To CCQE and Beyond

Results and prospects of latest CCQE-like analyses from the T2K near detectors

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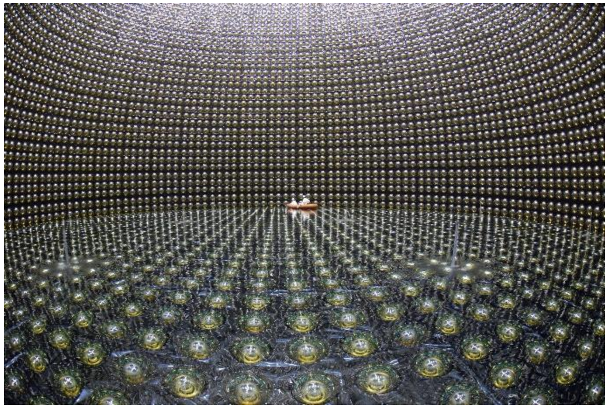
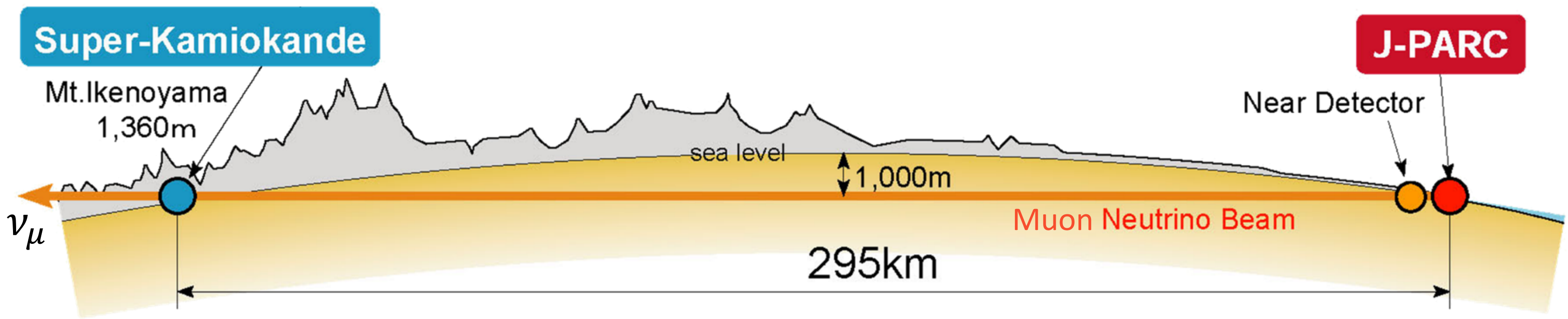
Overview

- The T2K experiment
- Motivation for measuring CCQE-like cross sections
- Flux and near detectors' details
- NuFact 15 recap
- CC0π on water cross section using the PØD
- FGD1 analyses using proton information
  - CC0π using proton kinematics
  - CC0π using inferred kinematic imbalance
  - CC0π using transverse kinematic imbalance
- Other analyses
  - CC0π measurements from $\nu + \bar{\nu}$ joint fit
  - CC0π at INGRID
  - Extraction of free nucleon cross section using δp_{TT}
- Summary and future work

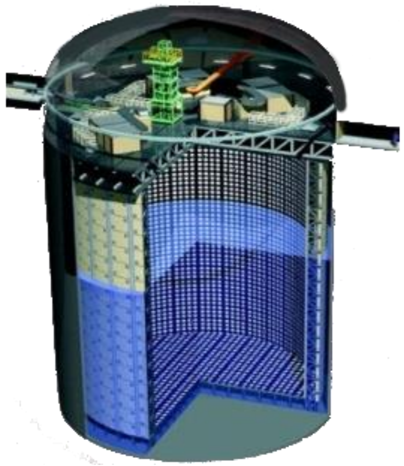


The T2K Experiment



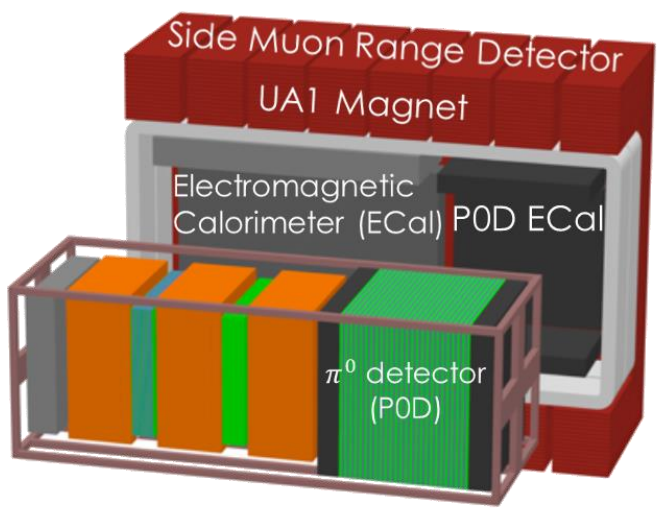
Far Detector

Super-Kamiokande

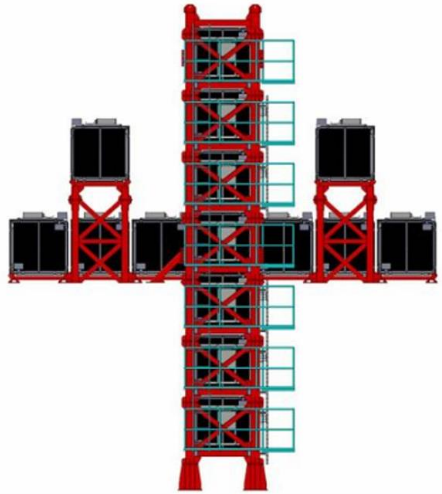


Near Detectors

Off-Axis: ND280

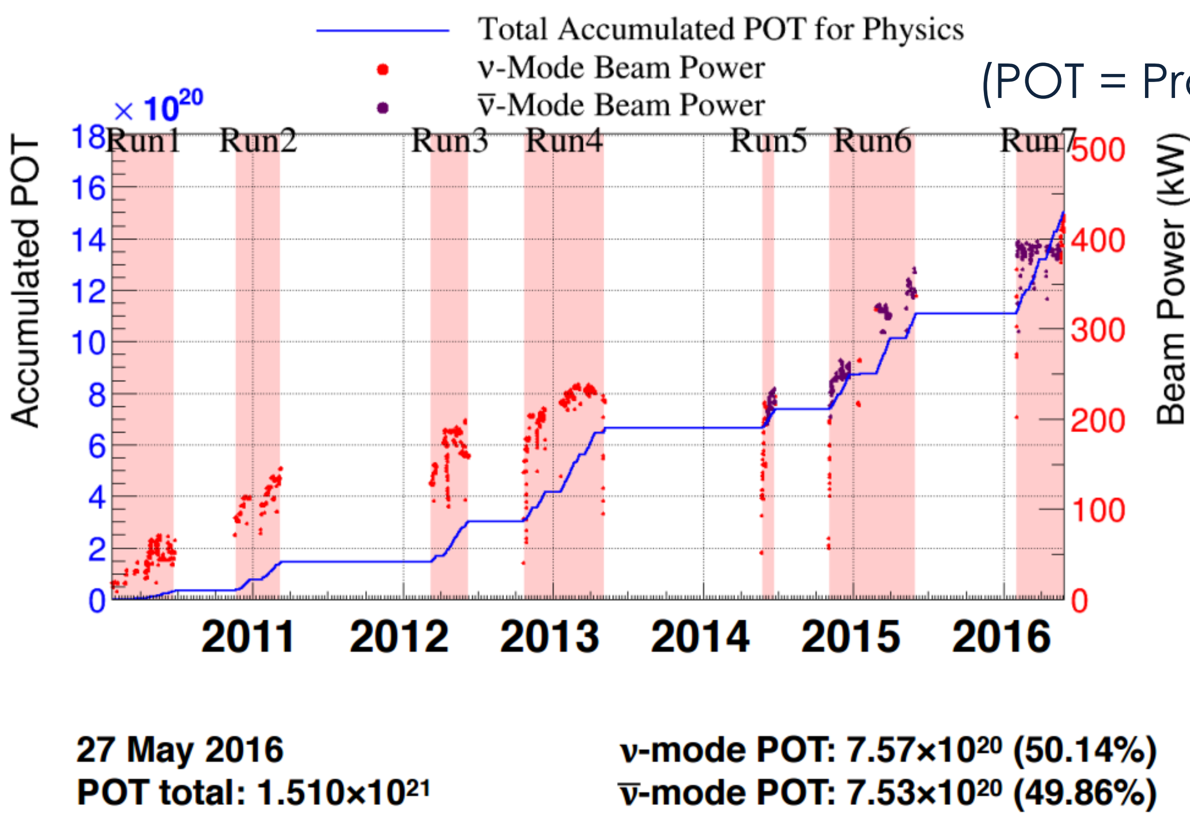


On-Axis: INGRID



Data Collection

(POT = Protons On Target)



- Continuous rise in beam power from ~225 kW (2014) to ~420 kW (2016)
- Using this to make world leading measurements of oscillation parameters (see talk by Benjamin Quilain – WG1, Tuesday, 14:00)

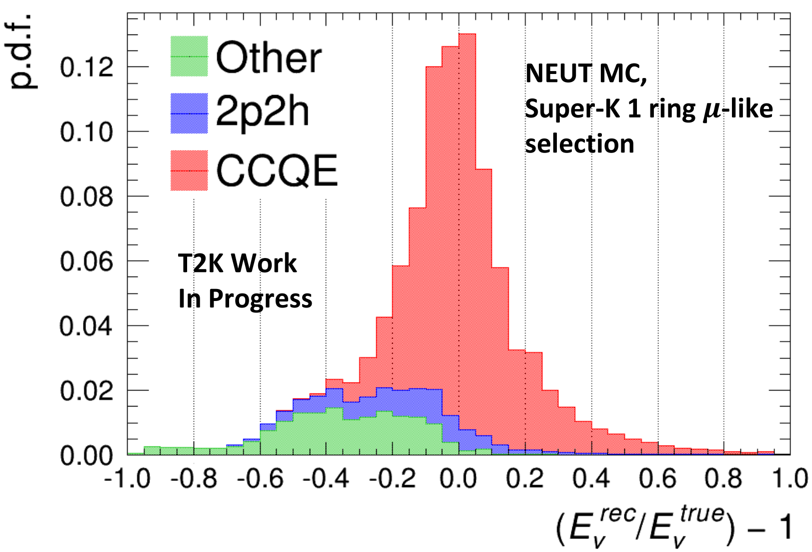
Neutrino Scattering and OA

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

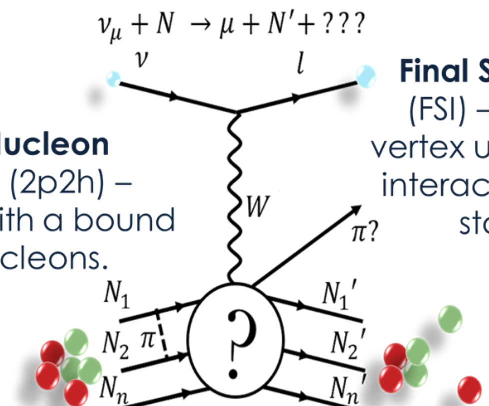
- Can reconstruct using observed μ assuming **stationary target** and **elastic scattering**

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

Bias due to Fermi Moton and CCnonQE components



Nucleon-Nucleon Correlations (2p2h) – interaction is with a bound state of nucleons.

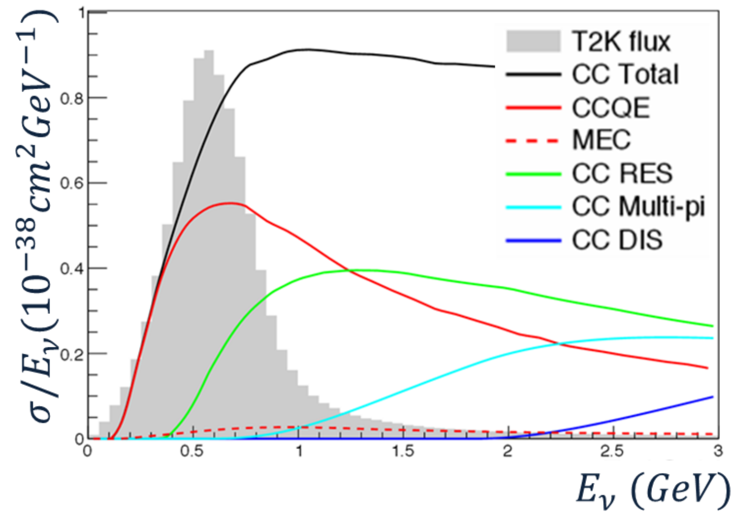


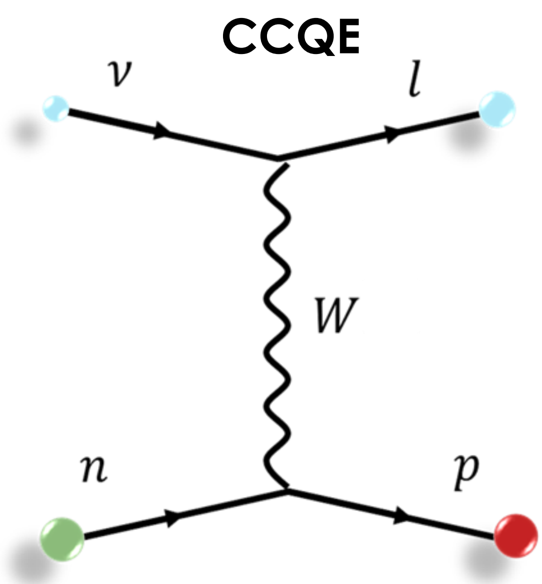
Final State Interactions (FSI) – hadrons exiting vertex undergo additional interactions → extra final state particles.

Fermi Motion (FM) – The target in the initial state has non-zero momentum.

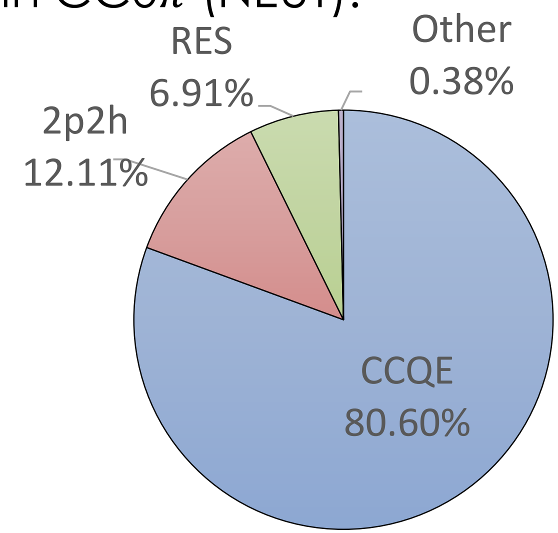
Neutrino Scattering and OA

- Essential to understand $\nu - N$ scattering to control the bias
  - CCQE particularly important for T2K
- Probe using CC0π cross sections
  - Less FSI model dependence
  - Simplest channel to probe nuclear effects.

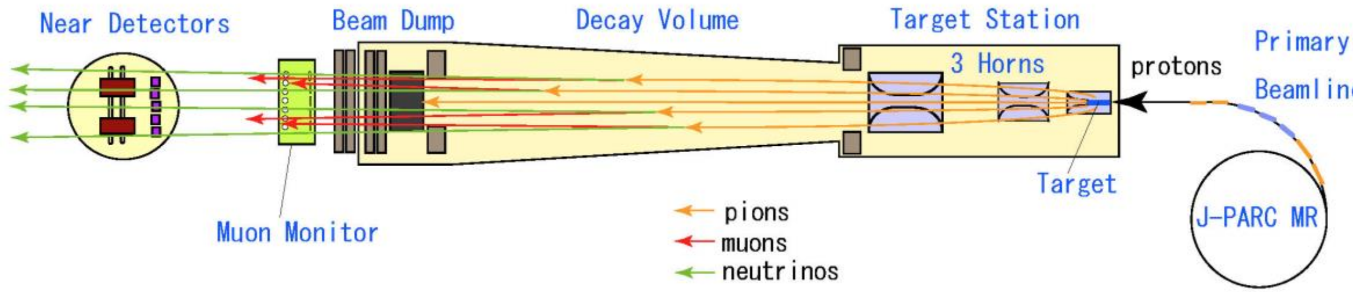


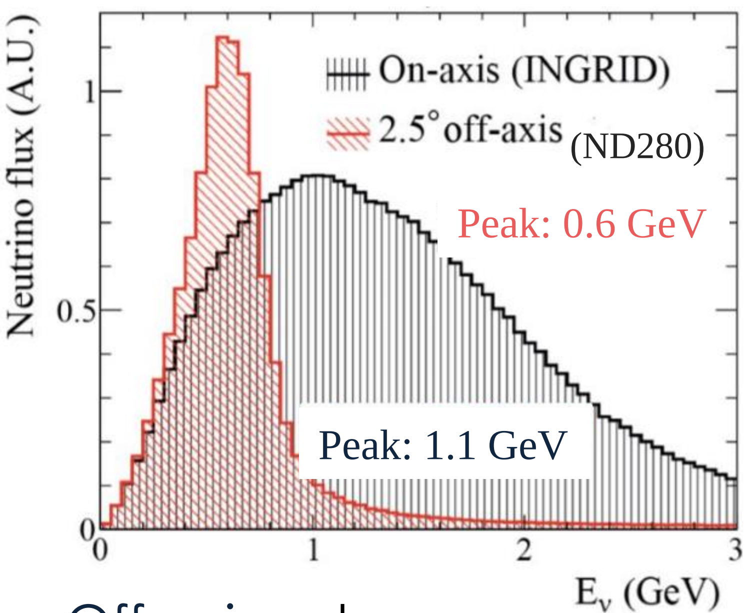


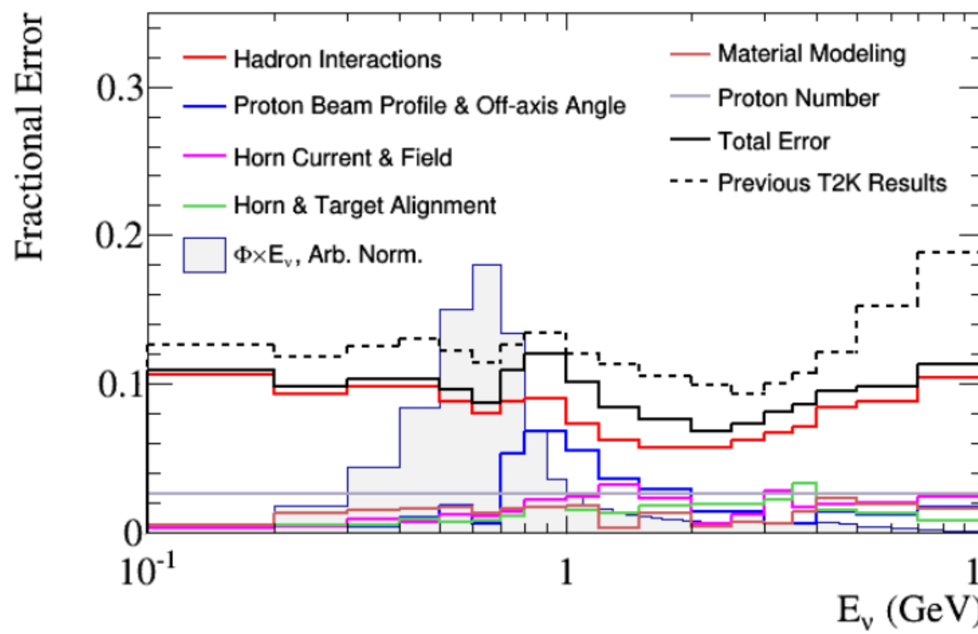
Interaction Modes in CC0π (NEUT):



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 (see talk at WG1+2 session on Thursday 10:45)

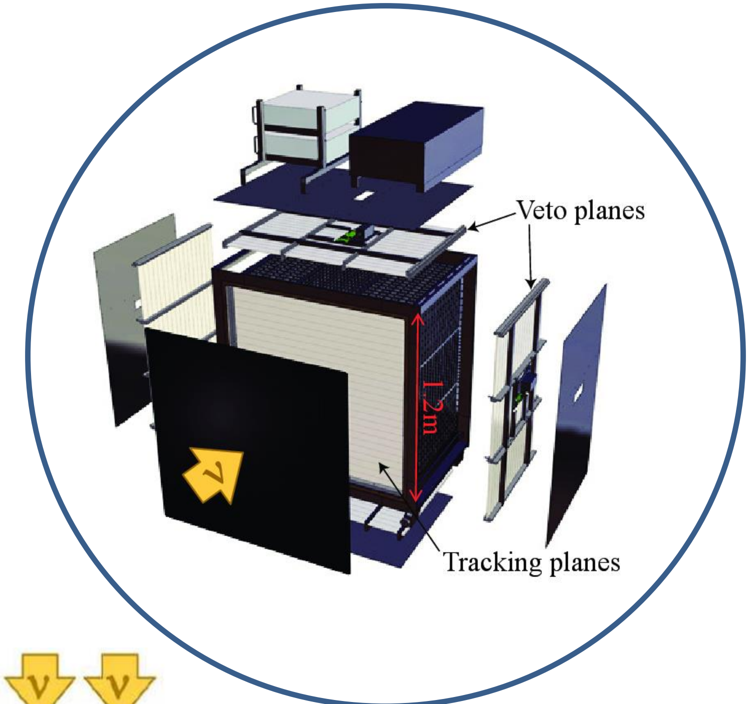
Phys. Rev. D 87, 012001

INGRID (on axis)

On Axis ~ 1.1 GeV

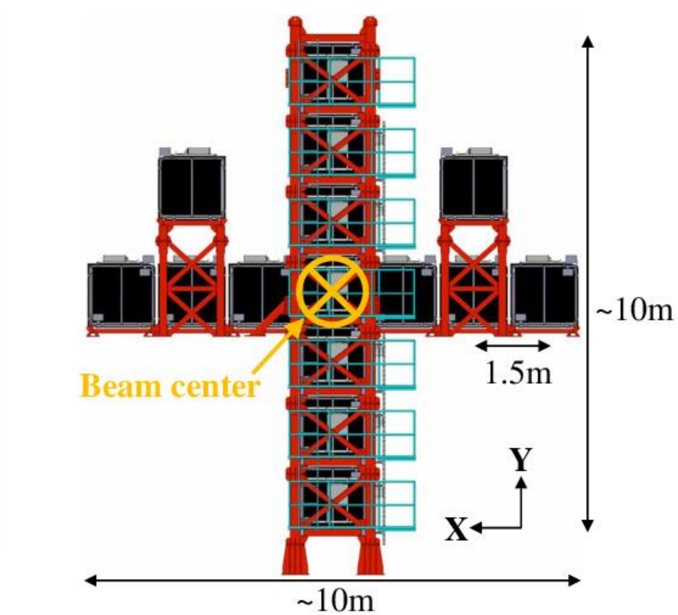
Peak E_ν

Off Axis ~ 0.6 GeV

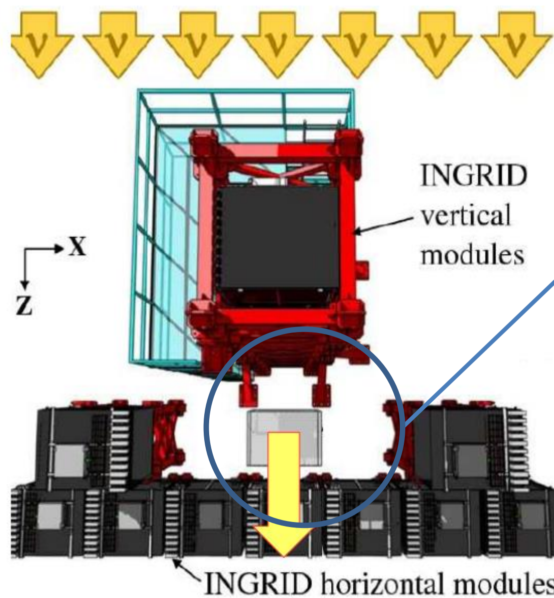


INGRID Modules: Stacks of scintillator bars interleaved with Iron sheets.

