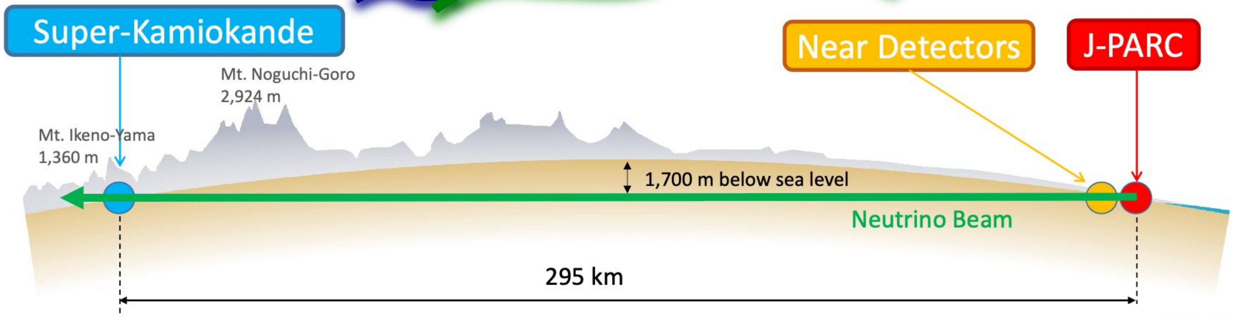
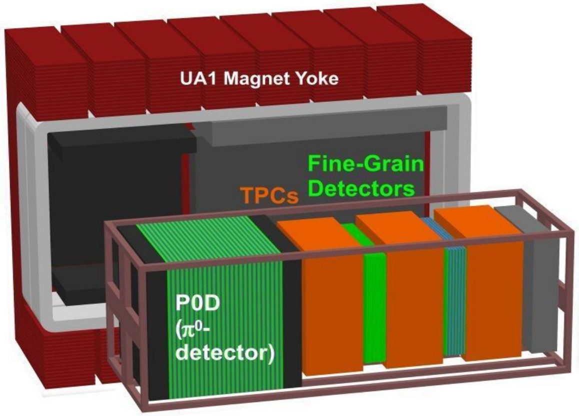
Recent T2K Neutrino Cross-sections Measurements

David Hadley on behalf of the T2K Collaboration

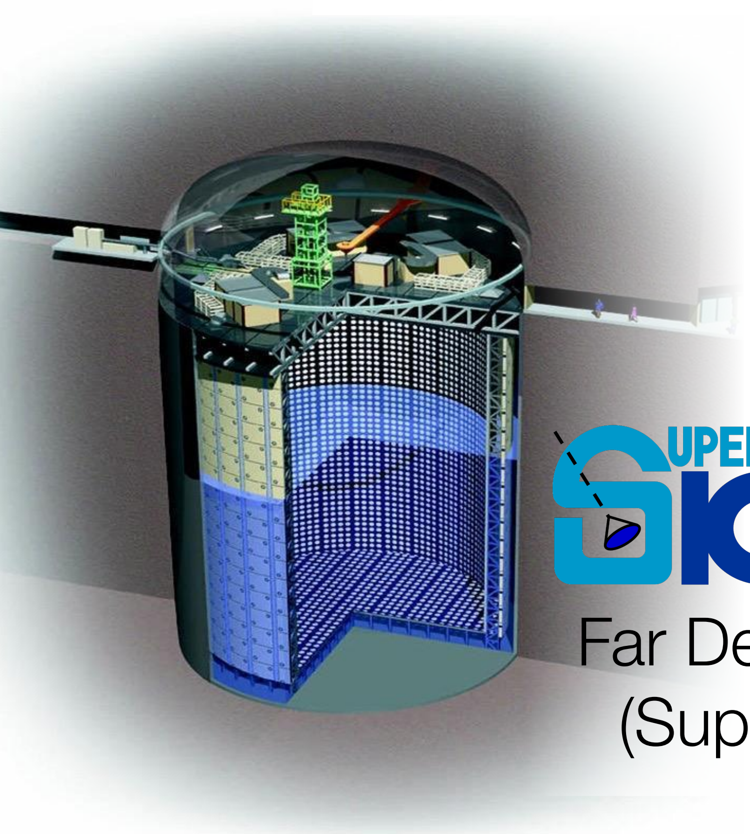
EPS-HEP 2023, 2023-08-23

T2K

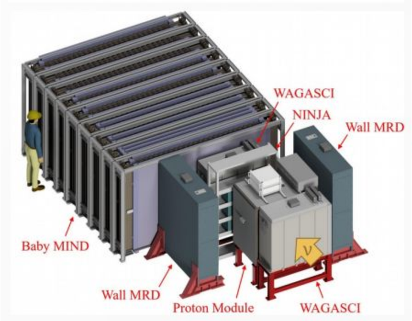


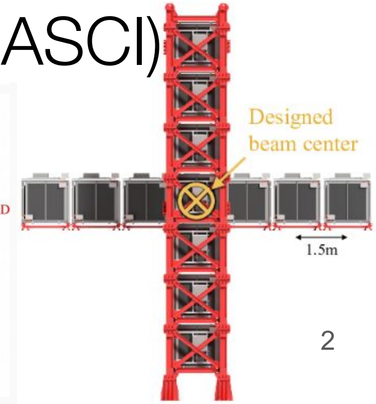


Near Detectors
(ND280+INGRID+WAGASCI)

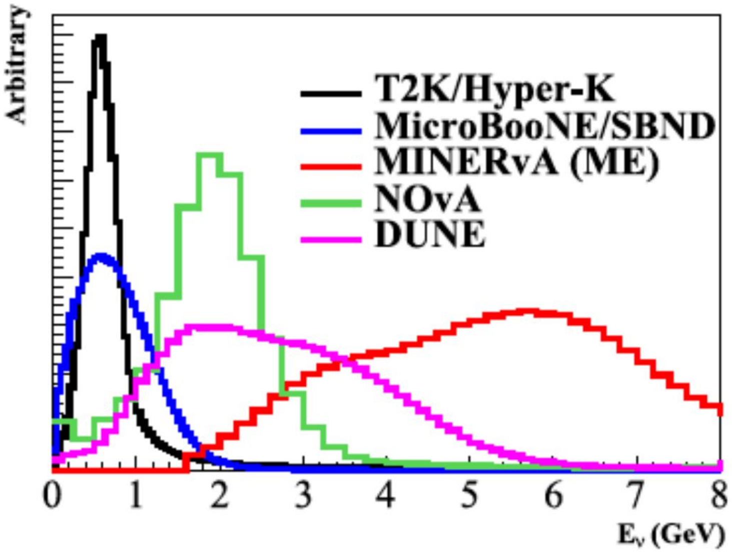


Far Detector
(Super-K)





Neutrino Nucleus Interaction Physics is crucial for Neutrino Oscillations



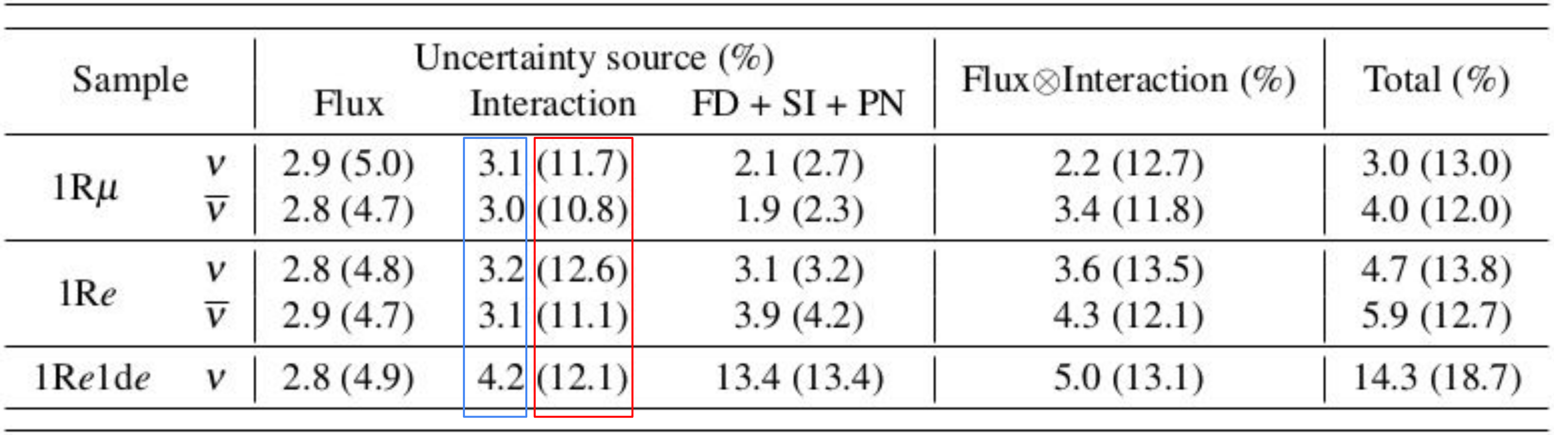
$$R(\vec{\mathbf{x}}) = \underbrace{\overbrace{\Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}})}^{\text{Near}} \times P(\nu_A \rightarrow \nu_B)}_{\text{Far}}$$

