Measurement of Energy-dependent Inclusive Muon Neutrino Charged-Current Cross Section at MicroBooNE

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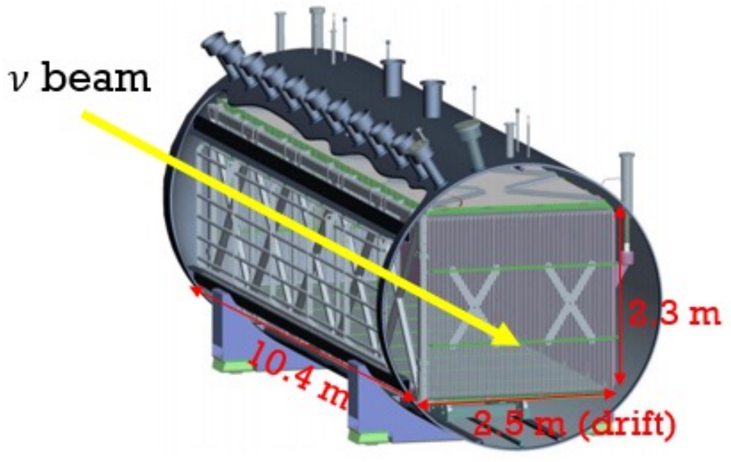
For the MicroBooNE collaboration

Brookhaven Forum, Nov 4th 2021

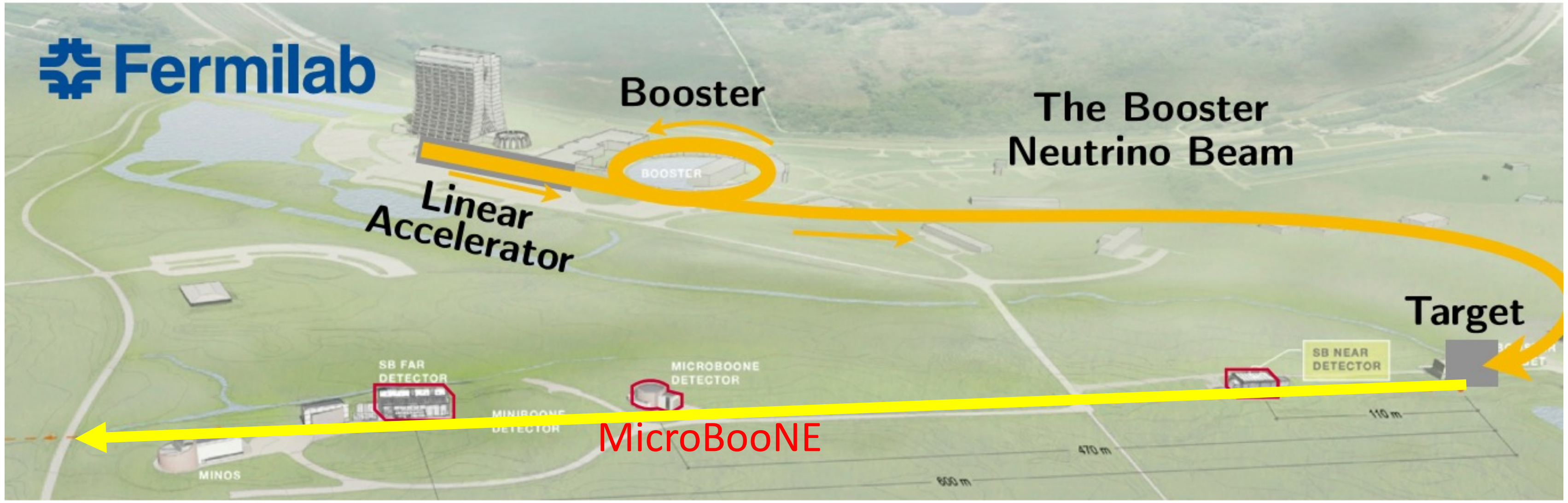
MicroBooNE Overview

- <u>Micro</u> <u>Booster</u> <u>N</u>eutrino <u>E</u>xperiment
  - Accelerator ν experiment at Fermilab
  - LArTPC with 85 ton active mass
  - Near-surface operation

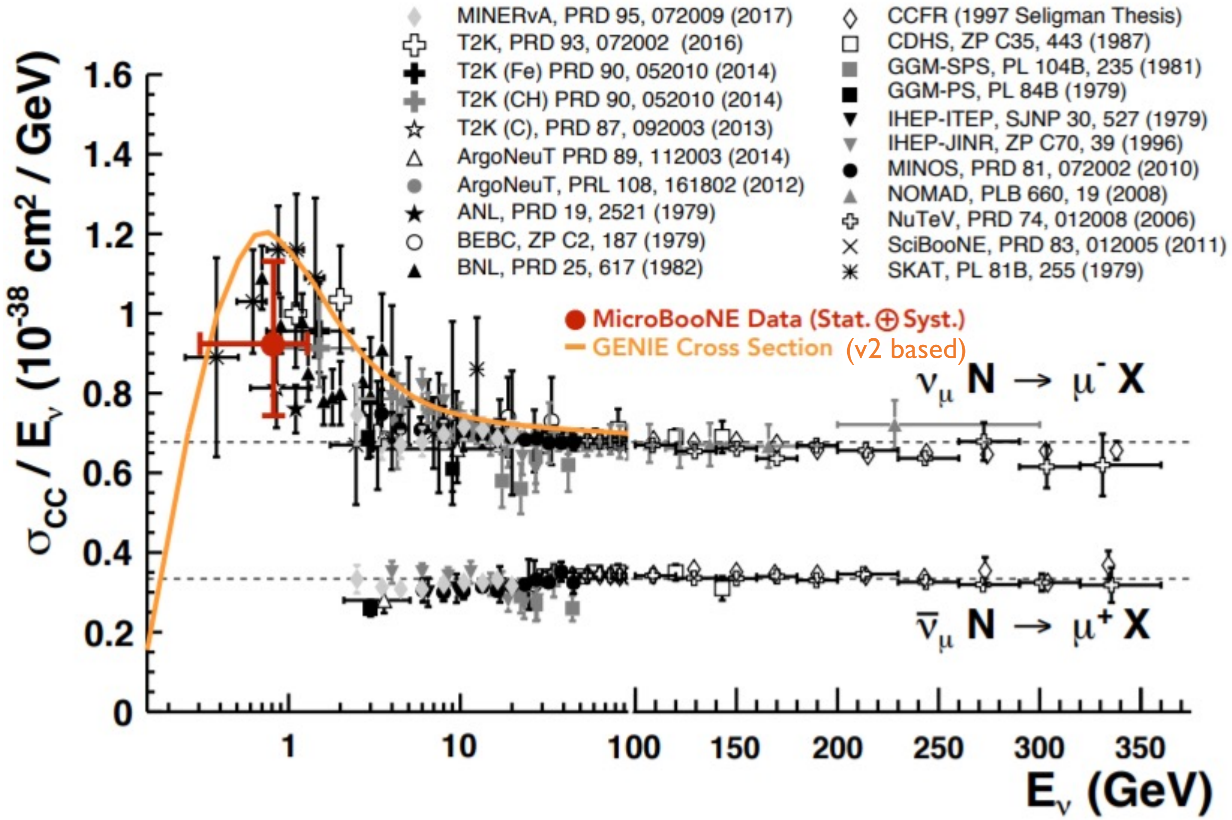
- Main physics goals:
  - Investigate MiniBooNE low-energy excess (plenary session II this morning, by Bonnie F.)
  - Measure ν-Ar interaction cross-sections