<u>Front View :</u>



<u>Top View :</u>



Proton Module: Fully active polycarbonate scintillator tracker.

ND280 (off axis)

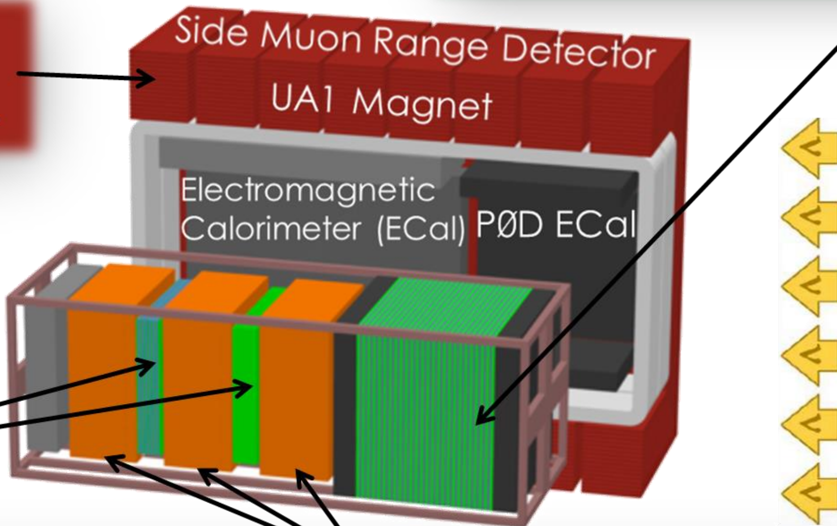
On Axis ~ 1.1 GeV

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.

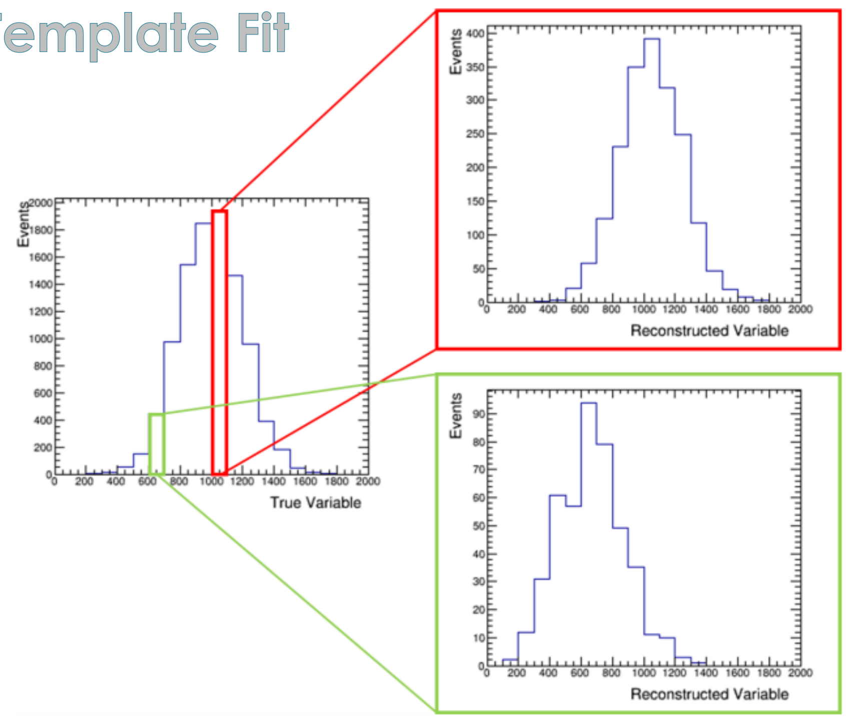
Time Projection Chambers (TPC): Excellent tracking allows high-resolution charged-particle momenta and accurate particle ID.

From Reconstruction to Truth

- Measure ***selected*** number of $CC0\pi$ events in bins of a ***reconstructed*** quantity
- Need the ***total*** number of $CC0\pi$ events in bins of a ***true*** quantity

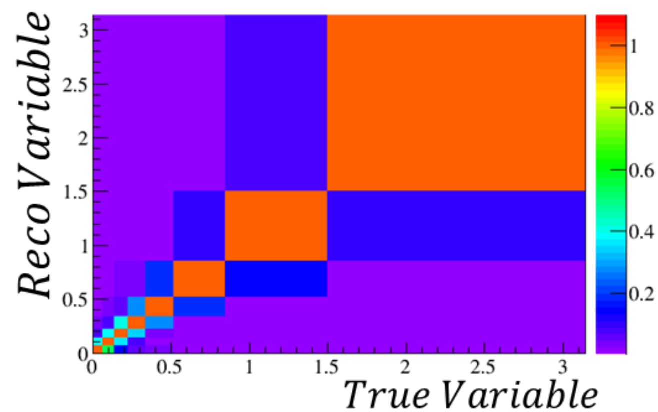
Two Methods

Template Fit



- True bin → Reco Template
- Vary MC template norm to fit data
- Apply efficiency correction

Matrix Unfold



- Use MC to build unsmearing matrix
- Apply unsmearing matrix + efficiency correction to data

Previously at NuFact

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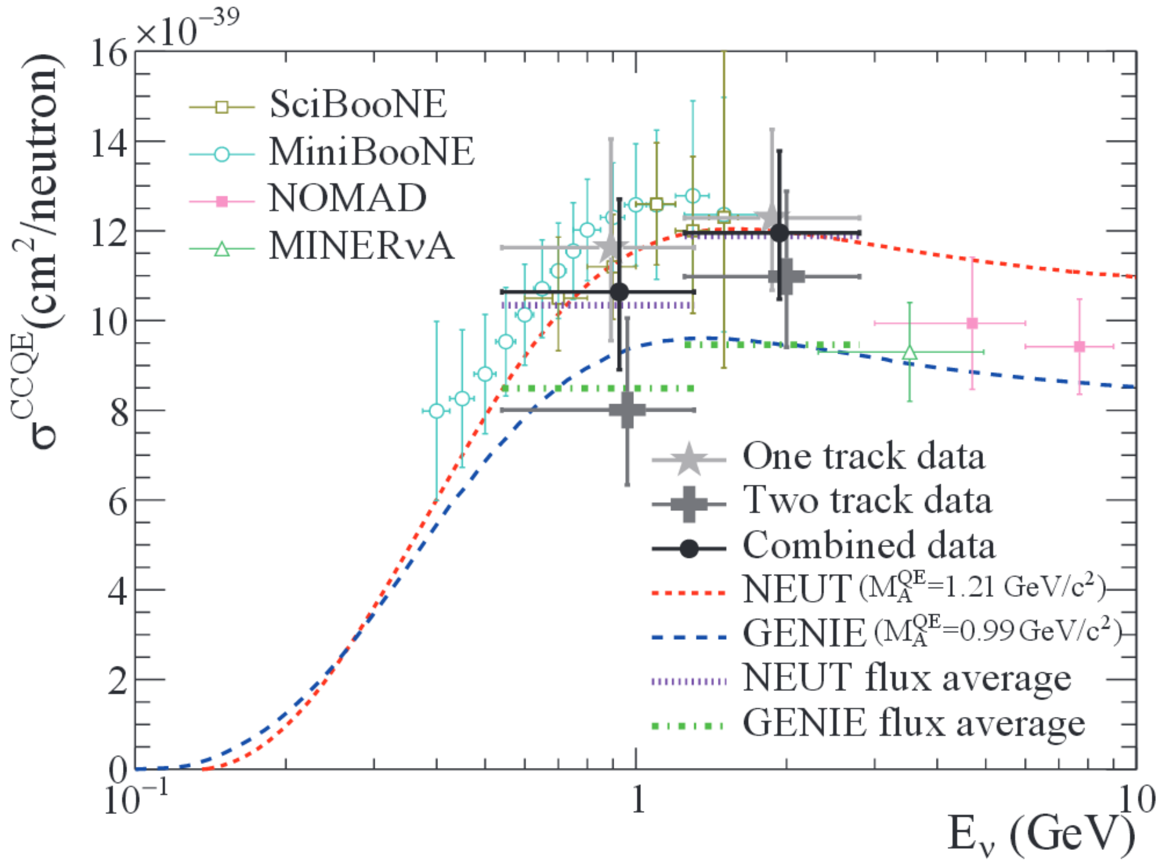
INGRID On-Axis CCQE Result

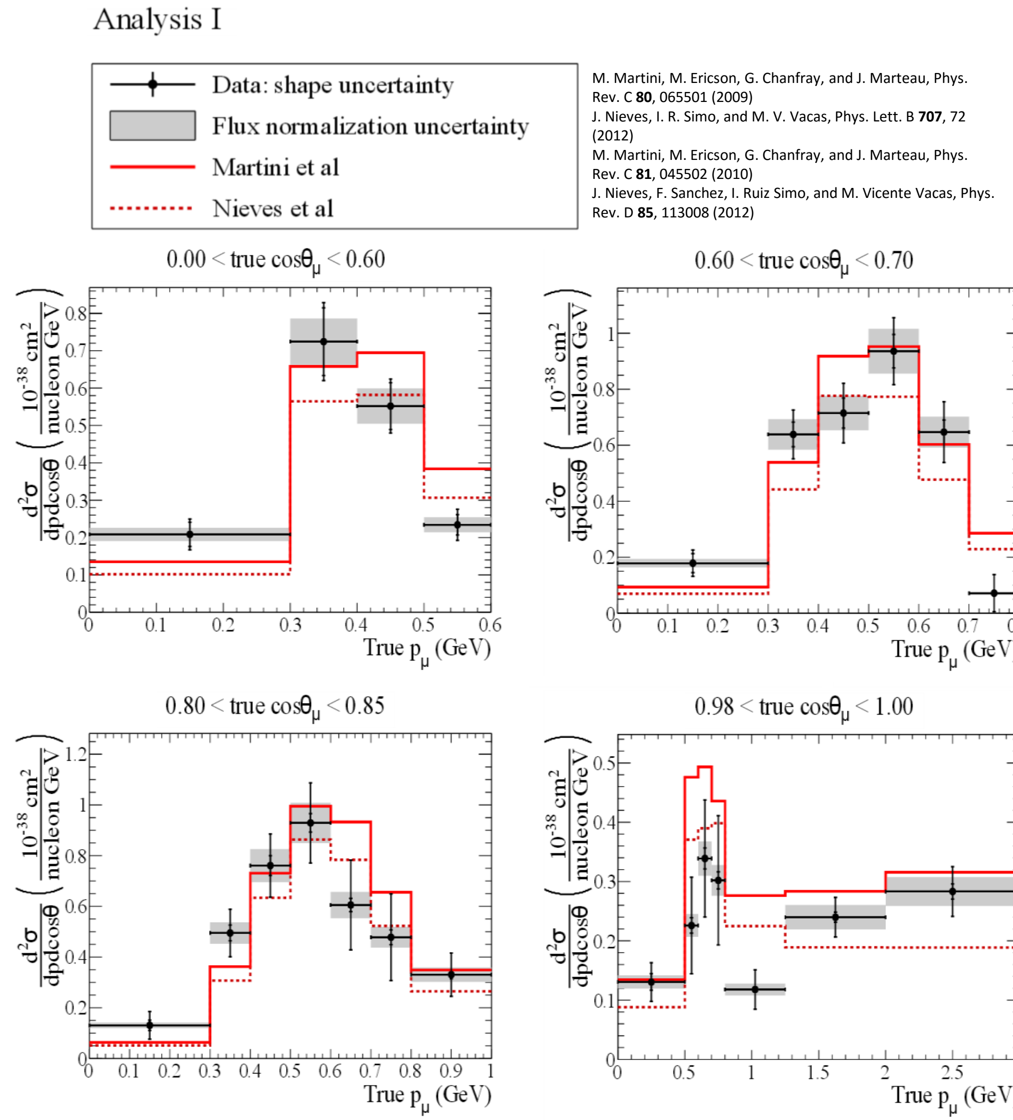
- Carbon Target
- 2-bin measurement in neutrino energy
- Split into 1- and 2-track samples
- Used cuts on muon and proton kinematic variables to enhance purity
- Result depends on nuclear model used and the presence of 2p2h



Detector: INGRID **Target:** Carbon **Signal:** CCQE **Unfolding**: N/A **Status:** Phys. Rev. D **91**, 112002

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 2p2h models

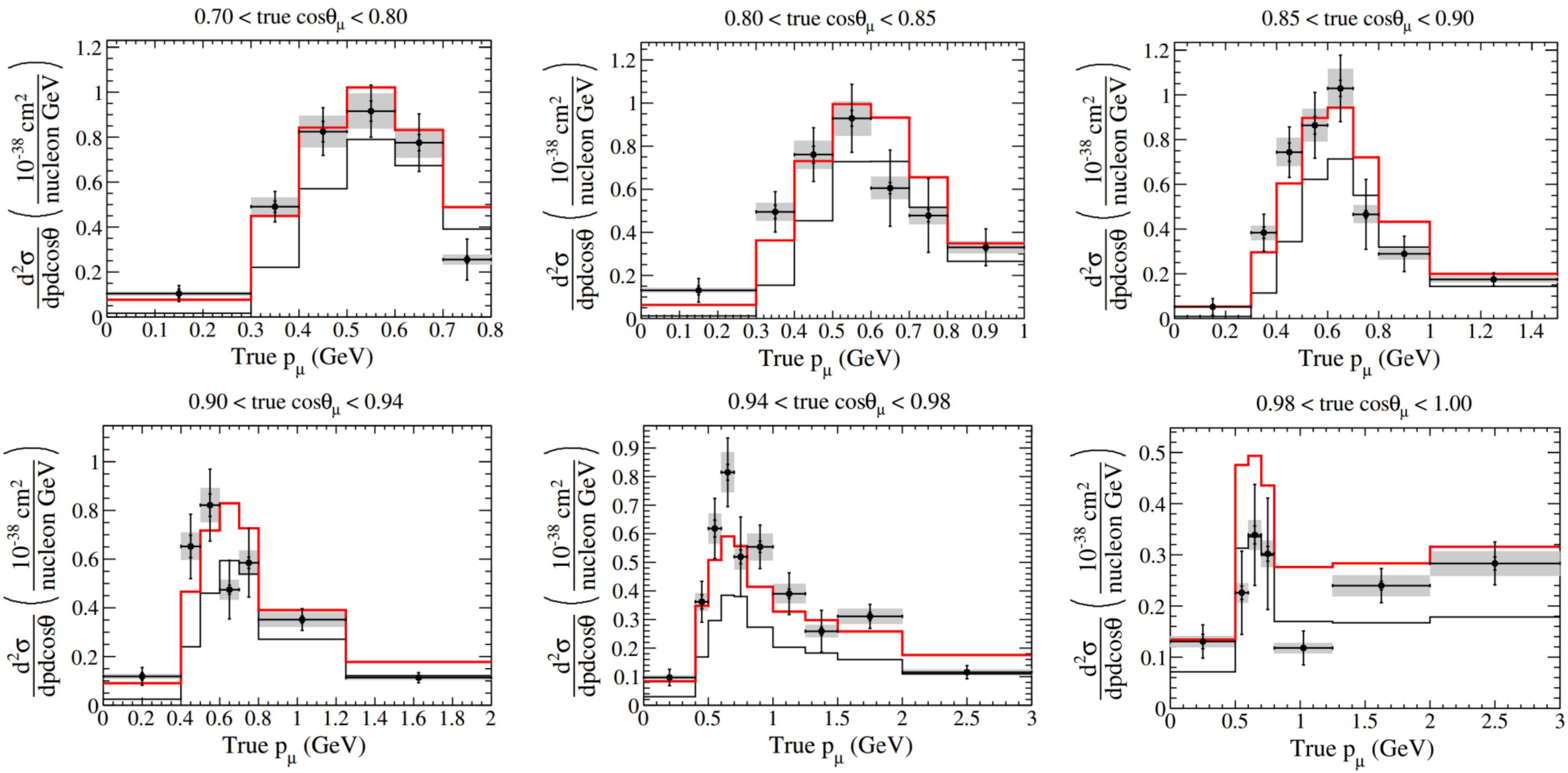


M. Martini, M. Ericson, G. Chanfray, and J. Marteau, Phys. Rev. C **80**, 065501 (2009)
J. Nieves, I. R. Simo, and M. V. Vacas, Phys. Lett. B **707**, 72 (2012)
M. Martini, M. Ericson, G. Chanfray, and J. Marteau, Phys. Rev. C **81**, 045502 (2010)
J. Nieves, F. Sanchez, I. Ruiz Simo, and M. Vicente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

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

ND280 Off-Axis CC0π Result

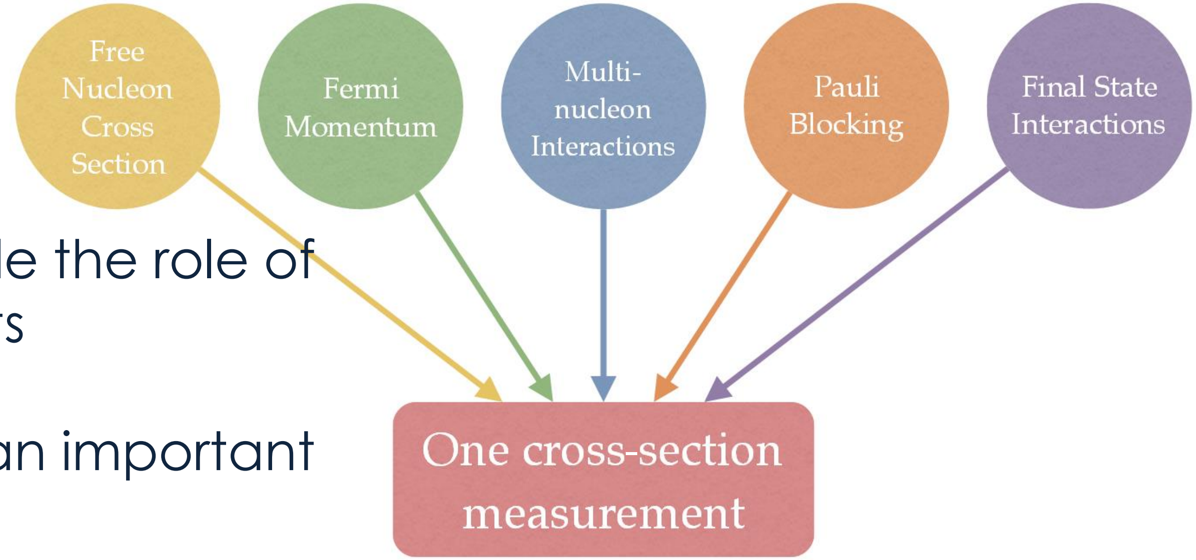
- Results compared to Martini *et al.* model **with(red)**/**without(black)** 2p2h
- Data prefer a 2p2h contribution



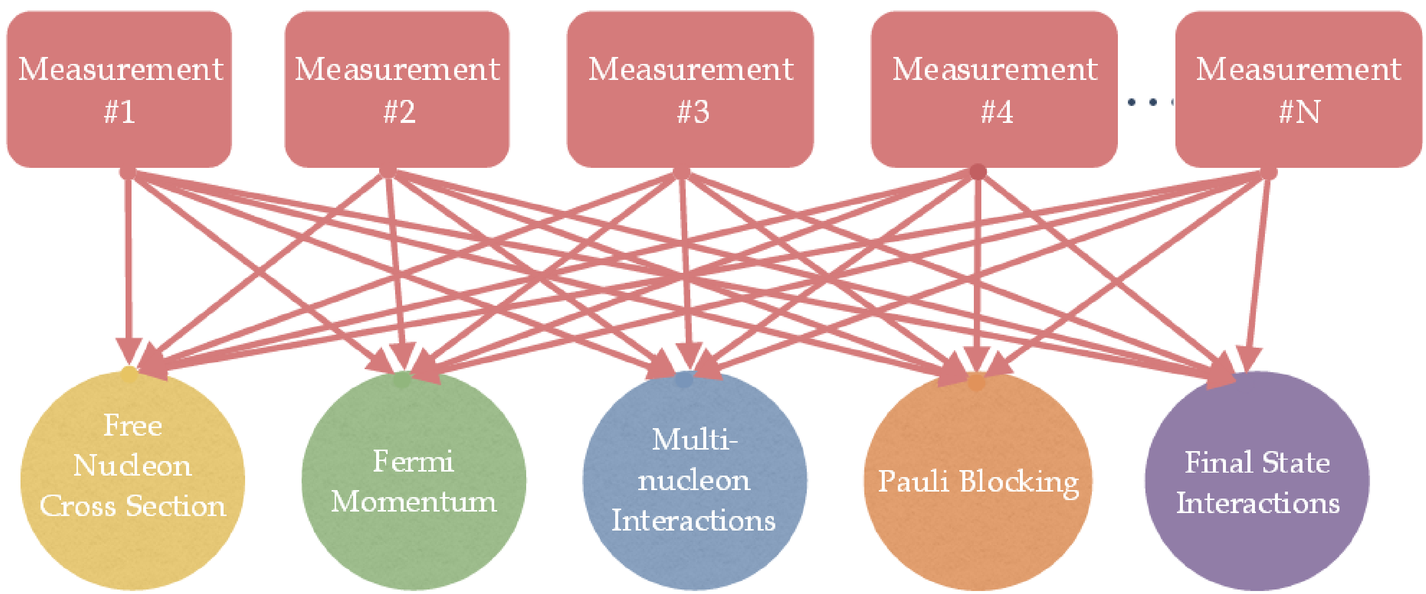
Detector: ND280 – FGD1 **Target:** Carbon **Signal:** CC0π **Unfolding**: Matrix + Fit **Status:** Phys. Rev. D **93**, 112012

What next?

