Charged-Current Pion Production in T2K

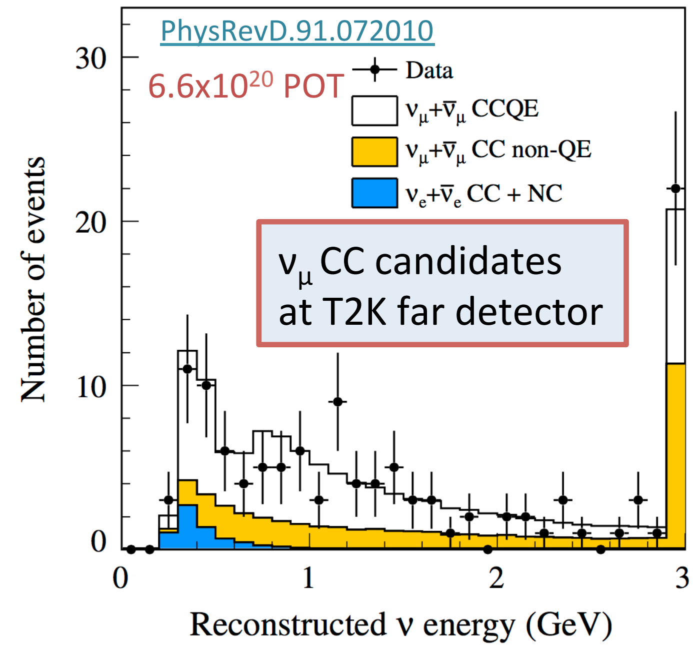
S. V. Cao
Kyoto University
(On behalf of the T2K collaboration)

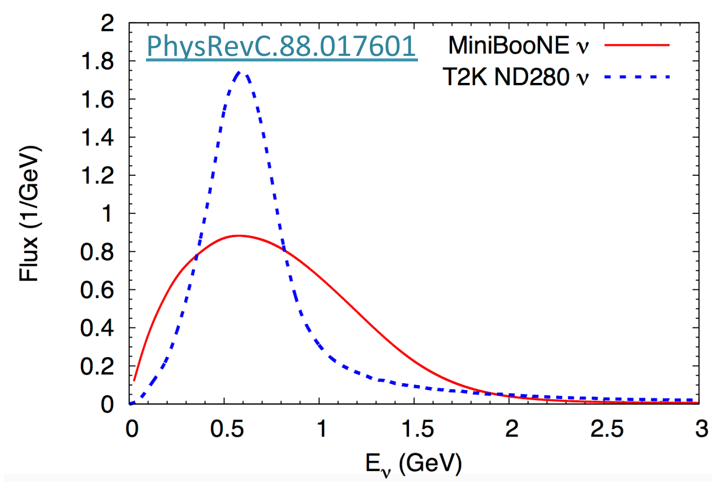
Outline

- ✧ Introduction
- ✧ Charged pion production
  - ✧ In water, off-axis
- ✧ Coherent pion production
  - ✧ In carbon, on-axis
  - ✧ In carbon, off-axis
- ✧ Summary

Needs of π-production in T2K

- Needed for oscillation analysis
  - Main background around oscillation dip
  - Energy misreconstruction
- π-production itself: FSI model (π absorption, scattering, charge exchange…)
- Dominant background to charged-current quasielastic scattering measurements
  - Pion absorption
  - Detector inefficiency
- Also background to other cross-section measurements
- T2K shares same energy peak (0.6 GeV) as MiniBooNE → Compare results

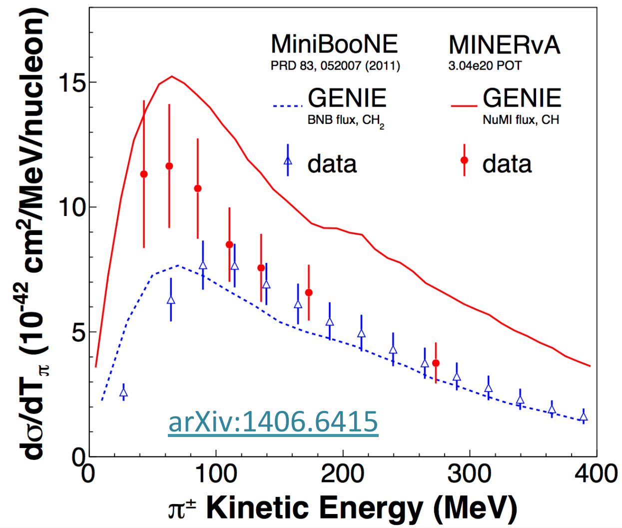




Needs of π-production in T2K (cont'd)

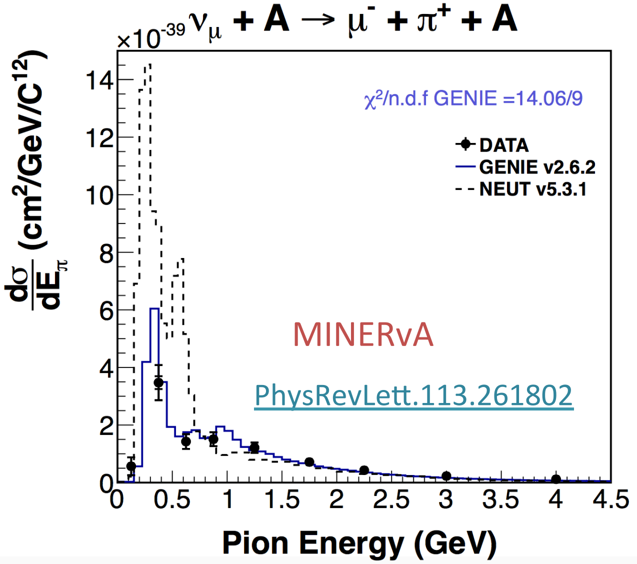
Outstanding issues:

- ✧ CC1π^+: inconsistency between MINERvA and MiniBooNE in overall normalization and pion kinematics
- ✧ CC1π coherent: MINERvA observed this rare interaction above 1.5 GeV, but prediction overestimated at low E_π



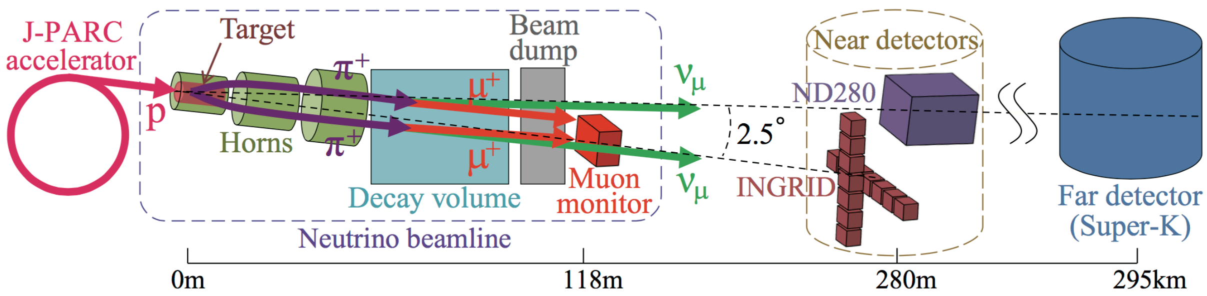
T2K important keys to these issues:

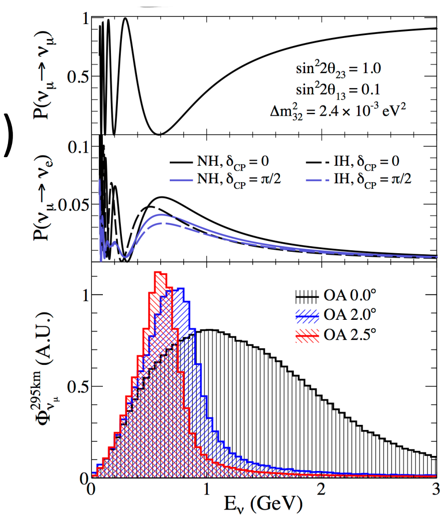
- ✧ Fairly clean N-Δ coupling information (narrow peak at Δ resonance); multiple targets (^{12}C, ^{16}O,…) for FSI constraints
- ✧ CC1π coherence below 1.5 GeV (~0.8 GeV for off-axis, ~1.5 GeV for on-axis)



The T2K experiment

- High intensity, pure muon (anti) neutrino beam
- The world's first off-axis designed neutrino experiment
  - Far Detector (SK) is 2.5^0 off the beam's axis
  - Narrow band beam, peaked at oscillation maximum (0.6 GeV)





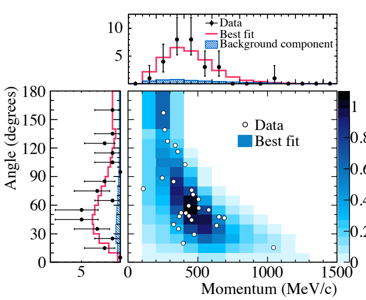
- Primary goal is to measure precisely neutrino oscillations

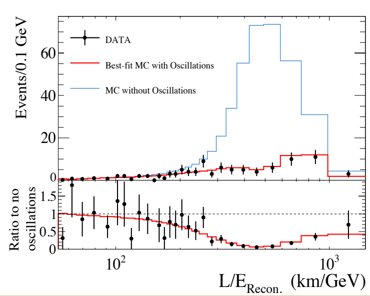
$\nu_\mu \to \nu_e$ — [PRL 112, 061802 (2014)]

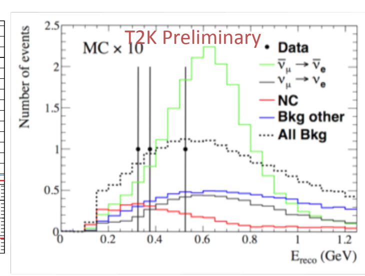
$\nu_\mu \to \nu_\mu$ — [PRL. 112, 181801 (2014)]

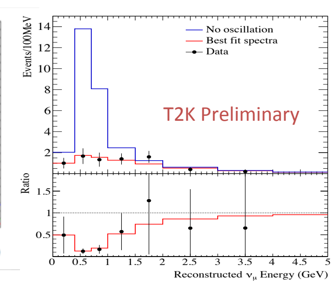
$\bar{\nu}_\mu \to \bar{\nu}_e$ — Paper preparation

$\bar{\nu}_\mu \to \bar{\nu}_\mu$ — Paper preparation









Stay tuned for:

- Observe $\bar{\nu}_\mu \to \bar{\nu}_e$
- CP phase
- Unknowns…

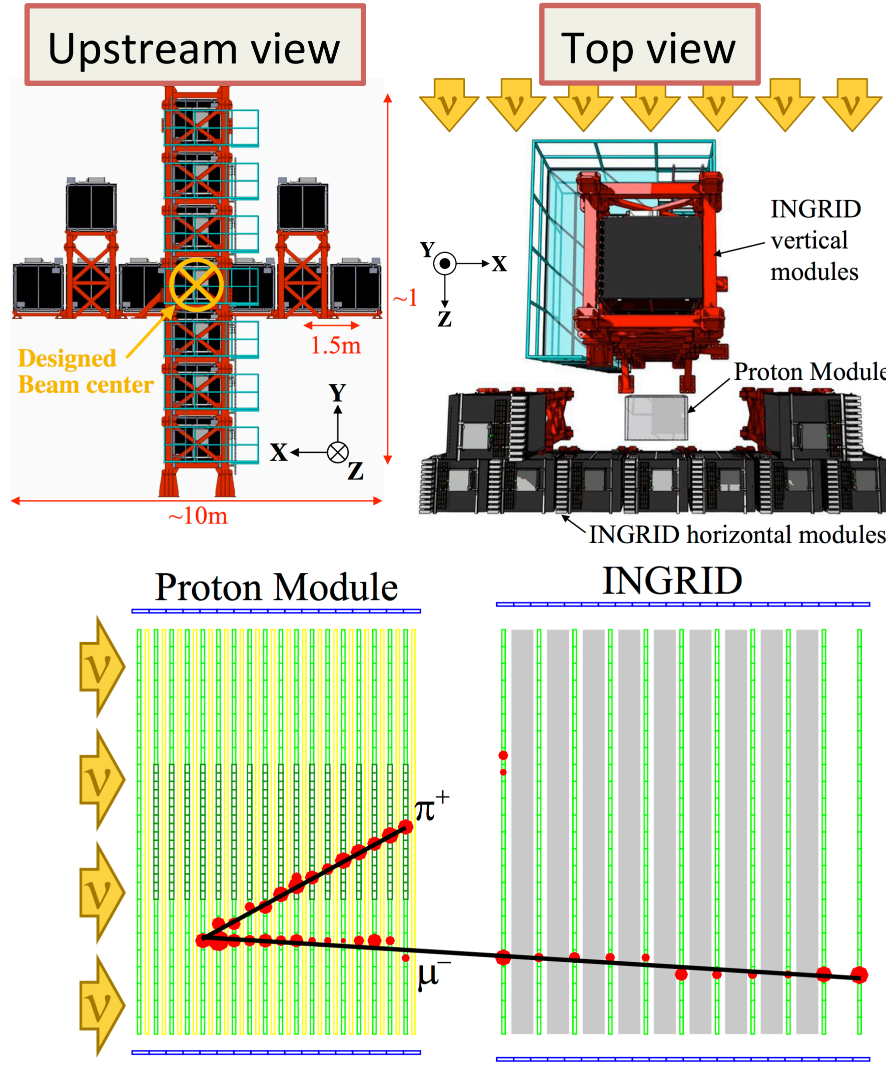
T2K on-axis detector: INGRID

Designed for measuring ν beam intensity, direction and profile

- ✧ 16 scintillator-steel interleaved "standard" modules formed a cross shape (7.1 tons/each)
- ✧ Fully active scintillator Proton Module to detect protons and pions specifically for cross-section studies.

Key features for cross-section:

- ○ Broad flux spectrum, mean ~1.51 GeV
- ○ Target materials: scintillator and iron
- ○ Large number of interactions

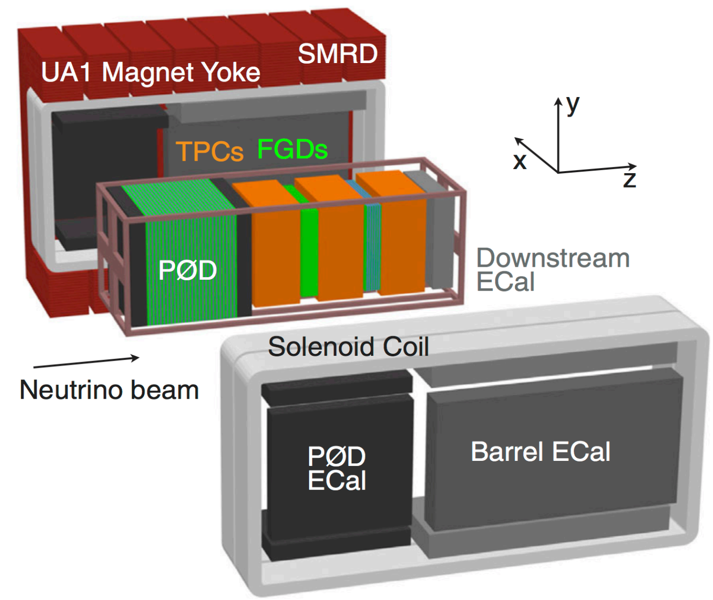


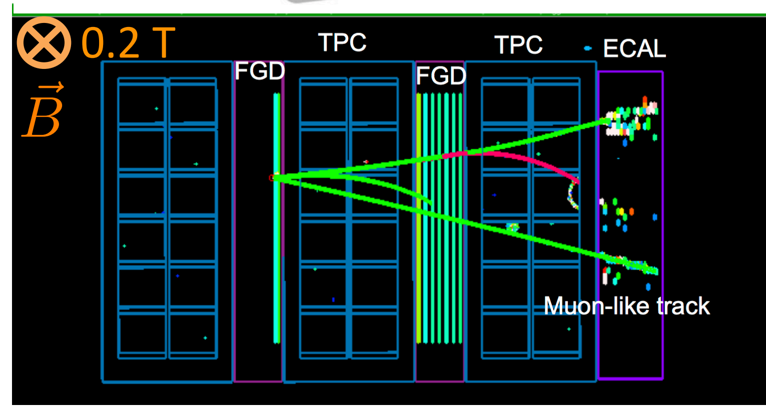
Display of MC event interacted in Proton Module and μ tracked by INGRID

