24/02/17

To CCQE and Beyond

The latest cross-section results from T2K

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For the T2K Collaboration

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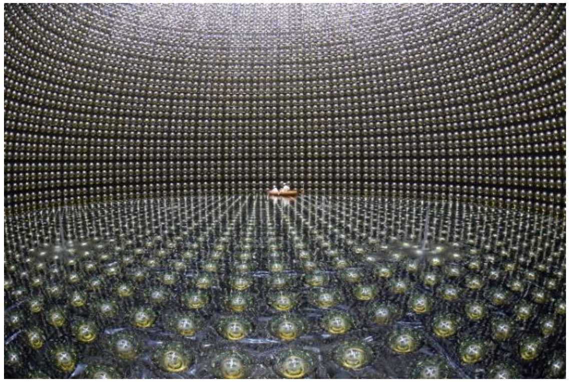
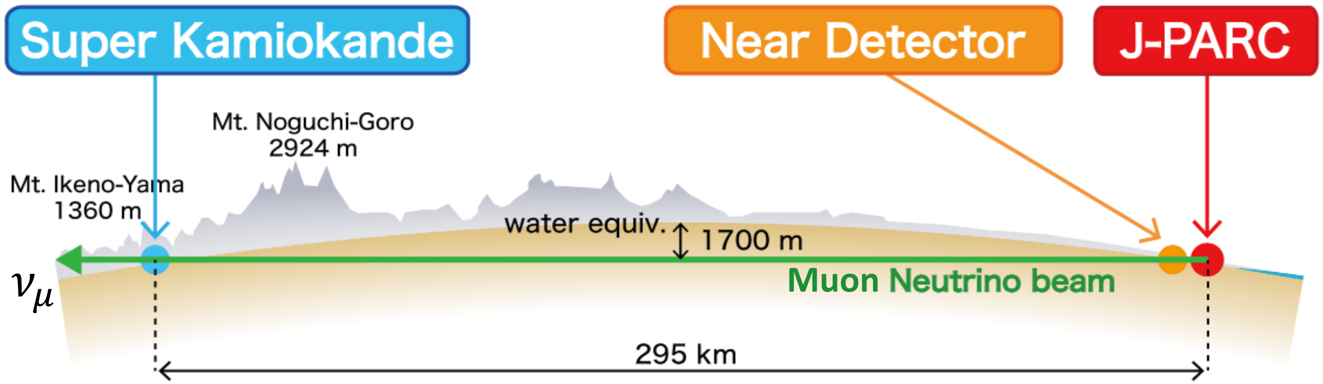
Overview



- Neutrino interactions at T2K
- Previous T2K cross-section results
- Cross sections using proton information
  - $CC0\pi$ using proton kinematics
  - $CC0\pi$ using transverse kinematic imbalance
- Summary and future work

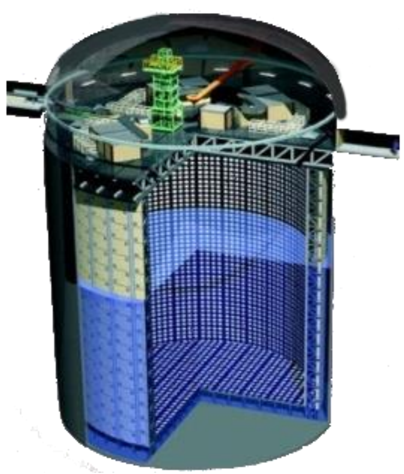
The T2K Experiment



Use off-axis beam to give a narrow neutrino energy spread

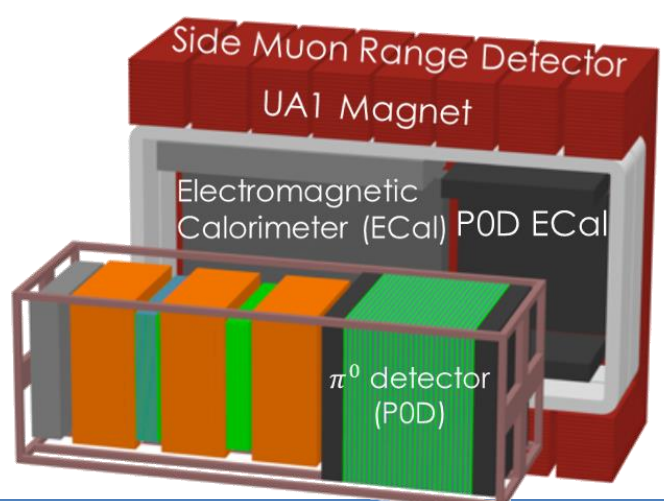
Far Detector (Off-Axis)

Super-Kamiokande

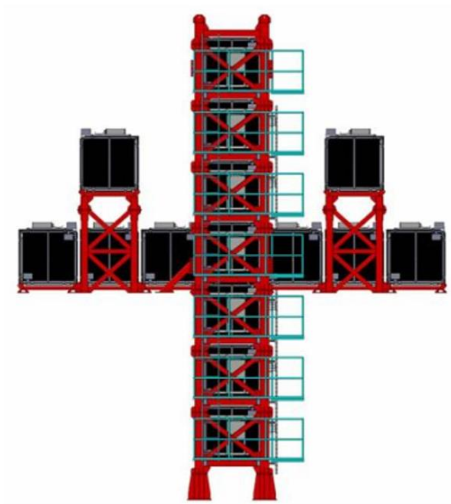


Near Detectors

Off-Axis: ND280



On-Axis: INGRID



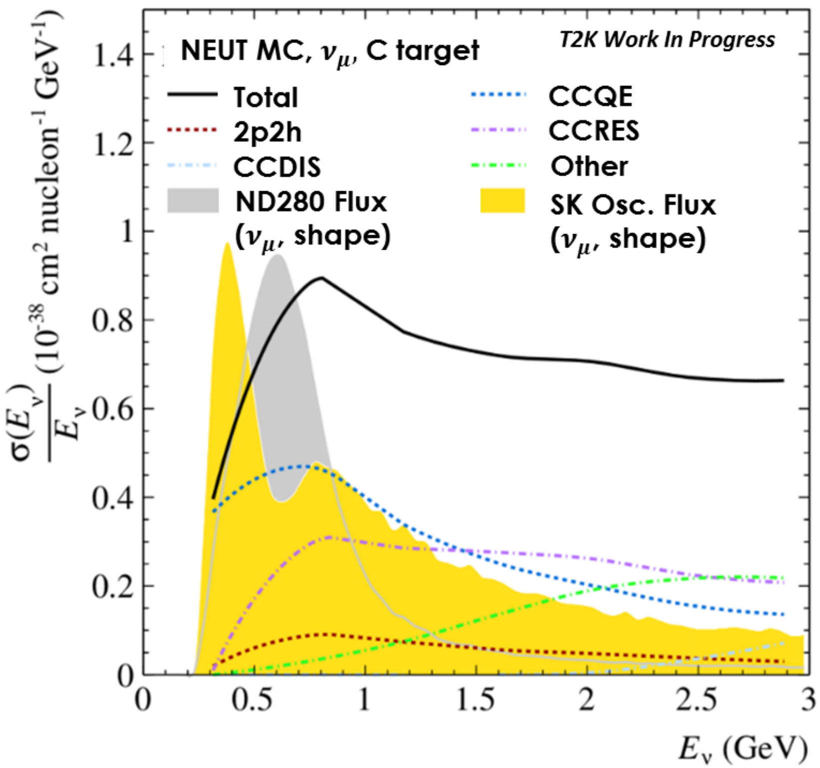
ν-Interactions and Osc. Analysis

Fractional error on the number of expected events at SK with and without ND280

	ν_μ sample $1R_\mu$ FHC	ν_e sample $1R_e$ FHC	$\bar{\nu}_\mu$ sample $1R_\mu$ RHC	$\bar{\nu}_e$ sample $1R_e$ RHC
ν flux w/o ND280	7,6%	8,9%	7,1%	8,0%
ν flux with ND280	3,6%	3,6%	3,8%	3,8%
ν cross section w/o ND280	7,7%	7,2%	9,3%	10,1%
ν cross section with ND280	4,1%	5,1%	4,2%	5,5%
ν flux+cross section	2,9%	4,2%	3,4%	4,6%
Final or secondary hadron int.	1,5%	2,5%	2,1%	2,5%
Super-K detector	3,9%	2,4%	3,3%	3,1%
Total w/o ND280	12,0%	11,9%	12,5%	13,7%
Total with ND280	**5,0%**	**5,4%**	**5,2%**	**6,2%**

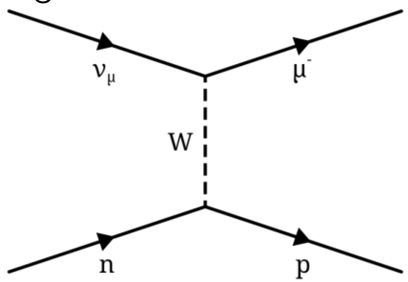
- Largest systematic uncertainty comes from neutrino interaction uncertainties

Neutrino Interactions at T2K



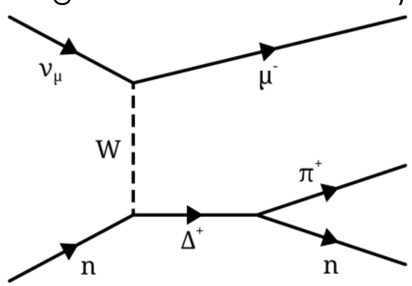
CCQE

(Charged-Current Quasi-Elastic)



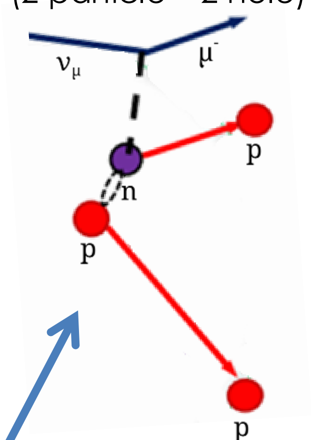
CCRES

(Charged-Current Resonant)

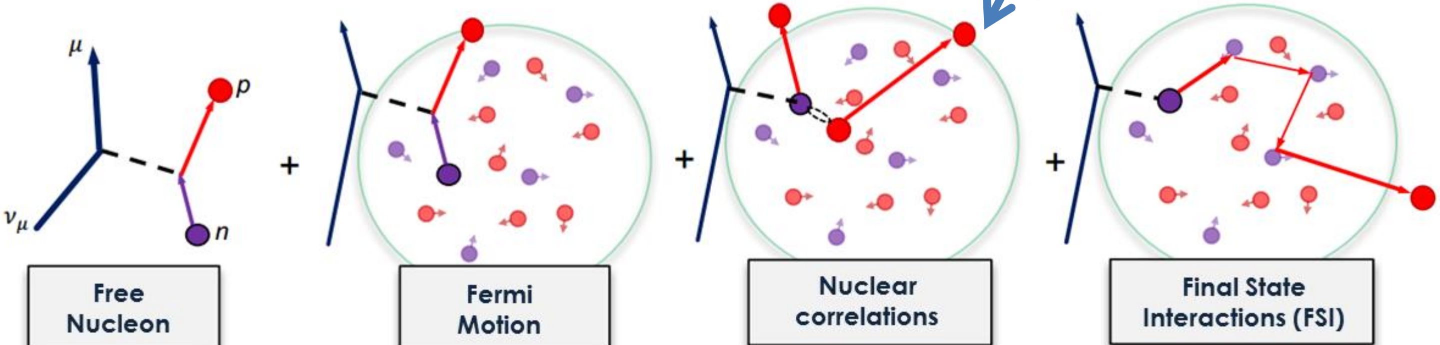


2p2h

(2 particle – 2 hole)