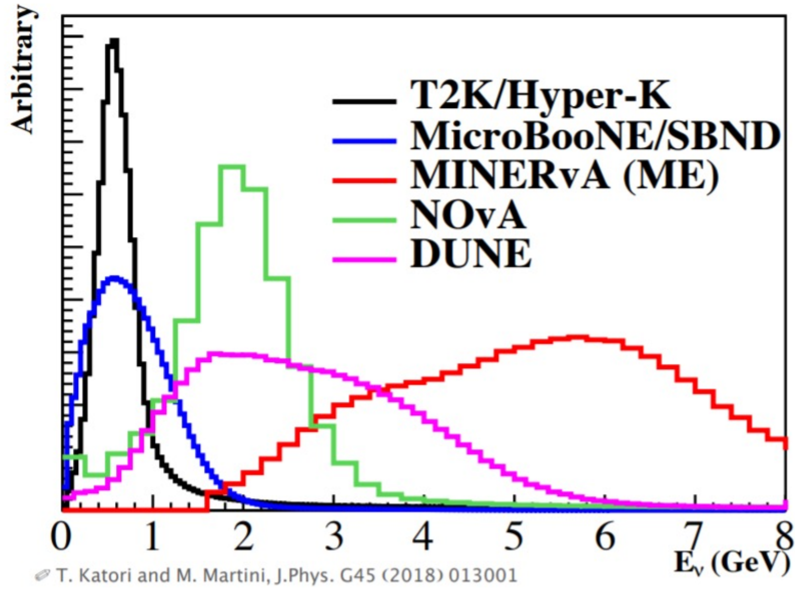


MicroBooNE detector



Measurements of Inclusive ν_μ Charged-Current (CC) Cross Section



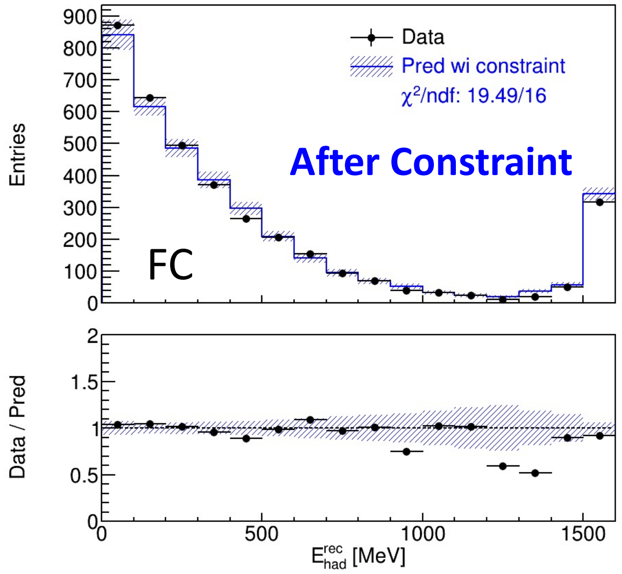


Review of Particle Physics
PDG, PTEP 2020 (2020) 8, 083C01

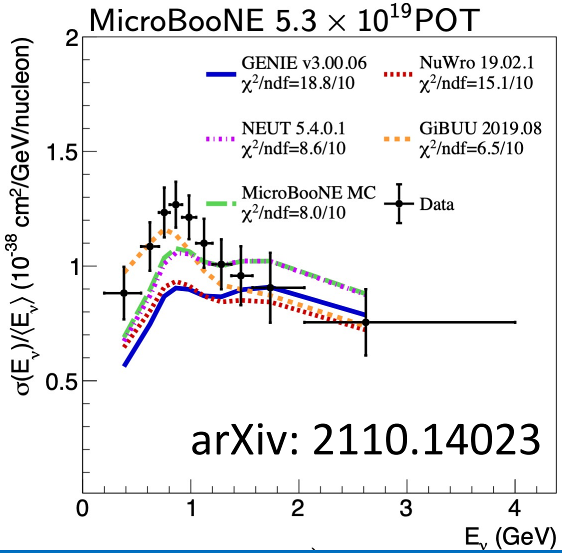
- One of the most important systematics for precision accelerator neutrino oscillation measurement
- **Energy-dependent** inclusive cross section is a good test of overall modeling of all the interaction processes, and form a good basis for the study of various exclusive interaction processes

Highlights in This Talk

- Stringent model validation for hadronic missing energy performed with a formalism of conditional constraint

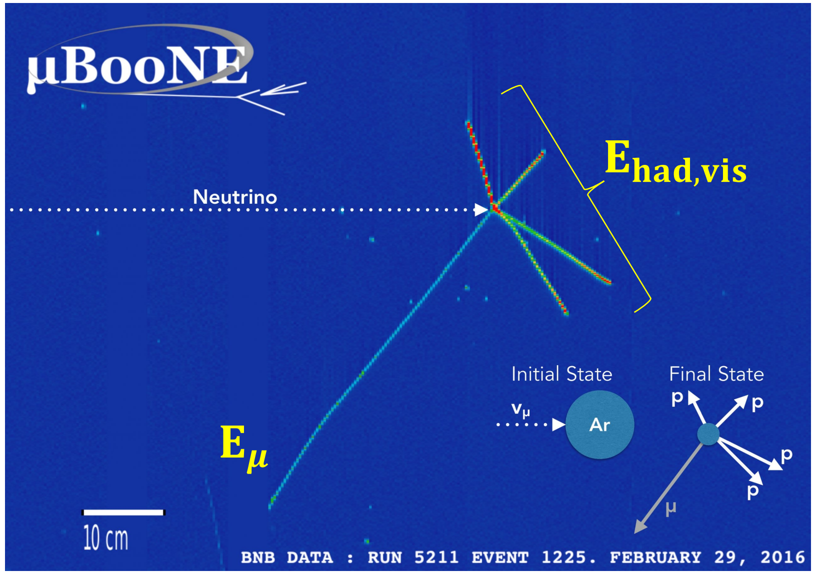


- Measurement of energy-dependent inclusive ν_μCC cross section



Energy Model Validation: True E_ν to E_ν^{rec}

- Neutrino energy modeling is also critical for neutrino oscillation measurements
- Key challenge: verify the modeling of the undetectable missing hadronic energy



True energy components:

$$\boxed{E_\nu = E_\mu + E_{had,vis} + E_{had,missing}}$$

Calorimetric energy reconstruction:

$$\boxed{E_\nu^{rec} = E_\mu^{rec} + E_{had,vis}^{rec}}$$

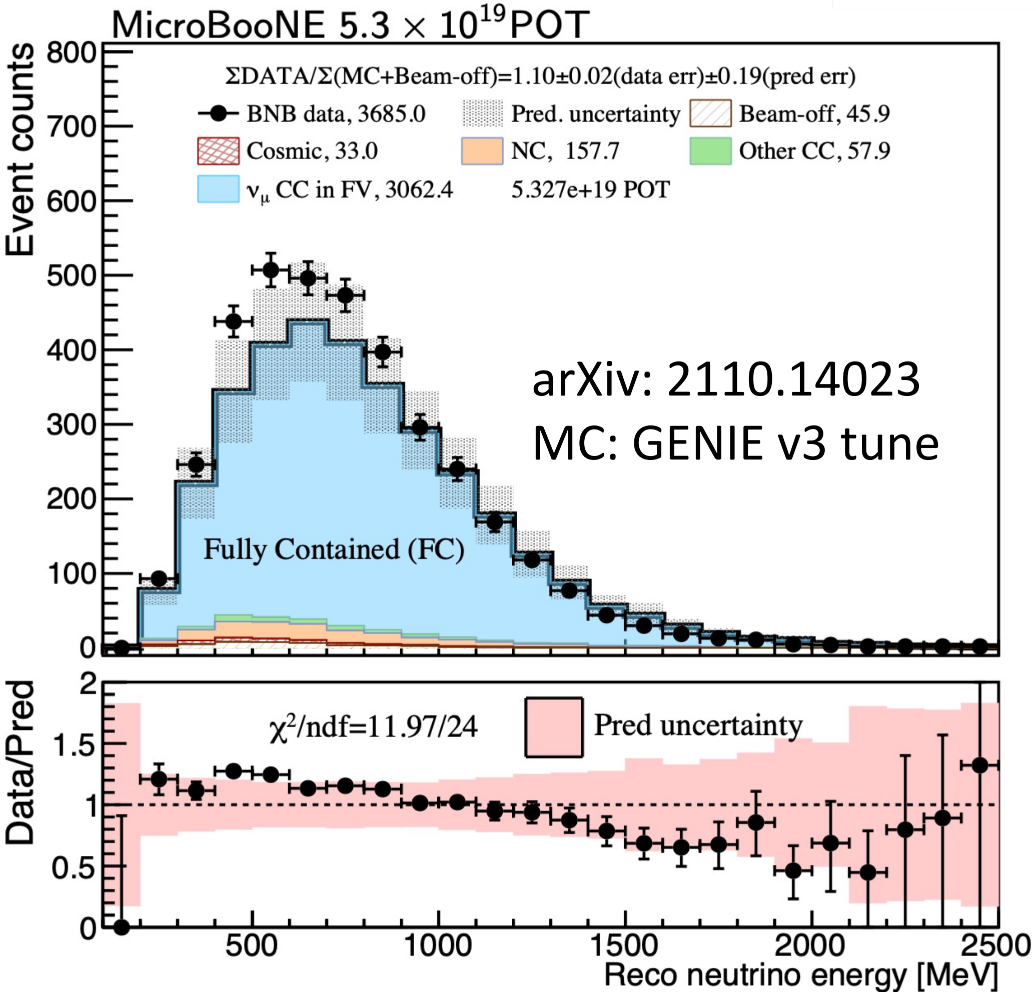
- We overcome this challenge leveraging LArTPC's simultaneous measurements of lepton energy and visible hadronic energy
  - We measure two differential cross sections ($d\sigma/dE_\mu$, $d\sigma/d\nu$) in addition to the total cross section $\sigma(E_\nu)$

Verify the modeling of the missing hadronic energy at MicroBooNE

Selection of Inclusive Charged-Current ν_μ Interactions

	Efficiency	Purity	Cosmic-μ rejection
Trigger	1	5e-5	1
Generic-ν detection	80%	65%	7e-6
ν_μCC **(Fully & Partially Contained)**	**68%**	**92%**	7e-7

- Achieved excellent cosmic-μ rejection
  - Wire-Cell reconstruction: JINST 16 (2021) 06, P06043
  - Generic-ν detection:
    - arXiv:2012.07928, Phys. Rev. Applied 15, 064071 (2021)
- The **high-statistics** event selection allows for high-precision/multi-dimensional cross-section measurements