T2K off-axis detector: ND280

Aim to understand unoscillated ν beam: constrains flux and cross-section parameters

- ✧ **Tracker,** composed of Fine-Grained Detector (FGD) and Time Projection Chamber (TPC), is central part
  - o Two FGDs: active target w/ scintillator only (FGD1) or scintillator-water interleaved (FGD2)
  - o Three TPCs: mainly Argon (95%) filled, for momentum measurement and particle ID
- ✧ π^0 **detector (POD)** for water-scintillator target and π^0 tagging
- ✧ **Electromagnetic calorimeters (ECal)** to detect gamma rays and reconstruct π^0
- ✧ **Side muon range detectors (SMRD)** to tag entering cosmic muons or side-exiting muons





Key features for cross-section:

- o Narrow flux spectrum , mean ~ 0.85 GeV
- o Multiple targets: scintillator, water, argon, lead
- o High final state ID resolution, charge separation

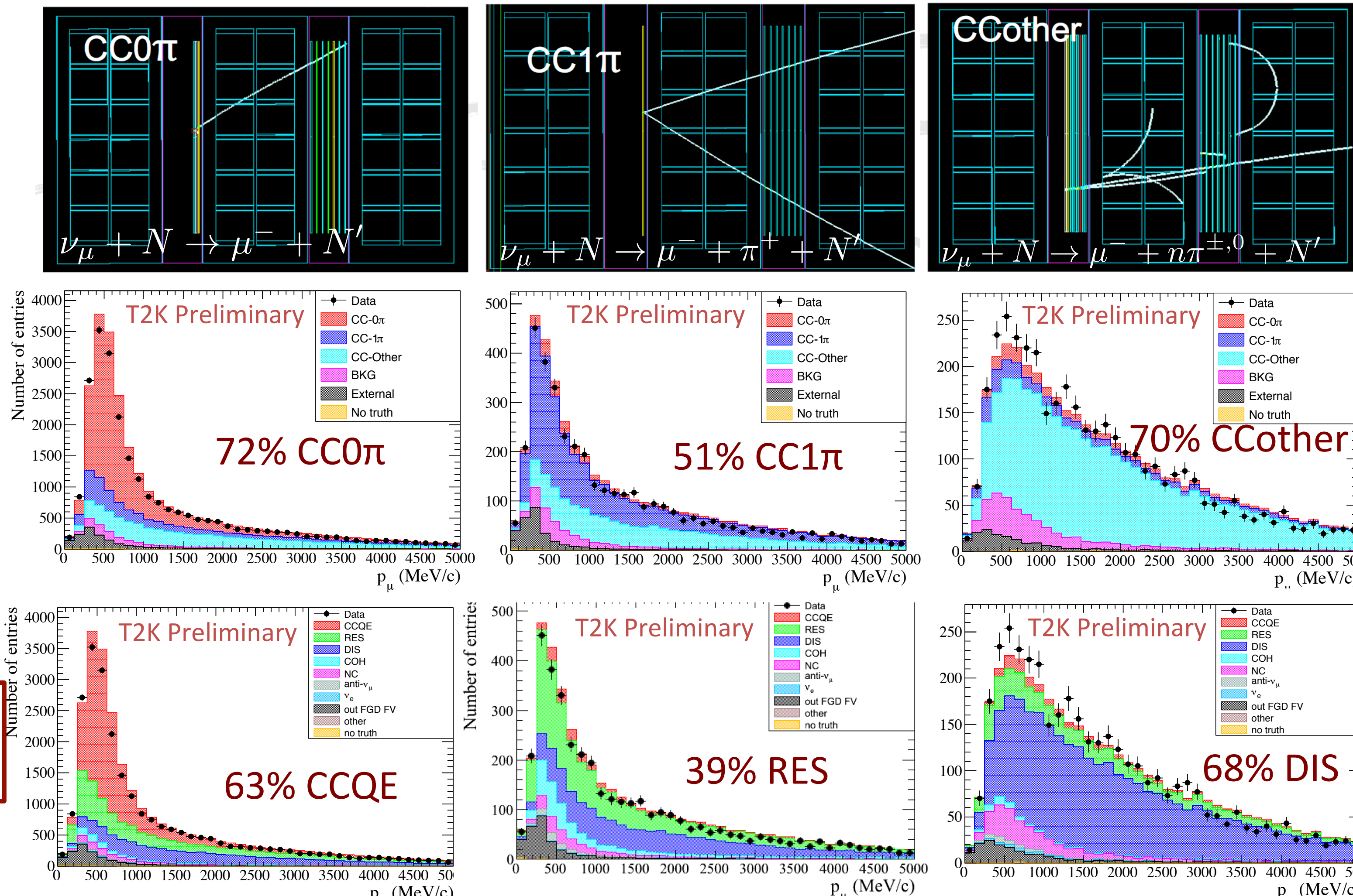
T2K interaction topologies

✧ Final state topologies based on the true particles exiting the nucleus (takes advantage of ND280 high final state ID resolution)

Topology definition

Breakdown by final state ID

Breakdown by ν generator truth



T2K recent pion production measurements

Various activities on pion production are ongoing at T2K near detectors.
This talk highlights measurements which are official only.

① CC1π^+

✧ CC1π^+ in water (ND280-FGD2)

② CC1π^+ coherent

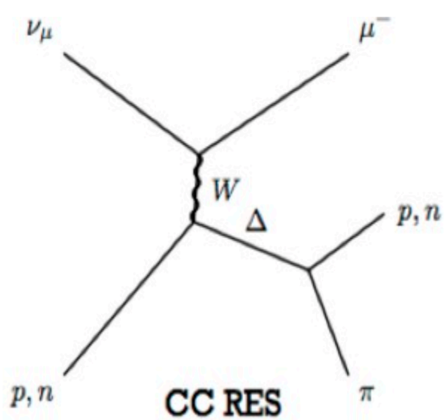
✧ CC1π^+ coherence in carbon (ND280-FGD1)

✧ CC1π^+ coherence in carbon (INGRID)

① CC1π^+

✧Signal definition $\nu_\mu + N \rightarrow \mu^- + \pi^+ + N'$

✧Main contribution from resonance



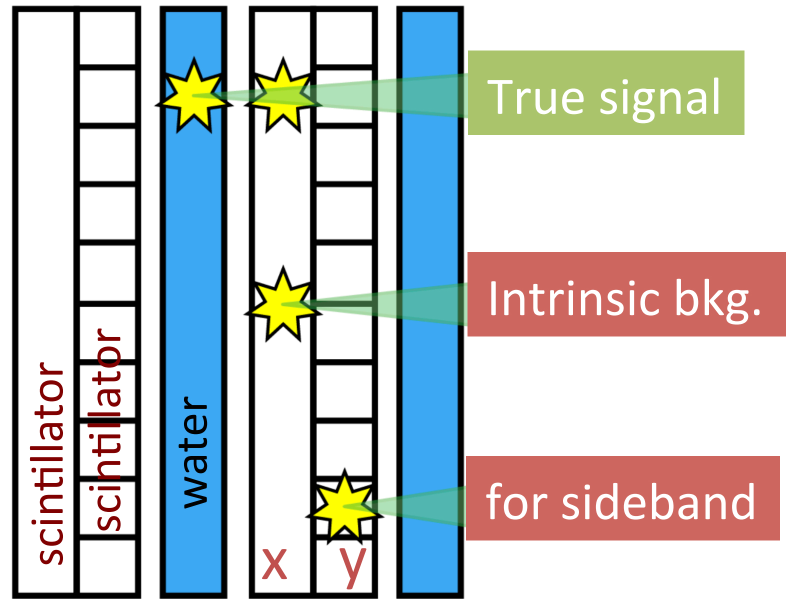
Simulation: Rein-Sehgal model

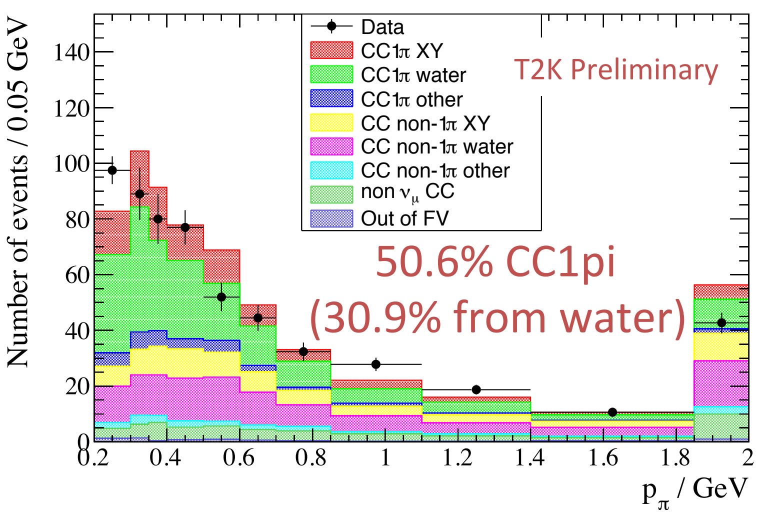
✧NEUT ("official" ν generator)

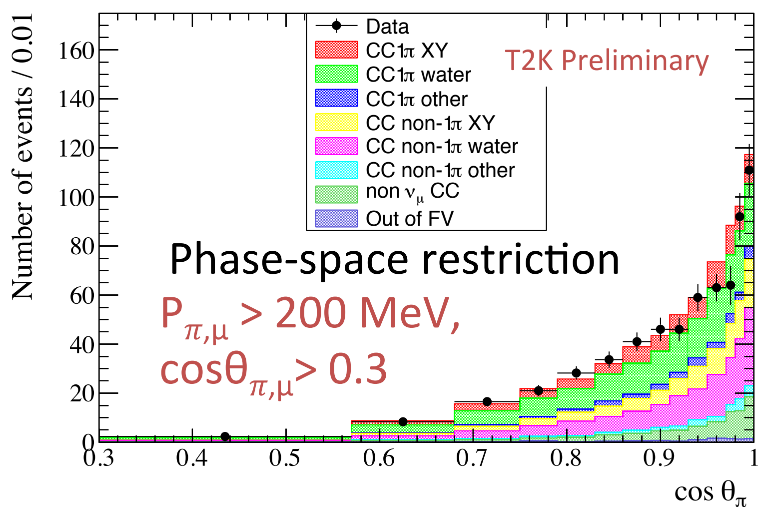
✧GENIE (alternative ν generator)

CC1π^+ in Water (ND280-FGD2)

- Signal: CC w/ 1 π^+ in water layer of FGD2
- Event selection:
  - Negative muon-like track (TPC)
  - Positive pion-like track (TPC ID)
  - Reject events w/ π^0 (ECal)
  - Muon-like track starts in x-scintillator layer
- Phase-space restriction applied to remove areas of low detector acceptance
- Dominant backgrounds:
  - CC 1π^+ in scintillator layers (XY)
  - CC non-1π^+ (dominated by DIS)



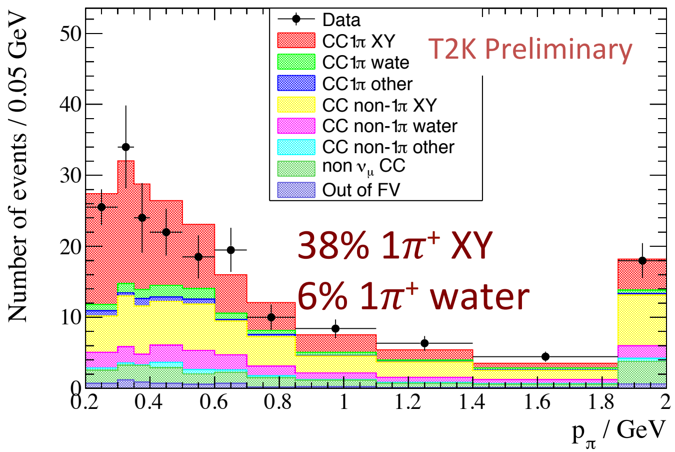




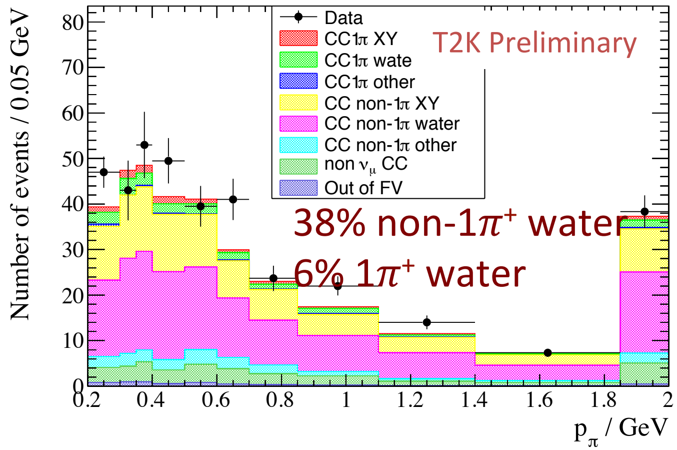
CC1π^+ in Water (ND280-FGD2)(cont'd)

- Two control samples to constrain background

CC1π^+ scintillator



CC-other water-enhanced

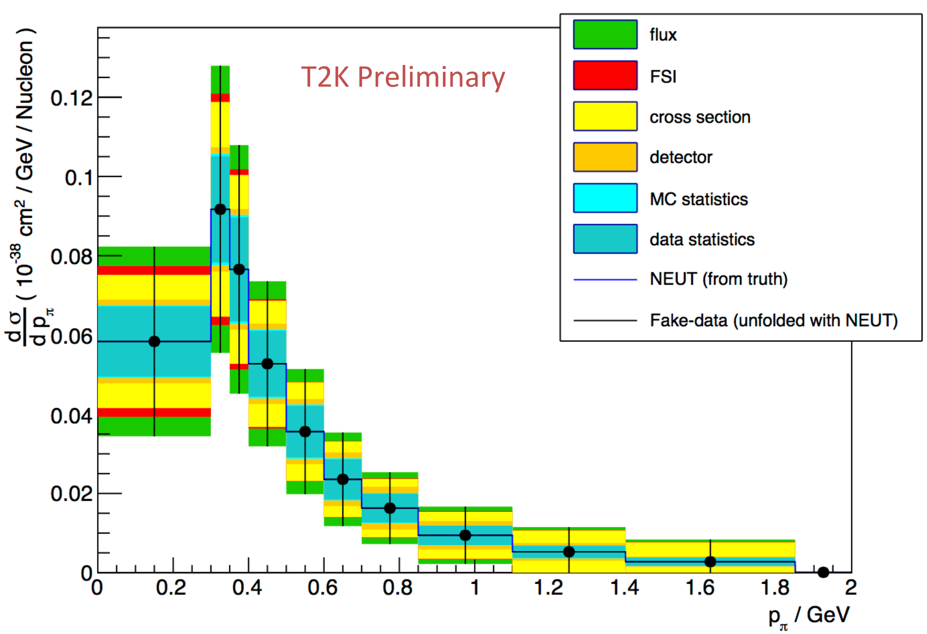


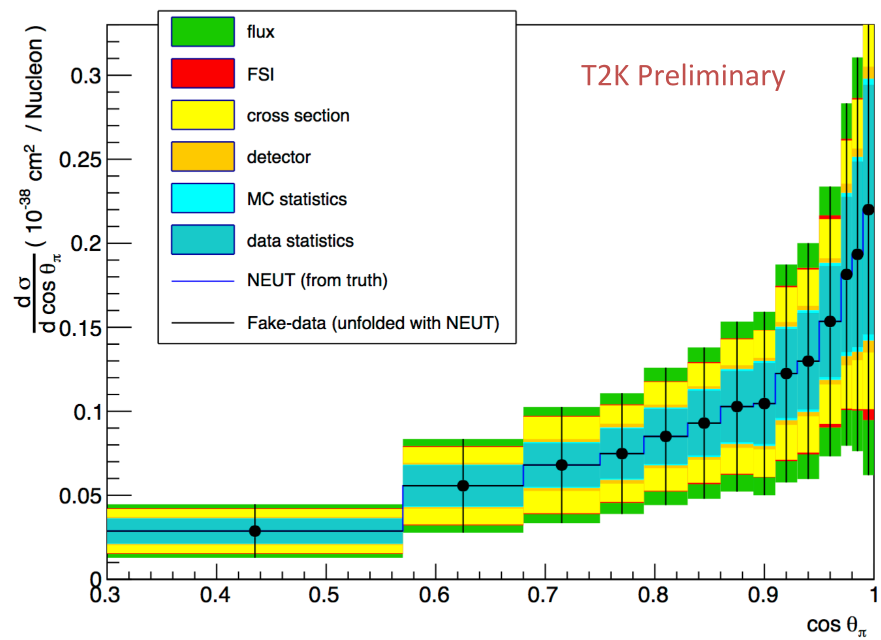
- Flux-integrated differential cross section based on Bayesian unfolding method
  - In muon kinematics
  - In pion kinematics
  - In muon-pion angle
  - In neutrino reconstructed energy

$$\left\langle \frac{\partial \sigma}{\partial X} \right\rangle_k = \frac{N_k^{unfolded}}{\epsilon_k N_{targets} \Phi \Delta X_k}$$

