Latest neutrino cross-section results from T2K

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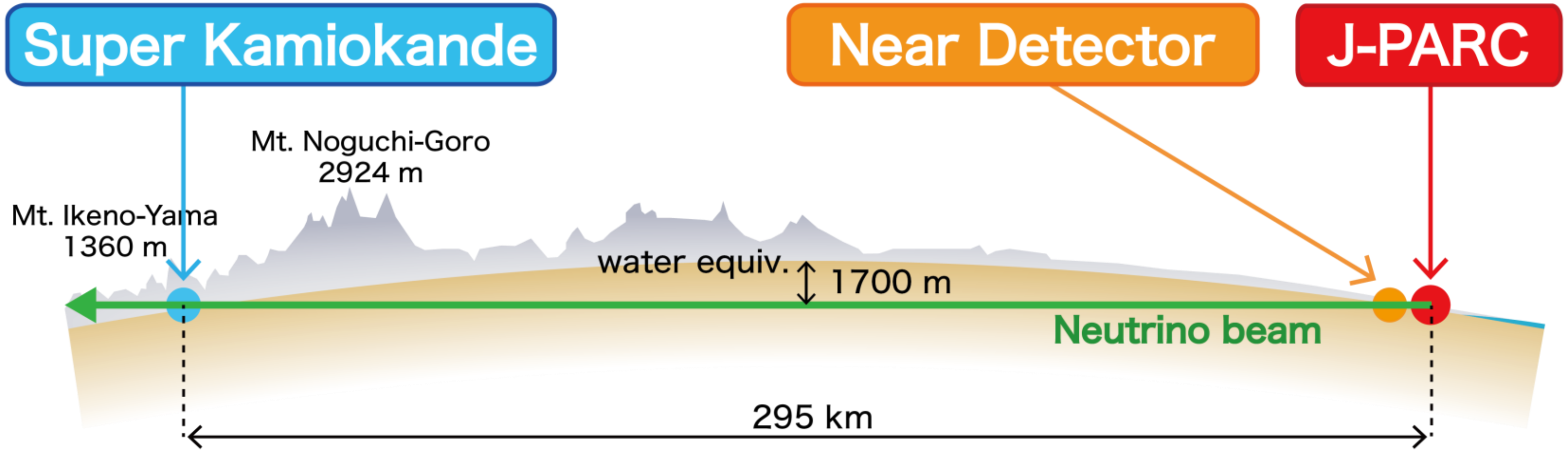
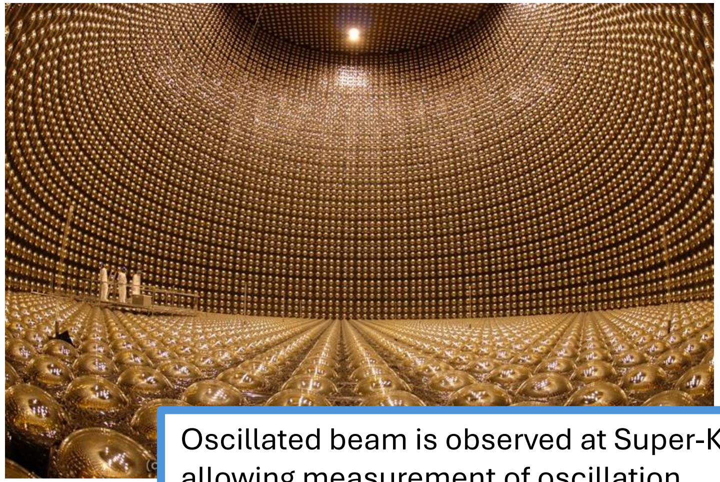
XXI Workshop on Neutrino Telescopes, October 1st 2025

T2K overview



- Long-baseline **neutrino oscillation experiment** in Japan
  - Running since 2010
  - 295 km baseline, 0.6 GeV peak neutrino energy
  - Far detector 2.5° off-axis
  - Sensitive to CP-violation, mixing angle θ_{23} and mass splitting Δm^2_{23}
- Largest systematic uncertainty for oscillation measurements is currently **neutrino interaction modelling**
  - Important to make precise cross-section measurements to improve our understanding of neutrino-nucleus interactions
  - These measurements can be done at our near detectors



Oscillated beam is observed at Super-K, allowing measurement of oscillation parameters

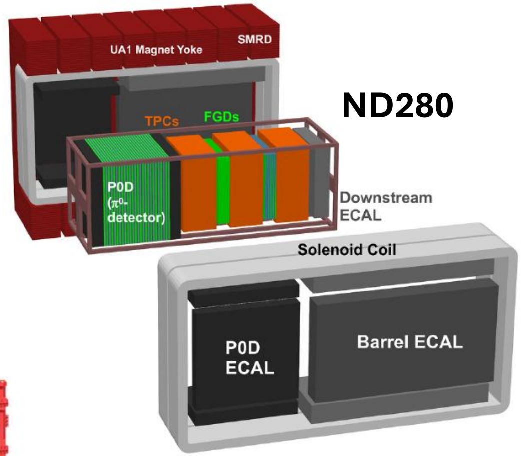
Beam of (anti-)neutrinos produced at J-PARC

Near detector suite

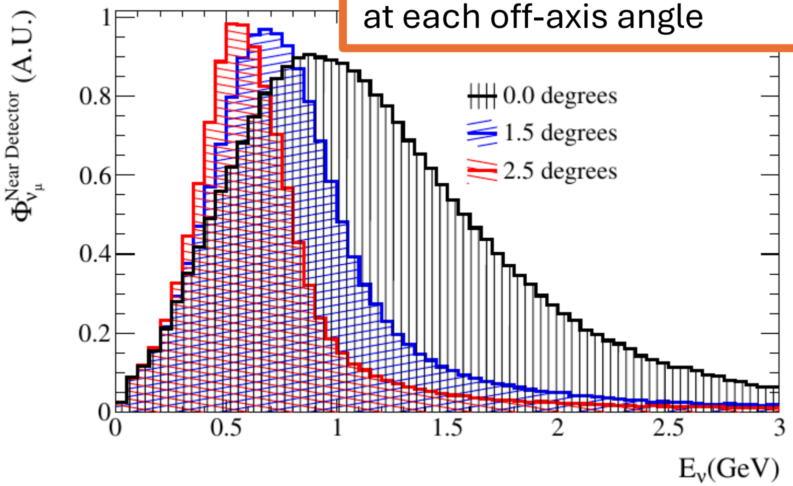
ND280:
- Active scintillator and passive water targets (FGD1 and FGD2)
- Three TPCs for tracking
- Magnetised (0.2 T)
- Measurements on carbon and oxygen
- Same off-axis angle as Super-K

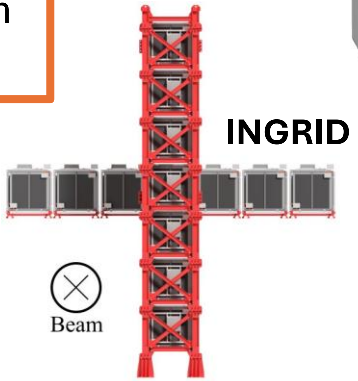
INGRID:
- On-axis, unmagnetized detector
- Iron-scintillator alternating layers
- Monitors direction and intensity of beam

WAGASCI/BabyMIND:
- Water/CH lattice target (WAGASCI)
- Magnetised (1.5 T) iron muon range tracking detector (BabyMIND)