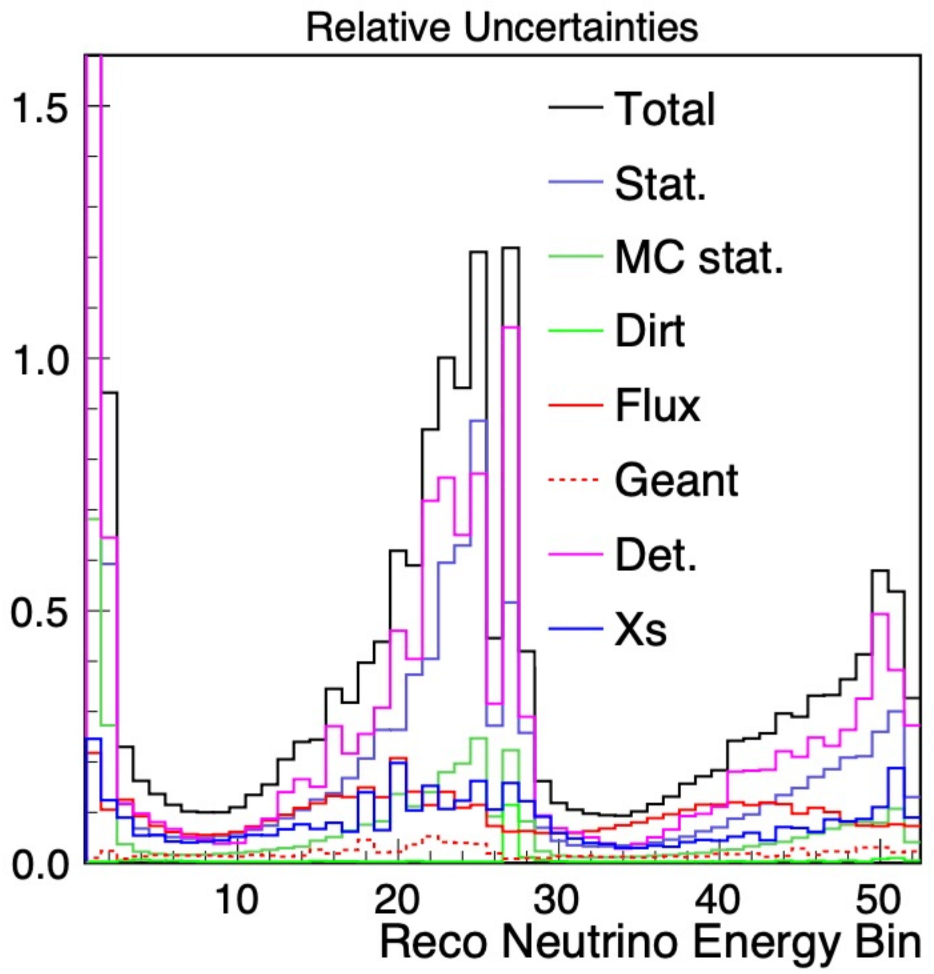


Calorimetric energy:

$$E_\nu^{rec} = E_\mu^{rec} + E_{had}^{rec}$$

Systematic Uncertainties

- BNB neutrino flux uncertainty
  - MiniBooNE: Phys. Rev. D79, 072002
- Neutrino cross section uncertainty
  - GENIE-v3 with the MicroBooNE tune: arXiv:2110.14028
- Detector systematics
  - TPC, Light, Space Charge, Recombination
  - Bootstrapping approach
- Hadron-argon interaction uncertainty
  - GEANT4 reweight
- MC statistical uncertainty
  - Bayesian approach
- Dirt systematics
  - Materials outside the cryostat



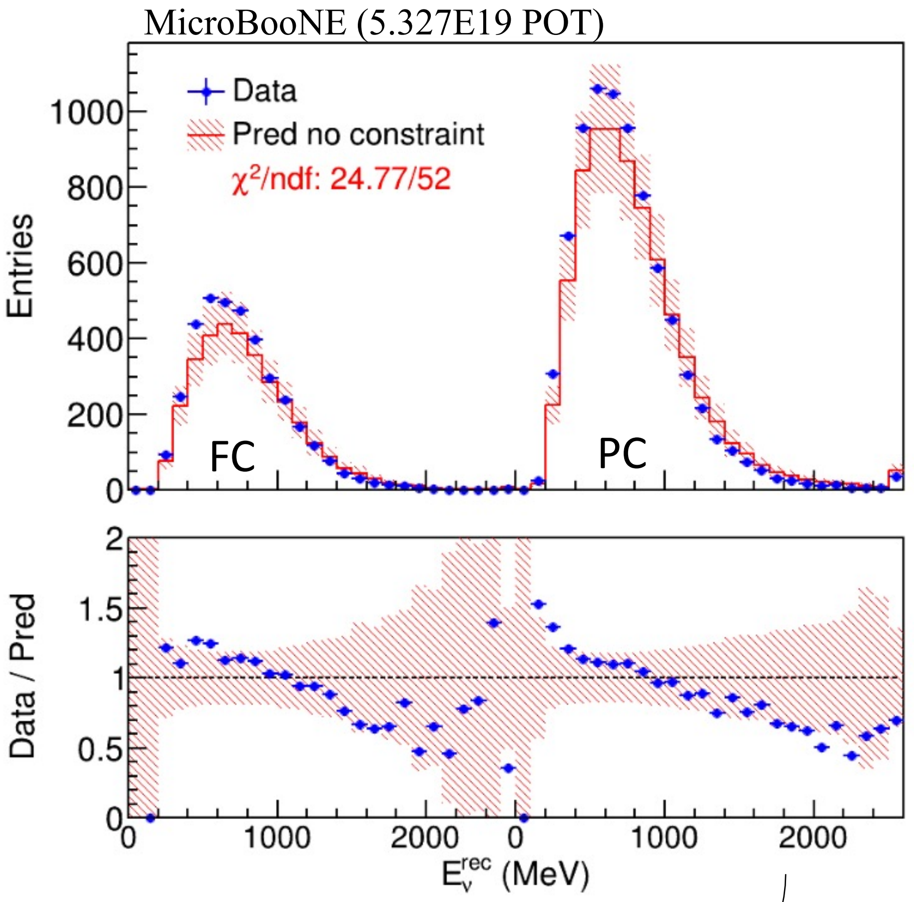
Fully contained (FC) Partially contained (PC)

Model Validation: Goodness-of-Fit (GoF)

- A covariance matrix is built from the full systematics (flux, Xs, detector, MC statistics) and statistics

$$\chi^2 = (M-P)^T \times Cov_{full}^{-1}(M,P) \times (M-P)$$

- χ^2/ndf: goodness-of-fit for the overall model
- A reasonable GoF of $\mathbf{E_\nu^{rec}}$ indicates data-MC difference can be well covered by systematics
- Overestimation of part of uncertainties could hide the potential bias in other part
  - This can be solved with conditional covariance formalism



Calorimetric energy:

$$\mathbf{E_\nu^{rec}} = \mathbf{E_\mu^{rec}} + \mathbf{E_{had}^{rec}}$$

Conditional expectation & covariance

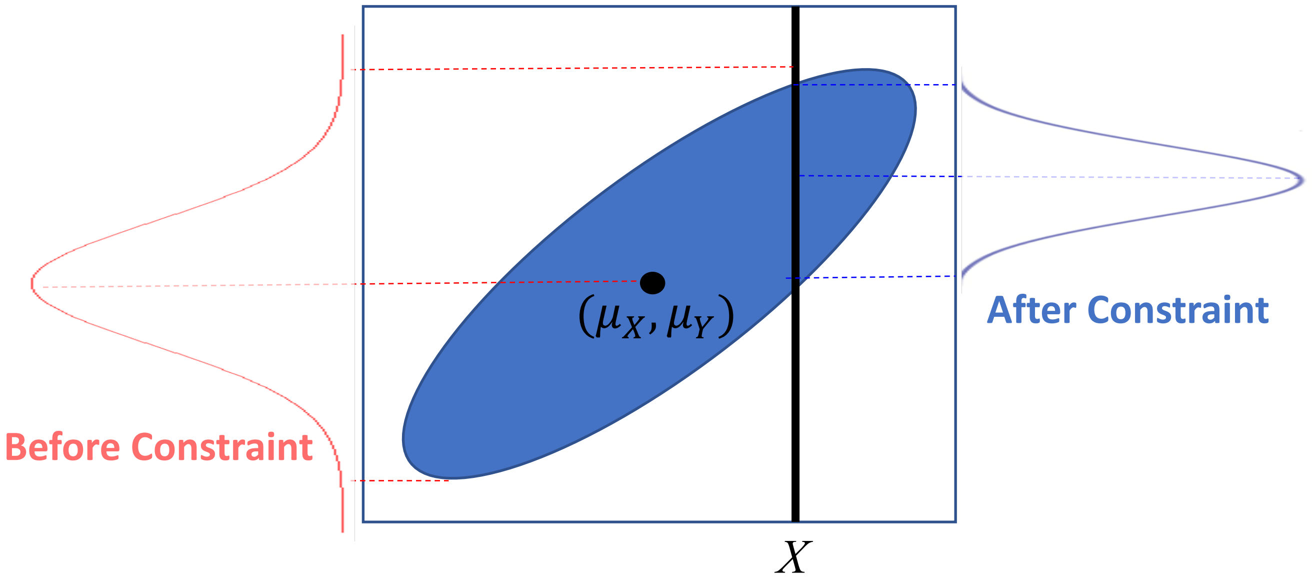
Conditional expectation & covariance

$$\boldsymbol{\mu}_{X,Y} = \begin{pmatrix} \mu_X \\ \mu_Y \end{pmatrix}, \qquad \boldsymbol{\Sigma}_{X,Y} = \begin{pmatrix} \Sigma_{XX} & \Sigma_{XY} \\ \Sigma_{YX} & \Sigma_{YY} \end{pmatrix}$$

$$\mu_{Y|X} = \mu_Y + \Sigma_{YX}\Sigma_{XX}^{-1}(X - \mu_X)$$

$$\boldsymbol{\Sigma}_{Y|X} = \boldsymbol{\Sigma}_{YY} - \boldsymbol{\Sigma}_{YX}\boldsymbol{\Sigma}_{XX}^{-1}\boldsymbol{\Sigma}_{XY}$$

