To CCQE and Beyond

The latest charged-current pionless cross-section measurements from T2K

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For the T2K Collaboration

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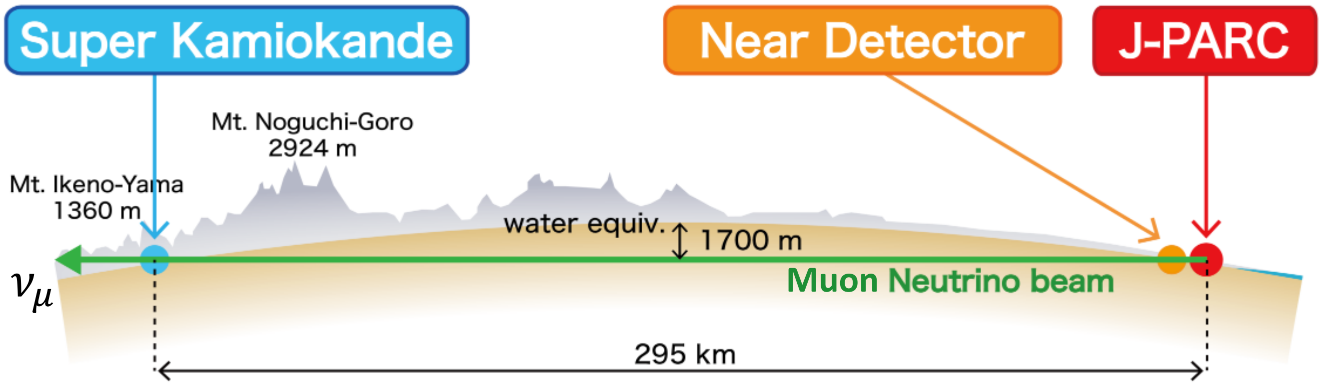
T2K

UNIVERSITY OF OXFORD

Overview

- T2K and ND280
- CC0π cross-section results at T2K
- Cross sections using proton information
  - CC0π using proton kinematics
  - CC0π using transverse kinematic imbalance
- Future work and Summary

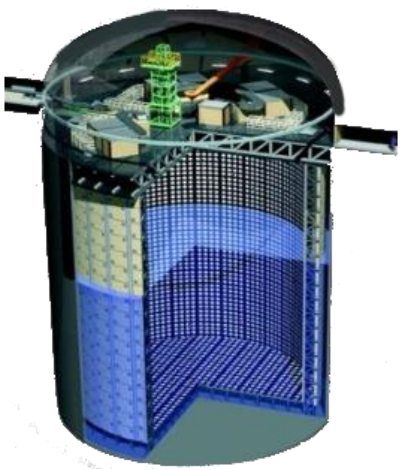
The T2K Experiment



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

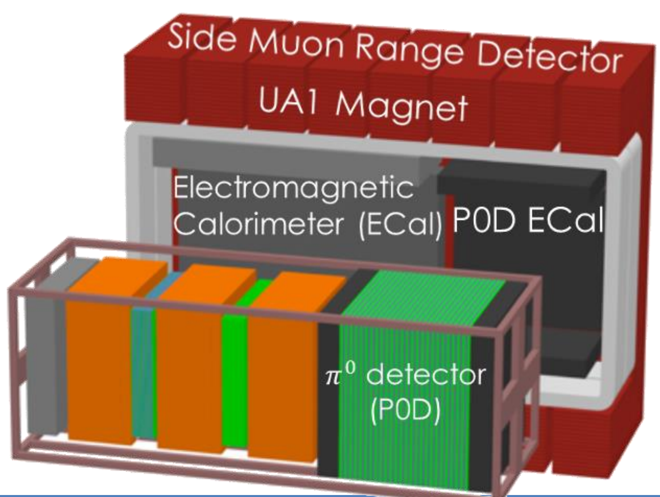
Far Detector (Off-Axis)

Super-Kamiokande

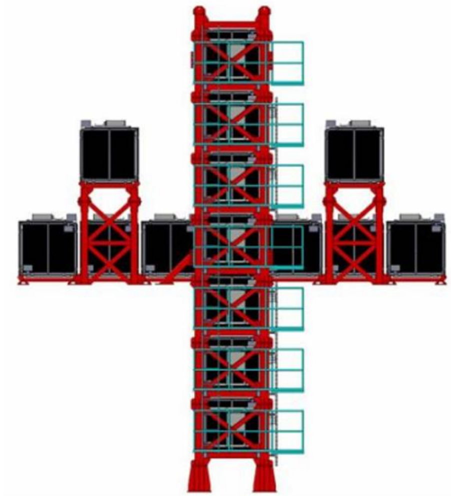


Near Detectors

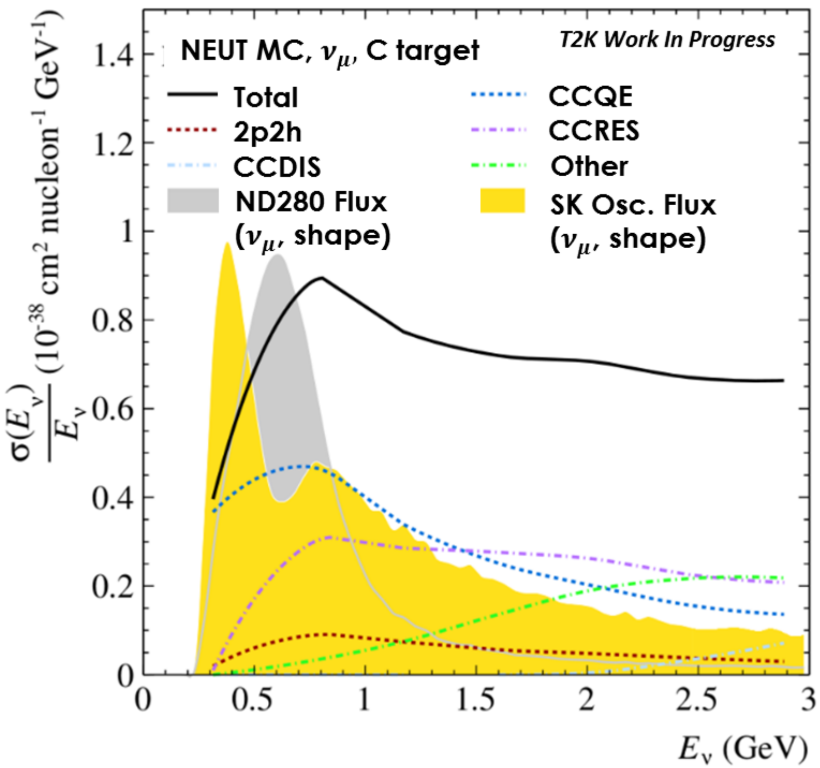
Off-Axis: ND280



On-Axis: INGRID

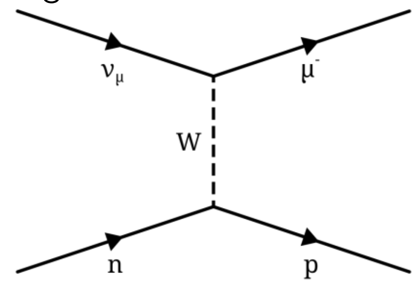


Neutrino Interactions at T2K



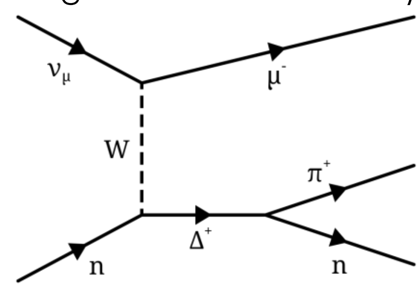
CCQE

(Charged-Current Quasi-Elastic)



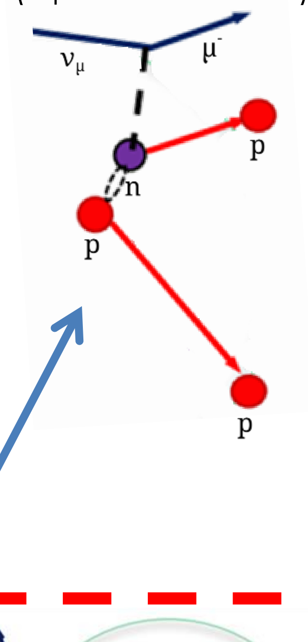
CCRES

(Charged-Current Resonant)

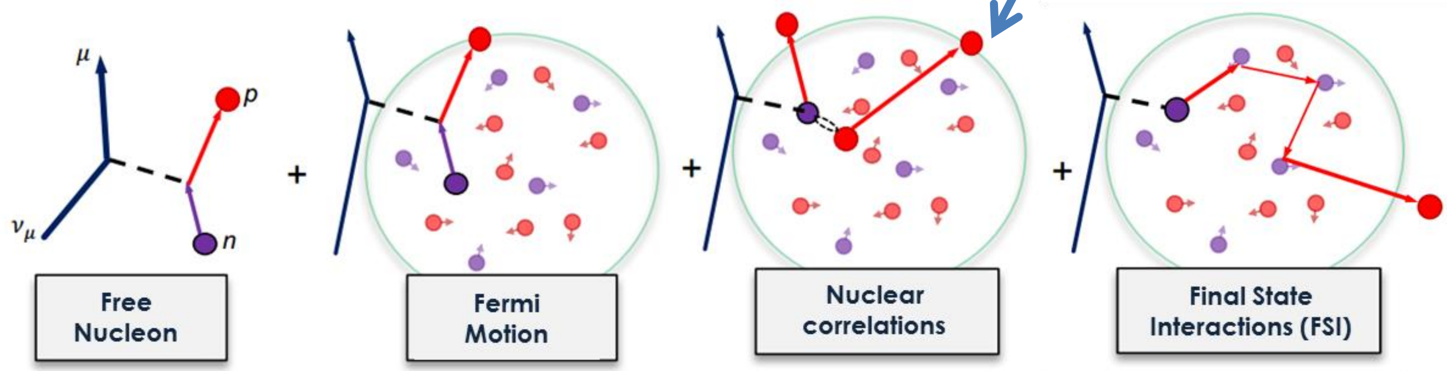


2p2h

(2 particle – 2 hole)

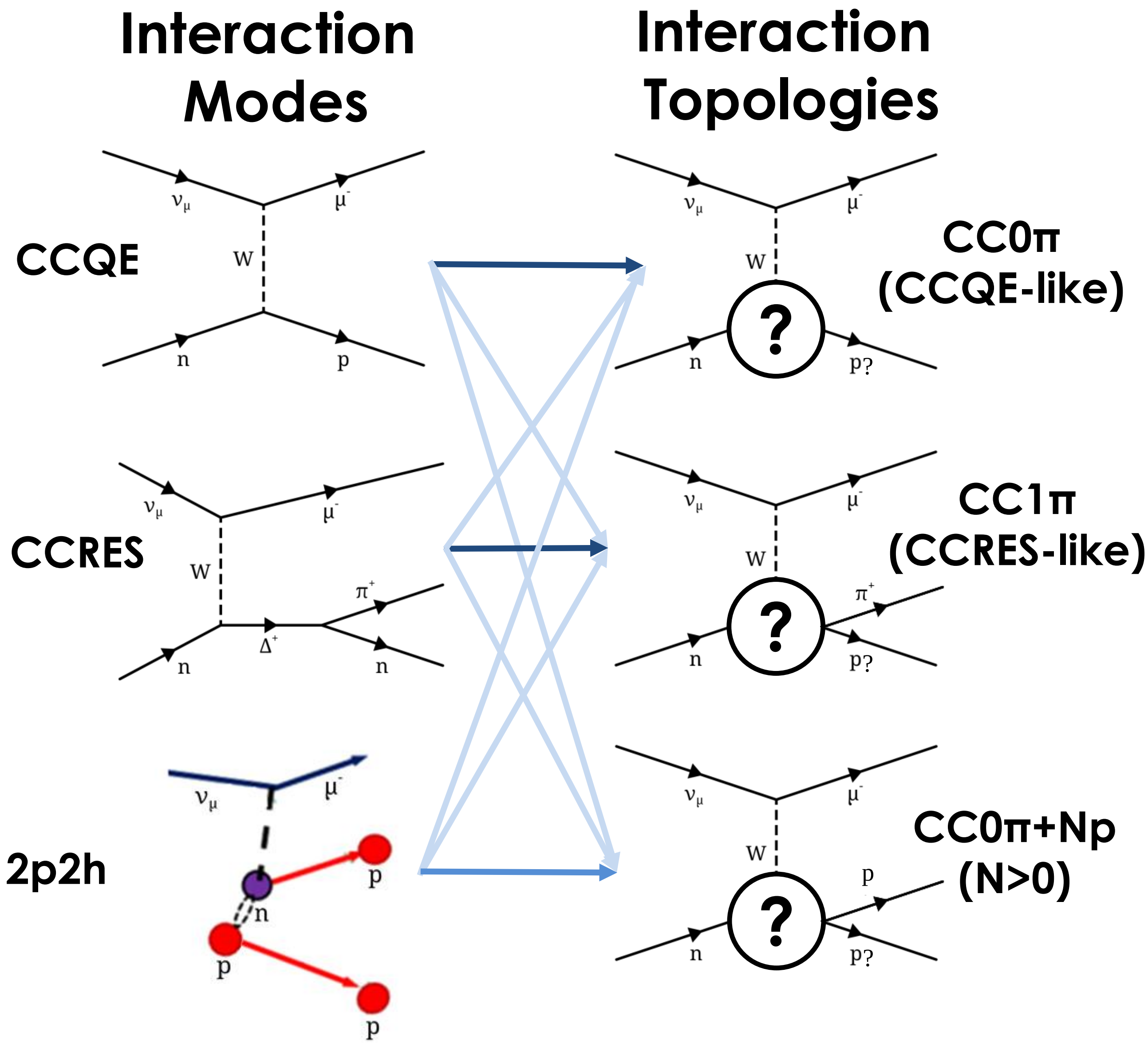


Nuclear Effects

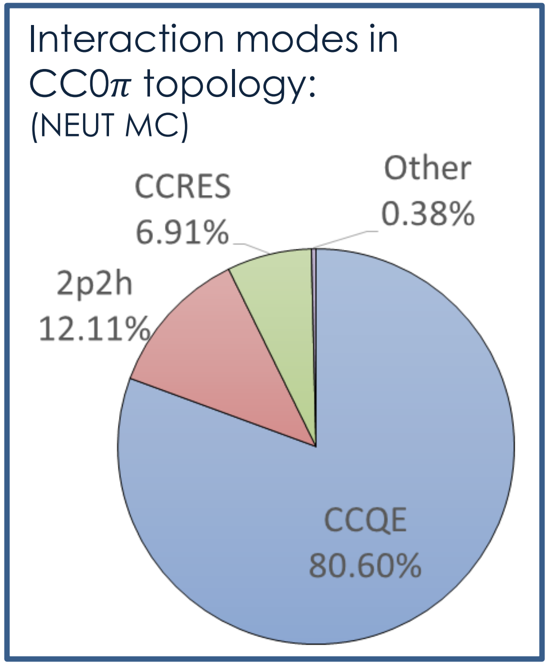


Diagrams by Patrick Stowell

What can we measure



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



ND280 (off axis)

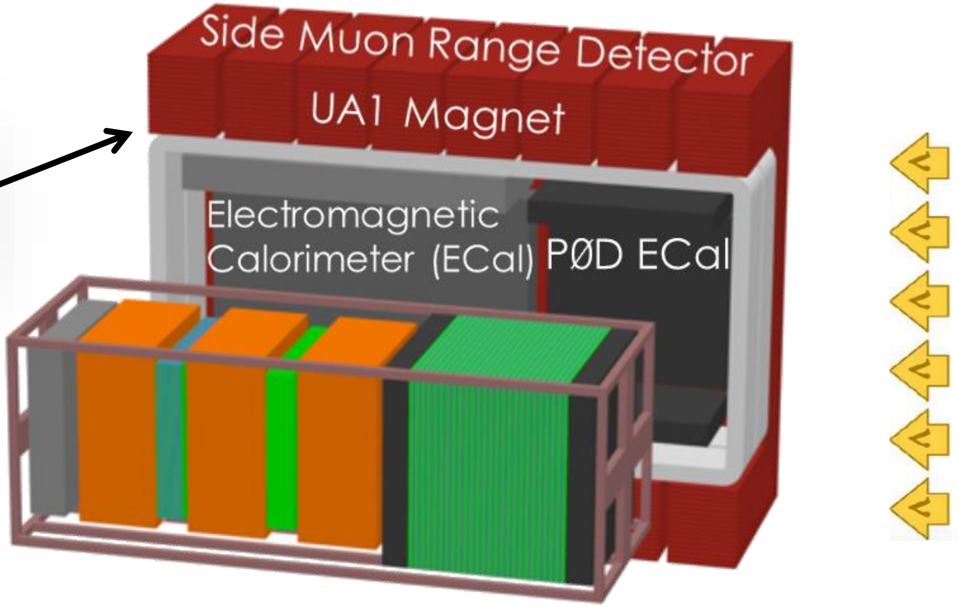
Peak E_ν

On Axis ~ 1.1 GeV

Off Axis ~ 0.6 GeV

Former UA1 Magnet:

- Provides 0.2 T field



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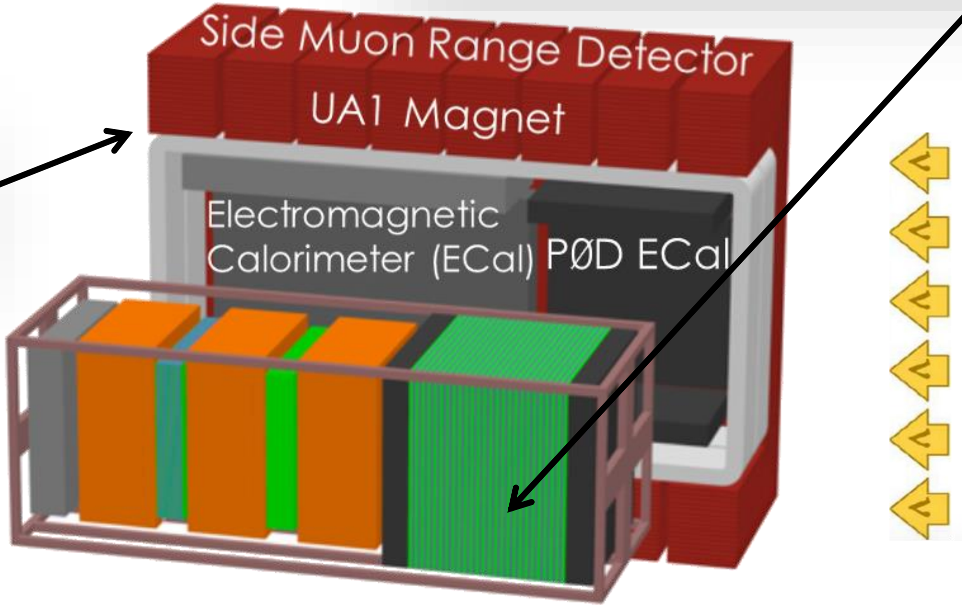
π^0 detector (PØD):

