# T2K results on neutrino cross-sections

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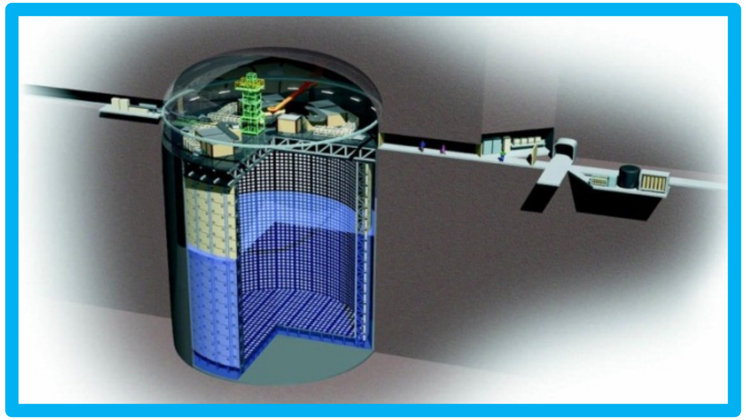
on behalf of the T2K collaboration

October 24, 2023

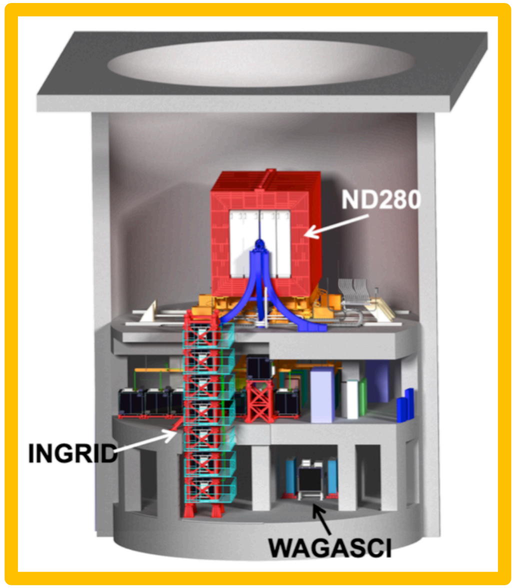
Neutrino Telescopes 2023

Istituto Veneto di Scienze, Lettere ed Arti

# The T2K Experiment



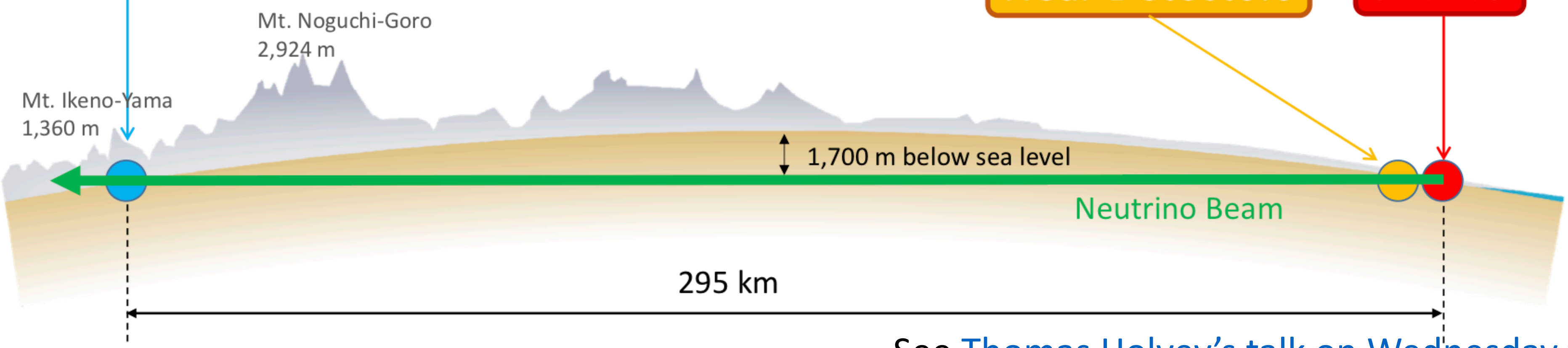
Super-Kamiokande





Near Detectors

J-PARC




See [Thomas Holvey's talk on Wednesday](#) for more details

# Why neutrino cross-sections are important

- In oscillation analysis, predicted event rate $\mathrm{N_{pred}}$ is directly affected by neutrino cross-sections $\boldsymbol{\sigma}$

$$\mathrm{N_{pred}} = \mathrm{P}_{\upsilon_\mu \to \upsilon_e} \times \boldsymbol{\sigma} \times \textbf{Neutrino Flux} \times \textbf{Target} \times \textbf{Detector Efficiency}$$

- Better understanding of neutrino cross-sections is crucial for neutrino oscillation analysis since it affects background estimation and energy reconstruction

- Neutrino cross-sections consist as one of the largest systematic uncertainty sources in neutrino oscillation analysis, for example:
  - In T2K recent publication on oscillation analysis, 1 ring $\upsilon_e$ sample:
  - 3.2% (cross-section) out of 4.7% (total uncertainty)

Eur. Phys. J. C 83, 782 (2023)

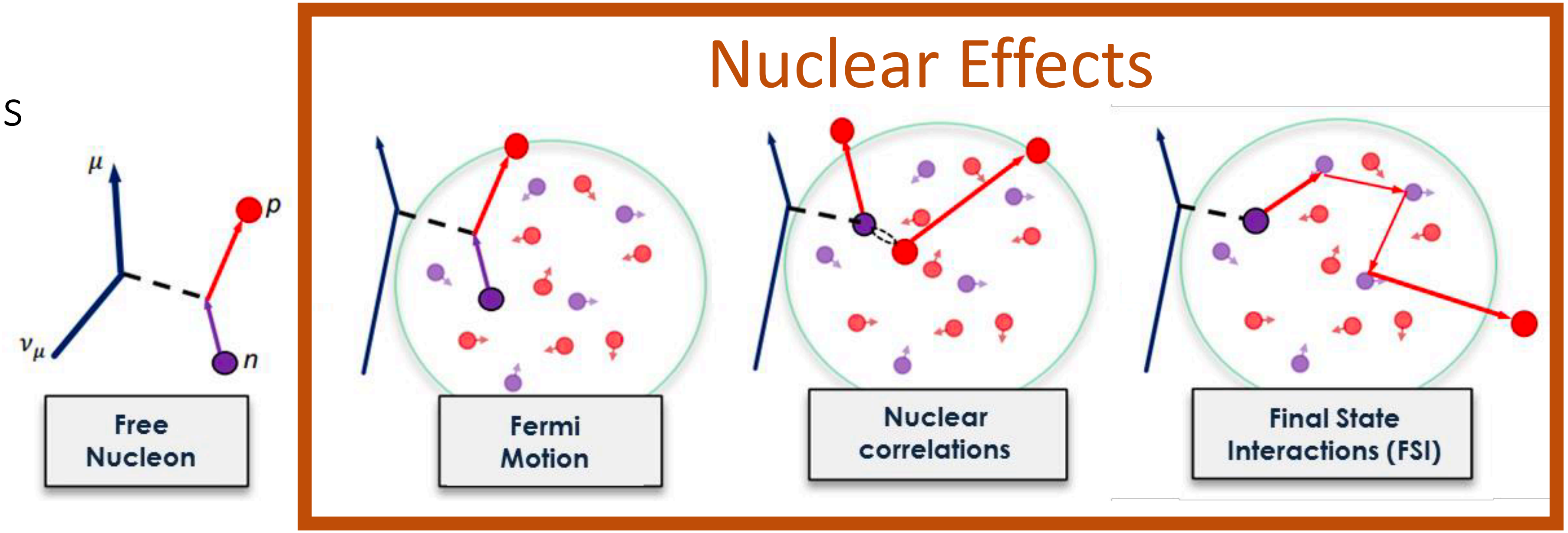
See Adrien Blanchet's talk on Wednesday for more details

- Precise constraining of neutrino cross sections is crucial for future neutrino oscillation experiments as not to limit statistical uncertainties

# What do we measure

- Neutrino interactions are convoluted by nuclear effects

- To minimize model dependence, we measure interaction 'topologies' (outgoing state from nucleus)



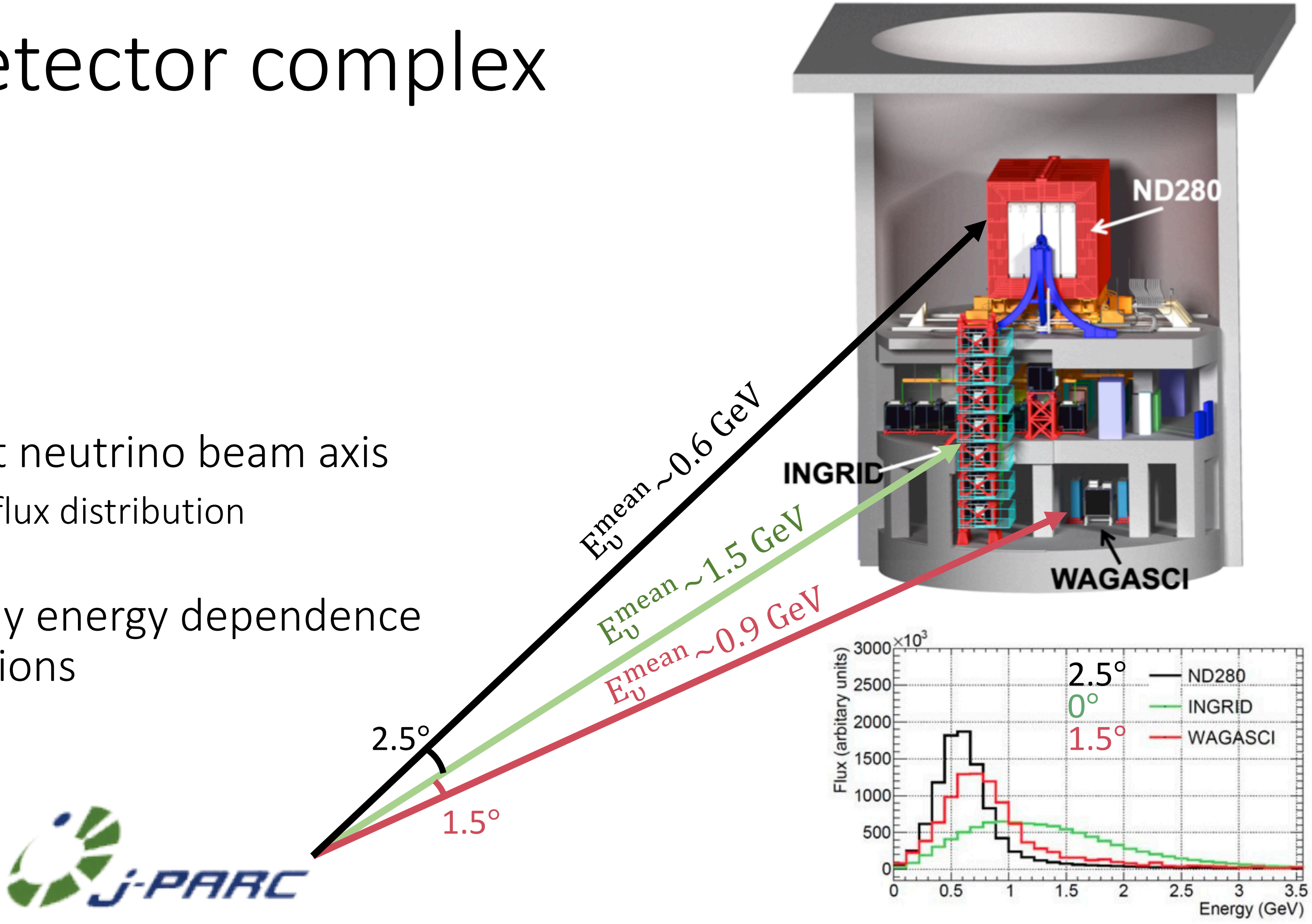

Diagrams by Patrick Stowell

Events are typically classified based on

- Neutrino type
- Interaction mode (charged/neutral current)
- Outgoing particles from the nucleus

