Measurement of the ν_μ Charged Current Quasielastic Scattering Cross Section on Water with the T2K Off-Axis Near Detector

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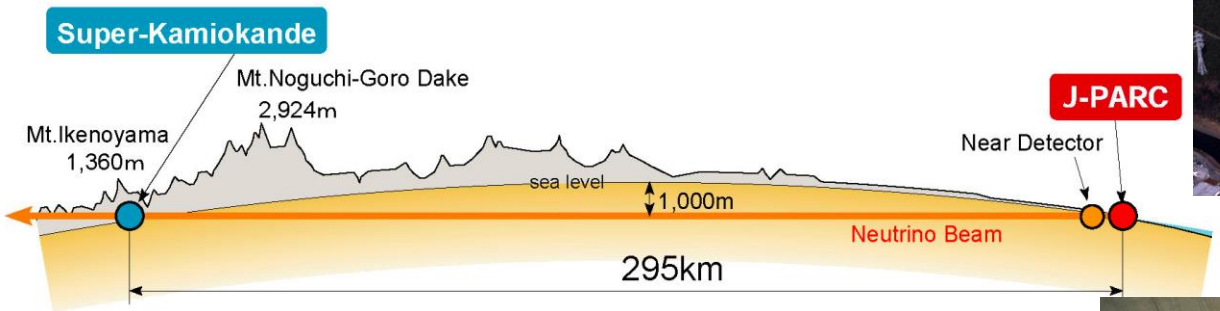
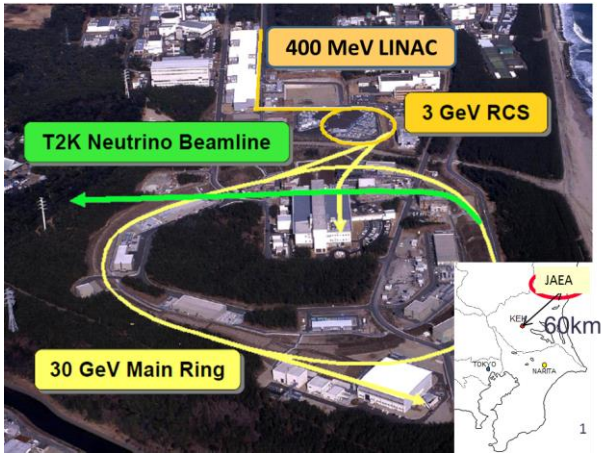
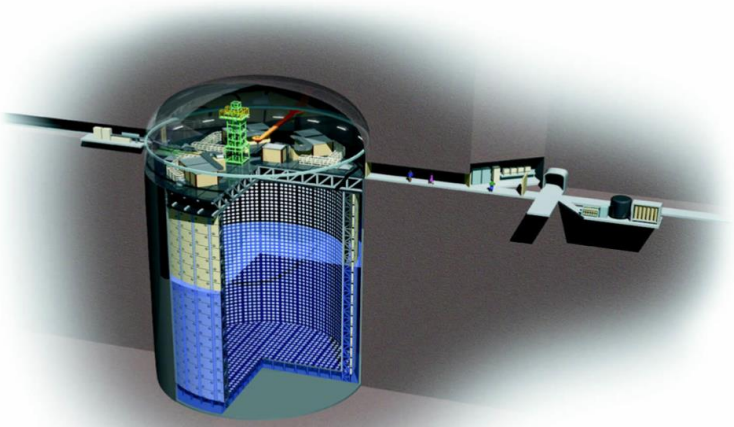
The T2K Experiment

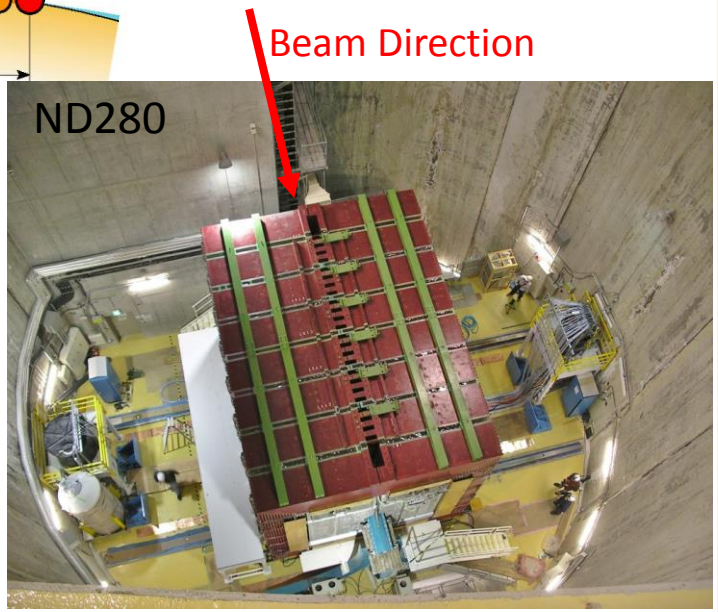
- Create beam of ν_μ at J-PARC accelerator in Tokai, Ibaraki
- Measure oscillations at Super-Kamiokande (SK)
- SK is off-axis, have on-axis and off-axis near detectors



