Neutrino Cross Section Measurements at T2K

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ON BEHALF OF THE T2K COLLABORATION

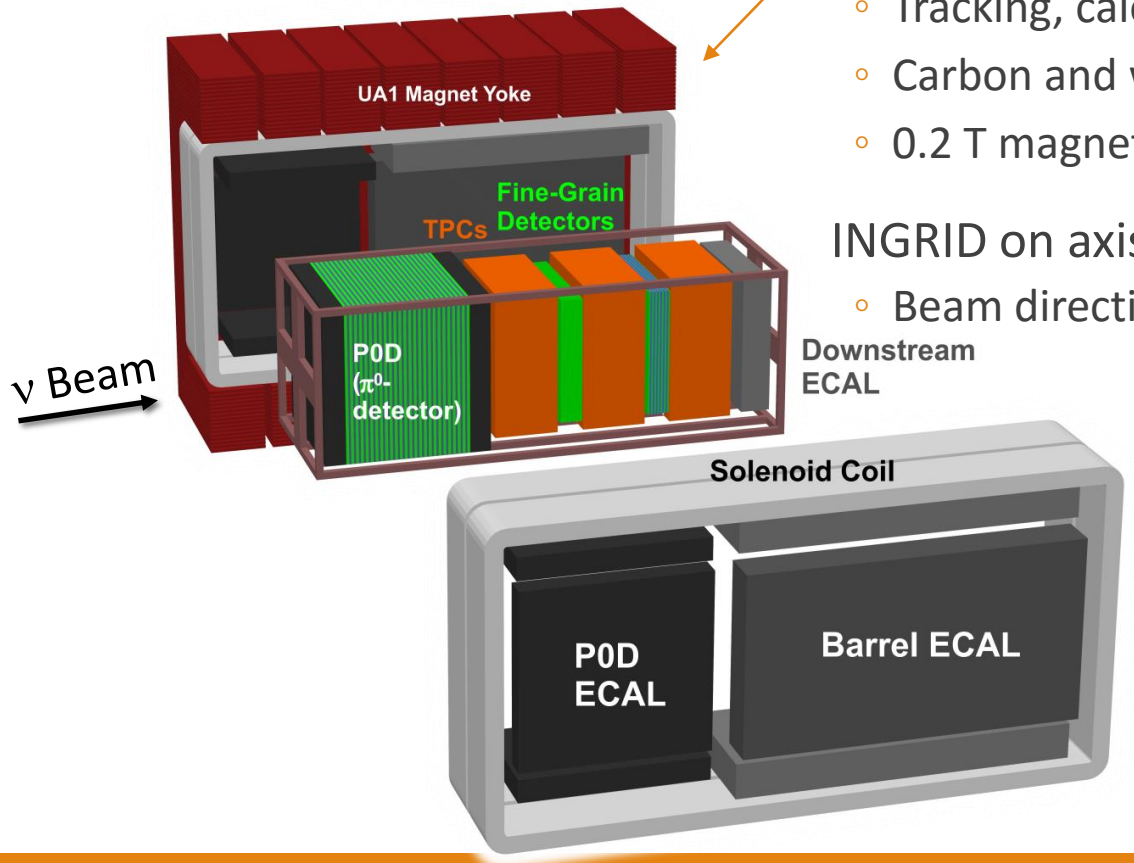
The T2K Near Detectors

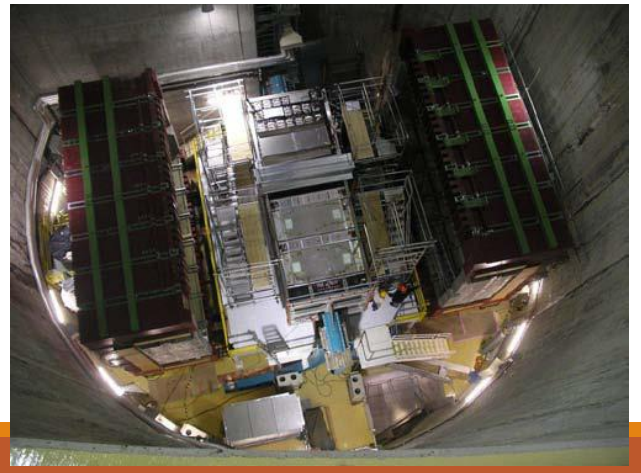
ND280 2.5° off axis in line to SK

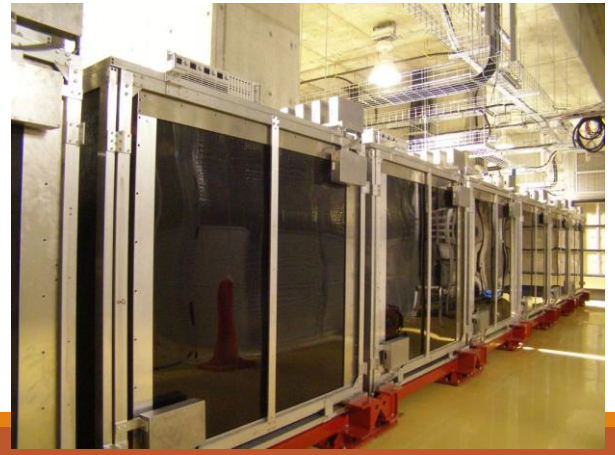
- Tracking, calorimetry and muon detectors
- Carbon and water targets
- 0.2 T magnetic field

INGRID on axis detector

- Beam direction and rate

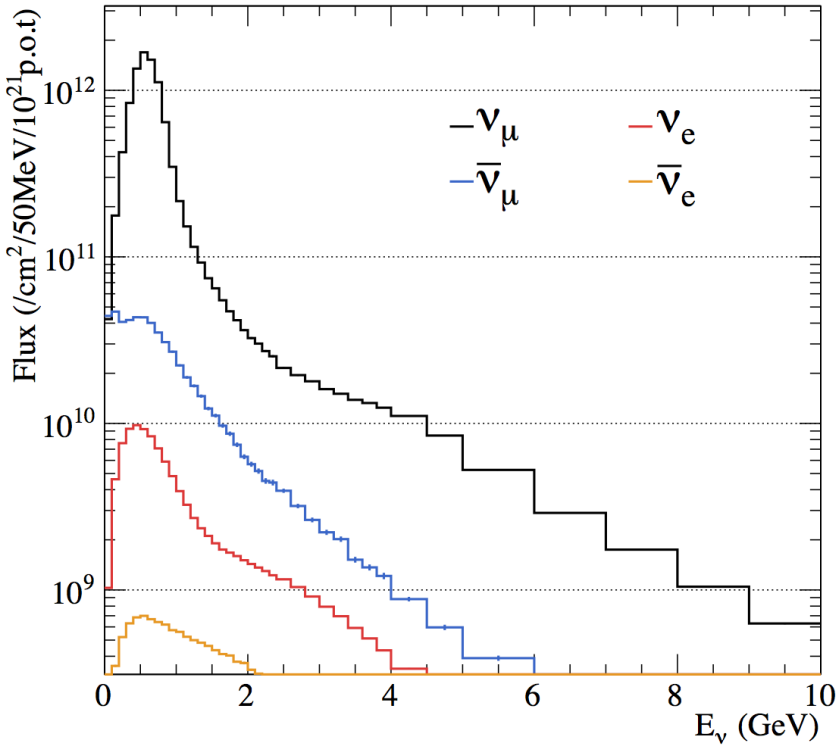




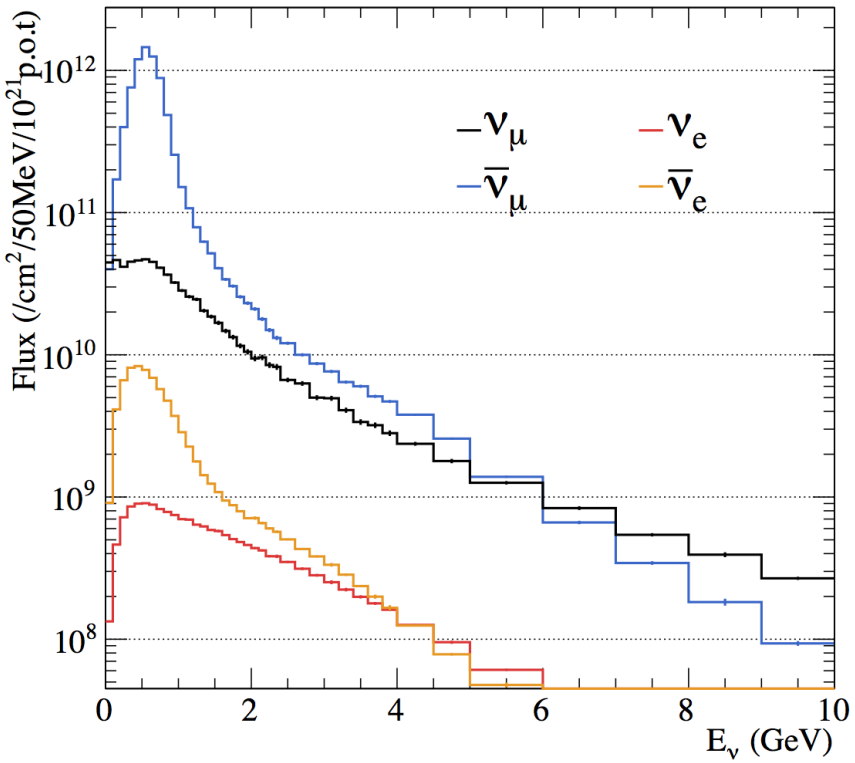


Neutrino Flux at ND280

Forward Horn Current “Neutrino Mode”



Reverse Horn Current “Anti-neutrino Mode”

