First Measurement of the Electron Neutrino Charged Current Pion Production Cross Section on a Carbon Target at ND280

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The T2K Experiment

Tōkai-to-Kamioka (T2K) is a long-baseline neutrino experiment in Japan which aims to precisely measure parameters of the Pontecorvo–Maki–Nakagawa–Sakata matrix by studying $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ oscillations from a 0.6 GeV beam:

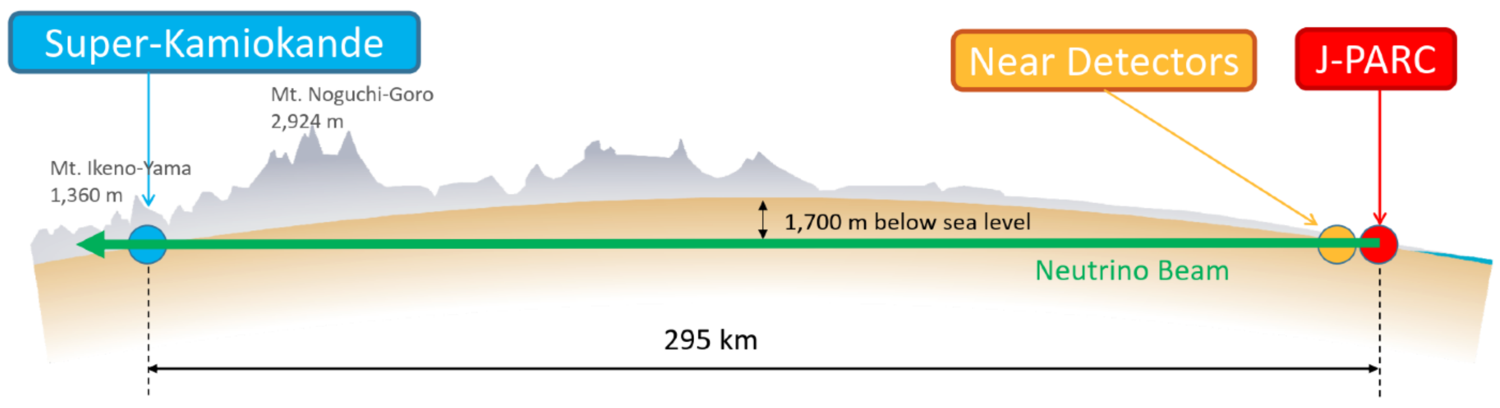

Figure 1. Cross-sectional schematic of the T2K experiment, from [1].

ND280 is the 2.5° off-axis near detector with several important purposes:

- Measures ν-A interaction cross sections and initial beam flux
- Characterises initial beam composition 0.2 km from the source

