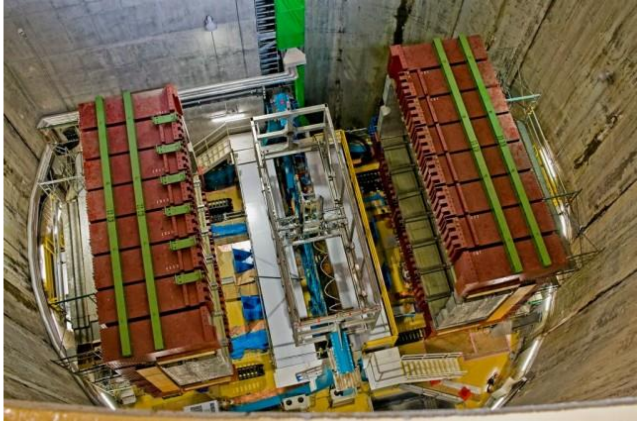
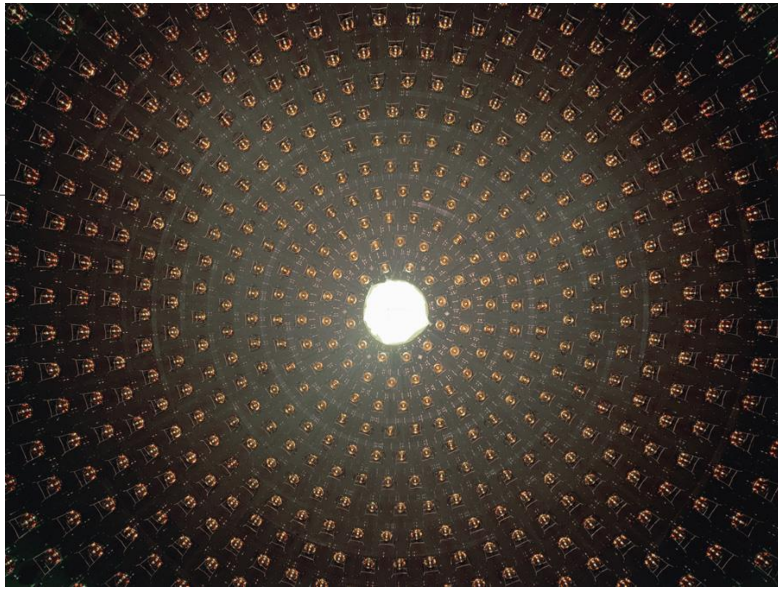


Exploring GENIE and Real-World Data through **Simulation Tuning**



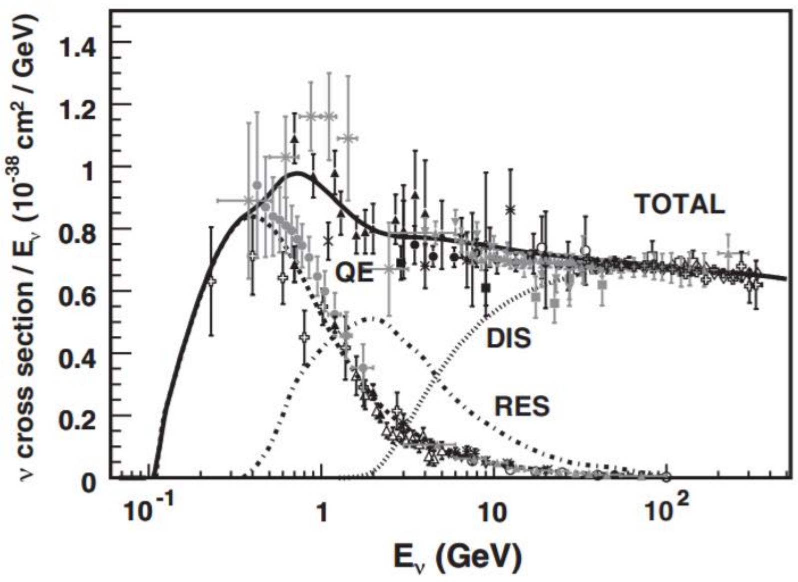
Richie Diurba (University of Minnesota), Kirsty Duffy (Fermilab),
Steve Dytman (University of Pittsburgh), Steven Gardiner (Fermilab)

New Directions in Neutrino-Nucleus Scatters (NDNN) 2021

NuSTEC

Basics of Simulation Tuning

- Neutrino cross section uncertainties are significant uncertainties in oscillation analyses.
    - T2K's CP-violating measurement had an over 5% total systematic uncertainty for cross section modeling.
        - At least 83% of the total systematic uncertainty
- Simulation tuning is a method of creating a new central-value simulation.
    - Obtained by reweighting simulation parameters to another dataset.
    - Allows experiments to constrain and quantify cross section modeling uncertainties.
- Creates a theory-driven fit for experimental and theoretical evaluations.



Charged current muon neutrino cross section data with a fit to both inclusive and exclusive channels. These fits could constitute a tuned simulation and used to generate Monte Carlo as a function of E_ν.

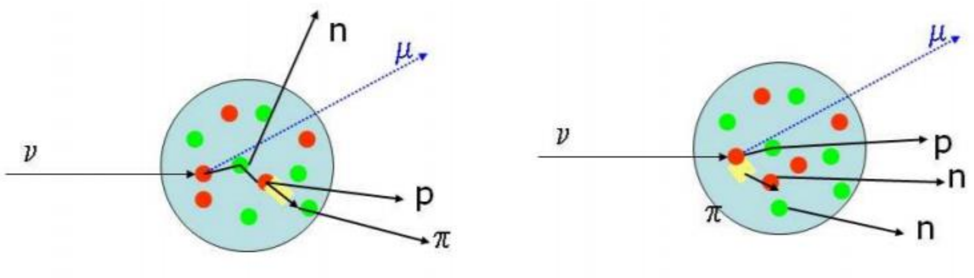
J. A. Formaggio and G. P. Zeller, From *eV to EeV: Neutrino cross sections across energy scales*, *Rev. Mod. Phys.* **84** (Sep, 2012) 1307–1341.

Motivations for Tuning

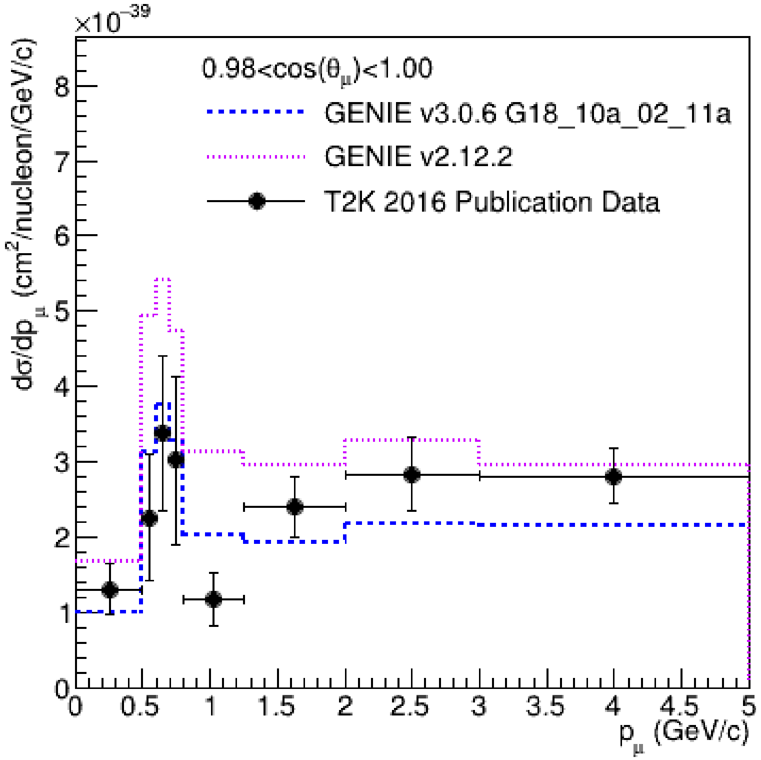
GENIE collaboration, *Nuclear Instruments and Methods* ***A614*** (2010) 87–104, [0905.2517].

- Event generators show clear differences with real-world data.
  - GENIE will be the focus for this presentation.

Possible Differences between Data and Simulation:
- Normalization of exclusive channels
- Principal interaction modeling
- FSI modeling



Charged current neutrino interaction with pion production (left) and pion absorption (right)



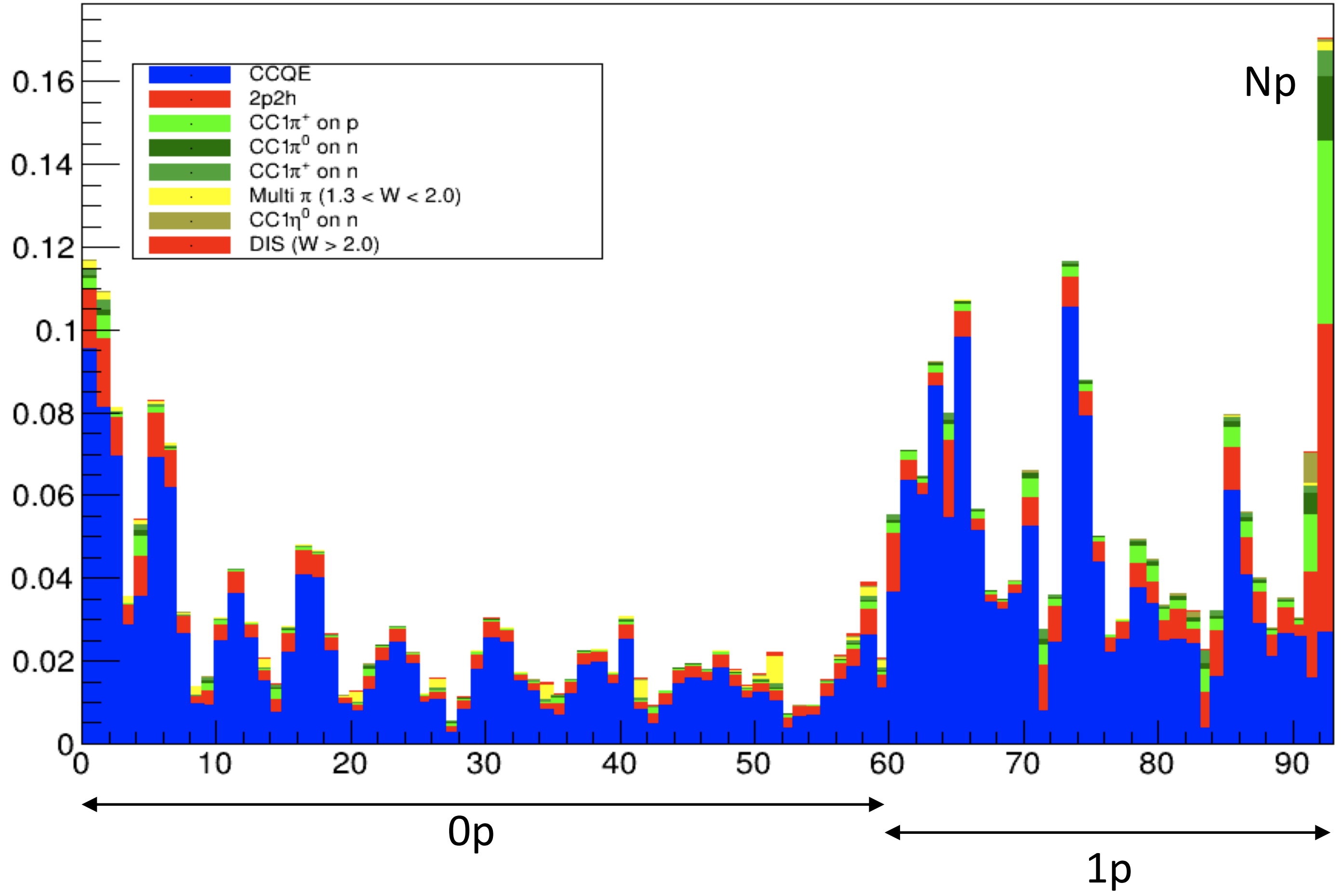
Cross section as a function of lepton moment for the most forward-going bin of T2K CC0π data.