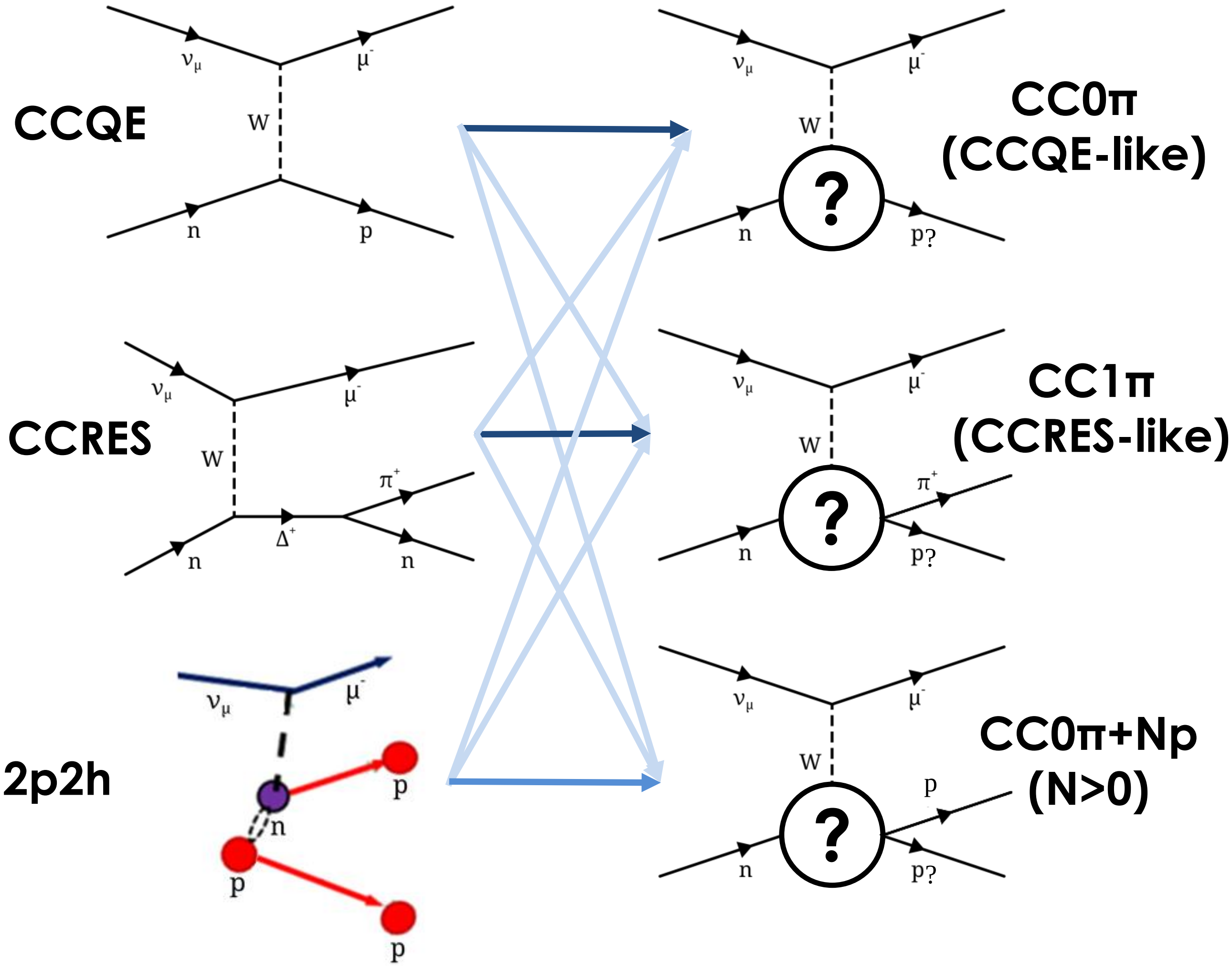
Nuclear Effects



Diagrams by Patrick Stowell

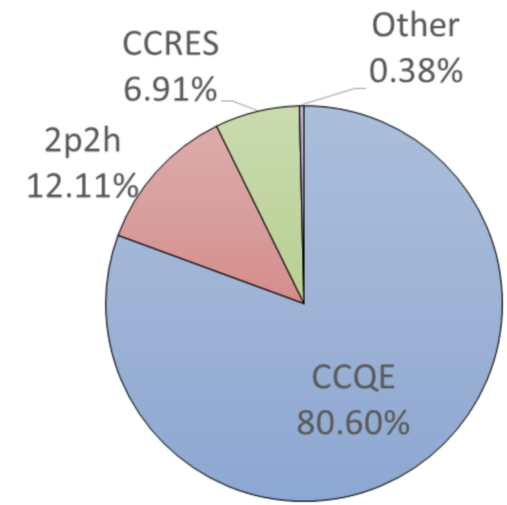
What can we measure

Interaction Modes | **Interaction Topologies**

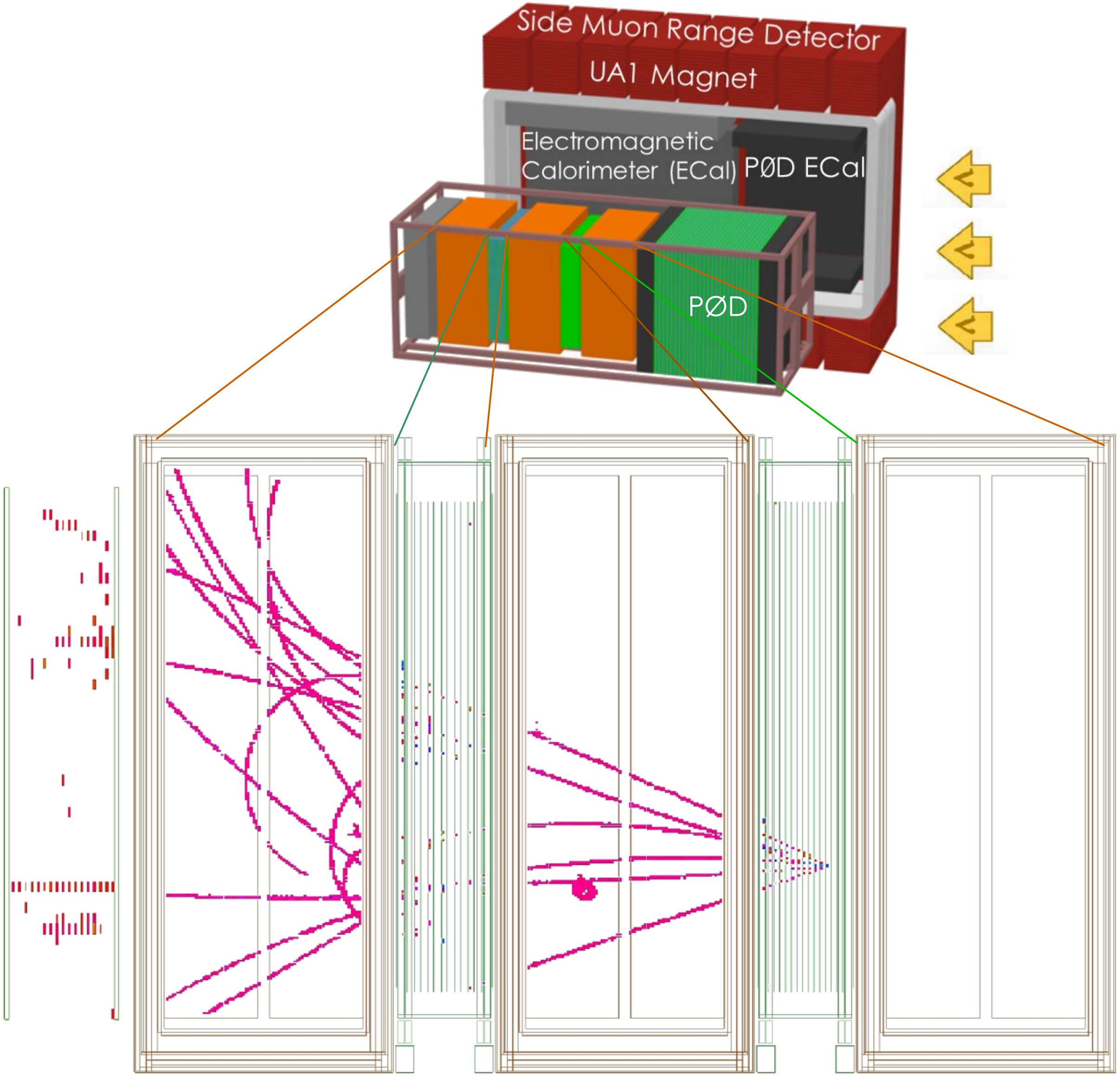


- Nuclear effects obfuscate interaction mode
- To minimise model dependence we measure interaction topologies

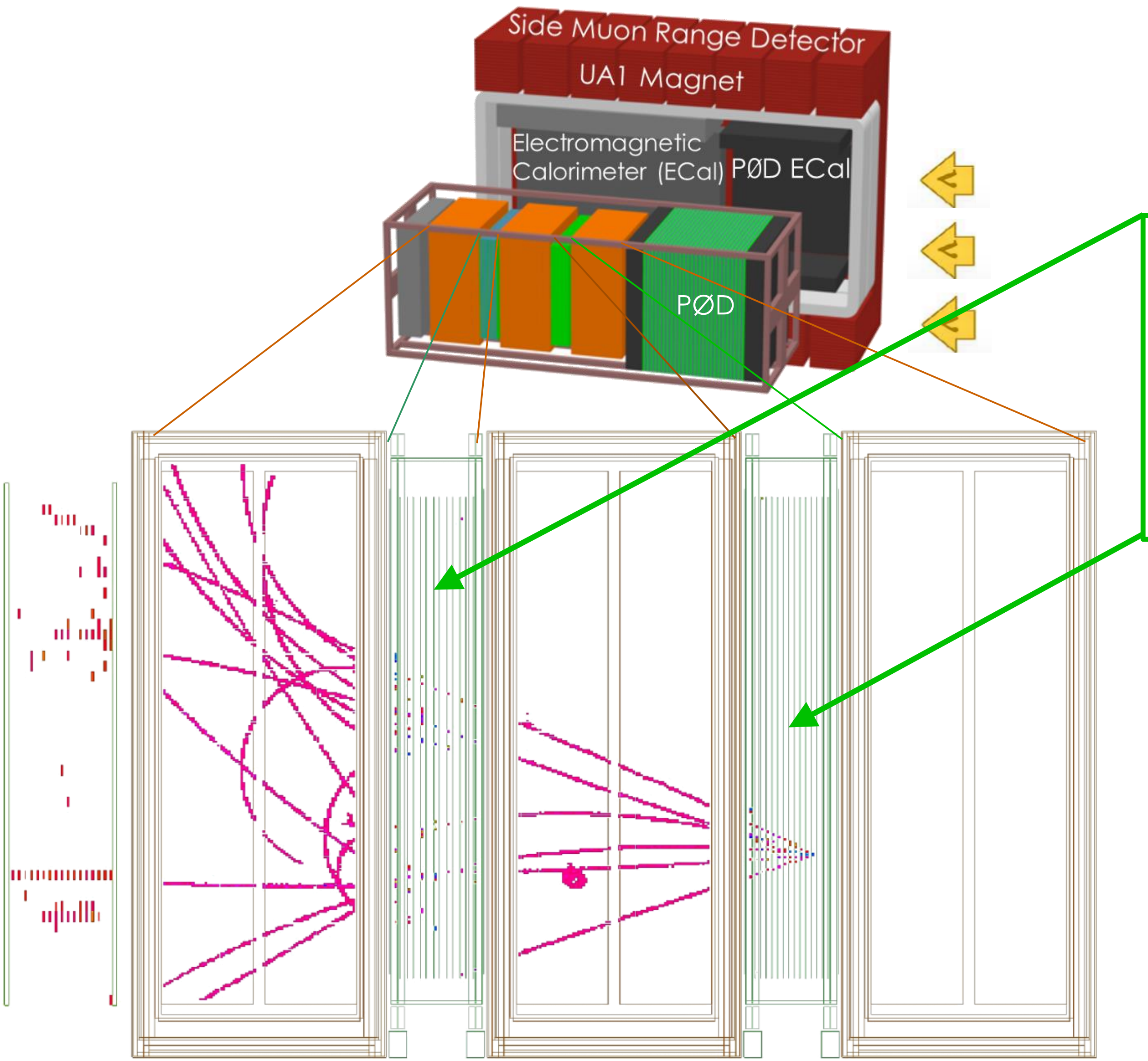
Interaction modes in CC0π topology:
(NEUT MC)



ND280 (off axis near detector)



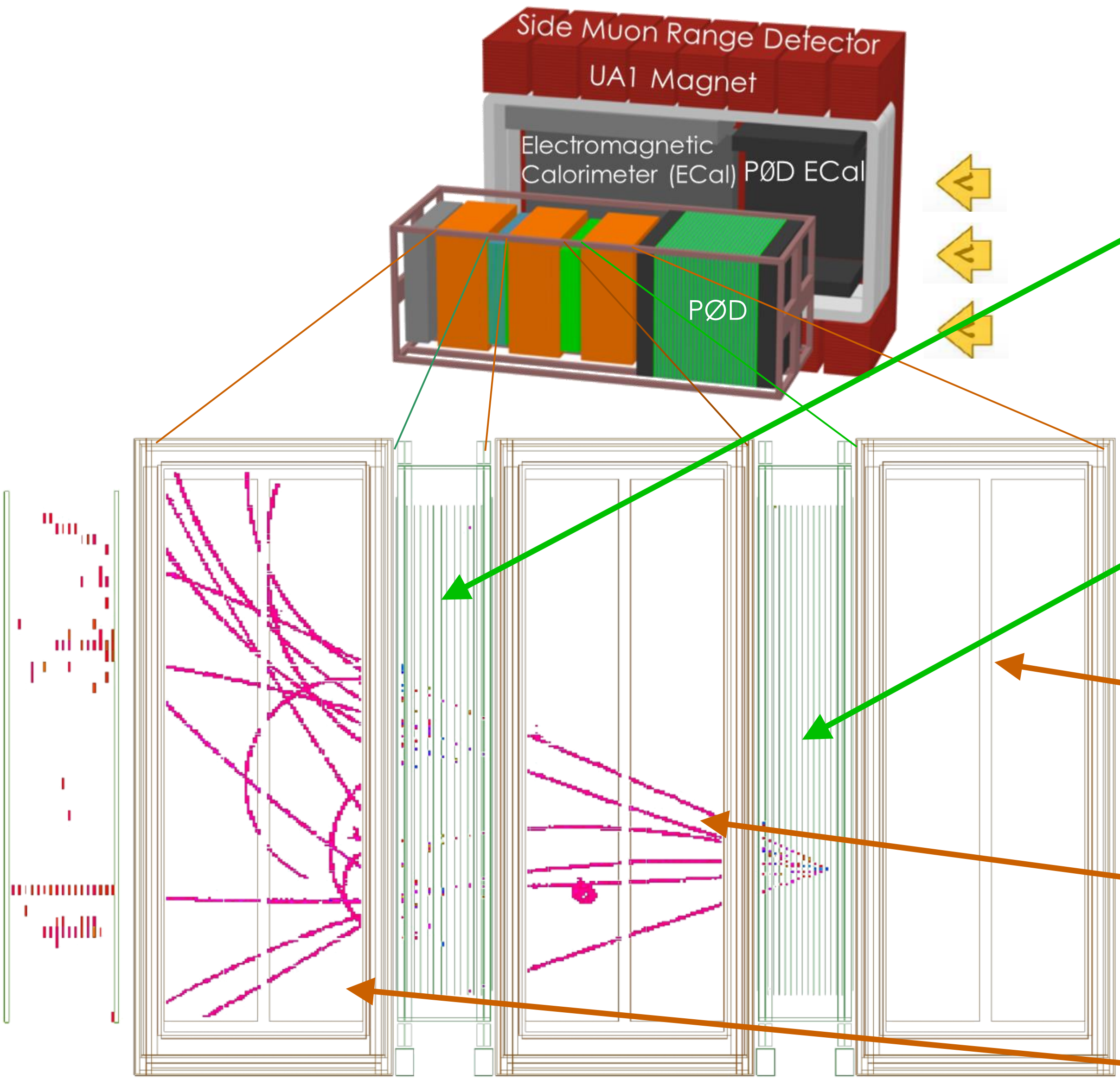
ND280 (off axis near detector)



Fine-Grained Detectors (FGD 1 & 2):

- CH scintillator tracker
- Target for ν
- FGD2 contains water

ND280 (off axis near detector)



Fine-Grained Detectors (FGD 1 & 2):

- CH scintillator tracker
- Target for ν
- FGD2 contains water

Time Projection Chambers (TPC):

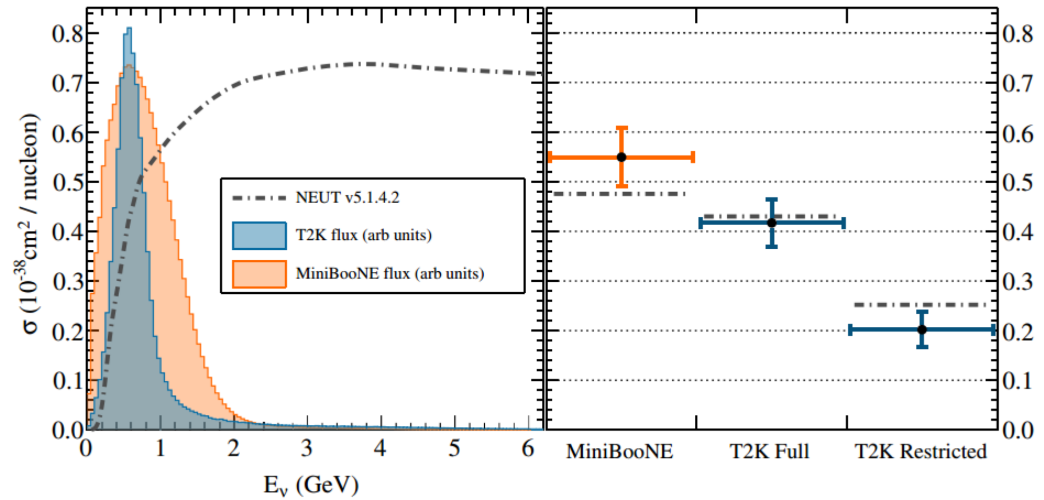
- Excellent tracking
- High-res charged-particle momenta
- Accurate particle ID

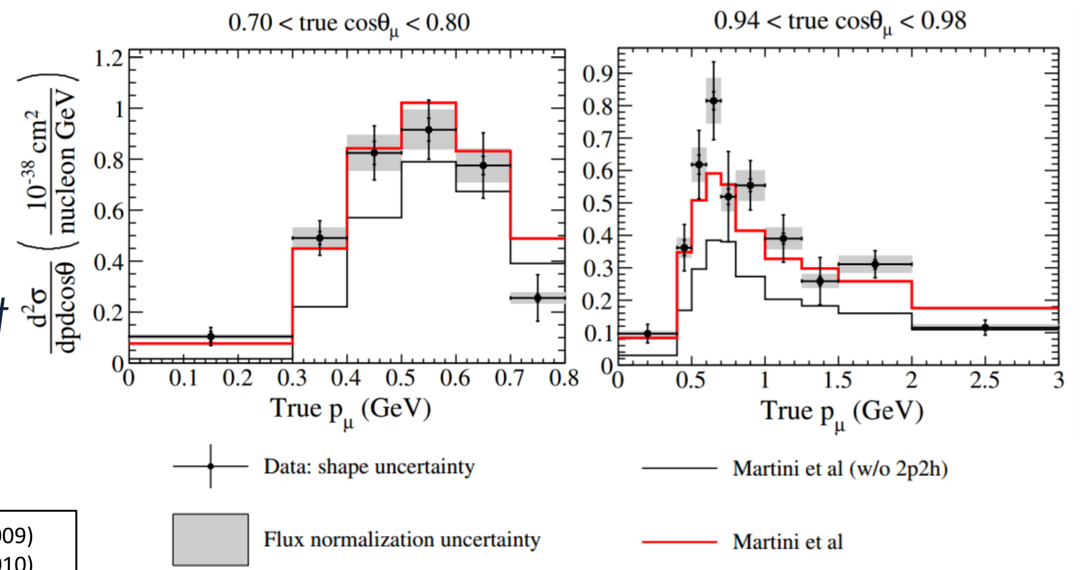
Previously on T2K …

- Neutrino interactions at T2K
- Previous T2K cross-section results
- Cross sections using proton information
  - CC0π using proton kinematics
  - CC0π using transverse kinematic imbalance
- Summary and future work

ND280 Off-Axis CC0π Result

- Uses FGD1 as a CH target alongside TPC for tracking
- **Flux integrated** double-differential **CC0π** cross section in final state muon kinematic variables $(p_\mu, \cos(\theta_\mu))$
- Split into two analyses with different selection and cross-section extraction strategies
  - Good agreement
- Results compared to Martini *et al.* model **with**/**without** 2p2h
  - Full results in the backups



