Recent Results and Future Prospects from the T2K Experiment

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NuSTEC NDNN

T2K
University of Colorado **Boulder**

Why study neutrino interactions?

Interesting in their own right.

We measure the neutrino event rate as the final states of neutrino—matter interactions.

Need to untangle neutrino interactions from oscillation probability.

Large to leading systematic uncertainty.

Event Rate

$$R(\vec{\mathbf{x}}) = \underbrace{\overbrace{\Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}})}^{\text{Near}} \times P(\nu_A \rightarrow \nu_B)}_{\text{Far}}$$

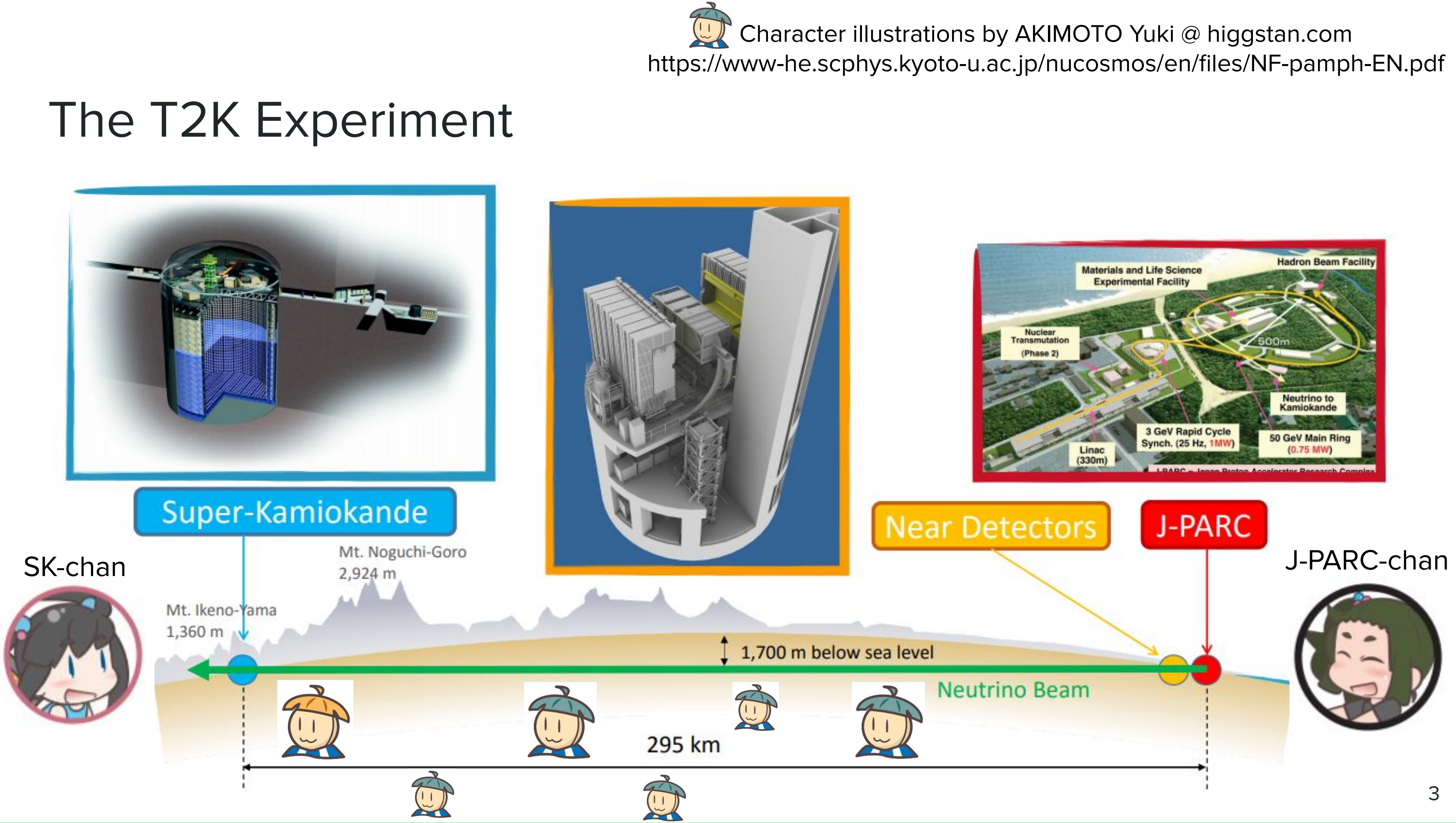
Fractional error (%) on event rate by error source and sample for T2K oscillation analysis.

https://arxiv.org/abs/2101.03779

	1-Ring μ		1-Ring e			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
SK Detector	2.4	2.0	2.8	3.8	13.2	1.5
SK FSI+SI+PN	2.2	2.0	3.0	2.3	11.4	1.6
Flux + Xsec (ND unconstrained)	14.3	11.8	15.1	12.2	12.0	1.2
Flux + Xsec (ND constrained)	3.3	2.9	3.2	3.1	4.1	2.7
Nucleon Removal Energy	2.4	1.7	7.1	3.7	3.0	3.6
$\sigma(\nu_e)/\sigma(\overline{\nu}_e)$	0.0	0.0	2.6	1.5	2.6	3.0
NC1γ	0.0	0.0	1.1	2.6	0.3	1.5
NC Other	0.3	0.3	0.2	0.3	1.0	0.2
$\sin^2\theta_{23} + \Delta m^2_{21}$	0.0	0.0	0.5	0.3	0.5	2.0
$\sin^2\theta_{13}$ PDG2018	0.0	0.0	2.6	2.4	2.6	1.1
All Systematics	5.1	4.5	8.8	7.1	18.4	6.0

Character illustrations by AKIMOTO Yuki @ higgstan.com
https://www-he.scphys.kyoto-u.ac.jp/nucosmos/en/files/NF-pamph-EN.pdf

The T2K Experiment



T2K Near Detectors: ND280

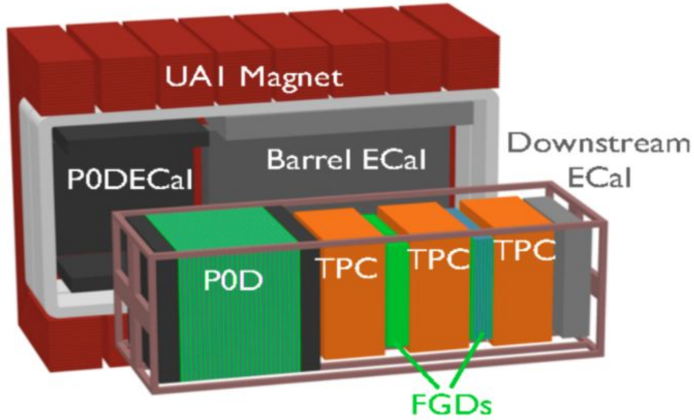
Off-axis detector (2.5 degrees, 0.6 GeV flux peak)