The T2K Collaboration, *Phys. Rev. D* **93** (2016) 112012.

The T2K Collaboration, *Phys. Rev. D* **98** (Aug, 2018) 032003.78.

T2K 2018 CC0π Data Tune Plan

- ND280 data sorted into three separate categories based on proton multiplicity.
- 0p is a double-differential and 1p is a triple-differential cross section with only diagonal errors used.



Truth-level distribution of event type as a function of global bin number.

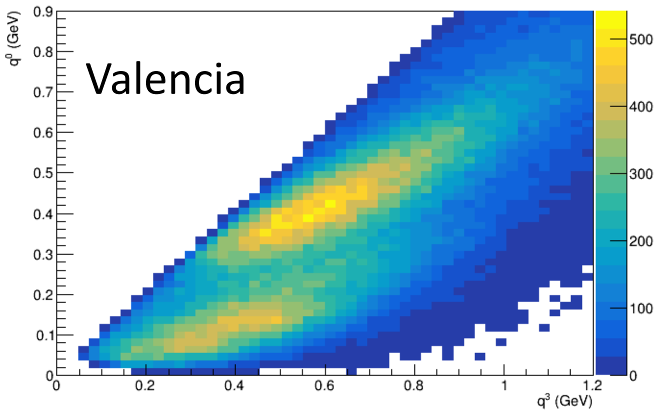
- Dataset re-analyzed from the same events of T2K 2016 CC0π ND280 data publication.
  - Data contains approximately $6*10^{20}$ P.O.T. taken from 2010-2013.

2p2h Cross Section Shape Reweighting

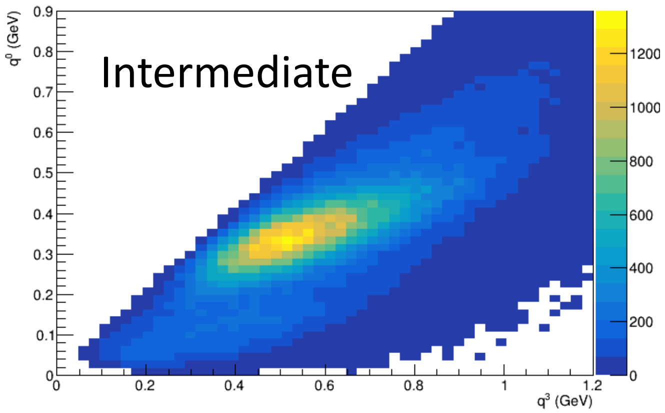
R. Gran, J. Nieves, F. Sanchez and M. J. V. Vacas, *Neutrino-nucleusquasi-elastic and 2p2h interactions up to 10 GeV*, *Phys. Rev. D* **88** (Dec 2013) 113007, [1307.8105].

- Only inclusive 2p2h predictions currently available in generators
- These vary widely in the differential **shape** as well as normalization
- Assess shape uncertainty by interpolating between two 2p2h models using a continuous parameter k.

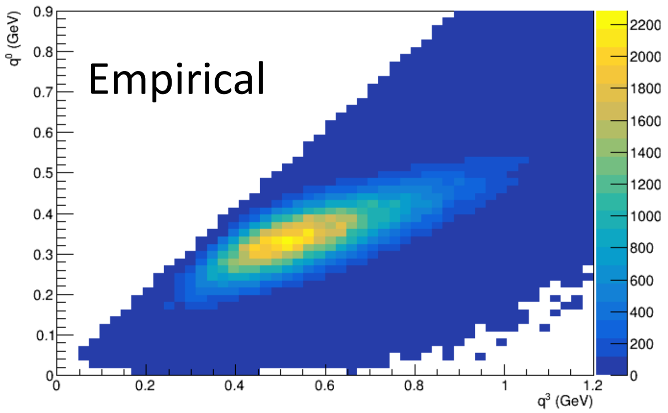
$k = 0$



$k = 0.5$



$k = 1$



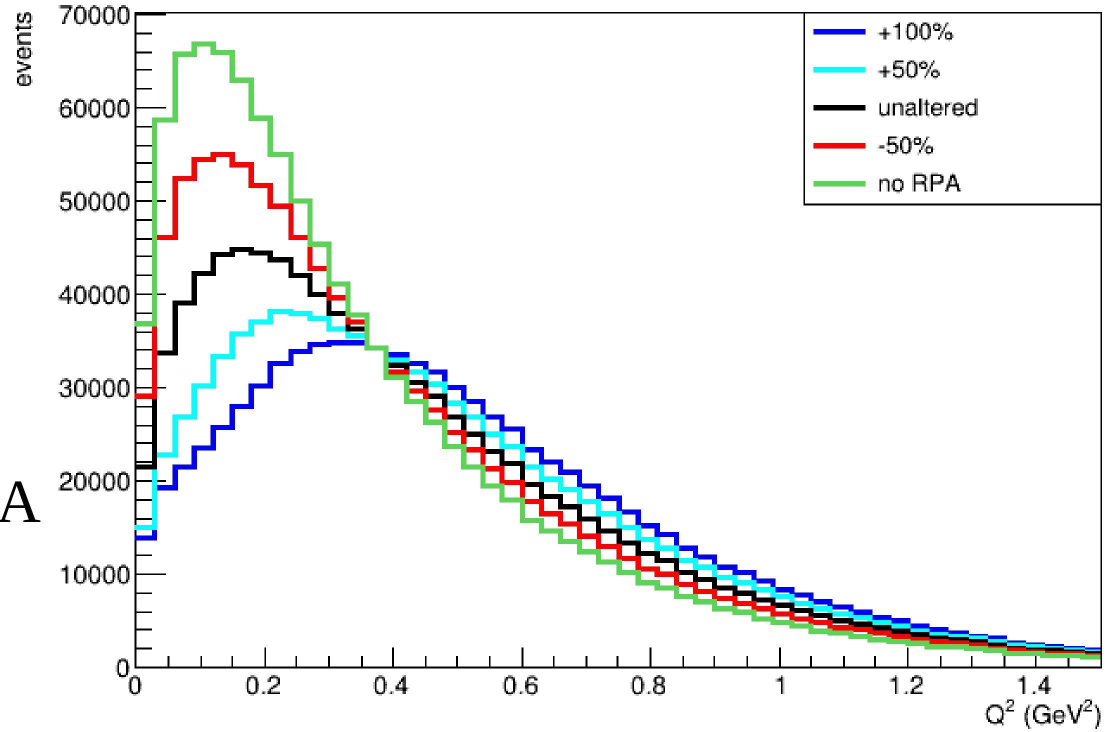
Reweighting of CCQE RPA corrections

R. Gran, J. Nieves, F. Sanchez and M. J. V. Vacas, *Neutrino-nucleusquasi-elastic and 2p2h interactions up to 10 GeV*, Phys. Rev. D **88** (Dec 2013) 113007, [1307.8105].

- Valencia CCQE models long-range correlations via the Random Phase Approximation (RPA)
  - New terms in the nucleon tensor $A^{\mu\nu} \rightarrow A^{\mu\nu}_{\mathrm{RPA}}$

- Tune strength of the RPA corrections using continuous parameter R
  - Linearly interpolate between unaltered Valencia RPA ($R = 100\%$) and no RPA correction ($R = 0\%$)

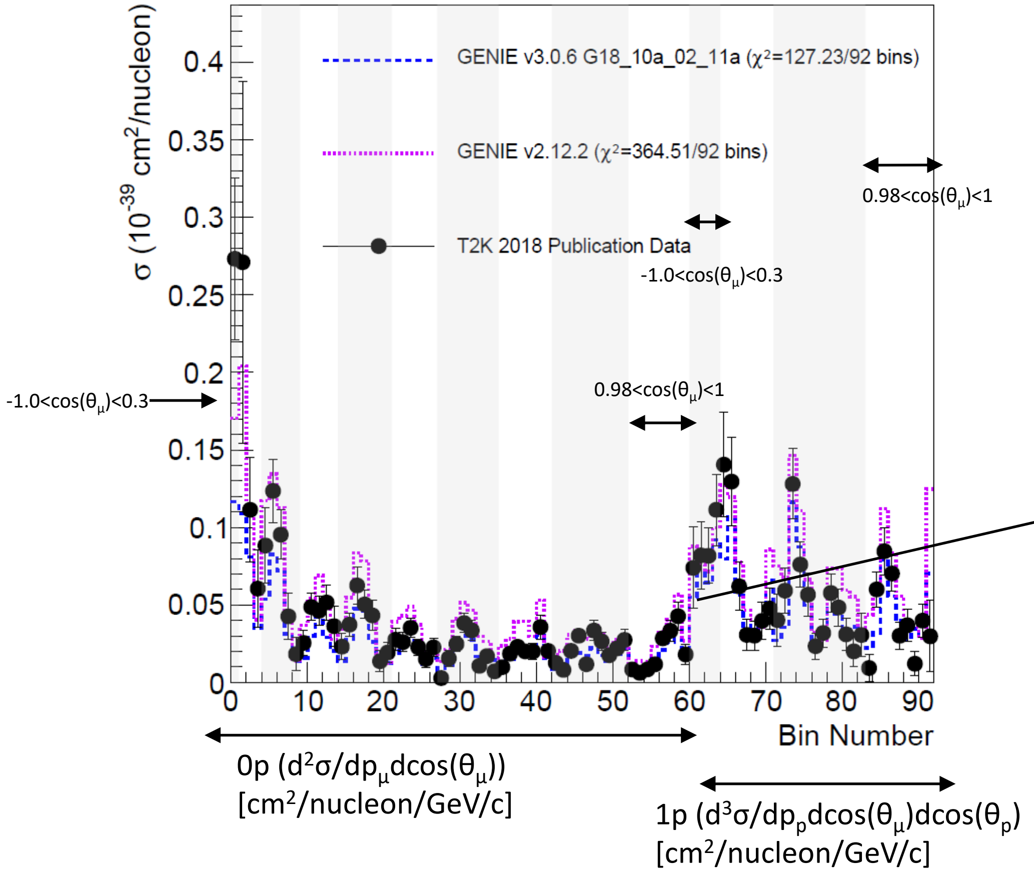
Distribution for CCQE ν_μ Events on 40Ar (MicroBooNE Flux)