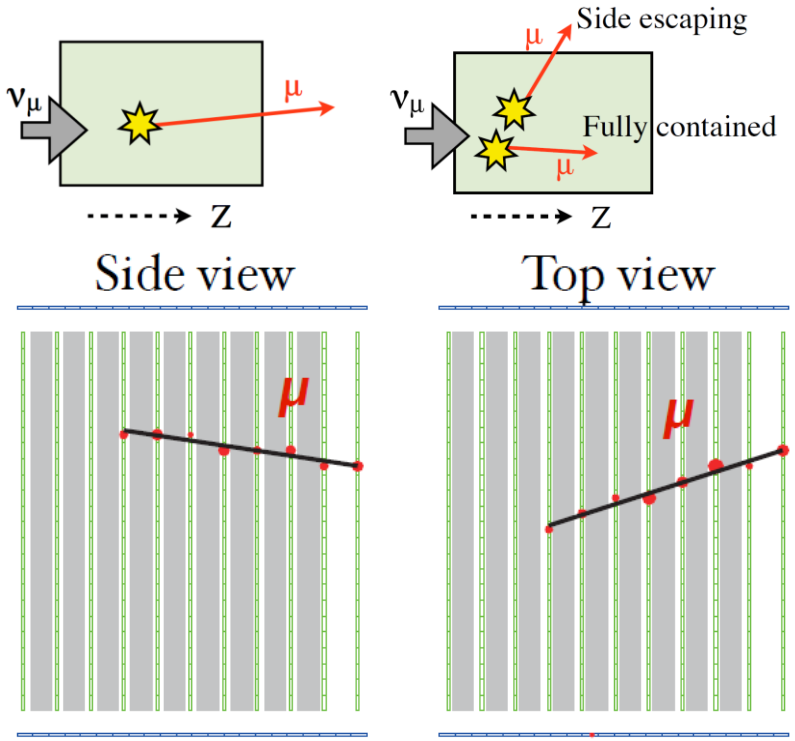


On-Axis Results: INGRID

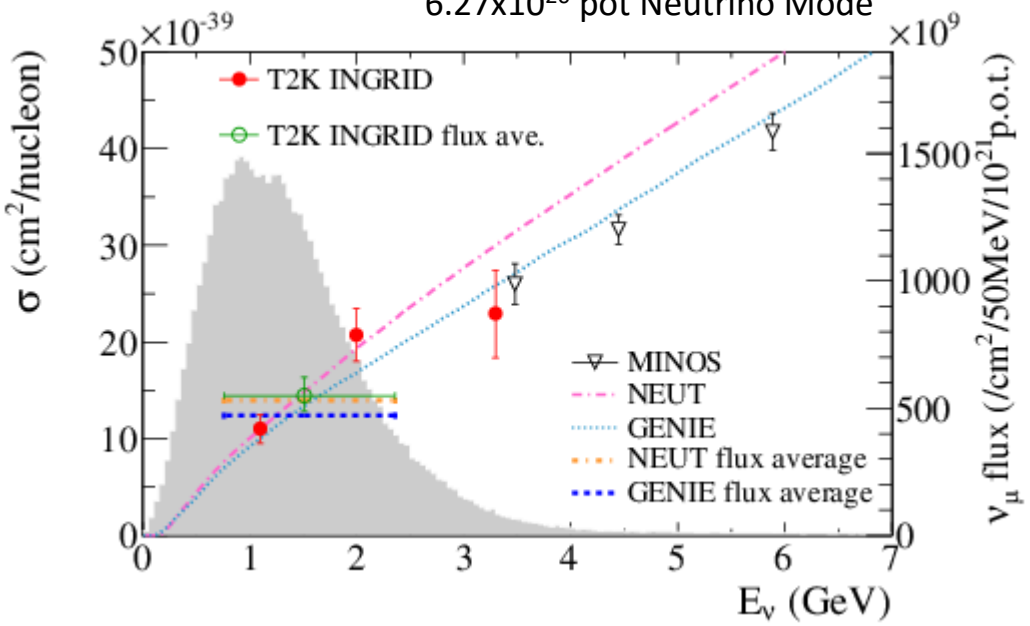
PRD 93 072002

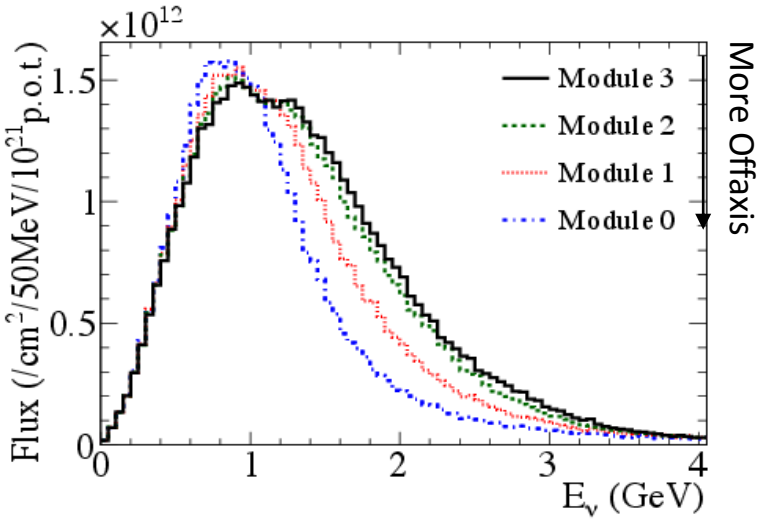
ν_μ CC Inclusive on Iron

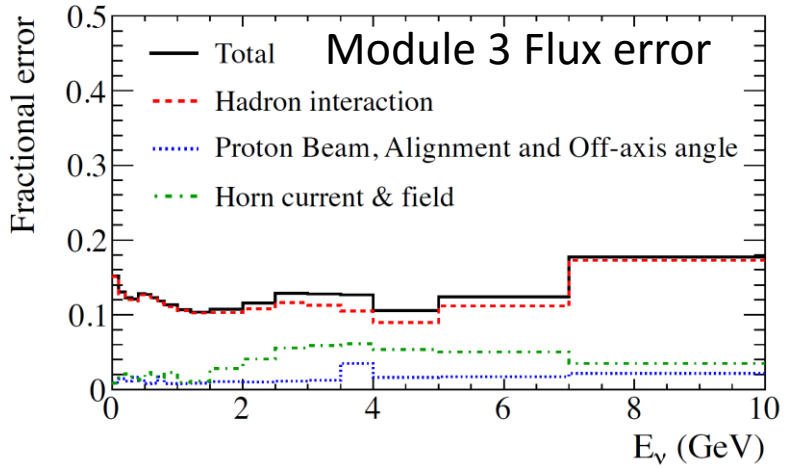
Exploit different fluxes in different modules
Fit cross section using distinct event topologies.



6.27x10^{20} pot Neutrino Mode







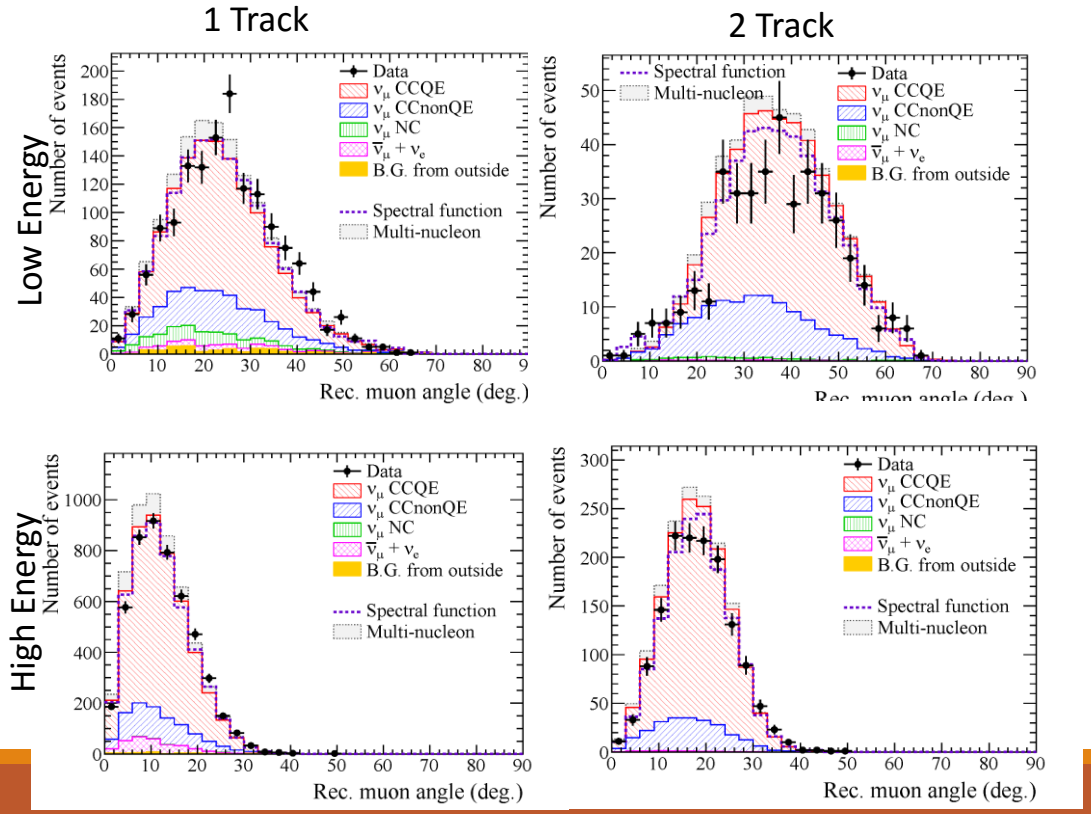
PRD 91 112002

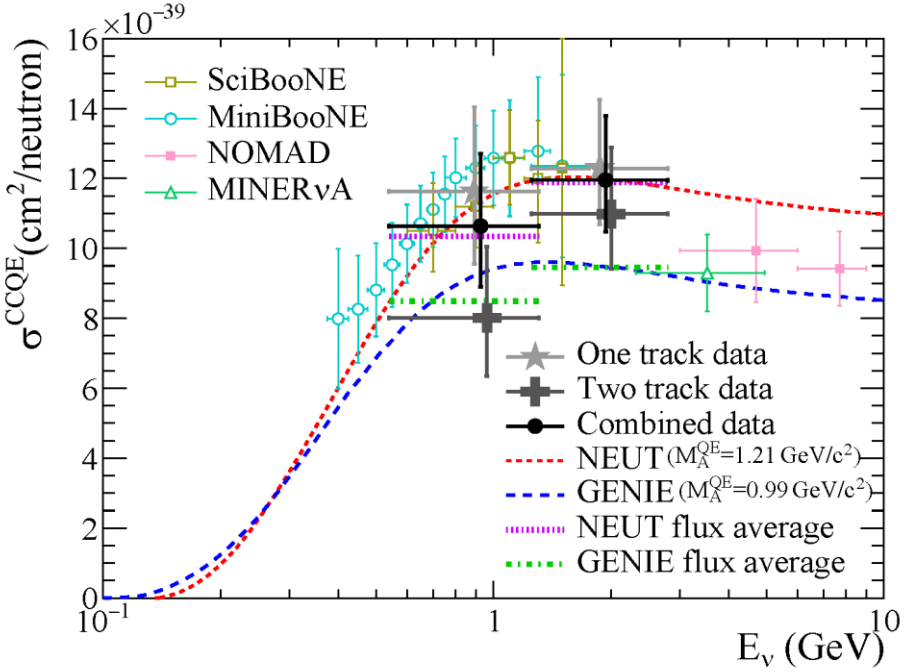
6.4x10^{20} pot Neutrino Mode

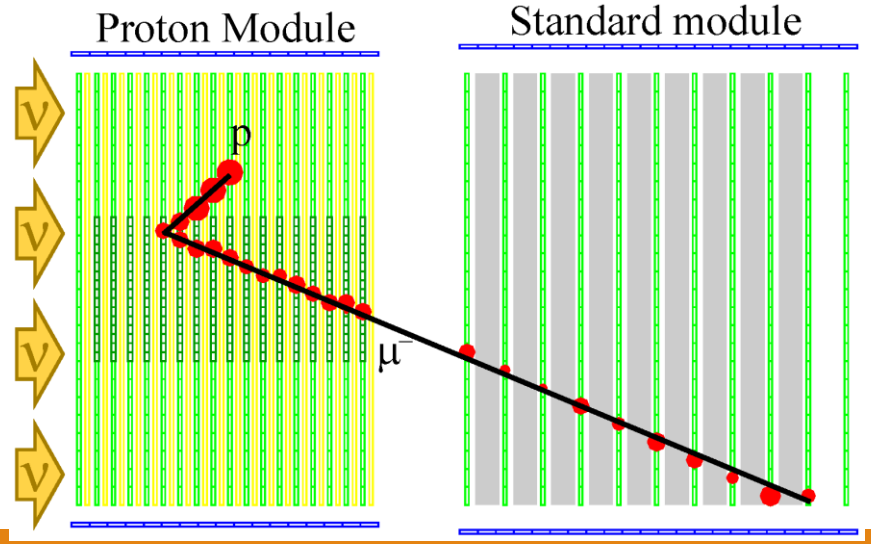
ν_μ CCQE on carbon

Use the proton module in front of central INGRID module

Data divided into samples based on topology and energy







Off-axis results: ND280

PRD 93 112012

ND280 Tracker: CC0π

In neutrino detectors we measure (at best) the final state

Nuclear effects are significant.

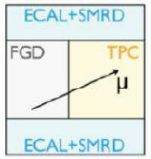
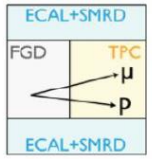
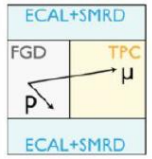
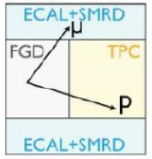
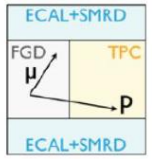
- Measure CC0π rather than CCQE
- Primary cross-section channel in T2K oscillation analysis.

