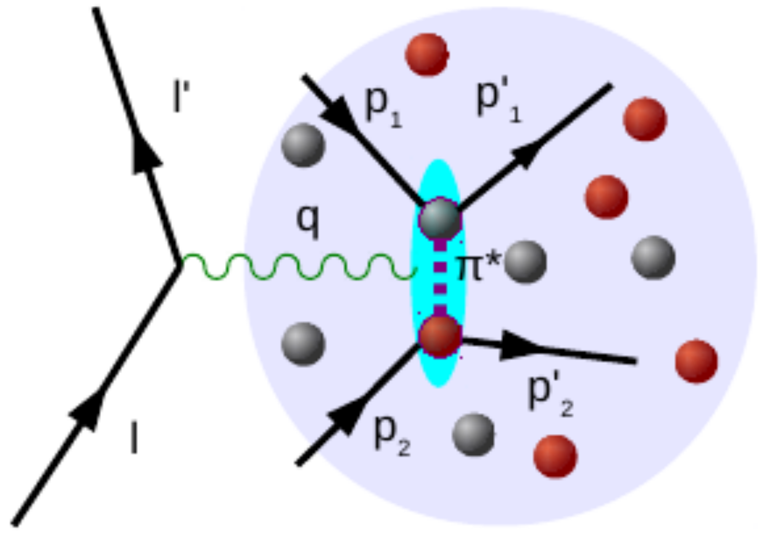
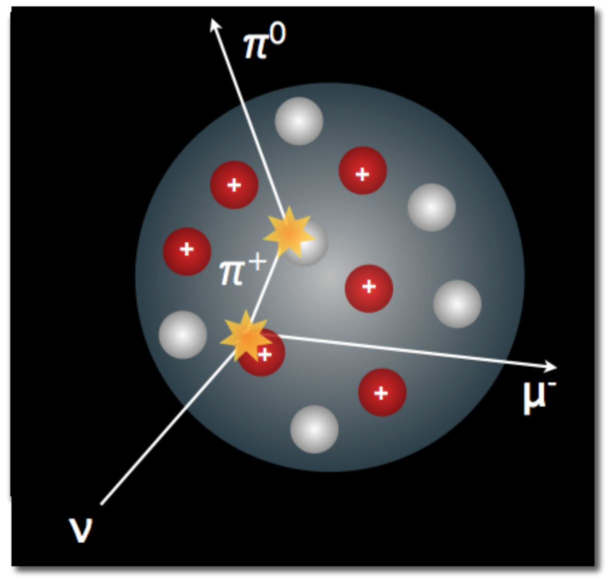
New CC0π GENIE Tune for MicroBooNE

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT





μBooNE

Steven Gardiner

2 February 2022

NuSTEC Cross Theory and Generators Working Group Seminar

Introduction

- Inaugural seminar for NuSTEC CTGWG

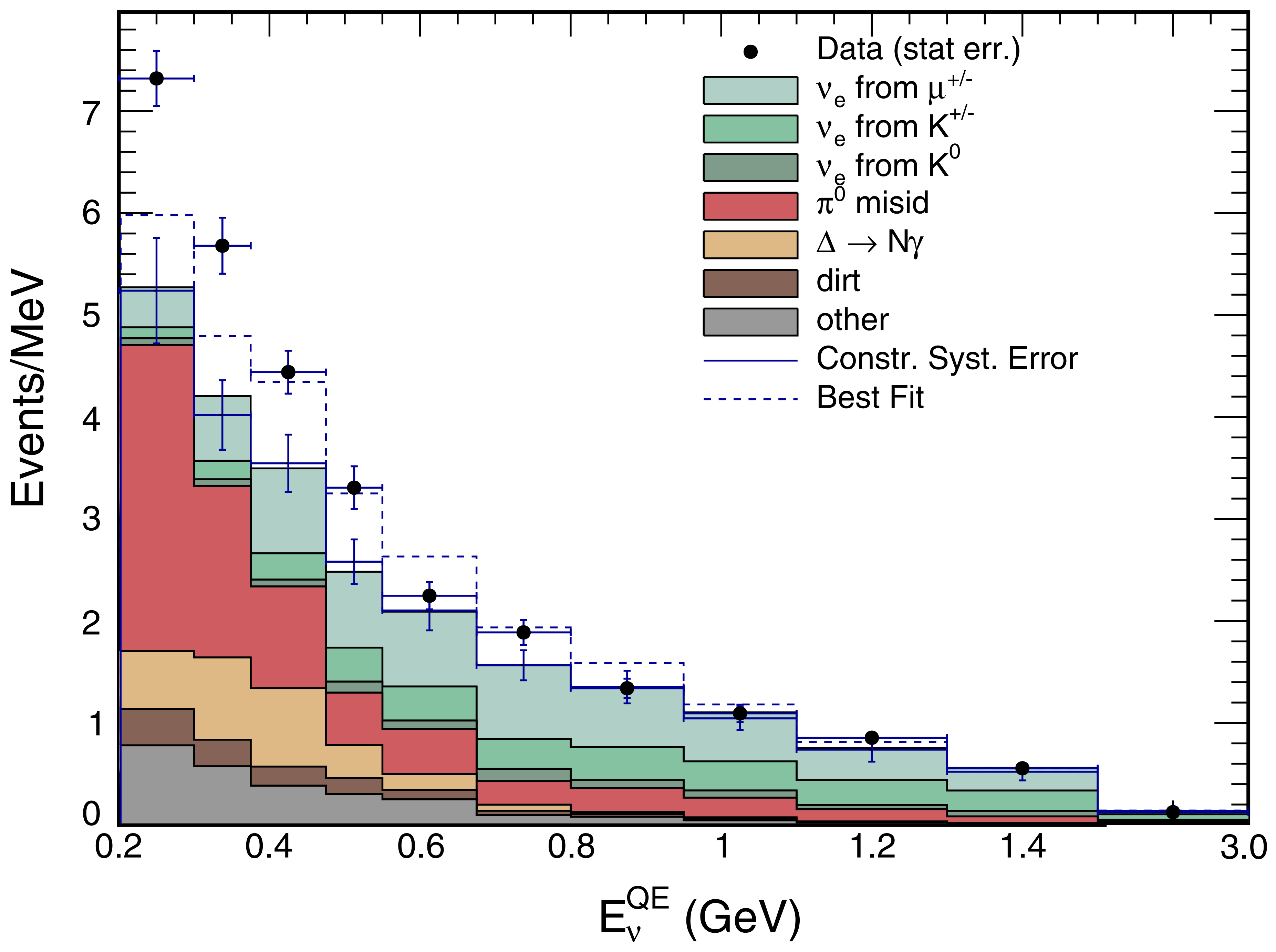
- I'm assuming that my audience
  - Already cares about neutrino cross sections and improving generators
  - Knows about nuclear effects and key terms like CCQE, GENIE, etc.

- This talk will explore the recent "MicroBooNE Tune" of GENIE (**arXiv:2110.14028**)
  - What was tuned and how
  - Connections to tunes by other experiments
  - Lessons learned along the way

The MicroBooNE experiment

- **Liquid argon time projection chamber** (LArTPC) in the Fermilab Booster Neutrino Beam
  - 60-ton active mass
- Investigate an anomaly seen by MiniBooNE in the same beam line
  - **Low Energy Excess** (LEE) of electron-like events
- Neutrino-argon cross-section measurements, BSM searches, detector R&D, etc.
- High-quality interaction modeling critical to a correct interpretation of MicroBooNE data
  - Starting point for further data-driven constraints

MiniBooNE Collaboration, [Phys. Rev. D 103, 052002 (2021)]

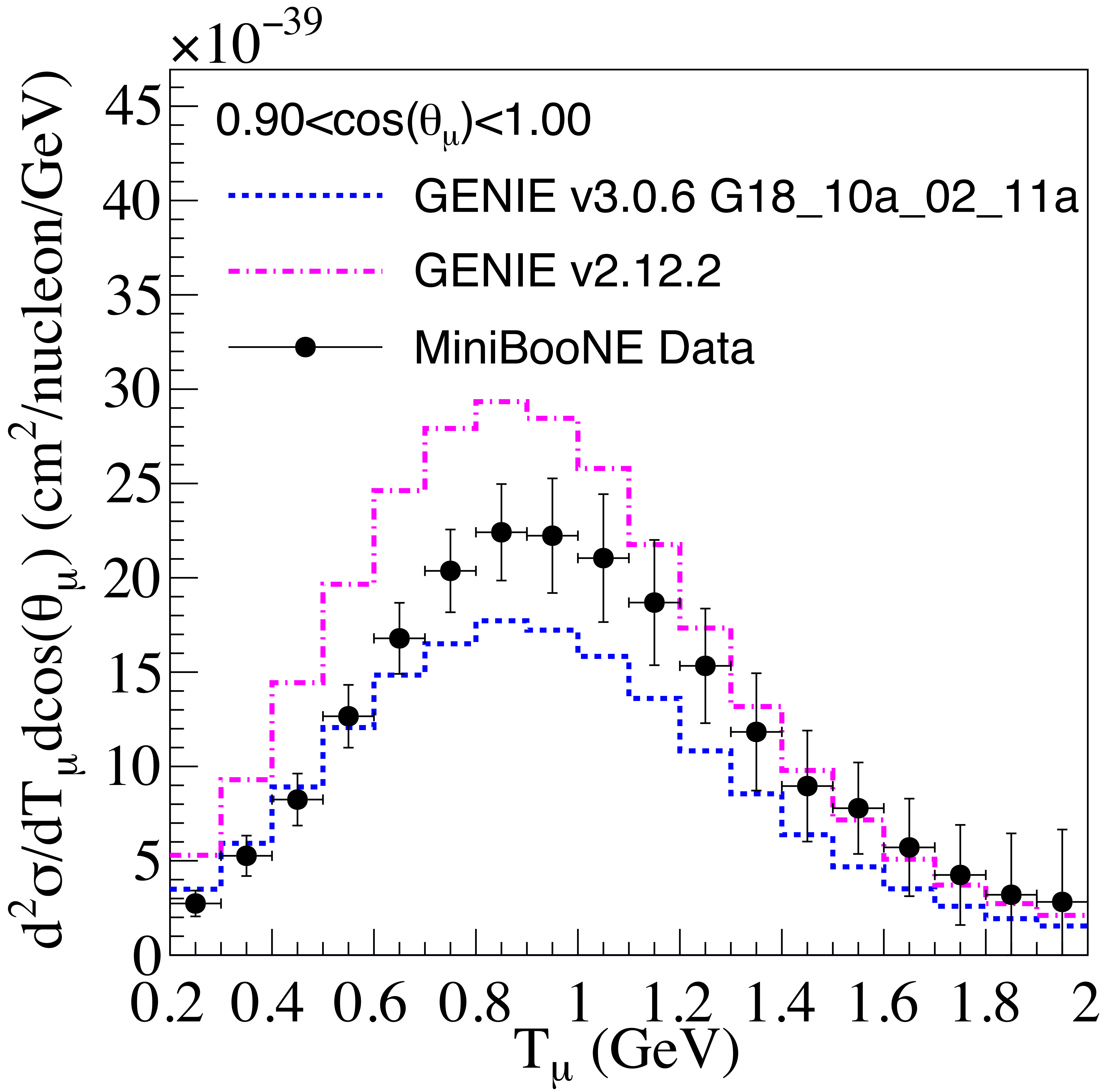


Recent generator tunes by neutrino experiments

- Tunes of GENIE presented by MINERvA, NOvA with some similarities
  - MnvGENIE v1: GENIE v2.8.4 with Valencia-style RPA, 2p2h (with extra tuning), nonresonant pion production down by 43%. **Phys. Rev. D 101, 112007 (2020)**
  - MnvGENIE v2: v1 plus RPA-like suppression of RES at low Q^2
  - NOvA: GENIE v2.12.2 with M_A = 1.04 GeV, MINERvA-style RPA for QE + RES, 57% reduction of nonresonant pion production, Empirical 2p2h with custom (q^0, $|\mathbf{q}|$) weights. **Eur. Phys. J. C 80, 1119 (2020)**
  - Newer NOvA model briefly described in **arXiv:2108.08219**.
- T2K uses a tuned version of NEUT. See **Phys. Rev. D 103, 112008 (2021)**.
- MicroBooNE has recently produced its own tune of GENIE
  - Opportunity to “compare notes” with the community
  - Similar choices, but details and implementation are different
  - Also some takeaways from the experience are worth exploring

Base model set for the tuning effort

- MicroBooNE has adopted the GENIE v3.0.6 G18_10a_02_11a model as a starting point for a dedicated tune
- **10a**: model set with key theory improvements for low energies
  - Local Fermi gas nuclear model
  - Valencia QE + 2p2h
  - Berger-Sehgal RES, Bodek-Yang DIS
  - Updated FSI treatment (hA2018)
- **02_11a**: Parameter tuning performed by GENIE on bubble-chamber data, focus on RES + DIS



MiniBooNE data from Phys. Rev. D 81, 092005 (2010)

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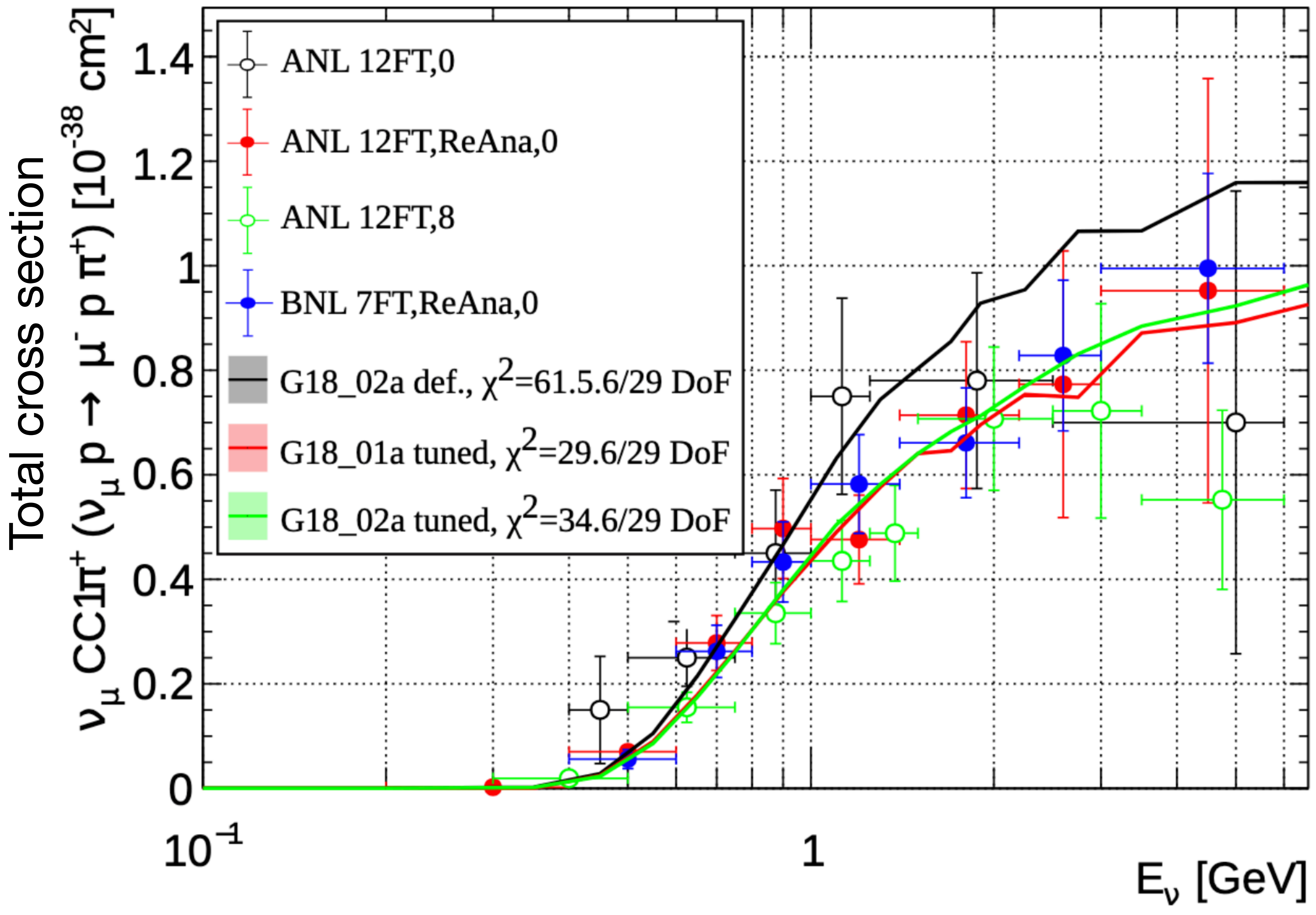
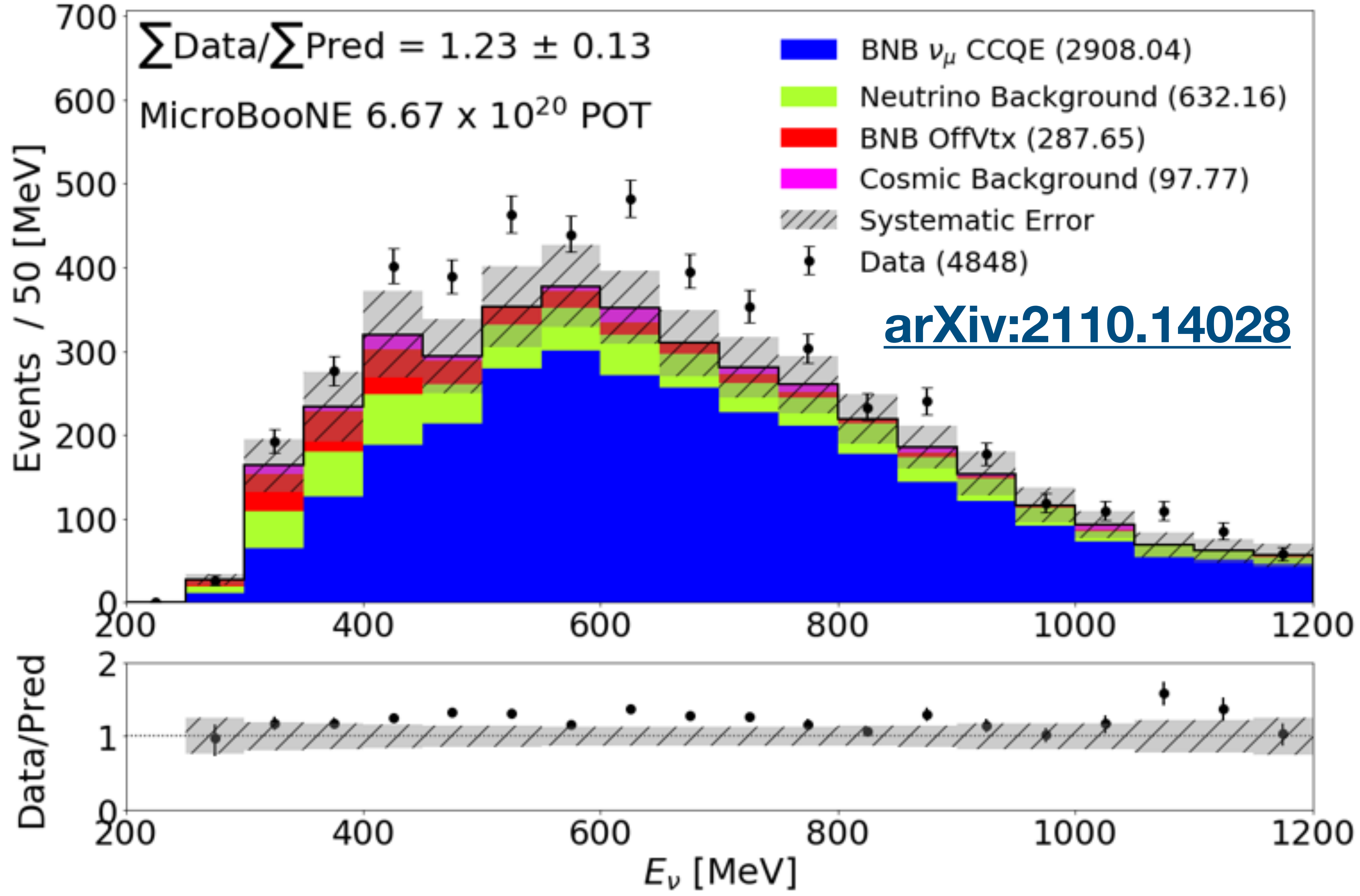
GENIE Collaboration, Phys. Rev. D 104, 072009 (2021)



