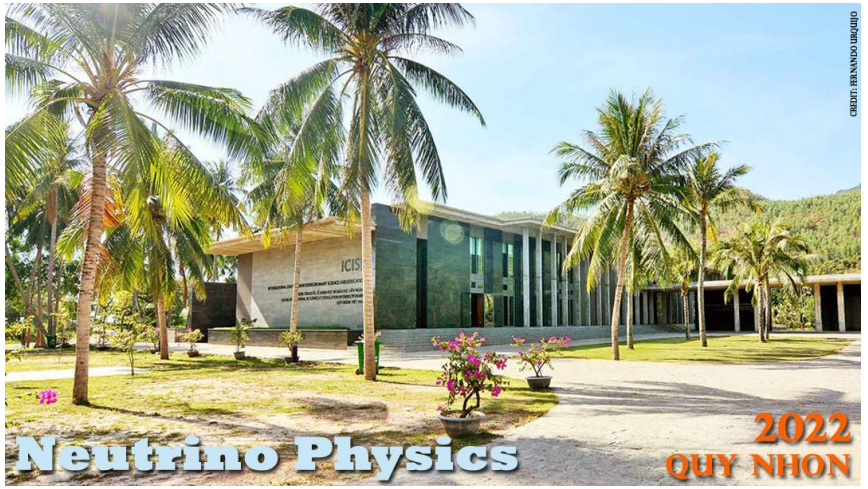
T2K latest results on neutrino-nucleus cross sections



18th Rencontres du Vietnam Conference

Caspar Schloesser

on behalf of the T2K Collaboration

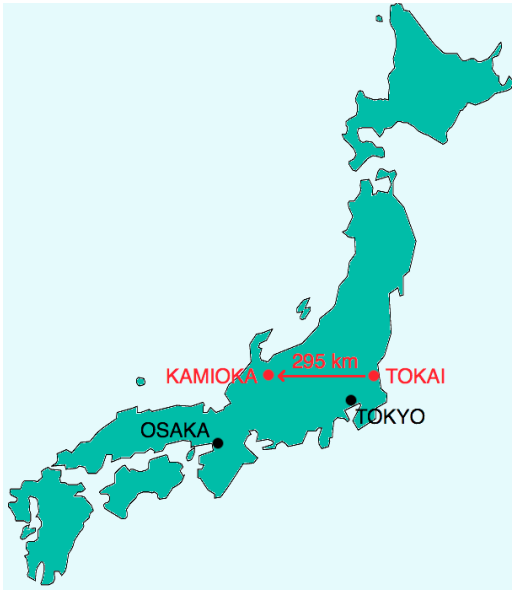
University of Geneva

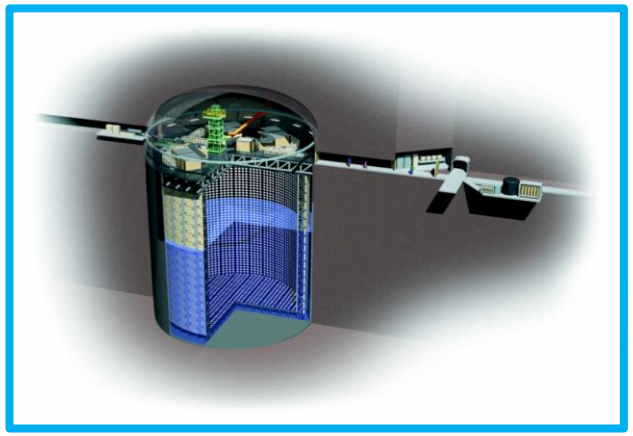
July 18th, 2022

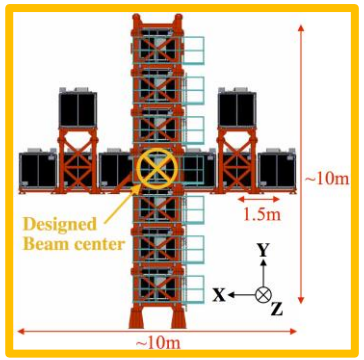
The T2K Experiment

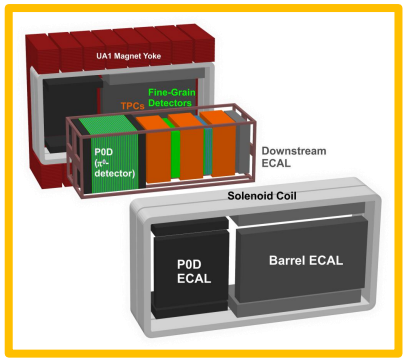
See Luke Pickering's talk on latest oscillation results

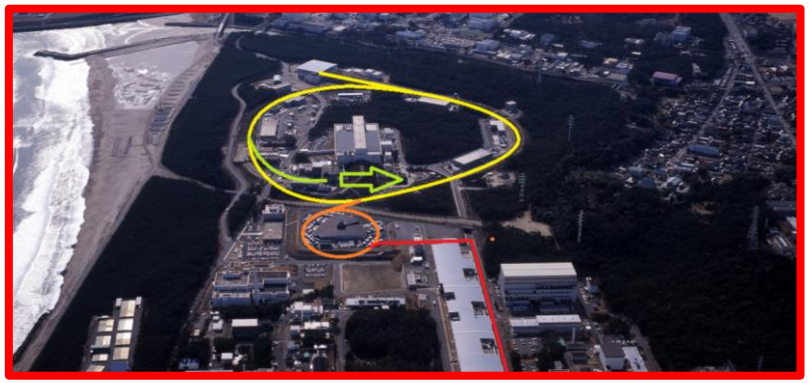
- Long-baseline neutrino oscillation experiment
- High intensity ν_μ / $\overline{\nu}_\mu$ beam produced at J-PARC
- Near Detectors
  - Measure unoscillated spectrum — 280 m from ν source
- Far Detector
  - Measure oscillated spectrum — 295 km from ν source

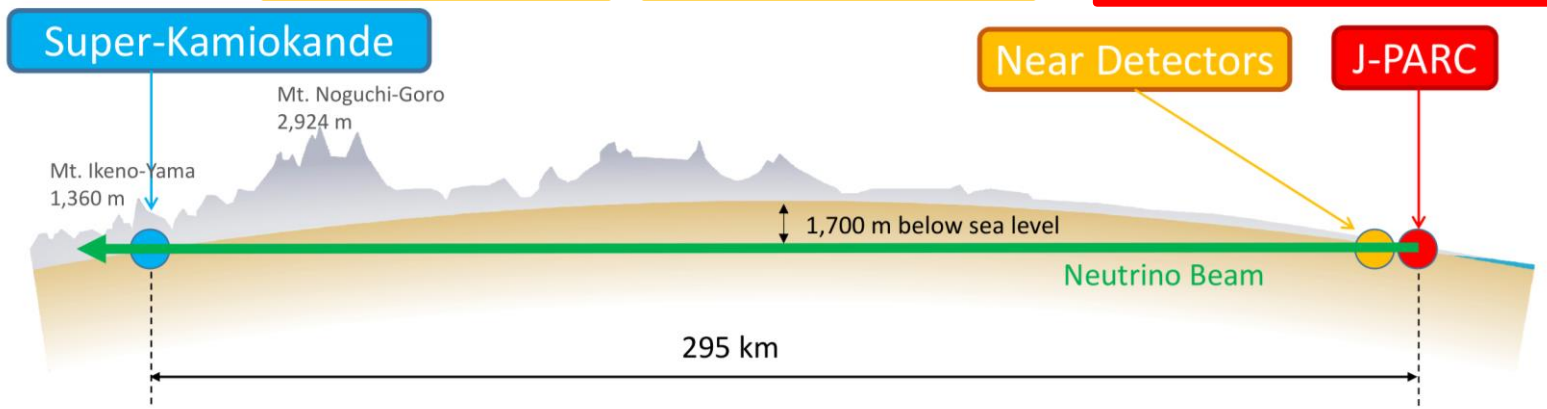












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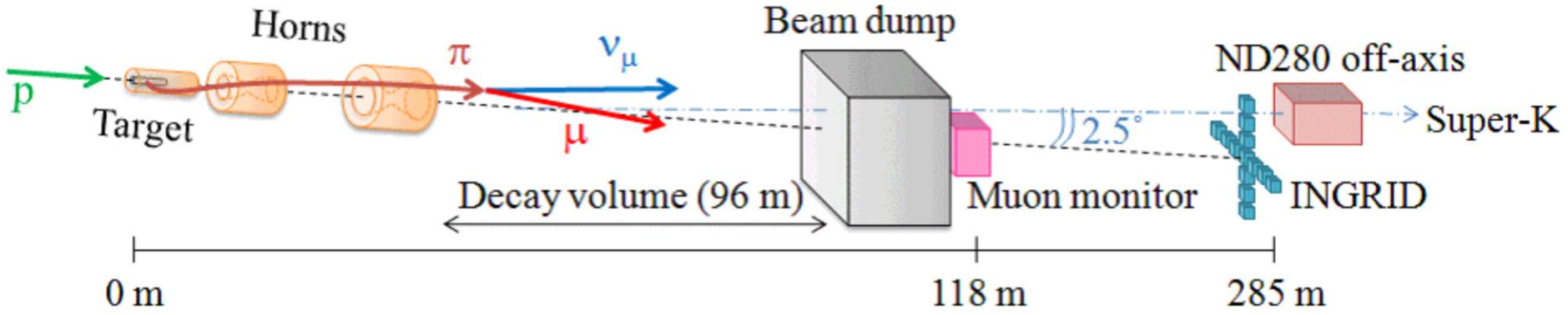
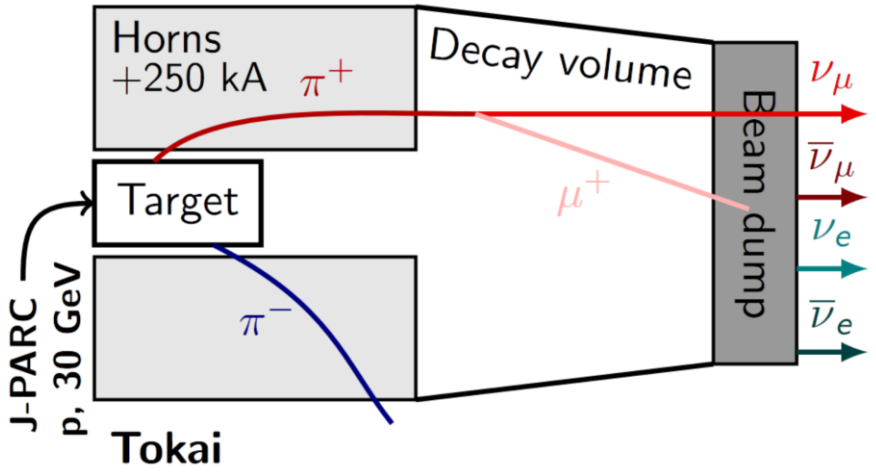
T2K