- Would like to disentangle the role of separate nuclear effects
- Current results provide an important piece of the puzzle



- Now need complementary measurements …



Excellent diagrams by Laura Fields

Ongoing measurements

- **CC0π water cross section in muon kinematics**
  - Measure of A-scaling, invaluable for OA

New PØD analysis

- **CC0π measurement using muon + proton kinematics**
  - Enhanced sensitivity to nuclear effects
- **CC0π measurement using composite variables**
  - Imbalance between the proton and muon can be a precision probe of nuclear effects

FGD1 ongoing analyses using proton information

- **CC0π using INGRID proton module**
  - Model-independent measurement at higher E_ν
- **CC0π neutrino/anti-neutrino joint fit**
  - $\sigma_{np-nh}/\sigma_{CCQE}(E_\nu)$ is substantially different for ν_μ and $\bar{\nu}_\mu$
- **Measurement of free-nucleon cross section using δp_{TT}**

Other FGD1 / INGRID analyses

N.B: T2K employs a blind cross-section analysis strategy
- Ongoing or recently completed analyses not applied to real data (remain "blind")

PØD - CC0π on water

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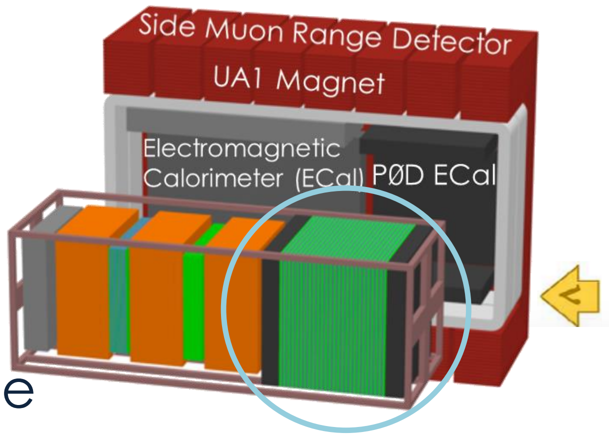
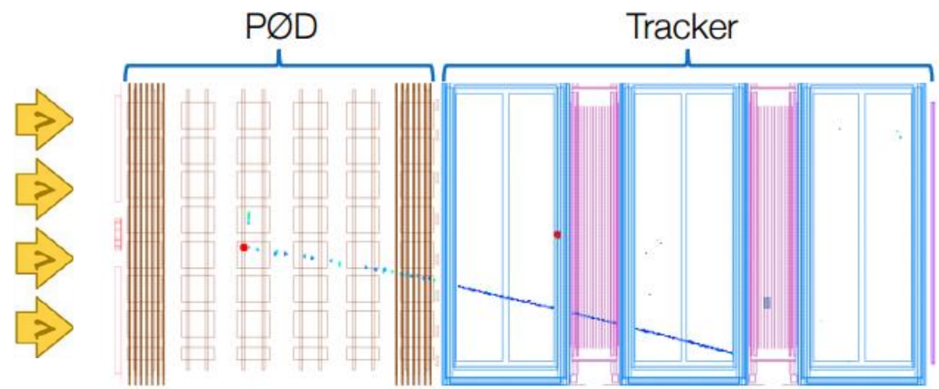


CC0π water cross section

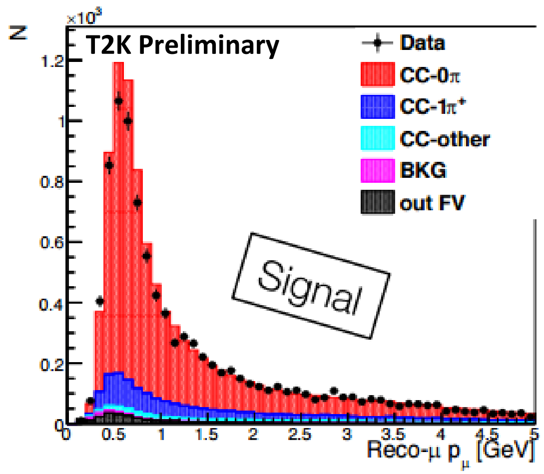
Contact:
Tianlu Yuan
tianlu.yuan@colorado.edu

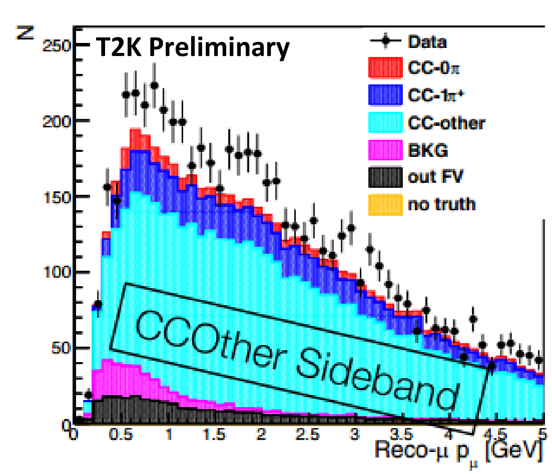
- Isolate CC0π events starting in the PØD
- Separate data taking periods into when PØD water target is full/empty → subtract to get water cross section



Event Selection

- Uses PØD as a target, requires TPC for tracking
- Aim to find single μ only
- Two control samples
  - **CC1π**: look for 2 PØD tracks and Michel e^-
  - **CCOther**: look for >2 PØD tracks



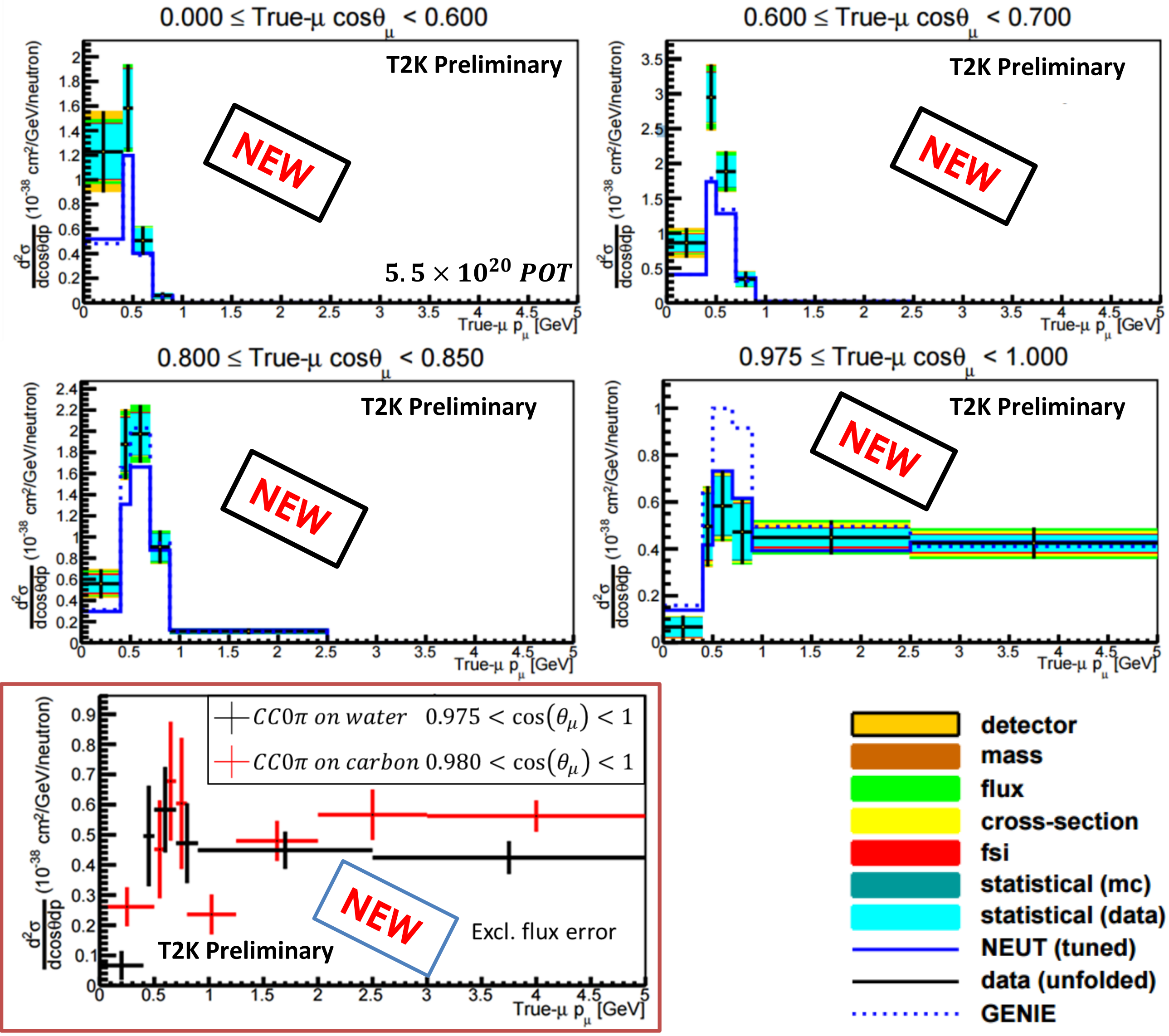


Detector: ND280 – PØD	**Target:** Water	**Signal:** CC0π	**Unfolding**: Matrix	**Status:** Unblind

CC0π water cross section

Contact:
Tianlu Yuan
tianlu.yuan@colorado.edu

- Construct flux integrated double-differential cross section
- Results compared to GENIE and NEUT predictions
- Can also compare to FGD1 CC0π on Carbon result
- Similar studies underway using FGD2 water layers to extract Oxygen:Carbon cross section ratio

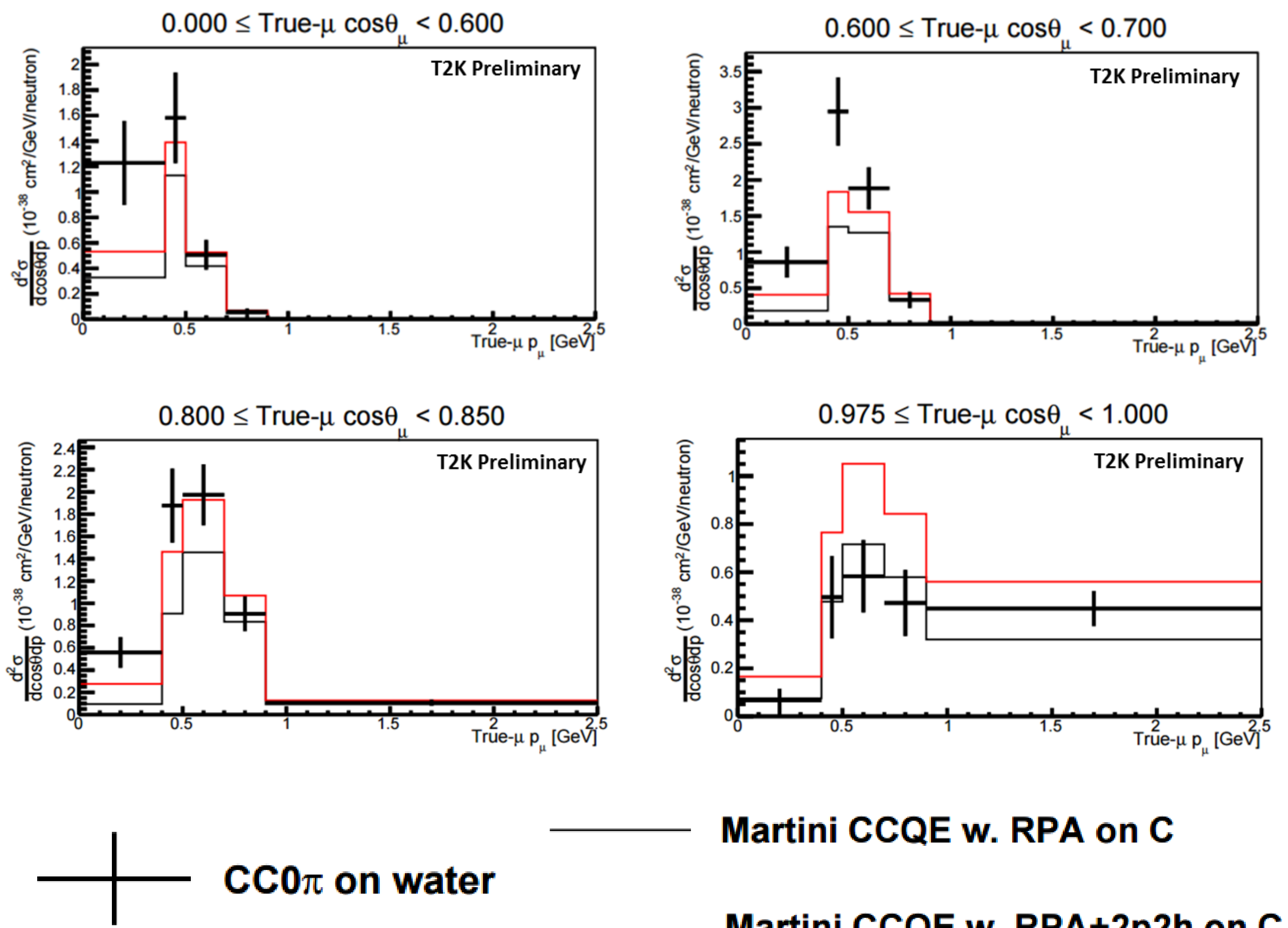


Detector: ND280 – PØD **Target:** Water **Signal:** CC0π **Unfolding**: Matrix **Status:** Unblind

CC0π water cross section

Contact:
Tianlu Yuan
tianlu.yuan@colorado.edu

- Compare results to RPA/RPA+2p2h on Carbon
- Data prefer 2p2h contribution
- Difficult to untangle role of A-Scaling



Detector: ND280 – PØD	**Target:** Water	**Signal:** CC0π	**Unfolding**: Matrix	**Status:** Unblind

FGD1 - CC0π + Np

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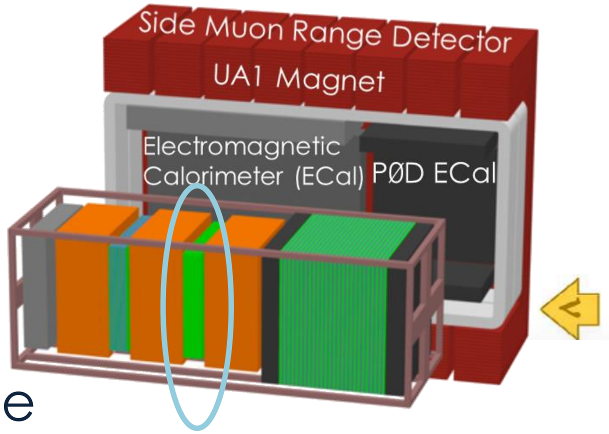
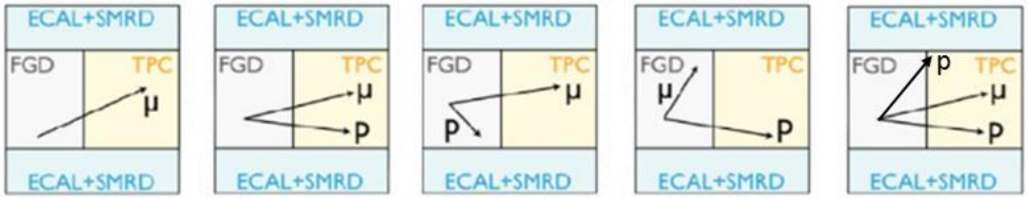


FGD1 CC0π Analyses

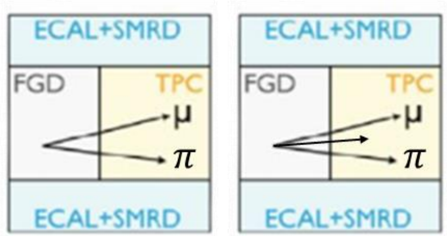
Signal



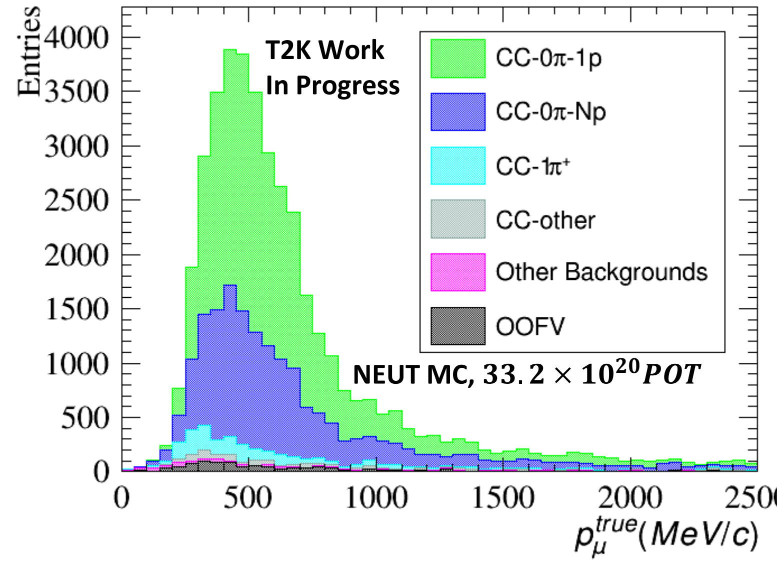
- Require one μ-like track or one μ-like and p-like track(s) starting in FGD1
- Use a Michel electron tag and ECal EM shower veto to reject 1π backgrounds
- Use of many samples gives wide kinematic acceptance

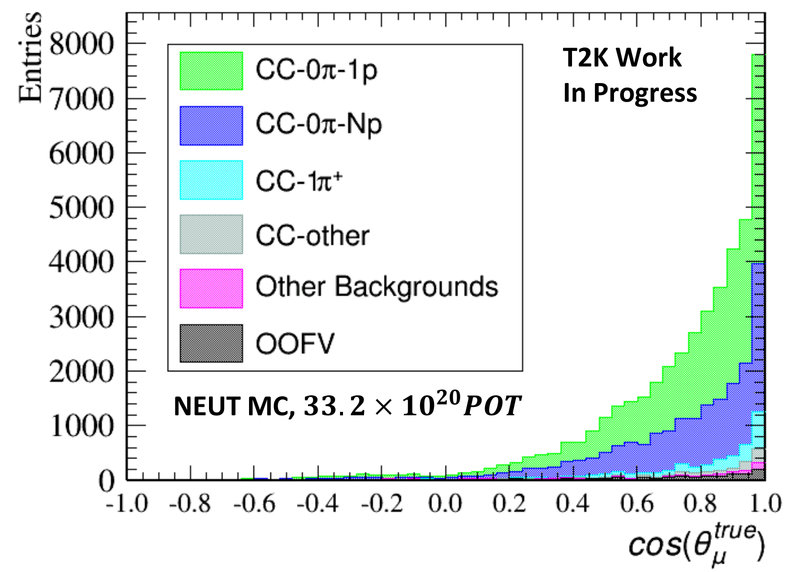
Sidebands

- Require extra π-like track(s)



CC1π CCOther

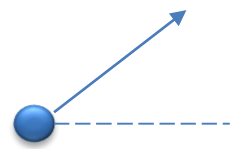


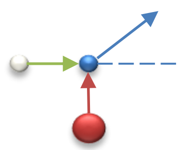


CC0π using $\mu + p$ kinematics

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

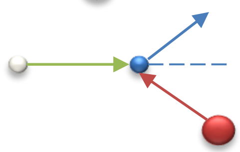
We may see a low-momentum, high-angle muon in a CC0π selection.



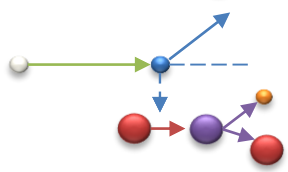


A low E_ν and transverse p_F

But this could come from …

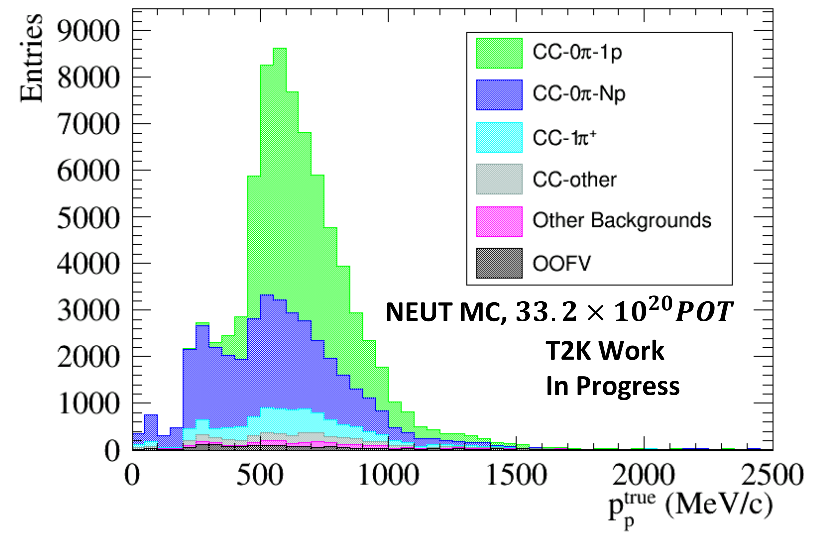


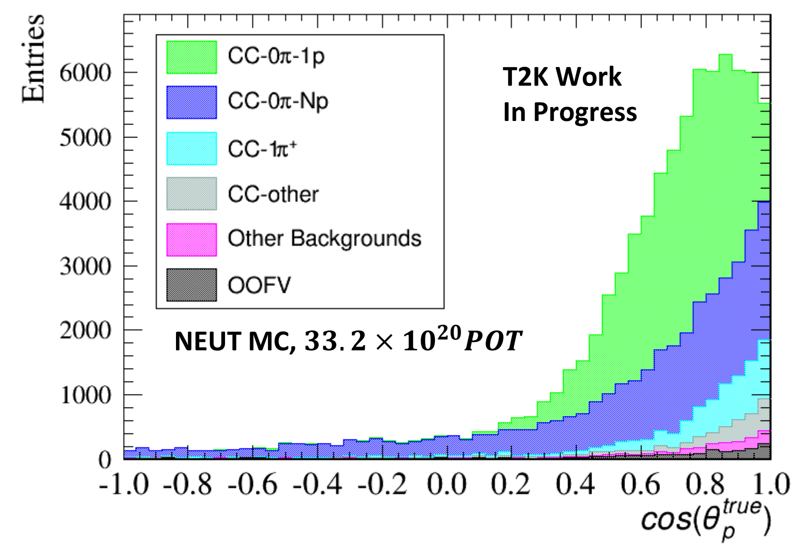
A high E_ν and large backward p_F



A high E_ν and large Q^2 → RES with π absorption

- Measuring p kinematics allows us to move beyond these assumptions





CC0π using $\mu + p$ kinematics

Contact:
Pierre Bartet
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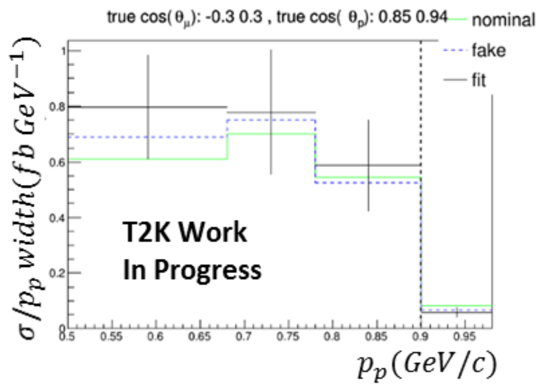
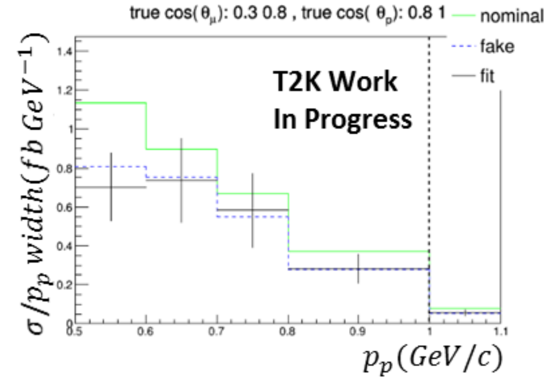
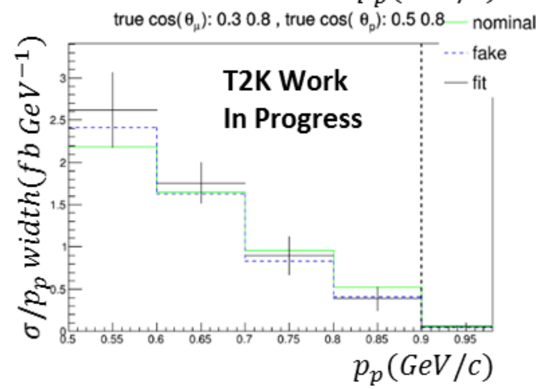
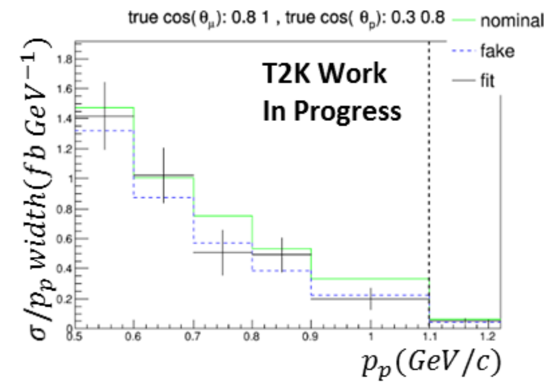
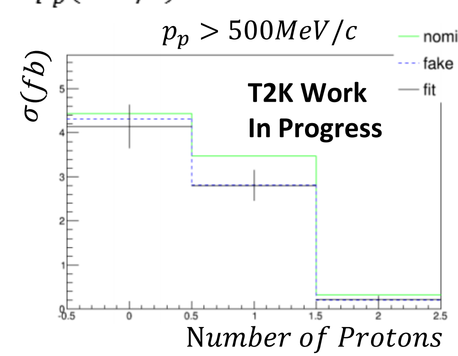
- Aim to measure CC0π cross section in bins of $\cos(\theta_\mu), \cos(\theta_p), p_p$ in samples with proton
- Use $\cos(\theta_\mu), p_\mu$ when no proton reconstructed
- Also measure proton multiplicity
- Construct flux-integrated double/triple-differential cross-section
- Fake data: GENIE*
- Nominal MC: NEUT