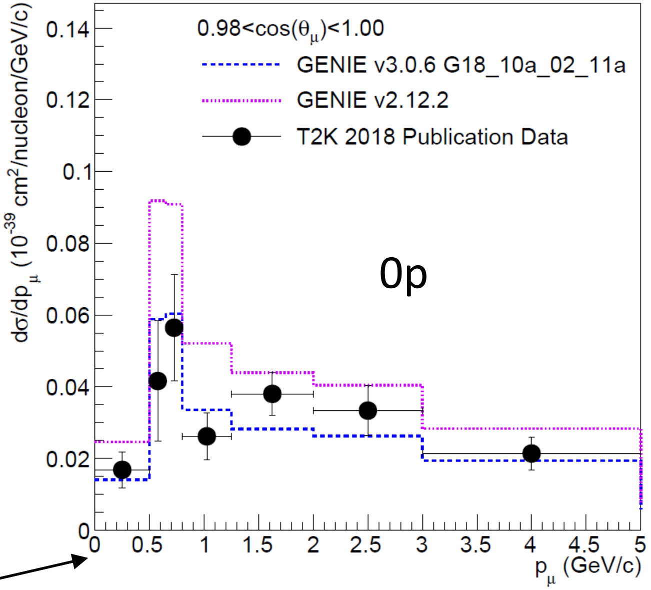


T2K 2018 Fitting Starting Point

P. Stowell, C. Wret, C. Wilkinson, L. Pickering, et. al., *NUISANCE*, JINST **12** (2017) P01016.

- Dataset: T2K 2018 ND280 CC0π(0p,1p)
- Fitting: NUISANCE with MINUIT
- Event Generator: GENIE v3.0.6 G18_10a_02_11a, which uses Valencia for CCQE, 2p2h, and LFG modeling





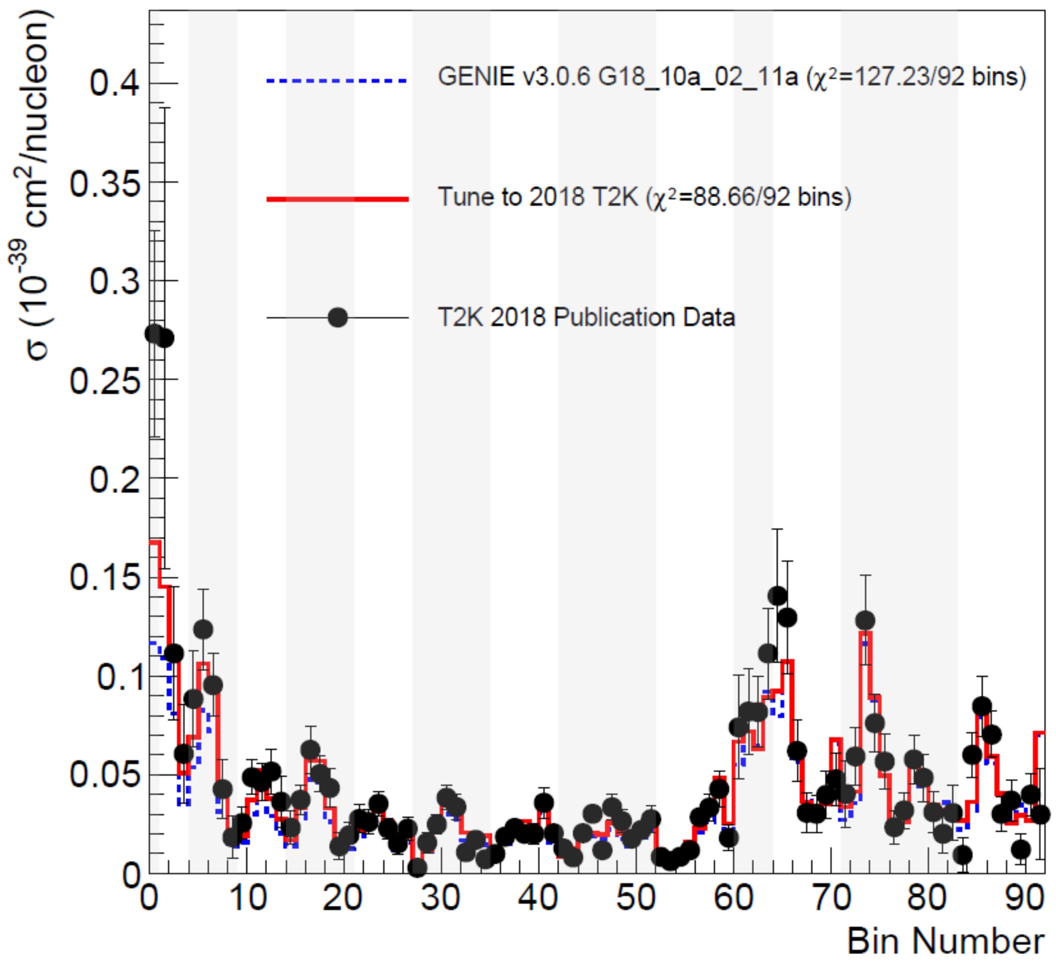
Parameters:
- NormCCQE
- Norm. 2p2h
- 2p2h cross section shape
- CCQE RPA
- Mean free path of the nucleon
  - FSI parameter if a proton is present.

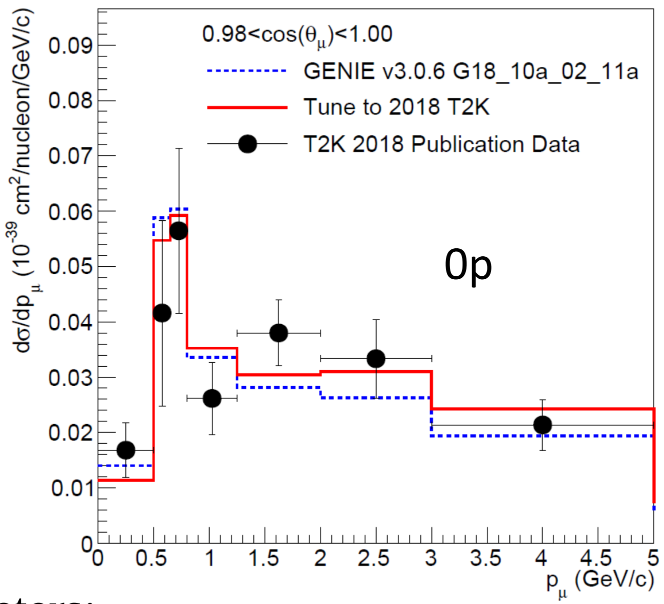
Comparison of 0p and 1p data with GENIE plotted by bin number.

Each shaded region is a slice of the cosine angle of the final-state muon.

Tune to 2018 T2K CC0pi Data with at Most One Proton

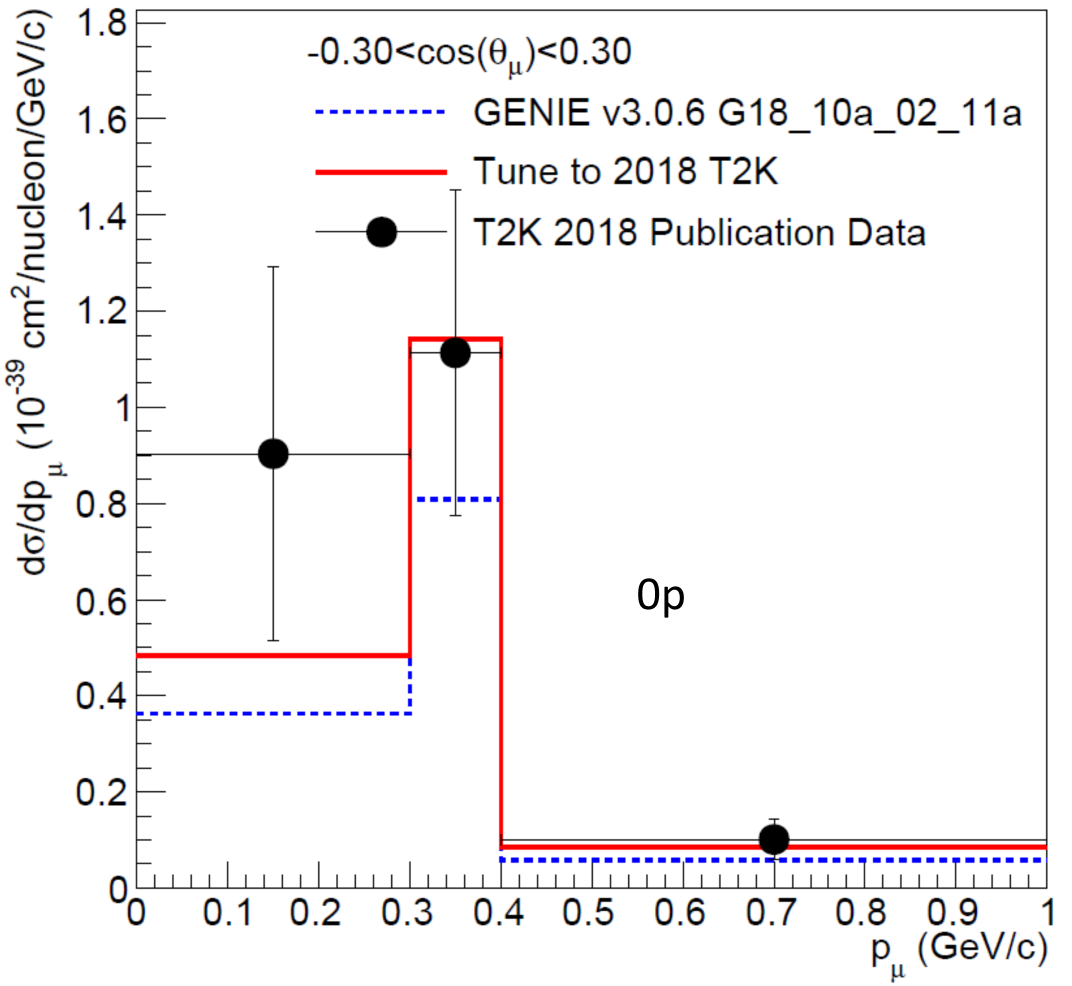
Fit to T2K 2018 CC0π with 0p and 1p in the final-state.