Motivation for tuning CC0π

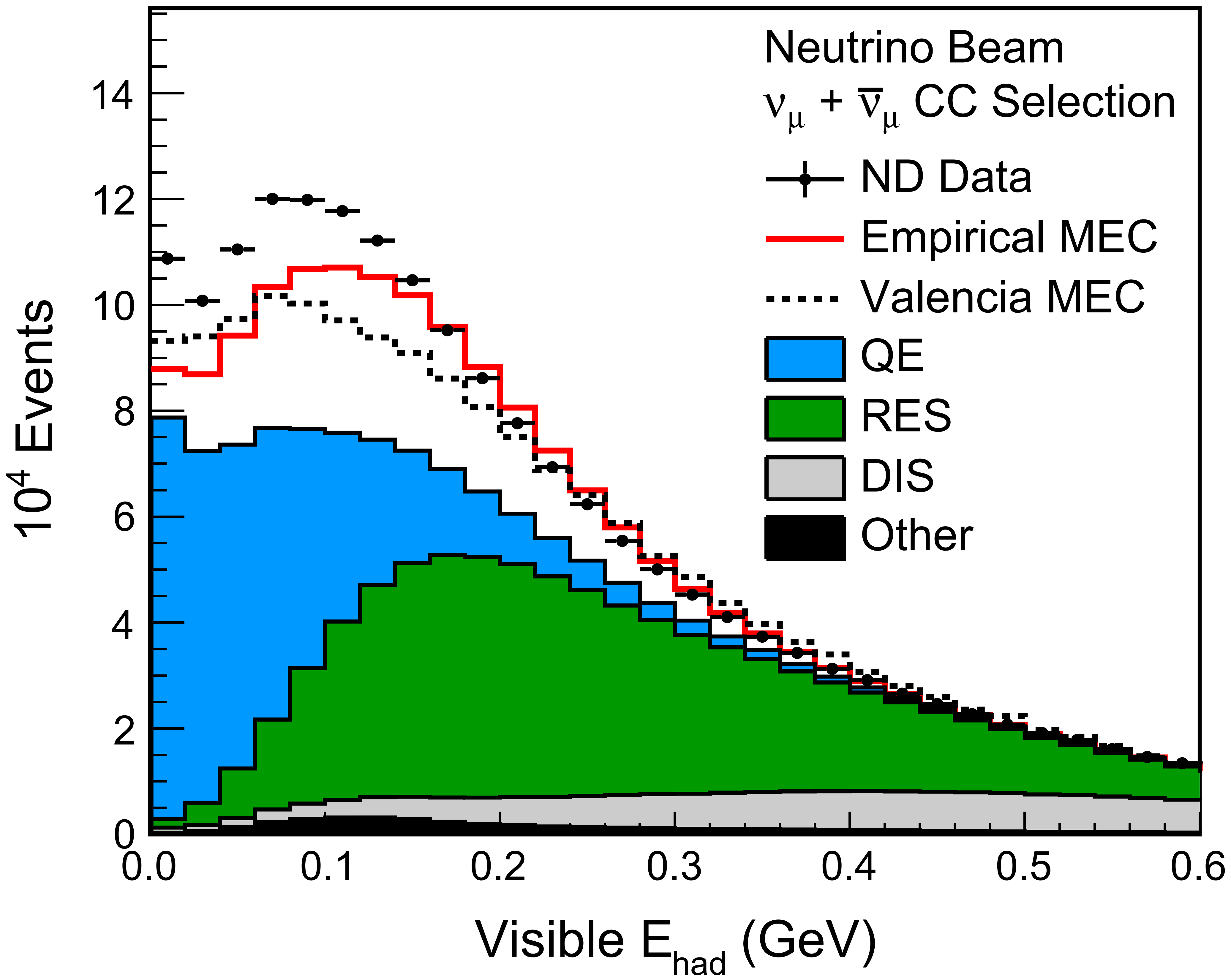
- Consistent deficit seen in many MicroBooNE data/MC comparisons
  - **ν_μ control sample** for CCQE-like LEE analysis

Untuned GENIE v3 model



arXiv:2110.14028

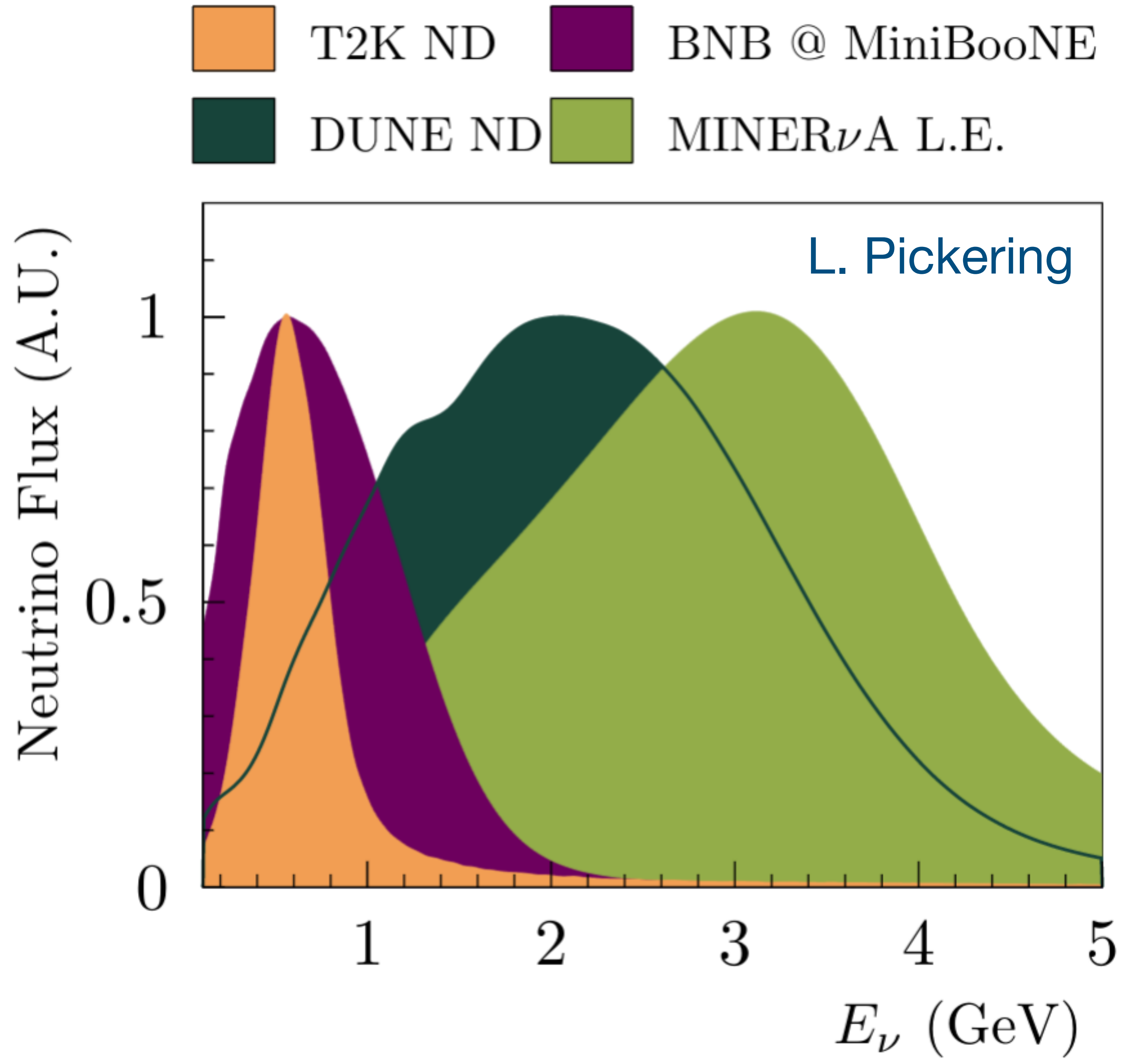
Eur. Phys. J. C 80, 1119 (2020)



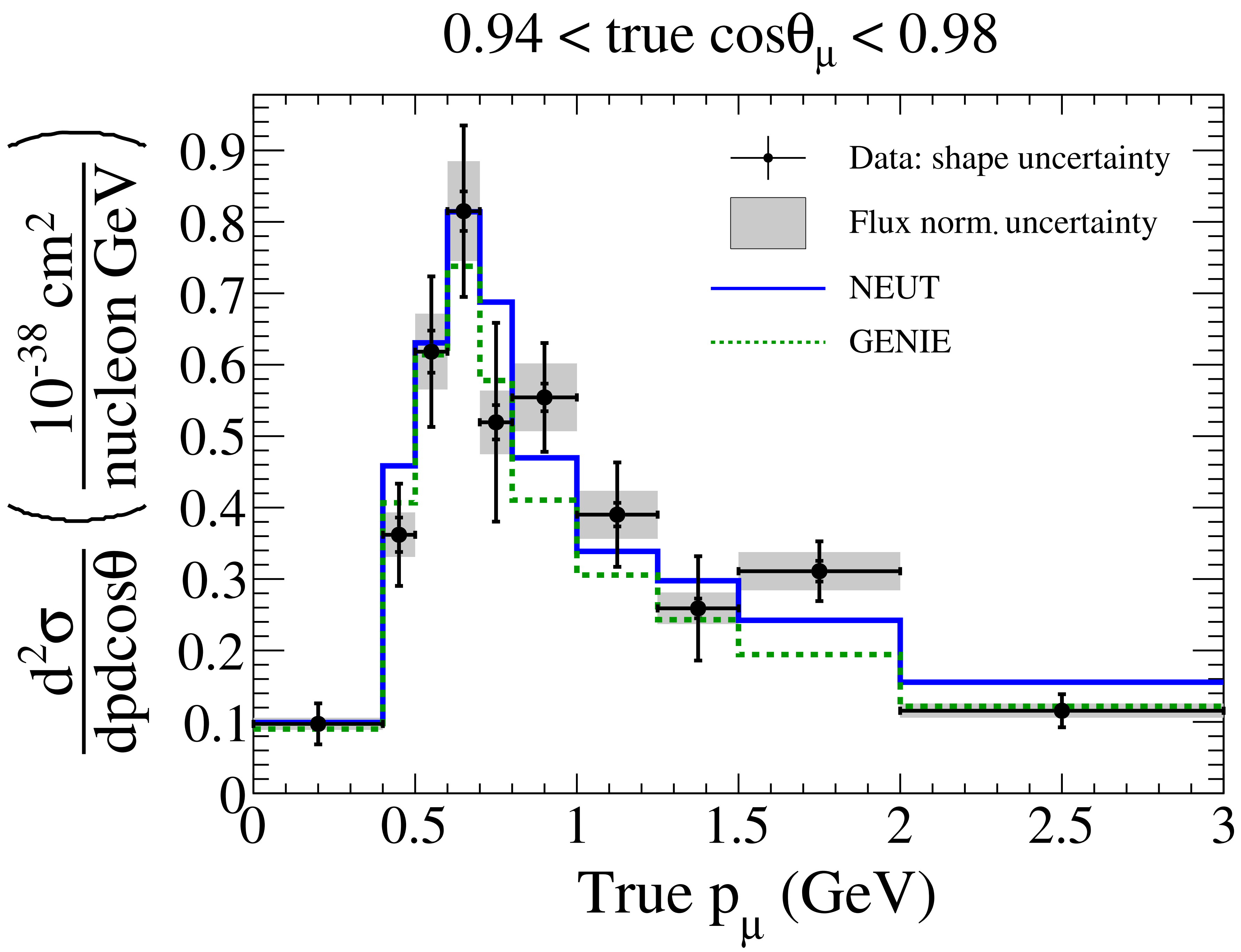
- Similar patterns seen in results from other experiments
  - **E_{had} spectrum** from NOvA near detector
- Motivate **systematics** on several important model parameters

Choice of reference data for tuning

- Mean BNB neutrino energy: ~0.8 GeV
  - Similar to J-PARC beam used by T2K
  - Lower than NuMI beam used by MINERvA and NOvA
- CC0π events are dominant, particularly at low energies
- Fits to high-energy experiments require much attention to inelastic modes (RES/DIS)
- Subtleties arise for fits to BNB experiments (possible double-counting of flux systematics, etc.)
- **T2K 2016 CC0π data chosen**
  - Independent measurement in a similar beam line
  - Double-differential in muon kinematics
- **Analysis I:** results reported over full angular range