- CH scintillator tracker
- Target for ν
- Interwoven heavy targets + drainable water bags



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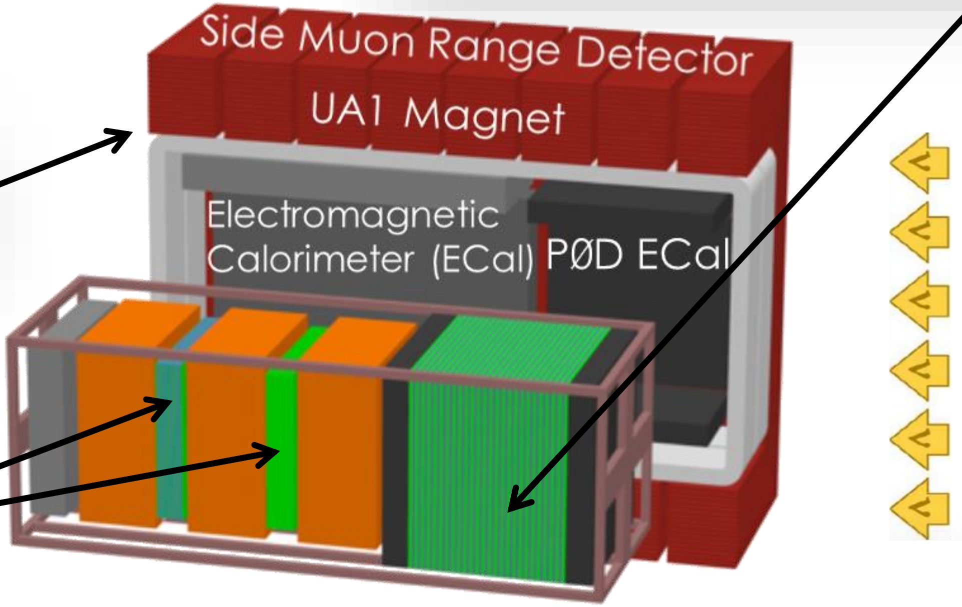

Fine-Grained Detectors (FGD 1/2):

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

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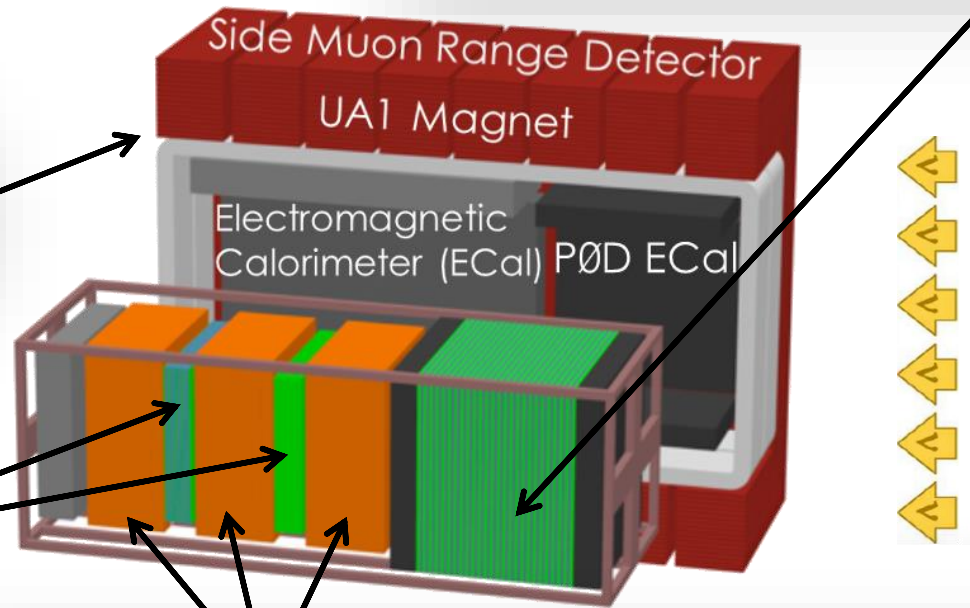


Fine-Grained Detectors (FGD 1/2):

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

Time Projection Chambers (TPC):

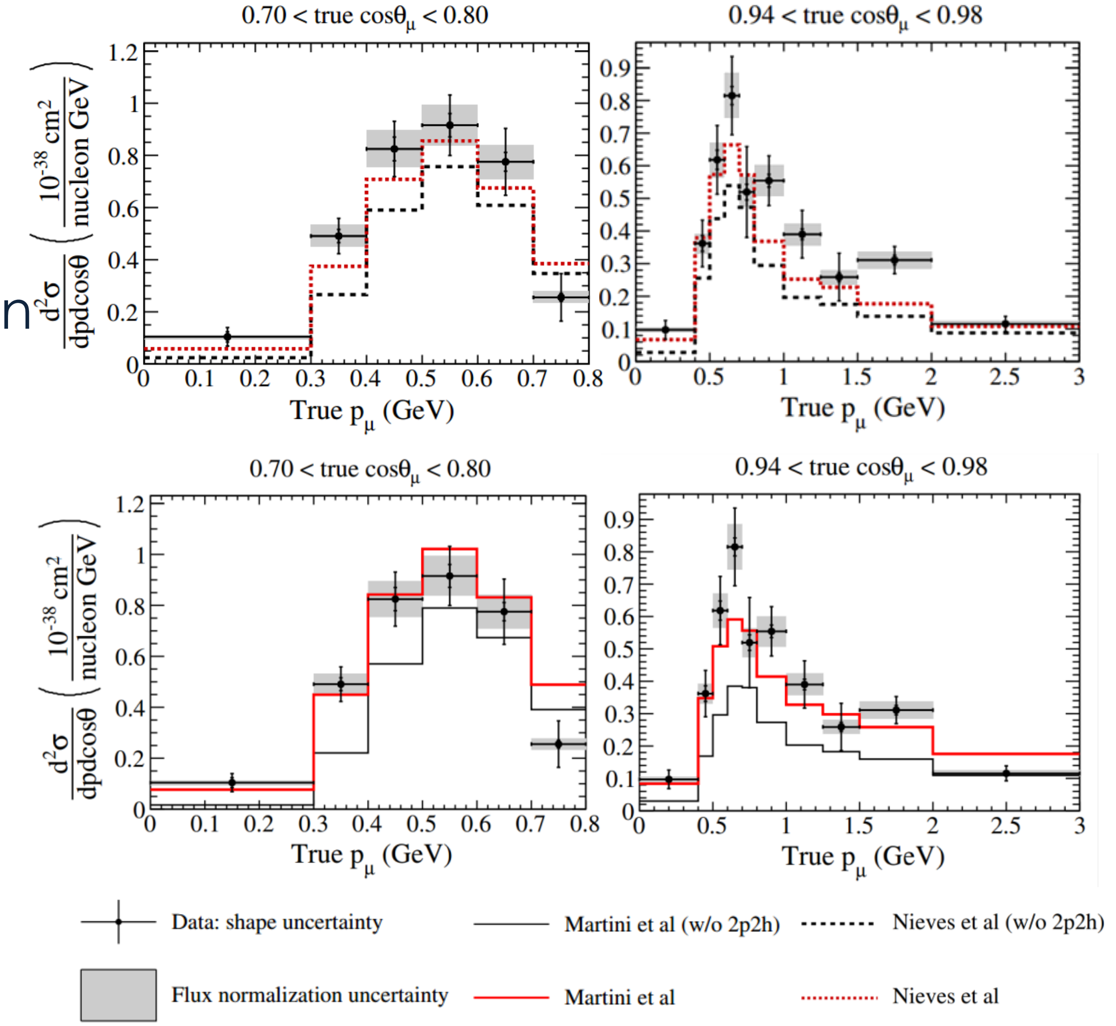
- High-res tracking
- Precise particle ID
- Accurate charged-particle momenta

Previously at T2K ...

- T2K and ND280
- CC0π cross-section results at T2K
- Cross sections using proton information
  - CC0π using proton kinematics
  - CC0π using transverse kinematic imbalance
- Future work and Summary

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 the Nieves and Martini models **with**/**without** 2p2h

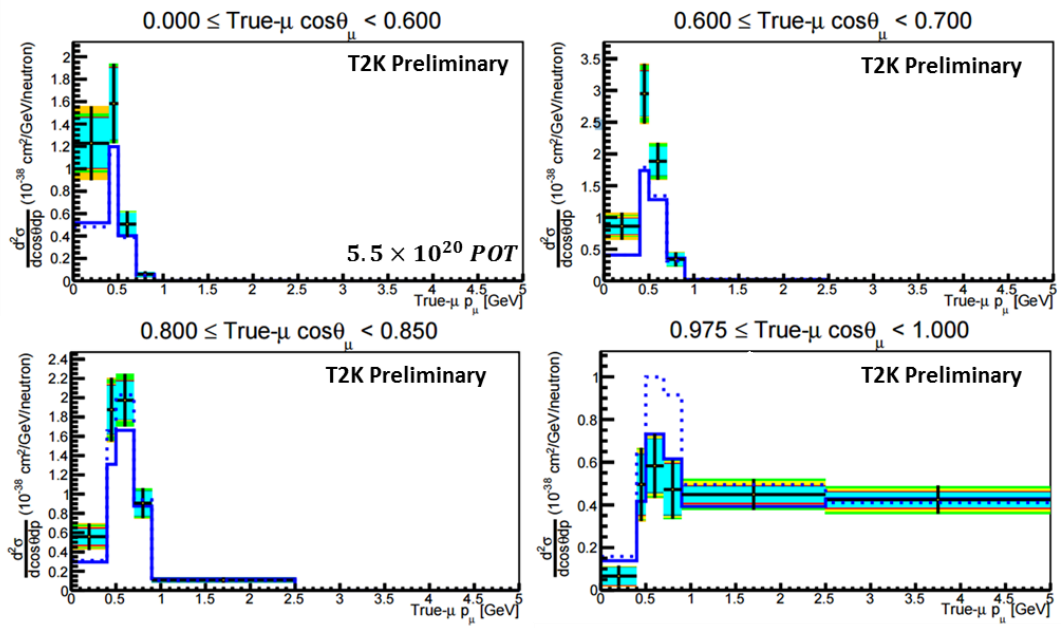


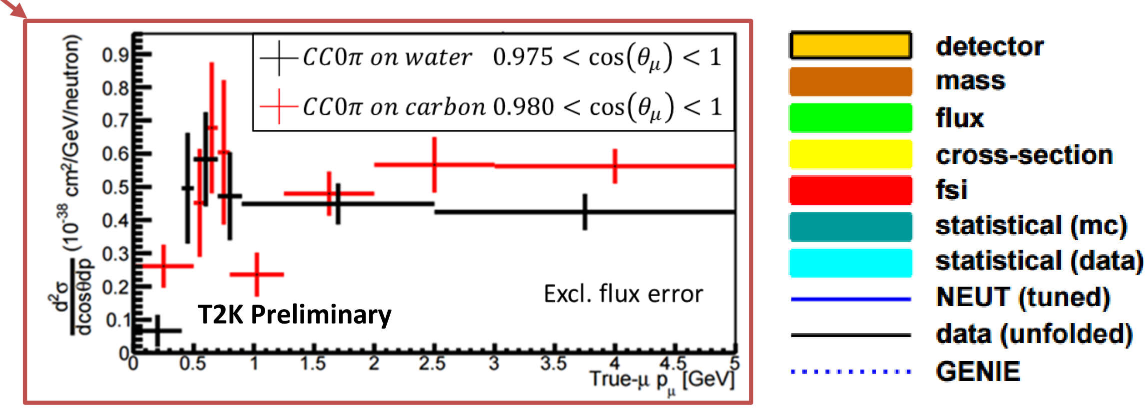
M. Martini, M. Ericson, G. Chanfray, and J. Marteau, Phys. Rev. C **80**, 065501 (2009)
M. Martini, M. Ericson, G. Chanfray, and J. Marteau, Phys. Rev. C **81**, 045502 (2010)
J. Nieves, I. R. Simo, and M. V. Vacas, Phys. Lett. B **707**, 72 (2012).
J. Nieves, F. Sanchez, I. Ruiz Simo, and M. Vicente Vacas, Phys. Rev. D **85**, 113008 (2012)

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

ND280 Off-Axis CC0π Result

- Uses PØD as a water target alongside TPC for tracking
- **Flux-integrated** double-differential **CC0π** cross section in final-state muon kinematic variables (p_μ, $\cos(\theta_\mu)$)
- Can also compare to FGD1 CC0π on Carbon result
- Similar studies underway using FGD2 water layers to extract Oxygen:Carbon cross-section ratio
- More details in these proceedings: ICHEP16, NuFact16

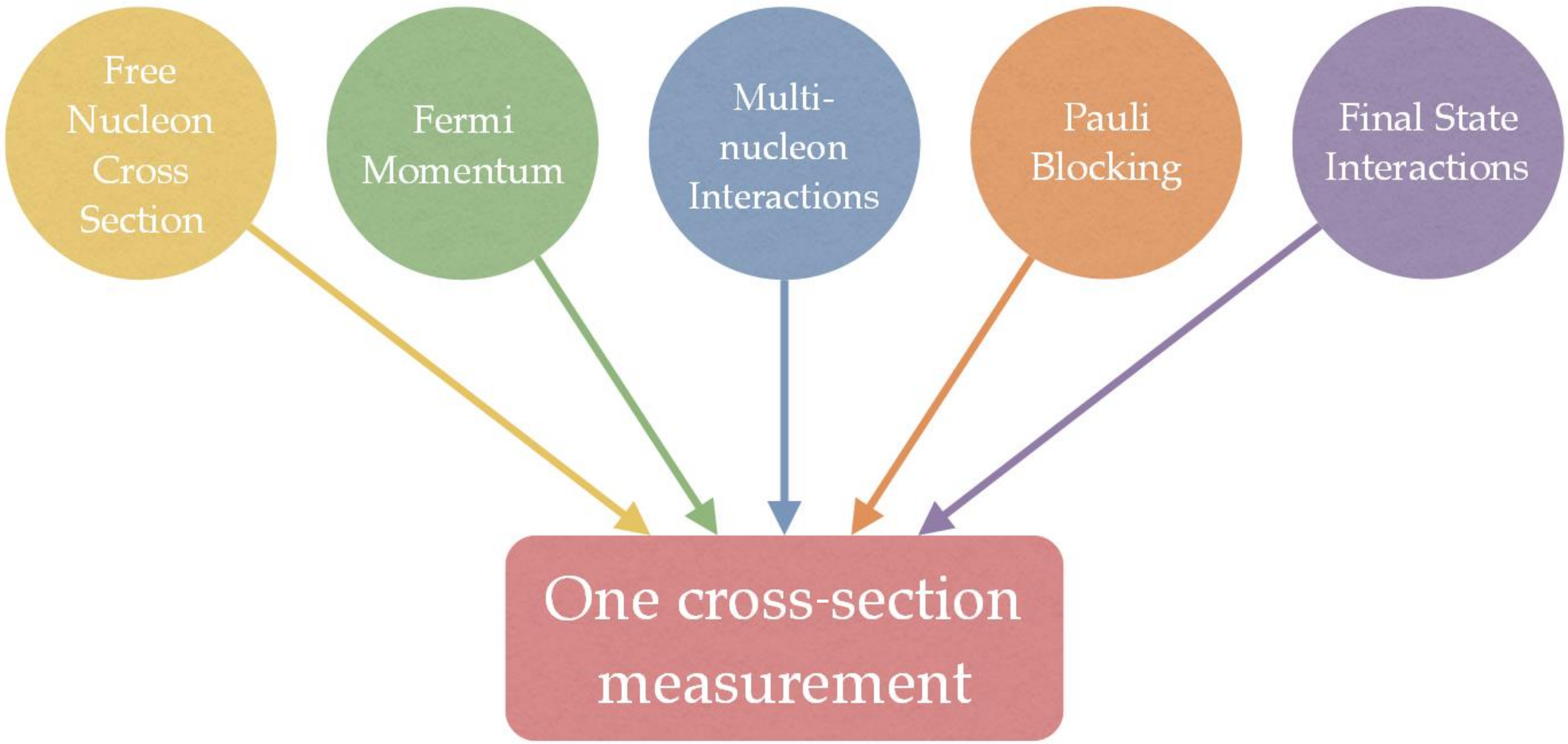




Detector: ND280 – PØD **Target:** Water **Signal:** CC0π **Variables:** μ-kinematics **Status:** Paper in preparation

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

- T2K and ND280
- CC0π cross-section results at T2K
- Cross sections using proton information
  - CC0π using proton kinematics
  - CC0π using transverse kinematic imbalance
- Future work and Summary

Measuring proton kinematics

- μ-kinematics only tell us everything about $\nu + N$ scattering assuming a **stationary target** and an **elastic scatter**

- Proton kinematics allows a new handle on nuclear effects

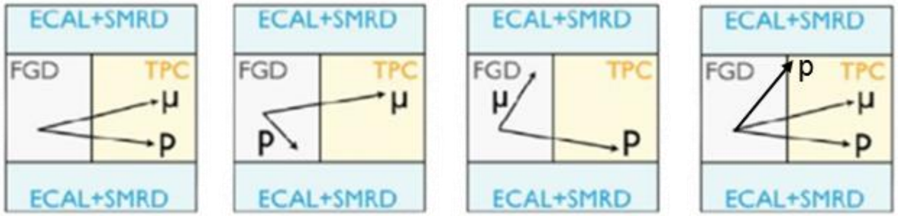
- Simulations have weak predictive power to describe proton kinematics
  - Nuclear effects are very difficult to model
  - First time looking at proton predictions for T2K
  - ➢ **Essential to ensure minimal dependence on simulation**

- Measure fiducial cross section
- Minimise role of MC in unfolding

See slides from State of The Nu-tion

Event Selection

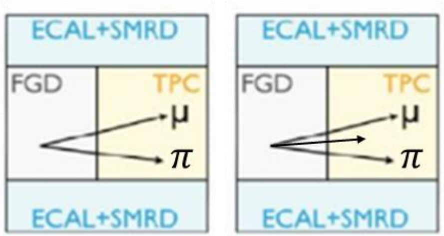
Signal



- Require one μ-like and p-like track(s) starting in FGD1 (CH target)
- Use a Michel electron tag and ECal EM shower veto to reject 1π backgrounds
- Use of many samples gives wide kinematic acceptance

