T2K latest results on neutrino-nucleus cross sections

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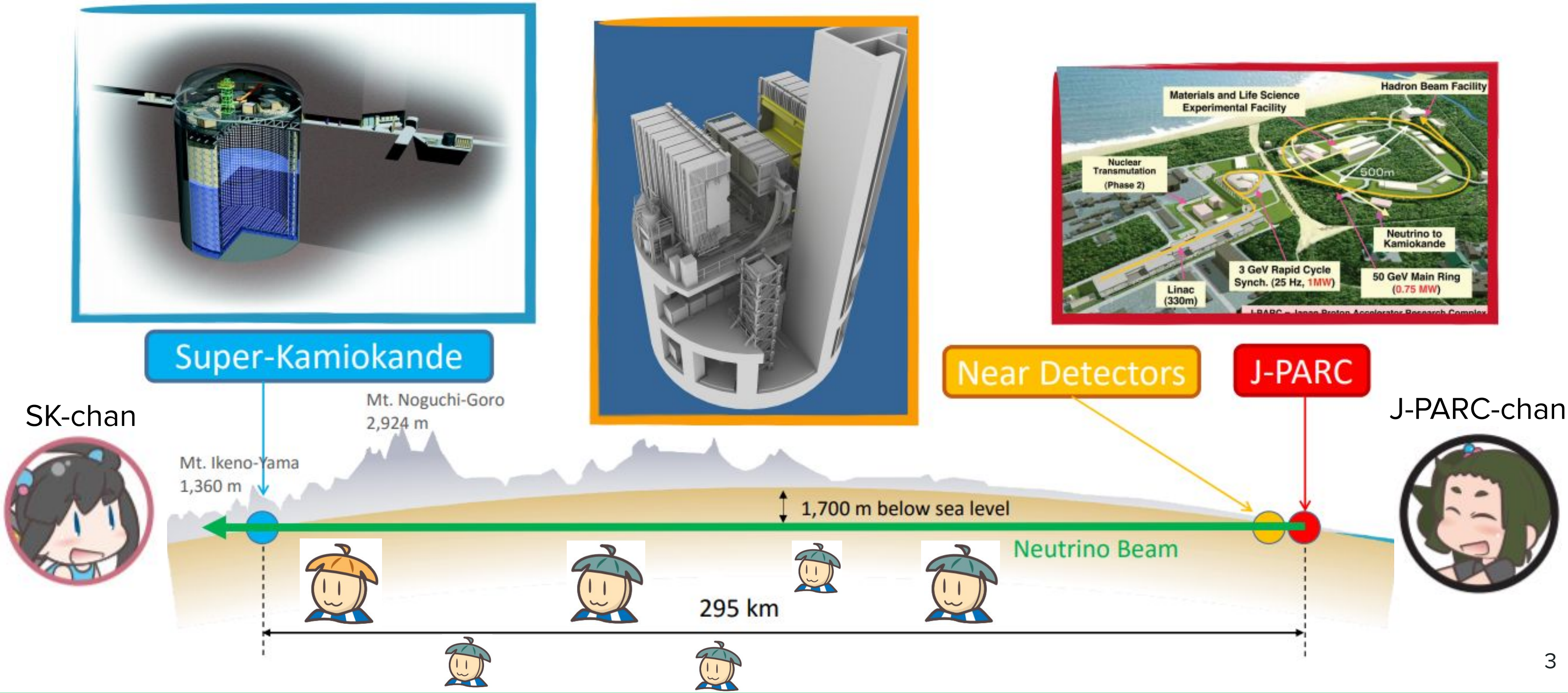
T2K University of Colorado **Boulder**

Outline

- Introduction to T2K
- Analysis strategy
- On-/Off-axis analysis
- Coherent pion-production analysis
- Summary

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)

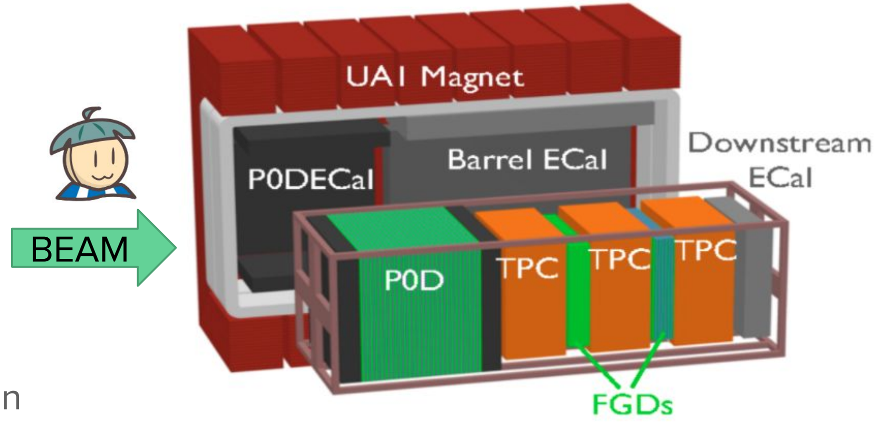
Fine Grained Detectors (FGDs)

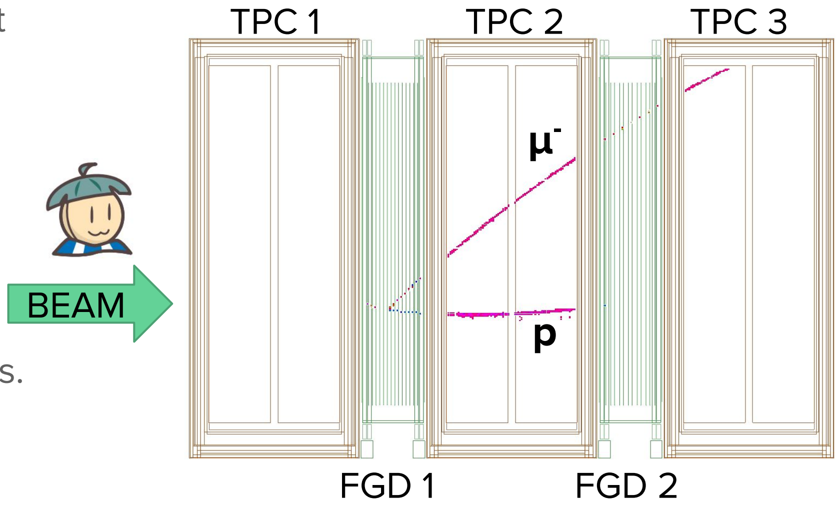
- Plastic scintillator tracker
- FGD1 & 2 active carbon (CH) neutrino-interaction target
- FGD2 passive water neutrino-interaction target layers

Time Projection Chambers (TPCs)

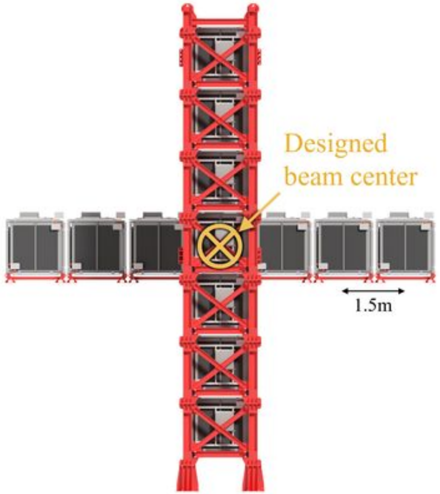
- Tracking detectors
- Charged particle momentum
- Particle identification

Highly capable tracking detector with multiple targets. Very good at measuring forward going particles, however is less efficient at high angles.





T2K Near Detectors: INGRID



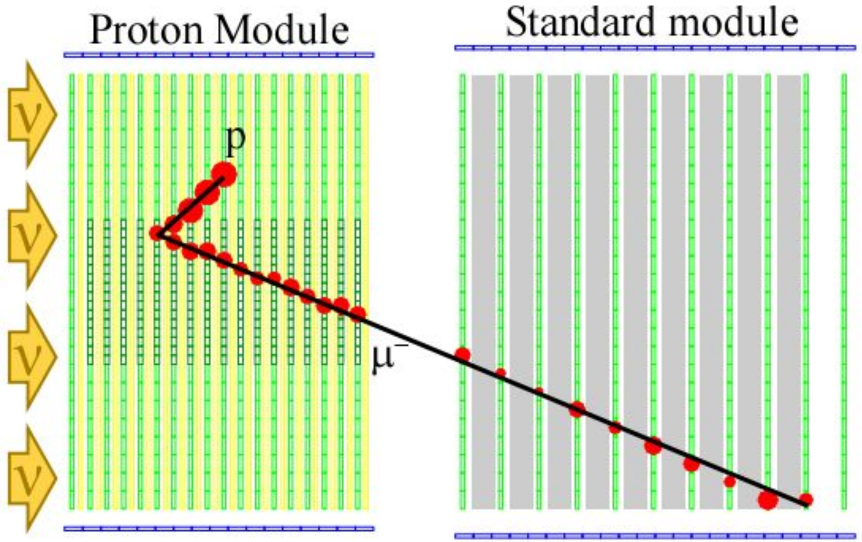
On-axis detector (1.1 GeV flux peak)