Current and future accelerator based neutrino beams span ~ 100 MeV - 10 GeV

Uncertainties do not exactly cancel in near-to-far extrapolation due to oscillation probability

Depend on interaction model to do this extrapolation

Interaction Model is the Dominant Source of Systematic Uncertainty in the T2K Oscillation Analysis



Sample		Uncertainty source (%)			Flux⊗Interaction (%)	Total (%)
		Flux	Interaction	FD + SI + PN		
1Rμ	ν	2.9 (5.0)	3.1 (11.7)	2.1 (2.7)	2.2 (12.7)	3.0 (13.0)
	$\bar{\nu}$	2.8 (4.7)	3.0 (10.8)	1.9 (2.3)	3.4 (11.8)	4.0 (12.0)
1Re	ν	2.8 (4.8)	3.2 (12.6)	3.1 (3.2)	3.6 (13.5)	4.7 (13.8)
	$\bar{\nu}$	2.9 (4.7)	3.1 (11.1)	3.9 (4.2)	4.3 (12.1)	5.9 (12.7)
1Re1de	ν	2.8 (4.9)	4.2 (12.1)	13.4 (13.4)	5.0 (13.1)	14.3 (18.7)

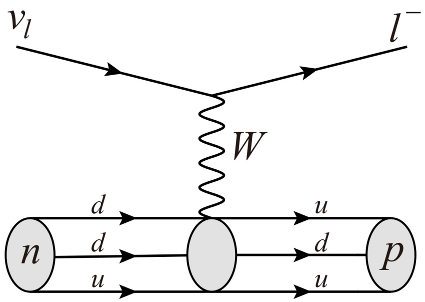
arXiv:2303.03222 [hep-ex]

~ 12% (~3%) uncertainty before (after) near detector constraint

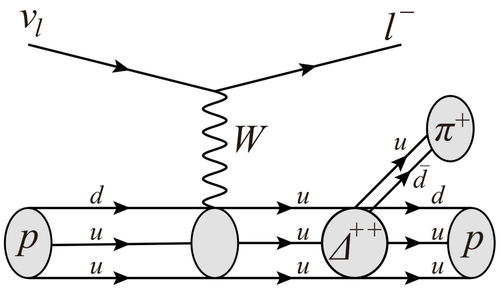
We will need to reduce these systematic uncertainties for future high statistics experiments (DUNE + Hyper-K)

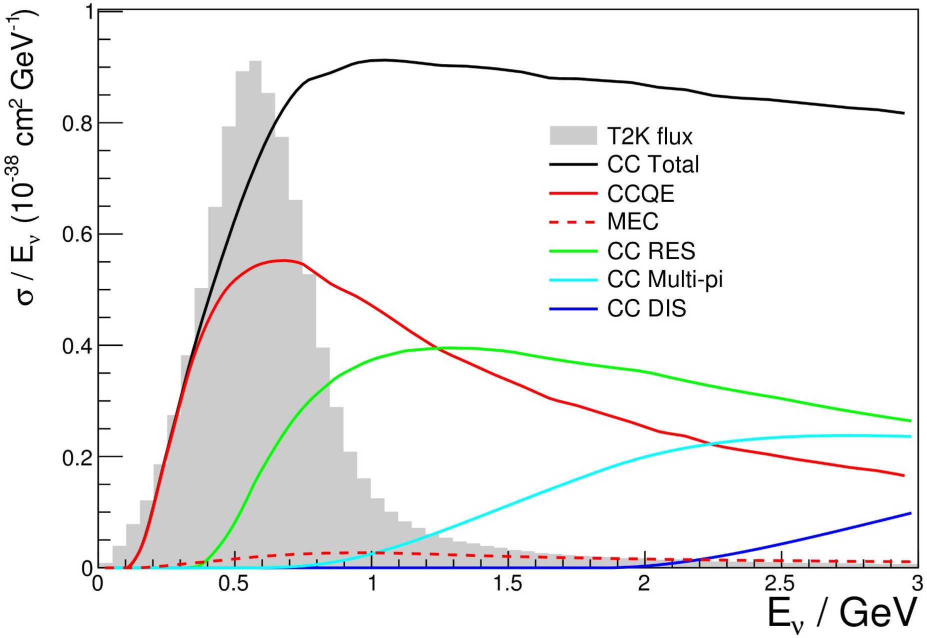
Neutrino Interactions at T2K

Charged Current Quasi-elastic (CCQE)



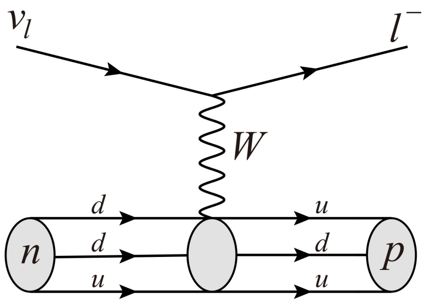
Resonant Pion Production (CCRES)



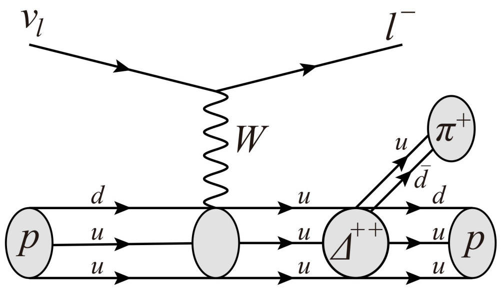


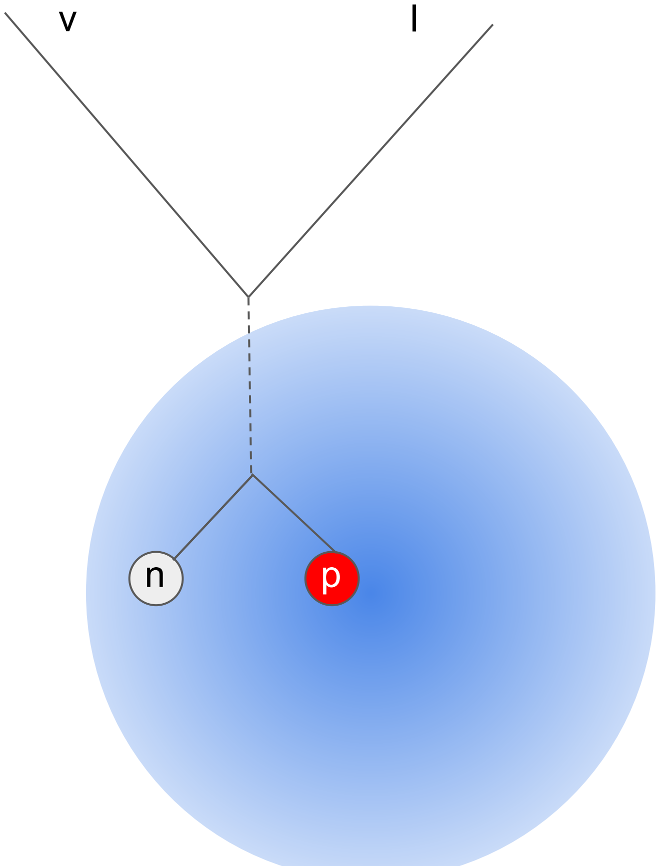
Neutrino-Nucleus Interactions at T2K

Charged Current Quasi-elastic (CCQE)



Resonant Pion Production (CCRES)