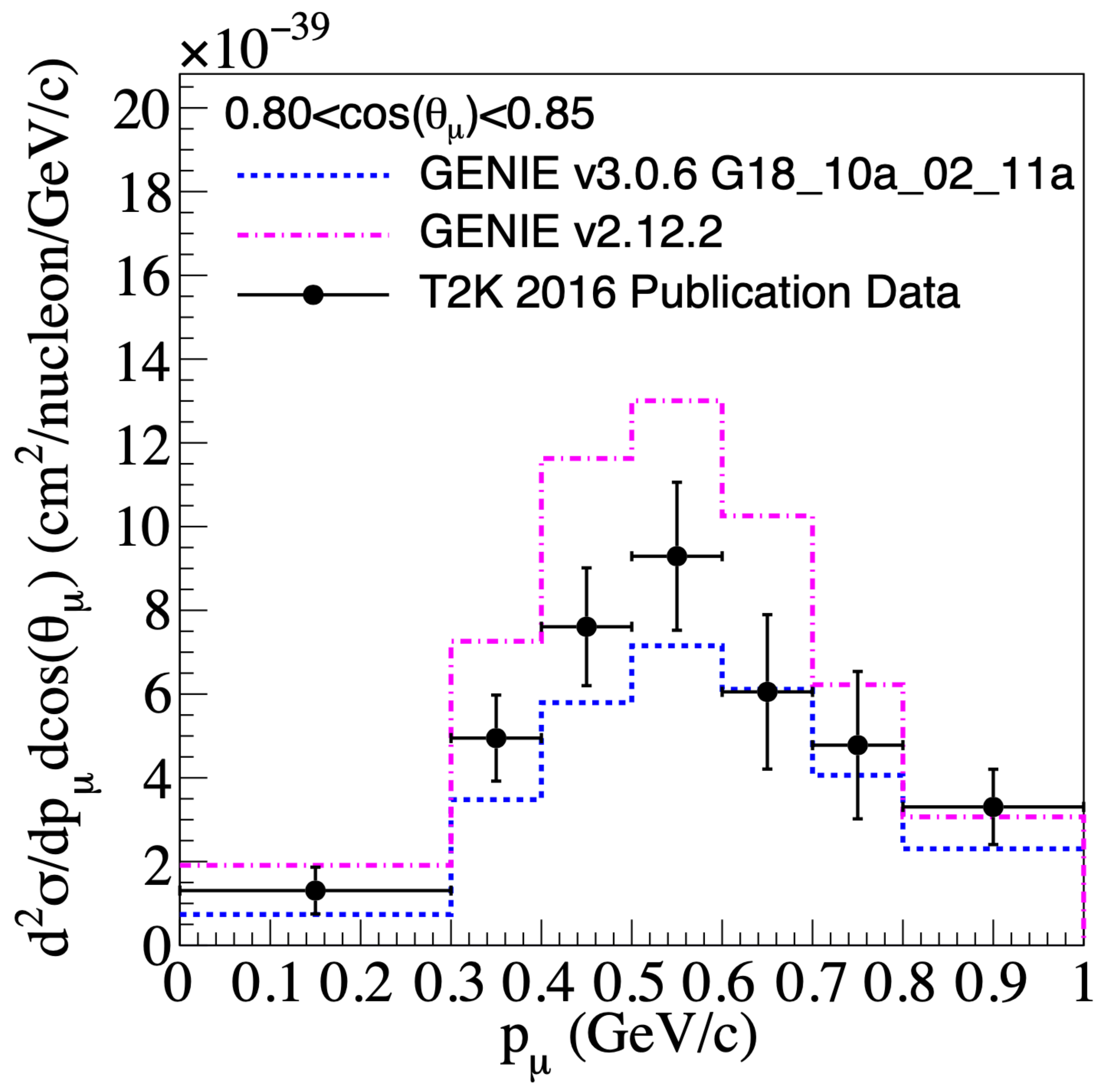


T2K Collaboration, Phys. Rev. D 93, 112012 (2016)

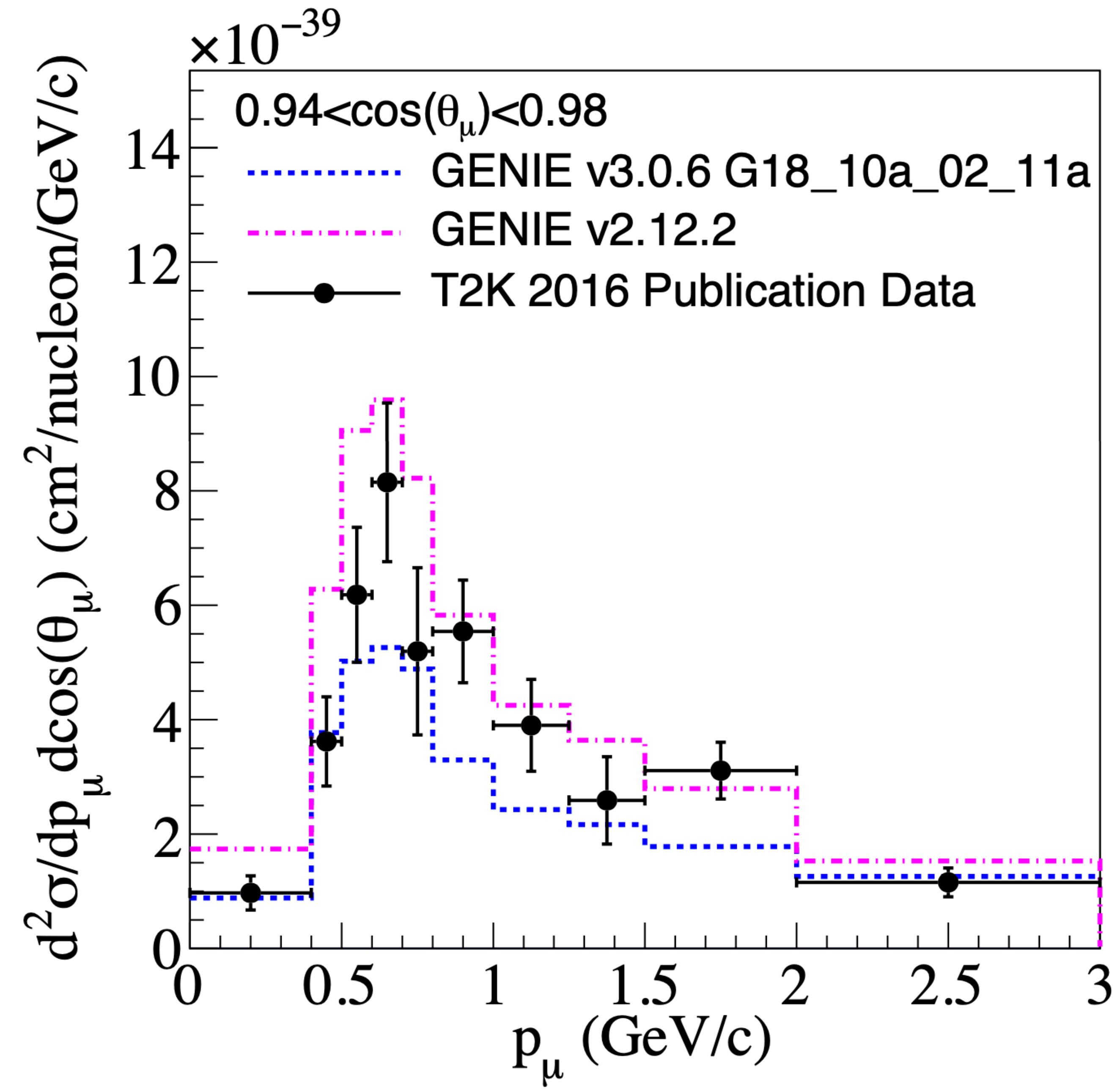


A "theory-driven tune" for MicroBooNE

- GENIE provides a comprehensive model: many aspects could potentially be tuned
- We chose a small number of parameters that
  1. Reflect known uncertainties in models of CC0π cross sections
  2. Cannot (easily) be constrained by existing electron-nucleus datasets (e.g., k_F excluded)
  3. Can plausibly be constrained by the T2K 2016 dataset
- **Adopted list**: two QE and two 2p2h parameters
  - CCQE axial mass and RPA strength
  - CC 2p2h normalization and shape



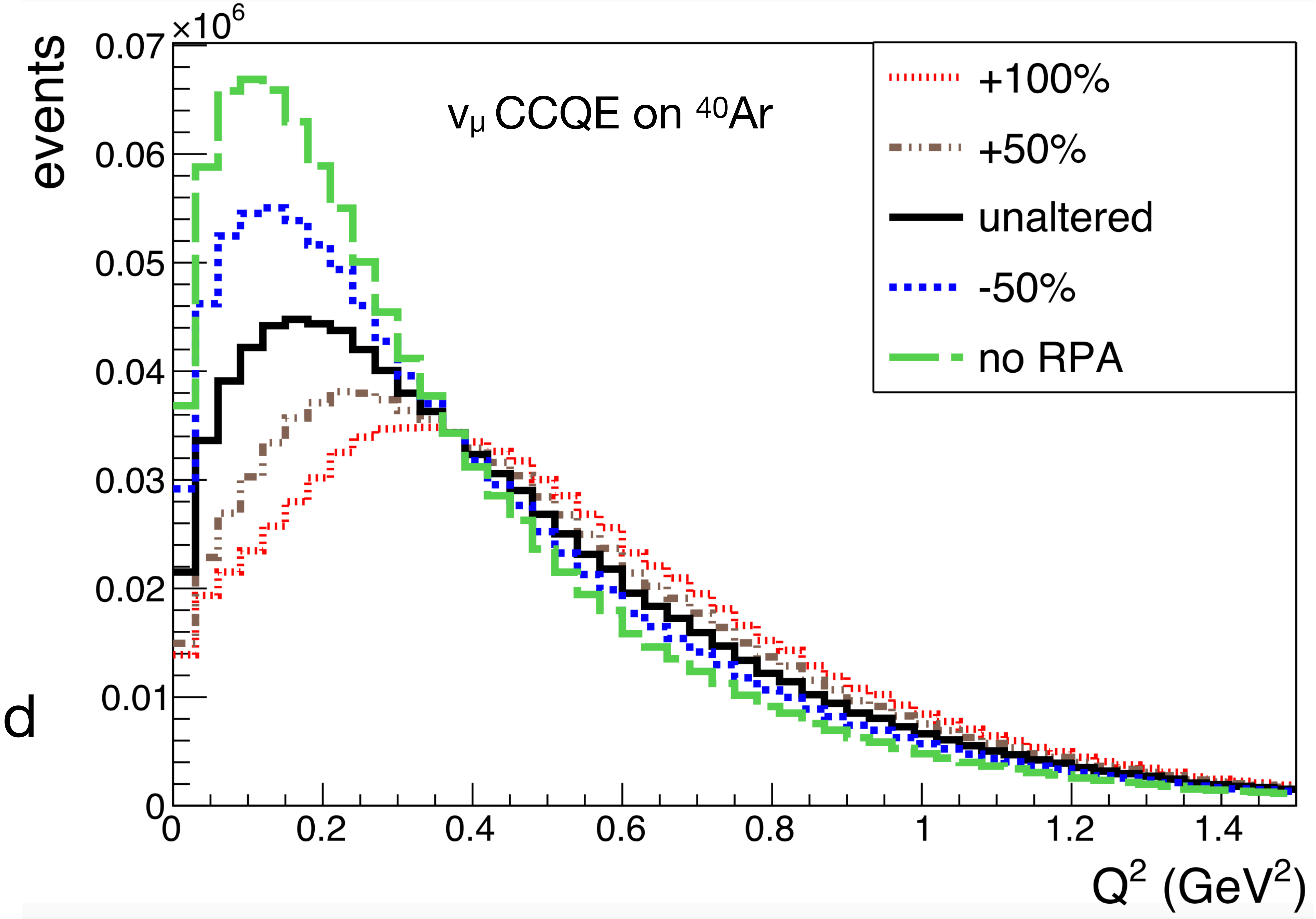
T2K data from Phys. Rev. D 93, 112012



CCQE RPA strength

$$\frac{d\sigma}{d\mathbf{x}} = (1-k)\frac{d\sigma^{\text{RPA}}}{d\mathbf{x}} + k\frac{d\sigma^{\text{no RPA}}}{d\mathbf{x}}$$

- Adjusts CCQE cross section to account for long-range nucleon-nucleon correlations
  - Most obvious effect is a suppression at low Q^2
  - Evaluated by the Valencia group using the **R**andom **P**hase **A**pproximation

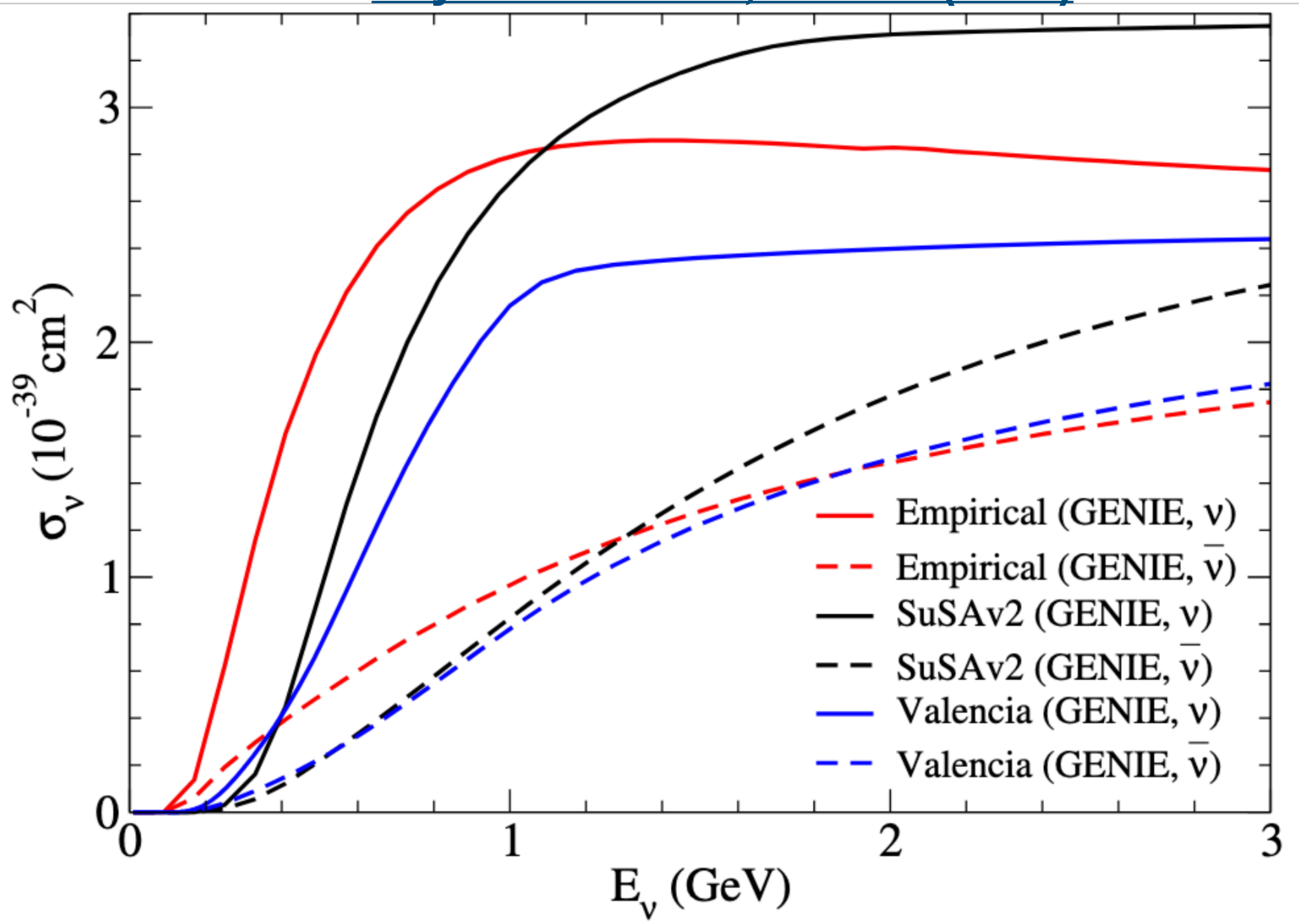


- We implement an interpolation between the Valencia correction and no correction at all

CC 2p2h normalization and shape

- The available models differ widely in both their overall normalization and shape in lepton kinematics
- We treat these differences in our fit using two parameters
  - Simple rescaling of the CC 2p2h total cross section
  - Shape-only morphing between Valencia and GENIE Empirical

Phys. Rev. D 101, 033003 (2020)



Joint (q^0, |**q**|) distributions across the parameter space for shape variable k (BNB ν_μ CC 2p2h on argon)