CC1 π^+ in Water (ND280-FGD2)(cont'd)

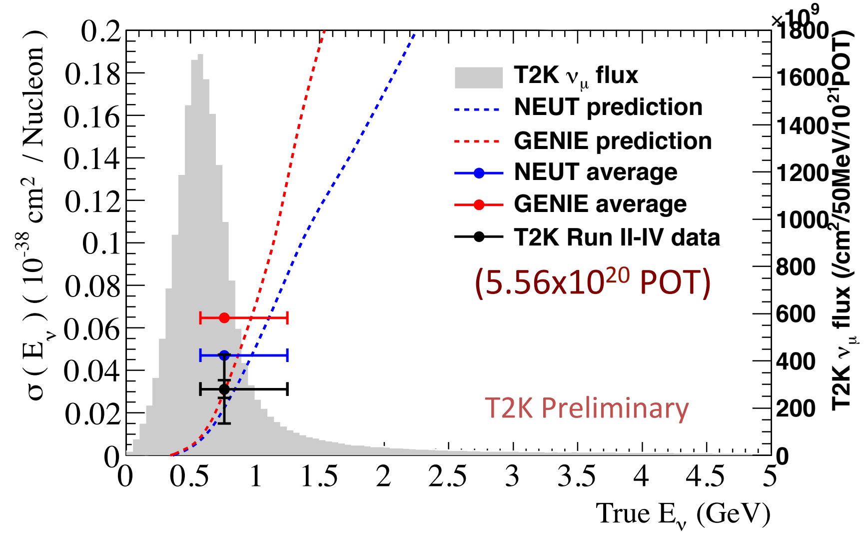
	p_{π^+}	$\cos\theta_{\pi^+}$	p_{μ^-}	$\cos\theta_{\mu^-}$	$\cos\theta_{\mu^+,\pi^+}$
Flux-averaged σ	4.706	4.706	4.706	4.706	4.706
Total stat. error	0.452	0.486	0.460	0.475	0.474
Total syst. error	2.138	2.160	2.070	2.212	2.205
Fractional uncertainties in %					
Data statistics	9.20	9.87	9.34	9.61	9.62
MC statistics	2.74	3.04	2.91	3.06	3.01
Theory cross-section	31.20	32.46	29.38	32.81	33.60
FSI	7.69	6.98	6.85	7.45	6.53
Flux	30.68	30.27	30.51	31.36	30.62

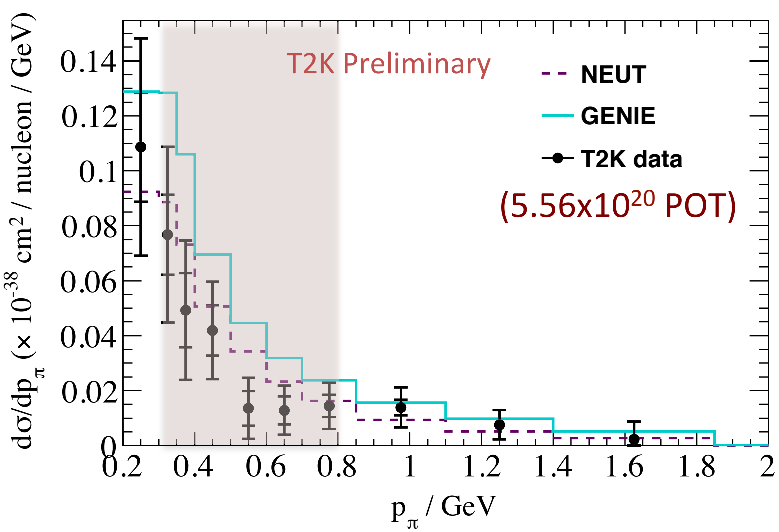


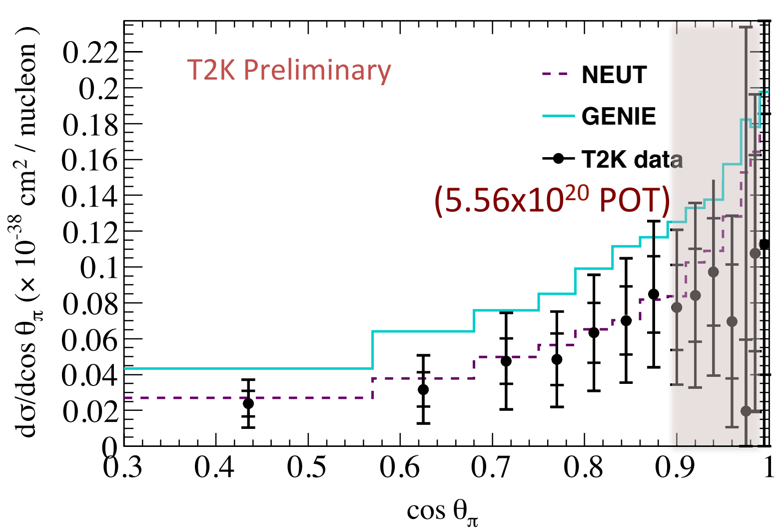


CC1 π^+ in Water (ND280-FGD2)(cont'd)

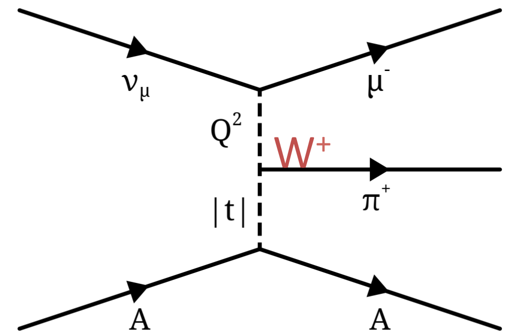
- Data lower than GENIE prediction (same as MiniBooNE result)
- Suppression observed specifically
  - $P_{\pi+} > 0.3$ GeV & $P_{\pi+} < 0.8$ GeV
  - $\cos\theta_{\pi+} > 0.9$ (coherent channel contribution is significant)

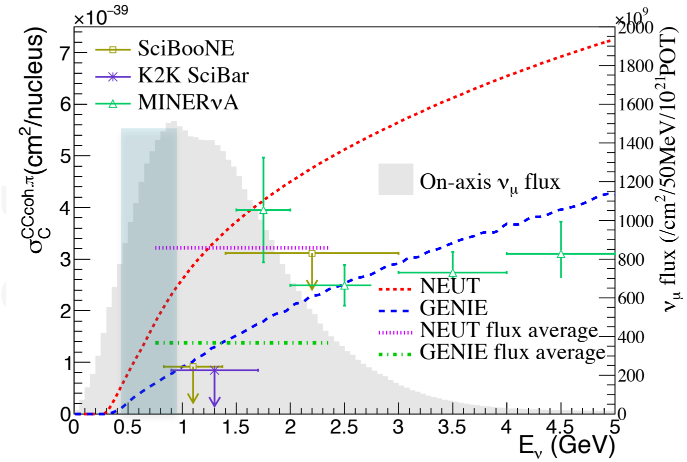






- ✧ Interesting features
  - ✧ Pion created from off-shell W boson despite small nucleus binding energy (~10s MeV)
  - ✧ Very small four-momentum transfer, $|t| \sim \hbar^2/R^2$ to leave nucleus in its ground state
  - ✧ Small angle scattering of produced lepton
- ✧ Puzzle: K2K and SciBooNE found no evidence of CC coherent below 1.5 GeV but NC coherent signal was clearly observed at same energy





② CC1π^+ coherent

- ✧ CC1π^+ coherence in carbon (ND280-FGD1), ~ 0.8 GeV
- ✧ CC1π^+ coherence in carbon (INGRID), ~1.5 GeV

Coherent in Carbon (ND280-FGD1)

✧ Phase-space restriction:

$p_{\mu,\pi} > 0.18$ GeV; $\theta_{\mu,\pi} < 70°$; $p_\pi < 1.6$ GeV

✧ Event pre-selection (CC1π^+)

- ✧ Negative muon-like track
- ✧ Positive pion-like track

✧ Additional cuts to enhance coherent interaction

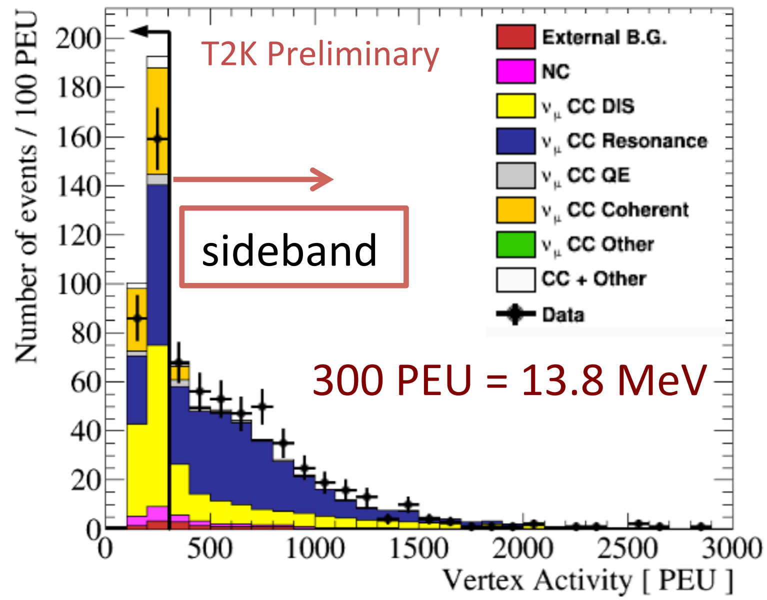
- ✧ Vertex activity (<300 Photon Equivalent Unit (PEU))
- ✧ t-momentum transfer (<0.15 GeV^2)

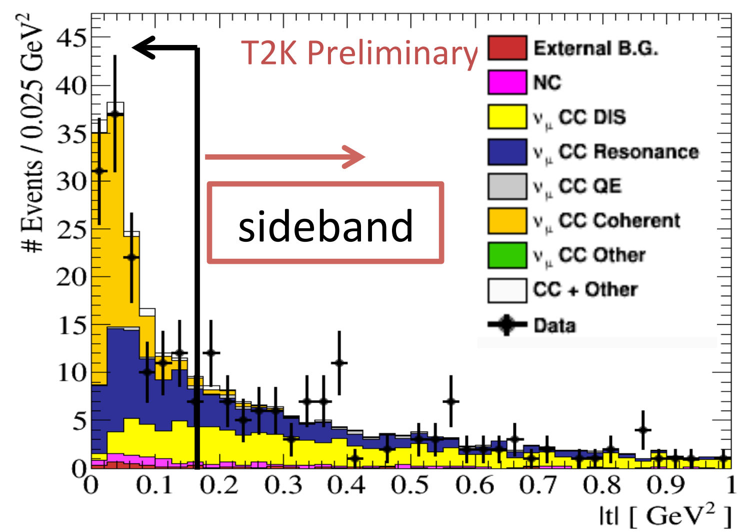
✧ Event reduction:

Step	Data	Efficiency	Purity
Start			
ν_μ Inclusive	20508	0.83	0.009
Coherent Initial Selection	1199	0.47	0.081
Pion Particle ID	857	0.43	0.100
Vertex Consistency	665	0.40	0.110
Vertex Activity	246	0.37	0.274
$\|t\|$ cut	126	0.36	0.440

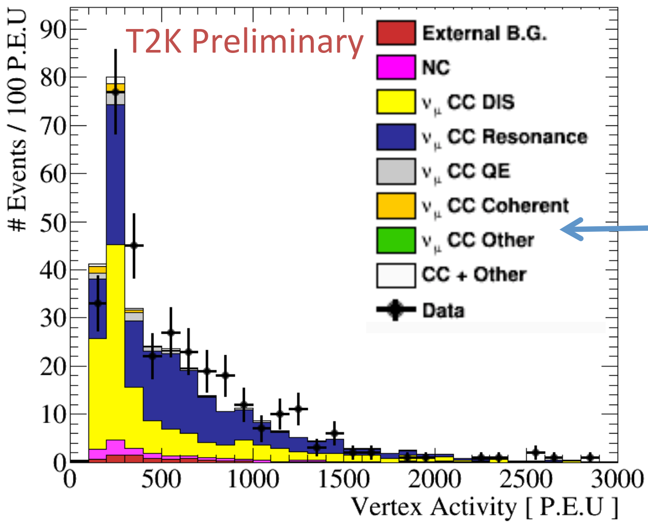
✧ Dominant backgrounds:

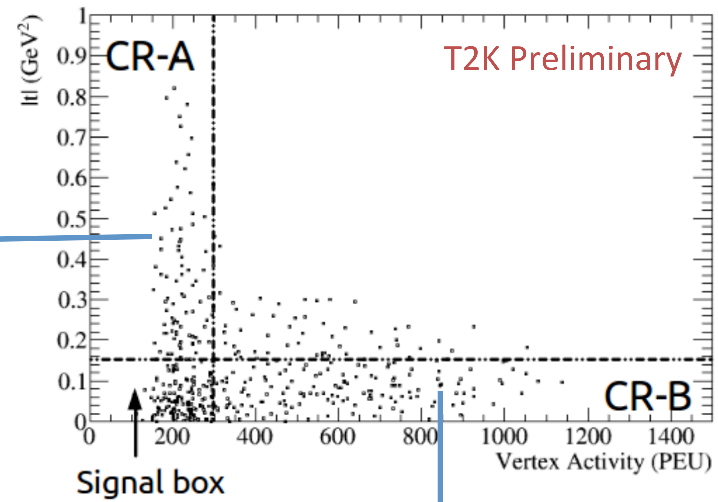
48% resonance, 34% deep-inelastic

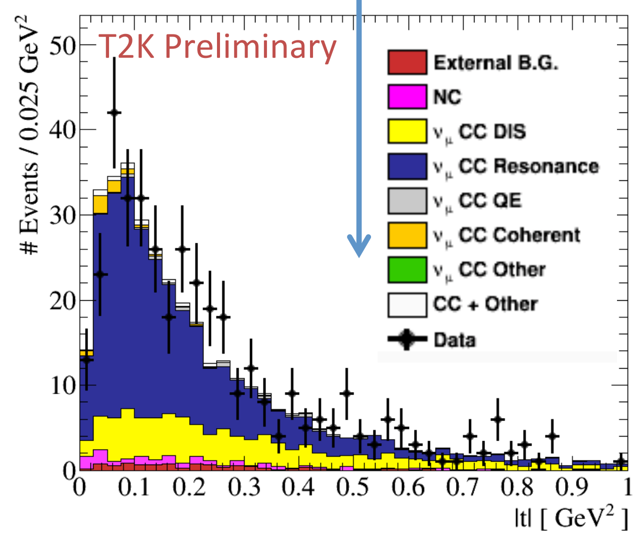




Coherent in Carbon (ND280-FGD1)



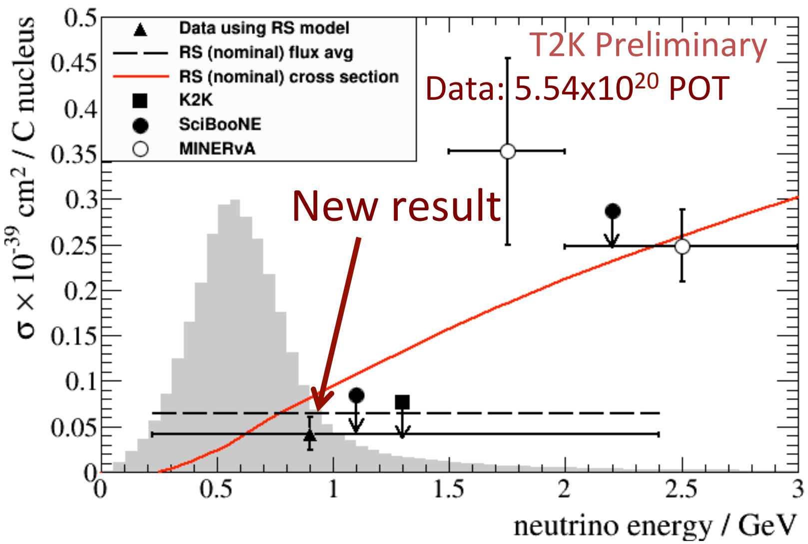


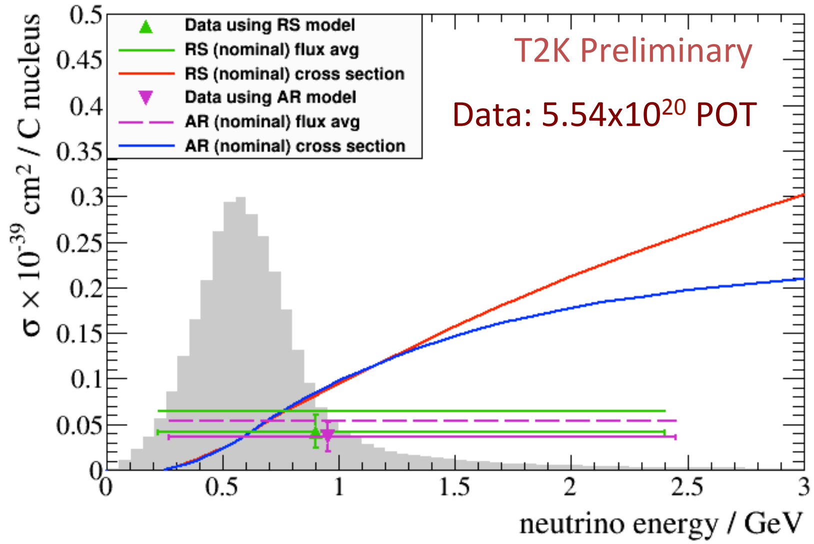


- Sidebands to constrain expected N_0 of backgrounds in the signal box
- Background estimate method
  - Split sidebands into bins of reconstructed invariant hadronic mass, W
  - Normalization parameters to fit pion momentum template for each W bin
  - Background in signal box is retuned based on fitted normalization parameters.

