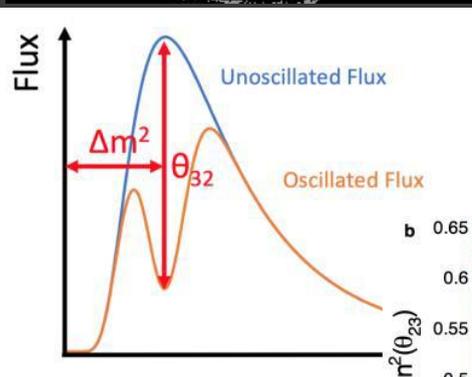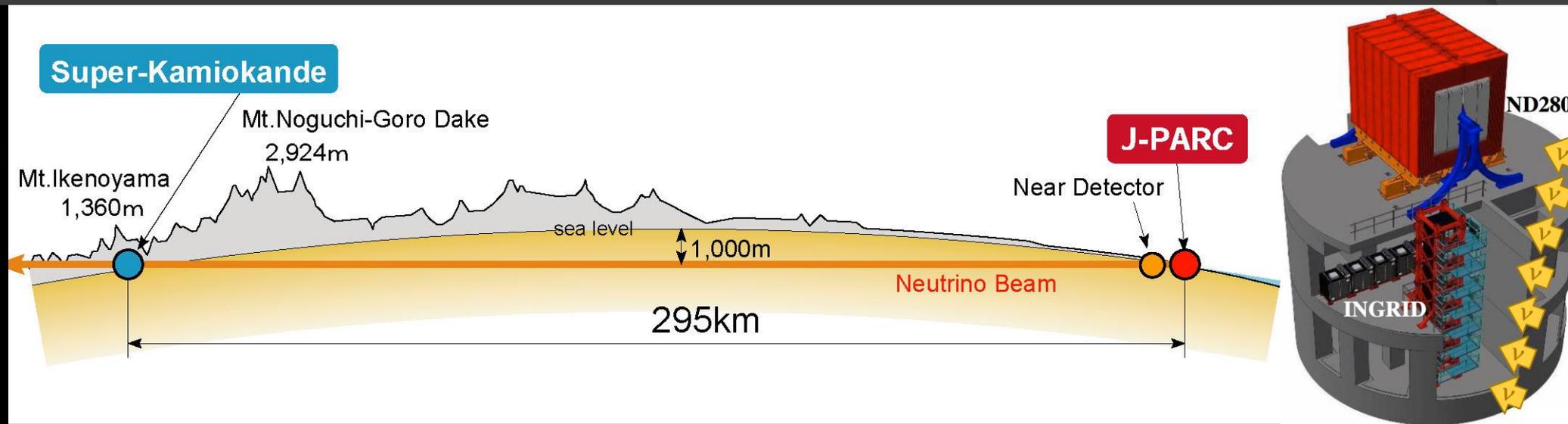# Neutrino Cross-Section Results From T2K

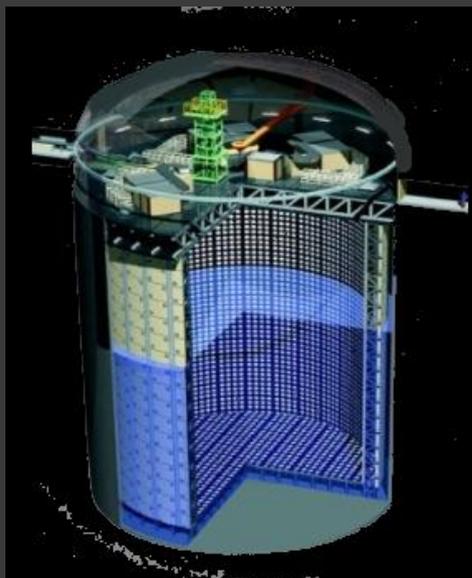M. Tzanov, Louisiana State University

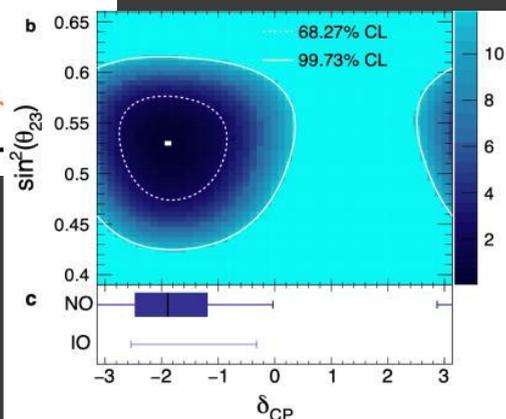on behalf of the T2K Collaboration

Lepton-Photon 2025, Madison, WI, August 2025
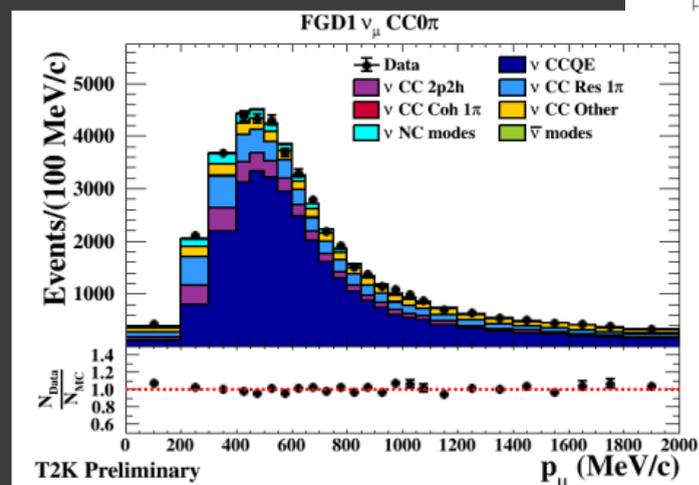
The T2K Experiment

T2K is a state-of-the-art long-baseline neutrino oscillation experiment.
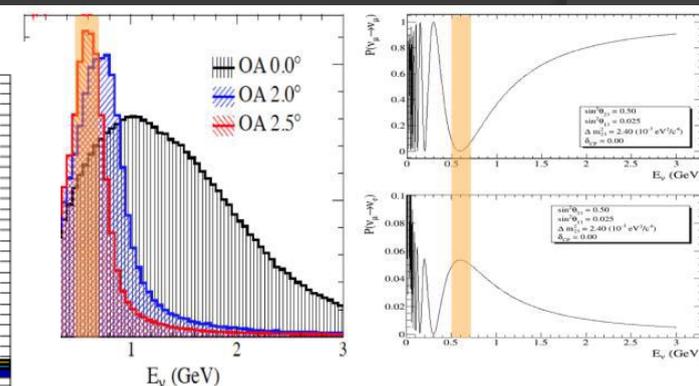

SK oscillated flux measurement

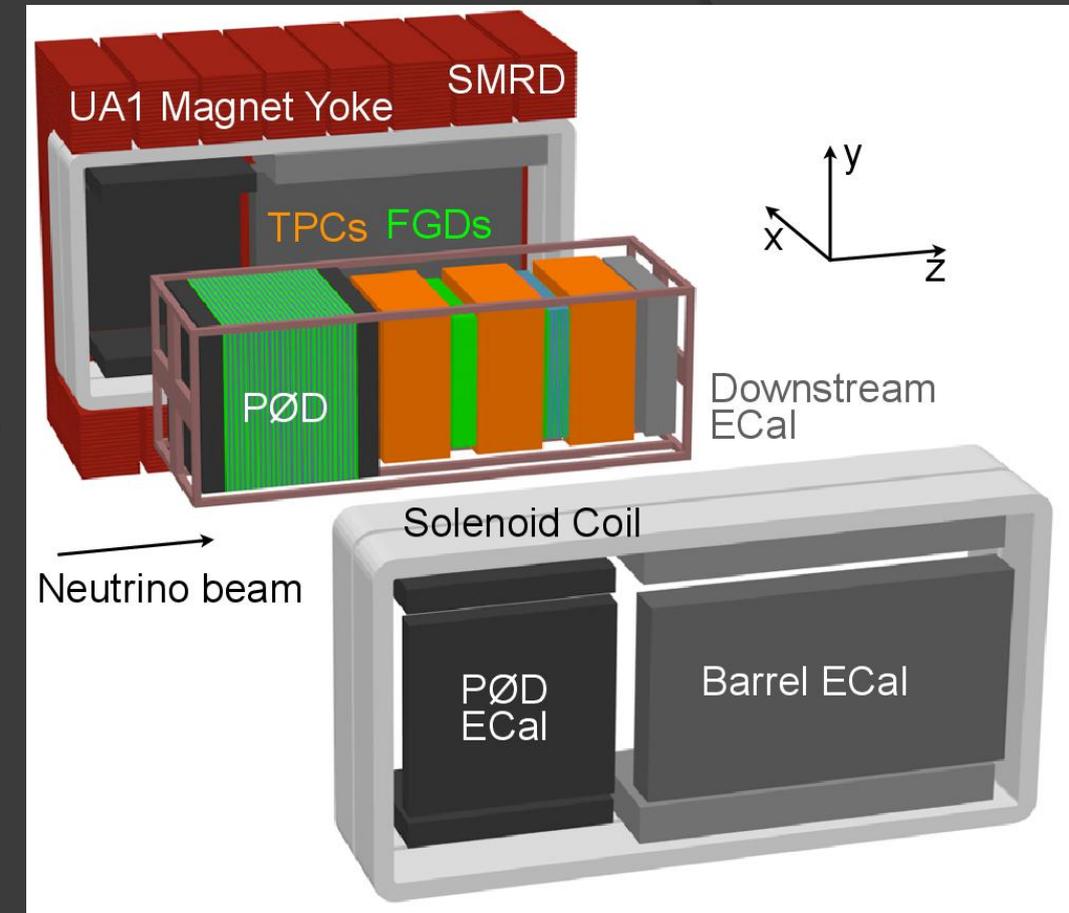ND280 rate measurement/constraint

J-PARC Off-axis ν beam

Off-Axis Near Detector Complex ND280 (Classic)