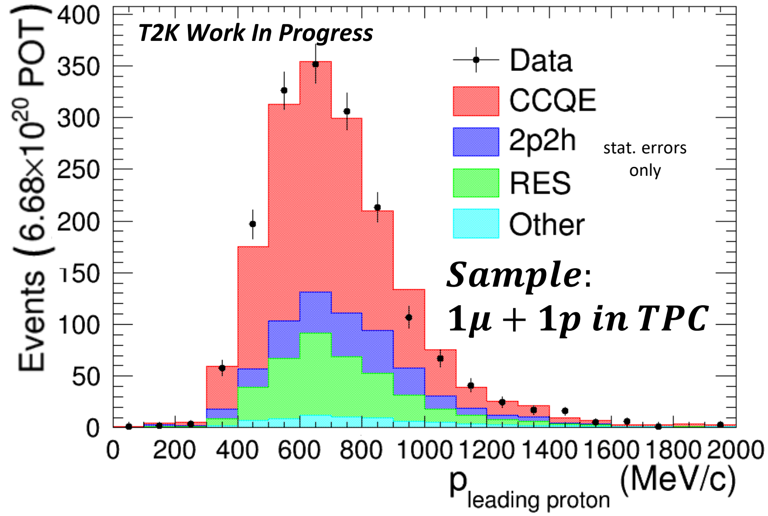
Sidebands

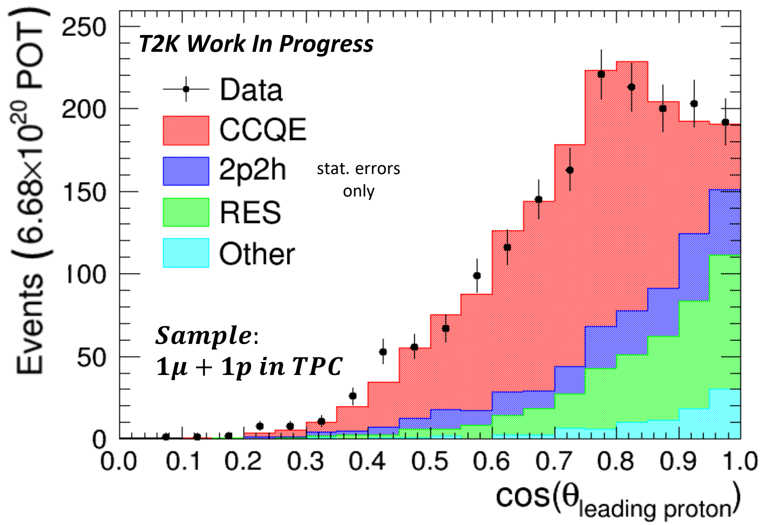
- Require extra π-like track(s)



CC1π CCOther

Reconstructed kinematics

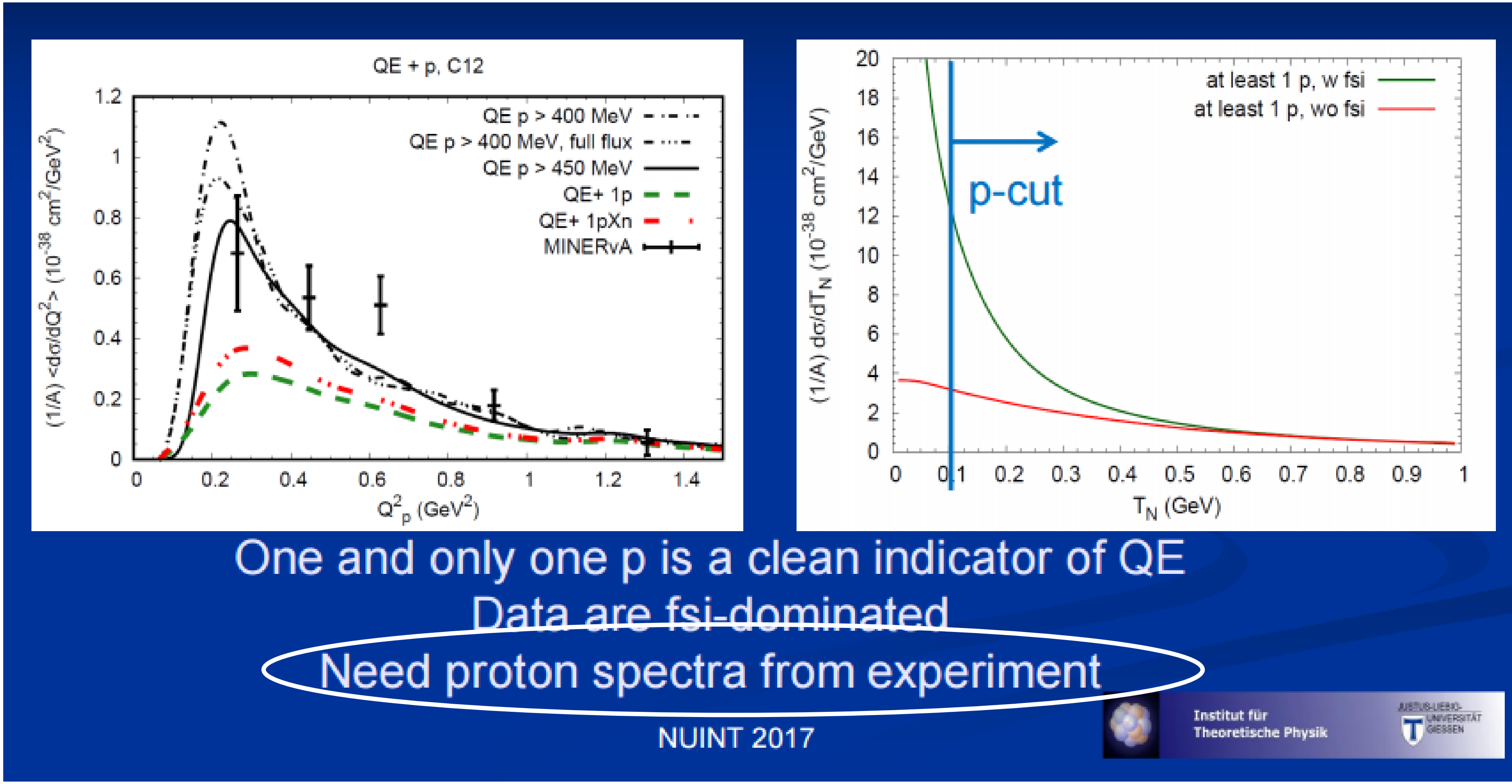




NEUT 5.3.3.2; Benhar SF; $M_A = 1.21$;
Nieves et al. 2p2h; Area normalised to data

O. Benhar, *et al.*, Phys. Rev. D **72**, 053005 (2005)
J. Nieves, I. R. Simo, and M. J. V. Vacas, Phys. Rev. C **83**, 045501 (2011)

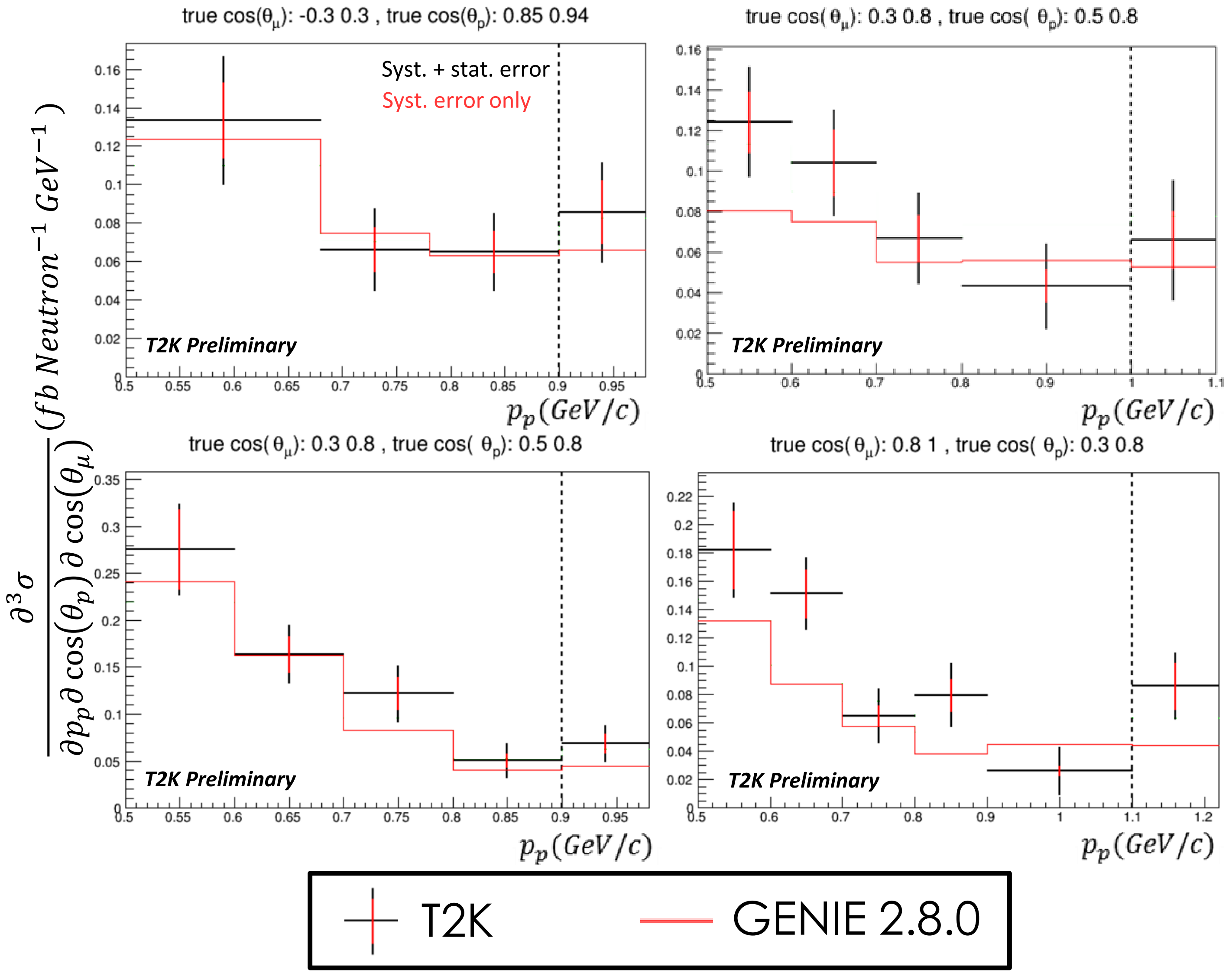
A request from yesterdays GiBUU talk



CC0π using $\mu + p$ kinematics

Measure fiducial flux-integrated **CC0π + Np** cross section in bins of $\cos(\theta_\mu), \cos(\theta_p), p_p$

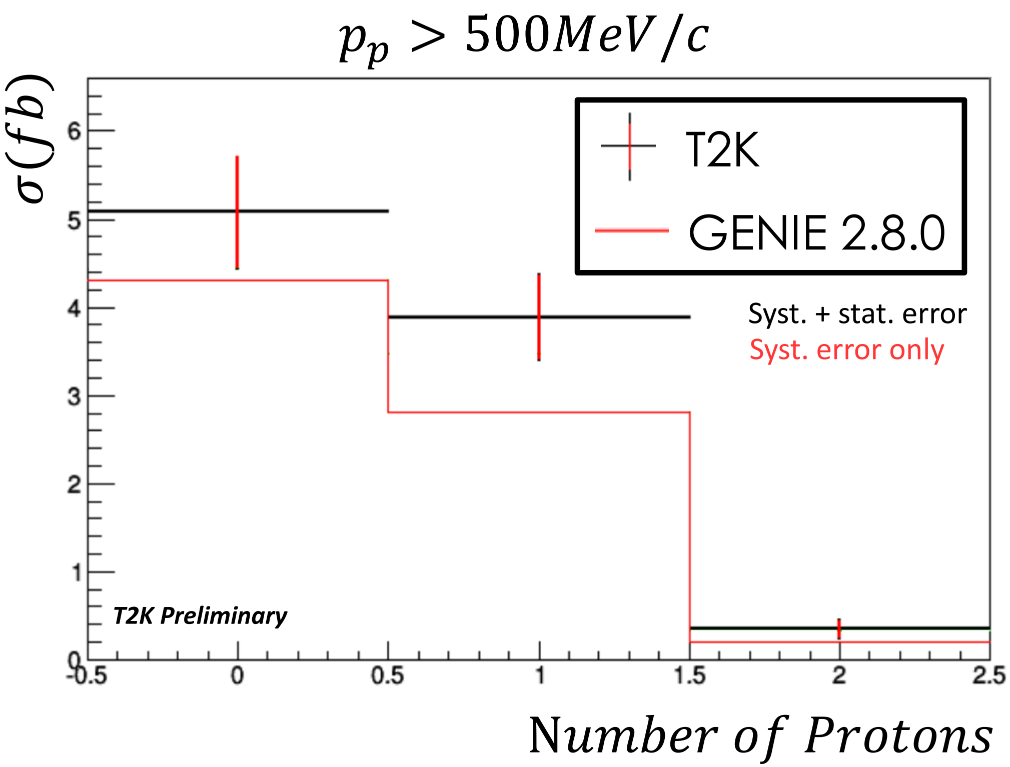
Subset of bins shown – full binning covers all kinematic phase-space with $p_p > 500\ MeV/c$



Detector: ND280 – FGD1 **Target:** CH **Signal:** CC0π+Np **Variables:** $\mu + p$ kinematics **Status:** Paper in preparation

CC0π using $\mu + p$ kinematics

- Cross-section extraction method also allows simultaneous extraction of number of protons with $p_p > 500\ MeV/c$
- Observe interesting excess over GENIE prediction (which has no 2p2h contribution)



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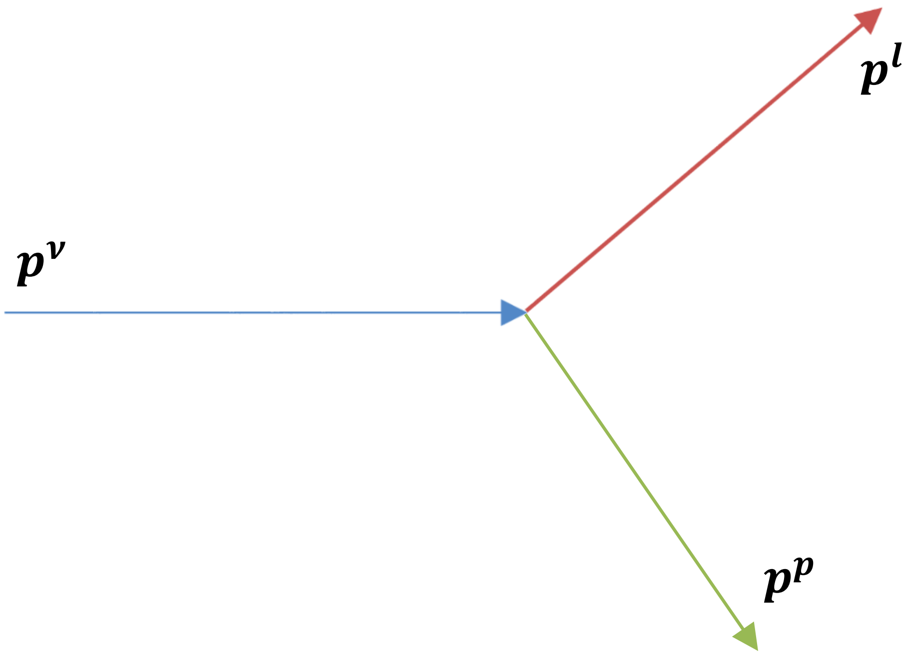
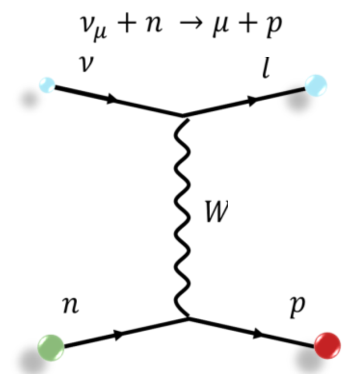
Single Transverse Variables

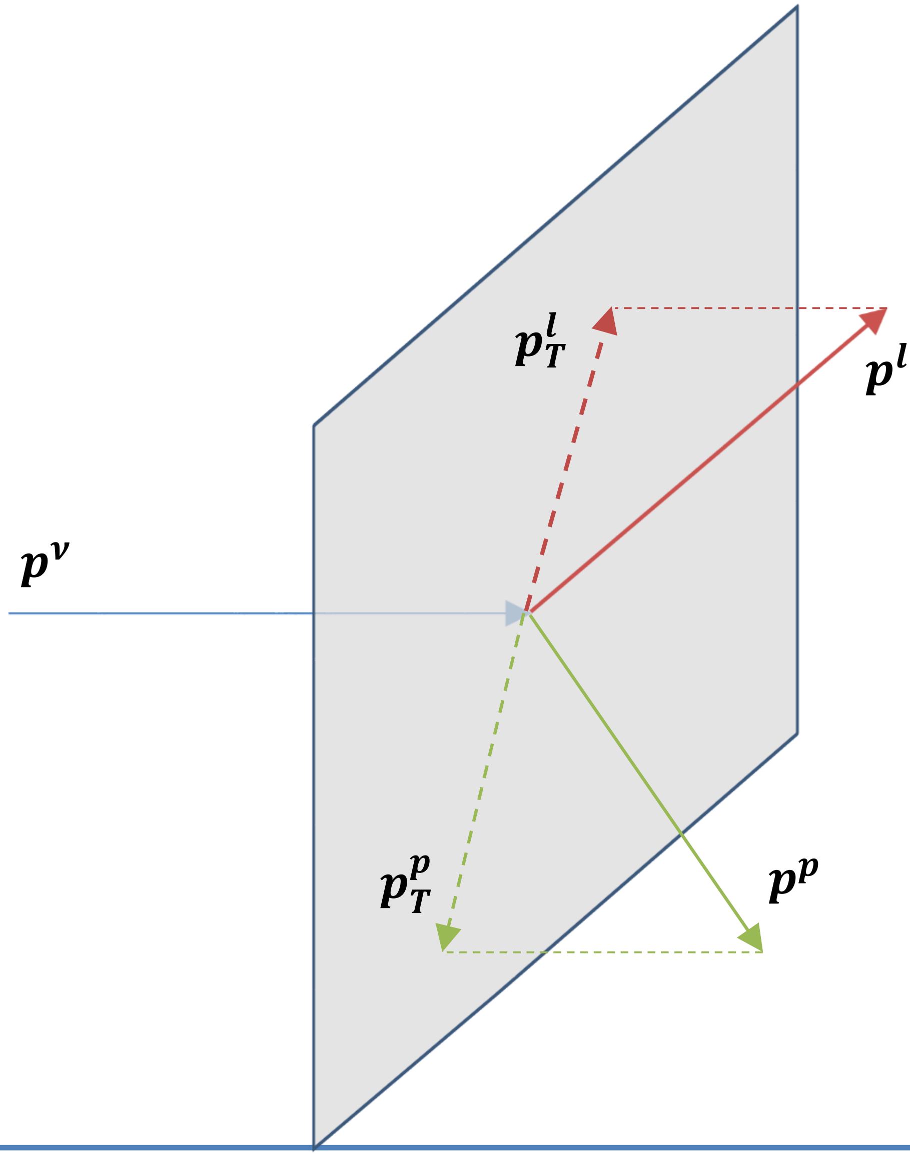


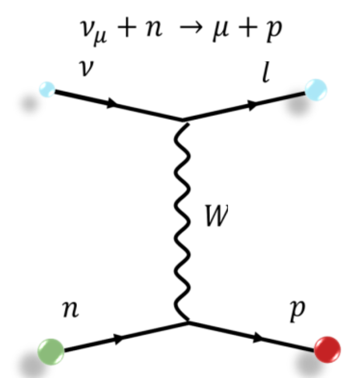


No nuclear Effects

Detector: ND280 – FGD1 **Target:** CH **Signal:** CC0π+Np **Variables:** single-transverse **Status:** Paper in preparation

