Recent T2K Neutrino-Nucleus Cross Section Results

Xingyu Zhao, on behalf of the T2K Collaboration

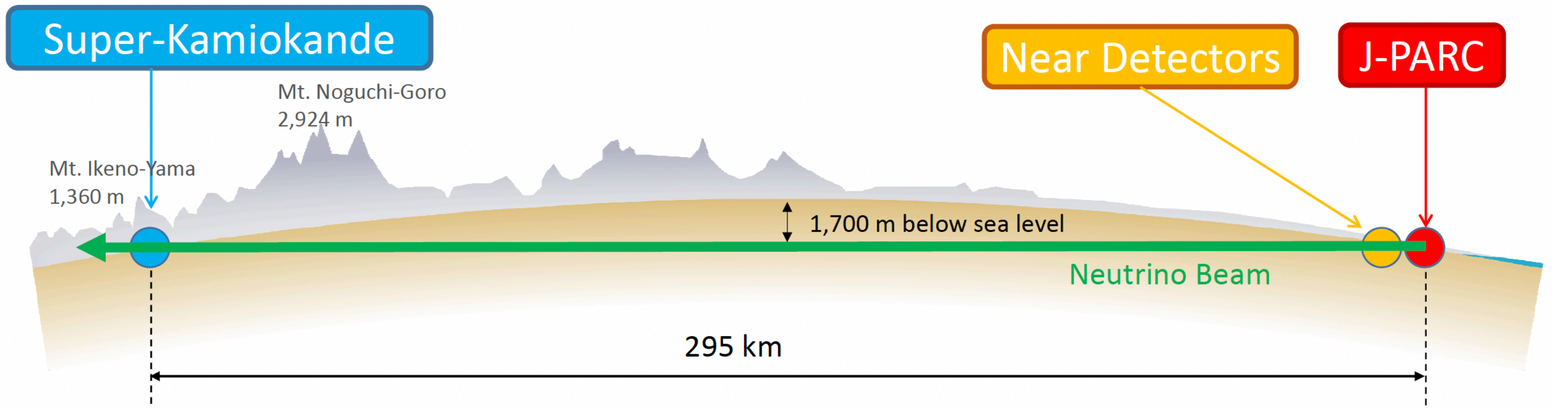
EPS-HEP 2025

2025-7-9

T2K Experiment

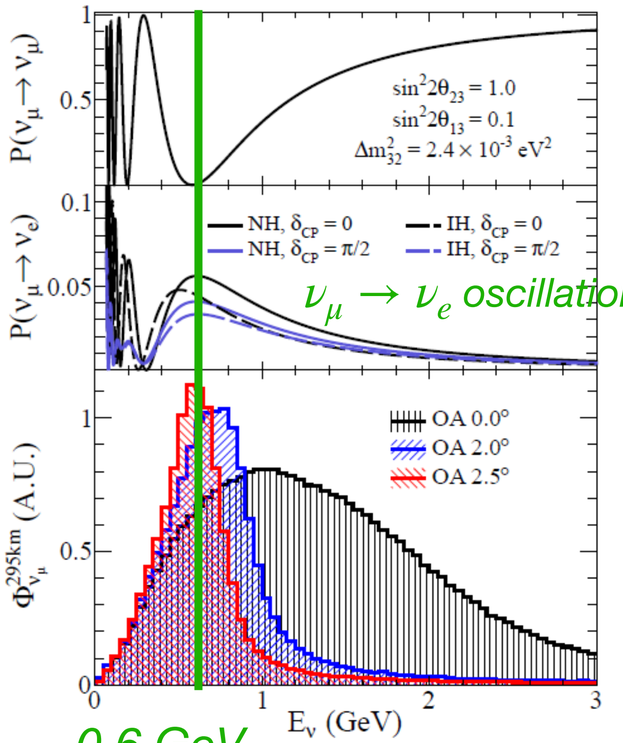
- Tokai-to-Kamioka (T2K), located in Japan.
  - *Neutrino beam (mainly ν_μ / $\bar{\nu}_\mu$) produced by J-PARC.*
  - *Near detectors and far detector Super-K.*
- Neutrino beam peaked at ~ 0.6 GeV (2.5˚ off-axis).
- Sensitivity to CP-violation phase δ_{CP}, mixing angle θ_{23} and mass splitting $|\Delta m^2_{32}|$.

→ *776. Results from the T2K Experiment. 2025-7-7, 9:05.*



Plot from T2K

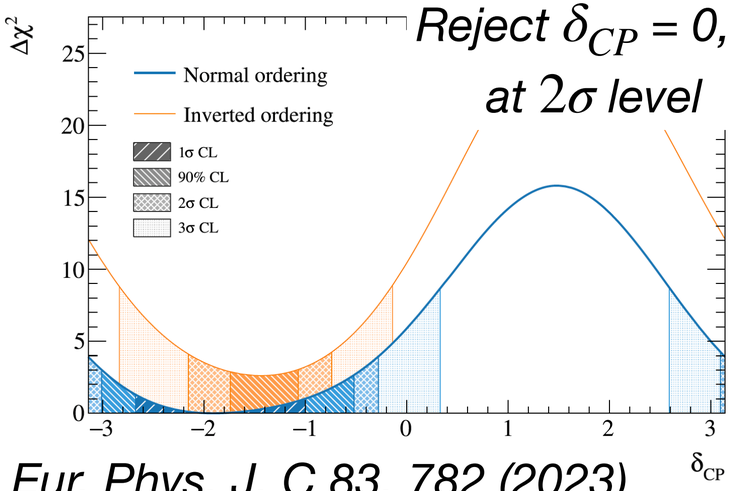
Plot from T2K



$\nu_\mu \to \nu_e$ oscillation maximum

~ 0.6 GeV

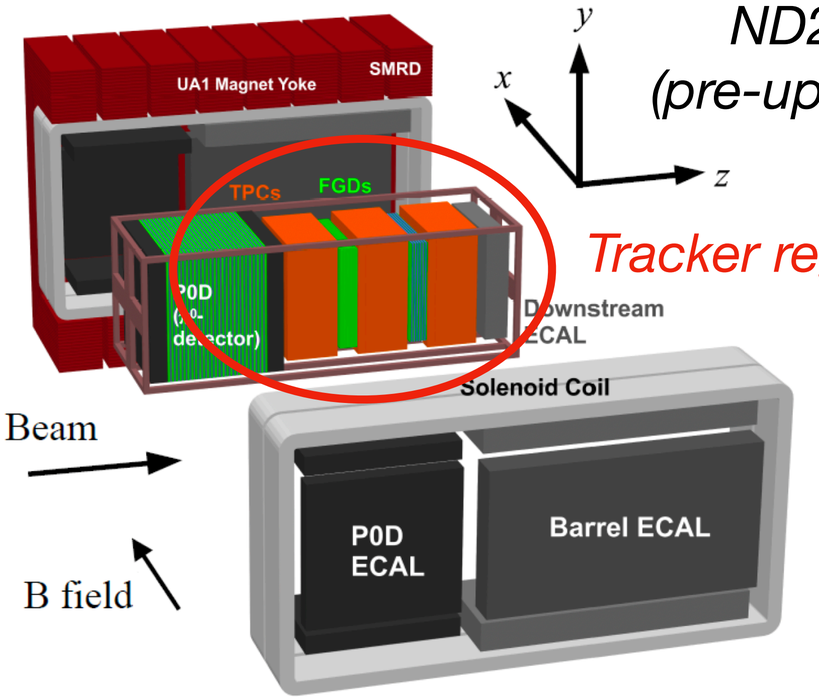
Reject $\delta_{CP} = 0, \pi$ at 2σ level



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

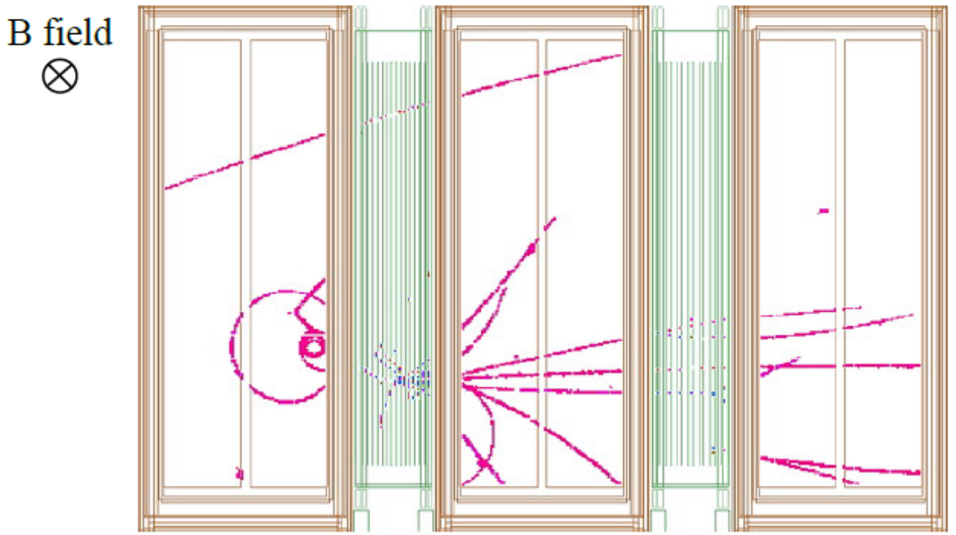
Near Detector ND280

- E_ν ~ 0.6 GeV, 2.5˚ off-axis.
- This talk focuses on the pre-upgrade:
  - Two fine grained scintillator detectors (FGDs).
    - *Main target for neutrino interactions.*
    - *FGD1 composed of scintillator (carbon).*
    - *FGD2 composed of scintillator (carbon) + water (oxygen, main target for Super-K).*
  - Three time projection chambers (TPCs).
    - *0.2T B-field to measure charged particles.*
  - Surrounding electromagnetic calorimeters (ECALs) to measure energy depositions.



ND280 (pre-upgrade)

Plots from T2K



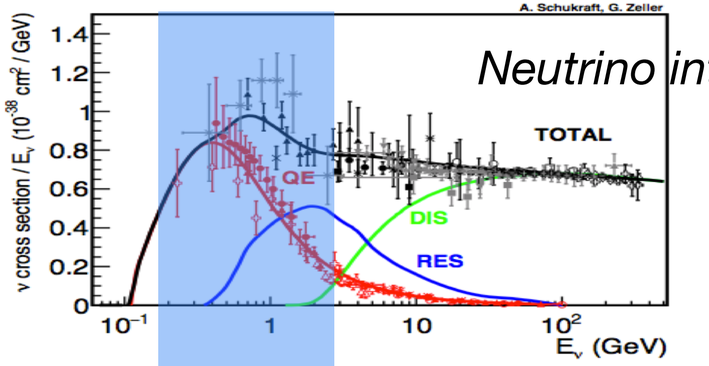
A neutrino event recorded in the tracker region

Neutrino Interactions at T2K

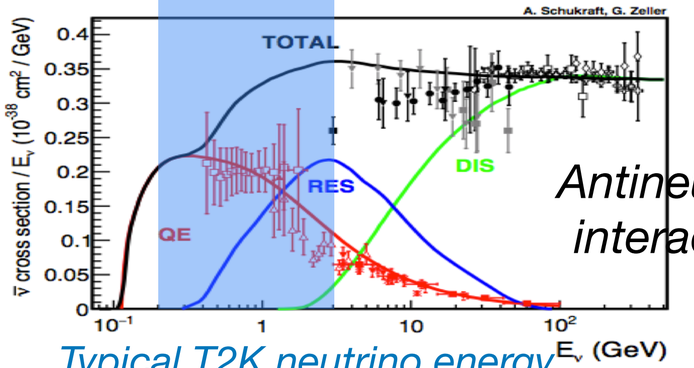
- Dominant interaction type - charge-current quasi-elastic (CCQE).
- Reconstruct neutrino energy (E_ν) with CCQE formula, but it is biased and smeared by nuclear effects (nucleon initial state, multi-nucleon interaction, final state interaction).

  → *Largest systematic uncertainty in oscillation measurement.*
- Need better understanding of nuclear effects to reduce systematics.