Neutrino energy distribution at each off-axis angle





2.5° off-axis

on-axis

1.5° off-axis

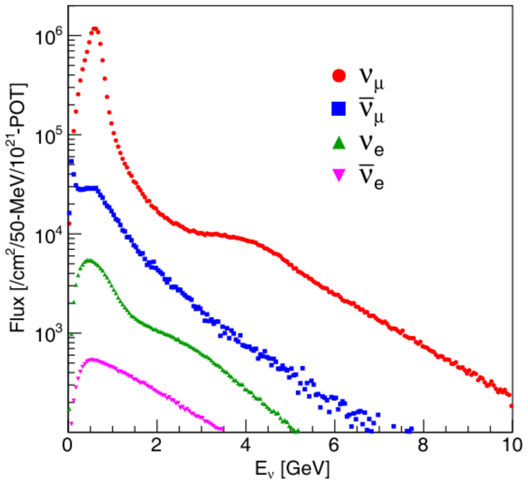
(Anti-)neutrino beam from J-PARC

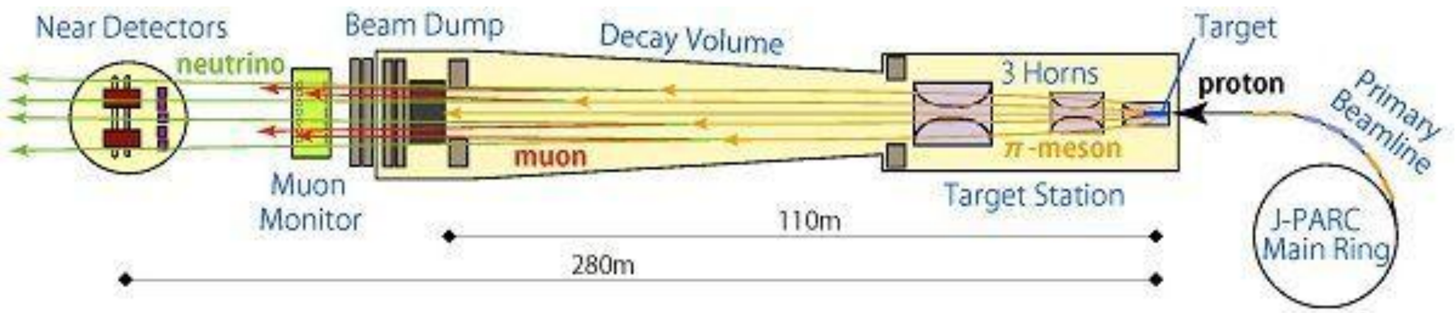
T2K flux model

$$N_i^{exp}(E_\nu) = P(\nu_\alpha \to \nu_\beta) \times \sigma_i(E_\nu) \times \Phi_\nu(E_\nu) \times \varepsilon_i(E_\nu)$$

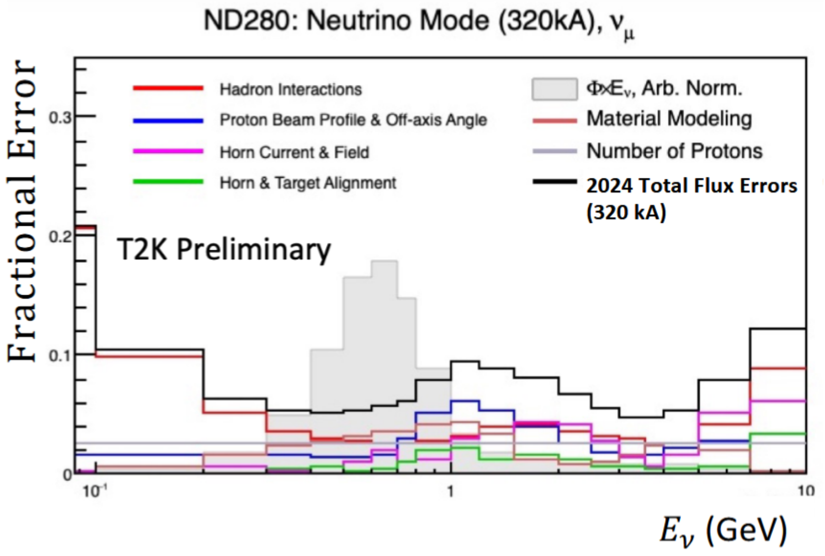
Cross-section

It is important for both oscillation and cross-section measurements to understand the **neutrino flux**



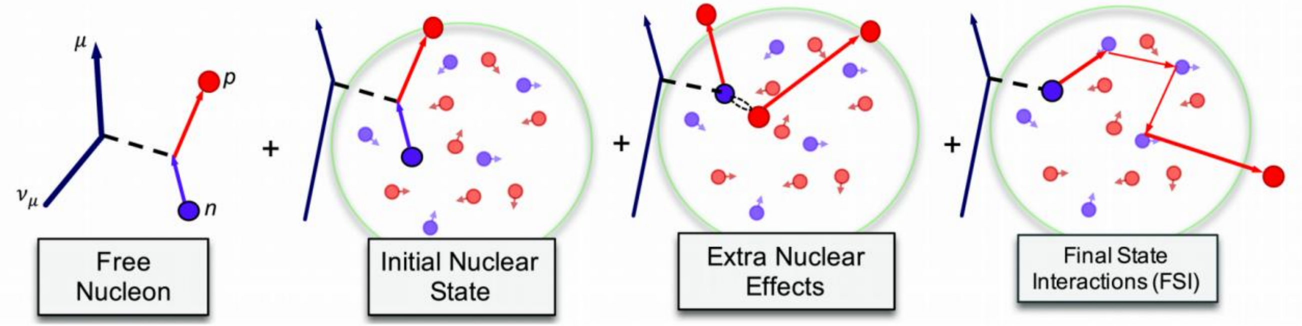


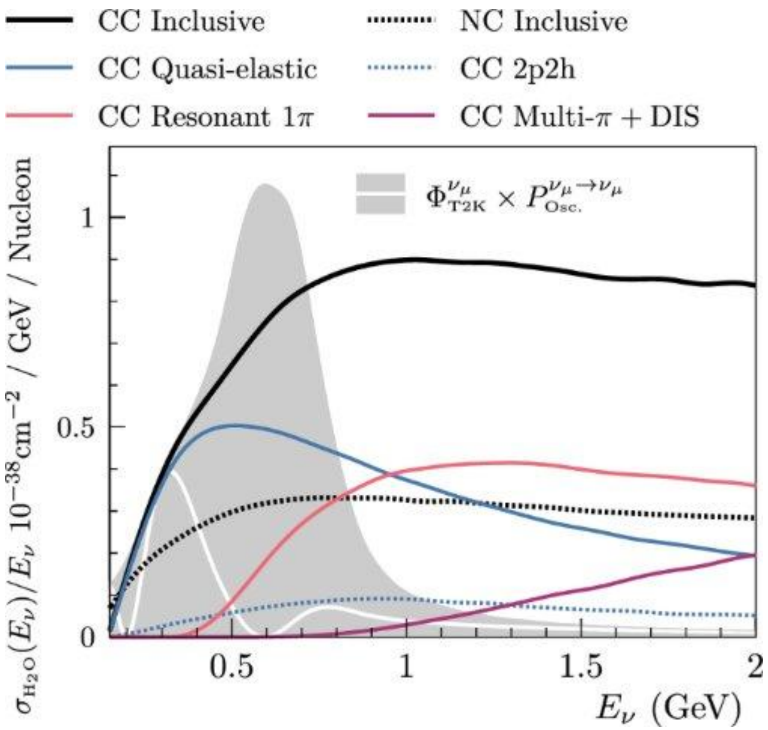
- Systematics dominated by uncertainties on **hadron production** cross-section
- External data from NA61 and other experiments are used for **flux tuning**, using both thin 2 cm target and replica 90 cm target data to constrain models
- This allows reduction of the flux uncertainties to around 6% at peak (reduced from ~20%)



Neutrino interactions at T2K

At the T2K beam energy there is a mixture of interaction channels - **CCQE** is the dominant interaction, with sub-dominant contributions from CC-RES and DIS