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

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

CC0π and inferred kinematic imbalance

Contact:
Jiae Kim
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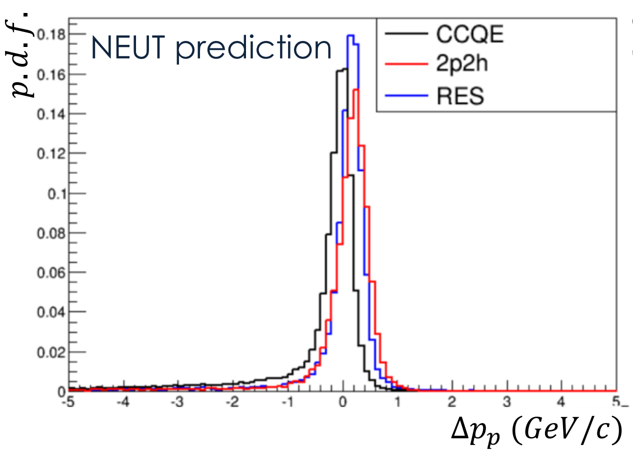
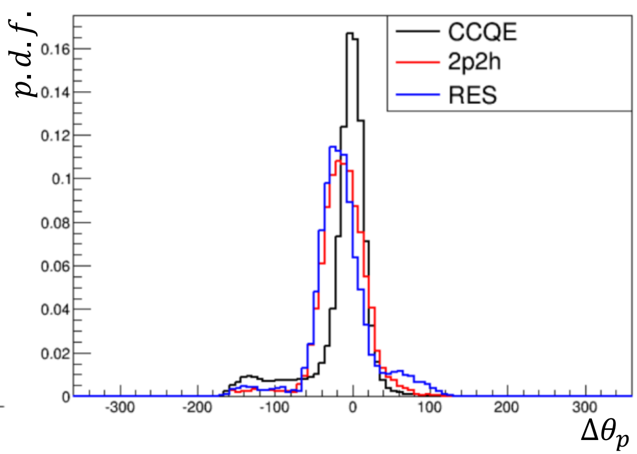
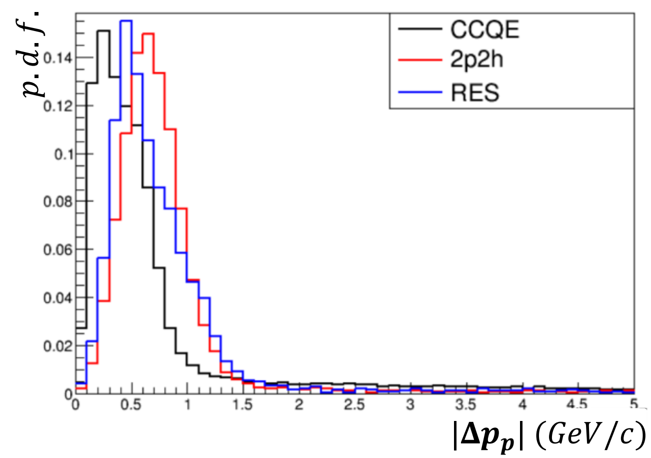
- Can use proton and muon kinematics to form variables specifically engineered to probe nuclear effects
- Under **stationary target** and **elastic scattering** assumptions can infer proton kinematics from measured μ
- Non-zero imbalance between inference and measured proton indicates presence of nuclear effects or CC-non-QE interaction
- Measure:







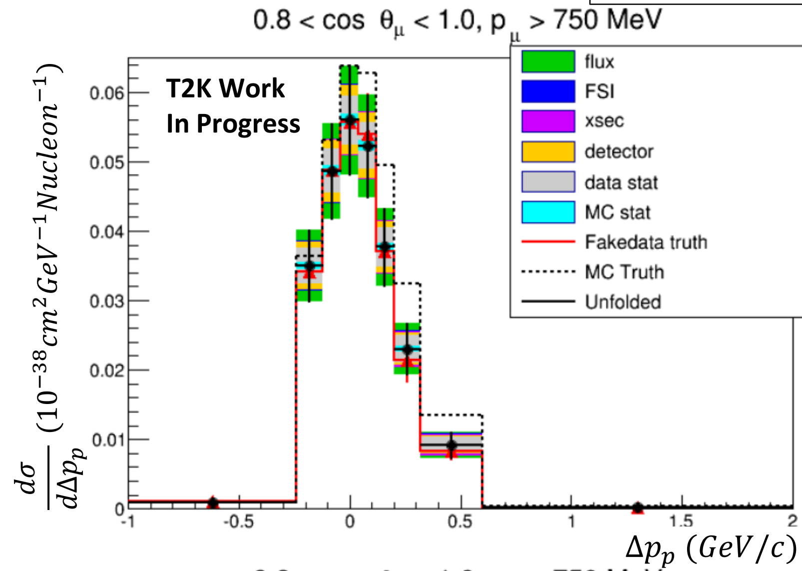
$\Delta p_p = |\boldsymbol{p}_p^{inferred}| - |\boldsymbol{p}_p^{measured}|$ $\Delta\theta_p = \theta_p^{inferred} - \theta_p^{measured}$ $|\Delta\boldsymbol{p}_p| = |\boldsymbol{p}_p^{inferred} - \boldsymbol{p}_p^{measured}|$

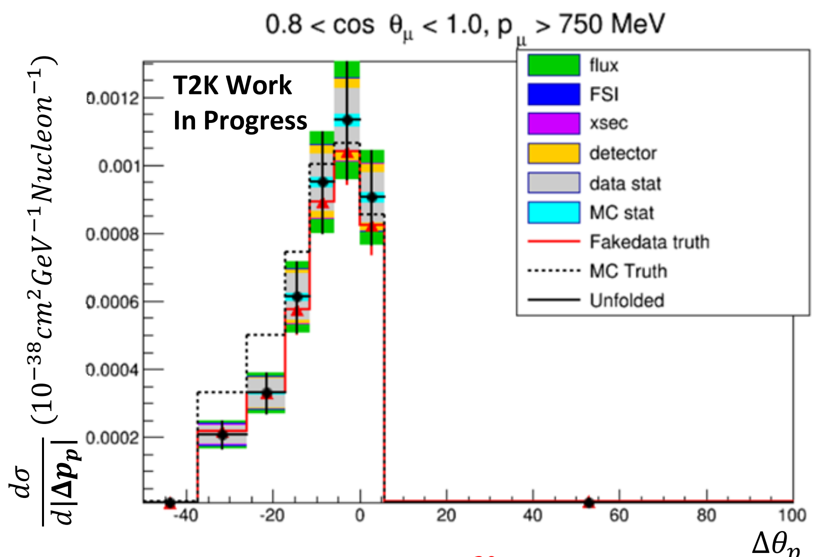
Detector: ND280 – FGD1 **Target:** Carbon **Signal:** CC0π+Np **Unfolding**: Matrix **Status:** Blind

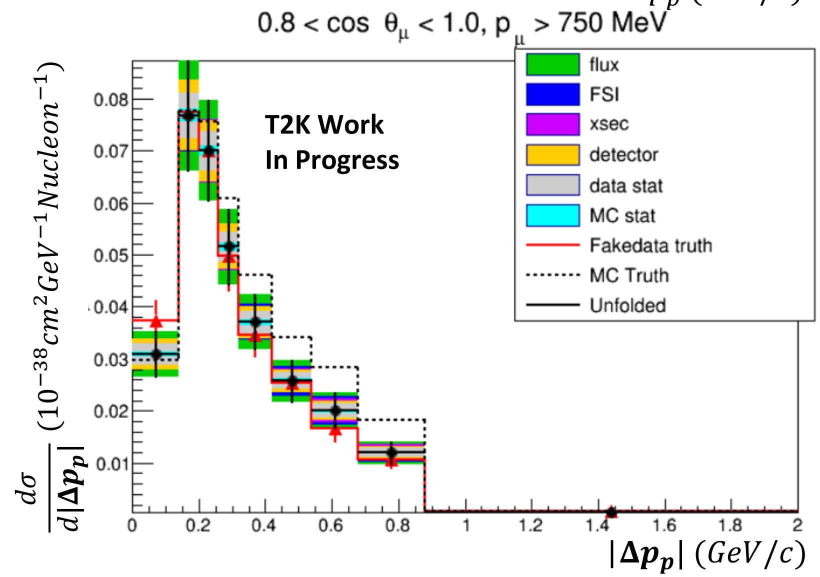
CC0π and inferred kinematic imbalance

Contact:
Jiae Kim
jiae@phas.ubc.ca

- CC1π sideband using Michel e^- tag
- Measure inferred kinematics in bins of $p_\mu, \cos(\theta_\mu)$
- Fake data: GENIE*
- Nominal MC: NEUT



