# Measurement of the muon neutrino CC1$\pi^+$ cross section on water with pion kinematics at the T2K near detector ND280

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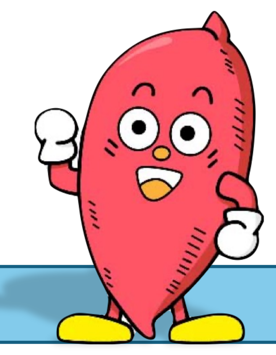

## The T2K Experiment

- T2K is a long-baseline oscillation experiment based in Japan measuring $\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_e(\bar{\nu}_e)$ oscillations from a 0.6 GeV beam
- Systematic error budget dominated by neutrino-nucleus interaction modelling uncertainty [1]
- The off-axis near detector ND280 provides constraints to oscillation measurements, and makes $\nu-A$ interaction measurements
- ND280 is composed of multiple sub-detectors, including:
  - ➢ 2 **F**ine-**G**rained **D**etectors – main target mass of CH or H2O
  - ➢ 3 **T**ime **P**rojection **C**hambers – particle ID, momentum and charge measurements
  - ➢ **E**lectromagnetic **Cal**orimeters – track/shower separation

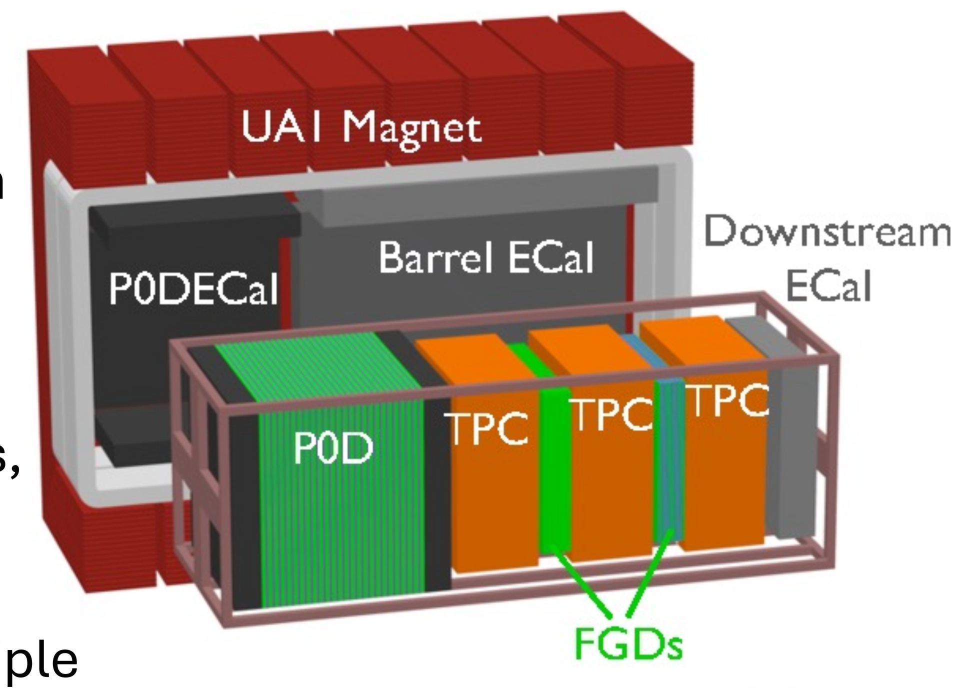


Fig 1: ND280 exploded view [2]

## Sample selection

- The interaction signal required is $\nu_\mu$CC1$\pi^+$ in FGD1 or 2:

$$\nu_\mu + N \rightarrow \mu^- + \pi^+ + A$$

where $N$ can be CH or $H_2O$, and $A$ is a final state containing no additional mesons

- Phase space constraints are applied:

$$p_\mu > 200\text{ MeV}, \quad \cos\theta_\mu > 0.3, \quad 50\text{ MeV} < p_\pi < 1500\text{ MeV}$$