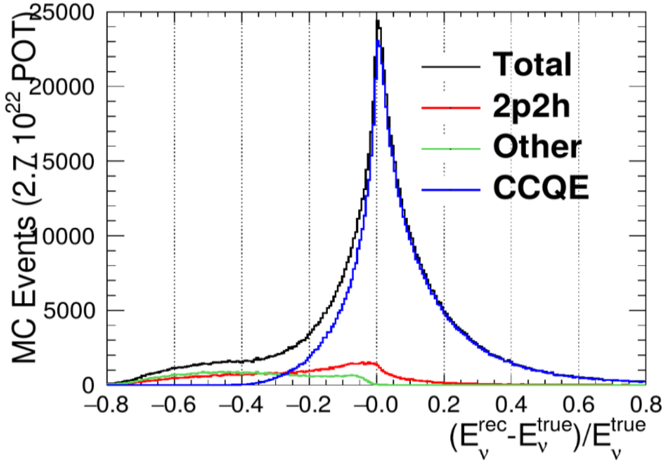




In order to model neutrino interactions we need to consider:

- Nucleon is not free but **part of a nucleus** e.g. in oxygen or carbon target
- Additional nuclear effects such as **2p2h**
- **Final state interactions (FSI)** e.g. pion absorption, scattering

- All these effects can lead to smearing and bias in the reconstructed neutrino energy



Interaction topologies

- Measurements are made on **topologies** (eg CC0π1p, CC1π) rather than interaction modes (eg CCQE)
- Split here by the different **leptonic** and **hadronic** sides than can lead to a specific topology

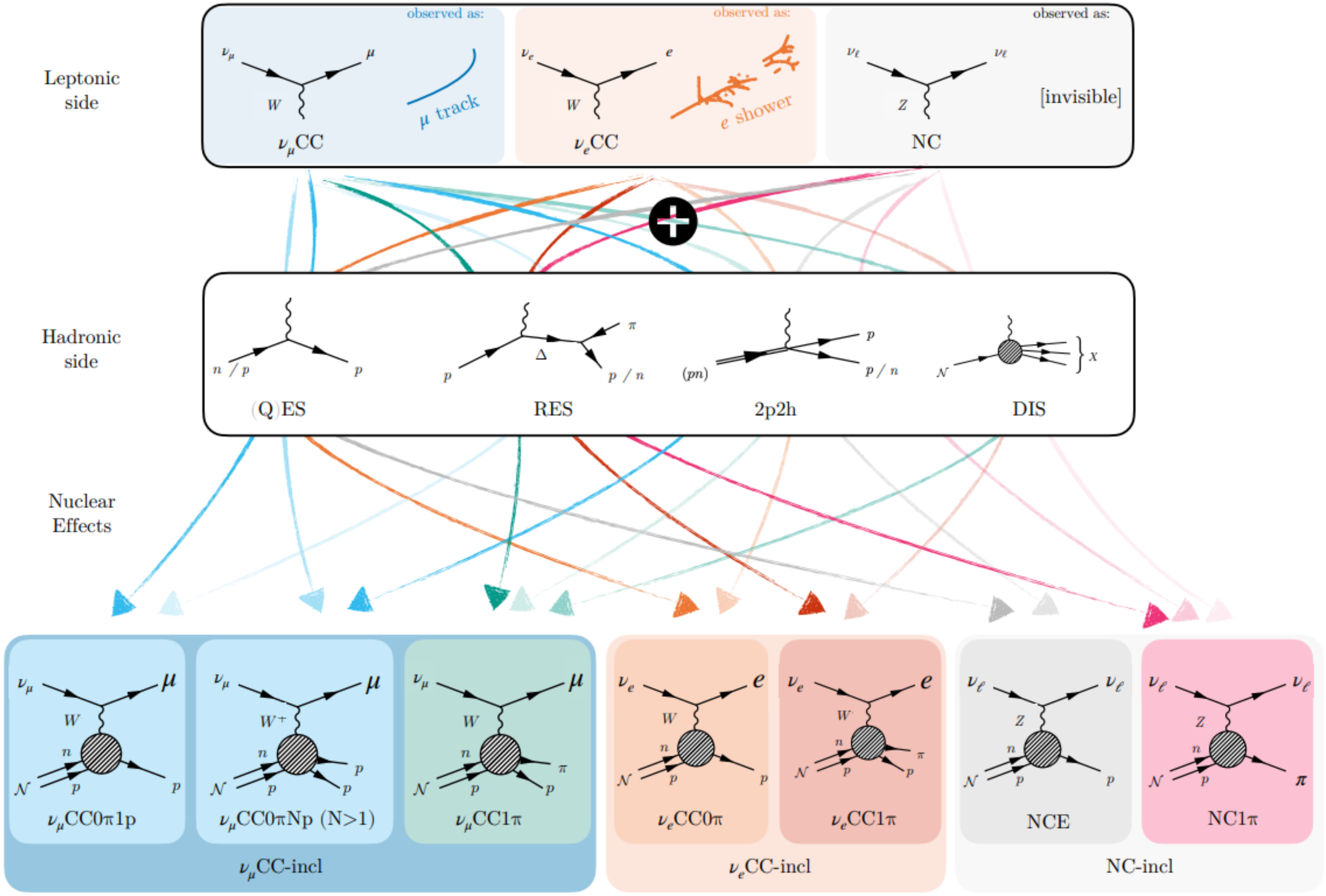


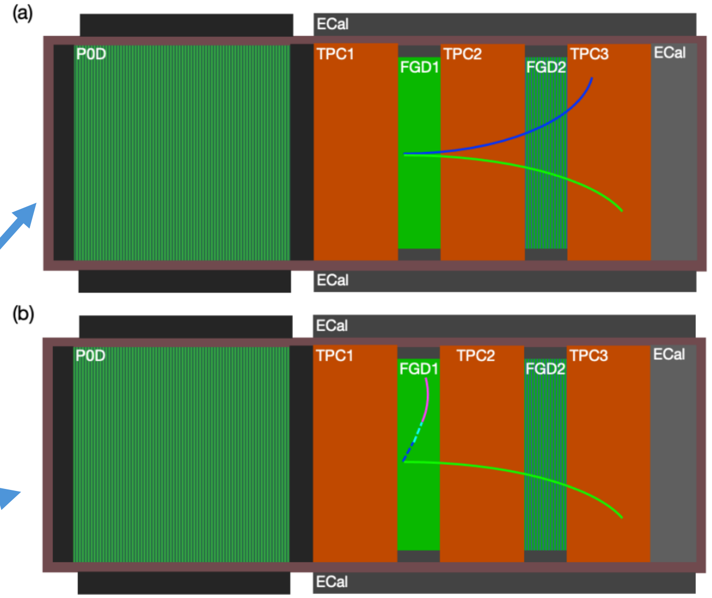
Diagram from K. Lachner talk at NuFact 2025

T2K cross-section measurements

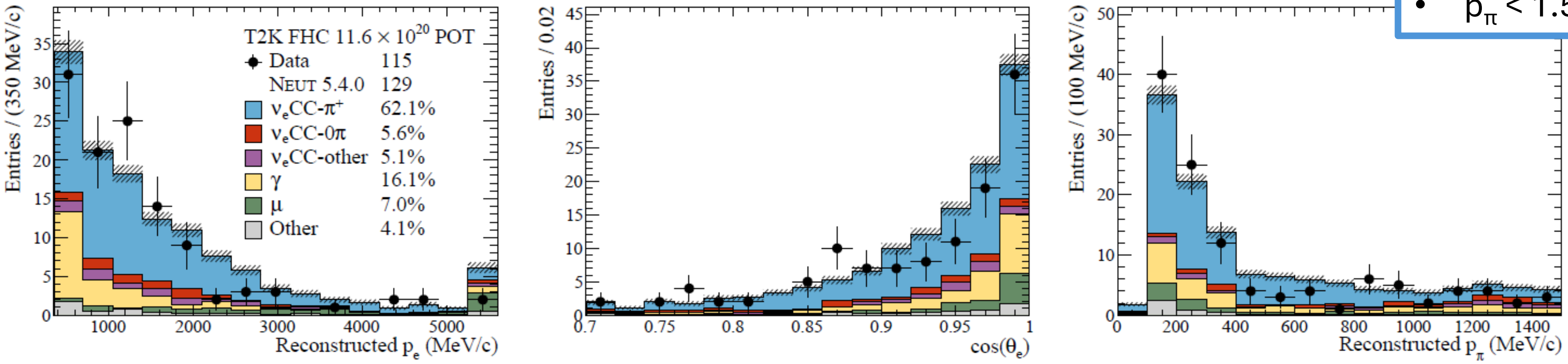
T2K has published many cross-section measurements in many different channels in the last 15 years – here I highlight some recent results