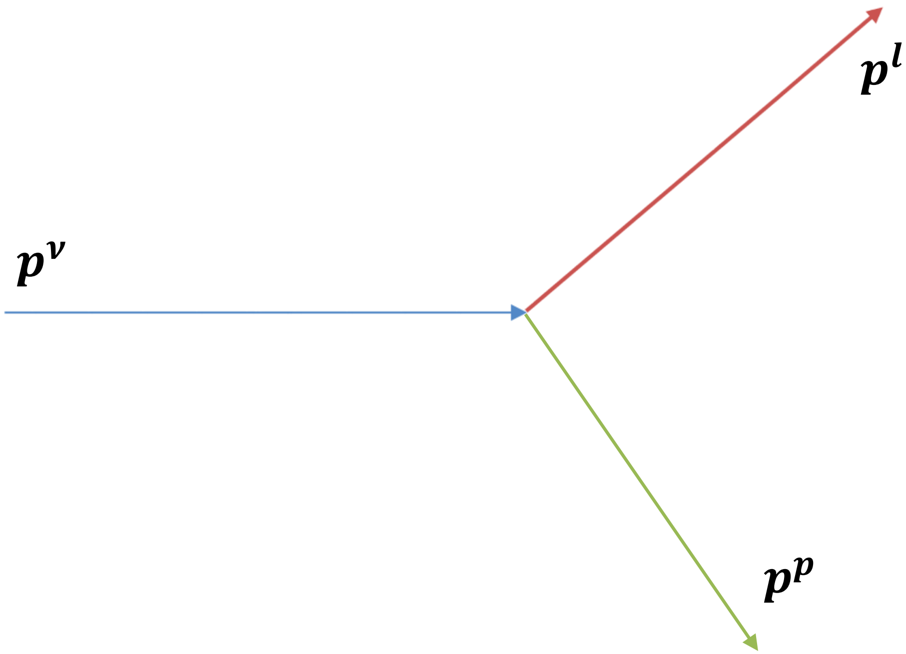


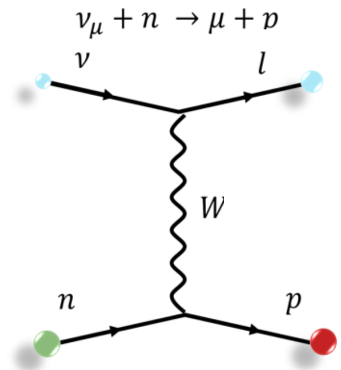


* GENIE fake data contains 5.73×10^{20} POT ~T2K runs 2-4

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

Single Transverse Variables

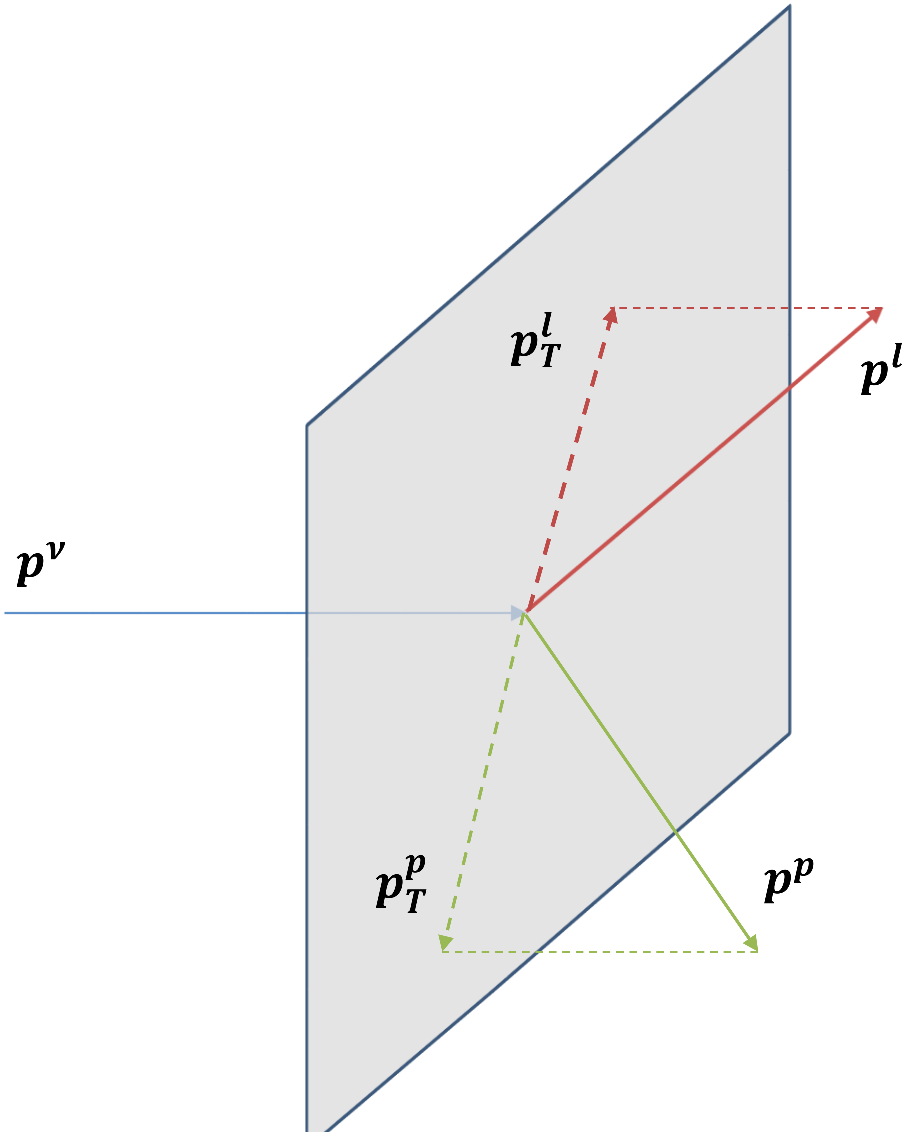


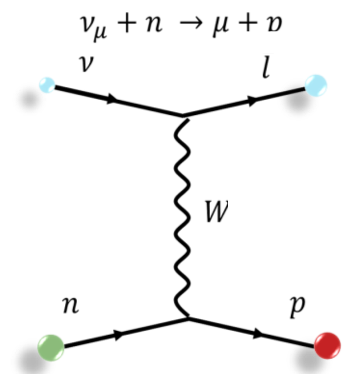


No nuclear Effects

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

Single Transverse Variables



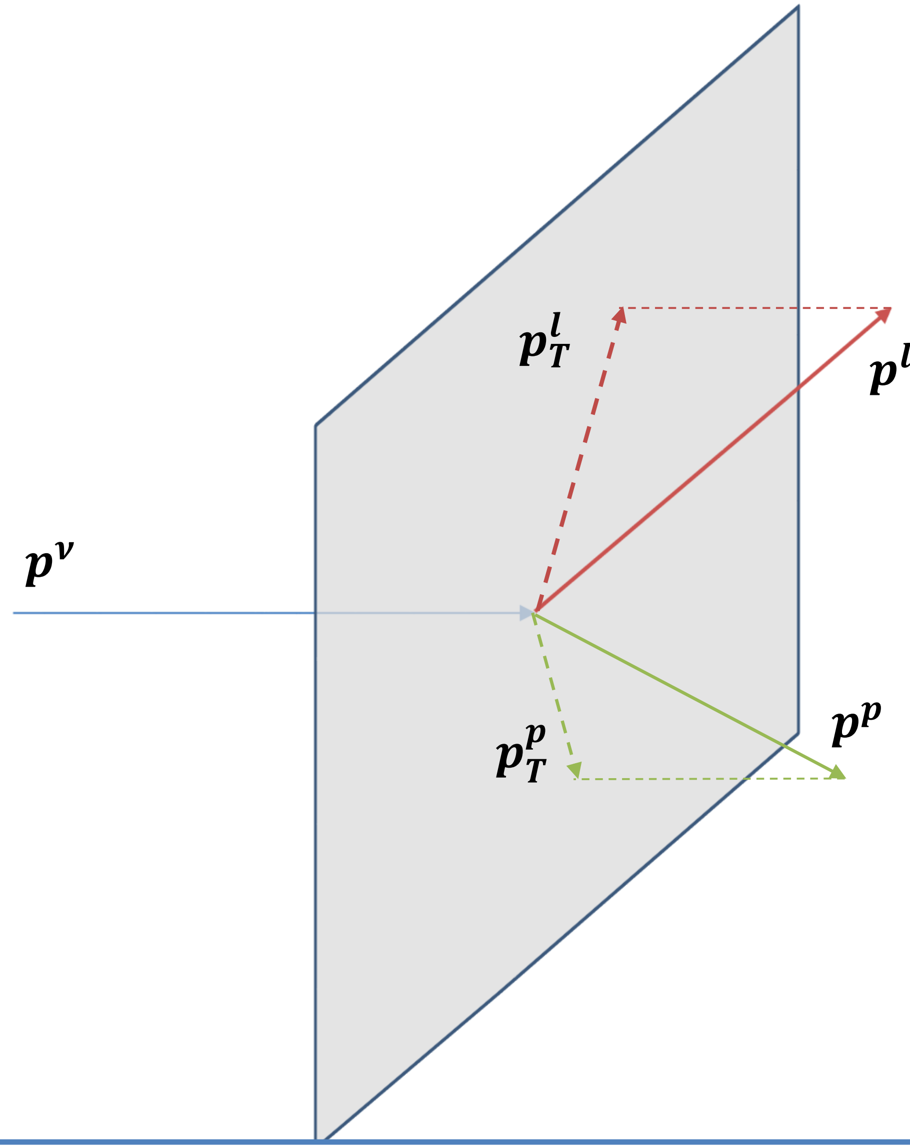


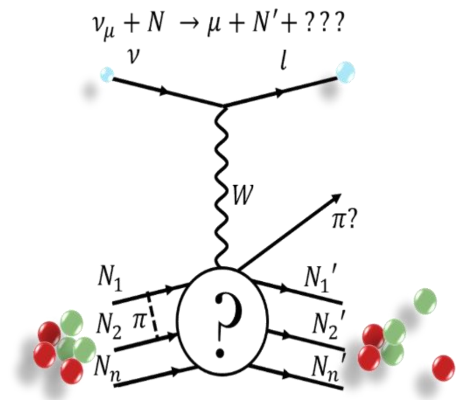
No nuclear Effects

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

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

Single Transverse Variables



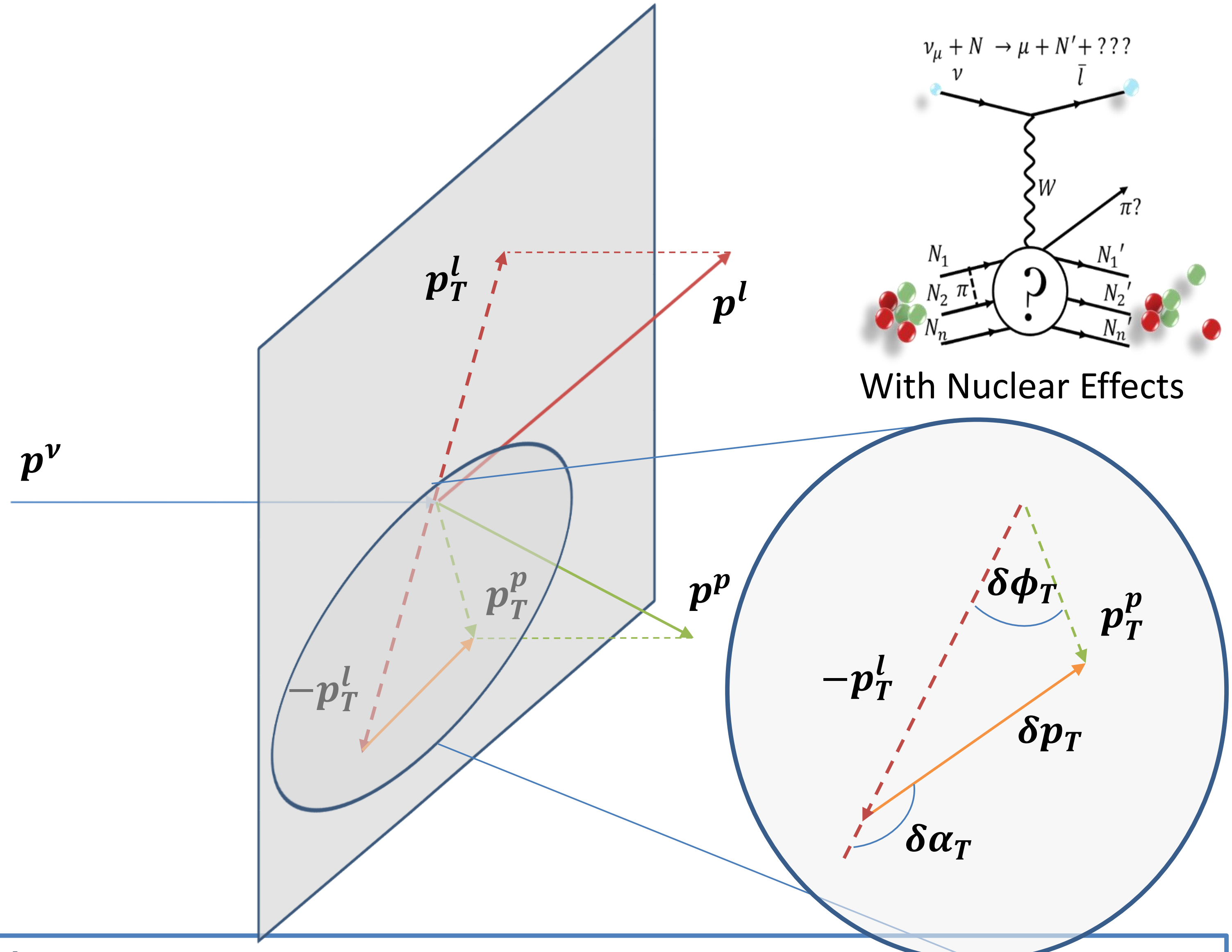


With Nuclear Effects

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

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

Single Transverse Variables



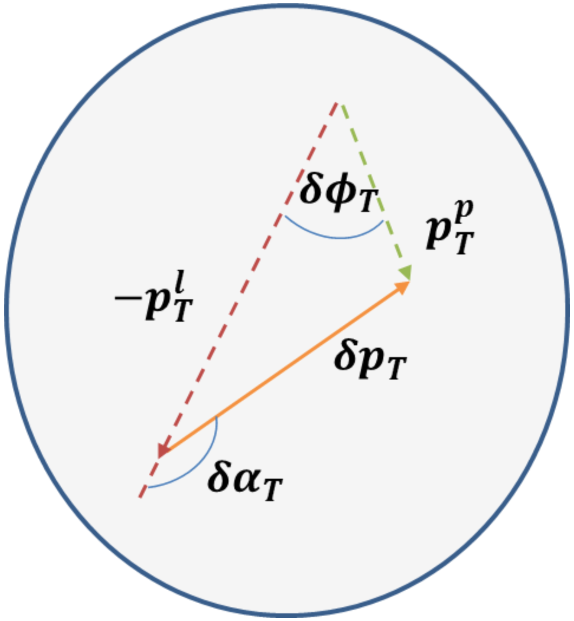
Detector: ND280 – FGD1 **Target:** Carbon **Signal:** CC0π+Np **Unfolding**: Fit **Status:** Blind

CC0π and transverse imbalance

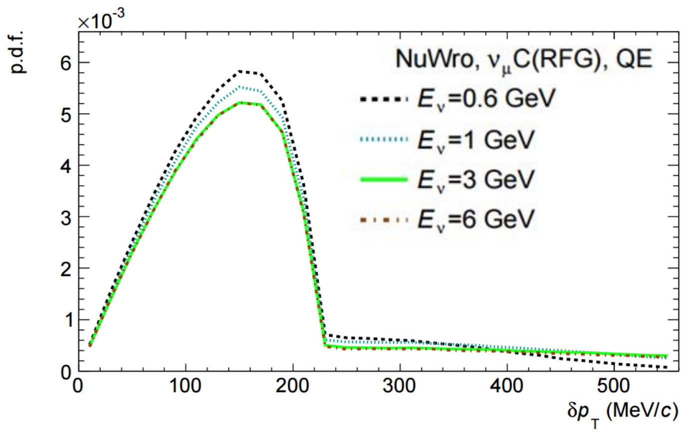
Contact:
Stephen Dolan
s.dolan@physics.ox.ac.uk

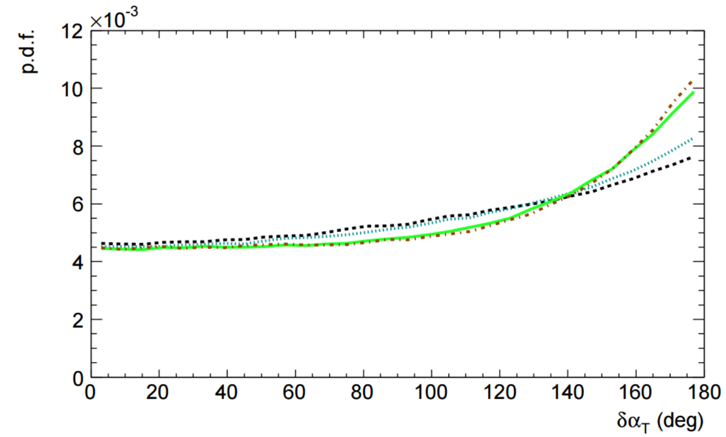
- 3 single transverse variables (STV) characterise imbalance in plane transverse to incoming ν *

- For CCQE case any deviation from $\delta p_T = 0$, $\delta\phi_T = 0$ is indicative of nuclear effects



- Minimal dependence on E_ν for δp_T and $\delta\alpha_T$



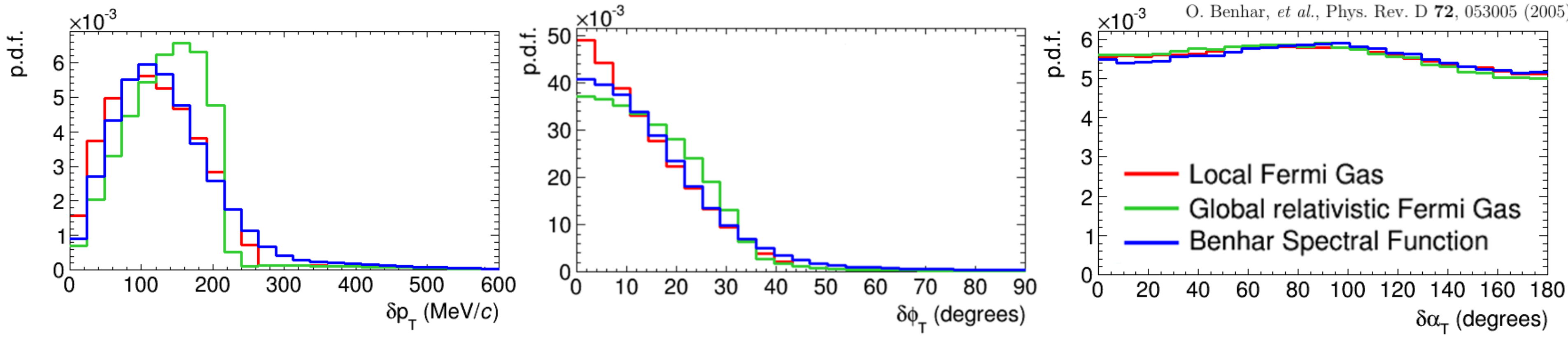


*Phys. Rev. C **94**, 015503

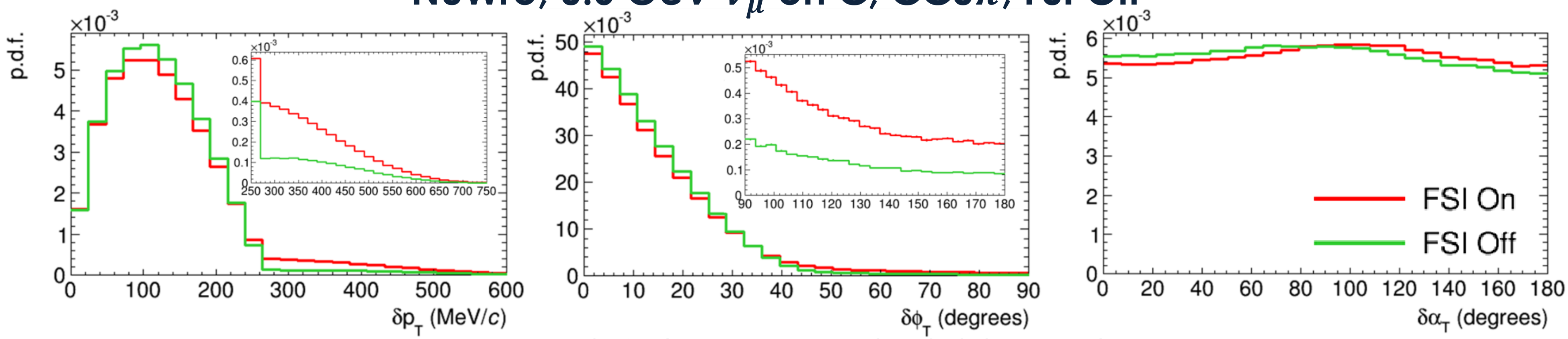
Detector: ND280 – FGD1	**Target:** Carbon	**Signal:** CC0π+Np	**Unfolding**: Fit	**Status:** Blind

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

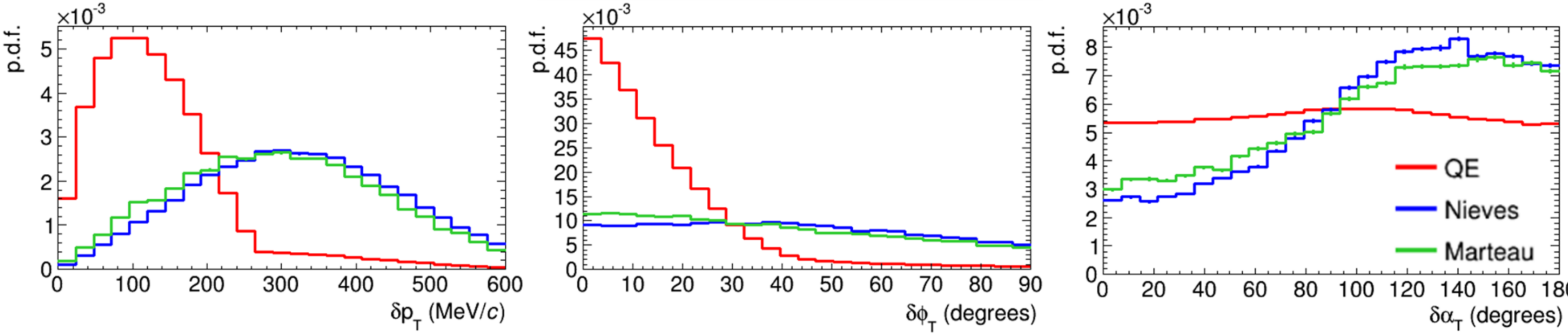
Quasi-real CC0Pi selection, keep events within rough ND280 acceptance :

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

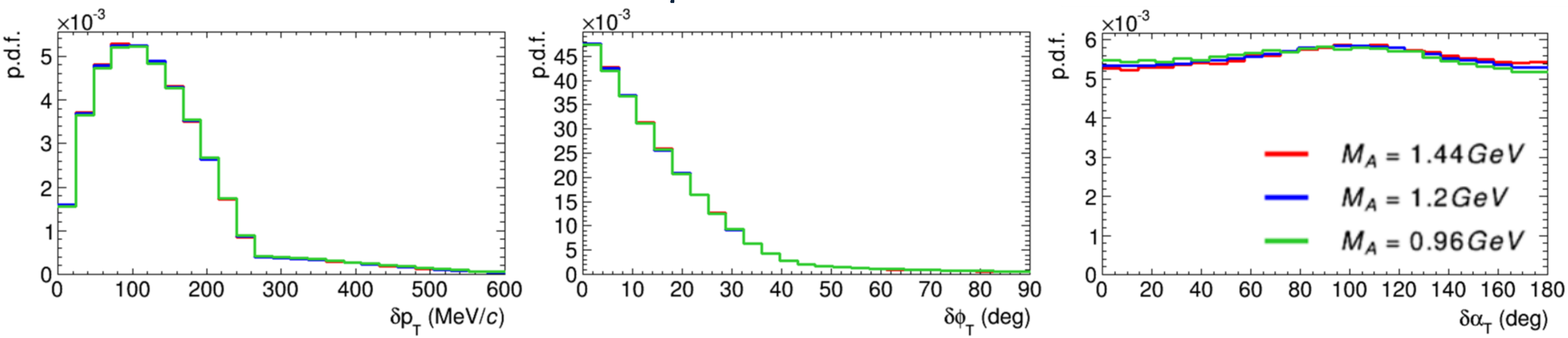
Detector: ND280 – FGD1 **Target:** Carbon **Signal:** CC0π+Np **Unfolding**: Fit **Status:** Blind

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

CC0π in STV

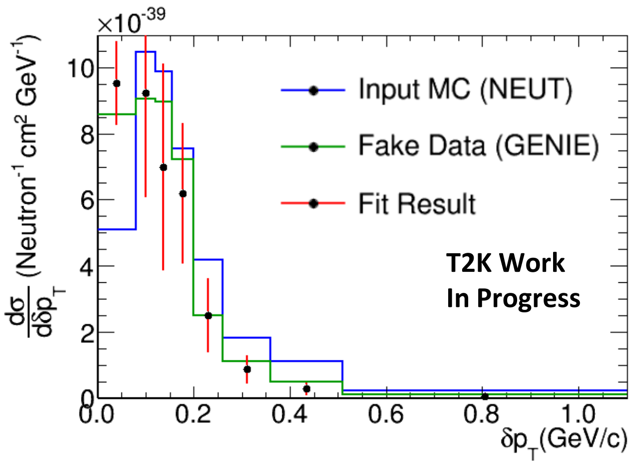
Contact:
Stephen Dolan
s.dolan@physics.ox.ac.uk

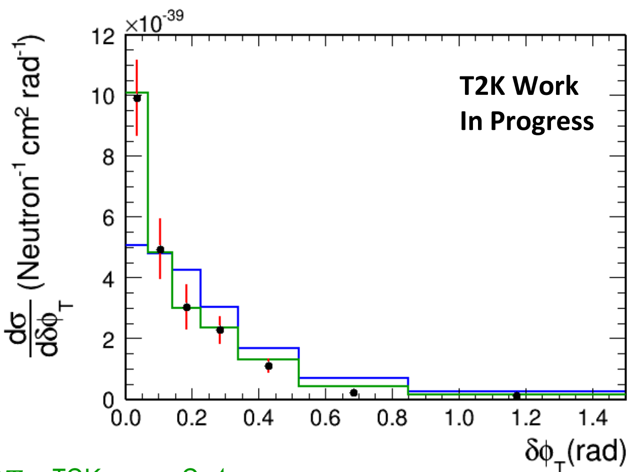
- Restrict cross section to ND280 acceptance

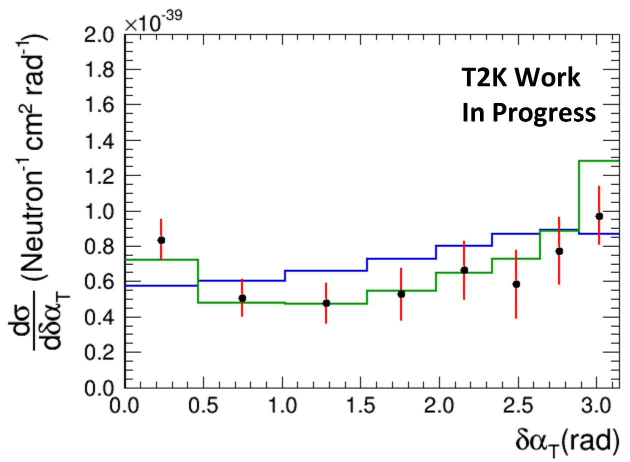
$$\left\{ \begin{array}{l} p_\mu > 250\ MeV/c \\ \cos(\theta_\mu) > -0.6 \\ 450\ MeV/c < p_\mu < 1\ GeV/c \\ \cos(\theta_p) > 0.4 \end{array} \right.$$

- Use a regularised template fit to unfold
  - Useful to deal with large STV smearing
  - Regularisation insists cross-sections should be smooth

- Fake data: GENIE*
- Nominal MC: NEUT





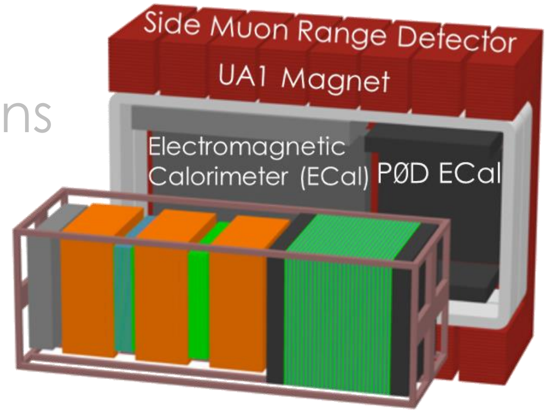


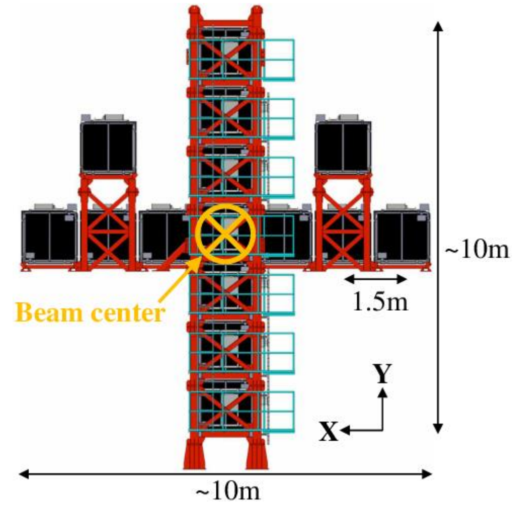
* GENIE fake data contains 5.73×10^{20} POT ~T2K runs 2-4

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

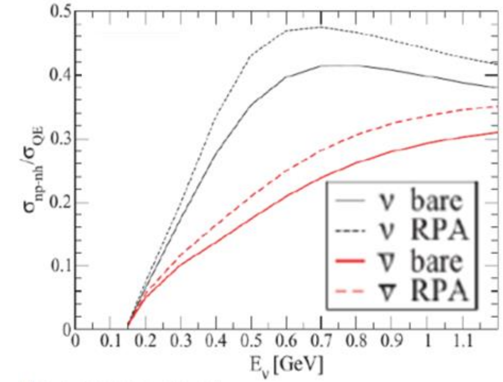
FGD - CC0π + Np

- The T2K experiment
- Motivation for measuring CCQE-like cross sections
- Flux and near detectors' details
- NuFact 15 recap
- CC0π on water cross section using the PØD
- FGD1 analyses using proton information
  - CC0π using proton kinematics
  - CC0π using inferred kinematic imbalance
  - CC0π using transverse kinematic imbalance
- Other analyses
  - CC0π measurements from $\nu + \bar{\nu}$ joint fit
  - CC0π at INGRID
  - Extraction of free nucleon cross section using δp_{TT}
- Summary and future work





Other Analyses



- **CC0π $\nu + \bar{\nu}$ joint fit**

  Contact: Ciro Riccio, **riccioc@na.infn.it**

  - 2p2h contribution is different for ν and $\bar{\nu}$ *
  - Aim to extract $\bar{\nu}$ double-differential cross section in $p_\mu, \cos(\theta_\mu)$ with $\nu + \bar{\nu}$ sum, difference, asymmetry

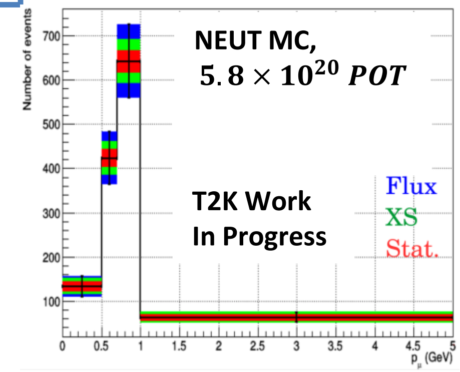
Detector: ND280 – FGD1 **Target:** Carbon **Signal:** CC0π **Unfolding**: Fit **Status:** Blind

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

- **INGRID CC0π Analysis**

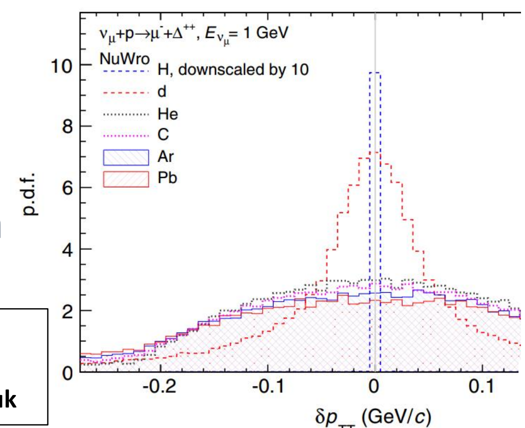
  Contact: Benjamin Quilain, **quilain@llr.in2p3.fr**

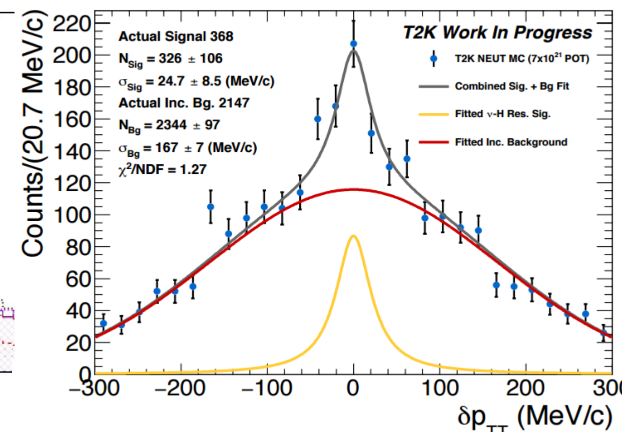
  - Extract CC0π on Carbon in $p_\mu, \cos(\theta_\mu)$ in proton module ($E_\nu^{peak} \sim 1.2\ GeV$)
  - Complements similar FGD1 analysis ($E_\nu^{peak} \sim 0.6\ GeV$)



Detector: INGRID **Target:** Carbon **Signal:** CC0π **Unfolding**: Matrix **Status:** Blind

- **CC1π1p on hydrogen**
  - Use δp_{TT} to isolate H in composite target **
  - Measure Δ^{++} production
  - Free of nuclear effects





** XG Lu:
PHYSICAL REVIEW. D **92**, 051302(R)

Contact:
David Coplowe,
david.coplowe@lmh.ox.ac.uk

Detector: ND280 – FGD1 **Target:** Hydrogen **Signal:** CC1π1p **Unfolding**: Fit **Status:** Blind