  → *Probed by neutrino-nucleus cross section measurements.*



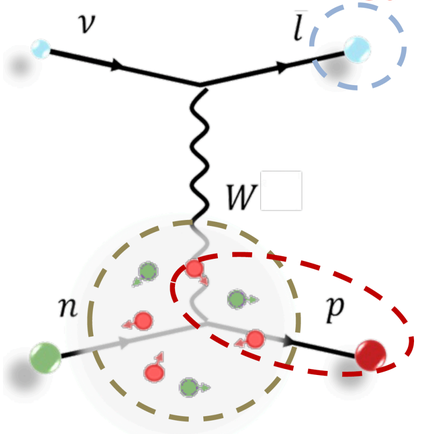
Neutrino interaction



Antineutrino interaction

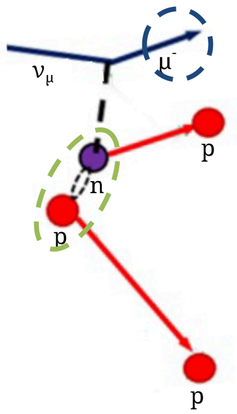
Typical T2K neutrino energy

Fermi motion + removal energy



+

2p2h



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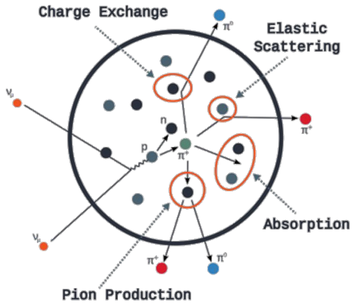
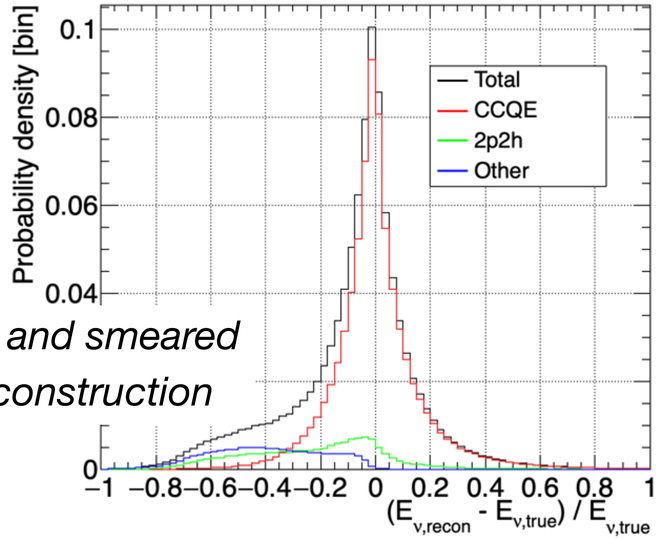
FSI



+ ... =

Biased and smeared E_ν reconstruction



Cross Section Measurement at T2K

- Cross section extracted with the **template fit method.**
  - *Template built with nominal Monte Carlo (MC), which has many parameters implemented to provide enough freedom to vary its shape + norm and match with data.*
  - *Parameters include signal template (free) + systematic parameters (constrained by priors).*
  - *The cross section results are the template reweighted by fitted parameters.*

$$\chi^2(\vec{\theta}) = \chi^2_{stat}(\vec{\theta}) + \chi^2_{syst}(\vec{\theta}_{syst})$$ *Minimize χ^2 by MC / data comparison*

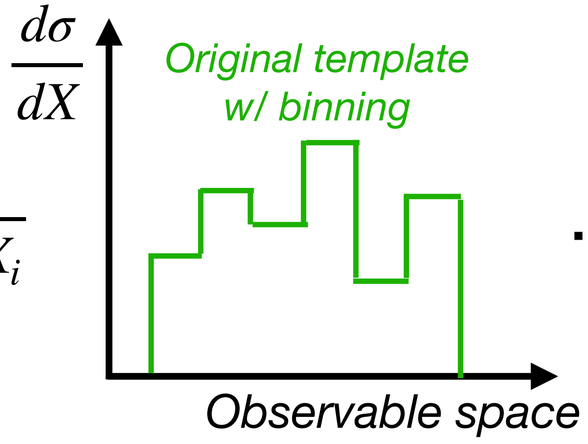
MC *Data*

$$2\sum_j^{reco}\left(\beta_j N_j^{exp}(\vec{\theta}) - N_j^{obs} + N_j^{obs}\log\frac{N_j^{obs}}{\beta_j N_j^{exp}(\vec{\theta})} + \frac{(\beta_j-1)^2}{2\sigma^2_{\beta_j}}\right)$$

Prior systematics constraints

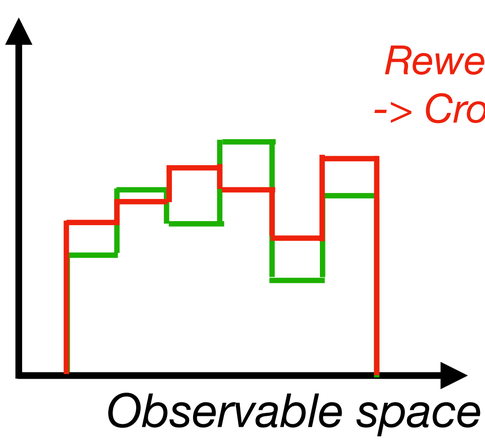
$$(\vec{\theta}_{syst} - \vec{\theta}^{prior}_{syst})^t (V^{cov}_{syst})^{-1} (\vec{\theta}_{syst} - \vec{\theta}^{prior}_{syst})$$

$$\frac{d\sigma_i^T}{dX_i} = \frac{N^T_{sig,i}}{\Phi_\nu \cdot N_T \cdot \epsilon_i^T} \cdot \frac{1}{\Delta X_i}$$



Inject fitted parameters

Reweight



Reweighted template
-> Cross section result

Systematics Model

- Four systematic sources are included in the measurement:

Detector simulation / reconstruction
- *Evaluated by data / MC differences with dedicated control samples.*
- *Sources include e.g. sub-detector track matching, particle identification, momentum measurement, etc.*

Predicted number from MC template

$$N_j^{exp}(\vec{\theta}) = \sum_{sig\in j} \omega_{sig}(\vec{\theta}) + \sum_{bkg\in j} \omega_{bkg}(\vec{\theta})$$

Sig temp. para.

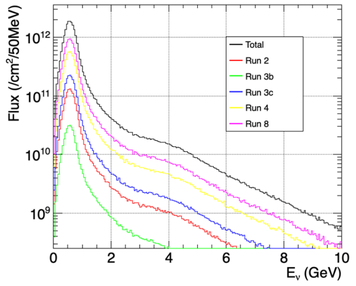
$$\begin{cases} \omega_{sig}(\vec{\theta}) = t_i \times d_j \times f_k \times \prod_a^{sig,model} R_a(x_a) \\ \omega_{bkg}(\vec{\theta}) = d_j \times f_k \times \prod_a^{bkg,model} R_a(x_a) \end{cases}$$

Inject fitted parameters

$$\frac{d\sigma_i^T}{dX_i} = \frac{N_i^T}{\Phi_\nu \cdot N_T \cdot \epsilon_i^T} \cdot \frac{1}{\Delta X_i}$$

Modeling of neutrino interaction
- *Consider model parameters, e.g. M_A^{QE}, M_A^{RES}, etc.*
- *Parameters constrained by external measurements.*
- *Systematics implemented at event-by-event level.*

Incoming neutrino flux
- *Tuned by NA61 2010 replica target experiment.*

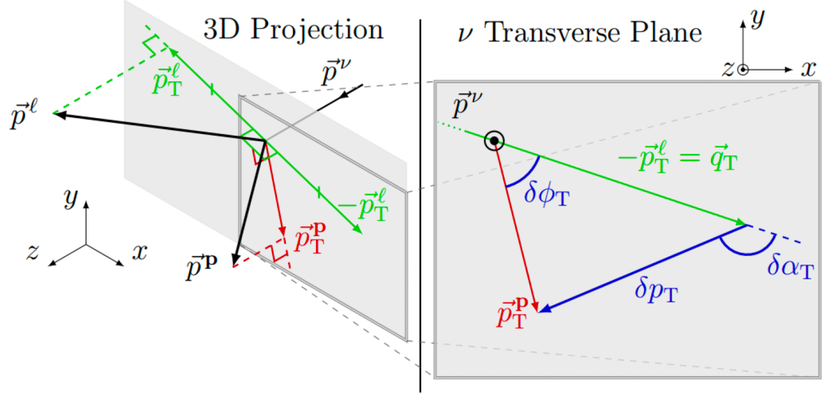


Nucleus target number
- *Uncertainties come from the material mass measurements.*

$$\begin{cases} N_T^C = (7.403 \pm 0.035) \times 10^{29} \\ N_T^O = (2.396 \pm 0.018) \times 10^{29} \end{cases}$$

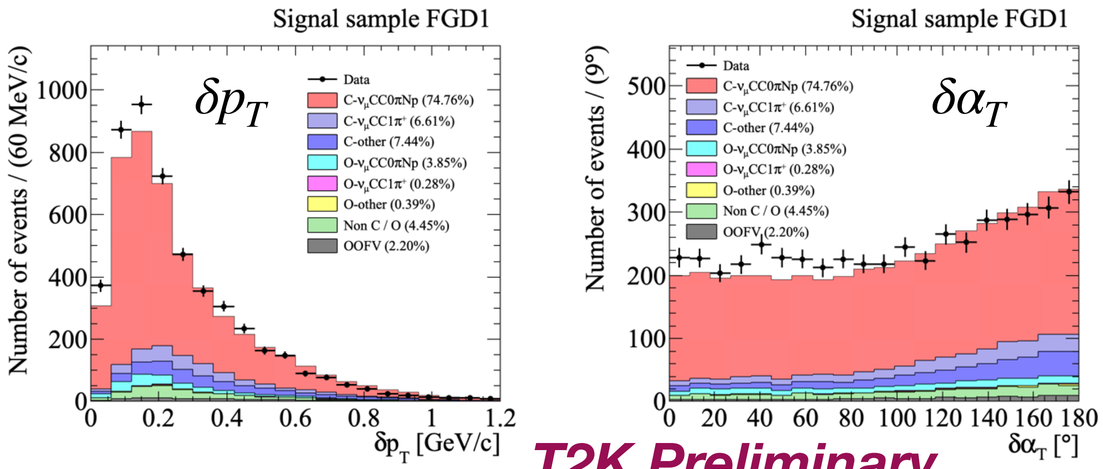
ν_μ CC0πNp Cross Section on C + O with 2D TKI

- Transverse kinematic imbalance (TKI).
  - *Phys. Rev. C 94, 015503 (2016).*



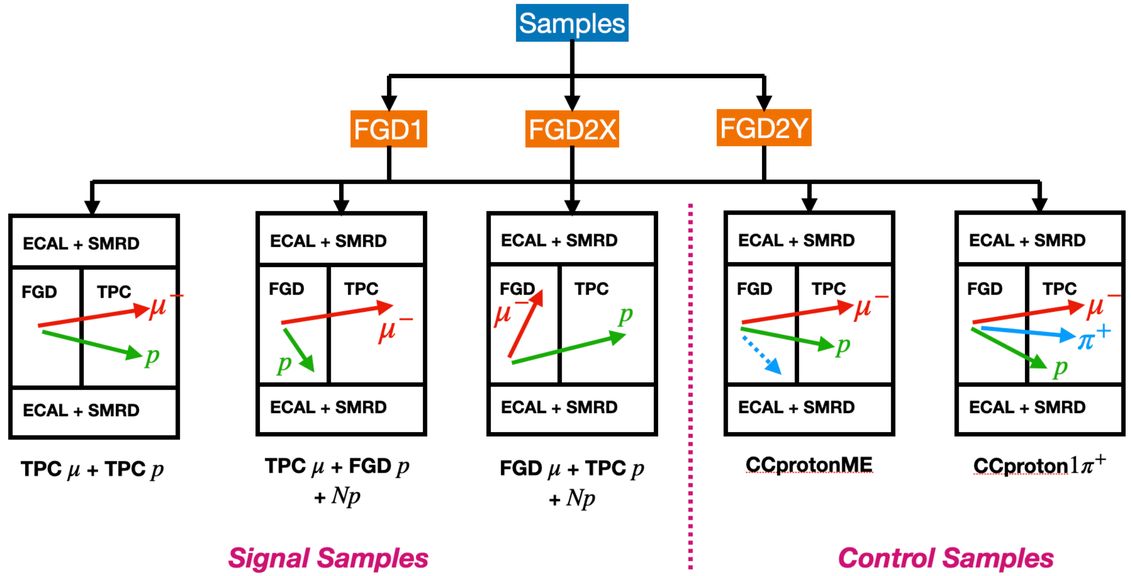
Plot from Phys. Rev. D 98, 032003 (2018)

- Analysis observables:
  - δp_T - $\delta\alpha_T$ and p_N - $\cos\theta_\mu$ correlations.



T2K Preliminary

- Signal sample: $\nu_\mu + X \rightarrow X' + \mu^- + Np$ (CCQE-like).
- Improvements from the previous analysis:
  - *Carbon and oxygen joint analysis, better particle identification (PID) and double differential TKI.*



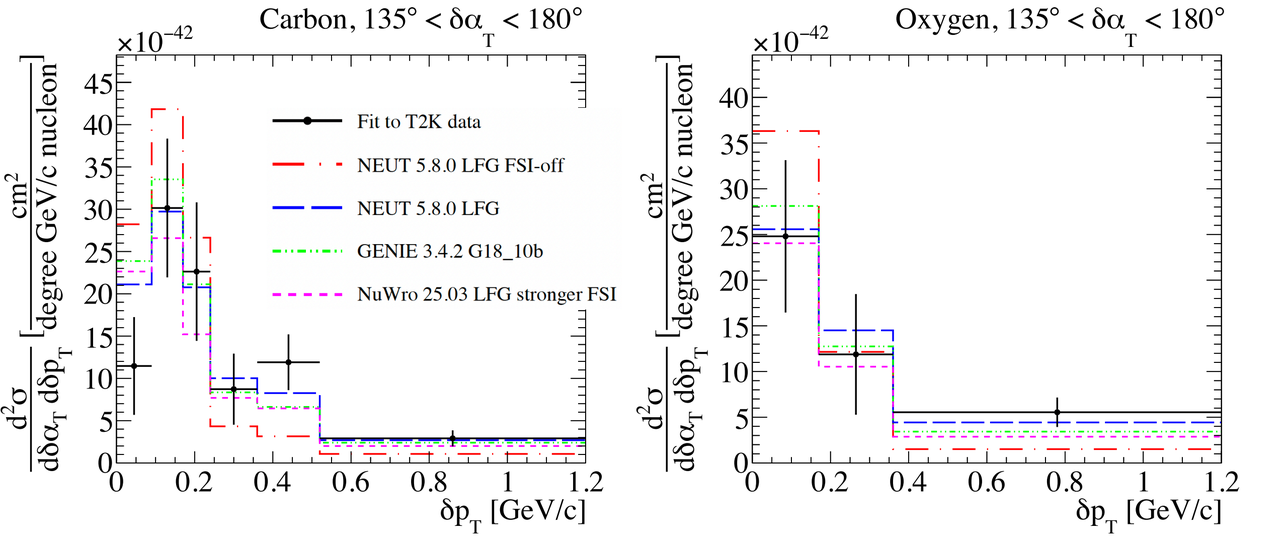
- Phase space cut on muon / proton kinematics.