- Three signal samples selected based on method of pion detection, targeting different regions of pion phase space
- Michel electron (ME) pion signal sample tags untracked pions via the delayed hits
- Technique developed to reconstruct pion momentum via measured range of ME from interaction vertex [3]
- This provides measurement of pion kinematics below tracking threshold
- Three control samples dedicated to main backgrounds – multi-pion events and CC0pi events with protons misidentified as pions
- Factor of two increase in statistics over previous measurement [4], in addition to extended phase space and focus on pion kinematics

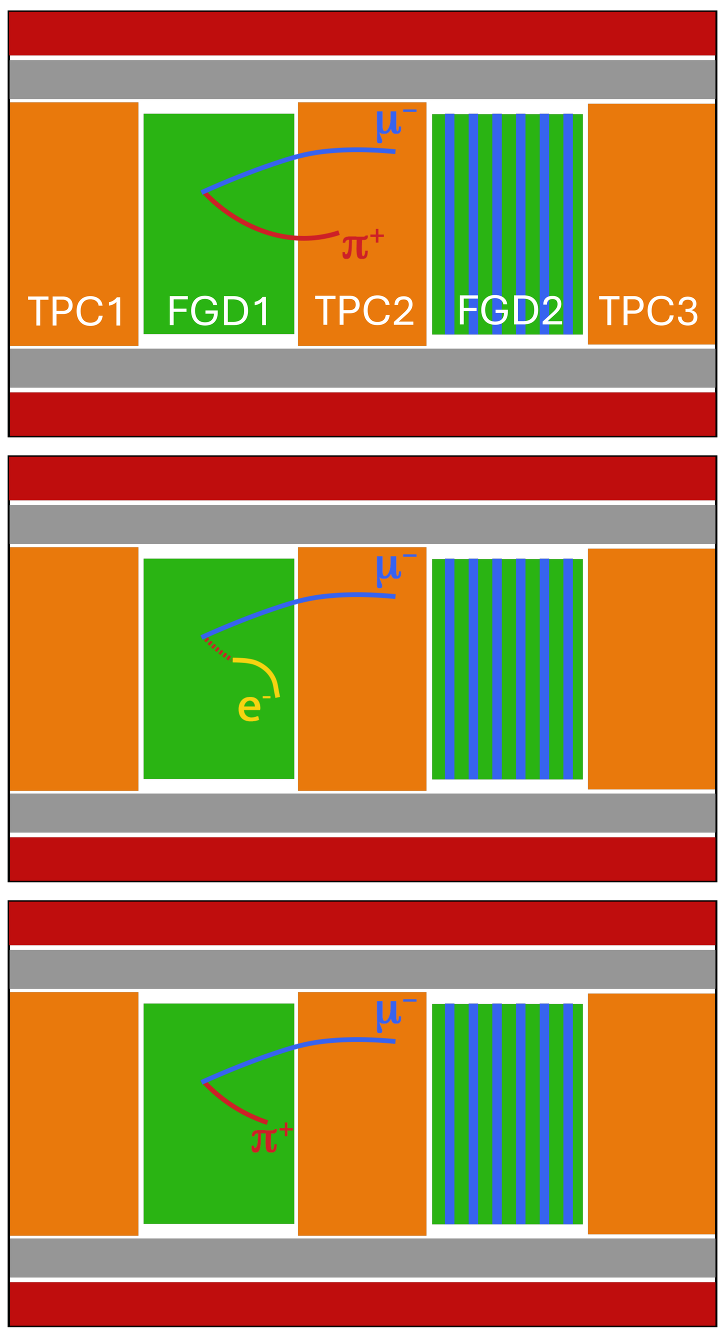


Fig 2 (above): TPC pions (top), ME pions (middle) and isolated FGD pions (bottom) event topologies

