MicroBooNE CC0π Tuning

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NuXTract - NuSTEC Workshop - CERN

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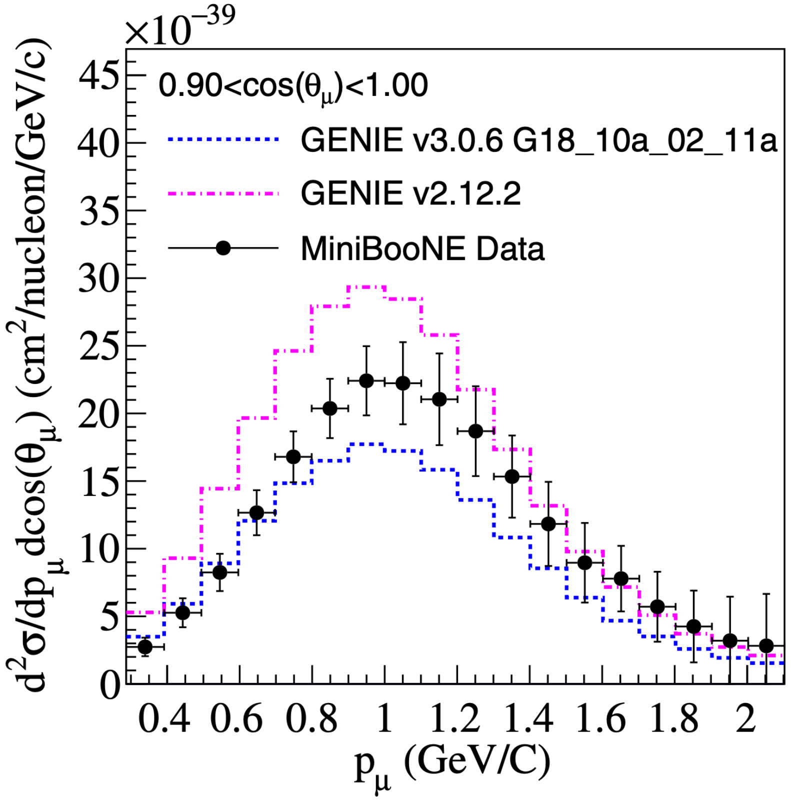
Motivation for MicroBooNE GENIE Tune

- MicroBooNE physics goals include search for Low-Energy Excess in ν_e events and cross section measurements
- Initial MicroBooNE cross section measurements utilized GENIE v2.12.2 to model interactions
- Interaction models were good enough to make measurements without significant biases
- Updated GENIE v3 models show improvement when compared with MiniBooNE data, but still have some deficiencies



Phys. Rev. D 81, 092005 (2010), arXiv:1002.2680 [hep-ex].

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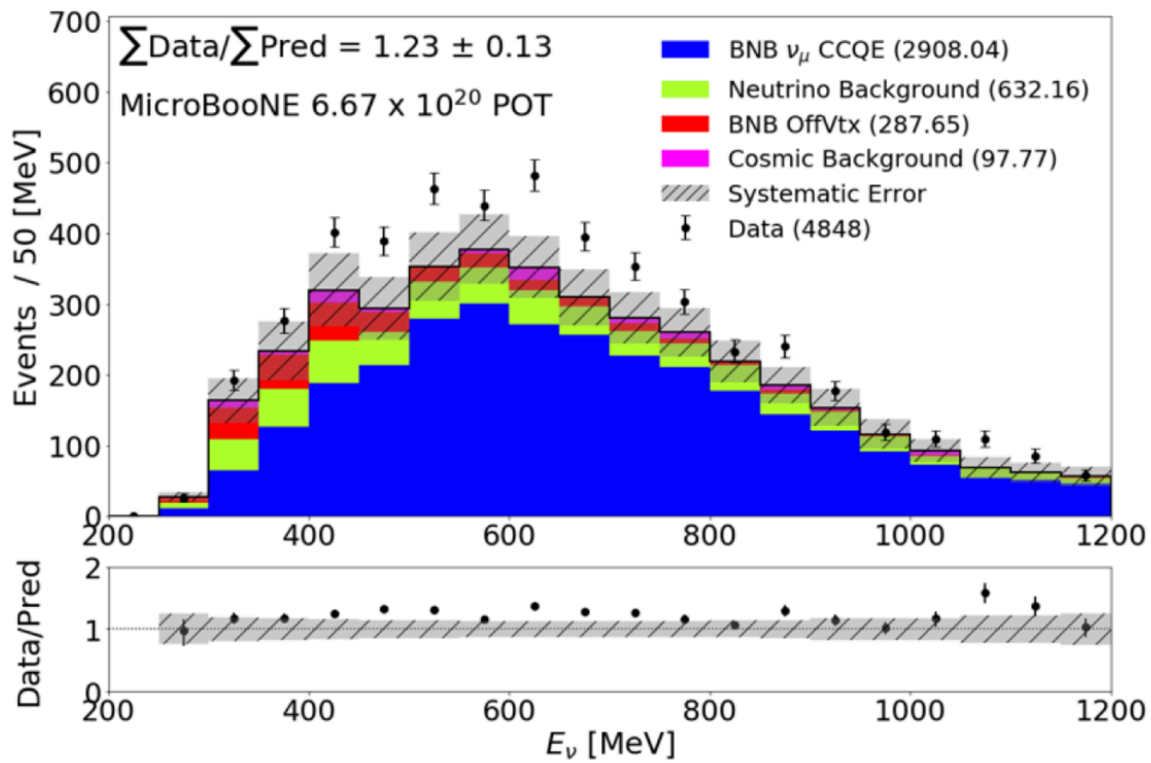
Motivation for MicroBooNE GENIE Tune

- Low-Energy Excess searches utilize three important tools
  - selection focused on low-energy ν_e candidates
  - exclusive selection focuses on CCQE and CC2p2h energy region
  - ν_μ sideband regions constraints

MicroBooNE 1e1p Deep Learning LEE Search



Reconstructed E_ν in 1u1p sideband sample

Phys. Rev. D105, 112003 (2022)