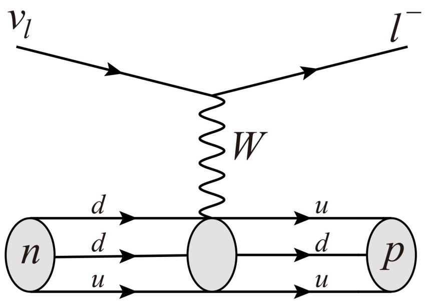




Nucleon initial state momentum and binding energy

Neutrino-Nucleus Interactions at T2K

Charged Current Quasi-elastic (CCQE)



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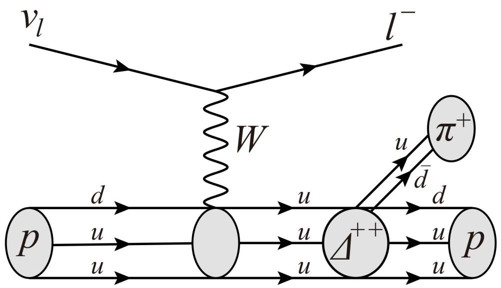
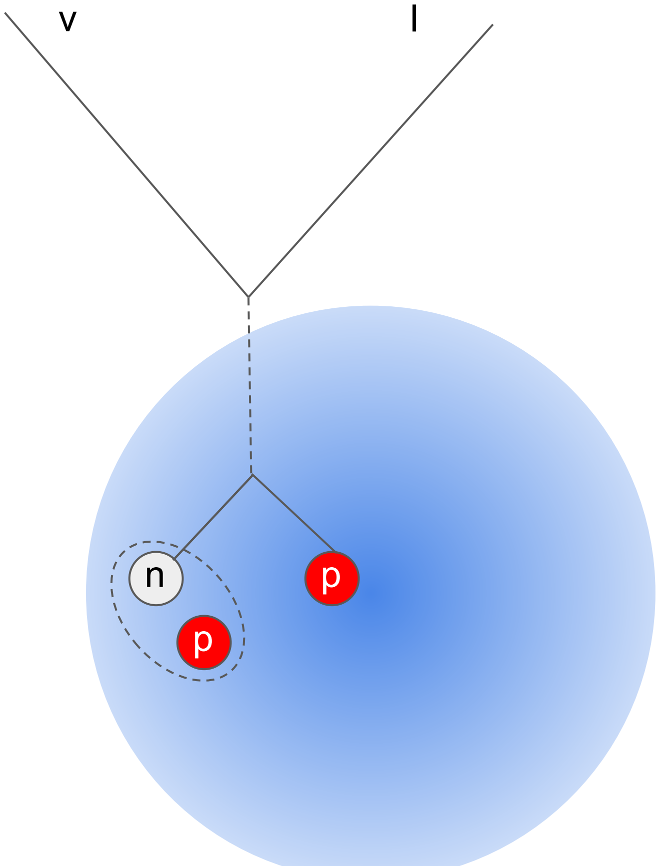
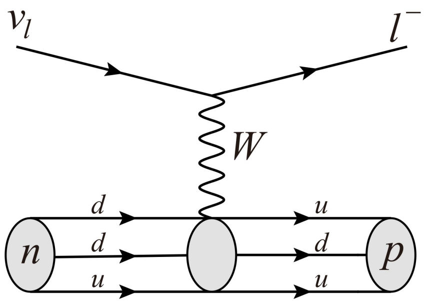




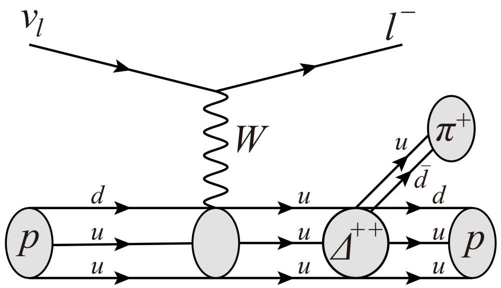
Nucleon initial state momentum and binding energy
Interactions involving multiple nucleons

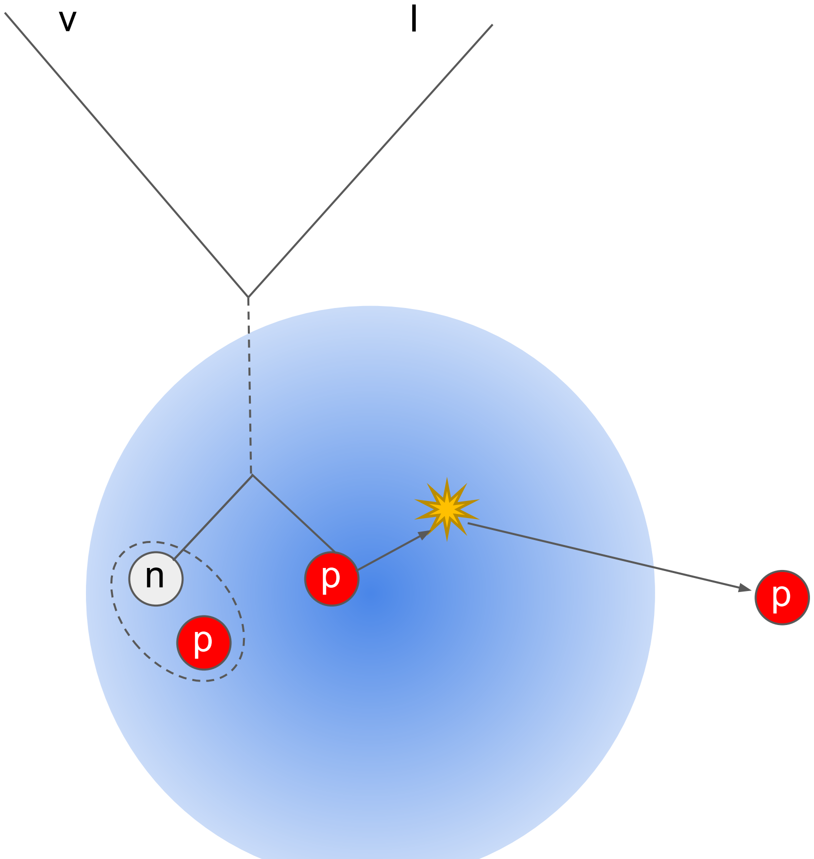
Neutrino-Nucleus Interactions at T2K

Charged Current Quasi-elastic (CCQE)



Resonant Pion Production (CCRES)

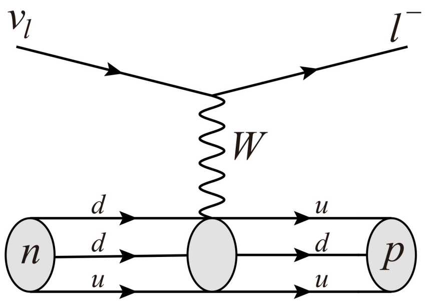




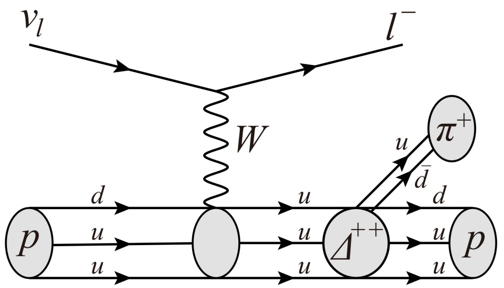
Nucleon initial state momentum and binding energy
Interactions involving multiple nucleons
Final state interactions