Single Transverse Variables



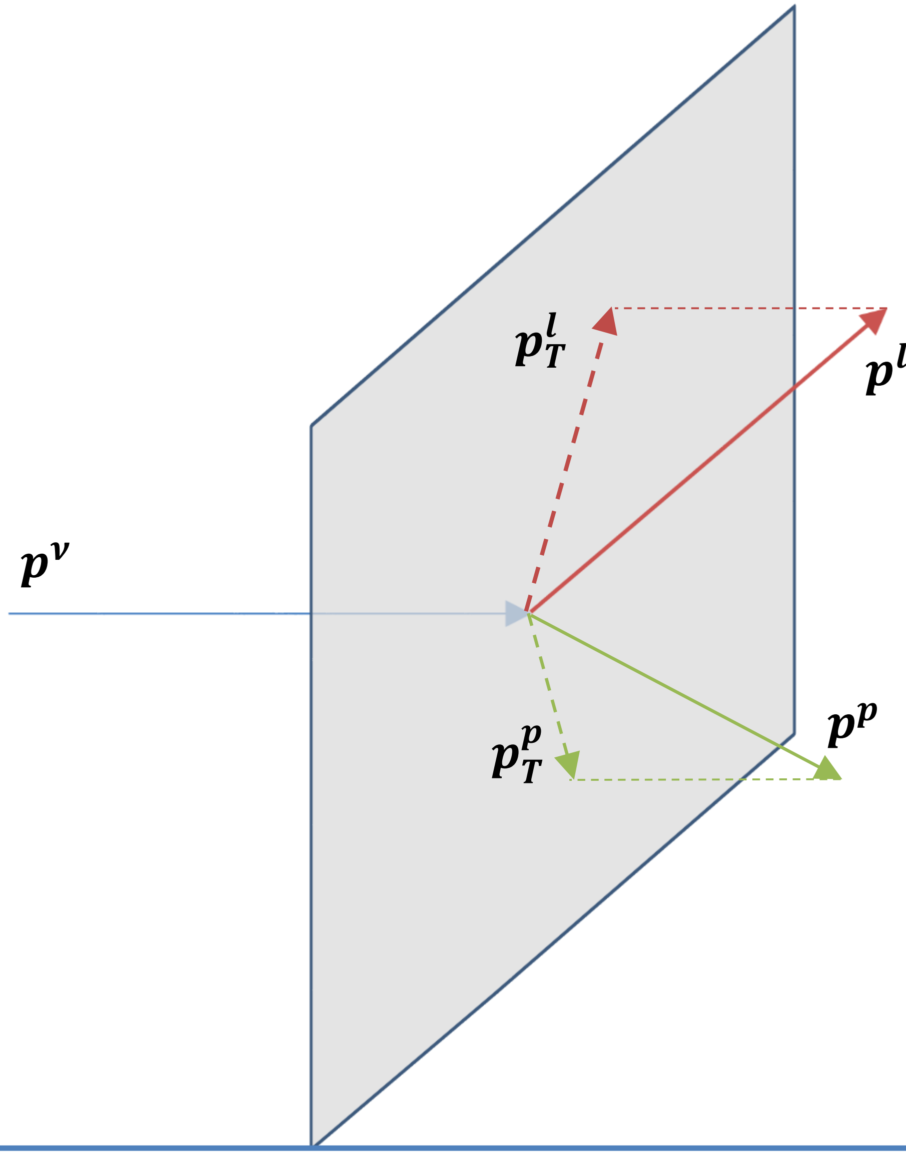


No nuclear Effects

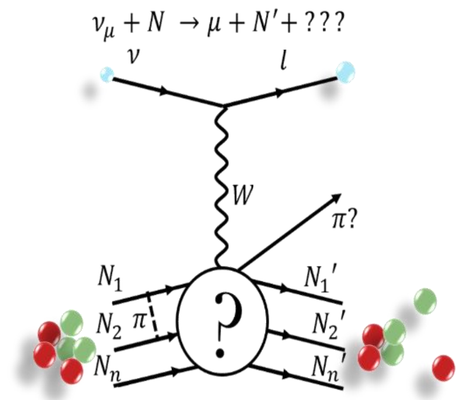
$$p^l_T = -p^p_T$$

Detector: ND280 – FGD1 **Target:** CH **Signal:** CC0π+Np **Variables:** single-transverse **Status:** Paper in preparation

Single Transverse Variables



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

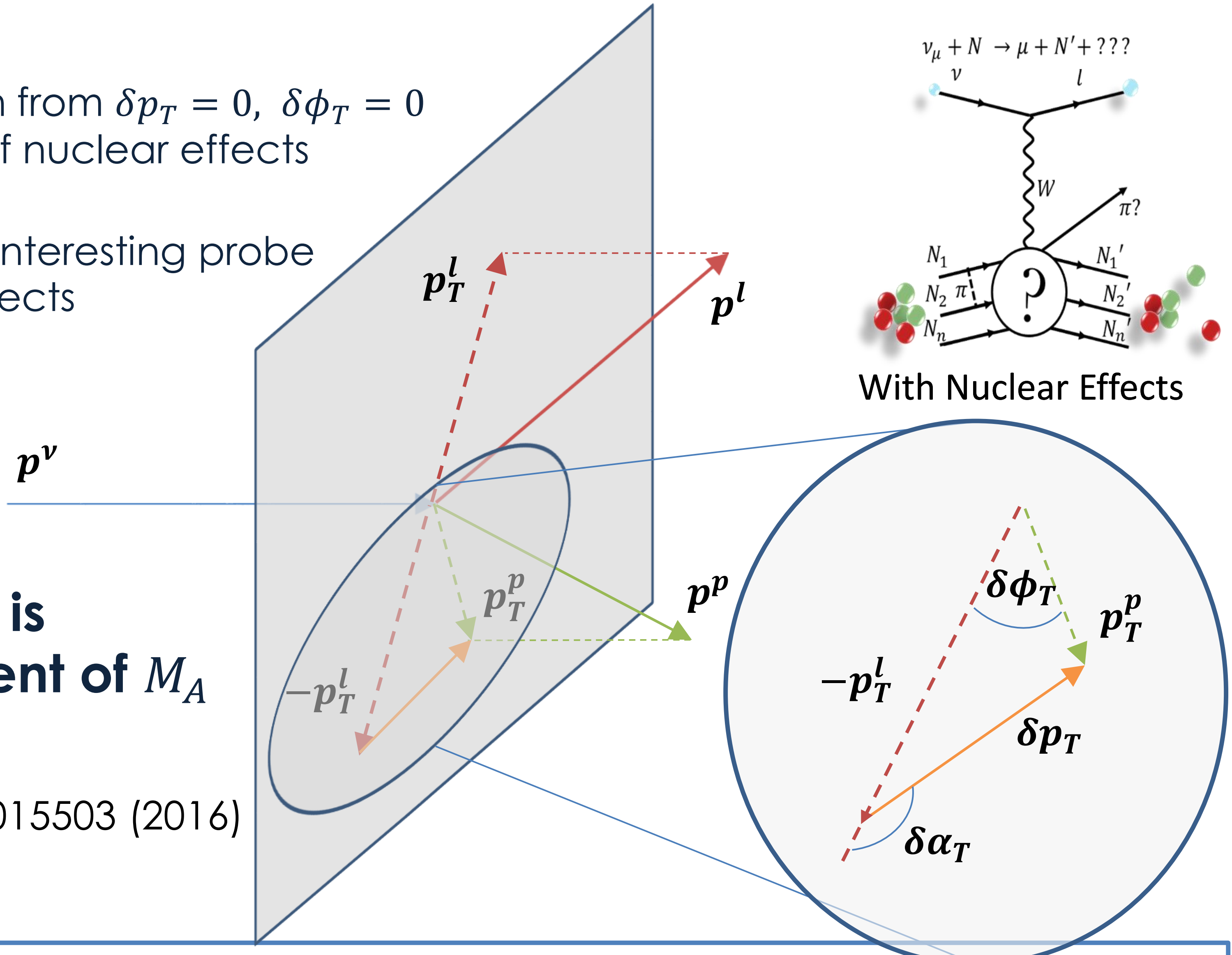


With Nuclear Effects

Detector: ND280 – FGD1 **Target:** CH **Signal:** CC0π+Np **Variables:** single-transverse **Status:** Paper in preparation

Single Transverse Variables

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



- **STV shape is independent of M_A**

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

Detector: ND280 – FGD1 **Target:** CH **Signal:** CC0π+Np **Variables:** single-transverse **Status:** Paper in preparation

CC0π+Np in STV

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

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

- Extract cross section using a binned likelihood fit with a **data driven** regularisation
- Compare results to predictions available from plethora of generators using NUISANCE

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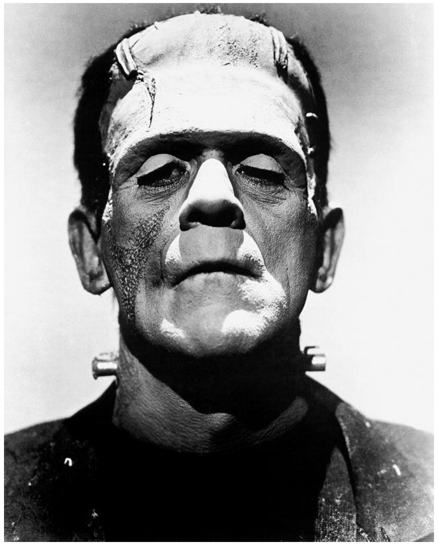
- Extract cross section using a binned likelihood fit with a **data driven** regularisation
- Compare results to predictions available from plethora of generators using NUISANCE
- Prepare for some franken-models!



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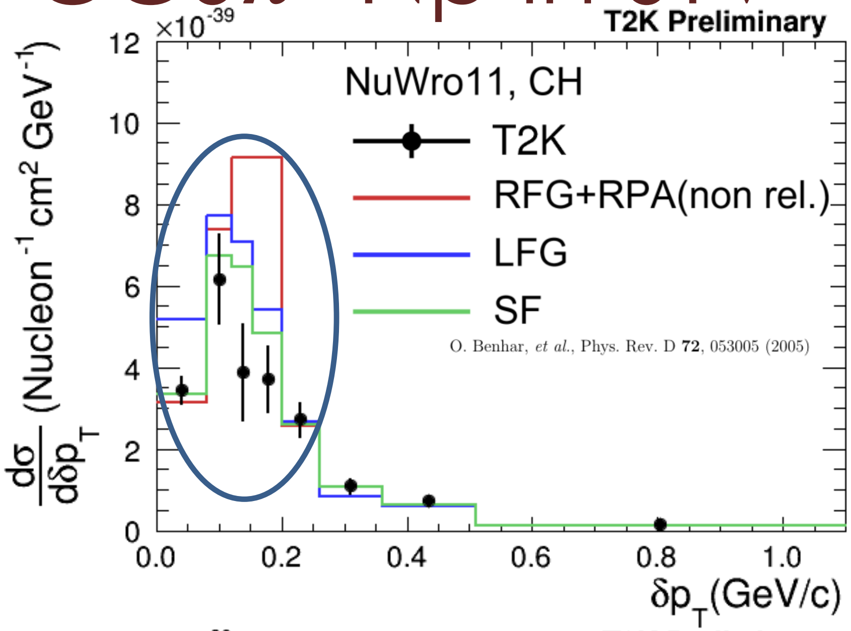
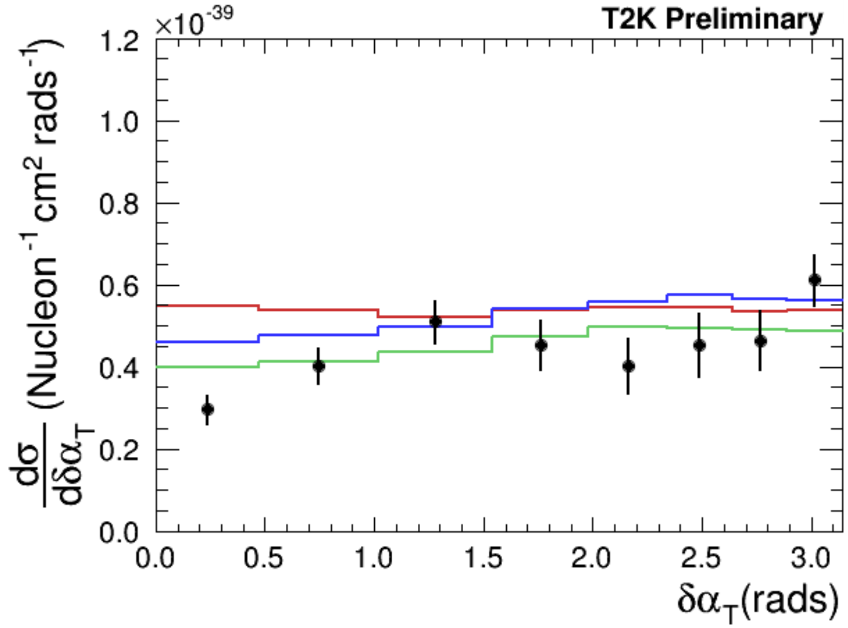
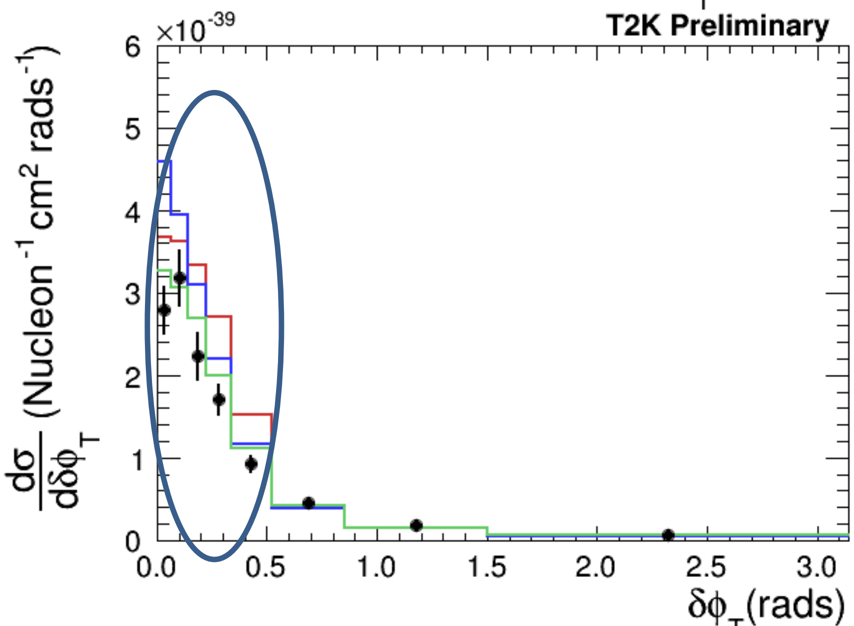
CC0π+Np in STV

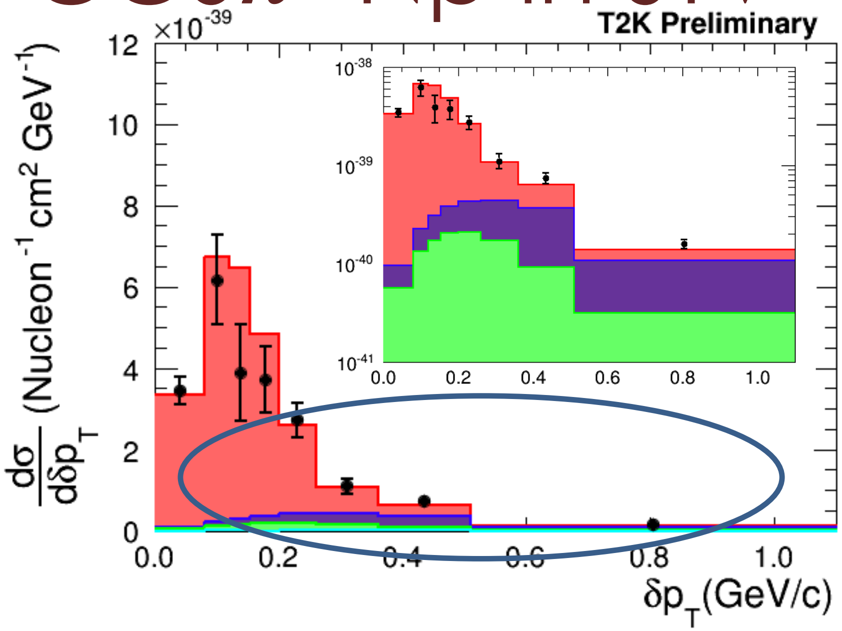


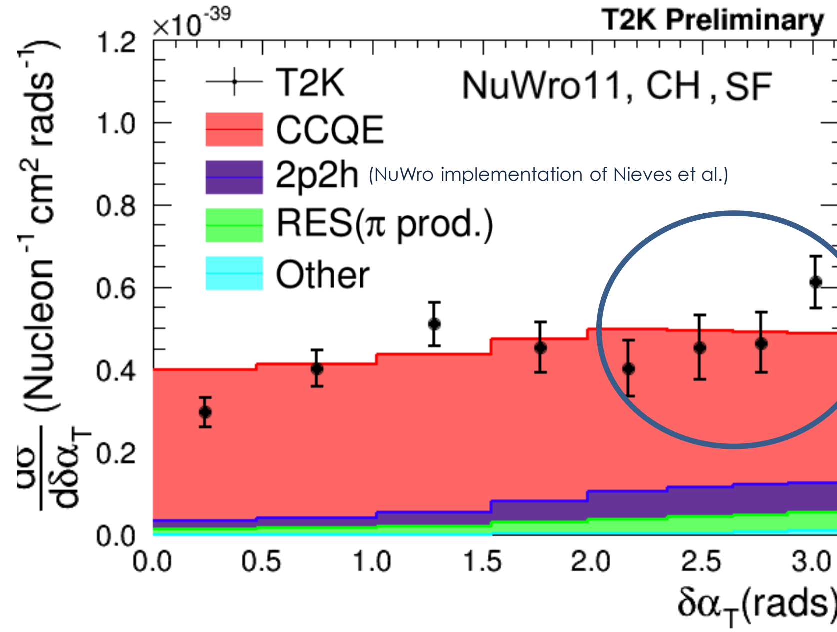


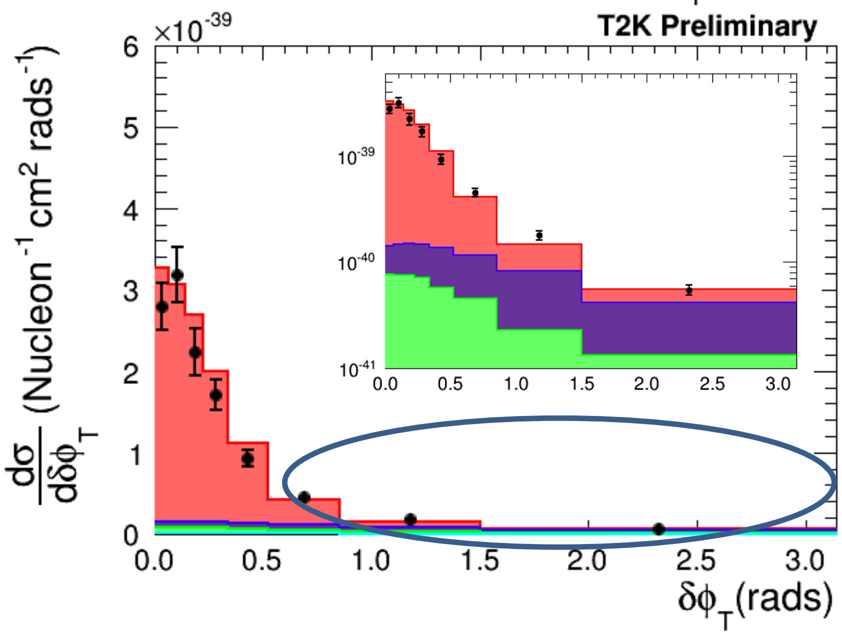


- The peak position and early bins in δp_T and $\delta \phi_T$ tell us about **Fermi Motion**.