Standard Modules

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

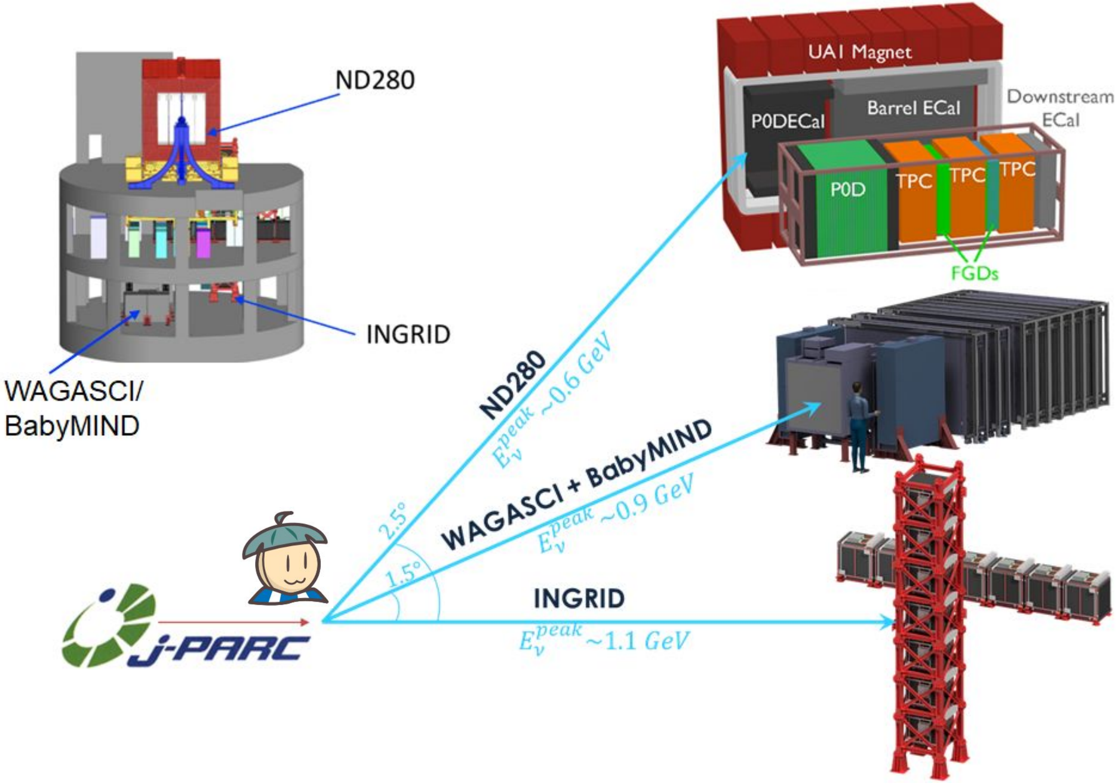
Proton Module

- All scintillator tracking module
- Carbon (CH) neutrino-interaction target
- No longer on-axis



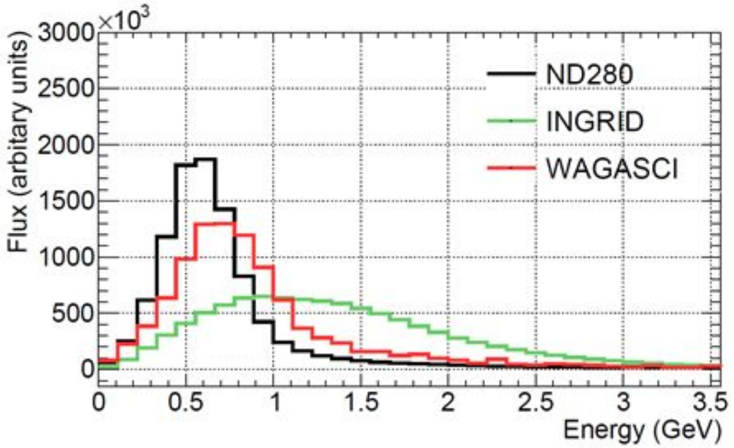
Primary job is to function as a beam monitor, but with the proton module can be used for cross-section measurements.

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?

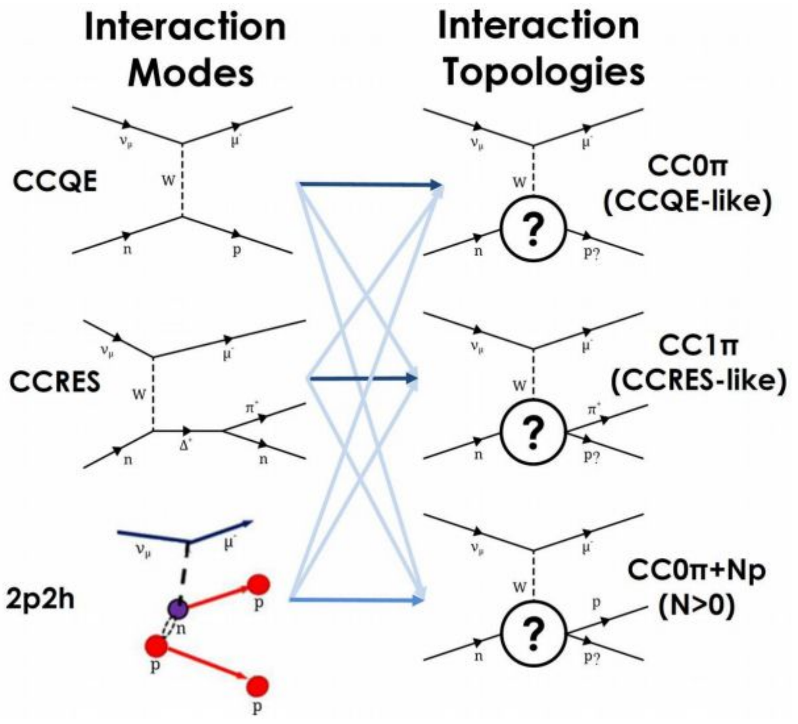
Detectors measure total event rate.

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 (FSI) in the nucleus.

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



Likelihood fit and Unfolding

Measure **selected number** of **events** in a **reconstructed variable** -- what the detector saw.

Want the **total number** of **signal events** in a **true variable** -- what physically happened.

Simplifying, this requires the following three main corrections:

- **Efficiency correction**: going from selected number to true number of events.
- **Background constraint**: going from all events to signal events.
- **Unfolding**: process of removing detector effects from the data.

For a much more in-depth presentation on T2K cross-section analysis methods: https://indico.fnal.gov/event/48064/

Binned likelihood fit

Analyses uses a binned template likelihood fit to the number of selected events simultaneously across all samples, minimizing twice the negative log-likelihood ratio.

Total chi-square: the test statistic minimized by the fit.

$$\chi^2 = \chi^2_{\text{stat}} + \chi^2_{\text{syst}} = -2\ln\mathcal{L}_{stat} - 2\ln\mathcal{L}_{syst}$$

Poisson likelihood: how well the MC matches the data.

$$-2\ln\mathcal{L}_{stat} = \sum_{j}^{\text{bins}} 2\left(N_j^{\text{exp}} - N_j^{\text{obs}} + N_j^{\text{obs}}\ln\frac{N_j^{\text{obs}}}{N_j^{\text{exp}}}\right)$$

Penalty term: penalizes fit for moving systematic parameters away from nominal.

$$-2\ln\mathcal{L}_{syst} = \sum_{p} (\vec{p} - \vec{p}_{\text{prior}})\left(V^{\text{syst}}_{\text{cov}}\right)^{-1}(\vec{p} - \vec{p}_{\text{prior}})$$

Note: the Poisson likelihood includes the effect of finite MC statistics using a variation of the Barlow–Beeston method in the actual fit.

Cross Section Extraction

Differential 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.

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

Bin width correction.

Bin-by-bin efficiency correction in analysis binning.

Integrated flux.

Number of targets.

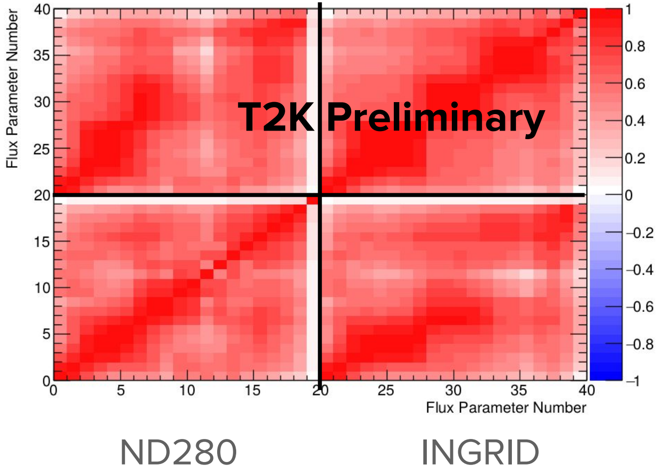
On-/Off-Axis Analysis

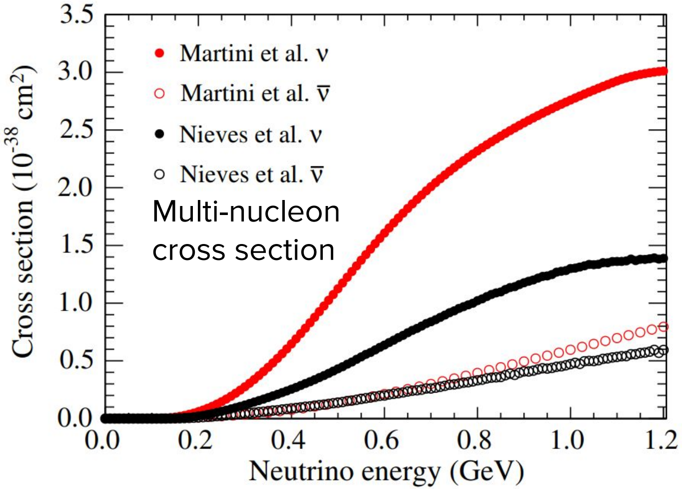
Simultaneous fit using data from both ND280 and INGRID.

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

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

Study energy dependence of neutrino interaction processes.



