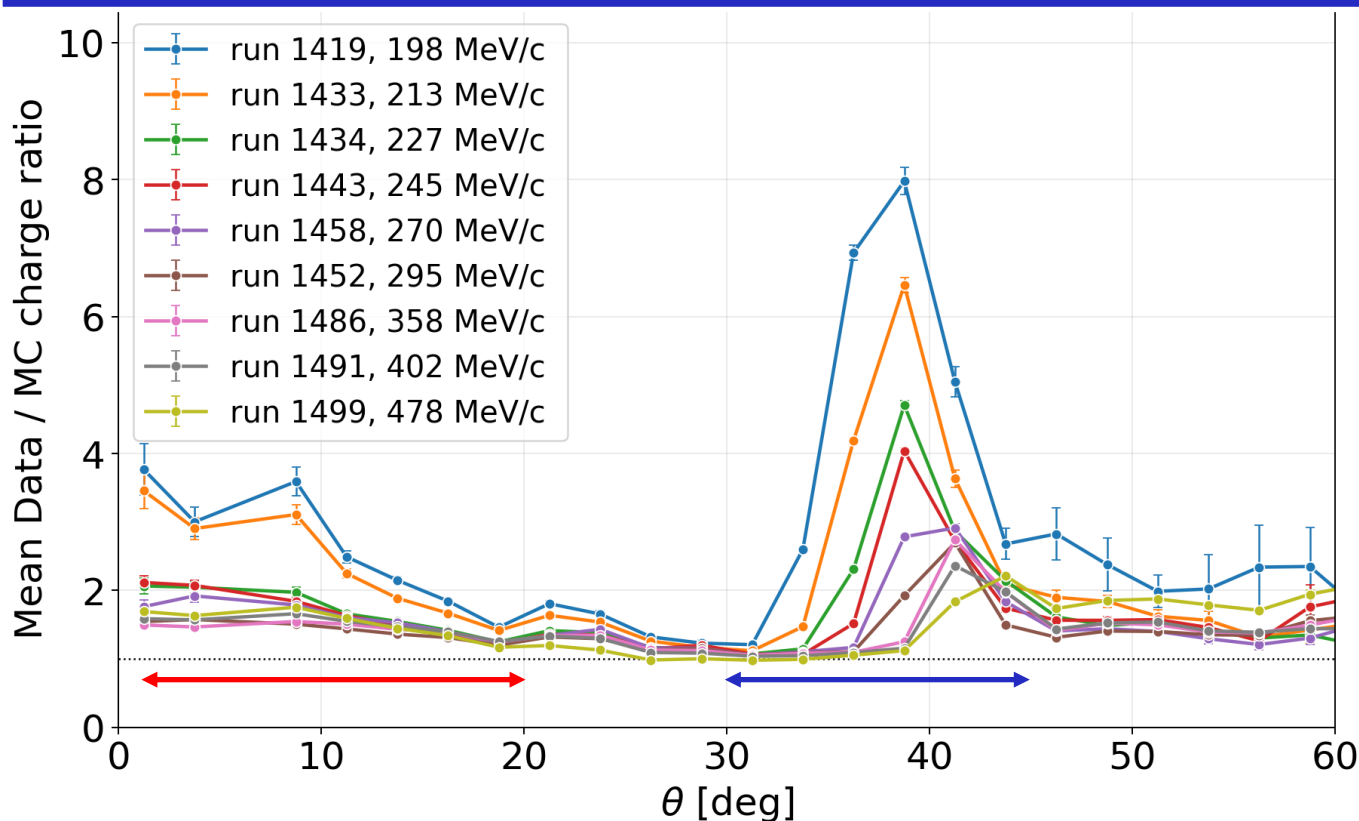
- We would like to calibrate the detector responses.
 - However,
 - The current Monte Carlo simulation has discrepancy with data.
 - Each calibration source (e.g. cosmic muon) makes bias due to factors such as source direction.
- The muon beam sample produces light emission similar to that of pions, and are less to be scattered.
 - Precise calibration of PMTs is possible using a high-statistics muon beam.
 - Using muons as a control sample can reduce sensitivity to common detector-response uncertainties (e.g. angular response, relative efficiency).
- Muons can be selected with a high purity using information from the beam monitor.