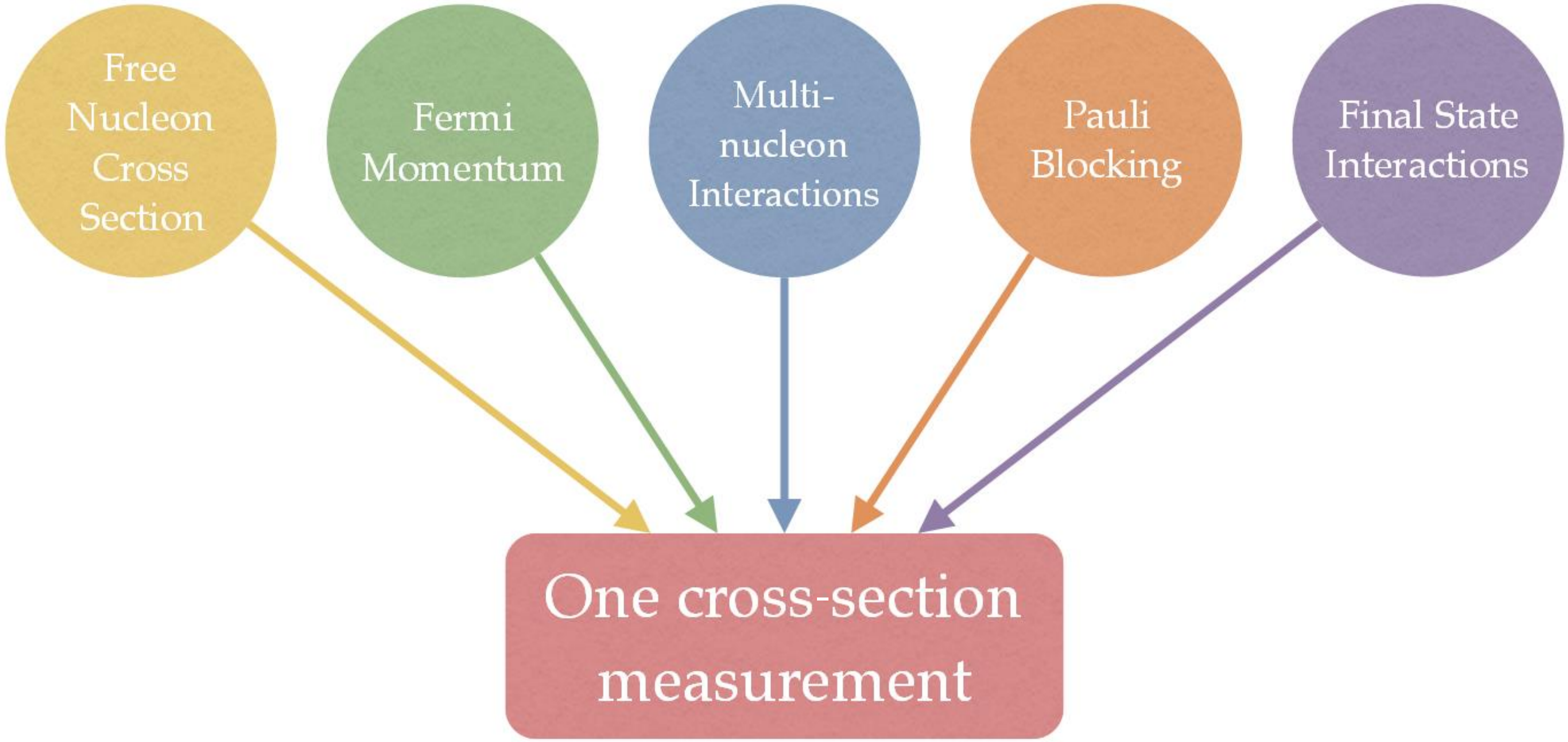


M. Martini, M. Ericson, G. Chanfray, and J. Marteau, Phys. Rev. C **80**, 065501 (2009)
M. Martini, M. Ericson, G. Chanfray, and J. Marteau, Phys. Rev. C **81**, 045502 (2010)

Detector: ND280 – FGD1 **Target:** Carbon **Signal:** CC0π **Variables:** μ-kinematics **Status:** Phys. Rev. D **93**, 112012

What next?

Diagram by Laura Fields



- Would like to disentangle the role of separate nuclear effects and the free nucleon cross-section.

- Current results provide an important piece of the puzzle but further complementary measurements are needed…

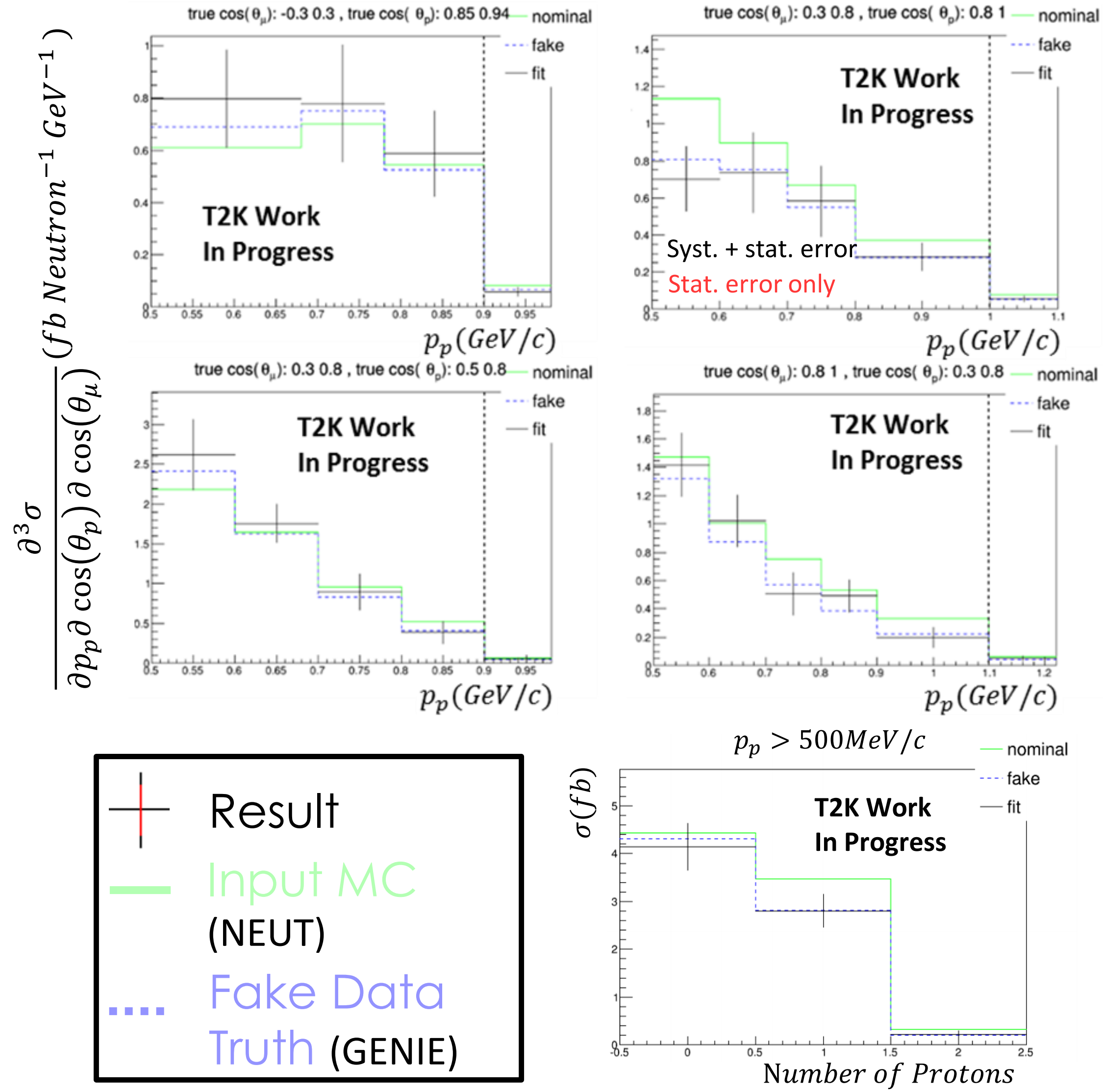
Measuring proton kinematics

- Allows new handle on nuclear effects
- Results will be compared to **NEUT** and **GENIE** neutrino interaction simulations
  - Both plausible widely used models
  - NEUT has a 2p2h contribution, GENIE does not (in versions used here)
- Simulations have weak predictive power to describe proton kinematics
  - Nuclear effects are very difficult to model
  - First time looking at proton predictions
  - ➢ **Need to ensure minimal dependence on simulation**

- Measure fiducial cross section
- Minimise role of MC in unfolding (minimal regularisation)

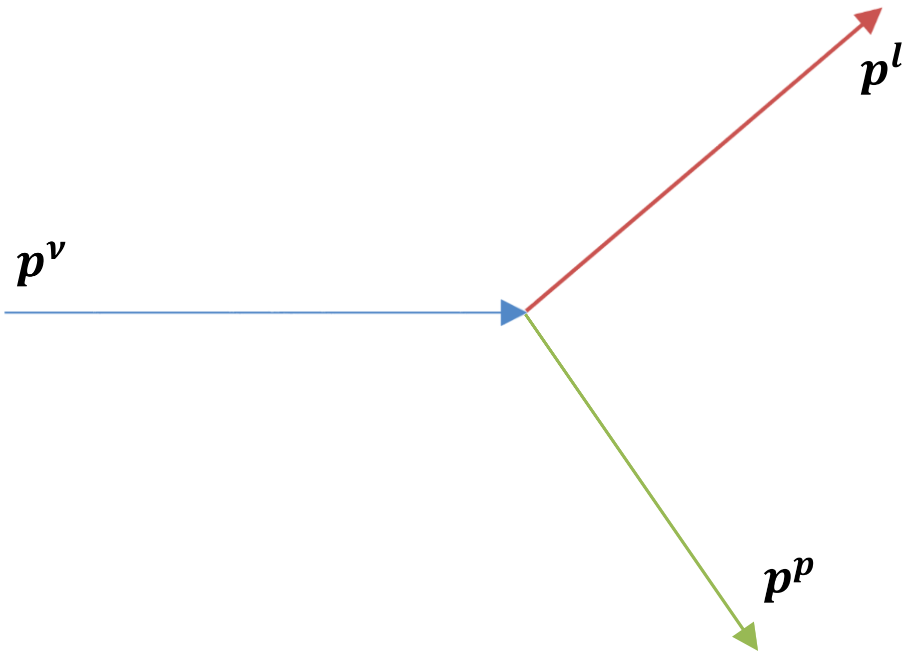
CC0π using $\mu + p$ kinematics

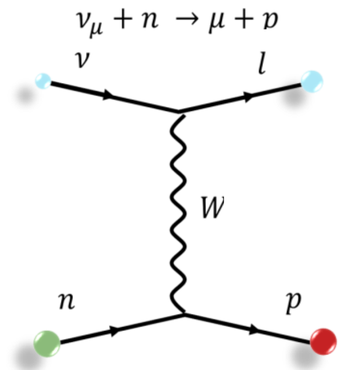
- Uses FGD1 as a CH target alongside TPC for tracking
- Measure fiducial flux-integrated $\mathbf{CC0\pi + Np}$ cross section in bins of $\cos(\theta_\mu), \cos(\theta_p), p_p$
- Restrict phase space (p_p>500MeV/c)
- Can also measure proton multiplicity
- Fake data study (blind) – real results coming soon



Detector: ND280 – FGD1 **Target:** Carbon **Signal:** CC0π+Np **Variables:** $\mu + p$ kinematics **Status:** Blind

Single Transverse Variables

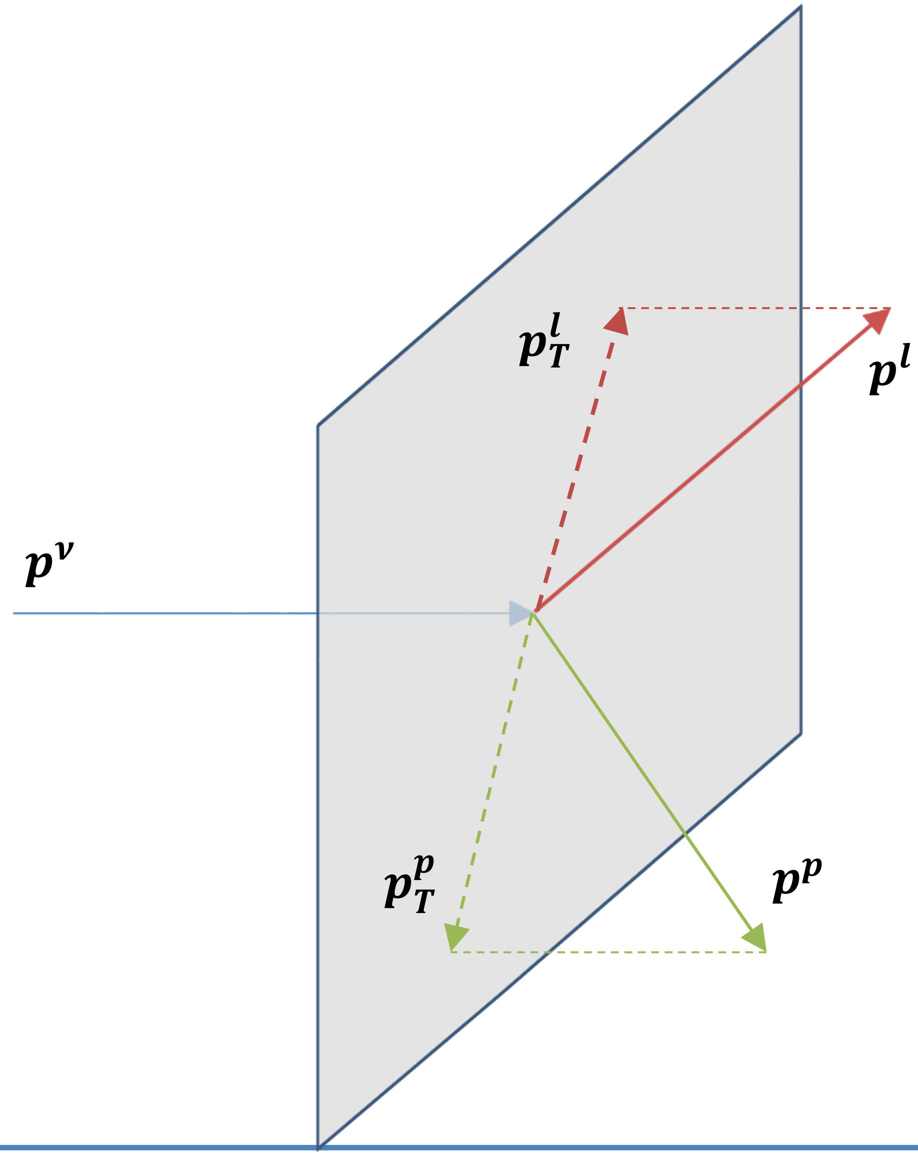


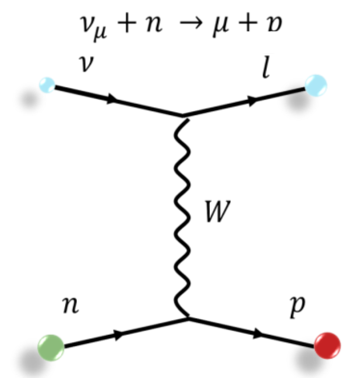


No nuclear Effects

Detector: ND280 – FGD1 **Target:** Carbon **Signal:** CC0π+Np **Variables:** single-transverse **Status:** New