* A variant of Gaussian Process regression

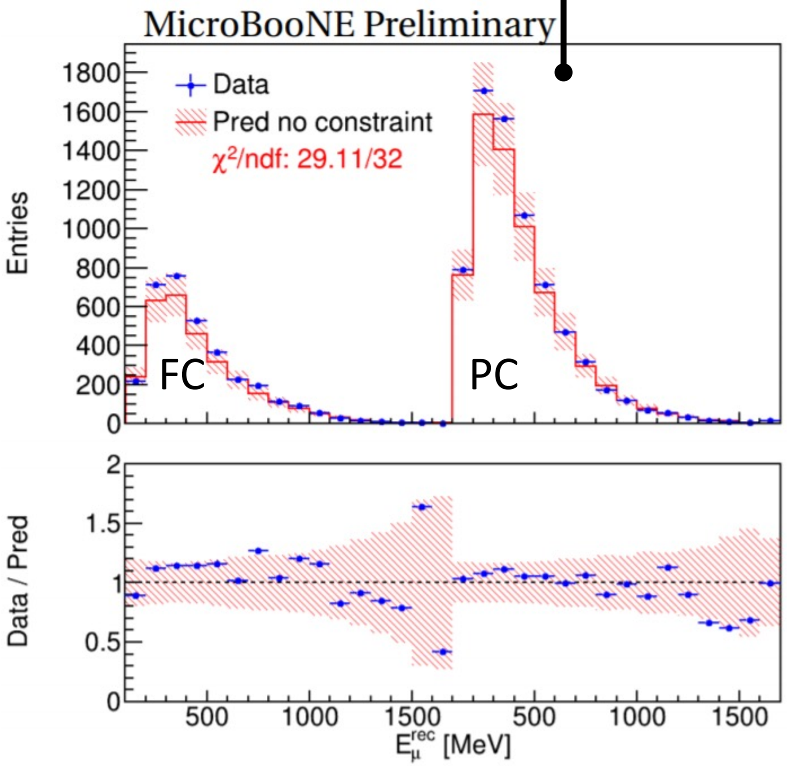


- In-situ model correction on both mean (μ) and covariance (Σ) with "sideband"
- Avoid over-tuning of MC model (flux, cross section, reinteraction, etc.)
- **For example, $\mu(E_{had}^{rec} \mid \mathrm{E}_{\mu}^{\mathrm{rec}})$ and $\Sigma(E_{had}^{rec} \mid \mathrm{E}_{\mu}^{\mathrm{rec}})$ are the mean and covariance of E_{had}^{rec} dsitribution after constraint to $\mathrm{E}_{\mu}^{\mathrm{rec}}$ distribution**
  - Reduce common systematics
  - Estimate correlated statistical uncertainty with bootstrapping (sampling w/ replacement)

Model Validation: $\mathrm{M}(\mathbf{E}_{\mu}^{\mathbf{rec}})$ vs. $\mu(\mathbf{E}_{\mu}^{\mathbf{rec}})$

- LArTPC can separate lepton and hadronic energy from charged-current interactions

$$\mathbf{E}_{\nu} = \mathbf{E}_{\mu} + \mathbf{E}_{\mathbf{had,vis}} + \mathbf{E}_{\mathbf{had,missing}}$$



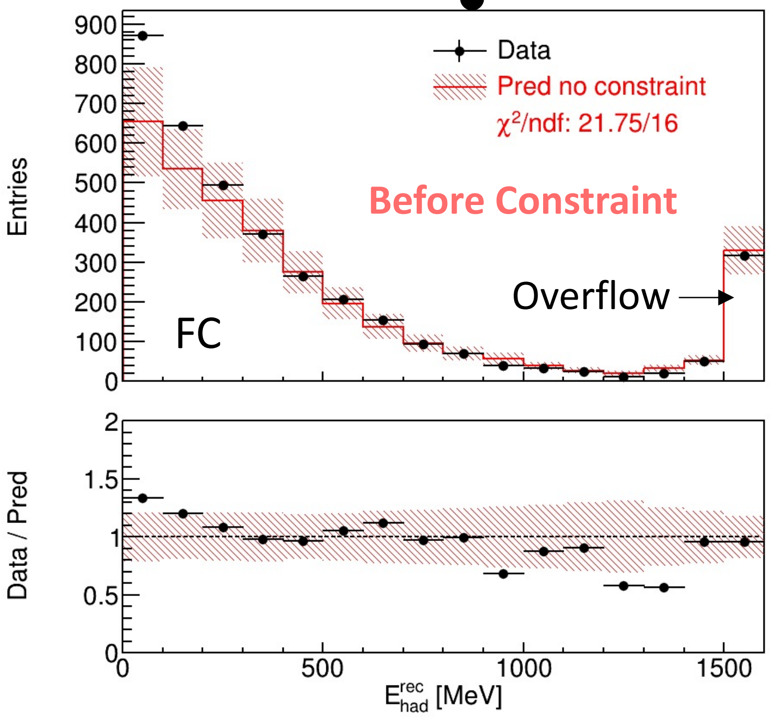
FC: fully-contained events in the fiducial volume (FV)
PC: partially contained events in the FV
Goodness-of-fit test:
$\chi^2 = (M\text{-}\mu)^{\mathsf{T}} \cdot \Sigma^{-1} \cdot (M\text{-}\mu)$

- Good agreement within model uncertainty given that χ^2/ndf = 29.11/32

Model Validation: $M(\mathbf{E}_{\mathbf{had}}^{\mathbf{rec}})$ vs. $\mu(\mathbf{E}_{\mathbf{had}}^{\mathbf{rec}})$

- LArTPC can separate lepton and hadronic energy from charged-current interactions

$$\mathbf{E}_{\nu} = \mathbf{E}_{\mu} + \mathbf{E}_{\mathbf{had,vis}} + \mathbf{E}_{\mathbf{had,missing}}$$



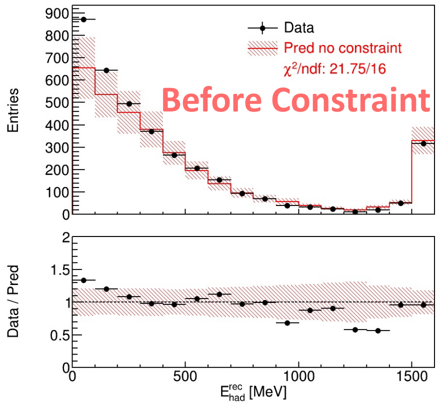
- Excess at low hadronic energy
- Mis-modeling of hadronic missing energy given neutrino flux reasonably well known?
- χ^2/ndf is reasonable but large uncertainty could hide the potential bias

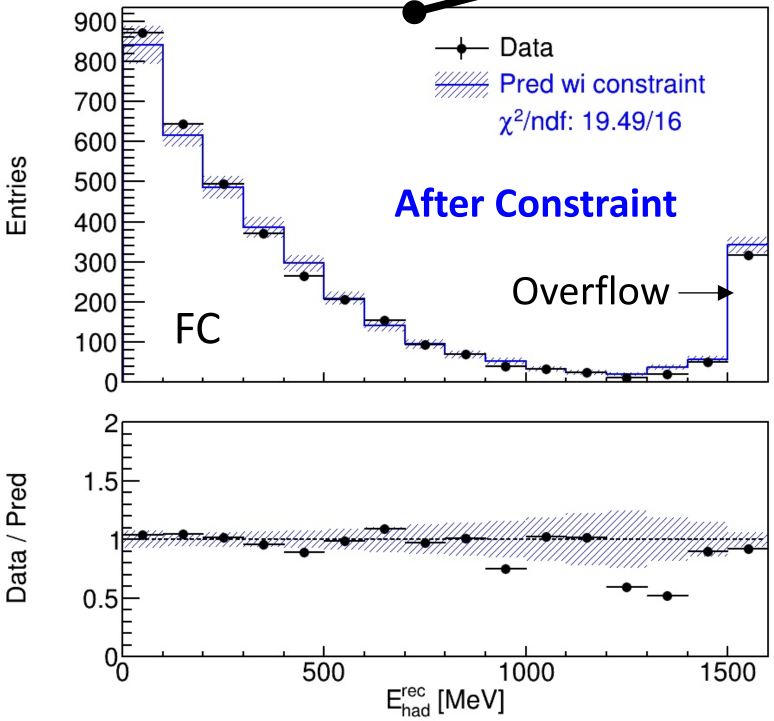
Solution: lepton-side measurement can be used to constrain the overall model (flux, cross section, etc.)