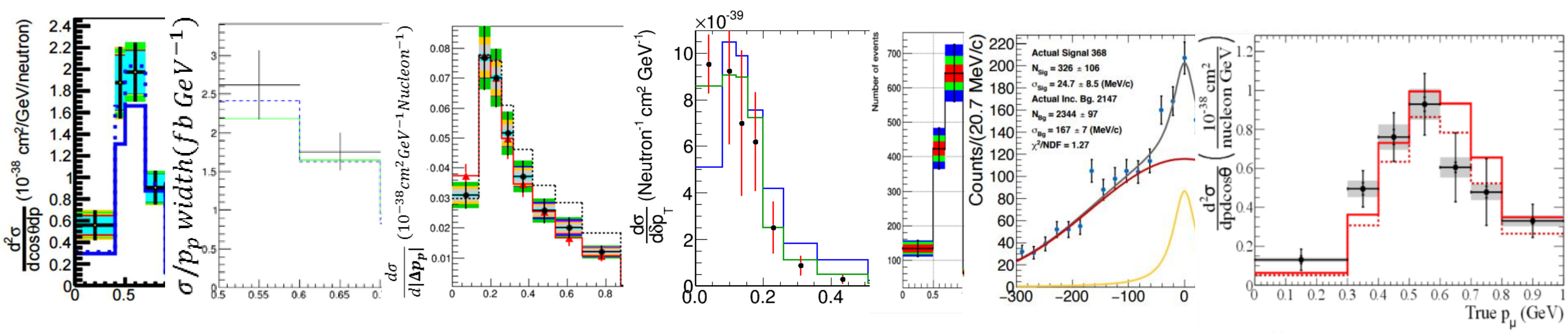
Summary

- T2K is measuring cross-sections of exclusive final-state topologies
  - This talk: CC0π
  - Talk by Erez Reinherz-Aronis: CCInc, CC1π+, NCE (WG2, Friday, 10:45)

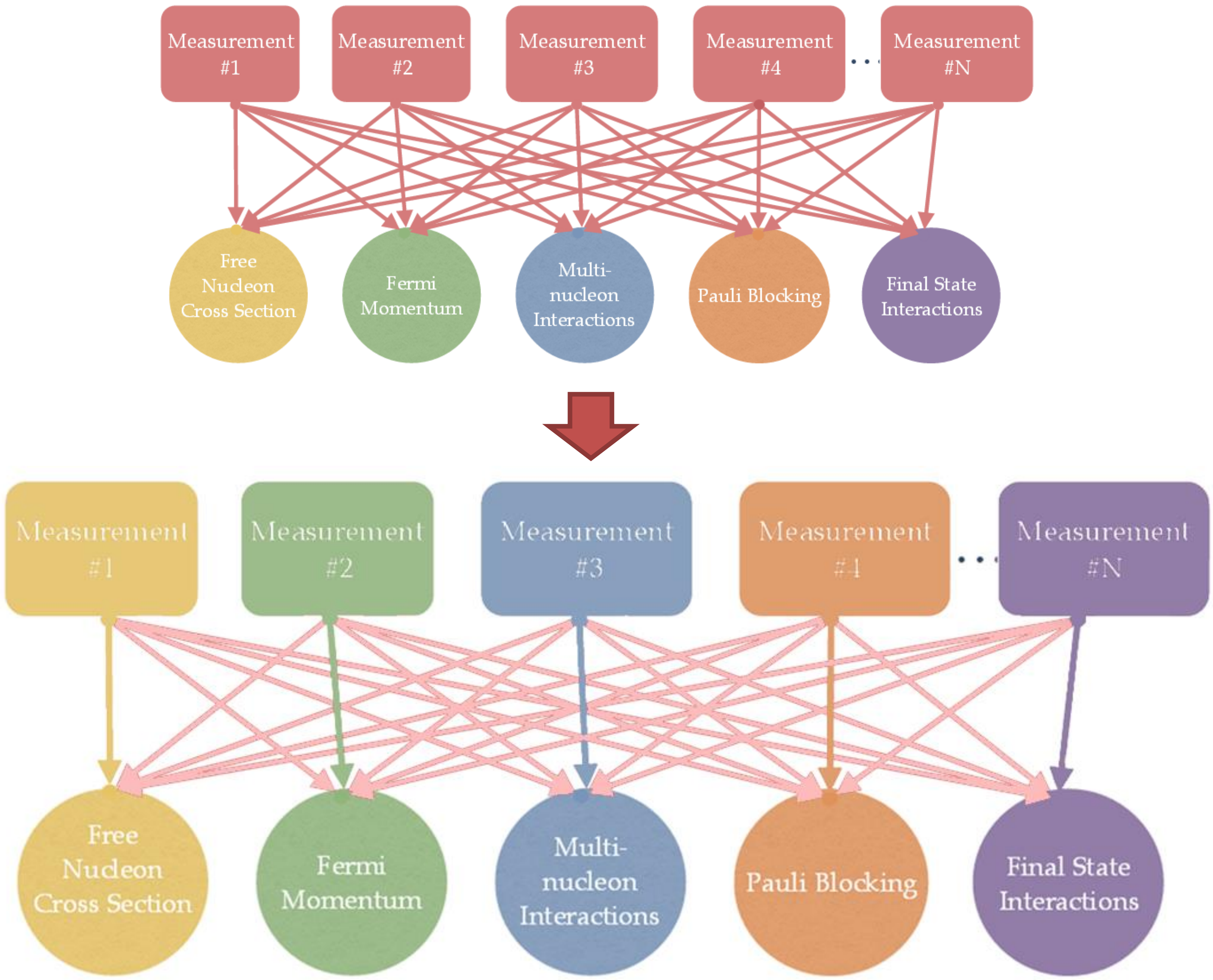
- Lots going on in T2K cross-section analyses – many results coming soon!

- First CC0π water cross section has been measured

- Many new techniques in use to complement each other and existing results
  - Analyses specifically engineered to probe nuclear effects



The Future



Measurement #1
Measurement #2
Measurement #3
Measurement #4
Measurement #N
Free Nucleon Cross Section
Fermi Momentum
Multi-nucleon Interactions
Pauli Blocking
Final State Interactions
Measurement #1
Measurement #2
Measurement #3
Measurement #4
Measurement #N
Free Nucleon Cross Section
Fermi Momentum
Multi-nucleon Interactions
Pauli Blocking
Final State Interactions

Thank you for listening

cảm ơn

Ongoing measurements

- **CC0π water cross-section in muon kinematics**
  - Measure of A scaling, invaluable for OA

Detector: ND280 – PØD	**Target:** Water	**Signal:** CC0π	**Unfolding**: Matrix	**Status:** Unblind

- **CC0π measurement using muon + proton kinematics**
  - Enhanced sensitivity to nuclear effects

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

- **CC0π measurement using inferred kinematics**
  - Imbalance as a precision probe of nuclear effects

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

- **CC0π measurement using STV**
  - Imbalance as a precision probe of nuclear effects

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

- **CC0π using INGRID proton module**
  - Model independent measurement at higher E_ν

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

- **CC0π neutrino/anti-neutrino joint fit**
  - $\sigma_{np-nh}/\sigma_{CCQE}(E_\nu)$ is substantially different for ν_μ and $\bar{\nu}_\mu$

Detector: INGRID	**Target:** Carbon	**Signal:** CC0π	**Unfolding**: Matrix	**Status:** Blind

- **Measurement of free-nucleon cross-section using δp_{TT}**

Detector: ND280 – FGD1	**Target:** Hydrogen	**Signal:** CC1π1p	**Unfolding**: Fit	**Status:** Blind

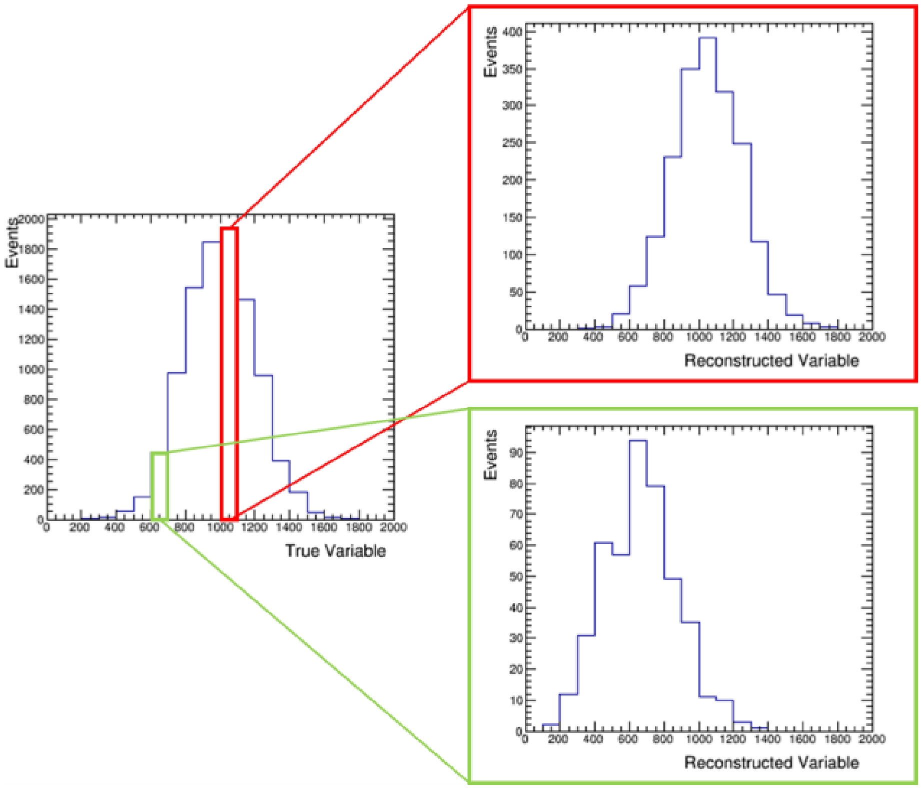
New PØD analysis

Ongoing FGD1 analyses using proton information

Other FGD1 / INGRID analyses

BACKUPS

Likelihood Fitting



- Each true bin has some template in reconstructed bins.
- Varying the number of events in a true bin applies a normalisation factor to the corresponding recon template.
- Vary templates until reconstructed distribution best fits the data

- I.e minimise: $\chi^2_{stat} = \sum_{j}^{recobins} 2(N_j^{MC} - N_j^{obs} + N_j^{obs} ln \frac{N_j^{obs}}{N_j^{MC}})$

Fitting summary

- The best fit parameters are those that minimise the following likelihood:

$$\chi^2 = \chi^2_{stat(fit\,goodness)} + \chi^2_{syst(penalty)} + \chi^2_{reg}.$$

$$\chi^2_{stat} = \sum_{j}^{recobins} 2(N_j^{MC} - N_j^{obs} + N_j^{obs} ln \frac{N_j^{obs}}{N_j^{MC}})$$

$$\chi^2_{syst} = (\vec{a}^{syst} - \vec{a}^{syst}_{prior})(V^{syst}_{cov})^{-1}(\vec{a}^{syst} - \vec{a}^{syst}_{prior})$$

$$\chi^2_{reg} = p_{reg} \sum_i (c_i - c_{i-1})^2$$

Systematics in the fitter

- Add term to the fit

$$\chi^2_{syst} = (\vec{a}^{syst} - \vec{a}^{syst}_{prior})(V^{syst}_{cov})^{-1}(\vec{a}^{syst} - \vec{a}^{syst}_{prior})$$

- The fit is able to constrain systematic parameters (mostly through control regions) but picks up a penalty if it moves far from the prior.
- **Detector Systematics** (e.g. TPC momentum resolution):
  - Make many toy experiments, each varying detector properties we are unsure of.
  - Produce covariance matrix which tells the fit the overall uncertainty in the number of events in each bin and how this correlates between bins.
- **Model Systematics** (e.g. $M_{A,RES}$, pion FSI):
  - Use covariance matrix produced from external data fits which tells us the uncertainty on model parameters.
  - Make splines that tell the fitter how to reweight the MC if we alter model parameters that describe the background In the fit.
- **Flux Systematics**:
  - Use covariance matrix produced by beam group which tells us the uncertainty on the flux in bins of neutrino energy.
  - Store the neutrino energy of each event in the fit.

Regularising the fitter

- Reaching a fit result is an 'ill posed problem' -> there are often degeneracies in the fit solutions.

- E.g. can often lower a particular template scaling parameter so long as we raise the adjacent parameters
  - Strong anti correlations between bins!

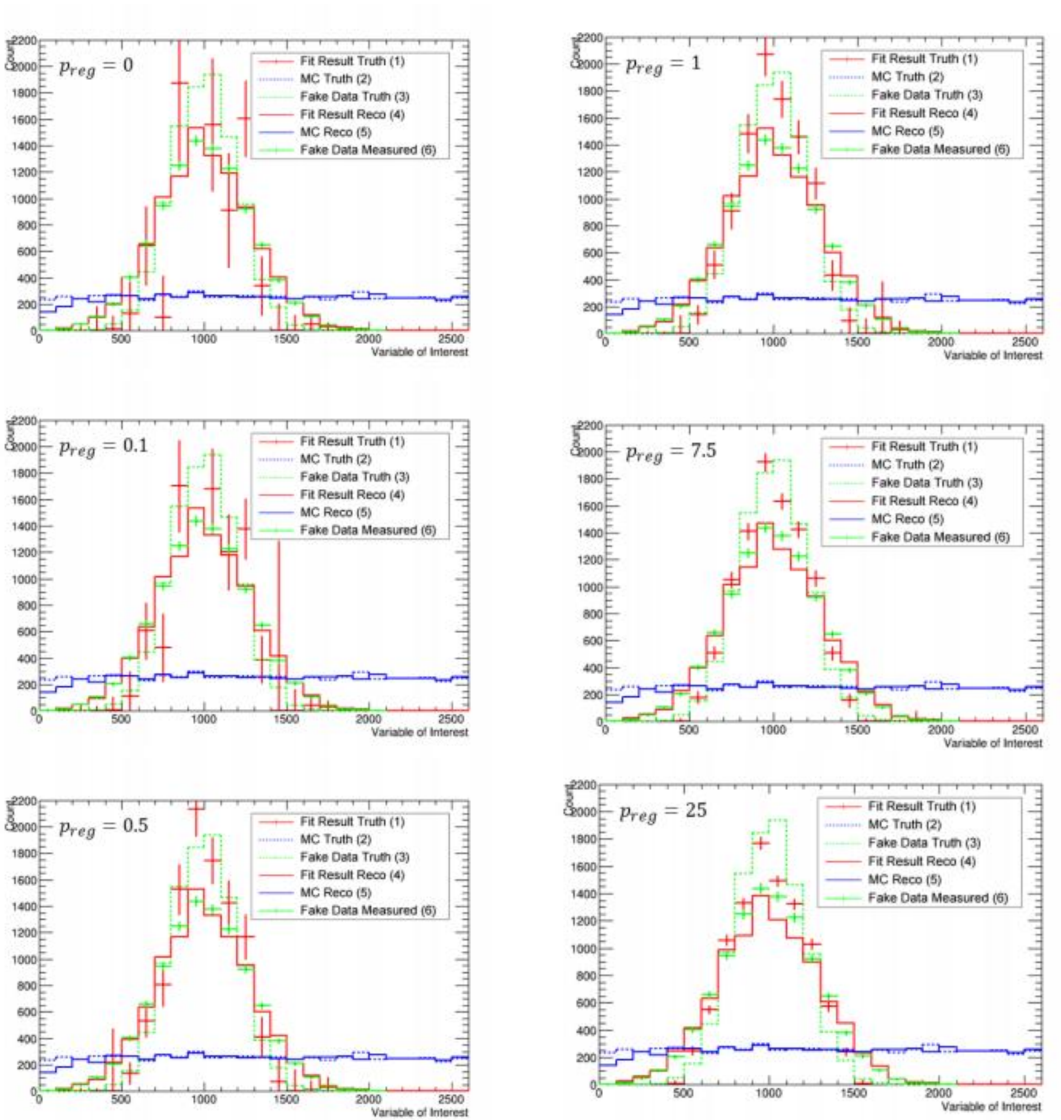
- Can resolve with regularisation: $\chi^2_{reg} = p_{reg} \sum_i (c_i - c_{i-1})^2$
  - Add another term
  - Regularisation loosely ties bins together

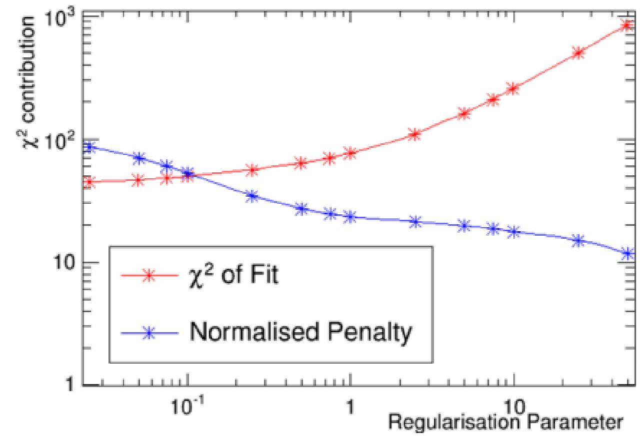
- But how to choose the best p_{reg}?

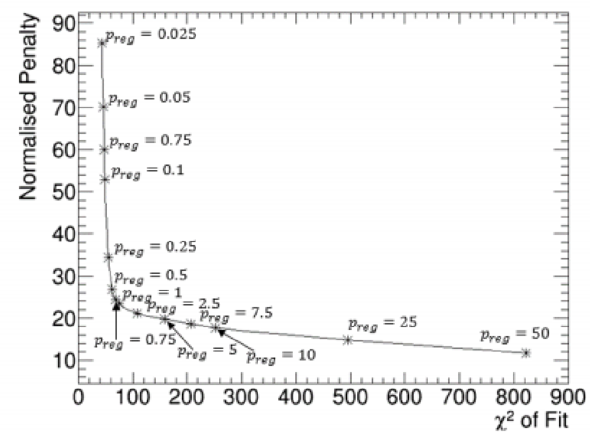
- Want to have the maximum smoothing impact with the minimal effect on the χ^2 of the fit.
  - This problem is well studied, can choose p_{reg} using the "L-Curve".

- Toy example fitting a Gaussian from a flat prior in backups.

Regularising the fitter







SIAM Rev., 34(4), 561580 (1992).

Regularisation

More detail:
https://www.mat.tuhh.de/lehre/material/RegLS.pdf

- Penalty term in my fit from regularisation:

$$\chi^2_{reg} = p_{reg} \sum_i (c_i - c_{i-1})^2$$

This looks like a rather non χ^2-like term slapped onto the fit…

But could also write it as: $\chi^2_{reg} = p_{reg}\left(\boldsymbol{p} - \boldsymbol{p_{prior}}\right)(\boldsymbol{V_{cov}})^{-1}\left(\boldsymbol{p} - \boldsymbol{p_{prior}}\right)$

$$(\boldsymbol{V_{cov}})^{-1} = \begin{bmatrix} 1 & -1 & 0 & \cdots & 0 \\ -1 & 2 & -1 & \ldots & 0 \\ 0 & -1 & 2 & \ddots & 0 \\ \vdots & \vdots & \ddots & \ddots & -1 \\ 0 & 0 & 0 & -1 & 1 \end{bmatrix}$$

Or to make the matrix non-singular:

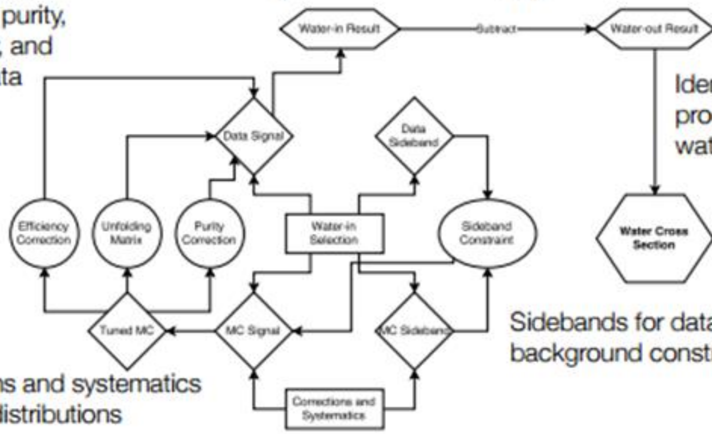
$$(\boldsymbol{V_{cov}})^{-1} = \begin{bmatrix} 1 & -1 & 0 & \cdots & 0 \\ -1 & 2 & -1 & \ldots & 0 \\ 0 & -1 & 2 & \ddots & 0 \\ \vdots & \vdots & \ddots & \ddots & -1 \\ 0 & 0 & 0 & -1 & 2 \end{bmatrix}$$

- Applying a penalty term in this way makes regularisation enter the fit identically to model parameters.
- In fact in some sense the application of regularisation *is* a model that says cross sections should be smooth relative to their prior.
- The uncertainty in the smoothness model is then $1/\sqrt{p_{reg}}$.

PØD - CC0π on water

Analysis Strategy

MC used to generate purity, efficiency, and unfold data



Identical procedure for water-out

Sidebands for data-driven background constraint

Corrections and systematics alter MC distributions

The number of events on oxygen is given by

$$N_i^O = \frac{U_{ij}^w N_j^w}{\varepsilon_i^w} - R\frac{U_{ij}^a N_j^a}{\varepsilon_i^a}$$

Data

MC

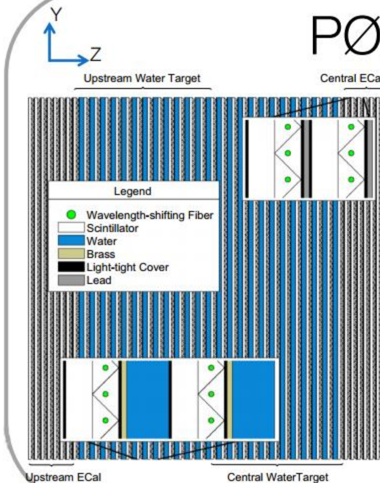
i and j indicate true and recon bins, N is the number of events in the bin, R the flux normalization ratio, ε the selection efficiency, and U the unfolding matrix.

Then the cross section is

$$d\sigma_i = \frac{N_i^O}{F^w N_n D_i},$$

where F is the integrated flux, N_n the number of nucleons, and D_i the bin width.

PØD

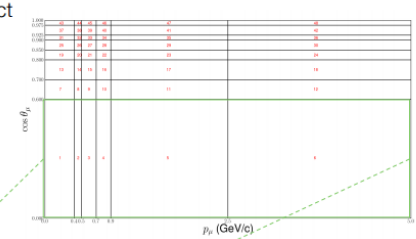


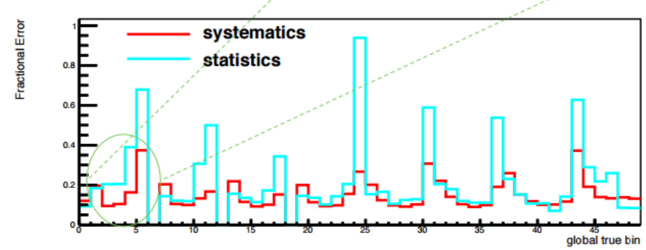
- PØD-ECals consist of alternating layers of scintillator and lead
- Water target consists of alternating layers of scintillator, brass, and water
- Scintillation measured with wavelength-shifting fiber, readout via MPPCs
- Water can be drained!