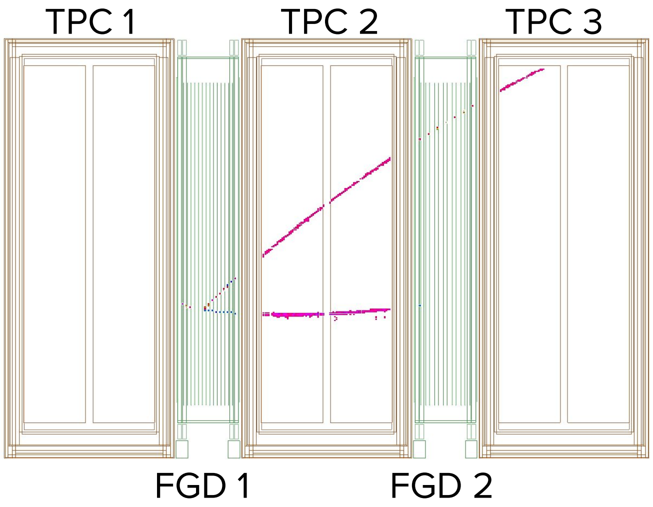
Fine Grained Detectors (FGD’s)

- Plastic scintillator tracker
- FGD1 & 2 carbon target (CH)
- FGD2 has water target layers

Time Projection Chambers (TPC’s)

- Tracking detectors
- Charged particle momentum
- Particle ID





T2K Near Detectors: INGRID

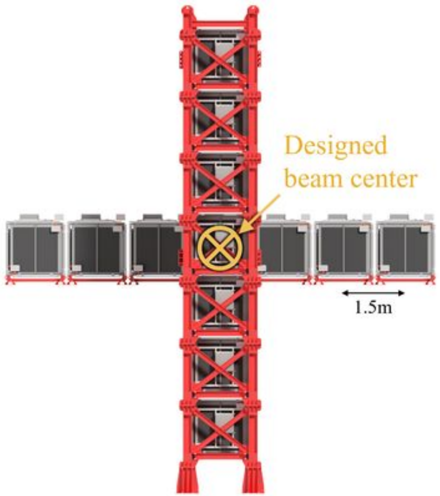
On-axis detector (1.1 GeV flux peak)

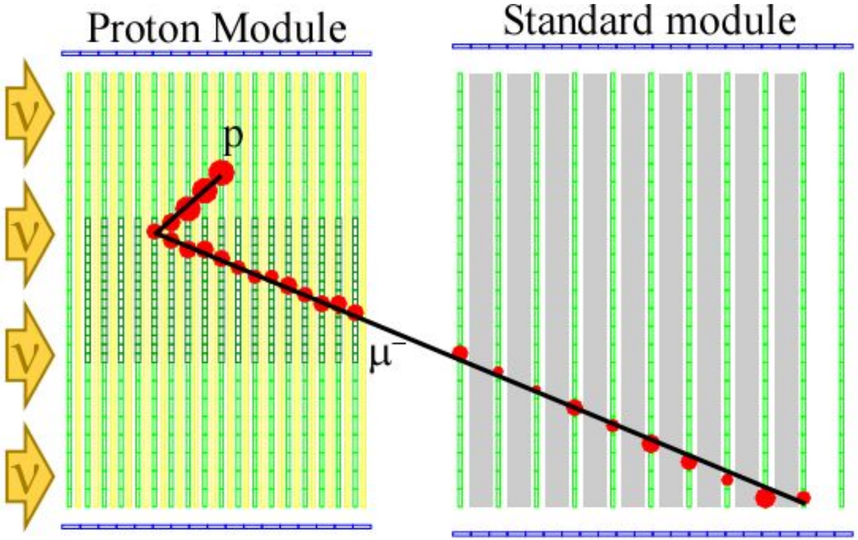
Standard Modules

- Iron and scintillator modules
- Large target mass
- Muon range detector

Proton Module

- All scintillator tracking module
- Carbon target
- No longer on-axis





T2K Near Detectors: WAGASCI

Off-axis detector (1.5 degrees, 0.86 GeV flux peak)

WAGASCI

- Plastic scintillator for tracking
- 3D grid structure
- Water target

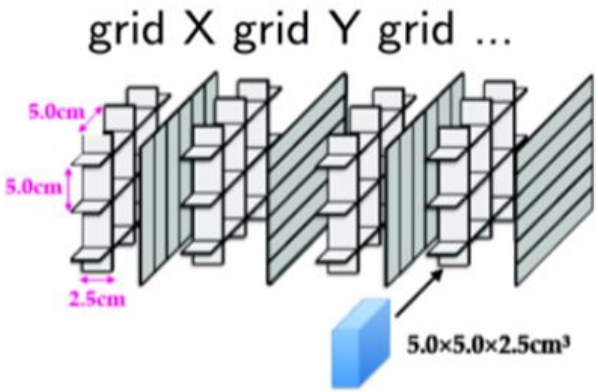
Proton Module

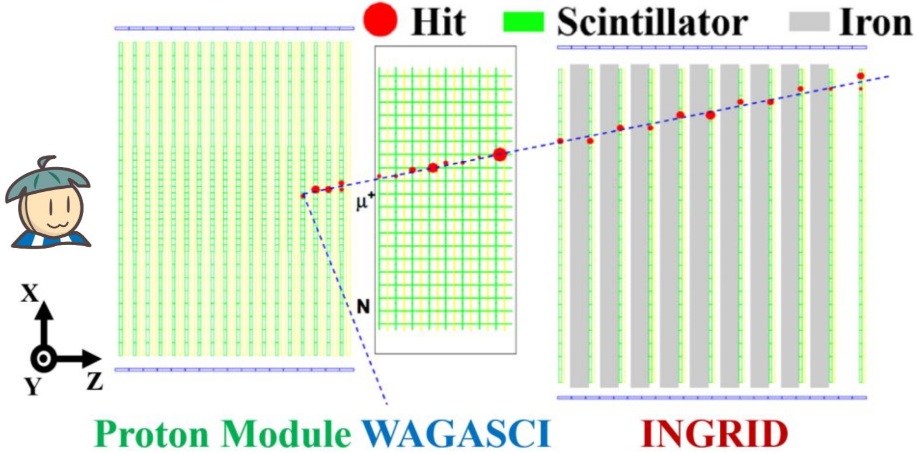
- Same as before, now off-axis
- Carbon target and tracking