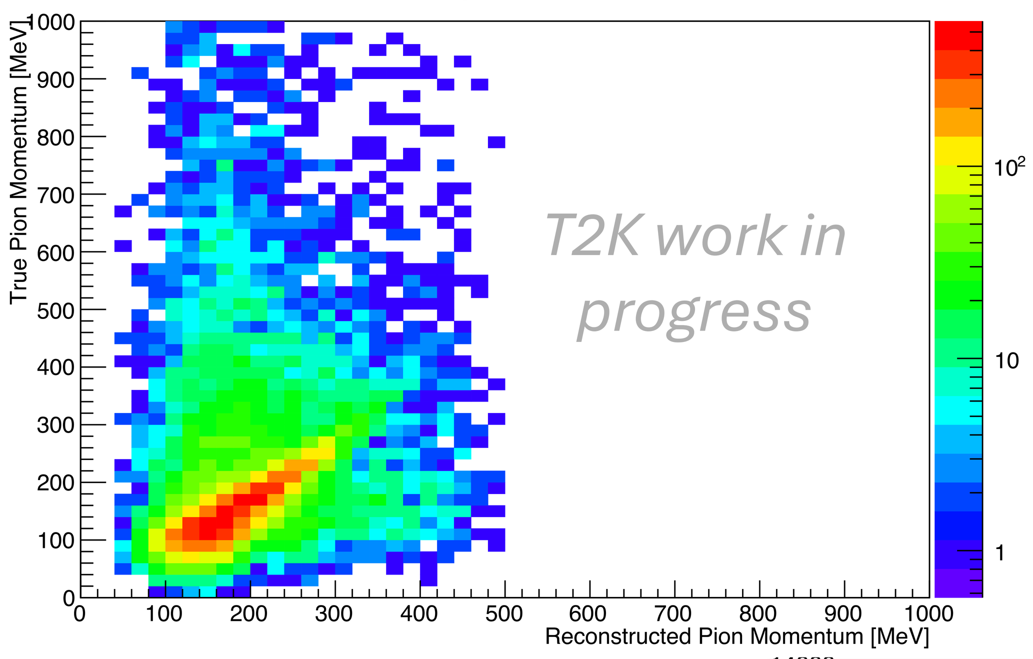


Fig 3 (above): True vs. reconstructed pion momentum for pions tagged via presence of Michel electrons

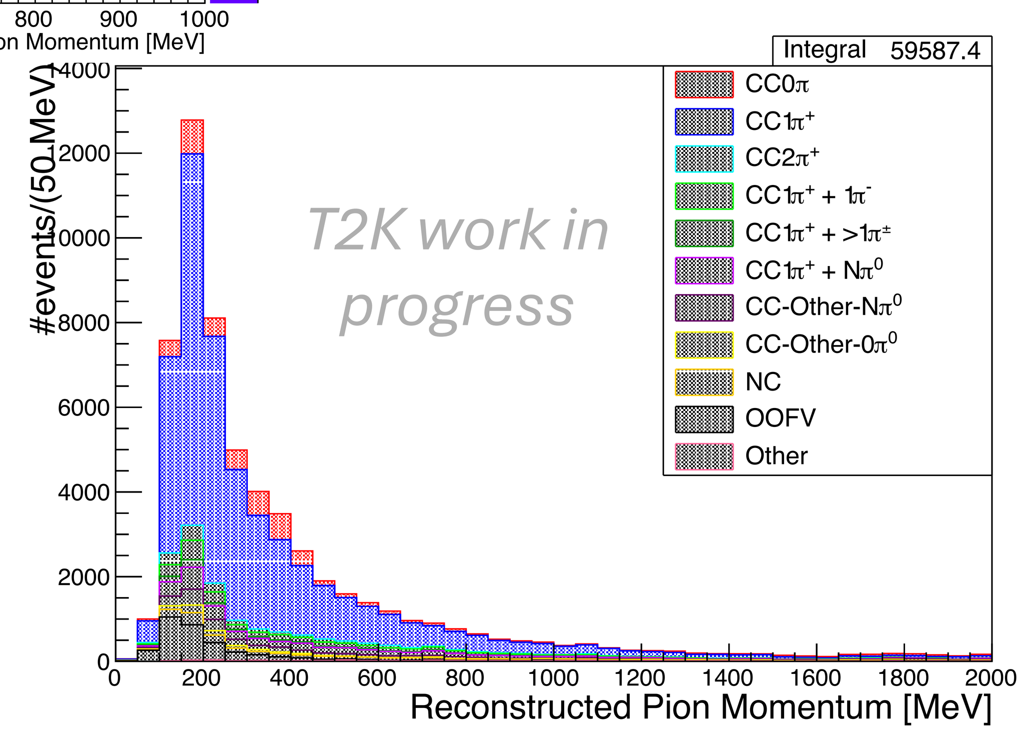


Fig 4 (right): Reconstructed pion momentum for the total CC1$\pi^+$ sample

## Cross section calculation and efficiency correction

- Differential cross section calculated as:

$$\left(\frac{d\sigma^\alpha}{dx}\right)_i = \frac{N_i^{sig,\alpha}}{\epsilon_i^\alpha \Phi N_T^\alpha} \times \frac{1}{\Delta x_i}$$

where $N_i^{sig,\alpha}$ is the number of signal events on target $\alpha$ (CH or $H_2O$) in the $i^{th}$ bin, $\epsilon_i^\alpha$ is the efficiency in that bin, $\Phi$ the integrated flux and $N_T^\alpha$ the number of nucleons for target $\alpha$. $\Delta x_i$ is the width of the bin

- Extraction performed using a binned template likelihood fit
- The binning choice is important for efficiency corrections – if efficiency changes within a bin, we rely on model assumptions
- Use fine-binned efficiency corrections:
  - ➢ Use narrow bins for efficiency correction. This ensures eff. within bin is unchanging, but leads to a high statistical error
  - ➢ Integrate to wider bins to reduce error, maintaining correct error coverage [6]

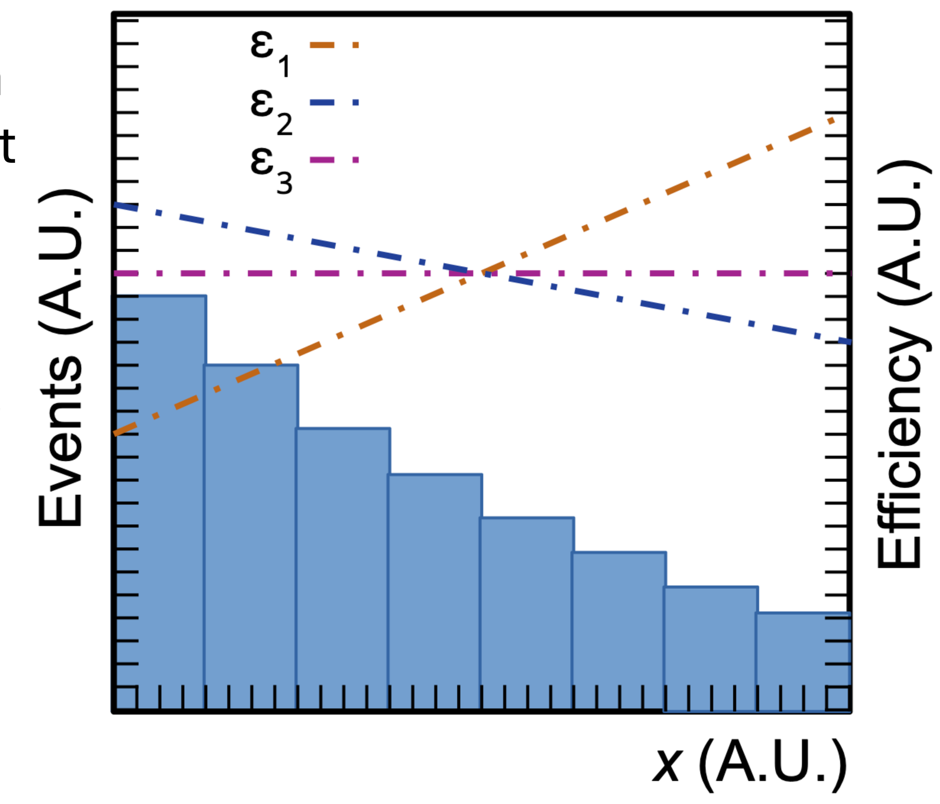


Fig 5: Example of differing efficiency shapes which integrate to the same value [5]