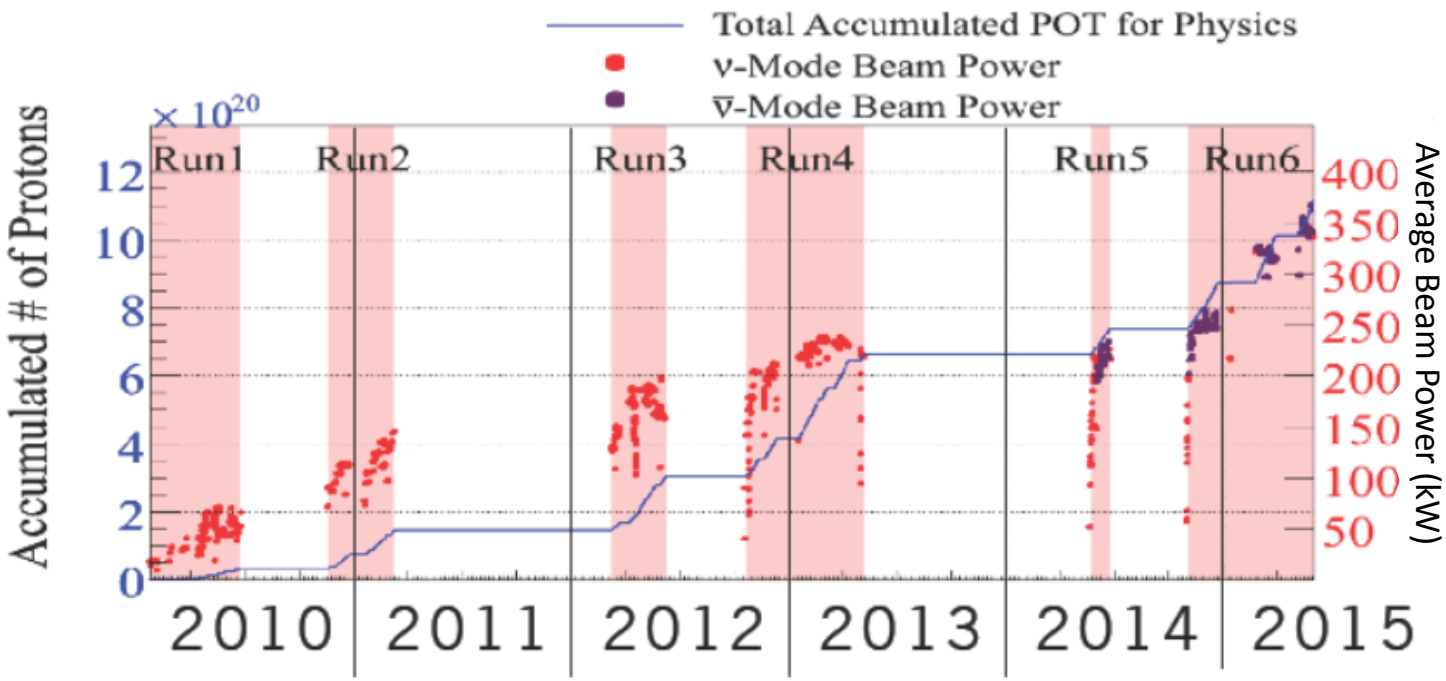




Super-Kamiokande

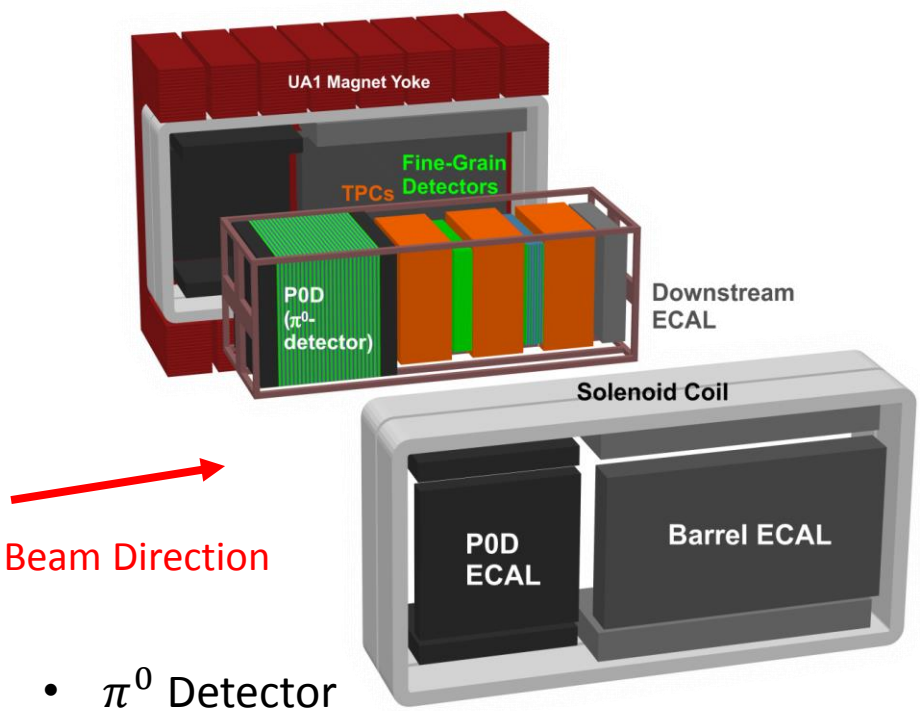


T2K Collected Beam

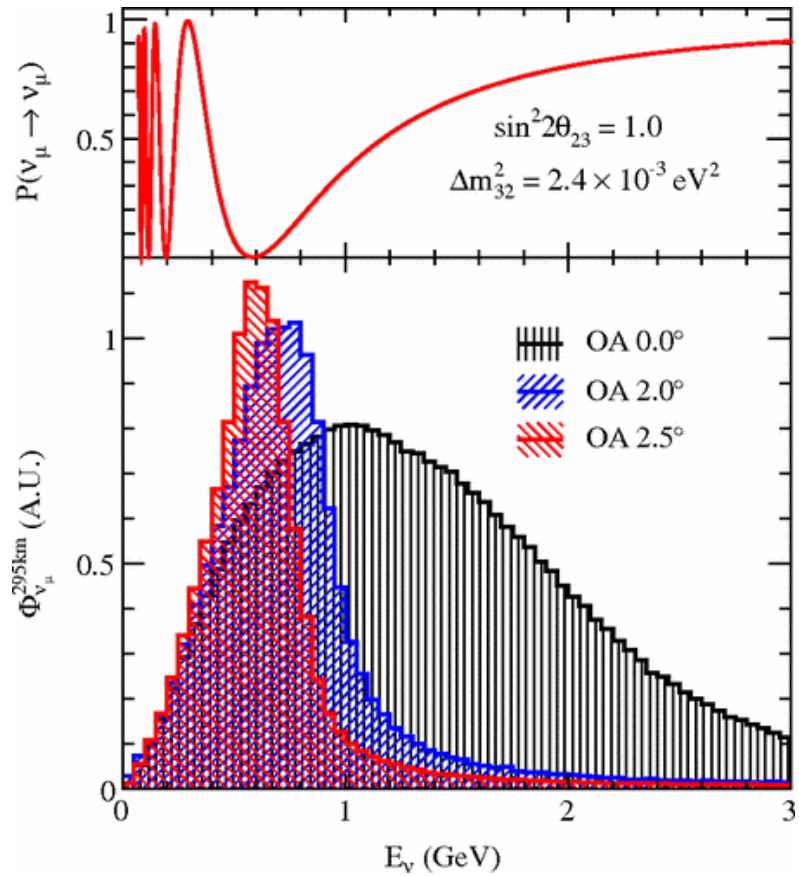


- ν Mode: 7.00 x 10^{20} Protons on Target (POT)
- $\bar{\nu}$ Mode: 4.04 x 10^{20} POT
- This measurement: Using Run 1-4 ν Data