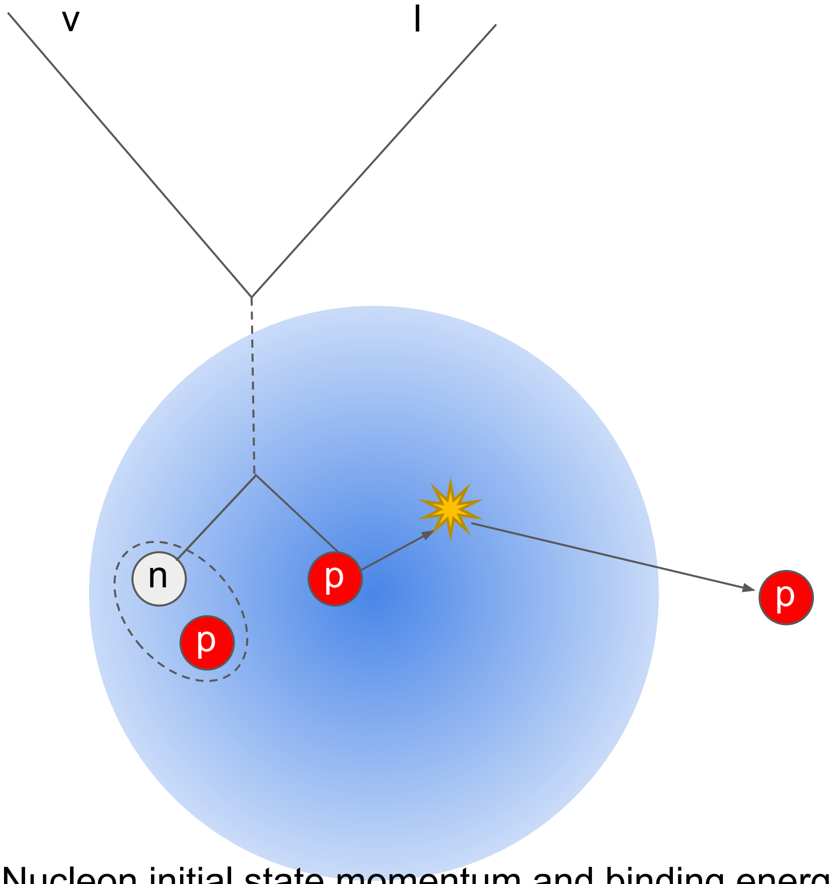
Neutrino-Nucleus Interactions at T2K

Charged Current Quasi-elastic (CCQE)



Resonant Pion Production (CCRES)

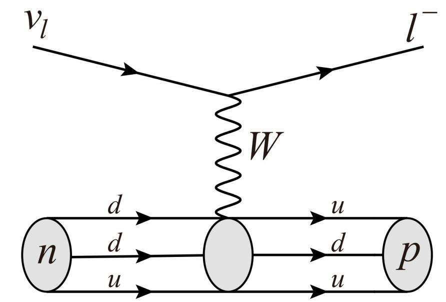




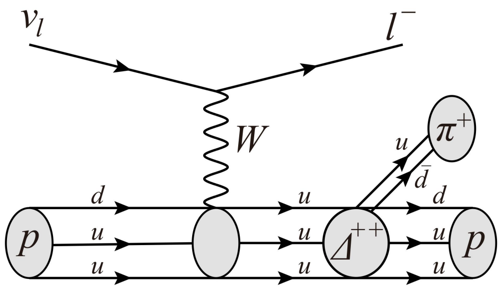
Nucleon initial state momentum and binding energy
Interactions involving multiple nucleons
Final state interactions
Remnant nucleus, Pauli blocking, nuclear medium etc

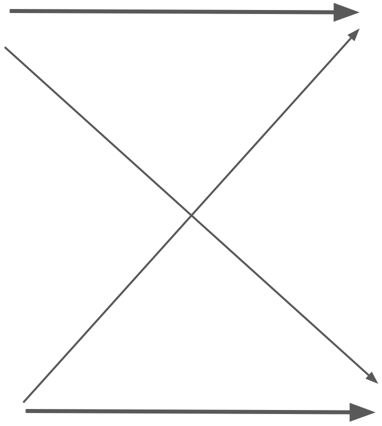
Neutrino-Nucleus Interactions at T2K

Charged Current Quasi-elastic (CCQE)



Resonant Pion Production (CCRES)





CC0π

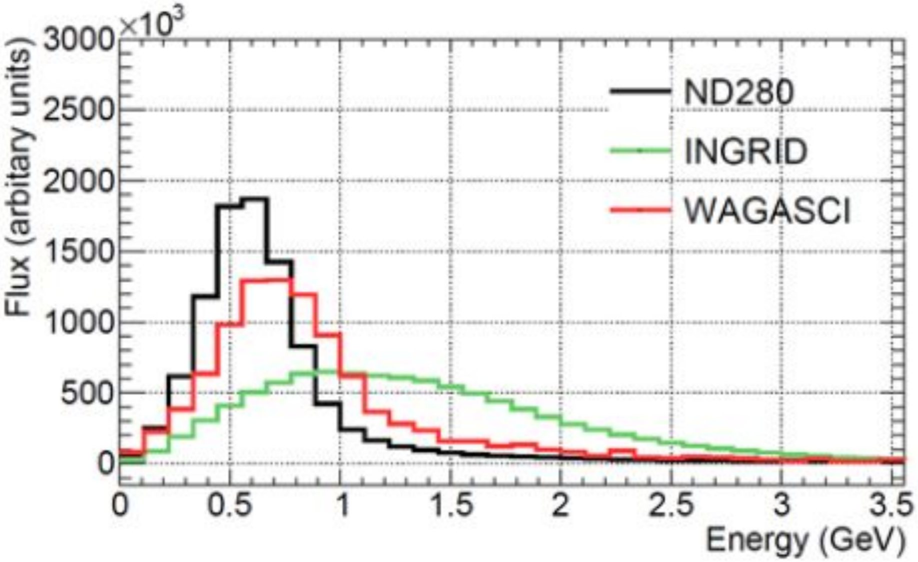
$$\nu + A \rightarrow l^- + 0\pi + A' + X$$

CC1π

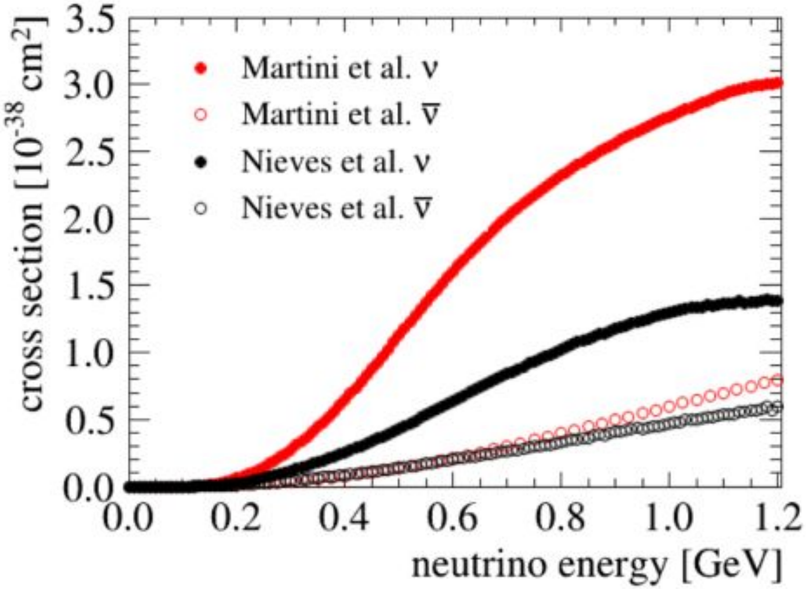
$$\nu + A \rightarrow l^- + 1\pi^+ + A' + X$$

Measure final state topologies

Joint Cross Section Measurement Using Multiple Flux and Near Detectors



Predictions of multi-nucleon xsec



Detectors exposed to different neutrino flux with correlated uncertainty

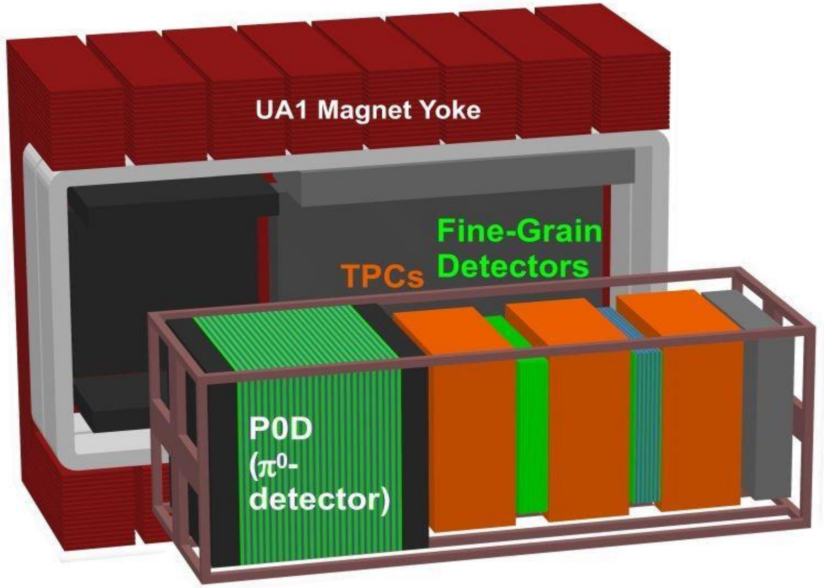
Joint measurement of CC0π cross section at on and off-axis detectors