Particle	Momentum	Angle
Muon	$0.225 < p < 10$ GeV/c	$\cos\theta >$ -0.6
Proton	$0.525 < p < 1.1$ GeV/c	$\cos\theta > 0.3$

ν_μ CC0πNp Cross Section on C + O with 2D TKI

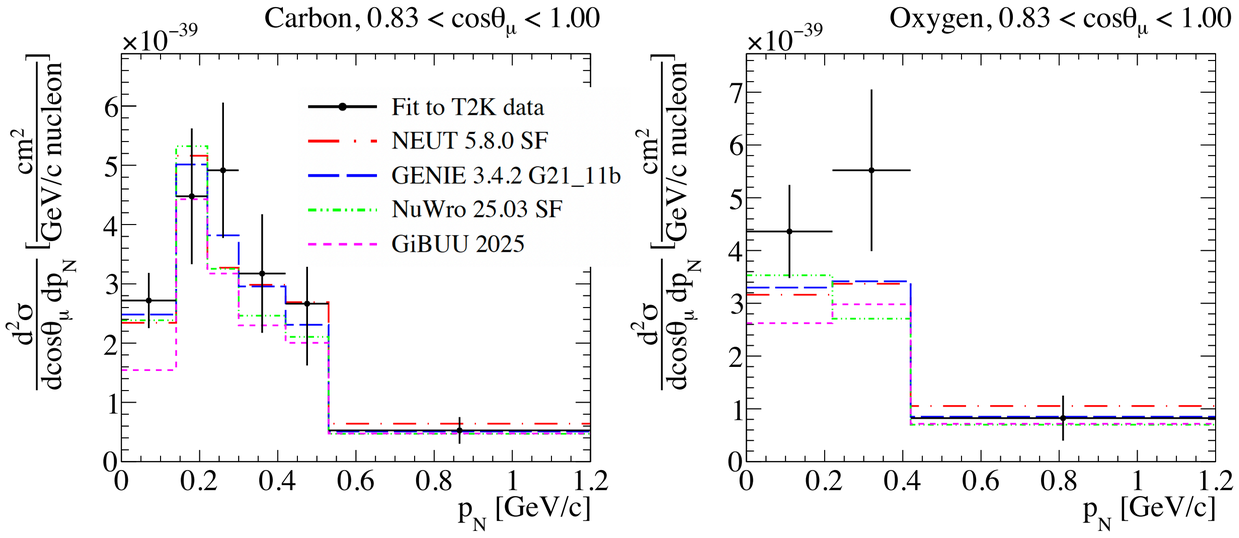
δp_T - $\delta\alpha_T$ Correlation

- Data prefers NEUT cascade model to describe FSI, given local Fermi gas as nucleon initial state model.



p_N - $\cos\theta_\mu$ Correlation

- Data slightly prefers the spectral function model to describe nucleon initial state.



T2K Preliminary

Model	P-value		
	C + O	C only	O only
NEUT 5.8.0 LFG w/o FSI	0.00	0.00	0.00
NEUT 5.8.0 LFG w/ FSI	0.01	0.06	0.42
GENIE 3.4.2 G18_10b (hN2018)	0.00	0.00	0.28
NuWro 25.03 LFG w/ stronger FSI	0.00	0.00	0.31

Model	P-value		
	C + O	C only	O only
NEUT 5.8.0 SF	0.50	0.71	0.35
GENIE 3.4.2 G21_11b (SuSAv2)	0.43	0.63	0.37
NuWro 25.03 SF	0.60	0.70	0.38
GiBUU 2025 (transport)	0.01	0.05	0.14

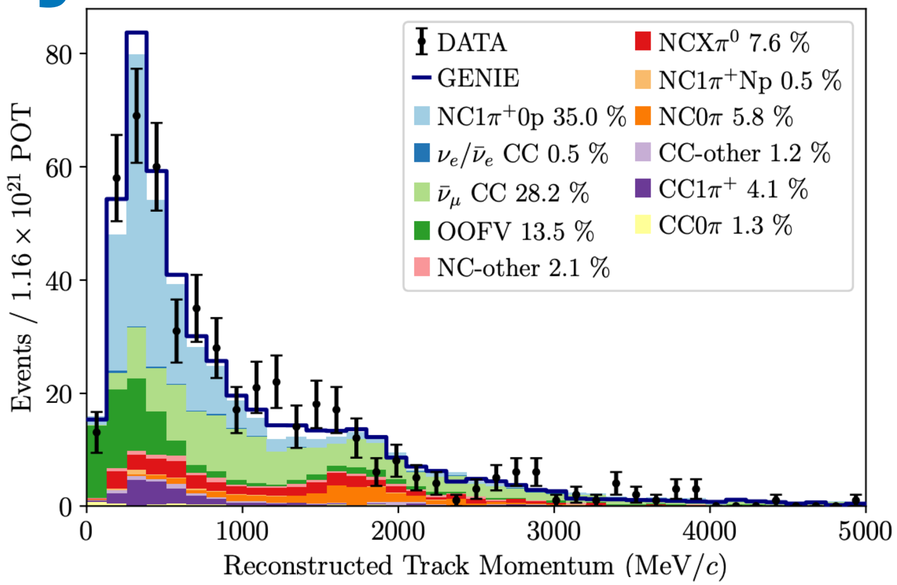
Publication in preparation

NC$1\pi^+$ Cross Section on Hydrocarbon

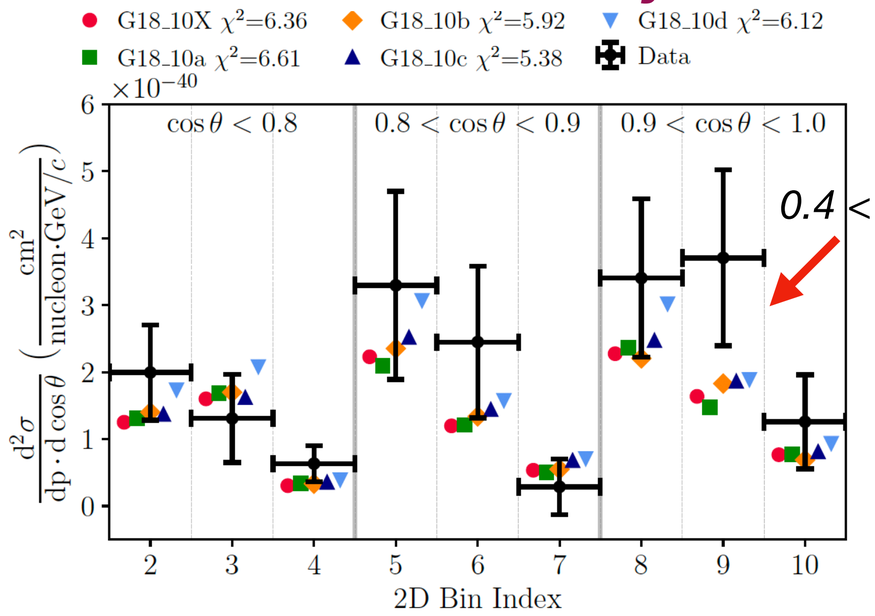
arXiv: 2503.06849
arXiv: 2503.06843

- Main background contributing to ν_μ disappearance signal in neutrino oscillation measurements.
- Signal sample: $\nu + p \rightarrow \nu + n + \pi^+$.
- Phase space cut: $\cos\theta_\pi > 0.5$, $0.2 < p_\pi < 1.0$ GeV/c.
- Data slightly prefers a higher total cross section.
- More variations from FSI models than generator overall predictions, emphasizing the need to improve our understanding of FSI.

Model	σ (cm^2 / nucleon)	p-value
Data	$(6.07 \pm 1.22) \times 10^{-41}$	-
GENIEv3 AR23_20i_00_000	4.02×10^{-41}	0.093
NuWro v19.02.2	4.33×10^{-41}	0.153
NEUT v5.6.2	4.11×10^{-41}	0.108
G18_10X	3.99×10^{-41}	0.089
G18_10a	4.07×10^{-41}	0.100
G18_10b	4.24×10^{-41}	0.133
G18_10c	4.42×10^{-41}	0.176
G18_10d	5.26×10^{-41}	0.507



T2K Preliminary



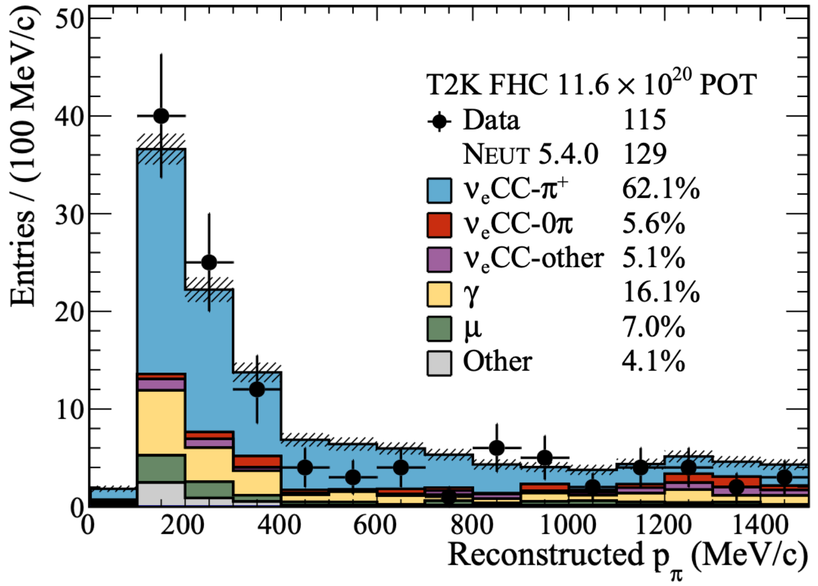
$0.4 < p_\pi < 0.6$ GeV/c

ν_e CCπ^+ Cross Section on Carbon

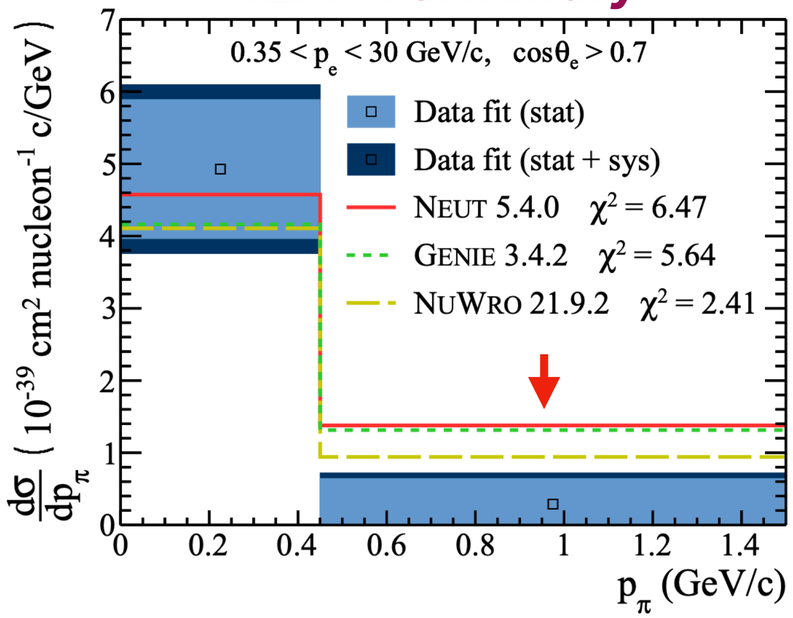
arXiv: 2505.00516

- Sub-dominant interaction channel contributing to ν_e appearance signal in neutrino oscillation measurements.
- Signal sample: $\nu_e + A \rightarrow X + e^- + \pi^+$.
- Phase space cut: $0.35 < p_e < 30$ GeV/c, $\cos\theta_e > 0.7$, $p_\pi < 1.5$ GeV/c.
- Data favors a lower total cross section and lower differential cross section at high pion momentum which are not covered by generators.

Generator	σ (10^{-39} cm^2 nucl^{-1})	p-value
NEUT 5.4.0	3.51	0.30
GENIE 3.4.2	3.25	0.59
NUWRO 21.9.2	2.84	0.89
Data	2.52 ± 0.60	-



T2K Preliminary



Summary

- The T2K near detector ND280 enables us to perform various neutrino cross section measurements to improve our understanding of neutrino-nucleus interactions.
  - *The modeling of these interactions contribute to the largest systematic uncertainty in the current long-baseline neutrino oscillation measurements.*
- Most recent cross section results with ND280 were presented:
  - ν_μ *CC*$0\pi Np$ *interactions on carbon and oxygen with double differential TKI.*
  - *NC*$1\pi^+$ *interactions on hydrocarbon.*
  - ν_e *CC*π^+ *interactions on carbon.*
- The currently running ND280 upgrade is expected to provide more precise cross section measurements thanks to the improved detector performances and higher beam intensity.