Systematic Errors

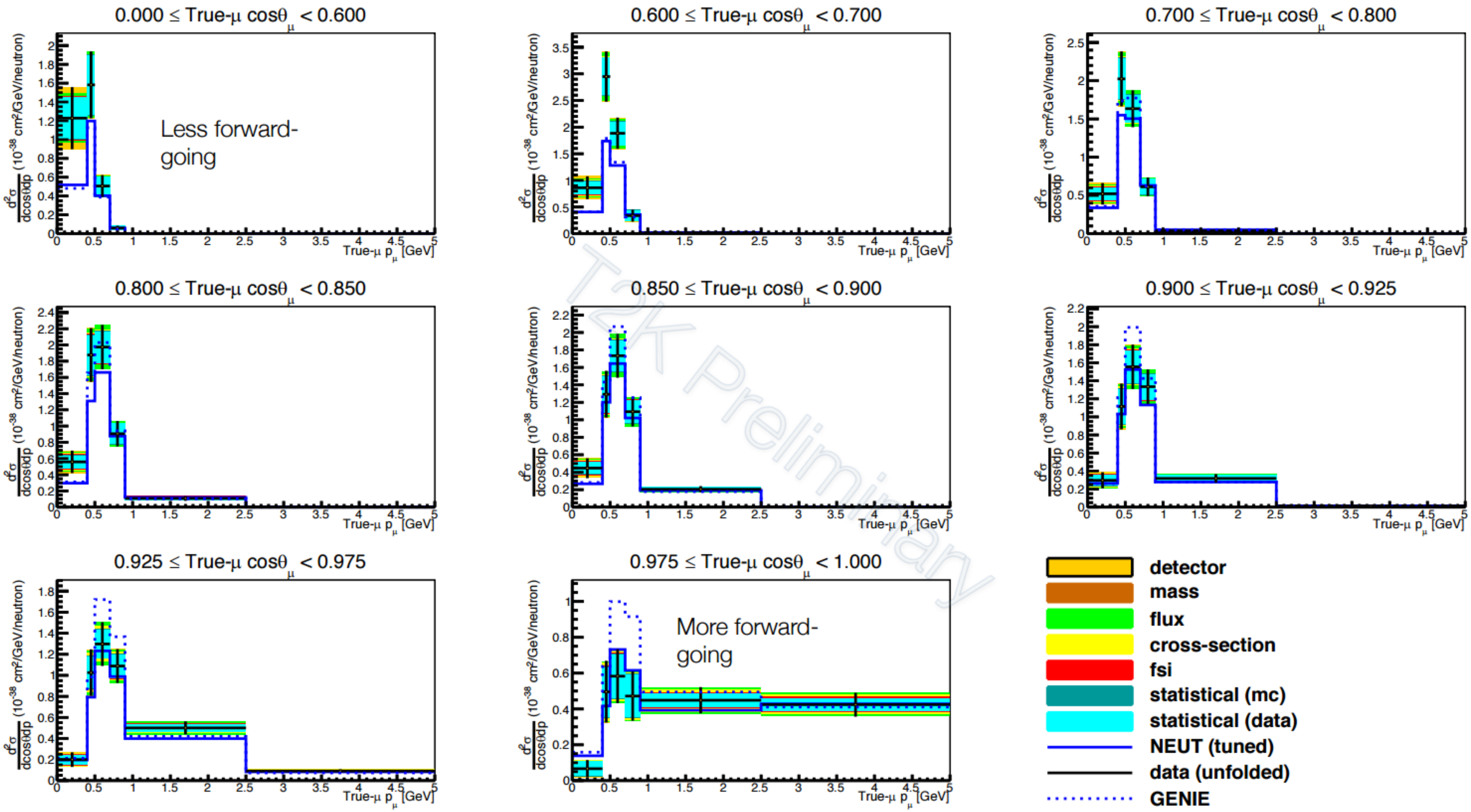
- Corrections include: flux tuning, interaction model correction, EMC effect tuning, and pile-up correction
- Systematics include: flux uncertainties, interaction model uncertainties, and detector uncertainties
- Numerical propagation via throws of perturbed MC distributions
- Largest source is the flux uncertainty

Binned in Muon Kinematics

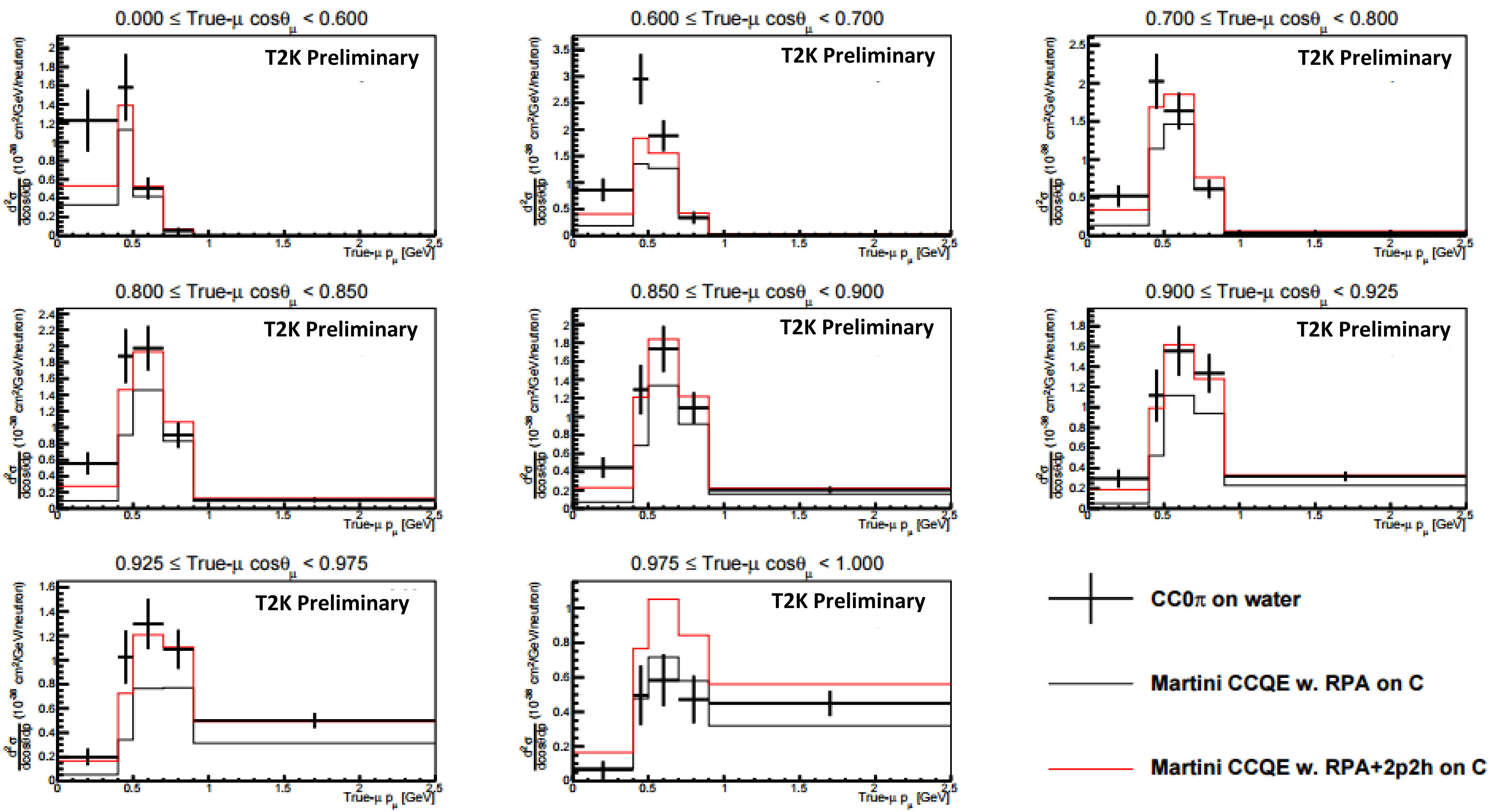




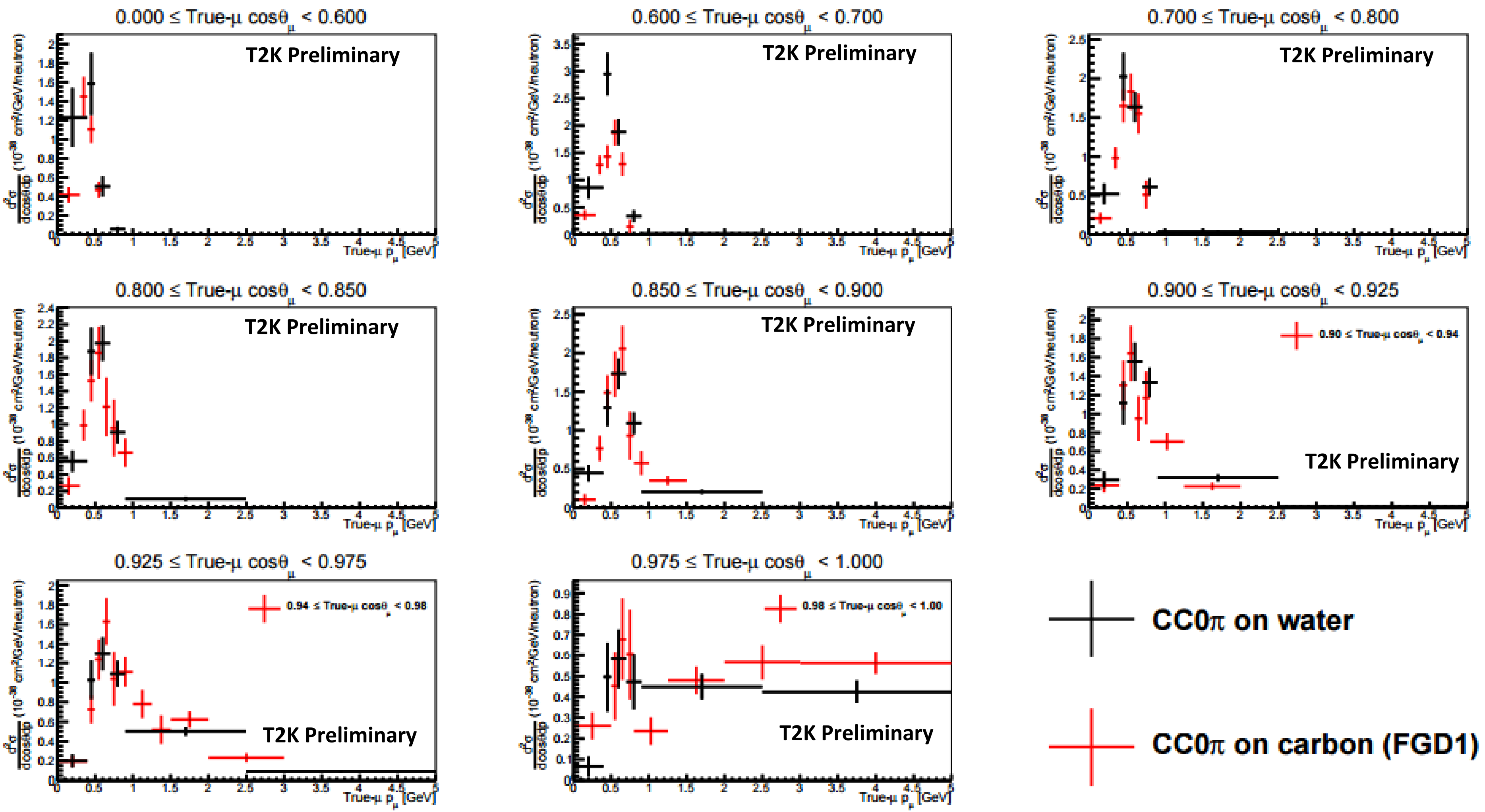
PØD - CC0π on water



PØD - CC0π on water



PØD - CC0π on water



FGD2 Oxygen Cross Section

Contact:
Margherita Buizza Avanzini
buizza@llr.in2p3.fr

- Measure the cross section on **oxygen** and **carbon** simultaneously fitting events starting in FG2 water and carbon layers

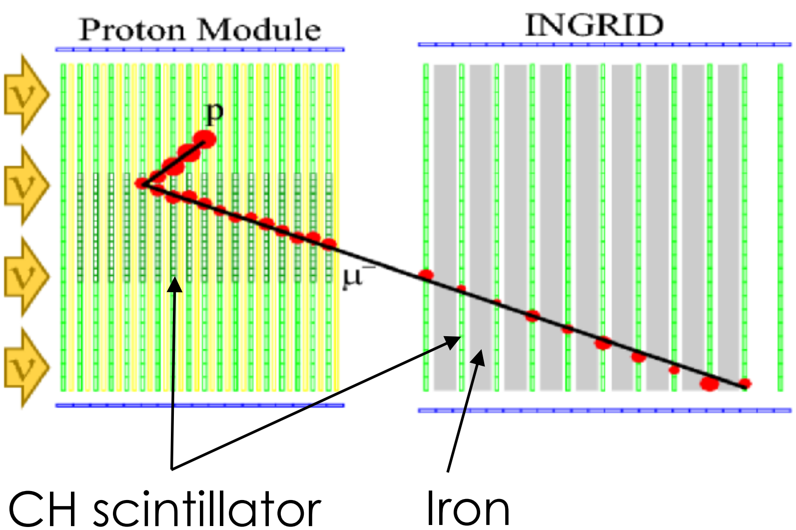
$$N = \left(\underbrace{c_i N^{sig,C}_{i,\alpha,MC}}_{\text{Carbon}} + \underbrace{o_i N^{sig,O}_{i,\alpha,MC}}_{\text{Oxygen}} + \underbrace{N^{bkg}_{i,\alpha,MC}}_{\text{Separate background control regions}}\right) \times \underbrace{f\left(r^{\det}_{\alpha}, a^{model}_{\alpha}, \Phi\right)}_{\text{systematics parameters for O and for C (with proper correlation)}}$$

$i = p_\mu, \cos\theta_\mu$ bins
α = X and Y FGD2 layers

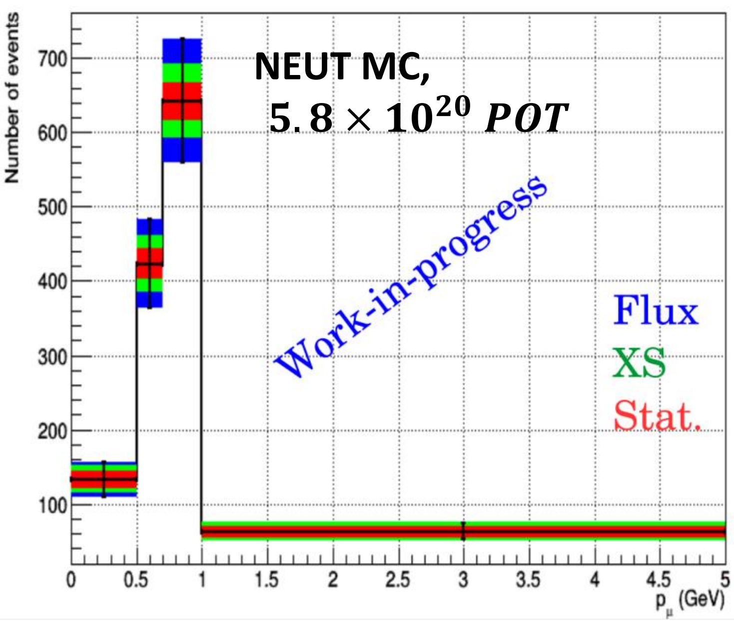
- Extract flux integrated Oxygen cross section and ratio oxygen/carbon flux integrated cross sections

$$\boxed{\frac{d\sigma}{dp_\mu} = \frac{o_i N^{sig,O}_{MC}}{\Phi \cdot N^{FV,O}_{neutrons} \cdot \Delta p_\mu}} \qquad \boxed{\frac{o_i N^{sig,O}_{MC} \,/\, N^{FV,O}_{neutrons}}{c_i N^{sig,C}_{MC} \,/\, N^{FV,C}_{neutrons}}}$$

INGRID CC0Pi Analysis

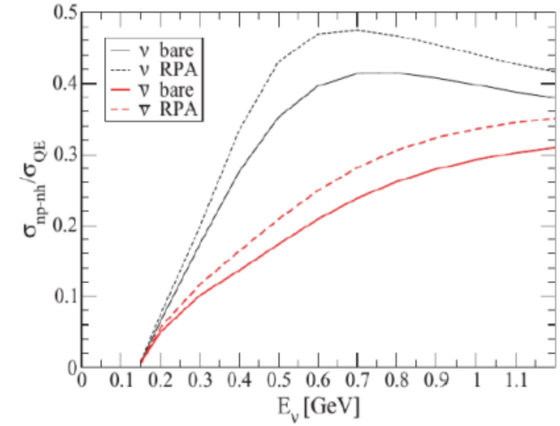


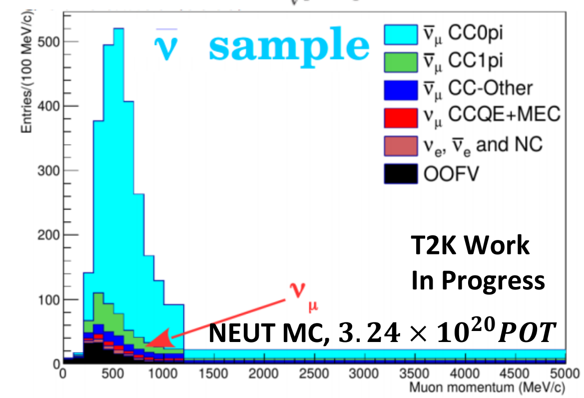
- Select 1 μ-like track beginning in the proton module
- Measure θ_μ^{rec} and d_μ^{rec} - distance penetrated through the iron (no B field)
- Unfold into θ_μ^{true} and p_μ^{true}
- Build double differential cross-section
- With 4 momentum bins and 5 angular bins uncertainty is 10%-20%
- Blind analysis

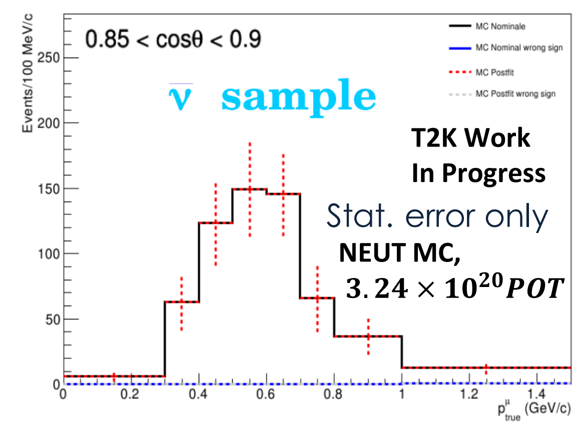


CC0Pi $\nu + \bar{\nu}$ joint fit

- 2p2h contribution is different for ν and $\bar{\nu}$ *
- Comparison of $\nu + \bar{\nu}$ can help identify 2p2h
- Aim to extract $\bar{\nu}$ double differential cross-section in $p_\mu, \cos(\theta_\mu)$ alongside $\nu + \bar{\nu}$ sum, difference and asymmetry
- Uses extra high angle and backward $\mu^{+/-}$ samples
- Cross-section extraction via a likelihood template fit
- Blind analysis







3.24x10^20 POT

* M Martini: PHYSICAL REVIEW C 80, 065501 (2009), PHYSICAL REVIEW C 81, 045502 (2010)

CC0Pi $\nu + \bar{\nu}$ joint fit measurements

$c_i^{\bar{\nu}} N_i^{\bar{\nu}\, MC\, CC0\pi}, c_i^{\nu} N_i^{\nu\, MC\, CC0\pi}$ **= (what we measure) number of CC0π events in 'true' muon p, cosθ bins**

Extract 3 measurements:

- **CC0π $\bar{\nu}$ flux integrated cross-section**

$$\frac{d\sigma^{\bar{\nu}}}{dp_\mu\, d\cos\theta_\mu} = \frac{c_i^{\bar{\nu}} N_i^{\bar{\nu}\, MC\, CC0\pi}}{\Phi^{\bar{\nu}} \cdot N_{protons}^{FV} \cdot \Delta p_\mu \Delta \cos\theta_\mu}$$

- **sum, difference and ν-$\bar{\nu}$ xsec** → allow to disentangle different terms of xsec (compare with 2p2h models)

$$\frac{d(\sigma^{\nu} \pm \sigma^{\bar{\nu}})}{dp_\mu\, d\cos\theta_\mu} = \frac{1}{\Delta p_\mu \Delta \cos\theta_\mu} \left[\frac{c_i^{\bar{\nu}} N_i^{\bar{\nu}\, MC\, CC0\pi}}{\Phi^{\bar{\nu}} \cdot N_{protons}^{FV}} \pm \frac{c_i^{\nu} N_i^{\nu\, MC\, CC0\pi}}{\Phi^{\nu} \cdot N_{neutrons}^{FV}} \right]$$

- **asymmetry of ν-$\bar{\nu}$ xsec** → direct effect on δ_{CP} measurement

$$\frac{d(\sigma^{\nu} - \sigma^{\bar{\nu}})}{d(\sigma^{\nu} + \sigma^{\bar{\nu}})} = \frac{c_i^{\bar{\nu}} N_i^{\bar{\nu}\, MC\, CC0\pi} / (\Phi^{\bar{\nu}} \cdot N_{protons}^{FV}) - c_i^{\nu} N_i^{\nu\, MC\, CC0\pi} / (\Phi^{\nu} \cdot N_{neutrons}^{FV})}{c_i^{\bar{\nu}} N_i^{\bar{\nu}\, MC\, CC0\pi} / (\Phi^{\bar{\nu}} \cdot N_{protons}^{FV}) + c_i^{\nu} N_i^{\nu\, MC\, CC0\pi} / (\Phi^{\nu} \cdot N_{neutrons}^{FV})}$$

δp_{TT}

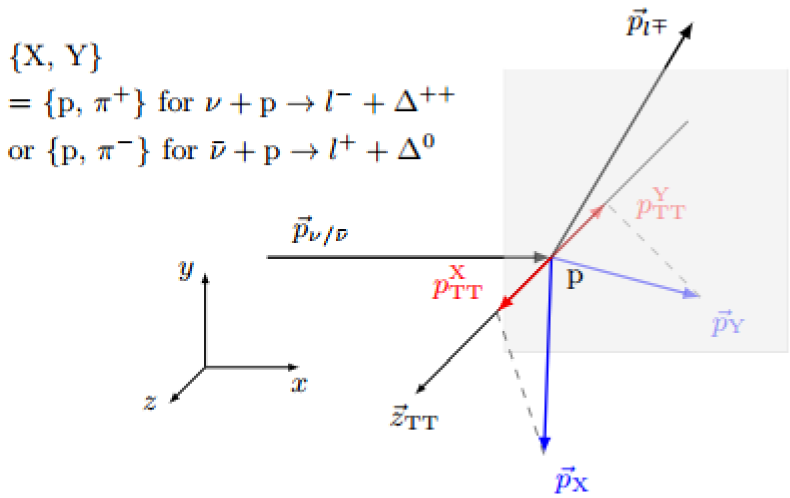
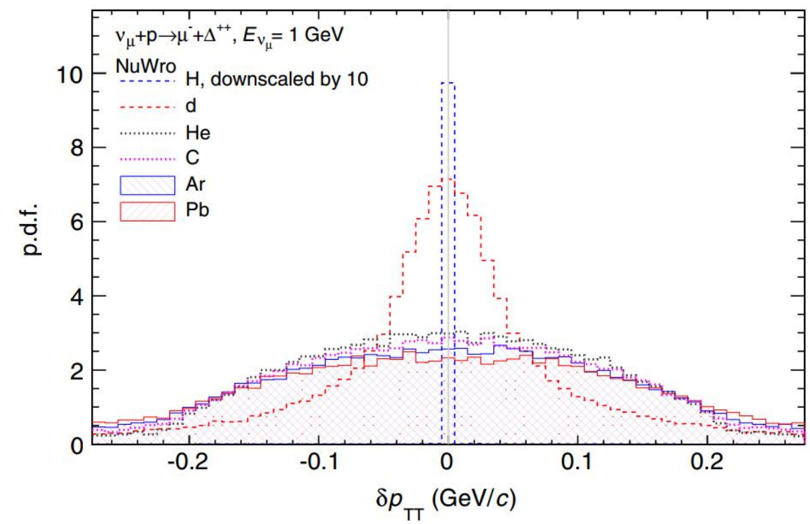


FIG. 1. Schematic illustration of the double-transverse kinematics. The incoming and outgoing particle momenta are represented by $\vec{p}_\nu$ and $\vec{p}_l$, $\vec{p}_p$ and $\vec{p}_\pi$, respectively. The double-transverse momentum imbalance, δp_{TT} is given by $p^p_{TT} + p^\pi_{TT}$ with respect to the axis $\vec{z}_{TT}$ defined by $\vec{p}_\nu \times \vec{p}_l$.