Model Validation: $M(\mathbf{E}_{\mathbf{had}}^{\mathbf{rec}})$ vs. $\mu(\mathbf{E}_{\mathbf{had}}^{\mathbf{rec}} \mid \mathbf{E}_{\mathbf{\mu}}^{\mathbf{rec}}, \cos\theta_{\mu}^{rec}, \mathrm{E}_{\nu})$

- LArTPC can separate lepton and hadronic energy from charged-current interactions

$$\mathbf{E}_{\boldsymbol{\nu}} = \mathbf{E}_{\boldsymbol{\mu}} + \underbrace{\mathbf{E}_{\mathbf{had,vis}} + \mathbf{E}_{\mathbf{had,missing}}}$$

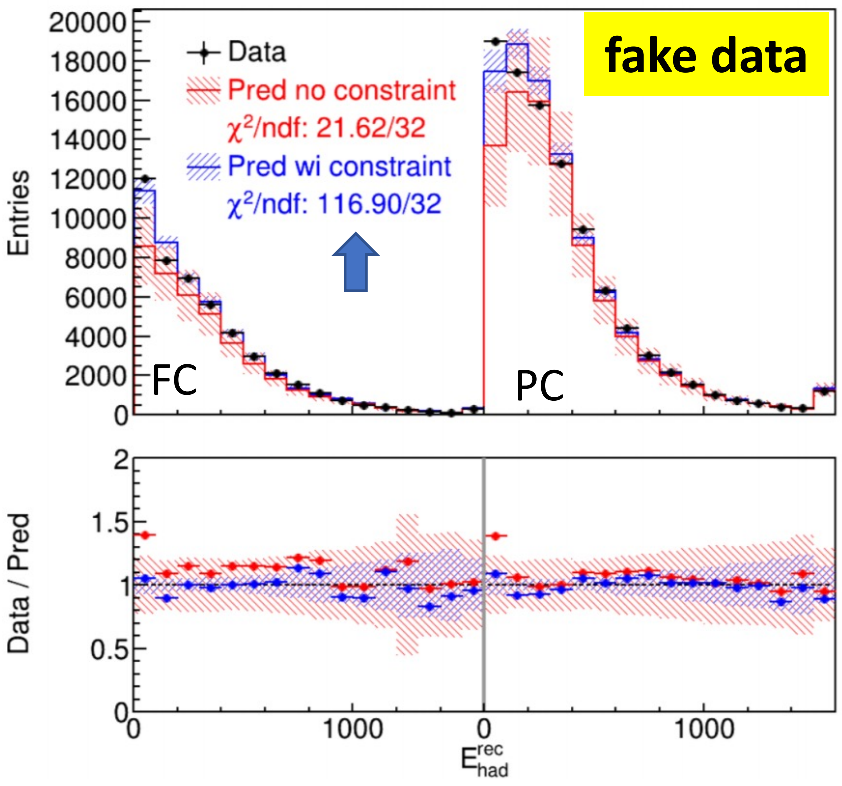




Measured muon kinematics are used to constrain the overall model (flux, cross section, etc.) for hadronic energy

- Significant reduction in overall systematic uncertainties (20% → 5%)
- No more excess at low hadronic energy with constraints from muon
- No sign of mis-modeling of the **hadronic missing energy**

Is the new method really working?



- Fake data (GENIE v2) shows a poor χ^2/ndf for $E_{\text{had}}^{\text{rec}}$ after constraint to muon kinematics

E_p^{rec} scaling factor	FC events (ndf=16)	PC events (ndf=16)	FC+PC (ndf=32)
0.95	2.55 (1.00)	4.08 (1.00)	5.34 (1.00)
0.90	8.90 (0.92)	17.13 (0.38)	21.05 (0.93)
0.85	18.66 (0.29)	39.45 (0.00)	47.01 (0.04)
0.80	32.95 (0.01)	67.88 (0.00)	80.60 (0.00)

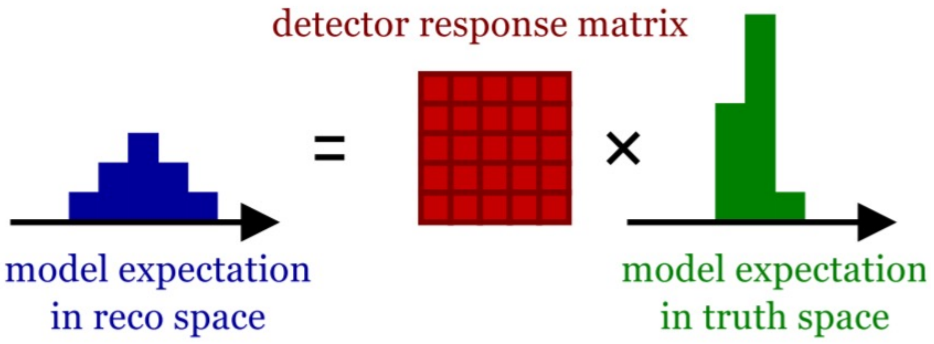
- χ^2/ndf has a significant increase with a shift of ~15% in the hadronic energy fraction allocated to protons (mimicking a variation of the proton-inelastic cross section)

The conditional constraint approach is sensitive to the underlying model difference

Cross Section Unfolding

Towards $\sigma(E)$ with Unfolding

- Understanding the cross section as a function of energy, $\sigma(E)$, is crucial for oscillation measurements
- We measure $\sigma(E)$ using Wiener-SVD unfolding [JINST, 12, P10002 (2017)]
  - Simplify procedure and maximize S/N ratio



$$\boxed{\boldsymbol{M_i} = \sum_{\boldsymbol{j}} \boldsymbol{R_{ij}} \cdot \boldsymbol{S_j} + \boldsymbol{B_i}}$$

i: bin in E_{rec}
j: bin in E_ν

* Covariance matrices are added to the measurement bin $\boldsymbol{M_i}$ through R_{ij}, B_i

Cross Section Extraction

Measurements | Flux | Cross section | Detector response | Selection efficiency | Background

$$M(E_{rec}) = POT \cdot T \cdot \int F(E_\nu) \cdot \sigma(E_\nu) \cdot D(E_\nu, E_{rec}) \cdot \varepsilon(E_\nu, E_{rec}) \cdot dE_\nu + B(E_{rec})$$

Refactorized

$$\boldsymbol{M_i = \sum_j R_{ij} \cdot S_j + B_i}$$

MicroBooNE's nominal MC (GENIE v3 tune) is used to determine R_{ij}

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Refactorized

$$\boldsymbol{M_i = \sum_j R_{ij} \cdot S_j + B_i}$$

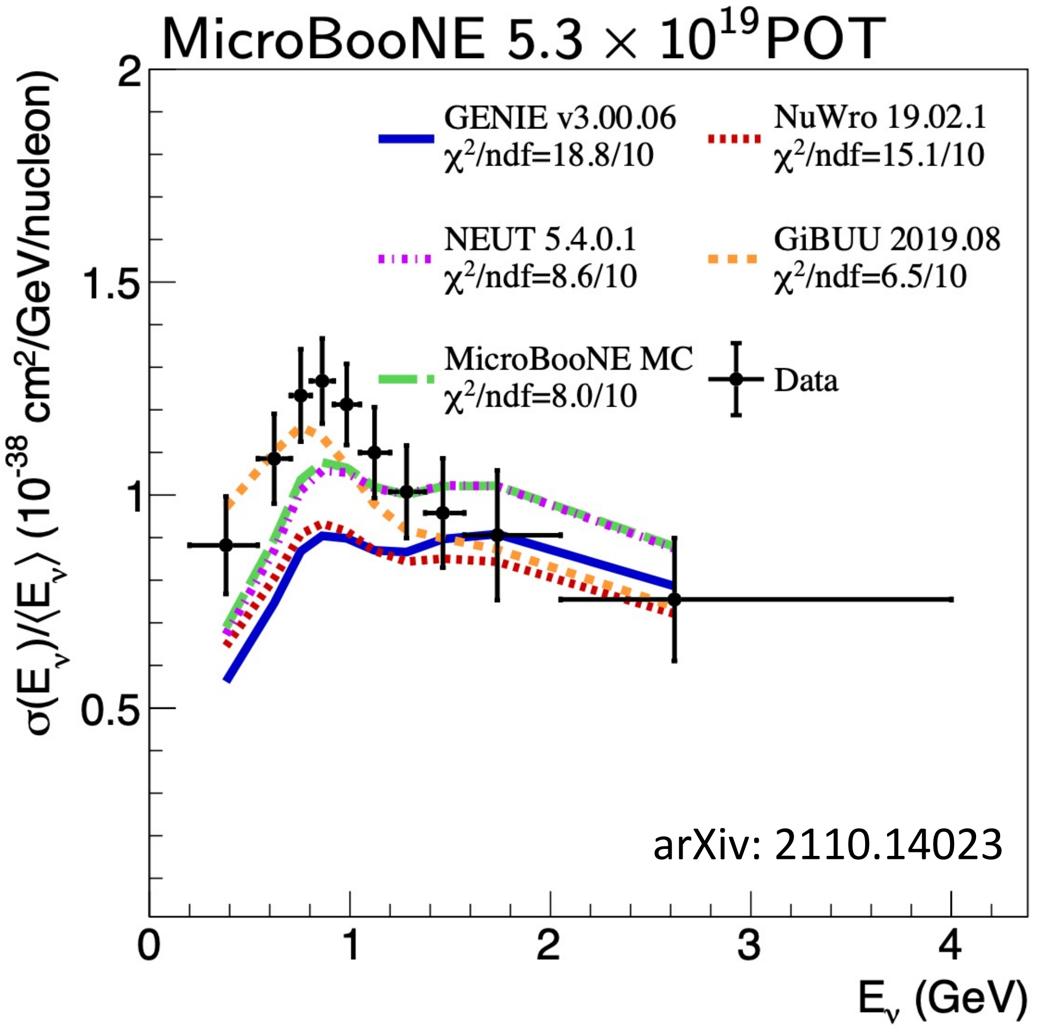
MicroBooNE's nominal MC (GENIE v3 tune) is used to determine R_{ij}

$$\boldsymbol{S_j = \frac{\int_j \bar{F}\left(E_{\nu\,\mathrm{j}}\right) \cdot \sigma\left(E_{\nu\,\mathrm{j}}\right) \cdot dE_{\nu\,\mathrm{j}}}{\int_j \bar{F}\left(E_{\nu\,\mathrm{j}}\right) \cdot dE_{\nu\,\mathrm{j}}}}$$