→ *771. The T2K ND280 Detector Upgrade. 2025-7-11, 8:30.*

Backup Slides

Basic Information

Definition of Differential Cross Section

- Measure cross section by counting number of signal events in a specific 2D TKI phase space region i.

$$N_i = N_T \int \sigma_i(E_\nu)\phi(E_\nu)\epsilon_i(E_\nu)dE_\nu$$

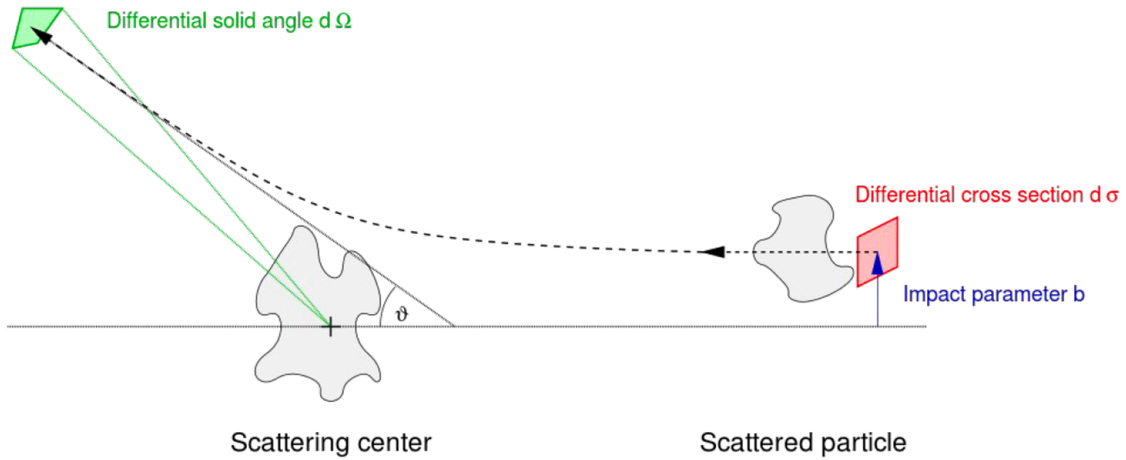
Assume averaged cross section and efficiency in region i.

$$N_i = N_T < \sigma_i >< \epsilon_i > \int \phi(E_\nu)dE_\nu$$

Flux-integrated cross section.

$$N_i = N_T < \sigma_i >< \epsilon_i > \Phi_\nu$$

$$< \sigma_i > = \frac{N_i}{\Phi_\nu \cdot N_T \cdot < \epsilon >}$$



Cross section formula used in this analysis

$$\frac{d\sigma_i^T}{(dXdY)_i} = \frac{N_i^T}{\Phi_\nu \cdot N_T \cdot \epsilon_i^T} \cdot \frac{1}{(\Delta X \Delta Y)_i}$$

Target T = carbon / oxygen

Binning $dXdY = d\delta\alpha_T d\delta p_T / dp_N d\cos\theta_\mu$

Neutrino-Nucleus Interaction Models Used in the Template MC

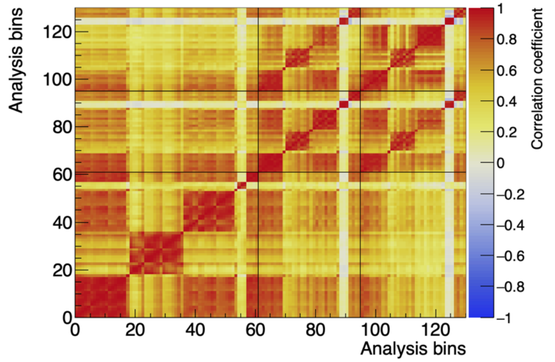
Channel	Model
Nucleon Initial State	Spectral function - CCQE Relativistic Fermi gas - other interactions
CCQE	Llewellyn Smith 1p1h model BBBA05 vector and axial-vector form factors
2p2h	Nieves et al. model
CCRES	Rein-Sehgal model with lepton mass correction
CCDIS	Use PYTHIA, GRV98 parton distribution function with Bodek-Yang correction

Systematics Model

- Four systematic sources are included in the measurement:

Detector simulation / reconstruction

- *Evaluated by data / MC differences with dedicated control samples.*



Predicted number from MC template

$$N_j^{exp}(\vec{\theta}) = \sum_{sig\in j} \omega_{sig}(\vec{\theta}) + \sum_{bkg\in j} \omega_{bkg}(\vec{\theta})$$

Sig temp. para.

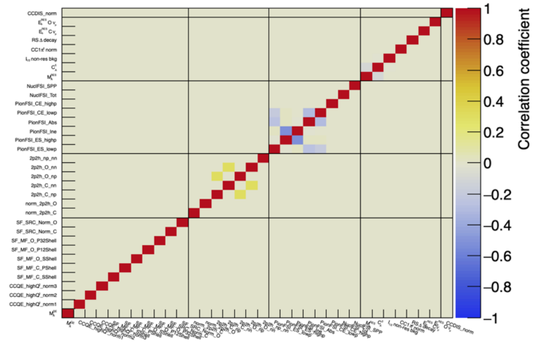
$$\begin{cases} \omega_{sig}(\vec{\theta}) = t_i \times d_j \times f_k \times \prod_a^{sig,model} R_a(x_a) \\ \omega_{bkg}(\vec{\theta}) = d_j \times f_k \times \prod_a^{bkg,model} R_a(x_a) \end{cases}$$

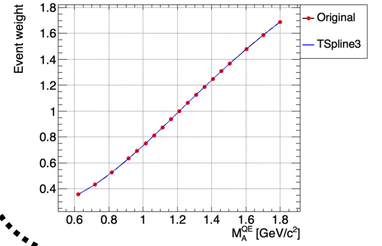
Inject fitted parameters

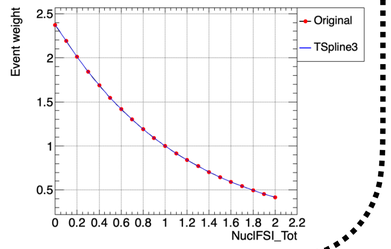
$$\frac{d\sigma_i^T}{dX_i} = \frac{N_i^T}{\Phi_\nu \cdot N_T \cdot \epsilon_i^T} \cdot \frac{1}{\Delta X_i}$$

Modeling of neutrino interaction

- *Parameters constrained by external measurements.*
- *Systematics implemented at event-by-event level.*

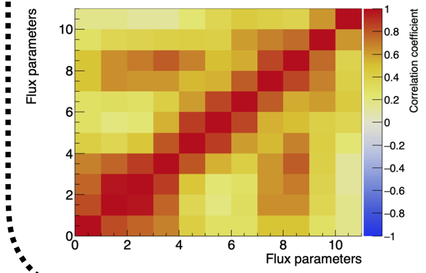


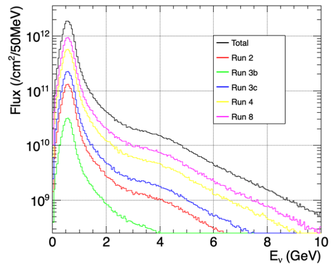




Incoming neutrino flux

- *Tuned by NA61 2010 replica target experiment.*





Nucleus target number

- *Uncertainties come from the material mass measurements.*

$$\begin{cases} N_T^C = (7.403 \pm 0.035) \times 10^{29} \\ N_T^O = (2.396 \pm 0.018) \times 10^{29} \end{cases}$$

Example of Detector and Neutrino Interaction Systematic Sources

Table 9.1: List of detector systematic sources included in this analysis.

Category	Systematic Uncertainty Source	Type
Interaction modeling	Proton SI	Weight
	Pion SI	Weight
Incoming neutrino direction	Neutrino parent decay position	Variation
External background	OOFV	Weight
	Pile-up	Weight
Global track reconstruction	Charge ID	Weight
	TPC-FGD matching	Weight
	FGD-ECAL matching	Weight
	Momentum by range resolution	Variation
TPC Reconstruction	TPC cluster efficiency	Weight
	TPC tracking efficiency	Weight
	B-field distortion	Variation
	TPC momentum scale	Variation
	TPC momentum resolution	Variation
	TPC PID	Variation
FGD Reconstruction	FGD hybrid tracking efficiency	Weight
	FGD2 backward migration	Weight
	FGD dE/dx momentum resolution	Variation
	FGD momentum bias from vertex migration	Variation
	FGD dE/dx PID	Weight
	FGD ME tagging efficiency	Weight
ECAL Reconstruction	ECAL tracking efficiency	Weight
	ECAL HIP PID	Weight

Table 9.5: List of neutrino interaction systematic sources included in this analysis.

Category	Systematic Uncertainty Source	Parameter Number
CCQE	M_A^{QE}	1
	High Q^2 normalization	3
	SF-MF shell normalization	5
	SF-SRC normalization	2
2p2h	Overall normalization	2
	MEC-NN contribution	4
	$nn - np$ pair contribution	1
FSI	Pion FSI	6
	Nucleon FSI (C, O, other)	2×3
SPP	Rein-Sehgal model parameters	3
	Δ resonance decay	1
	CCRES binding energy	2
	CC1π^0 normalization	1
Other	CCDIS normalization	1

ν_μ CC$0\pi Np$ Cross Section on C + O with 2D TKI

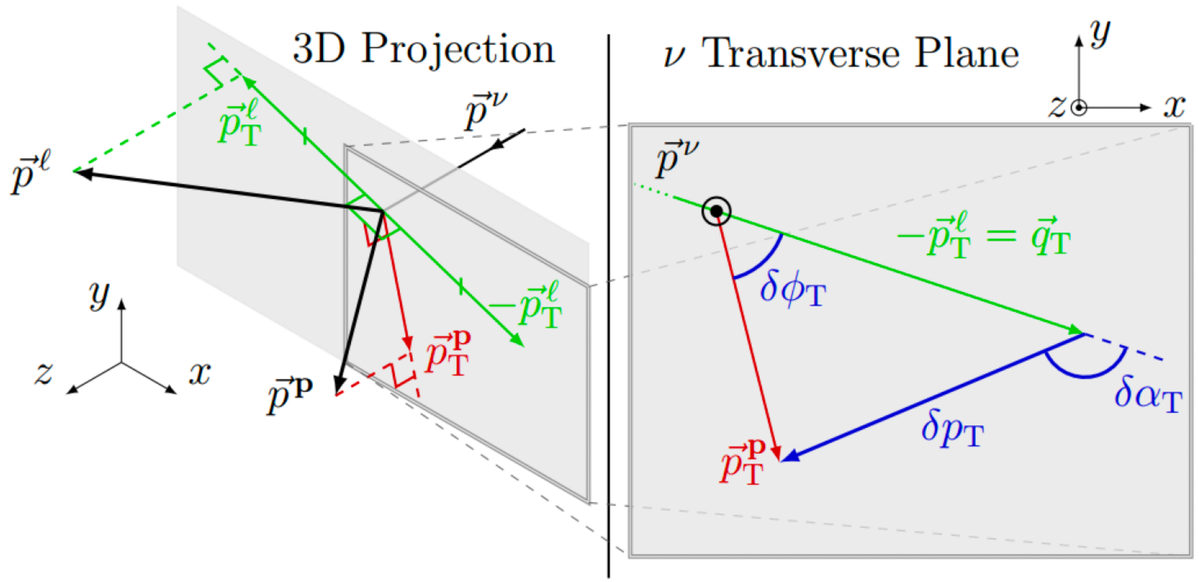
Analysis Observables

- Consider 3 variables:

① $\delta p_T = |\vec{p}_T^{\,\mu} + \vec{p}_T^{\,p}|$

② $\delta\alpha_T = \arccos \dfrac{-\vec{p}_T^{\,\mu} \cdot \delta\vec{p}_T}{p_T^{\mu} \cdot \delta p_T}$

③ $p_N = \sqrt{\delta p_T^2 + p_L^2}$



- The longitudinal momentum $p_L = \dfrac{1}{2}(M_A + p_L^{\mu} + p_L^{p} - E_{\mu} - E_p) - \dfrac{1}{2} \cdot \dfrac{\delta p_T^2 + M_{A'}^2}{M_A + p_L^{\mu} + p_L^{p} - E_{\mu} - E_p}$

- Residual nuclear mass $M_{A'} = M_A - M_p + \langle\epsilon\rangle_p$.

Selection Statistics

- The measurement uses T2K neutrino mode (FHC) data collected between 2010 and 2017 during Run 2 to 8.
- The ND280 data sample has ~ 11.61×10^{20} protons on target (POT) in total.