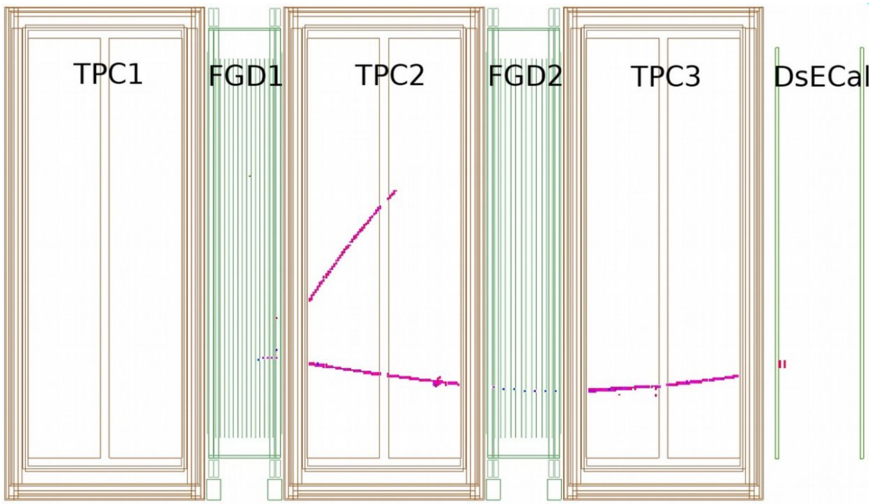
Sensitivity to energy dependence of neutrino interaction processes

Understanding energy dependence is absolutely critical for oscillation physics

arXiv:2303.14228 [hep-ex]

ND280 (2.5° off-axis, Eν ~ 0.6 GeV)



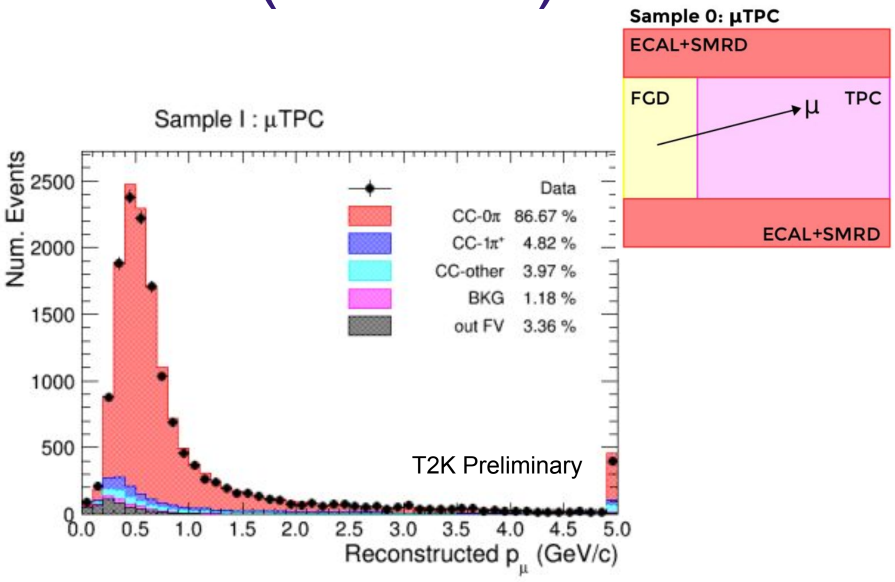


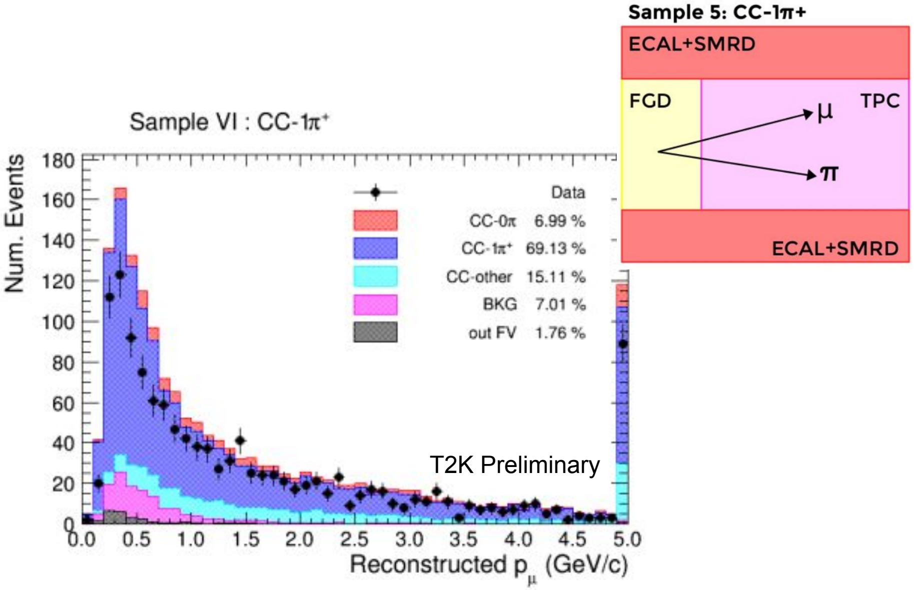
Fine Grained Detector (FGD1) is and active plastic scintillator tracking detector that provides target mass and vertex reconstruction

Time Projection Chambers (TPCs) provide track momentum measurement and PID

Detectors sit inside the UA1 magnet

ND280 (Off-axis) selection

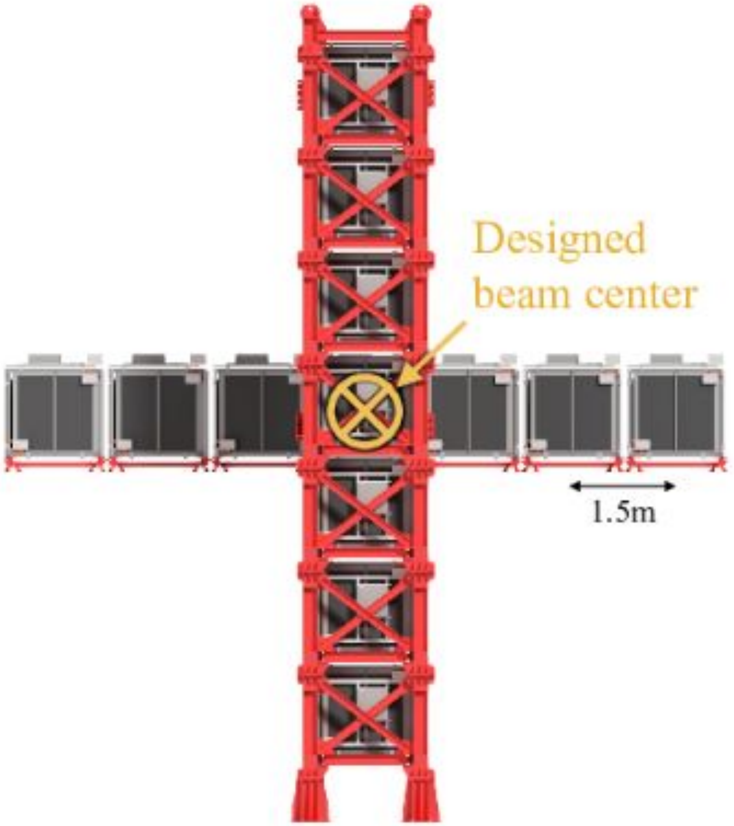


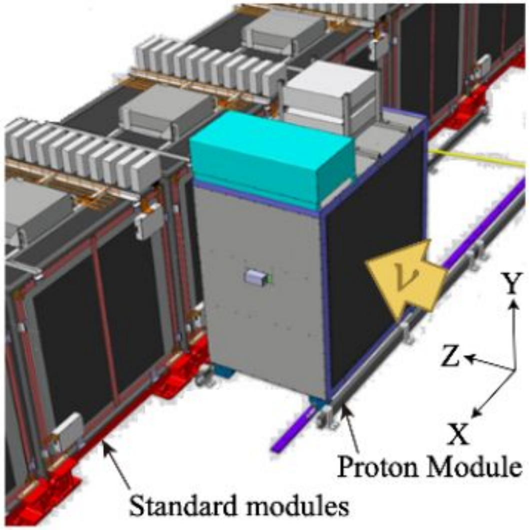


ND280 sample is split into multiple signal samples based on number of muon and protons detected and which sub-detectors they enter