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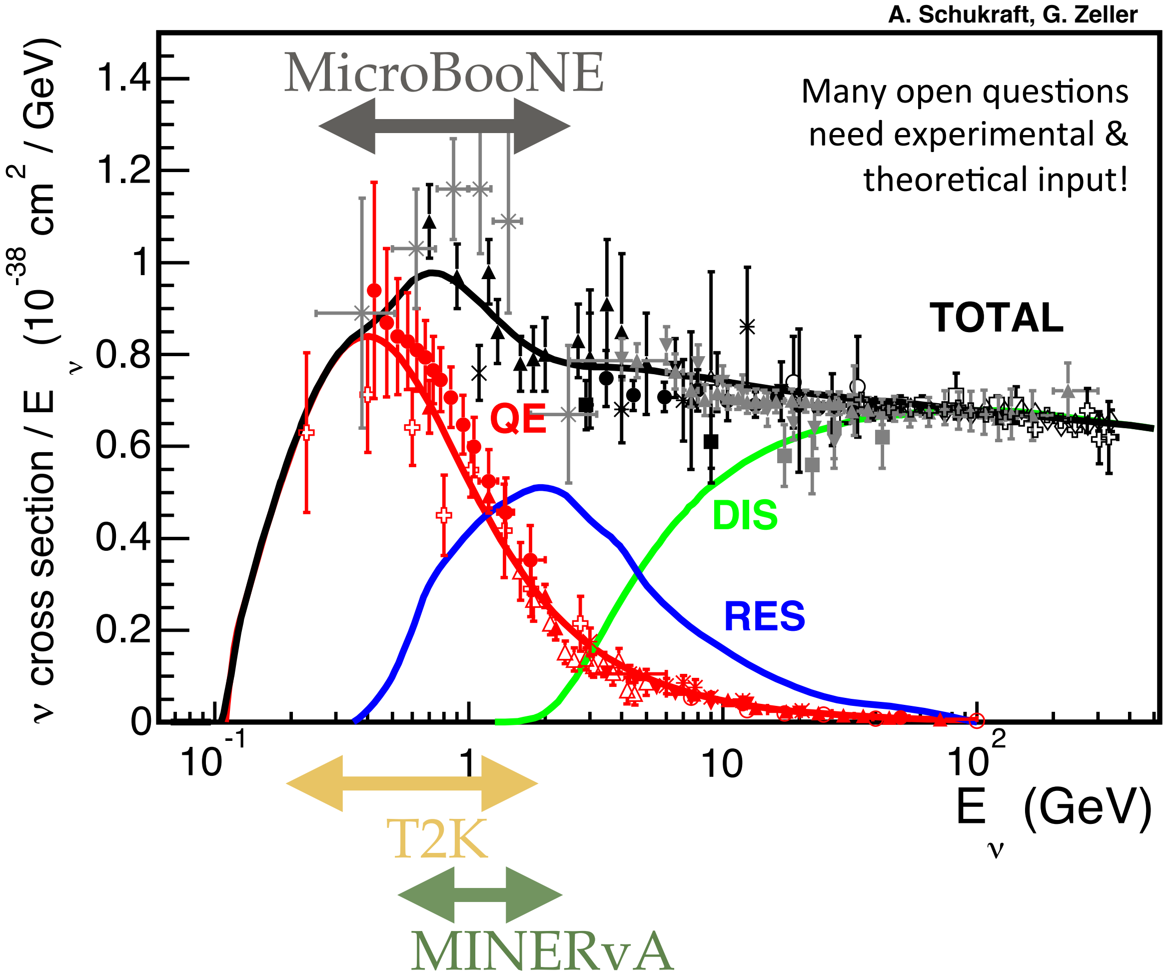
How to tune interaction models?

- largest discrepancy in GENIE v2 based measurements at low visible energy
  - mostly CCQE and CC2p2h
- nature of LEE searches have dominate backgrounds from CCQE and CC2p2h
- LEE analyses were using ν_μ sidebands for constraint, so can't double count by tuning to MicroBooNE data
- considerable datasets from MINERvA, but higher beam energy with different contributions of CCQE, CC2p2h, RES, and DIS
- T2K beam has most similar energy profile and pion-less cross section measurements available



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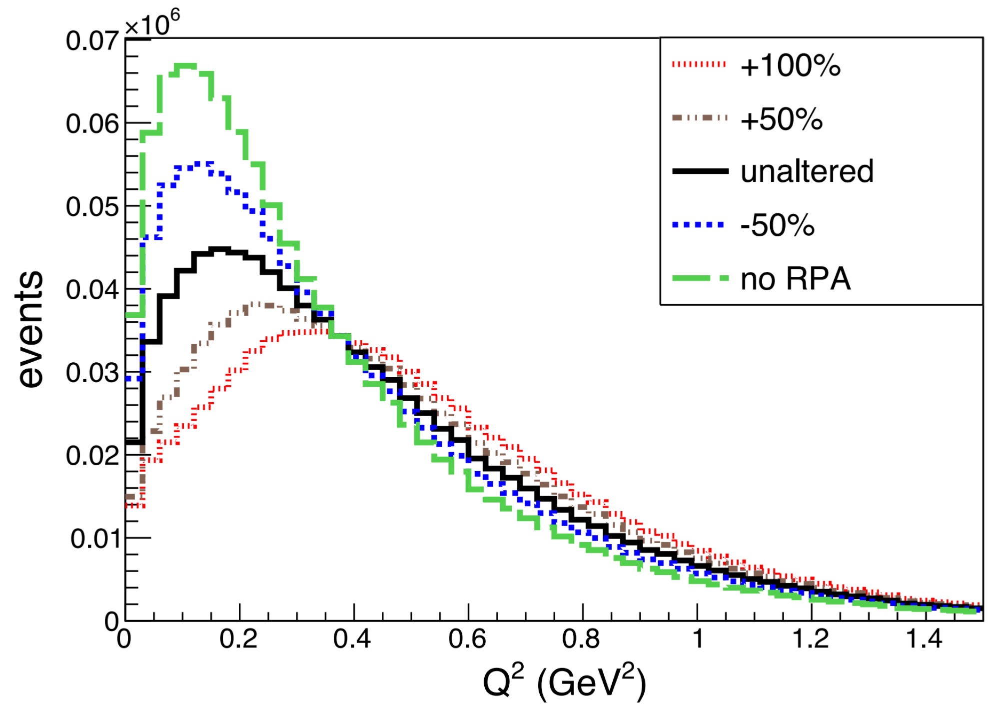
What to tune?

- GENIE v3 G18_10a_02_11a model chosen for central model - updated with (at the time 2020) new models from Valencia Group for CCQE and CC2p2h
- for each model, look to fit the shape and normalization of each to data
- CCQE - Axial mass in the dipole form factor (norm and Q^2 shape), Valencia RPA correction (Q^2 shape)
- CC2p2h - direct absolute normalization and Q^2 shape variation between Valenica and GENIE Emperical
- some parameters avoided
    - FSI parameters associated with proton production
    - Fermi momentum - neutrino data doesn't serve as good of a constraint as electron scattering

Q^2 variation for different RPA correction strengths



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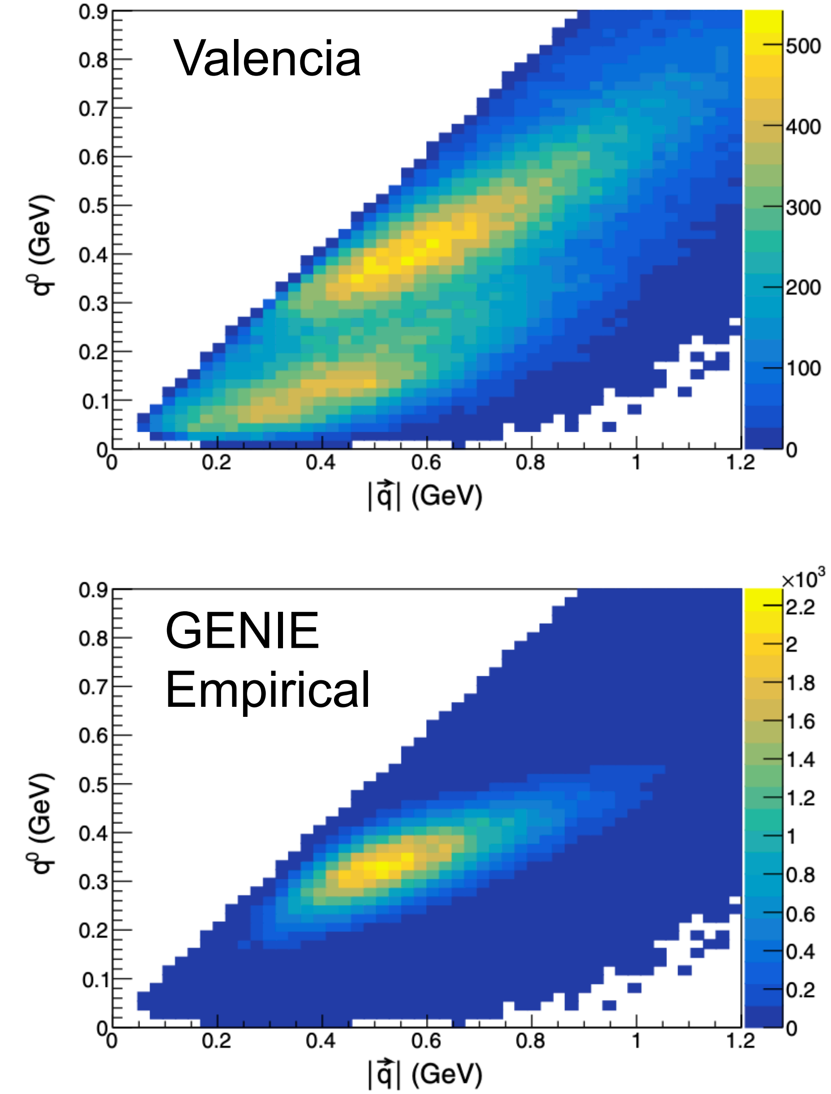
<u>CC2p2h Models</u>
Energy transfer vs |momentum transfer|