Single Transverse Variables



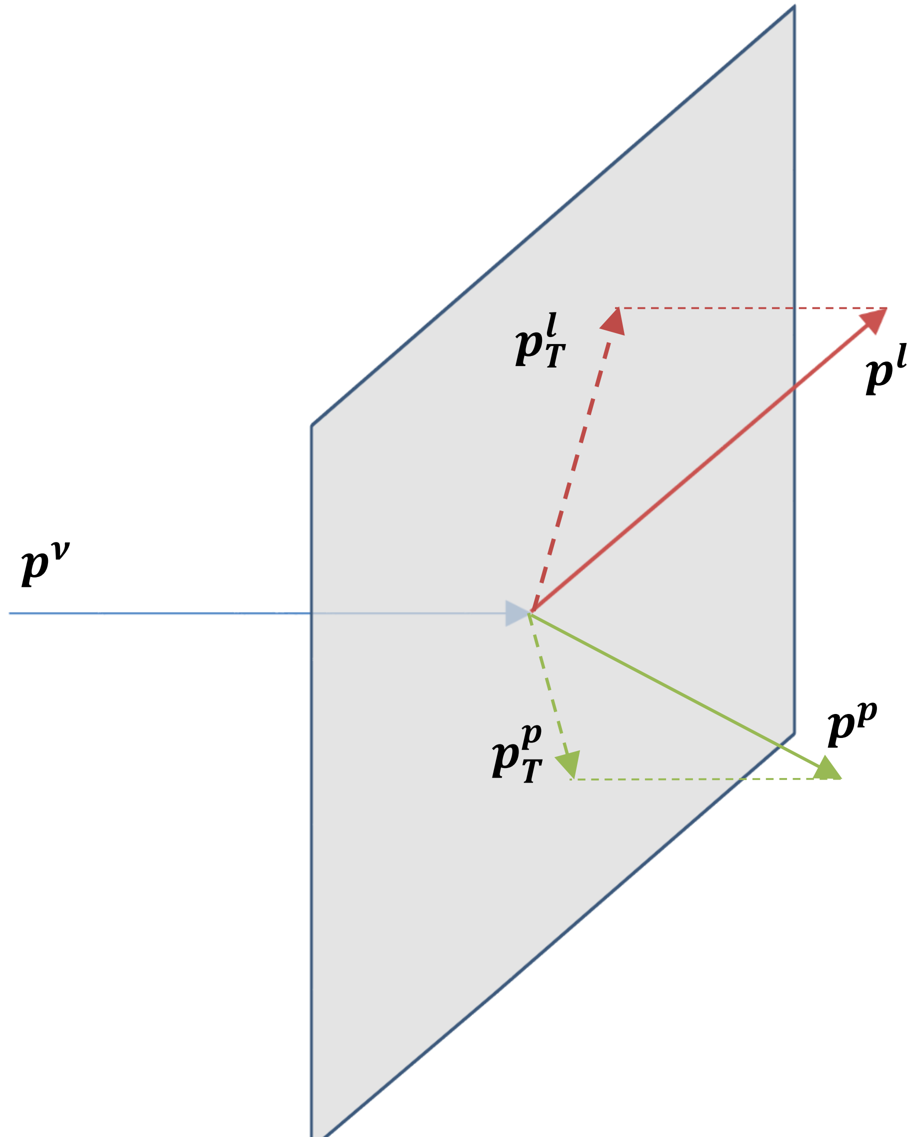


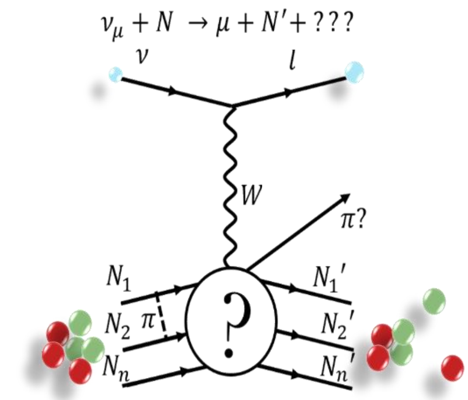
No nuclear Effects

$$p_T^l = -p_T^p$$

Detector: ND280 – FGD1 **Target:** Carbon **Signal:** CC0π+Np **Variables:** single-transverse **Status:** New

Single Transverse Variables





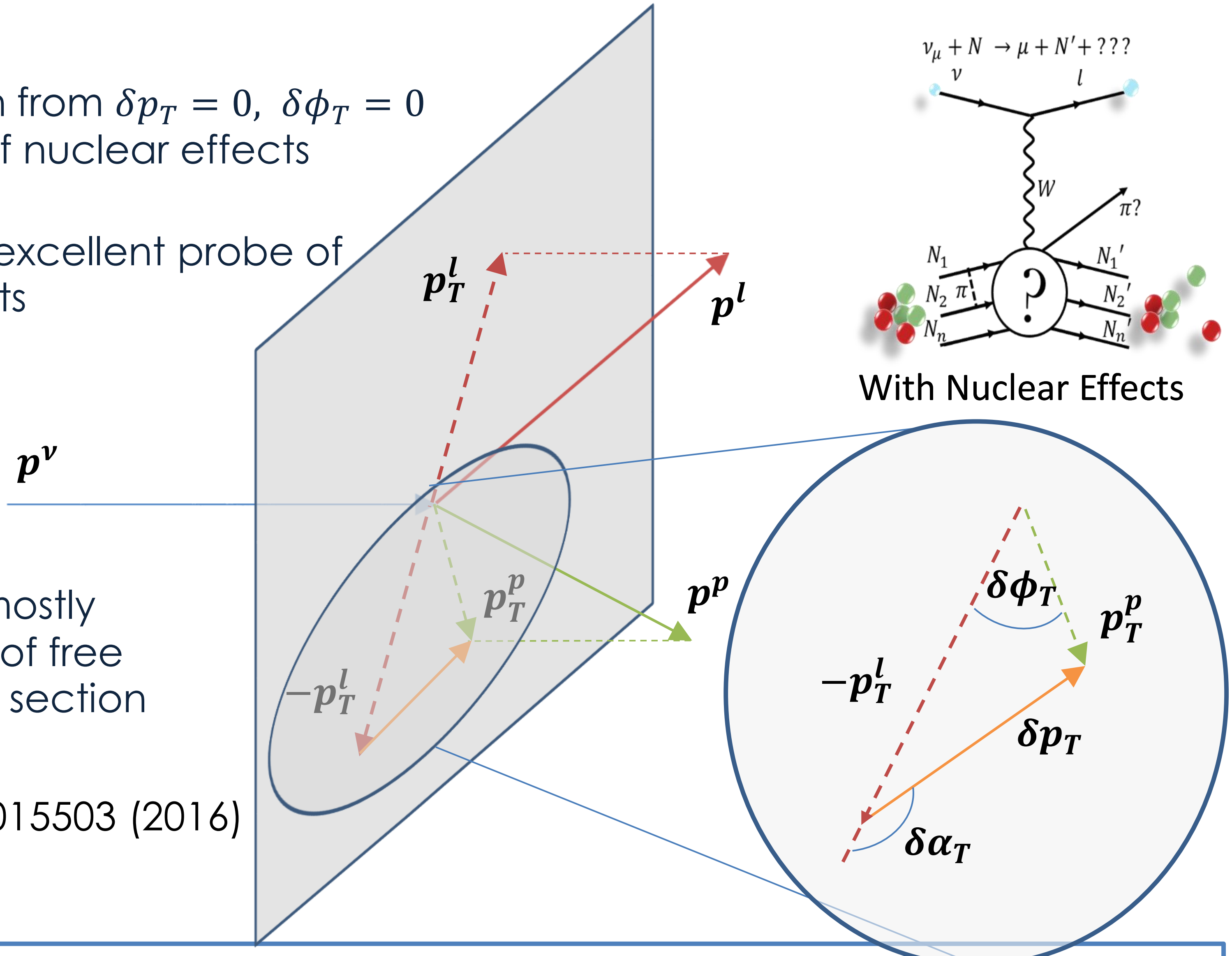
With Nuclear Effects

$$p_T^l \neq -p_T^p$$

Detector: ND280 – FGD1 **Target:** Carbon **Signal:** CC0π+Np **Variables:** single-transverse **Status:** New

Single Transverse Variables

- Any deviation from $\delta p_T = 0,\ \delta\phi_T = 0$ is indicative of nuclear effects
- STVs offer an excellent probe of nuclear effects



- STV shape is mostly independent of free nucleon cross section

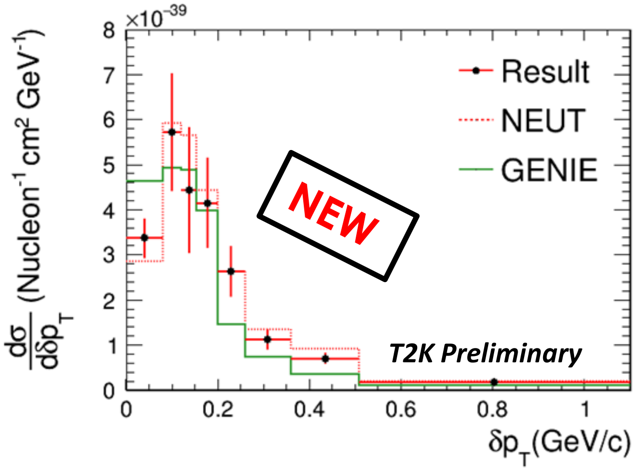
Phys. Rev. C **94**, 015503 (2016)

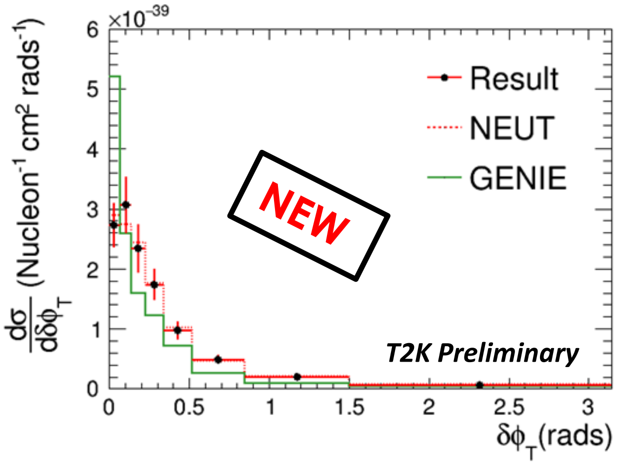
Detector: ND280 – FGD1 **Target:** Carbon **Signal:** CC0π+Np **Variables:** single-transverse **Status:** New

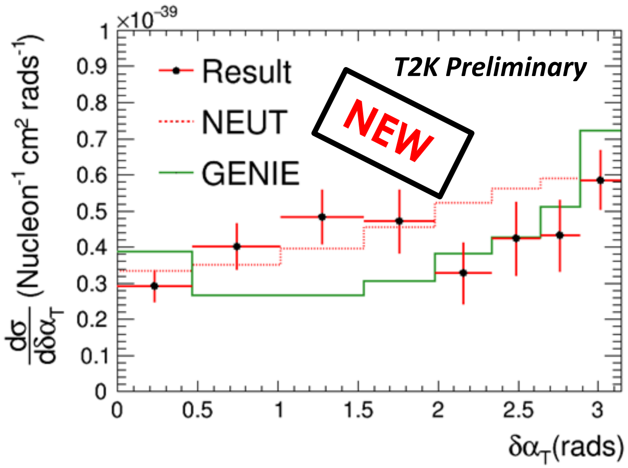
CC0π+Np in STV

- Measure fiducial flux-integrated CC0$\pi + Np$ cross section **in bins of STV**
- Restrict cross section to ND280 acceptance

$$\begin{cases} p_\mu > 250\ MeV/c \\ \cos(\theta_\mu) > -0.6 \\ 450\ MeV/c < p_\mu < 1\ GeV/c \\ \cos(\theta_p) > 0.4 \end{cases}$$

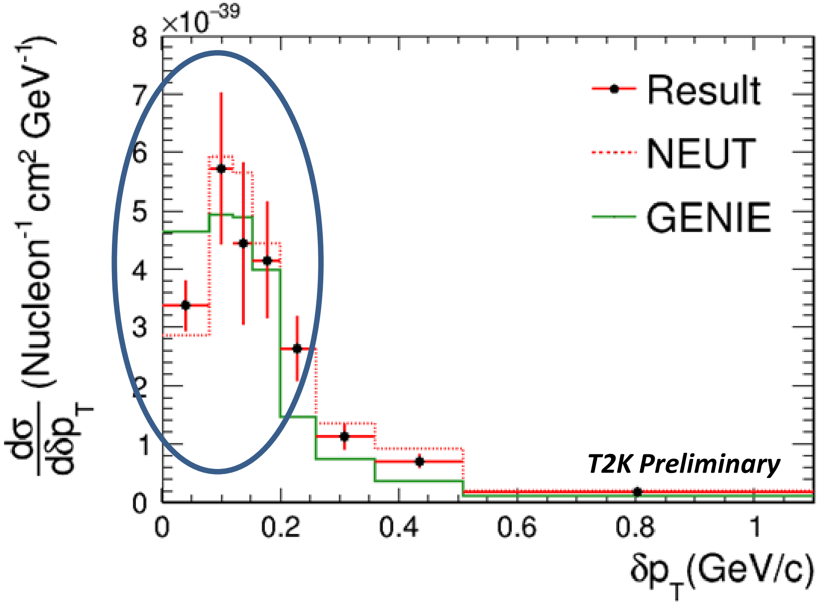


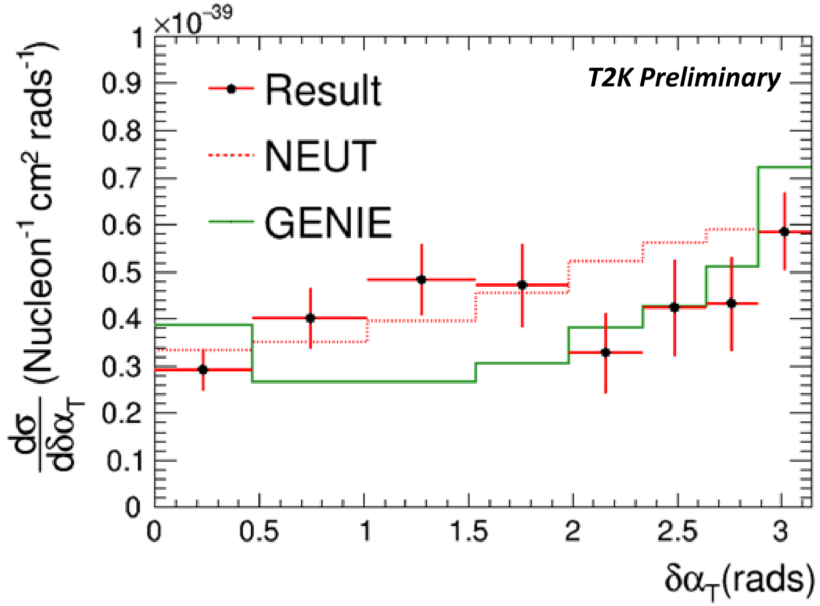


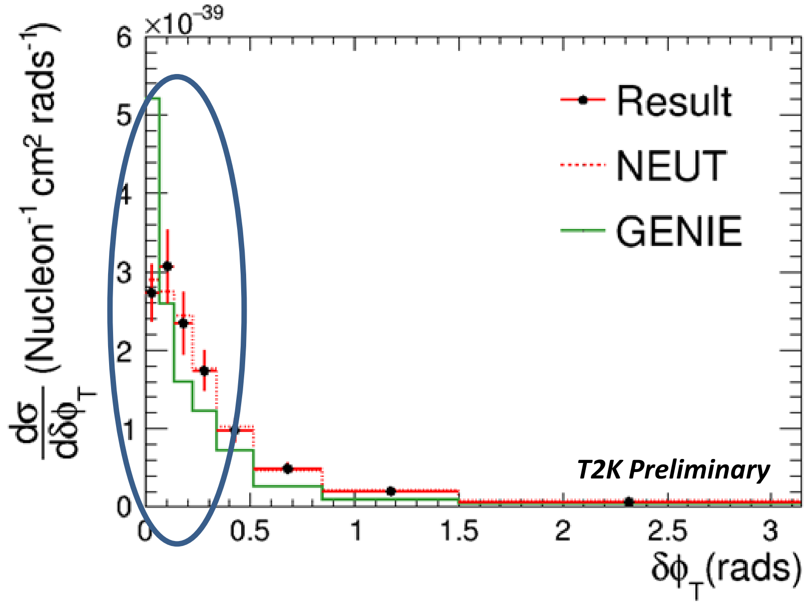


Detector: ND280 – FGD1 **Target:** Carbon **Signal:** CC0π+Np **Variables:** single-transverse **Status:** New