IPS = in phase space

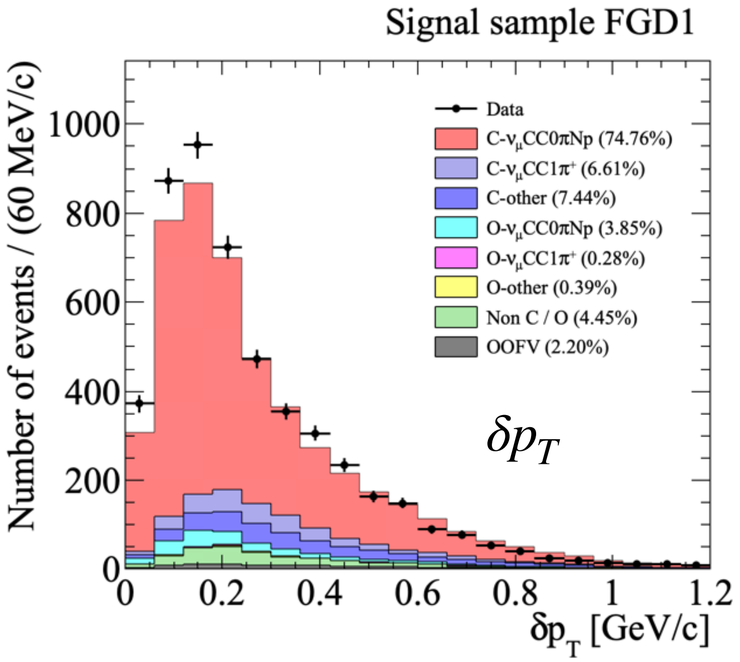
Sample	Case	Data	MC	Data (IPS)	MC (IPS)
TPC μ + TPC p	FGD1	3226	3522.7 ± 59.4	2259	2498.9 ± 50.0
	FGD2X	2550	2693.2 ± 51.9	1803	1934.3 ± 44.0
	FGD2Y	869	895.8 ± 29.9	600	649.5 ± 25.5
TPC μ + FGD p (+ Np)	FGD1	2833	2942.8 ± 54.2	1425	1473.2 ± 38.4
	FGD2X	926	920.0 ± 30.3	768	713.2 ± 26.7
	FGD2Y	304	323.1 ± 18.0	242	236.7 ± 15.4
FGD μ + TPC p (+ Np)	FGD1	1940	1869.1 ± 43.2	1312	1278.9 ± 35.8
	FGD2X	1062	1022.5 ± 32.0	739	710.2 ± 26.7
	FGD2Y	471	386.3 ± 19.7	321	266.8 ± 16.3

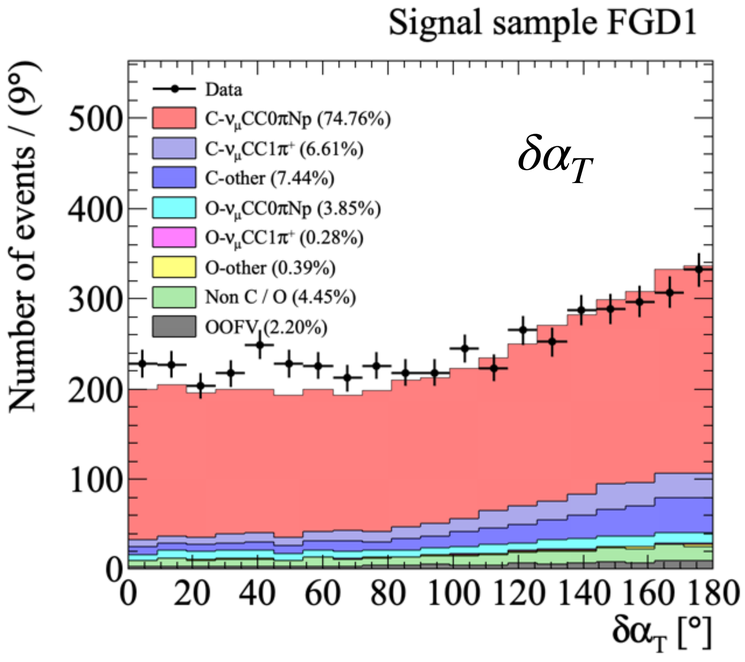
Sample	Case	Data	MC	Data (IPS)	MC (IPS)
CCproton ME	FGD1	477	500.5 ± 22.4	283	329.6 ± 18.2
	FGD2X	211	238.8 ± 15.5	162	177.3 ± 13.3
	FGD2Y	79	78.1 ± 8.8	57	56.5 ± 7.5
CCproton $1\pi^+$	FGD1	353	332.7 ± 18.2	227	204.7 ± 14.3
	FGD2X	323	301.7 ± 17.4	199	205.4 ± 14.3
	FGD2Y	106	95.6 ± 9.8	69	66.8 ± 8.2

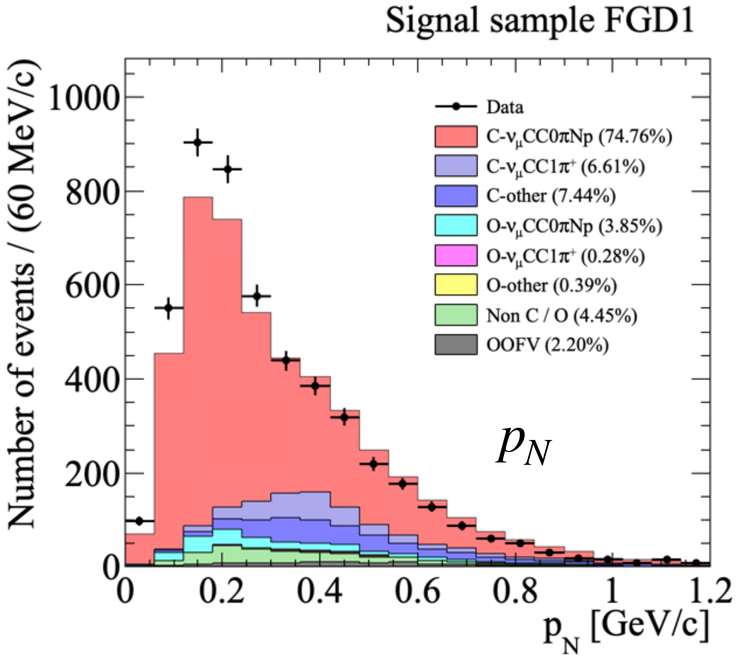
T2K Preliminary

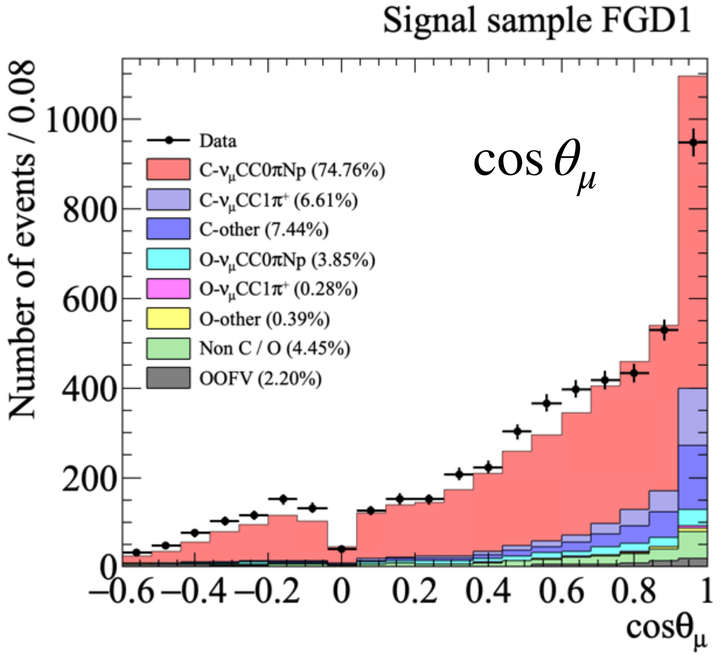
Selection Distributions

T2K Preliminary





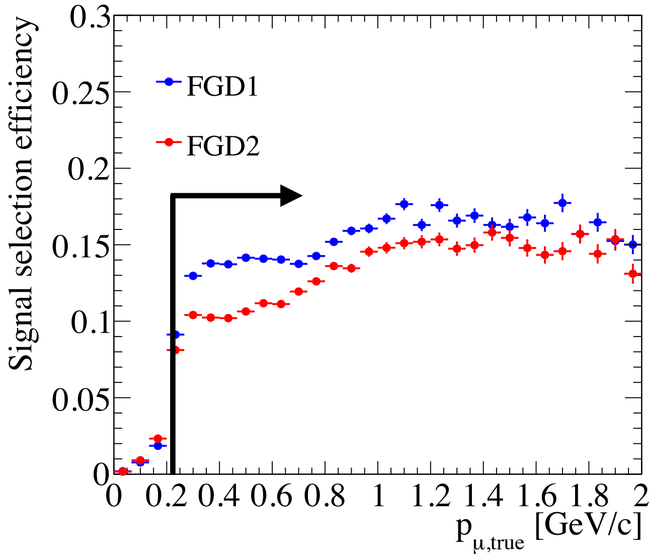


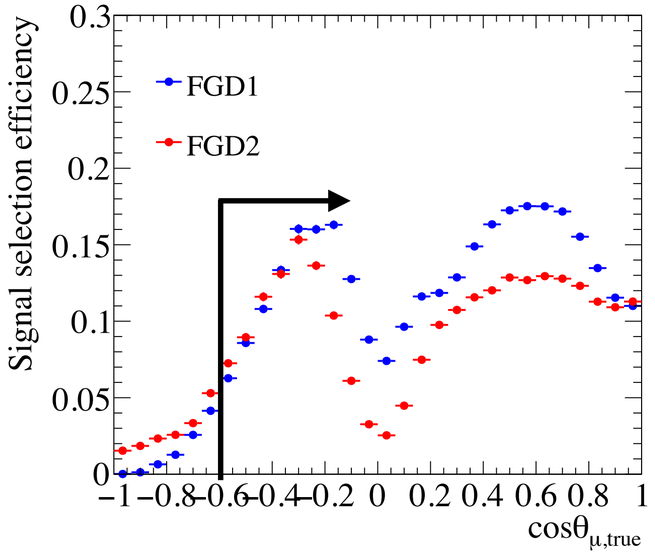


Phase Space Constraint

T2K Preliminary

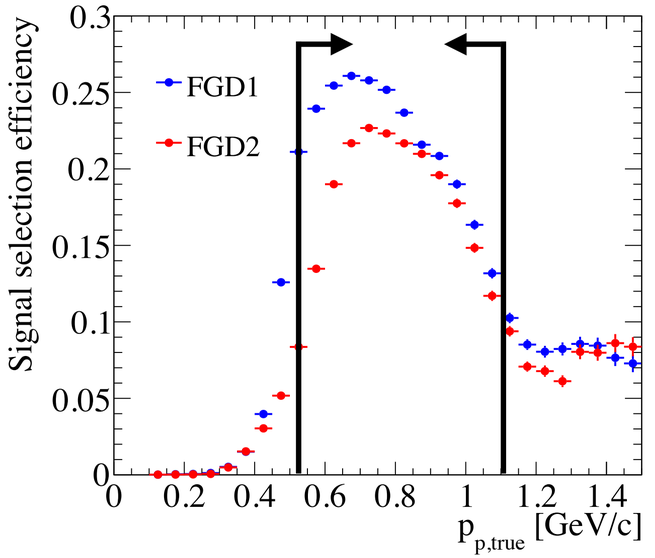
Muon momentum

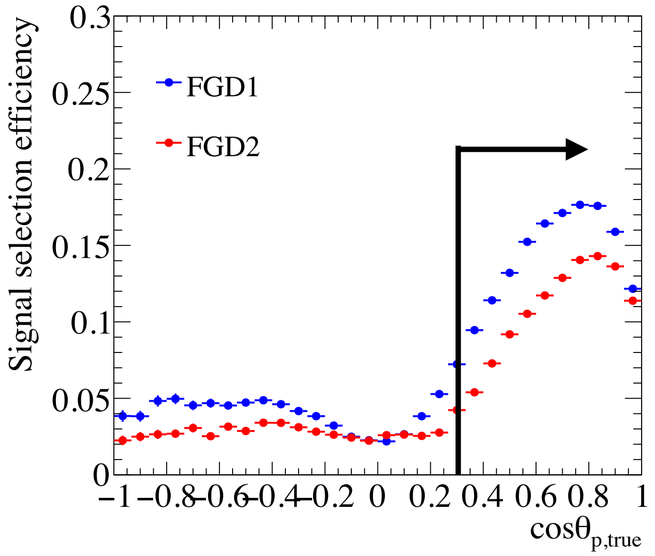




Muon angle

Proton momentum



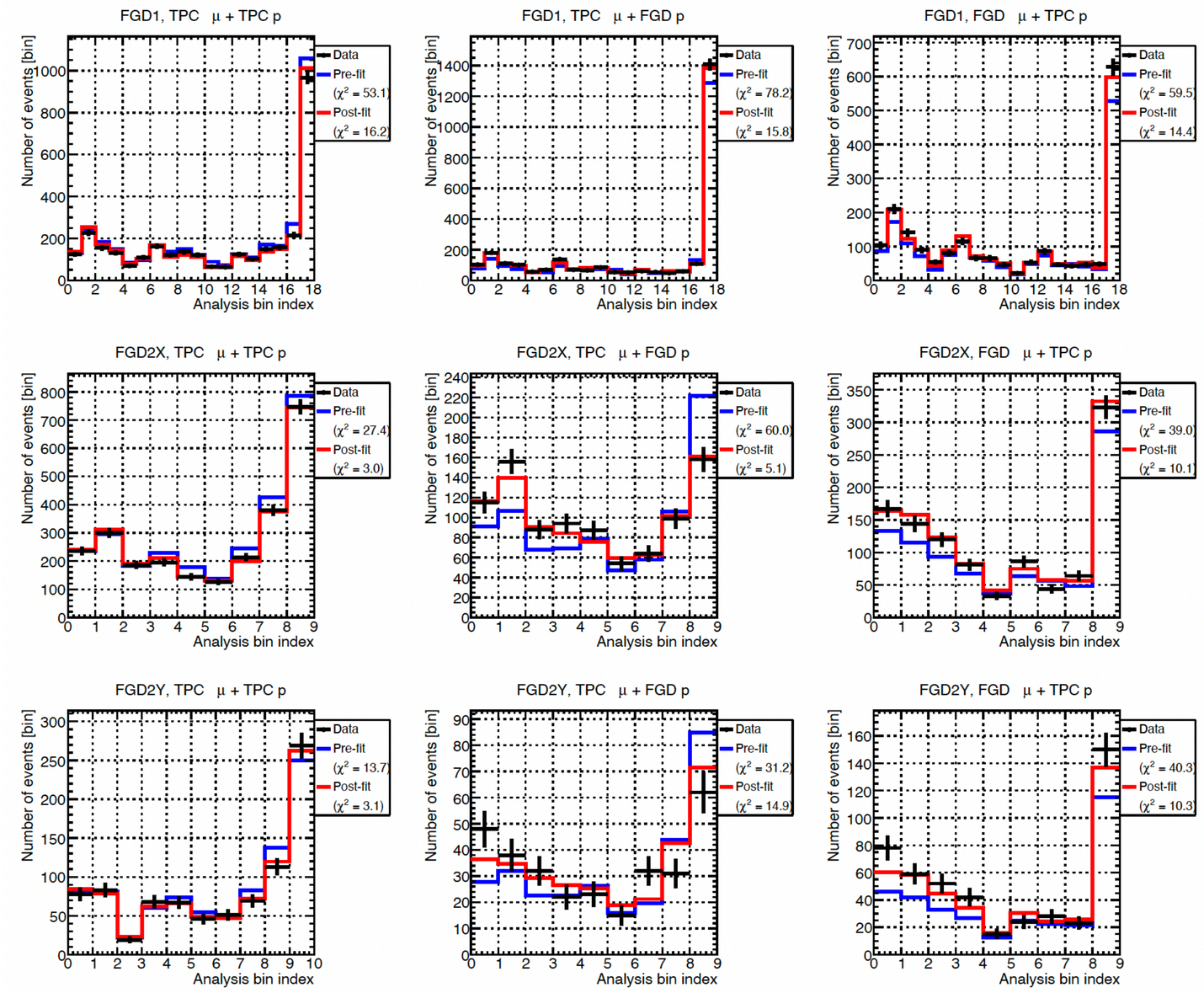


Proton angle

Signal Sample Distributions (Pre-/Post-fit)