Coherent in Carbon (ND280-FGD1) (cont'd)

- An excess of 45±18, with 2.2σ significance
- Two models used to estimate signal efficiency
  - Rein-Seghal: PCAC model; relate with pion-nucleus elastic scattering, use "officially" in event generators, valid for high energy neutrino, less reliable at < 2 GeV
  - Alvarez-Ruso: Microscopic model; excitation of Δ resonance, full quantum mechanical treatment, valid up to 5 GeV





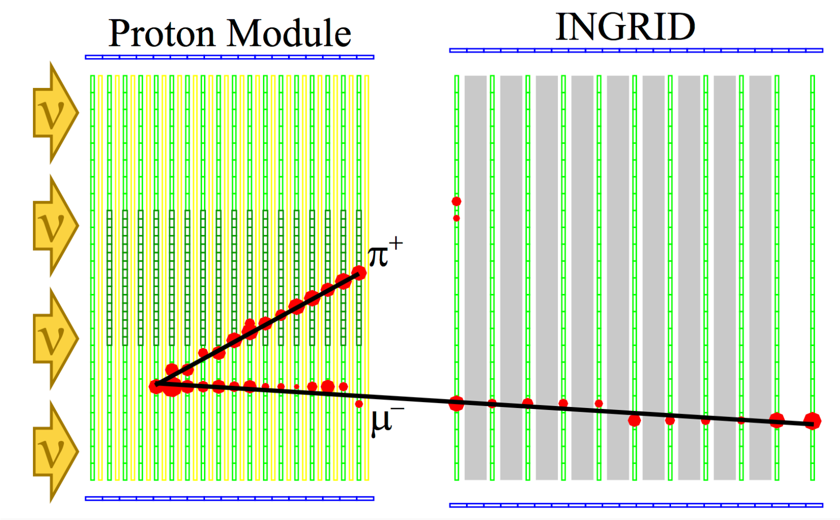
Rein-Seghal: $\langle \sigma_{CC;Coh;C} \rangle_{RS} = (3.2 \pm 0.8(stat)^{+1.3}_{-1.2}(sys)) \times 10^{-40}\ \mathrm{cm}^2/^{12}C\ \mathrm{nucleus}$

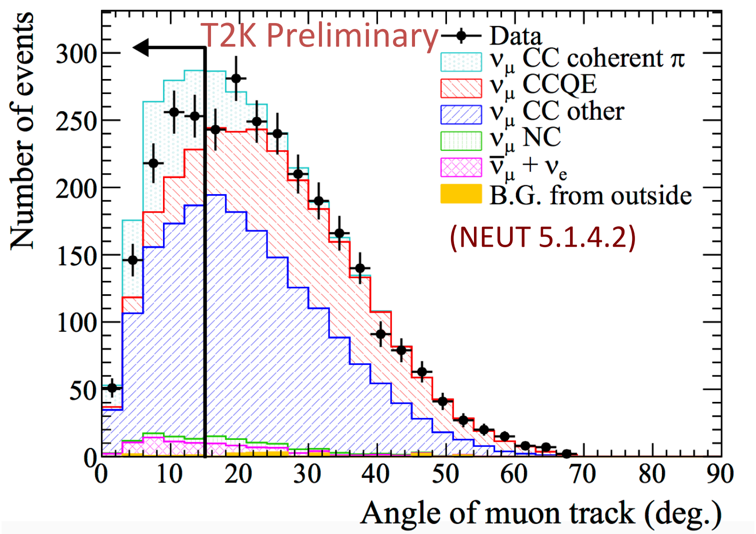
Alvarez-Ruso: $\langle \sigma_{CC;Coh;C} \rangle_{AR} = (2.9 \pm 0.7(stat)^{+1.1}_{-1.1}(sys)) \times 10^{-40}\ \mathrm{cm}^2/^{12}C\ \mathrm{nucleus}$

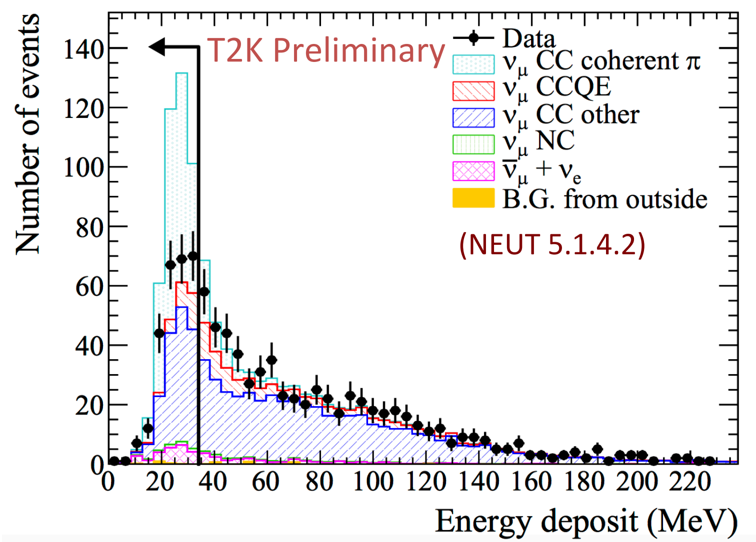
→ Statistical power limited to distinguish between two models

CC coherent in Carbon (INGRID)

- ✧ Challenging:
  - ✧ Pion momentum is not well-reconstructed → impossible to reconstruct |t|-transfer
  - ✧ Unavoidable model-dependence
- ✧ Coherent interaction enhanced:
  - ✧ Muon angle scattering (<15^0)
  - ✧ Energy deposit around vertex (<37 MeV)





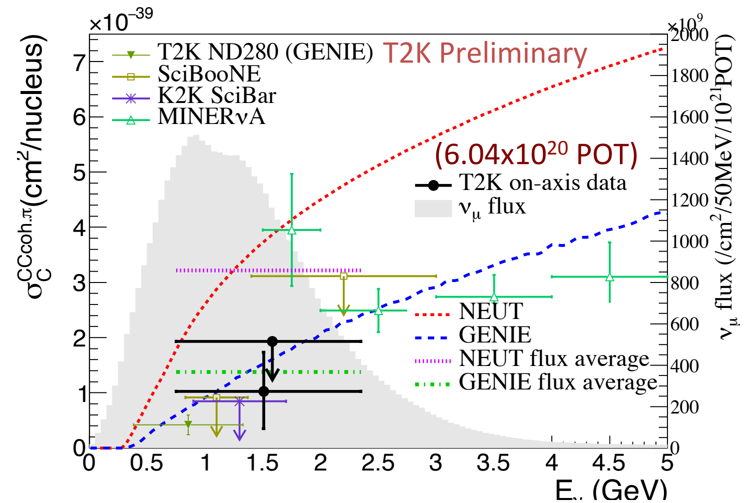


CC coherent in Carbon (INGRID) (cont'd)

✧ Flux-averaged cross section

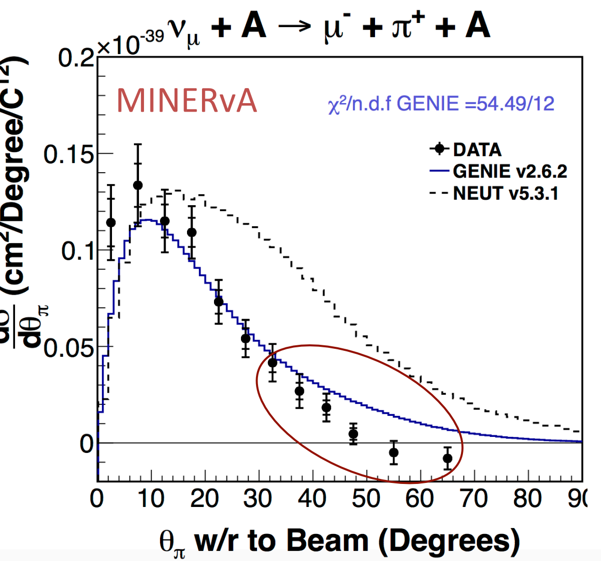
$$\sigma_{\mathrm{CCcoh.}\pi} = \frac{N_{\mathrm{sel}} - N_{\mathrm{BG}}}{\phi T \varepsilon}$$

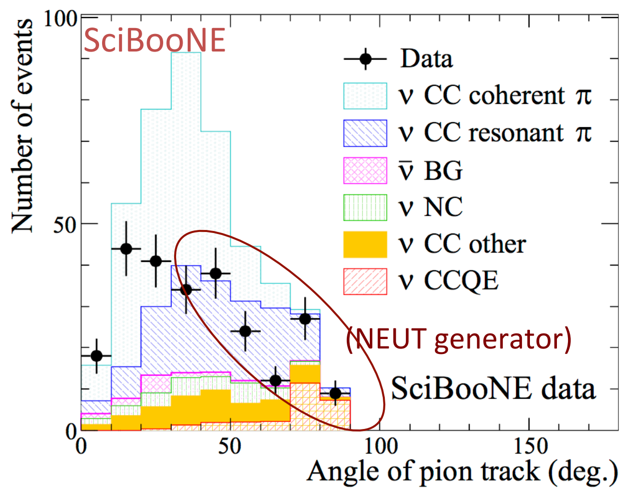
N_{sel}	N_{BG}	ϕ	T	ε
271.90	202.94	$3.025\times10^{13}\mathrm{cm}^{-2}$	1.384×10^{28}	0.1604

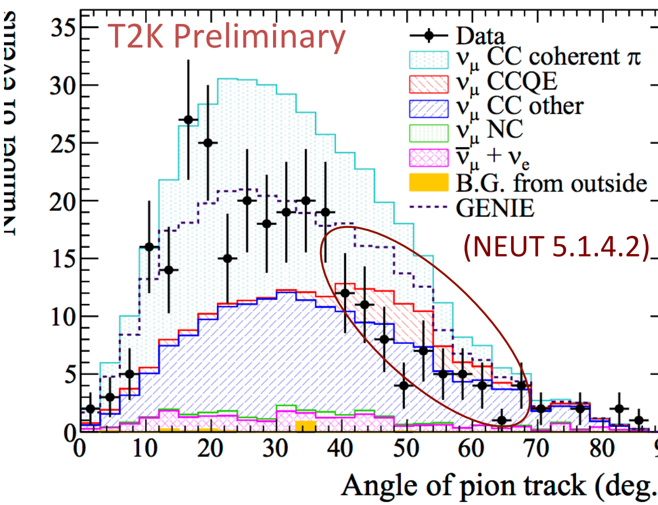


✧ Systematics ~60%, dominated by CC resonance

✧ 1.7σ data excess, suppression observed at high pion track angle

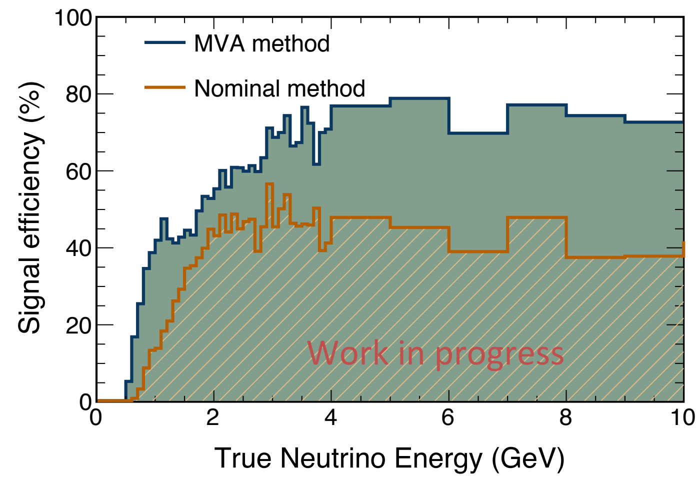


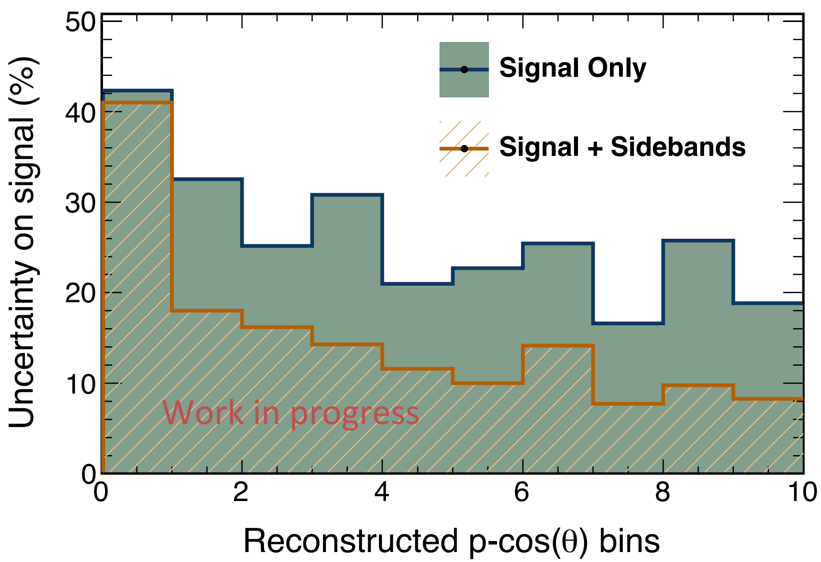


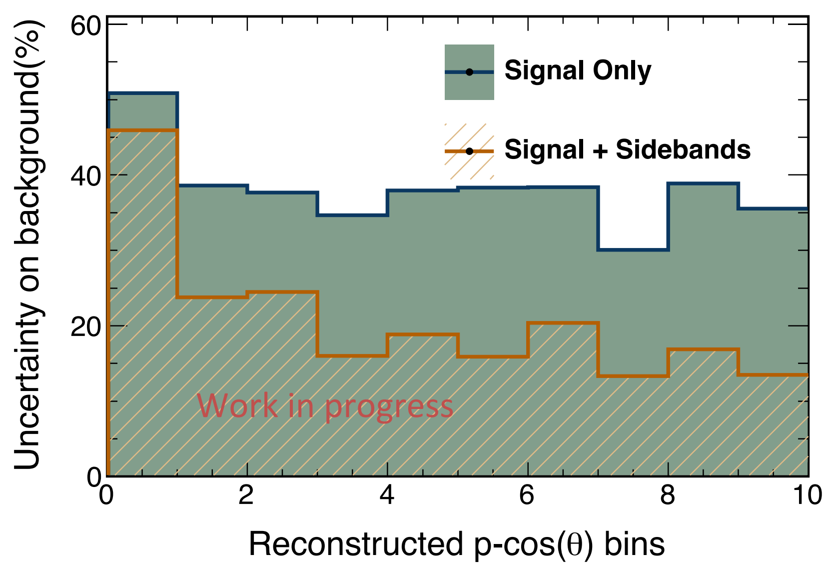


CC coherent in Carbon (INGRID) (cont'd)