Refurbished UA1 magnet providing
0.2 T magnetic field surrounding

o ND280 Tracking detector :
 - Two Fine Grained Detectors (FGDs) – main neutrino targets.
    FGD1 consists of layers of 10x10 mm plastic scintillator
    bars instrumented with Multi-Pixel Photon Counters (MPPCs).

 - Three Time Projection Chambers (TPCs) filled mainly with
    Ar gas provide particle ID based on dE/dx and momentum
    measurement.

o Side Muon Range Detector (SMRD)

o EM Calorimeters

o π^0 detector (P0D)

The T2K Collaboration

~560 members, 75 Institutes, 15 countries

Belgium
Ghent U.

Canada
TRIUMF
York U.

CERN

France
CEA Saclay
LLR E. Poly.
LPNHE Paris
ILANCE

Germany
RWTH Aachen
Universität Mainz

Hungary
Eötvös Loránd U.

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
Keio U.
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U.
Osaka City U.
Tohoku U.
Institute of Science Tokyo
Tokyo Metropolitan U.
Tokyo U of Science
U. Tokyo
Yokohama National U.
University of Toyama

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroclaw U.

Russia
INR
JINR

Spain
IFAE, Barcelona
U. Autonoma Madrid
U.Sevilla

Switzerland
ETH Zurich
U. Bern
U. Geneva

United Kingdom
Imperial C. London
King's College London
Lancaster U.
Oxford U.
Royal Holloway U.L.
STFC/Daresbury
STFC/RAL
U. Glasgow
U. Liverpool
U. Sheffield
U. Warwick

USA
Boston U.
Duke U.
U. Houston
Louisiana State U.
Michigan State U.
SLAC
Stony Brook U.
U. C. Irvine
U. C. Boulder
U. Minnesota
U. Pennsylvania
U. Pittsburgh
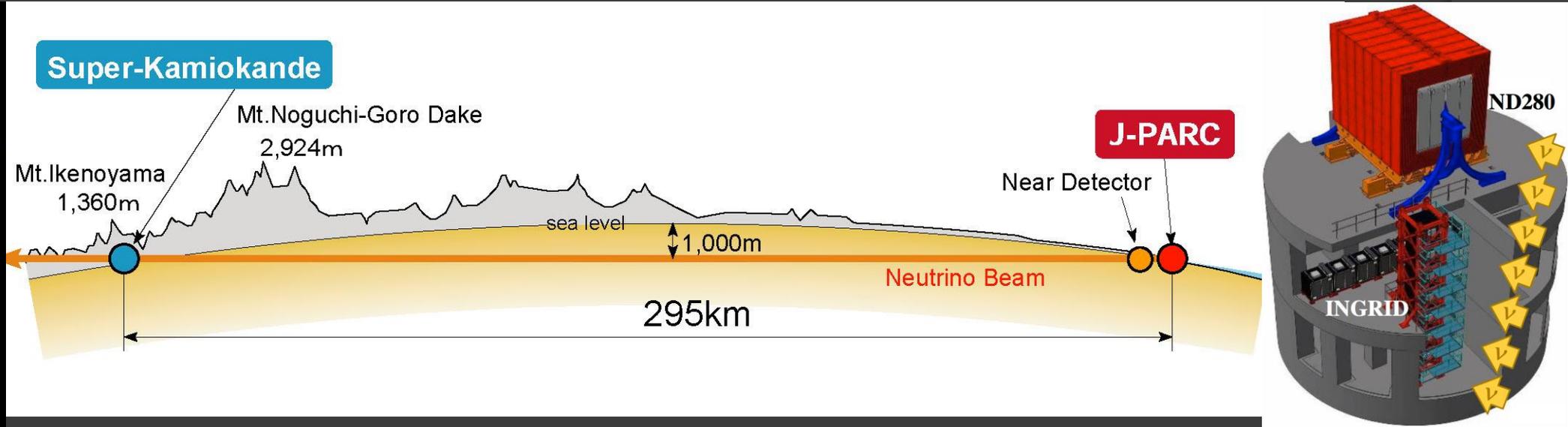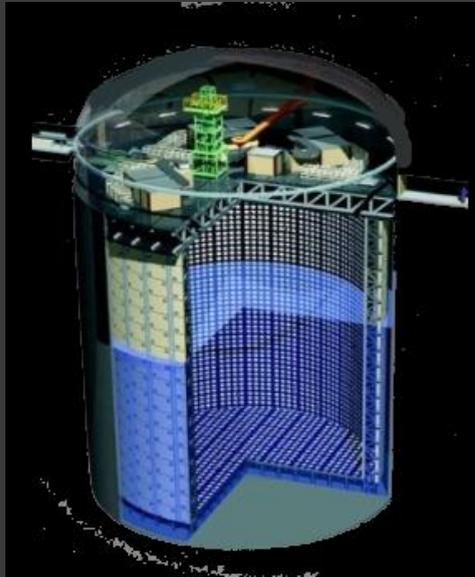U. Rochester
U. Washington
SDSMT
LBNL

Vietnam
IFIRSE
Hanoi Univ. Science

The T2K Experiment – Latest Results

T2K is a long-baseline neutrino oscillation experiment:

Measurement of the neutrino oscillation parameters:

Measurements of neutrino oscillation parameters from the T2K experiment using 3.6E21 protons on target
Eur.Phys.J.C 83 (2023) 9, 782

See more oscillation results in Jaafar Chakrani's talk.

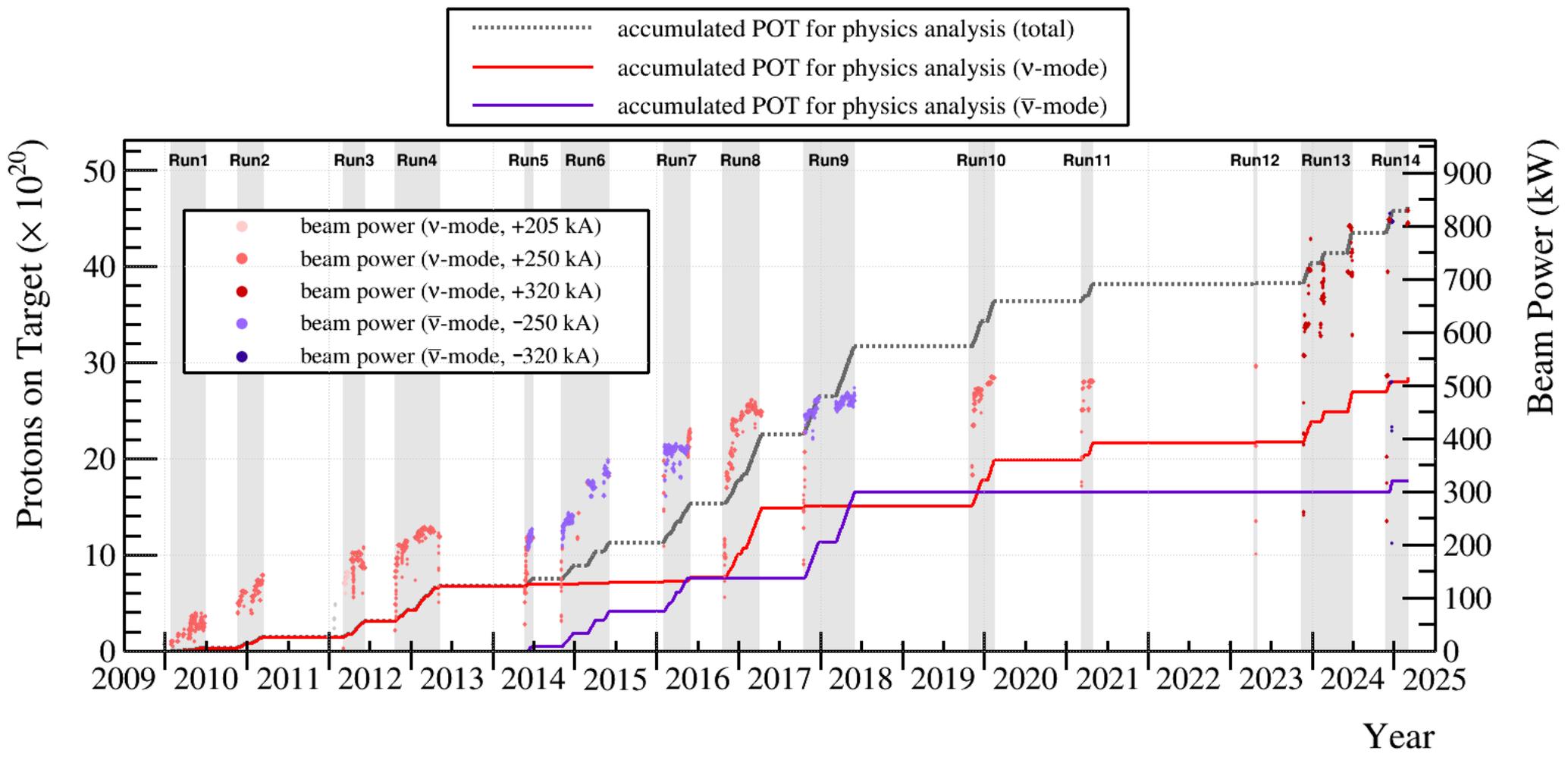Measurements of neutrino cross sections in the near detector:

New cross section measurements
Phys. Rev. D 112, 032003 (2025)
Phys. Rev. D 108, 112009 (2023)
Phys. Rev. D 108, 092009 (2023)

T2K Beam Power

Total POT: 4.6×10^{21}
- ν-mode – 2.8×10^{21}
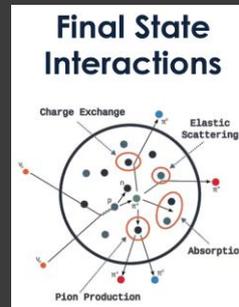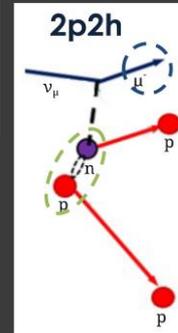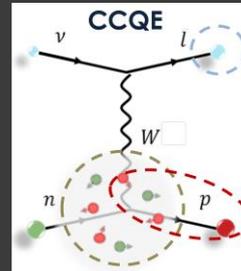- $\bar{\nu}$-mode – 1.8×10^{21}

Peak Power: 829kW

Neutrino Interactions at T2K

o   A mix of interaction channels in the region of ~1GeV

o   Nuclear targets, O and C, complicate the final state
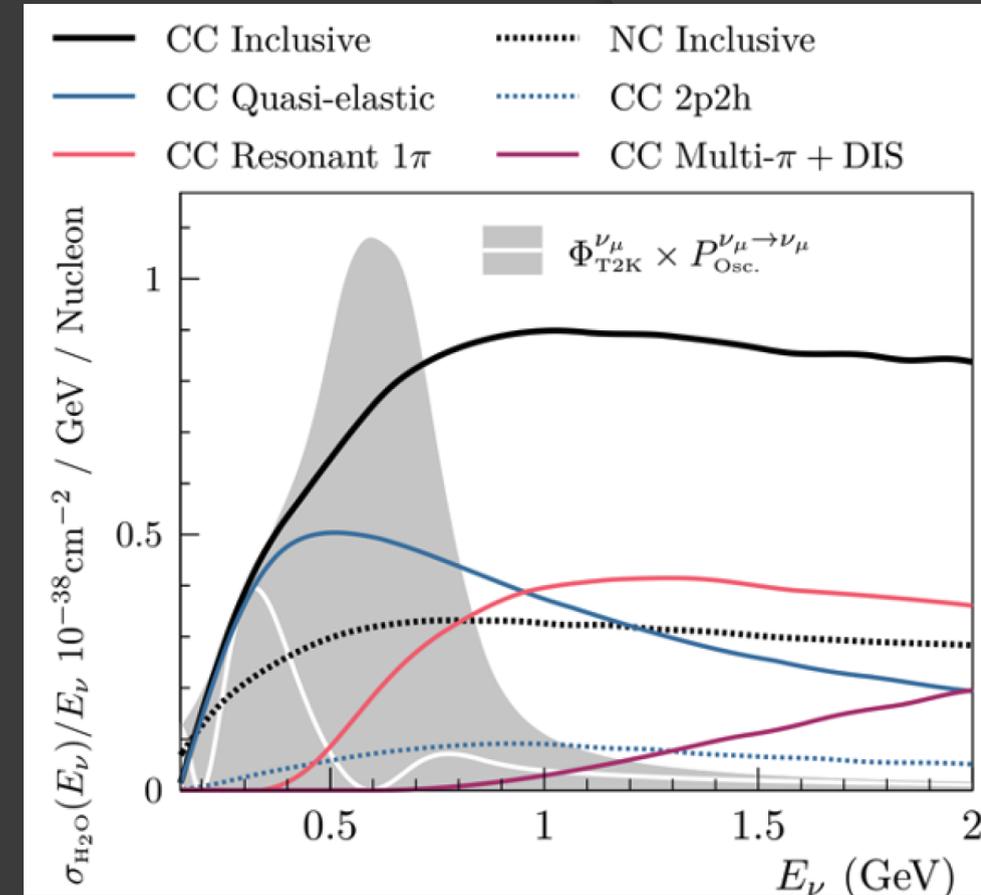
    o   Fermi Motion

    o   Interacting target nucleons 2p-2h

    o   Final State Interactions

o   Leads to a bias and smearing in neutrino energy reconstruction

The neutrino interaction model is the largest systematic uncertainty for neutrino oscillation measurements.
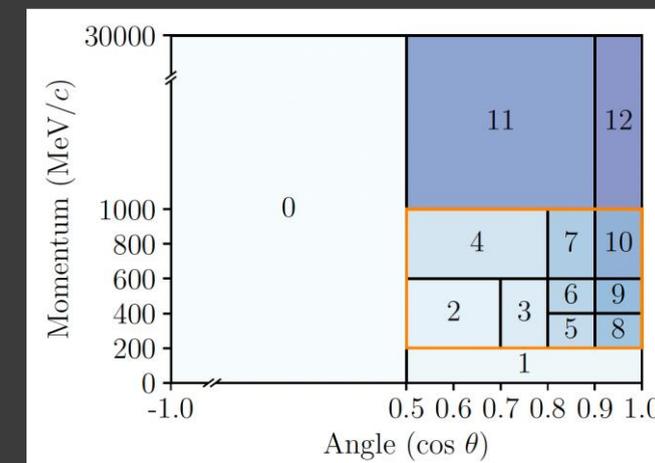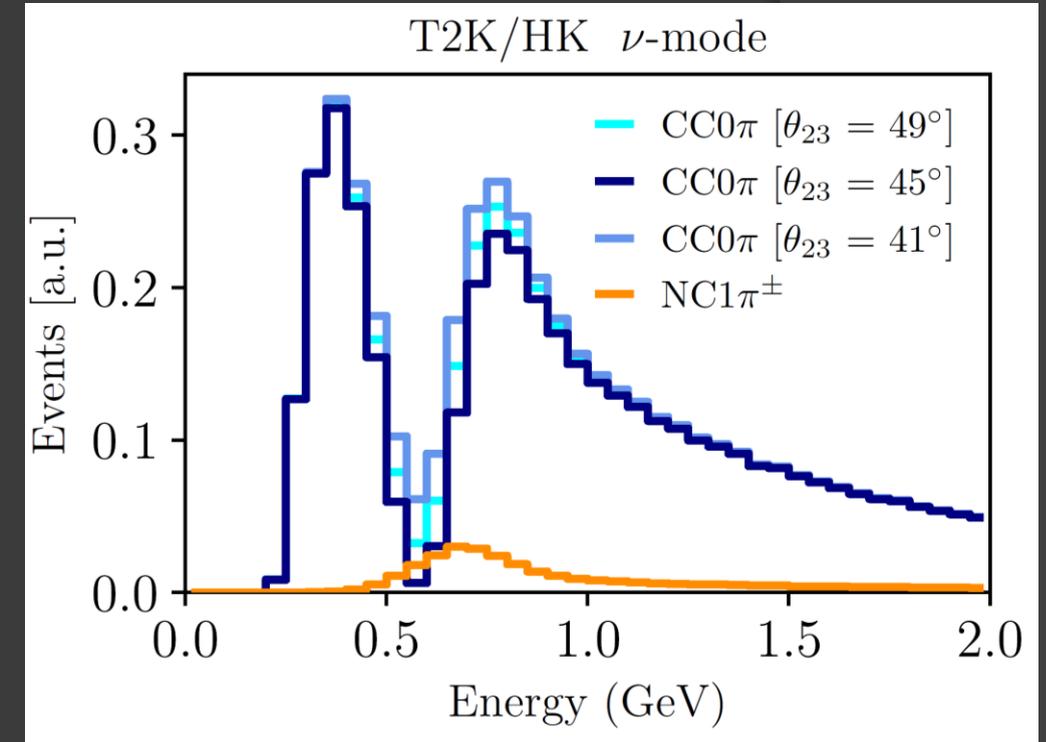
T2K Neutrino Cross Sections Measurements

T2K has been at the forefront of both neutrino cross section measurements and neutrino interactions modeling.