ν_e CCπ^+ on Carbon

- First measurement of electron neutrino-induced charged current pion production on C
  - Sub-dominant contribution to ν_e appearance in oscillation measurements
- Target is FGD1 of ND280
- Two selection samples:
  - Pion escapes FGD1 and enters TPCs
  - Pion decays to Michel electron in FGD1



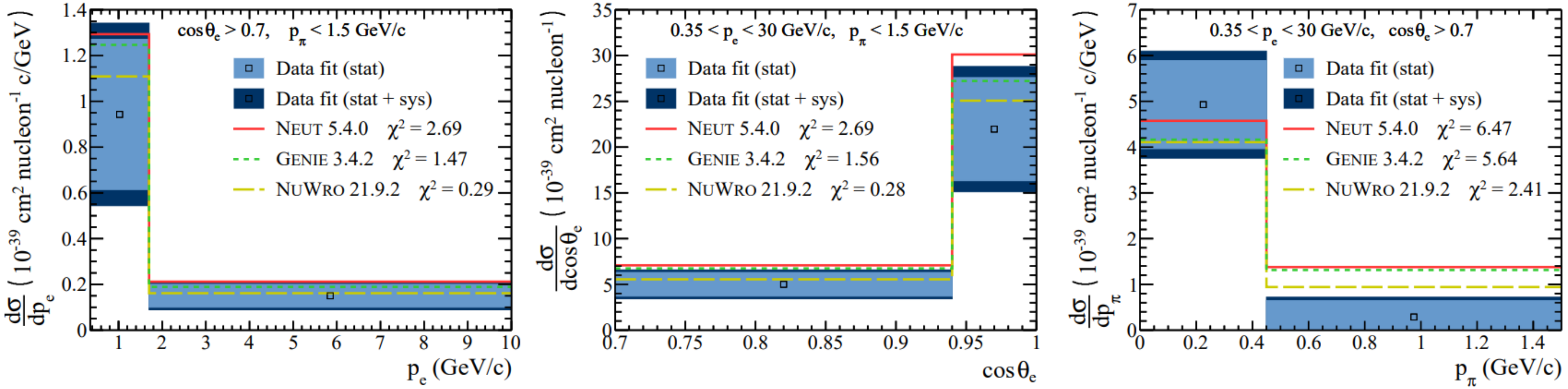
Signal region:
- $0.35 < p_e < 30$ GeV/c
- $\cos\theta_e > 0.7$
- $p_\pi < 1.5$ GeV/c



Comparison of data with NEUT prediction for electron momentum angle and pion momentum

Pre-print: arXiv:2505.00516

ν_e CCπ^+ on Carbon



Differential measurement in electron momentum, angle and pion momentum phase space

Results:
Measured total flux integrated cross-section:
$(2.52 \pm 0.60) \times 10^{-39}$ cm^2/nucl.

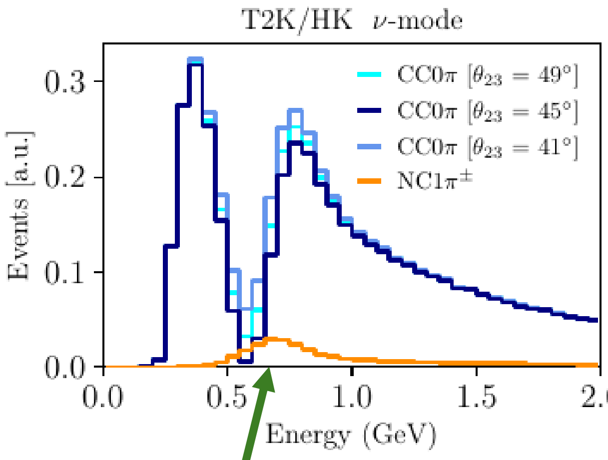
Overall data favours a **lower than predicted** cross-section, especially for high pion momentum:
- 2.4σ discrepancy w/ GENIE
- 2.5σ discrepancy w/ NEUT

Generator	σ (10^{-39} cm^2 nucl^{-1})	p-value
NEUT 5.4.0	3.51	0.30
GENIE 3.4.2	3.25	0.59
NUWRO 21.9.2	2.84	0.89
Data	2.52 ± 0.60	-

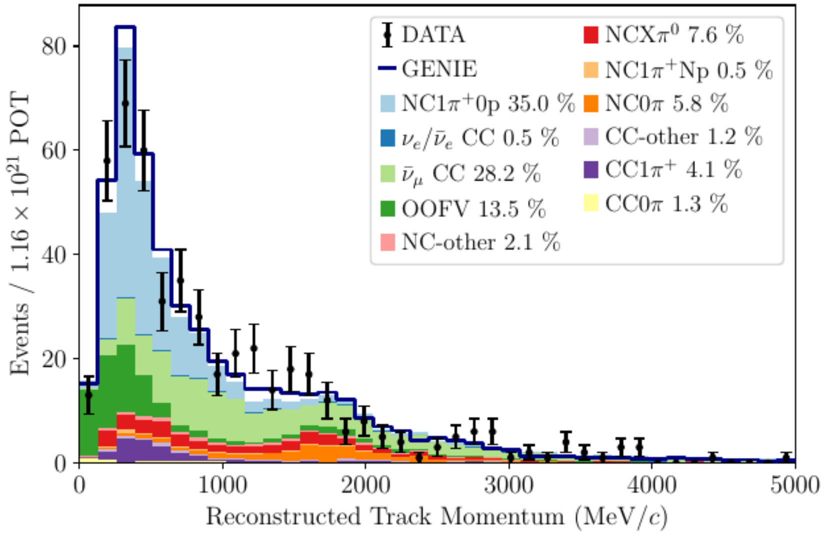
Pre-print:
arXiv: 2503.06849
arXiv: 2503.06843

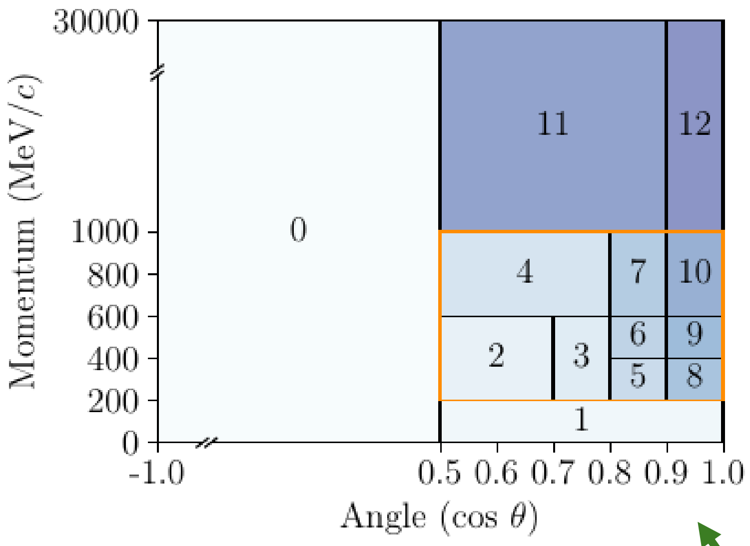
NC1π^+ interactions on CH

Motivation: neutral current 1π⁺ is an important background for muon neutrino disappearance if the pion is misidentified as a muon