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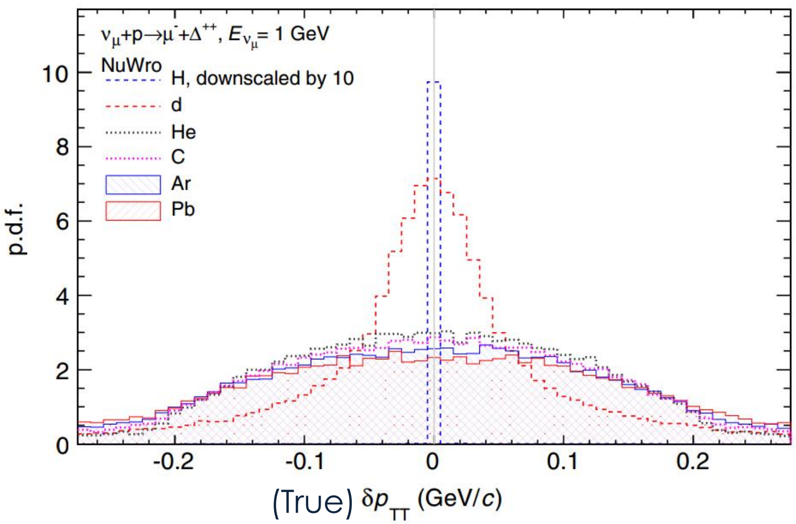
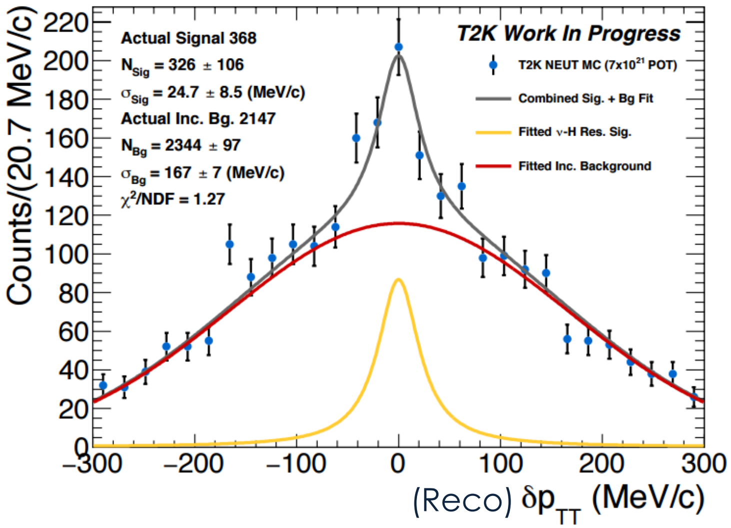
CC1p1π on hydrogen

- Cross-section measurement on H allows measure of $\sigma(\nu + p)$ without nuclear effects
- Can use δp_{TT} to isolate H content of composite target *

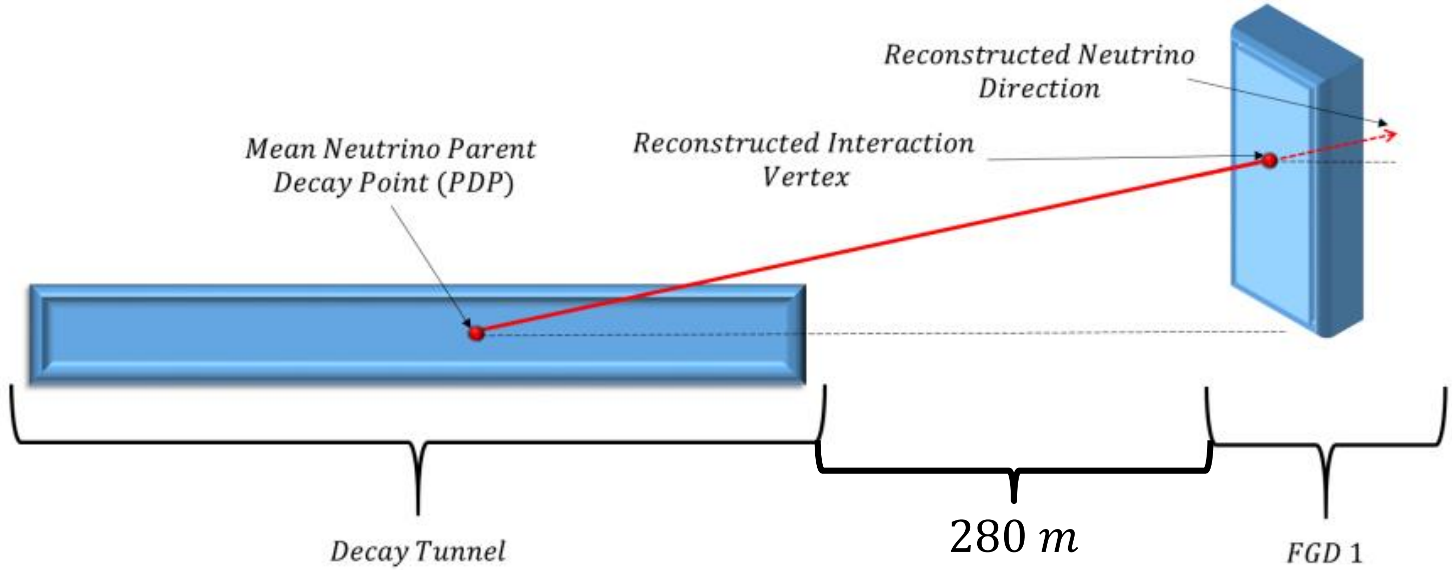


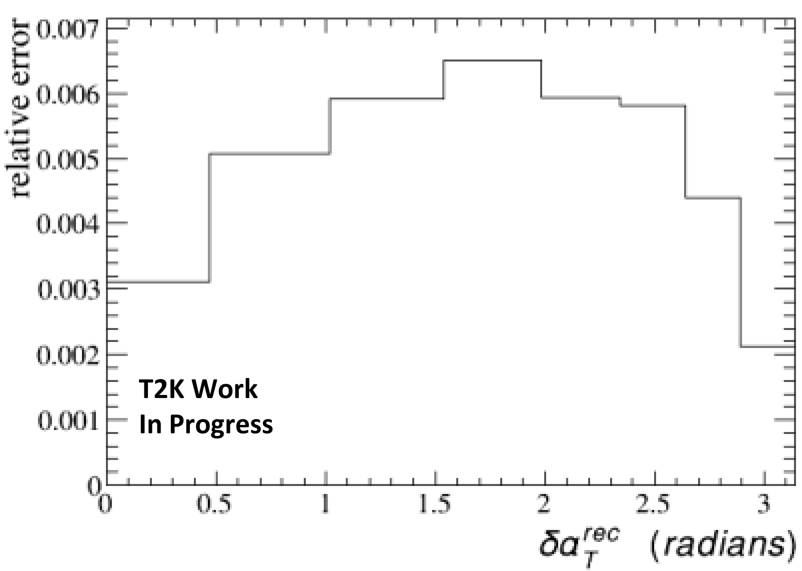


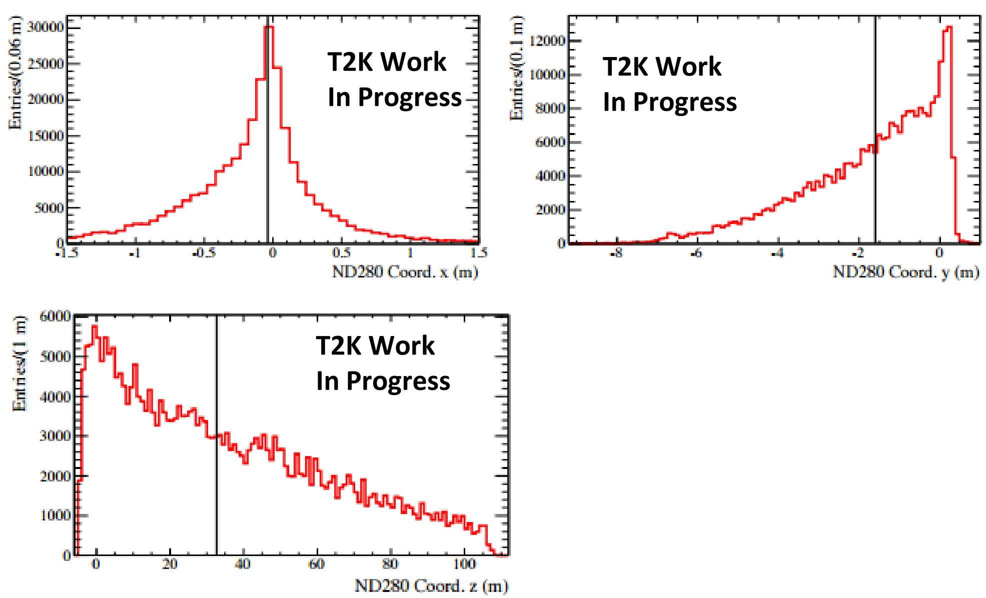
- Aim to measure Δ^{++} production on H

* Phys. Rev. D **92**, 051302(R)

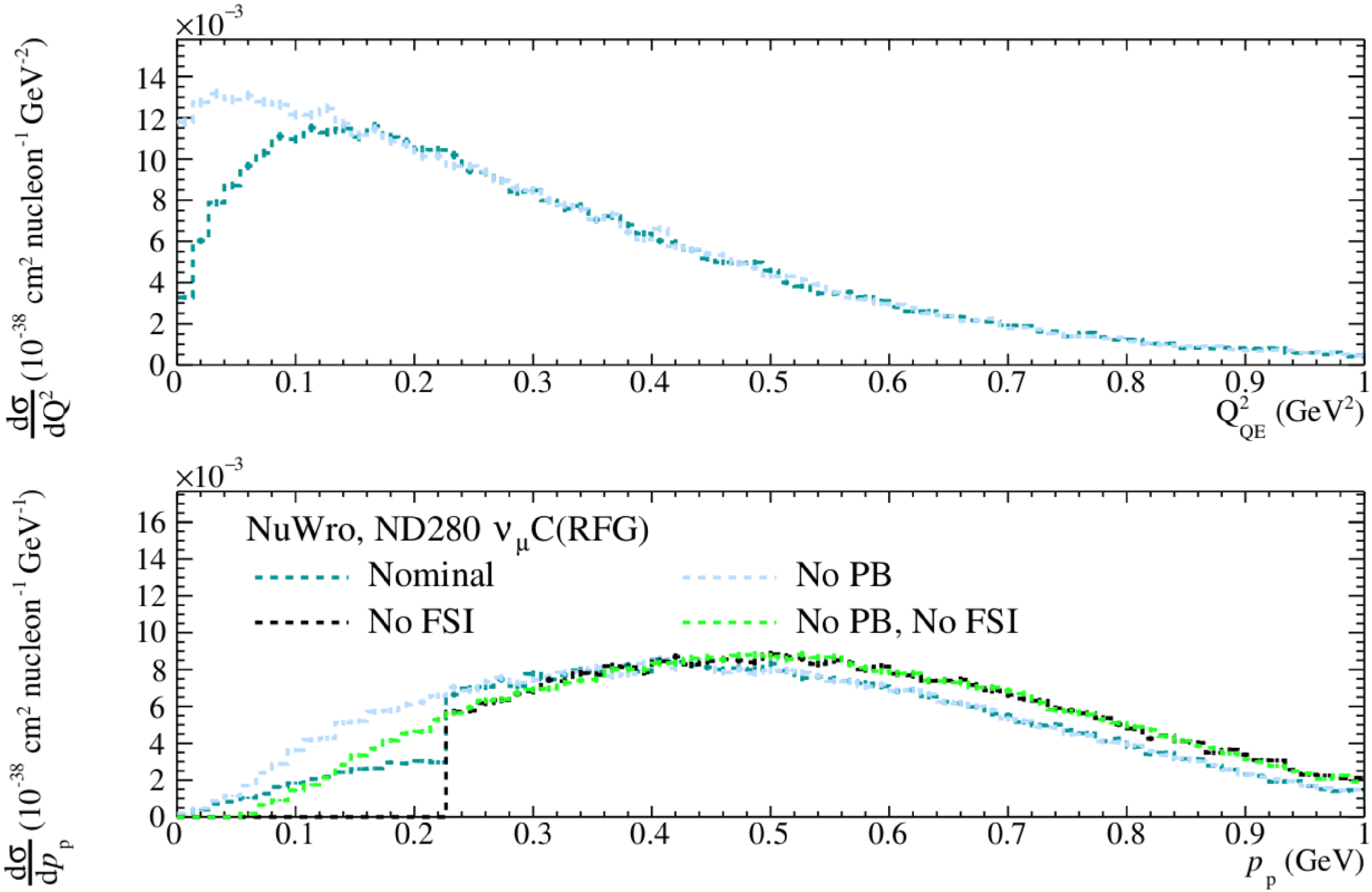
Reconstructing the Neutrino Direction



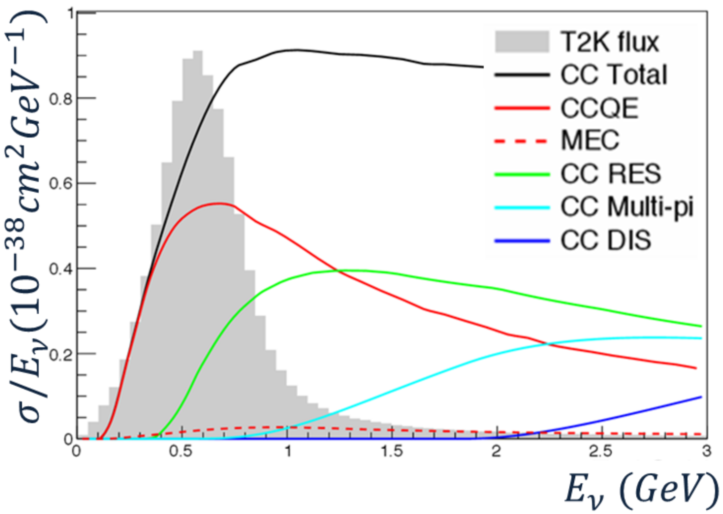


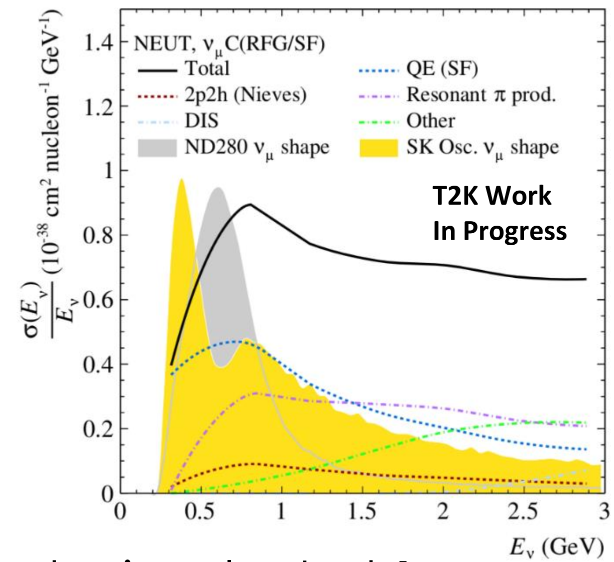


Pauli Blocking

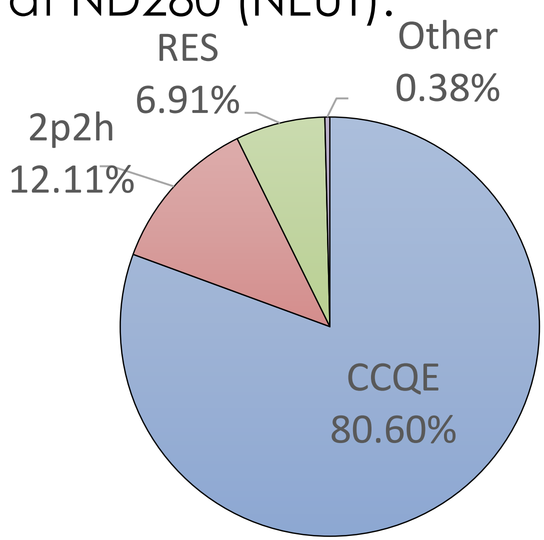


Neutrino Scattering and OA

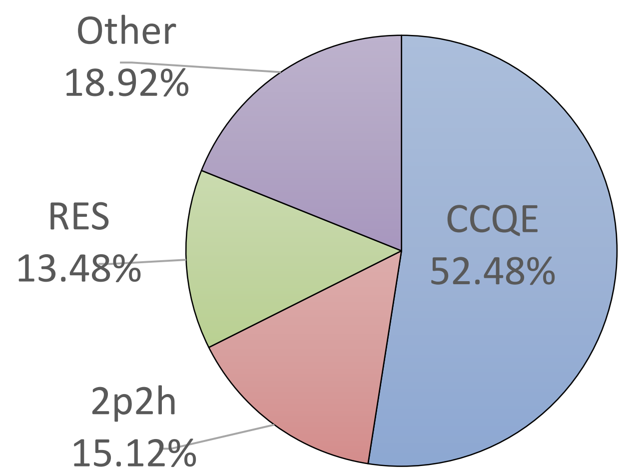




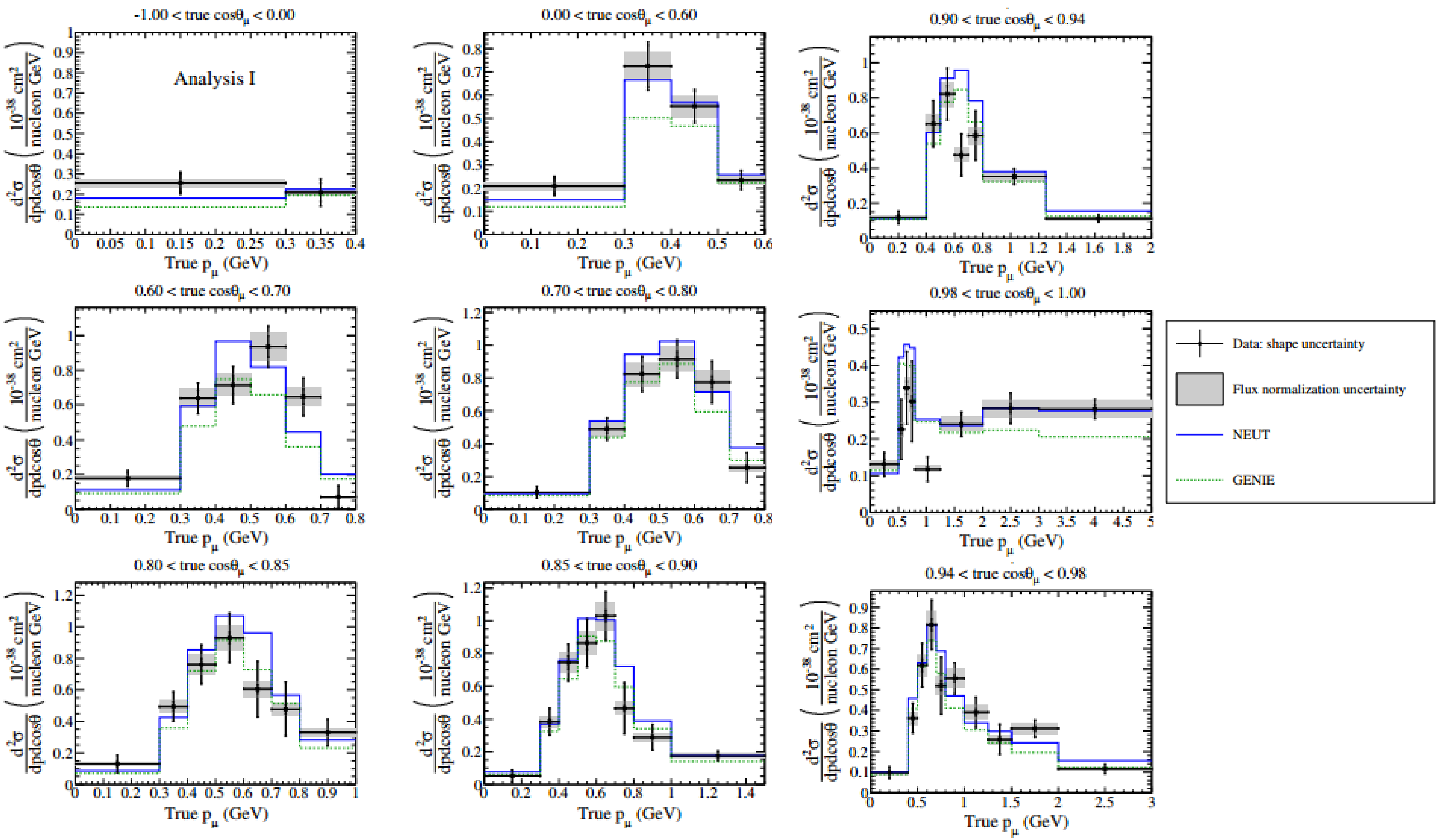
Interaction Modes in all CC0π events at ND280 (NEUT):



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



ND280 Off-Axis CC0π Result



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