The T2K Beamline

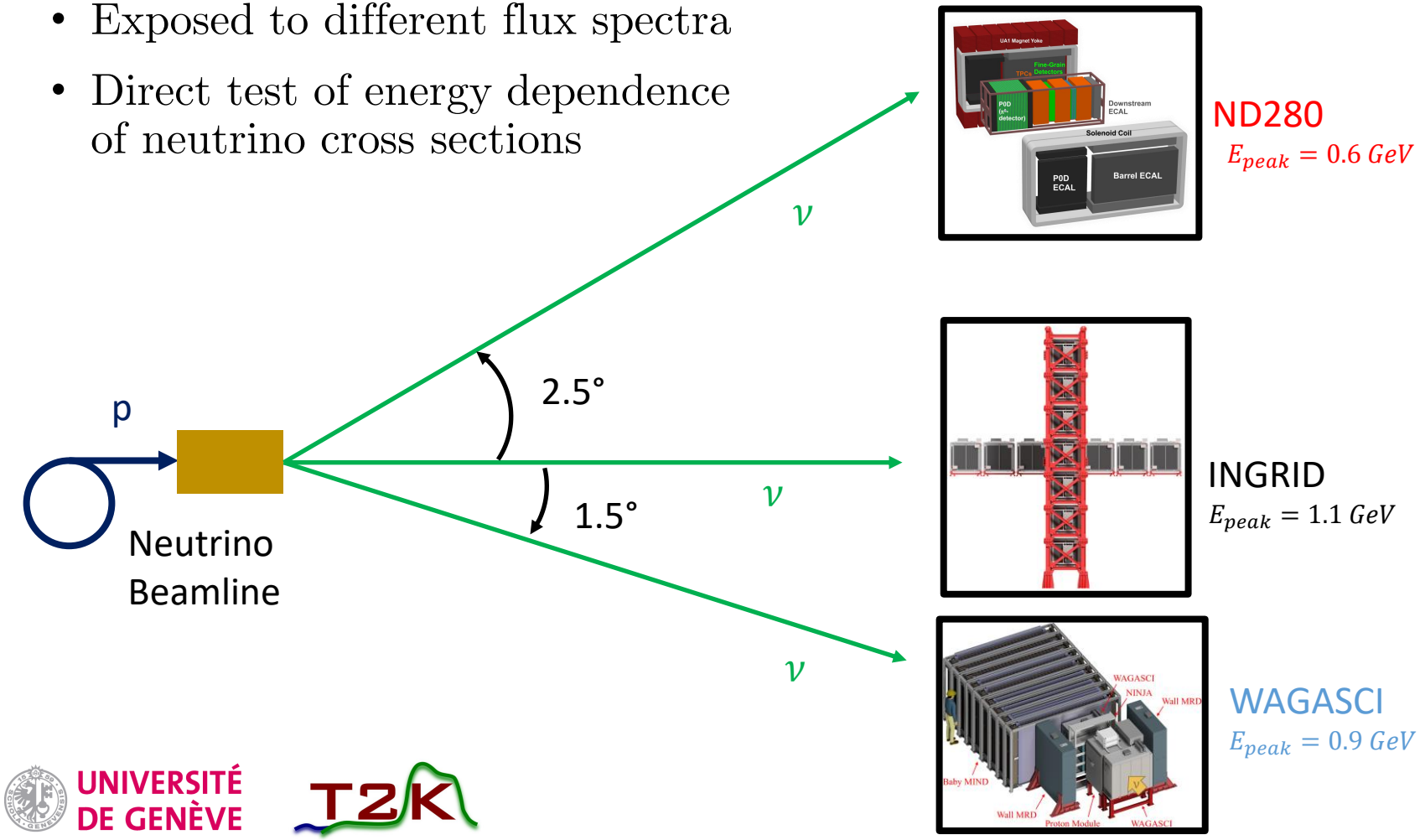


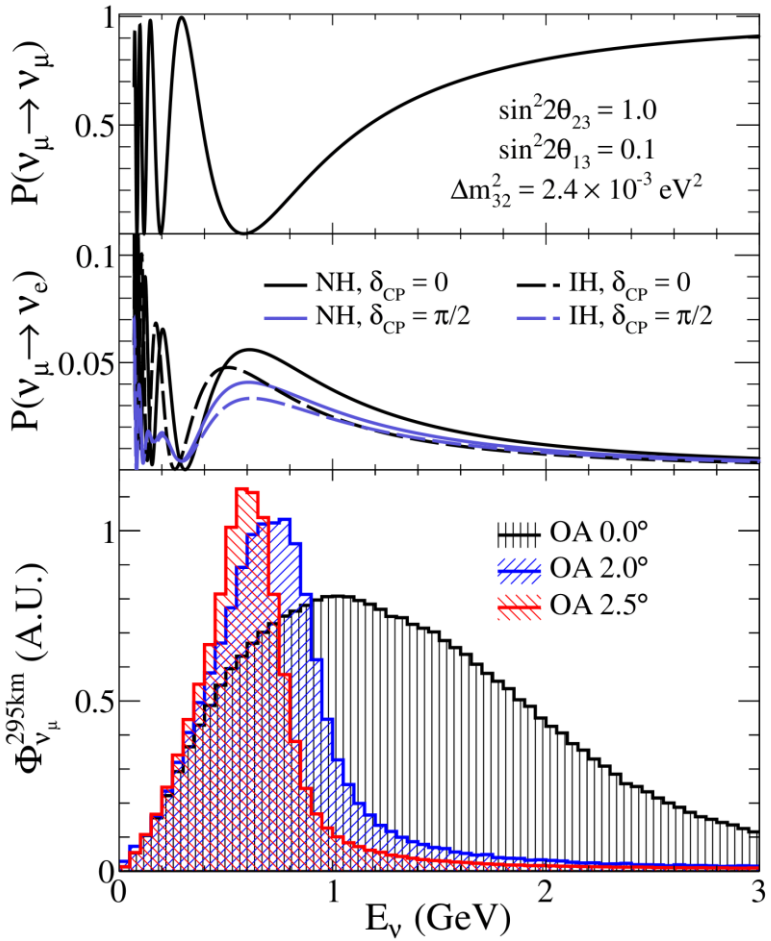
- 30 GeV proton beam produced at J-PARC
- Incident on carbon target producing $\pi^{\pm}, K^{\pm}$
- Pions/Kaons are focused by 3 electromagnetic focusing horns
  - Run in ν / $\overline{\nu}$ mode by switching horn polarity
- Then decay to muons and neutrinos in 100 m long decay volume
- Pions/muons stopped and monitored in beam dump
- Neutrinos continue to near/far detectors



The T2K Near Detectors

- Various near detectors situated at different angles
- Exposed to different flux spectra
- Direct test of energy dependence of neutrino cross sections





Motivation for Neutrino-Nucleus Cross Sections

- We don't measure the ν flux, we measure event rates:

$$\text{Event rate} = \overbrace{\Phi_\nu(E_\nu) \times \sigma(E_\nu) \times \epsilon(E_\nu)}^{\text{Near Detector}} \times \underbrace{P(\nu_\mu \to \nu_{\mu,e})}_{\text{Far Detector}}$$

Neutrino Flux | Interaction Cross Section | Detector Efficiency | Oscillation Probability

- Different flux, target and acceptance for near and far detectors

Motivation for Neutrino-Nucleus Cross Sections

- Neutrino physics is entering the precision era
- Cross section effects must be disentangled from oscillation probability
- Cross sections are leading source of systematic uncertainty
- Insights into nuclear effects

Fractional uncertainty on event rate in %

	1-Ring μ		1-Ring e			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
Flux and (ND unconstrained)	14.3	11.8	15.1	12.2	12.0	1.2
cross-section (ND constrained)	3.3	2.9	3.2	3.1	4.1	2.7
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
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
$\sin^2\theta_{23}$ and Δm^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

PRD 103, 112008 (2021)

