# Neutrino Charged Pion Production on Water in Extended Phase Space Using Michel Electron Reconstruction in the T2K Near Detector

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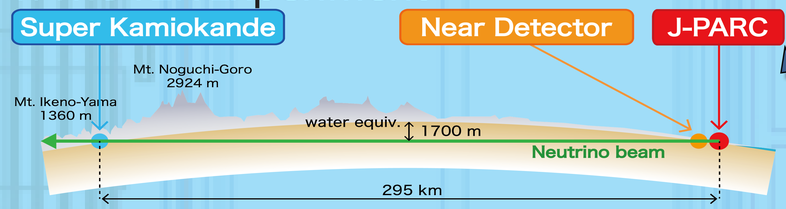
## 1. The T2K Experiment

***Figure 1: T2K baseline diagram.***

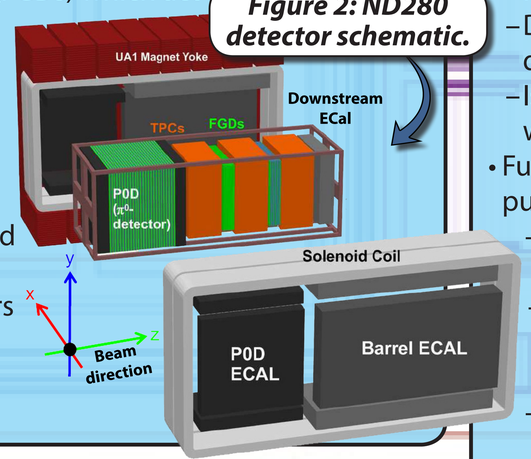



- T2K (Tokai-to-Kamioka) is a long baseline accelerator neutrino experiment, designed with the aim of studying neutrino oscillations via $\nu_\mu$-disappearance and $\nu_e$-appearance.
- A muon neutrino or anti-neutrino beam is generated at J-PARC, and directed toward the Super-Kamiokande detector, 295 km away.
- Narrow-band off-axis beam peaked at ~600 MeV.
- The near detector complex situated 280 m downstream provides constraints for oscillation measurements, along with measuring various interaction channels.

## 2. The ND280 Near Detector

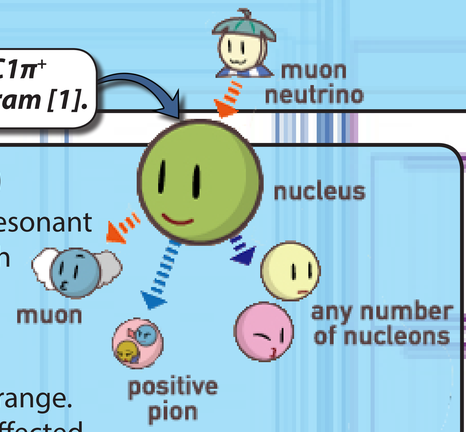
- 0.2 T magnetised detector, at the same off-axis angle as Super-K.
- Tracker region is composed of:
  - Two Fine-Grain Detectors (FGDs) which act as targets - FGD1 is made of plastic scintillator, FGD2 of scintillator and water.
  - Three Time Projection Chambers (TPCs) - used for momentum measurements, particle and charge ID.
- Electromagnetic calorimeters (ECals) surround the tracker region, used to measure showering particles.

***Figure 2: ND280 detector schematic.***




## 3. CC1$\pi^+$ in ND280

***Figure 3: CC1$\pi^+$ topology diagram [1].***

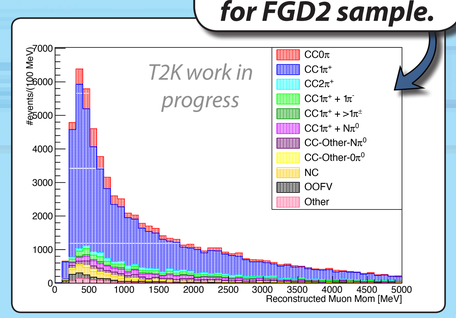



- Around peak T2K energy, resonant interactions begin to switch on.
- Pion production is dominated by resonant interactions in T2K energy range.
- Neutrino interactions are affected by complex intranuclear processes, and altered by final state interactions.
- To avoid model dependence, classify events by observed final state topology: one muon, one positive pion, no other mesons.
- Previous differential measurement performed in muon kinematics [2], analysis will include new data, updated selection, pion kinematic information.