Control samples used to measure the pion background contamination from the data

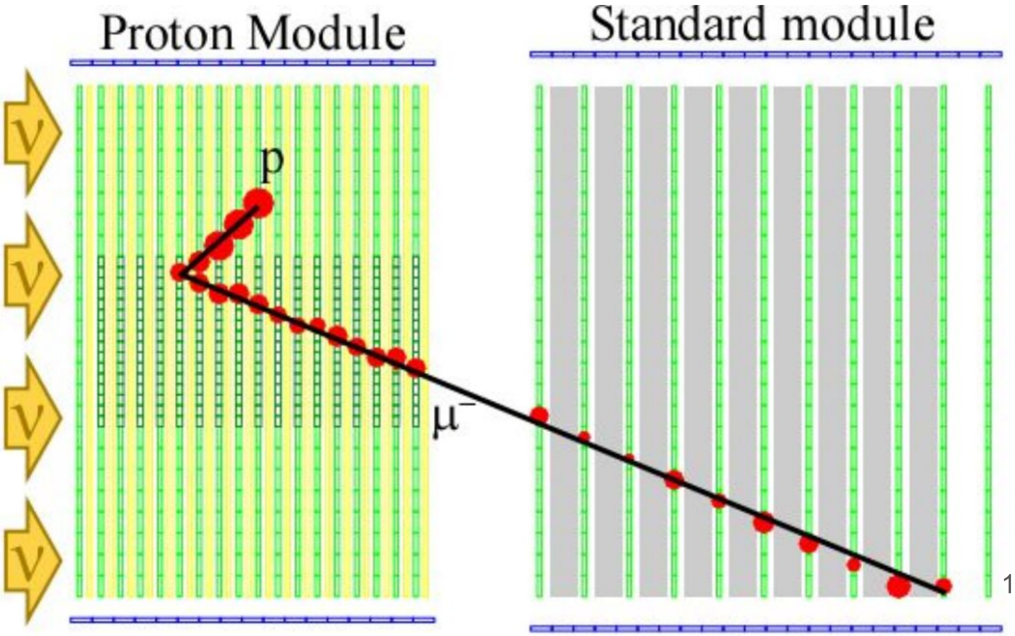
INGRID (2.5° on-axis, Eν ~ 1.1 GeV)



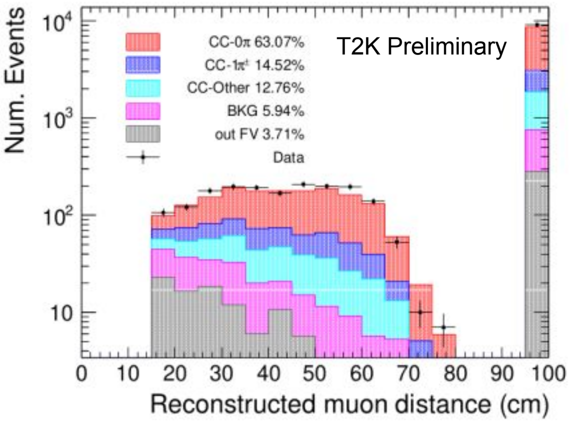


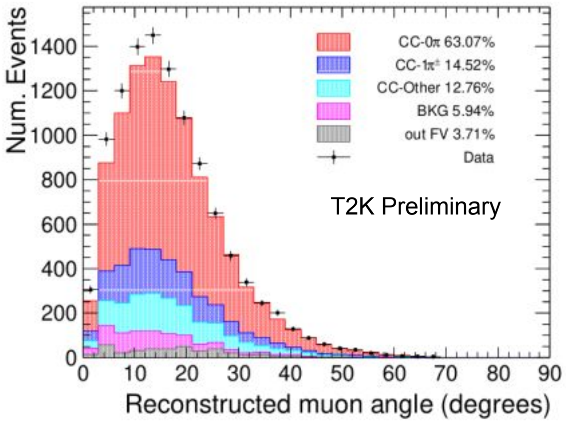
Proton Module is fully active scintillator tracking detector provides target mass and vertex and track reconstruction

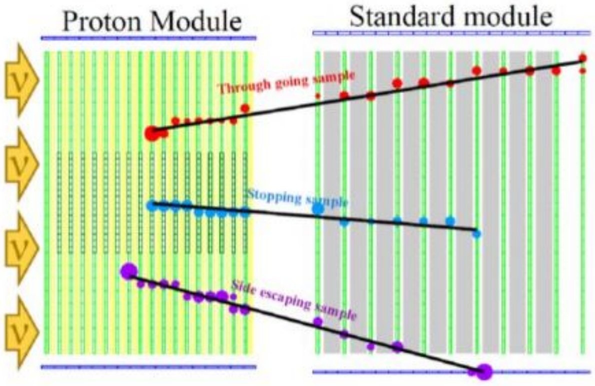
Standard module consists of alternating scintillator and iron layers and is used as a range detector in this analysis

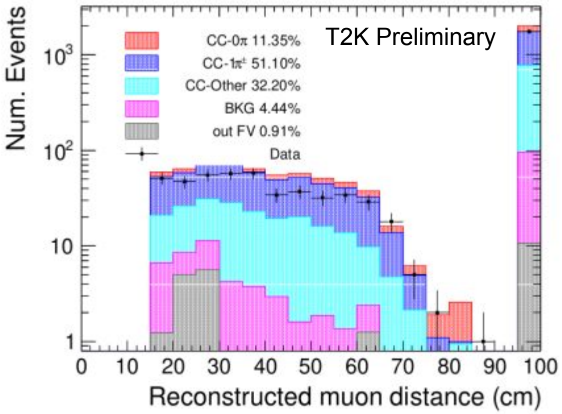


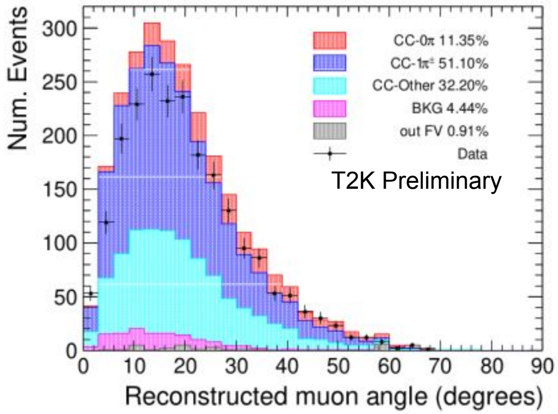
INGRID (On-axis) selection









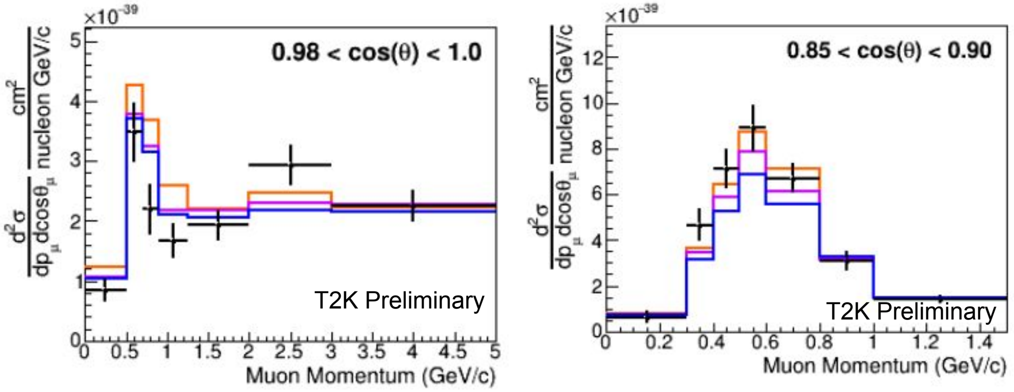


INGRID has no B field, can only measure momentum from range for stopping events

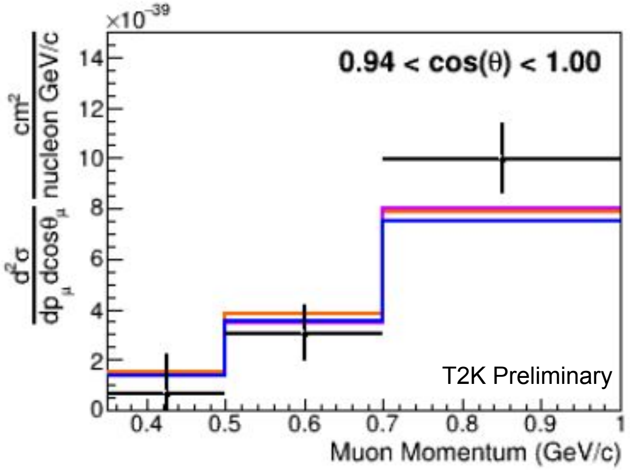
Control samples used to measure the pion background contamination from the data