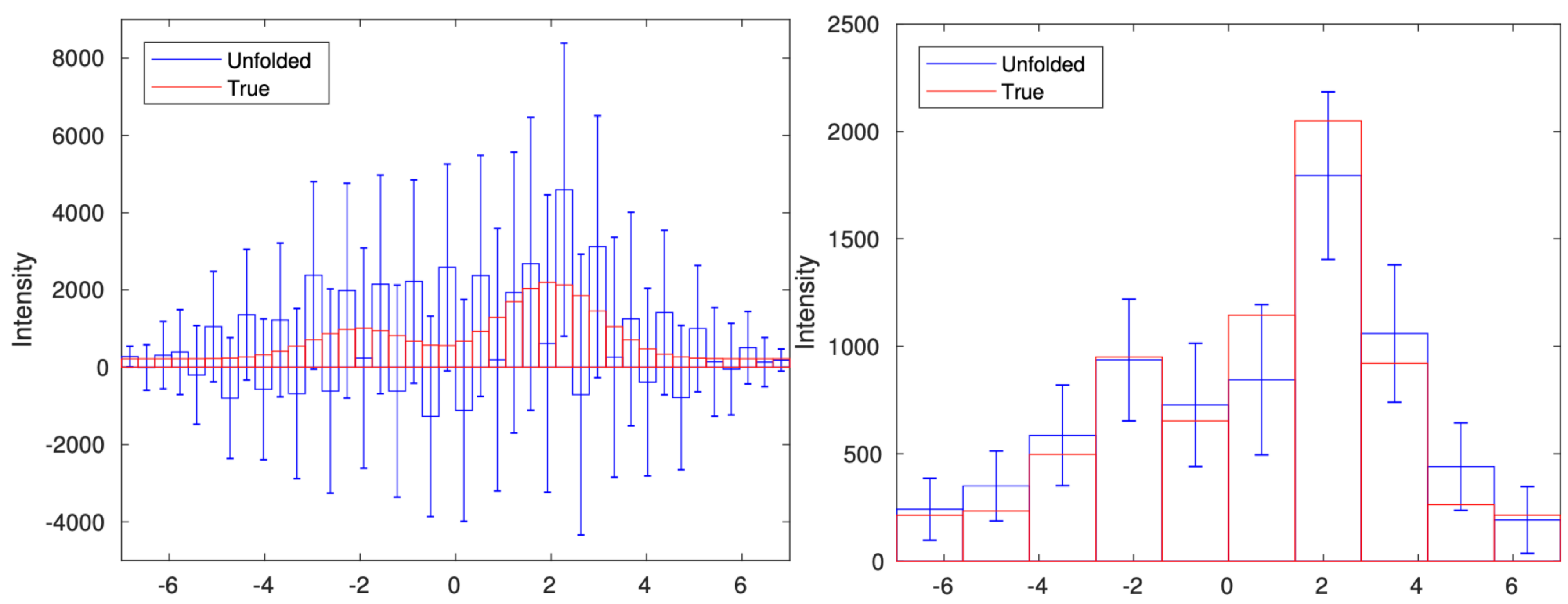


Fig 6: Perform efficiency correction in fine binned scheme (left), then collapse to wider bins to reduce stat. error (right) [6]

## Measurement plan and status

- Perform fit and efficiency corrections in fine 4-dimensional binning scheme $(p_\mu, \cos\theta_\mu, p_\pi, \cos\theta_\pi)$ – yields 4D cross section, but statistically limited
- Integrate over muon kinematic bins, to retrieved 2D cross section measurement in $(p_\pi, \cos\theta_\pi)$
  - ➢ Can also integrate over pion bins to make measurement in muon kinematics, and keep correlations between muon and pion 2D measurements
- Large array of fake data studies performed to stress test the fitter and assess biases
- Fit has been unblinded to real ND280 data – results to come soon!

## References

[1] Abe, K. et al., Eur. Phys. J. C 83, 782 (2023)
[2] The T2K experiment, http://t2k-experiment.org
[3] S. Jenkins, PoS (NuFact2021) 087 (2021)
[4] Abe, K. et al., Phys. Rev. D **95**, 012010, 26 January 2017
[5] Figure courtesy of D. Cherdack
[6] M. Kuusela, Introduction to Unfolding: A Statistician's Perspective, PHYSTAT-nu 2019, CERN