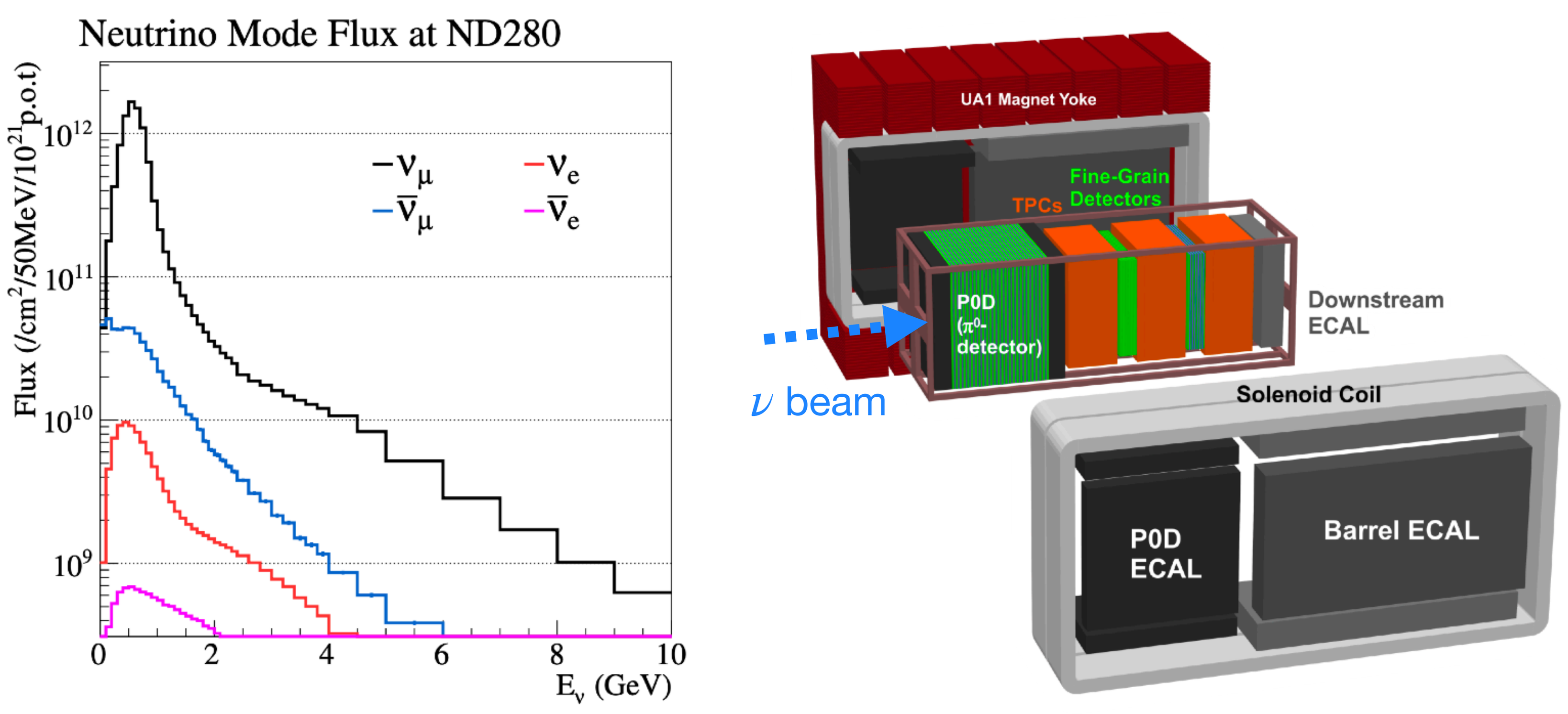

Figure 2. The neutrino flux at ND280 (left) and an exploded schematic of the ND280 near detector (right). Both figures are taken from [2].

The ND280 sub-detectors serve several important purposes:

- **Fine-grain detectors** (FGDs) act as target masses, mainly CH and H_2O
- **Time projection chambers** (TPCs) measure particle charge and momentum
- **Electromagnetic calorimeters** (ECals) perform track-shower separation

Analysis Overview

The channel being studied in this analysis is $\nu_e \mathrm{CC}\pi^+$ in FGD1:

$$\nu_e + \mathrm{CH} \to e^- + \pi^+ + X$$

- Contributes to ν_e appearance at T2K and is therefore sensitive to δ_{CP}; it will become more important with higher statistics and reduced systematics
- Far detector samples exhibit statistically significant event excesses [3]

Phase space constraints:

$$0.35 < p_e < 30\ \mathrm{GeV}/c, \quad \cos\theta_e > 0.7, \quad p_\pi < 1.5\ \mathrm{GeV}/c\,.$$

Only 355 $\nu_e \mathrm{CC}\pi^+$ events predicted to occur in pre-upgrade ND280 dataset.

Two signal samples, both require the interaction vertex to occur in FGD1:

(a) **TPC sample** - pion enters sub-detector modules downstream of FGD1
(b) **FGD sample** - pion remains in FGD1 and decays to a Michel electron