δp_T - $\delta \alpha_T$ Space

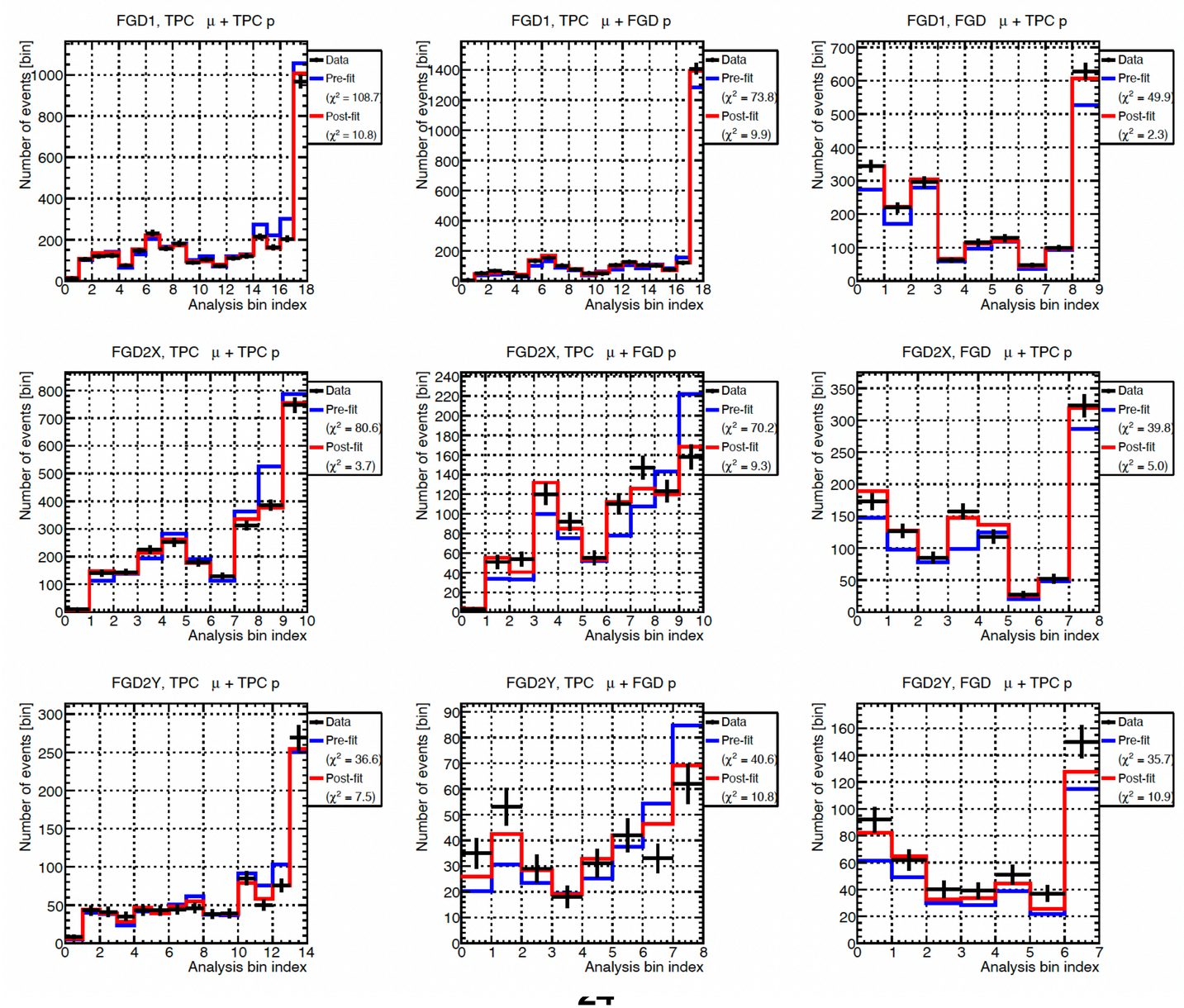
T2K Preliminary



Signal Sample Distributions (Pre-/Post-fit)

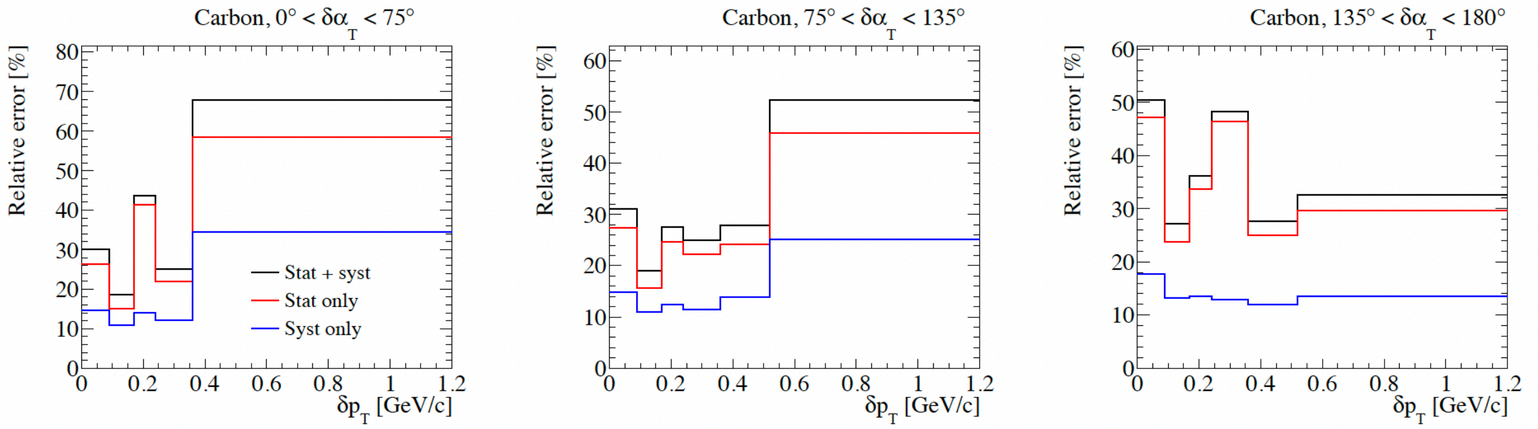
p_N - $\cos\theta_\mu$ Space

T2K Preliminary



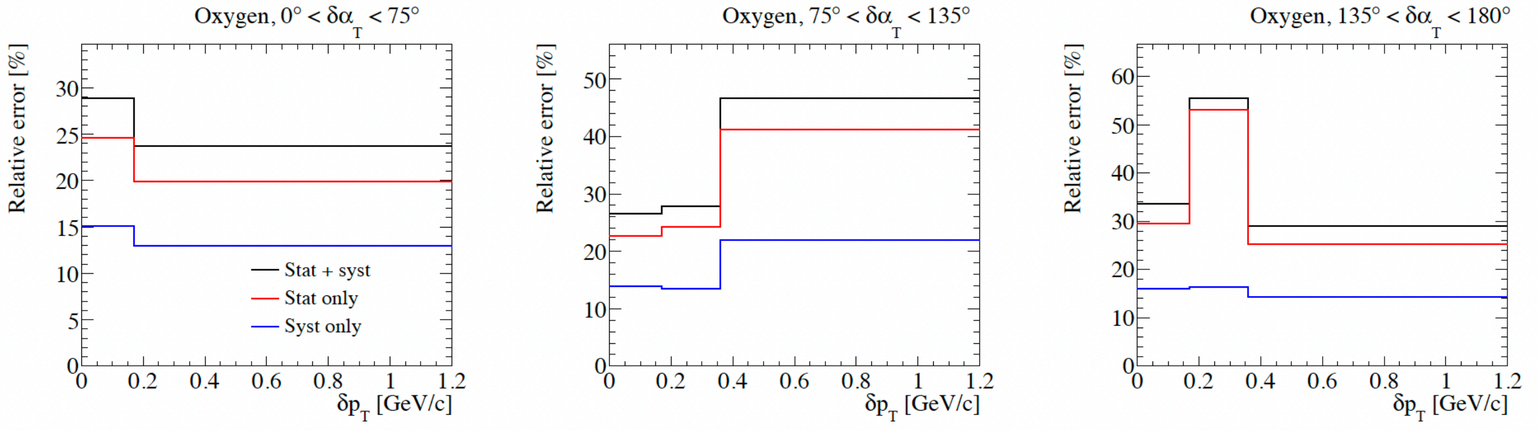
Relative Error of Cross Section Measurement