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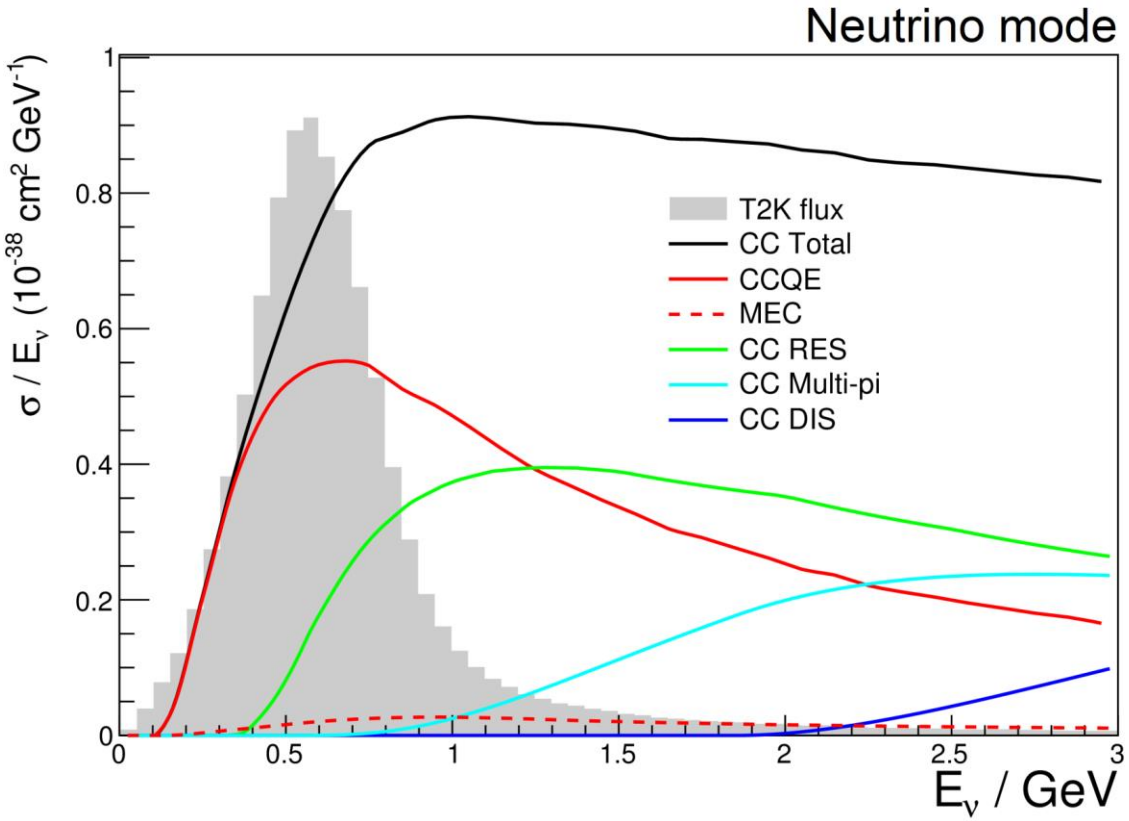
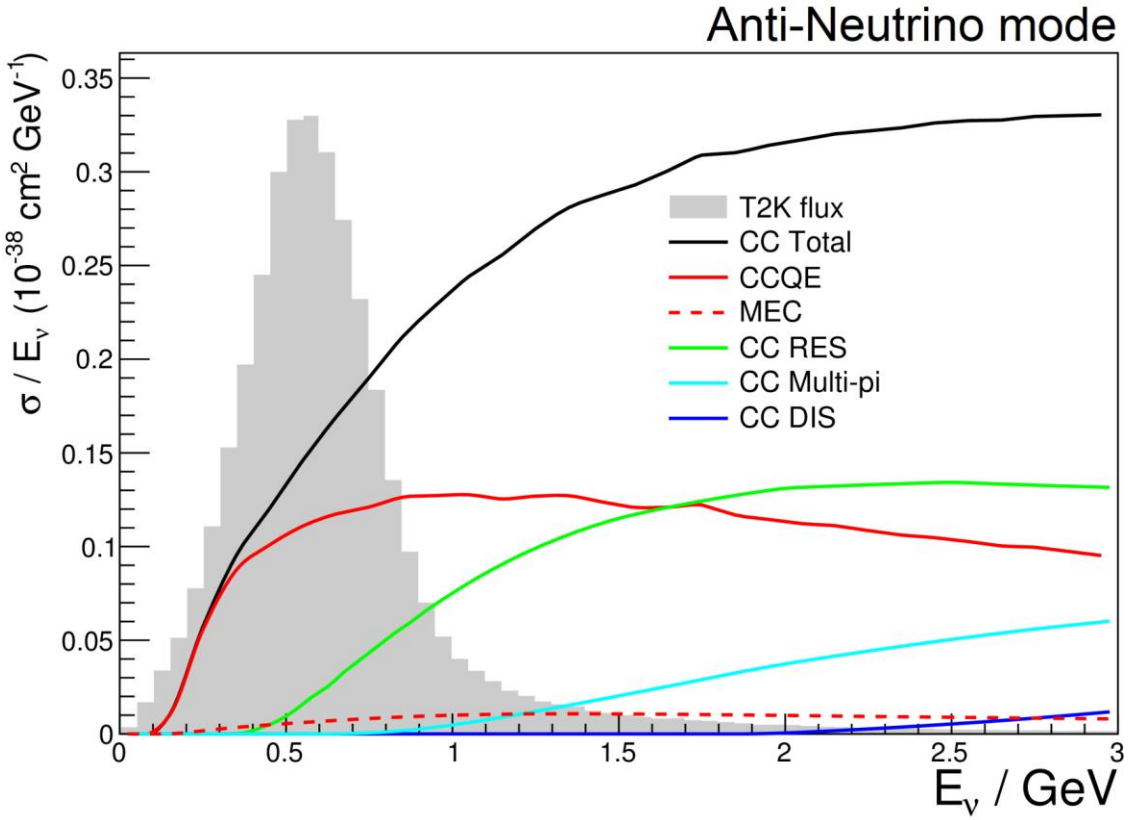
Neutrino Interactions at T2K





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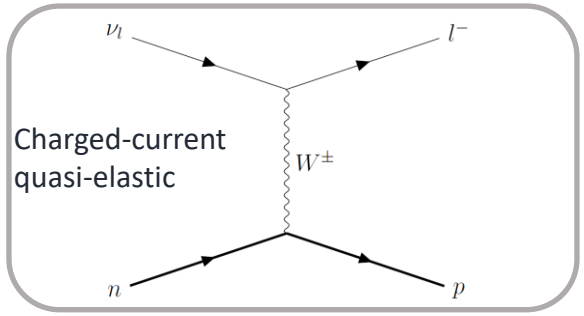
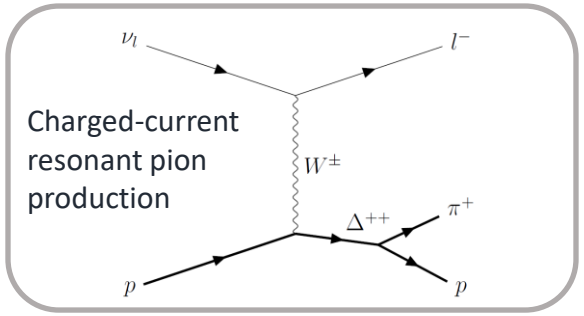
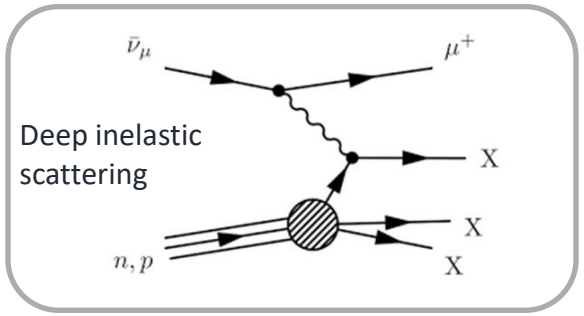
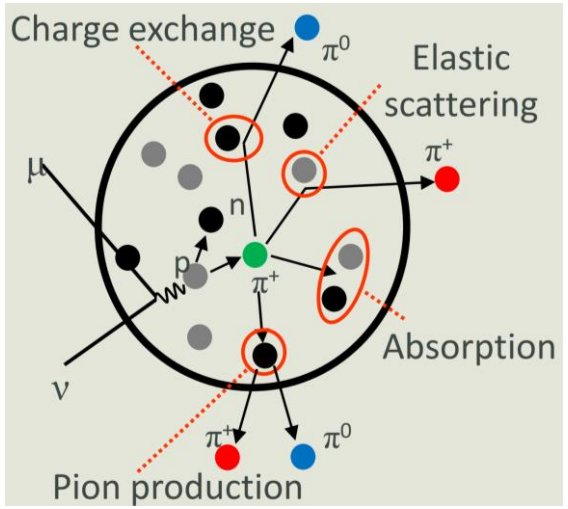
Cross Section Measurements

Initial Neutrino Interaction

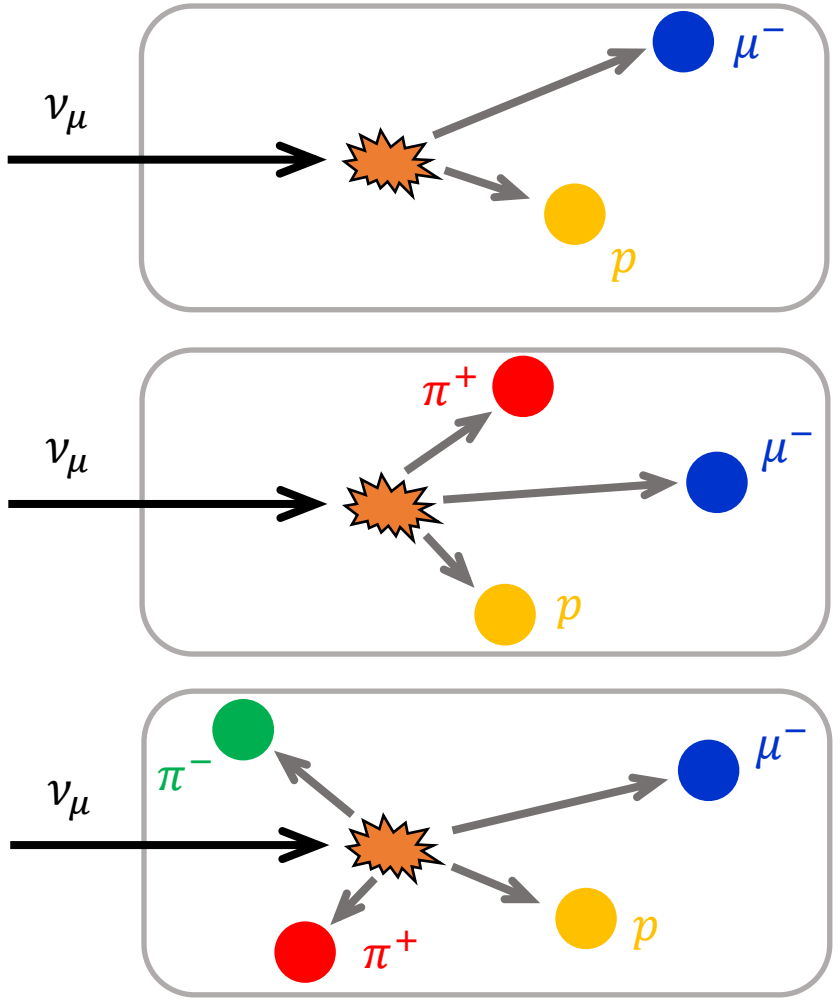








Observed Event Topology



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T2K

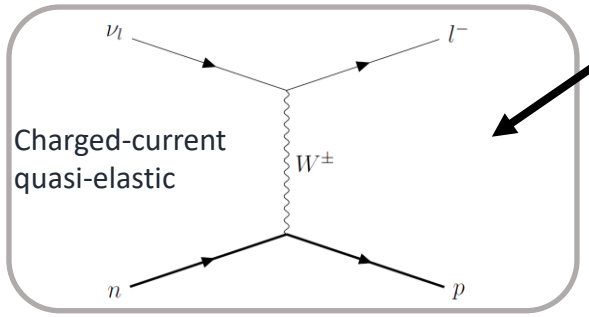
Cross Section Measurements

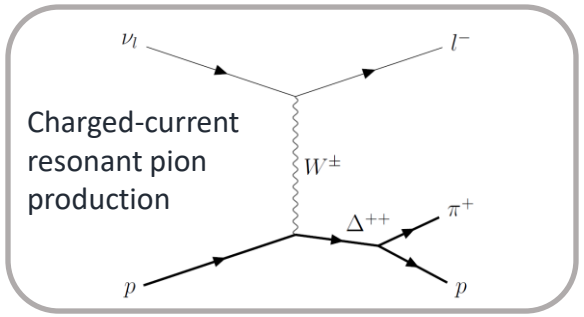
Initial Neutrino Interaction

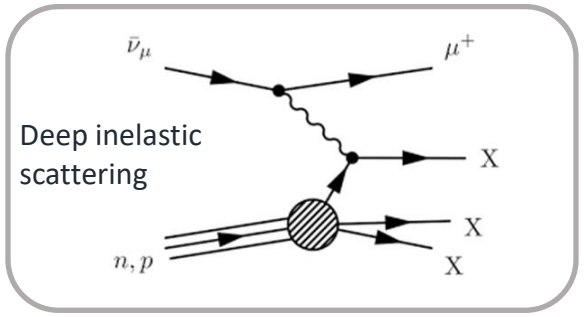
Is my CC0π CCQE?