The ND280 Off-Axis Near Detector



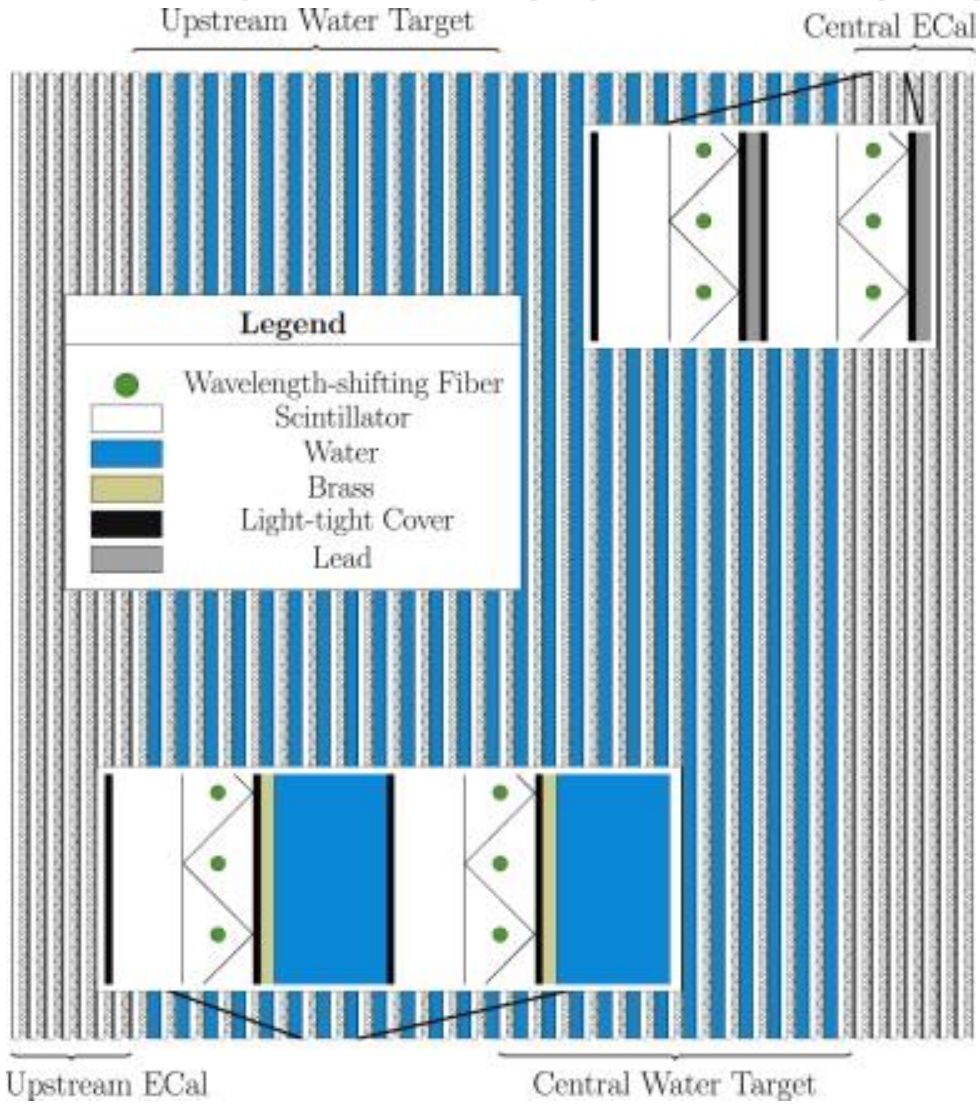
Off-axis measurement gives narrower energy spectrum!



- π^0 Detector
- Tracker:
  - 3 TPCs
  - 2 Fine Grained Detectors (FGDs)
- Electromagnetic calorimeters (ECals)
- Muon detectors (in magnet yoke)

Nucl. Instr. Meth. A. 659 (2011), pp 106-135.