CC0π+Np in STV

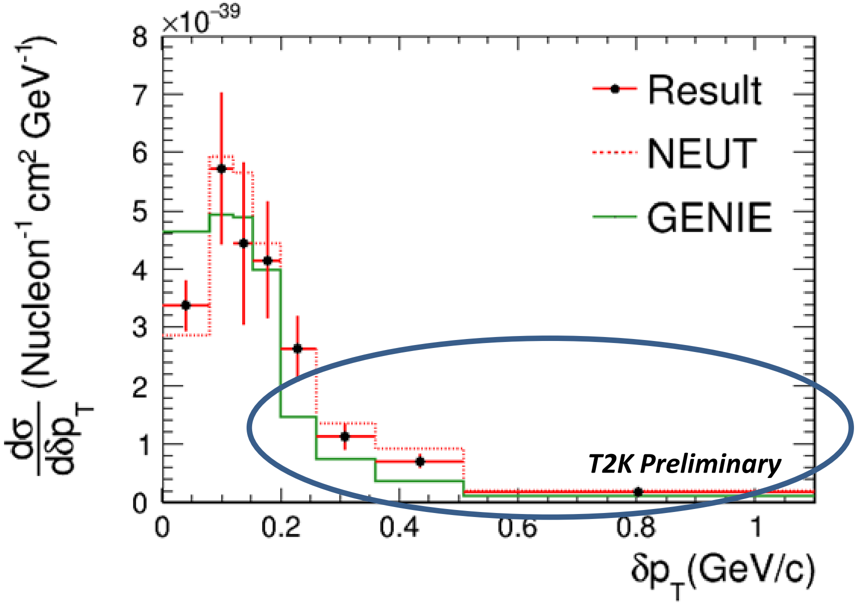


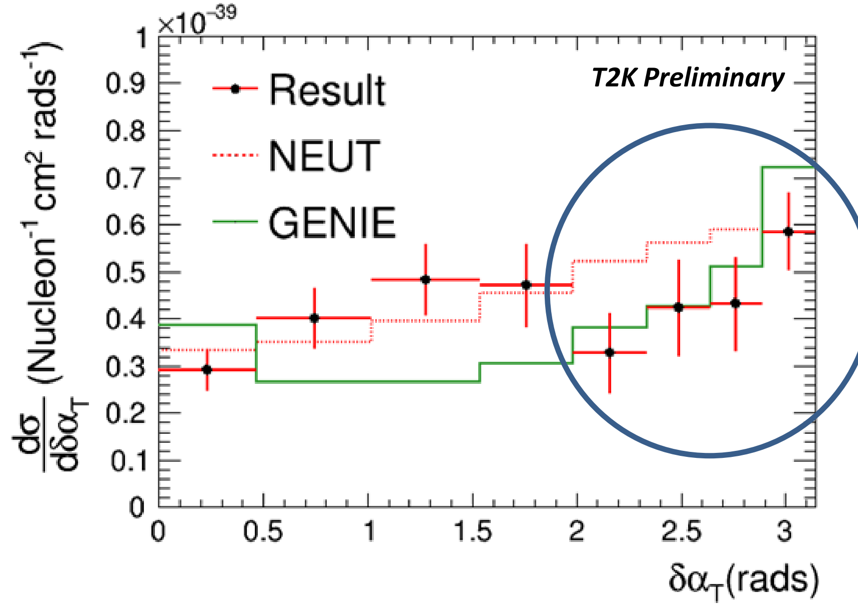


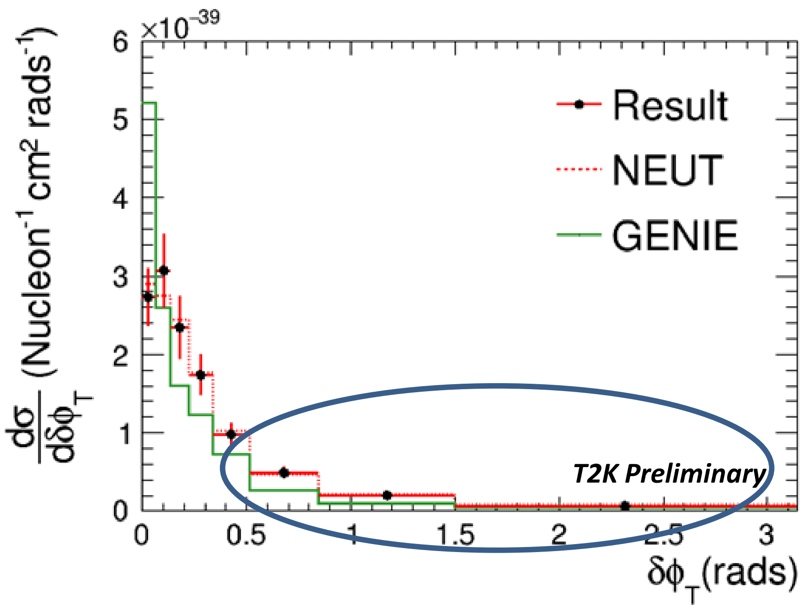


- The peak position and early bins in δp_T and $\delta \phi_T$ tell us about **Fermi Motion**.

CC0π+Np in STV

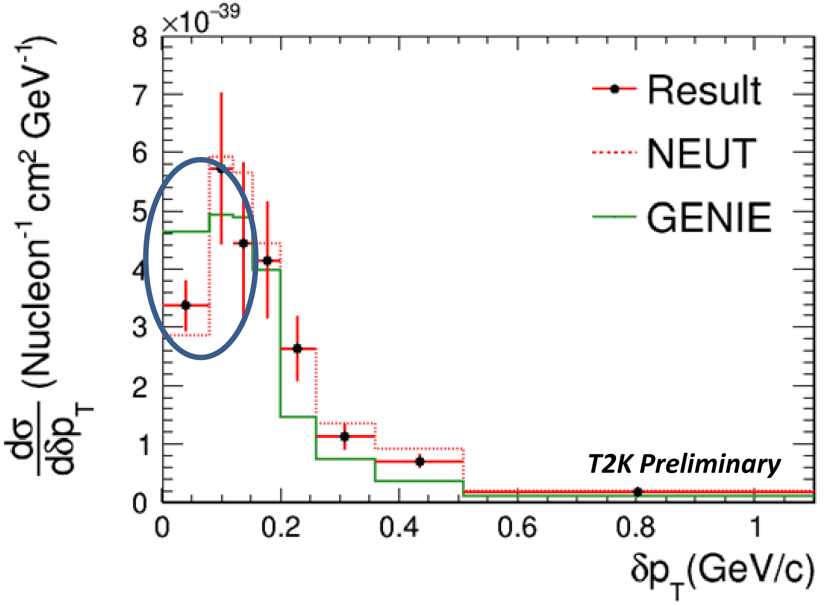


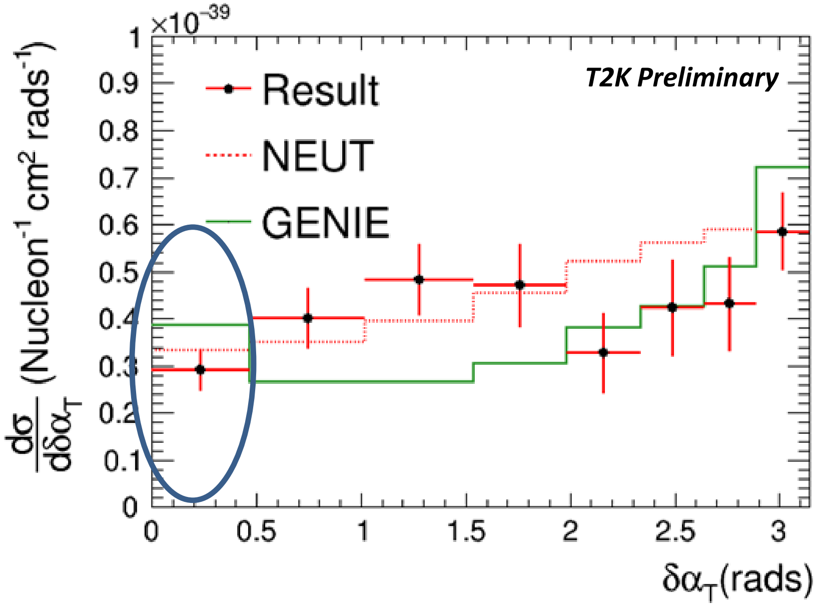


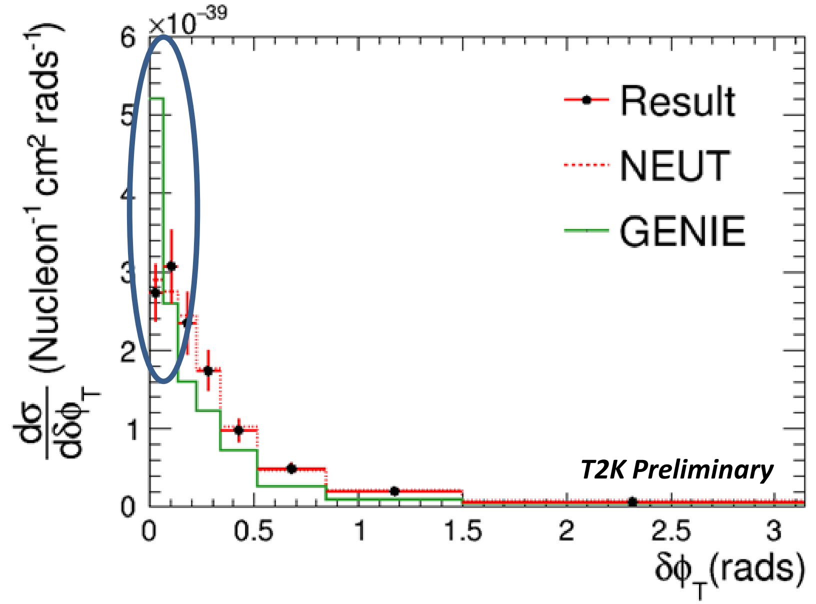


- The peak position and early bins in δp_T and $\delta\phi_T$ tell us about Fermi Motion.
- The tails in δp_T and $\delta\phi_T$ and the extent of the rise at large $\delta\alpha_T$ indicate the energy transfer through **FSI** processes.
  - Also sensitive to **2p2h**

CC0π+Np in STV



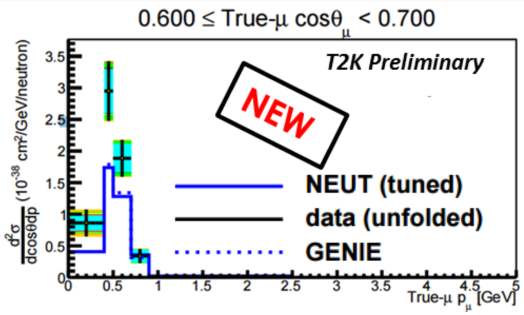


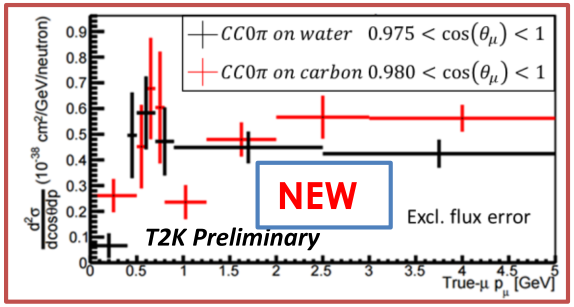


- The peak position and early bins in δp_T and $\delta\phi_T$ tell us about Fermi Motion.
- The tails in δp_T and $\delta\phi_T$ and the extent of the rise at large $\delta\alpha_T$ indicate the energy transfer through FSI processes.
  - Also sensitive to 2p2h
- These differences between NEUT and GENIE are correlated.
  - From nucleon FSI model differences

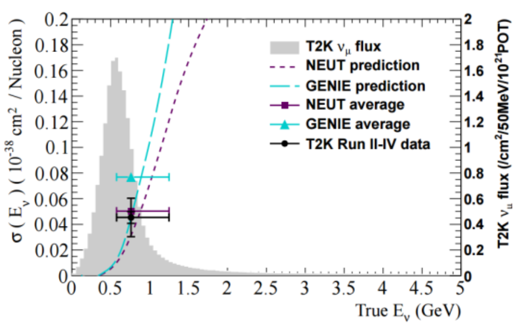
Other new results

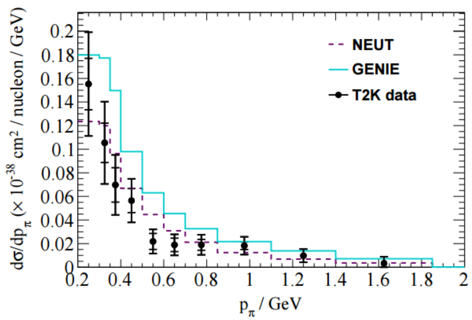
- Use PØD to measure **CC0π** cross section on water
- Compare to T2K result on Carbon → Probe of A-scaling





See proceedings from NuFact and ICHEP 2016

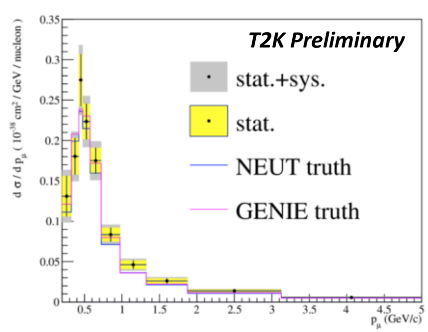


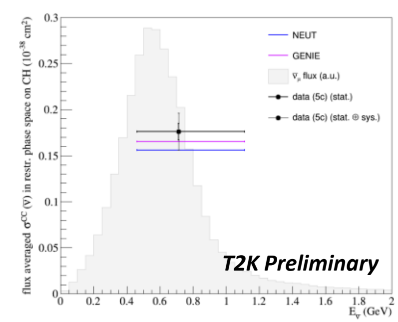


See arXiv:1605.07964 [hep-ex]

- Use FGD2 to measure **CC1π** cross section on water
- Results differential in muon and pion kinematics (separately)

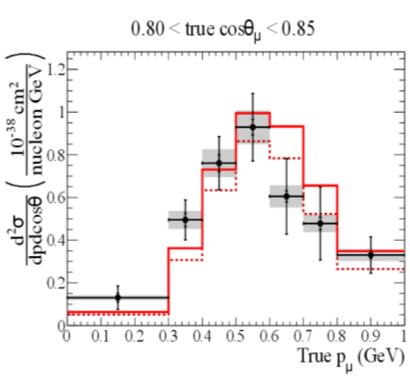
- Anti-neutrino **CC-Inclusive** cross-section on carbon using FGD1
- Results differential in muon momentum and angle (separately)

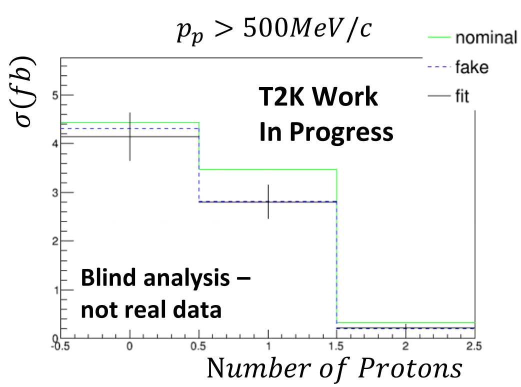


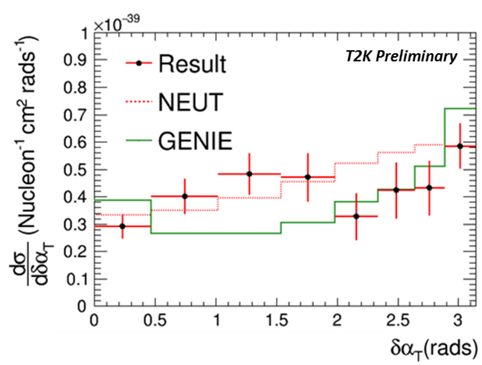


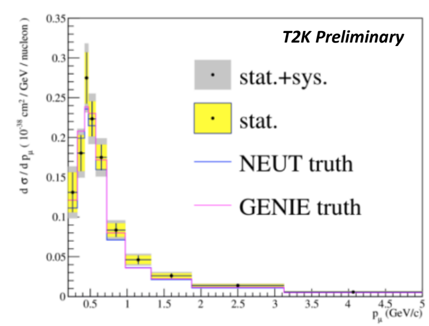
Summary

- T2K is measuring cross-sections of exclusive final-state topologies
- New techniques in use to complement each other and existing results
  - Analyses specifically engineered to probe nuclear effects
- T2K's first measurement using proton kinematics
- First measurement of neutrino cross sections in single transverse variables
- First ever measurement of $\delta\alpha_T$
- Many more results coming soon!