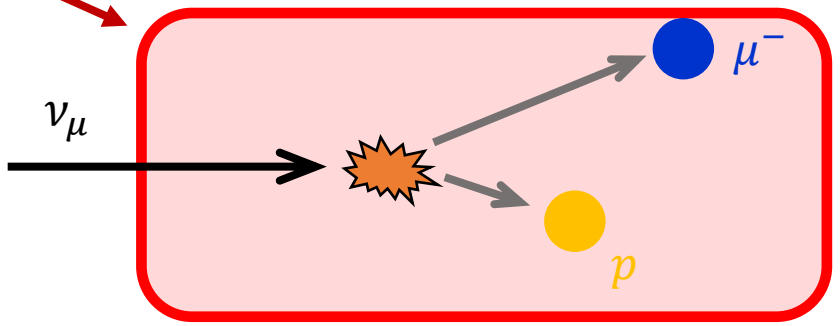
My CC0π is simply CC0π!

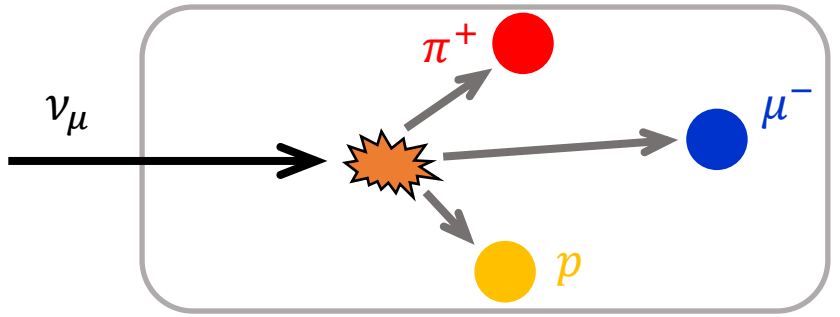
Observed Event Topology

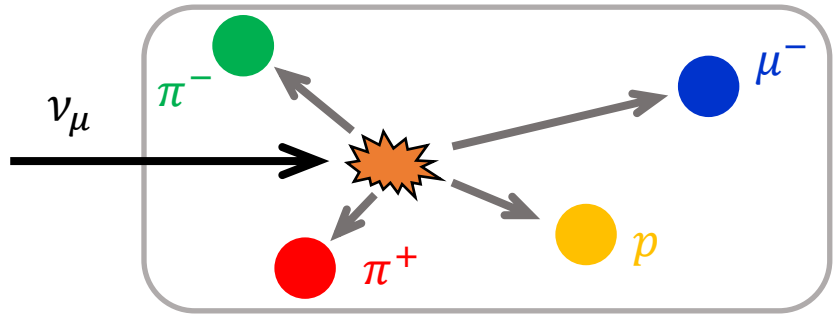












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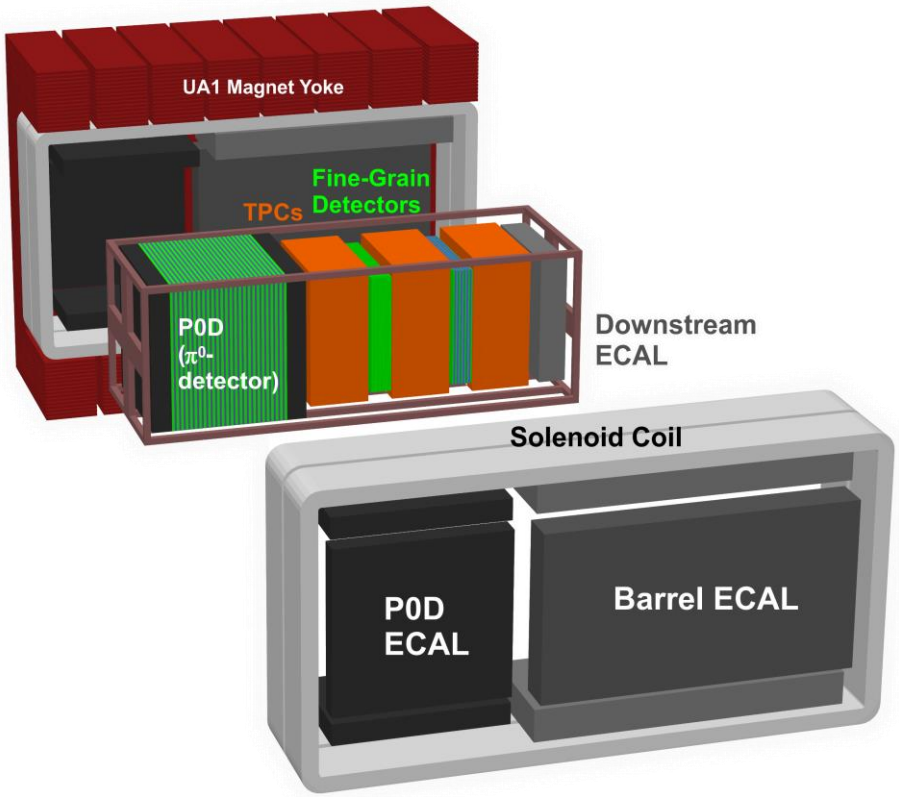
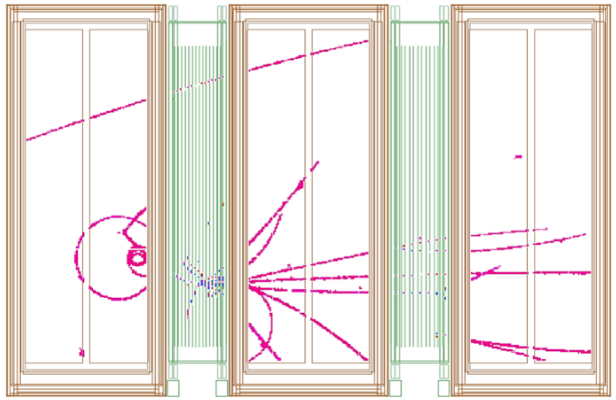
The T2K ND280 Near Detector



- 2.5 degrees off-axis → 0.6 GeV peak energy
- Large dipole magnet produces 0.2 T
- Magnet instrumented with side muon range detectors (SMRD)
- π^0 Detector (P0D) measures pions
- 3 gas argon Time Projection Chambers (TPCs) reconstruct particle momentum and charge
- 2 Fine-Grain Detectors (FGDs) act as detector targets, provide vertex info and consist of xy layers of
  - CH bars (FGD1)
  - CH bars alternated with H2O layers (FGD2)
- Electromagnetic Calorimeter (ECAL) surrounds these elements
  - Distinguish tracks from showers



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T2K

Latest Cross Section Results

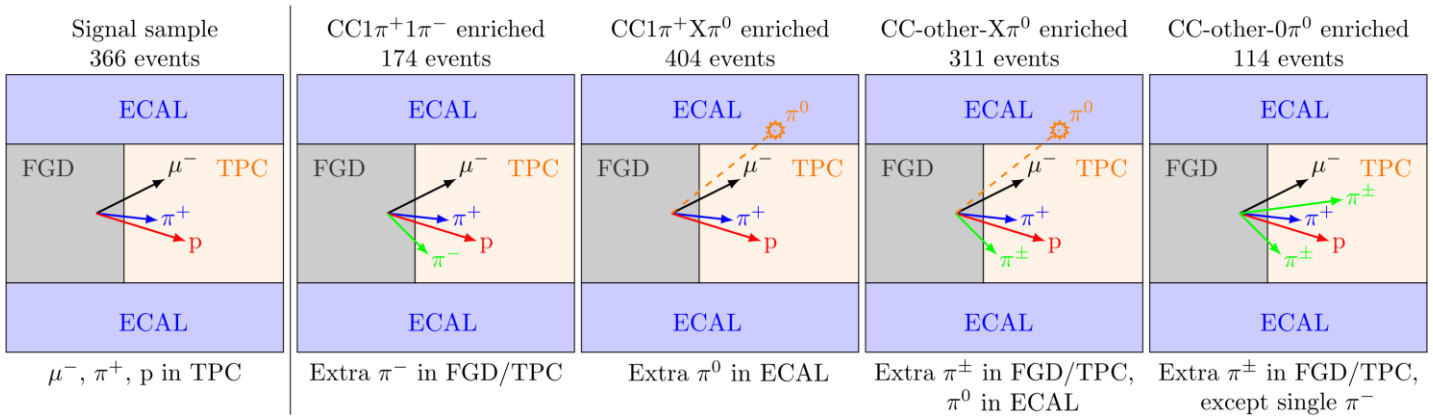
- 2.5° off-axis
  - ν_μ CC-$1\pi^+Np$ Transverse Kinematic Imbalance
  - ν_eCC & $\overline{\nu}_e$CC Cross Sections
  - Joint ν_μ Carbon+Oxygen CC0π Cross Section
- 1.5° off-axis
  - $\overline{\nu}_\mu$ & $\overline{\nu}_\mu + \nu_\mu$ CC$0\pi0p$ Cross Section on Hydrocarbon and Water
- 0° + 2.5° joint analysis
  - Sneak Peek

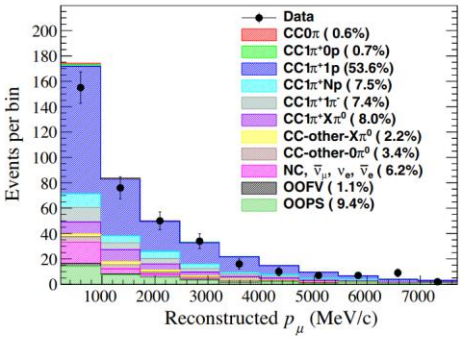
ν_μ CC-1π^+Np Transverse Kinematic Imbalance

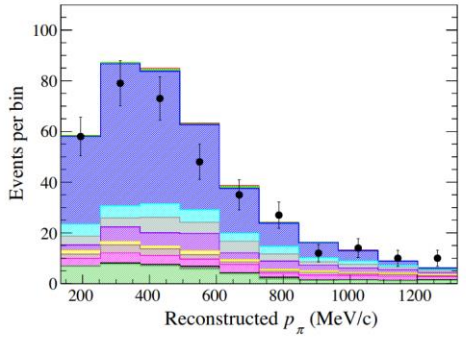
$N \geq 1$

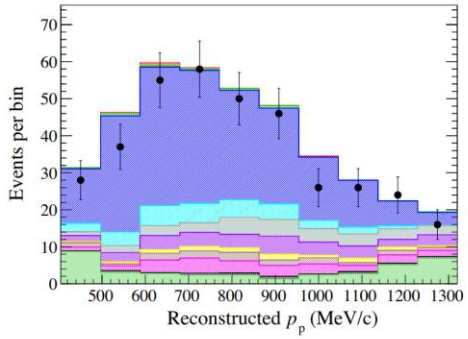
PRD 103, 112009 (2021)