Interactions on correlated nucleons important

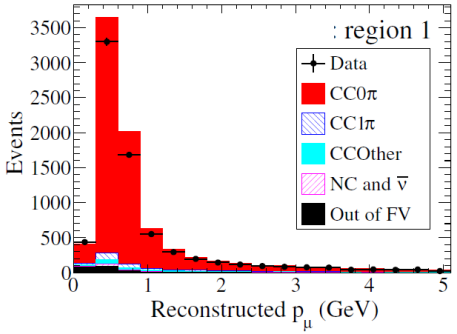
- Nieves and Martini models

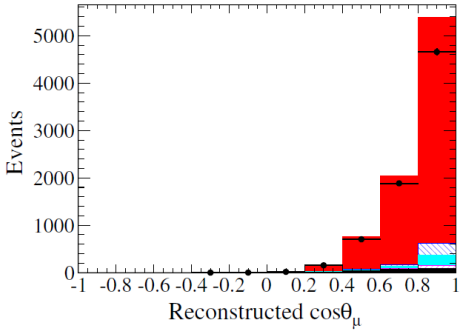
Two analyses

- Fit with additional samples to extend phase space
  - Use control samples with one or more pions
- Bayesian unfolding in restricted phase space

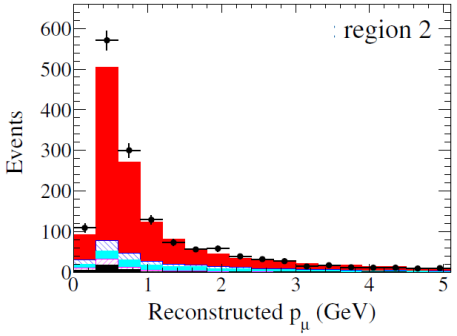
	(1)	(2)	(3)	(4a)	(4b)
CCQE topology					
topology description	• μ_{cand} is FGD-TPC track • p_{cand} not reconstructed	• both μ_{cand} and p_{cand} are FGD-TPC tracks	• μ_{cand} is FGD-TPC track • p_{cand} is FGD-only track	• p_{cand} is FGD-TPC track • μ_{cand} is FGD track: a) not fully contained b) FGD-only track	