Nominal-flux averaged cross section

* Proper treatment of flux shape uncertainty: PhysRevD.102.113012

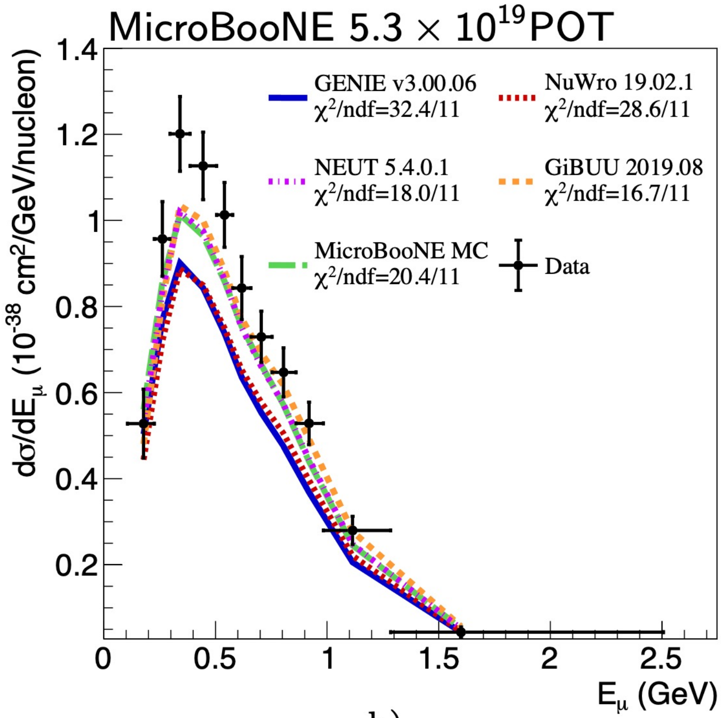
Result (I): Total Cross Section $\sigma(\mathrm{E})$



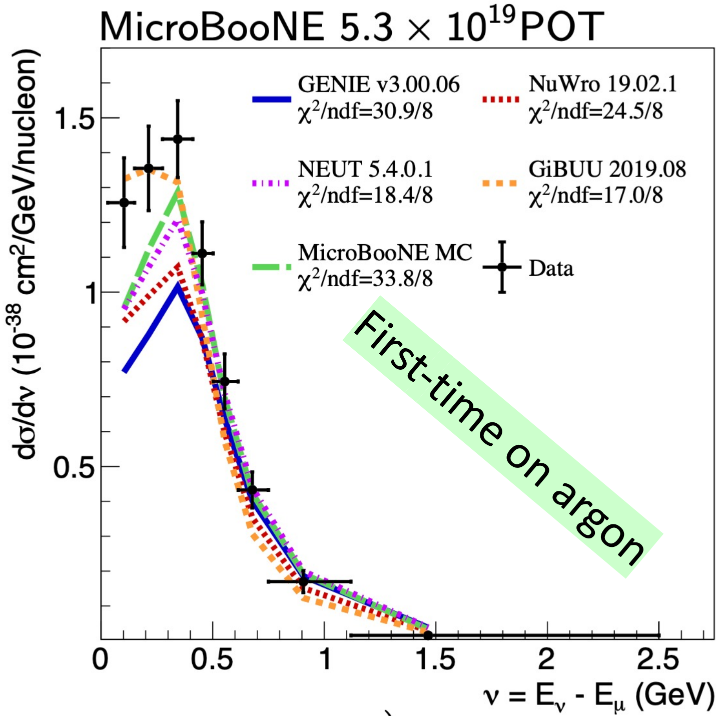
- Wiener regularization applied to each generator's model prediction for a proper data comparison
- GiBUU, NEUT and MicroBooNE GENIE tune all give reasonable agreement

Result (II): Differential Cross Section

arXiv: 2110.14023



b)



c)

- Differential cross section as a function of:
  - Muon energy: reasonable agreement in shape but differ in normalization for all generators
  - Hadronic energy transfer: GiBUU gives best agreement at low energy transfer

Summary

- More stringent model validation for hadronic missing energy performed with a formalism of conditional constraint to muon kinematic distributions
  - Enabled by a high-performance inclusive ν_μCC selection (92% purity, 68% efficiency) using Wire-Cell reconstruction at MicroBooNE

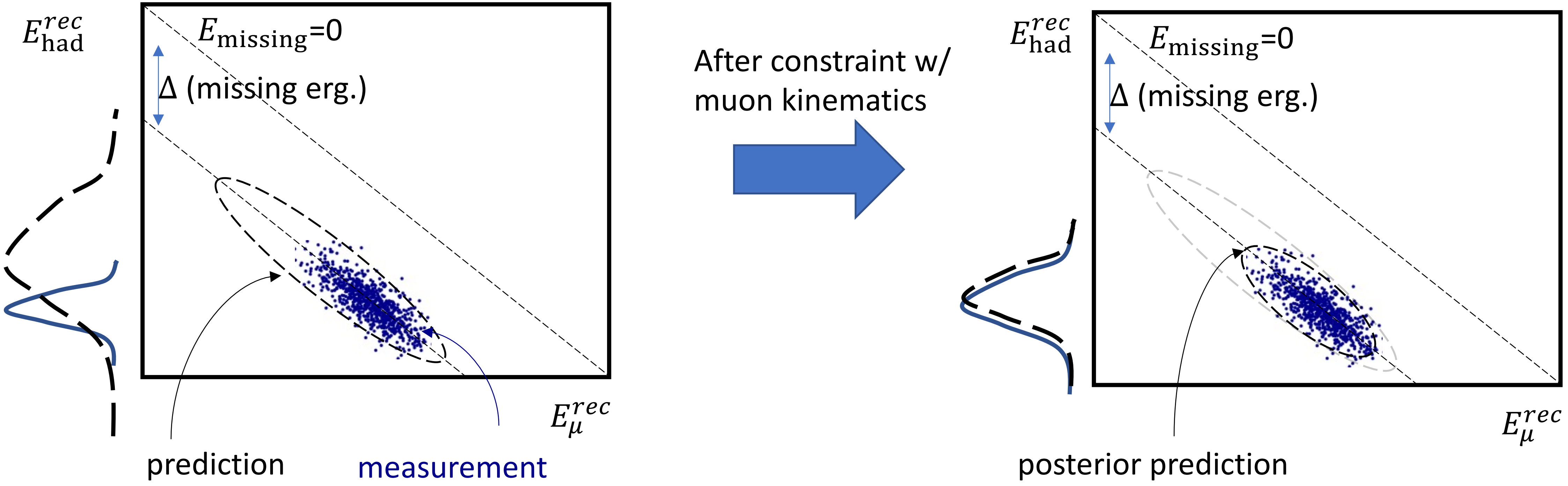
- Differential cross section $\mathrm{d}\sigma/\mathrm{dE}_\mu$ and the first-time measurement of $\mathrm{d}\sigma/\mathrm{d}\nu$ & total cross section $\sigma(\mathrm{E})$ on argon are extracted with the Wiener-SVD unfolding procedure
  - **Results are compared with the state-of-the-art prediction: GiBUU agrees the best**

- Ongoing analysis with one order magnitude more data (~7E20 POT) targeting multi-dimensional differential cross sections

Backup Slides

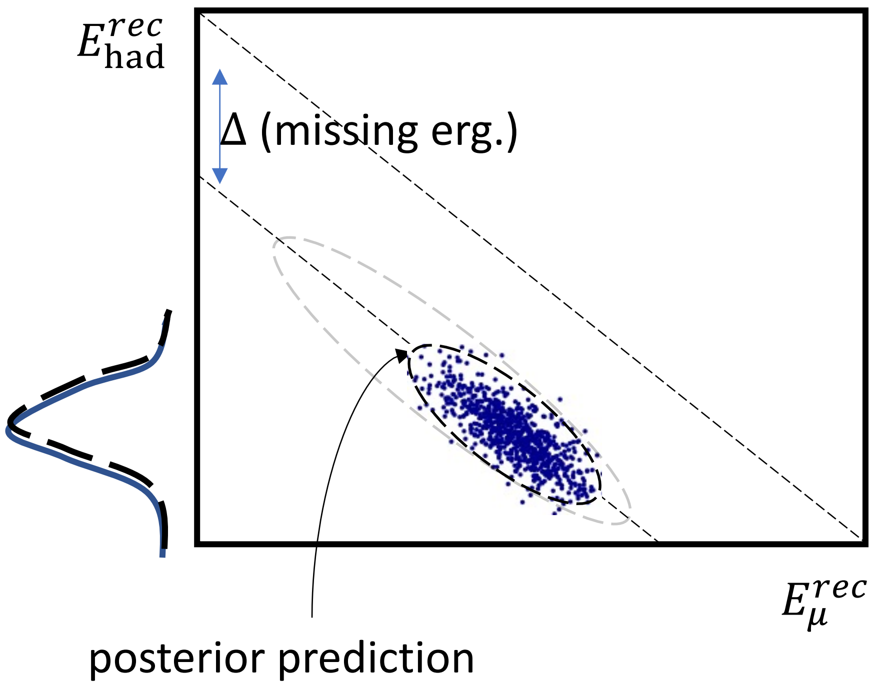
Strategy for Further Validating the Hadronic Missing Energy