- $\nu_\mu + A \rightarrow \mu^- + \pi^+ + p + A'$
- Interactions in FGD1 (CH target)
- TKI calculated between outgoing muon, pion and highest momentum proton
  - Lepton-hadron correlations in transverse plane to ν direction
- Sensitive to initial nuclear state and final state interactions (FSI)
- Jointly fit signal and control regions to constrain background









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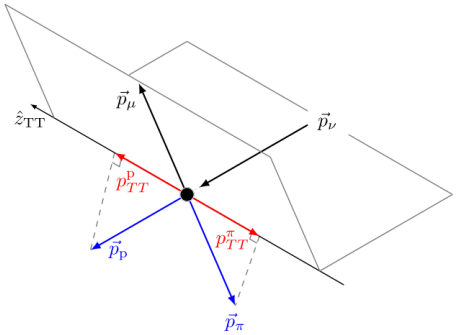
T2K

ν_μ CC-$1\pi^+Np$ Transverse Kinematic Imbalance

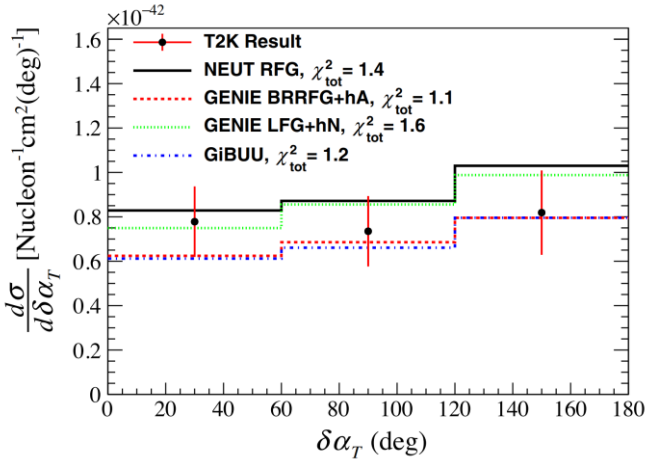
$N \geq 1$

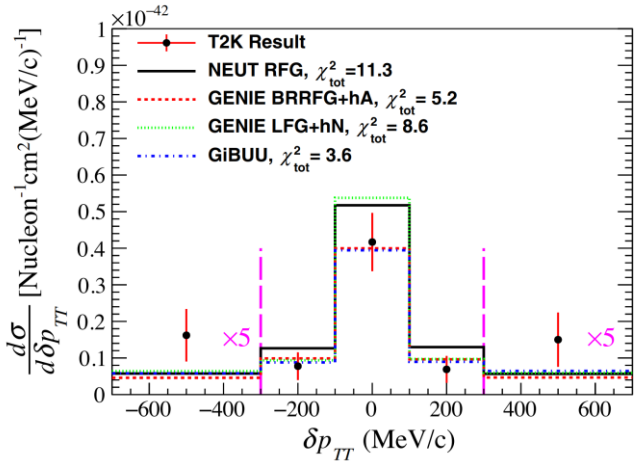
PRD 103, 112009 (2021)

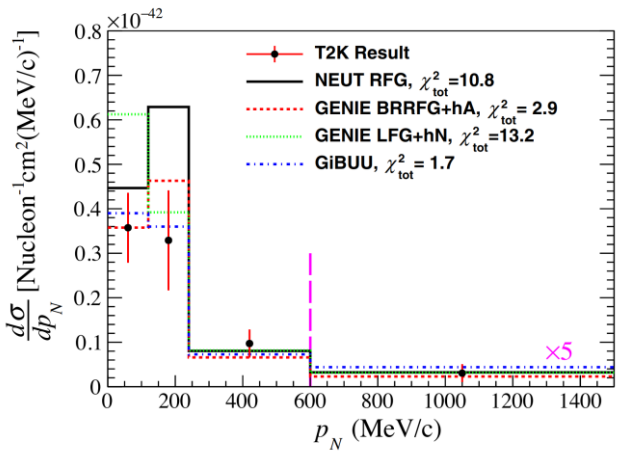
- Transverse boosting angle $\delta\alpha_T$ sensitive to FSI
  - Indicates if proton has been accelerated or decelerated
- $\delta p_{TT} = p^{\pi}_{TT} + p^{p}_{TT}$
  - Would be zero with no nuclear effects
  - Distribution is broadened by initial fermi motion and FSI
- $p_N = \sqrt{\delta p_T^2 + p_L^2}$
  - Probes Fermi motion similar to δp_{TT}
  - Peak shifted by FSI + long tail

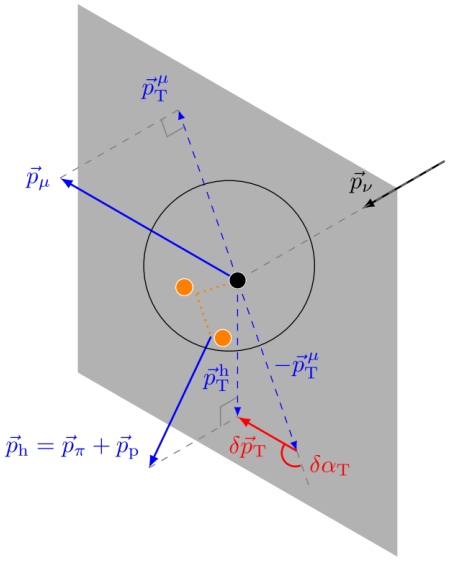


(a) $\delta p_{TT} = p^{\pi}_{TT} + p^{p}_{TT}$.







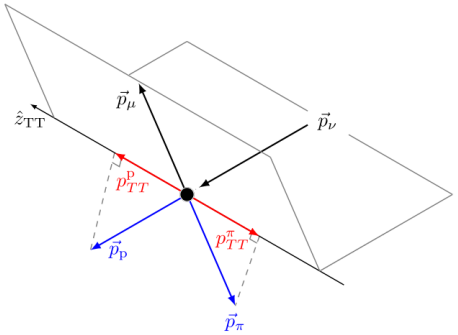


ν_μ CC-$1\pi^+ Np$ Transverse Kinematic Imbalance

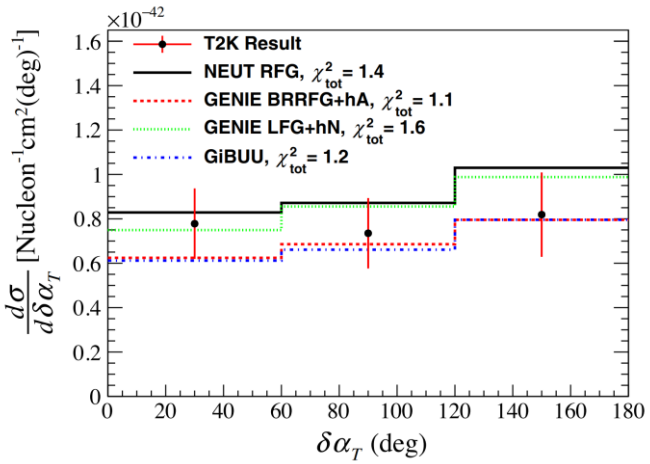
$N \geq 1$

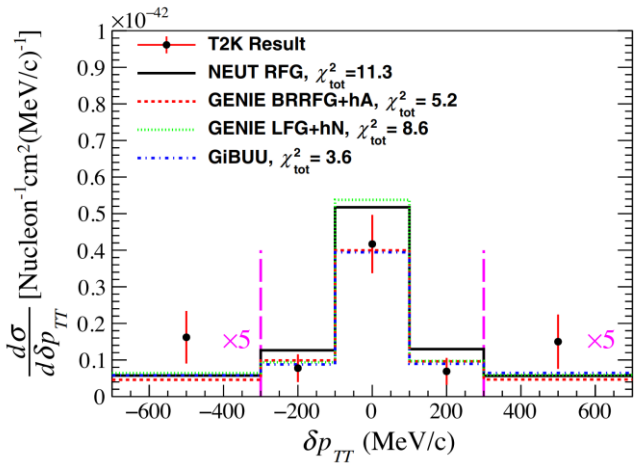
PRD 103, 112009 (2021)

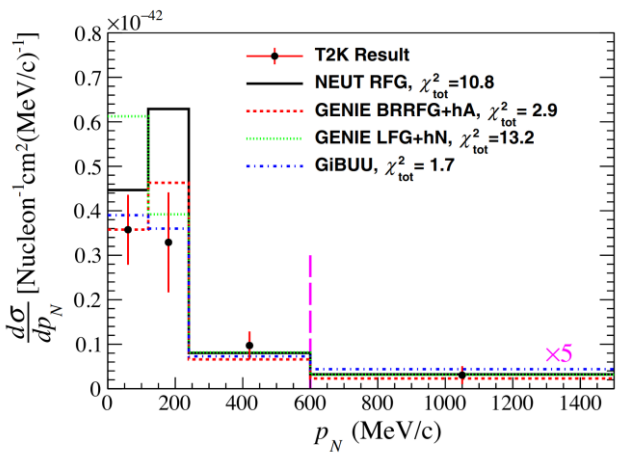
- Simple Fermi gas models (RFG & LFG) show larger disagreement with data
  - Fermi motion might not be well modelled
- Limited sensitivity for $\delta\alpha_T$ due to phase space constraints
- Overall, the data slightly prefers the GIBUU model
  - Includes more realistic nuclear ground state and more complete FSI modeling
- We are still statistically limited
- ND280 upgrade will increase statistics and extend the phase space at low energy and high angles

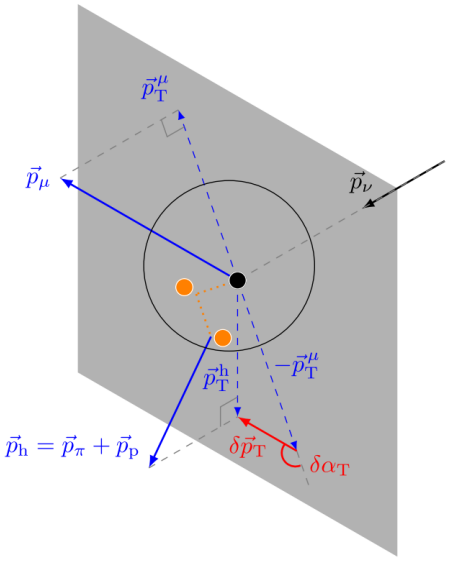


(a) $\delta p_{TT} = p^{\pi}_{TT} + p^{\mathrm{p}}_{TT}$.