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Tune parameters and variations

	Default GENIE v3 value	Variation	effect
M_A CCQE	0.961242 GeV	free	normalization and Q^2 shape CCQE
Valencia RPA Correction	100%	free	normalization and Q^2 shape CCQE
CC2p2h Normalization	1	free	normalization CC2p2h
mixture of Valencia and Empriical	0 (Valencia)	0 to 1 (1 = Empirical GENIE)	shape CC2p2h

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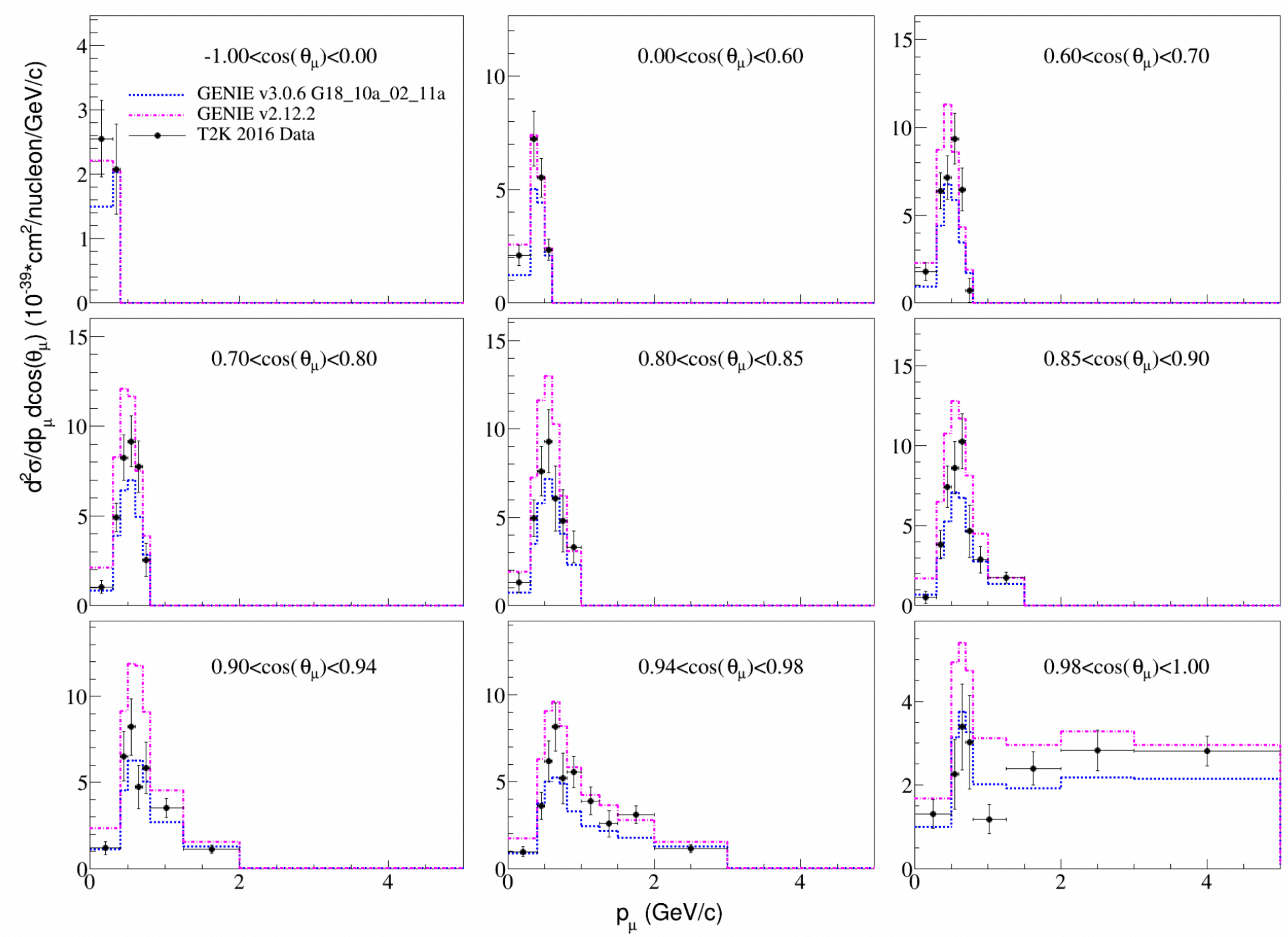
Fit to T2K data

- published CC0π cross-section data - Phys. Rev. D **93**, 112012 (2016)
- binned likelihood fit performed in four signal and two control regions
- 2D differential cross section in muon momentum and angle
- reweighting performed using GENIE reweighting package v1.0.4
- excluded highest muon momentum bin
    - 67 bins -> 58 bins
    - small cross sections and small absolute uncertainties were driving fit results
    - high momentum muons are not a significant part of MicroBooNE dataset
- only diagonal terms from covariance matrix to avoid unphysical results



GENIE v3.0.6 G18_10a_02_11a 115.31/67 bins
GENIE v2.12.1 284.31/67 bins
MicroBooNE Tune 63.77/67 bins

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Final MicroBooNE Tune parameters

	MaCCQE fitted value	CC2p2h Norm. fitted value	CCQE RPA Strength fitted value	CC2p2h Shape fitted value	T2K $\chi^2_{\text{diag}}/\text{N}_{\text{bins}}$
Nominal (untuned)	0.961242 GeV	1	100%	0	106.7/58
Fit MaCCQE + CC2p2h Norm.	1.14 ± 0.07 GeV	1.61 ± 0.19	100% (fixed)	0 (fixed)	71.8/58
Fit MaCCQE + CC2p2h Norm + CCQE RPA Strength	1.18 ± 0.08 GeV	1.12 ± 0.38	$(64 \pm 23)\%$	0 (fixed)	69.7/58
Fit MaCCQE + CC2p2h Norm + CCQE RPA Strength + CC2p2h Shape	1.10 ± 0.07 GeV	1.66 ± 0.19	$(85 \pm 20)\%$	$1^{+0}_{-0.74}$	52.5/58

- important cross check is stability of the result when allowing for greater fit variables
- uncertainties shown are post-fit given by MINUIT
- incorporated into MicroBooNE analyses uncertainties