- On-going efforts to improve analysis:
  - Increase signal significance (multi-variate approach to select candidate event)
  - Use sidebands to control the dominant background (CC resonance and CC deep-inelastic scattering)
  - More than 2.5σ excess can be achieved if data agrees with GENIE prediction







Up-coming results & Prospects

Up-coming results:

- ✧ CC1π^+ in Carbon (ND280-FGD1) ← Under review
- ✧ CC1π^+ in water (ND280-P0D) ← under review
- ✧ CC1π^+ with proton identification (ND280-FGD1)
- ✧ CC1π^+ coherent in water (ND280-FGD2)

Prospects:

- ✧ CC1π^0 in water (ND280-P0D)
- ✧ CC1π^+ in carbon (INGRID)

T2K has near detectors in two different neutrino fluxes simultaneously

→ unique capacity to make comparisons, joint fit

Summary

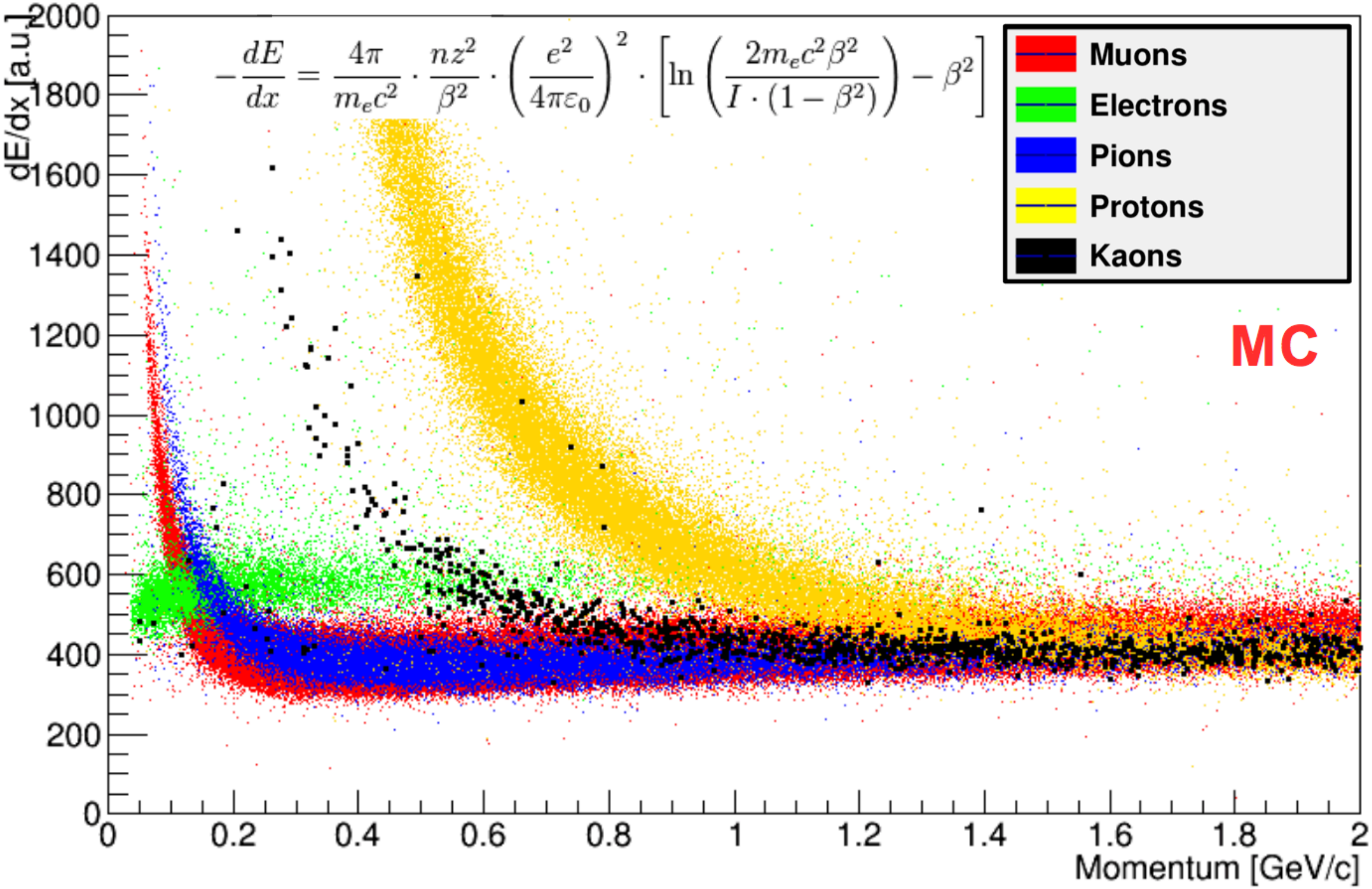
- ✧ Various cross-section measurements with fine final-state resolution, thank to ND280 structures

- ✧ First exclusive CC1π^+ in water indicated suppression at
  - ✧ low momentum ($P_{\pi+} > 0.3$ GeV & $P_{\pi+} < 0.8$ GeV)
  - ✧ small pion scattering ($\cos\theta_{\pi+} > 0.9$)

- ✧ First experimental evidence of CC1π^+ coherent below 1.5 GeV

- ✧ Stay tuned for more interesting results!!!

Backup: dE/dx w/ TPC



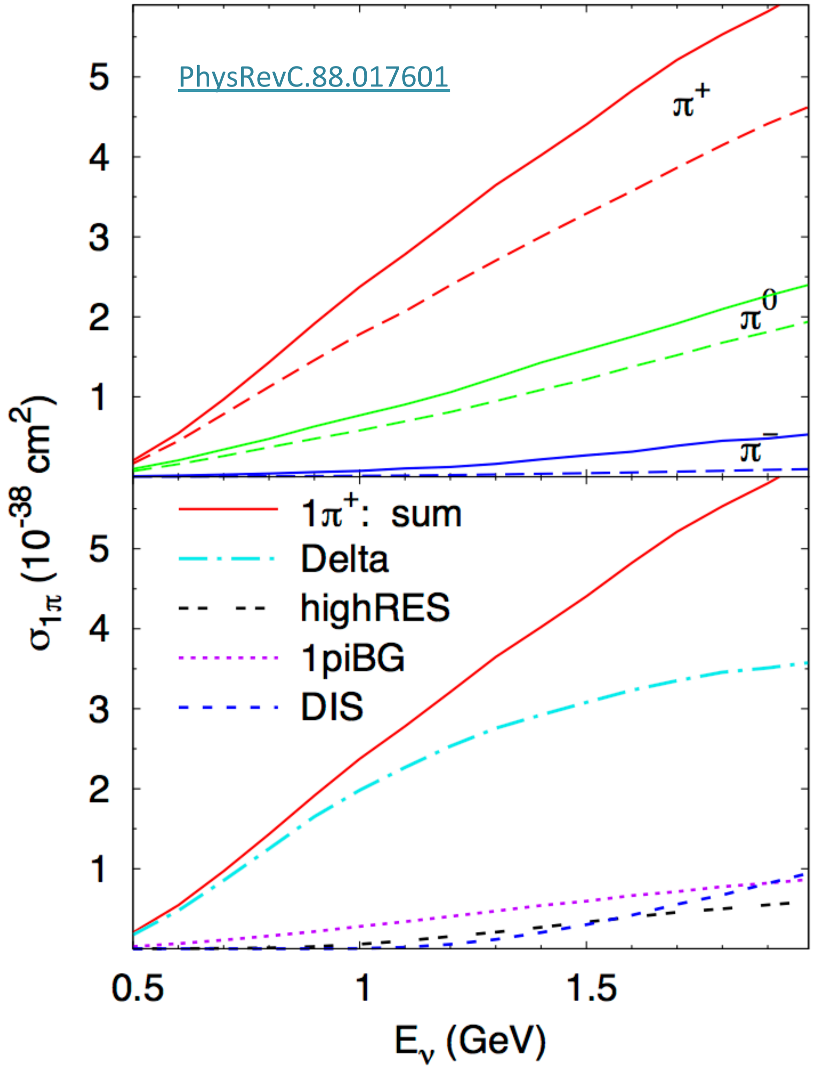
Backup: GENIE vs NEUT

- ✧ NEUT: 5.1.4.2 vs GENIE: 2.8.0
- ✧ Differences:
  - ✧ Default values of model parameters

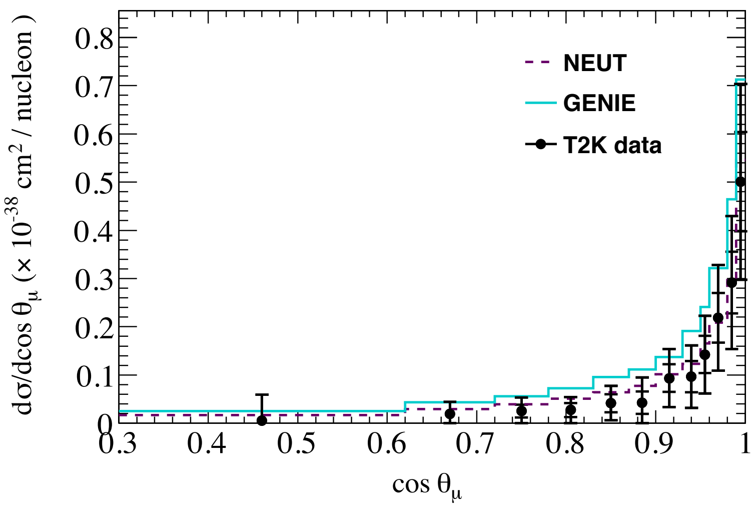
	NEUT	GENIE
MACCQE	1.21 GeV/c^2	0.99 GeV/c^2
MARes	1.21 GeV/c^2	1.12 GeV/c^2
Threshold for res. meson prod.	2.0 GeV/c^2	1.7 GeV/c^2

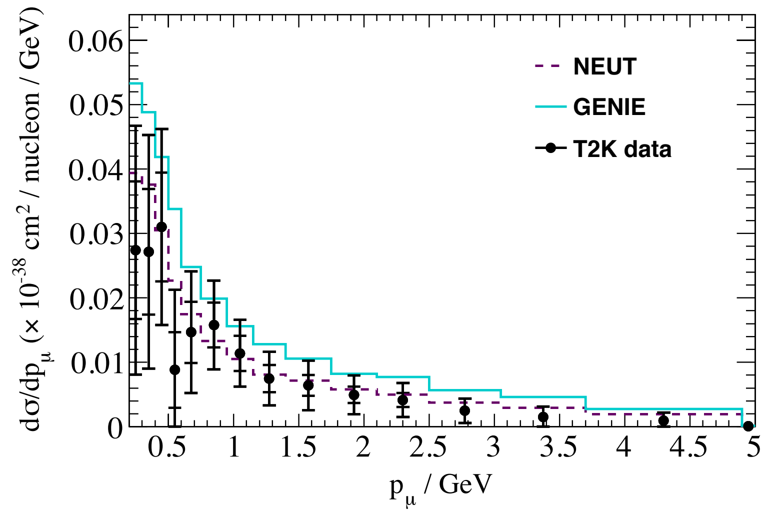
  - ✧ Model for off-shell scattering (Smith-Moniz vs Bodek-Ritchie)
  - ✧ Determine pion multiplicity (W-dependent function vs AGKY)
  - ✧ Coherent pion production: GENIE use a revised version of Rein-Sehgal (include lepton mass term effect & update pion-nucleon cross-section)

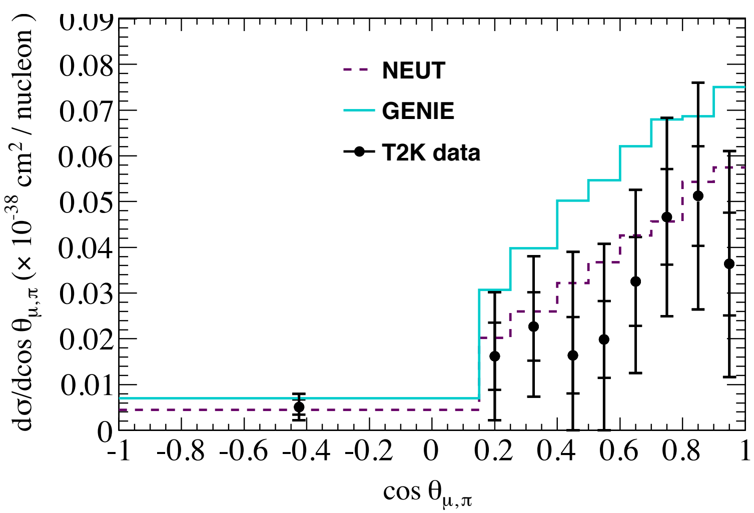
Backup: Pion production

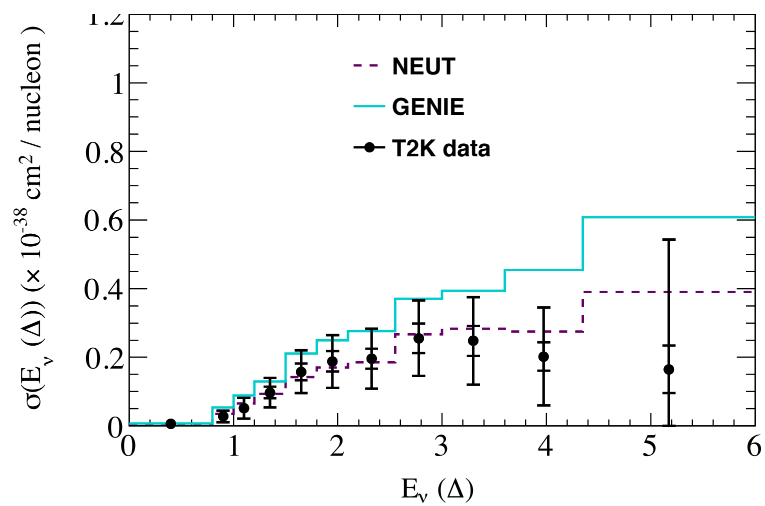


Backup: $CC1\pi^+$ in Water



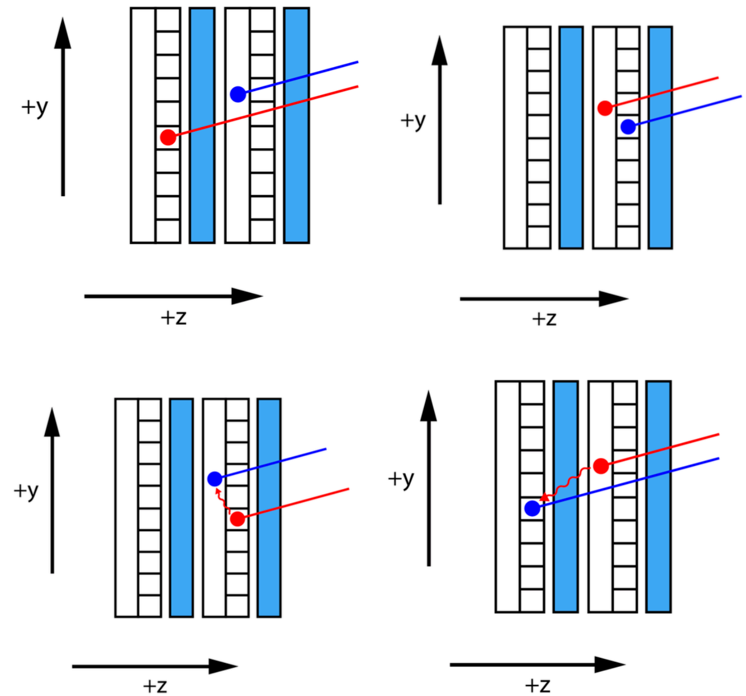






CC1π^+ in Water: Event migration

- Migration (both forward and backward)
- Study
  - Going-through sample
  - Mask some FGD layer
  - Rerun reconstruction to verify that vertex reconstructed at first non-masked layer