CC0π+Np in STV

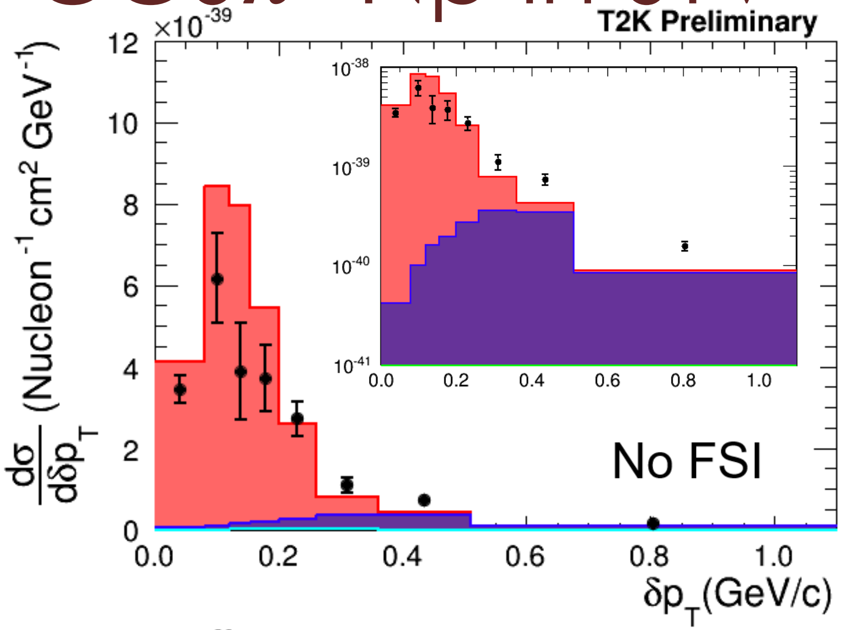


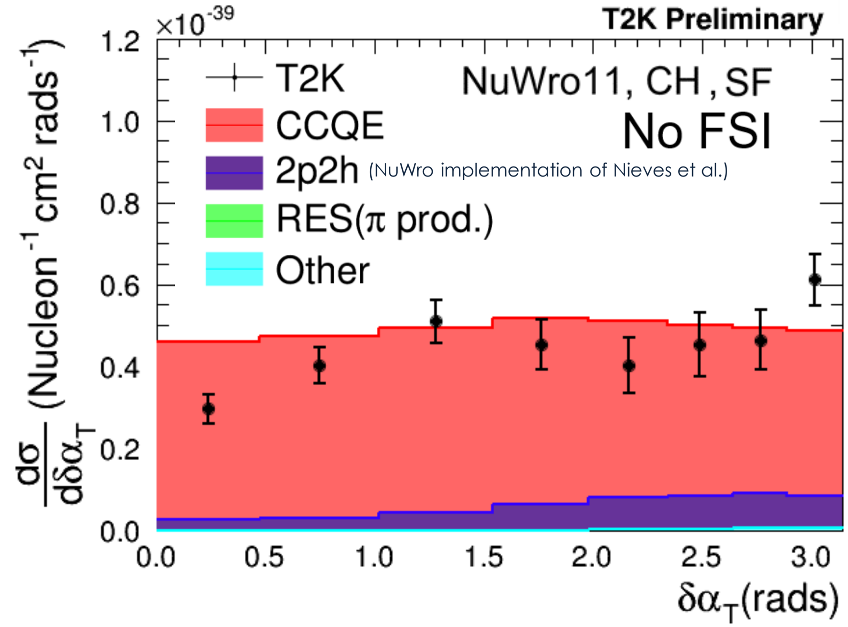


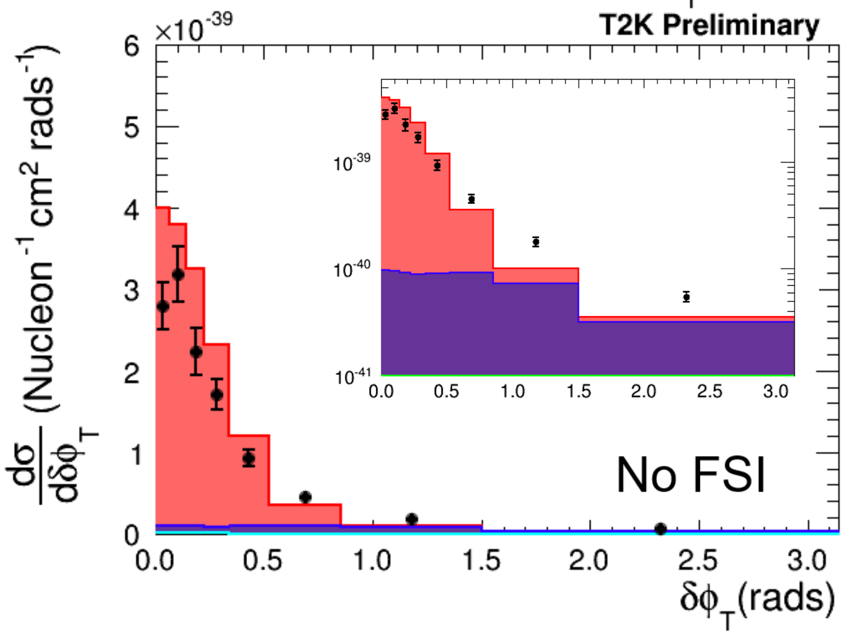


- The peak position and early bins in δp_T and $\delta\phi_T$ tell us about **Fermi Motion**.
- The tails in δp_T and $\delta\phi_T$ and the extent of the rise at large $\delta\alpha_T$ partially isolate the effects of Fermi Motion from **2p2h**.

CC0π+Np in STV

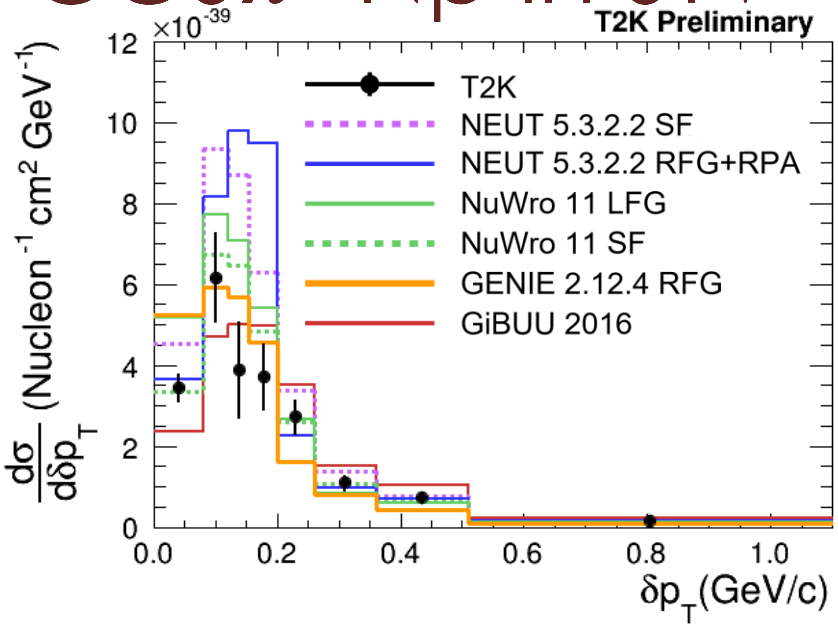


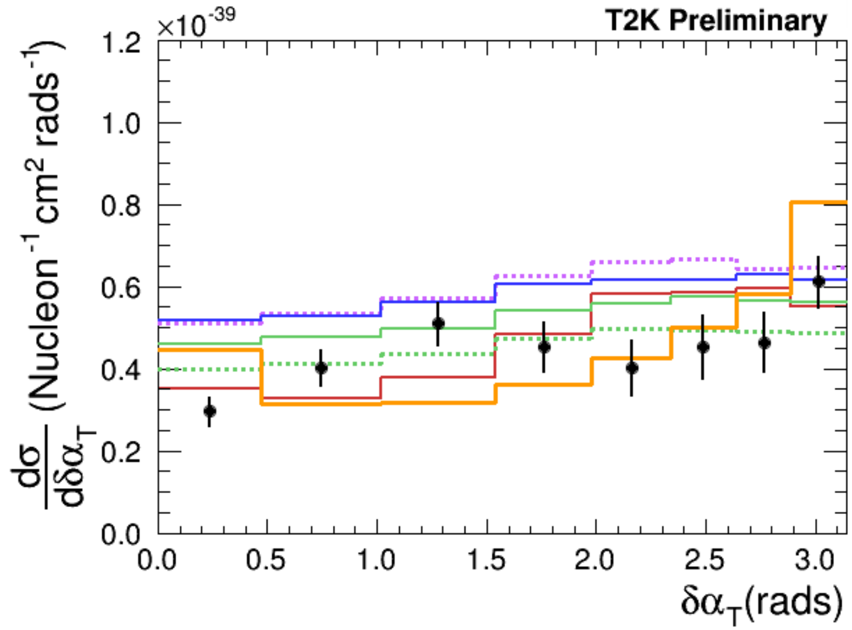


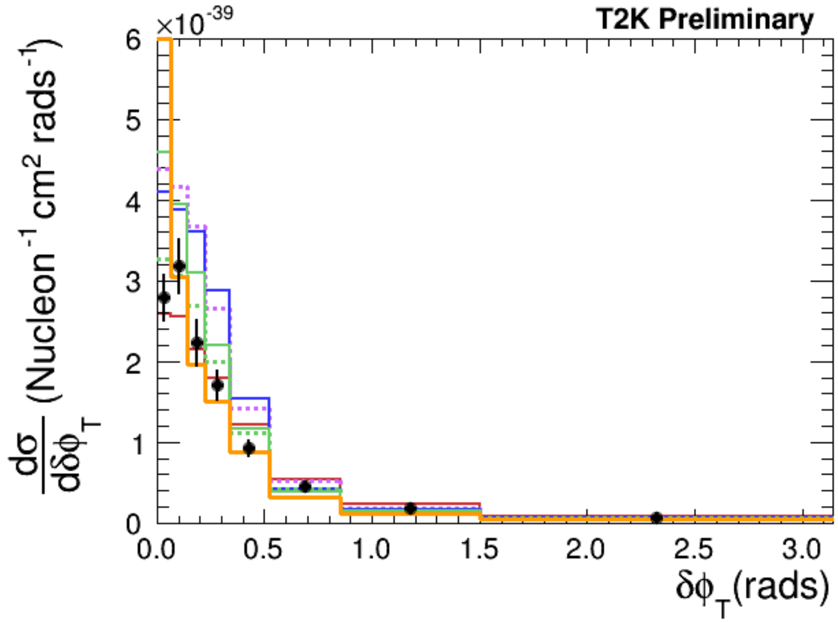


- The peak position and early bins in δp_T and $\delta\phi_T$ tell us about **Fermi Motion**.
- The tails in δp_T and $\delta\phi_T$ and the extent of the rise at large $\delta\alpha_T$ partially isolate the effects of Fermi Motion from **2p2h**.
- Weaker **FSI** causes a relative deficit of events in the tails, but an increased normalisation.

CC0π+Np in STV







Generator Comparisons

- Plenty of separation
- Result disfavours a `Fermi cliff' in δp_T
- GENIE shape in first bin of each STV related to FSI model ("hA")
- Nuclear effect isolation

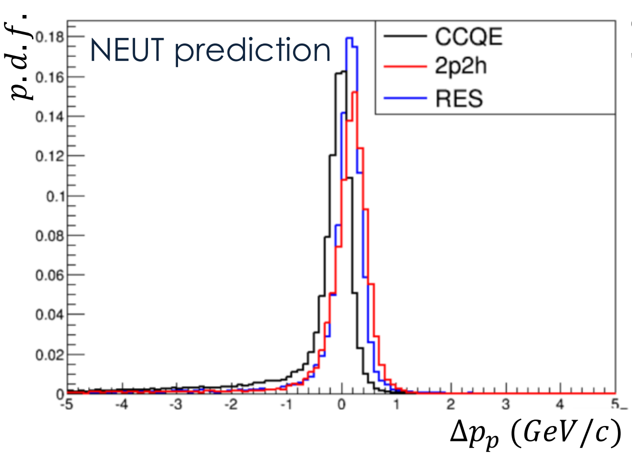
Future work and Summary

- T2K and ND280
- CC0π cross-section results at T2K
- Cross sections using proton information
  - CC0π using proton kinematics
  - CC0π using transverse kinematic imbalance
- Future work and Summary

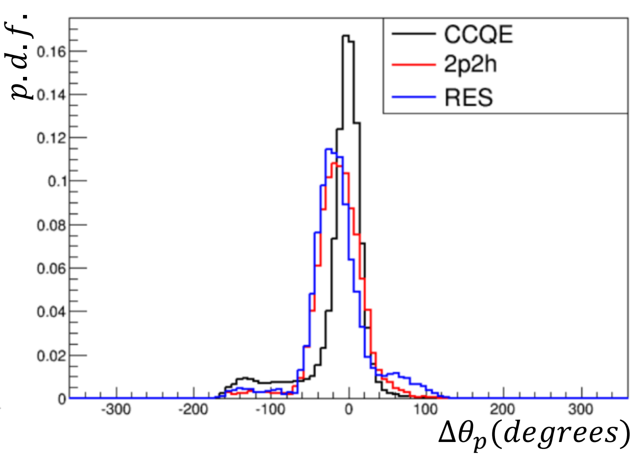
Future work with protons

CC0π and inferred kinematic imbalance

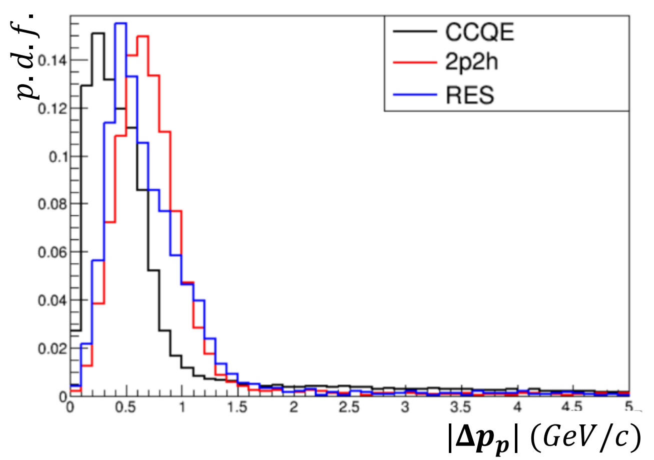
- Under **stationary target** and **elastic scattering** assumptions can infer proton kinematics from measured μ
- Non-zero imbalance between inference and measured proton indicates presence of nuclear effects or CC-non-QE interaction
- Measure (using FGD1 as a CH target with TPCs for tracking):



$$\Delta p_p = |\boldsymbol{p_p^{inferred}}| - |\boldsymbol{p_p^{measured}}|$$

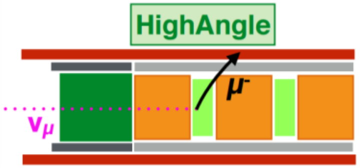


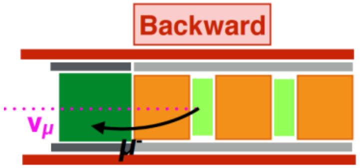
$$\Delta \theta_p = \theta_p^{inferred} - \theta_p^{measured}$$



$$|\boldsymbol{\Delta p_p}| = |\boldsymbol{p_p^{inferred}} - \boldsymbol{p_p^{measured}}|$$

Future work





- **4π angular coverage** (See Alfonso's CCInc talk)
  - Make more use of the ECals and TOF information
  - Can achieve ~ 4π acceptance with reasonable ϵ

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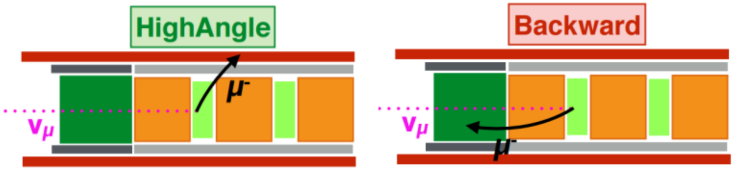

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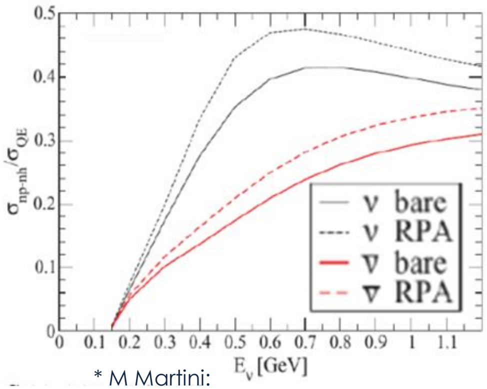
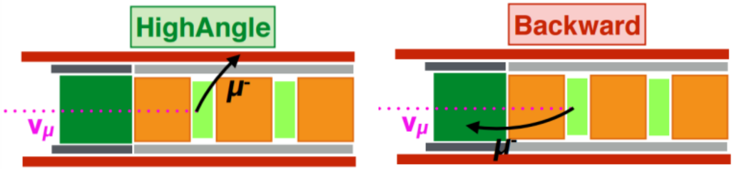
Detector: ND280 – FGD1 **Target:** CH **Signal:** CC0π **Variables:** μ-kinematics