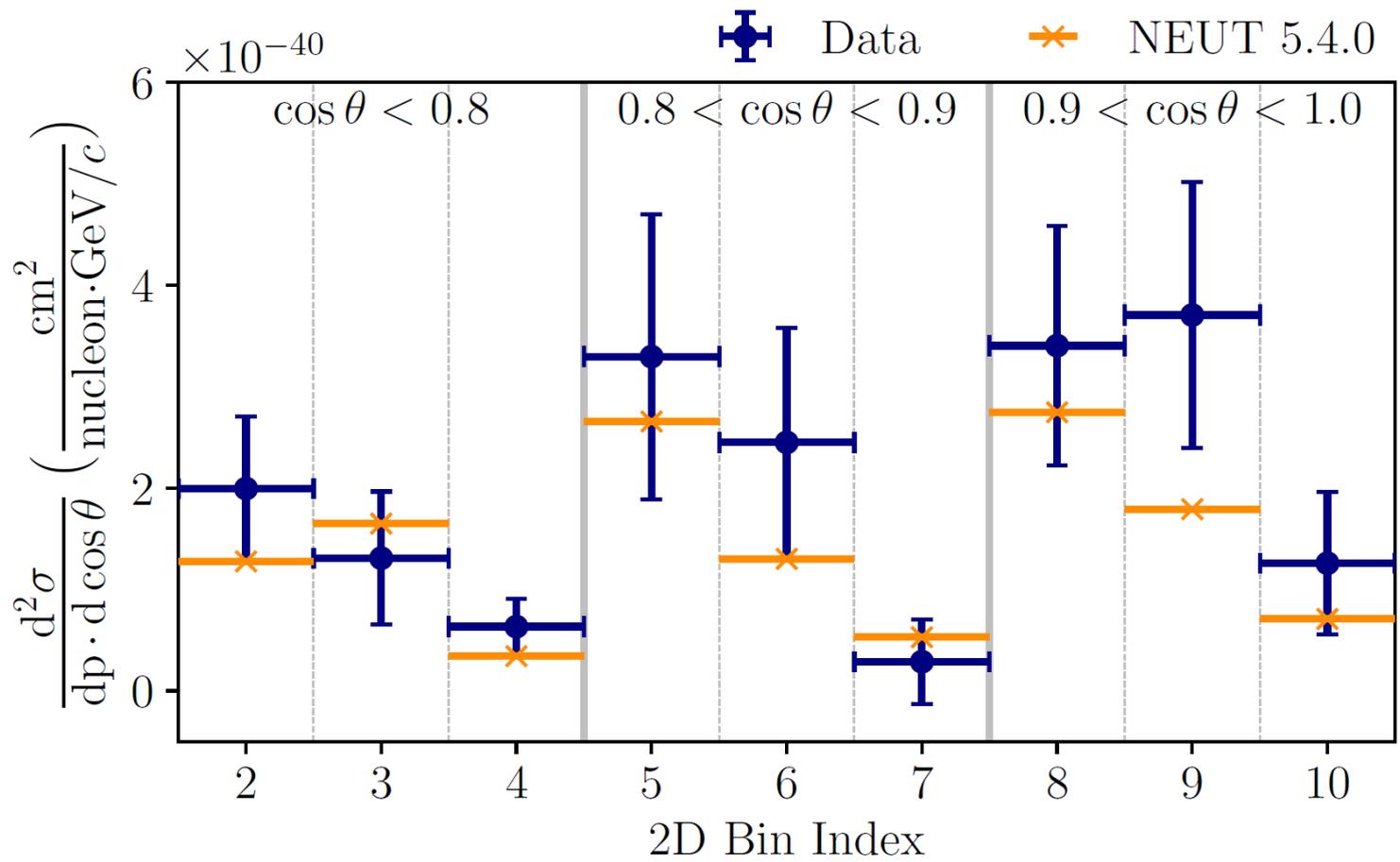|	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
$\sigma^{CC-inc}_{\overset{(-)}{\nu}_\mu}$	On C (FGD1)	On Fe, CH (INGRID)		On Fe (INGRID)	On C, O, H, Cu (P0D)	2D on C (FGD1)	On water, C, Fe (INGRID)			Inclusive $\overset{(-)}{\nu}_\mu$ charged-current		
$\sigma^{CC-inc}_{\overset{(-)}{\nu}_e}$		On C (FGD1)	On water (P0D)				nu+anti-nu, on CH (FGD1)			Inclusive $\overset{(-)}{\nu}_e$ charged-current		
$\sigma^{CC0\pi}_{\overset{(-)}{\nu}_\mu}$	$\overset{(-)}{\nu}_\mu$ charged-current pionless	QE on C (INGRID)	QE on C (FGD1)	On CH (FGD1)	On water (P0D)	TKI, On CH (FGD1)	nu+anti-nu, on CH (FGD1)	On O, C (FGDs)	Anti-nu, on water (P0D)	On water, CH (WAGASCI +PM)	On CH (ND280+ INGRID)	On water, CH (WAGASCI-BabyMIND)
$\sigma^{NC0\pi}_{\overset{(-)}{\nu}}$		On O (Super-K)					QE on O, nu+anti-nu (Super-K)			$\overset{(-)}{\nu}$ neutral-current pionless		
$\sigma^{CC1\pi}_{\overset{(-)}{\nu}_\mu}$	$\overset{(-)}{\nu}_\mu$ charged-current with a pion in the final state			COH on C (FGD1)	On water (FGD2)		1 pi+, on CH (FGD1)	1 pi+, TKI, on C (FGD1)		COH on C, nu+anti-nu		
$\sigma^{CC\pi}_{\overset{(-)}{\nu}_e}$	$\overset{(-)}{\nu}_e$ charged-current with a pion in the final state									Pion(s), on CH (FGD1)		
$\sigma^{NC1\pi}_{\overset{(-)}{\nu}}$	$\overset{(-)}{\nu}$ neutral-current with a pion in the final state				1 pi0, on water (P0D)					1 pi+, on CH (FGD1), PRL & PRD		

Neutral Current π^+ Production

o Important background for muon disappearance
  o Due to particle mis-ID
  o Modifies the depth of the disappearance maximum

o Signature in ND280 is a positive minimum ionizing track.

o $\bar{\nu}_\mu CC$ events are the largest background for this channel

o Measurement phase space: $0.2 < p_{\pi^+} < 1.0$ *GeV/c,* and $\cos\vartheta_{\pi^+} > 0.5$, $p_p < 0.2$ *GeV/c*

o Differential measurement in pion kinematics.

Submitted for publication to PRL and PRD
release (arXiv:2503.06843v3 and arXiv:2503.06849v3)

Neutral Current π^+ Production

- ○ Largest sample of $\nu NC\pi^+$ to date.

- ○ Sizable variations in FSI models.