Flux averaged cross-section measured as a function of muon momentum and angle with correlations between on and off-axis measurements

Off-axis (example angular slices)

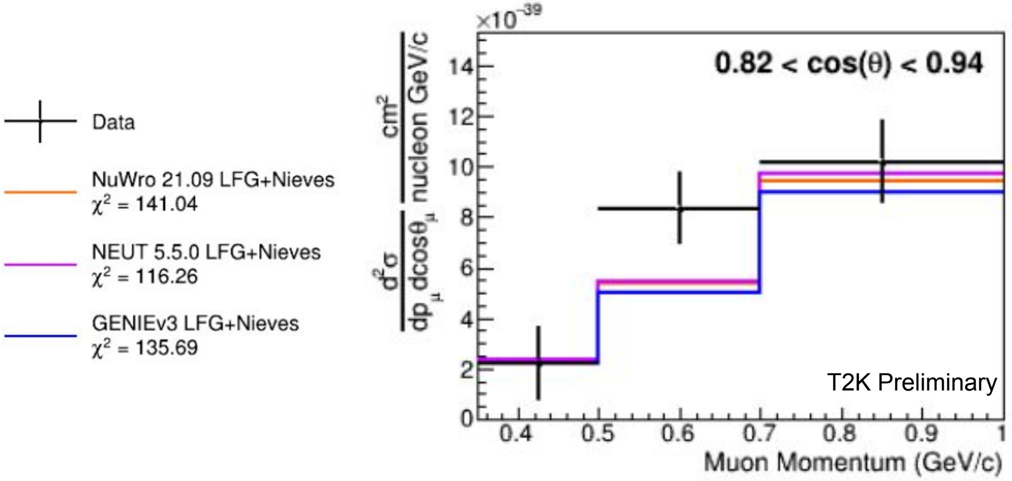


On-axis (example angular slices)



*χ*2 comparison of various MC predictions to data (ndof=70)

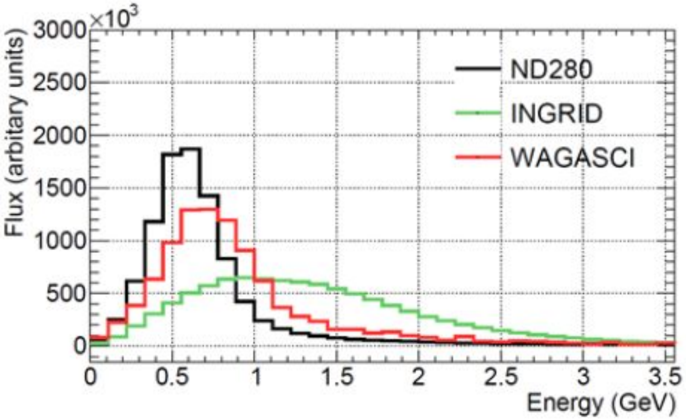
Model	ND280	INGRID	Joint
Nominal MC (NEUT)	136.34	18.21	158.71
NEUT LFG+Nieves	106.46	11.46	116.26
NEUT SF+Nieves $M_A = 1.03$	194.88	14.36	209.18
NEUT SF+Nieves $M_A = 1.21$	158.71	9.98	170.93
NuWro SF+Nieves	122.74	15.68	137.02
NuWro LFG+Nieves	125.88	12.75	141.04
NuWro LFG+SuSAv2	121.57	11.13	135.38
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

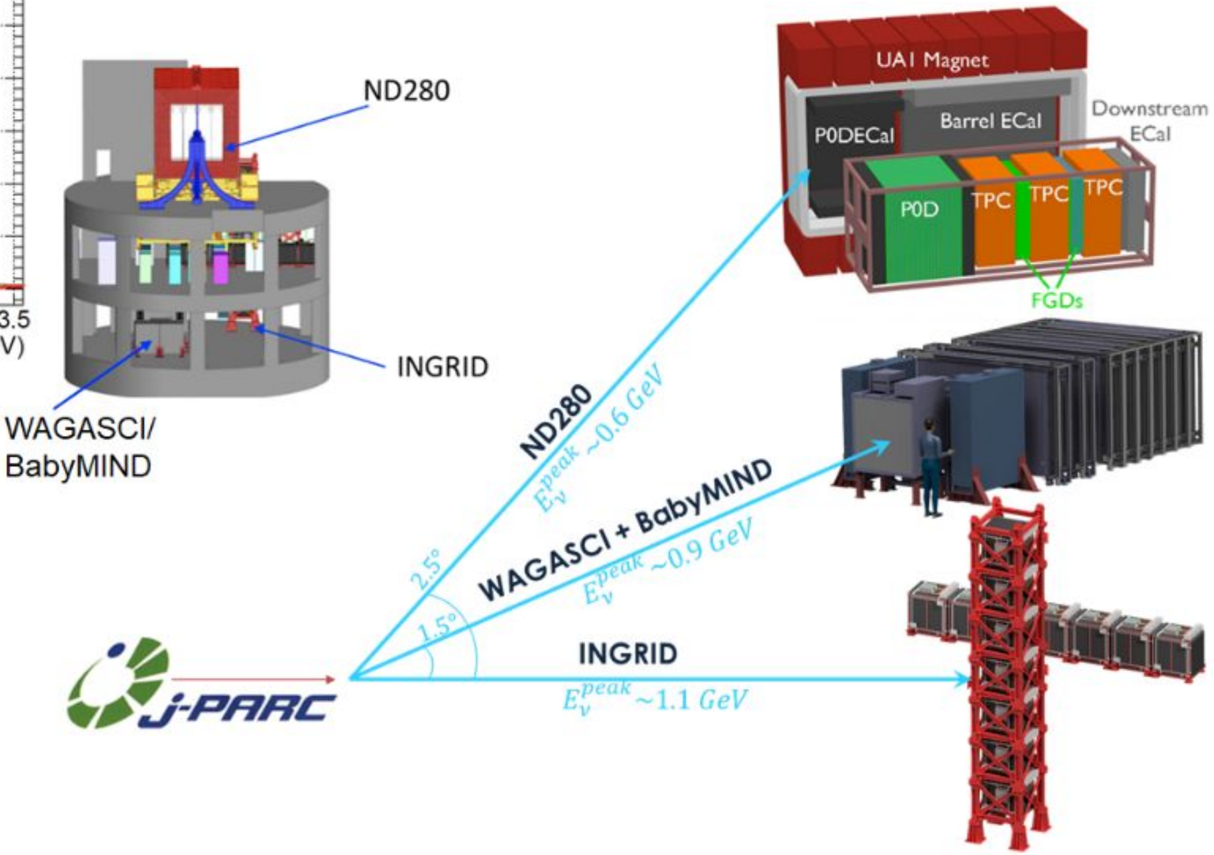


No model tested gave good agreement with the measurement across all kinematics and both fluxes

arXiv:2303.14228 [hep-ex]

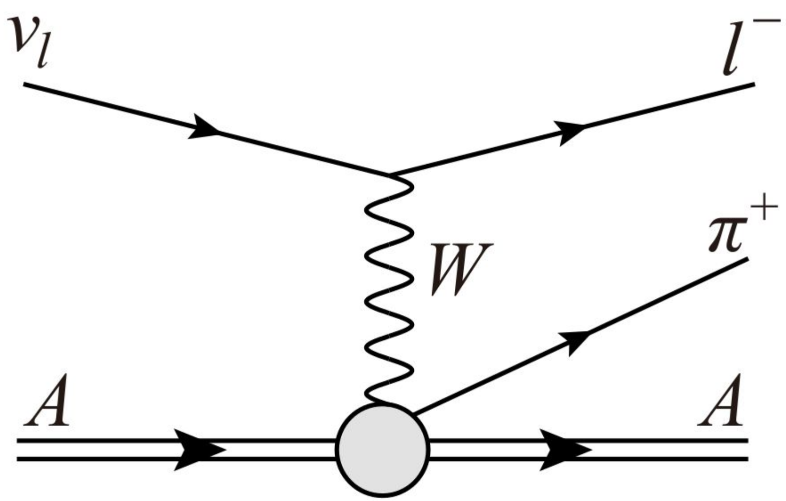
Future Measurements with WAGASCI





On-going work to extend this analysis to include the WAGASCI detector at 1.5° off-axis