* M Martini:
PHYSICAL REVIEW C **80**, 065501,
PHYSICAL REVIEW C **81**, 045502

Future work



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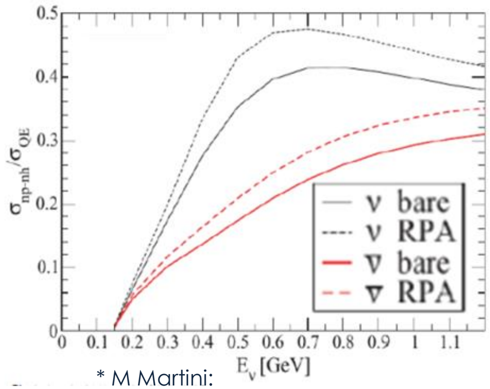
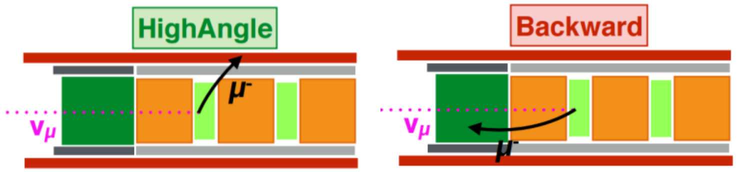


* M Martini:
PHYSICAL REVIEW C **80**, 065501,
PHYSICAL REVIEW C **81**, 045502

- **$\bar{\nu}$CC0π on water using PØD**
  - Use PØD to measure $\bar{\nu}$ on water to complement CH result above

Detector: ND280 – PØD **Target:** Water **Signal:** CC0π **Variables:** μ-kinematics

Future work



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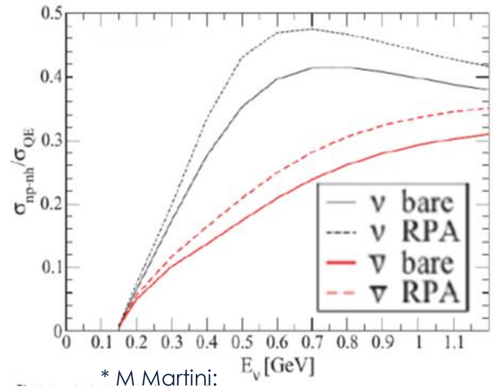

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* M Martini: PHYSICAL REVIEW C **80**, 065501, PHYSICAL REVIEW C **81**, 045502

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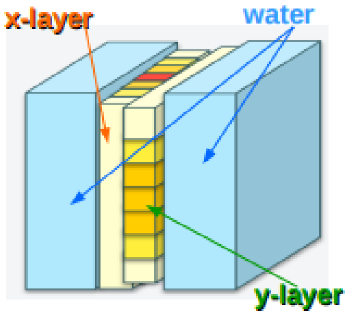
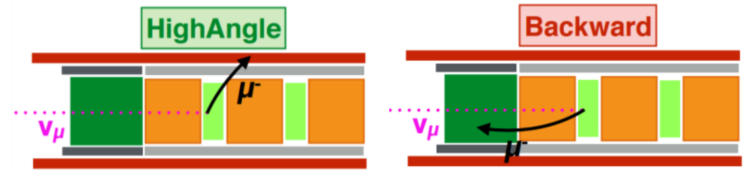


- **νCC0π on water using FGD2**
  - Use FGD2 water layers to measure CC0π on water

Detector: ND280 – FGD2 **Target:** Water **Signal:** CC0π **Variables:** μ-kinematics

Future work



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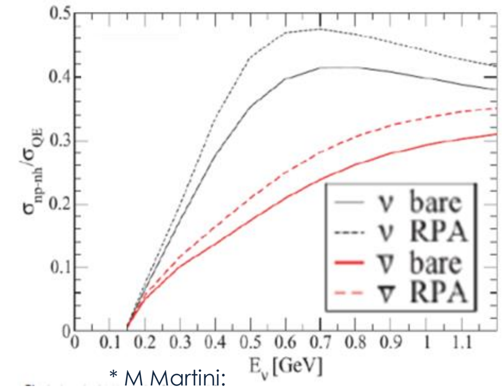

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PHYSICAL REVIEW C **80**, 065501,
PHYSICAL REVIEW C **81**, 045502

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Detector: ND280 – PØD **Target:** Water **Signal:** CC0π **Variables:** μ-kinematics

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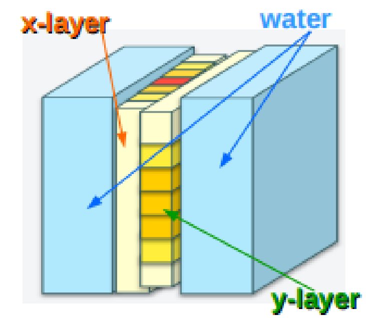
  - Use FGD2 water layers to measure CC0π on water

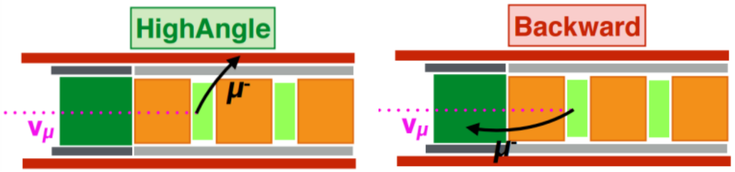


Detector: ND280 – FGD2 **Target:** Water **Signal:** CC0π **Variables:** μ-kinematics

- **INGRID CC0π Analysis**
  - Use INGRID ($E_\nu^{peak} \sim 1.2\ GeV$) to compliment FGD1 analysis ($E_\nu^{peak} \sim 0.6\ GeV$)

Detector: INGRID **Target:** CH **Signal:** CC0π **Variables:** μ-kinematics

Future work



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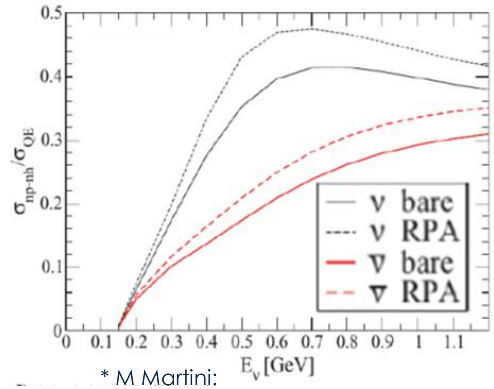

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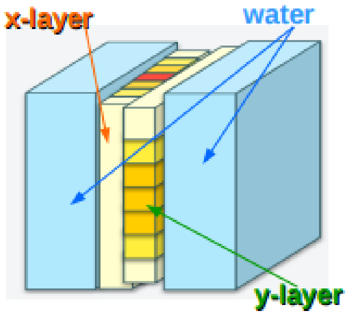
  - Use FGD2 water layers to measure CC0π on water



Detector: ND280 – FGD2 **Target:** Water **Signal:** CC0π **Variables:** μ-kinematics

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  - Use INGRID ($E_\nu^{peak} \sim 1.2\ GeV$) to compliment FGD1 analysis ($E_\nu^{peak} \sim 0.6\ GeV$)

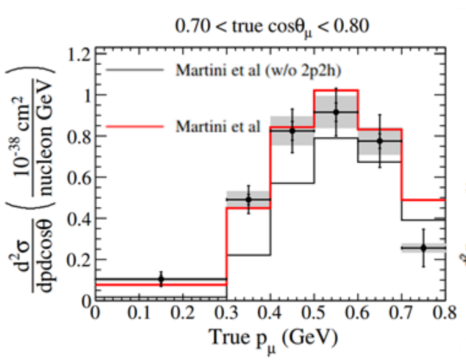
Detector: INGRID **Target:** CH **Signal:** CC0π **Variables:** μ-kinematics

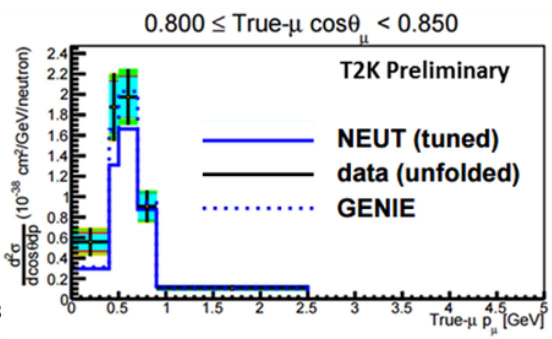
- **Combine it all!**

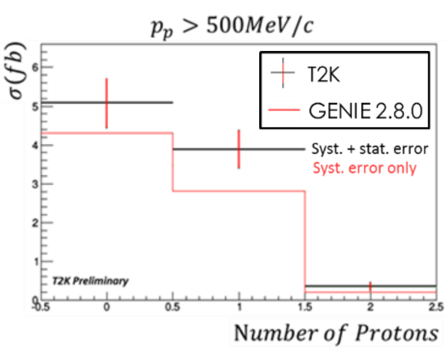
Detector: FGD1+2 (+ INGRID) **Target:** CH+H_2O **Signal:** CC0π(+Np) **Variables:** ???

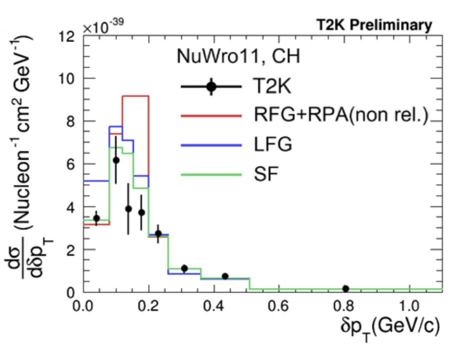
Summary

- 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 has made its first measurements using **proton kinematics**
  - Including a measure of **single-transverse kinematic imbalance**
  - Interesting model separation and nuclear effect isolation
- Many more results coming soon!







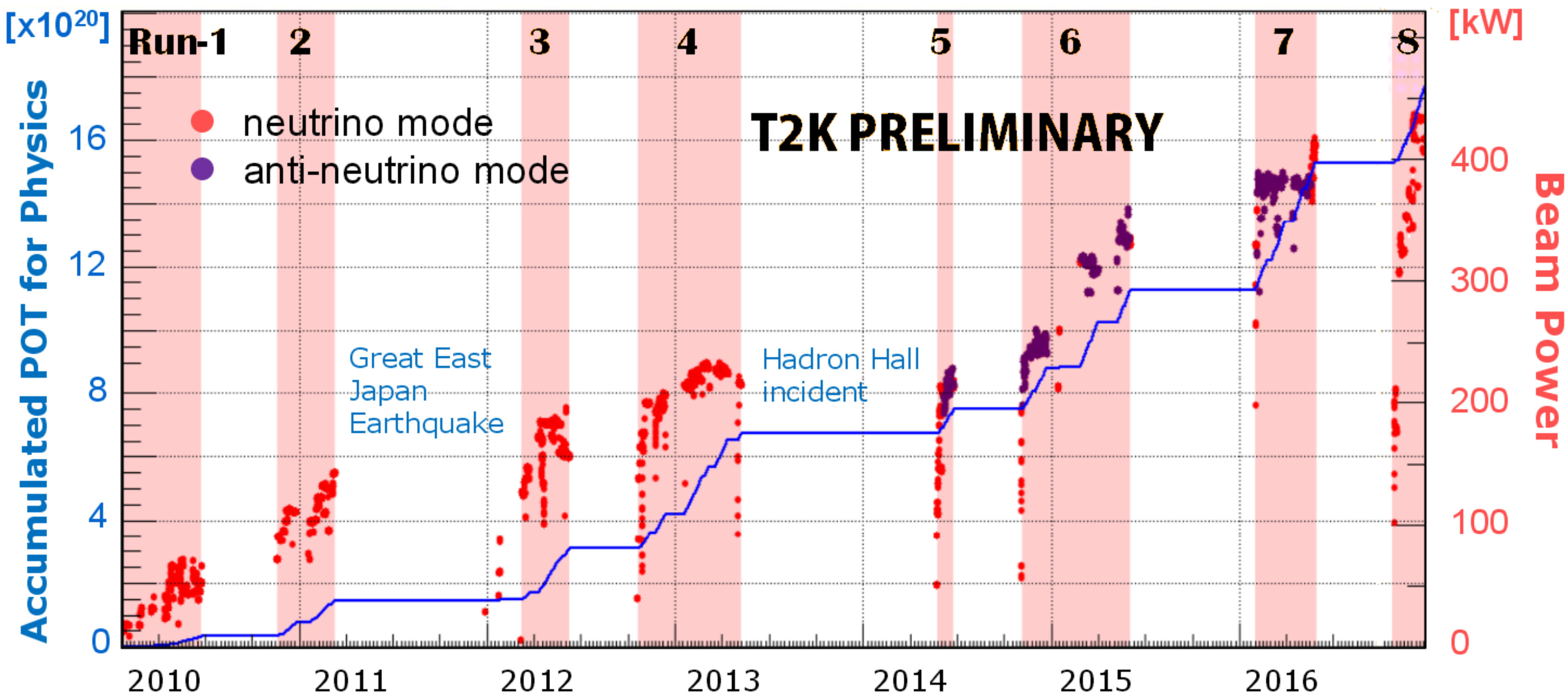


Thank you for listening

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)

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%**

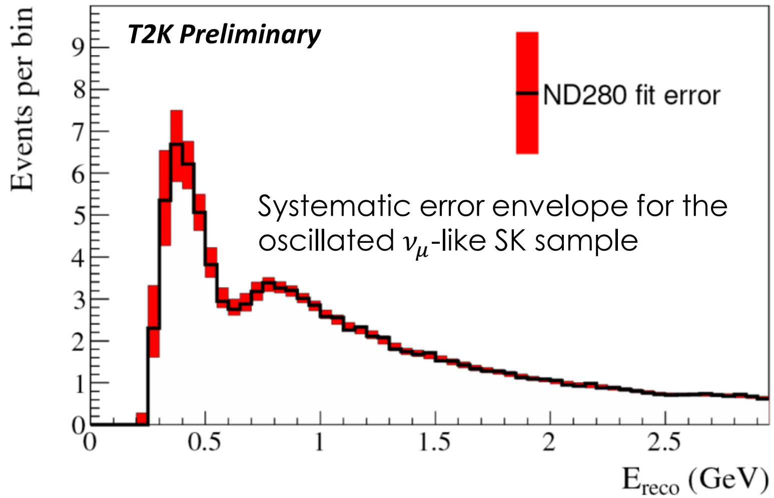
- Largest systematic uncertainty comes from neutrino interaction uncertainties

Neutrino Interactions 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



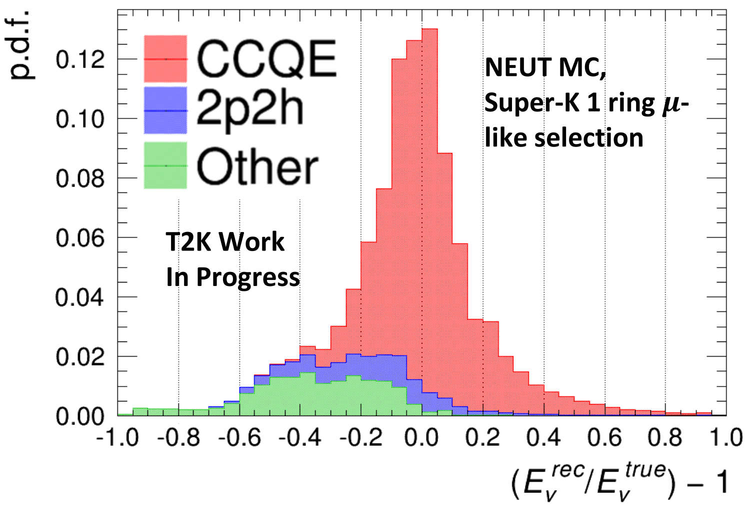
Systematic error envelope for the oscillated ν_μ-like SK sample

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

Neutrino Interactions and OA

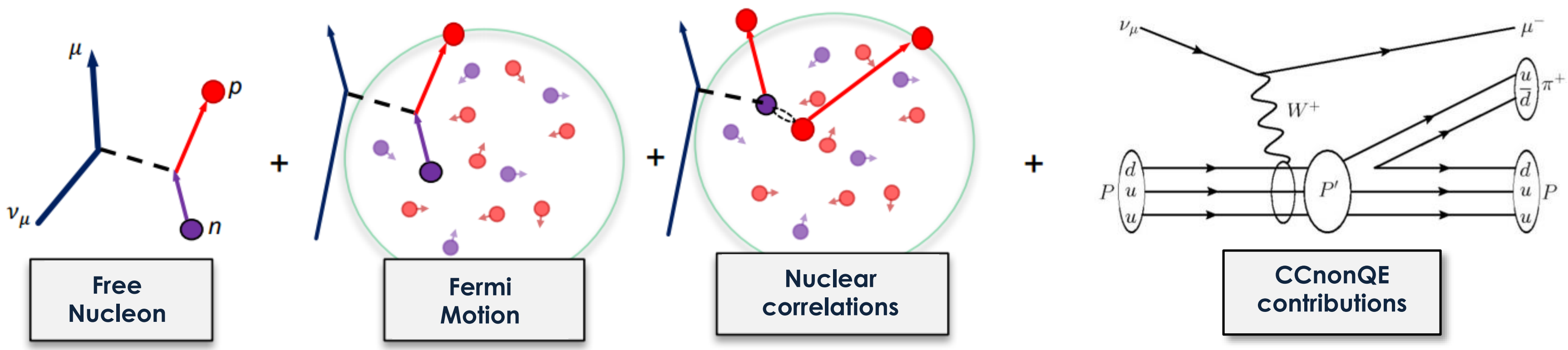
- Find E_ν^{reco} using observed μ at SK assuming **stationary target** and **elastic scattering**

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



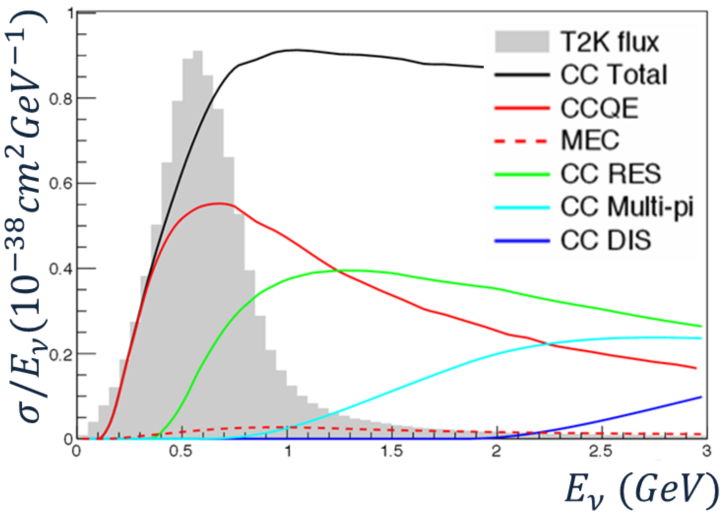
Bias due to:

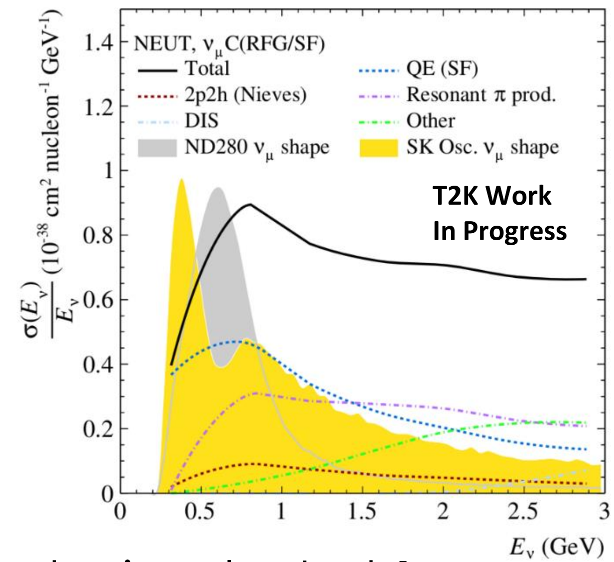
- **Fermi motion in the initial nuclear state**
- **Nucleon-nucleon correlations**
- **CCnonQE contamination in the selection.**