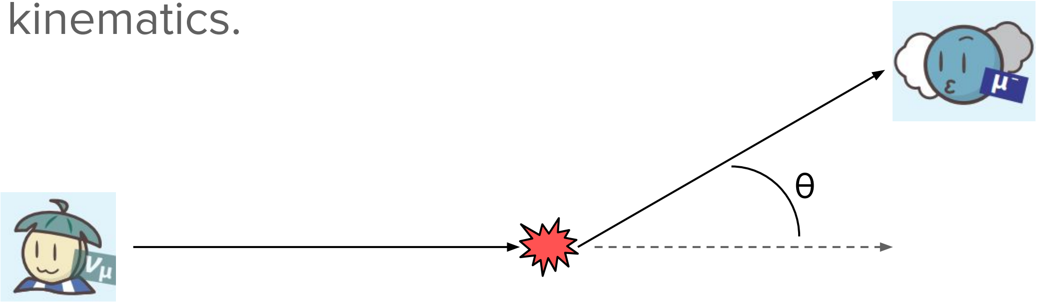


On-/Off-Axis Selection Overview

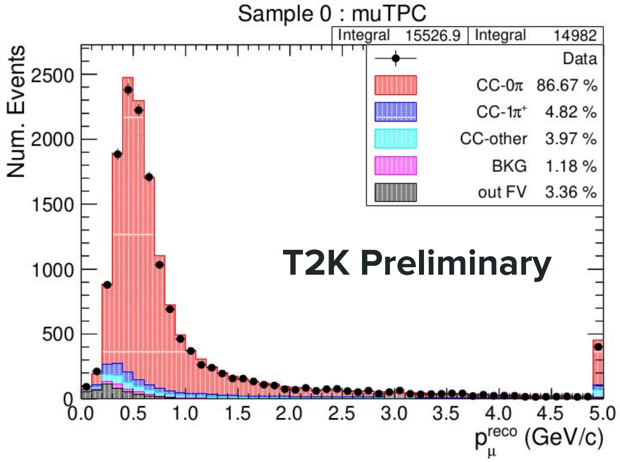
CC0pi signal definition: **one negatively charged muon**, **zero pions**, and **any number of hadrons** detected in the final state where the vertex was reconstructed in the FGD1 or Proton Module fiducial volume.

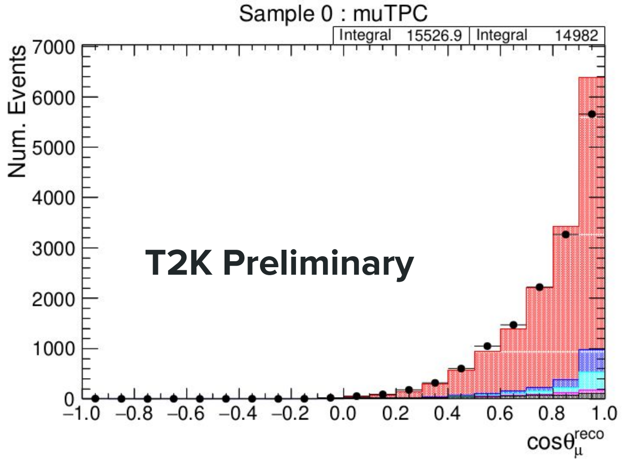
Signal samples are categorized by the (sub-)detectors used in the event, and the analysis includes several control samples to constrain background events.

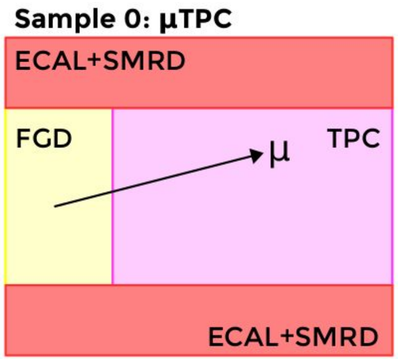
Events are characterized by muon kinematics, and the extracted cross section is double differential in the muon kinematics.



Off-axis ND280 selection





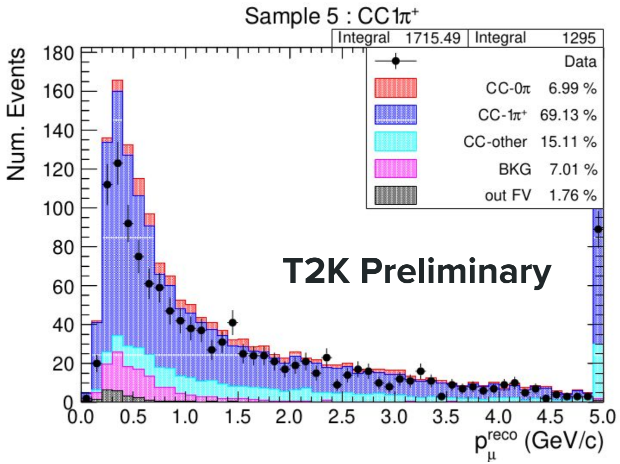


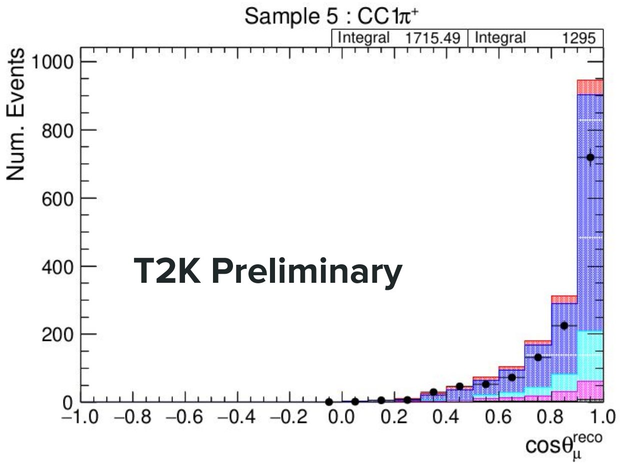
Example of an ND280 signal sample showing the reconstructed muon momentum and cos(angle).

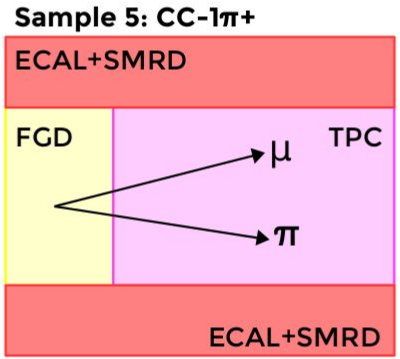
This sample requires a muon to reach the TPC and no other detected particles, and is the largest sample. Analysis includes 5 total signal samples.

Colored histogram shows the nominal MC prediction separated by topology with the measured data overlaid.

Off-axis ND280 selection





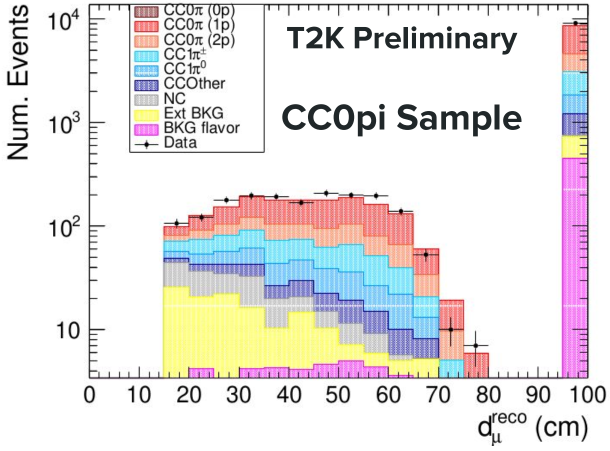


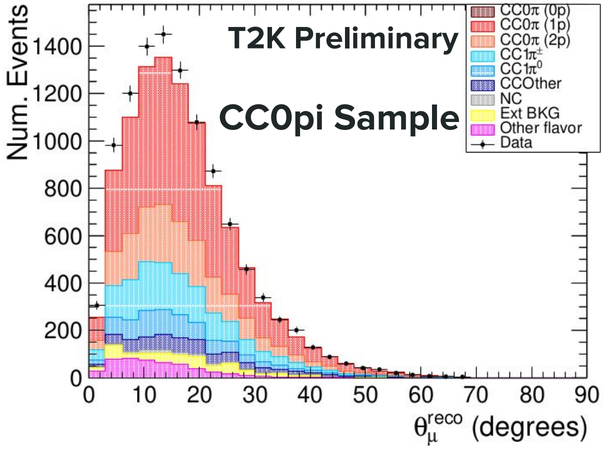
Example of an ND280 control sample showing the reconstructed muon momentum and cos(angle).

This sample requires a muon and charged pion to reach the TPC with no other detected particles. Analysis includes two additional ND280 control samples.

Colored histogram shows the nominal MC prediction separated by topology with the measured data overlaid.

On-axis INGRID selection

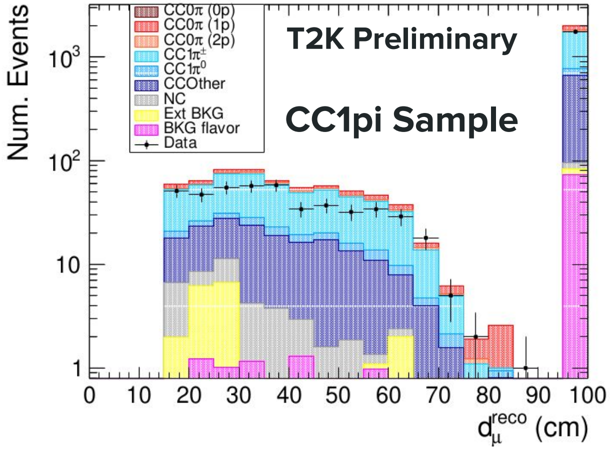


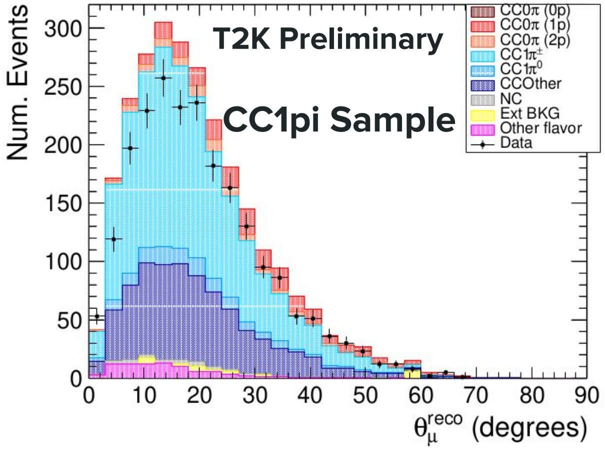


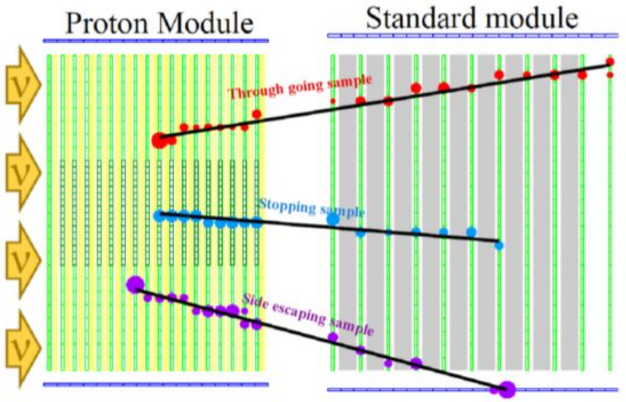
INGRID through-going and stopping samples.