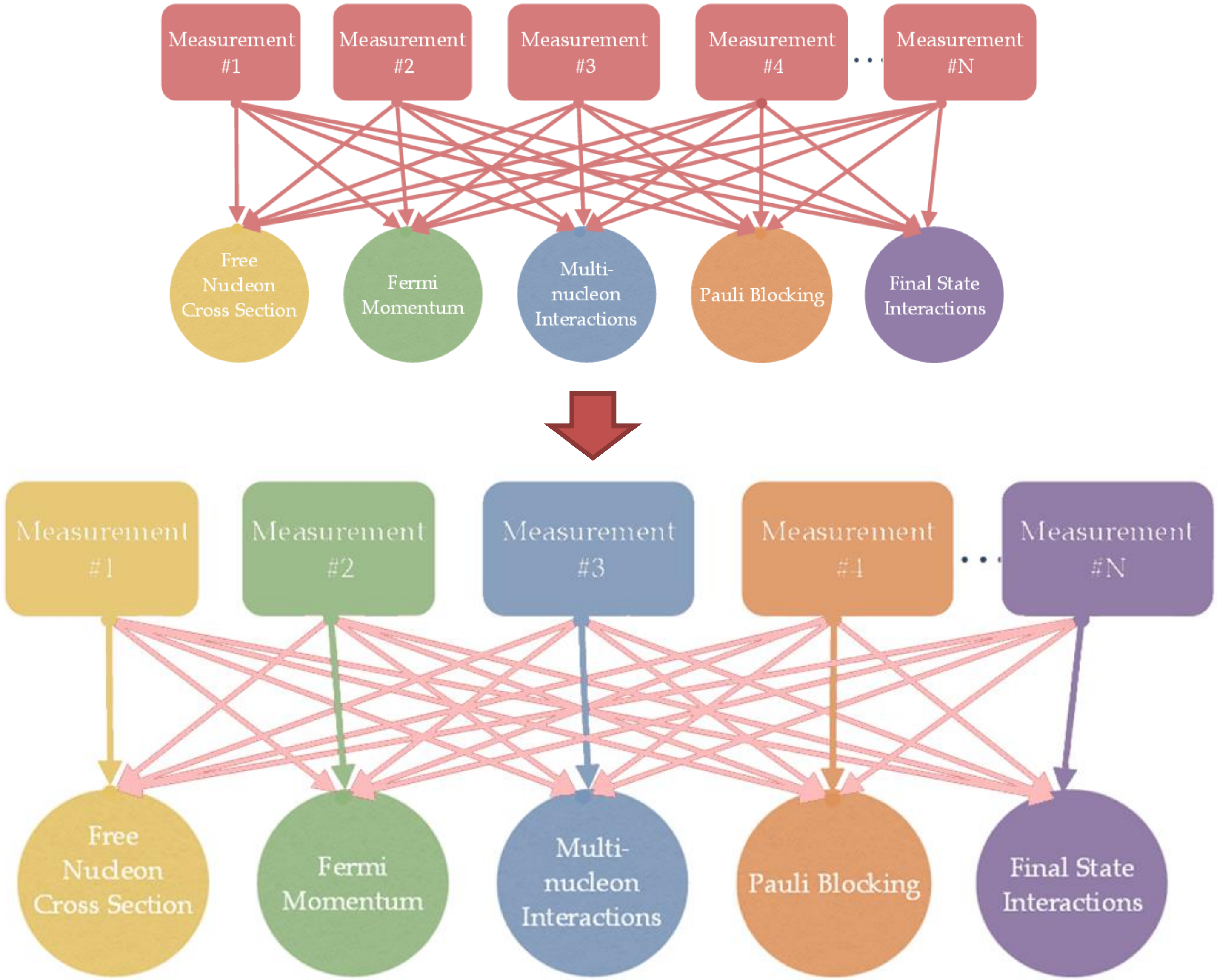






The Future

Diagram by Laura Fields

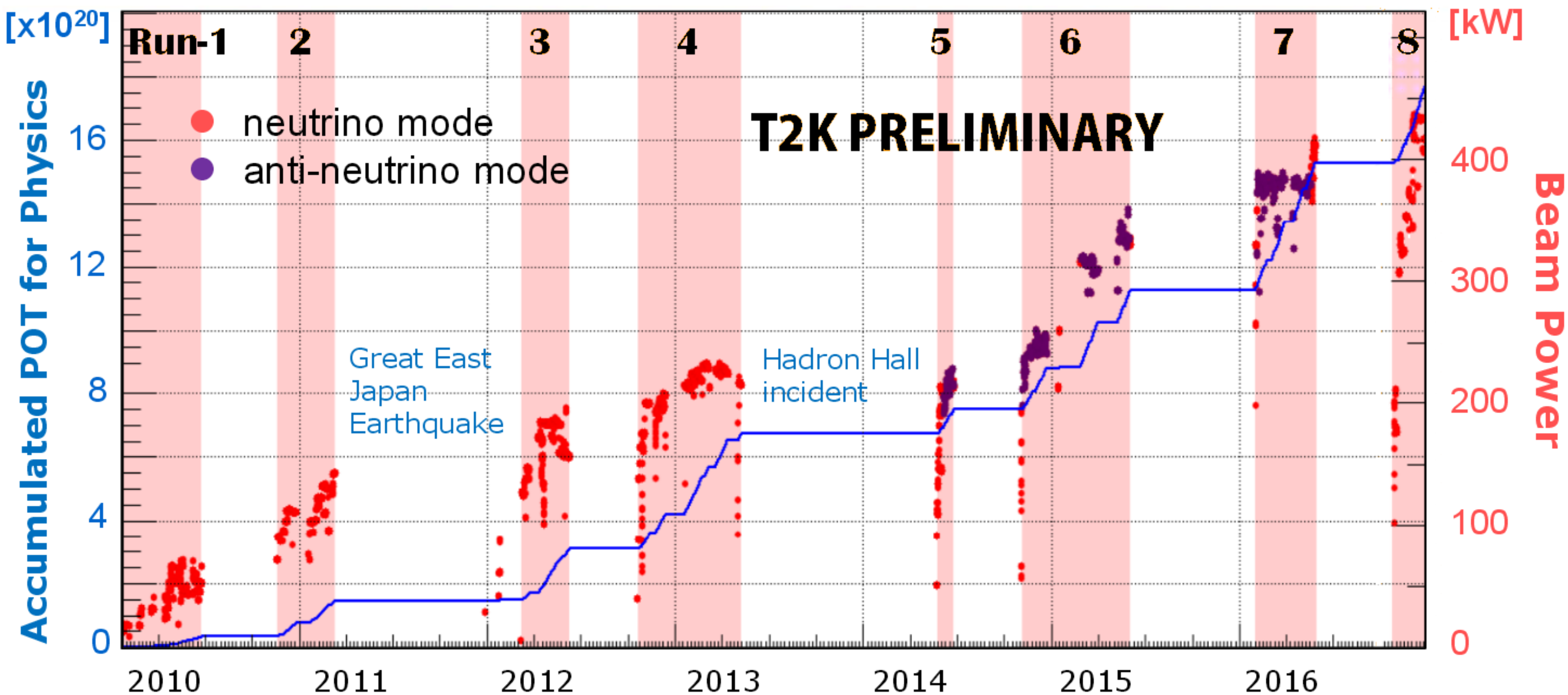


Thank you for listening

BACKUPS

Data Collection

(POT = Protons On Target)



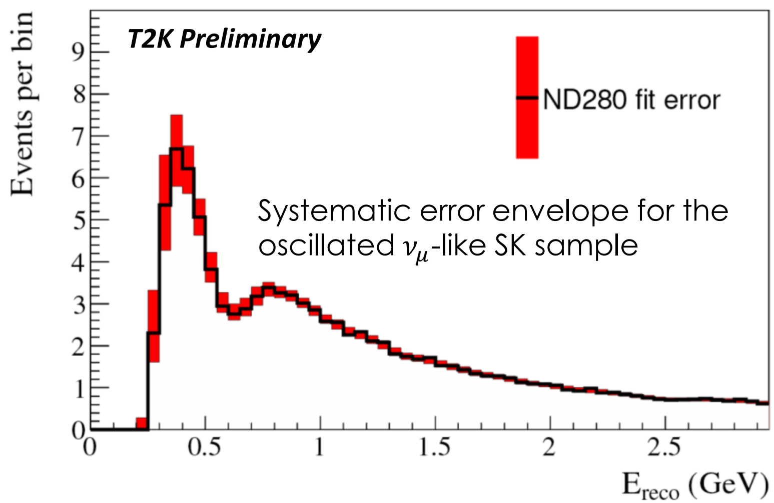
- Continuous rise in beam power from ~225 kW (2014) to ~450 kW (2017)
- Using this to make world leading measurements of oscillation parameters (see talk by Raj Shah)

Neutrino Interactions and OA

- Oscillation analysis (OA) requires E_ν spectrum (or similar)

$$N_{pred}(E_\nu^{reco}) = \Phi(E_\nu^{true})\,\sigma(E_\nu^{true})\,P(\alpha \to \beta, E_\nu^{true})\,\epsilon(E_\nu^{true})\,S(E_\nu^{true}, E_\nu^{reco})$$

$N_{pred}(E_\nu^{reco})$	=	Expected number of events
$\Phi(E_\nu^{true})$	=	Neutrino flux
$\sigma(E_\nu^{true})$	=	Interaction cross sections
$P(\alpha \to \beta, E_\nu^{true})$	=	Oscillation probability
$\epsilon(E_\nu^{true})$	=	Selection efficiency
$S(E_\nu^{true}, E_\nu^{reco})$	=	Smearing matrix

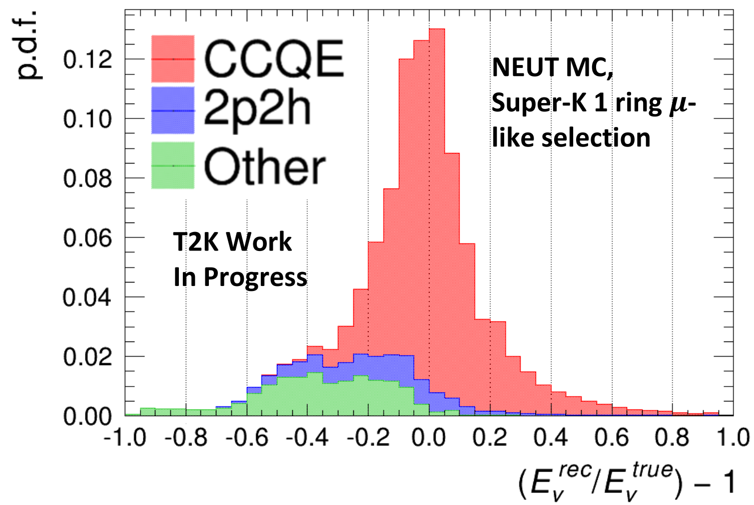


- Our largest OA systematic comes from neutrino interaction uncertainties (4%-6% out of 5%-7%)

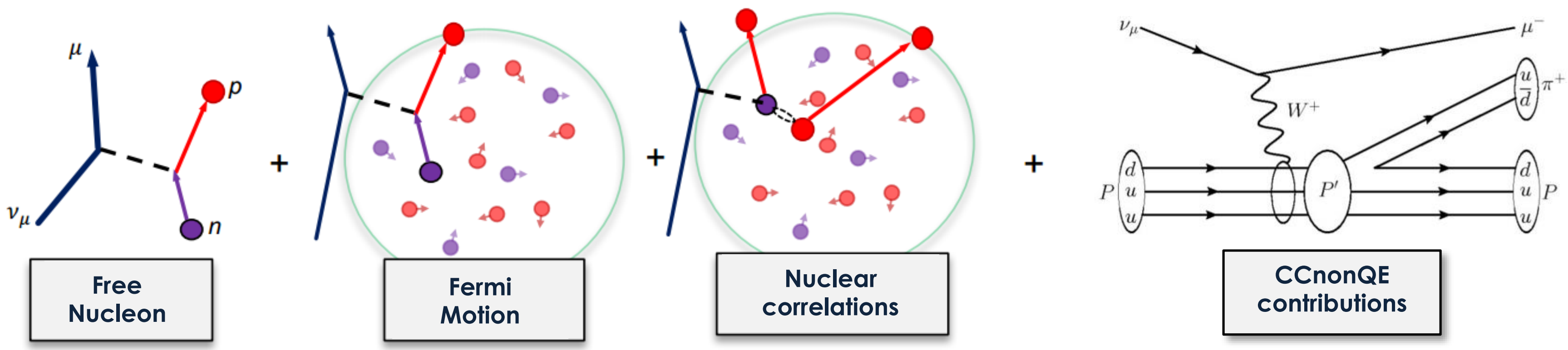
Neutrino Interactions and OA

- Find E_ν^{reco} using observed μ at SK assuming **stationary target** and **elastic scattering**

$$E_\nu^{reco} = \frac{m_p^2 - m_n^2 - m_\mu^2 + 2m_n E_\mu}{2(m_n - E_\mu + p_\mu \cos(\theta_\mu))}$$

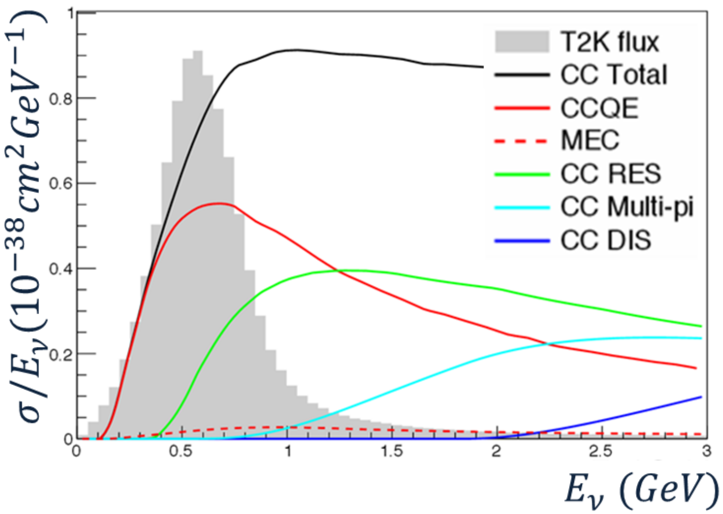


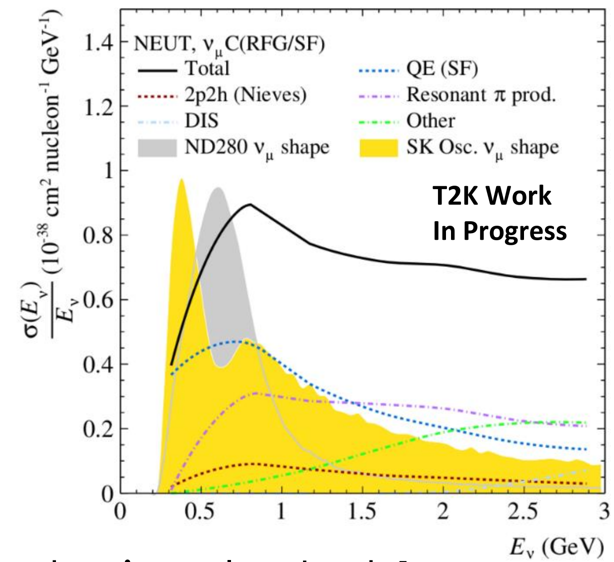
Bias due to:
- **Fermi motion in the initial nuclear state**
- **Nucleon-nucleon correlations**
- **CCnonQE contamination in the selection.**



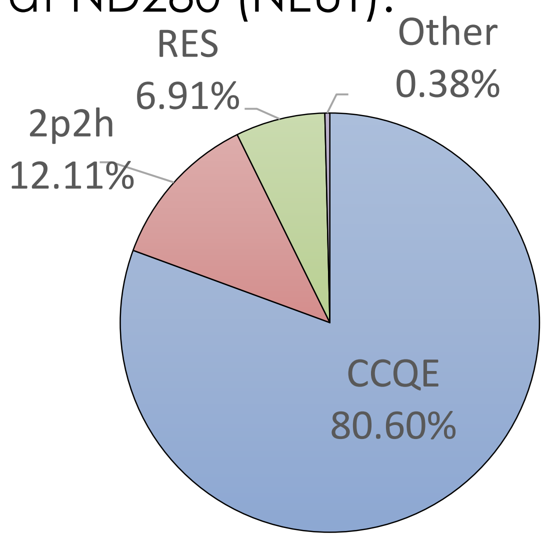
Diagrams by Patrick Stowell

Neutrino Scattering and OA

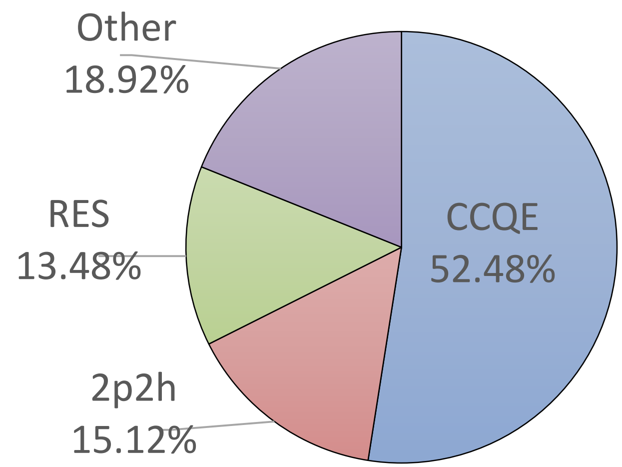




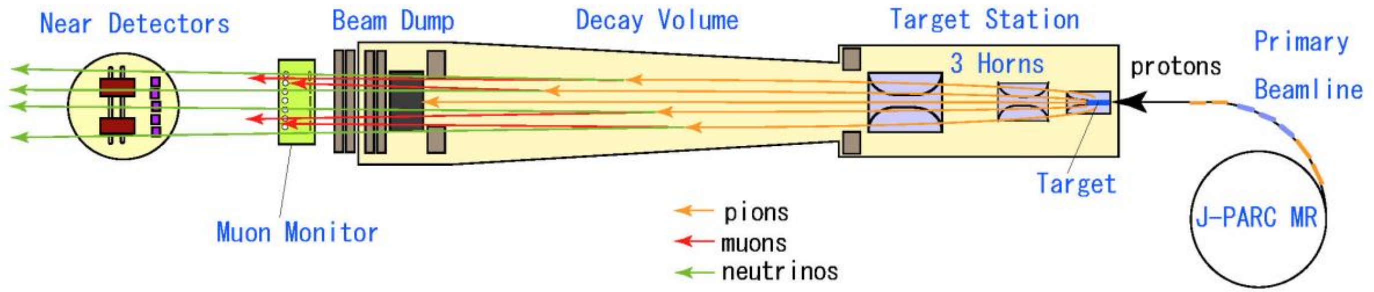
Interaction Modes in all CC0π events at ND280 (NEUT):