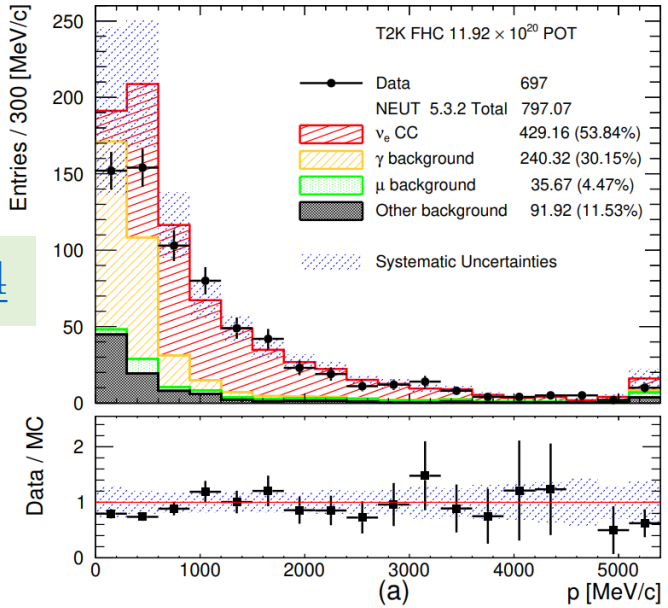


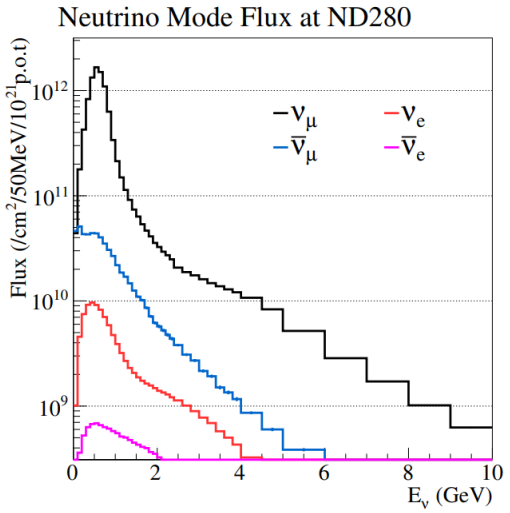


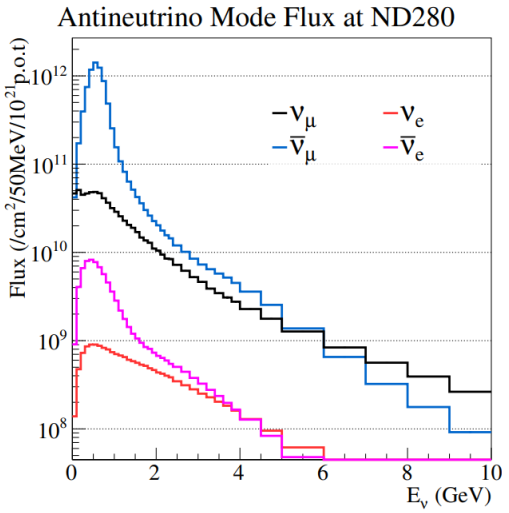
ν_eCC & $\bar{\nu}_e$CC Cross Sections

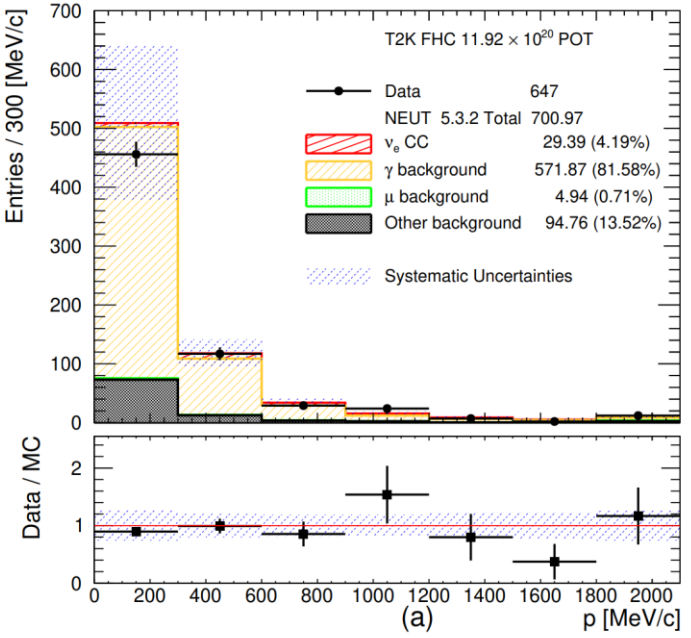
- T2K beam has intrinsic irreducible ν_e / $\bar{\nu}_e$ contamination from $K^{\pm}, \mu^{\pm}$ decays
- Major uncertainty in δ_{CP} measurements
- 3 signal samples:
  - ν-mode: CCν_e
  - $\bar{\nu}$-mode: CCν_e & CC$\bar{\nu}_e$
- Major γ background from π^0 production
  - Constrained with dedicated control sample

JHEP10 (2020) 114





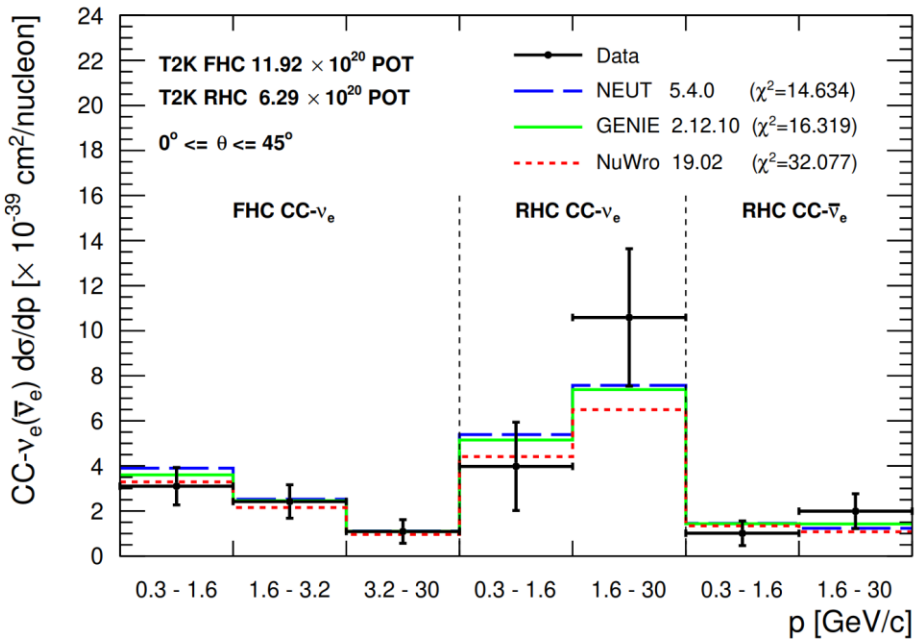




ν_eCC & $\bar{\nu}_e$CC Cross Sections

JHEP10 (2020) 114

- Challenging signal sample
- Data agrees best with NEUT and GENIE models
- Limited detector acceptance
  - $p_e > 0.3$ GeV
  - $\theta_e < 45$ deg
- Results are statistically limited
- Irreducible background in δ_{CP} measurements
  - $\nu_\mu \rightarrow \nu_e$
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- First CC$\bar{\nu}_e$ result since Gargamelle measurement in 1979
- Increased statistics and reduction of γ background with ND280 upgrade

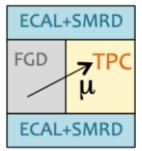
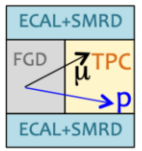
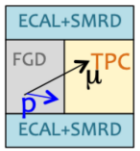
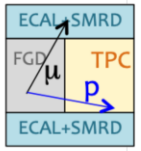
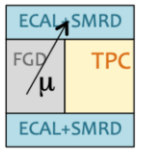


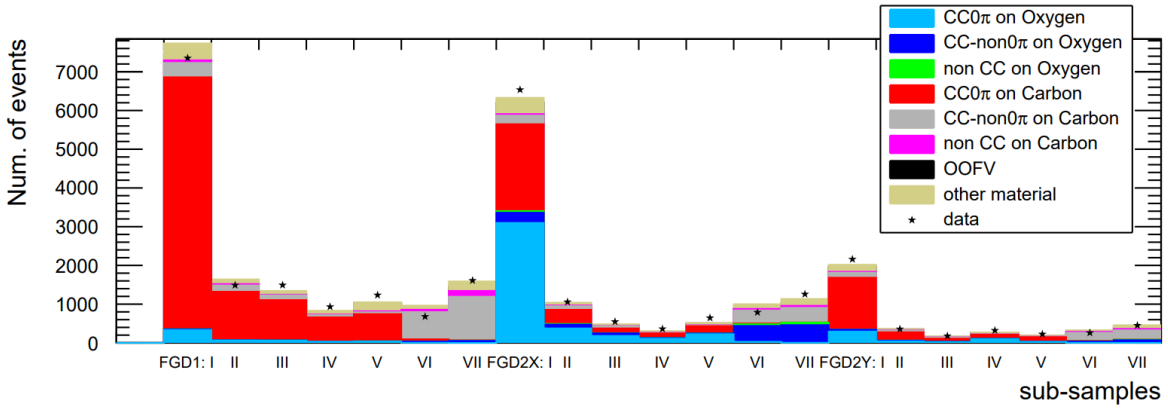
Generator	$p - \cos(\theta)$ χ^2 (ndof = 13)	p-only χ^2 (ndof = 7)	$\cos(\theta)$-only χ^2 (ndof = 6)
NEUT 5.4.0	14.63	5.82	5.34
GENIE 2.12.10	16.32	4.16	4.55
NuWro 19.02	32.08	4.52	5.08

Joint ν_μ Carbon+Oxygen CC0π Cross Section

PRD 101, 112004 (2020)

- FGD1 (C) and FGD2 (C+O) samples used
- 5 signal samples based on muon & proton directions
- 2 control samples to constrain backgrounds
- C & O double differential cross sections extracted simultaneously in joint fit
  - Exploit correlations in detector, flux and interaction systematics

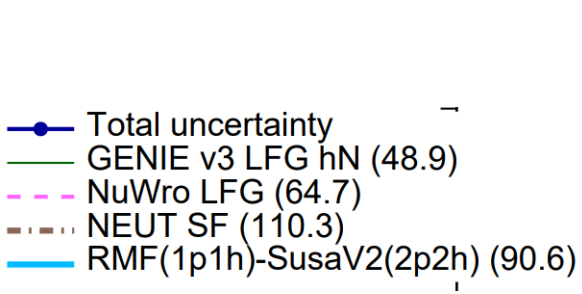
	I – μTPC	II – μTPC+pTPC	III – μTPC+pFGD	IV – μFGD+pTPC	V – μFGD
Signal sample					
Description	Single μ candidate tracked in TPC	Both μ and *p* candiates are tracked in the TPC	μ tracked in the TPC and : • 1*p* tracked in the FGD • or multi *p*	μ tracked in FGD/Ecal and: • 1 *p* tracked in the TPC • or 1 *p* tracked in the TPC + multi *p* • or multi *p*	μ_{FGD} only reconstructed in the FGD/ Ecal