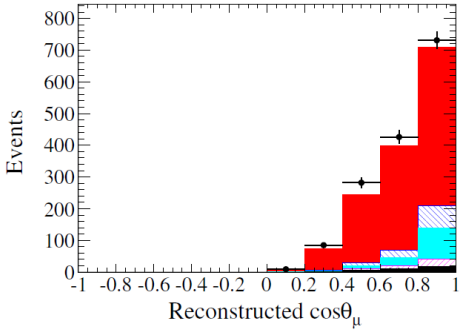
μ in TPC
No proton candidate



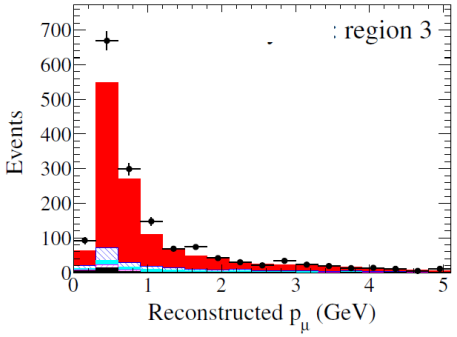


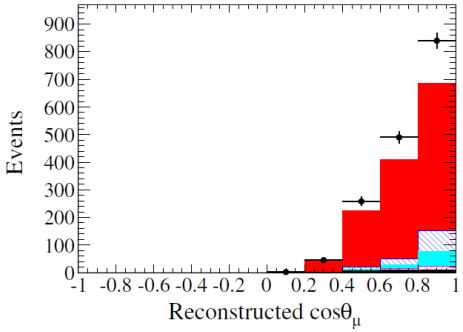
μ in TPC
proton in TPC



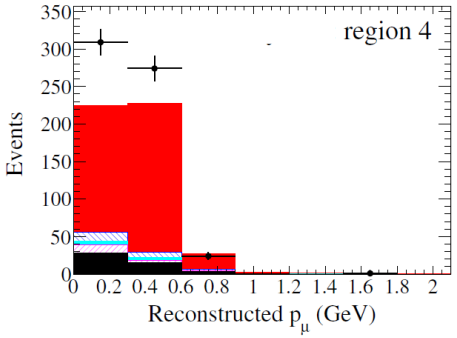


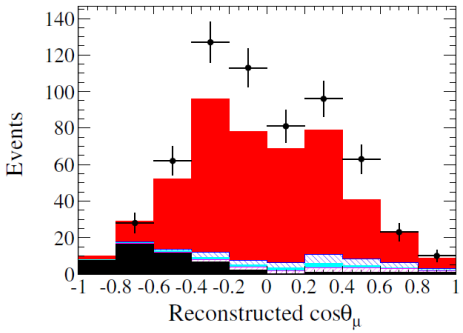
μ in TPC
proton FGD





μ in FGD (ECAL, SMRD)
proton in TPC

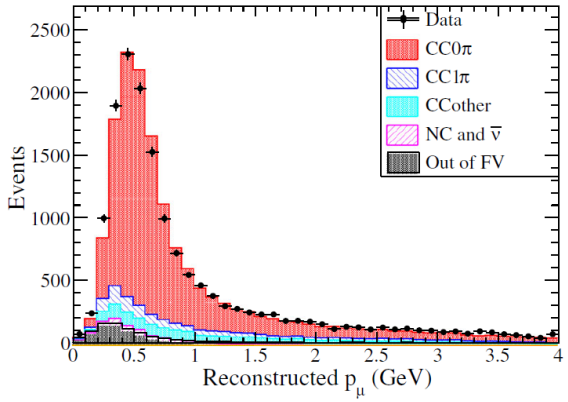


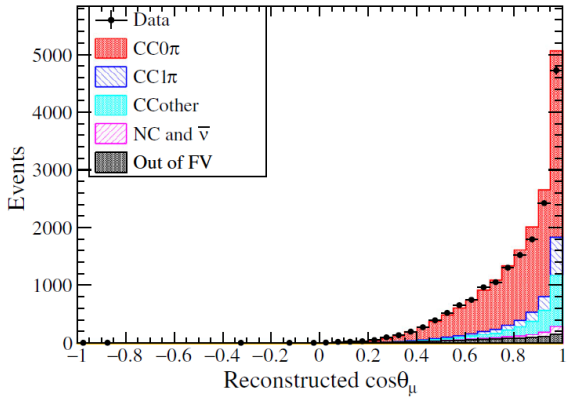


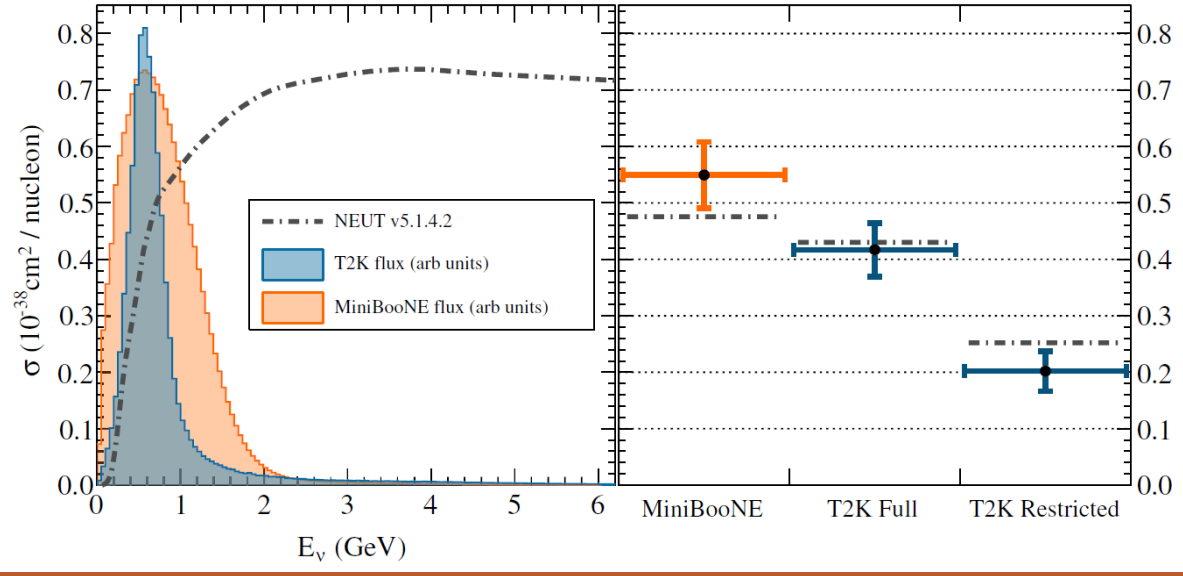
PRD 93 112012

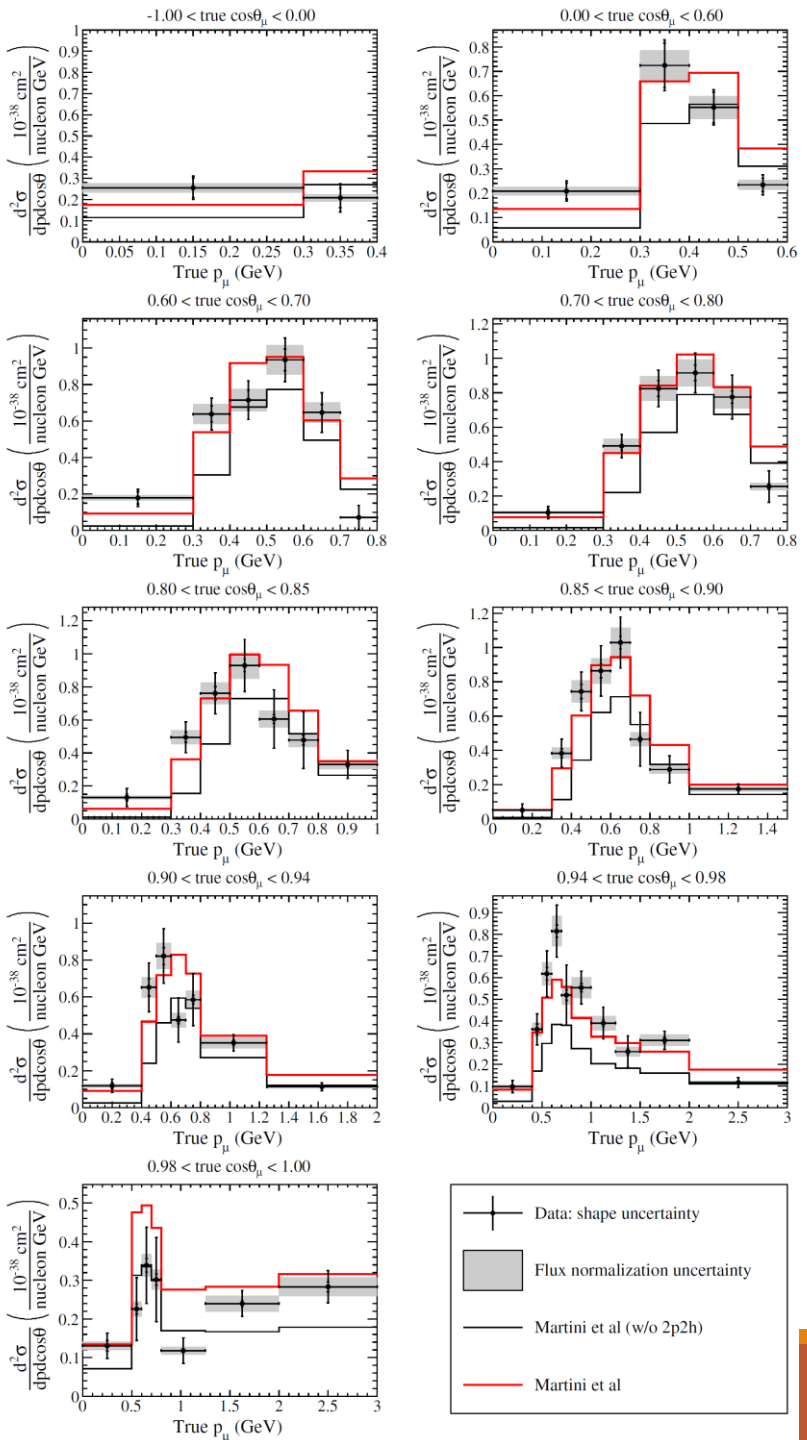
5.73x10^{20} pot
Neutrino Mode

ND280 Tracker: CC0π









See Poster by Tianlu Yuan
Poster Session on Monday

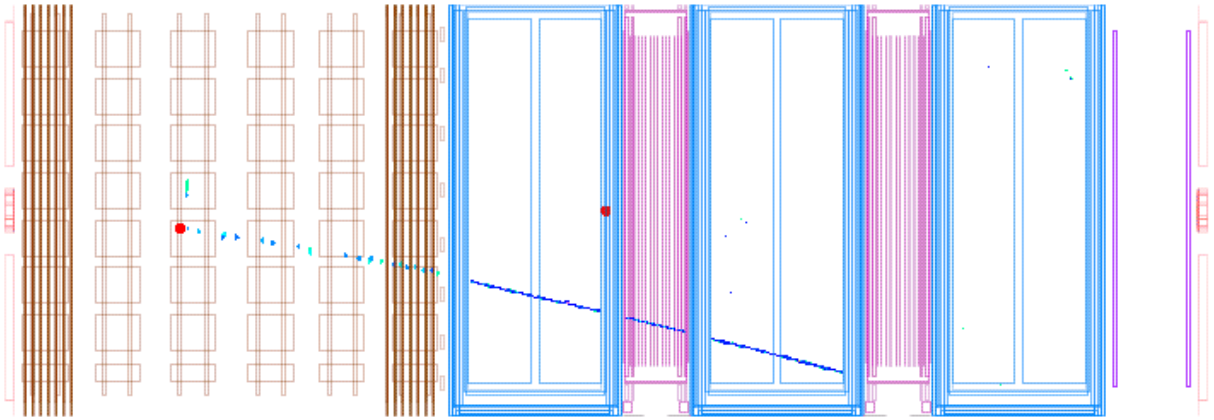
P0D CC0π on Water

Use CC0π events in the P0D

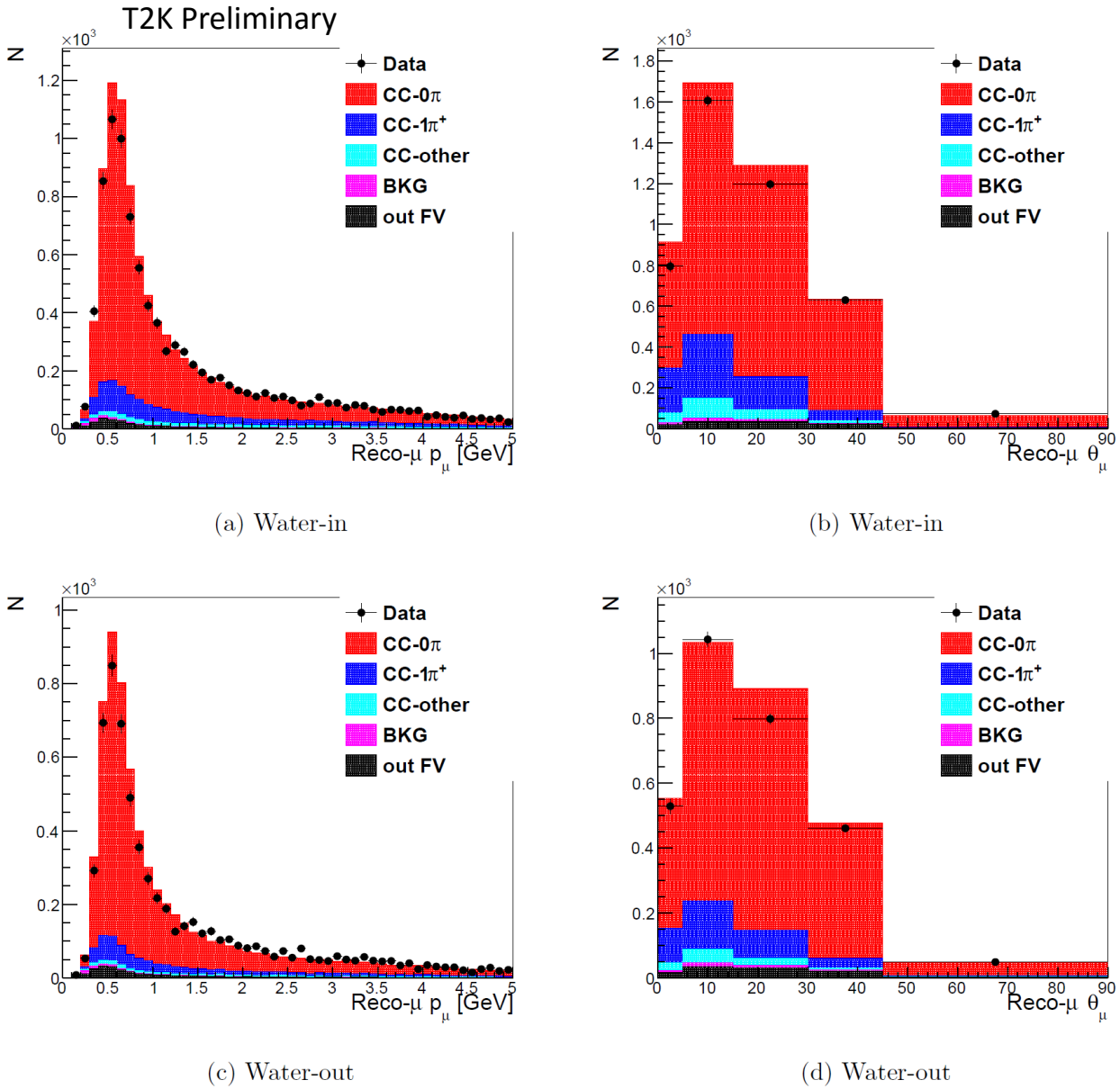
Require that the muon enter the TPC

P0D runs with water in and water out periods

Use subtraction and Bayesian unfolding to extract cross section.



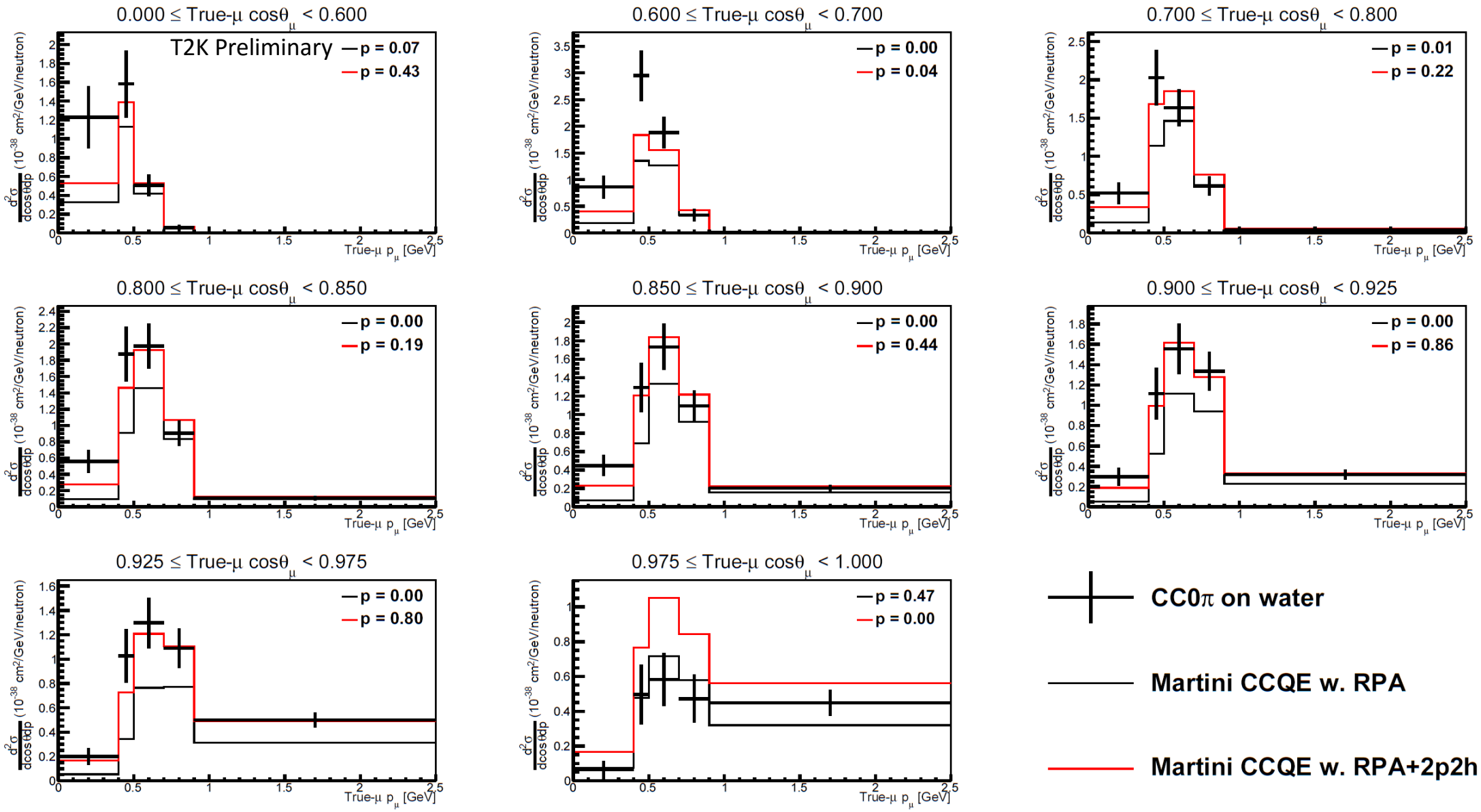
5.8x10^{20} pot Neutrino Mode



(a) Water-in (b) Water-in

(c) Water-out (d) Water-out

P0D CC0π on Water



ND280 CC1π^+ Cross Sections

To improve understanding of cross sections want to look at more explicit channels

Exploit tracking performance of ND280 to reconstruct more complex final states

CC1π^+ two MIP-like tracks

- Can also identify pion through Michel electron in FGD
- Muon and Pion kinematics can be measured