Charged Current Coherent Pion Production in ND280



Rare neutrino interaction

Scatter of entire nucleus

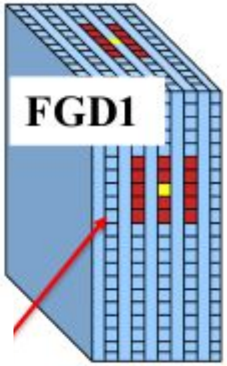
No exchange of quantum numbers with nucleus

Nucleus remains intact

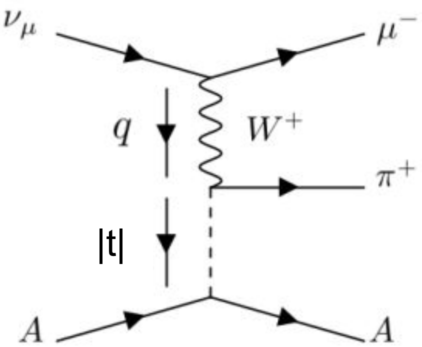
Contributes to oscillation measurements and has large uncertainties

New measurement of anti-neutrino CC coherent cross section (paper in preparation)

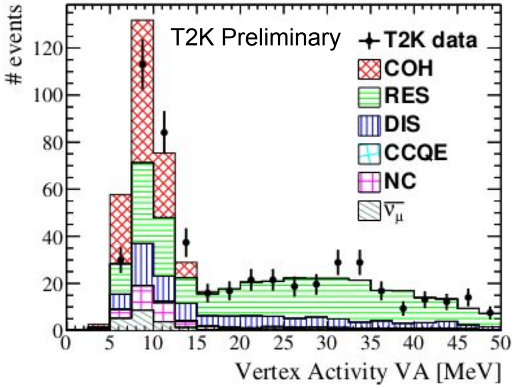
Charged Current Coherent Pion Production Selection

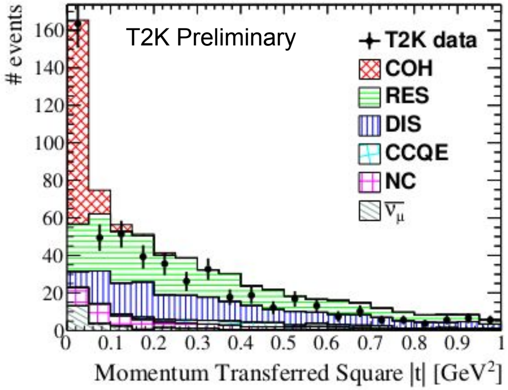


Vertex activity

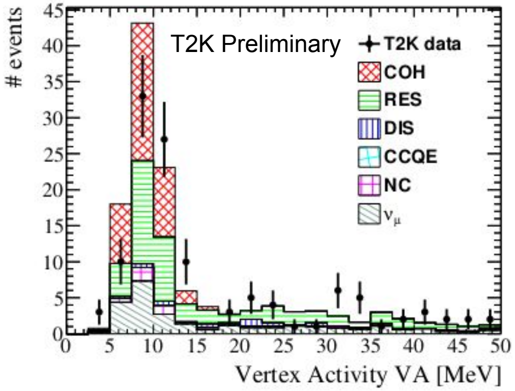


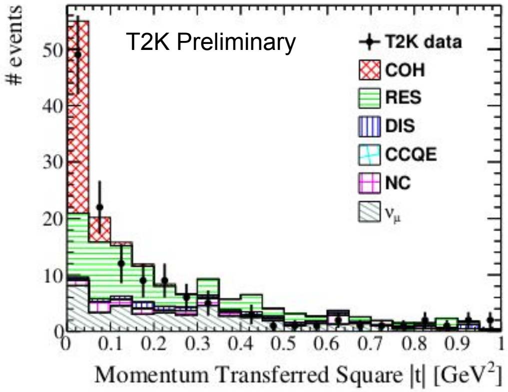
ν



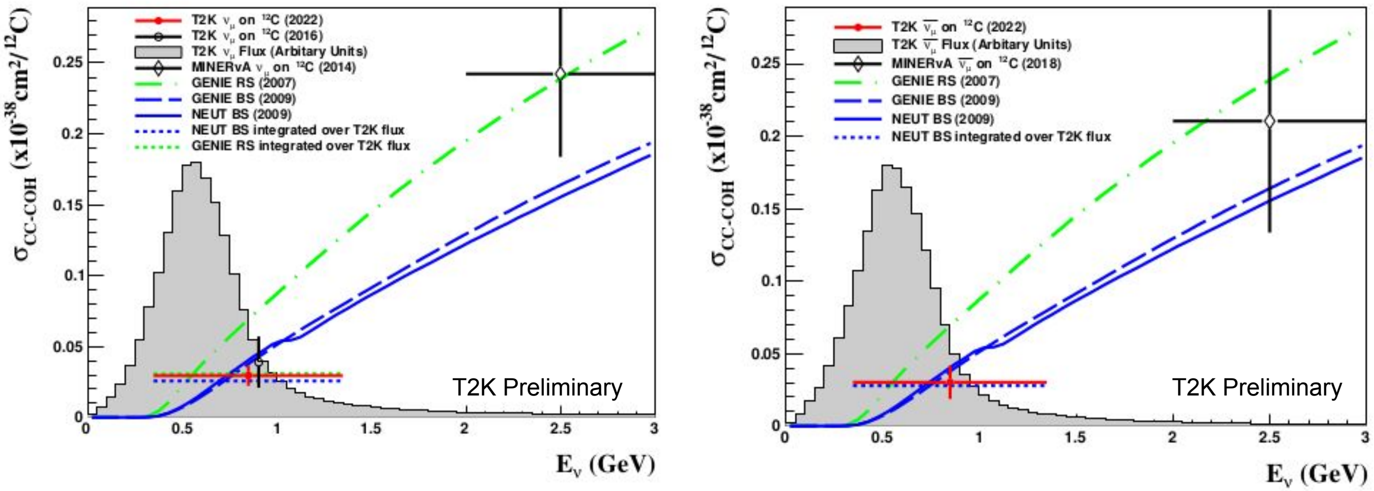


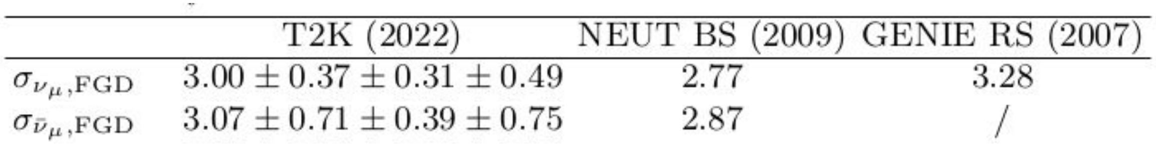
$\bar{\nu}$





Measured Charged Current Coherent Pion Production Cross Section





	T2K (2022)	NEUT BS (2009)	GENIE RS (2007)
$\sigma_{\nu_\mu,\mathrm{FGD}}$	$3.00 \pm 0.37 \pm 0.31 \pm 0.49$	2.77	3.28
$\sigma_{\bar{\nu}_\mu,\mathrm{FGD}}$	$3.07 \pm 0.71 \pm 0.39 \pm 0.75$	2.87	/

First anti-neutrino measurement of this process at this energy

Neutrino uncertainty reduced 43% → 23% from previous result

Measurement is consistent with the Berger-Seghal model

More Reading

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 [hep-ex])

Measurements of the charged current coherent νμ and ν̄ μ cross-sections on Carbon by T2K

(TBA)

Measurements of neutrino oscillation parameters from the T2K experiment using 3.6×10^21 protons on target

(arXiv:2303.03222 [hep-ex], accepted by EPJC)

T2K