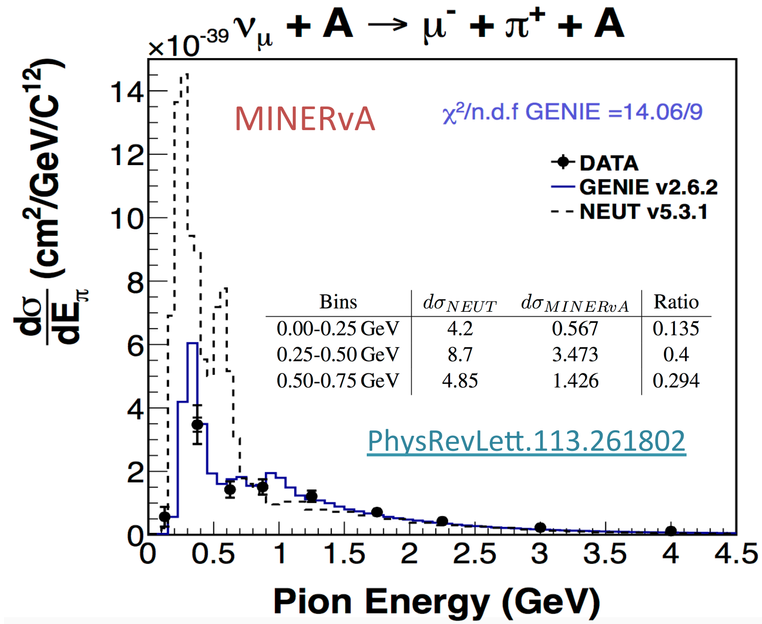


mask	FGD1 MC	FGD1 data	FGD2 MC	FGD2 data
1/3 FGD up to Y	0.960 ± 0.006	0.941 ± 0.008	0.960 ± 0.006	0.948 ± 0.007
1/3 FGD up to X	0.949 ± 0.007	0.930 ± 0.008	0.949 ± 0.006	0.933 ± 0.008
2/3 FGD up to Y	0.966 ± 0.005	0.948 ± 0.007	0.962 ± 0.005	0.944 ± 0.007
2/3 FGD up to X	0.960 ± 0.006	0.945 ± 0.007	0.962 ± 0.005	0.947 ± 0.007

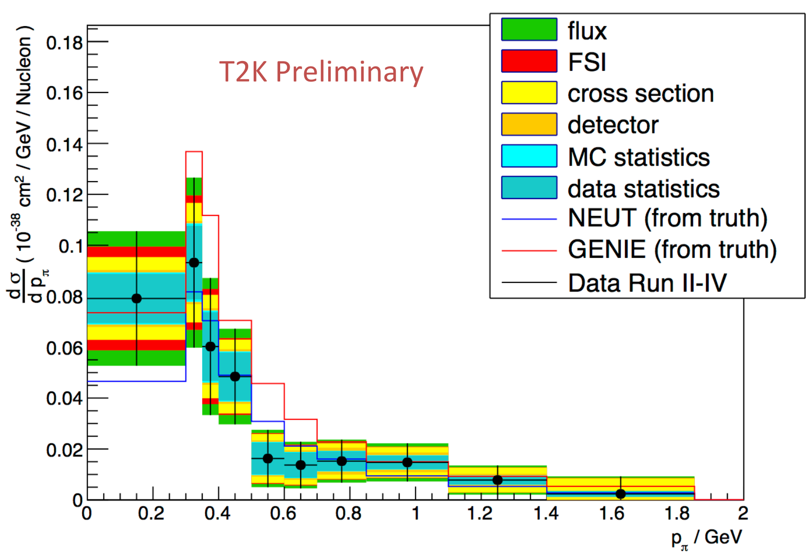
	CC Inclusive	CC0π-like	CC1π^+-like	CC Other-like
Matched scintillator to scintillator	31.16 %	31.14 %	33.27 %	30.43 %
Matched water to x layer	39.75 %	40.98 %	40.70 %	35.75 %
Gap	12.48 %	12.11 %	10.32 %	14.39 %
Forward scintillator to scintillator	3.69 %	3.70 %	4.07 %	3.51 %
Backward scintillator to scintillator	5.39 %	4.98 %	5.02 %	6.73 %
Forward water to scintillator	2.14 %	2.09 %	1.83 %	2.40 %
Backward water to scintillator	5.39 %	4.99 %	4.78 %	6.79 %

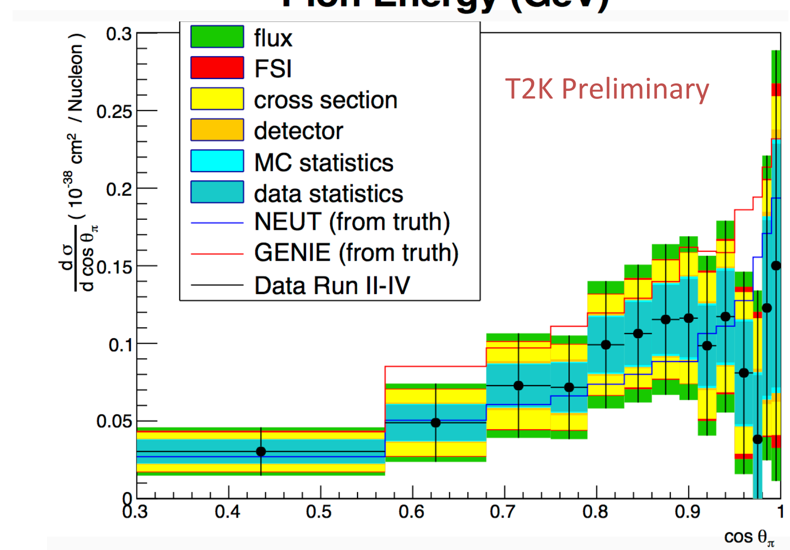
CC1 π^+ in Water (ND280-FGD2)(cont'd)

- Effort to reweight NEUT with MINERvA coherent measurement
- Suppression is smaller, but still visible
  - $P_{\pi+} > 0.5$ GeV & $P_{\pi+} < 0.7$ GeV
  - $\cos\theta_{\pi+} > 0.9$



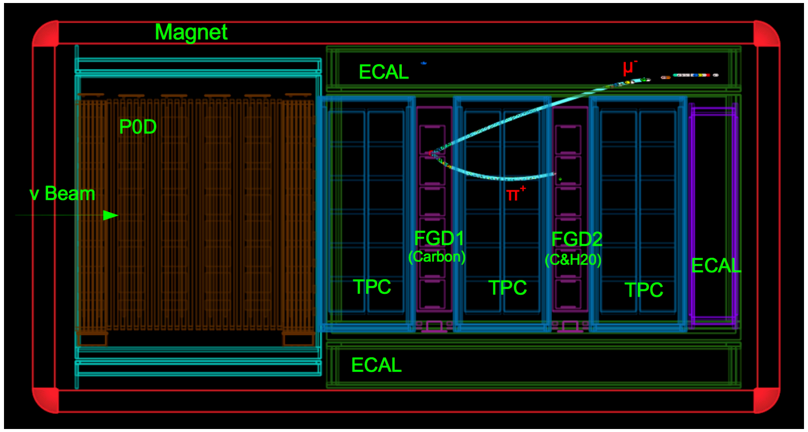
Bins	$d\sigma_{NEUT}$	$d\sigma_{MINERvA}$	Ratio
0.00-0.25 GeV	4.2	0.567	0.135
0.25-0.50 GeV	8.7	3.473	0.4
0.50-0.75 GeV	4.85	1.426	0.294

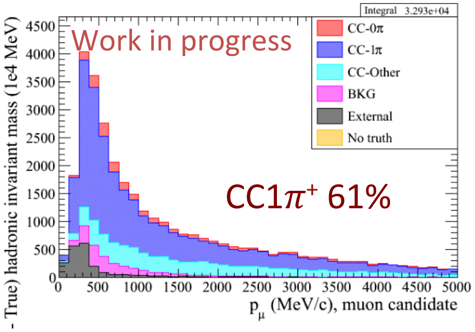


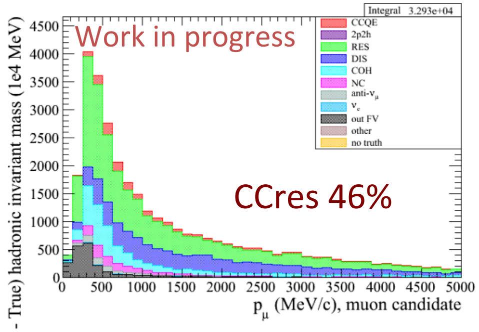


CC1π^+ in Carbon (ND280-FGD1)

- Phase space restriction
  - 0.18 GeV < P_π < 1.6 GeV, $\theta_{\pi,\mu}$<70^0
- Event selections
  - Negative muon-like track
  - π^+-like track
  - No π^- in TPC, no $e^\pm$ in TPC or ECAL
- Backgrounds
  - Dominated by CC-other (22%)
  - Detailed in table
- Three control samples are used
  - CC0π1P: to control CC0π bkg
  - CCother1π^+: to control CCNπ bkg
  - CCother1$e^\pm$: to control CCXπ^0 bkg





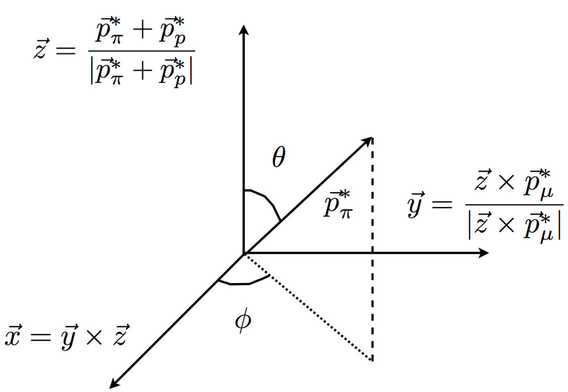


BKG type	Topology Composition (%)
CC-0-pion	15.5
CCXπ^0	28.7
CCNπ	26.2
Background	14.9
Out of FGD 1 FV	14.6

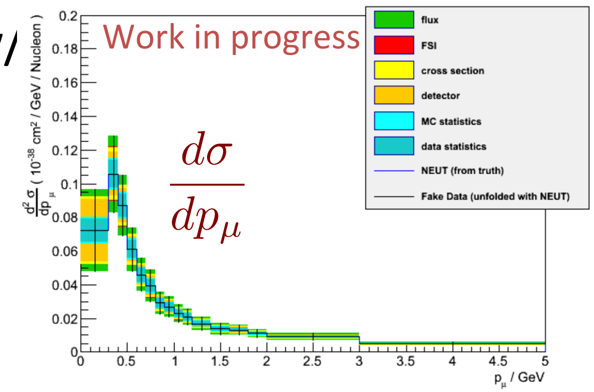
CC1π^+ in Carbon (ND280-FGD1)

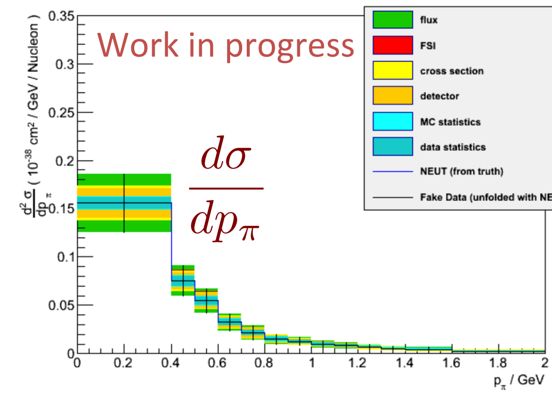
~2300 candidates (MC), results w/ respect to several variables:

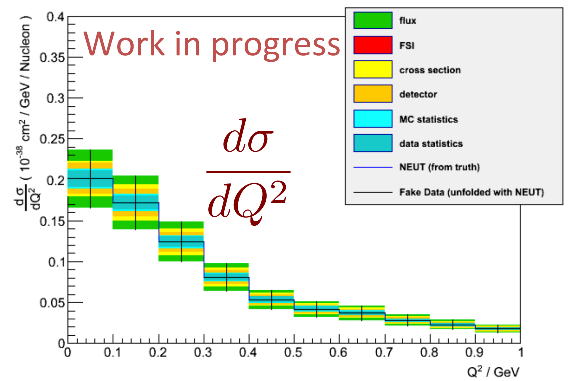
- Reconstructed ν energy
- Muon kinematics (double differential, Q^2, Q_3)
- Pion kinematics
- Muon-pion angles
- Hadron invariant mass
- Angles in Adler system, to compare to ANL data

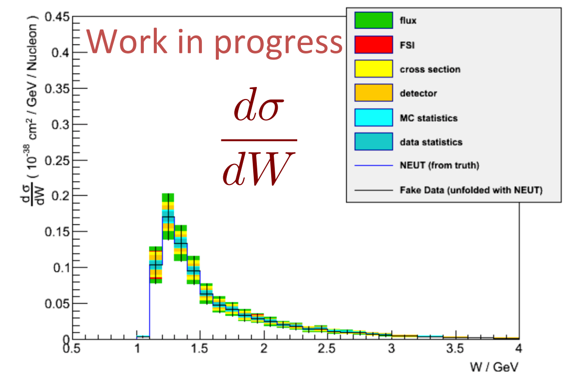


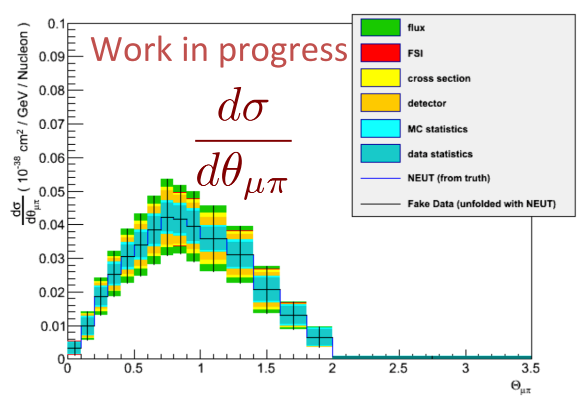
Analysis is under review.