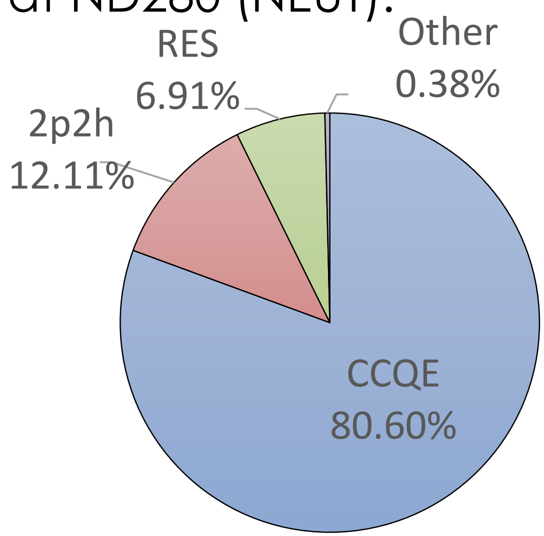
Diagrams by Patrick Stowell

Neutrino Scattering and OA

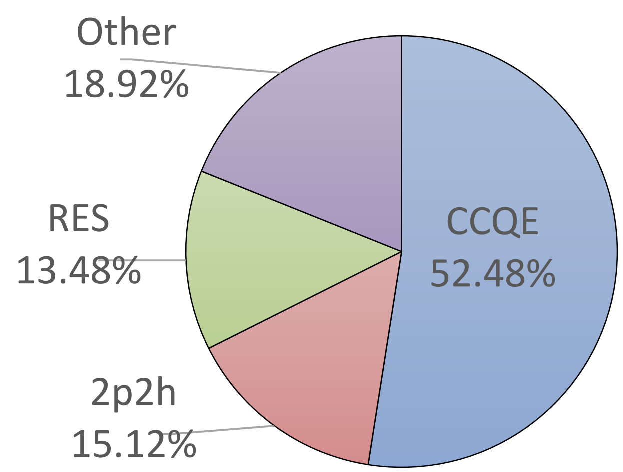




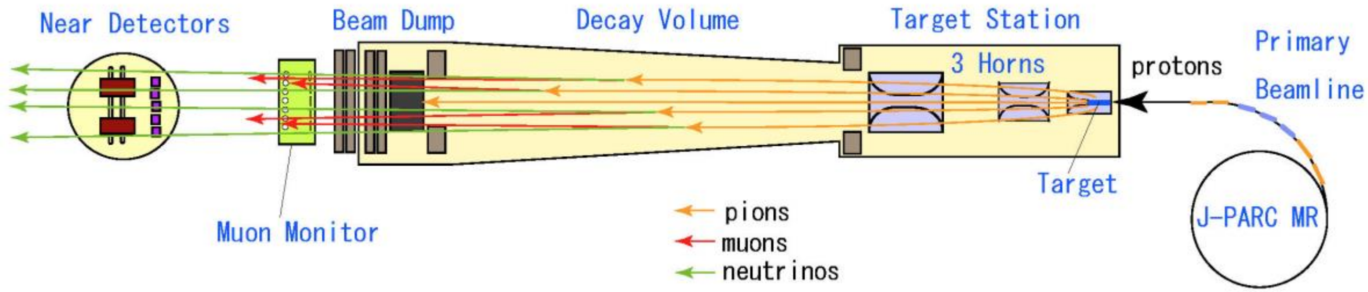
Interaction Modes in all CC0π events at ND280 (NEUT):

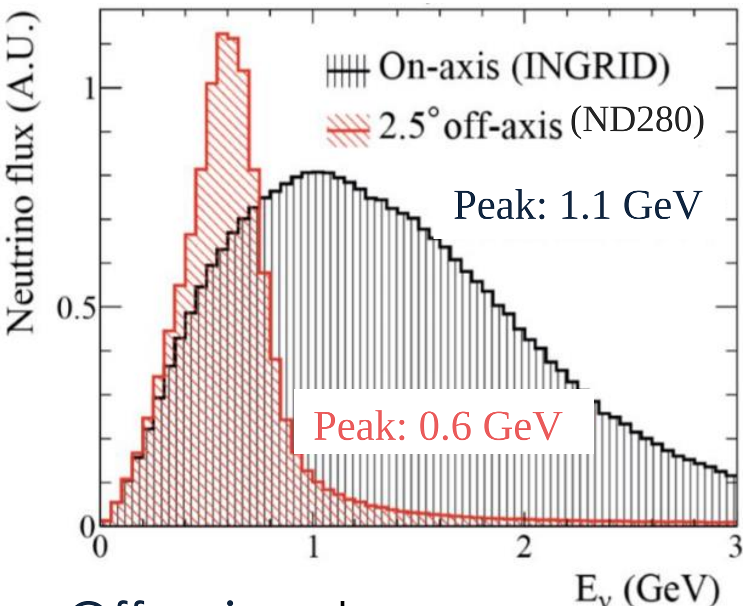


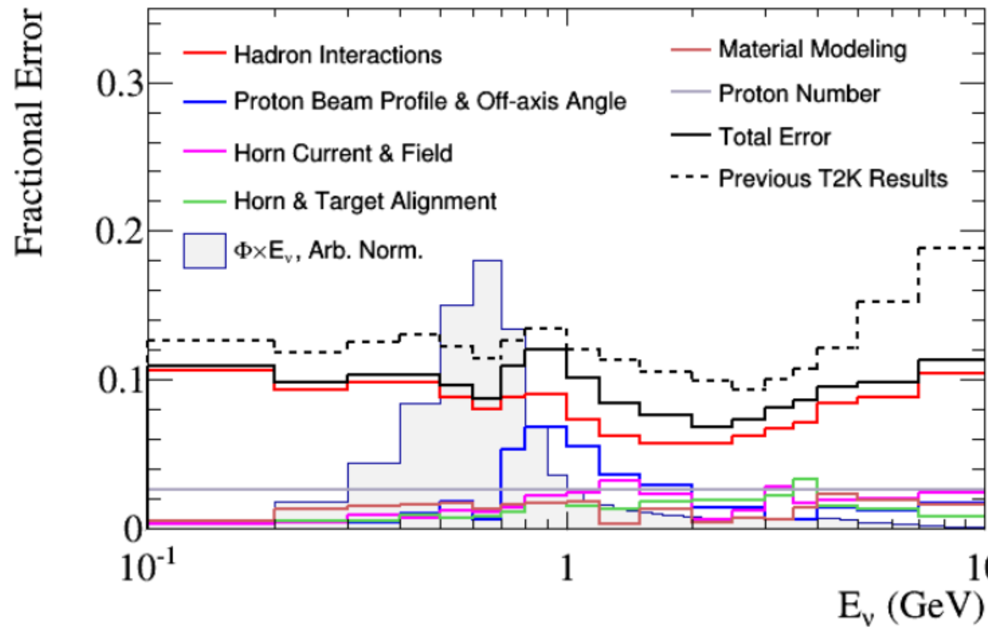
Interaction Modes in selected 1 ring μ-like events at SuperK(NEUT):



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)

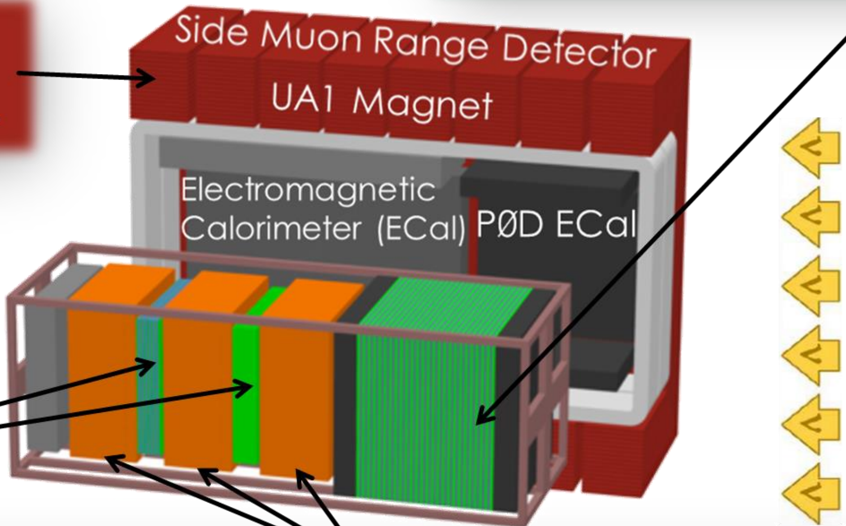
On Axis ~ 1.1 GeV

Peak E_ν

Off Axis ~ 0.6 GeV

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

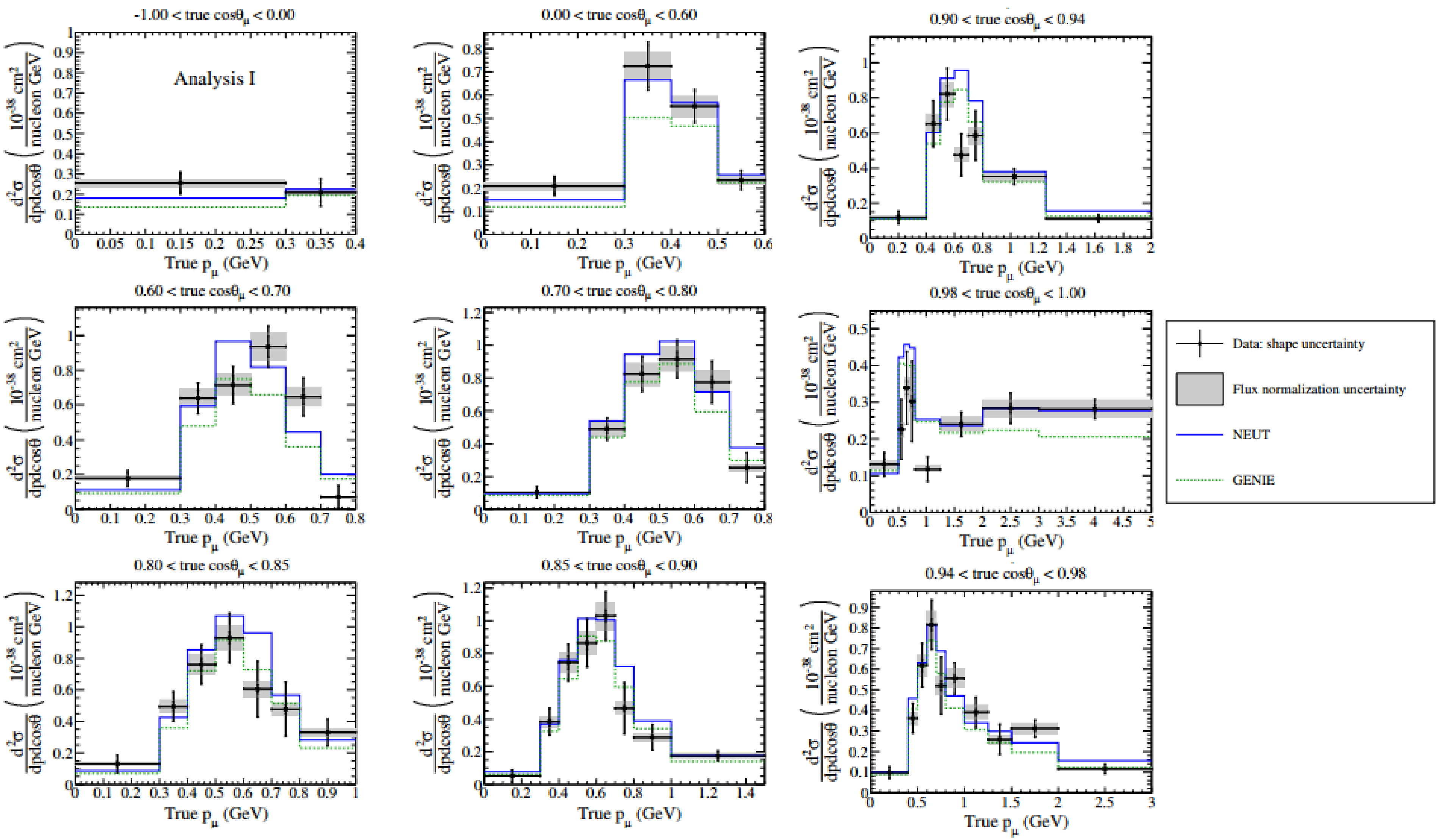
UA1 Magnet: Provides 0.2 T field.



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.

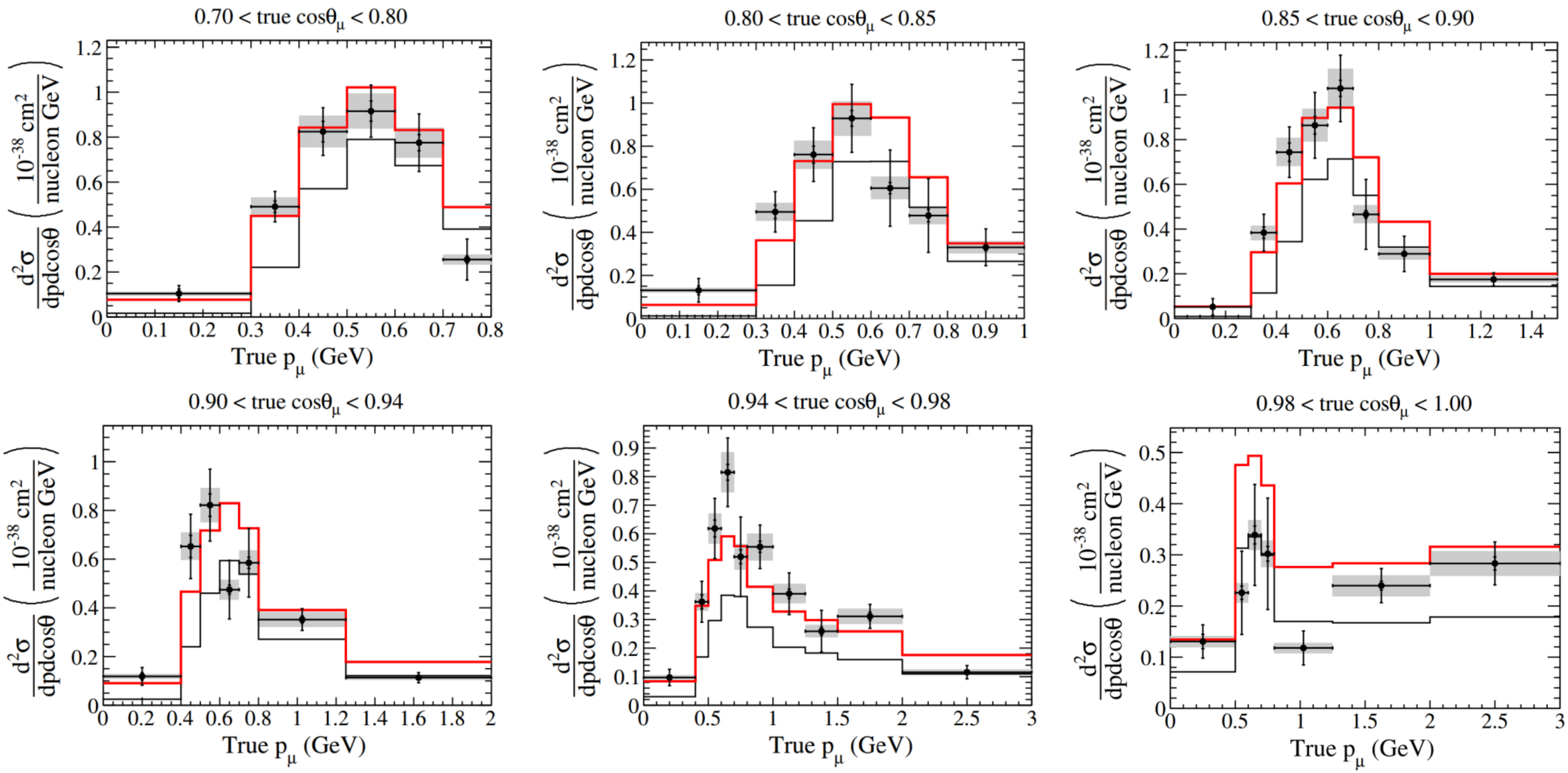
ND280 Off-Axis CC0π Result



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

ND280 Off-Axis CC0π Result

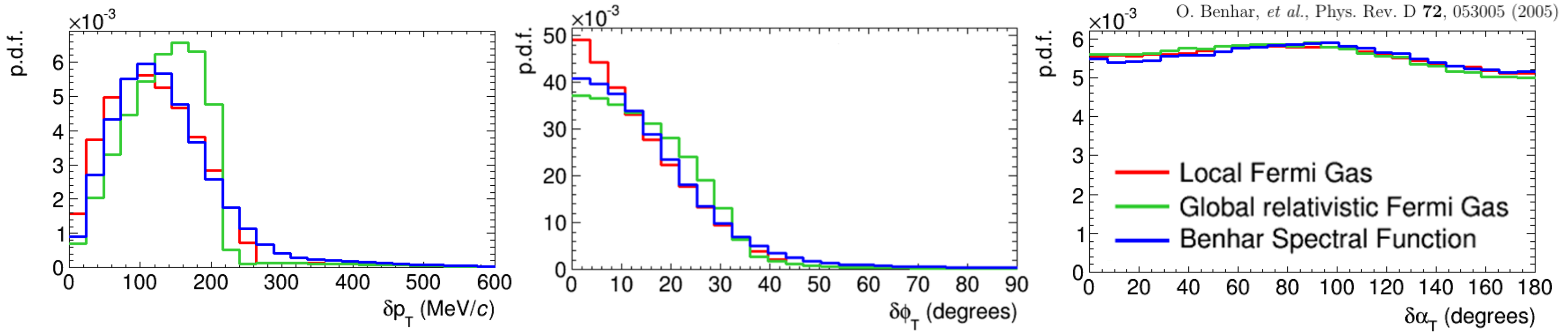
- Results compared to Martini *et al.* model **with(red)**/**without(black)** 2p2h
- Data prefer a 2p2h contribution