Background events are near the "oscillation dip" where muon neutrino oscillation probability is maximal – important to measure



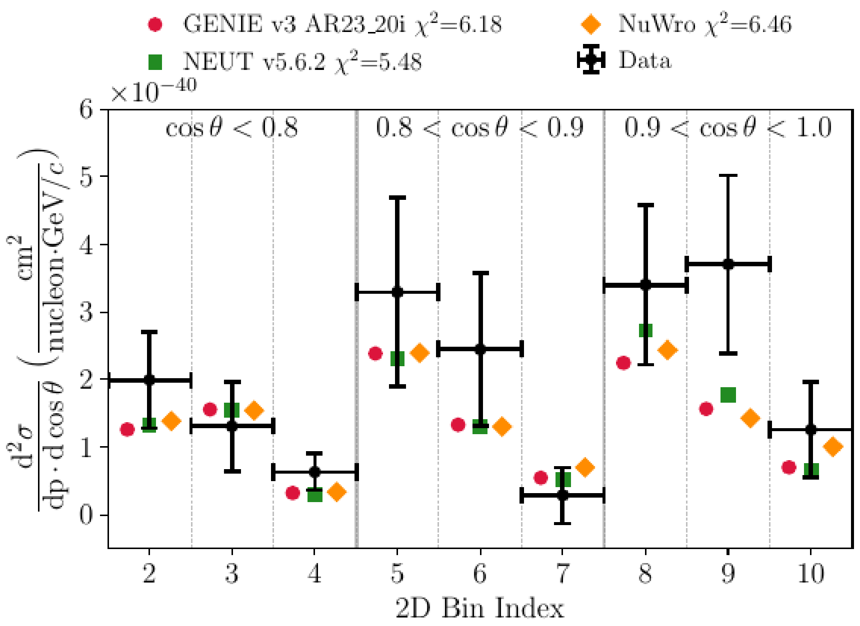


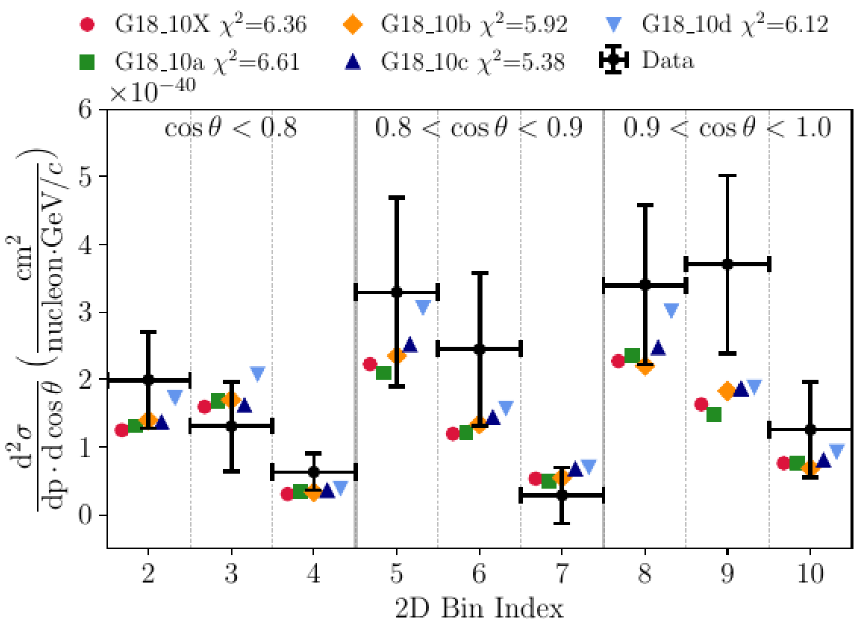
- Target is the FGD1 of ND280 (hydrocarbon)
- **Signal definition:** π⁺ with momentum between 0.2 and 1 GeV, and cosθ>0.5, no detectable proton (momentum < 0.2 GeV)
- Two-dimensional **binning in pion momentum and angle** – 13 bins total
- Largest background is from anti-muon neutrino CC events

NC1π^+ interactions on CH

Pre-print:
arXiv: 2503.06849
arXiv: 2503.06843

Results:
- Double differential cross-section measurement, flux averaged cross-section (6.07±1.22) ×10^{-41} cm^2/nucl.
- Comparison of **different generators** (left): weak preference for 30% higher cross-section than prediction
- Comparison of **different FSI models with GENIE** (right): best agreement with G4 Bertini cascade model (marked G18_10d in blue on the plot), more significant variation than with nuclear models





First measurement in this channel since bubble chamber experiments in the 1970s

Transverse kinematic inbalance

Transverse kinematic inbalance (TKI) variables are defined in the plane perpendicular to neutrino motion and can be a useful tool to **probe nuclear effects**

The concept of TKI measurements was pioneered in Phys. Rev. C 94, 015503 (2016)

Variables:

- **δp_T:** Magnitude of total transverse momentum vector
- **$\delta \alpha_T$:** Angle between total transverse momentum vector and reversed muon transverse momentum vector
- **p_N:** Initial momentum of the target nucleon (see Phys. Rev. C 95, 065501 (2017) & Phys. Rev. C 99, 055504 (2019))

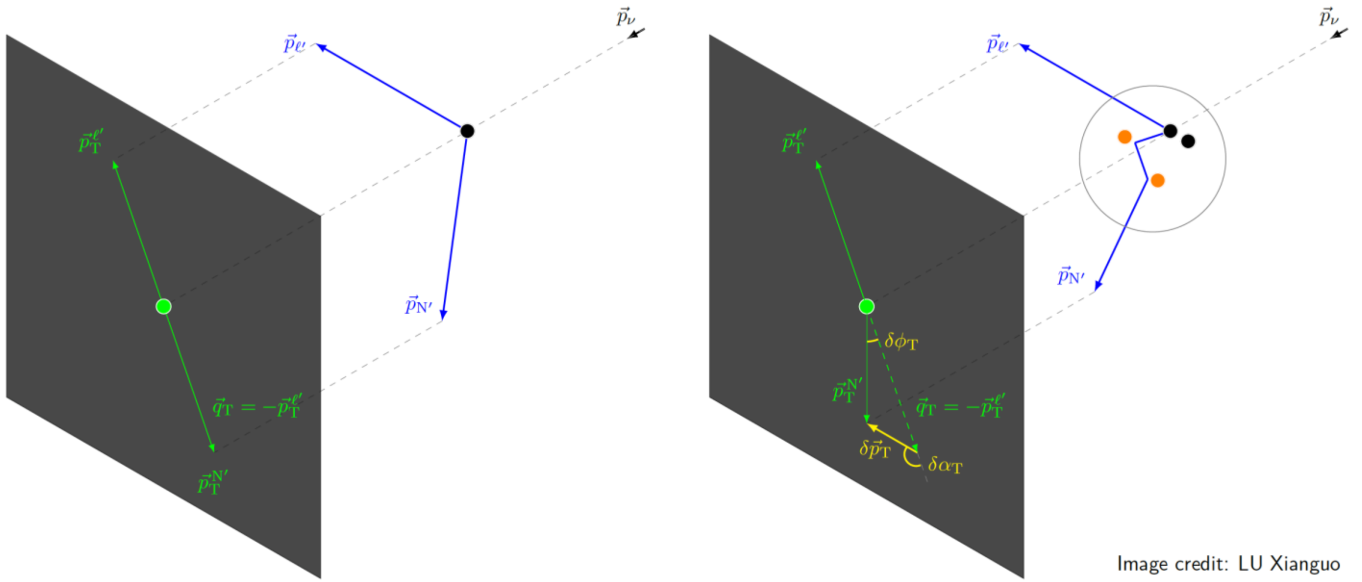
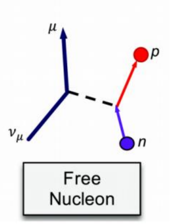