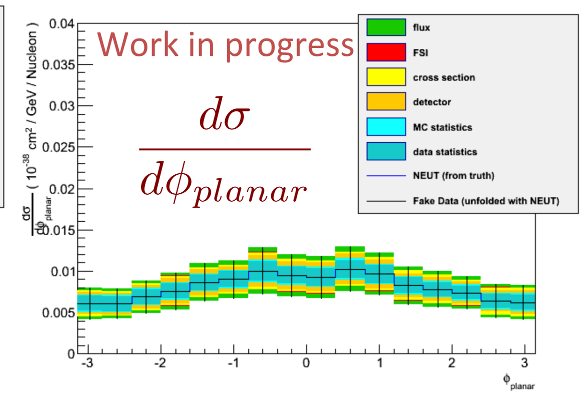




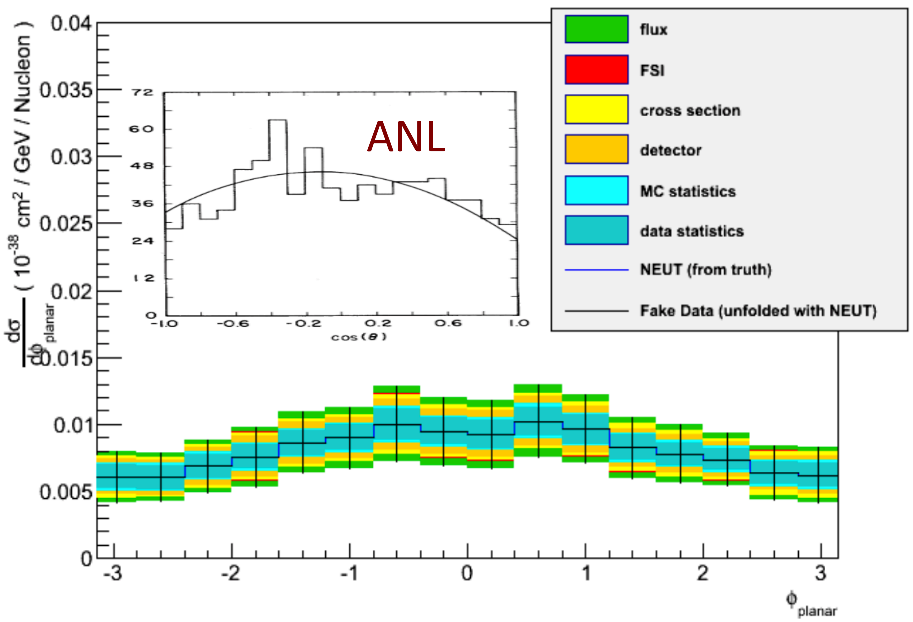


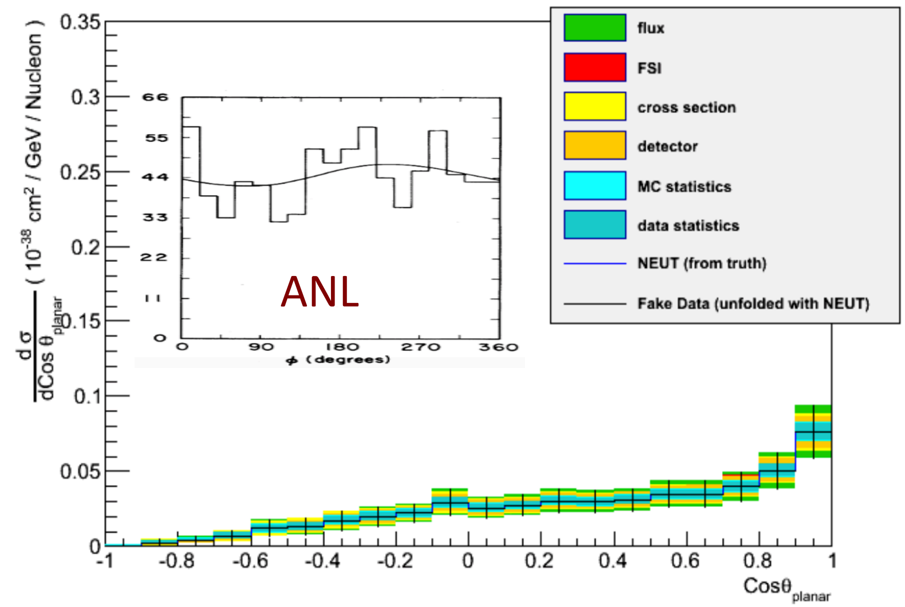




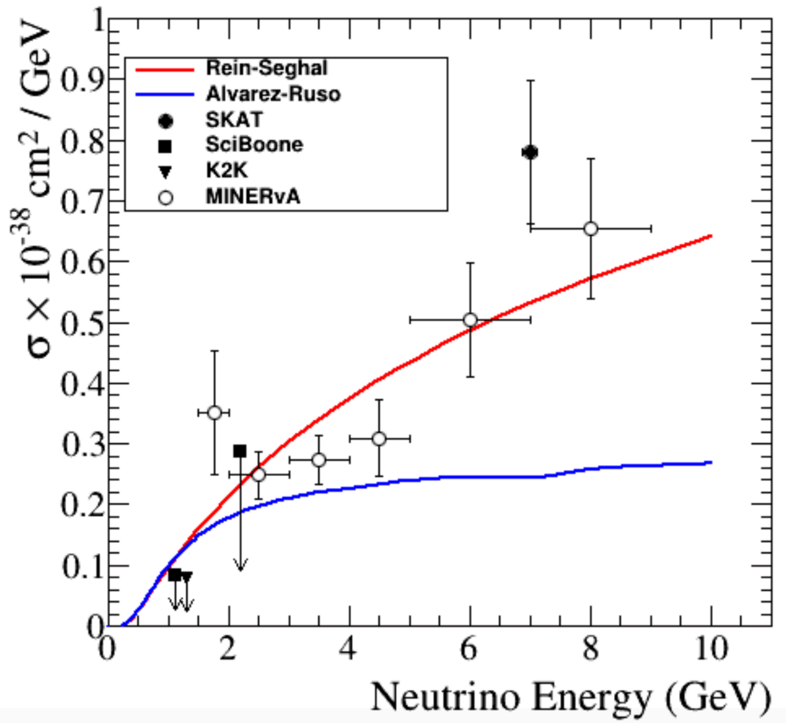


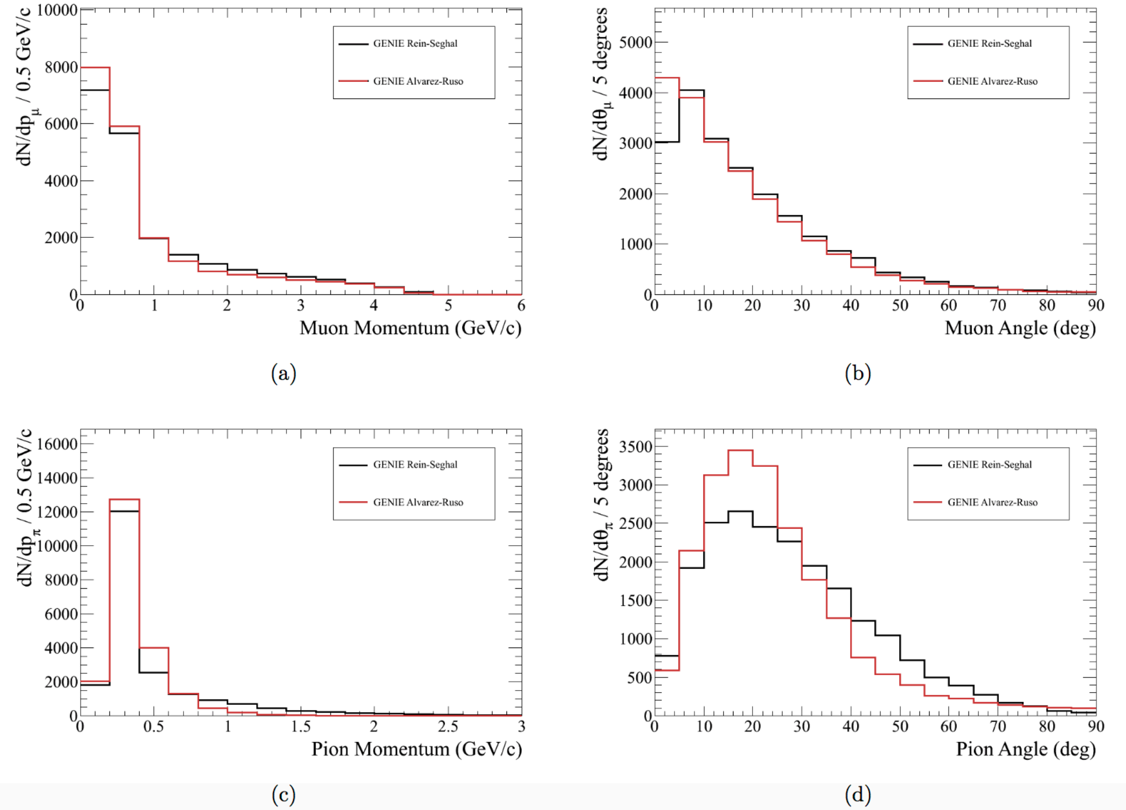
Backup: CC1π^+ in Carbon (ND280-FGD1)





Backup: Coherent RS vs AR

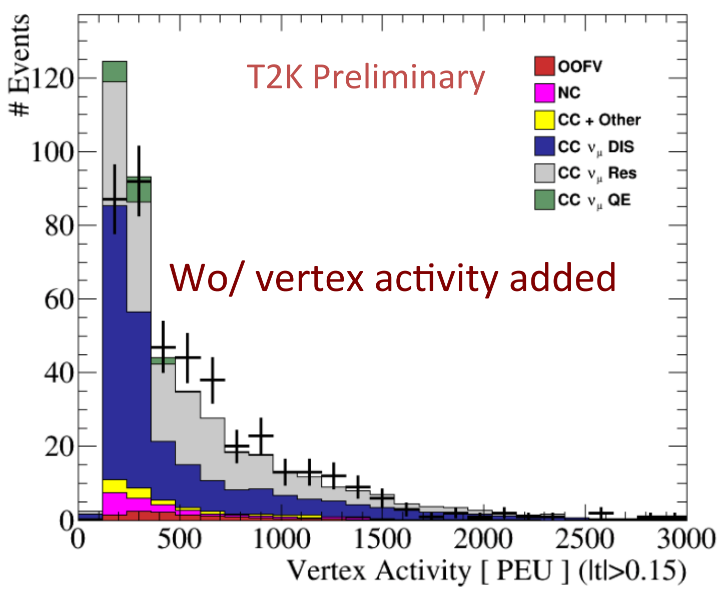


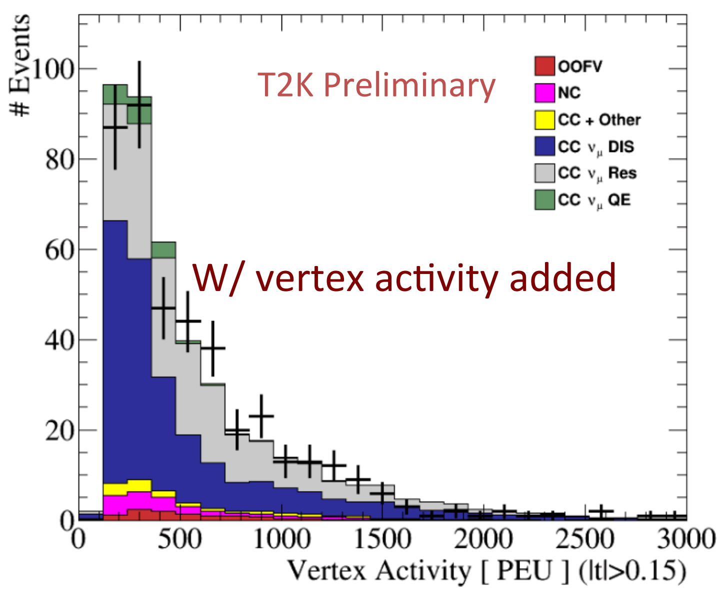


Coherent in Carbon (ND280-FGD1) (cont'd)

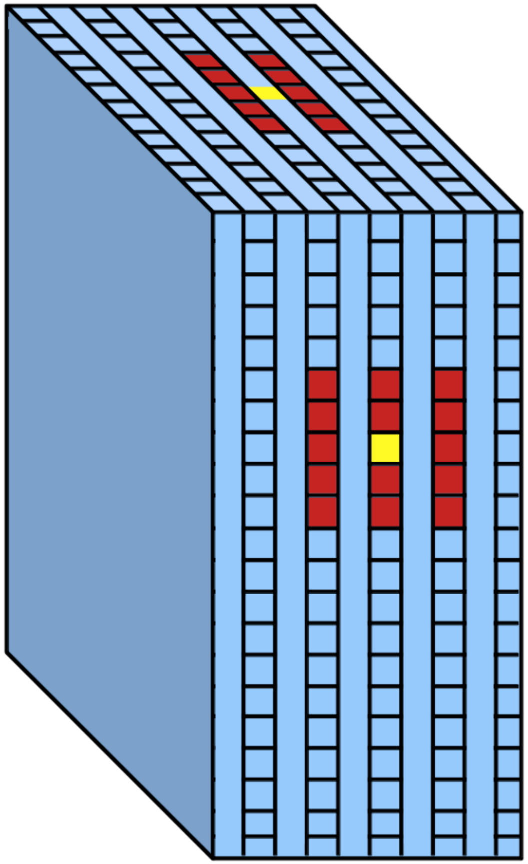
- Dominated systematics: Background model and vertex activity model
- Vertex activity model:
  - Single particle-gun protons are generated isotropically [0-250 MeV]
  - Vertex activity for protons formed
  - Extra vertex activity is added randomly 25% of MC events scattering off a neutron

Systematic Source	Error on Background
Flux	4.0
W^2 scale covariance (stat)	6.4
Background model	12.0
Vertex Activity model	9.0
Pion reinteractions	3.6
OOFV interactions	0.6
Vertex Activity	4.5
Charge reconstruction	0.6
Momentum Scale	0.5
Momentum Resolution	0.6
TPC PID	0.3
Total Systematic Uncertainty	17.9

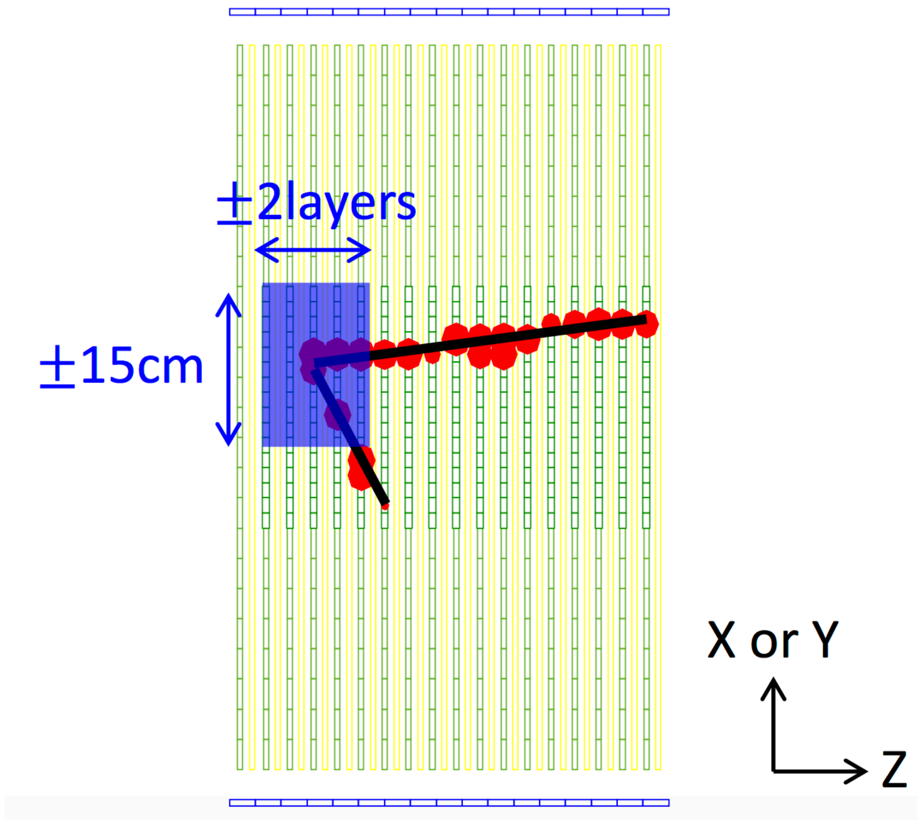




Backup: Vertex activity



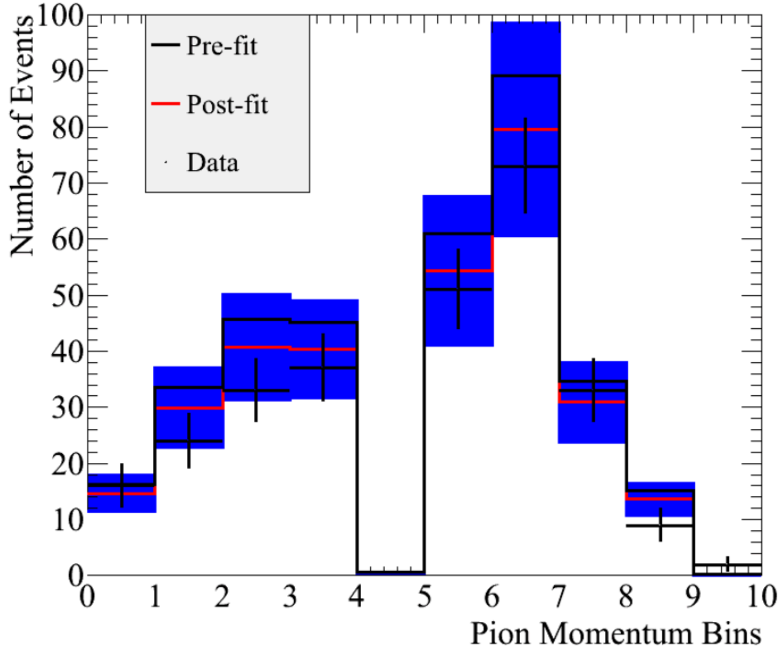
FGD1



Proton Module

Backup: Coherent FGD1

Bin Label	Scale factor (PS1)
$W \leq 1.1$	0.89 ± 0.21
$1.1 < W \leq 1.4$	0.89 ± 0.22
$1.4 < W \leq 2.0$	0.89 ± 0.21
$2.0 < W$	0.89 ± 0.19
Other	1.0