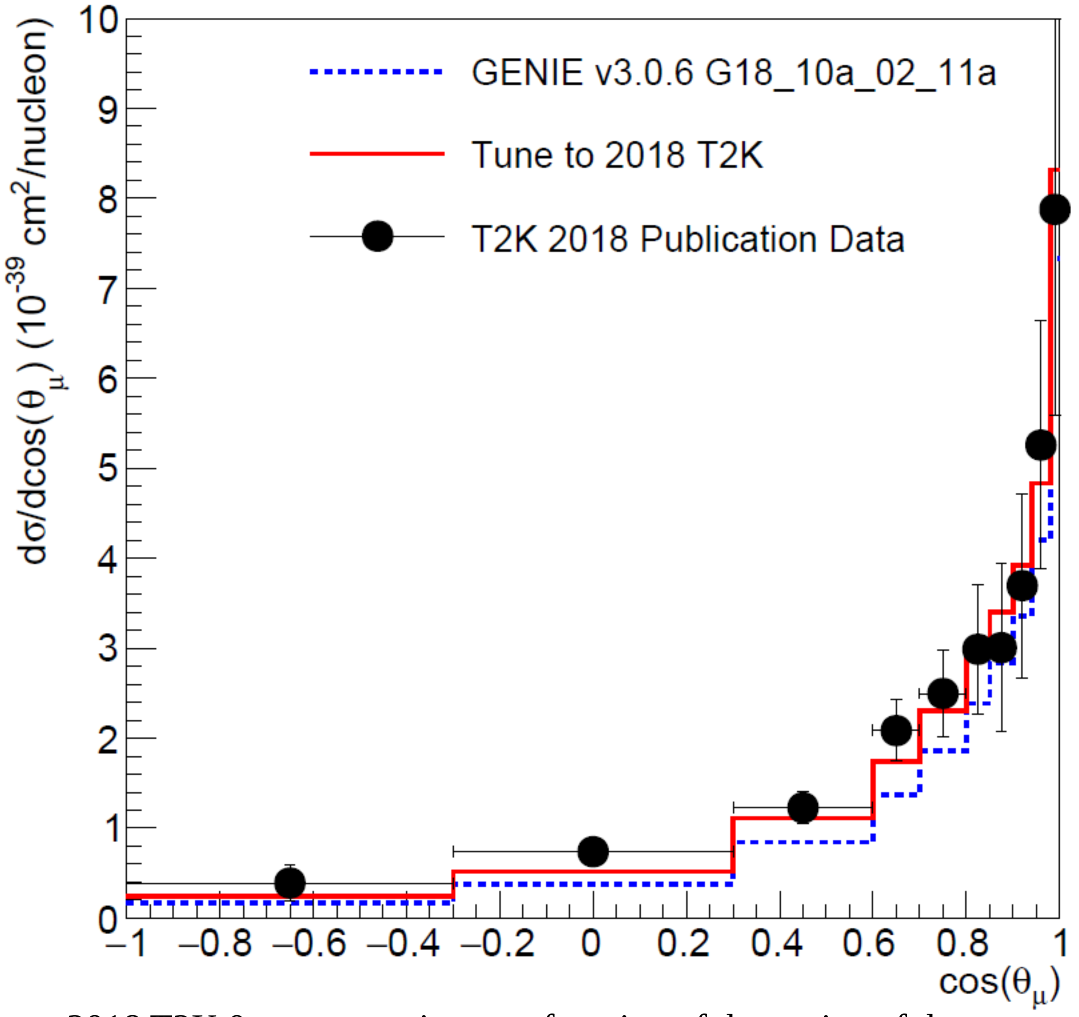
- Tuned parameters:
  - Norm. CCQE: 92.4%±9.9%
  - Norm. 2p2h: 42.5%±16.5%
  - 2p2h Cross Section Shape: 1±0.78
    - Tune prefers GENIE empirical 2p2h model
  - RPA CCQE parameter: 78%±13%
    - Less low Q^2 suppression (Nominal: 100%)
  - Mean free path of nucleons: 22%±11%
    - More nucleon FSI interactions (Nominal: 100%)

Comparing the Tune to Slices of the Cross Section



2018 T2K cross section data for near-perpendicular muon angle bins.

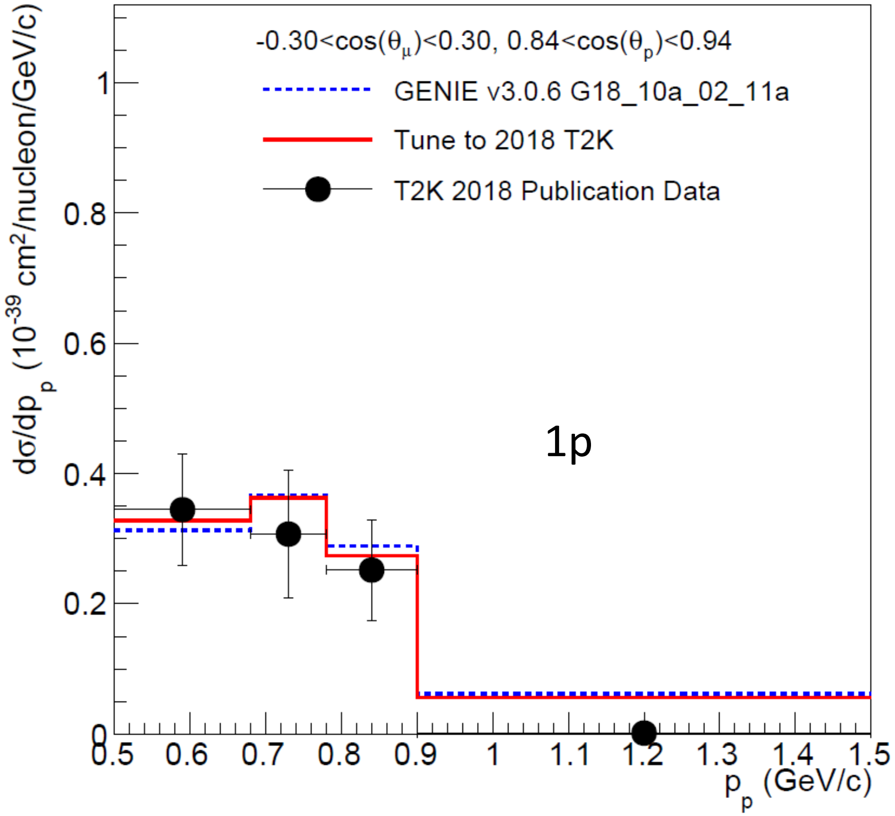
Comparing the Tune to Slices of the Cross Section

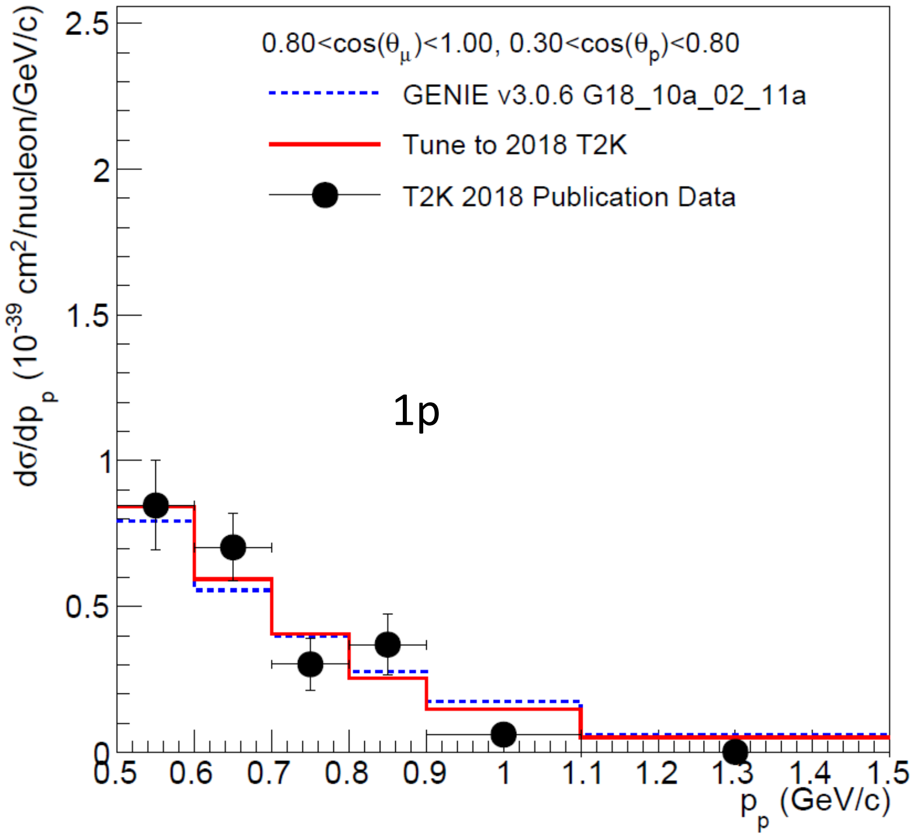


2018 T2K 0p cross section as a function of the cosine of the muon angle.

Comparing the Tune to Slices of the Cross Section

Tune makes minimal performance improvements on 1p bins.



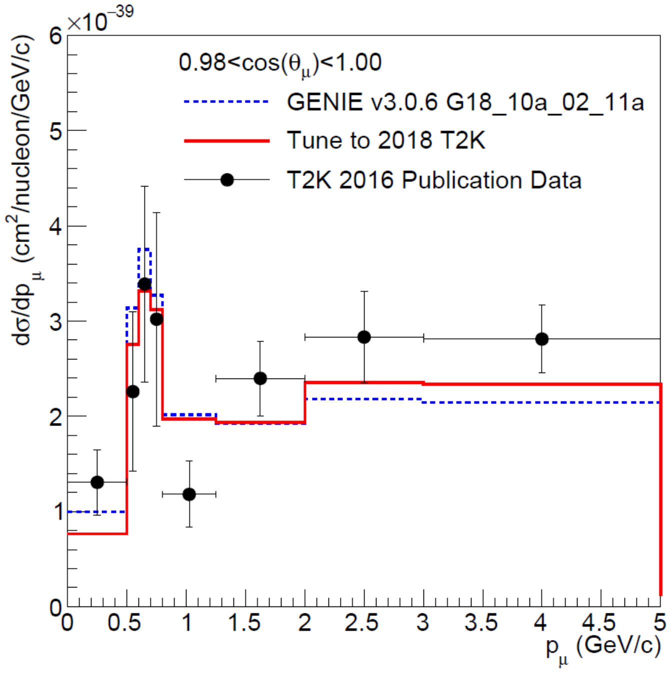


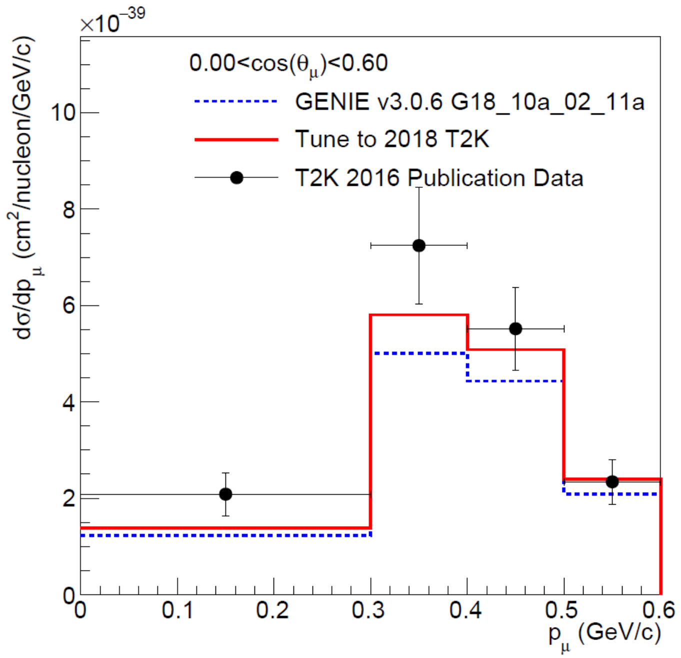
Slices of the 2018 T2K 1p cross section in slices of muon and proton angle.