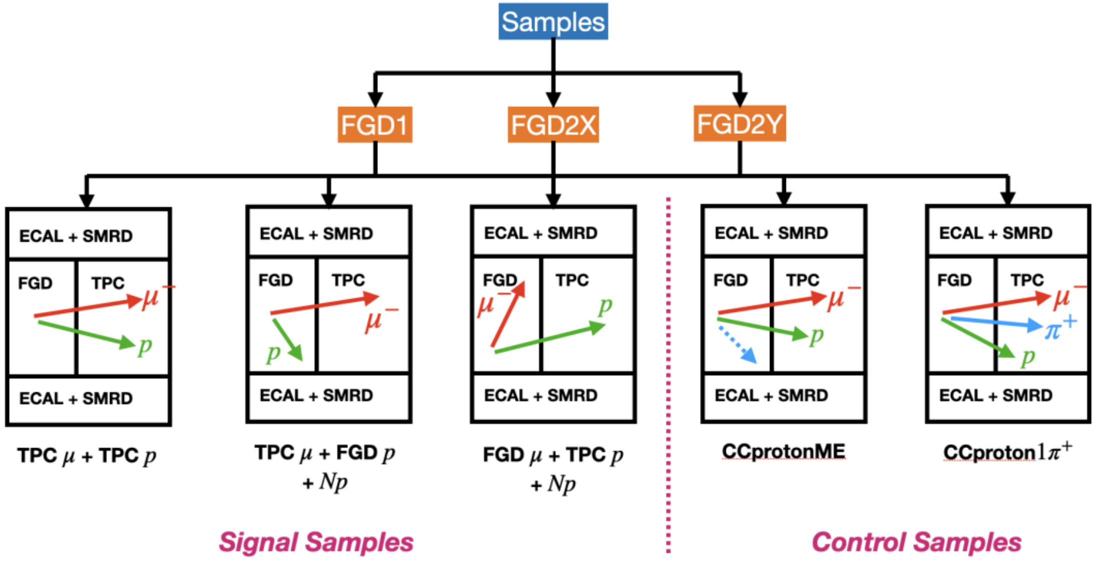
Image credit: LU Xianguo

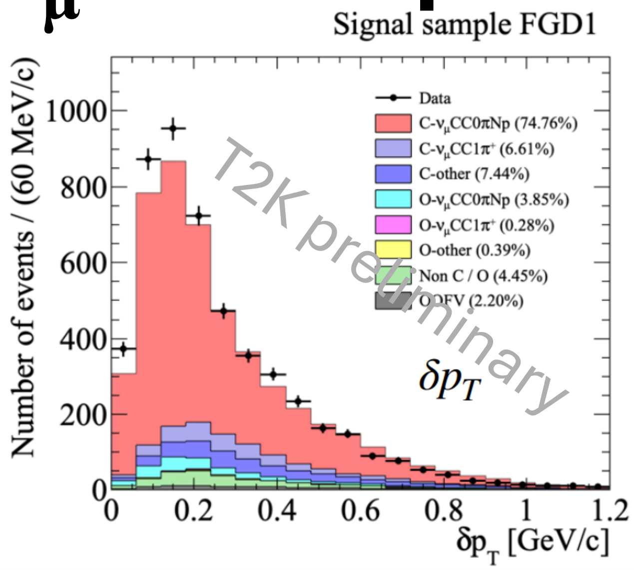
If interaction was on a free nucleon, the momentum in the transverse plane would balance out

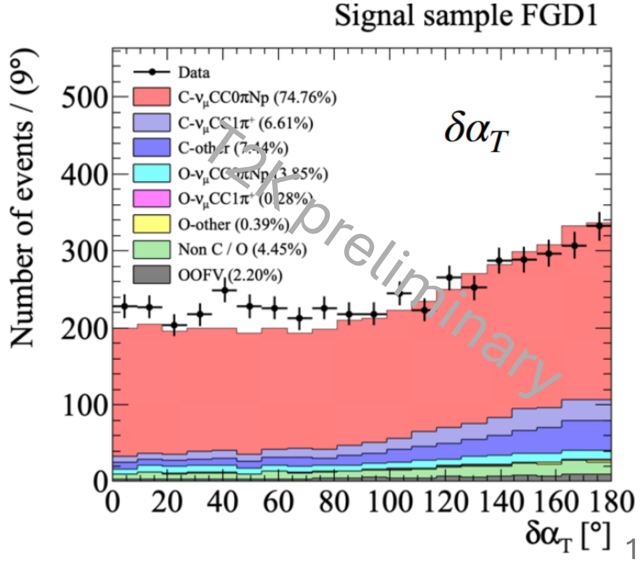


Any inbalance observed is a direct probe of nuclear effects

TKI cross-section measurement: ν_μCC0πNp







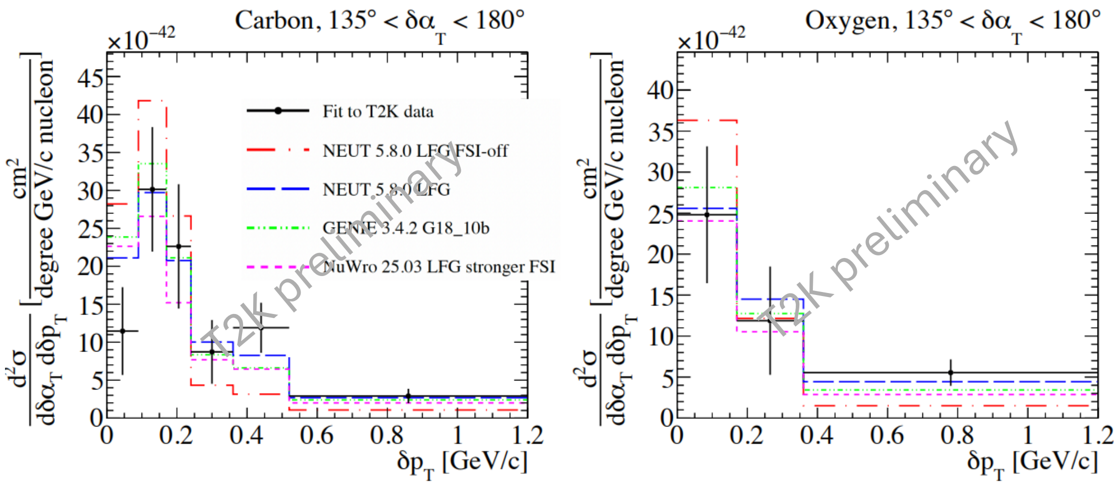
New measurement:

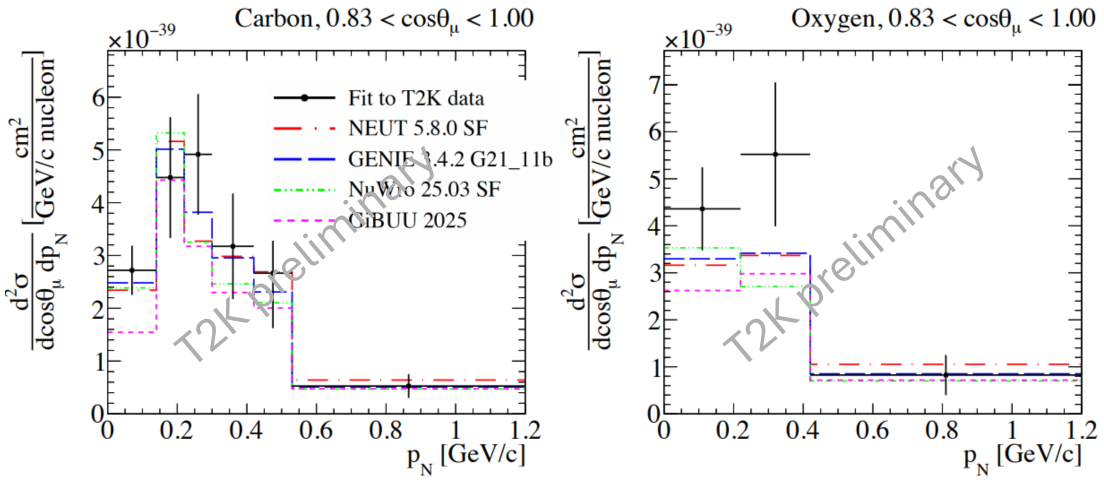
- Combines successful techniques from previous T2K results:
  - Previous TKI measurement PRD 98, 032003 (2018)
  - Carbon and oxygen joint measurement PRD 101, 112004 (2020)
- Target is both FGD1 and FGD2 of ND280, signal is ν_μ CC0πNp interactions
- More statistics than previous measurements (~2x more)
- Better PID and double differential TKI variables

TKI cross-section measurement: $\nu_\mu CC0\pi Np$

Results:

- Double-differential TKI variables used in aim to disentangle nuclear effects - **δp_T- $\delta\alpha_T$** and **p_N-cos(θ_μ)**
- Measurement on carbon and oxygen





Comparison of FSI models, assuming Fermi gas initial state model:

- Best agreement with NEUT cascade model

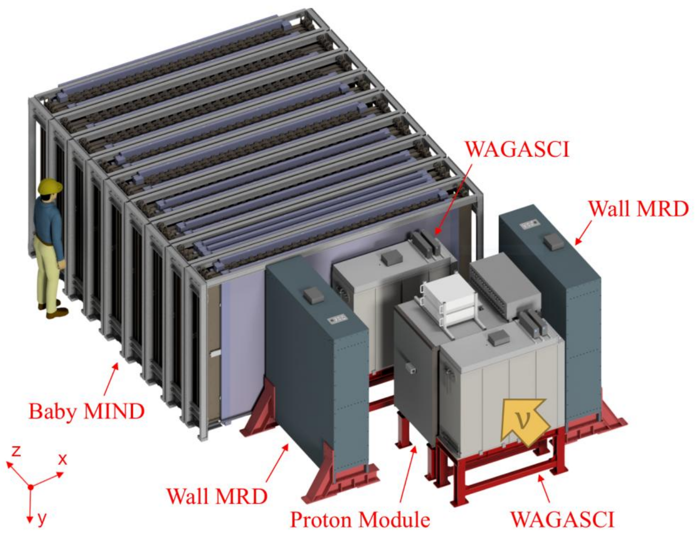
Comparison of models for nuclear initial state:

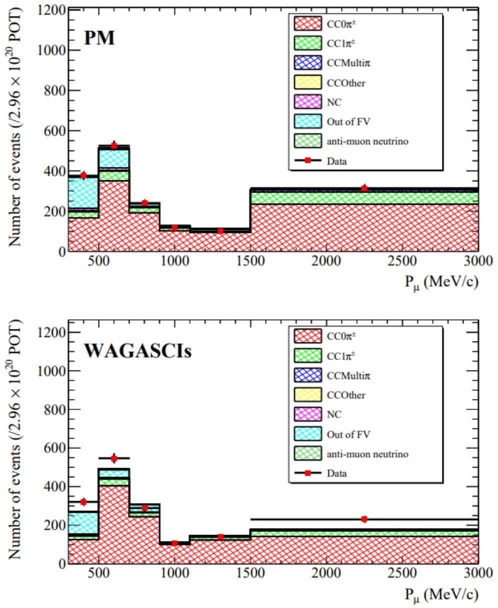
- Slight preference for spectral function (SF) model

Pre-print: arXiv:2509.07814

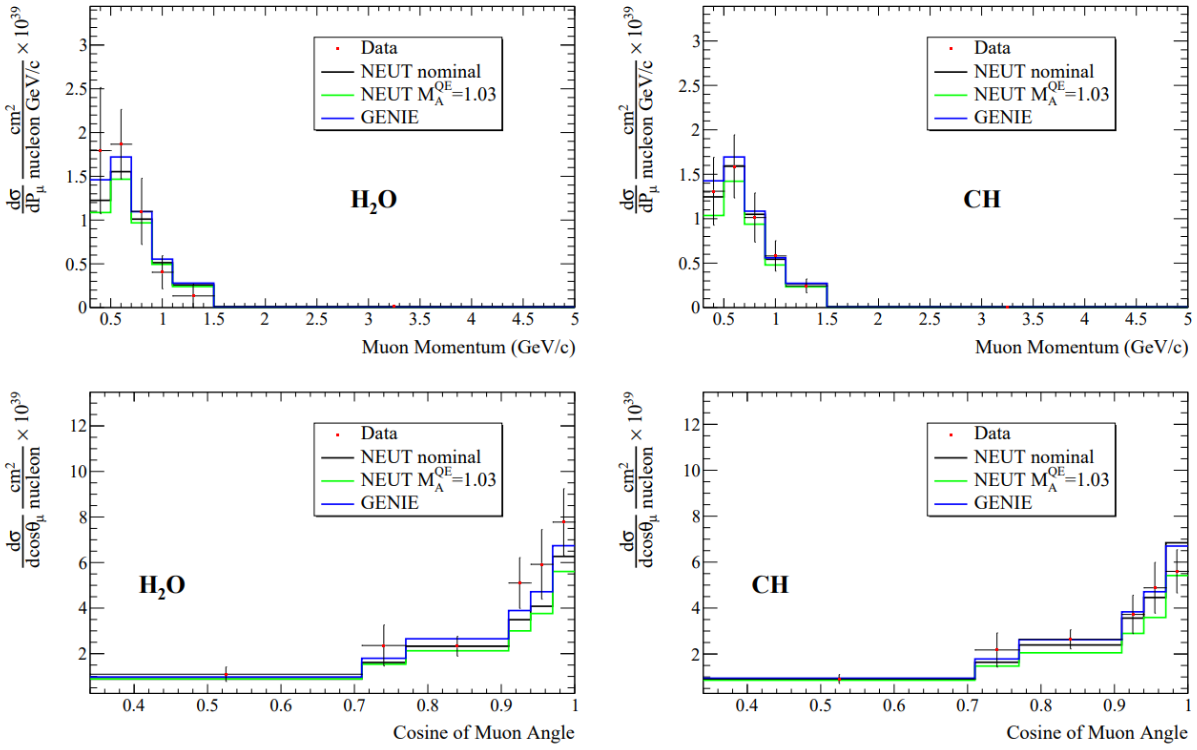
ν_μCC0π on CH and H_2O

Measurement at WAGASCI-BabyMIND





WAGASCI: 3D volumes of water surrounded by plastic scintillator: 80% H_2O + 20% CH (1 ton total).
Proton module: Perpendicular bars of plastic scintillator (1 ton total).