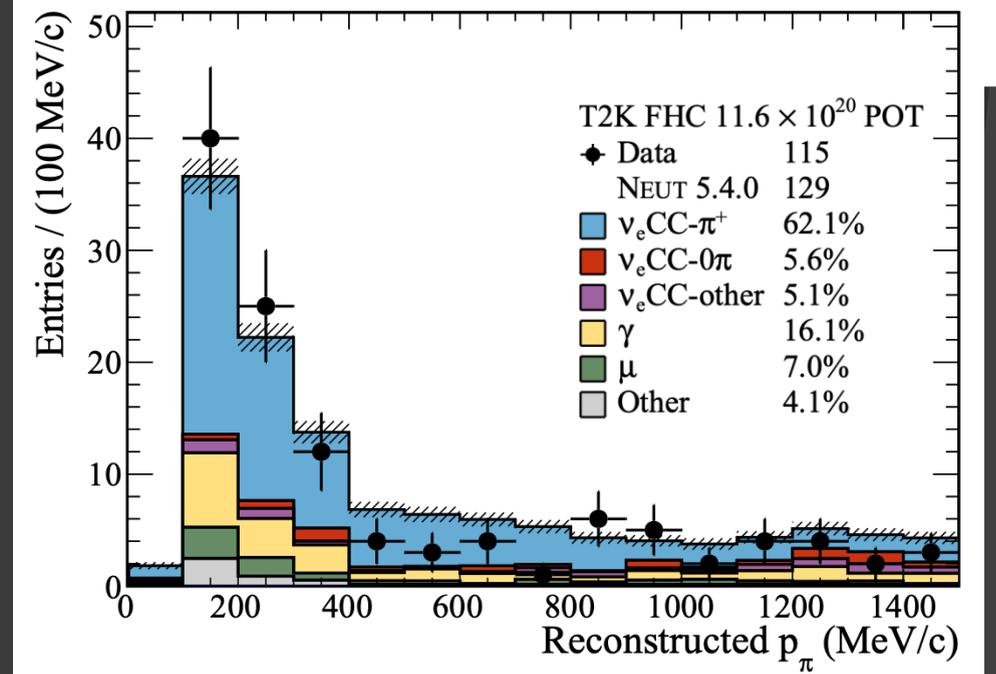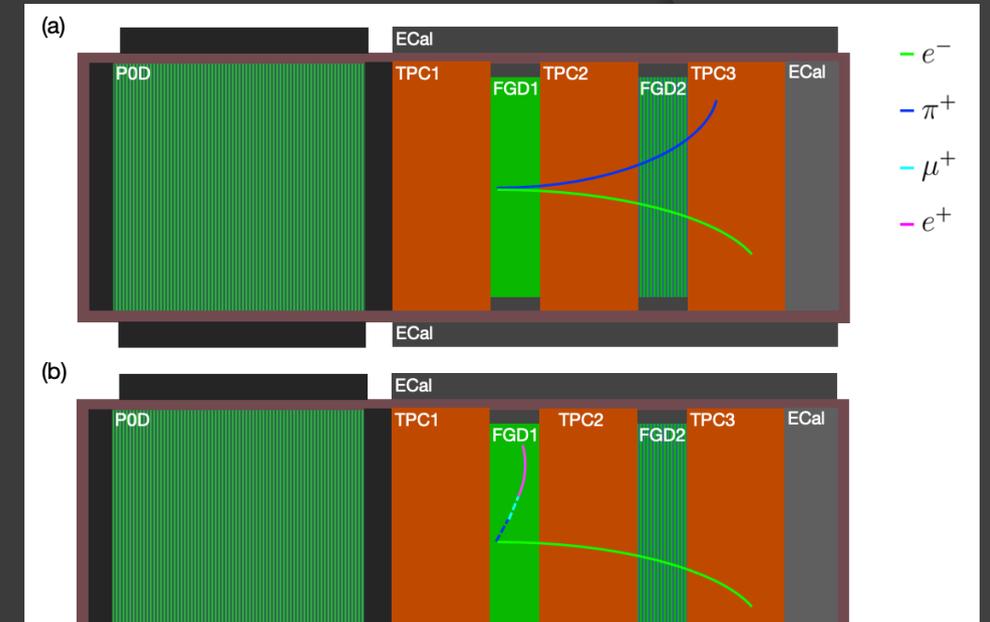- ○ Data prefers higher cross section.

- ○ When compared to models:

For NEUT 5.6.2: χ^2 is 5.48/9 dof
For GENIE v3 AR23_20i: χ^2 is 6.18/9 dof

Submitted for publication to PRL and PRD
release (arXiv:2503.06843v3 and arXiv:2503.06849v3)

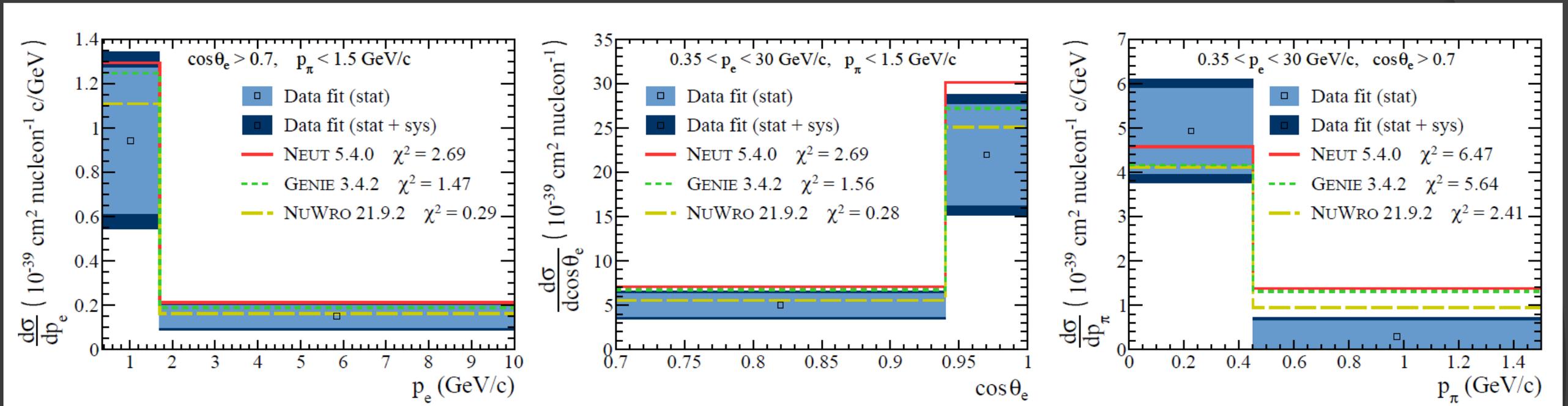# Charged-Current π^+ Production in ν_e-Carbon Interactions

- Important as a signal channel for ν_e appearance.
  - 2-rings
  - sub-dominant signal channel ~10%
  - Accounts for a ~3% systematic on δ_{CP}

- Signatures in ND280:
  - electron track along with a positive minimum ionizing track.
  - electron track (TPC) and FGD Michel tag from $\pi^+ \to \mu^+ \to e^+$

- Measurement phase space: $p_{\pi+} < 1.5$ *GeV/c*; $0.35 < p_{e-} < 30$ *GeV/c*, and $cos\ \vartheta_{e-} > 0.7$

- Differential measurements in electron kinematics and pion momentum.

- $\nu_\mu CC\gamma$ control sample

Submitted for publication https://doi.org/10.48550/arXiv.2505.00516

Charged-Current π^+ Production in ν_e-Carbon Interactions

o Data prefers lower total cross section and lower cross section at high pion momentum. (Not covered by models)

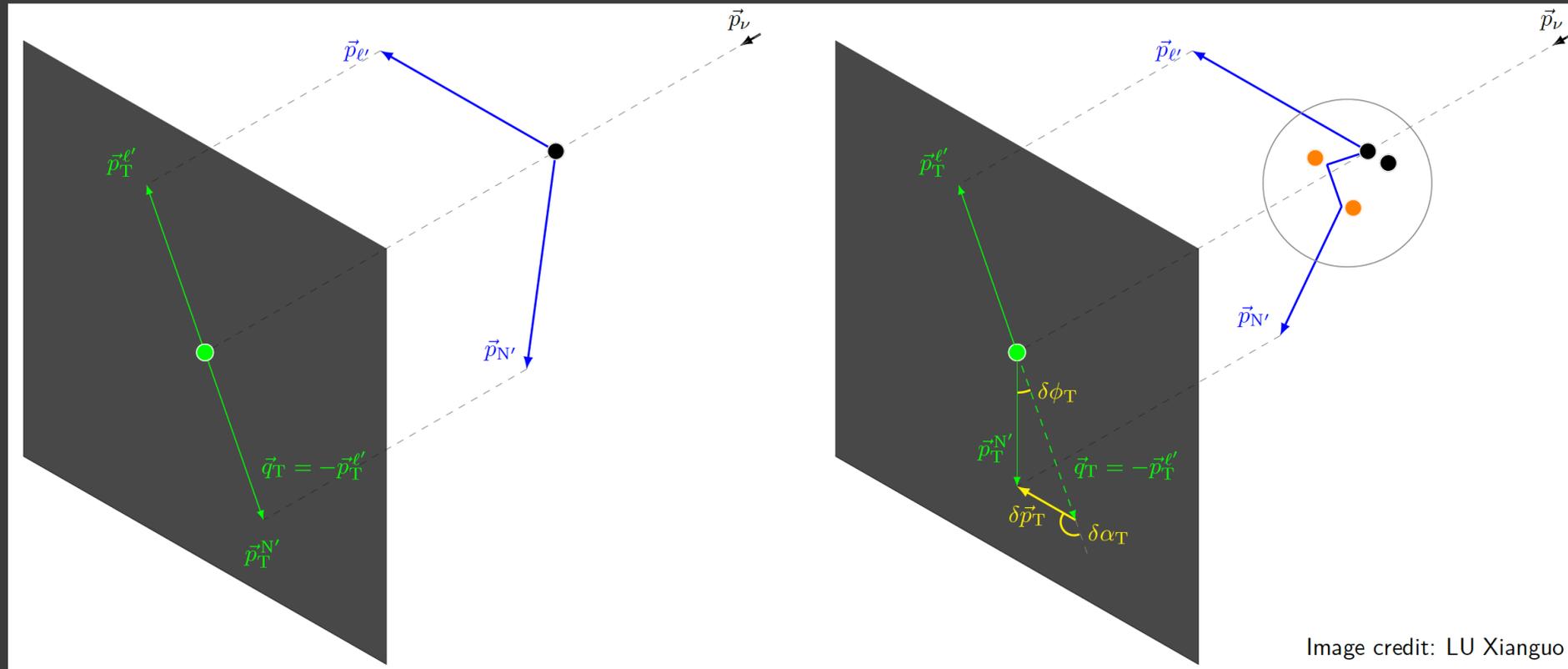o Systematics uncertainty is dominated by the interaction model uncertainty.