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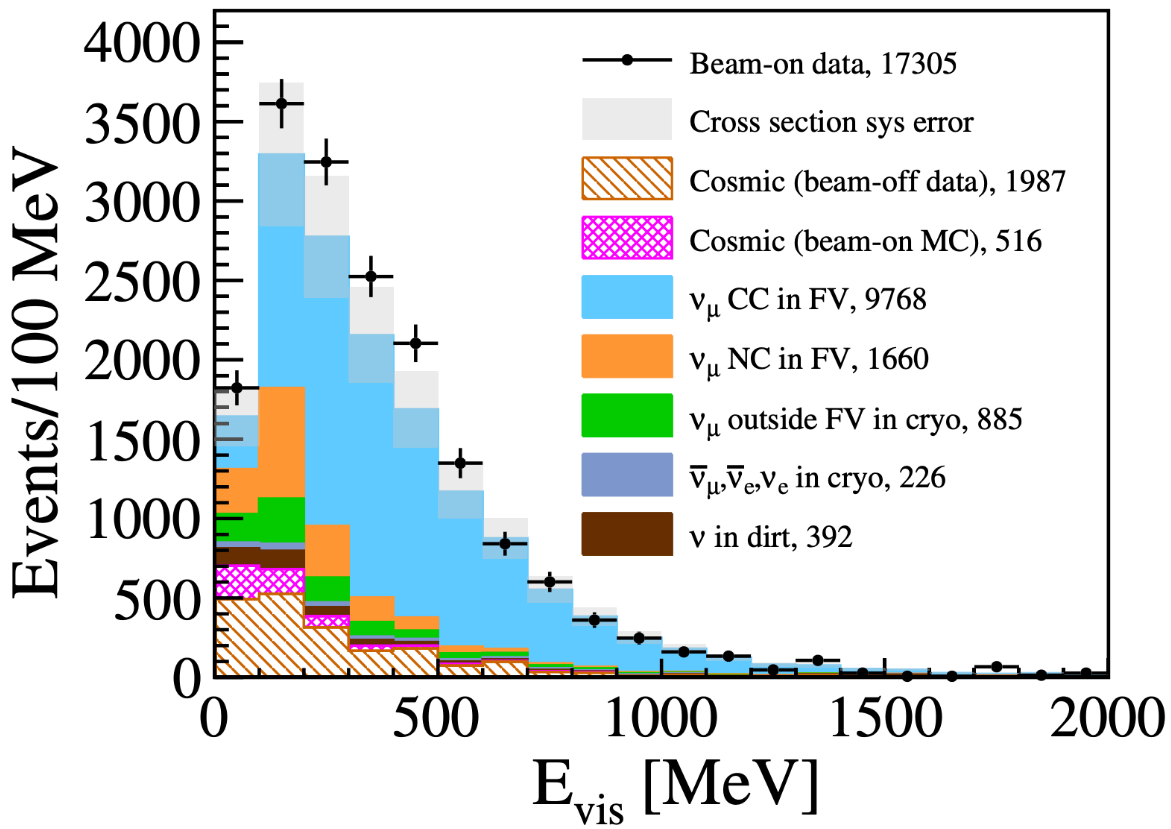
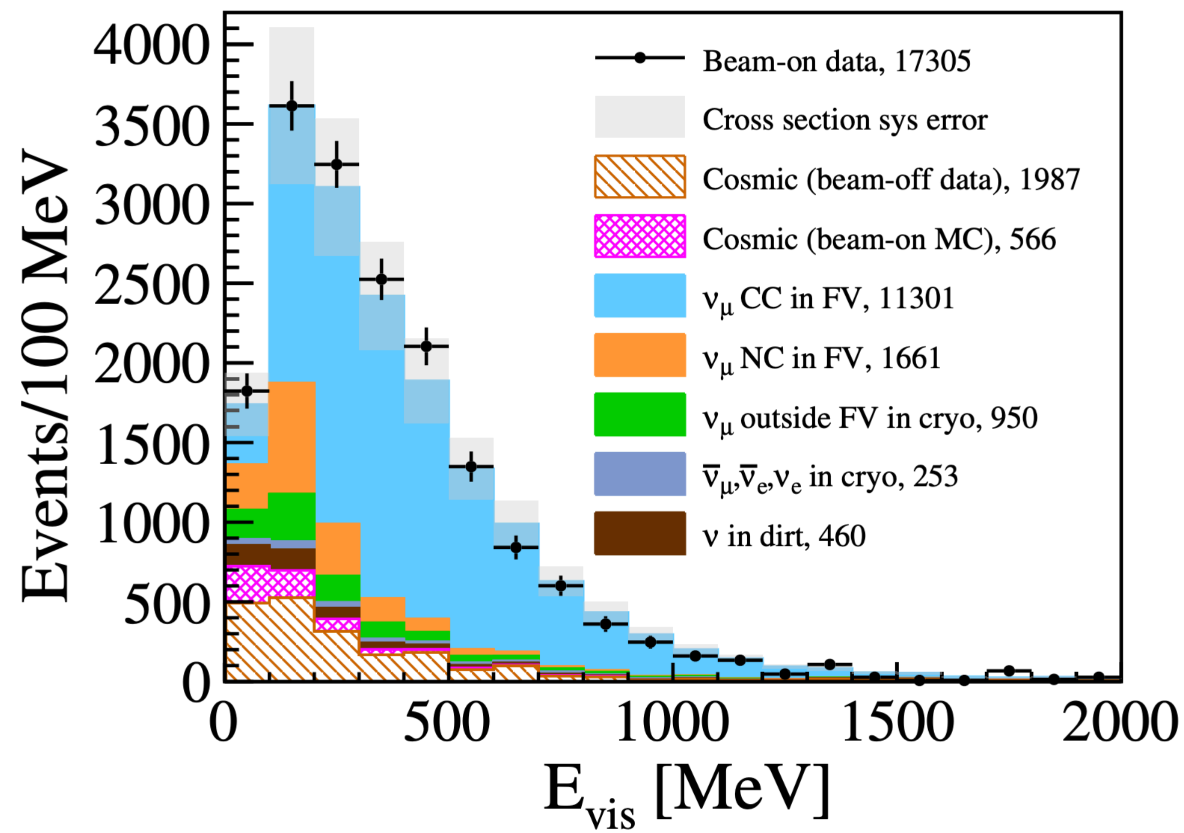
Updated MicroBooNE Model results - Visible Energy in Inclusive ν_μ Selection