δp_T - $\delta \alpha_T$ Space



(a) Carbon

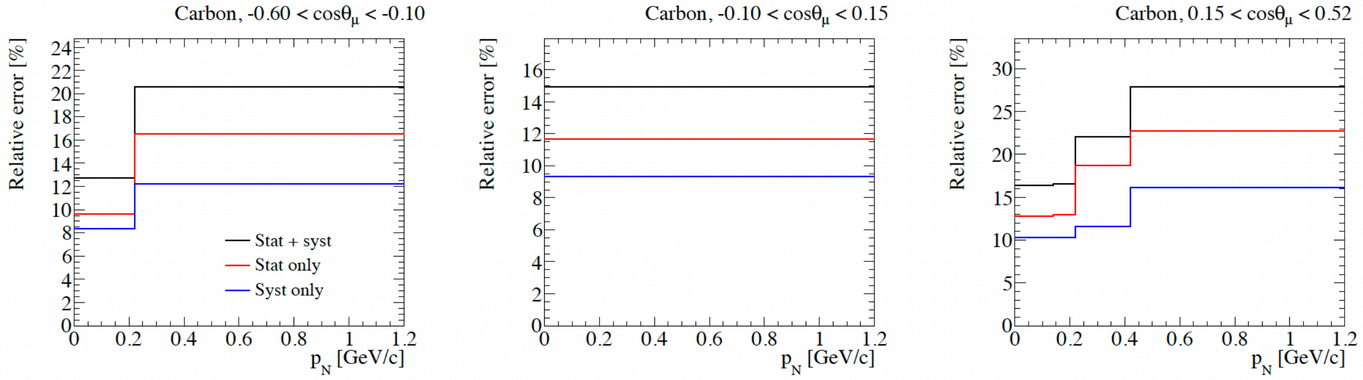
T2K Preliminary

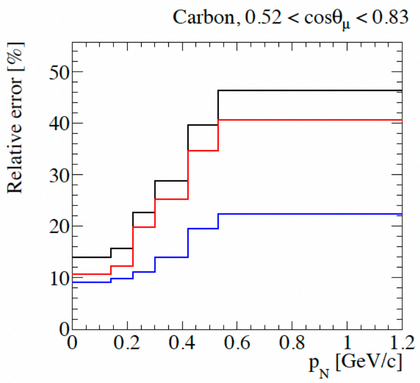


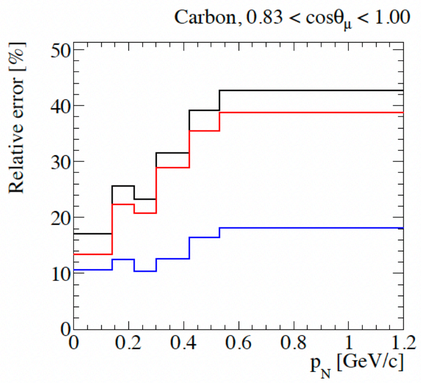
(b) Oxygen

Relative Error of Cross Section Measurement

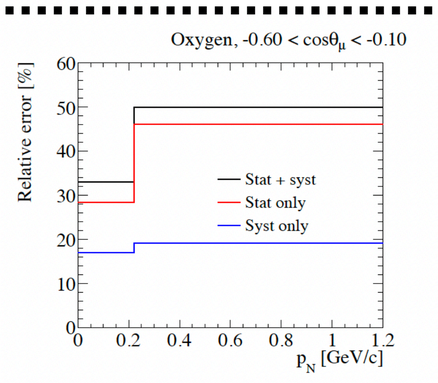
p_N - $\cos\theta_\mu$ Space

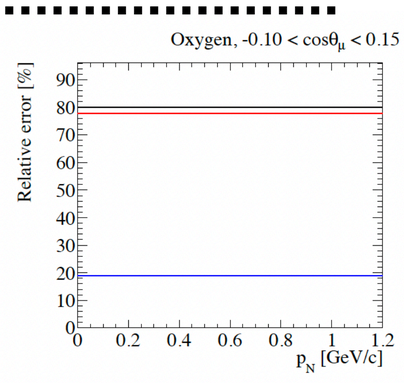


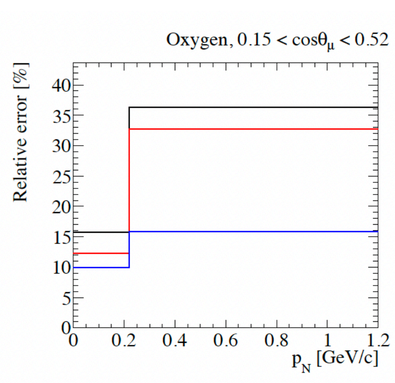


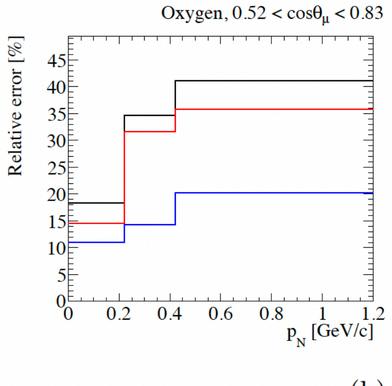


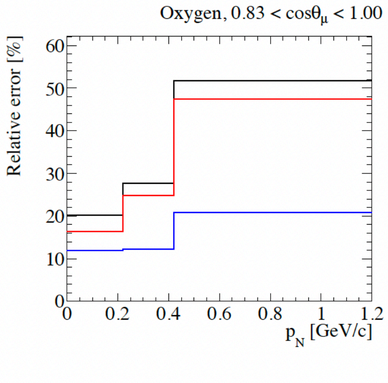
T2K Preliminary







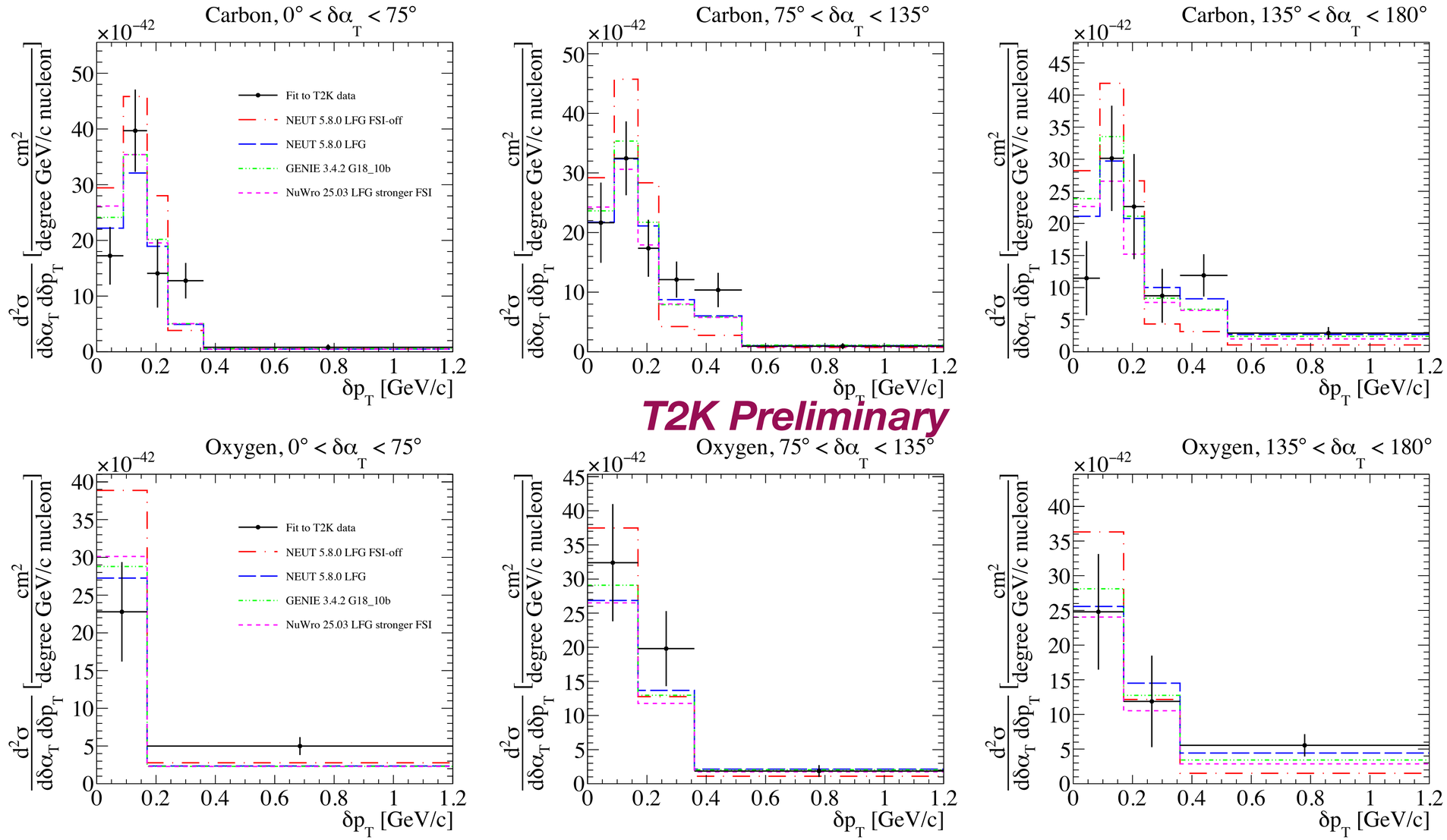




(b) Oxygen

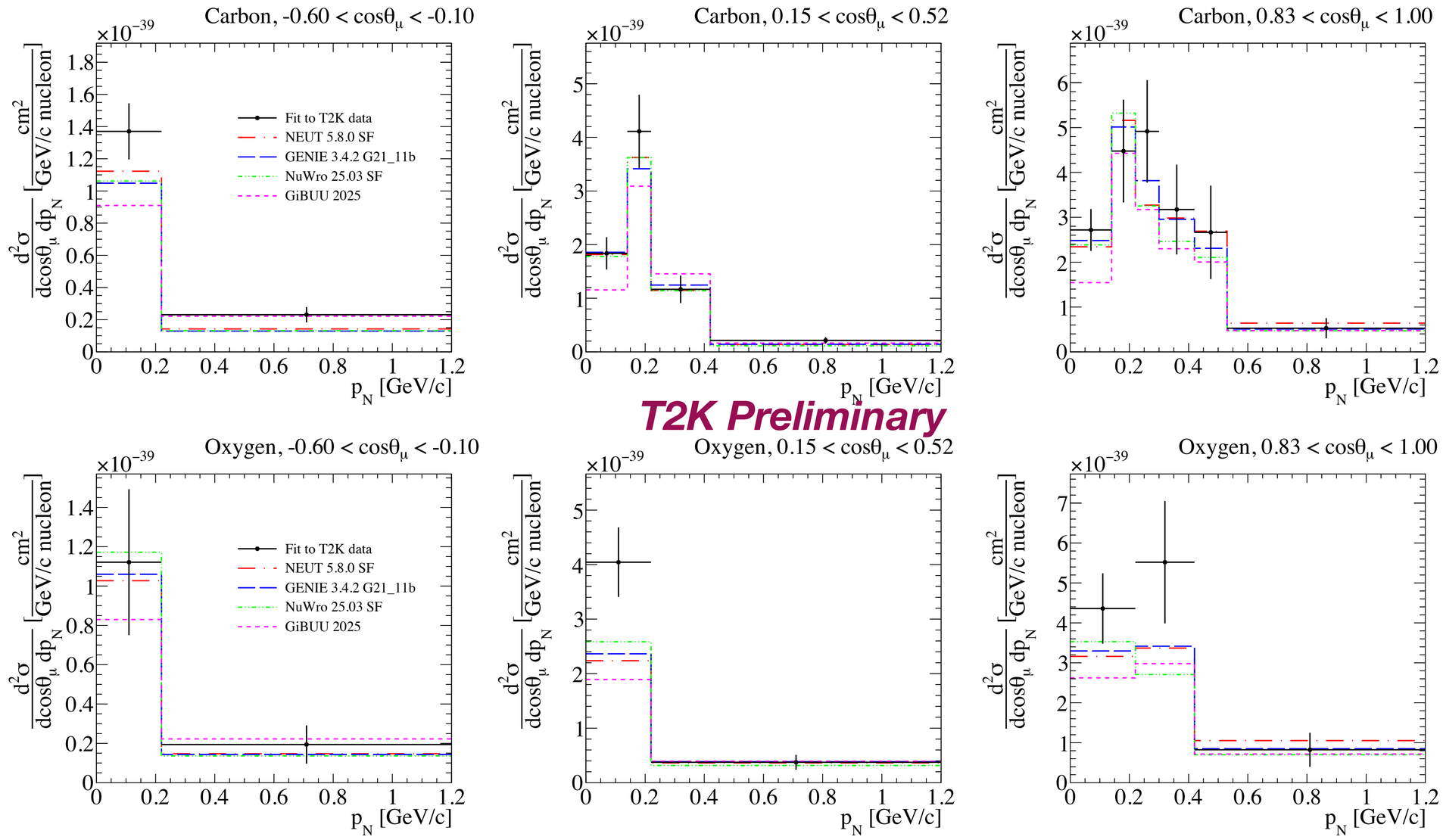
ν_μ CC0πNp Cross Section on C + O with 2D TKI

δp_T - $\delta\alpha_T$ Correlation Results



ν_μ CC0πNp Cross Section on C + O with 2D TKI

p_N - cos θ_μ Correlation Results

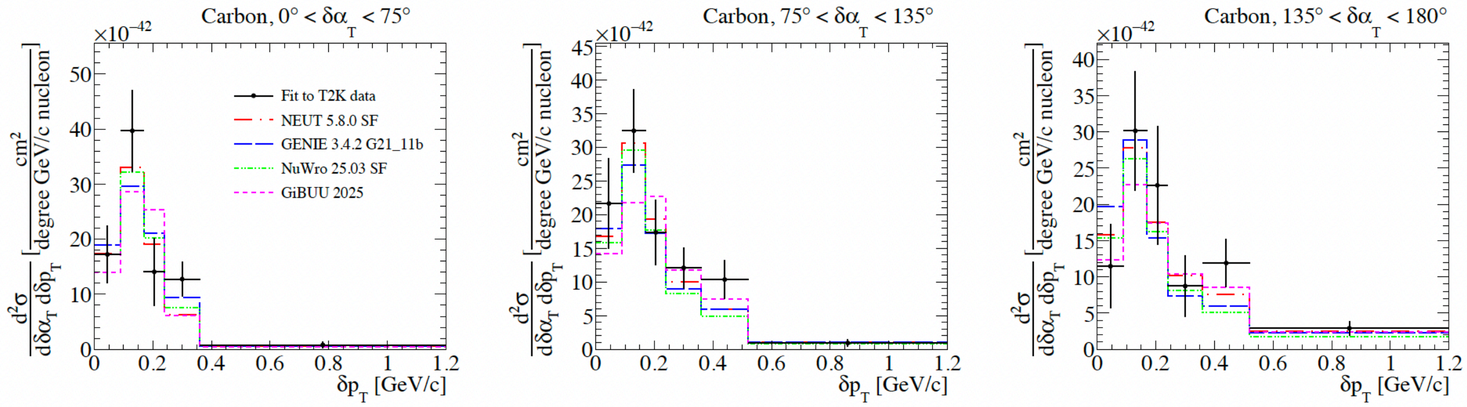


Model Comparison

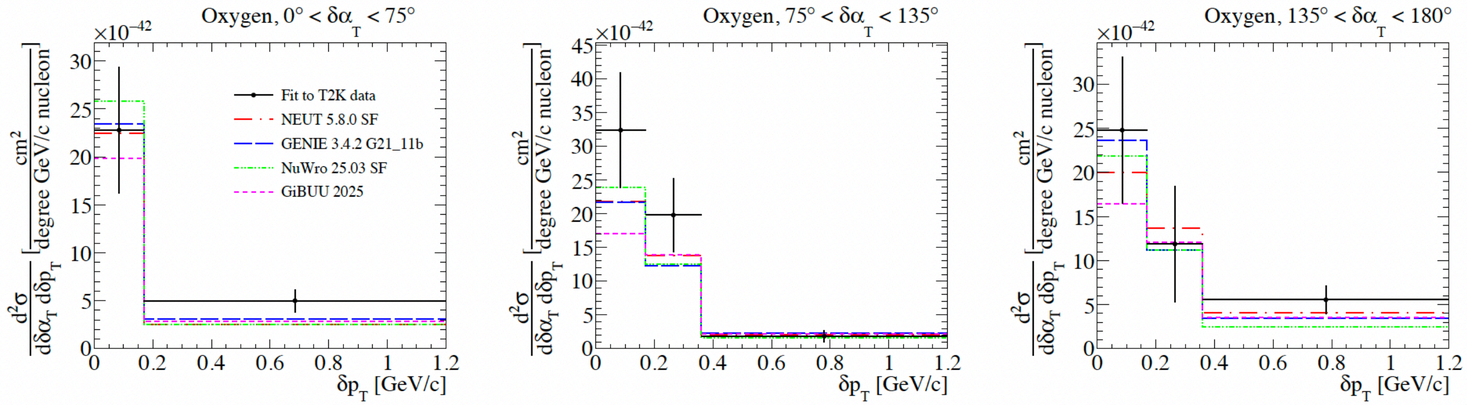
δp_T - $\delta \alpha_T$ Space

χ^2 (p-value)	N_{bin}	NEUT 5.8.0 SF	GENIE 3.4.2 G21_11b	NuWro 25.03 SF	GiBUU 2025
C + O	25	20.4 (0.73)	27.4 (0.34)	20.9 (0.70)	34.8 (0.09)