# The near detector complex

- Multiple detectors:
  - ND280
  - INGRID
  - WAGASC
- Multiple angles w.r.t neutrino beam axis
  - ➢ Different neutrino flux distribution
- Opportunity to study energy dependence of neutrino interactions



# Recent results

# 1. $\upsilon_\mu CC\text{–}1\pi^+ Xp$ Transverse Kinematic Imbalance

Phys. Rev. D **103**, 112009

Forward Horn Current (FHC) beam at 2.5 deg off-axis

Off axis detector

- UA1 magnet, 0.2T field
- Time Projection Chambers (TPC)
- Fine Grained Detectors (FGD)
    - FGD1: Scintillator tracker (CH)
    - FGD2: Scintillator tracker with water (CH and $H_2O$)
    - Also serve as $\upsilon$ interaction target

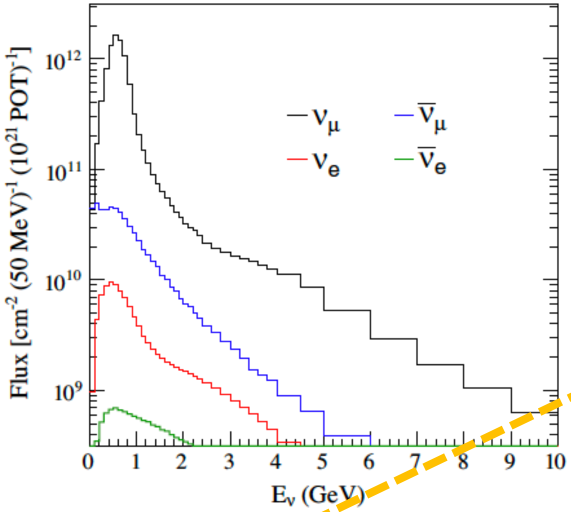
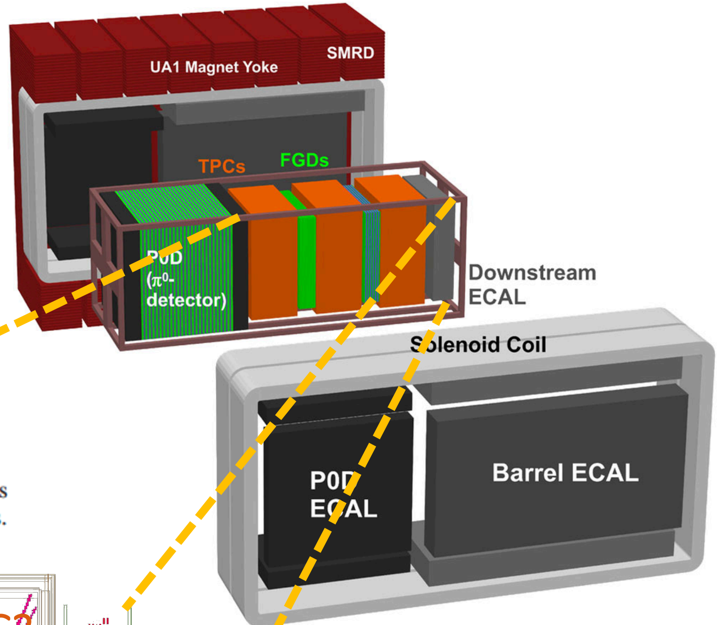
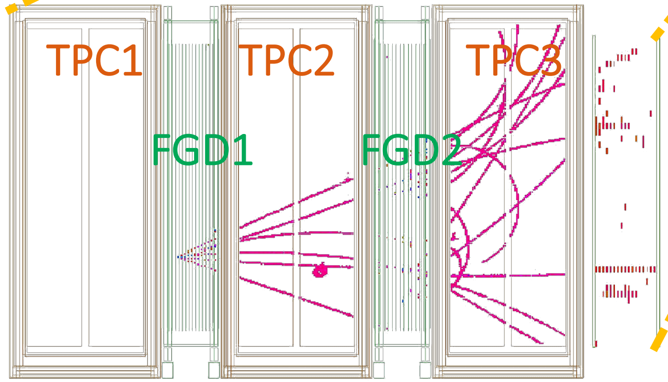



FIG. 2. The flux prediction for ND280 in neutrino-mode is shown as well as the contributions from different neutrino flavors.



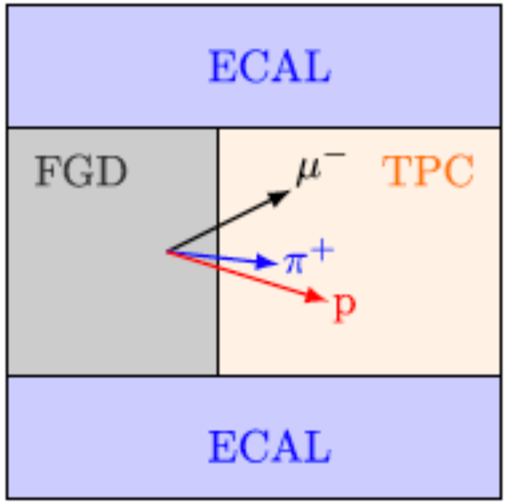



# 1. $\nu_\mu CC-1\pi^+ Xp$ Transverse Kinematic Imbalance

Phys. Rev. D **103**, 112009

Signal, interaction happens on FGD1 (CH)

- Single $\mu^-$
- Single $\pi^+$
- $\geq$1 proton




$\mu^-$, $\pi^+$, p in TPC

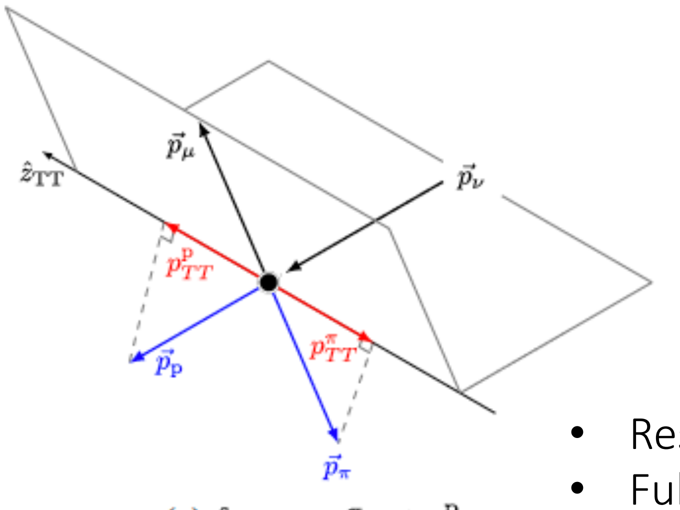
TKI variables are calculated from outgoing $\pi^+$ and highest momentum proton

TKI variables are sensitive to nuclear effects

# 1. $\upsilon_\mu CC{-}1\pi^+ Xp$ Transverse Kinematic Imbalance

Phys. Rev. D **103**, 112009

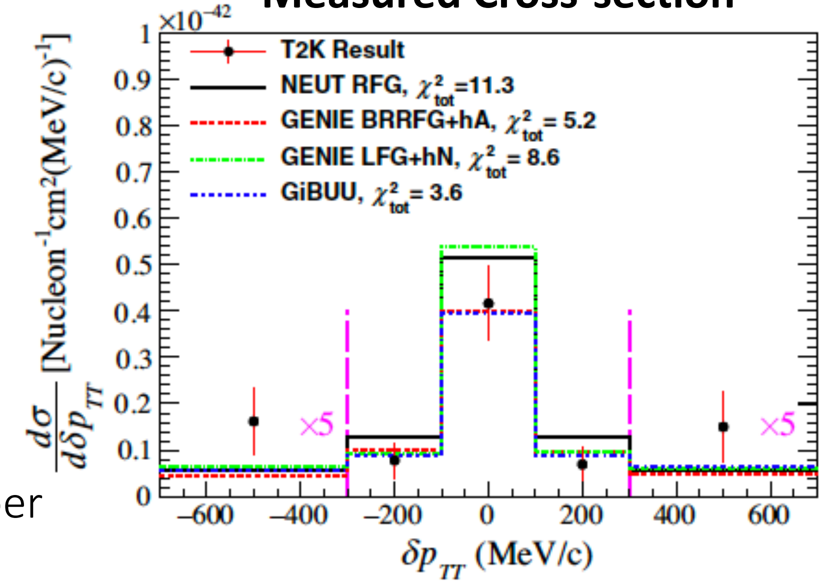
## $\delta p_{TT}$ - Double-transverse momentum imbalance




(a) $\delta p_{TT} = p^{\pi}_{TT} + p^{p}_{TT}$.

- Results are statistically limited
- Full results are available in the paper

**Measured Cross-section**




## Expectation

- $\delta p_{TT}$ = 0 if no nuclear effects
- Initial Fermi motion, nucleon-nucleon correlation, FSI smear the distribution

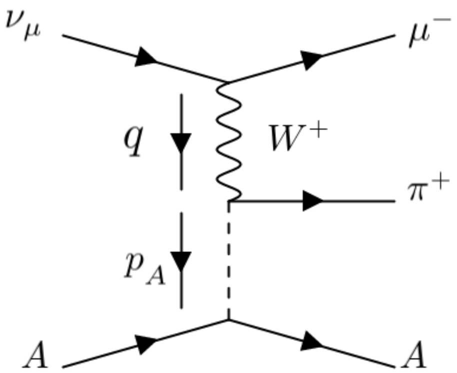
- The simple Fermi gas models (RFG and LFG) show a large disagreement
- Data show a slight preference for GiBUU, which uses a more realistic nuclear ground state to handle all interaction channels consistently.