Standard Module

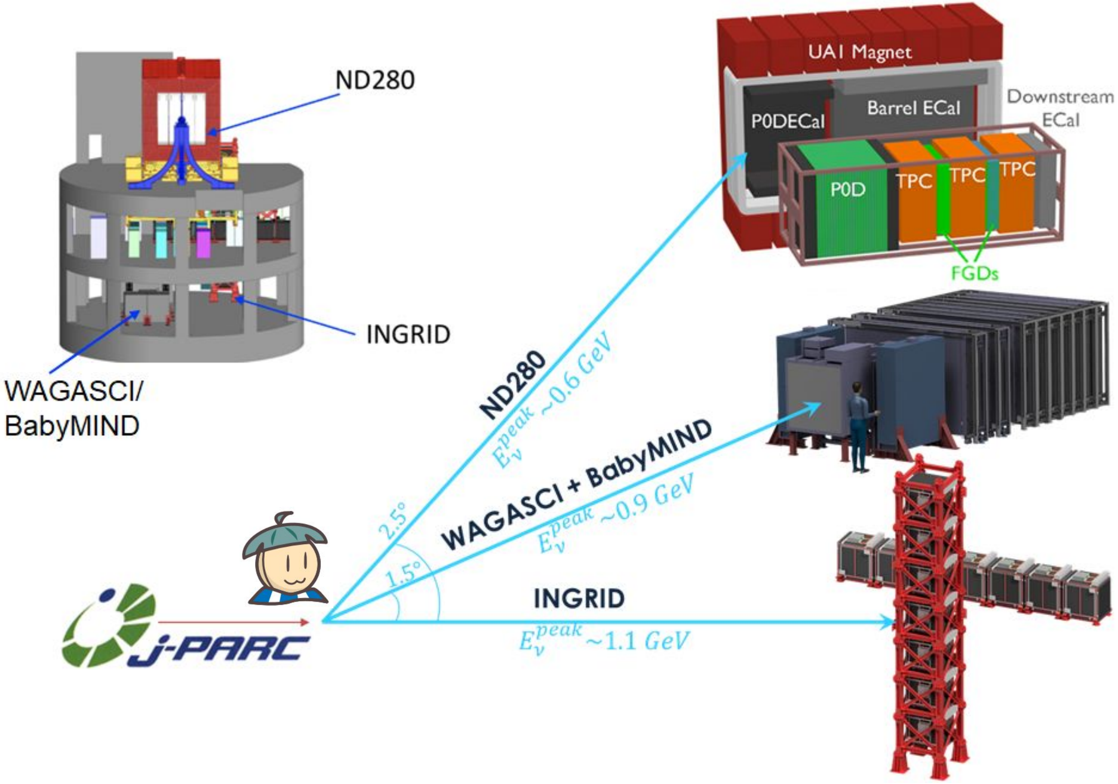
- Same as before
- Muon range detector

Shown here is the commissioning setup.



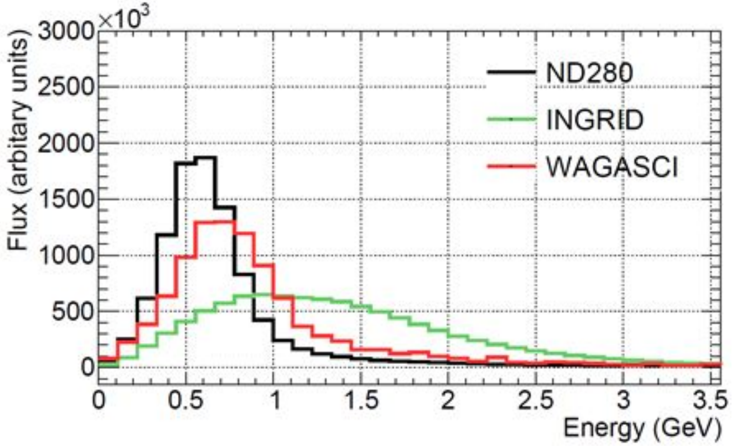


T2K Near Detector Complex



Arrangement of the different T2K near detectors.

Each detector is centered at a different on-/off-axis angle.



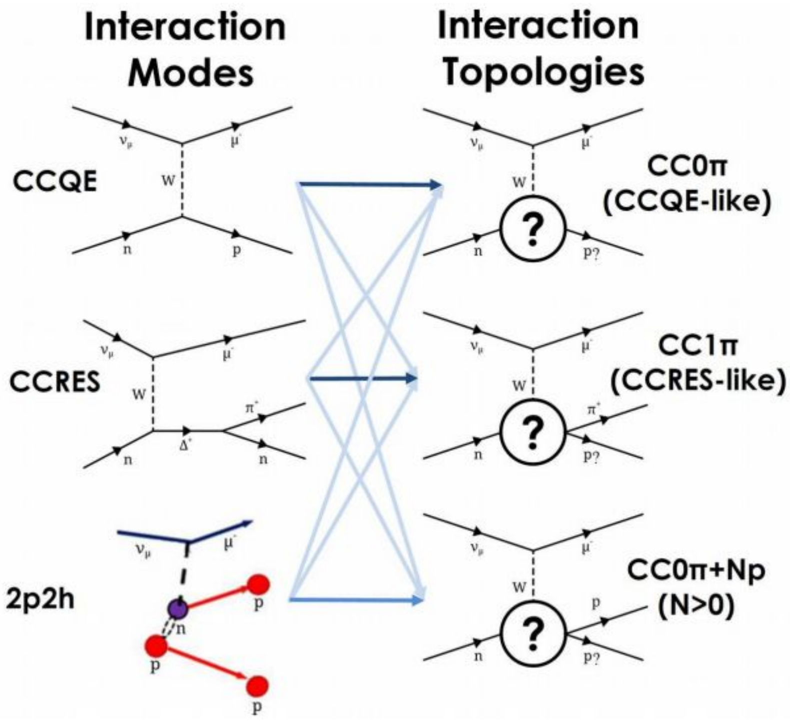
What to measure?

Signal definition by observed final state particles in the detector.

Referred to as a topology. For example, the CC0pi topology.

Can not resolve nucleon-level processes due to further interactions and detector effects.

Removes large (but not all) model dependence in extracted cross section.



Cross Section Extraction

Cross section as a function of kinematic variables X in some bin i.

Number of signal events from statistical fit.

Includes background constraint and unfolding.

$$\frac{d\sigma}{dx_i} = \frac{N_i}{\epsilon_i \, T \, \Phi \, \Delta x_i}$$

Bin width correction.

Bin-by-bin efficiency correction in analysis binning.

Integrated flux for each detector.

Number of targets for each detector.