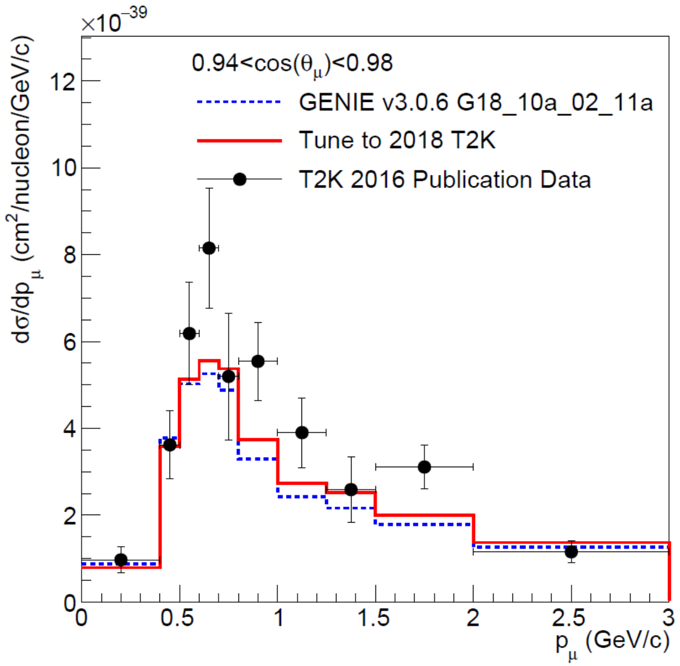
Comparing the Tune to the 2016 T2K Publication

The 2018 T2K data tune also improves the agreement to the cross section measured in the 2016 T2K publication.

This makes sense as both publications come from the same data-taking period.



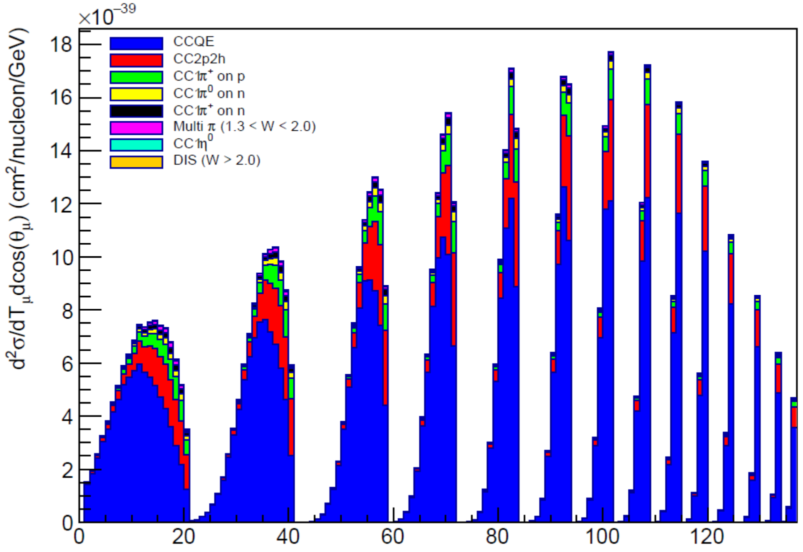




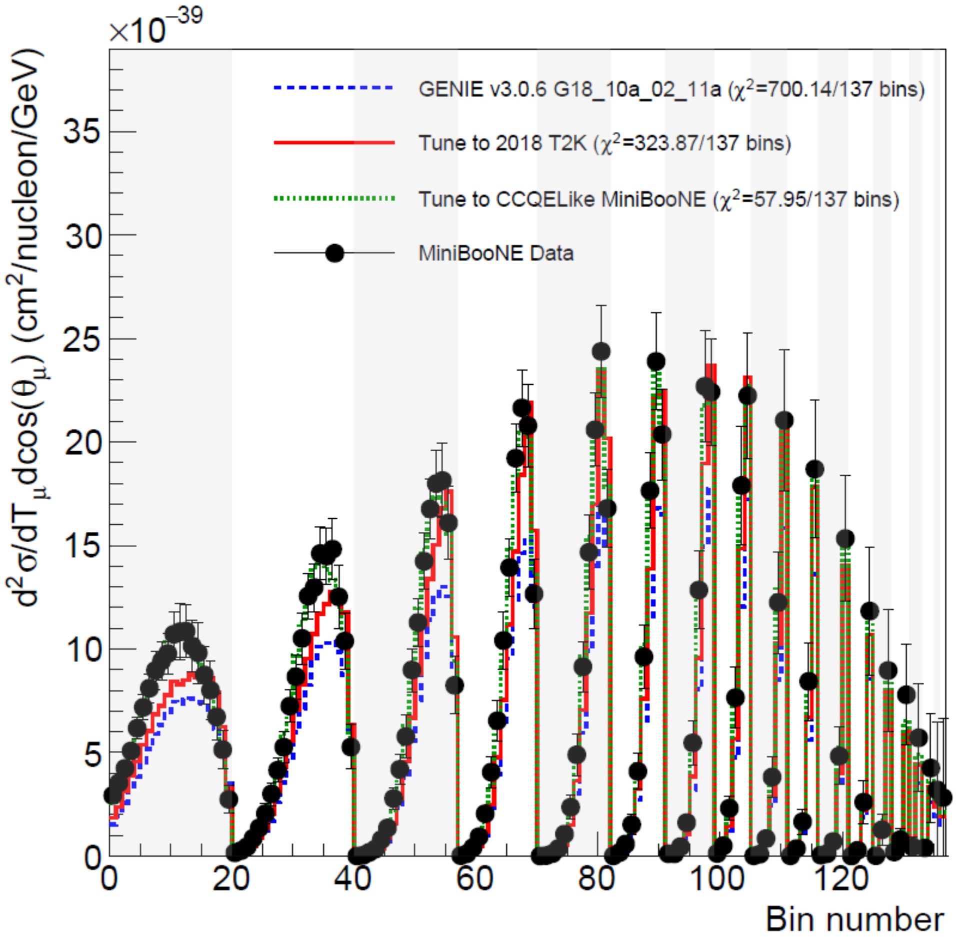
MiniBooNE CCQELike Tune

MiniBooNE collaboration, A. Aguilar-Arevalo et al., *Phys. Rev. D* **81**(2010) 092005, [1002.2680].

- Best to compare it to an alternate tune with a similar dataset.
  - We chose MiniBooNE double-differential CCQELike data
  - CH2 target with plenty of statistics.
- Tuned parameters to MiniBooNE:
  - Norm. CCQE: 154%±25%
  - Norm. 2p2h: 47%±54.5%
  - 2p2h Cross Section Shape: 1±0.76
    - Tune prefers GENIE empirical 2p2h model
  - RPA CCQE parameter: 116%±30%
  - Mean free path of nucleons: 33%±78%



MiniBooNE CCQELike cross section separated by exclusive cross section of the event.

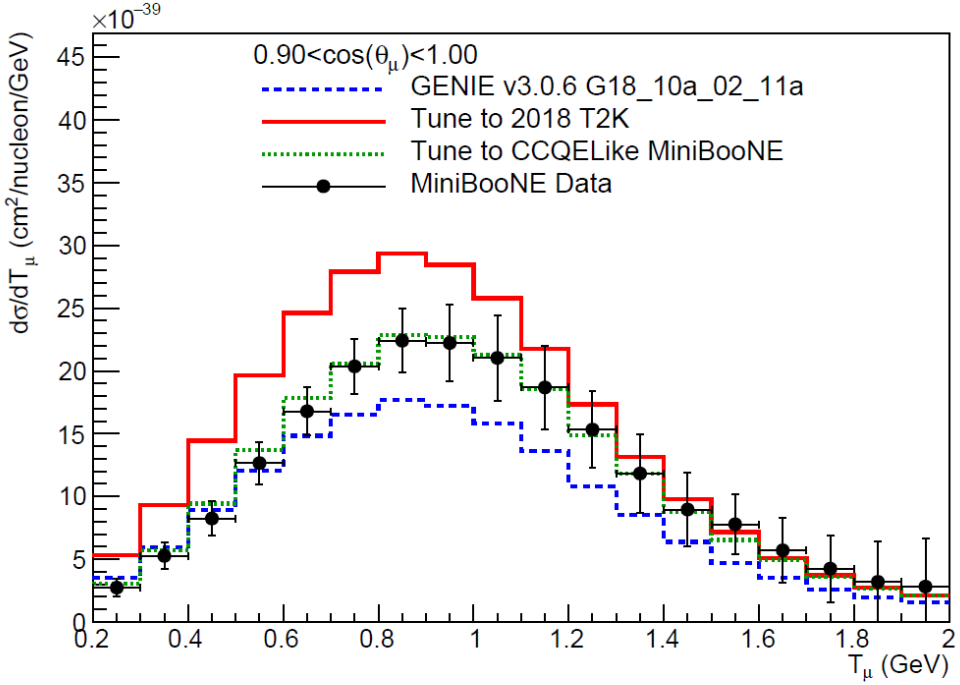


MiniBooNE CCQELike cross section. Each shaded region is a lepton kinematic energy bin. These bins are 0.1 GeV slices and start at 0.2 GeV and end at 2 GeV.

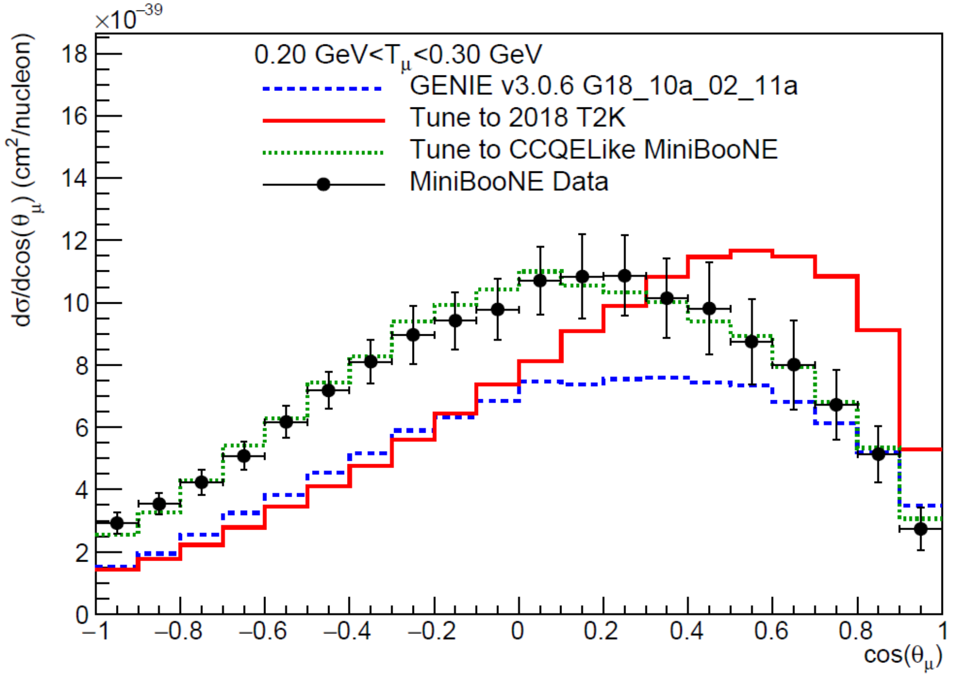
Errors do not come from a covariance matrix. Therefore, χ – values may not be fully accurate.