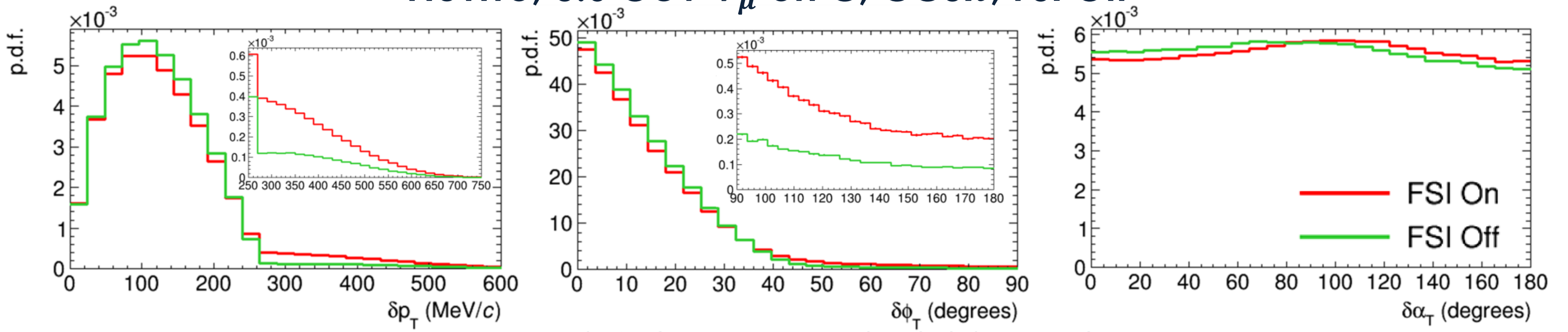
Detector: ND280 – FGD1 **Target:** Carbon **Signal:** CC0π **Status:** Phys. Rev. D **93**, 112012

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



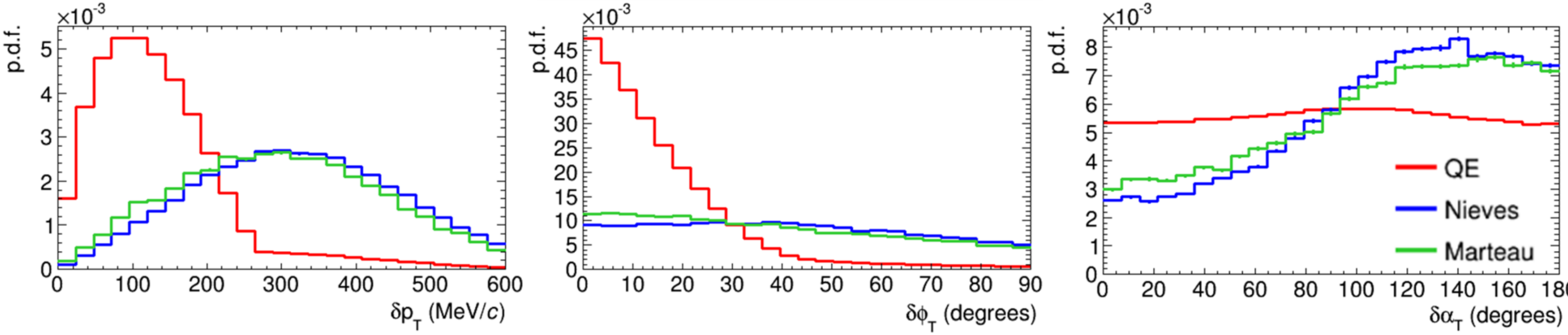
NuWro, 0.6 GeV ν_μ on C, CC0π, LFG

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

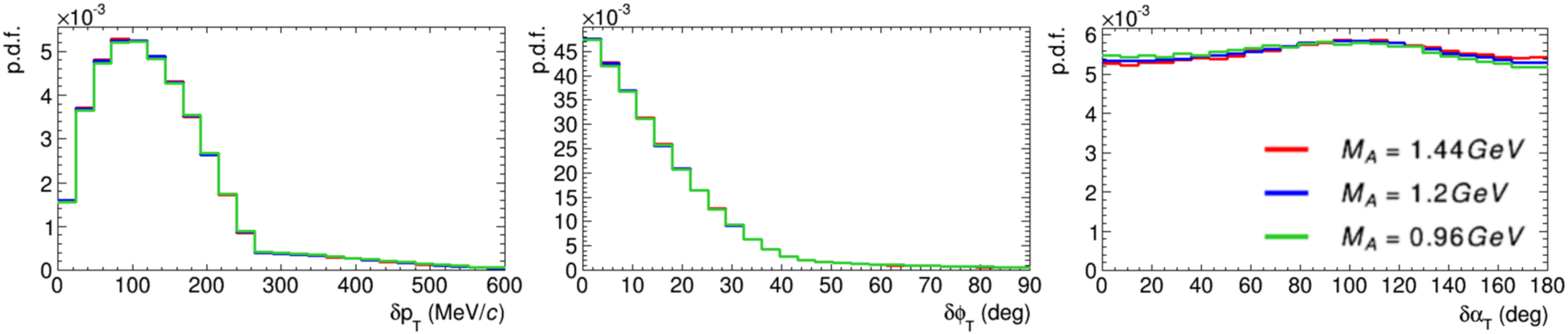
No Pions, 1 Muon, >0 Protons. $p_\mu > 250\ MeV, p_p > 450\ MeV, \cos(\theta_\mu) > -0.6, \cos(\theta_p) > 0.4$

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)



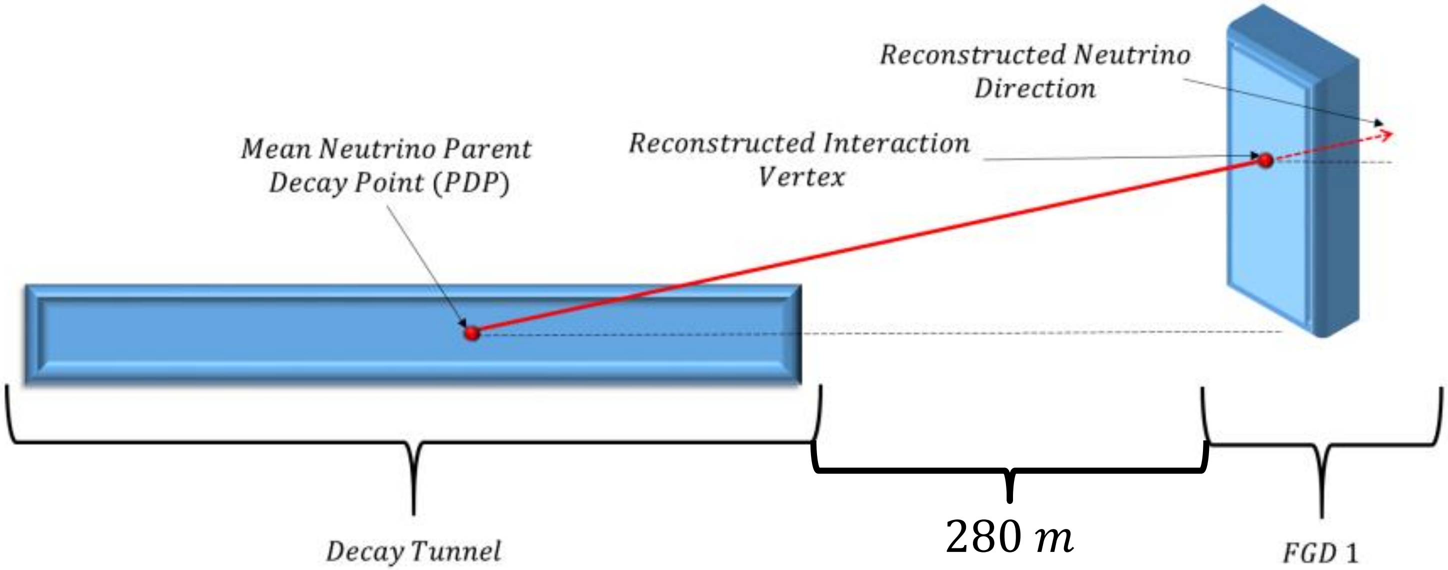
NuWro, 0.6 GeV ν_μ on C, CC0π, FSI On, LFG

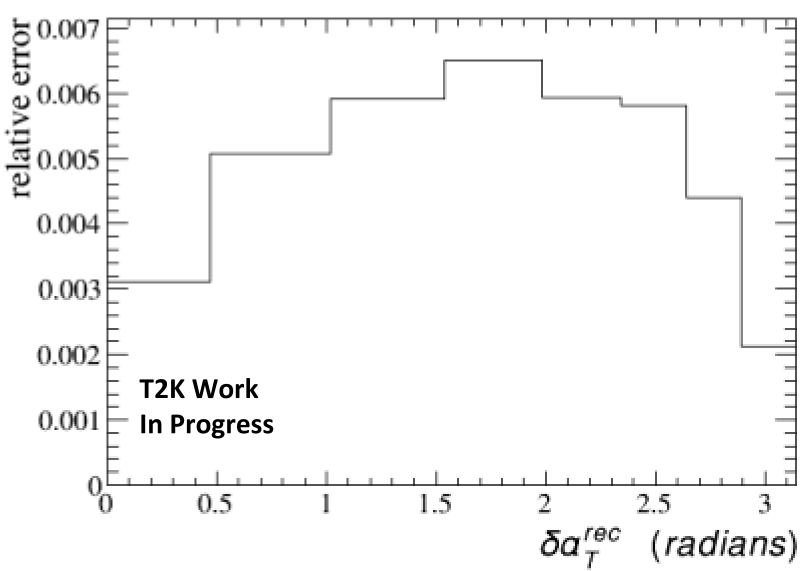


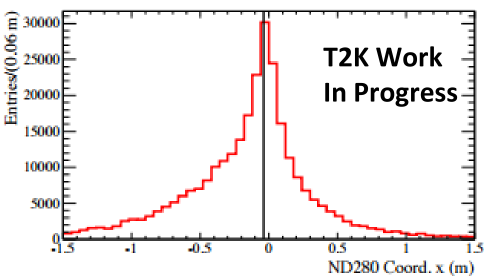
NuWro, 0.6 GeV ν_μ on C, CC0π, FSI On, LFG

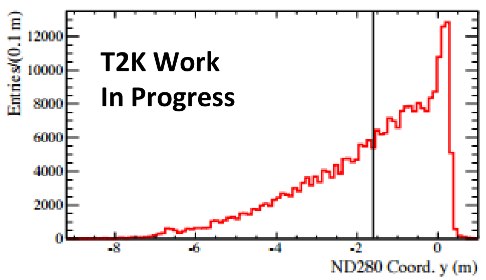
- STV shape invariant with M_A
  - No ambiguity over M_A or nuclear effect contributions (MiniBooNE M_A puzzle)

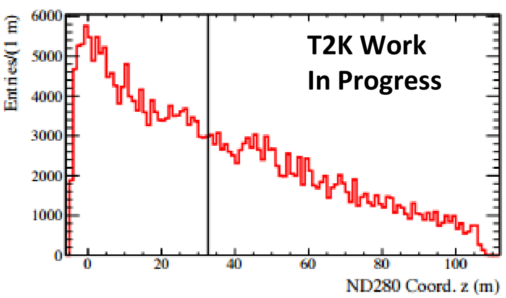
Reconstructing the Neutrino Direction





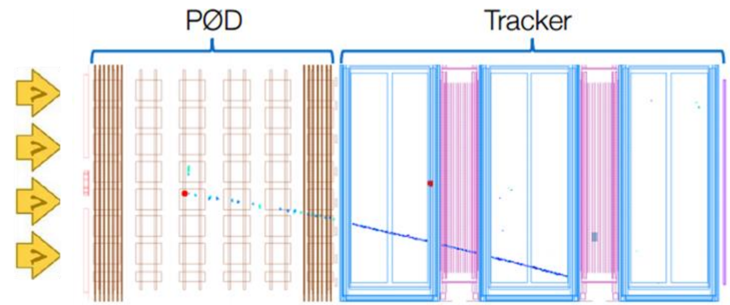


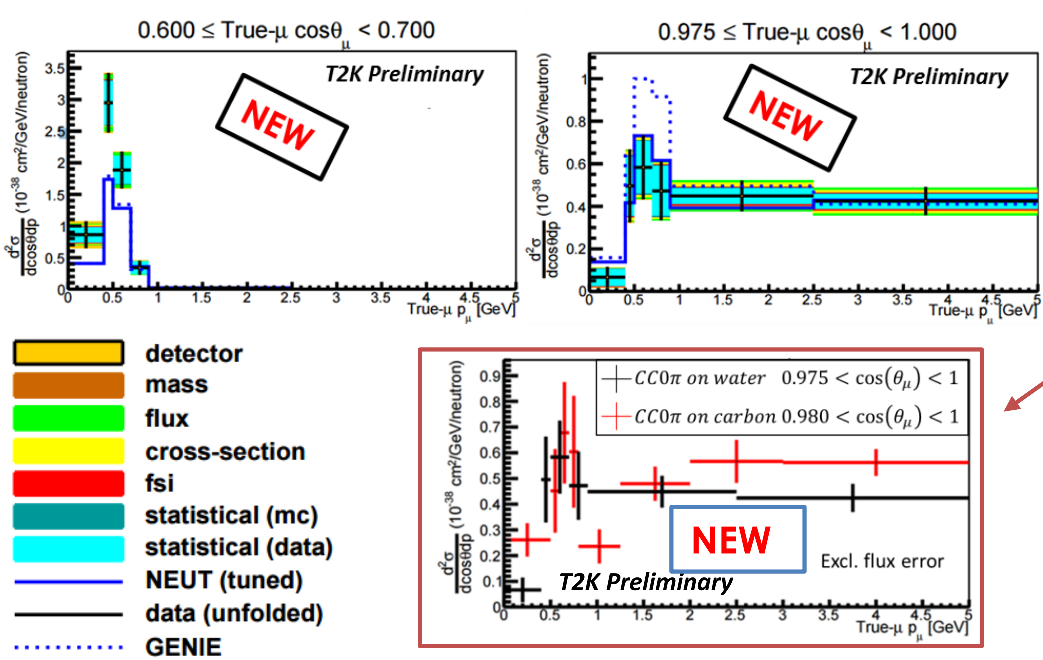




CC0π water cross section

- 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

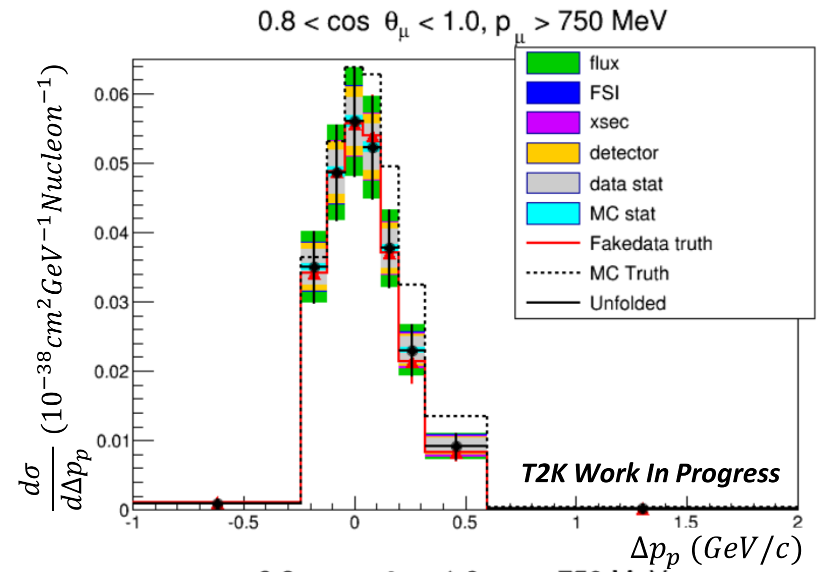


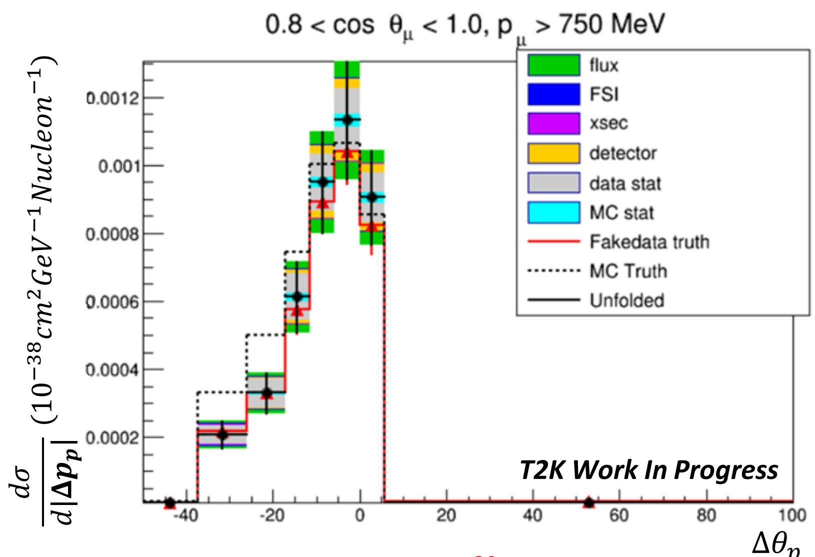


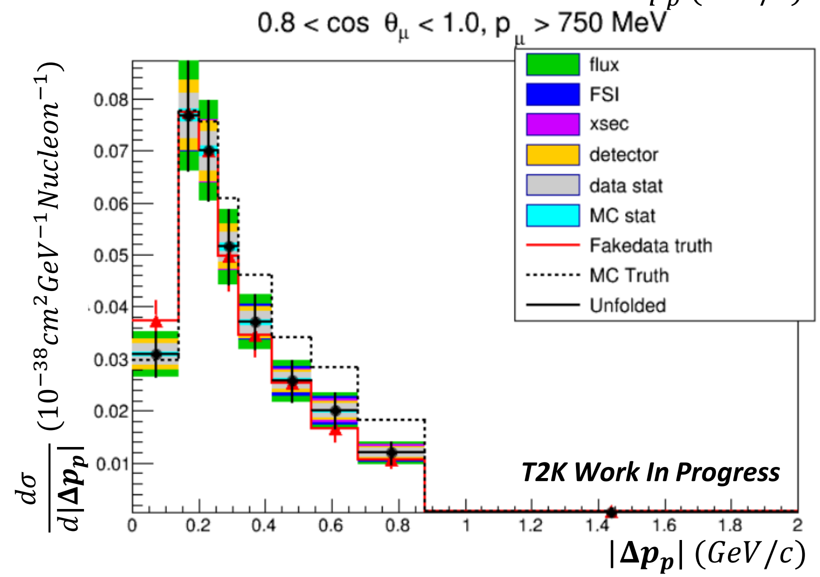
- Construct **CC0π** flux integrated double-differential cross section in $p_\mu, \cos(\theta_\mu)$
  - Compare MC predictions
- Compare to FGD1 CC0π on Carbon result
- Similar studies underway using FGD2 water layers to extract Oxygen:Carbon cross section ratio

CC0π and inferred kinematic imbalance

- Measure inferred kinematics in bins of $p_\mu, \cos(\theta_\mu)$
- Restrict proton phase-space: $p_p > 450\ MeV/c, \cos(\theta_p) > 0.4$
- **Fake data**: GENIE*
- Nominal MC: NEUT







* GENIE fake data contains $5.73 \times 10^{20}\ POT$ ~T2K runs 2-4