The ND280 π^0 Detector (P0D)

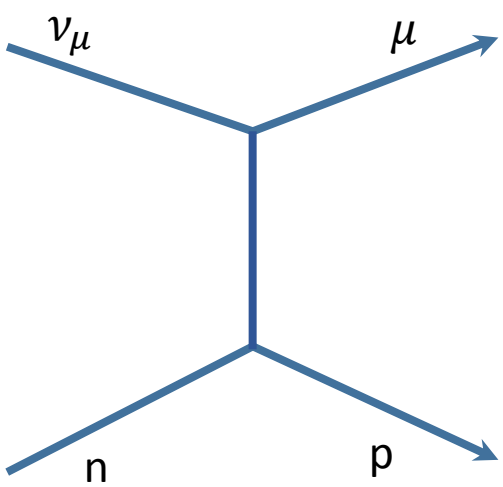


- ECals: Scintillator & Lead
- Water target: Scintillator, Brass, & Water
- Water can be drained for measurement with just non-water materials

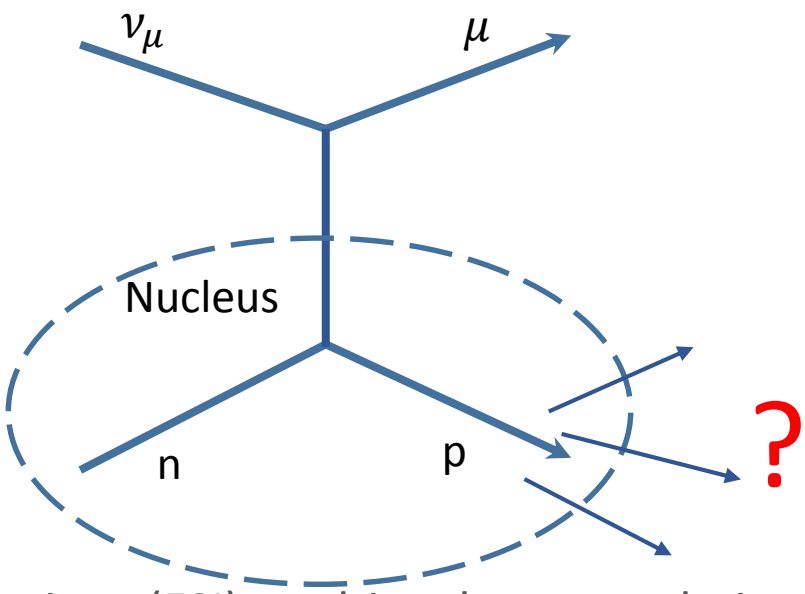
Nucl. Instr. Meth. A. 686 (2012), pp. 48-63.

The CCQE Cross Section

- Dominant event type seen in T2K ν_μ disappearance analysis
- SK has a water target, ND280 a mix of scintillator, water, brass, lead, etc.
- Few published cross section measurements on water target



The CC0π Cross Section

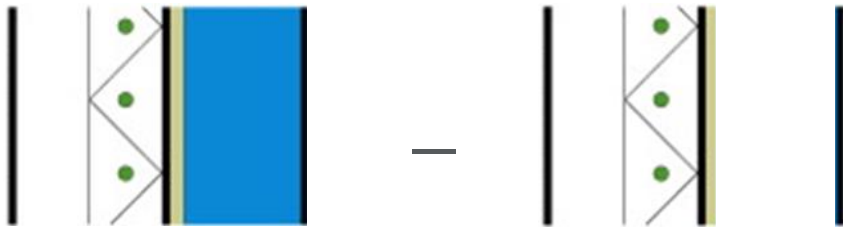


- Final state interactions (FSI), multinucleon correlations and other effects mean that a variety of final states are measured
- Rather than measure the CCQE cross section, we use a topological definition of the signal:
  - Charge current (muon candidate found)
  - No pions
  - Any number of nucleons
- We refer to this as the CC0π topology

Measuring the Water Cross Section

- We want a flux-averaged double differential cross section of ν_μ CC0π interactions on water

$$\left\langle \frac{d^2\sigma}{dp_\mu d\cos\theta_\mu} \right\rangle =$$



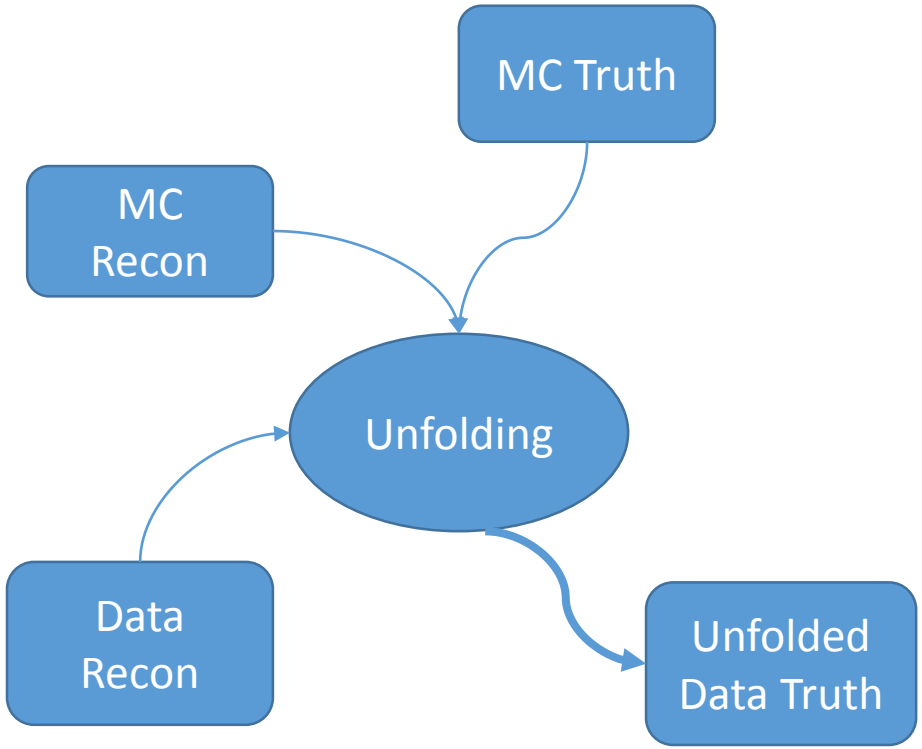
(water (w) in P0D) (air (a) in P0D)

$$\left\langle \frac{d^2\sigma(p_i,\theta_i)}{dp_\mu d\cos\theta_\mu} \right\rangle = \frac{U(N_i^w - B_i^w)}{\Delta_i \phi^w \varepsilon_i^w} - \frac{U(N_i^a - B_i^a)}{\Delta_i \phi^a \varepsilon_i^a}$$