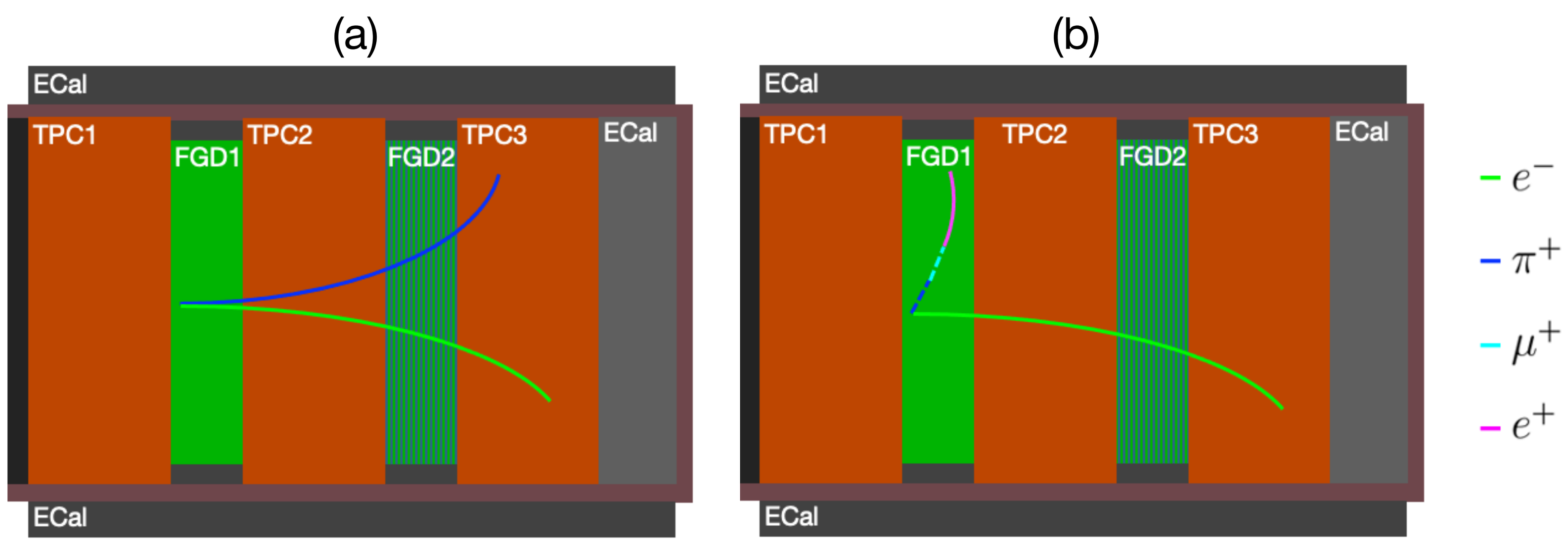

Figure 3. An event display graphic of ND280 showing events which enter the TPC sample (a) or the FGD sample (b).

Two control samples used by the fit target the main γ backgrounds from $\nu_\mu \mathrm{CC}\pi^0$ and $\mathrm{NC}\pi^0$ interactions where $\pi^0 \to 2\gamma$, followed by $\gamma \to e^+e^-$.

Main goal is to measure $\nu_e \mathrm{CC}\pi^+$ cross section in FGD1. A side was goal to investigate event rate excesses of this process recorded in [3] with a dedicated ND280 analysis. However, this covers a different region of phase space due to large photon backgrounds at low p_e present in ND280.

Neutrino-Nucleus Cross Sections

The neutrino oscillation event rate model predicts

$$N^{\exp}(E_\nu) \simeq P(E_\nu) \times \Phi(E_\nu) \times \sigma(E_\nu) \times \epsilon(E_\nu)$$

where E_ν: energy, P: oscillation probability, Φ: flux, ϵ: efficiency and σ: neutrino-nucleus cross sections; σ tends to be the dominant systematic uncertainty. The most common neutrino-nucleon interactions at T2K are:

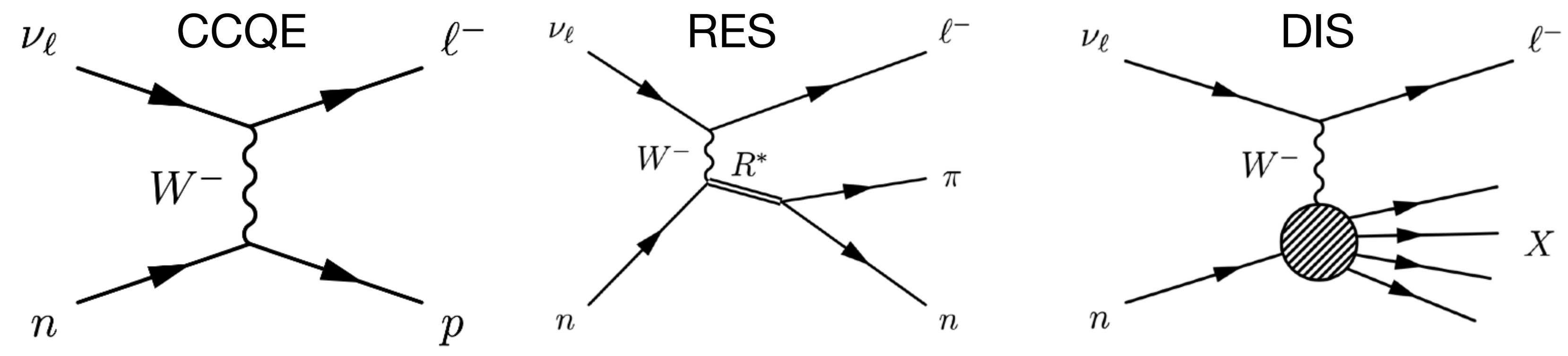

Figure 4. Example Feynman diagrams of common neutrino-nucleon interactions. This shows charged-current quasi elastic scattering (left), resonant pion production (centre) and deep inelastic scattering (right).