Veto multiple pions with extra track and ECAL π^0 veto

Higher multiplicity control samples to manage backgrounds

Carbon cross section → FGD1

Water cross section → FGD2

Coherent production

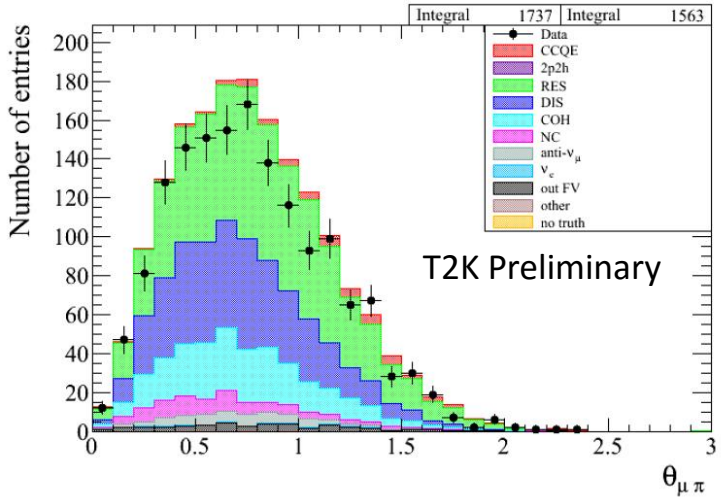
CC1π^+ Cross Section on Carbon

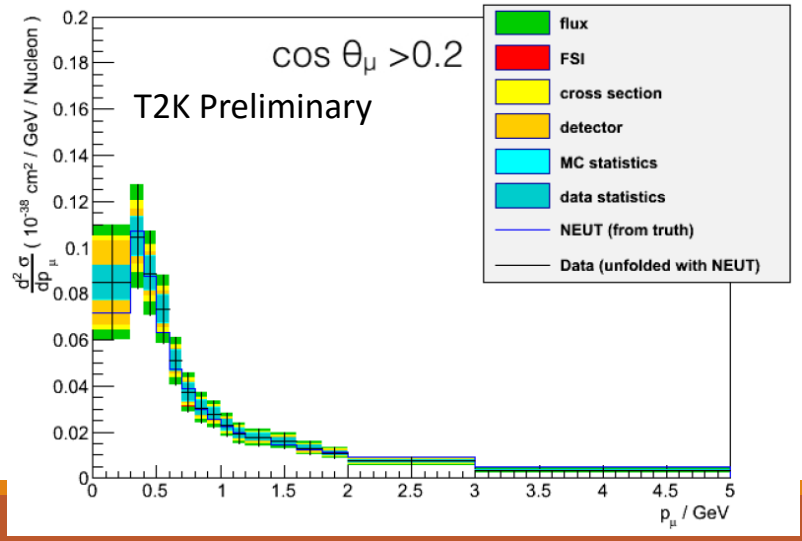
5.6x10^{20} pot Neutrino Mode

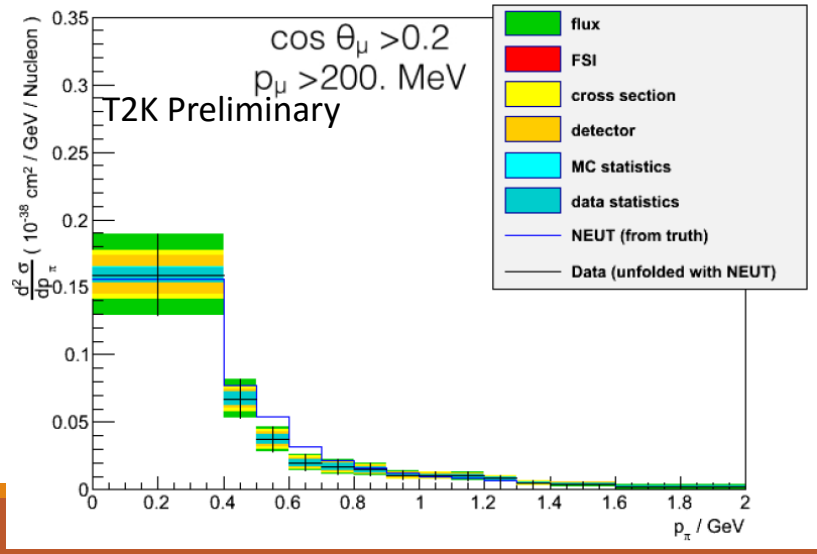
Multiple tracks open up additional variables to consider

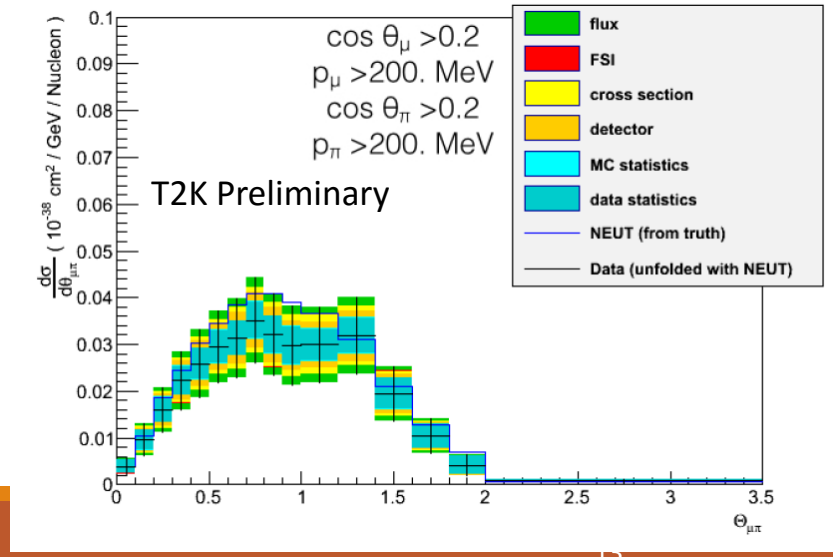
- Can give insight into underlying physics

Bayesian unfolding with control samples for backgrounds









arXiv:1605.07964

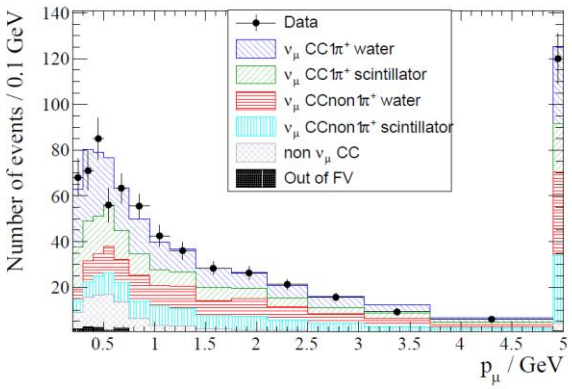
CC1π^+ Cross Sections on Water

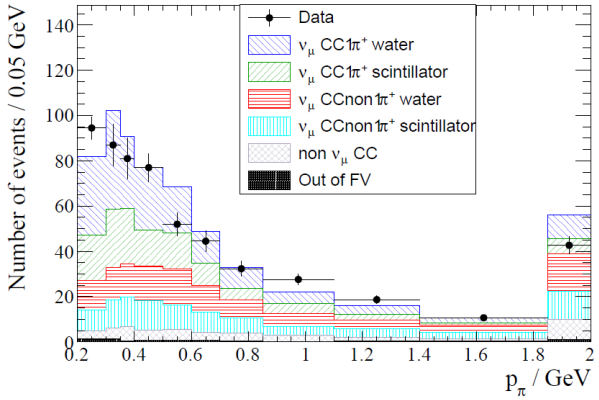
Exploit that water target in FGD2 is always followed by an x-layer.

- Create carbon-enriched and water-enriched samples depending on reconstructed vertex location

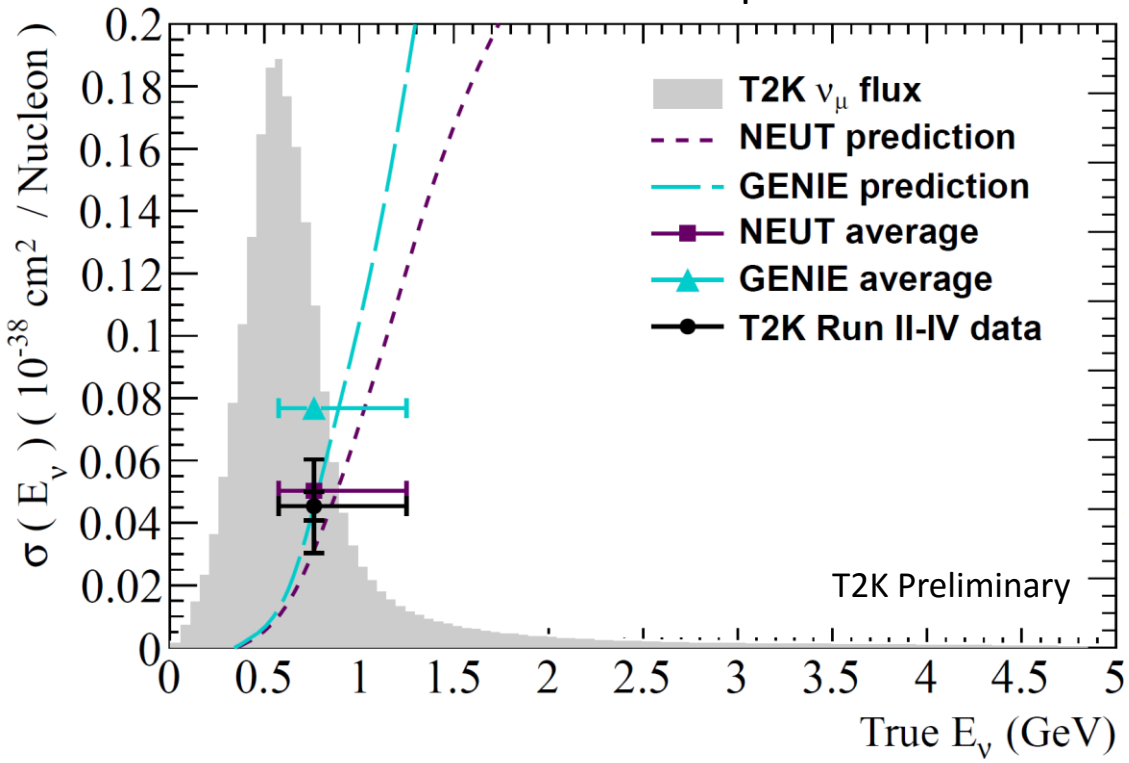
Used in a Bayesian unfolding with background subtraction

T2K Preliminary





5.6x10^{20} pot Neutrino Mode



p_μ > 200 MeV $\cos(\theta_\mu)$ > 0.3
p_π > 200 MeV $\cos(\theta_\pi)$ > 0.3

arXiv:1604.04406

Coherent π^+ Production

Search for coherent π^+ production on carbon

In coherent production, only the lepton and pion will leave the nucleus in the final state

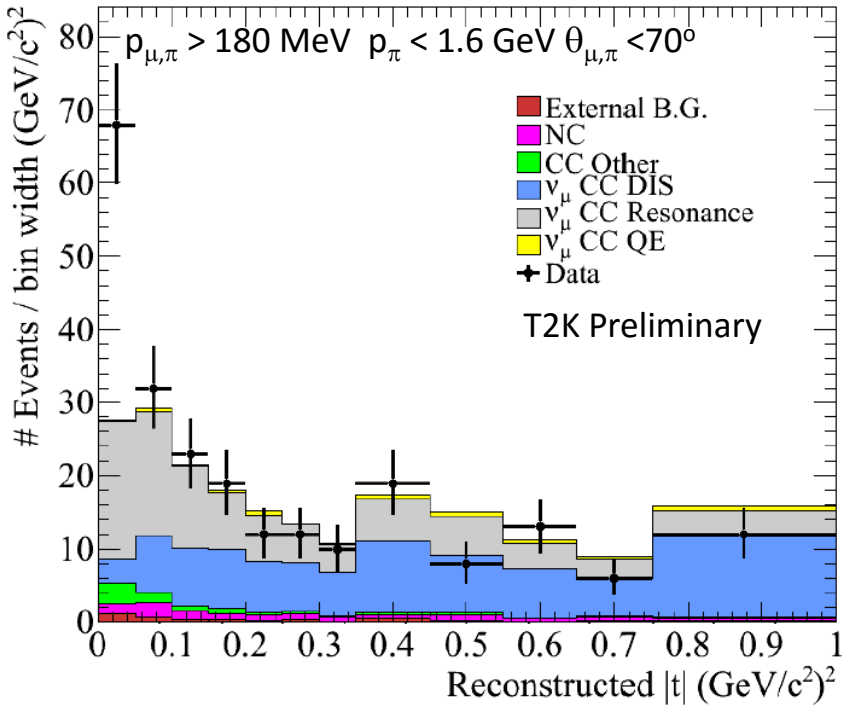
Look for lack of vertex activity to select coherent production

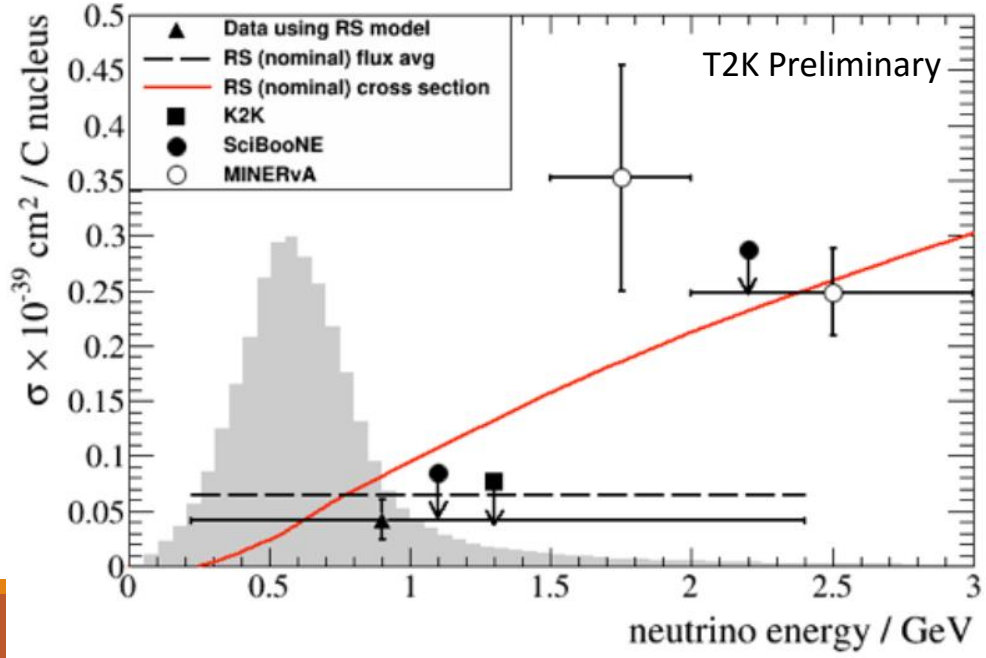
Look for excess of events at low 4-momentum transfer to the nucleus