CC 2p2h normalization and shape

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  - Simple rescaling of the CC 2p2h total cross section
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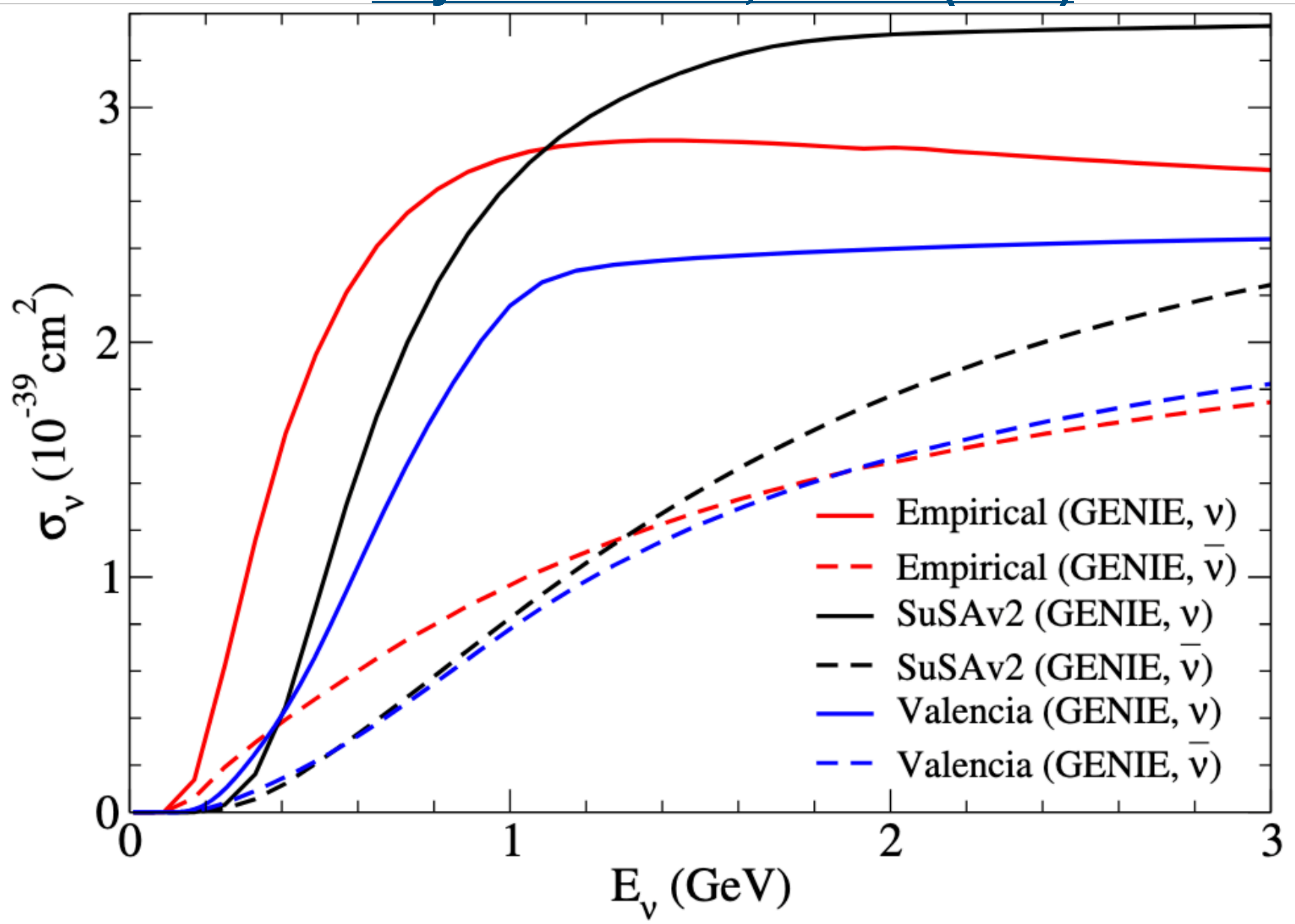
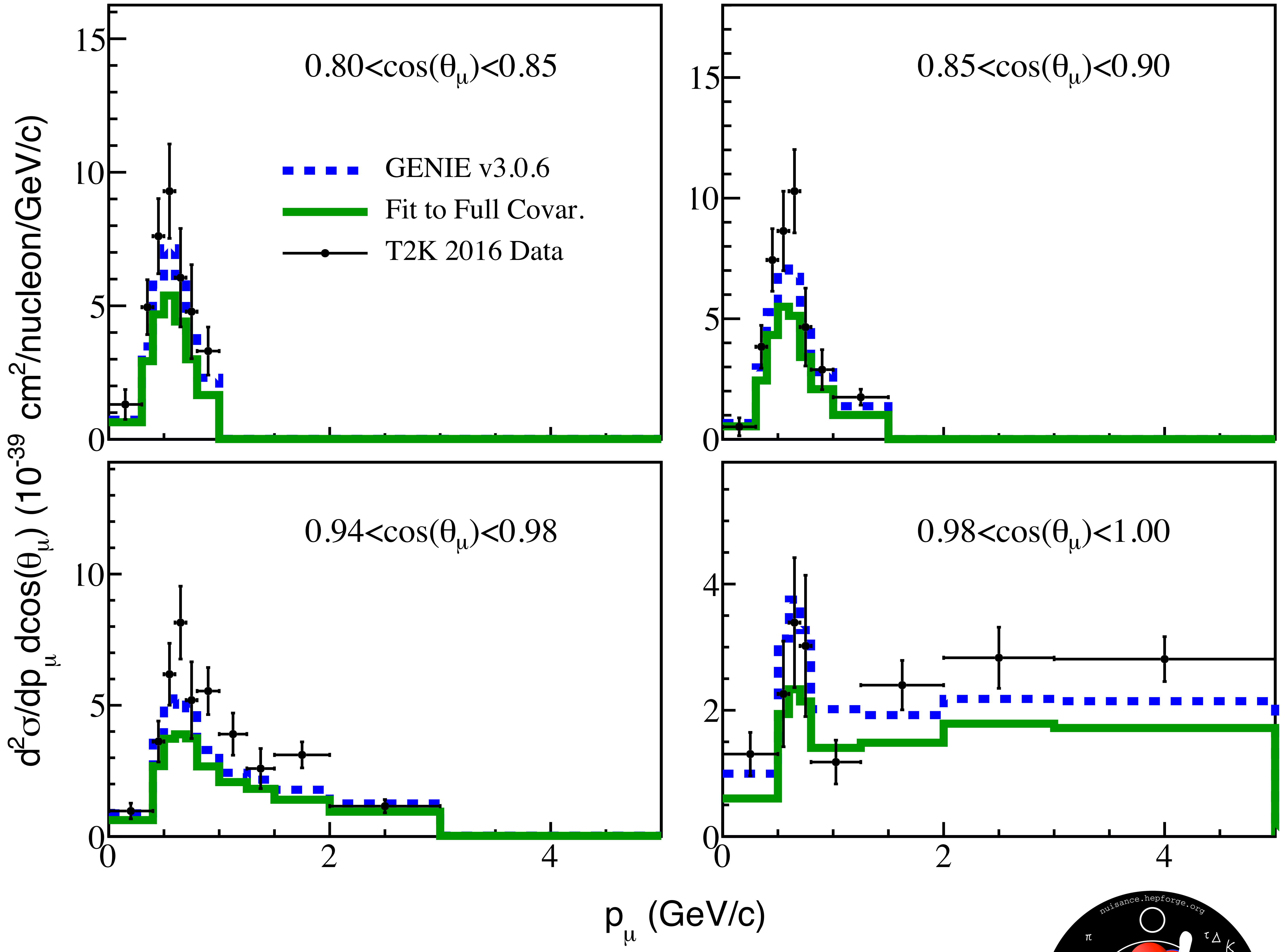
Phys. Rev. D 101, 033003 (2020)



$$P(T_\ell, \cos\theta_\ell) = (1-k)\frac{1}{\sigma^{\text{Valencia}}}\frac{d\sigma^{\text{Valencia}}}{dT_\ell\, d\cos\theta_\ell} + k\,\frac{1}{\sigma^{\text{Empirical}}}\frac{d\sigma^{\text{Empirical}}}{dT_\ell\, d\cos\theta_\ell}$$

Fit to T2K data: a problem emerges

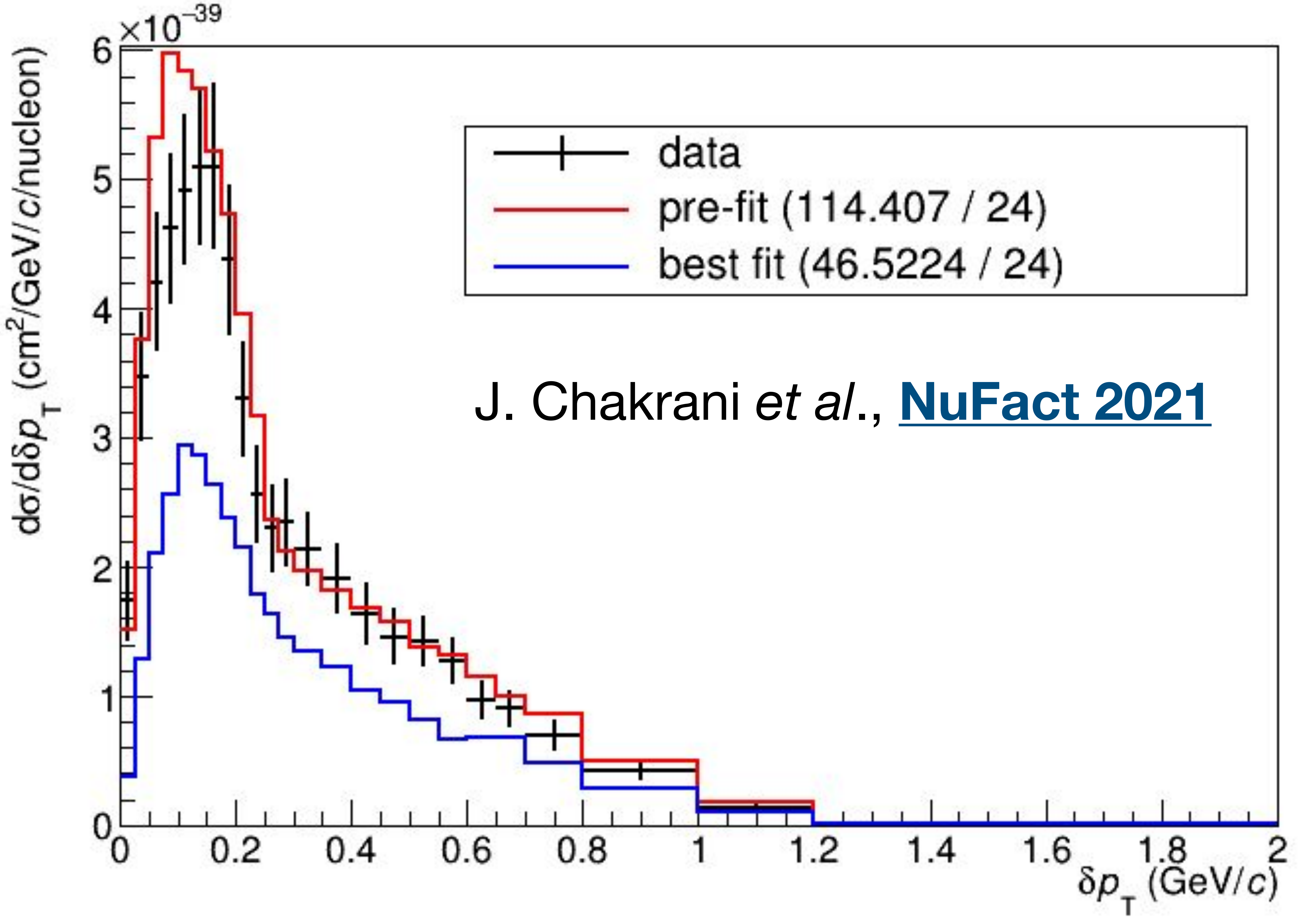
- NUISANCE used with slight modifications to accommodate our new parameters
- Add parameters one-by-one in a series of fit attempts
  - Full 4-parameter fit shown
- Published covariance matrix used in χ^2 goodness-of-fit calculations
- Initial results were **suspiciously low**



Fitting performed using the NUISANCE framework: J. Instrum. 12 P01016 (2017)

Peelle's Pertinent Puzzle

- **NEUT fit** to MINERvA CC0π δp_T
- NuWro fit to MINERvA CC0π data: **Phys. Rev. C 102, 015502 (2020)**
- Unphysically low fit results!
  - Significant bin-to-bin correlations
  - "Ordinary" covariance matrix: *absolute* uncertainty constant
- Compensate for poor fit with lower normalization (larger *relative* uncertainty)



J. Chakrani *et al*., **NuFact 2021**

Simple workaround: just ignore correlations (use diagonal covariance matrix elements only)

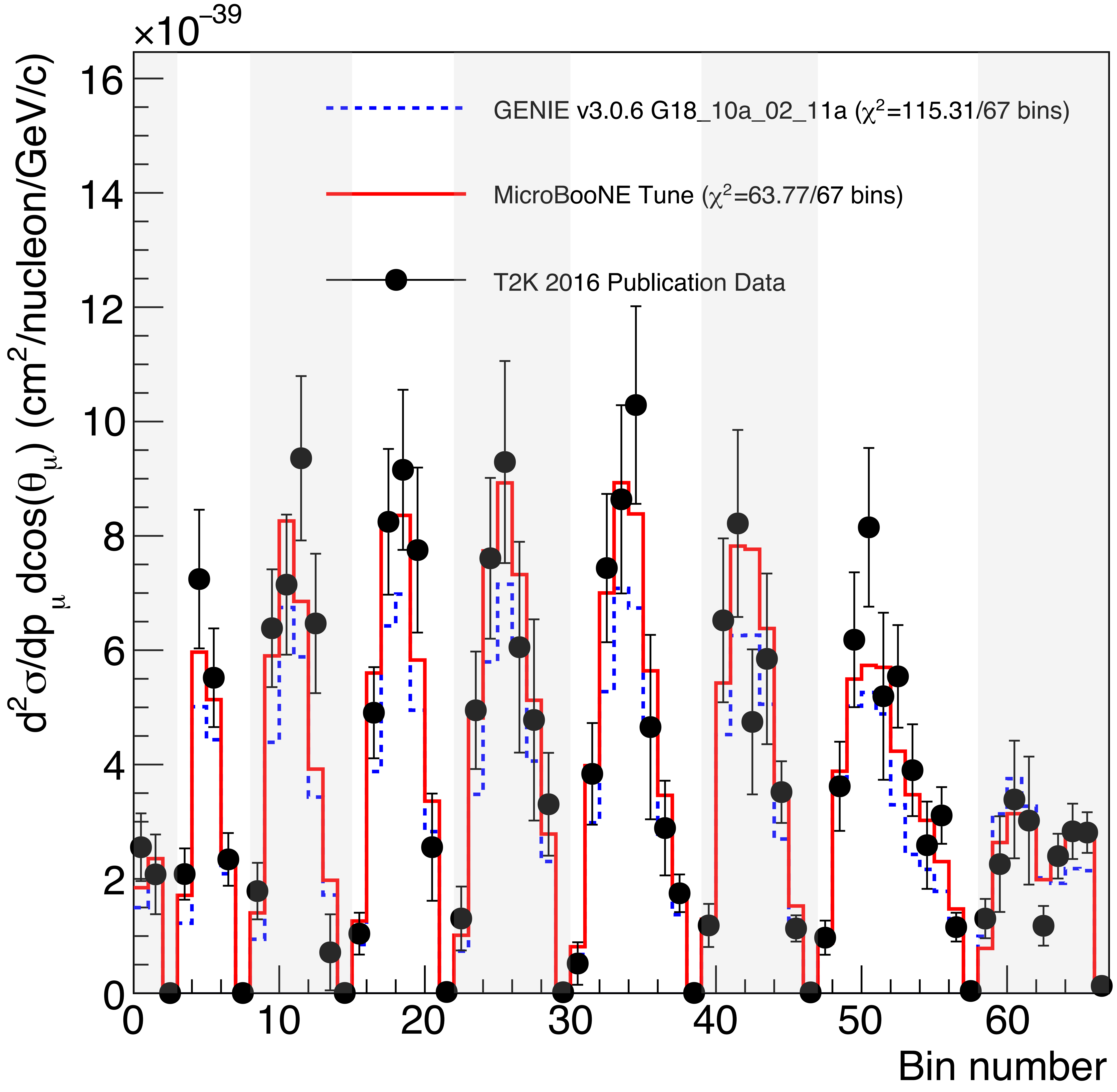
Fit to T2K data: neglect bin-to-bin correlations

- Series of 4 fits, final uncertainties inflated to approximately cover intermediate variations

	MaCCQE fitted value	CC2p2h Norm. fitted value	CCQE RPA Strength fitted value	CC2p2h Shape fitted value	T2K χ^2/N_{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±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±20)%	$1^{+0}_{-0.74}$	52.5/58

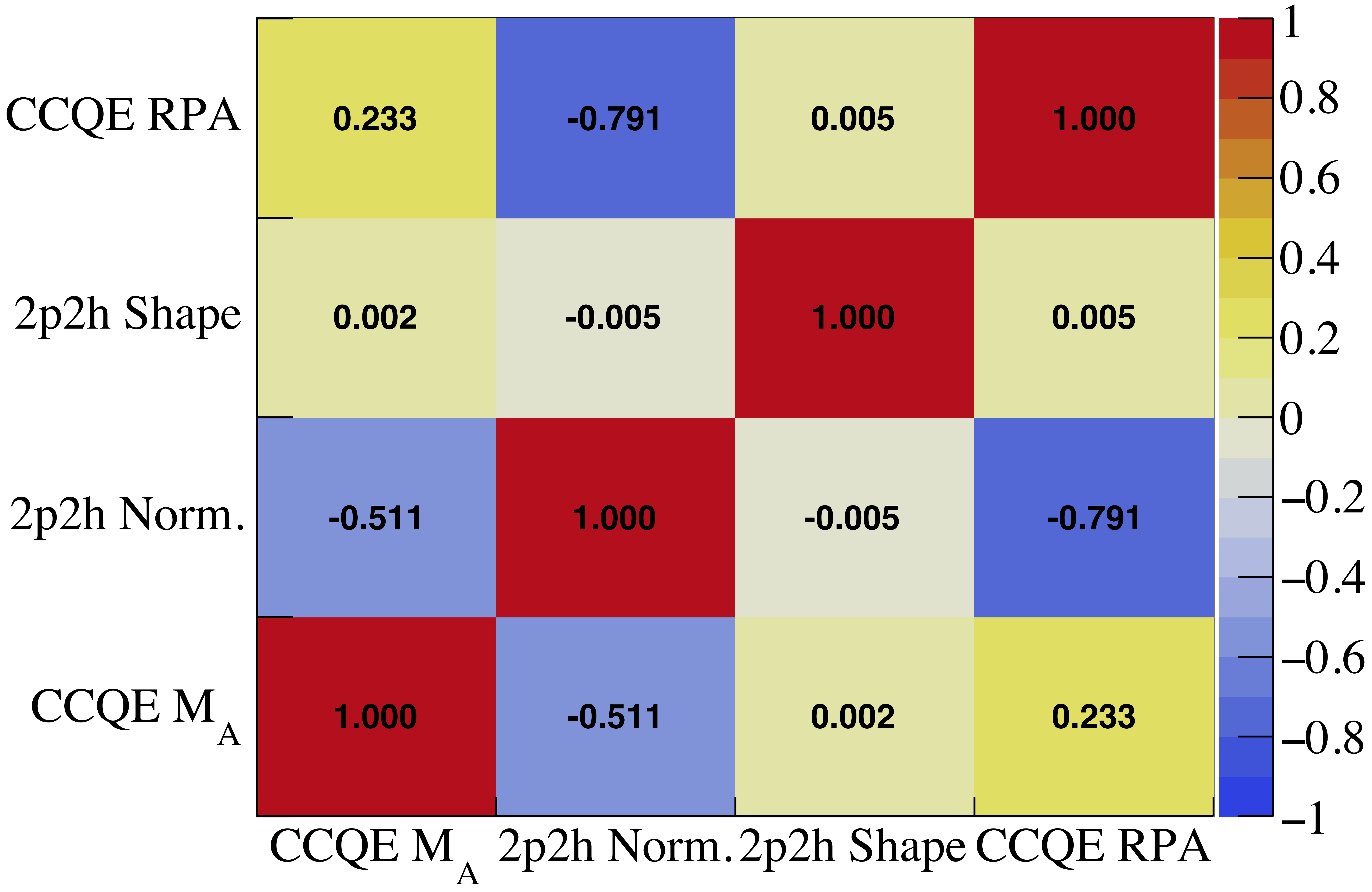
Fit to T2K data: neglect bin-to-bin correlations