Results Overview 

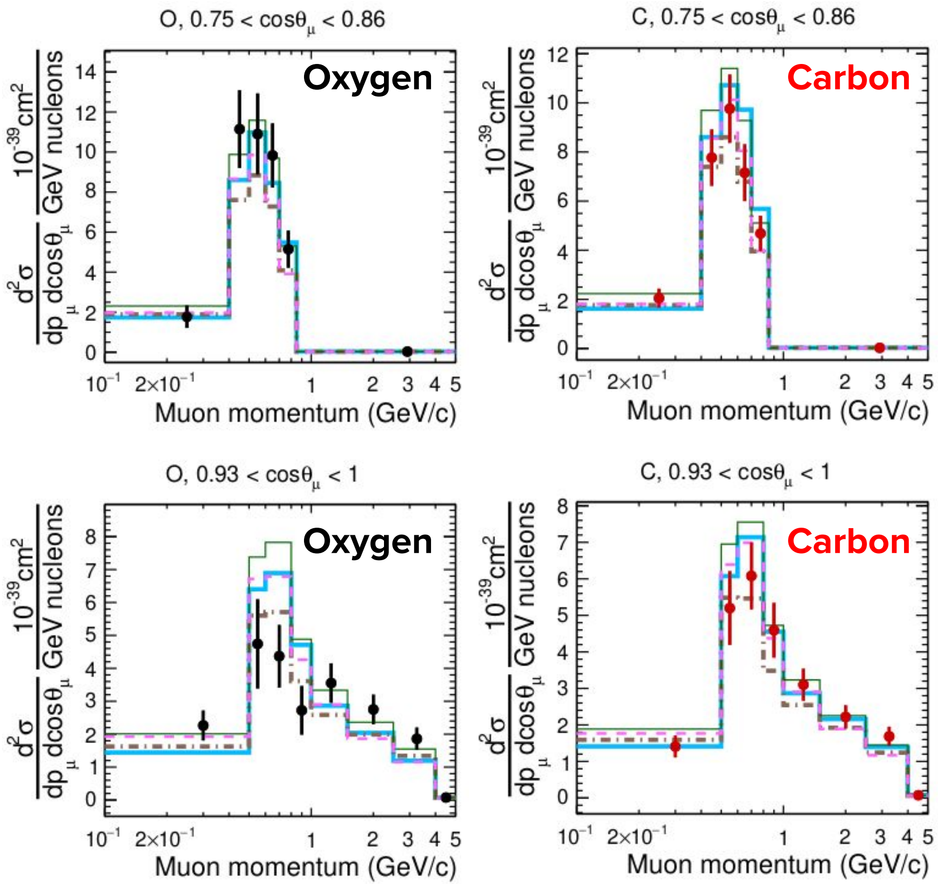
Recent results published or available on arXiv.

- Neutrino CC0pi on carbon and oxygen w/ ND280
- Neutrino and antineutrino CC0pi on carbon w/ ND280
- Antineutrino CC0pi on water and carbon w/ WAGASCI
- Electron (anti)neutrino inclusive on carbon w/ ND280
- CC1pi+ Transverse Kinematic Imbalance (TKI) w/ ND280

CC0pi : Measurements of events with a charged lepton, any number of protons (or neutrons), and zero pions in the final state.

CC1pi : Measurements of events with a charged lepton, any number of protons (or neutrons), and a single charged pion in the final state.

Neutrino Carbon & Oxygen CC0pi

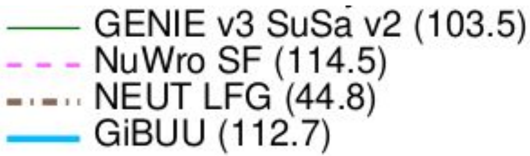


Simultaneous fit of interactions on carbon and oxygen.

With the exception of the LFG, no model fits all the data well.

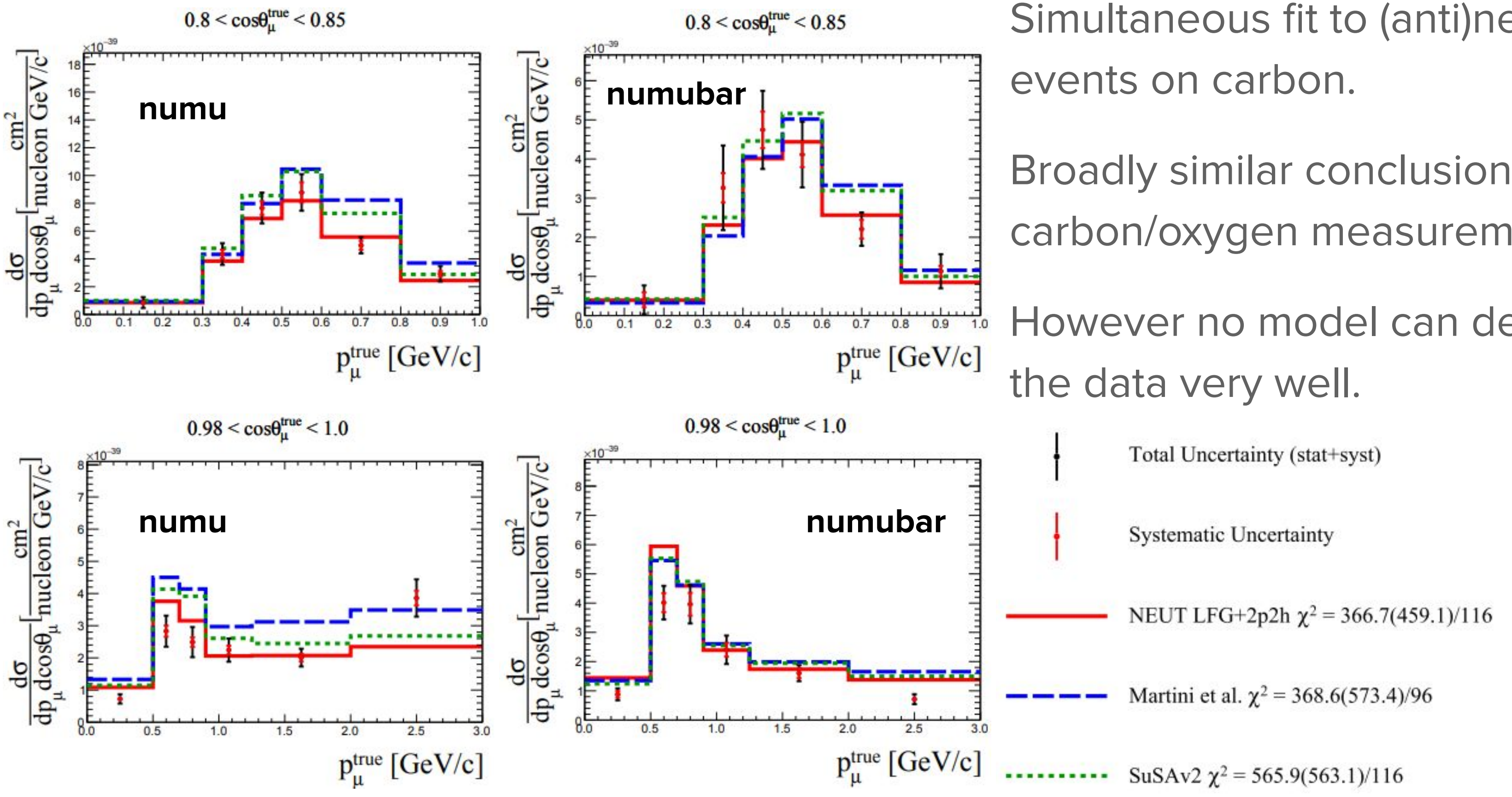
Data shows a suppression of event rate compared to MC at forward angles and medium momentum.