# 2. $\nu_\mu$ and $\bar{\nu}_\mu$ CC-COH on C

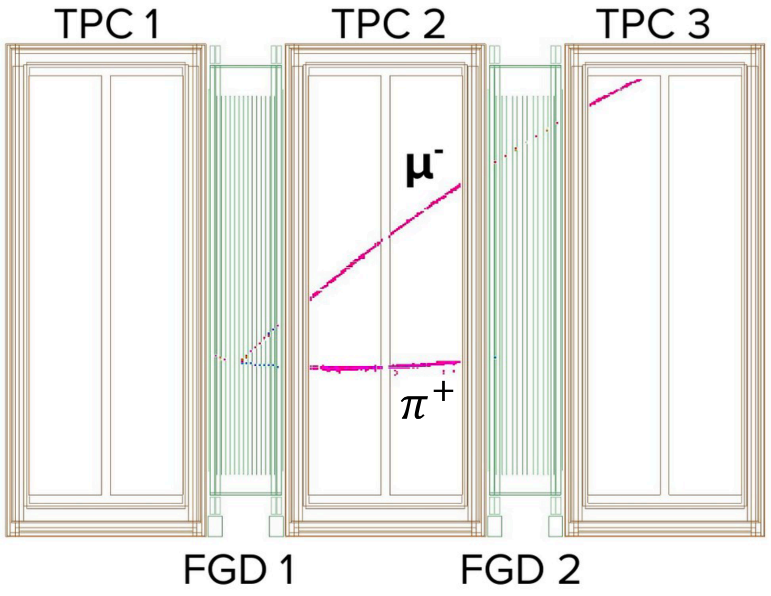
arXiv:2308.16606
Accepted by PRD 10 days ago!

Signal, coherent interaction happens on FGD1 (CH)

- Single $\mu^-$
- Single $\pi^+$
- No other particles




$$|p_A|^2 = |q - p_\pi|^2 = |t|$$

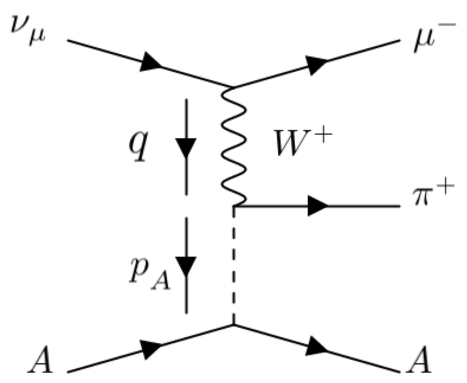


# 2. $\upsilon_\mu$ and $\bar{\nu}_\mu$ CC-COH on C

arXiv:2308.16606
Accepted by PRD 10 days ago!

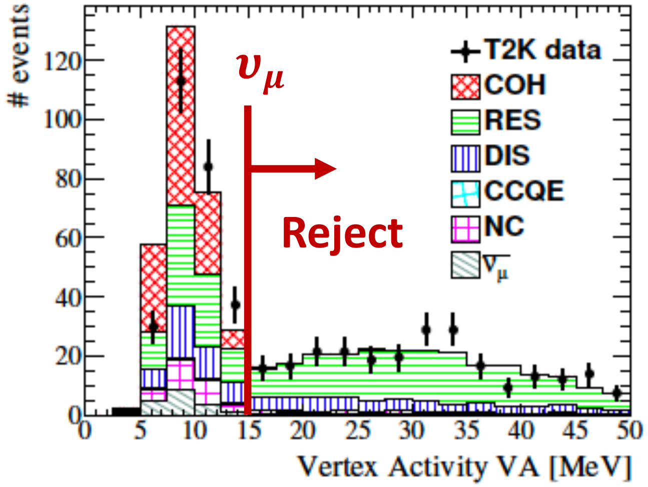
Observable variables

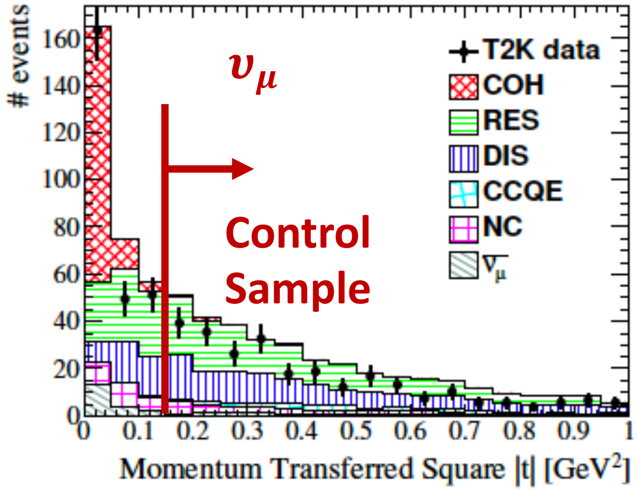
- |t|: magnitude of the square of the four-momentum transfer to the nucleus, small to maintain coherence
- Vertex Activity (VA): energy deposited in a ~ (5cm)$^3$ volume around the vertex




$$|p_A|^2 = |q - p_\pi|^2 = |t|$$

**Selected samples**



# 2. $\nu_\mu$ and $\bar{\nu}_\mu$ CC-COH on C

arXiv:2308.16606
Accepted by PRD 10 days ago!

## $\nu_\mu$ cross-section:

- Update measurement from 2016
- Uncertainty reduced by a half
- Better background constraint for oscillation analysis

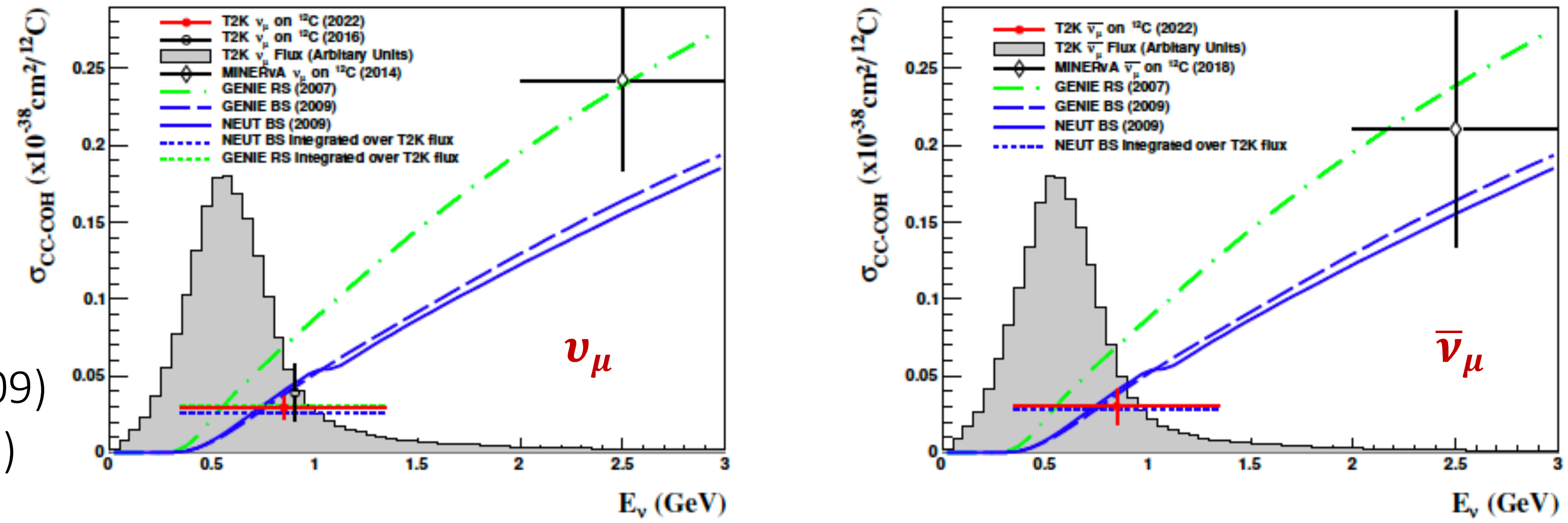
## $\bar{\nu}_\mu$ cross-section:

- First measurement in T2K

## Compatible with flux integrated models:

- NEUT 5.4.0 Berger-Sehgal (2009)
- GENIE 2.8.0 Rein-Sehgal (2007)

**Measured Cross-sections**

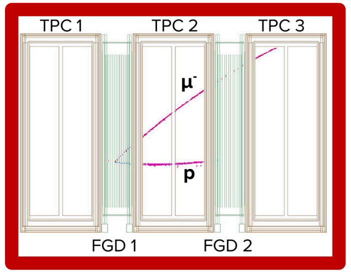


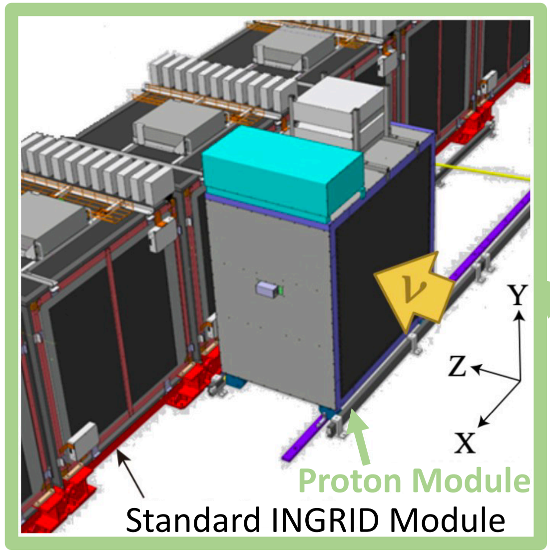
# 3. $\upsilon_{\mu}$ CC-0$\pi$ on CH On/Off Axis

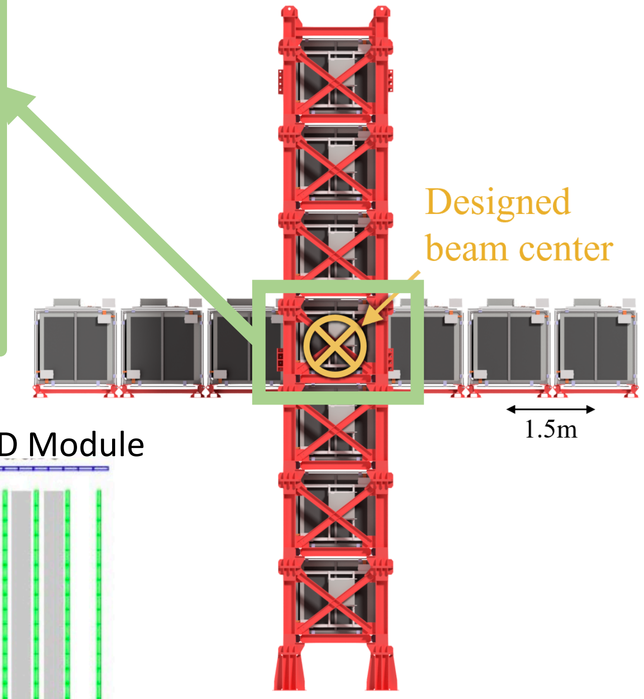
arXiv:2303.14228
Under Review by PRD

Signal, interaction happens on FGD1 (off axis) and INGRID Proton Module (on axis)