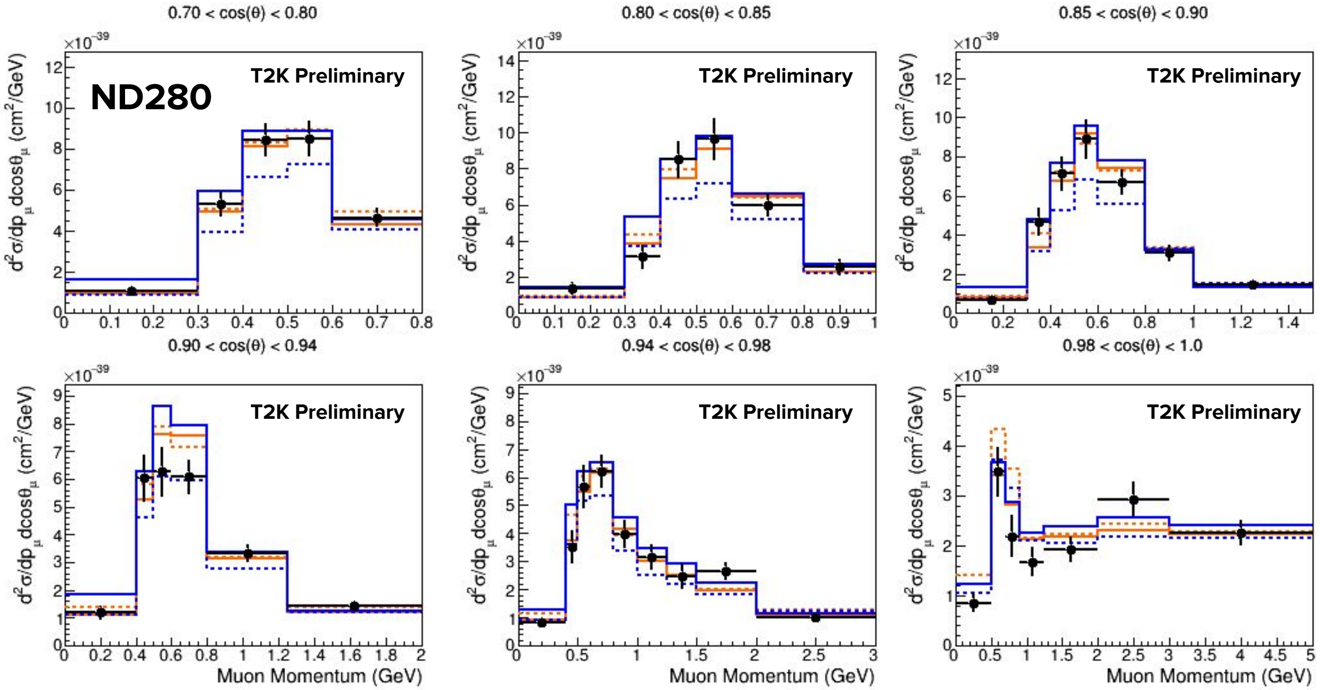
CC0pi samples on top, CC1pi samples on bottom.

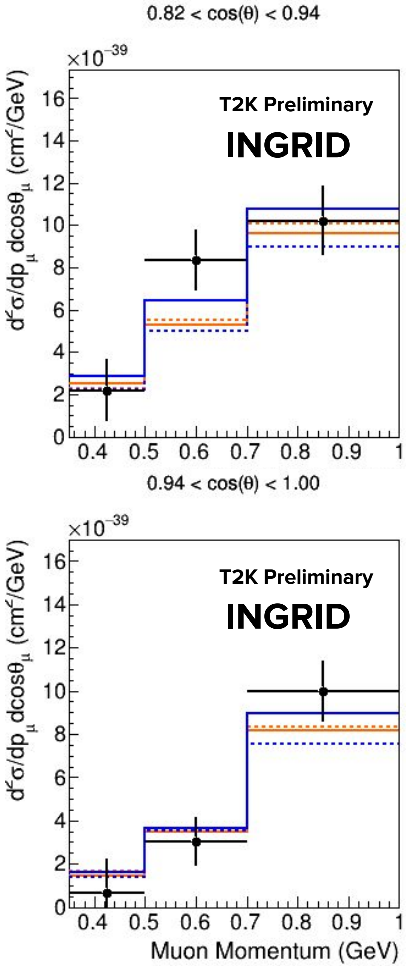
The last bin for the distance plots contains all through-going events.











Cross-section results for selected angle bins for ND280 and INGRID.

Total chi-square (70 bins):

NuWro 21.09 SF+Nieves	137.02
NuWro 21.09 LFG+SuSAv2	135.38
GENIE v3.06 BRRFG+EmpMEC	156.05
GENIE v3.06 LFG+Nieves	135.69

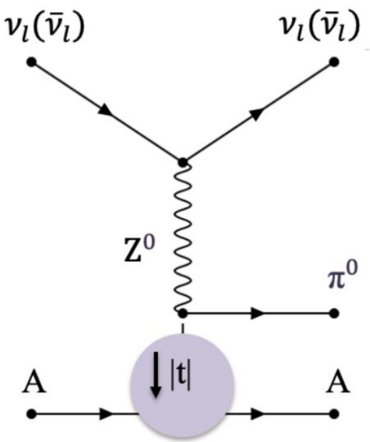
Note: The last momentum bin is not shown. All angle bins in backups.

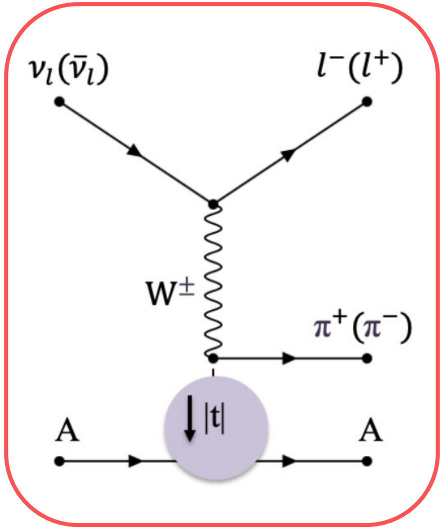
Charged-current Coherent Analysis

Measurement of (anti-)neutrino induced charged–current coherent pion production with ND280.

Relatively rare interaction channel, but can mimic oscillation signals.

By measuring charged–current coherent, constraints can be placed on neutral–current coherent production.



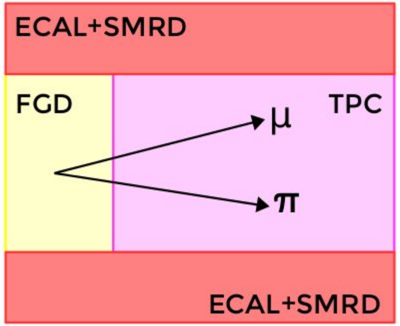


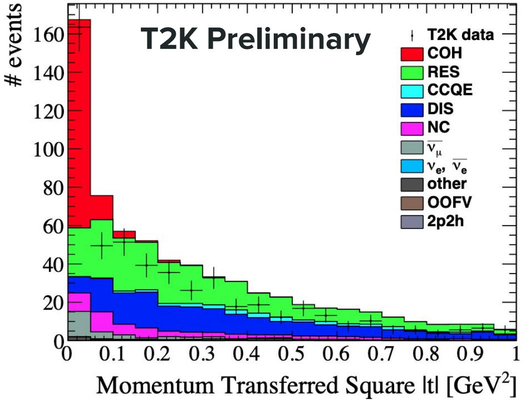
Charged-current: measured for this analysis

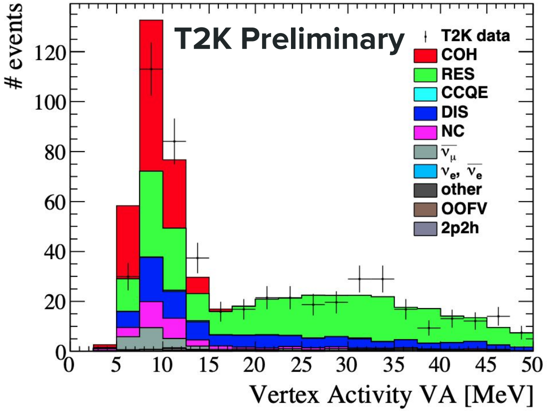
Coherent Selection

Signal definition: one charged muon, one charged pion, and no other particles detected in the final state where the reconstructed vertex is in the FGD fiducial volume.

Accept events with low vertex activity and low momentum transfer squared. Control samples for resonant pion and deep inelastic events are used to constrain the backgrounds.







RS = Rein–Sehgal Model
BS = Berger–Sehgal Model

Coherent Results

$$\sigma_{\mathrm{FGD1}}^{\text{CC-COH}} = \sum_i f_i F(A_i) \frac{\sigma_{^{12}\mathrm{C}}^{\text{CC-COH}}}{F(A_{\mathrm{C}})}$$

Total flux-integrated cross section for carbon calculated using two different nuclear scaling factors.

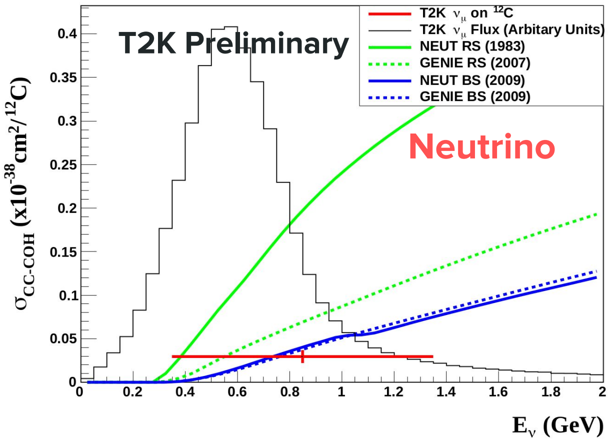
$A^{1/3}$ comes from the Rein-Sehgal paper (1987) and the **A^2** comes from the coherent interaction across all nucleons in the target.