Evaluating Tune Performances Through MiniBooNE Data

- General trend is that the T2K 2018 tune has a cross section shape that peaks at the most-forward bin. The shape shows clear differences with the MiniBooNE CCQELike fit in the muon angle phase space.



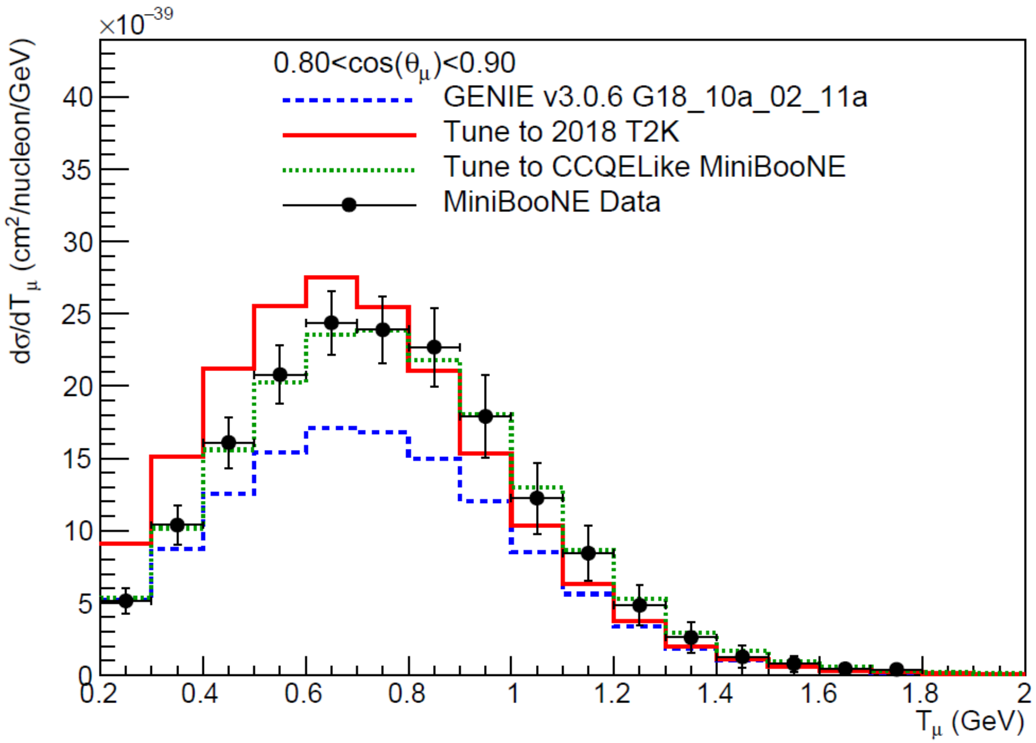
Most-forward bin cross section as a function of the lepton kinetic energy.

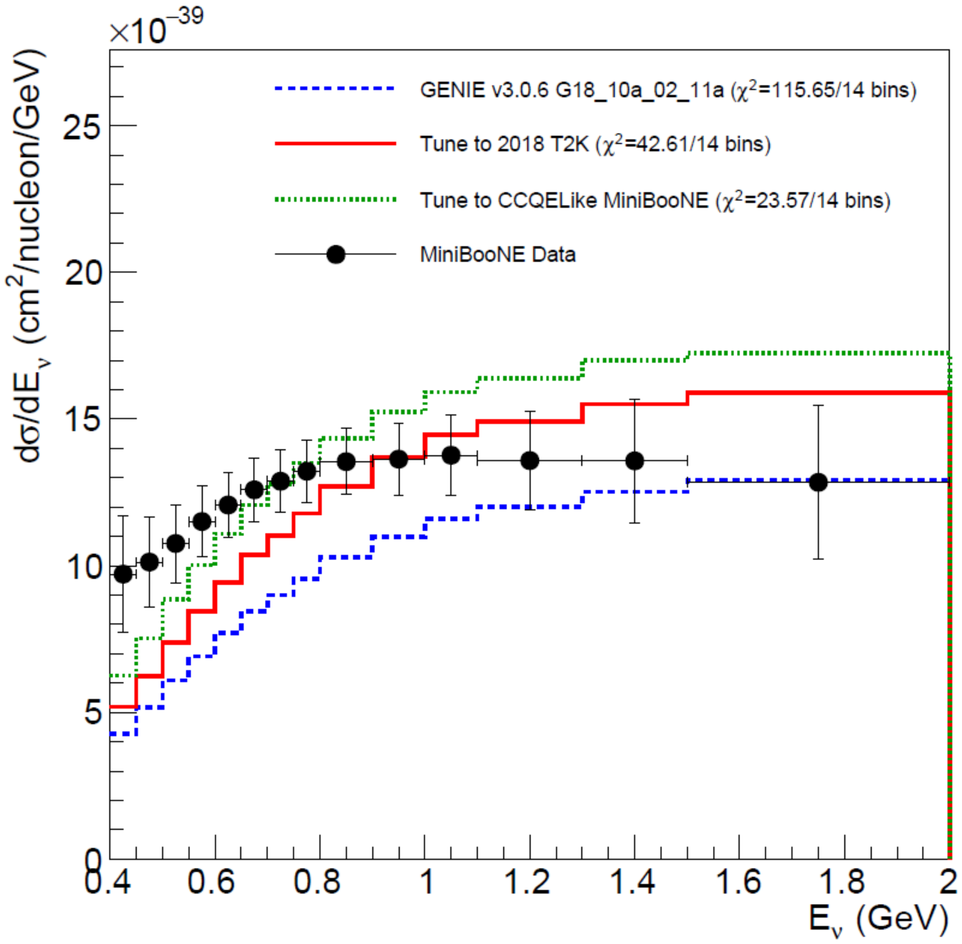


Lowest-energy bin cross section as a function of the cosine of the muon.

Tunes Compared to MiniBooNE CCQELike Data

- MiniBooNE data fits the normalization and shape well for slices of lepton kinetic energy.
  - However, tune has tensions when we change to a much more complicated variable, reconstructed neutrino energy.

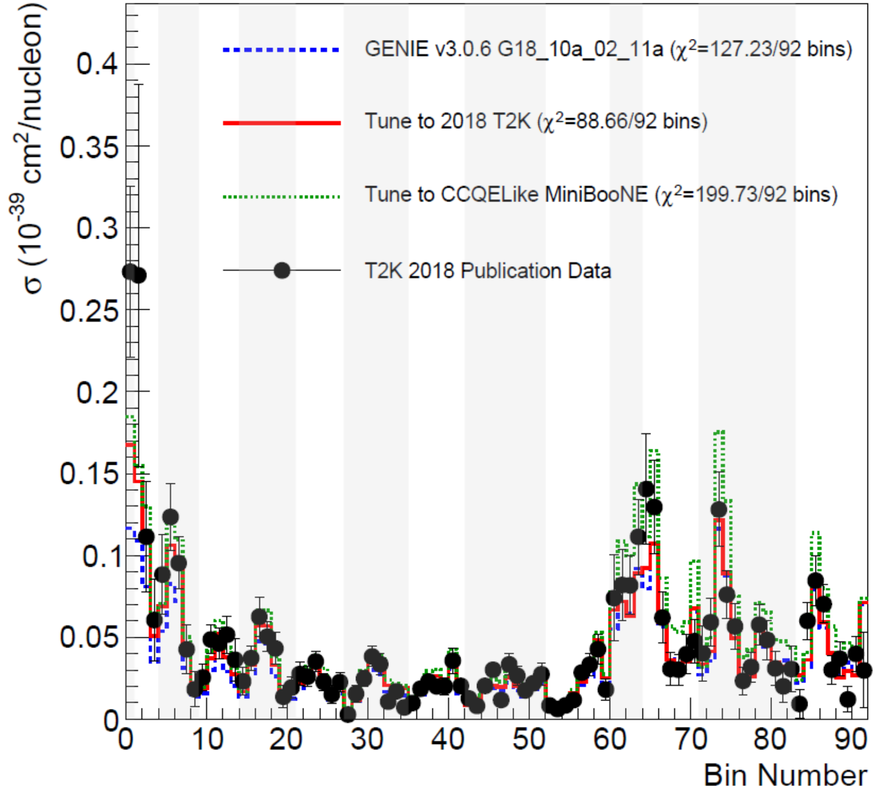




MiniBooNE data re-binned as a function of reconstructed neutrino energy.

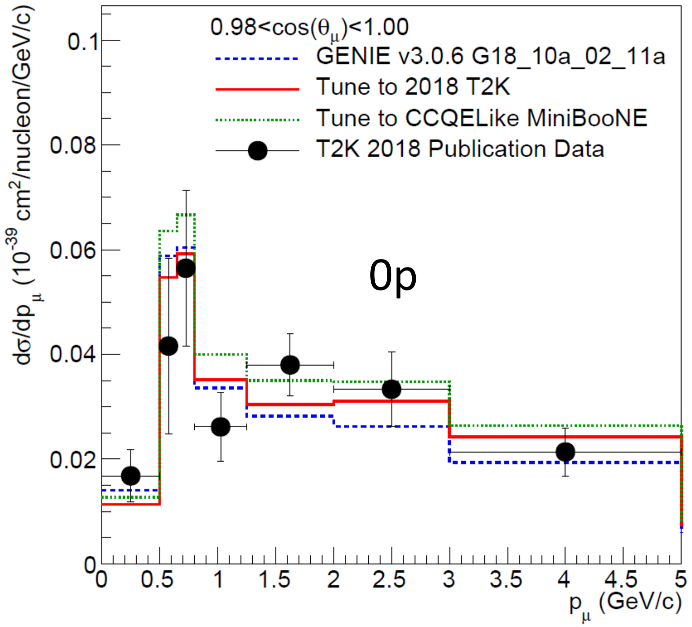
Tunes Compared to T2K Data

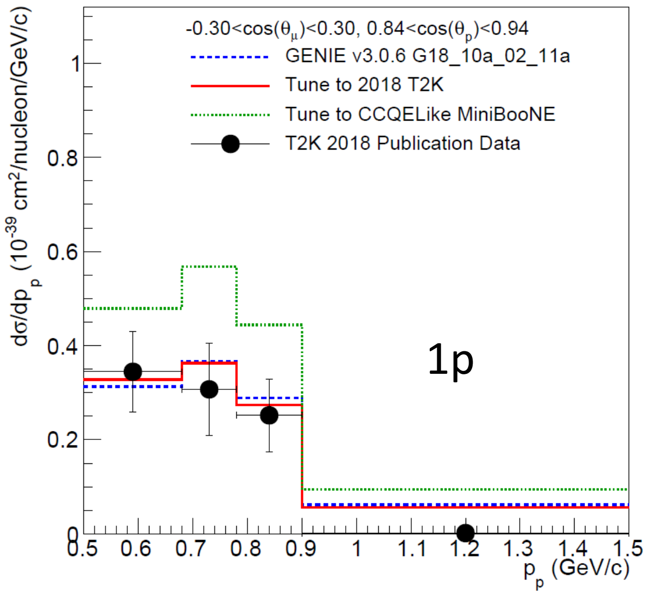
- However, the MiniBooNE tune has a normalization issue when we focus on 1p data.
- Remember, MiniBooNE 2D CCQELike is dependent on the final-state lepton only.