Event display



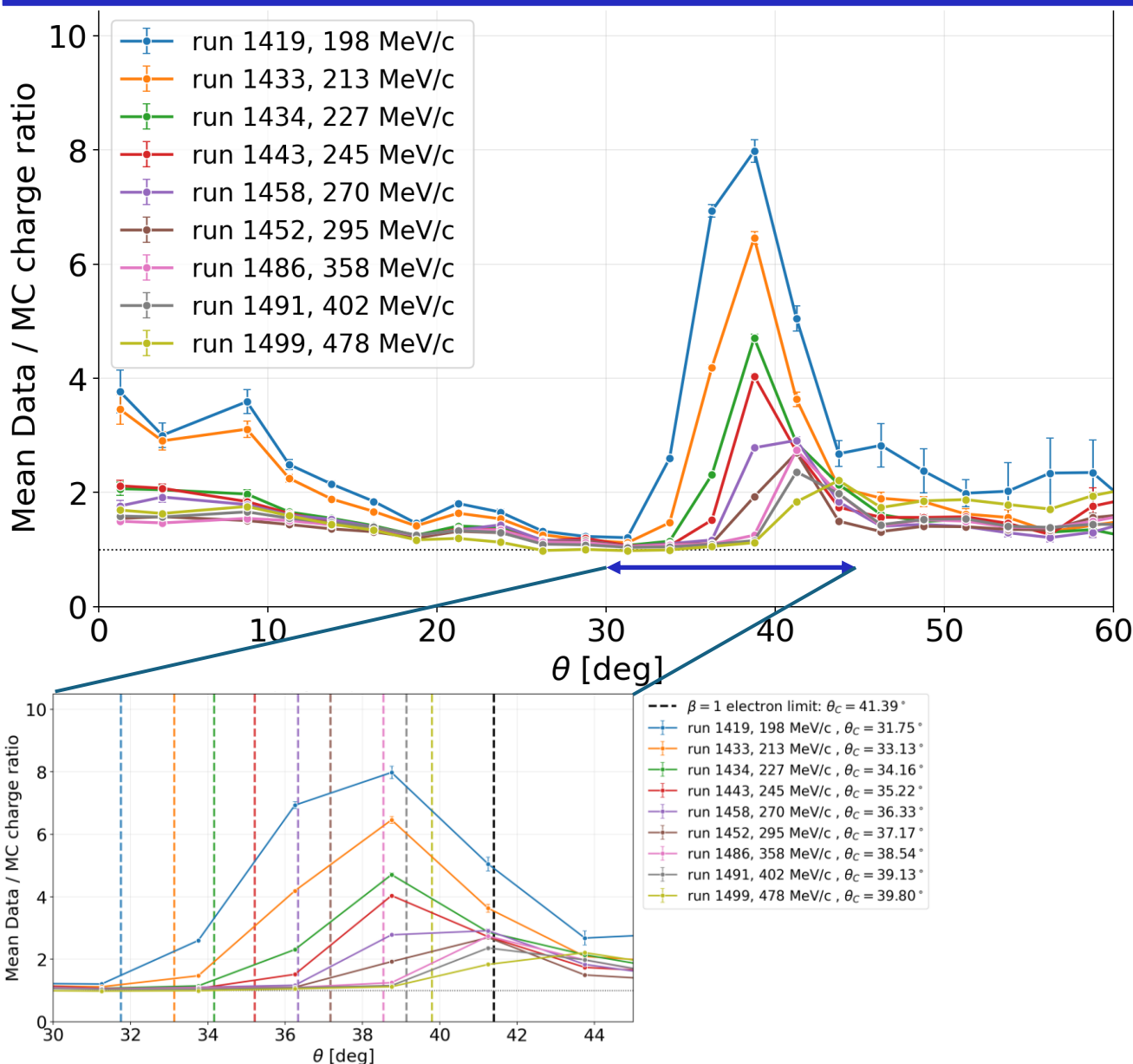
- 295 MeV/c muon
- Then I compared the mean PMT responses between data and MC over several beam momentum.