T2K Preliminary



(a) Carbon

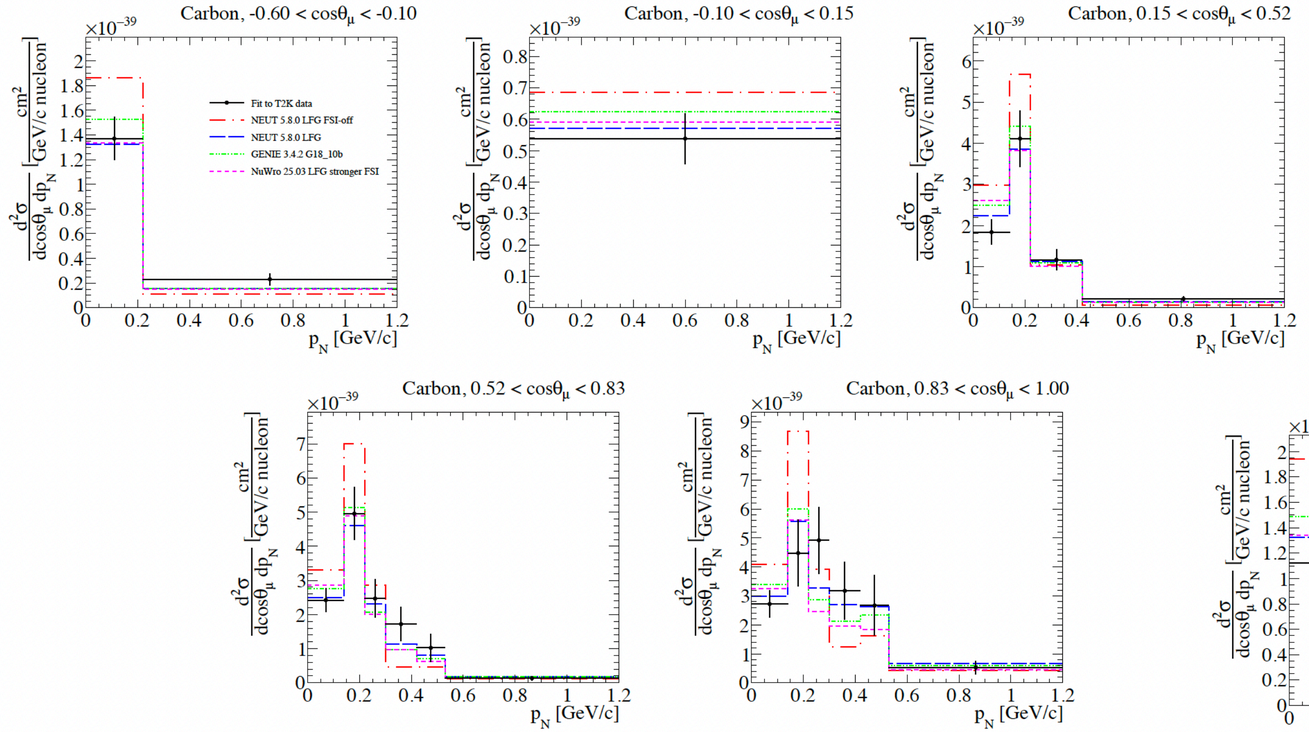


(b) Oxygen

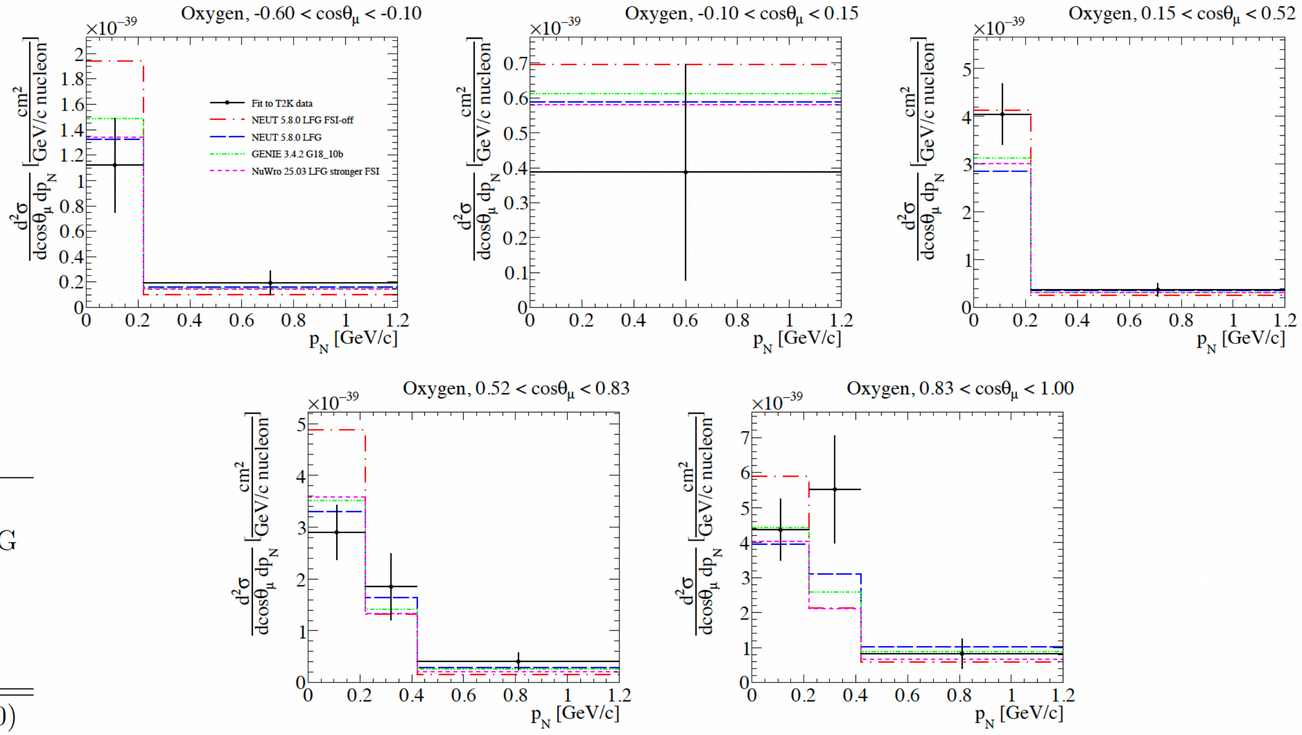
Model Comparison

p_N - $\cos\theta_\mu$ Space

T2K Preliminary



(a) Carbon

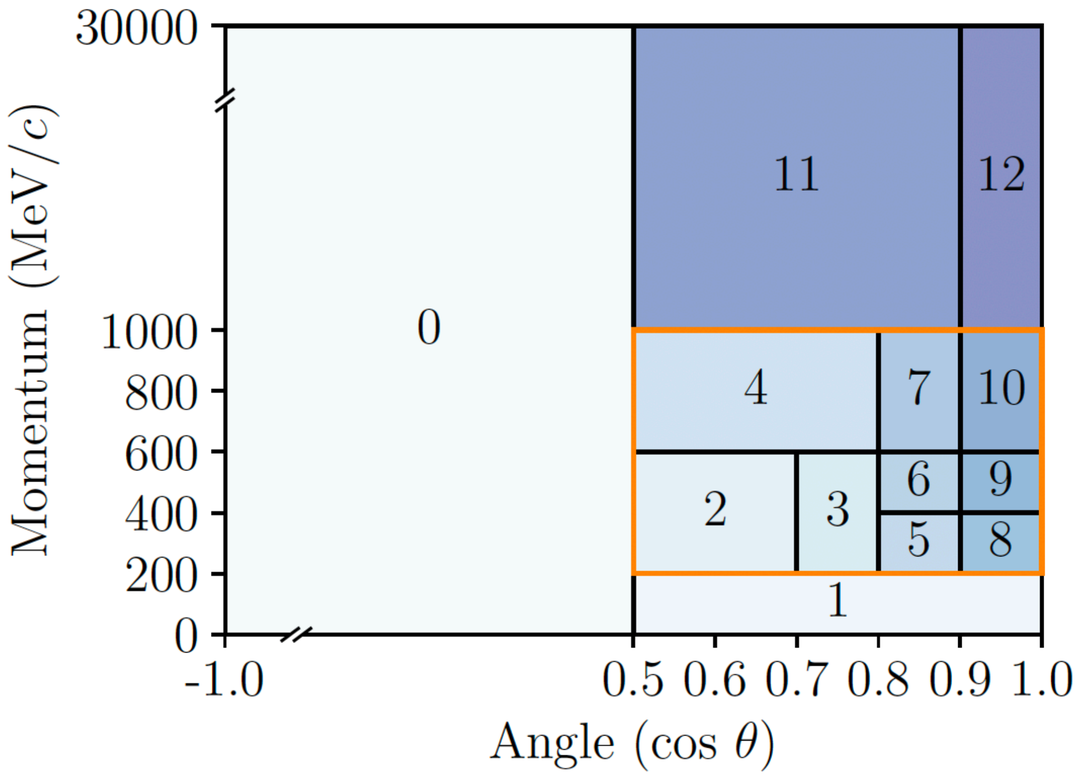


(b) Oxygen

χ^2 (p-value)	N_{bin}	NEUT 5.8.0 LFG + RPA FSI off	NEUT 5.8.0 LFG + RPA FSI on	GENIE 3.4.2 G18_10b	NuWro 25.03 LFG + RPA, MFP_N -50%
C + O	30	137.4 (0.00)	36.2 (0.20)	57.7 (0.00)	55.1 (0.00)

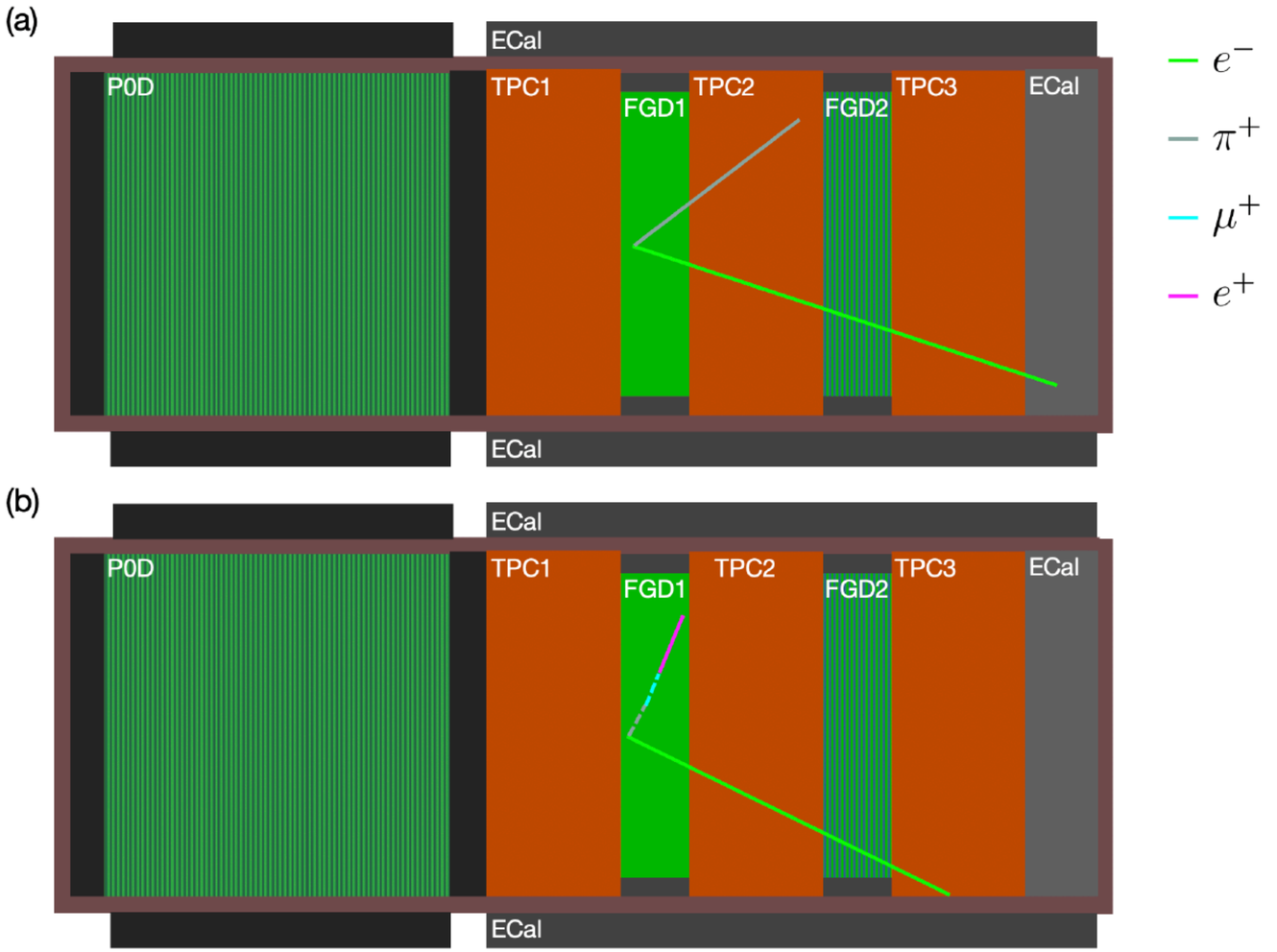
NC1π^+ Cross Section on CH

Cross Section Binning Scheme



ν_e CC$1\pi^+$ Cross Section on C

Signal Sample Scheme



TPC-π sub-sample

FGD-π sub-sample

T2K Preliminary