- Series of 4 fits, final uncertainties inflated to approximately cover intermediate variations
- Adopted **parameter values and uncertainties**:
  - CCQE axial mass: 1.1 ± 0.1 GeV
  - RPA strength: 85 ± 40% of Valencia correction
  - CC 2p2h normalization: 1.66 ± 0.5 times nominal
  - CC 2p2h shape: k = 1 → Empirical (uncertainty is taken to be the full [0,1] range)



Parameter correlations

- 2p2h shape: orthogonal to other parameters by design
- Strong negative correlation between 2p2h norm and CCQE parameters
- Some positive correlation between M_A and RPA
  - Both influence norm+shape



The “norm-shape” covariance matrix

- Avoid PPP by transforming to a new basis
  - One row contains normalization, the others shape
  - Relative uncertainties conserved under normalization changes

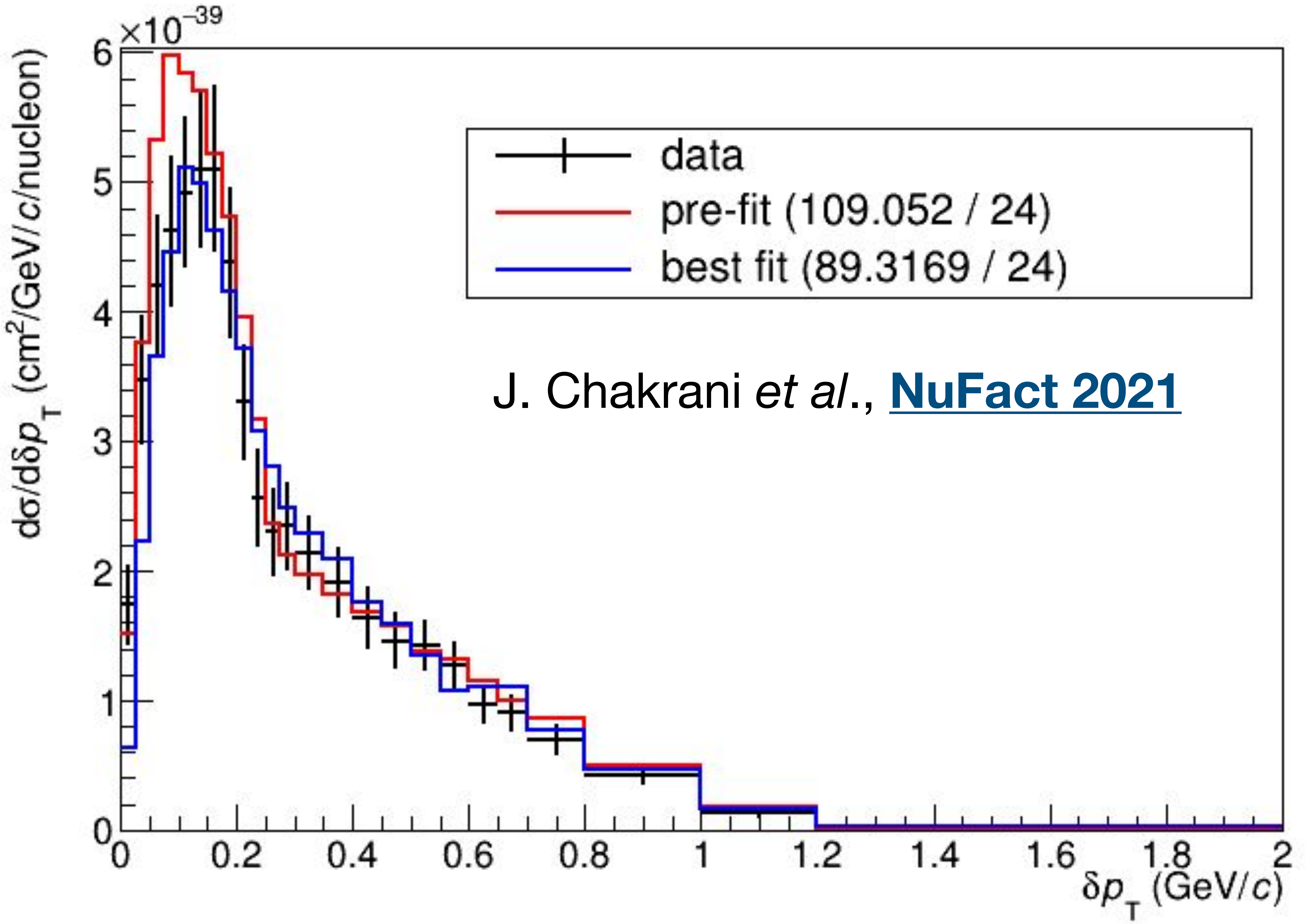
$$x_{\text{norm}} = \sum_i x_i \qquad\qquad y_i = \begin{cases} x_i / x_{\text{norm}} & i < N \\ x_{\text{norm}} & i = N \end{cases}$$

- The norm-shape covariance matrix Y can be computed from the original one X provided by an experiment. See [Phys. Rev. D 103, 113008 (2021)].
- Thanks to Jaafar Chakrani and Stephen Dolan for sharing their implementation

$$\chi^2_{\text{NS}} = \sum_{i,j} (y_i - y_i^{\text{MC}})\,(Y^{-1})_{ij}\,(y_j - y_j^{\text{MC}})$$

Application to MINERνA CC0π δpT

- Minimize χ^2_{NS} instead of the ordinary χ^2
- Fit result much more satisfactory
- What happens when we try this for the fits to T2K data?

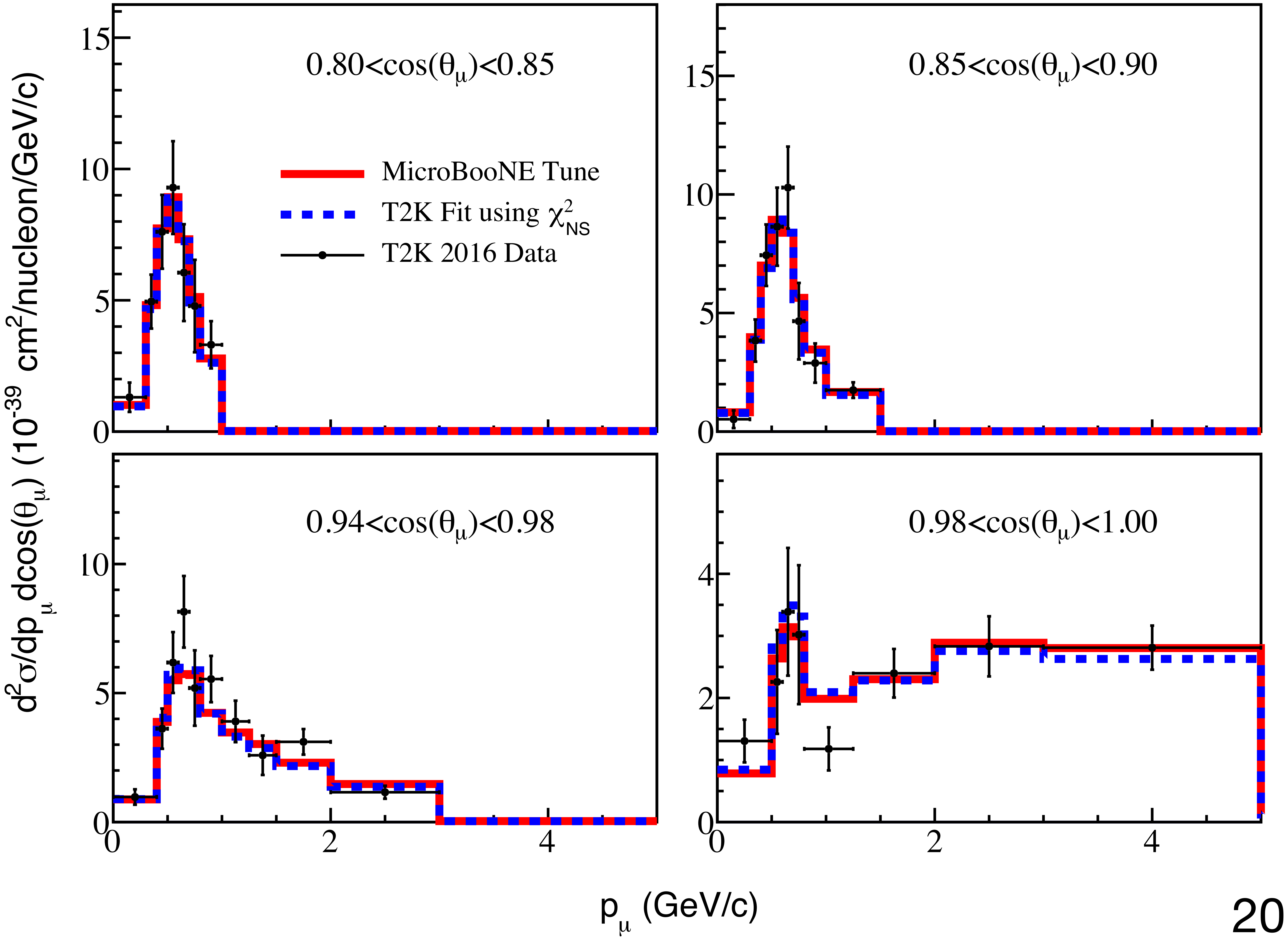


J. Chakrani *et al*., **NuFact 2021**

Alternative norm-shape T2K fit results

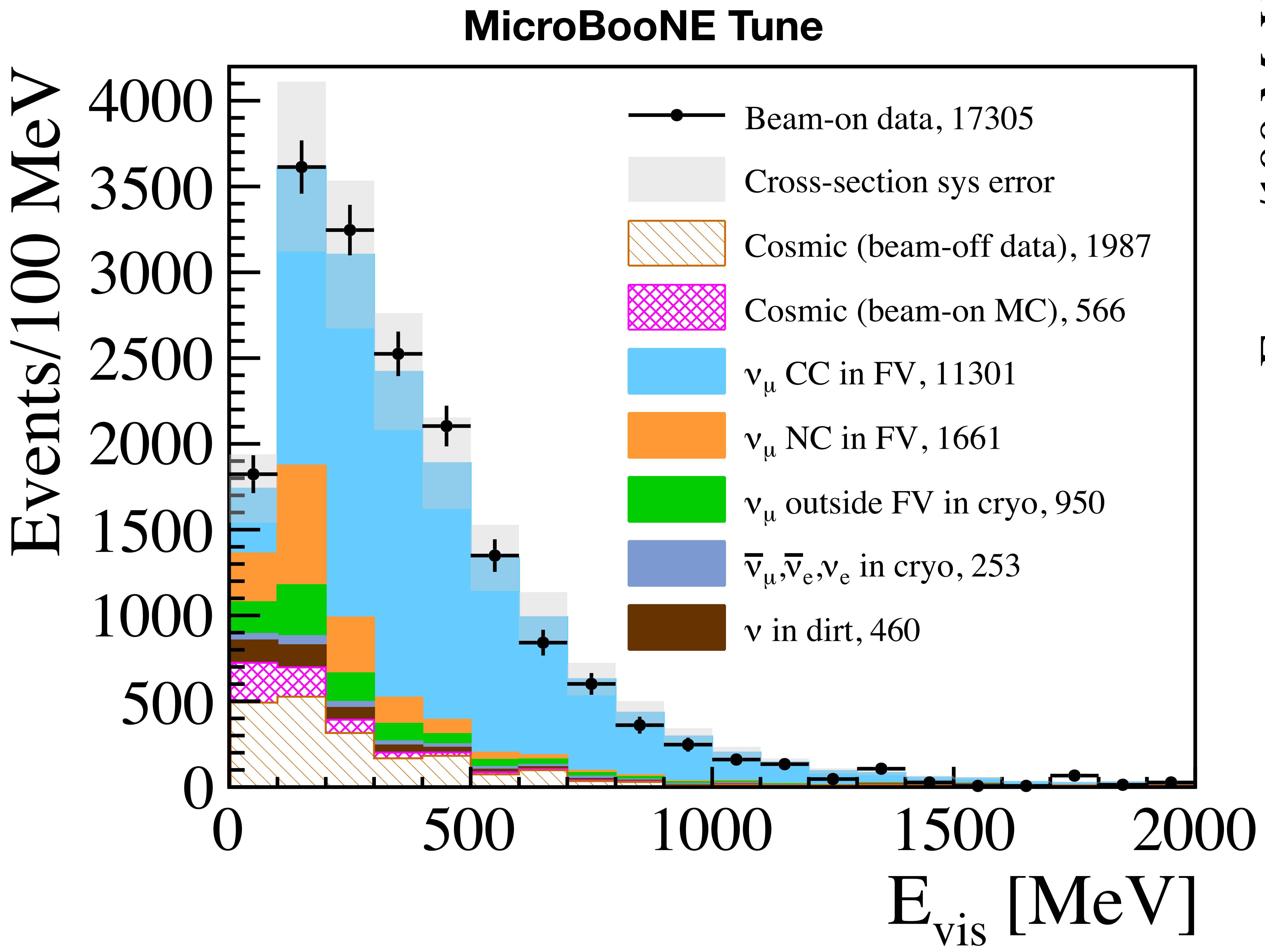
- Hard to distinguish from the MicroBooNE Tune model by eye
- Best-fit parameter values agree within uncertainties
  - "Diagonal-only" approach deemed sufficient in this case
- Should PPP influence how our data releases are presented?