This effect could be “explained” by RPA, but also through non-QE processes.



https://doi.org/10.1103/PhysRevD.101.112004

Neutrino & Antineutrino Carbon CC0pi



Full χ^2 (Shape-only χ^2) / DOF

Simultaneous fit to (anti)neutrino events on carbon.

Broadly similar conclusions as the carbon/oxygen measurement.

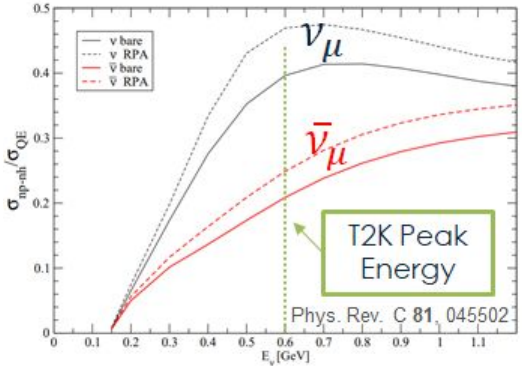
However no model can describe all the data very well.

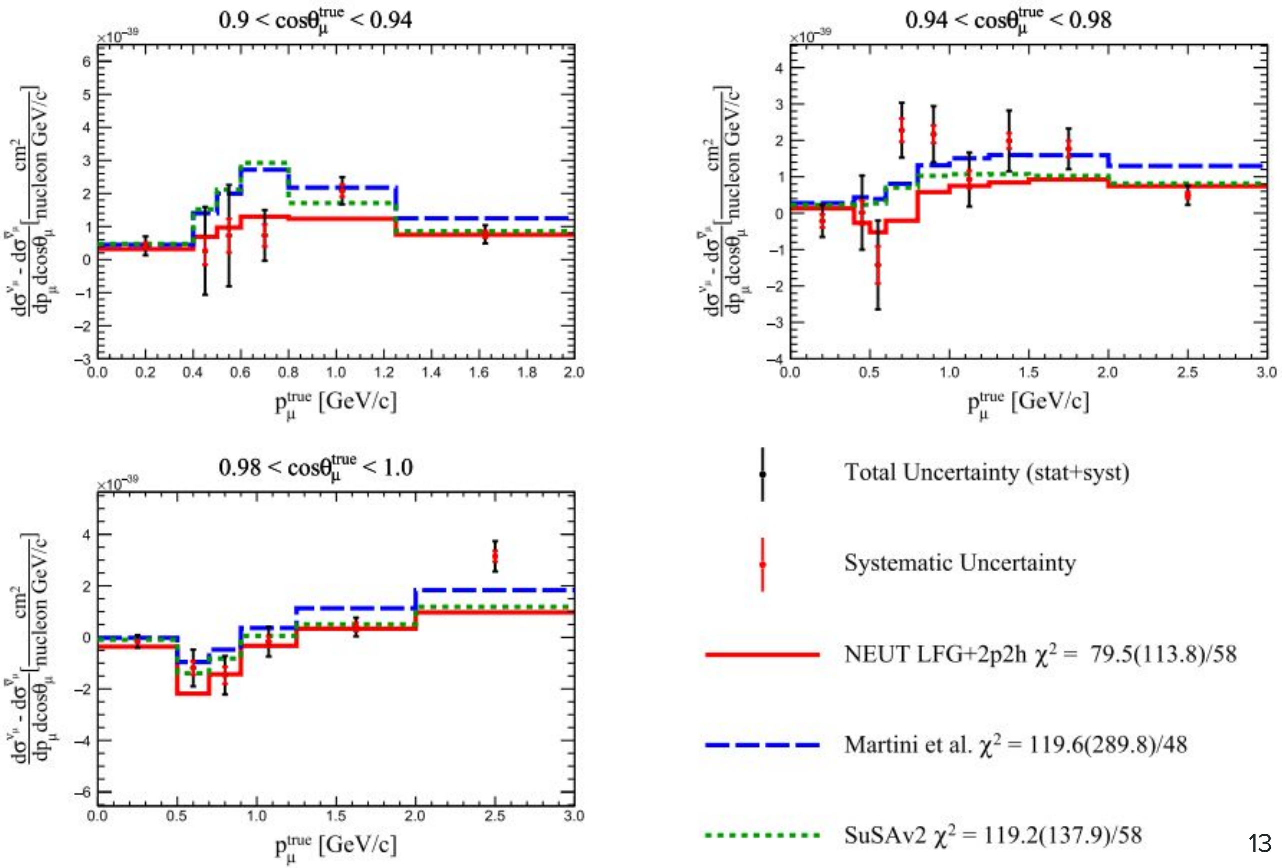
https://doi.org/10.1103/PhysRevD.101.112001

Neutrino & Antineutrino Carbon CC0pi

Difference between (anti)neutrino cross section sensitive to 2p2h models.

Limited by large experimental uncertainties and uncertainty in generator modelling.