- N: measured signal, B: expected background, ε: efficiency, ϕ: Integrated neutrino flux, Δ: Bin size factor
- U: Unfolding process

Iterative Bayesian Unfolding

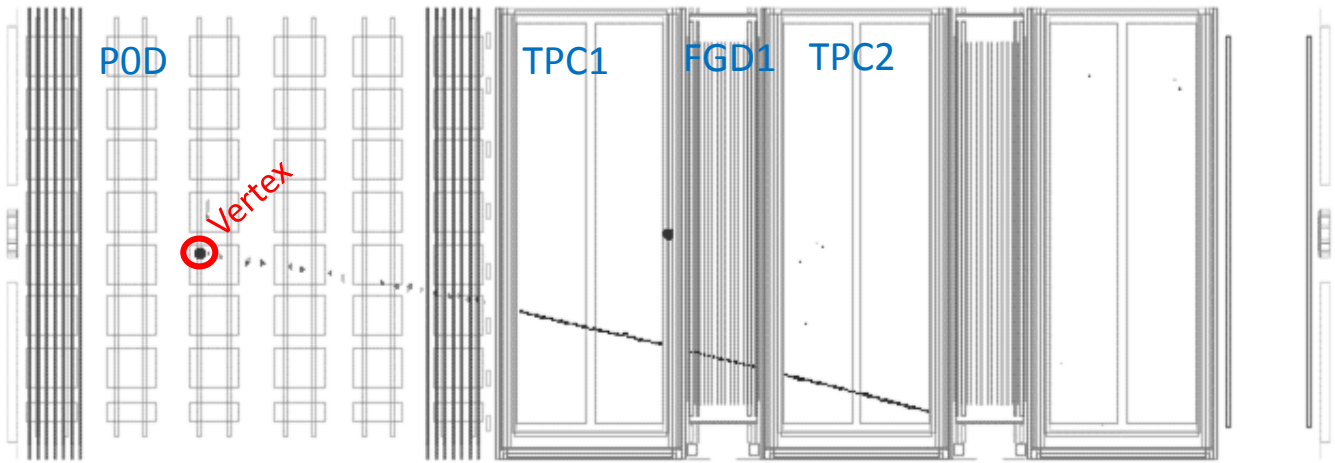
- Detector response in air and water data sets not the same



- Build "smearing matrix" describing migration from truth bins to measured bins
- Use Bayes' theorem & smearing matrix to reconstruct truth distributions from measured data
- Similar to matrix inversion but with more stable results

D'Agostini, Nucl. Instr. Meth. A. 362 (1995), pp 487-498.
D'Agostini. arXiv:1010.0632.

Event Selection

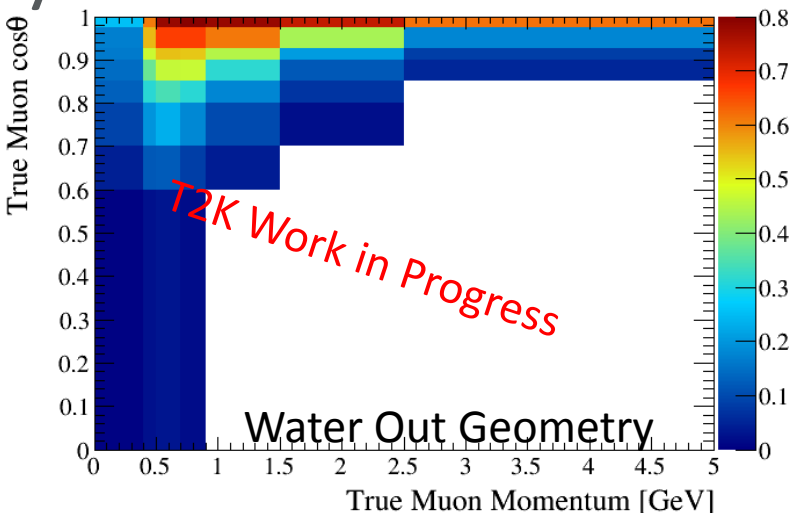


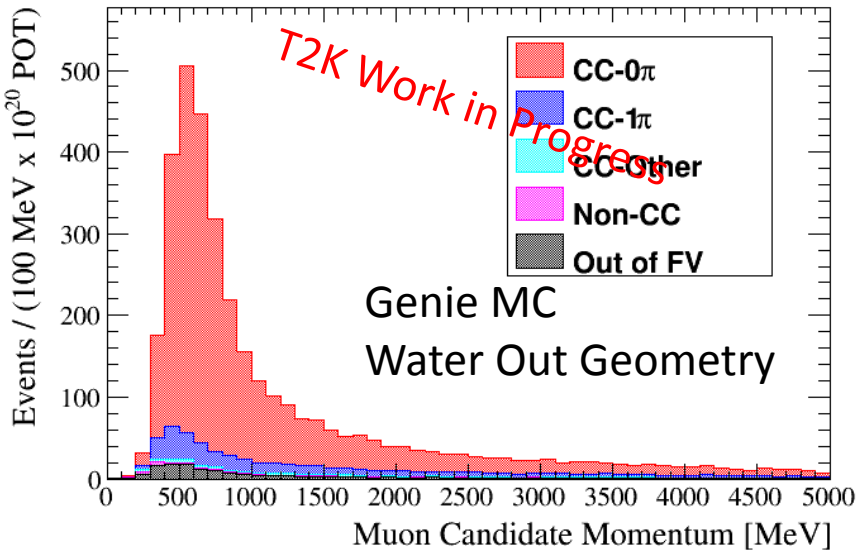
- Good beam, detector, & track quality
- Muon candidate is highest momentum negative track
- Vertex in the P0D water target fiducial volume
- Muon candidate appears in the P0D and tracker
- Only 1 reconstructed track in the P0D