Complete ν-A interaction descriptions require careful treatment of neutrino-nucleon cross sections, nuclear models and final-state interactions.

Events are categorised by topology as only the emergent particles are visible; measuring by topology also avoids model dependence on the true interaction.

Event Selection and Reconstruction

Event selection was developed from published $\overset{(-)}{\nu}_e\mathrm{CC}$ inclusive analysis [2]. Pion identification uses dE/dx as measured in the TPCs or Michel electron tagging. A novel feature of this analysis is the inclusion of very low momentum pions with kinematics reconstructed from Michel electron behaviour:

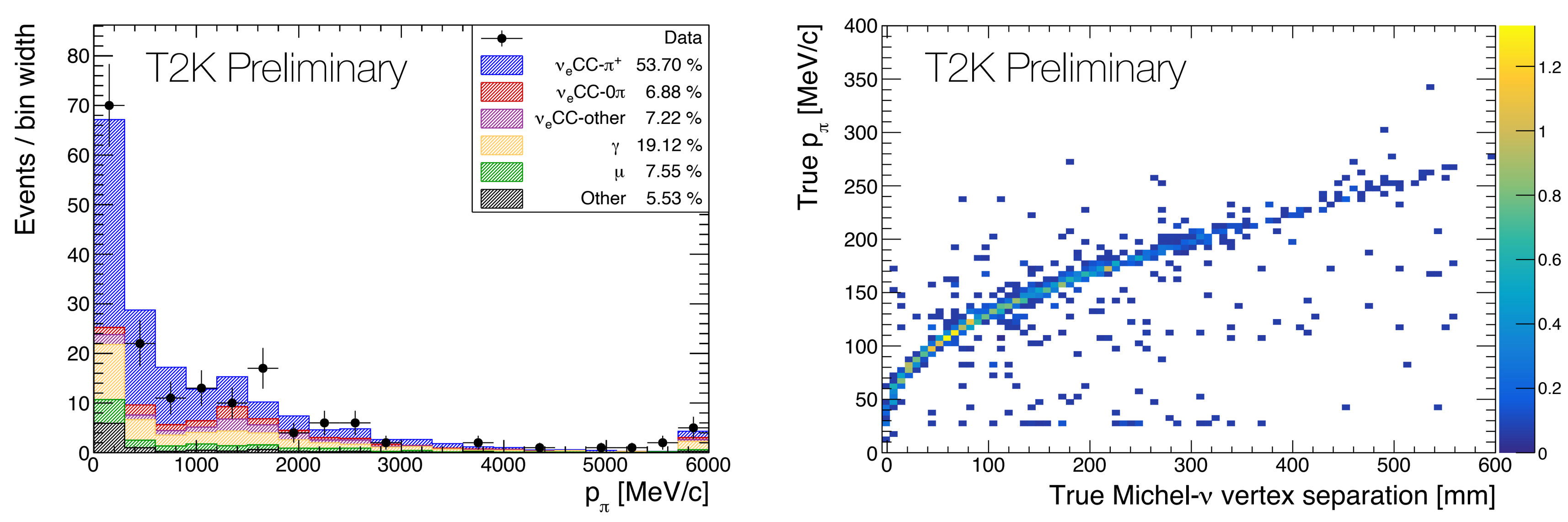

Figure 5. The reconstructed pion momentum distributions of events entering the signal samples (left) and the truth-level equivalence used to calculate pion momentum from Michel electrons (right).

The combined signal-enriched sample has a purity of $\sim 60\,\%$ and efficiency of $\sim 20\,\%$ in the restricted phase space.