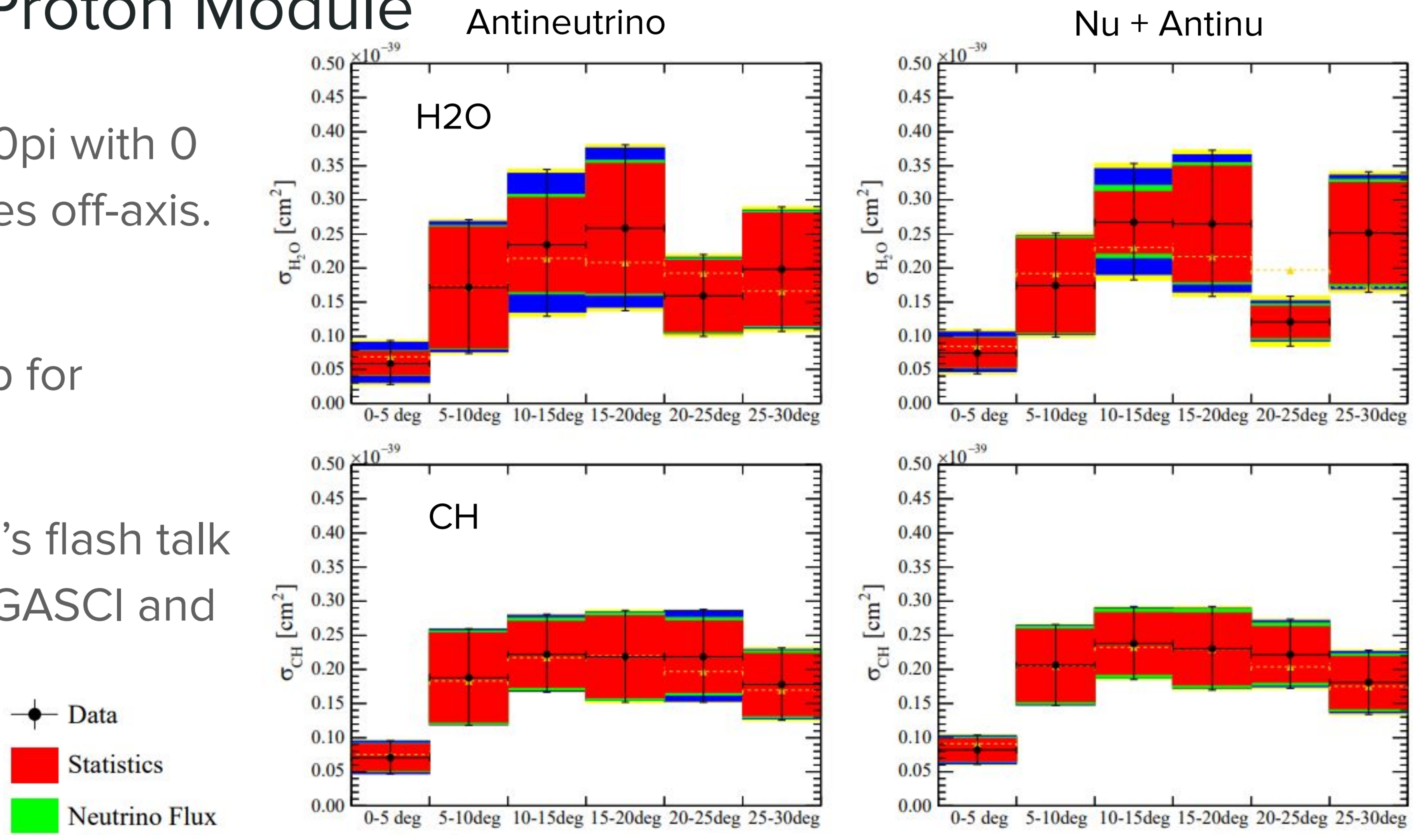


WAGASCI + Proton Module

Measurement of CC0pi with 0 protons at 1.5 degrees off-axis.

Performed with the commissioning setup for WAGASCI.

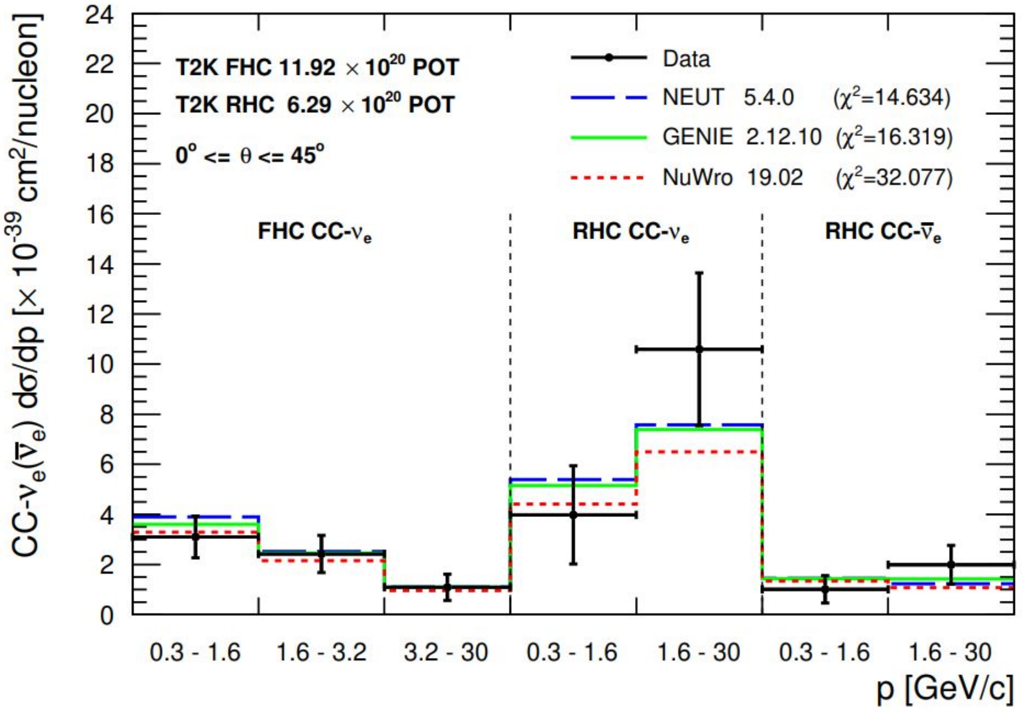
See Giorgio Pintaudi's flash talk for more info on WAGASCI and its capabilities.



	$\overline{\nu}_\mu$ cross section			$\overline{\nu}_\mu + \nu_\mu$ cross section		
	σ_{H_2O}	σ_{CH}	$\sigma_{H_2O}/\sigma_{CH}$	σ_{H_2O}	σ_{CH}	$\sigma_{H_2O}/\sigma_{CH}$
NEUT	0.74	0.16	0.81	5.93	0.33	5.76
GENIE	0.72	0.54	0.89	5.98	0.57	6.35

https://arxiv.org/abs/2004.13989

Electron Neutrino and Antineutrino



Generator	$p-\cos(\theta)$ χ^2 (ndof = 13)	p-only χ^2 (ndof = 7)	$\cos(\theta)$-only χ^2 (ndof = 6)
NEUT 5.4.0	14.63	5.82	5.34
GENIE 2.12.10	16.32	4.16	4.55
NuWro 19.02	32.08	4.52	5.08

Electron (anti)neutrino inclusive measurement on CH using FGD 1.

Limited phase-space set by detector limitations.

Newest nuebar measurement in over 40 years.