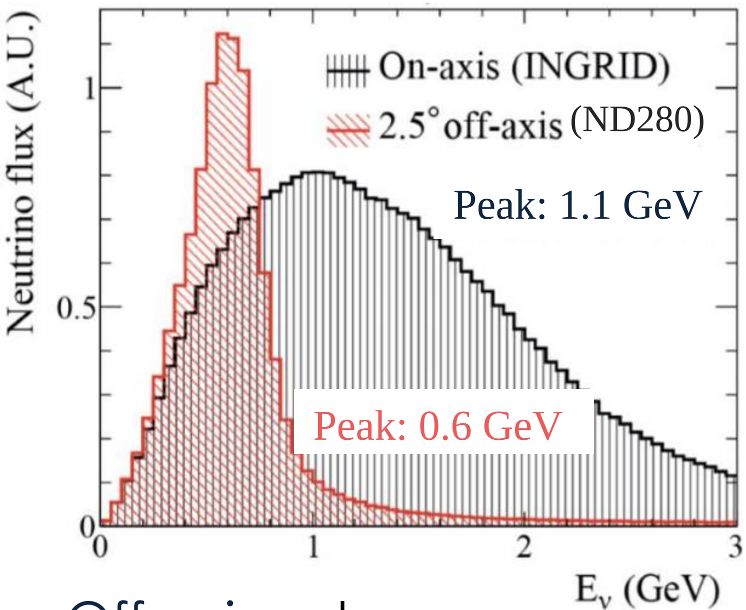


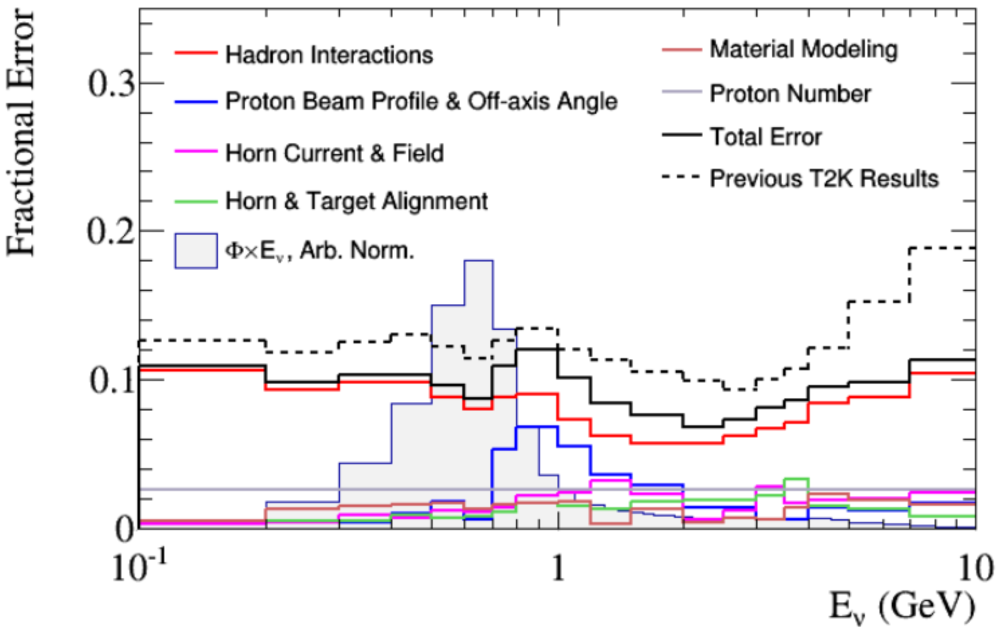
Interaction Modes in selected 1 ring μ-like events at SuperK(NEUT):



The Flux







- Off-axis ν_μ beam
  - Tightly-peaked at 600 MeV 2.5° off-axis towards SK
  - Low contamination from non-ν_μ components
  - Flux estimation aided by hadron production measurements from NA61/SHINE at CERN

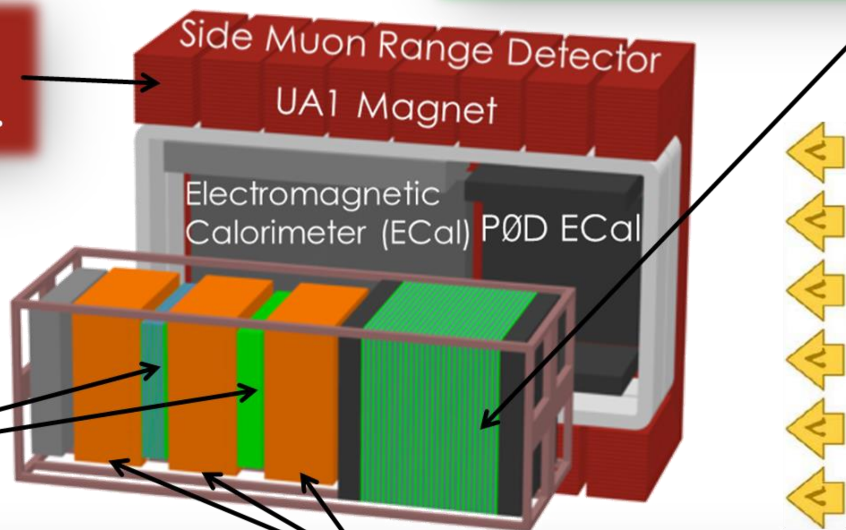
Phys. Rev. D 87, 012001

ND280 (off axis near detector)

Peak E_ν
On Axis ~ 1.1 GeV
Off Axis ~ 0.6 GeV

π^0 detector (PØD): Interwoven heavy targets, scintillator and drainable water bags affords water subtraction measurements.

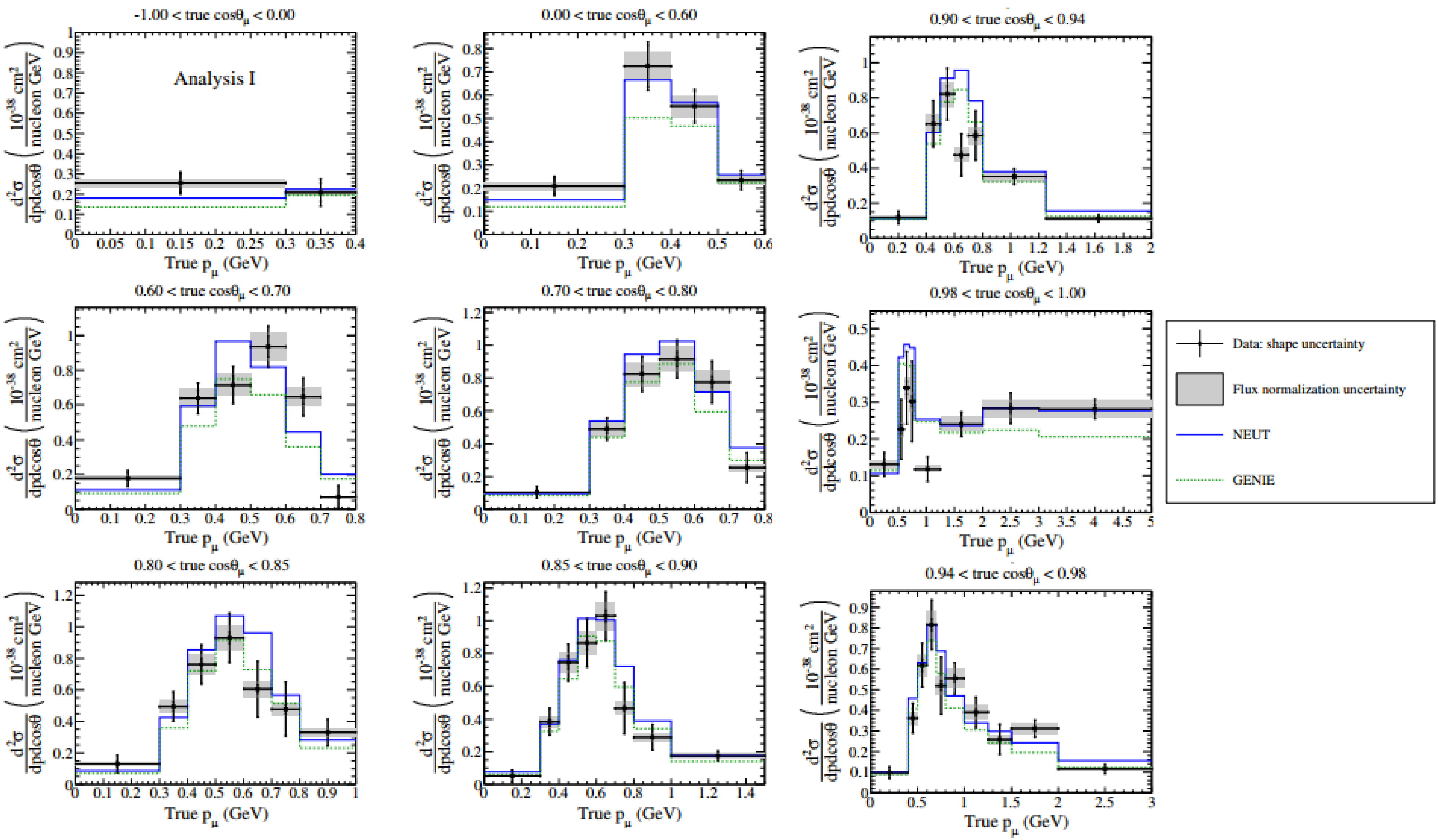
UA1 Magnet: Provides 0.2 T field.



Fine-Grained Detectors (FGD 1/2): Polycarbonate scintillator bars provide tracking & target mass. FGD 2 also contains water target layers.

Time Projection Chambers (TPC): Excellent tracking allows high-resolution charged-particle momenta and accurate particle ID.

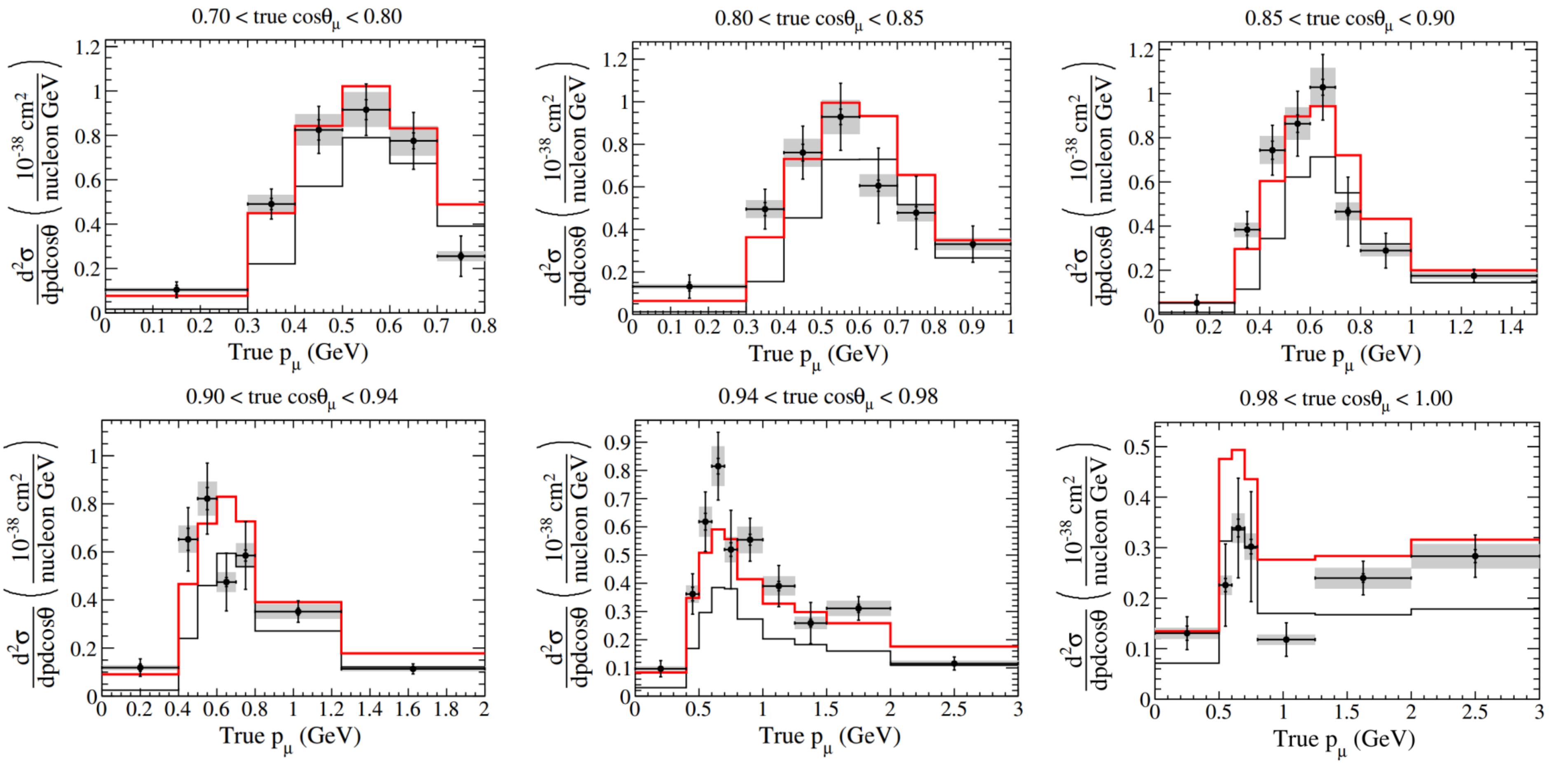
ND280 Off-Axis CC0π Result



Detector: ND280 – FGD1 **Target:** Carbon **Signal:** CC0π **Status:** Phys. Rev. D **93**, 112012

ND280 Off-Axis CC0π Result

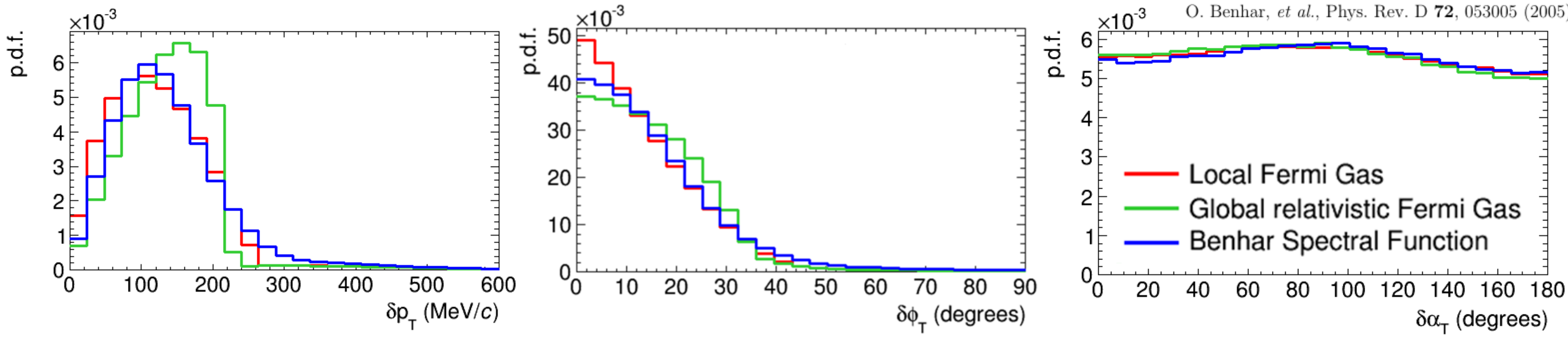
- Results compared to Martini *et al.* model **with(red)**/**without(black)** 2p2h
- Data prefer a 2p2h contribution