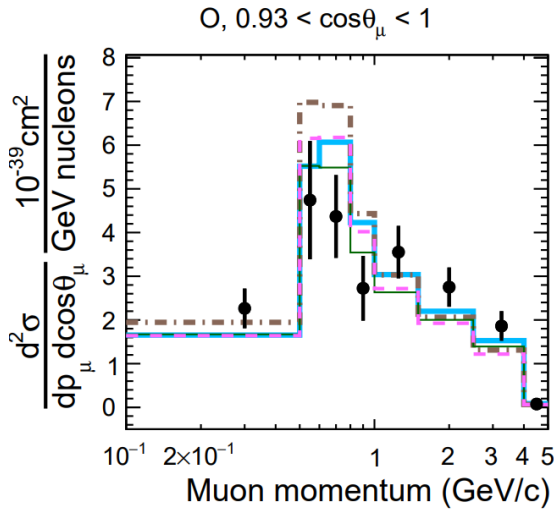


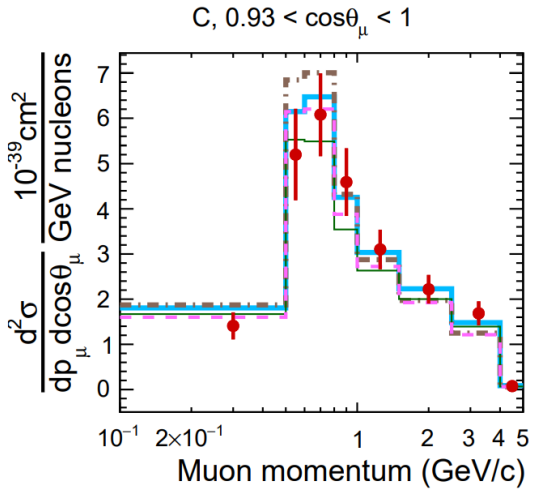
Joint ν_μ Carbon+Oxygen CC0π Cross Section

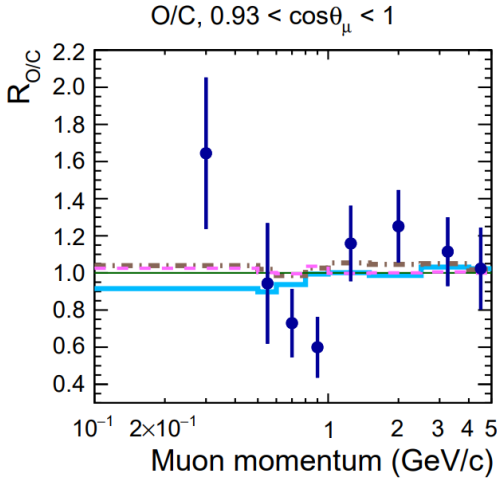
PRD 101, 112004 (2020)

- Measure C, O and C/O cross sections
- Simple CCQE Fermi gas model (LFG) preferred over more involved spectral functions or mean field models in forward bins
  - Highest contribution to χ^2 due to high statistics
  - Relatively poorly understood 2p2h and FSI effects are largest in this region relative to CCQE prediction
- In other regions all tested models give predictions compatible with data
- Model discrimination should improve by including hadron kinematics and extending analysis to $\overline{\nu}_\mu$









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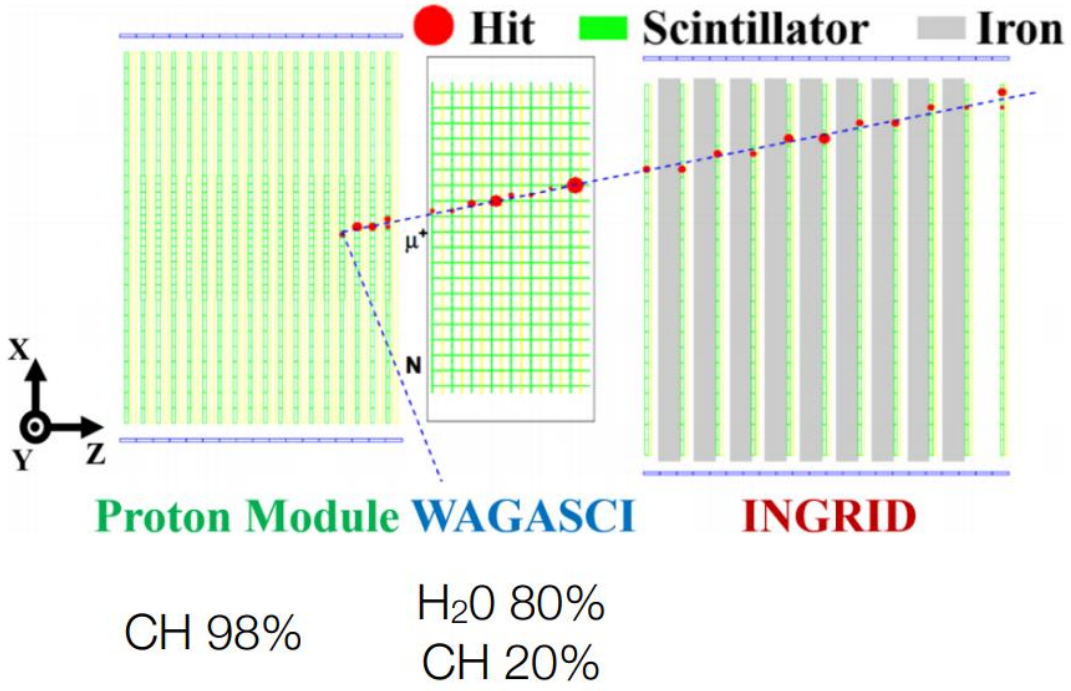
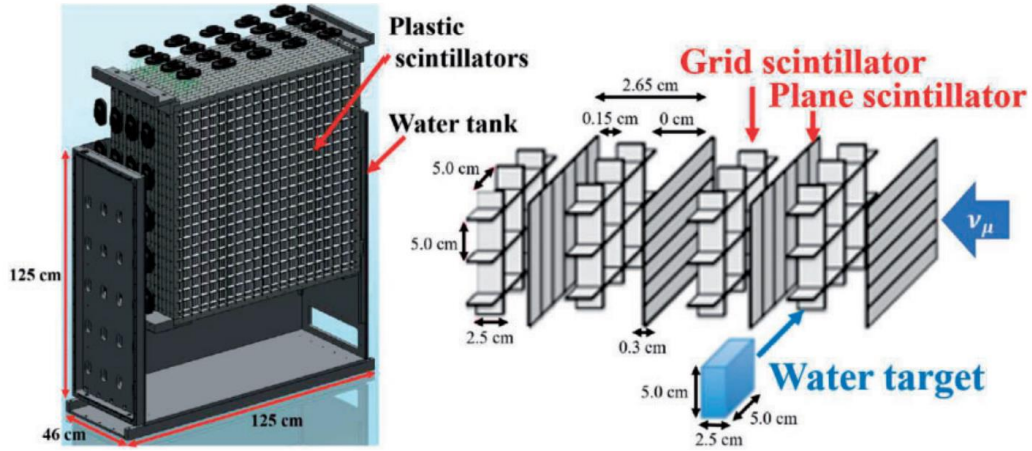
The WAGASCI Near Detector

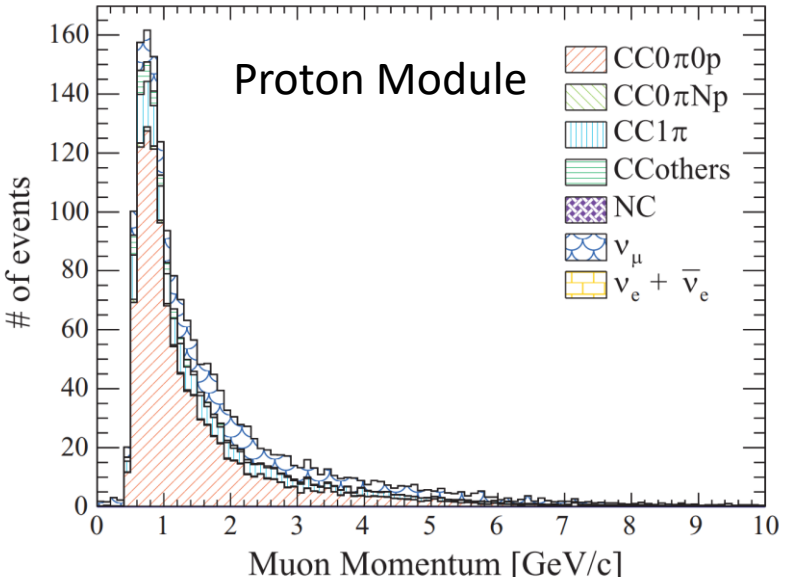
- 1.5 degrees off axis → 0.86 GeV peak energy
- 2 detectors with different targets
  - Proton module: CH
  - WAGASCI: H_20
- Downstream INGRID module is used as muon tracker
- No ν / $\overline{\nu}$ separation

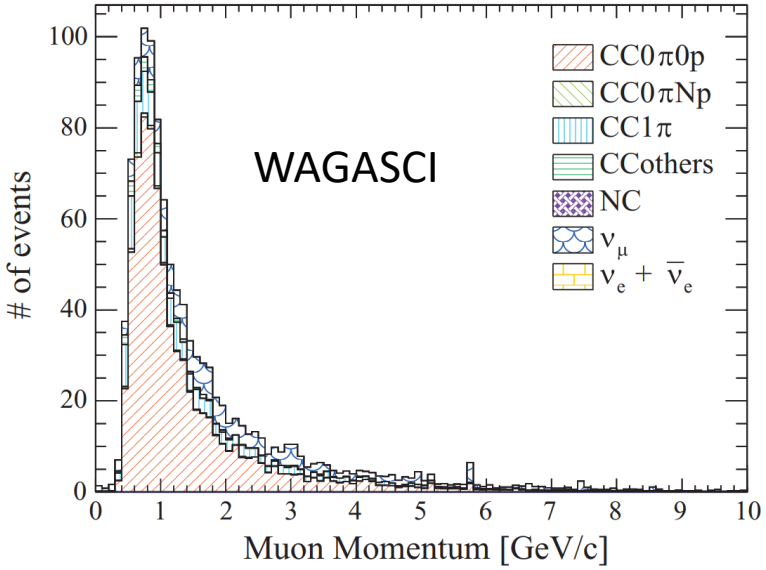




$\overline{\nu}_\mu$ & $\overline{\nu}_\mu + \nu_\mu$ CC0π0p Cross Section on Hydrocarbon and Water