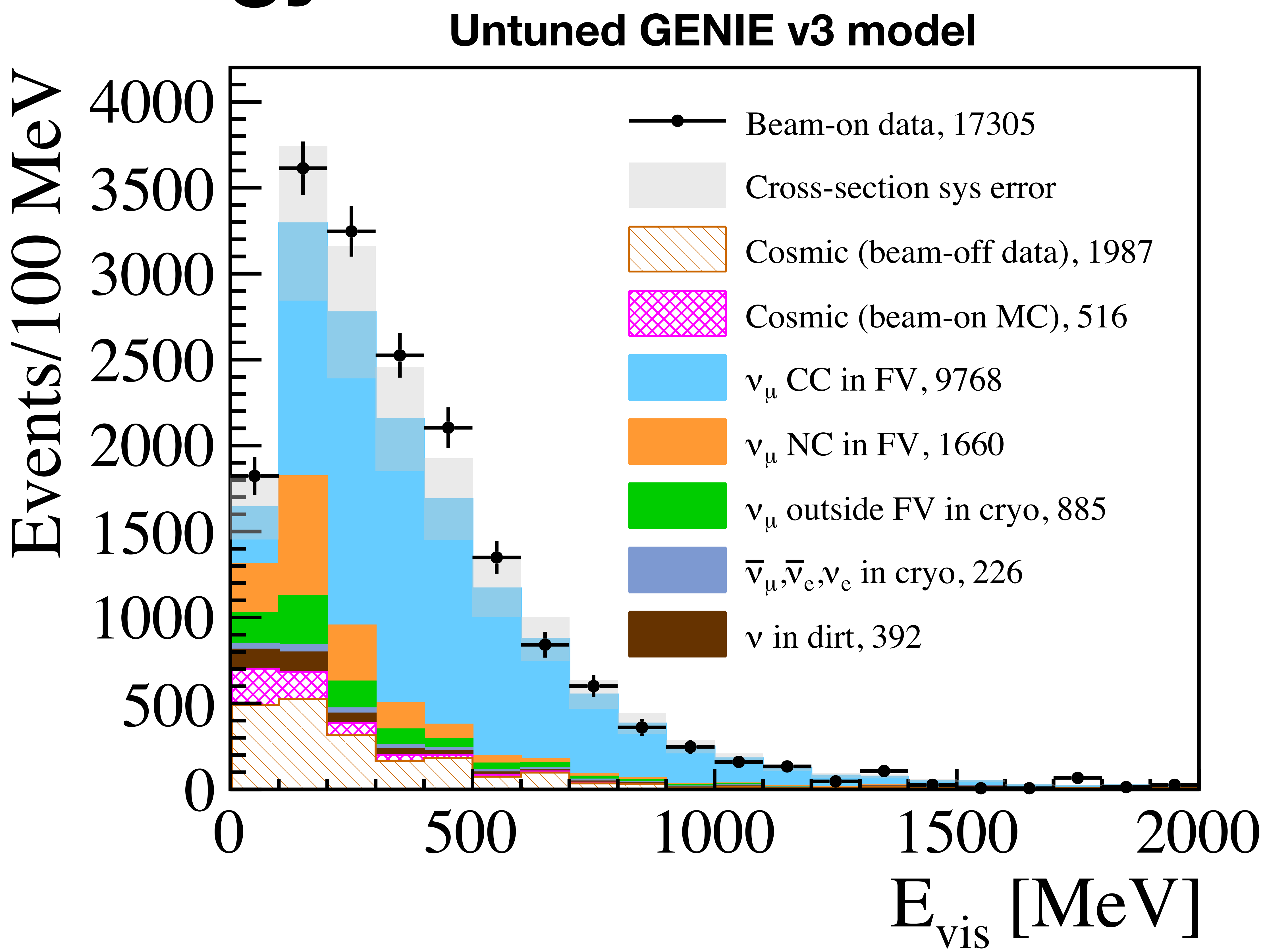
	MaCCQE fitted value	CC2p2h Norm. fitted value	CCQE RPA Strength fitted value	CC2p2h Shape fitted value	T2K χ^2_{diag}/N_{bins}
Nominal (untuned)	0.961242 GeV	1	100%	0	106.7/58
"MicroBooNE Tune"	1.10±0.07 GeV	1.66±0.19	(85±20)%	$1^{+0}_{-0.74}$	52.5/58
"Alternate fit"	1.04±0.10 GeV	1.44±0.42	(67±16)%	$0.91^{+0.09}_{-0.18}$	55.51/58



Before and after: CC inclusive visible energy

arXiv:2110.14028



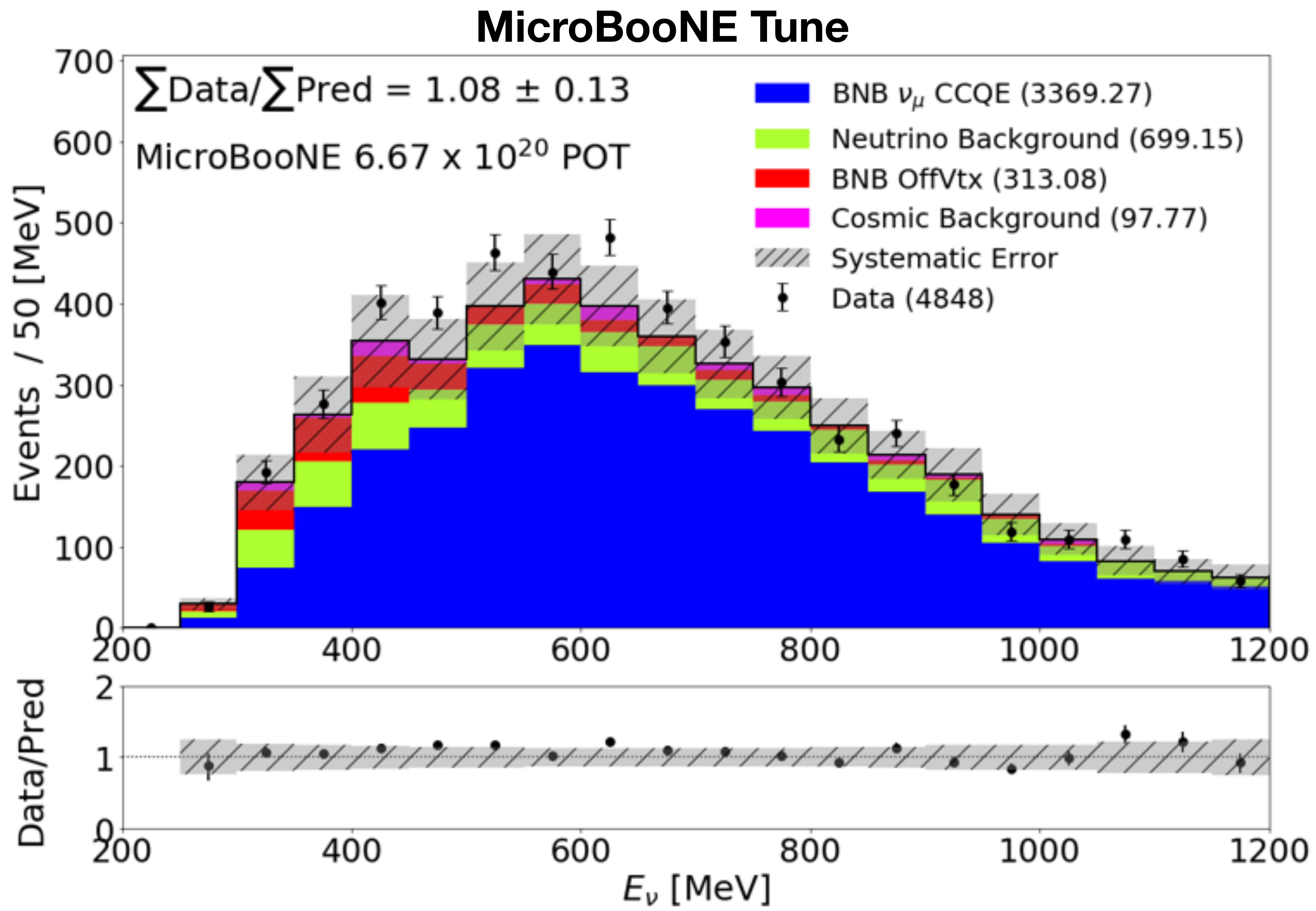


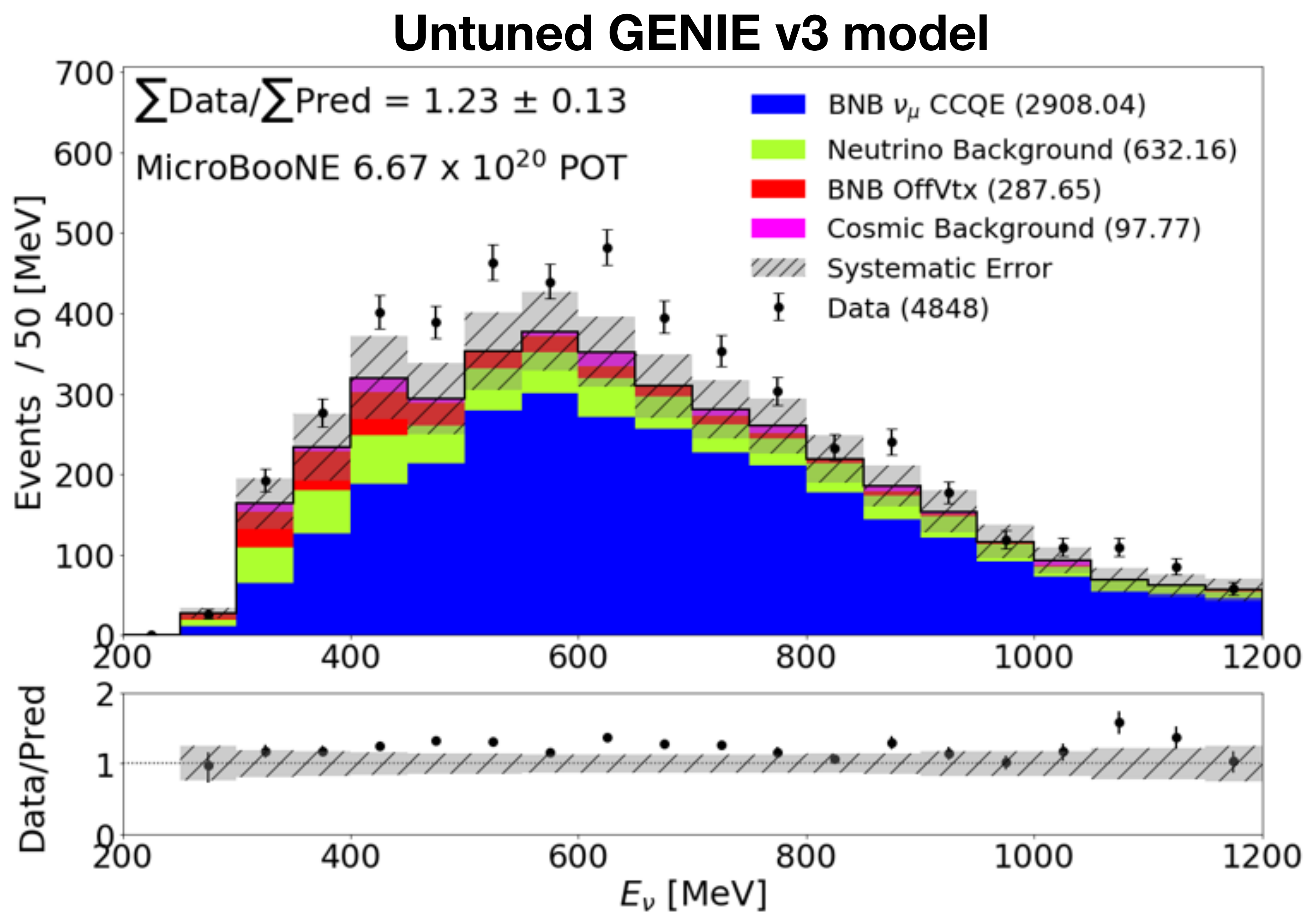
Improvements most noticeable in lowest E_{vis} bins

Data/MC ratio improves from 1.12 (untuned) to 1.01 (tuned)

Before and after: CCQE-like selection

arXiv:2110.14028

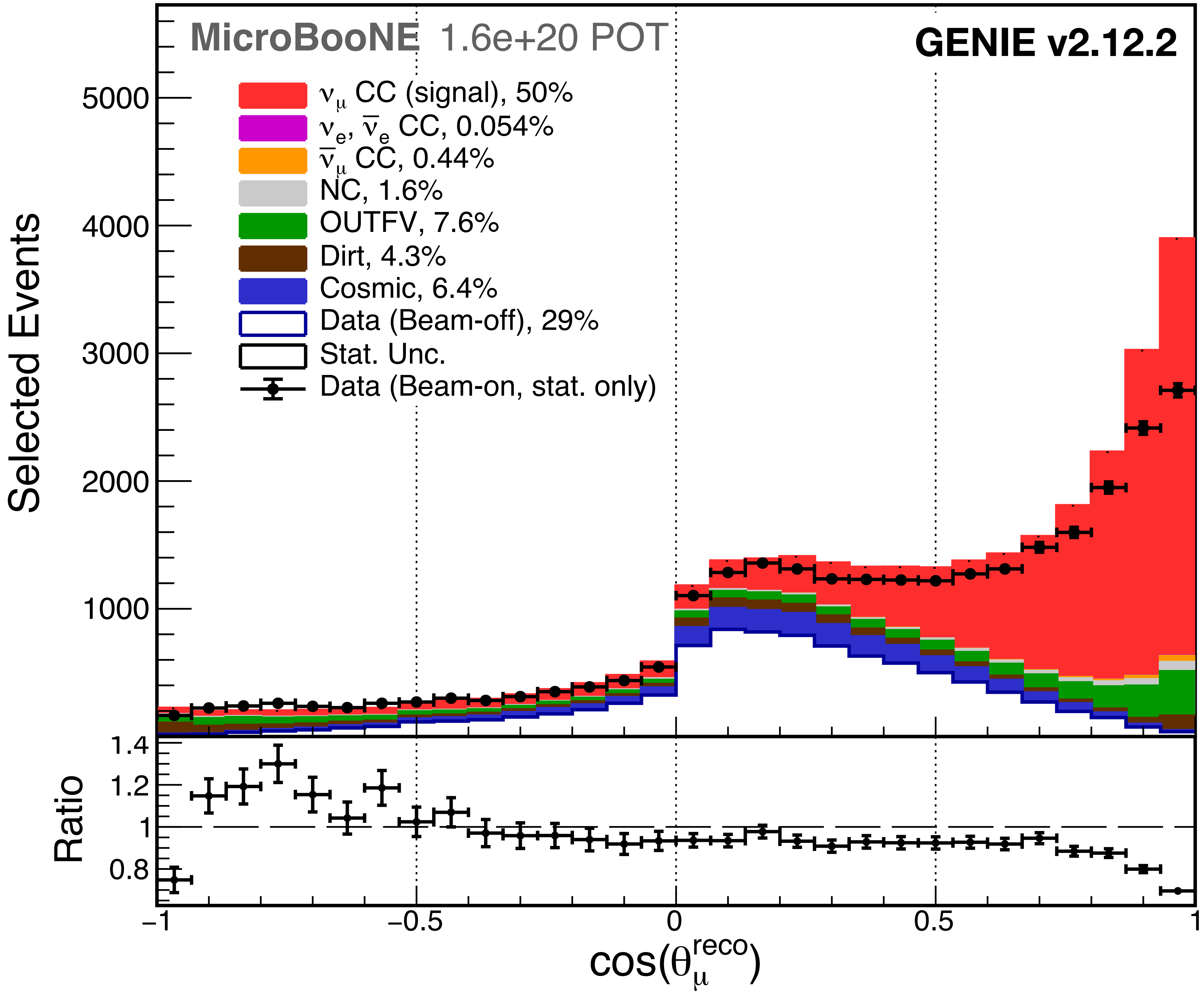




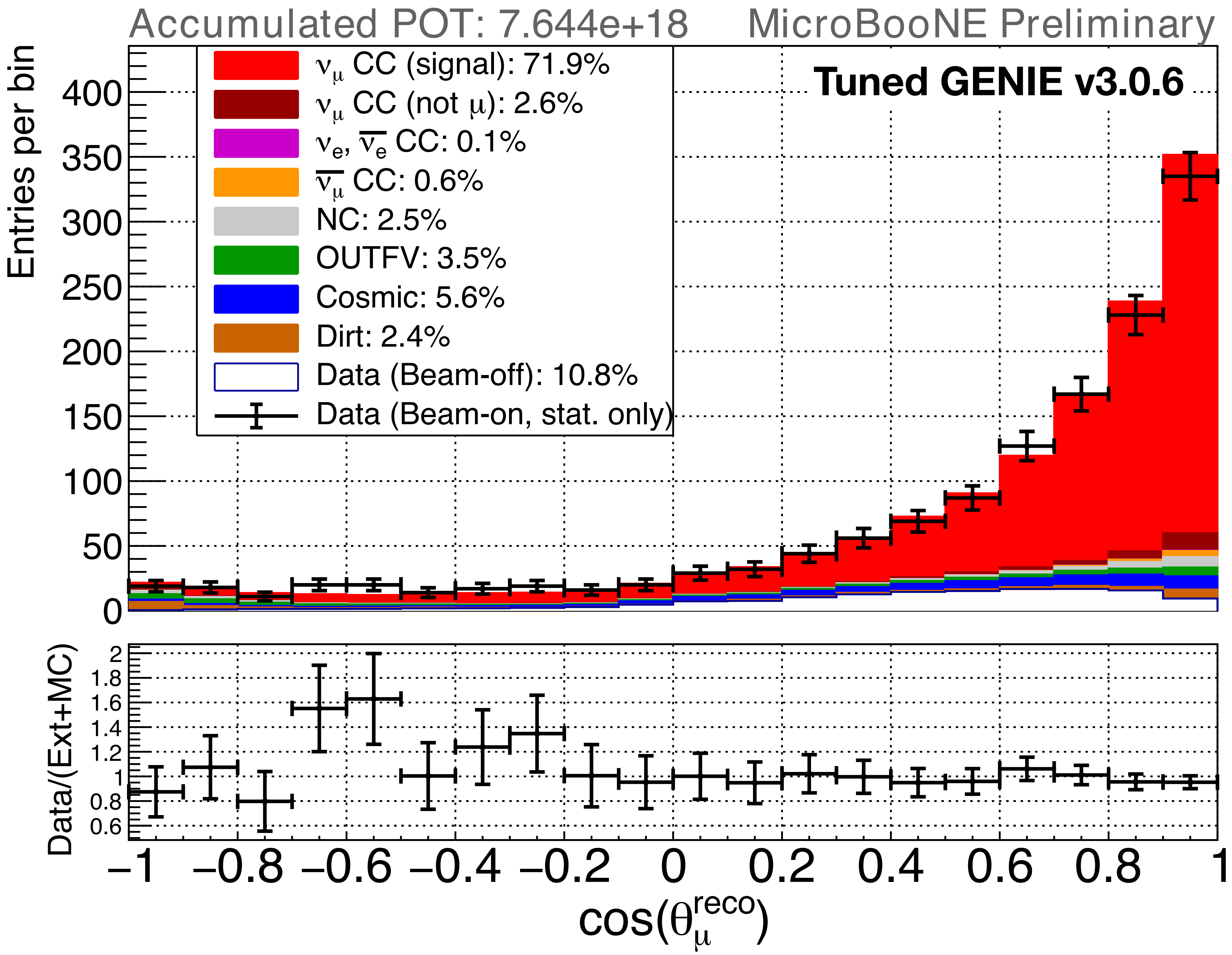
Improved agreement for reconstructed E_ν distribution