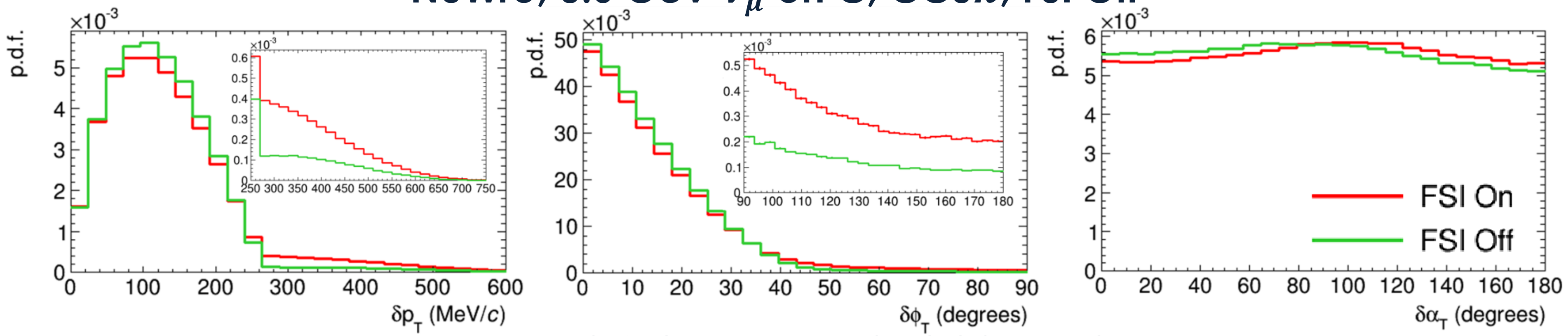
Detector: ND280 – FGD1	**Target:** Carbon	**Signal:** CC0π	**Status:** Phys. Rev. D **93**, 112012

CC0π in STV - Fermi Motion and FSI

- Moving from CCQE→CC0Pi+Np, STV still a probe of nuclear effects



NuWro, 0.6 GeV ν_μ on C, CC0π, FSI Off



NuWro, 0.6 GeV ν_μ on C, CC0π, LFG

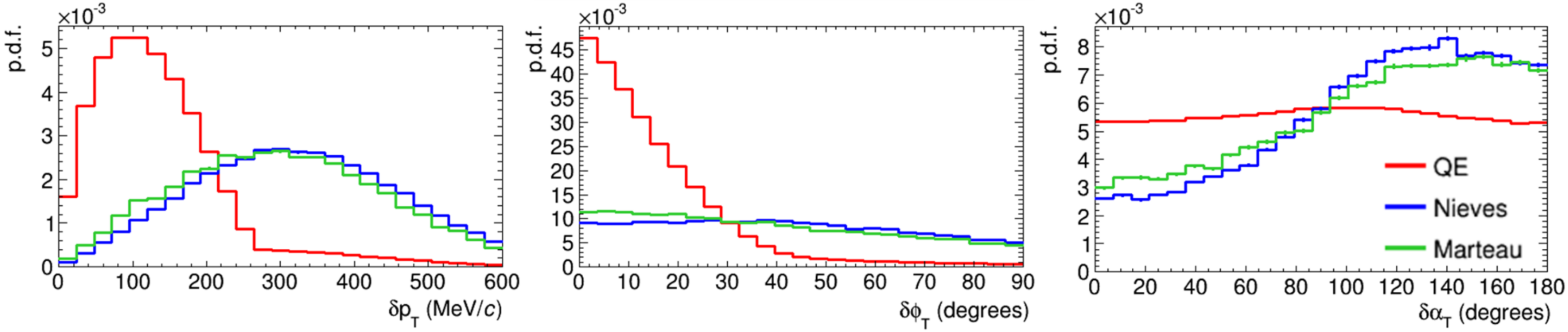
Quasi-real CC0Pi selection, keep events within rough ND280 acceptance :

No Pions, 1 Muon, >0 Protons. $p_\mu > 250\ MeV, p_p > 450\ MeV, \cos(\theta_\mu) > -0.6, \cos(\theta_p) > 0.4$

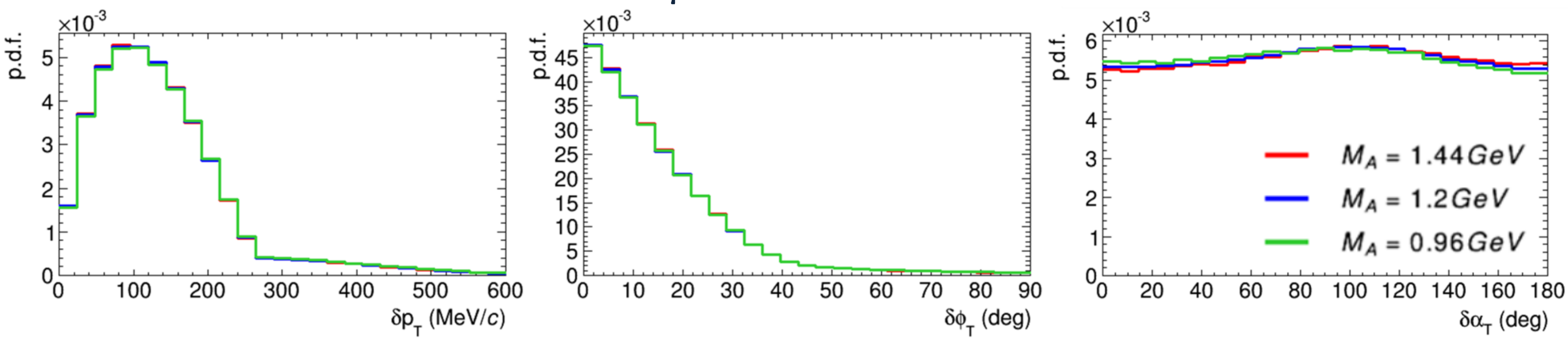
Detector: ND280 – FGD1 **Target:** Carbon **Signal:** CC0π+Np **Unfolding**: Fit **Status:** Blind

CC0π in STV - 2p2h and M_A

M. Martini, M. Ericson, G. Chanfray, and J. Marteau, Phys. Rev. C **80**, 065501 (2009) J. Nieves, I. R. Simo, and M. J. V. Vacas, Phys. Rev. C **83**, 045501 (2011)



NuWro, 0.6 GeV ν_μ on C, CC0π, FSI On, LFG

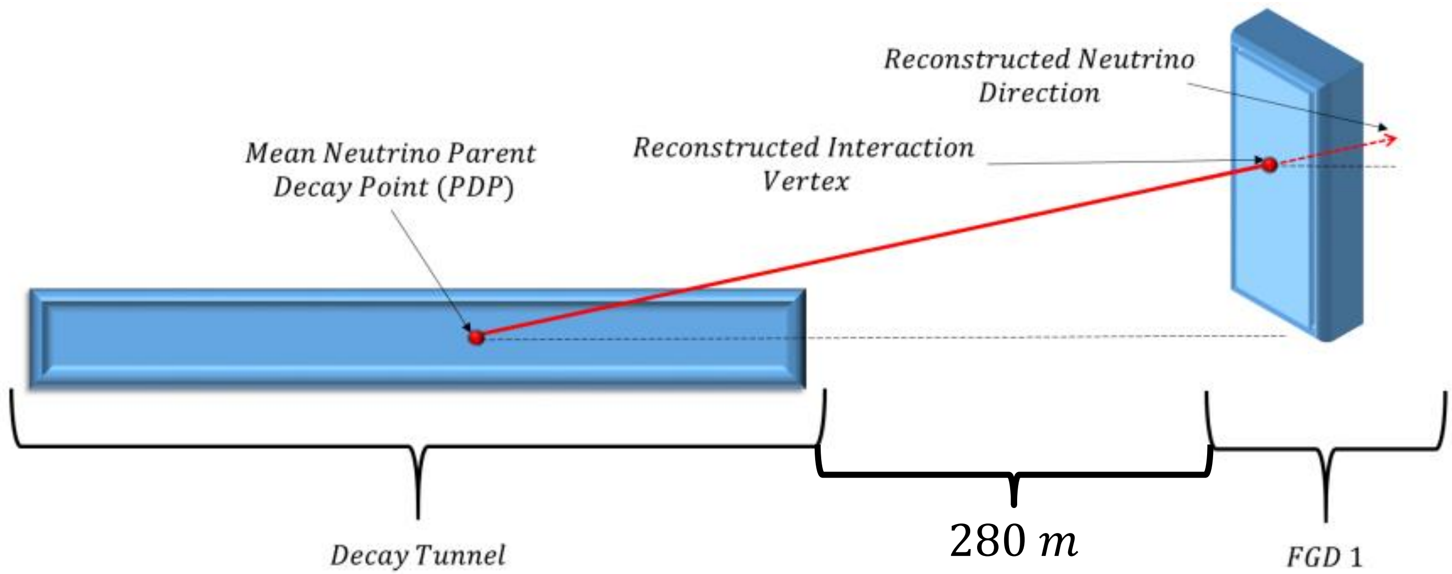


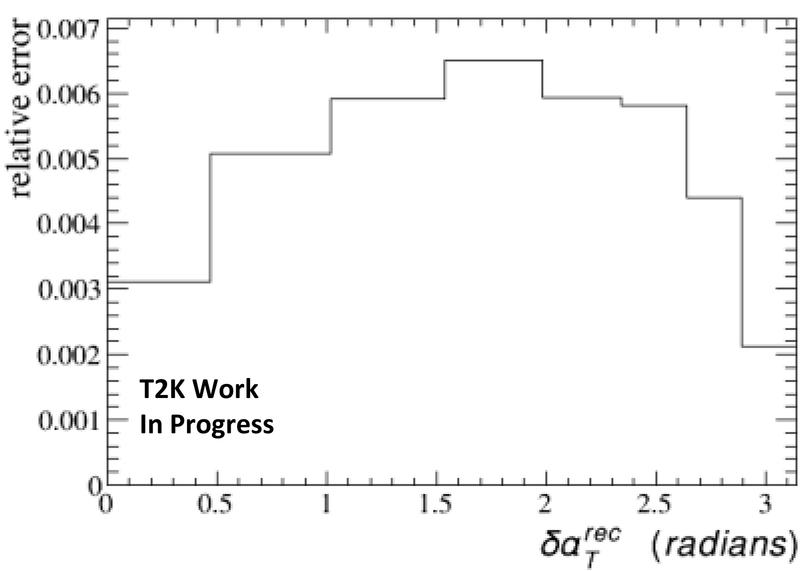
NuWro, 0.6 GeV ν_μ on C, CC0π, FSI On, LFG

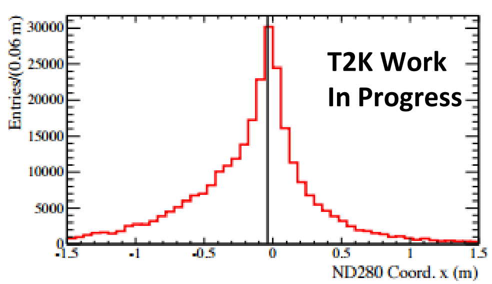
- STV shape invariant with M_A
  - No ambiguity over M_A or nuclear effect contributions (MiniBooNE M_A puzzle)

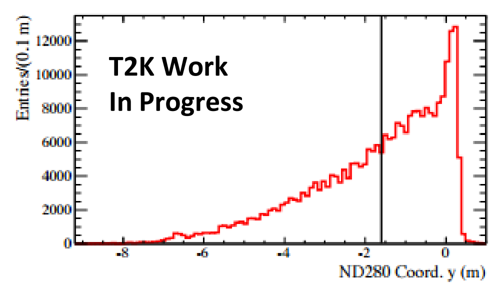
Detector: ND280 – FGD1	**Target:** Carbon	**Signal:** CC0π+Np	**Unfolding**: Fit	**Status:** Blind

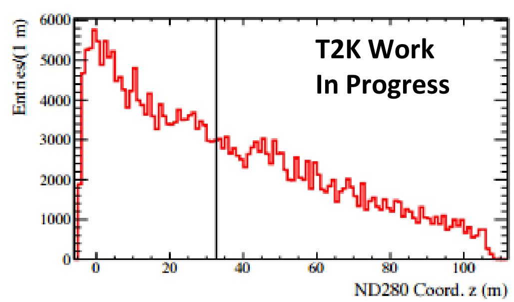
Reconstructing the Neutrino Direction







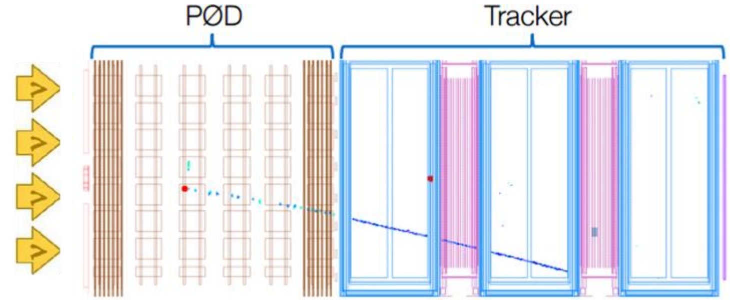


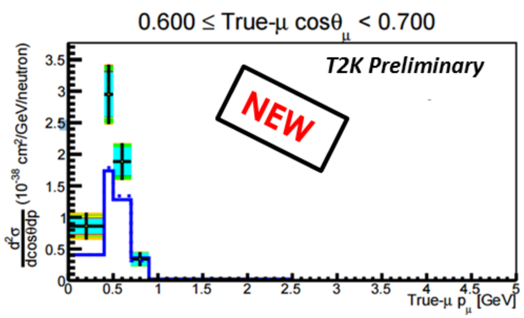


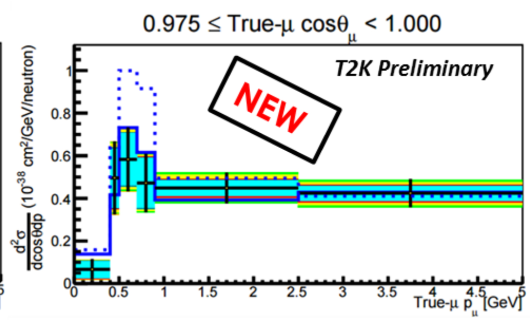
CC0π water cross section

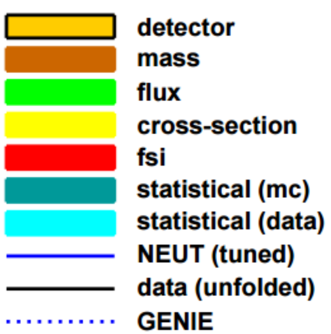
Contact:
Tianlu Yuan
tianlu.yuan@colorado.edu

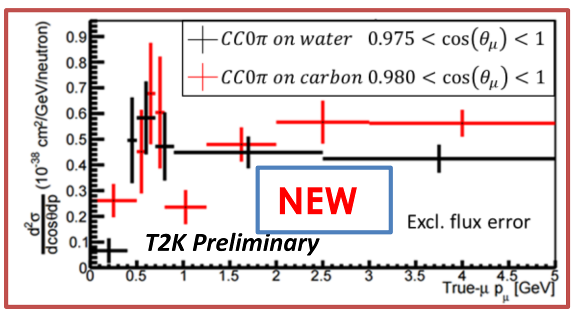
- Isolate CC0π events starting in the PØD, but use TPC for tracking
- Separate data taking periods into when PØD water target is full/empty
  - Subtract to get water cross section











- Construct **CC0π** flux integrated double-differential cross section in $p_\mu, \cos(\theta_\mu)$
  - Compare MC predictions
- Compare to FGD1 CC0π on Carbon result
- Similar studies underway using FGD2 water layers to extract Oxygen:Carbon cross section ratio

Detector: ND280 – PØD **Target:** Water **Signal:** CC0π **Status:** New