## 4. Event Selection

- Start by searching for muon candidate - require highest momentum negative track to be muon-like using particle identification (PID).
- Require exactly one positive pion, identified in one of three ways:
  - Pion-like TPC tracks for those that leave the FGD.
  - Decaying pions identified from delayed Michel electron (ME) in FGD.
  - Isolated FGD pion tracks consistent with pion PID.
- Further cuts applied to increase sample purity:
  - Require muon track ECal segment to be track-like, reducing $\mu^-/\pi^-$ confusion.
  - Remove events with isolated ECal objects consistent with $\pi^0$s.
  - Require muon positive time of flight from FGD to ECal - removes some out of fiducal volume background.

***Figure 4: Reconstructed muon kinematics for FGD2 sample.***




## 5. Analysis Status

- Selection and detector systematics mostly completed. Muon kinematics for FGD2 selection shows ~70% sample purity (Figure 4).
- Currently no ability to access pion kinematics from ME sample - working on reconstruction method to access this phase space:
  - Good correlation in MC truth between event and ME vertex separation and pion momentum (Figure 5). Same seen for angles to neutrino direction.
  - Use delayed FGD hits to estimate ME vertex position, calculate distance and angle to event vertex.
  - Use truth correlation to estimate momentum and angle, compare to truth (Figure 6).
- Figure 7 shows importance of including this information, low momentum pions are dominated by ME sample.

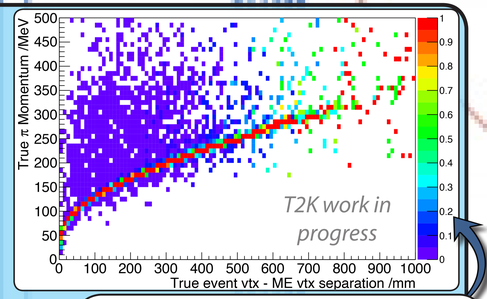



***Figure 5: True pion momentum vs separation between event and ME vertex.***

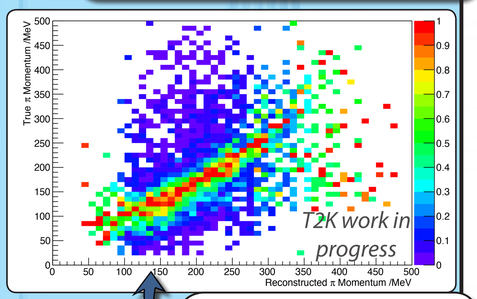
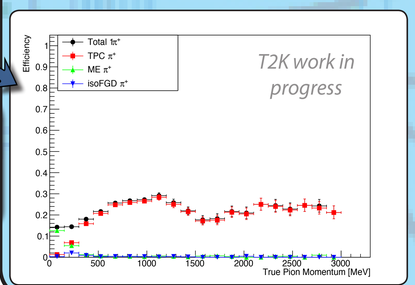



***Figure 6: True vs recon pion momentum for ME sample.***

***Figure 7: True efficiency as a function of pion momentum, for each sample.***




## 6. Conclusion and Further Plans

- Preliminary reconstruction shows good agreement (Figure 6).
- This already allows us to probe parts of the pion phase space that were previously inaccessible. Further improvements of the reconstruction are under investigation.
- Two control samples (CC-multi pion and CC1$\pi^+$ + N$\pi^0$) will be used to constrain background contribution.
- Measurement will be performed in both FGDs 1 and 2, to extract cross-section on water.

## References

[1] - Higgstan elementary particle illustrations: http://higgstan.com/particle-image/
[2] - L. Cremonesi *et al.*, Phys. Rev. D 95, 012010 (2017)