- $|t| = |(q-p_\pi)^2|$

Low t excess observed at 2.2σ

Coherent cross section consistent with but lower than models





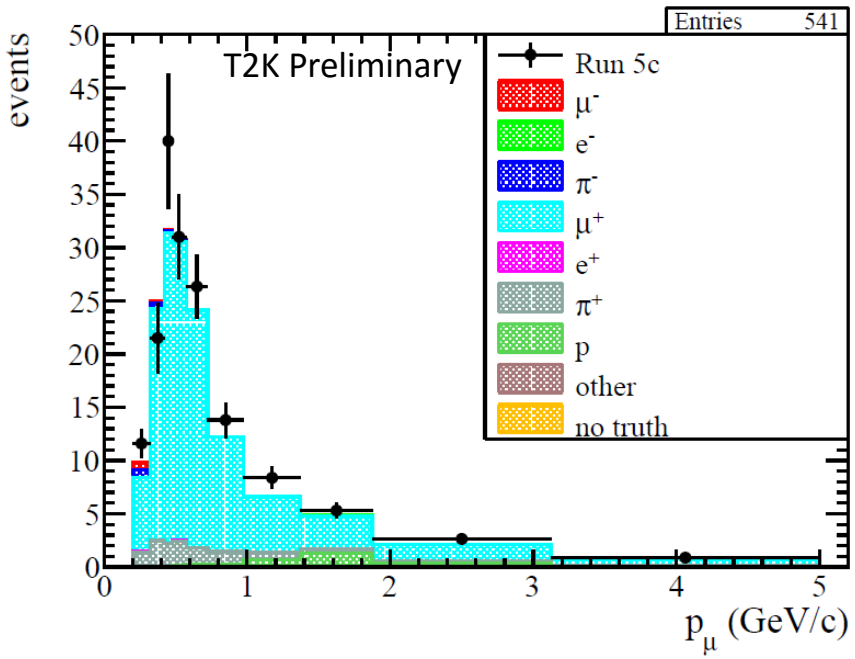
ND280 Antineutrinos

Highest momentum positive track FGD-TPC are selected

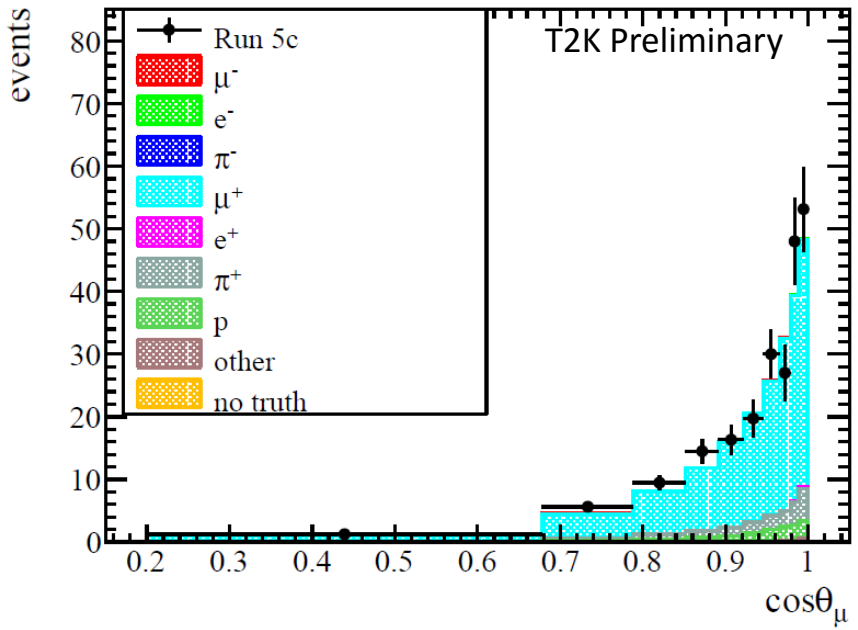
Quality, PID and Veto cuts applied

Control sample used to control protons

- These are hard to distinguish from muons in the 1-2 GeV region

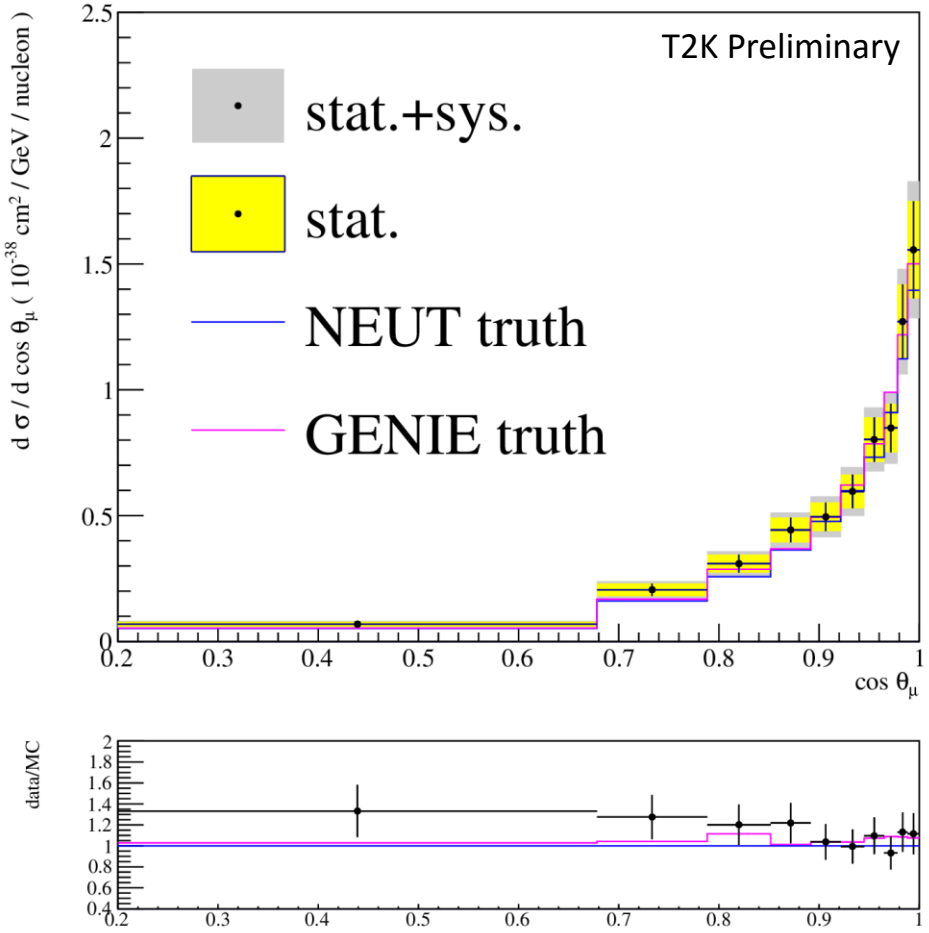


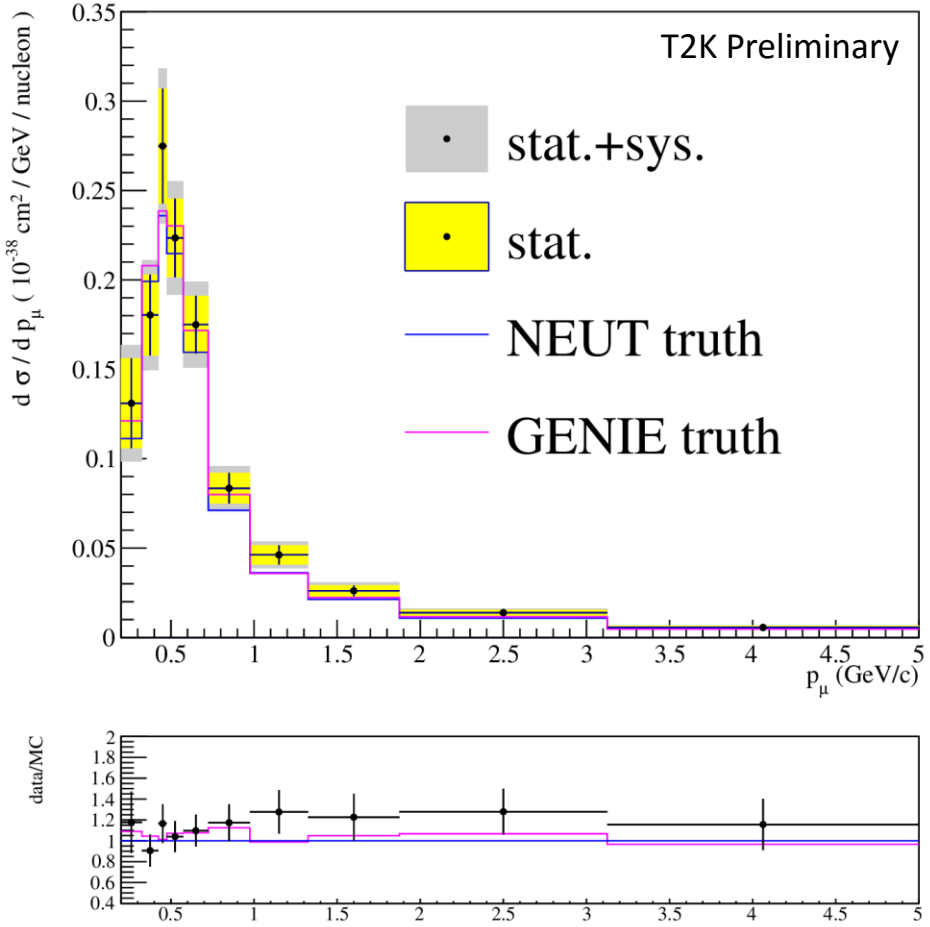
4.29x10^{19} pot Anti-Neutrino Mode



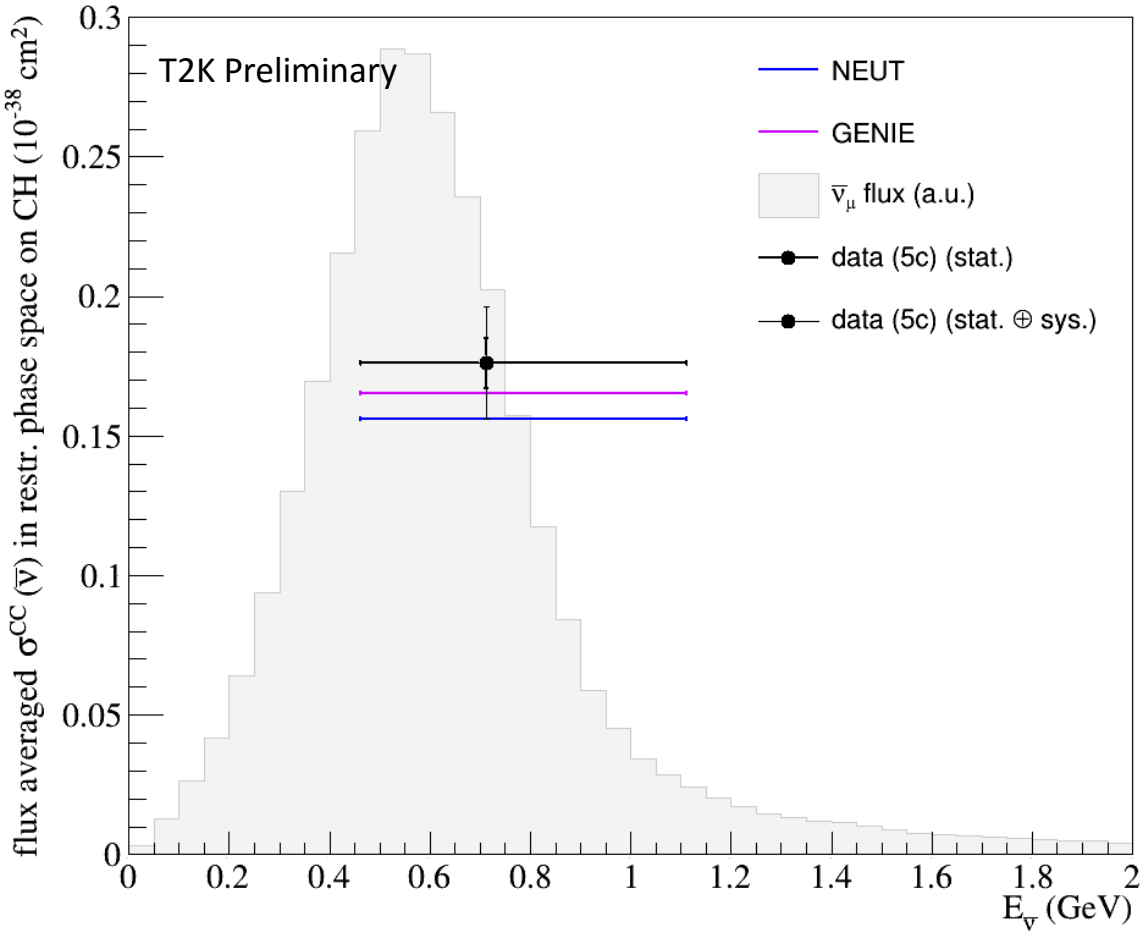
Restricted phase space:
$0.2 < p_\mu < 5$, $\cos(\theta_\mu) > 0.2$