Nue cross section projected to be a large uncertainty for δ_{CP} at Hyper-K

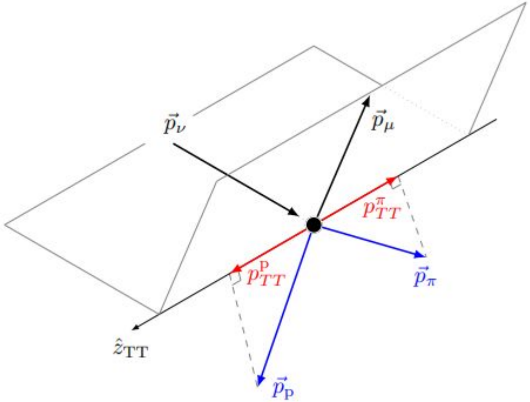
https://doi.org/10.1007/JHEP10(2020)114

CC 1pi+ Transverse Kinematic Imbalance

Calculate TKI variables between outgoing pion and highest momentum proton.

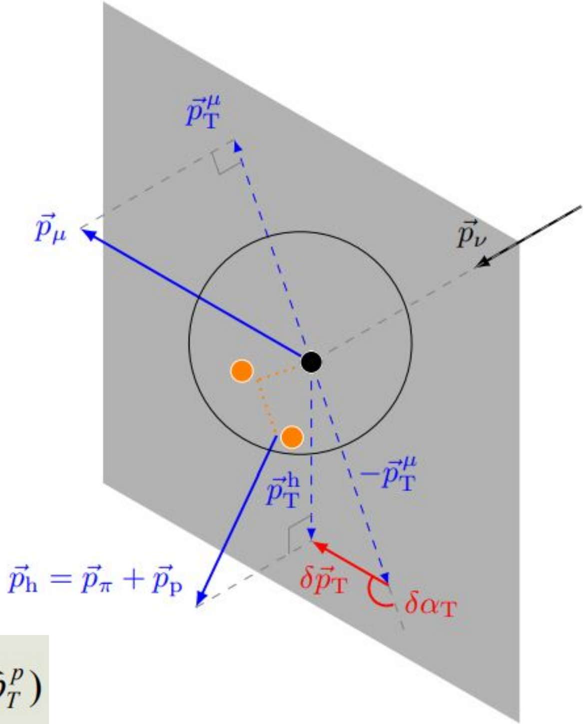
Double transverse momentum balance (δp_{TT}) sensitive to initial nuclear state.

Transverse boosting angle ($\delta\alpha_T$) sensitive to final state interactions



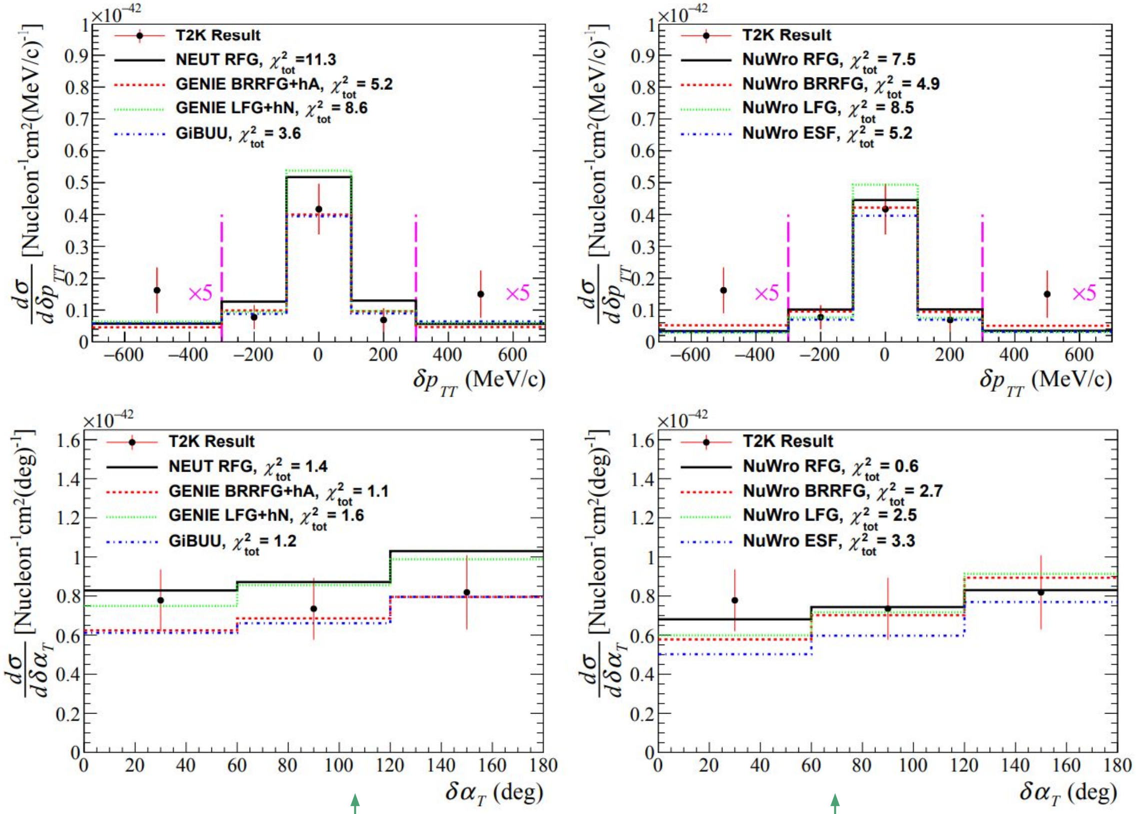
$$\delta\alpha_T = \cos^{-1}\frac{-\vec{p}_T^{\,\mu}\cdot\delta\vec{p}_T}{p_T^{\mu}\,\delta p_T}$$

$$\delta p_{TT} = p^{\pi}_{TT} + p^{p}_{TT} = \frac{\vec{p}^{\,\nu}\times\vec{p}_T^{\,\mu}}{\left|\vec{p}^{\,\nu}\times\vec{p}_T^{\,\mu}\right|}\cdot(\vec{p}_T^{\,\pi}+\vec{p}_T^{\,p})$$



https://arxiv.org/abs/2102.03346

CC 1pi+ Transverse Kinematic Imbalance



Same data points -- different models.

Some models show clear separation in the TKI variables.

TKI analysis shows slight preference for more “sophisticated” nuclear models.