Default GENIE v3 G18_10a_02_11a



MicroBooNE GENIE v3 Tune

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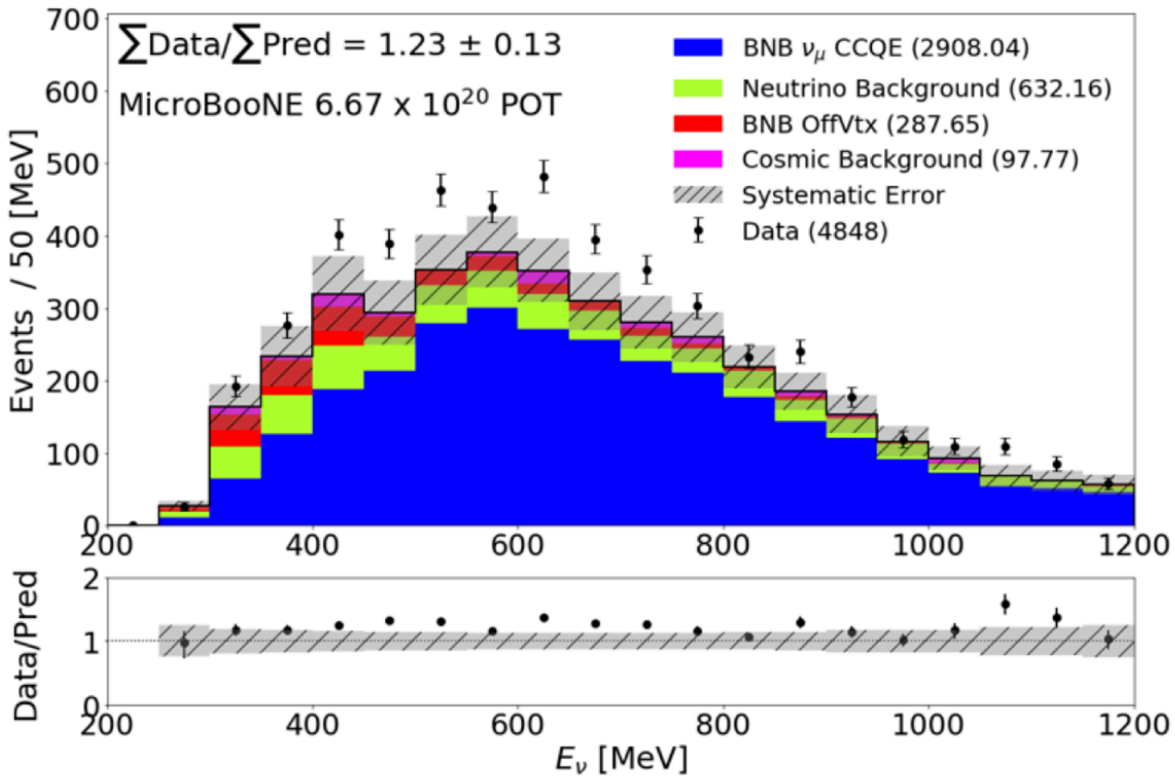
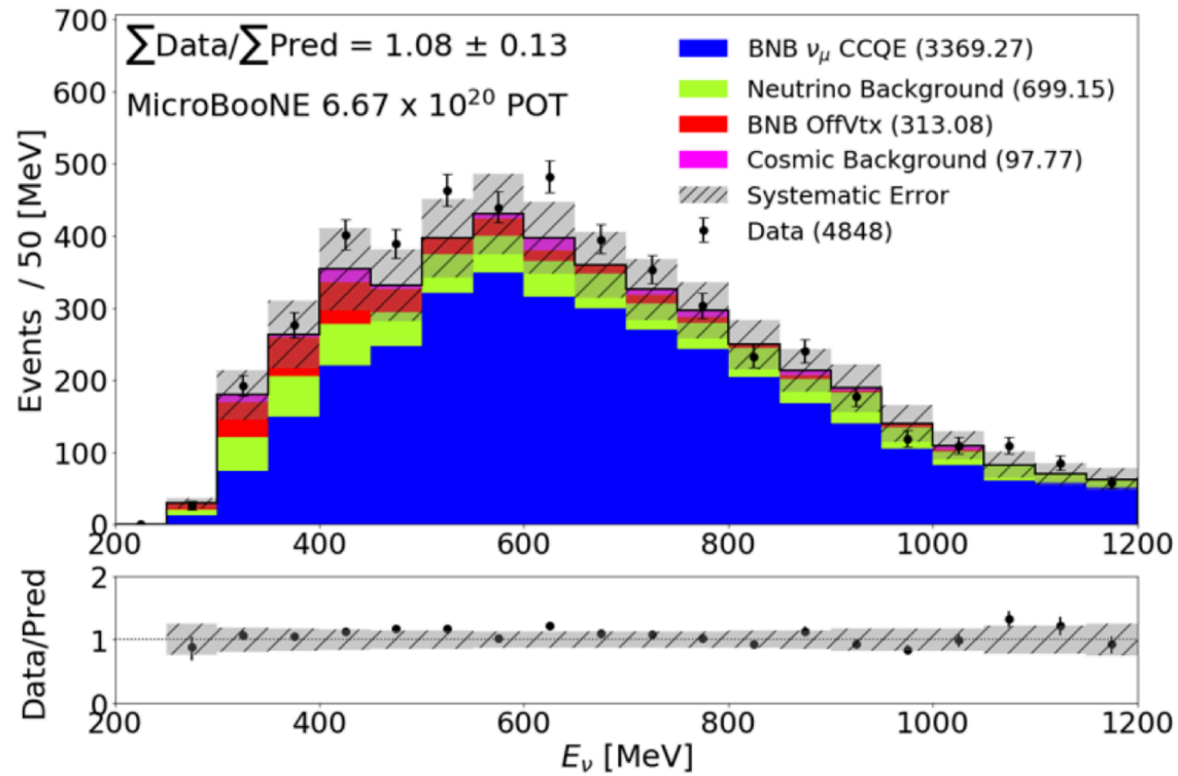
Phys. Rev. Applied 15, 064071 (2021)

Updated MicroBooNE Model results - Reco Neutrino Energy - ν_μ 1μ1p Selection



Default GENIE v3 G18_10a_02_11a



MicroBooNE GENIE v3 Tune

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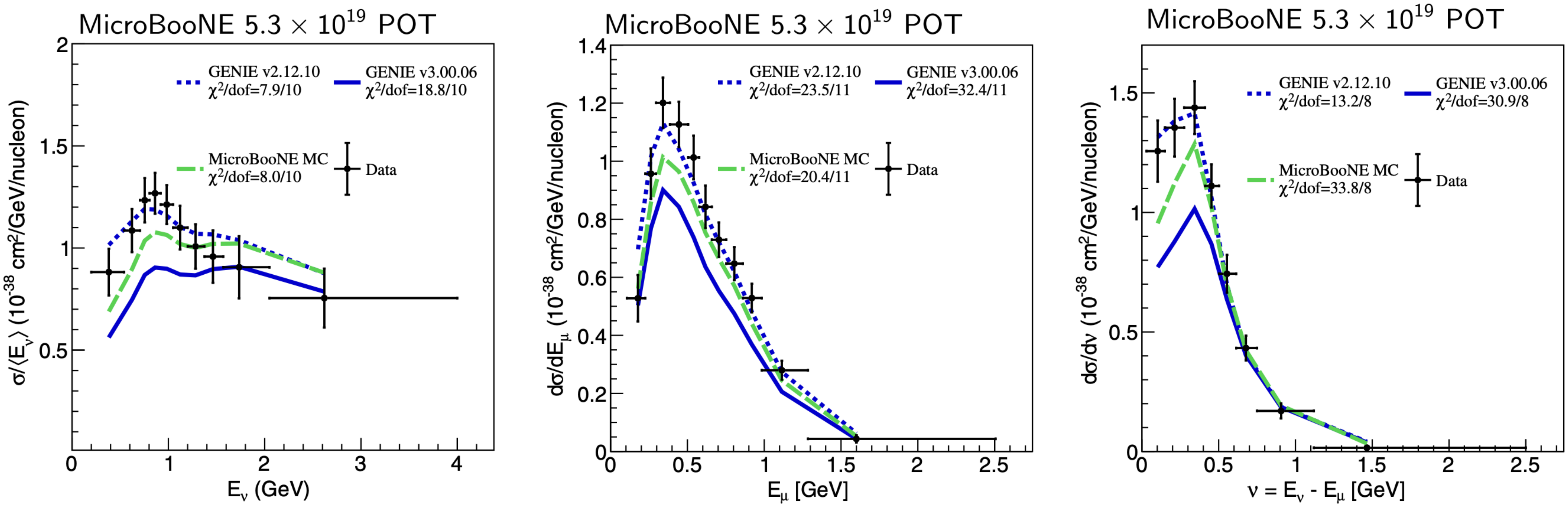
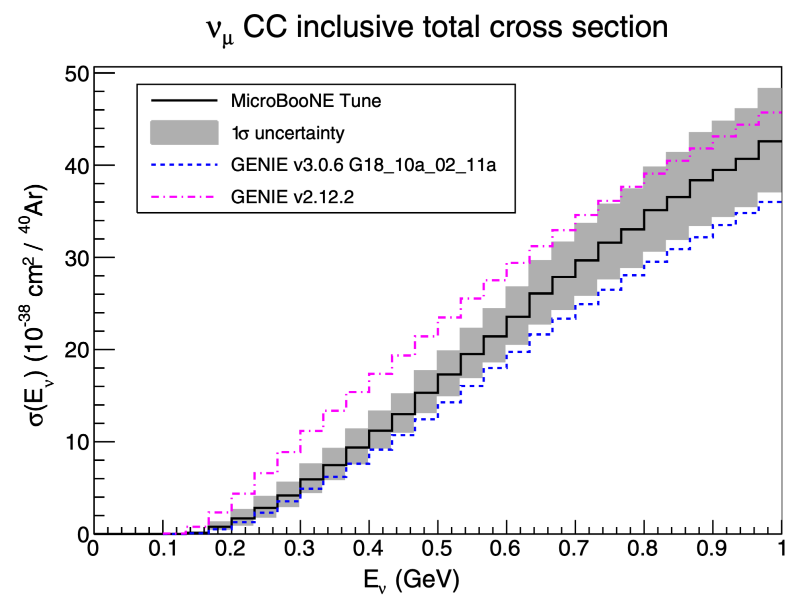
Updated MicroBooNE Model results - Inclusive CC ν_μ