Efficiency and Purity

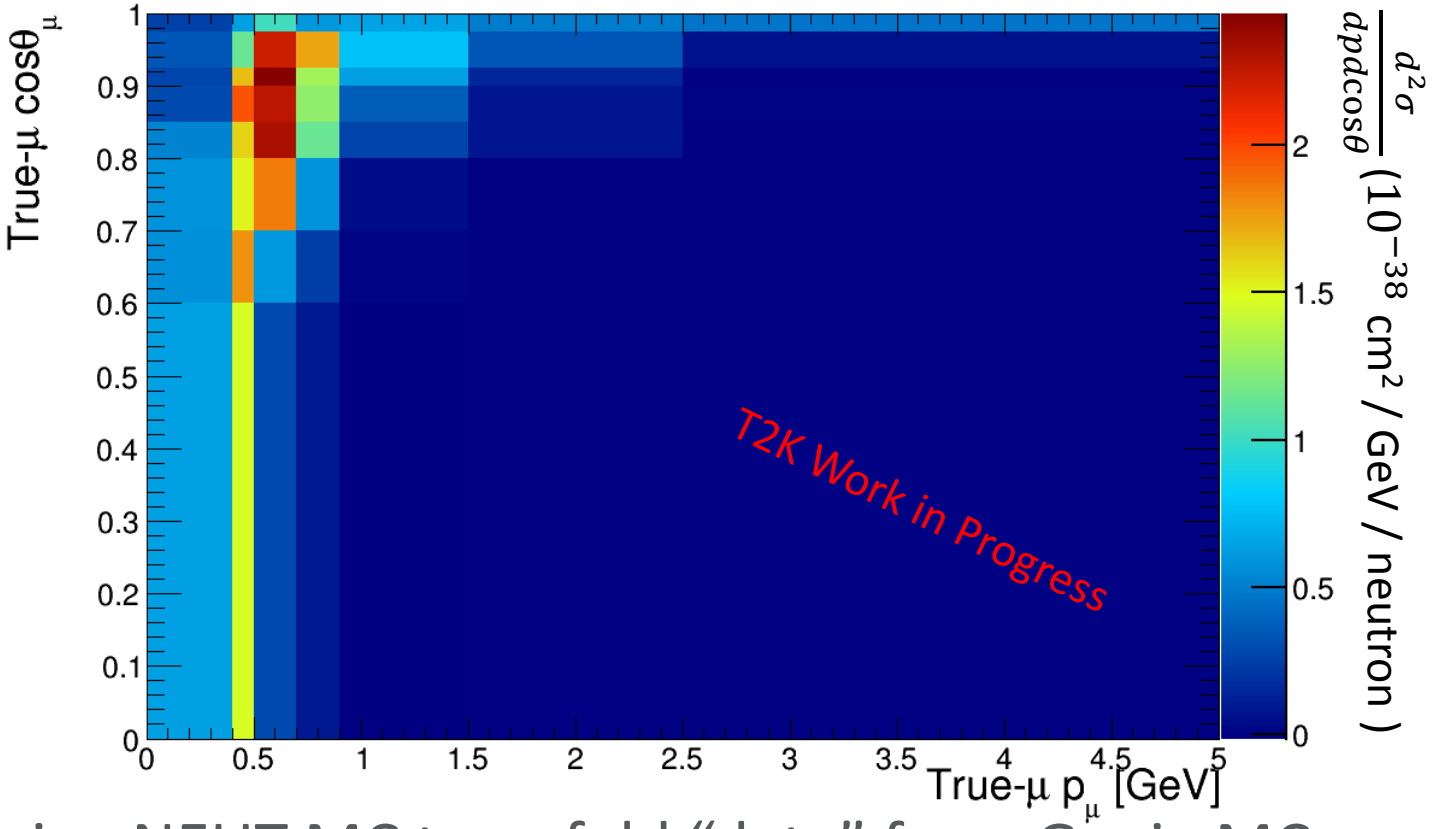
For all CC0π (not just water):

- Overall efficiency ~20%
  - Low efficiency at high angles, below ~500 MeV due to detector geometry
- Purity ~80%
  - CC1π topology the main background





Expected Signal



- Using NEUT MC to unfold "data" from Genie MC
- Systematic uncertainties still need to be finalized before looking at real data