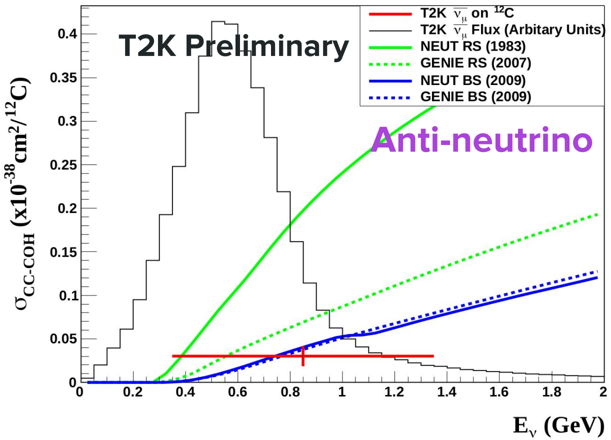
Neutrino result for carbon:

$$\sigma_{^{12}\mathrm{C}}^{\text{CC-COH}} = \begin{cases} \boxed{2.98 \pm 0.37(\text{stat.}) \pm 0.58(\text{syst.}) \times 10^{-40}\mathrm{cm}^2 \ (F(A) = A^{1/3}}) \\ 2.69 \pm 0.33(\text{stat.}) \pm 0.52(\text{syst.}) \times 10^{-40}\mathrm{cm}^2 \ (F(A) = A^2). \end{cases}$$

Anti-neutrino result for carbon:

$$\sigma_{^{12}\mathrm{C}}^{\text{CC-COH}} = \begin{cases} \boxed{3.05 \pm 0.71(\text{stat.}) \pm 0.84(\text{syst.}) \times 10^{-40}\mathrm{cm}^2 \ (F(A) = A^{1/3}}) \\ 2.75 \pm 0.64(\text{stat.}) \pm 0.76(\text{syst.}) \times 10^{-40}\mathrm{cm}^2 \ (F(A) = A^2). \end{cases}$$



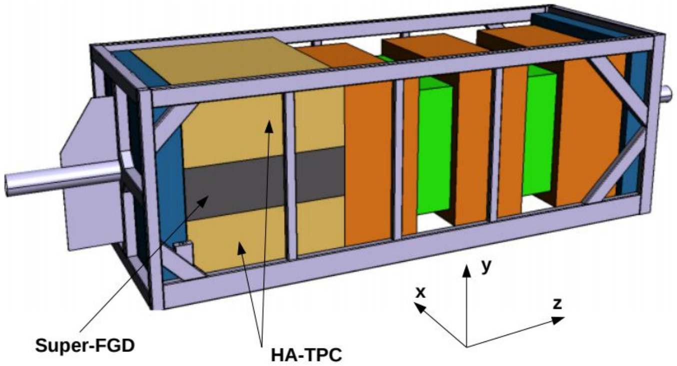


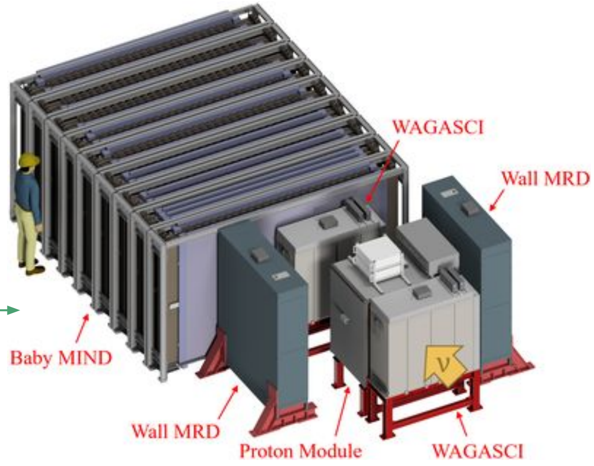
Aoi Eguchi's talk on ND280 Upgrade
https://indico.fnal.gov/event/53004/contributions/245852/

Analyses and Papers in Progress

Numerous T2K analyses and papers currently underway!

- On-/Off-axis CC0pi paper draft in progress
- Charged-current coherent pion paper draft in progress
- Neutrino CC1pi+ on water with pion kinematics
- Antineutrino CC1pi- on water
- Antineutrino CC1pi- on carbon (CH)
- Neutrino CC1K+ 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)
- Neutrino CC0pi on carbon and water using WAGASCI+BabyMind
- 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.

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

Important to continue to work with theorists and generator developers to improve predictions, and a lot of work is needed to achieve the goals for the next generation of neutrino experiments.

T2K May 2022 Collaboration Photo

Japan + CERN

We had to get creative.

Backup Slides

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

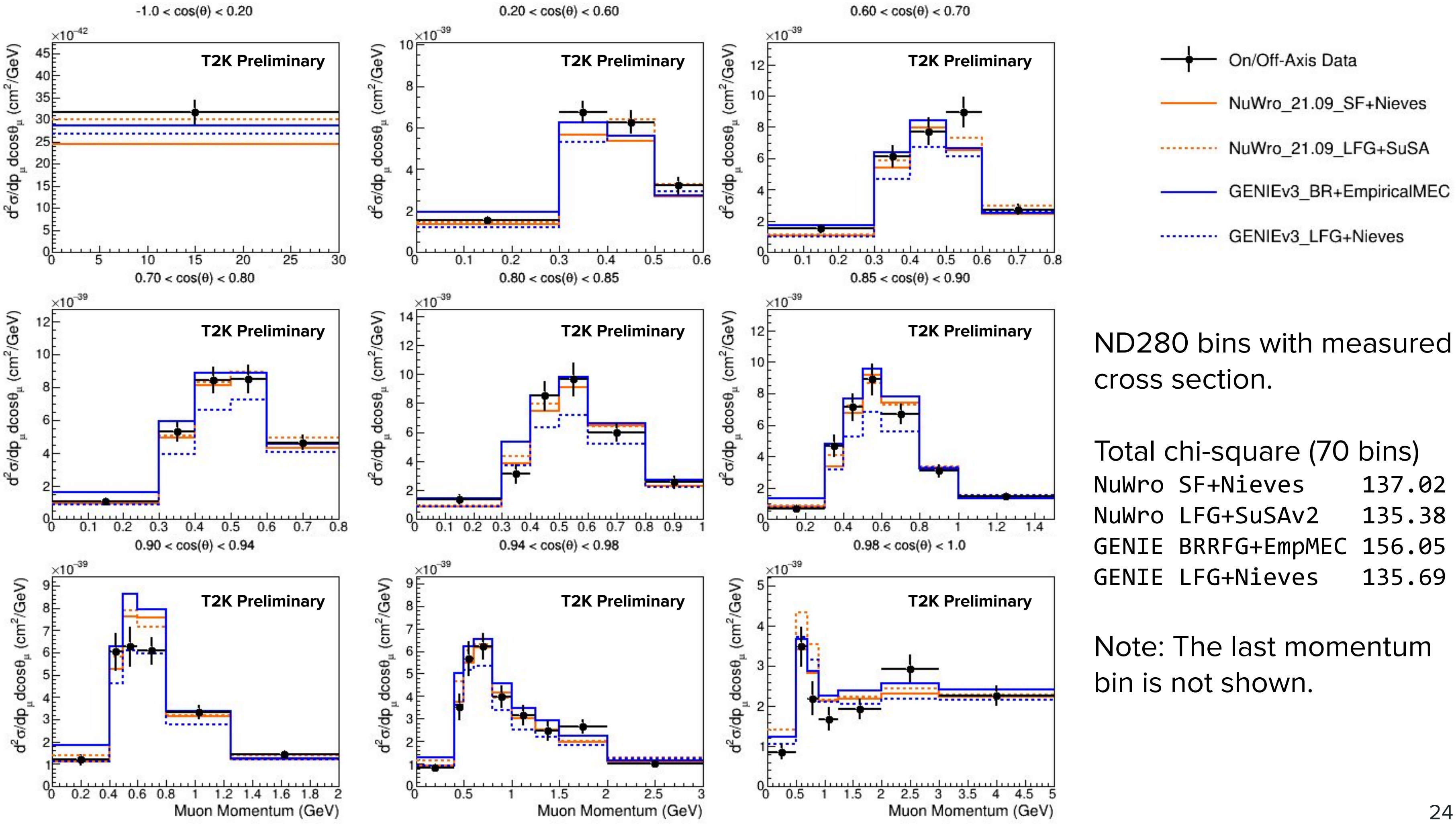
$$R(\vec{\mathbf{x}}) = \overbrace{\Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}})}^{\text{Near}} \times P(\nu_A \to \nu_B)$$

$$\underbrace{\Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}}) \times P(\nu_A \to \nu_B)}_{\text{Far}}$$

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



ND280 bins with measured cross section.