(ν_μ control sample for CCQE-like LEE analysis)

ν_μ CC inclusive angular distribution



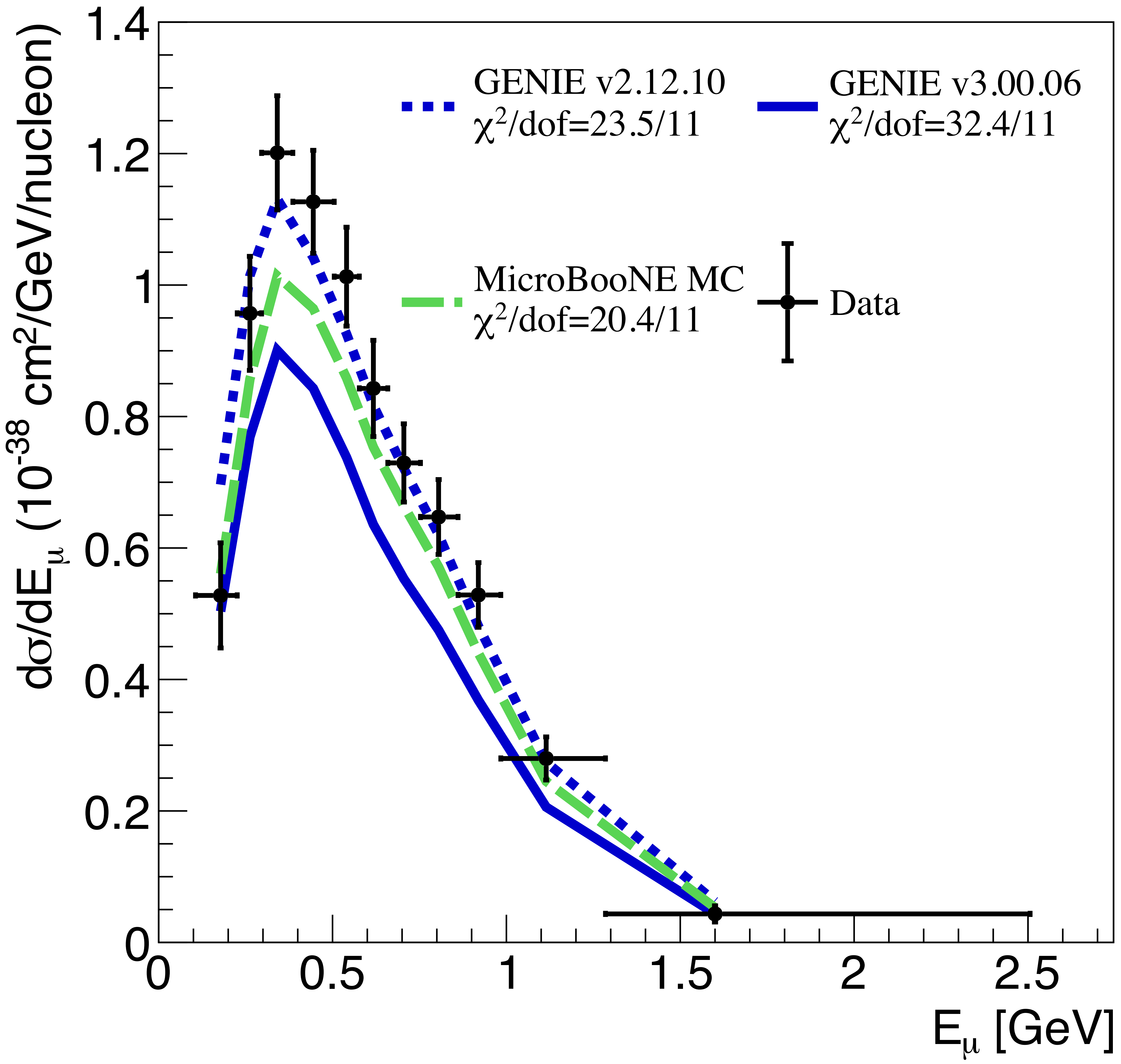
[Phys. Rev. Lett. 123, 131801 (2019)]

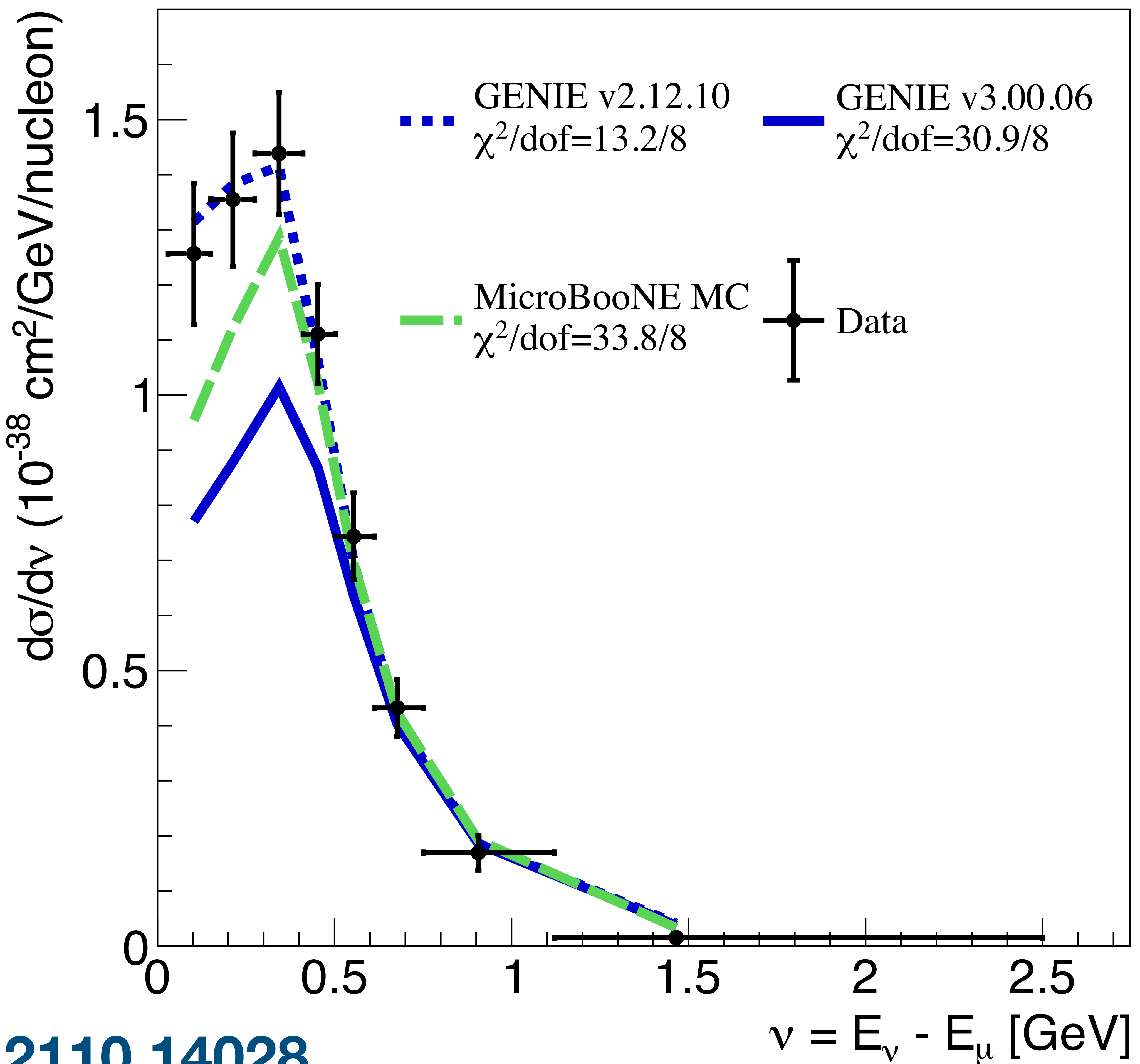


[MICROBOONE-NOTE-1069-PUB]

Not always a "slam dunk": CC inclusive cross sections

- The GENIE v2 central value is occasionally better in some regions of phase space
  - Notably at low ν. However, uncertainty coverage is adequate in that region.

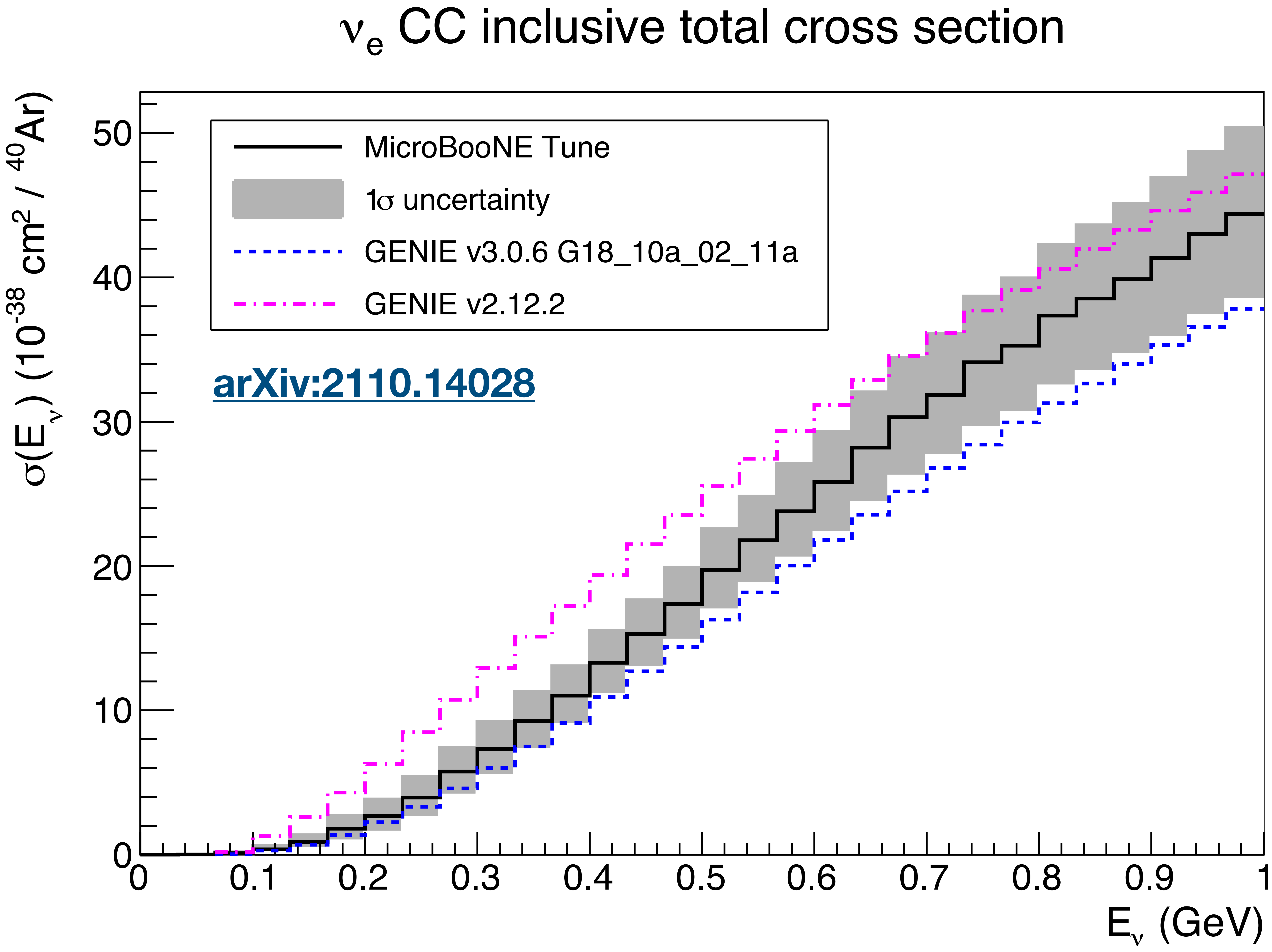




arXiv:2110.14028

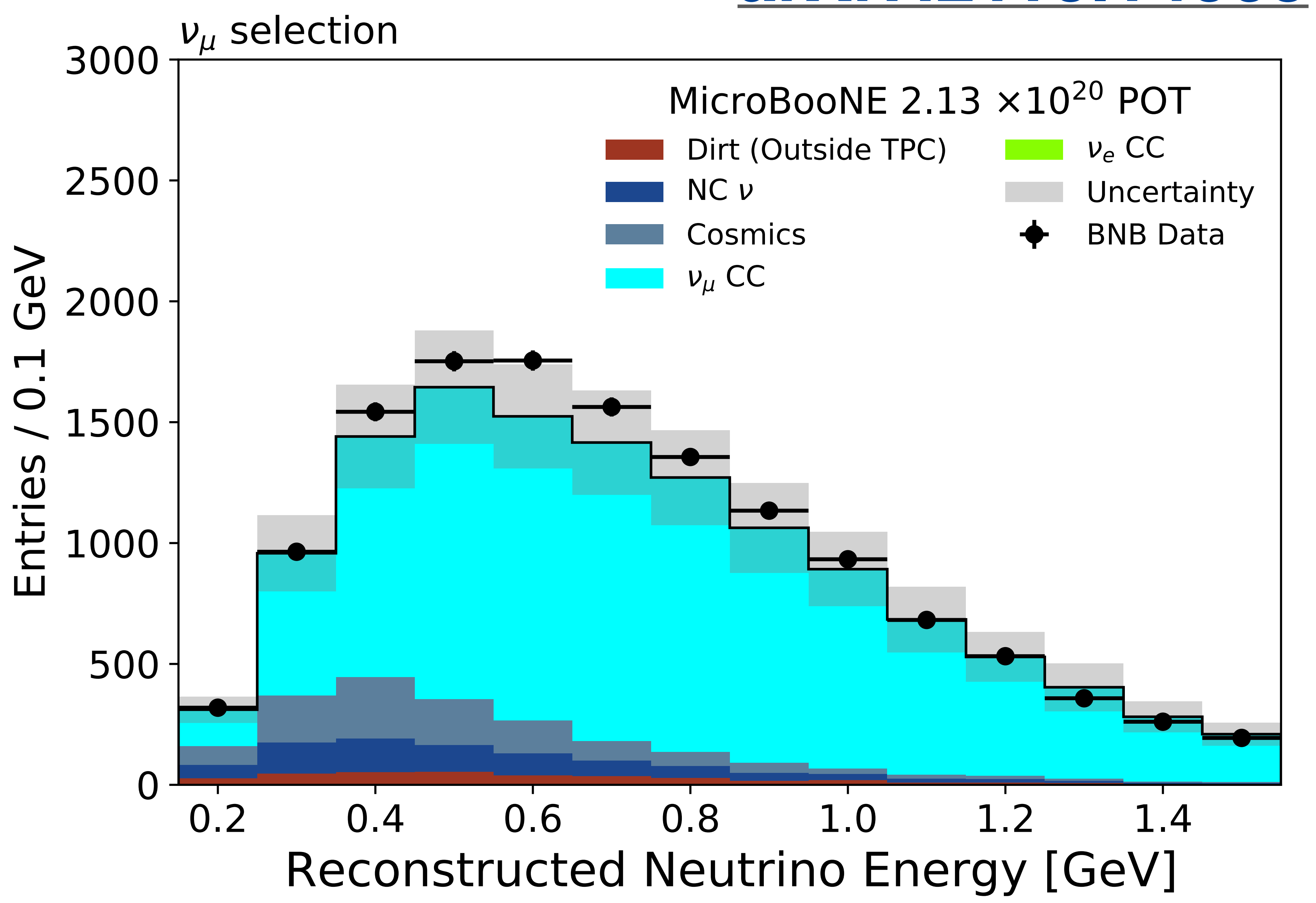
CC inclusive total cross sections

- Modest enhancement compared to untuned GENIE v3
- Significantly smaller than GENIE v2 at low energies
- Very similar behavior for ν_μ