T2K 2018 data with the MiniBooNE tune plotted on top of the nominal and 2018 T2K fit.

Slice of 0p cross section in 2018 T2K data.

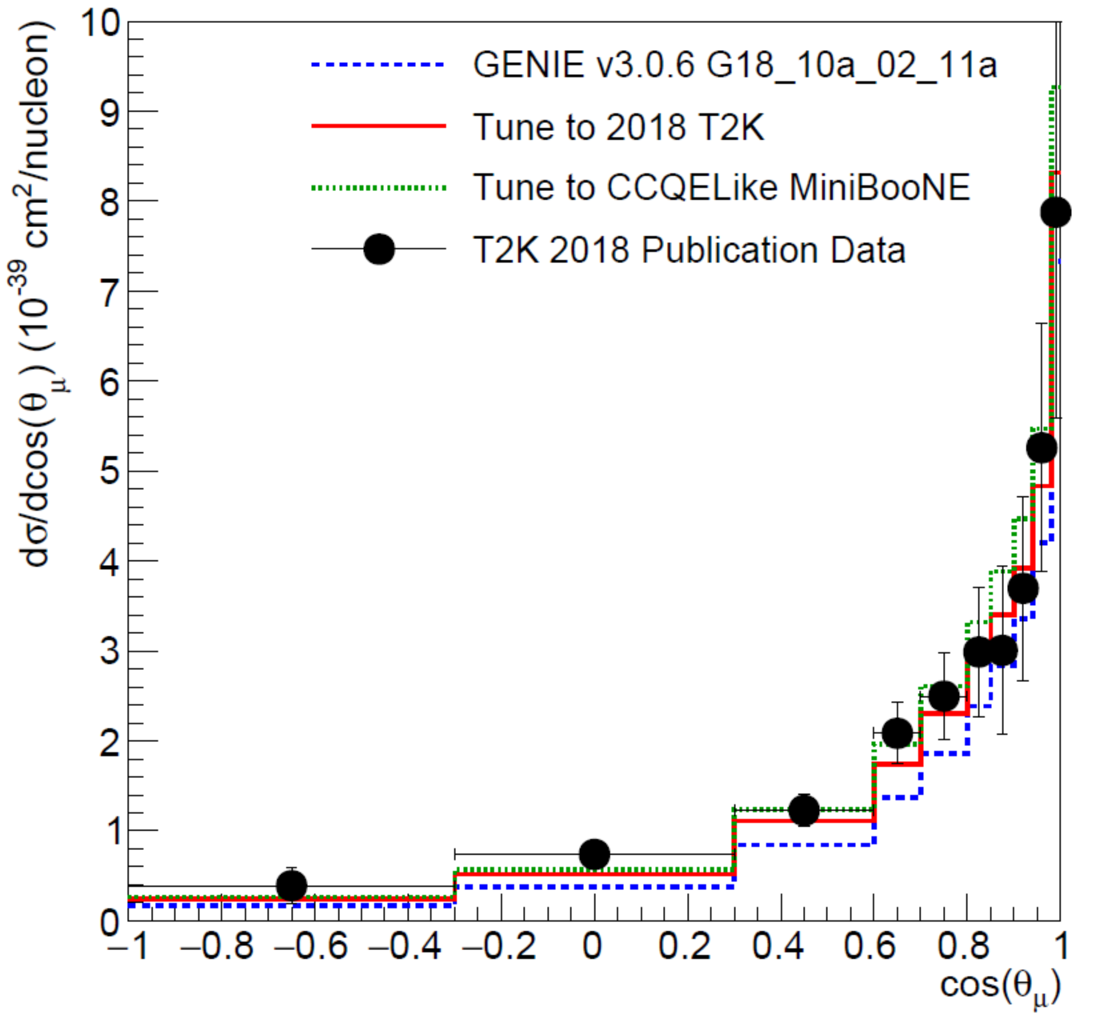




Slice of 1p cross section in 2018 T2K data.

Conclusions: Highlights from Tune

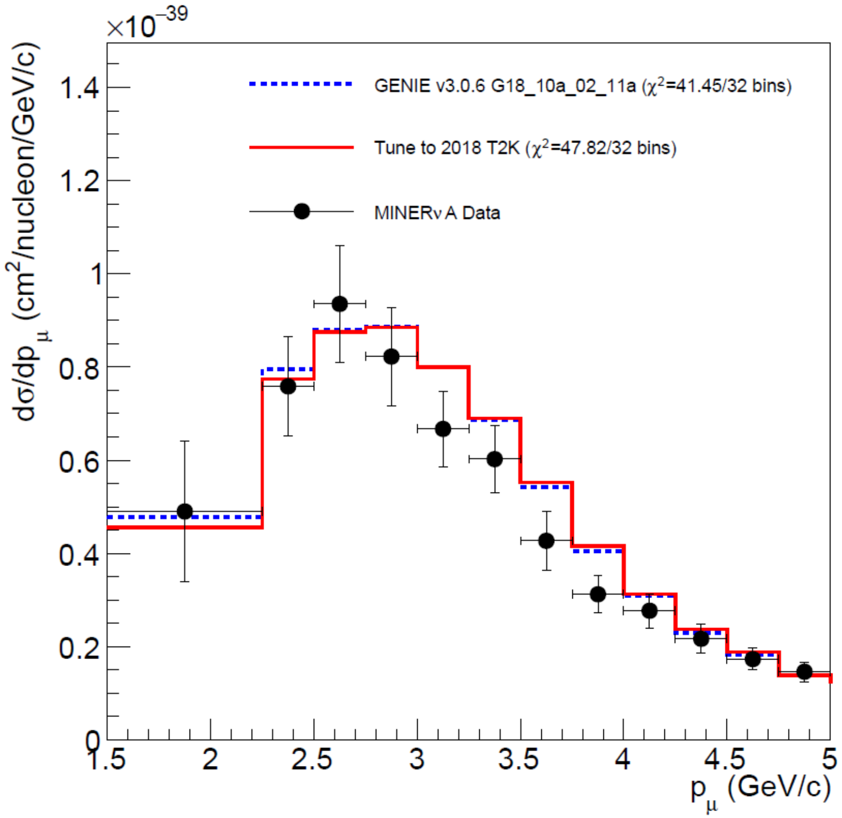
- Normalization of CCQE:
  - Smaller by around 8% in T2K 2018 fit, but larger by approximately 54% in MiniBooNE data.
- Normalization of 2p2h:
  - Both fits measure the normalization of 2p2h events at approximately 45% of their nominal value.
- 2p2h cross section shape:
  - Both fits prefer a GENIE empirical cross section shape.
- RPA CCQE:
  - The 2018 T2K fit and MiniBooNE CCQELike fit wants to lessen the effect by 22% and strengthen by 16%, respectively.
- Mean free path of the nucleon:
  - Both want a significant reduction of the mean free path, which translates to more FSI interactions, with values at 22% and 33%, respectively.



2018 T2K 0p cross section as a function of the cosine of the muon angle.

Conclusions

- Neutrino oscillation and cross section experiments need tuned simulations to handle modeling errors.
- Created a theory-driven approach by fitting five parameters to CC0π data.
- Successfully tuned GENIE in NUISANCE using T2K CC0π 2018 published data and MiniBooNE CCQELike data.
    - Tunes appear incompatible using current 5-parameter modeling.



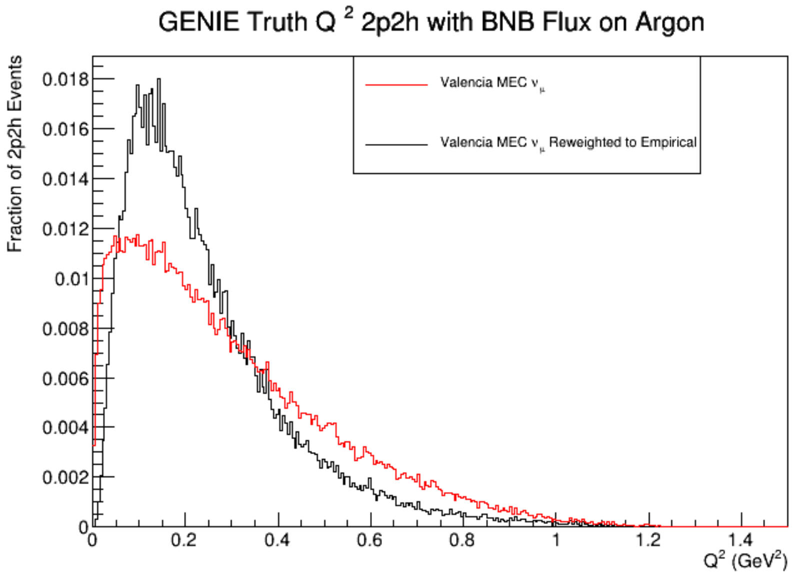
MINERvA STV cross section as a function of muon moment for events with no pions in the final-state.