Total chi-square (70 bins)

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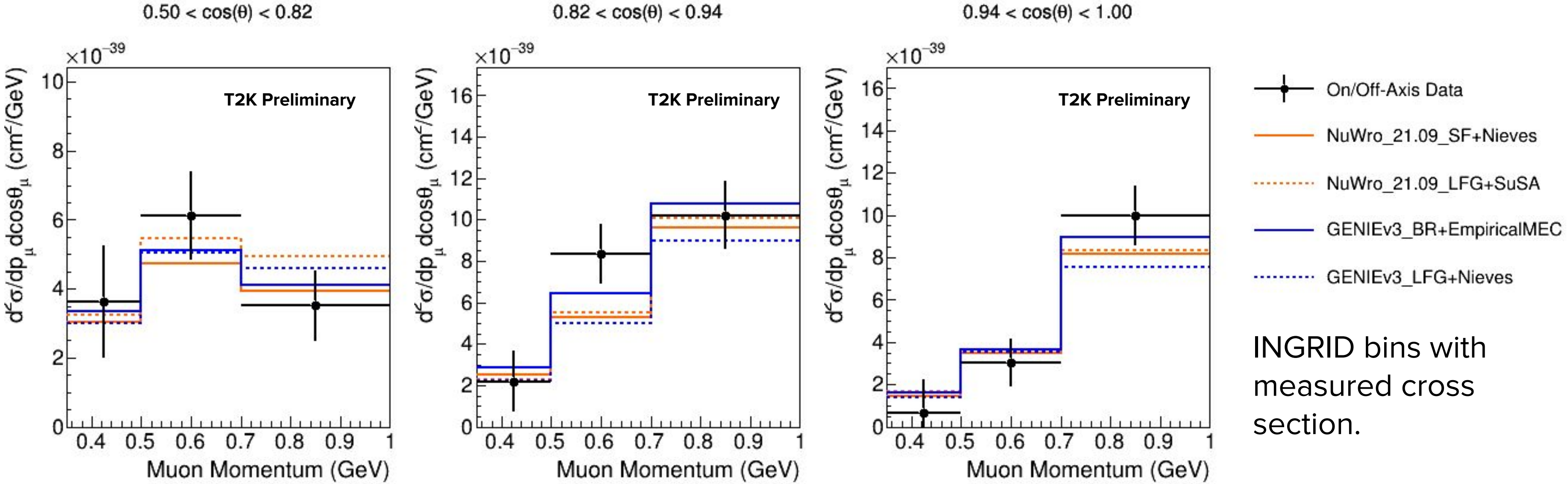
Note: The last momentum bin is not shown.



INGRID bins with measured cross section.

Note: The last momentum bin is not shown.

Flux Integrated Coherent Results

Flux integrated cross section extracted using all elements in FGD1 for both neutrino and antineutrino selections.

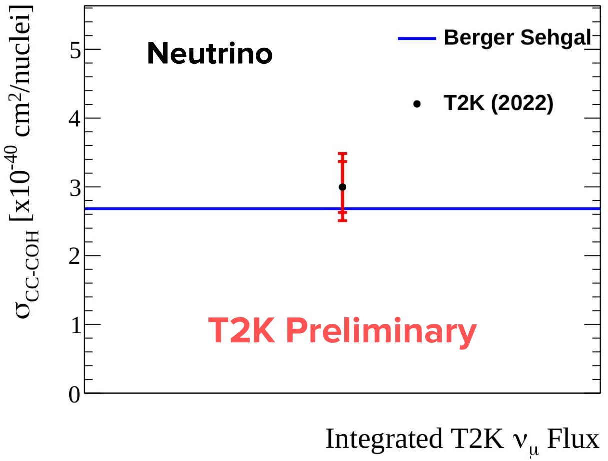
Neutrino results for FGD1:

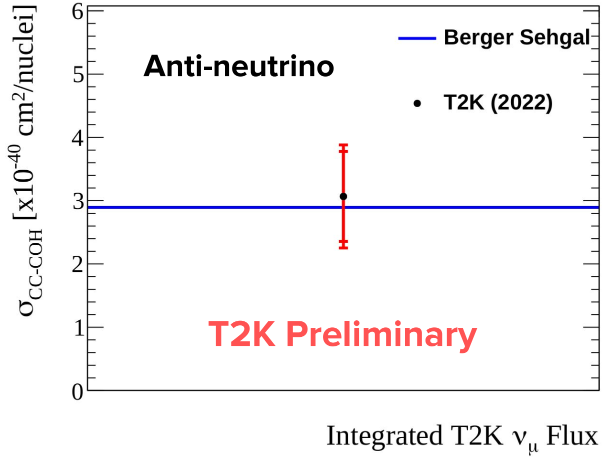
$$\sigma_{\text{FGD1}}^{\text{CC-COH}} = 3.00 \pm 0.37(\text{stat.}) \pm 0.58(\text{syst.}) \times 10^{-40}\text{cm}^2$$

Anti-neutrino results for FGD1:

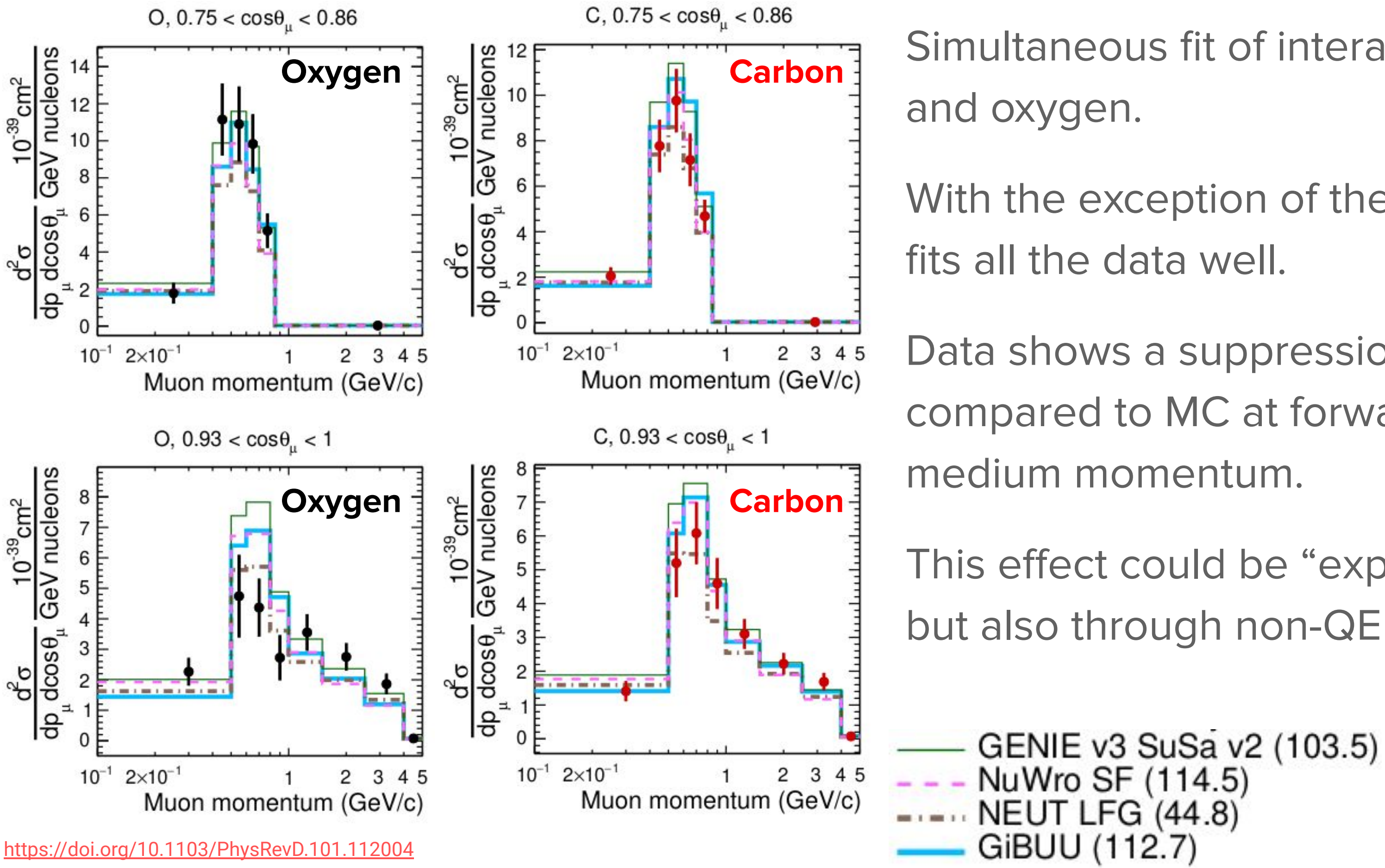
$$\sigma_{\text{FGD1}}^{\text{CC-COH}} = 3.07 \pm 0.71(\text{stat.}) \pm 0.85(\text{syst.}) \times 10^{-40}\text{cm}^2$$

Measurement above theoretical prediction from the Berger–Sehgal model, but well within uncertainties.





Neutrino Carbon & Oxygen CC0pi



Simultaneous fit of interactions on carbon and oxygen.

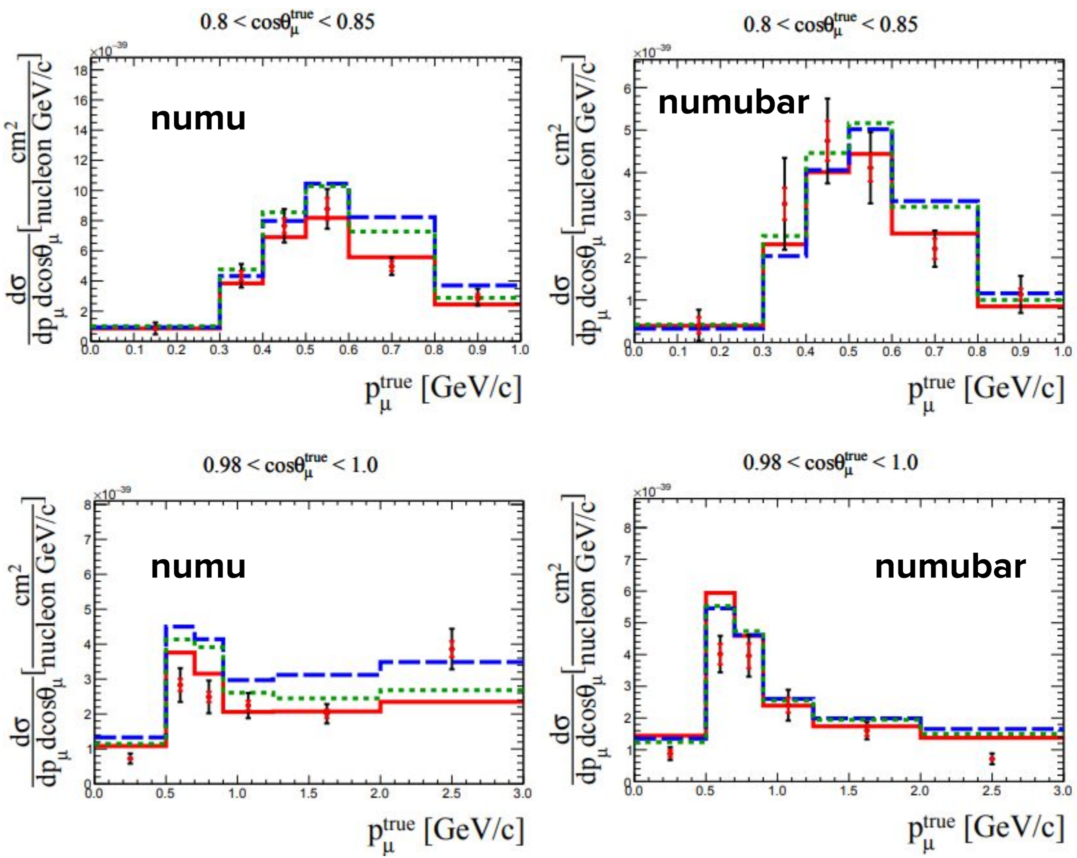
With the exception of the LFG, no model fits all the data well.