Unexpected data/MC excesses



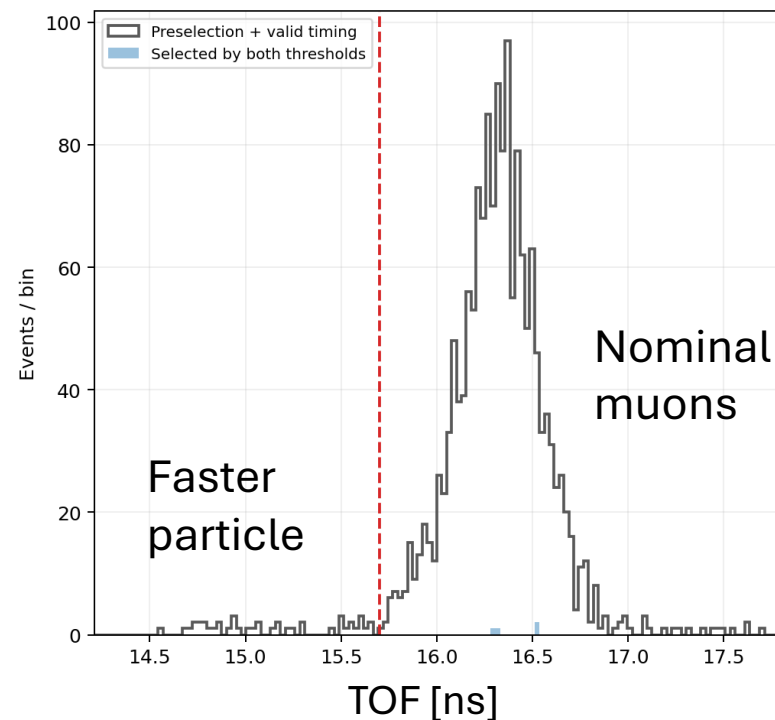
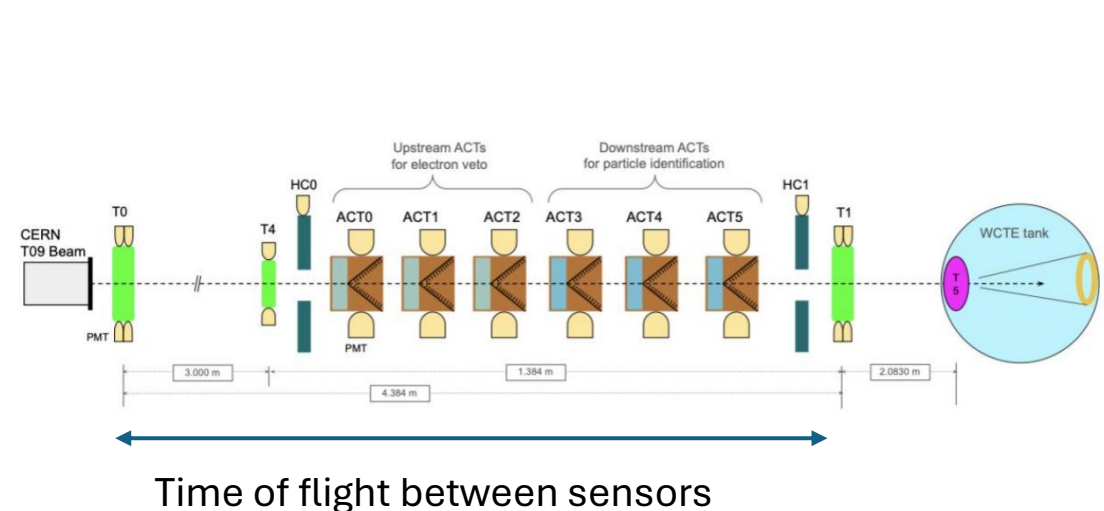
- I checked the data-MC ratio for angles θ of PMTs from beam line.
- Unexpected excesses appear in two angular regions, particularly at low beam momentum.
 - $\theta < 20^\circ$
 - $30^\circ < \theta < 45^\circ$
- I've investigated the two excesses.