Usage in the LEE analyses: CC0πNp

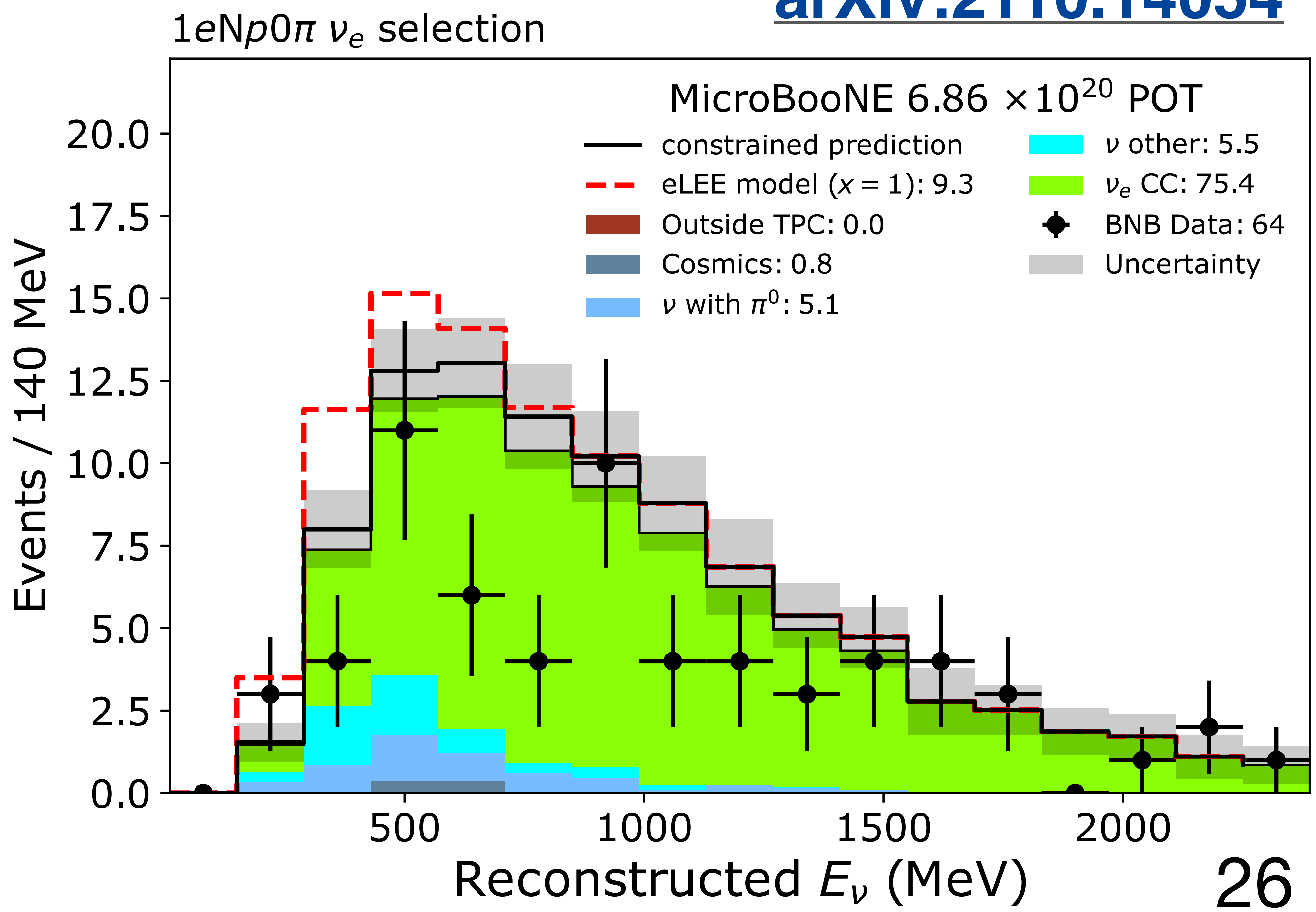
arXiv:2110.14065



- Seen to give a good treatment of ν_μ data within uncertainties
  - Reconstructed E_ν shown
  - Similar performance for angular distribution, etc.

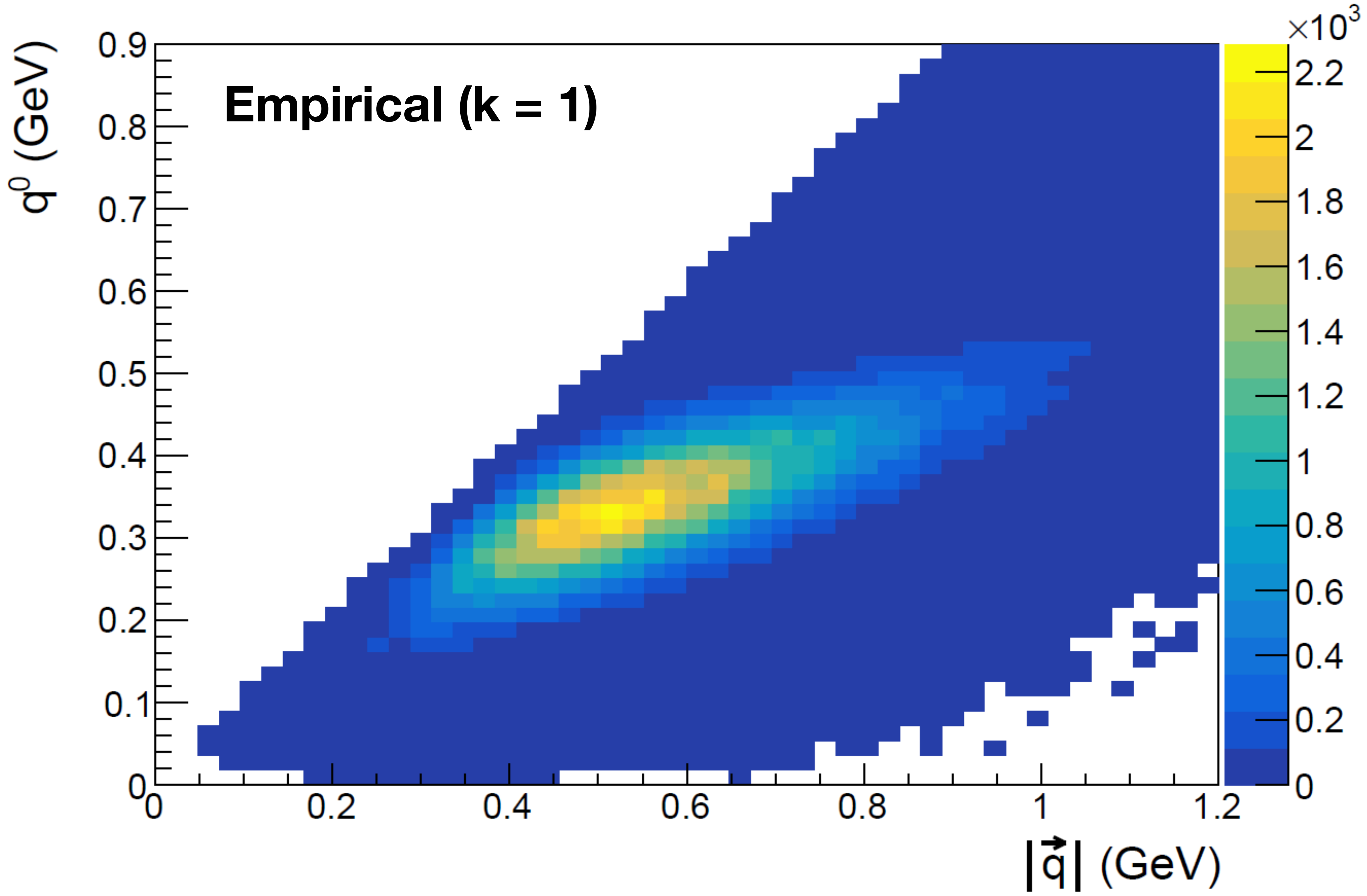
- Data-driven constraint applied in ν_e channel
  - Modest differences from unconstrained model
  - Generally within quoted uncertainties

arXiv:2110.14054

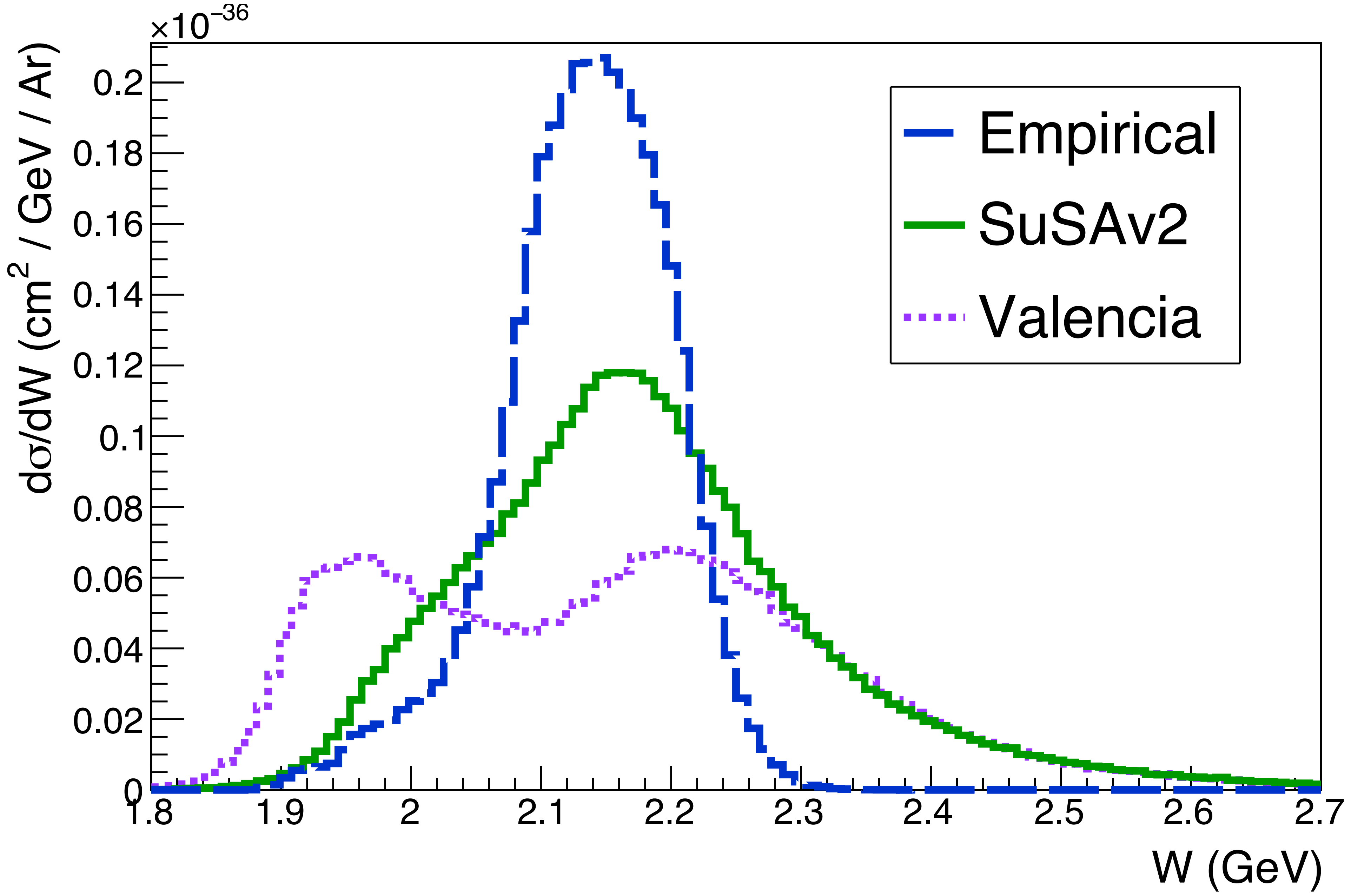


Some takeaways from the tune

- Best-fit prefers slight weakening of Valencia RPA corrections
  - Original calculation within fit uncertainty
- Weak preference for "**one peak**" Empirical 2p2h shape
  - More similar to **SuSAv2** than Valencia
  - Stronger preference in norm-shape alternative fit
- Agreement with MINERvA, NOvA that overall CC0π strength needs to be enhanced
  - An interesting difference exists . . .

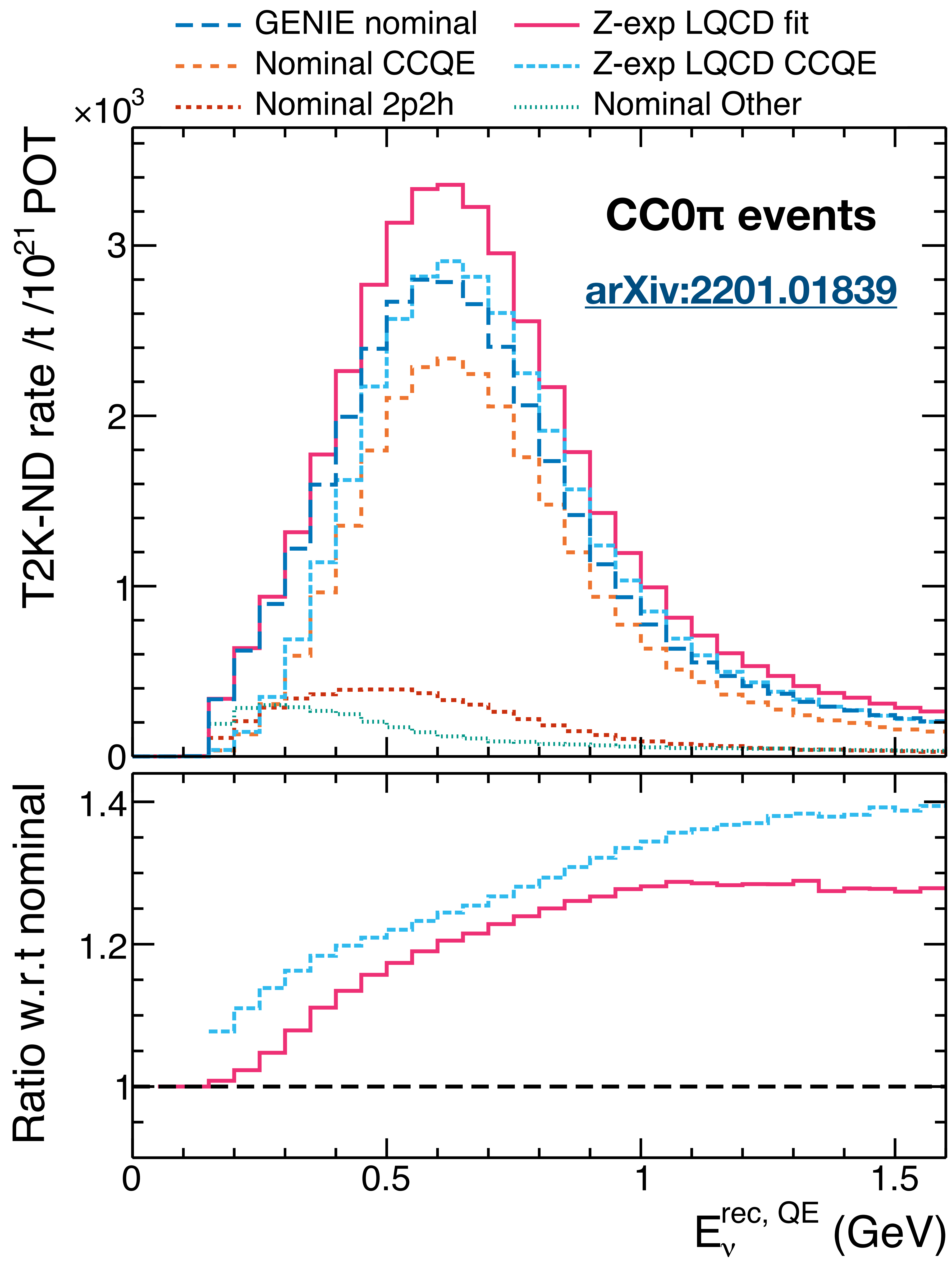


GENIE Collaboration, Eur. Phys. J. Spec. Top. (2021)



CCQE enhancement and lattice QCD

- The MicroBooNE Tune adopts an enhancement of CC QE *and* 2p2h
- Lattice QCD: ~20% increase CCQE strength
  - Consistent with mean weight of ~1.2 for MicroBooNE Tune CCQE events
  - Not a nuclear effect. This may thus translate well from T2K to MicroBooNE
- Worth further investigation
  - Not purely a normalization difference



New systematic uncertainties for GENIE Reweight

See "MicroBooNE Tune" paper for details (arXiv:2110.14028). Merged into GENIE v3.2.

Tune ingredients: RPA strength, CC 2p2h normalization + shape

- Coulomb_CCQE: EM potential used for Coulomb corrections (±30%)
- FracPN_CCMEC: isospin of initial struck nucleon pair (±20%)
- FracDelta_CCMEC: strength of Δ-like component in Valencia 2p2h (±30%)
- DecayAngMEC: angular distribution of outgoing nucleons
  - 0 = isotropic, 1 = $\propto \cos^2\theta$ (measured with respect to $\mathbf{q}$)
- NormCCCOH, NormNCCOH: total cross section for coherent π production (±100%)
  - Previous treatment incompatible with Berger-Sehgal COH model in GENIE v3
- ThetaDelta2NRad: angular distribution in $\Delta \to N + \gamma$
  - Similar to DecayAngMEC

Some limitations of the “MicroBooNE Tune” strategy

- No additional uncertainty assessed on the C → Ar scaling
  - However, chosen uncertainties are conservative (inflated from raw fit results)

- RPA and 2p2h shape variations each involve only one degree of freedom
  - Wide variations, but along a single “contour” in parameter space
  - Simple for fitting, but other options could have been attempted

- Method for PPP avoidance very simple
  - Likely inadequate for more complicated cases

Summary

- MicroBooNE has adopted its first tuned generator model
  - Used to bring out first LEE results last October
- CC0π enhancement appears similar to other tunes
  - Increase of both QE and 2p2h
- Next-generation effort can expand the scope
  - Hadronic degrees of freedom (e.g., proton FSIs)
  - Newer data, including MicroBooNE's
  - Electron scattering
- Goodness-of-fit has subtleties (e.g., PPP) that must be considered carefully

μBooNE

Genie

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