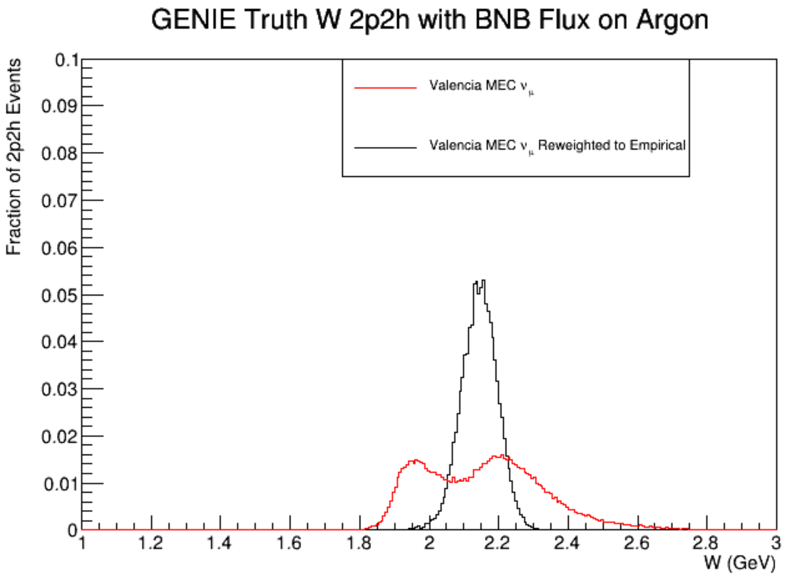
- Currently plan to extend our studies to higher energies (MINERvA and NOvA) and to higher A (MicroBooNE)

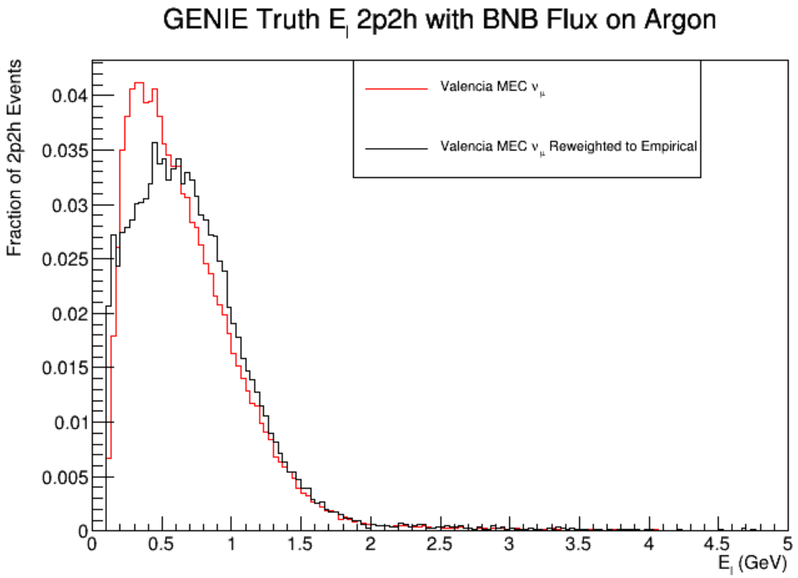
Back-up Slides

2p2h Cross Section Shape Sample Truth Plots

- Empirical and Valencia 2p2h differ in:
  - Momentum transfer (Q)
  - Invariant mass hadronization (W)
  - Lepton energy
  - Lepton angle







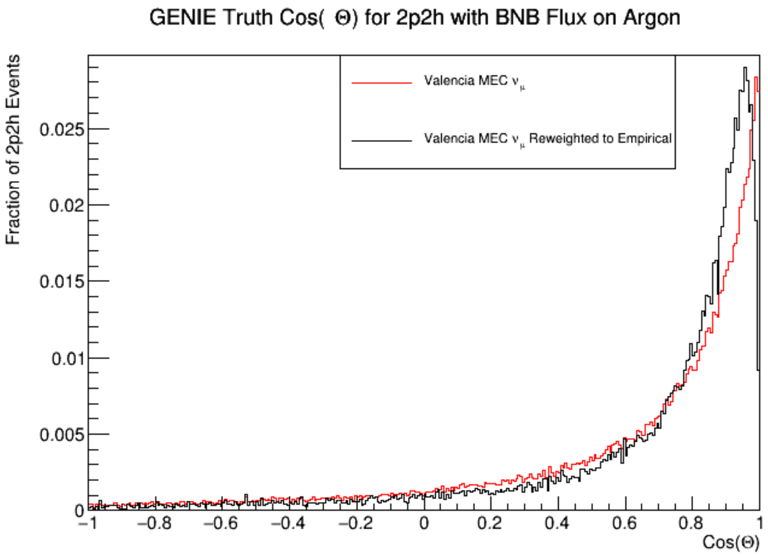


Table of T2K differential cross section binning

T2K 2016 CC0π Cross Section Binning

$\cos\theta_\mu$	p_μ (GeV)	Global bin numbers
-1.00, 0.00	0, 0.3, 0.4, 30	1–3
0.00, 0.60	0, 0.3, 0.4, 0.5, 0.6, 30	4–8
0.60, 0.70	0, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 30	9–15
0.70, 0.80	0, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 30	16–22
0.80, 0.85	0, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 1, 30	23–30
0.85, 0.90	0, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 1, 1.5, 30	31–39
0.90, 0.94	0, 0.4, 0.5, 0.6, 0.7, 0.8, 1.25, 2, 30	40–47
0.94, 0.98	0, 0.4, 0.5, 0.6, 0.7, 0.8, 1, 1.25, 1.5, 2, 3, 30	48–58
0.98, 1.00	0, 0.5, 0.6, 0.7, 0.8, 1.25, 2, 3, 5, 30	59–67

T2K 2018 CC0π(0p,1p) Cross Section Binning

TABLE III. Bins in muon and proton kinematics in which the multidifferential cross section is measured for the 0 proton sample (top) and the 1 proton sample (bottom).

$\cos\theta_\mu$	p_μ (GeV)
−1.0, −0.3	
−0.3, 0.3	0.0, 0.3, 0.4, 30
0.3, 0.6	0.0, 0.3, 0.4, 0.5, 0.6, 30
0.6, 0.7	0.0, 0.3, 0.4, 0.5, 0.6, 30
0.7, 0.8	0.0, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 30
0.8, 0.85	0.0, 0.4, 0.5, 0.6, 0.7, 0.8, 30
0.85, 0.9	0.0, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 1.0, 30
0.9, 0.94	0.0, 0.4, 0.5, 0.6, 0.7, 0.8, 1.25, 30
0.94, 0.98	0.0, 0.4, 0.5, 0.6, 0.7, 0.8, 1.0, 1.25, 1.5, 2.0, 30
0.98, 1.0	0.0, 0.5, 0.65, 0.8, 1.25, 2.0, 3.0, 5.0, 30

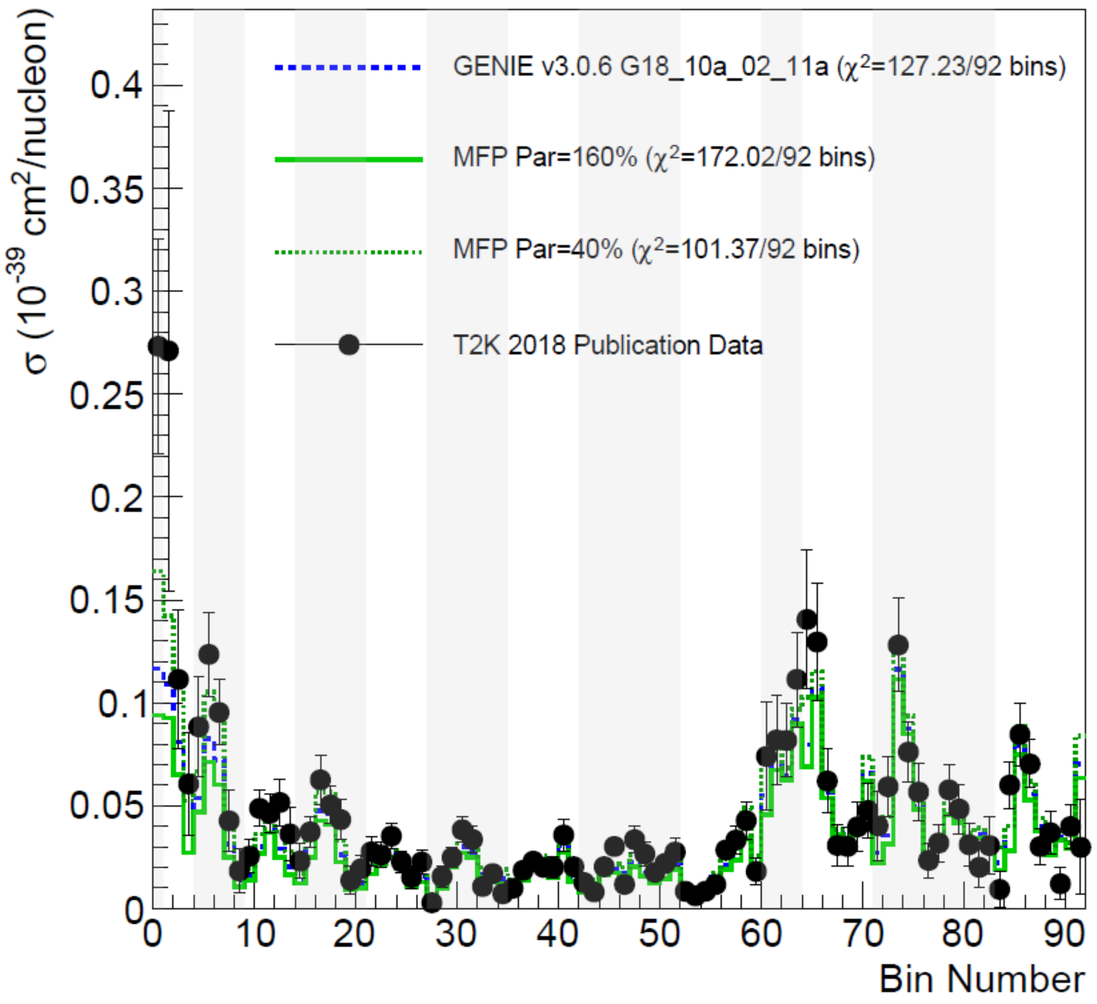
$\cos\theta_\mu$	$\cos\theta_p$	p_p (GeV)
−1.0, −0.3	−1.0, 0.87, 0.94, 0.97, 1.0	
−0.3, 0.3	−1.0, 0.75, 0.85	
	0.85, 0.94	0.5, 0.68, 0.78, 0.9, 30
	0.94, 1.0	
0.3, 0.8	−1.0, 0.3, 0.5	
	0.5, 0.8	0.5, 0.6, 0.7, 0.8, 0.9, 30
	0.8, 1.0	0.5, 0.6, 0.7, 0.8, 1.0, 30
0.8, 1.0	−1.0, 0.0, 0.3	
	0.3, 0.8	0.5, 0.6, 0.7, 0.8, 0.9, 1.1, 30
	0.8, 1.0	

Table of MiniBooNE differential cross section binning

T_μ (GeV) Range	$\cos\theta_\mu$ Range	Global bin numbers
0.2, 0.3	-1.00, 1.00	1–20
0.3, 0.4	-1.00, 1.00	21–40
0.4, 0.5	-0.7, 1.00	41–57
0.5, 0.6	-0.3, 1.00	58-70
0.6, 0.7	-0.2, 1.00	71-82
0.7, 0.8	0.1, 1.00	82-91
0.8, 0.9	0.2, 1.00	92-99
0.9, 1.0	0.4, 1.00	100-105
1.0, 1.1	0.4, 1.00	106-111
1.1, 1.2	0.5, 1.00	112-116
1.2, 1.3	0.5, 1.00	117-121
1.3, 1.4	0.6, 1.00	122-125
1.4, 1.5	0.7, 1.00	126-128
1.5, 1.6	0.7, 1.00	129-131
1.6, 1.7	0.8, 1.00	132-133
1.7, 1.8	0.8, 1.00	134-135
1.8, 1.9	0.9, 1.00	136
1.9, 2.0	0.9, 1.00	137

Global bin numbers for slices of muon kinetic energy with the range of the cosine of the muon angle. Each global bin is a slice of 0.1 GeV and 0.1 of the cosine of the angle.

Mean Free Path Reweighting



0p and 1p T2K 2018 cross section data plotted with global bin (left).

1p data as a function by cosine muon angle (bottom).