- Signal is single muon track with no pions or protons
- Phase space limited to regions with good efficiency
  - $\theta_\mu < 30$ deg
  - $p_\mu > 0.4$ GeV
- Significant ν_μ background
- Use Proton module as hydrocarbon target, WAGASCI as water target



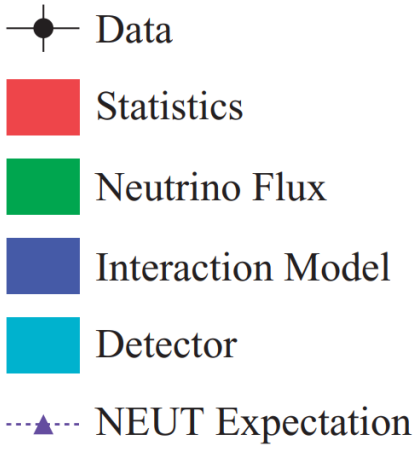


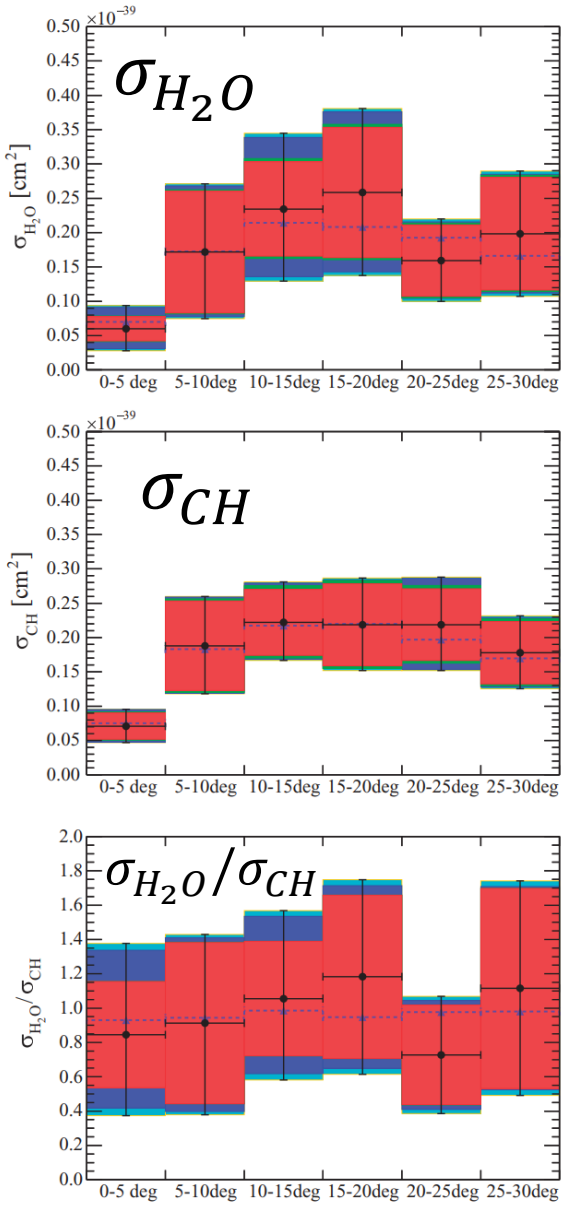
PTEP 4 (2021) 043C01

$\overline{\nu}_\mu$ & $\overline{\nu}_\mu + \nu_\mu$ CC0π0p Cross Section on Hydrocarbon and Water

- Good agreement between data and NEUT model
- First cross section measurement with WAGASCI detector at 1.5 degrees off-axis

χ^2	$\overline{\nu}_\mu$ 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

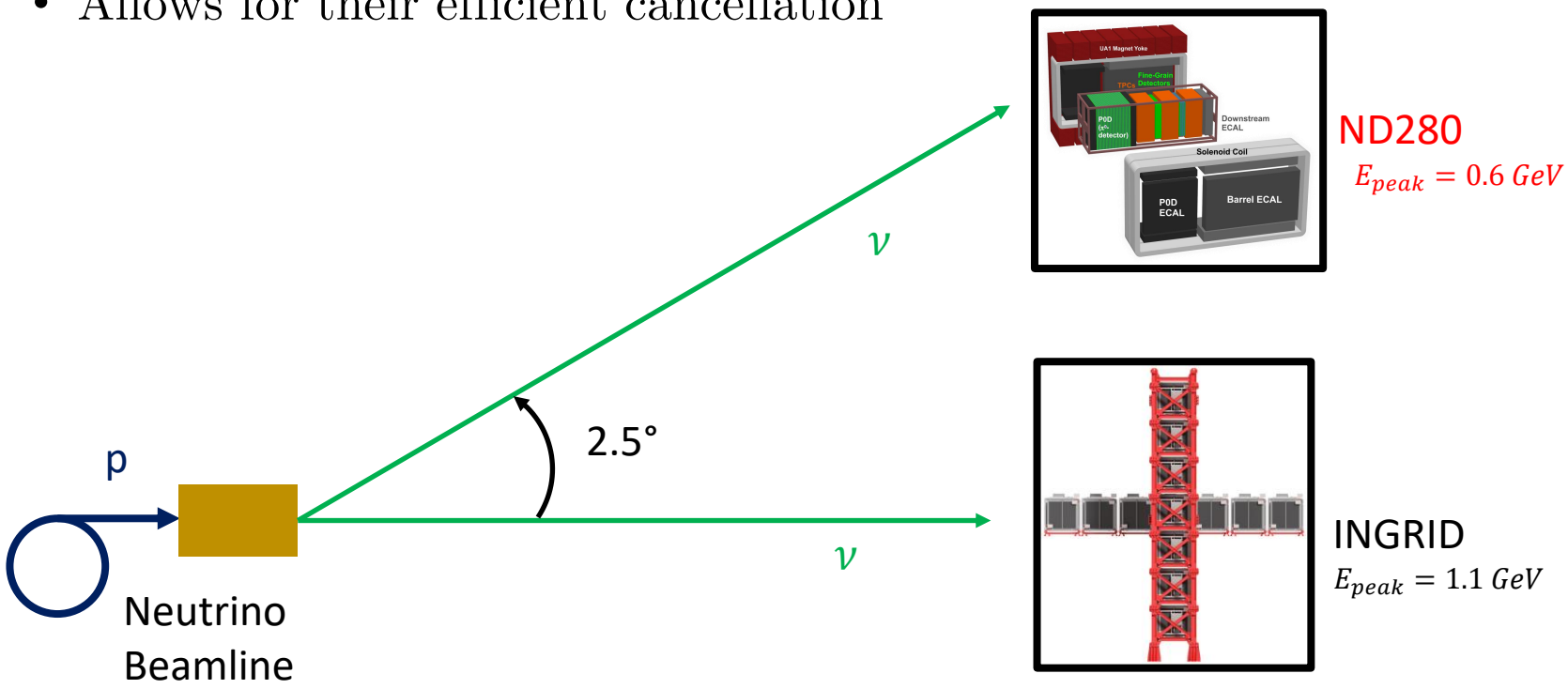




PTEP 4 (2021) 043C01

Sneak Peek: Joint on-/off-axis CC0π cross section

- First T2K multi-detector cross section measurement
- Direct probe of E_ν dependence
- Exploits correlations between the systematic uncertainties of the samples
  - Allows for their efficient cancellation

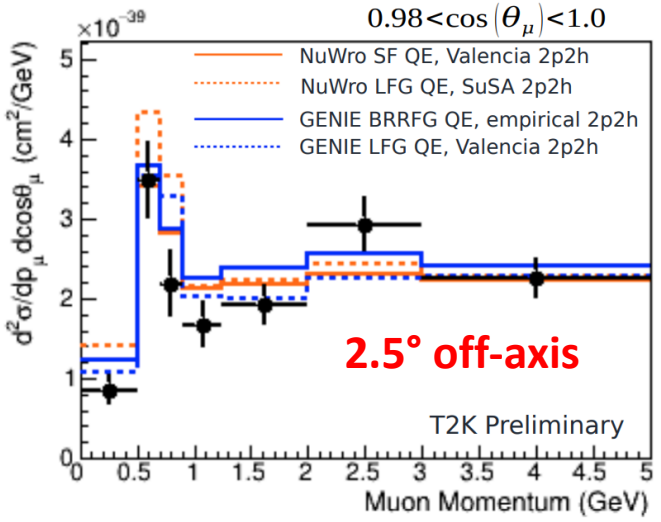


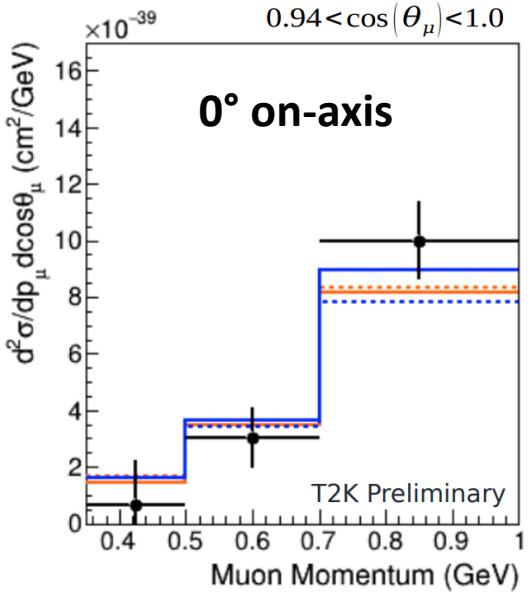
ND280

$E_{peak} = 0.6\ GeV$

INGRID

$E_{peak} = 1.1\ GeV$





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Summary and Outlook

- T2K continues to produce valuable cross section measurements of neutrino-nucleus interactions
- Minimal model dependency by performing measurements based on final observed topology
- Novel joint measurements in the pipeline – stay tuned!
- ND280 upgrade currently in progress – huge potential for new measurements

See Dung Thi Nguyen's talk on the T2K near detector upgrade

May 2022 dual site collaboration meeting

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Recent Publications

- Measurements of antinumu and antinumu+numu charged-current 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)
- First T2K measurement of transverse kinematic imbalance in the muon-neutrino charged-current single-π^+ production channel containing at least one proton, PRD 103, 112009 (2021)
- Measurement of the charged-current electron (anti-)neutrino inclusive cross-sections at the T2K off-axis near detector ND280, JHEP10(2020)114
- First measurement of the charged current anti-muon neutrino double differential cross section on a water target without pions in the final state, PRD 102, 012007 (2020)
- Simultaneous measurement of the muon neutrino charged-current cross section on oxygen and carbon without pions in the final state at T2K, PRD 101, 112004 (2020)
- First combined measurement of the muon neutrino and antineutrino charged-current cross section without pions in the final state at T2K, PRD 101, 112001 (2020)