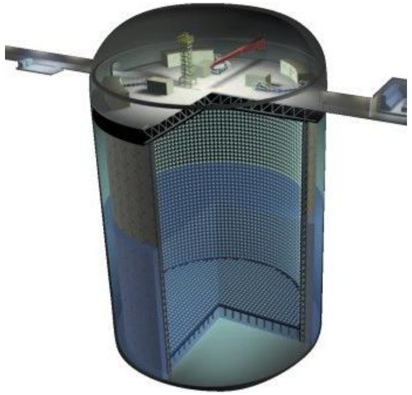


- First measurement of a ν_μ cross-section at WAGASCI with 1.5° off-axis (higher energy neutrino flux than ND280)
- Differential cross-section in muon momentum and angle
- Flux integrated cross-section:
  - (1.26±0.18) ×10^{-39} cm^2/nucl. on CH
  - (1.44±0.21) ×10^{-39} cm^2/nucl. on H_2O.
- Measurements generally consistent with predictions from NEUT and GENIE

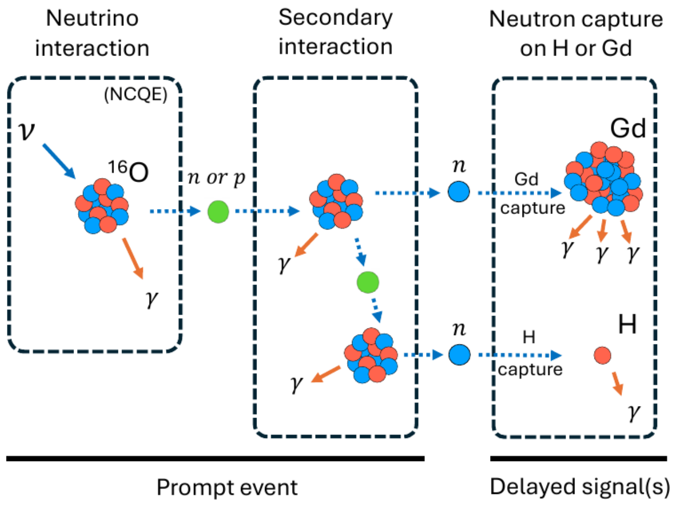
Published in Phys. Rev. D 112, 032003

Neutron Capture on Oxygen

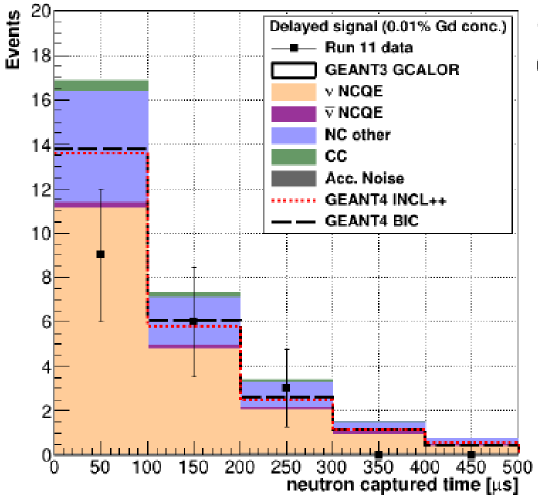
Measurement at Super-K

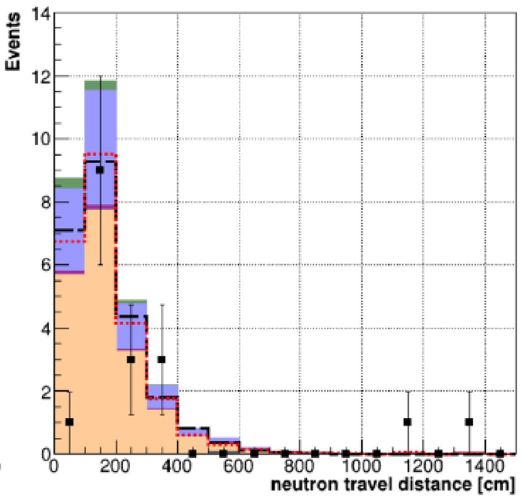


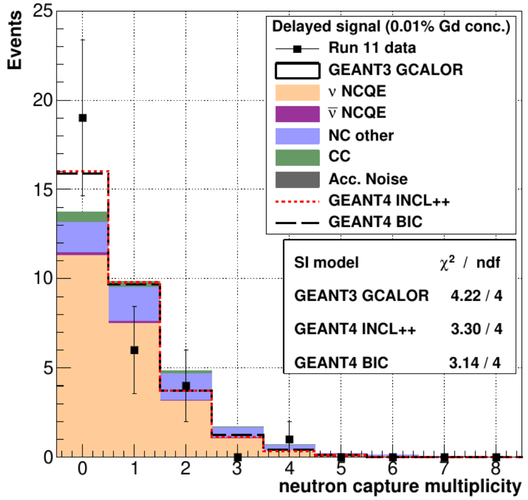
- Measurement using data from **Gadolinium loaded Super-K**
- First measurement of neutron capture multiplicity for NCQE on O
- Significant background for diffuse supernova neutrino background (DSNB) searches



- Neutrons are identified by **delayed gamma emission**
- Expected capture time is 115±1μs
- Rate measured using subtraction between data with beam on and beam off







Results:

- Flux-averaged mean neutron capture multiplicity

$1.37 \pm 0.33(stat)^{+0.17}_{-0.27}(sys)$

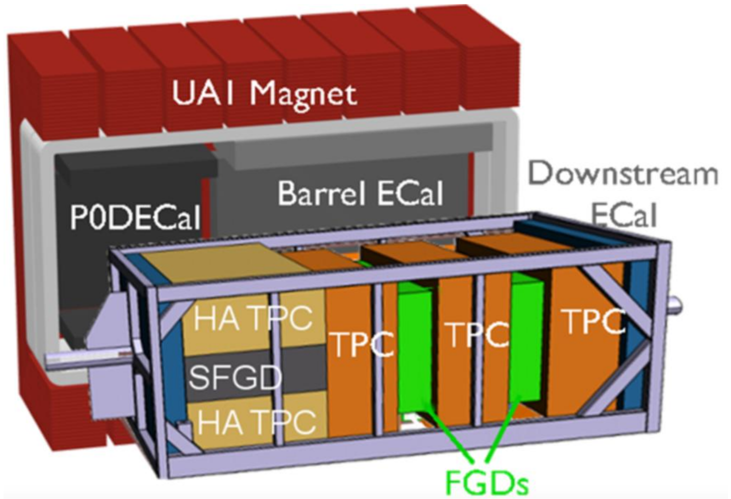
- Consistent with nominal predictions to within 2.2σ

Status of analyses

- ν_e CCπ^+ on C
  - Accepted to PRL, pre-print: arXiv:2505.00516
- NC1π^+ interactions on CH
  - Accepted to PRD & PRL, pre-prints: arXiv: 2503.06849, arXiv: 2503.06843
- ν_μCC0πNp TKI measurement
  - Paper in preparation.
- ν_μCC0π in WAGASCI-BabyMIND
  - Awaiting publication, pre-print: arXiv:2509.07814
- Neutron capture
  - Published in Phys. Rev. D 112, 032003

Other analyses to look out for:

- K$^+$ production in ν_μCC on carbon
- $\bar{\nu}_\mu$CC1π^- on carbon
- ν_μCC1π^+ with low-momentum pions on CH and H2O
- New analyses from ND280 upgrade!



See Gioele Reina's talk on *"First results from T2K's upgraded near detector"* on Thursday for more

+ more upgrade talks: Asit Srivastava, Matteo Feltre, Wataru Okinaga-san

Conclusions

- Cross-section measurements are essential for improving neutrino-nucleus interaction models and decreasing systematics for the oscillation analysis
- Latest cross-section measurements presented from three different T2K detectors:
  - ND280: ν_e CCπ^+ on C, NC1π^+ on CH, ν_μCC0πNp on C and O
  - WAGASCI/BabyMIND**:** ν_μCC0π on CH and H_2O
  - Gd loaded SK: neutron capture multiplicity on O
- Some tensions seen between measurements and generator predictions
- More measurements in preparation!
- ND280 has been upgraded and improvements such as lower threshold, high angle acceptance and sensitivity to neutrons will produce even higher precision cross-section measurements

Back up

T2K studies neutrino interactions with multiple detectors