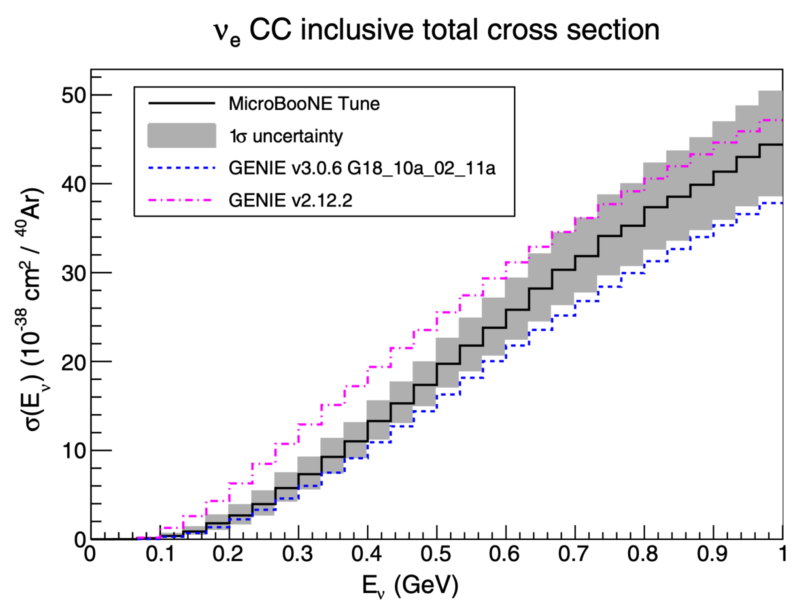


[Phys. Rev. Lett. 128, 151801 (2022)]

MicroBooNE Tune Uncertainty

	"MicroBooNE tune"		
Parameter	Central value	$+1\sigma$	-1σ
MaCCQE[a]	1.10 GeV	+0.1 GeV	−0.1 GeV
RPA_CCQE[b]	85%	+40%	−40%
Normccmec	166%	+50%	−50%
XSecShape_CCMEC	Empirical[c]	N/A	Valencia[d]
Coulomb_CCQE	Nominal	+30%	−30%
DecayAngMEC	Isotropic	Alternative[e]	N/A
FracPN_CCMEC	Valencia	+20%	−20%
FracDelta_CCMEC	Valencia	+30%	−30%
NormNCMEC	Nominal	+100%	−100%
ThetaDelta2NRad	Isotropic	Alternative[e]	N/A
NormCCCOH	Nominal	+100%	−100%
NormNCCOH	Nominal	+100%	−100%





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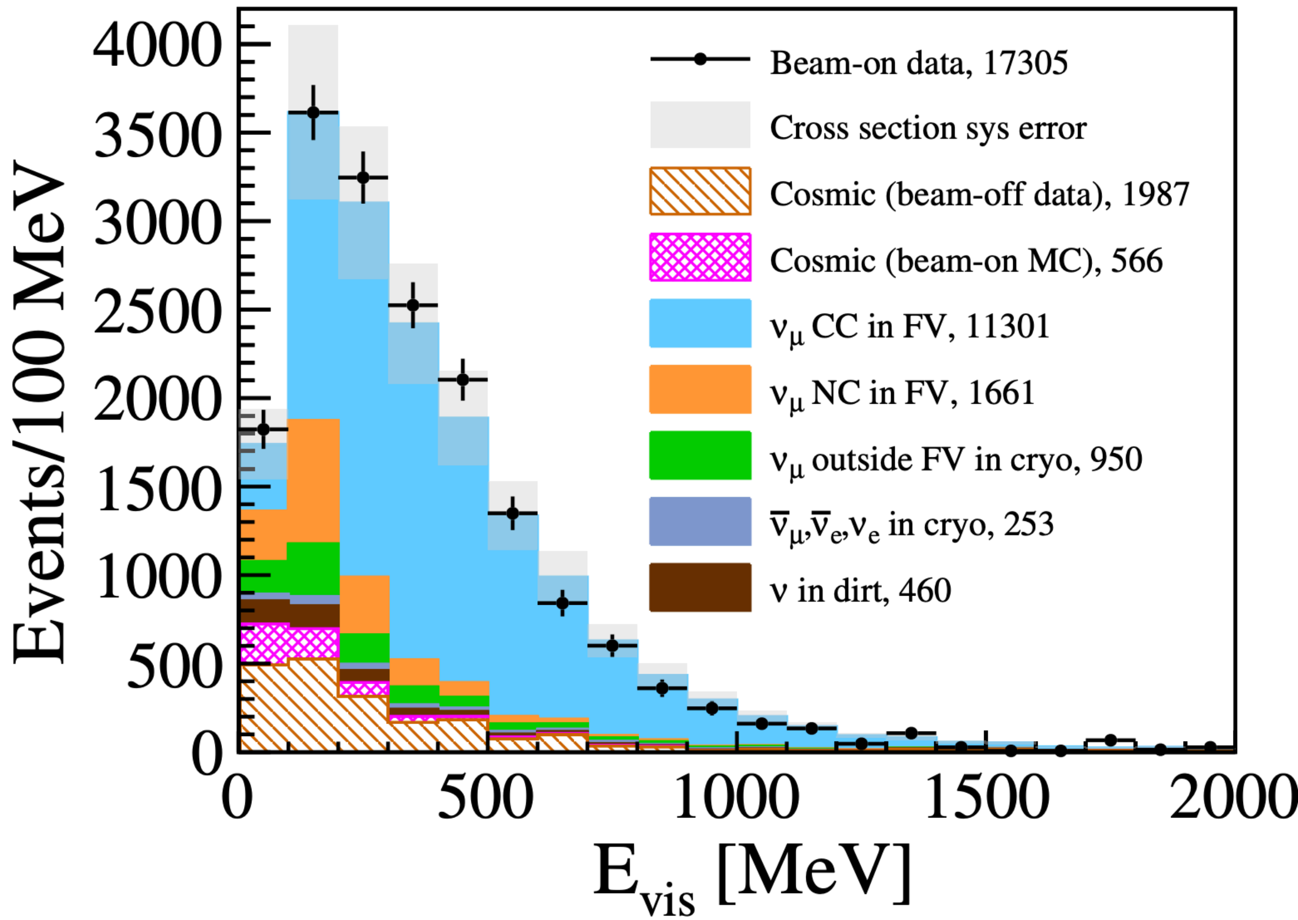
Summary

- **"New CC 0π GENIE model tune for MicroBooNE" Phys. Rev. D 105 (2022) 7, 072001**
- Tuned GENIE v3 with T2K CC0π measurements to produce a theory-motivated tune
- considerable improvement in modeling of CC interactions in MicroBooNE detector
- important development of data driven GENIE interaction uncertainties
- MicroBooNE Tune and uncertainties key component to the initial Low-Energy Excess searches
- Continue to be utilized for additional searches and cross section measurements



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Thank you!