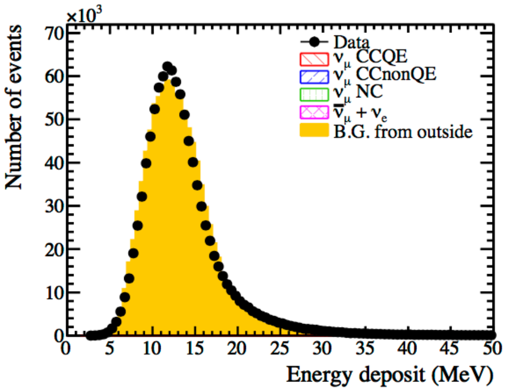


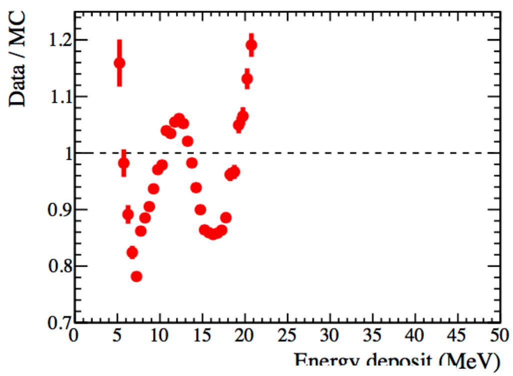
	$W < 1.1$	$1.1 < W < 1.4$	$1.4 < W < 2.0$	$2.0 < W$
$W < 1.1$	0.045	0.046	0.044	0.039
$1.1 < W < 1.4$		0.049	0.046	0.039
$1.4 < W < 2.0$			0.045	0.039
$2.0 < W$				0.038

Backup: Vertex activity

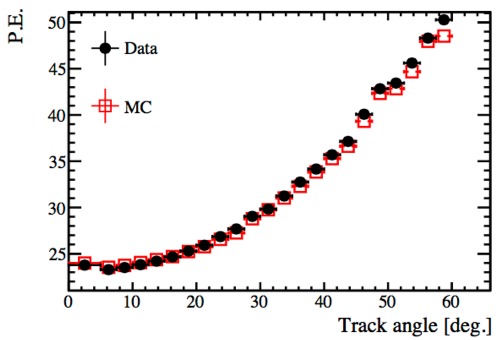
✧ Use sand muons enhanced

✧ Data-MC vertex activity difference is 2.7%

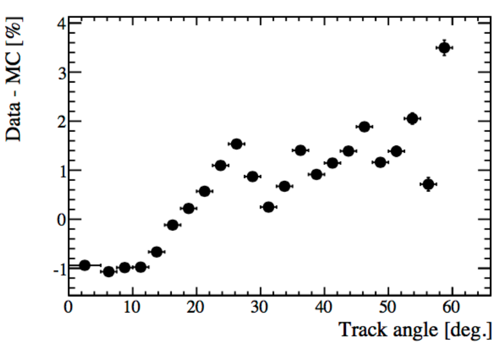




✧ Vary PE as function of track angle, simultaneously vary PE in vertex region → re-estimate cross-section. 13.6% differences used as systematics



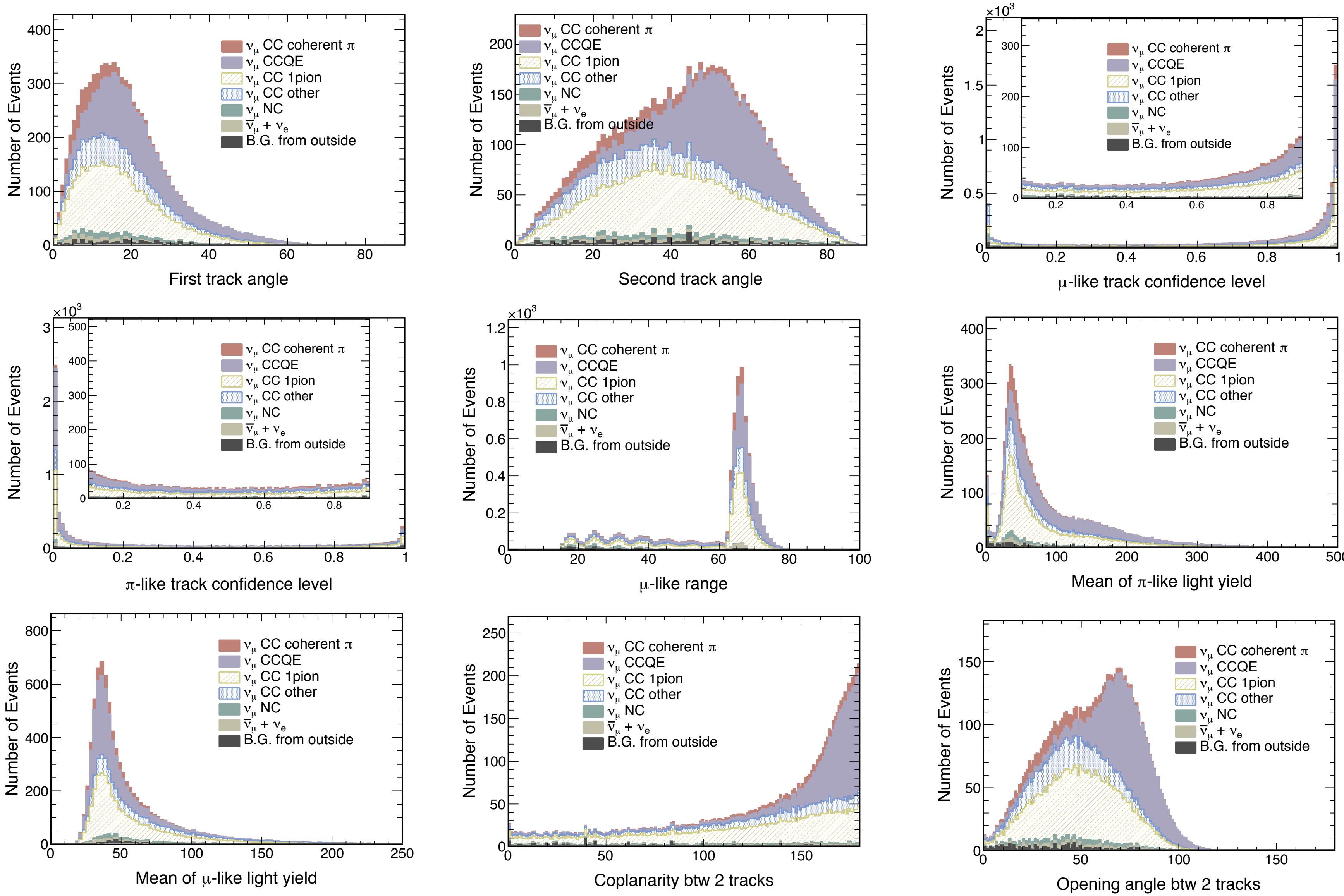
✧ Add up quenching effect based on Birk's law → 7.17%, and sum in quadrature 15.37%



Backup: INGRID coherent systematics

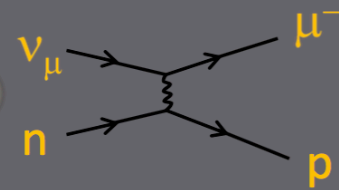
Item	Error
Neutrino flux	$-35.68\%/+43.20\%$
M_A^{QE}	$-11.20\%/+7.98\%$
M_A^{RES}	$-23.84\%/+21.39\%$
CCQE normalization (E_ν <1.5 GeV)	$-0.69\%/+0.68\%$
CCQE normalization (1.5< E_ν <3.5 GeV)	$-0.80\%/+0.79\%$
CCQE normalization (E_ν >3.5 GeV)	$-2.69\%/+2.67\%$
CC1π normalization (E_ν <2.5 GeV)	$-11.47\%/+11.17\%$
CC1π normalization (E_ν >2.5 GeV)	$-18.55\%/+18.21\%$
CC other E_ν shape	$-3.51\%/+3.41\%$
NC1π^0 normalization	$-0.46\%/+0.45\%$
NC1$\pi^\pm$ normalization	$-0.06\%/+0.06\%$
NC coherent π normalization	$-0.11\%/+0.11\%$
NC other normalization	$-0.81\%/+0.70\%$
π-less Δ decay	$-11.54\%/+13.11\%$
Spectral function	$-0.29\%/+0.00\%$
Fermi momentum	$-0.09\%/+0.17\%$
Binding energy	$-0.89\%/+0.92\%$
Pion absorption	$-6.06\%/+4.66\%$
Pion charge exchange (low energy)	$-0.41\%/+0.29\%$
Pion charge exchange (high energy)	$-3.02\%/+2.80\%$
Pion QE scattering (low energy)	$-6.12\%/+4.97\%$
Pion QE scattering (high energy)	$-0.46\%/+0.18\%$
Pion inelastic scattering	$-5.65\%/+5.04\%$
Nucleon elastic scattering	$-1.24\%/+1.11\%$
Nucleon single π production	$-4.01\%/+3.96\%$
Nucleon two π production	$-0.10\%/+0.27\%$
Target mass	$\pm0.90\%$
MPPC dark noise	$\pm0.74\%$
Hit efficiency	$\pm5.36\%$
Light yield	$\pm15.37\%$
Event pileup	$\pm0.31\%$
Beam-induced external background	$\pm0.00\%$
Cosmic-ray background	$\pm0.00\%$
2D track reconstruction	$\pm1.92\%$
Track matching	$\pm4.28\%$
3D tracking	$\pm12.73\%$
Vertexing	$\pm12.00\%$
Timing cut	$\pm0.00\%$
Veto cut	$\pm10.42\%$
Fiducial volume cut	$\pm14.38\%$
Secondary interactions	$\pm6.72\%$
Total	$-60.72\%/+63.95\%$

Backup: MVA for INGRID coherent



Fine Grained Detectors (FGDs)

- **Active target mass of ND280**
- **Finely grained for vertex resolution**
- **Reconstruct and identify short tracks**



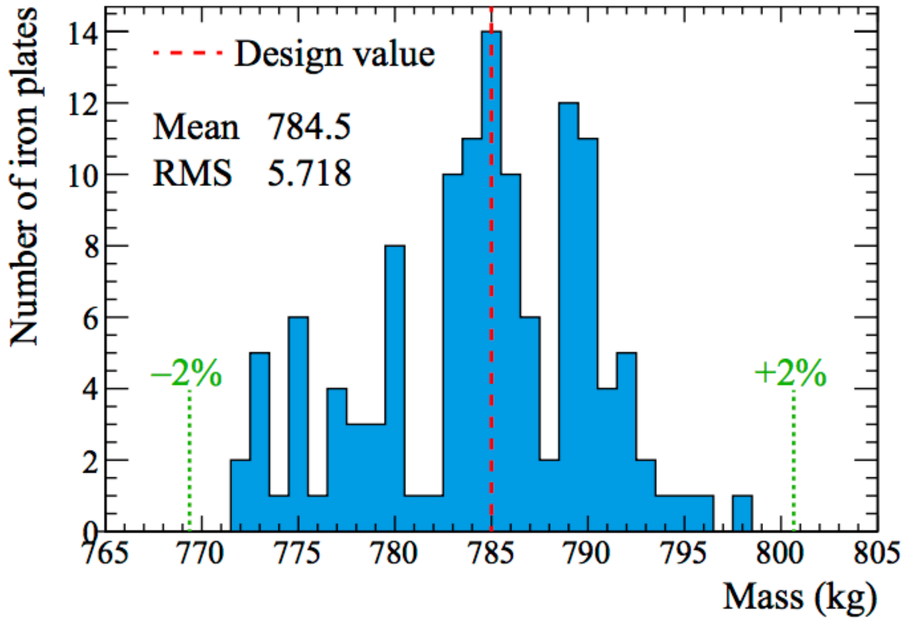
Key channel for oscillation analysis: Charged Current Quasi Elastic (CCQE)

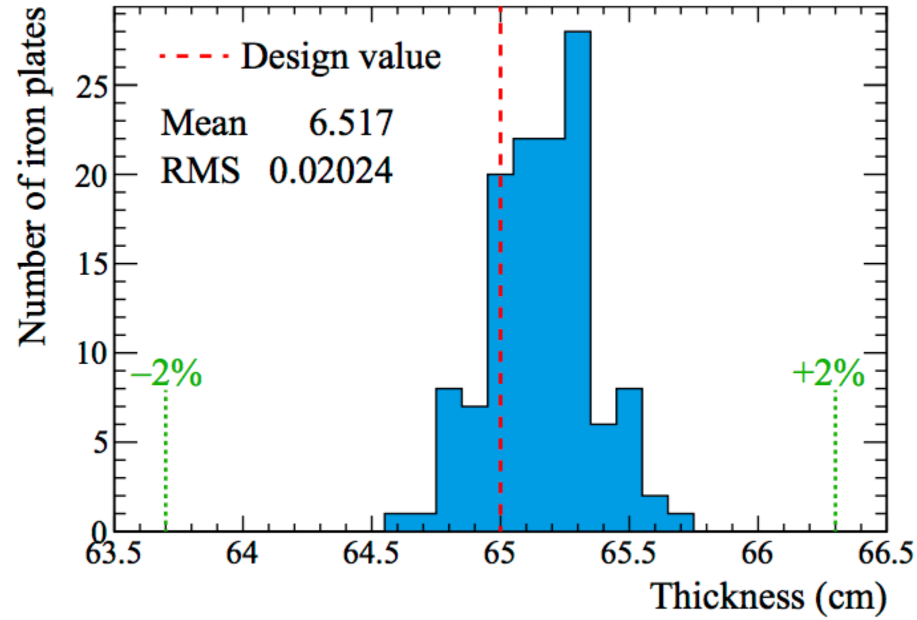
- Scintillator Bars: 9.6mm x 9.6mm x 1843mm
- FGD1: 15 modules (30 layers)
- FGD2: 7 modules (14 layers) + 6 water panels
- 8448 channels in total
- Each is ~1.1 ton

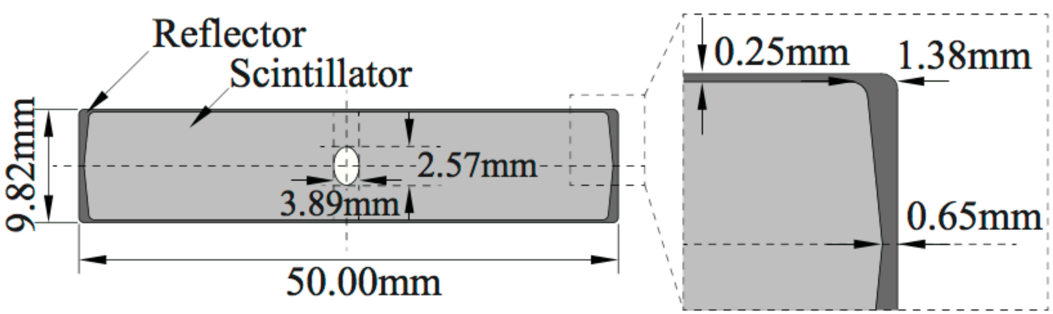
- Light from scintillator bars collected by Wavelength Shifting (WLS) fibers
- Propagates down fibers to Multi Pixel Photon Counters (MPPCs)

5

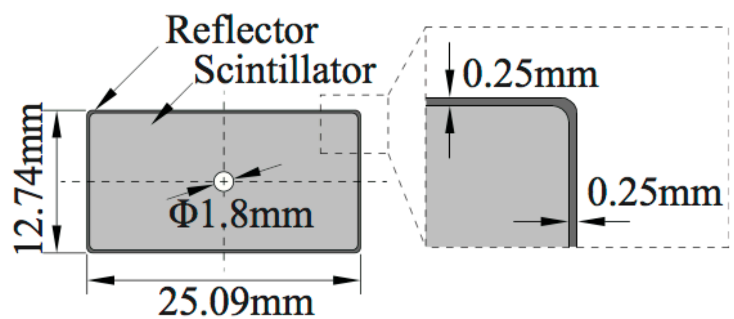
Backup: INGRID







(a) INGRID-type scintillator



(b) SciBar-type scintillator