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

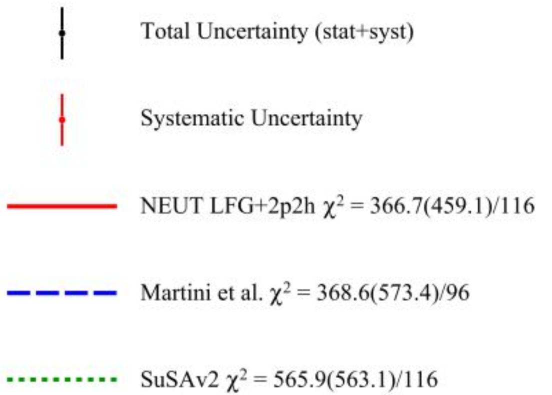
Neutrino & Antineutrino Carbon CC0pi



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.



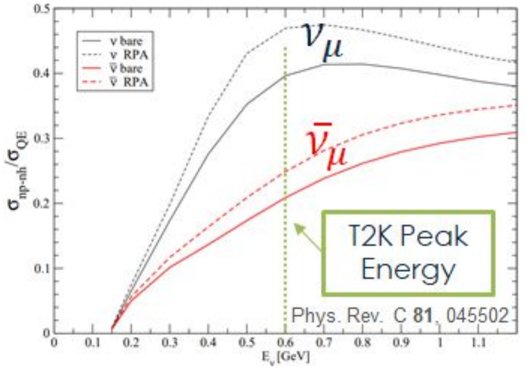
Full χ^2 (Shape-only χ^2) / DOF

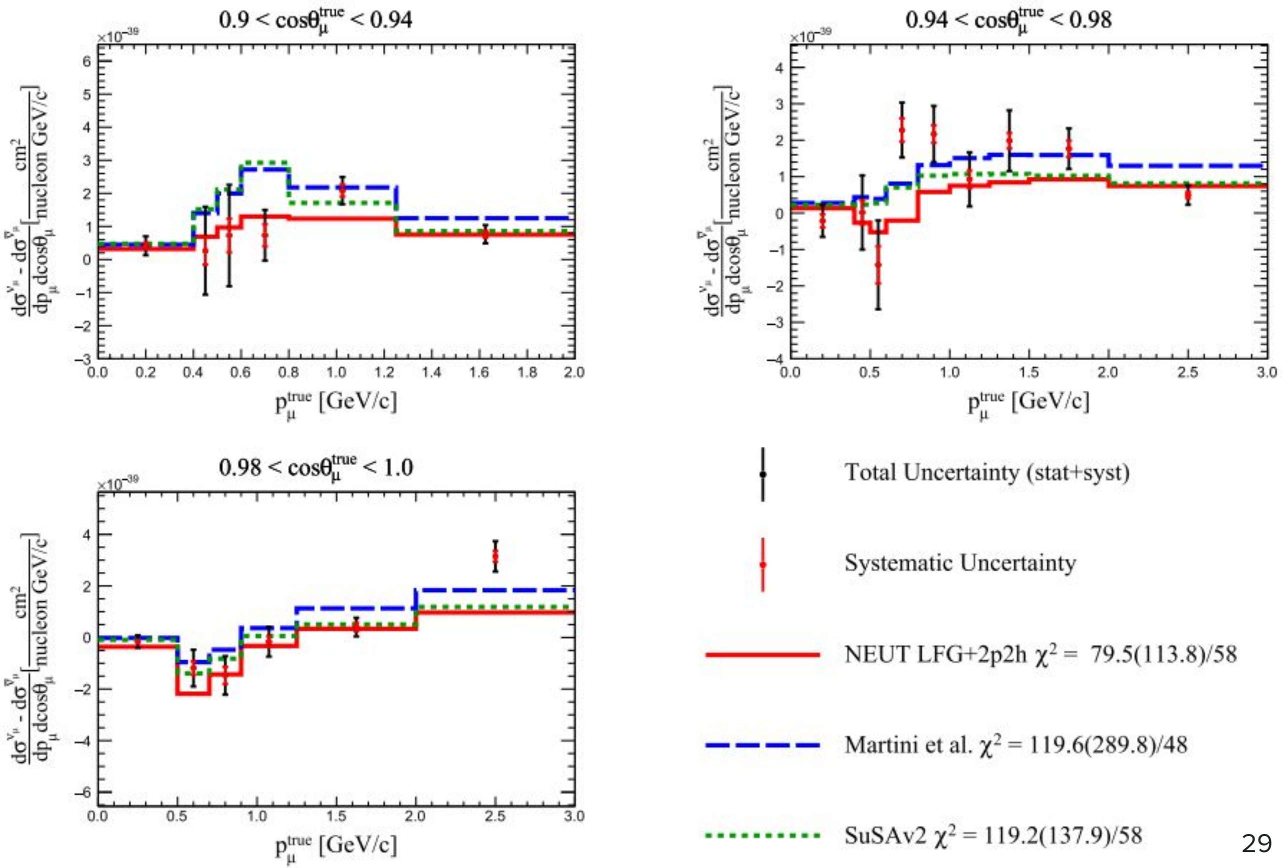
https://doi.org/10.1103/PhysRevD.101.112001

Neutrino & Antineutrino Carbon CC0pi

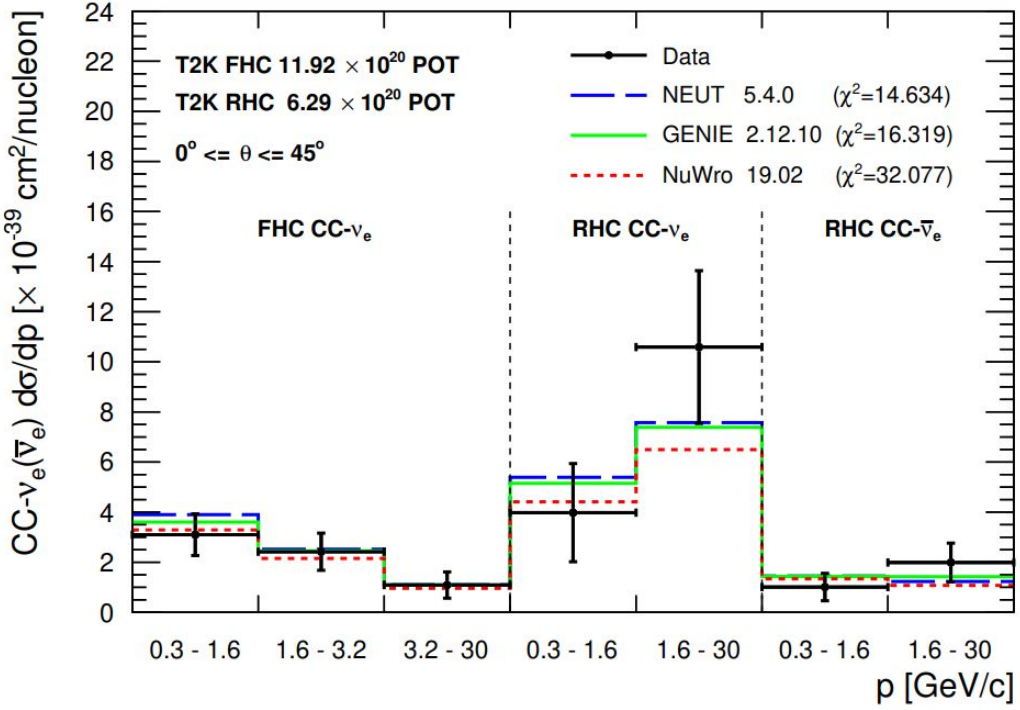
Difference between (anti)neutrino cross section sensitive to 2p2h models.

Limited by large experimental uncertainties and uncertainty in generator modelling.