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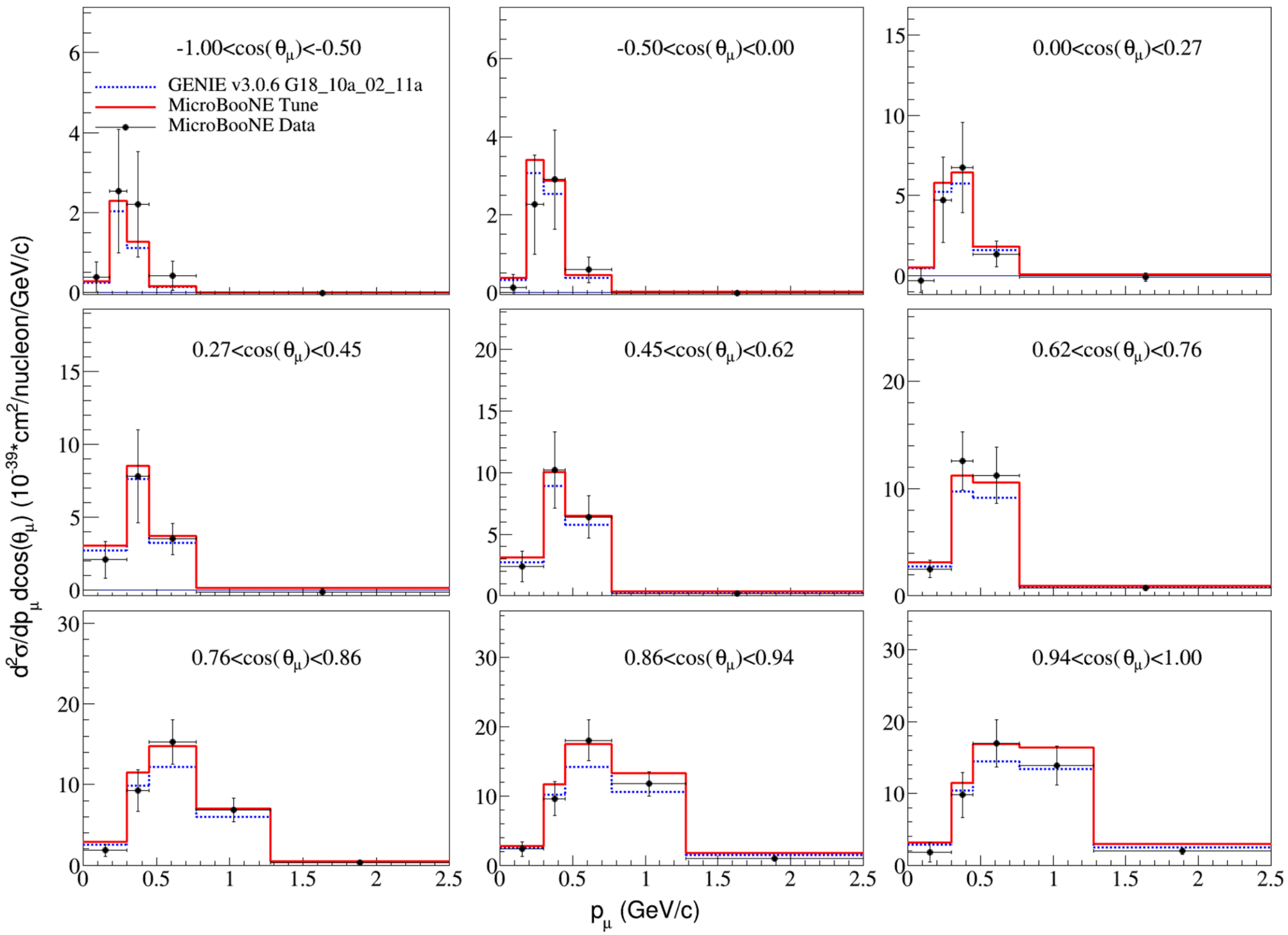
MicroBooNE Tune vs MicroBooNE Data

- flux integrated double differential cross section of inclusive ν_μ CC in muon momentum and angle
- GENIE v3
  (χ^2_{full}/N_{bins} =105.41/42)
- MicroBooNE Tune
  (χ^2_{full}/N_{bins} = 140.55/42)



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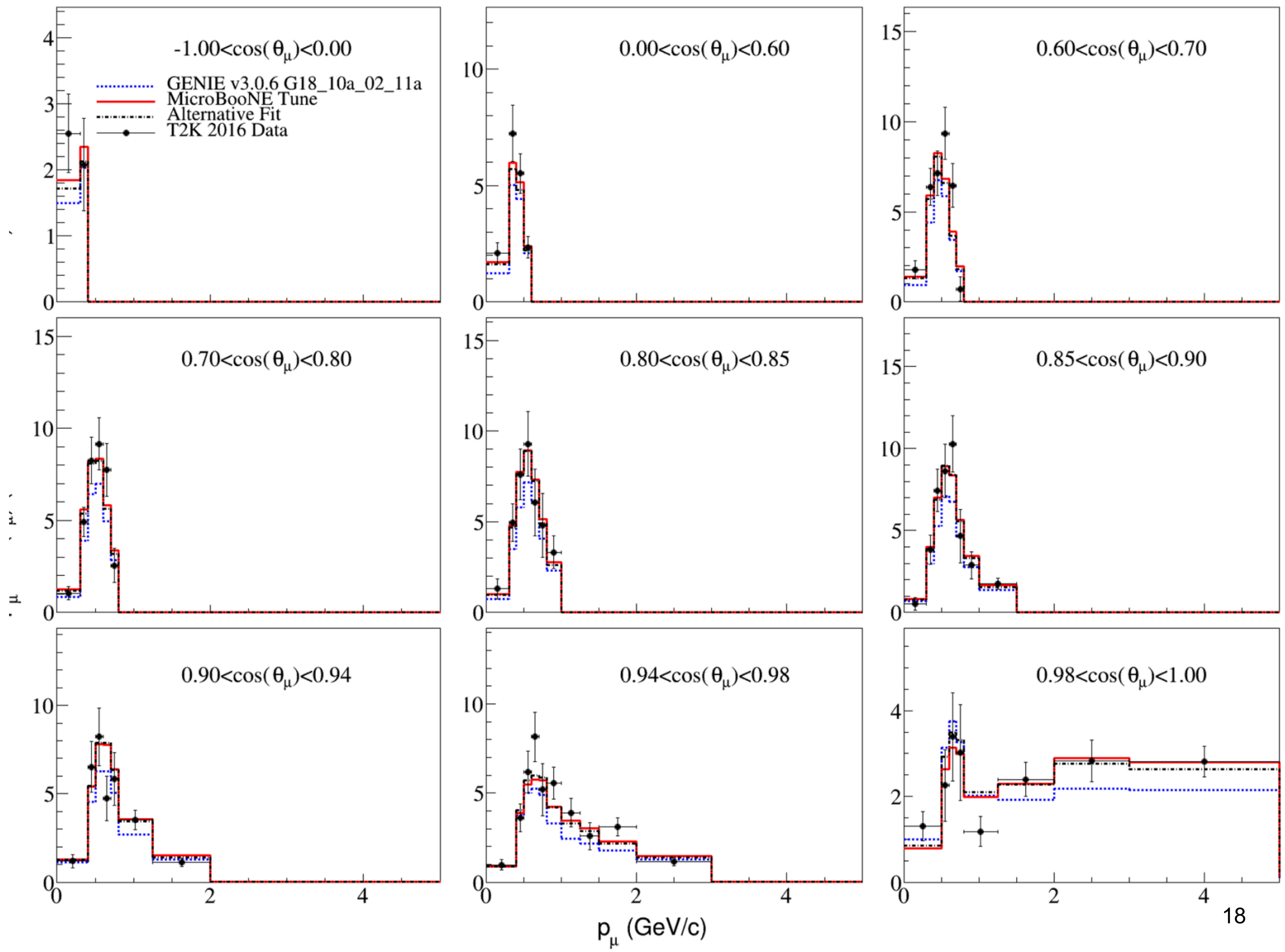
Fit to T2K data - alternate method suggested by Koch