- Single $\mu^{-}$
- No pions
- Any number of protons



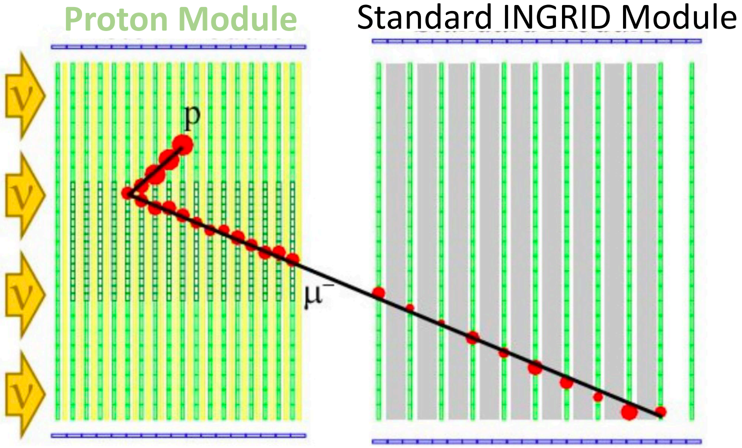




INGRID detector

## INGRID detector

- **Standard INGRID Module**: muon tracker (CH + Fe)
  - 14 modules form a cross
- Proton Module: scintillator tracking planes (CH)
  - In the center between vertical and horizontal standard module

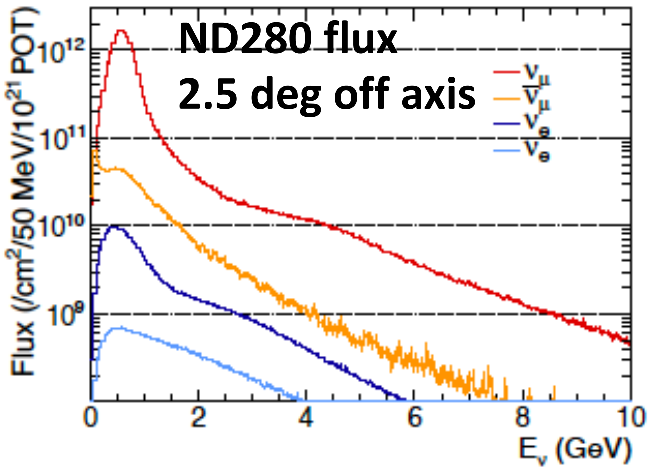


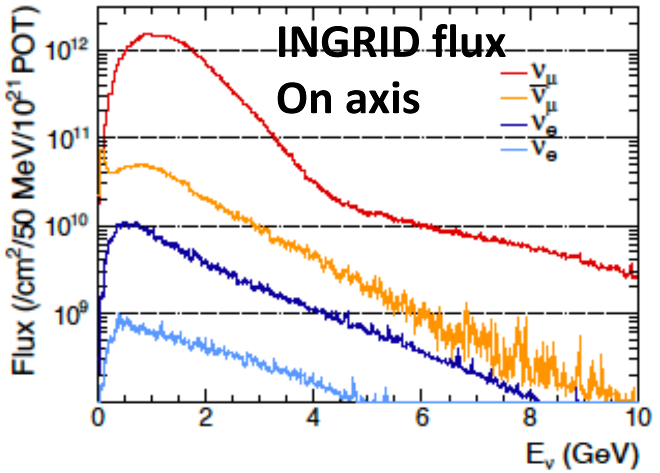
# 3. $\upsilon_\mu$ CC-0$\pi$ on CH On/Off Axis

arXiv:2303.14228
Under Review by PRD

First measurement using multiple detectors with correlated energy spectra at T2K

- Reduce the impact of the flux uncertainty
- Study the energy dependence of neutrino interactions



# 3. $\upsilon_\mu$ CC-0$\pi$ on CH On/Off Axis

arXiv:2303.14228
Under Review by PRD

70 degrees of freedom

- 58 ND280 bins
- 12 INGRID bins

Larger $\chi^2$ for ND280 due to ND280 having finer bins

Unique aspect:

- First time a joint cross-section fit has been made with two different fluxes simultaneously including correlations
- Compare how a given model does for ND280 and INGRID
- Compare how the full result with correlations is better or worse than naïve sum

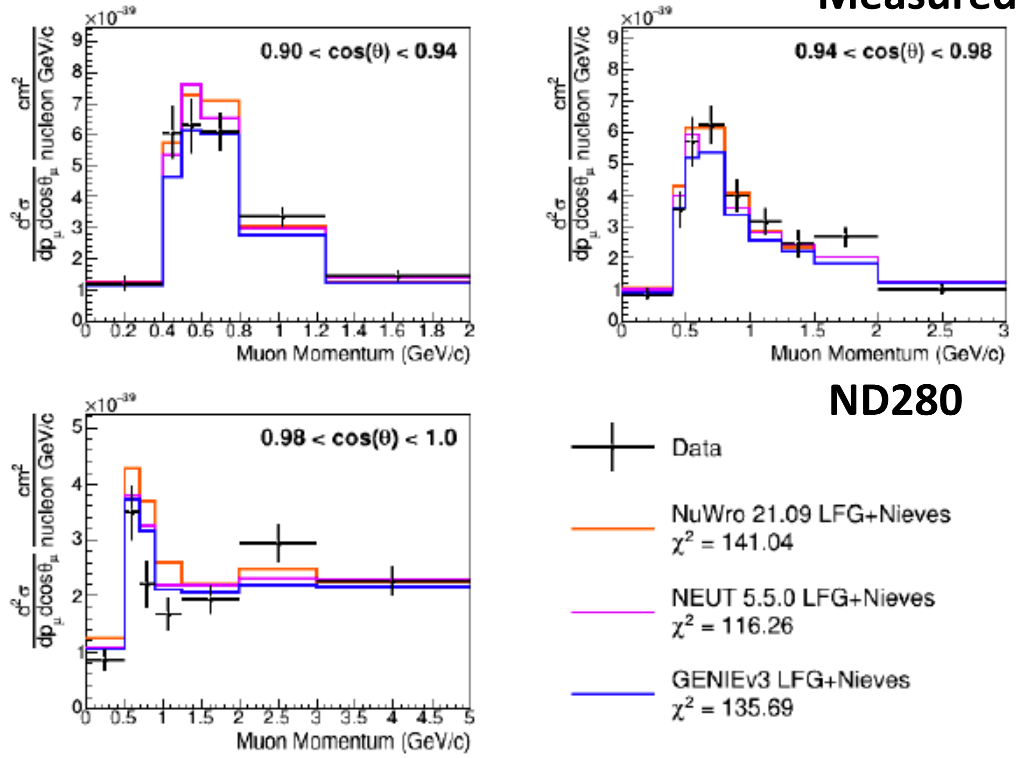
**$\chi^2$ models vs. data**

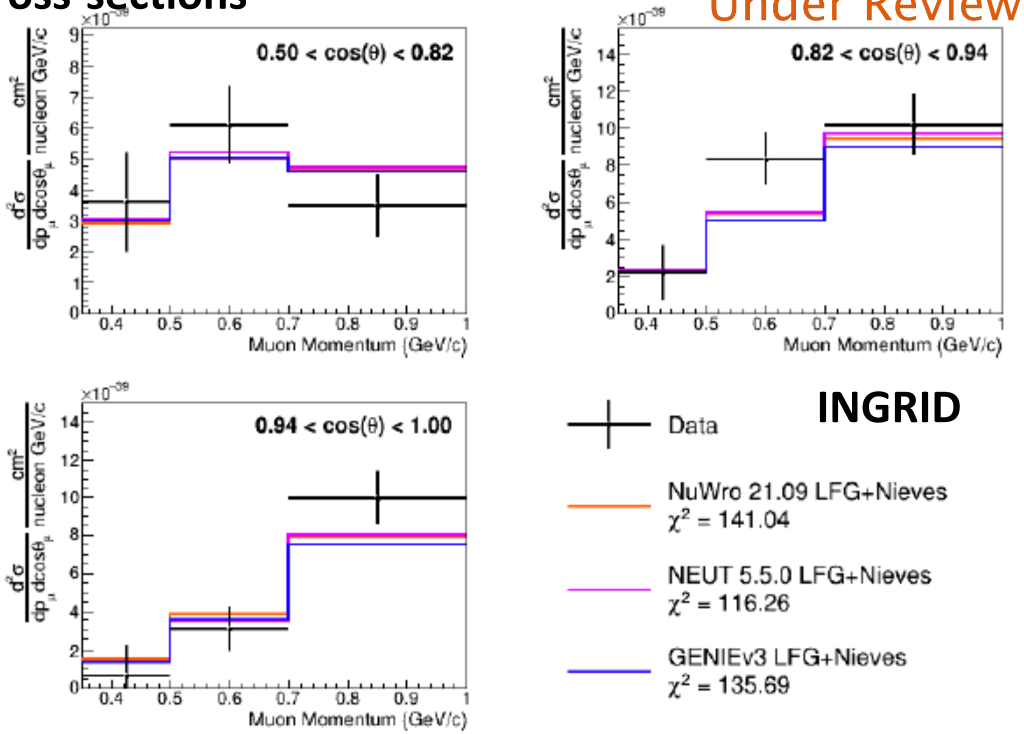
| Model | ND280 | INGRID | Joint |
|---|---|---|---|
| Nominal MC (NEUT) | 136.34 | 18.21 | 158.71 |
| NEUT LFG+Nieves | 106.46 | 11.46 | 116.26 |
| NEUT SF+Nieves $M_A = 1.03$ | 194.88 | 14.36 | 209.18 |
| NEUT SF+Nieves $M_A = 1.21$ | 158.71 | 9.98 | 170.93 |
| NuWro SF+Nieves | 122.74 | 15.68 | 137.02 |
| NuWro LFG+Nieves | 125.88 | 12.75 | 141.04 |
| NuWro LFG+SuSAv2 | 121.57 | 11.13 | 135.38 |
| NuWro LFG+Martini | 138.86 | 12.46 | 155.68 |
| GENIE BRRFG+EmpMEC | 141.40 | 12.80 | 156.05 |
| GENIE LFG+Nieves | 125.50 | 14.45 | 135.69 |

# 3. $\upsilon_\mu$ CC-0$\pi$ on CH On/Off Axis

arXiv:2303.14228
Under Review by PRD

**Measured Cross-sections**



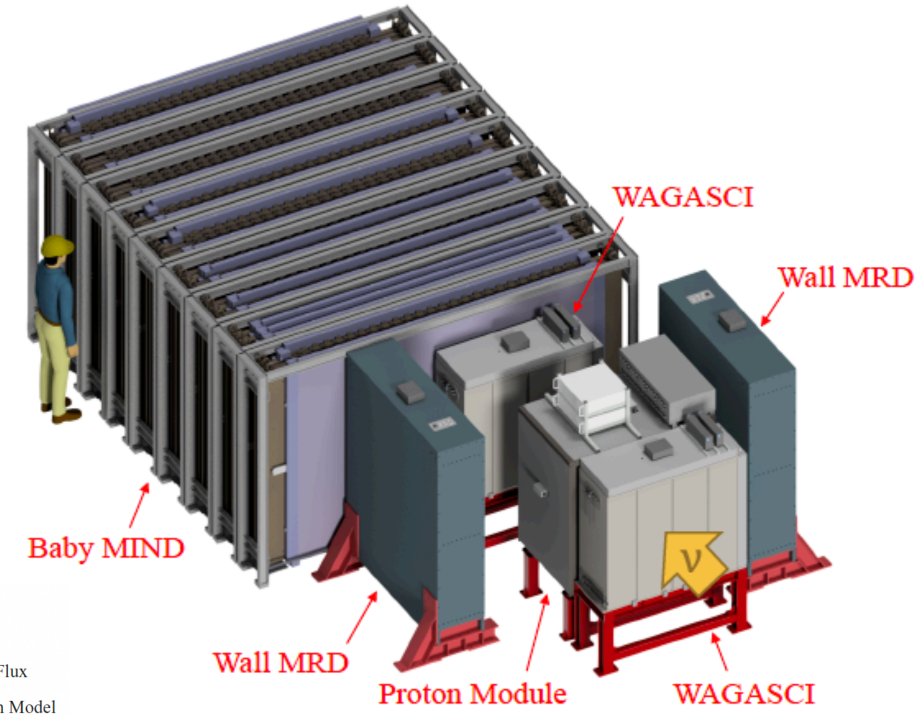




- Current models struggle to describe the data
- Consistent with previous measurement