- Consider an idea case: a mono-energetic neutrino beam
- The measured muon energy distribution can adjust the model prediction of hadronic energy and its uncertainty

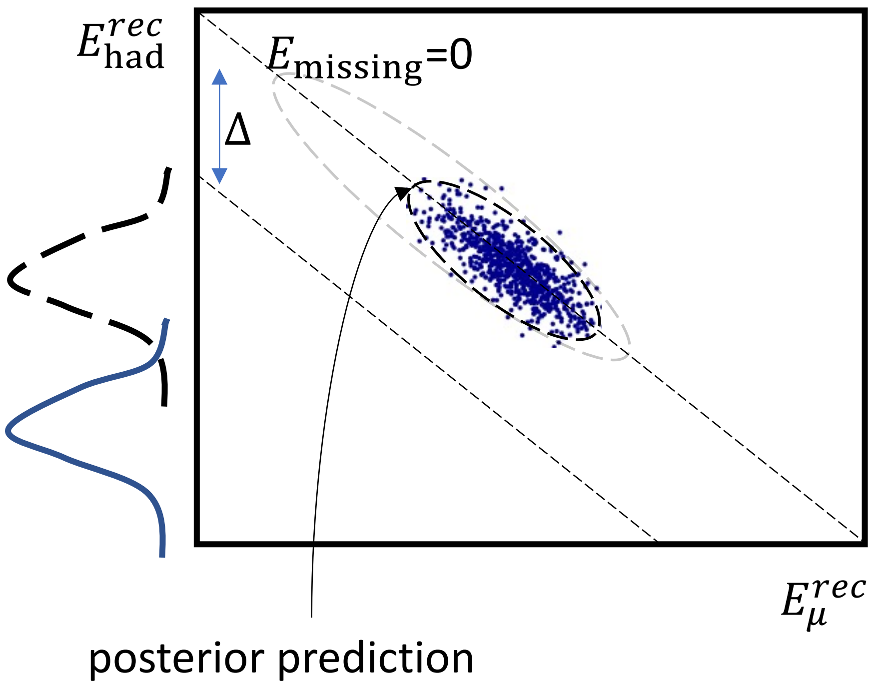


- We do not directly measure missing energy, while the agreement in the measured hadronic energy proves the proper modeling of missing energy

What if an incorrect modeling of missing energy?



(a) Correct model of missing energy

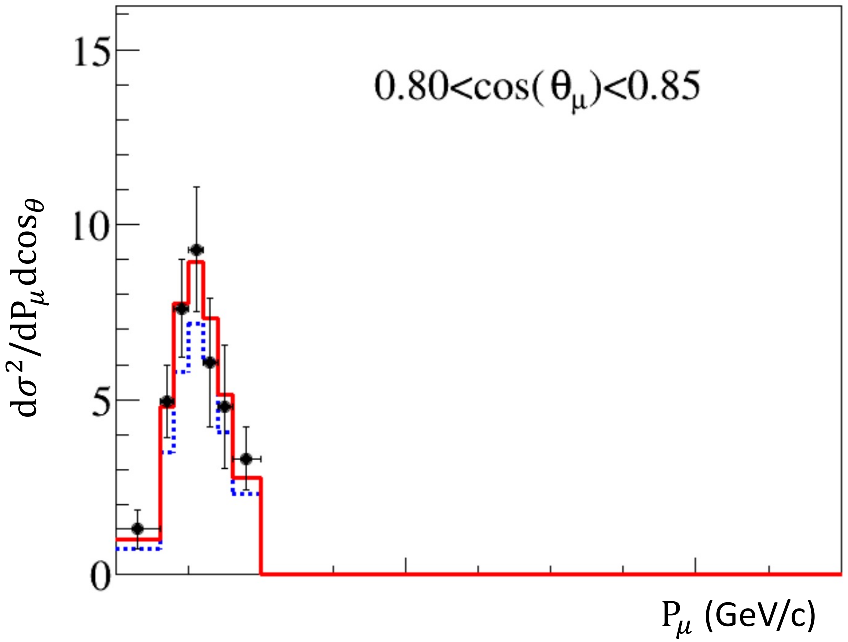


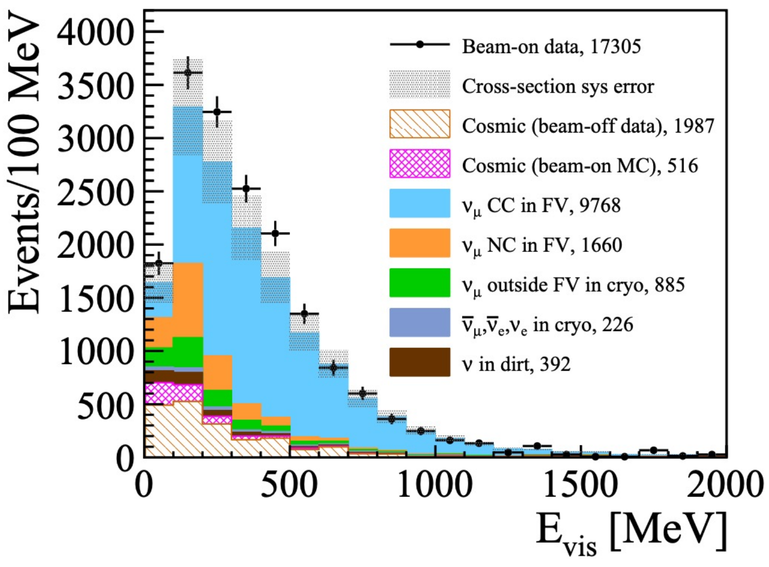
(b) Incorrect model of missing energy

- An incorrect missing energy model cannot give a consistent posterior prediction (after E_{μ}^{rec} constraint) of the measured E_{had}^{rec}
- The example here is just for illustration, the actual constraint relies on various kinematic distributions

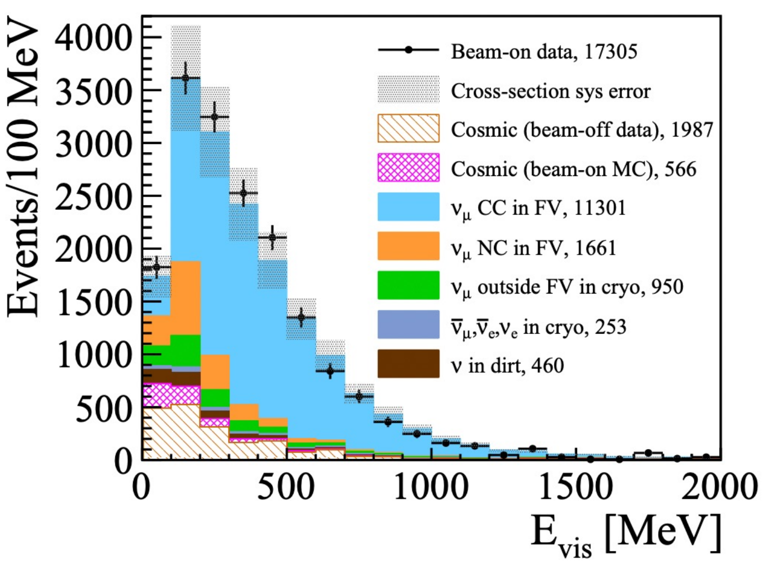
MicroBooNE GENIE Tune

- MicroBooNE has recently made significant upgrades to its neutrino interaction model (arxiv: 2110.14028)
  - GENIE v3 based RPA, 2p2h
  - Theory-driven tuning to T2K CC0π data





Before tuning



After Tuning

Cross Section Extraction

Measurements

ν_μ Neutrino Flux

ν_μCC cross section

Detector response matrix

Selection efficiency

Background

$$M(E_{rec}) = POT \cdot T \cdot \int F(E_\nu) \cdot \sigma(E_\nu) \cdot D(E_\nu, E_{rec}) \cdot \varepsilon(E_\nu, E_{rec}) \cdot dE_\nu + B(E_{rec})$$

$$\boldsymbol{M_i = \sum_j R_{ij} \cdot S_j + B_i}$$

$$\boldsymbol{S_j = \frac{\int_j \bar{F}(E_{\nu\,j}) \cdot \sigma(E_{\nu\,j}) \cdot dE_{\nu\,j}}{\int_j \bar{F}(E_{\nu\,j}) \cdot dE_{\nu\,j}}}$$

Nominal-flux weighted cross section

$$R_{ij} = \tilde{\Delta}_{ij}\, \boldsymbol{\tilde{F}_j} \qquad \boldsymbol{\tilde{F}_j = POT \cdot T \cdot \int_j \bar{F}(E_{\nu\,j}) \cdot dE_{\nu\,j}}$$