Systematics

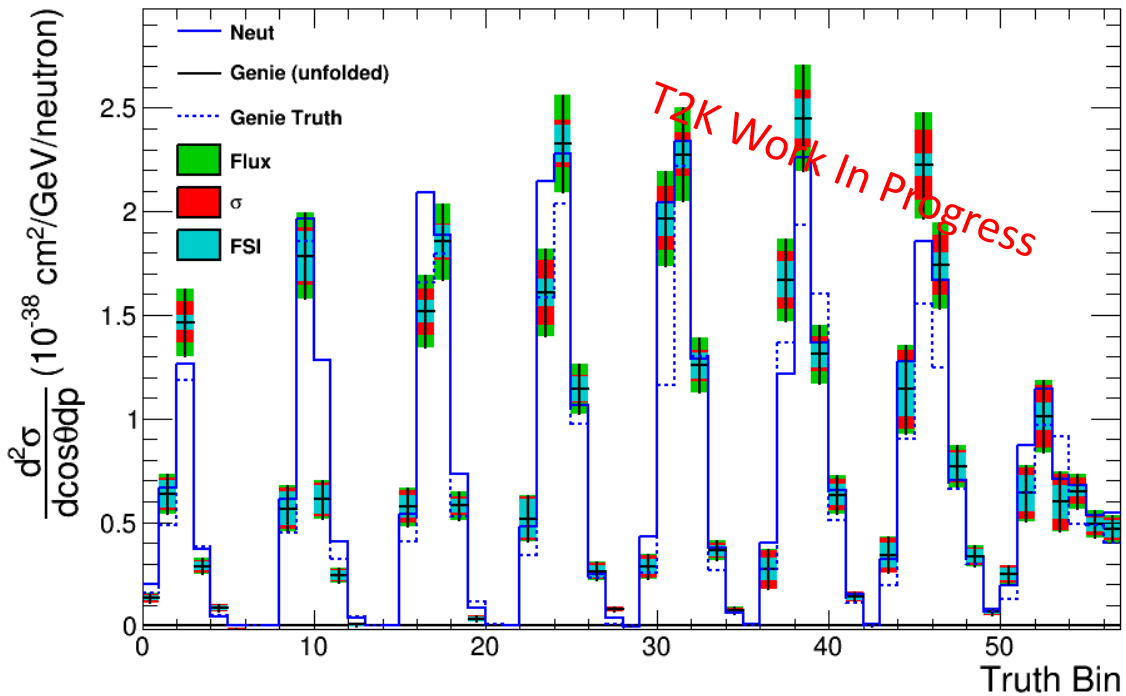
Several types:

1) Flux
2) Interaction (Cross section, final state interaction)
3) Detector

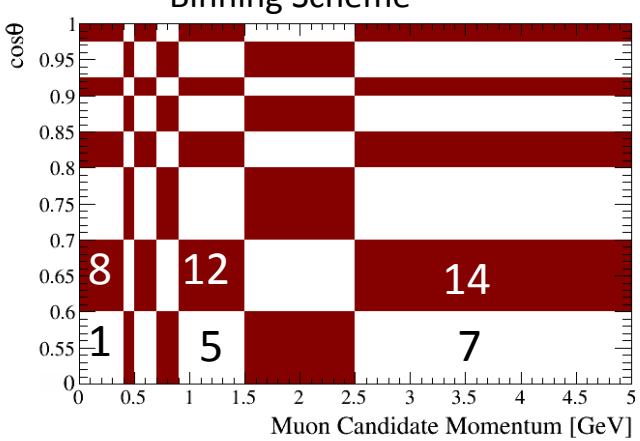
For 1) and 2)

- Flux known to about 10%, typically most important uncertainty in T2K cross section analyses
- Flux, cross section & FSI uncertainties propagated by varying the models and reweighting simulated pseudo-data accordingly