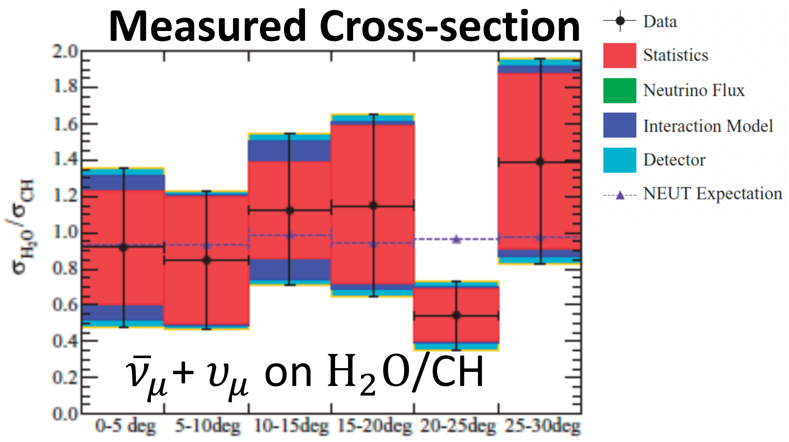
In the future the new WAGASCI and BabyMIND detectors at 1.5 deg off axis could be used to extend this analysis to use three energy spectra, and provide additional statistics

# Ongoing measurements

# 1. $\nu_\mu$ CC-0$\pi$ on $H_2O$ and CH



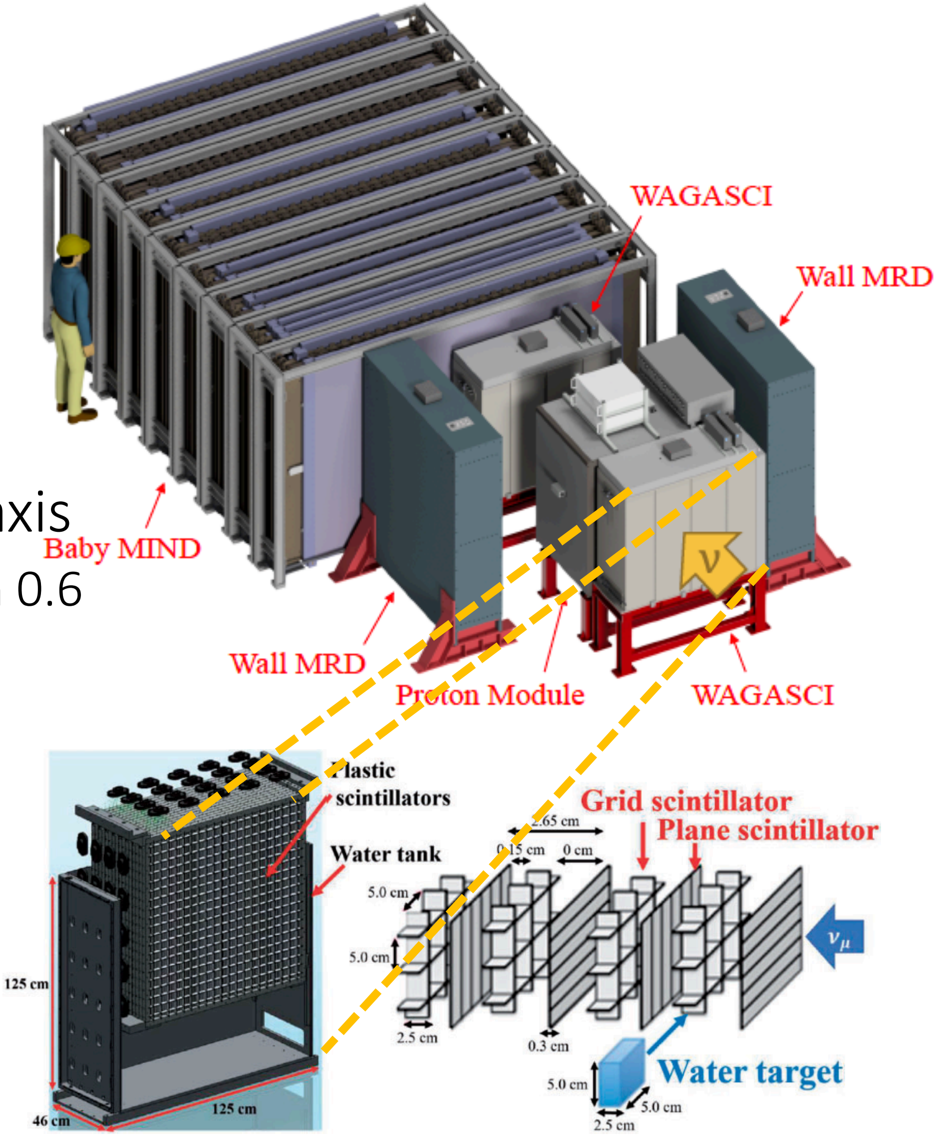

- Signal
  - Single $\mu$ like track
  - No pions
- There has been a result with a limited configuration of WAGASCI
  - $\bar{\nu}_\mu$ and $\bar{\nu}_\mu + \nu_\mu$ CC-0$\pi$0p
  - [Prog. Theor. Exp. Phys. 2021, 043C01]
  - Results agree with the NEUT model used in the T2K oscillation analysis




- This will be the first analysis with the full set of WAGASCI-BabyMIND detectors.

# 1. $\nu_\mu$ CC-0$\pi$ on $\mathrm{H_2O}$ and CH

- Signal
  - Single $\mu$ like track
  - No pions
- Upgraded WAGASCI-BabyMIND detectors at 1.5 deg off axis
  - WAGASCI: grid scintillator with high angle acceptance filled with 0.6 tons of water ($\mathrm{H_2O}$+CH)
  - Wall **M**uon **R**ange **D**etector (MRD): Scintillator tracking planes between iron planes
    - Increase detection efficiency for high-angle events
  - Baby MIND: With magnetic field inside iron planes
    - Can identify particle charges
- Unblinded results under publication board review.

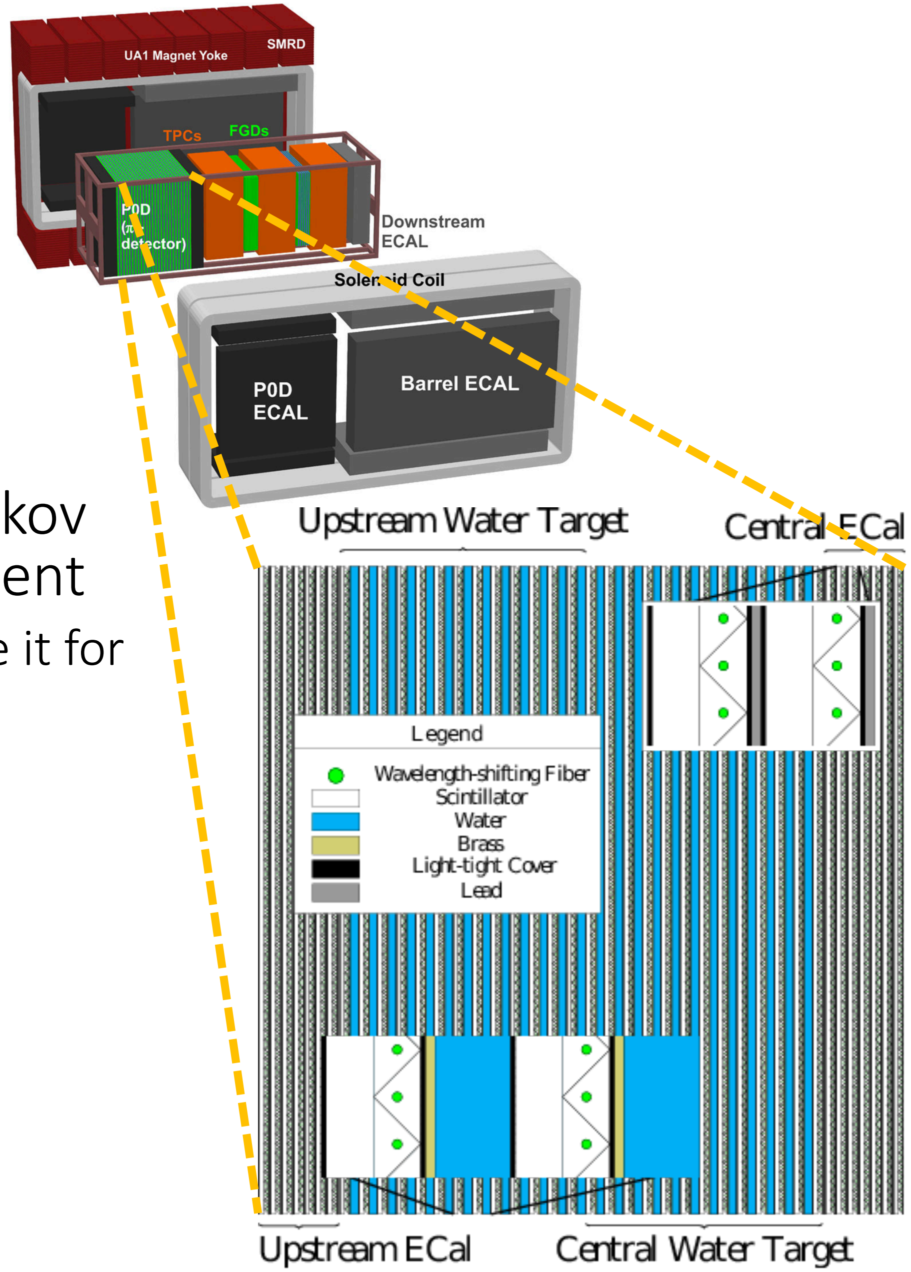


# 2. NC-1$\pi^0$ on $H_2O$

- Signal contains a single $\pi^0$
- One of the dominate background in $\nu_e$ appearance
- A novel analysis method using a Bayesian inference Markov Chain Monte Carlo (MCMC) for cross section measurement
  - It has been used for oscillation analysis, so the novelty is to use it for cross sections