- separate the correlations into normalization and shape components when calculating the χ^2
- shown on the plots as Alternate Fit
- fitted parameters were all within reported MINUIT uncertainties
- two χ^2 varied by less than 10%



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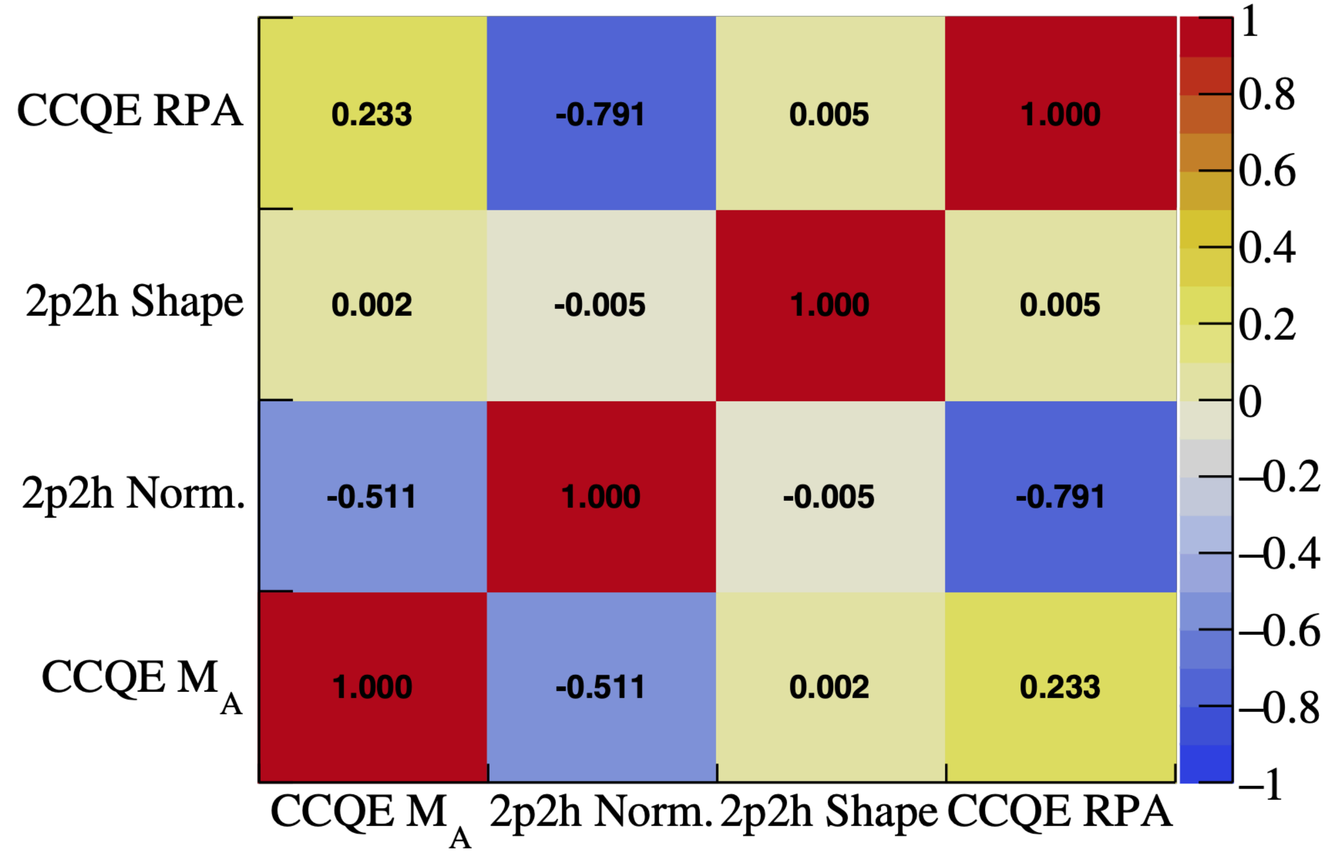
parameter correlation matrix



Alternate fit parameters and chi2

	MaCCQE fitted value	CC2p2h Norm. fitted value	CCQE RPA Strength fitted value	CC2p2h Shape fitted value	T2K $\chi^2_{\text{diag}}/\text{N}_{\text{bins}}$	T2K $\chi^2_{\text{Koch}}/\text{N}_{\text{bins}}$	T2K $\chi^2_{\text{full}}/\text{N}_{\text{bins}}$
Nominal (untuned)	0.961242 GeV	1	100%	0	106.7/58	149.83/58	97.56/58
"MicroBooNE tune"	1.10 ± 0.07 GeV	1.66 ± 0.19	$(85 \pm 20)\%$	$1^{+0}_{-0.74}$	52.5/58	110.58/58	103.84/58
"Alternate fit"	1.04 ± 0.10 GeV	1.44 ± 0.42	$(67 \pm 16)\%$	$0.91^{+0.09}_{-0.18}$	55.51/58	100.59/58	91.68/58

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GENIE v3 model sets

- events produced through several mechanisms
  - Meson Exchange Currents
  - Short Range Nucleon-Nucleon Correlations
  - Final State Interactions
- events generated with GENIE MicroBooNE Tune (G18_10a_02_11a) form base model set for determining efficiency and cross section extraction
  - QE & MEC tuned to external data

GENIE v3.0.6 Model Set	Nuclear Model	Interaction Model	Final State Interactions
MicroBooNE Tune (G18_10a_02_11a)	LFG	Nieves/Valencia (QE+MEC)	hA2018
G18_02a_00_000	RFG	Llewellyn Smith QE + Empirical MEC	hA2018
G18_10a_02_11a	LFG	Nieves/Valencia (QE+MEC)	hA2018
G21_11b_00_000	LFG	SuSAv2 (QE+MEC)	hN2018

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MicroBooNE TUNE Phys. Rev. D105, 072001 (2022)

PRD Publication

Obtaining a high-quality interaction model with associated uncertainties is essential for neutrino experiments. In this talk, we present a tune, as published in Phys. Rev. D 105 (2022) 7, 072001, of the charged-current pionless (CC0π) interaction cross section via the two major contributing theoretical processes—charged-current quasielastic and multinucleon interaction models—within version 3.0.6 of the GENIE neutrino event generator. Four parameters in these models determining normalization and shape are tuned to muon neutrino CC0π cross section data obtained in 2016 by the T2K experiment, which provides an independent set of neutrino interactions with a neutrino flux in a similar energy range to MicroBooNE's neutrino beam. Furthermore, we discuss future plans related to the development of a pi0-based tuned for the next-generation of our results.

Prospects for the future

- several recent differential measurements pion production explore resonant and DIS production models
- is a new tune justified by new CC 2p2h models?
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