Data uncertainties are large, but analysis clearly sensitive to nuclear physics.

https://arxiv.org/abs/2102.03346

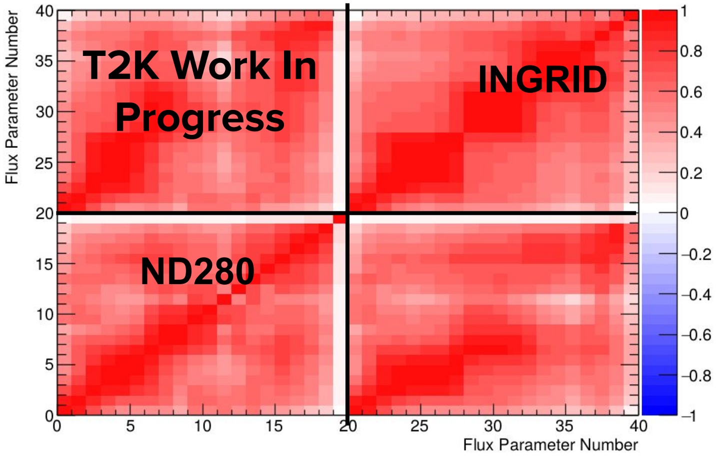
On-/Off-Axis Measurement (Coming Soon™)

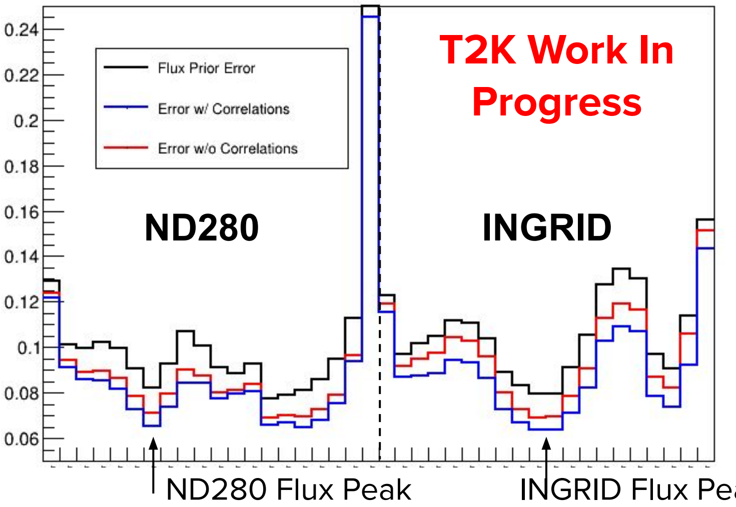
Simultaneous fit using data from both ND280 and INGRID.

On-/off-axis positions result in different, but highly correlated, neutrino flux distributions.

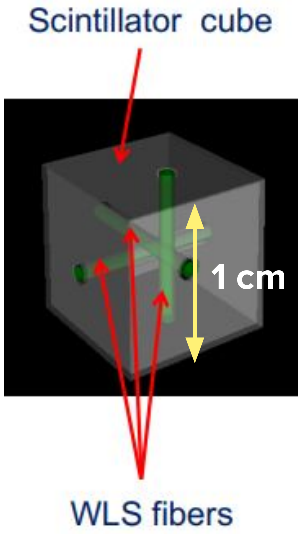
Provides an opportunity to break some of the degeneracy between flux and cross section effects.

Study energy dependence of neutrino interaction processes.





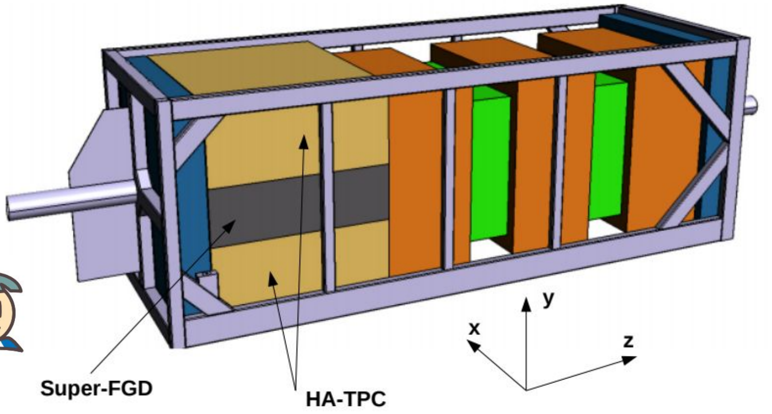
Future Detector Upgrades



ND280 is a good detector, but could be better and has some known limitations -- enter the ND280 Upgrade.

Install the Super FGD and two high-angle TPC's (and surrounding ToF panels) upstream of the current FGD/TPC arrangement.

- Larger angle acceptance
- 3D scintillator arrangement for Super FGD
- Lower threshold for tracking
- Nearly doubles target mass
- Neutron measurement capabilities



https://arxiv.org/abs/1901.03750

Analyses in Progress

Numerous T2K analyses currently underway!

- Neutrino and antineutrino CC-Coherent Pion Production
- Neutrino CC1pi+ on water with pion kinematics → **See flash talk by Sam Jenkins!**
- Antineutrino CC1pi- on water
- Antineutrino CC1pi- on carbon (CH)
- Neutrino CC0pi and CC1pi joint measurement
- Neutrino and antineutrino on-/off-axis CC0pi on carbon (CH)
- Neutrino neutral current quasi-elastic (NCQE)
- Electron neutrino and antineutrino on water in the P0D
- Neutral current single pi-zero on water in the P0D
- Neutrino CC0pi on carbon using hadronic energy kinematics

This material is based upon work supported by
the U.S. Department of Energy, Office of Science.

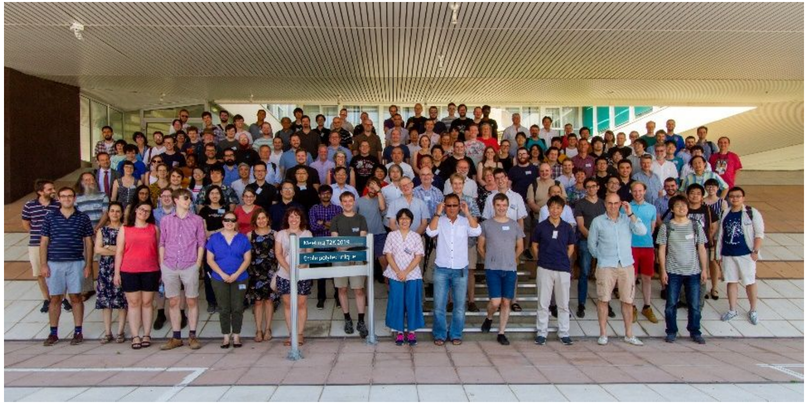
Summary

T2K is continuing to produce a variety of neutrino cross section measurements, and analyses are getting increasingly sophisticated

In general no model describes all the data -- important to work with theorists and generator developers to improve predictions.

Novel measurements provide new tests of specific features of models -- increases sensitivity to model differences.

The T2K Collaboration (July 2019)



A lot of work to be done by both theory and experiment to understand neutrino interactions to achieve goals for next-generation oscillation experiments.