Total cross section

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

o Transverse kinematic imbalance (TKI) variables – T2K concept described in Phys. Rev. C 94, 015503 (2016).
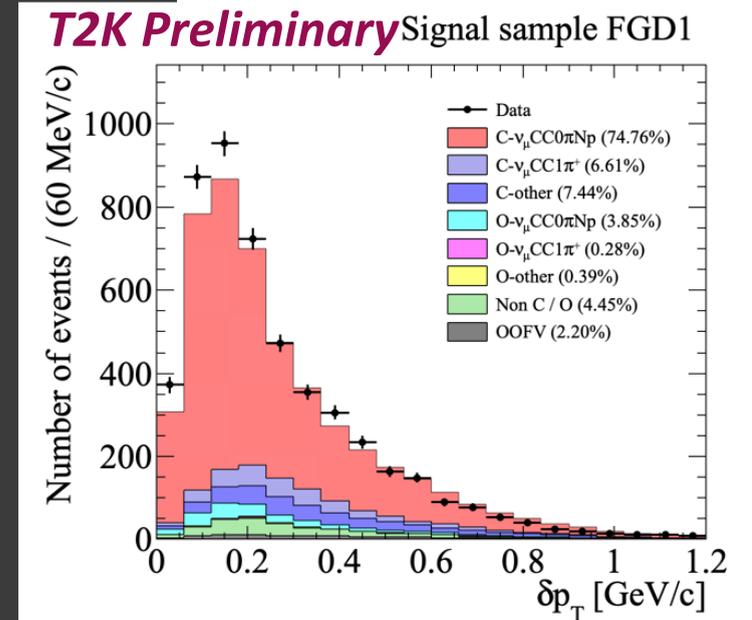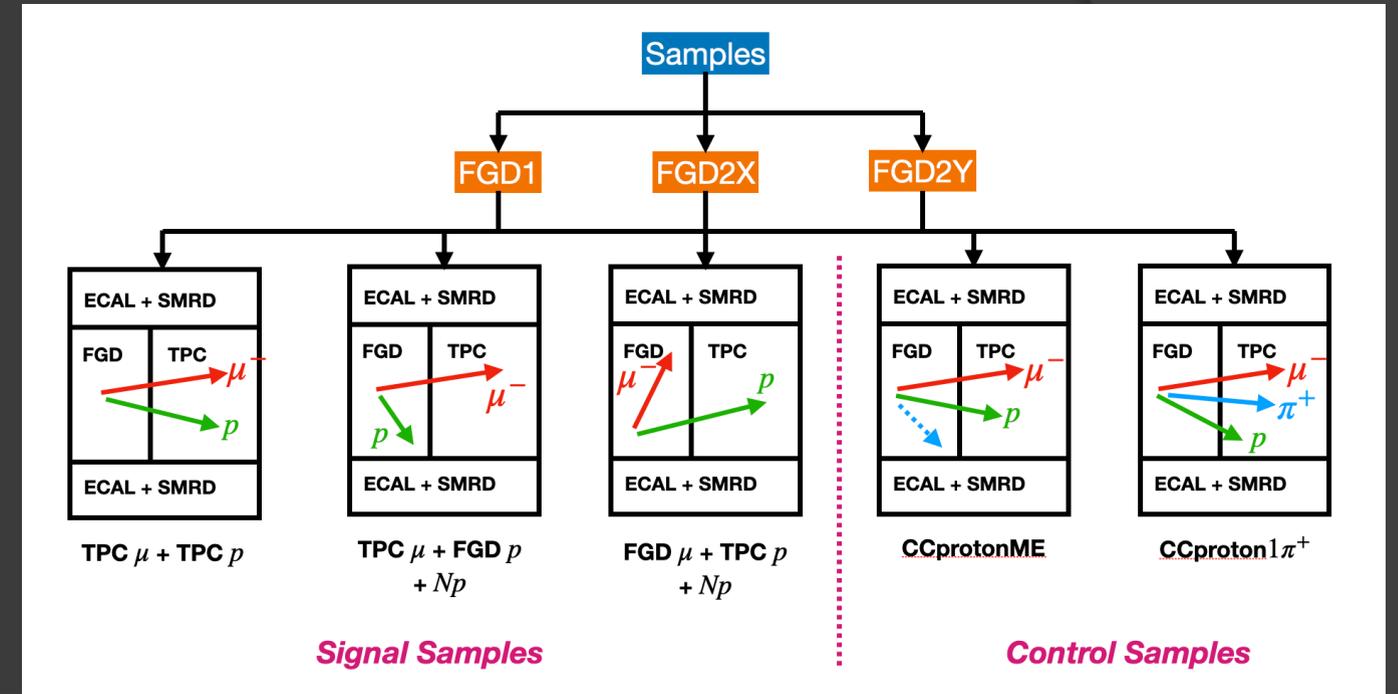

Image credit: LU Xianguo

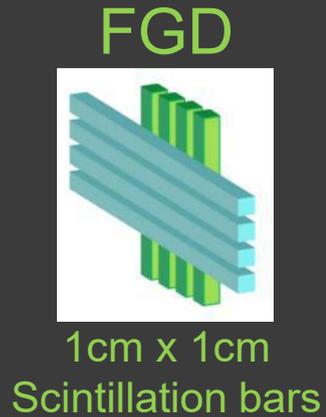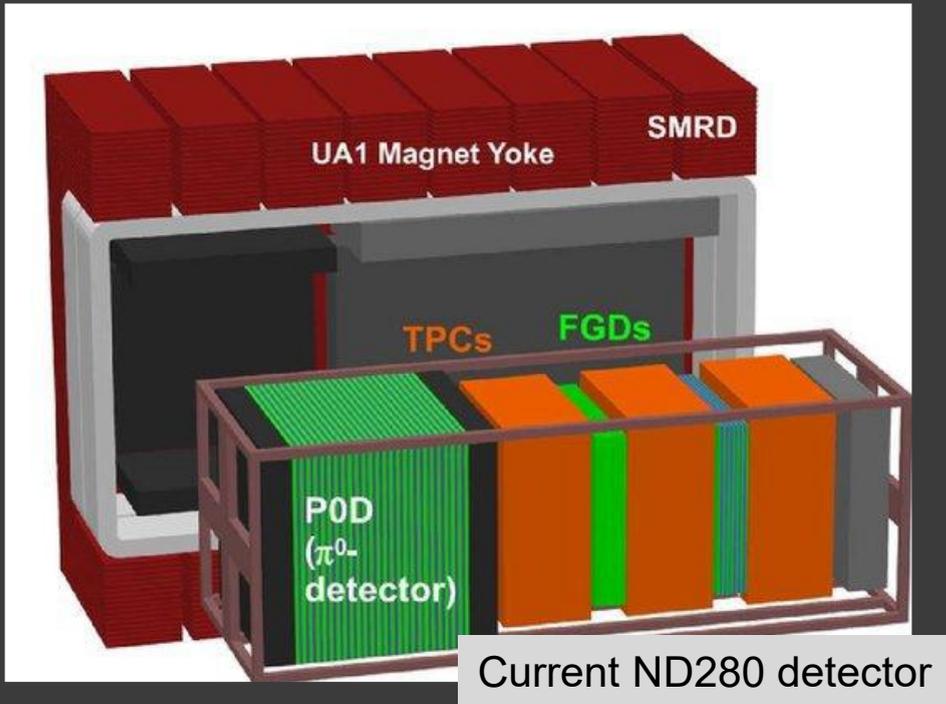δp_T - probes Fermi motion at the event peak and 2p2h at the tail.

$\delta \alpha_T$ - probes the FSI

TKI Cross Section Measurement $\nu_\mu CC0\pi Np$

- Important handle on nuclear effects.