- Pi0 Detector (P0D) at 2.5 deg off axis
  - Alternating scintillator, lead, and water layers
  - Water can be filled/drained
  - Two configurations enable measurement of interaction on water

- Fake data study finished, working on unblind results

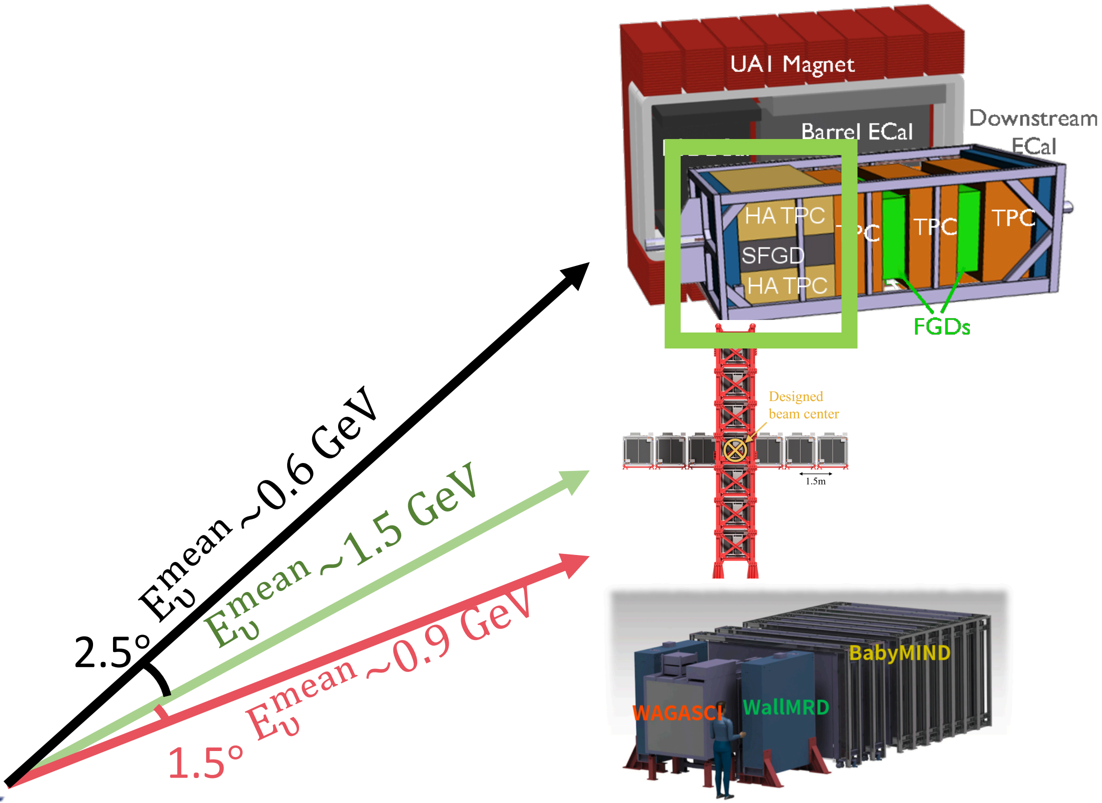


# Outlook

# Looking to the Future

Many analyses and papers coming soon!

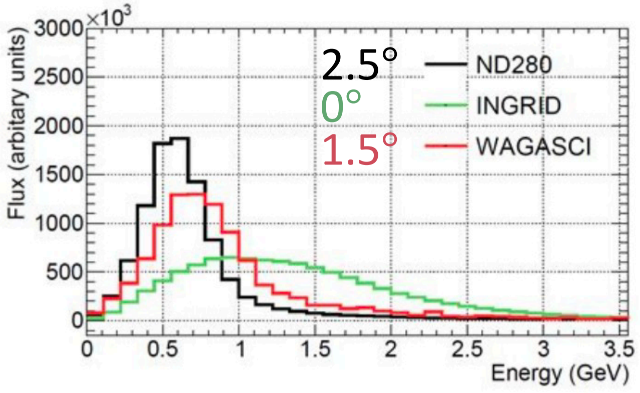
- WAGASCI/BabyMIND joint CH/water CC0pi
- $\nu_e$ CC1$\pi^+$ in FGD1
- Kaon in FGD1
- NC1$\pi^0$ in the P0D
- NC1$\pi^+$ in FGD1
- $\nu_\mu$ CC1pi on CH and Water
- …




New analysis strategy with the MCMC method work in progress

Detector upgrades

- WAGASCI/BabyMIND
- ND280 upgrade with SuperFGD and High Angle TPC
- See Weijun Li's talk on Thursday for more details



# Recent T2K results on neutrino cross-sections

- First measurement of muon neutrino charged-current interactions on hydrocarbon without pions in the final state using multiple detectors with correlated energy spectra at T2K, arXiv:2303.14228(2023)
- Measurements of the $\upsilon_\mu$ and $\bar{\nu}_\mu$-induced Coherent Charged Pion Production Cross Sections on $^{12}C$ by the T2K Experiment, arXiv:2308.16606 (2023)
- First T2K measurement of transverse kinematic imbalance in the muon-neutrino charged current single production channel containing at least one proton, PRD 103, 112009 (2021)
- Measurements of $\bar{\nu}_\mu$ and $\bar{\nu}_\mu + \upsilon_\mu$ CC cross-sections without detected pions or protons on water and hydrocarbon at a mean anti-neutrino energy of 0.86 GeV, Prog. Theor. Exp. Phys., 043C01 (2021)
- Measurement of the charged-current electron (anti-neutrino) inclusive cross sections at the T2K off-axis near detector, JHEP10, 114 (2020)
- Simultaneous measurement of the muon neutrino charged-current cross section on oxygen and carbon without pions in the final state at T2K, Phys. Rev. D 101, 112004 (2020)
- First combined measurement of the muon neutrino and anti-neutrino charged-current cross section without pions in the final state in T2K, Phys. Rev. D 101, 112001 (2020)
- Measurement of the muon neutrino charged current single production on hydrocarbon using T2K off axis near detector ND280, Phys. Rev. D 101, 012007 (2020)
- First measurement of the charged current anti-muon neutrino double differential cross section on a water target without pions in the final state, Phys. Rev. D 102, 012007 (2020)

# Thank you for your attention

# Backup

# Oscillation analysis uncertainty source table with caption

**Table 10** Uncertainties on the number of events in each FD sample broken down by source after (before)the fit to ND data. "FD + SI + PN" combines the uncertainties from the FD detector, secondary particle interactions (SI), and photo-nuclear (PN) effects. "Flux⊗Interaction" denotes the combined effect from the ND constrained flux and interaction parameters, and the unconstrained interaction parameters. The change in the "FD + SI + PN" uncertainties before and after the ND fit is an indirect effect due to the change of interaction mode fractions in the samples after the ND fit

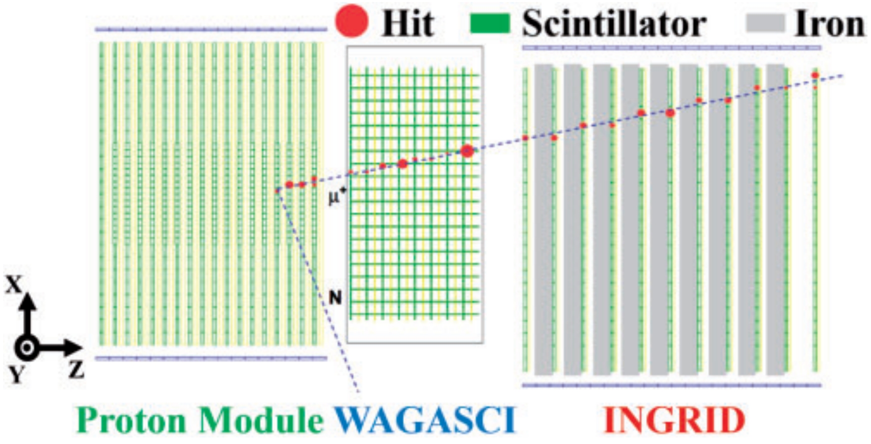
| Sample | | Uncertainty source (%) | | | Flux⊗Interaction (%) | Total (%) |
|---|---|---|---|---|---|---|
| | | Flux | Interaction | FD + SI + PN | | |
| 1R$\mu$ | $\nu$ | 2.9 (5.0) | 3.1 (11.7) | 2.1 (2.7) | 2.2 (12.7) | 3.0 (13.0) |
| | $\overline{\nu}$ | 2.8 (4.7) | 3.0 (10.8) | 1.9 (2.3) | 3.4 (11.8) | 4.0 (12.0) |
| 1R$e$ | $\nu$ | 2.8 (4.8) | 3.2 (12.6) | 3.1 (3.2) | 3.6 (13.5) | 4.7 (13.8) |
| | $\overline{\nu}$ | 2.9 (4.7) | 3.1 (11.1) | 3.9 (4.2) | 4.3 (12.1) | 5.9 (12.7) |
| 1R$e$1d$e$ | $\nu$ | 2.8 (4.9) | 4.2 (12.1) | 13.4 (13.4) | 5.0 (13.1) | 14.3 (18.7) |

# 0. $\bar{\nu}_\mu$ and $\bar{\nu}_\mu + \nu_\mu$ CC-0$\pi$0p on $\mathrm{H_2O}$ and CH

[Prog. Theor. Exp. Phys. 2021, 043C01]

Signal

- Single $\mu$ like track
- No pions
- No protons


Detectors

Proton Module: scintillator tracking planes (CH)

WAGASCI: grid scintillator with high angle acceptance filled with 0.6 tons of water ($\mathrm{H_2O}$+CH)

INGRID: muon tracker

# 0. $\bar{\nu}_\mu$ and $\bar{\nu}_\mu + \nu_\mu$ CC-0$\pi$0p on $\mathbf{H_2O}$ and CH

Prog. Theor. Exp. Phys. 2021, 043C01

Reverse Horn Current (RHC) beam at 1.5 deg off-axis

Limited phase space for good efficiency

- $\theta_\mu < 30$ deg
- $p_\mu > 400$ MeV

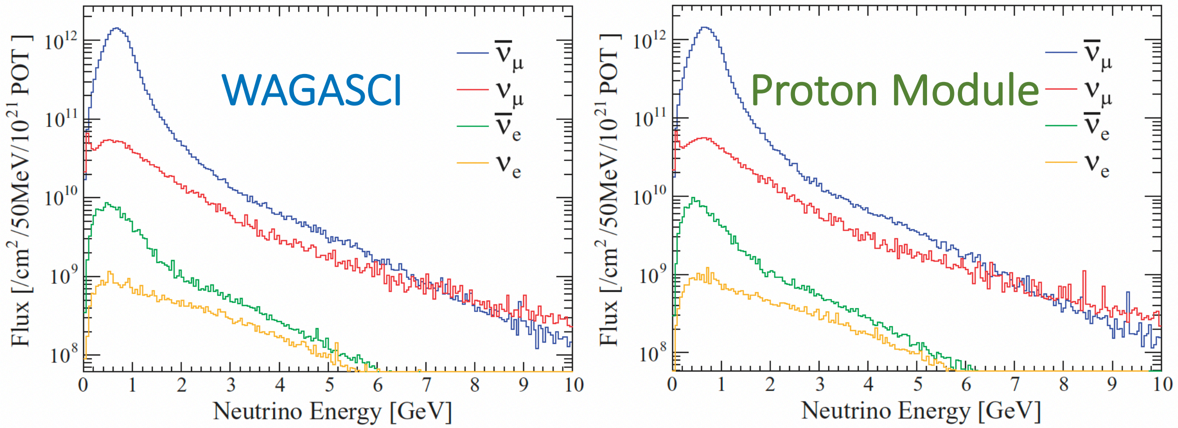



**Fig. 7.** Predicted (anti-)neutrino fluxes at the WAGASCI module (left) and the Proton Module (right).

**Table 5.** Calculated detection efficiencies of $\overline{\nu}_\mu$ and $\overline{\nu}_\mu + \nu_\mu$ CC events for each of the phase-space bins.