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

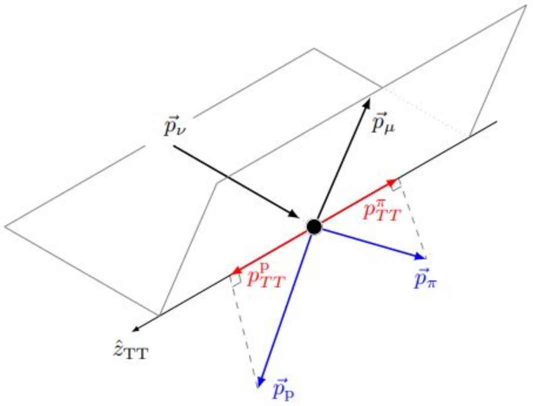
https://doi.org/10.1007/JHEP10(2020)114

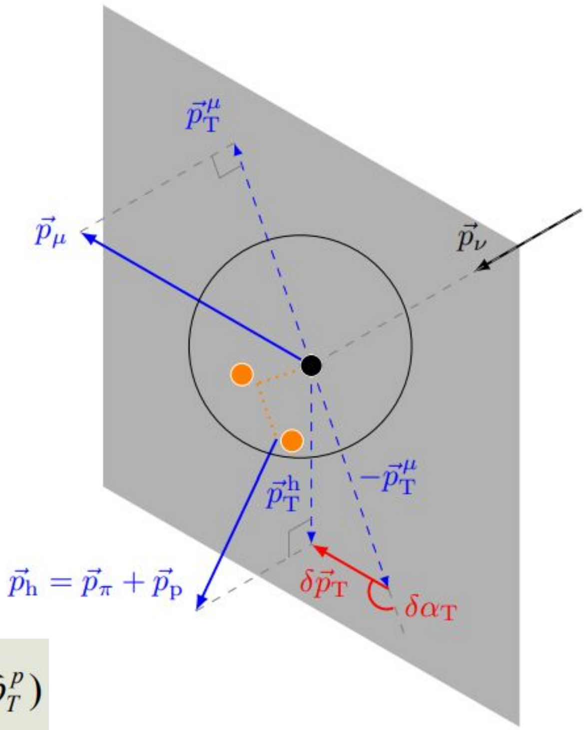
CC 1pi+ Transverse Kinematic Imbalance

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



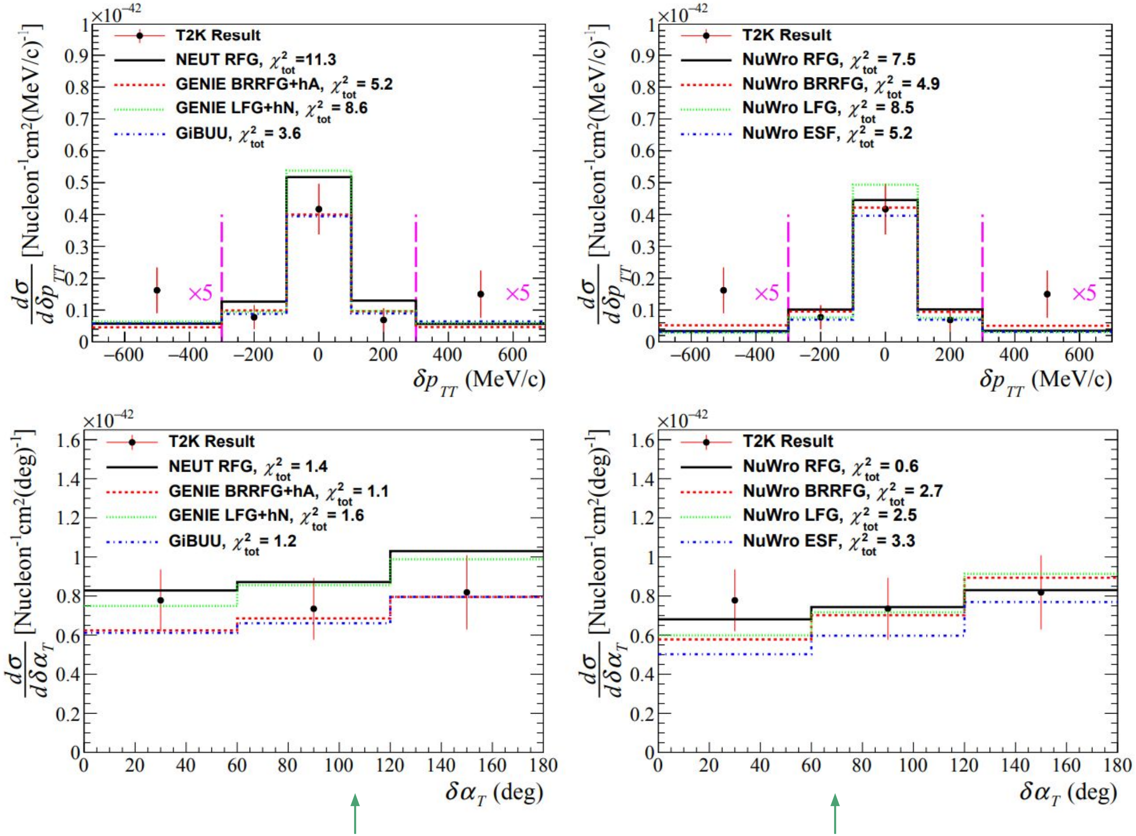


$$\delta\alpha_T = \cos^{-1}\frac{-\vec{p}_T^\mu \cdot \delta\vec{p}_T}{p_T^\mu \delta p_T}$$

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

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

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

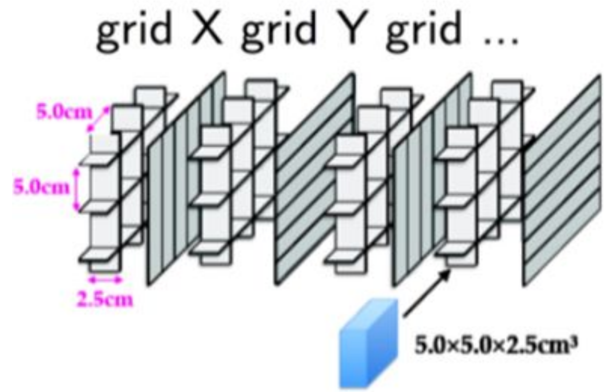
Proton Module

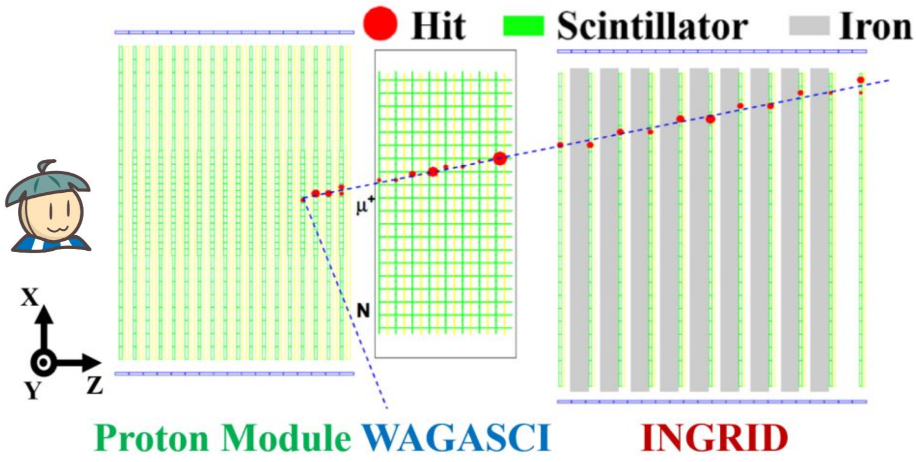
- Same as before, now off-axis
- Carbon target and tracking

Standard Module

- Same as before
- Muon range detector

Provides a water target with nearly 4pi coverage to match the phase-space and target at SK.
Shown here is the commissioning setup.

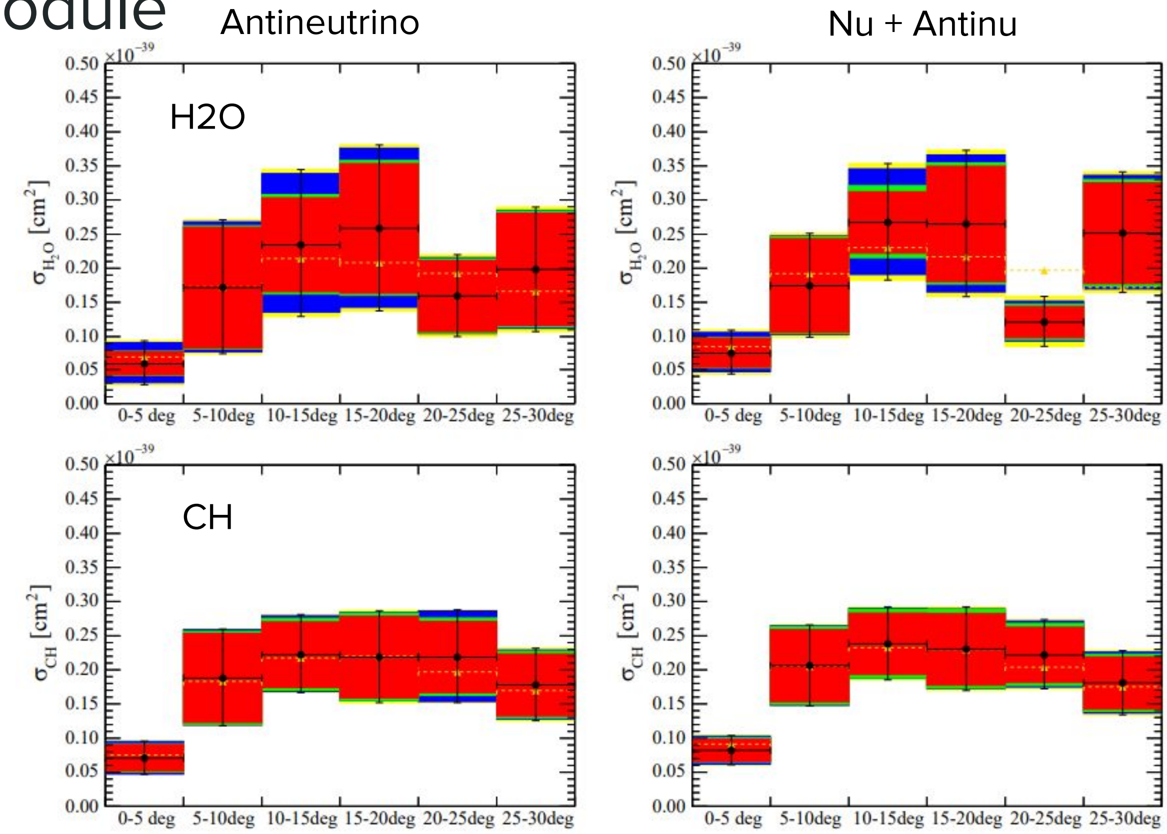


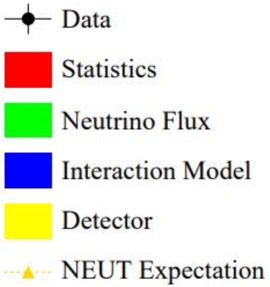


WAGASCI + Proton Module

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

Performed with the commissioning setup for WAGASCI.





	$\overline{\nu}_\mu$ 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