Results

The differential cross section values are calculated using the expression

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\hat{N}_i^{\mathrm{sig}}}{\epsilon_i \Phi N_T} \frac{1}{\Delta x_i},$$

where $\hat{N}_i^{\mathrm{sig}}$ is the number of signal events after background constraint, ϵ is the efficiency, Φ is the flux, N_T is the target mass (919.5 kg for FGD1 [2]), x is one of the input observables, Δx is the bin width and i is the bin index. The unfolding method uses a binned log-likelihood template parameter fit which yields a set of best-fit values for the event rate, flux and efficiency.

The total flux-integrated cross section and differential cross sections are

$$5.04 \pm {}^{0.94\ (\mathrm{stat.})}_{0.73\ (\mathrm{syst.})}\ [10^{-39}\ \mathrm{cm}^2\ \mathrm{nucleon}^{-1}\ ]\,.$$

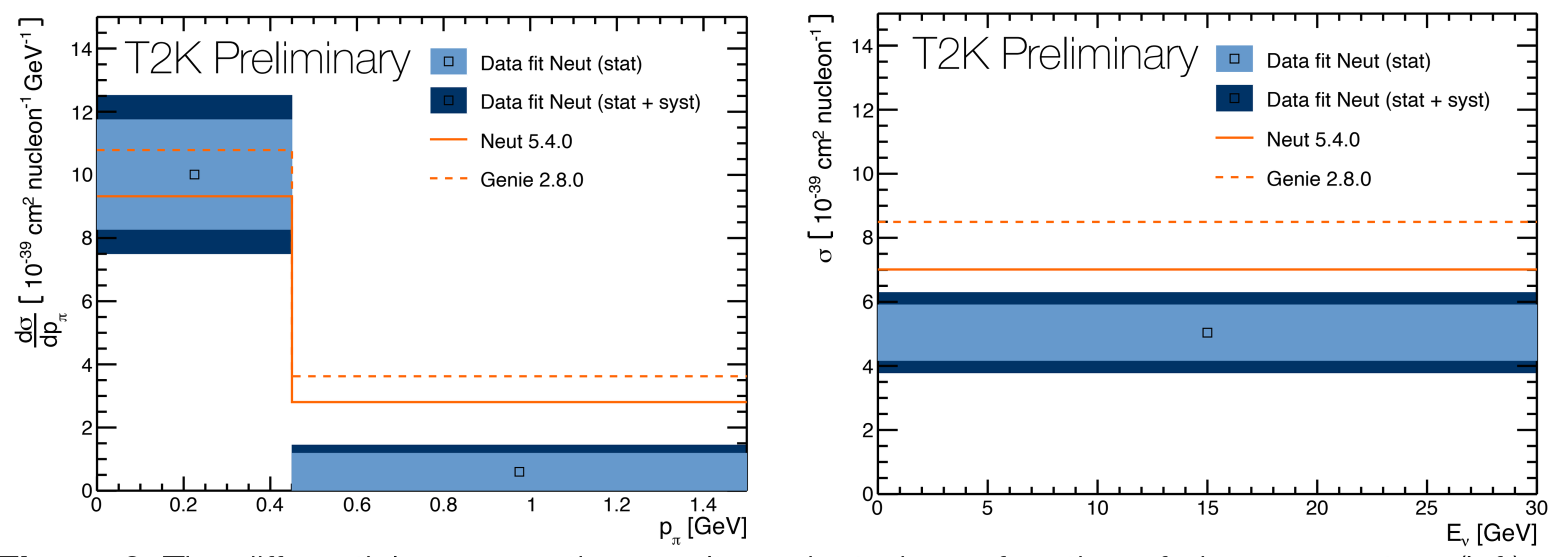

Figure 6. The differential cross section results projected as a function of pion momentum (left) and as the total flux-integrated result (right); comparisons with two event generators are shown.

Results over-predicted by both NEUT [4] and GENIE [5]; no signs of event excesses. Results resemble $\nu_\mu \mathrm{CC}1\pi^+$ cross section values in ND280 [6].

[1] T2K Collab., https: //t2k-experiment.org/t2k/
[2] T2K Collab., *JHEP* **10** (2020) 114
[3] T2K Collab., *Phys. Rev.* **D103** (2021) 112008
[4] Y. Hayato, *Acta. Phys. Polon.* **B40** (2009) 2477
[5] J. Tena-Vidal *et al.*, *Phys. Rev.* **D104** (2021) 072009
[6] T2K Collab., *Phys. Rev.* **D95** (2017) 012010