30° ~ 45° excesses



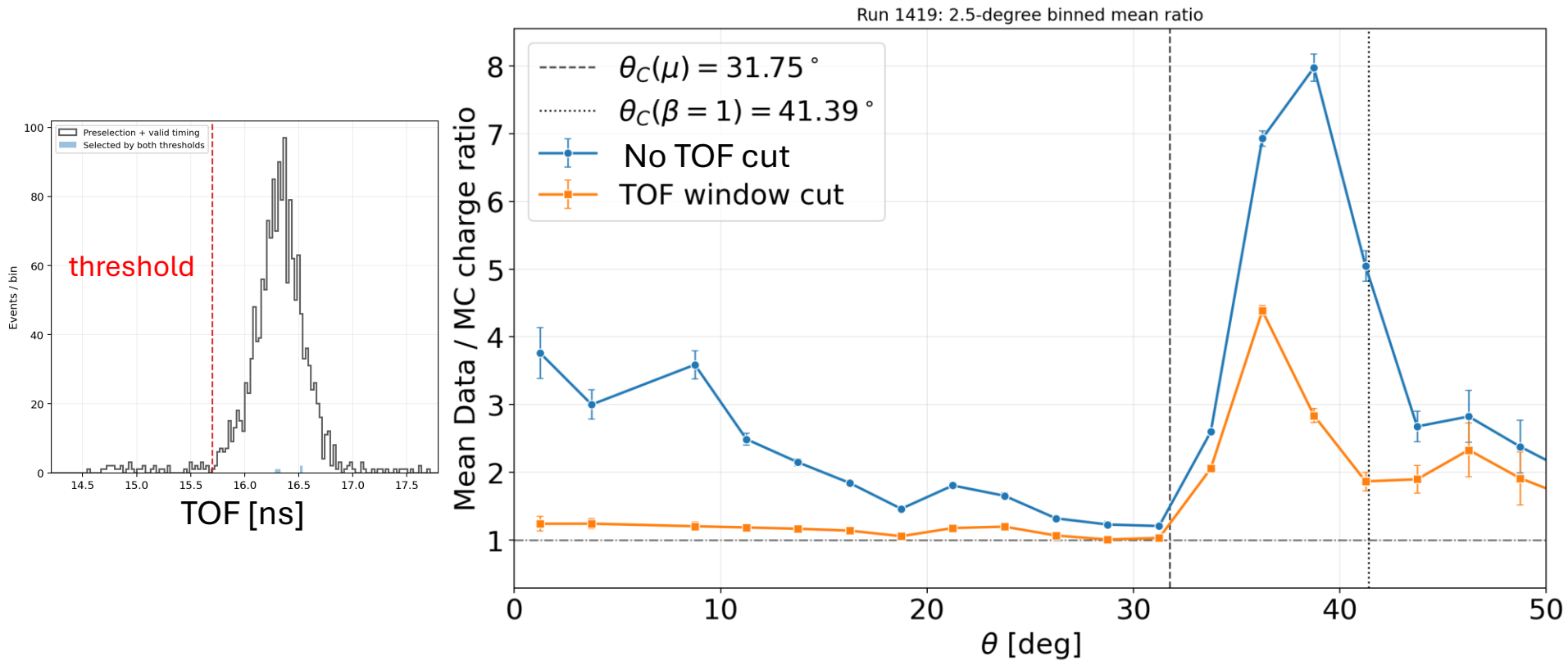
- The $30^\circ < \theta < 45^\circ$ region has huge differences.
- The dashed lines indicate the expected light emission angles
- The excess is consistent with the expected angles by faster particles.
→ This suggests contamination from high energy muons.

Contamination hypothesis



- TOF measures the particle velocity between two beam sensors.
→ low TOF particles=faster particles
- Events remain in the low-TOF region even after the muon selection.
→ This suggests fast-particle contamination that passes the muon selection, possibly higher-momentum muons.

TOF cut



- Events in the low-TOF tail (TOF < **15.7 ns**) were removed.
- Both excesses in $< 20^\circ$ and $30\text{--}40^\circ$ regions are strongly reduced.
→ This supports the hypothesis that fast-particle contamination is responsible for a large part of the Data/MC discrepancy!
- On the other hand, some excesses still remain. → Next step ToDo!

Summary

- The understanding of the pion interactions in water is important for neutrino event analysis and motivating pion measurements in WCTE.
- WCTE provides well-characterized and repeatable particle beams, enabling detailed validation of water-Cherenkov detector responses.
- During my stay at TRIUMF, I investigated the muon beam as a control sample of pion beam analysis, and found unexpected Data/MC excesses associated with a low-TOF component
- Removing the low-TOF component strongly reduces the excesses, suggesting contamination by particles faster than the nominal muon beam.
- Future plan:
 - Continue investigating the origin and momentum distribution of the beam contamination together with the WCTE/TRIUMF collaborators.
 - Continue this collaboration beyond the exchange period toward the pion–water cross-section measurement.

Life at TRIUMF



EPECR led to both substantial research progress and an ongoing collaboration beyond my stay at TRIUMF.

Thanks a lot!



Backup