Cross Section and Flux Systematics

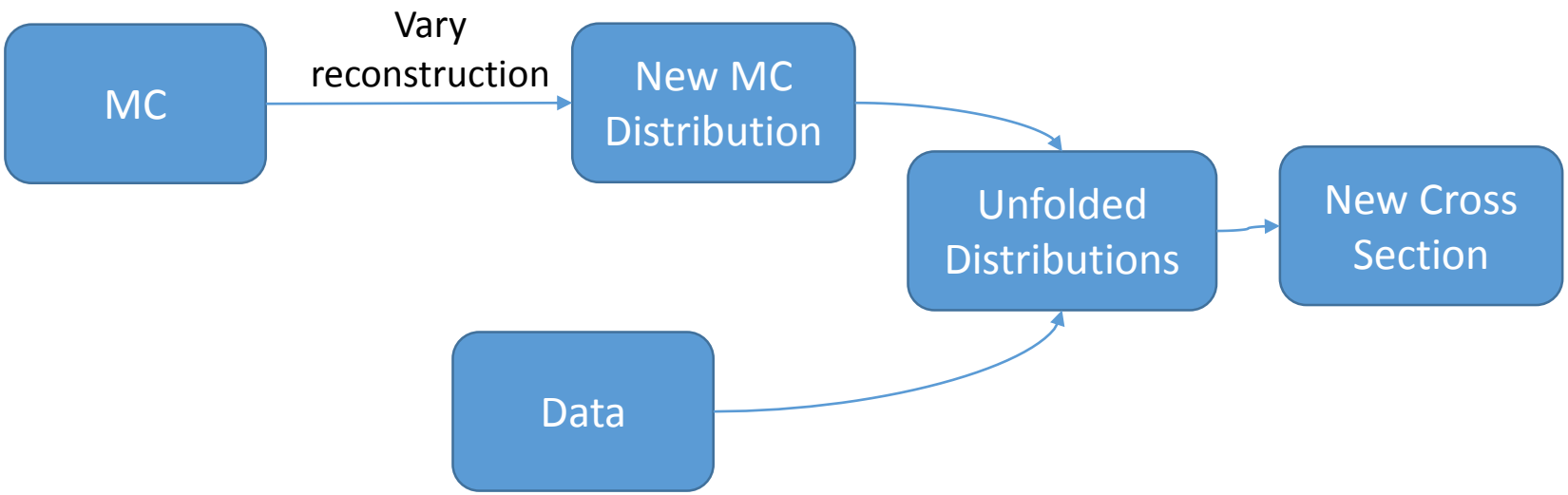


Muon Kinematics
Binning Scheme



- Using Neut MC to unfold small amount of toy "data" from Genie MC

Detector Systematics

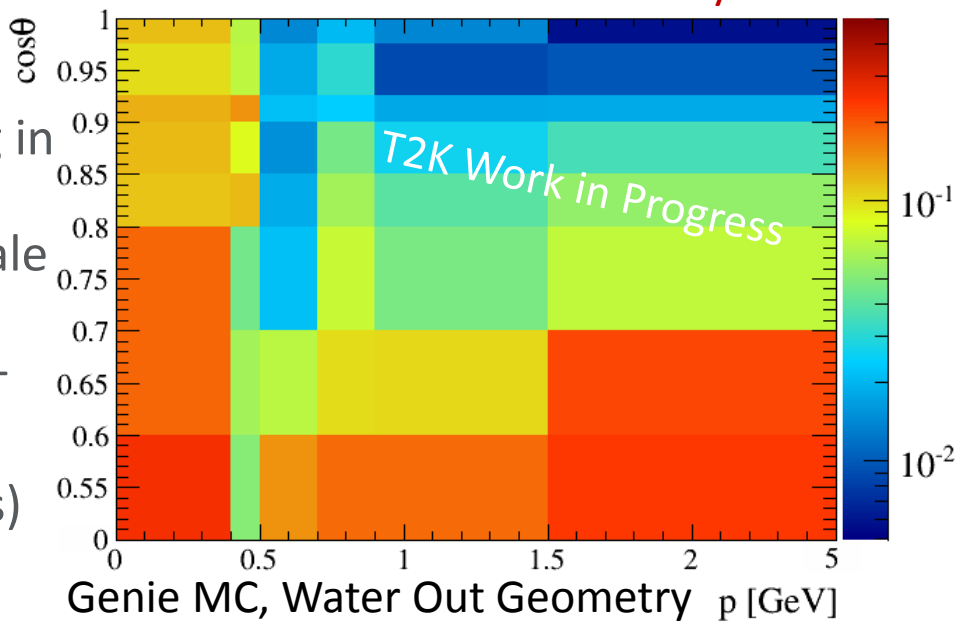


- Cover things like:
  - Momentum reconstruction
  - Direction reconstruction
  - Track efficiency
  - Charge reconstruction

Detector Systematic Example: Momentum Reconstruction

- Tracks built from Kalman filter algorithm
- Tracker (TPC/FGD) momentum systematics well understood
- P0D momentum systematics determined from cosmics stopping in the P0D fiducial volume
- Vary reconstructed momentum scale & resolution in MC events
- Initial studies: Uncertainties in pre-unfolded distributions of a few % except in low stats/high angle bins (many poorly reconstructed events)

Fractional uncertainty in pre-unfolded distribution due to momentum systematics



Genie MC, Water Out Geometry

Conclusions

- Have a well-developed plan for measuring the CC0π cross section on water
- Data for this measurement already collected
- Have implemented subtraction method for cross section extraction from ND280 data
- Treatment of systematics still in progress, expect results soon
- Starting to think about how to best combine this work with other T2K CC0π analyses

Backup Slides

Detector Systematics

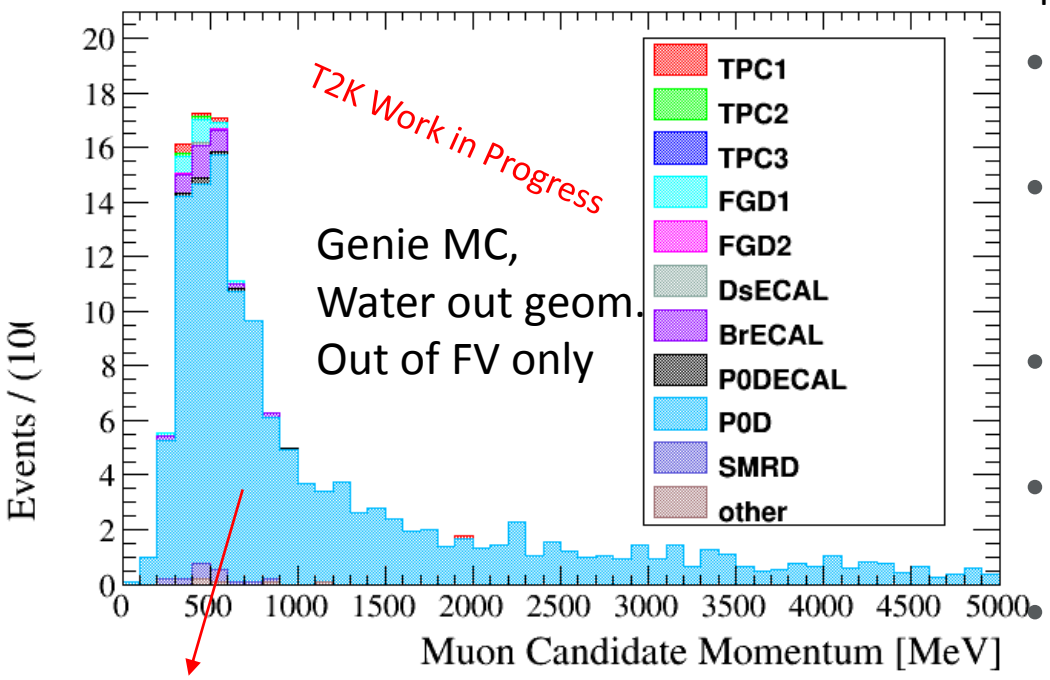
Systematic
P0D Momentum Loss Scale
Tracker Momentum Scale
P0D Momentum Loss Resolution
Tracker Momentum Resolution
Tracker Efficiency
P0D/Tracker Matching Efficiency
Out of Fiducial Volume Background
P0D Fiducial Mass Uncertainty
Direction Resolution
Track Pileup
Charge Mis-ID

- Most detector systematics are small effects
- Expect that flux/cross section/FSI uncertainties will be more important in end result

Systematic Example 2: Out of Fiducial Volume Events

Config	Out of FV
Water	2.89%
Air	4.02%

Expected fraction of selection fromGenie MC



P0D Backgrounds

- Tricky: Mix of detector & model uncertainties
- Small fraction of events in selection occur outside the fiducial volume
- Most are near edges of fiducial volume
- Should mostly cancel after subtraction
- Still working ways to constrain this background