| | $\overline{\nu}_\mu$ | | $\overline{\nu}_\mu + \nu_\mu$ | |
|---|---|---|---|---|
| True phase space | WAGASCI | Proton Module | WAGASCI | Proton Module |
| CCother | 0.194 | 0.237 | 0.233 | 0.289 |
| CC0$\pi$0p : 0–5° | 0.683 | 0.897 | 0.682 | 0.897 |
| CC0$\pi$0p : 5–10° | 0.738 | 0.896 | 0.729 | 0.892 |
| CC0$\pi$0p : 10–15° | 0.737 | 0.830 | 0.724 | 0.825 |
| CC0$\pi$0p : 15–20° | 0.679 | 0.694 | 0.674 | 0.693 |
| CC0$\pi$0p : 20–25° | 0.552 | 0.502 | 0.543 | 0.507 |
| CC0$\pi$0p : 25–30° | 0.391 | 0.305 | 0.387 | 0.302 |
| CC0$\pi$0p : 30–180° | 0.081 | 0.048 | 0.081 | 0.048 |
| Total | 0.372 | 0.397 | 0.355 | 0.395 |

# 0. $\bar{\nu}_\mu$ and $\bar{\nu}_\mu + \nu_\mu$ CC-0$\pi$0p on $\mathrm{H_2O}$ and CH

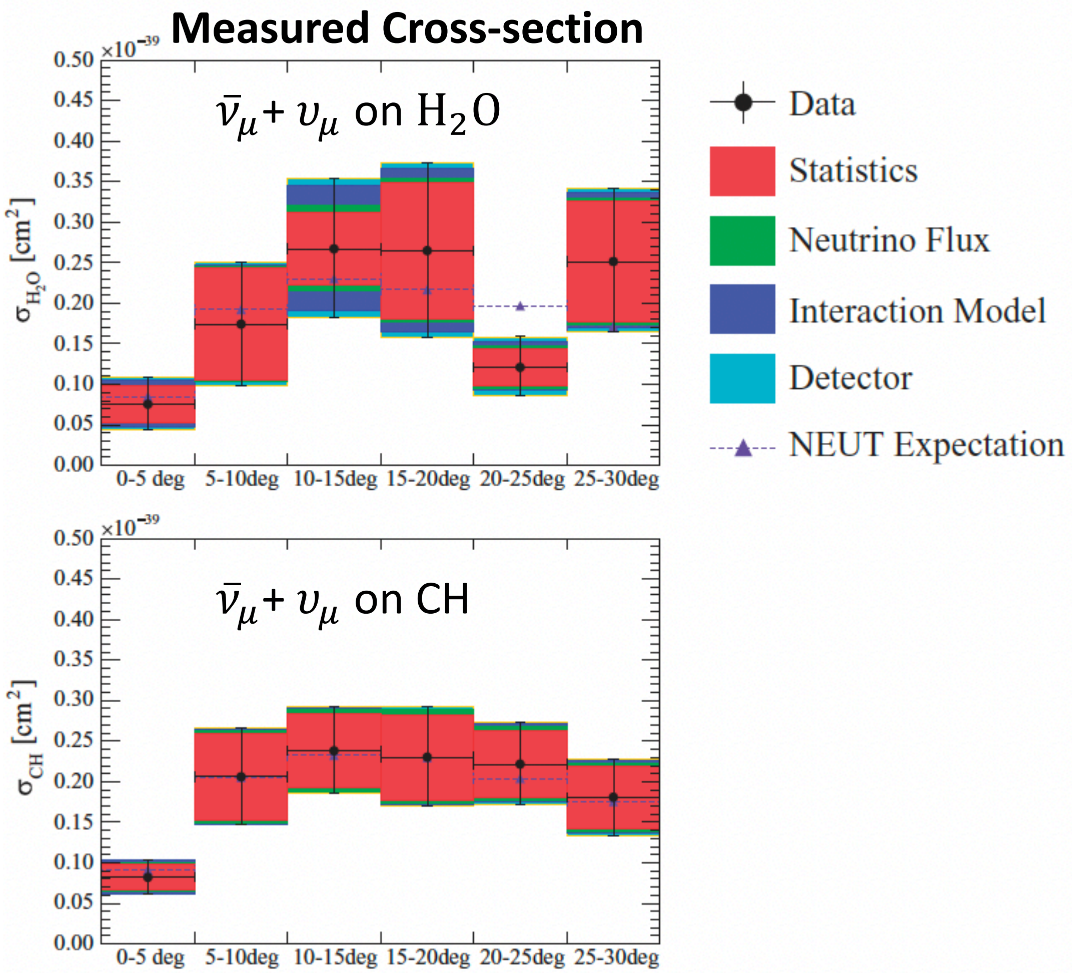
Prog. Theor. Exp. Phys. 2021, 043C01

$\bar{\nu}_\mu + \nu_\mu$ cross-section results on $\mathrm{H_2O}$ and CH are shown

Full results are available in the paper

- $\bar{\nu}_\mu$ cross-sections
- $\mathrm{H_2O}$-to-CH cross-section ratio

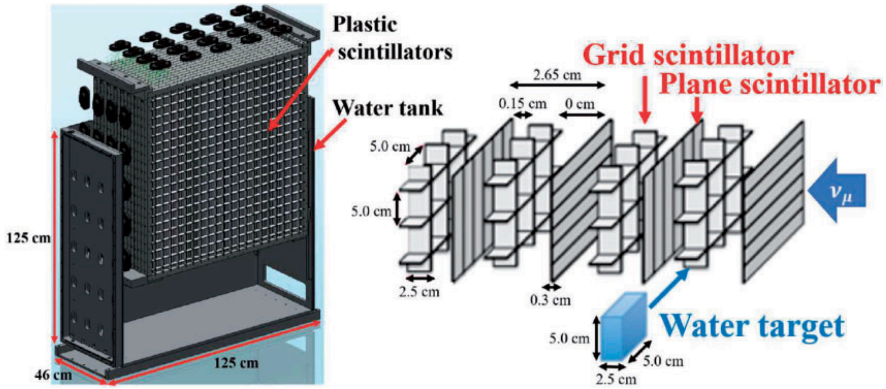
Results agree with the NEUT model used in the T2K oscillation analysis



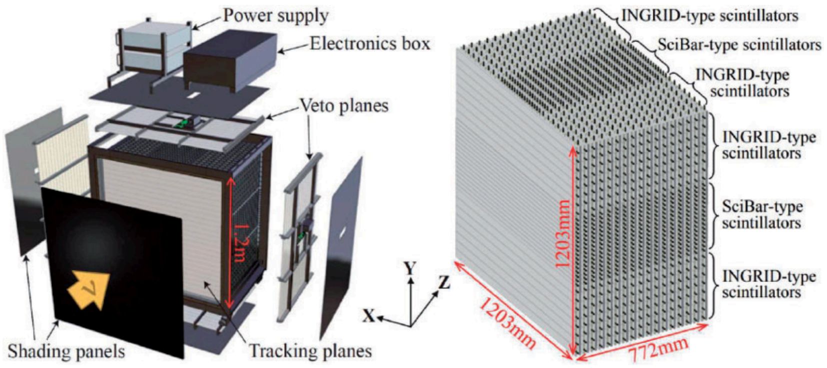
# 0. $\bar{\nu}_\mu$ and $\bar{\nu}_\mu + \nu_\mu$ CC-0$\pi$0p on $\mathrm{H_2O}$ and CH

[Prog. Theor. Exp. Phys. 2021, 043C01]

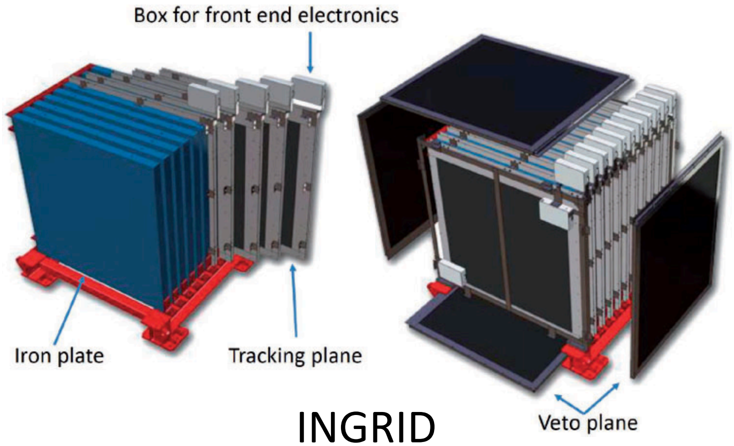
- Detector detailed structures




WAGASCI




Proton Module

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Prog. Theor. Exp. Phys. 2021, 043C01

DOF 8

Chi2 does not suggest mismatch

**Table 9.** Absolute $\chi^2$ values for the $\overline{\nu}_\mu$ and $\overline{\nu}_\mu + \nu_\mu$ cross-sections, with respect to the total uncertainty.

| | $\overline{\nu}_\mu$ cross-section | | | $\overline{\nu}_\mu + \nu_\mu$ cross-section | | |
|---|---|---|---|---|---|---|
| | $\sigma_{H_2O}$ | $\sigma_{CH}$ | $\sigma_{H_2O}/\sigma_{CH}$ | $\sigma_{H_2O}$ | $\sigma_{CH}$ | $\sigma_{H_2O}/\sigma_{CH}$ |
| NEUT | 3.19 | 11.34 | 1.71 | 7.06 | 2.63 | 6.87 |
| GENIE | 4.25 | 14.26 | 1.83 | 7.09 | 3.38 | 7.55 |

**Table 10.** Absolute $\chi^2$ values for the $\overline{\nu}_\mu$ and $\overline{\nu}_\mu + \nu_\mu$ cross-sections only for a muon angle less than 30 degrees, concerning the total uncertainty.