- Signal is a muon track with any number of proton tracks

- Carbon and oxygen joint analysis

- An improved particle identification (PID)

- Phase space:
  $0.225 < p_\mu < 10.0$ *GeV/c;* $\cos\theta_\mu > -0.6$
  $0.525 < p_p < 1.1$ *GeV/c;* $\cos\theta_p > 0.3$

- 2D differential TKI cross section in $\delta p_T : \delta\alpha_T$ and in $p_N : \cos\theta_\mu$
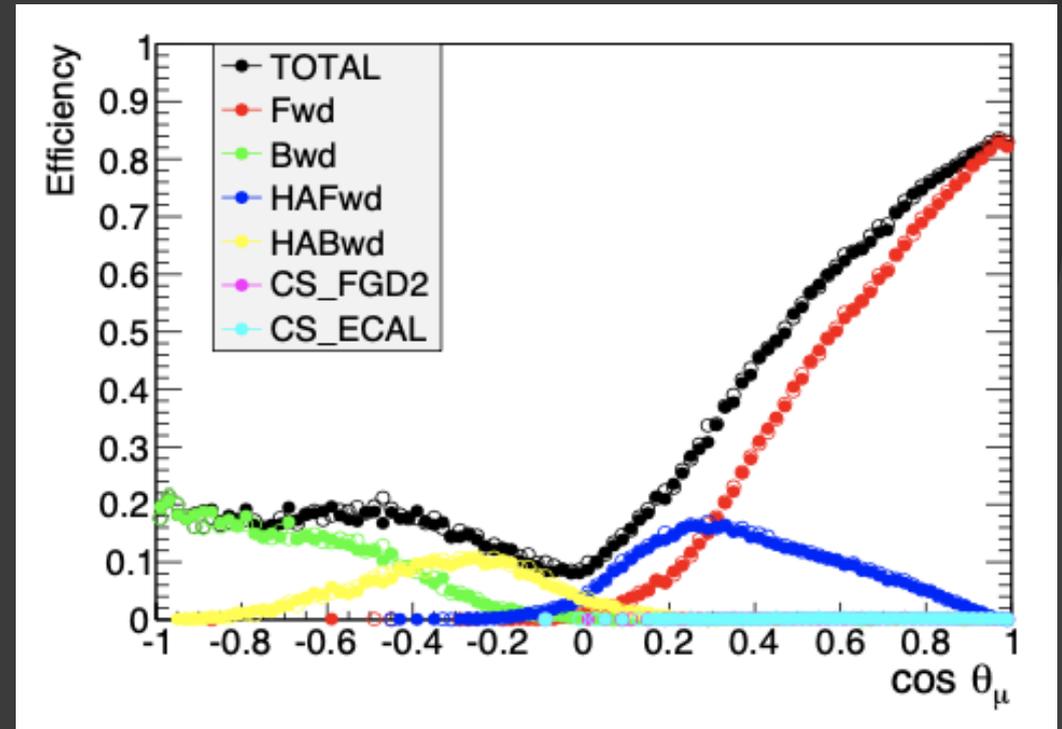
Limitations of the Classic ND280 Detector

Current ND280 detector

FGD

1cm x 1cm
Scintillation bars

Geometrical acceptance:
- o Mostly forward acceptance
- o Tracks w/o TPCs (high-angle)
- o Tracks w/o TPCs (low-momentum)
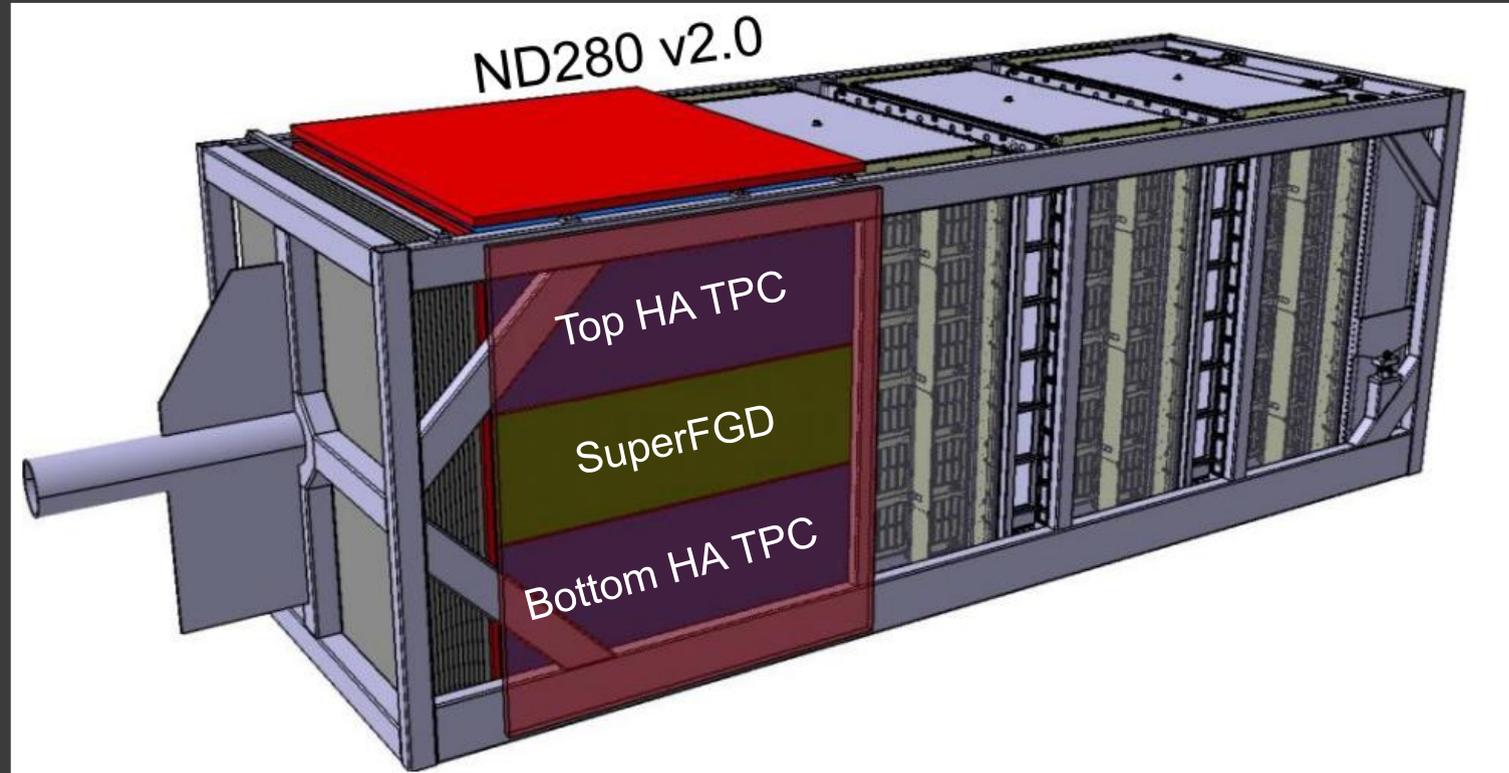
Kinematic regions with low efficiency

Detector response:
- o Limited timing information –
  no direction information
- o No neutron info
- o High detection threshold
- o Poor electron/photon separation

ND280 Detector Upgrade

ND280 Upgrade TDR:
arXiv:1901.03750

Installed and taking data since June 2024

ND280 v2.0

Top HA TPC

SuperFGD

Bottom HA TPC

2 High Angle TPC

Drift volume

MicroMegas

Module Frame

ν

NIM A 957, 163286 (2020)

1 SuperFGD

Scintillator cube

WLS fibers

JINST 13, P02006 (2018)
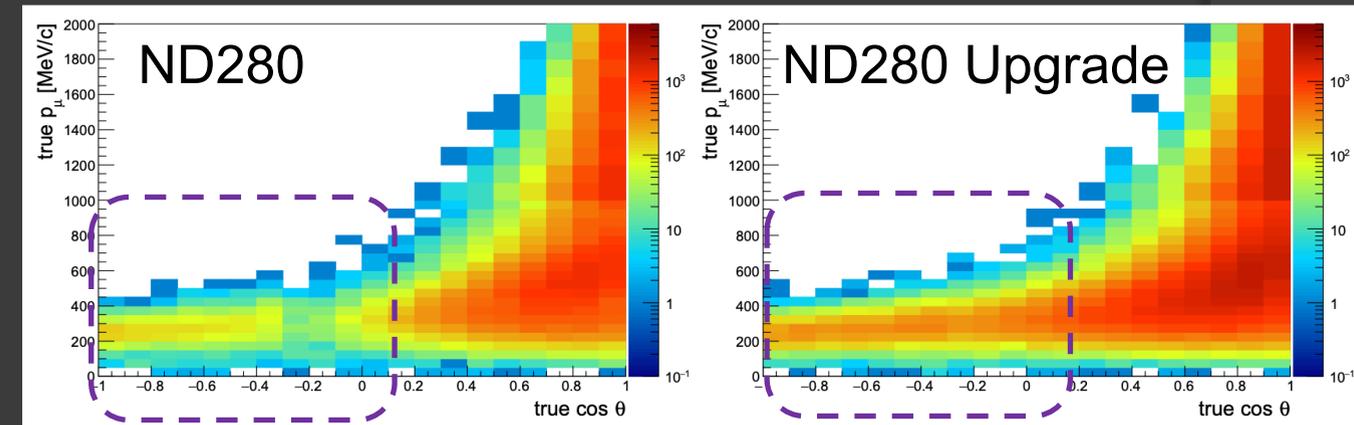**JINST 15, P12003 (2020)**