ND280 $\bar{\nu}_\mu$ CC Inclusive Cross Section on Carbon





ND280 $\bar{\nu}_\mu$ CC Inclusive Cross Section on Carbon



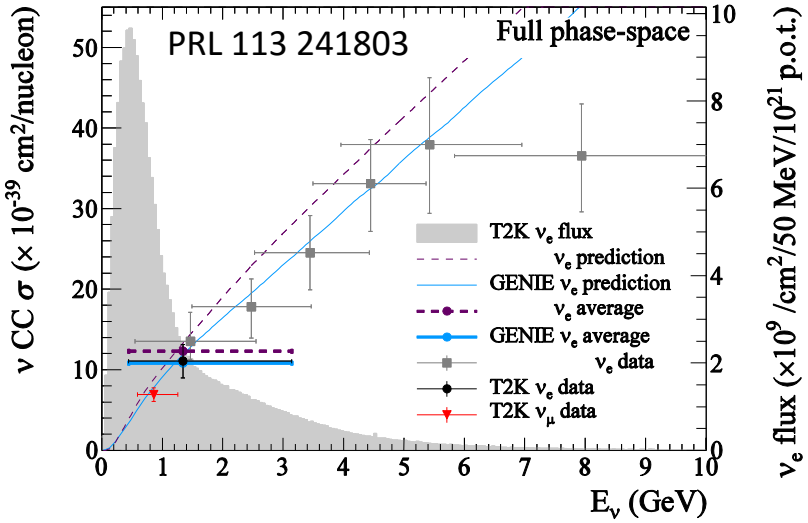
ND280 $\bar{\nu}_e$

T2K has previously published inclusive electron neutrino cross section results

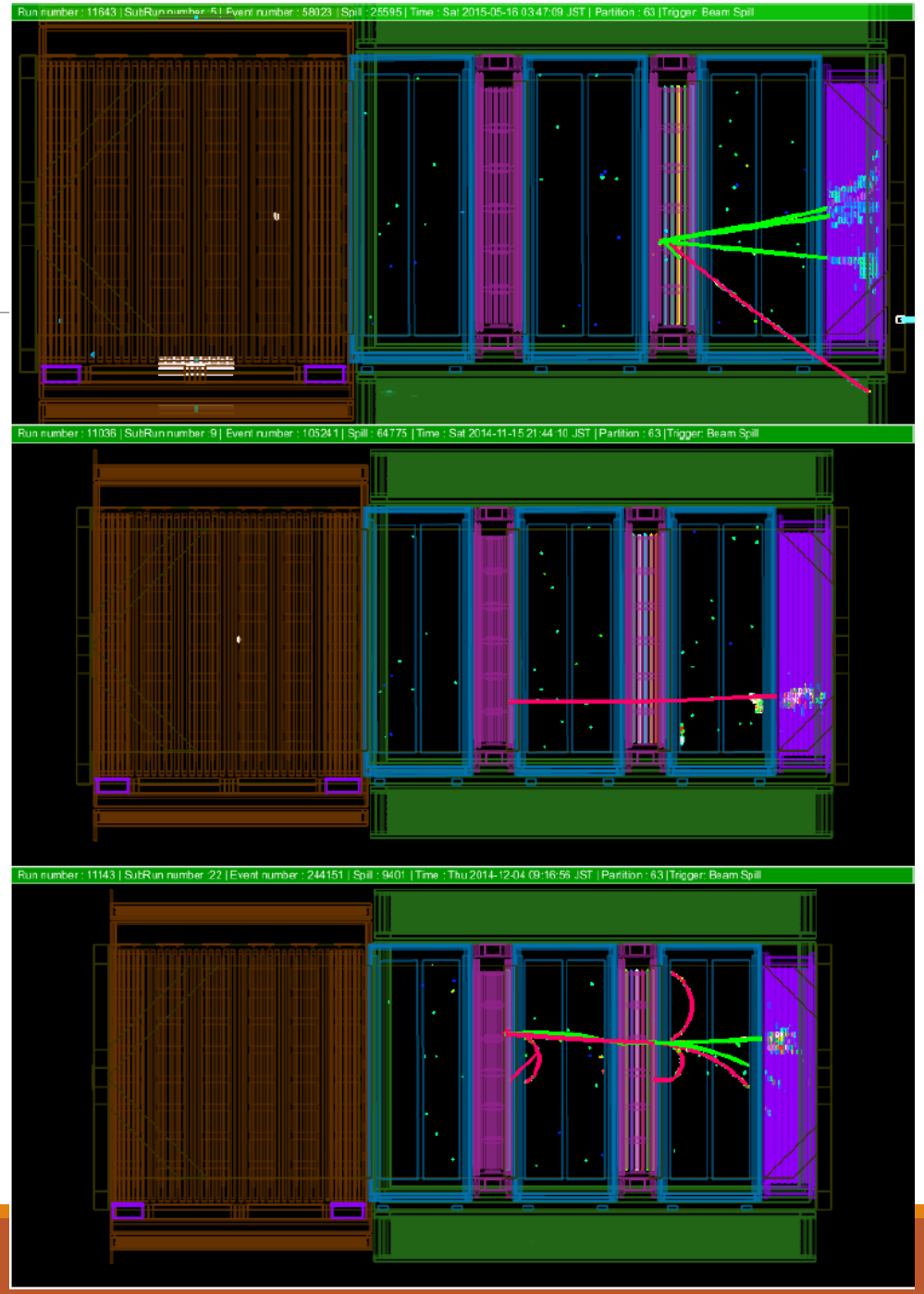
Measurement of positrons in the ND280 tracker is more challenging

- dE/dx for electrons and protons is approximately equal at 1 GeV

Additional selection criteria required for electron antineutrino measurements



Positron selection:
Efficiency 36%
Purity 62%
Protons 5%
Photons 21%



ND280 $\bar{\nu}_e$ results

3.67x10^{20} pot Anti-Neutrino Mode

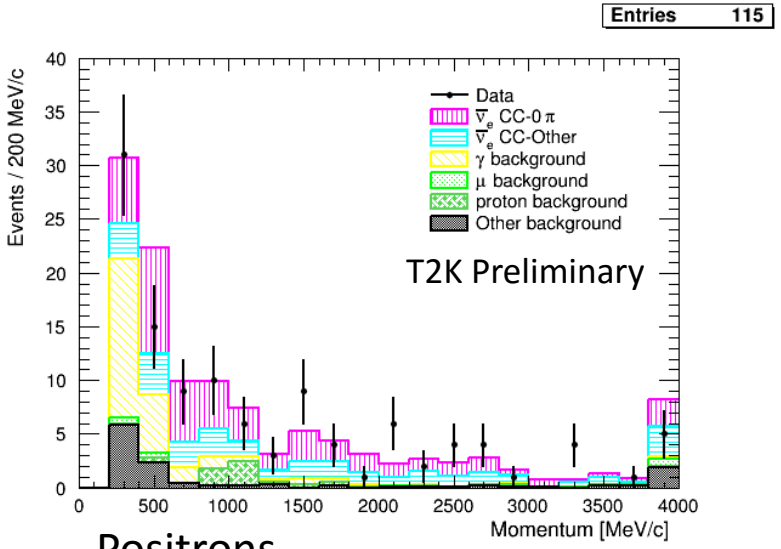
Joint fit of $\bar{\nu}_e$, ν_e and photon control sample

Confirm T2K prediction

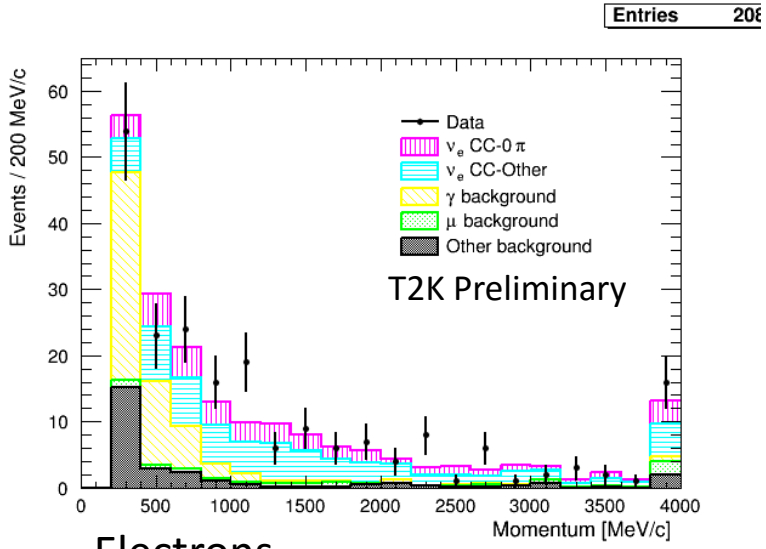
Cross section results to come.

Ratio of Data to Prediction

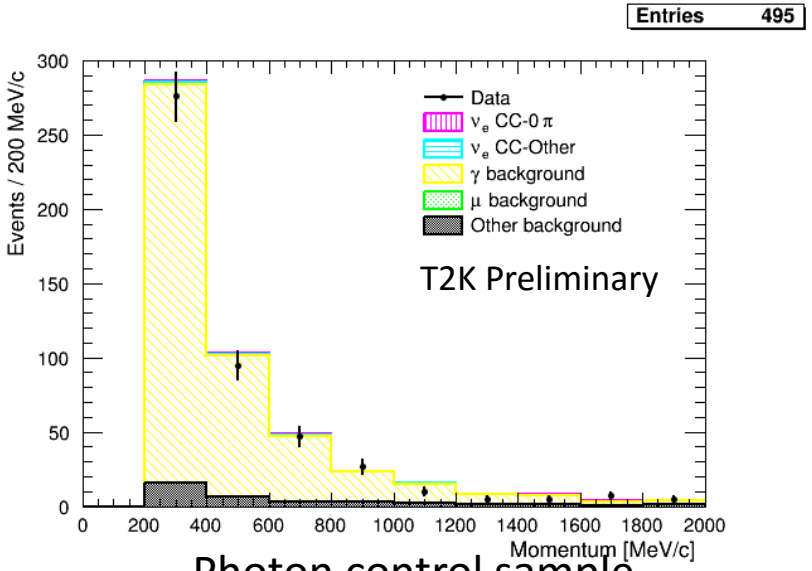
- $f(\nu_e) = 1.250 \pm 0.135(stats.) \pm 0.122(syst.)$
- $f(\bar{\nu}_e) = 1.142 \pm 0.144(stats.) \pm 0.132(syst.)$
- $f(\gamma) = 0.810 \pm 0.063(stats.) \pm 0.142(syst.).$