| | $\overline{\nu}_\mu$ cross-section | | | $\overline{\nu}_\mu + \nu_\mu$ cross-section | | |
|---|---|---|---|---|---|---|
| | $\sigma_{H_2O}$ | $\sigma_{CH}$ | $\sigma_{H_2O}/\sigma_{CH}$ | $\sigma_{H_2O}$ | $\sigma_{CH}$ | $\sigma_{H_2O}/\sigma_{CH}$ |
| 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 |

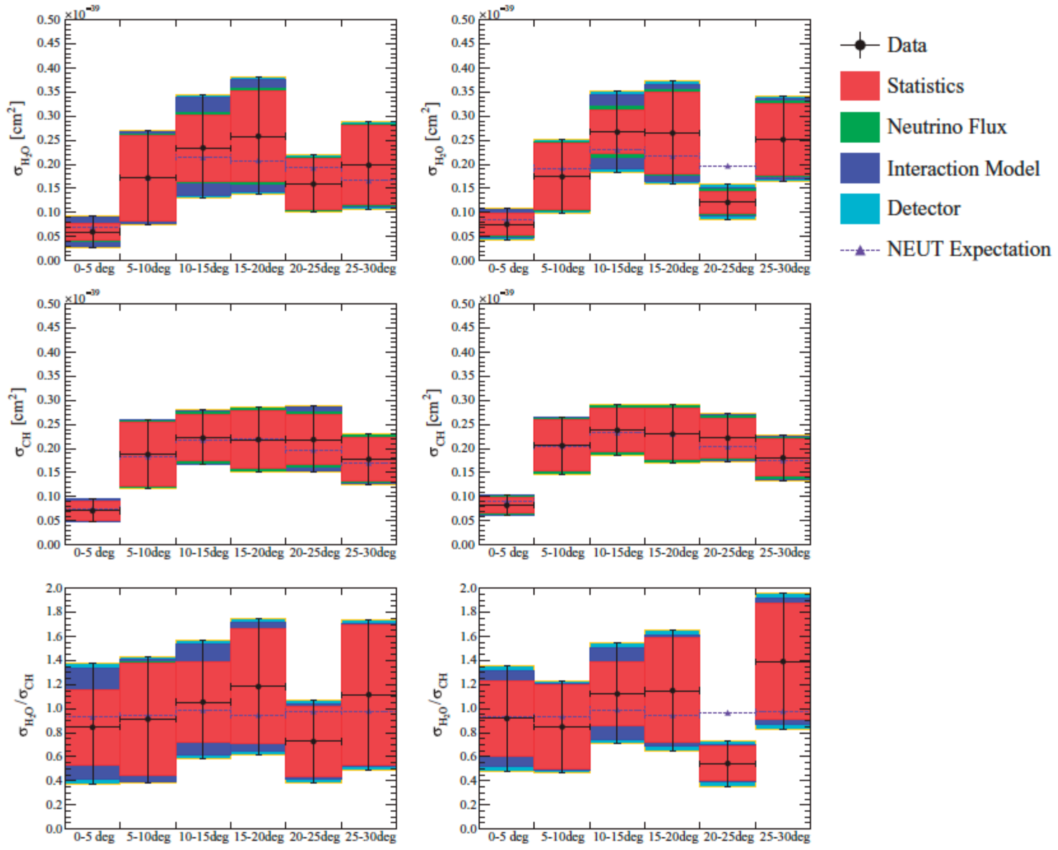



**Fig. 15.** Measured values for the differential $\overline{\nu}_\mu$ cross-section (left) and $\overline{\nu}_\mu + \nu_\mu$ cross-section (right). Top line: $\sigma_{H_2O}$. Middle line: $\sigma_{CH}$. Bottom line: $\sigma_{H_2O}/\sigma_{CH}$. Each plot shows the cumulative quadratic sum of the uncertainties from statistics, neutrino flux, neutrino-interaction model, and detector response.

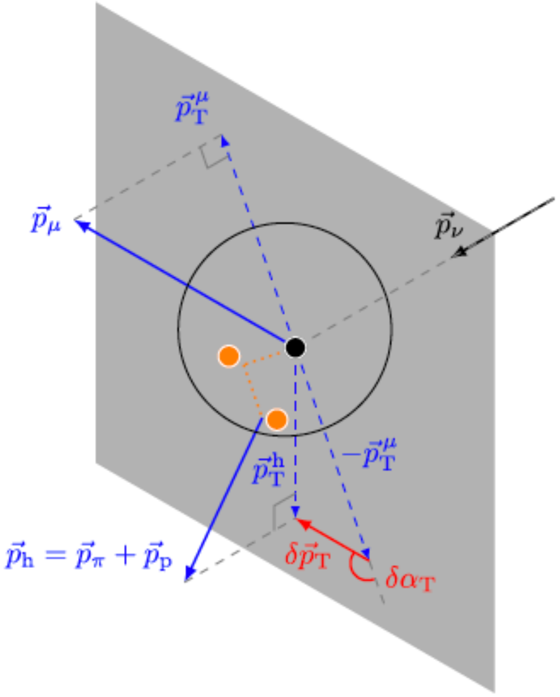
# 1. $\upsilon_\mu CC\text{–}1\pi^+ Xp$ Transverse Kinematic Imbalance

Phys. Rev. D **103**, 112009

$p_N$ - Initial nucleon momentum

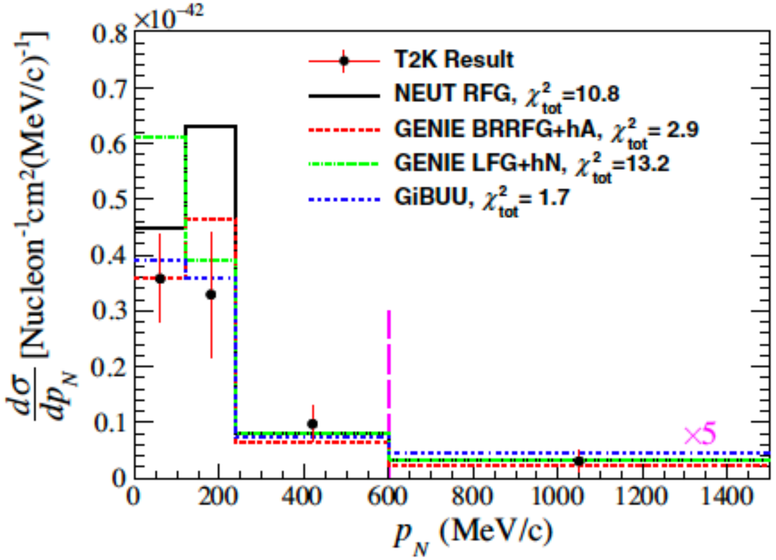
**Expectation**

- Probes the Fermi motion inside the nucleus
- FSI shifts the peak position and cause a long tail




$$p_N = \sqrt{\delta p_T^2 + p_L^2},$$

**Measured Cross-section**

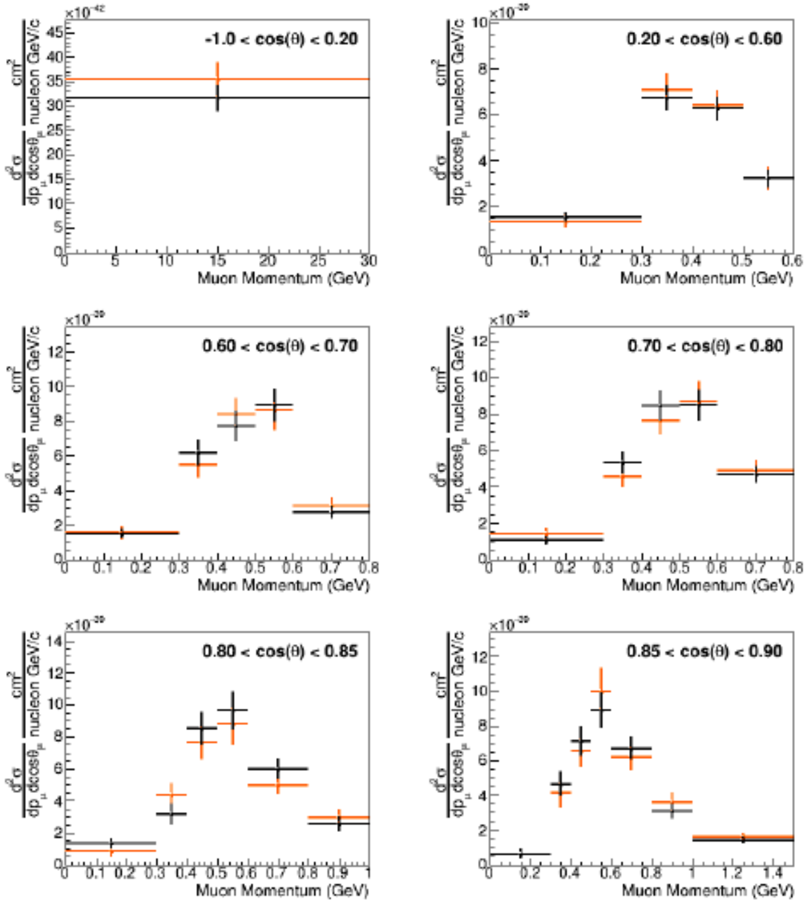



- Like $\delta p_{TT}$, a slight preference for GiBUU
- Results are statistically limited
- Full results are available in the paper

# 4. $\nu_\mu$ CC-0$\pi$ on CH On/Off Axis

arXiv:2303.14228
Under Review by PRD

- Comparison with previous measurement



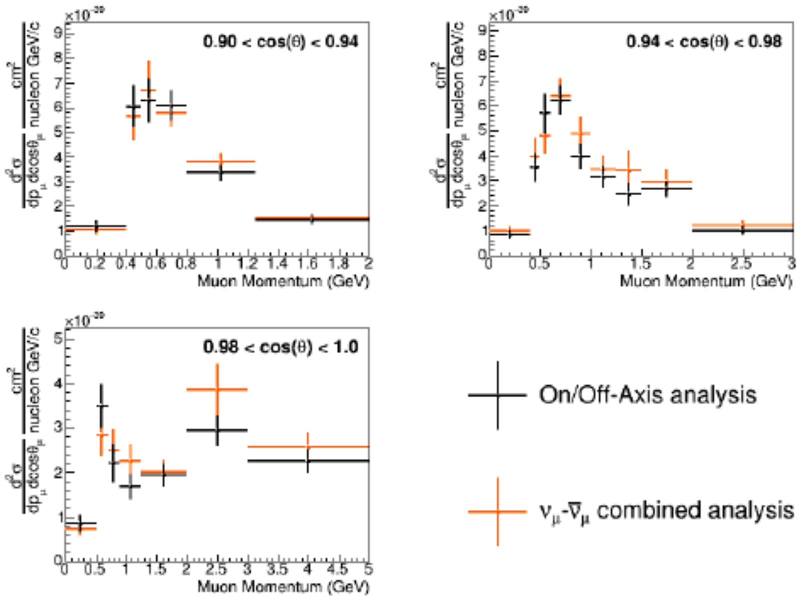




FIG. 28. Extracted ND280 cross section from this analysis compared to the neutrino analysis in Ref. [69]. The final momentum bin extending to 30 GeV/$c$ has been omitted for clarity.