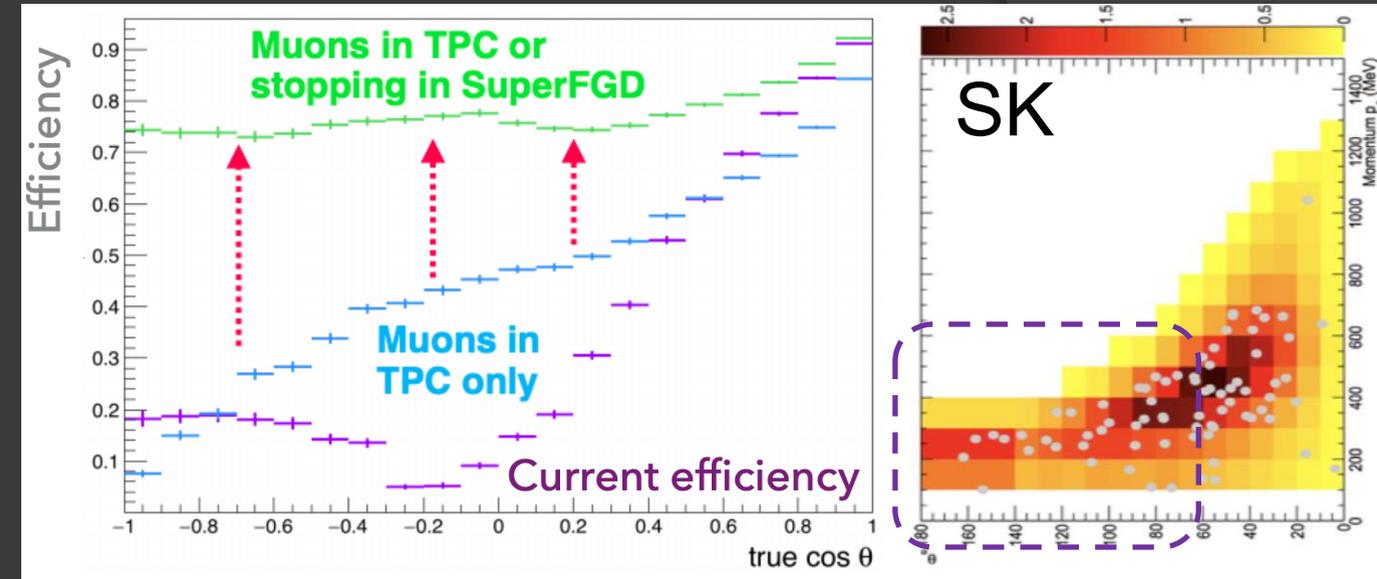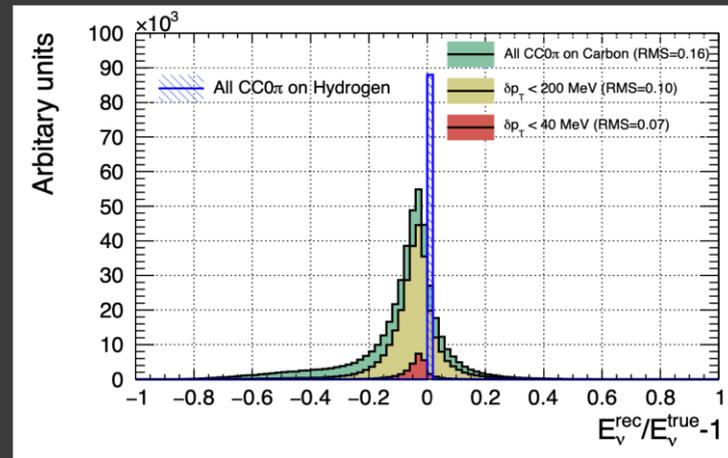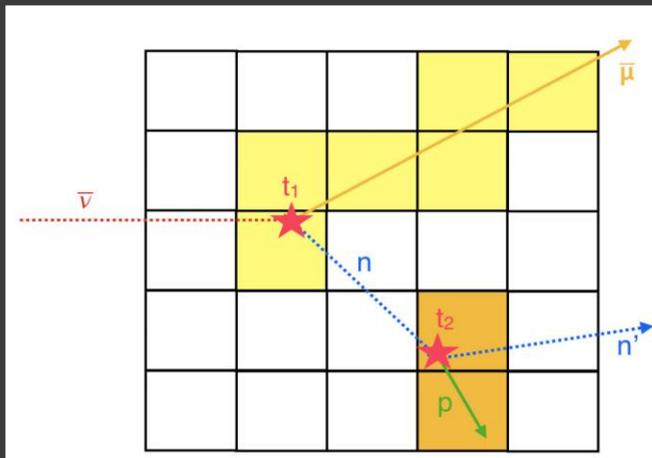6 TOF Panels

JPS Conf. Proc. 27, 011005 (2019)

ND280 Upgrade – Expected Performance

Improved kinematic range

- Better efficiency for all angles
- Coverage similar to SK
- Isotropically finely segmented
- 3D hadronic tracking
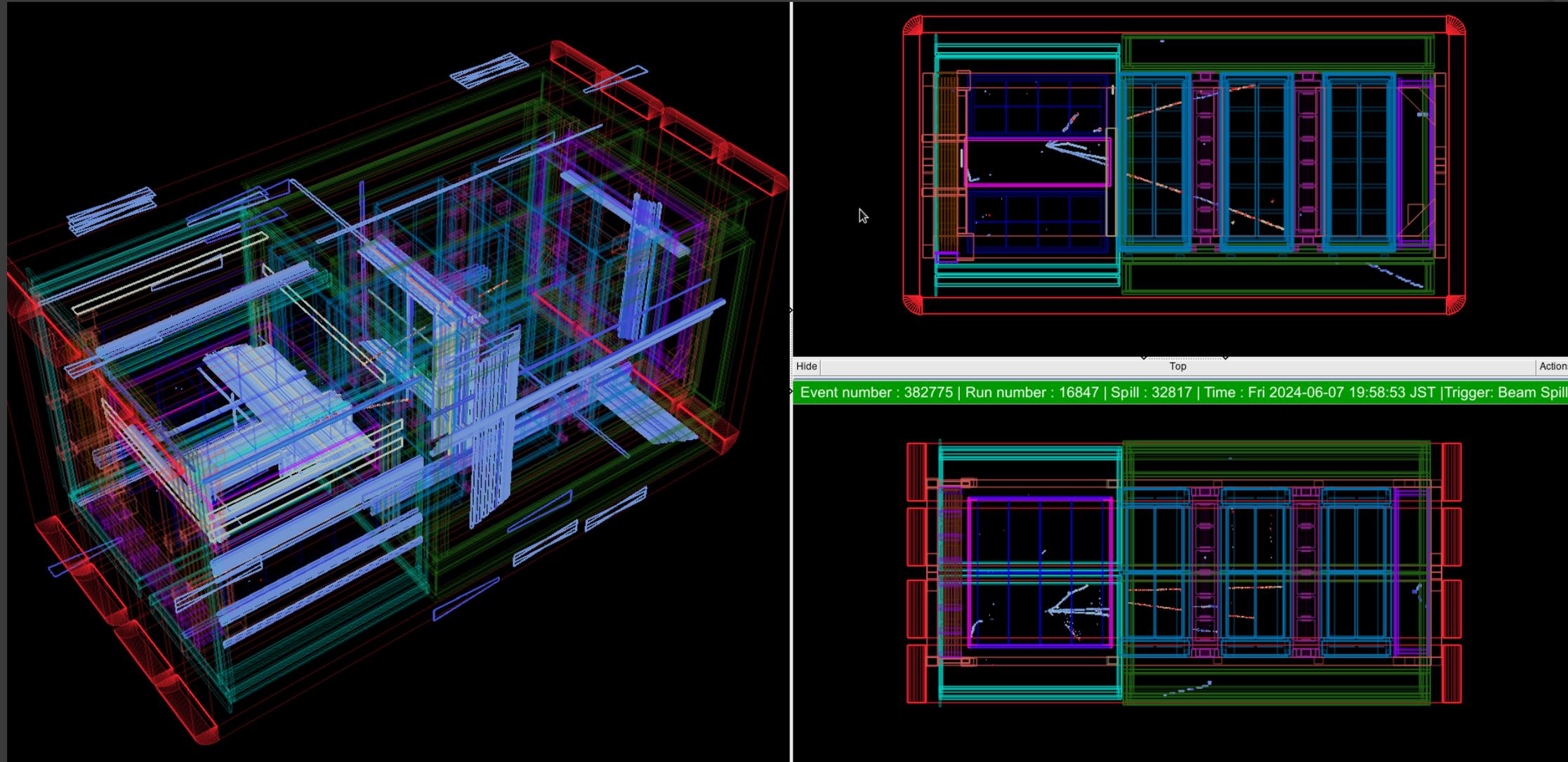- Good for transverse variable reconstruction

Neutron reconstruction from TOF
- Reduce neutrino energy bias

Much More to Come from T2K

Exciting time for the T2K collaboration with the new ND280 upgrade data.

First results from T2K's upgrade near detector are presented in a poster by Carrie Davis.

Thank You

T2K Collaboration

BACKUPS