Positrons



Electrons



Photon control sample

Summary and Outlook

T2K has a near detector suite that can measure cross sections in addition to its role in oscillation analyses

A number of neutrino mode cross-section results are available including exclusive channels to help pin down models

Antineutrino results are starting to come out

You can expect many more cross section results from T2K in the future

T2K Cross Section Results in this Talk

INGRID ν_μ CC Inclusive on iron : PRD 93 072002

INGRID ν_μ CCQE on carbon : PRD 91 112002

ND280 Tracker ν_μ CC0π on carbon: PRD 93 112012

ND280 P0D ν_μ CC0π on water : See Poster by Tianlu Yuan on Monday

ND280 Tracker ν_μ CC1π^+ on Carbon

ND280 Tracker ν_μ CC1π^+ on Water : arXiv:1605.07964

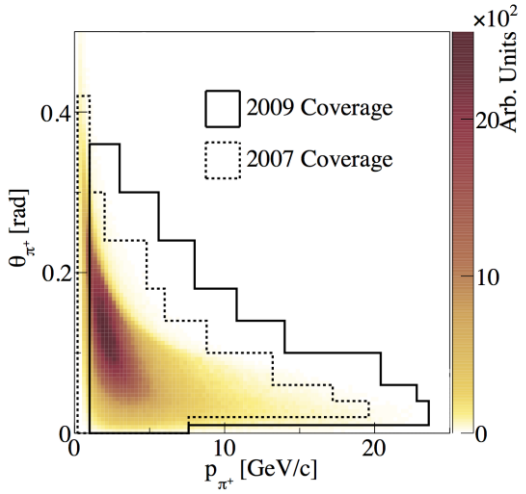
ND280 Tracker ν_μ CC coherent π^+ production on Carbon : arXiv:1604.04406

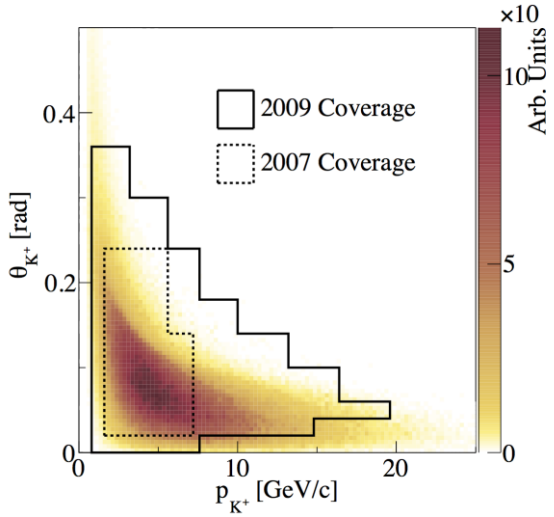
ND280 Tracker $\overline{\nu_\mu}$ CC Inclusive on Carbon

ND280 Tracker ν_e CC Inclusive on Carbon : PRL 113 241803

Backup

Flux Uncertainties

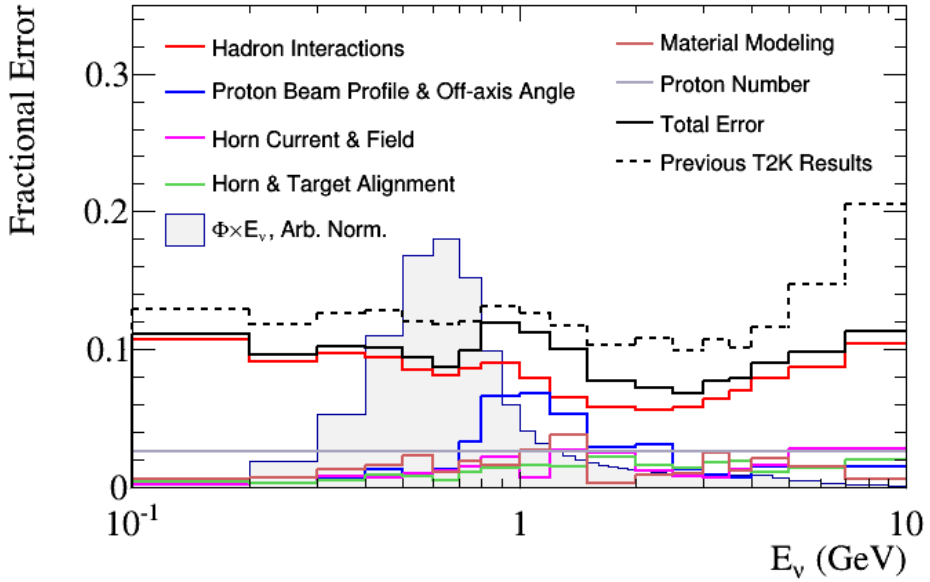




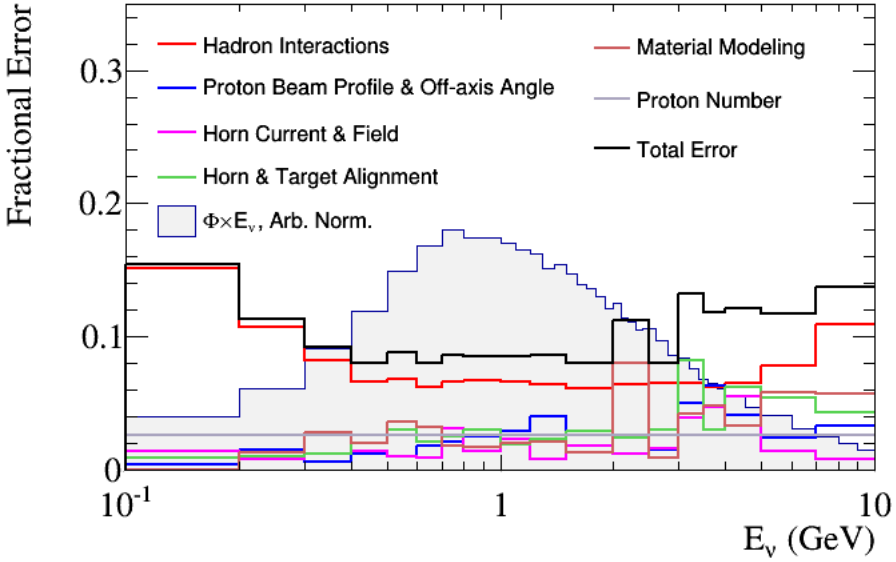
NA61 results crucial for reduction of flux uncertainties

Hadron production uncertainties still dominate

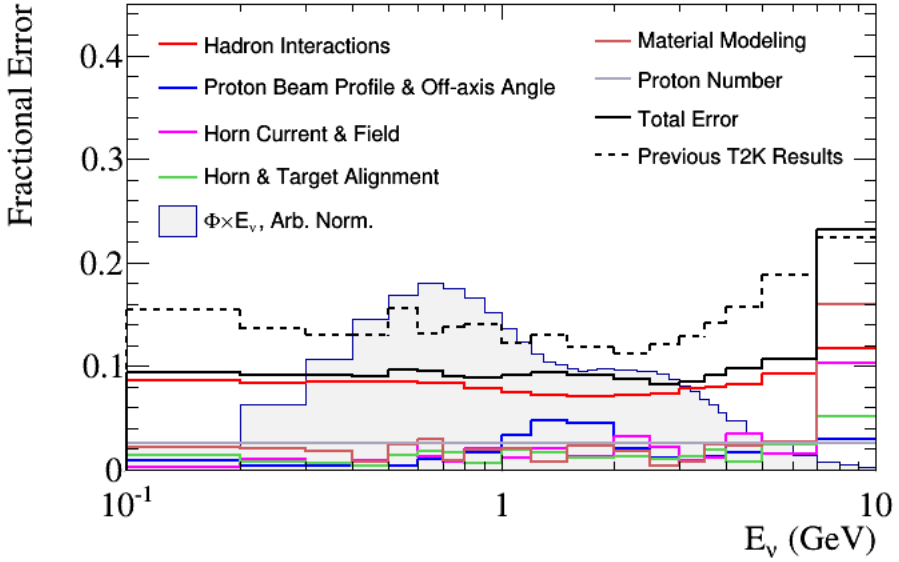
ND280 ν_μ Neutrino Mode



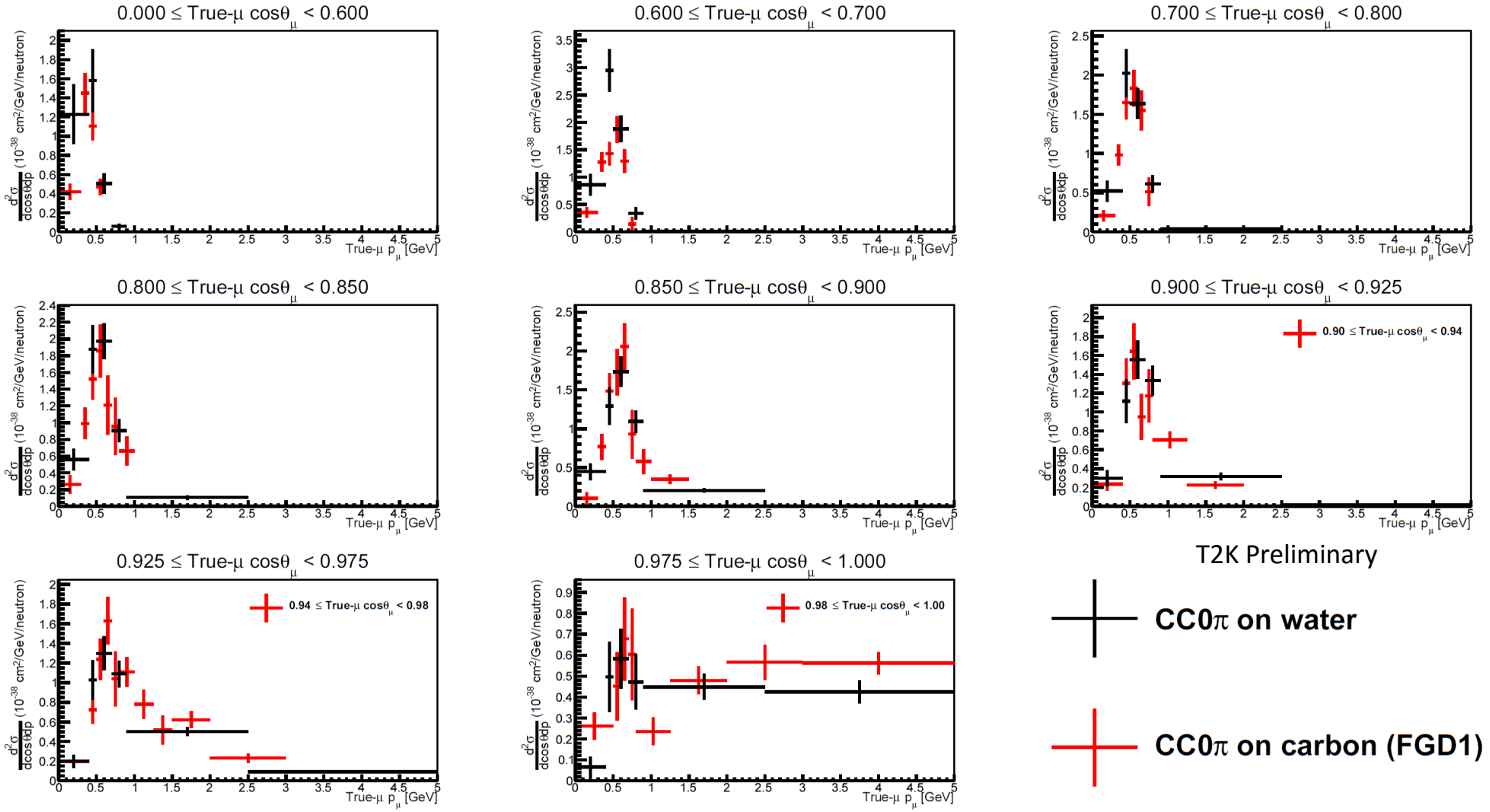
ND280 ν_μ Anti-Neutrino Mode



ND280 ν_e Neutrino Mode



CC0π Cross Section Comparison P0D to FGD



P0D CC0π on Water