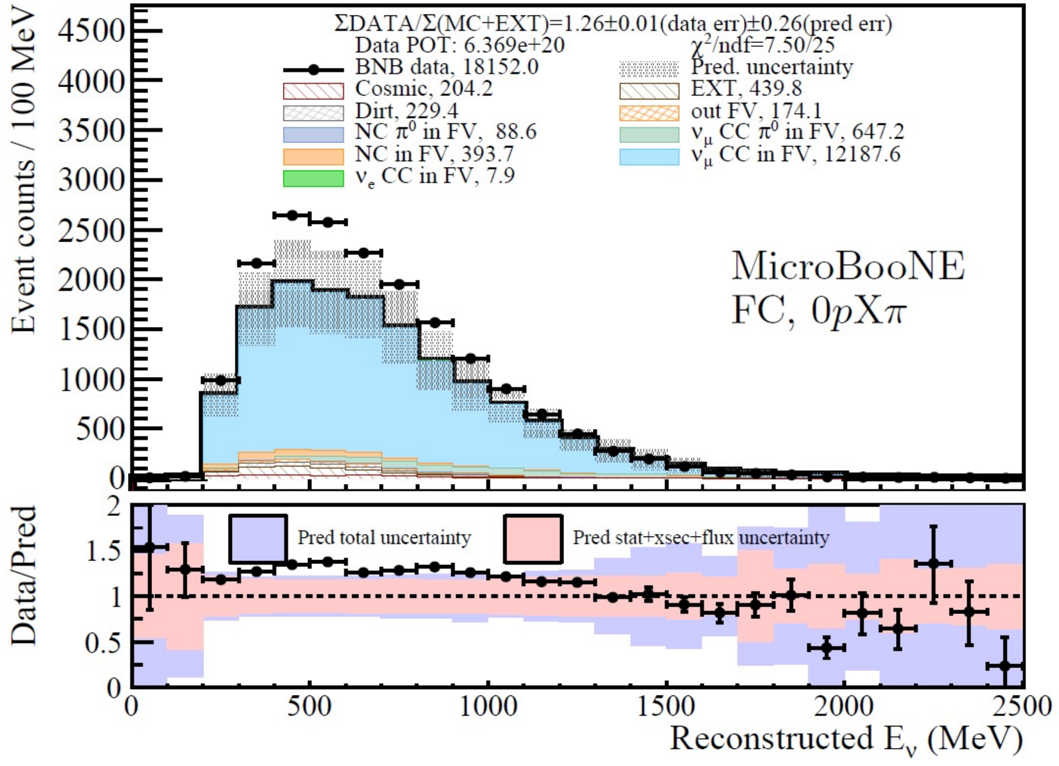
$$\tilde{\Delta}_{ij} = \frac{POT \cdot T \cdot \int_j F(E_{\nu\,j}) \cdot \sigma(E_{\nu\,j}) \cdot D(E_{\nu\,j}, E_{rec\,i}) \cdot \varepsilon(E_{\nu\,j}, E_{rec\,i}) \cdot dE_{\nu\,j}}{POT \cdot T \cdot \int_j \bar{F}(E_{\nu\,j}) \cdot \sigma(E_{\nu\,j}) \cdot dE_{\nu\,j}}$$

i: bin in E_{rec} $\quad$ j: bin in E_ν

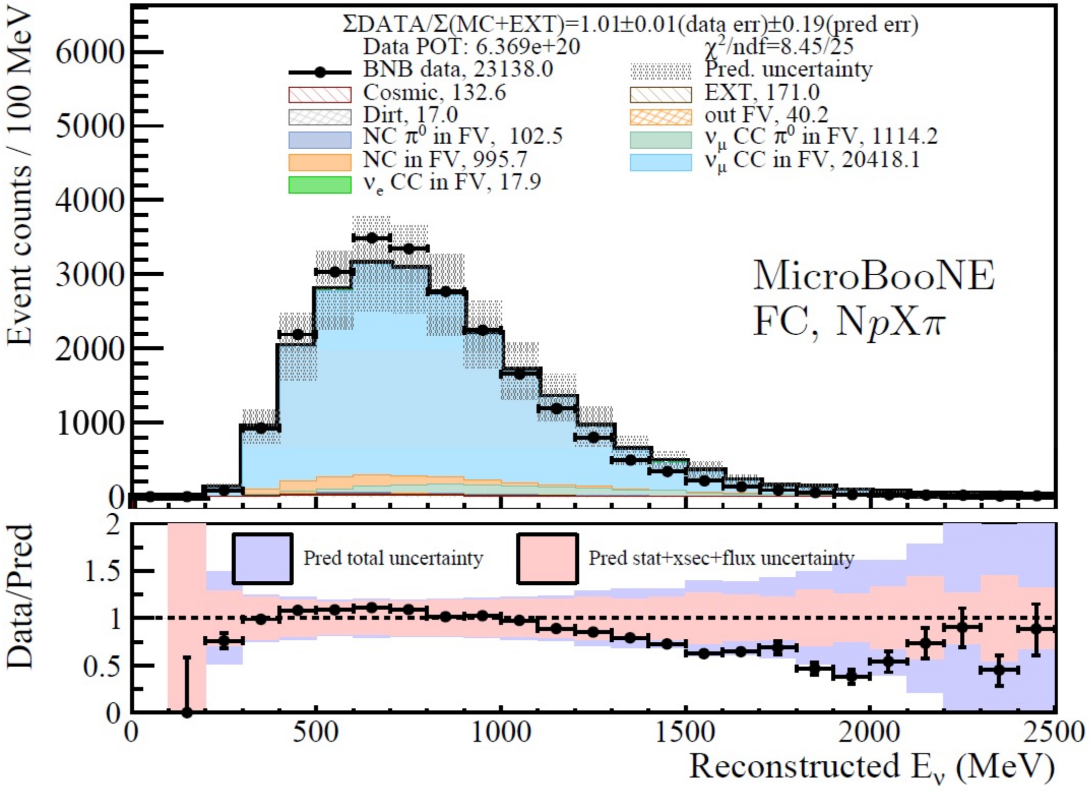
* Proper treatment of flux shape uncertainty: PhysRevD.102.113012

MicroBooNE's nominal MC (GENIE v3 tune) is used to determine R_{ij}

0p/Np separation in ν_μCC

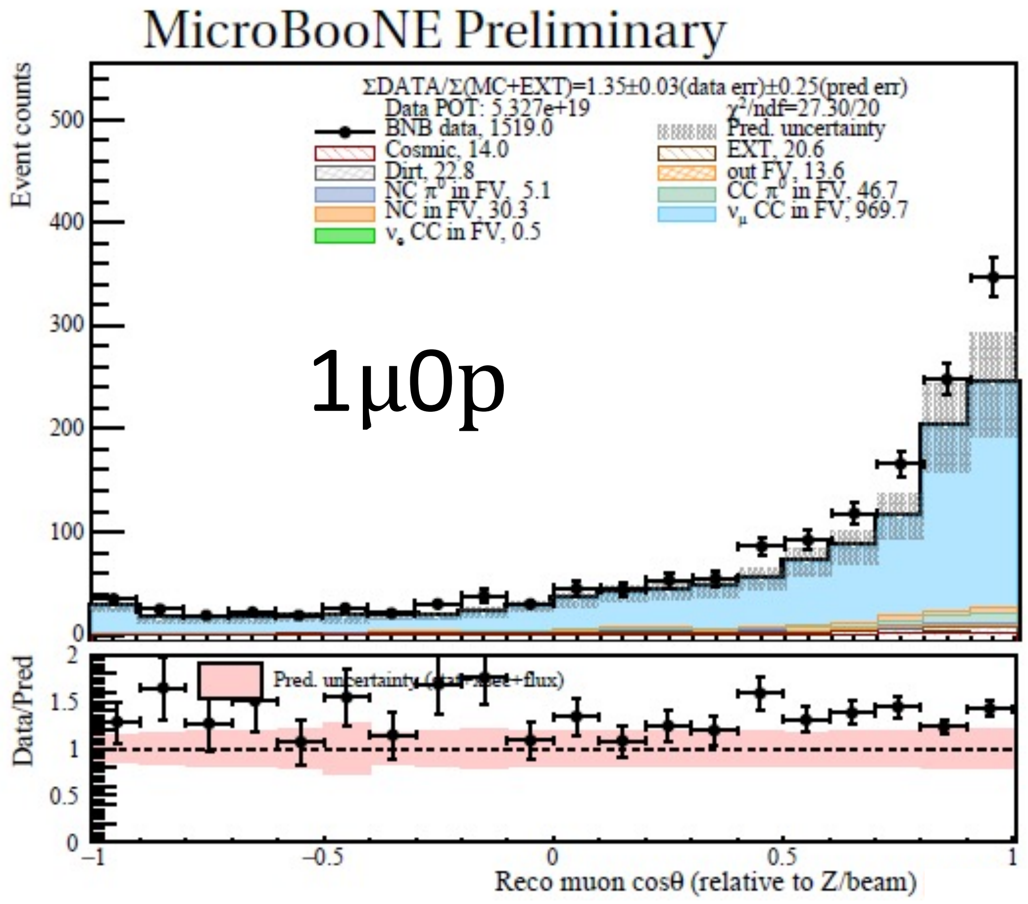


(a) FC ν_μ CC, $0pX\pi$

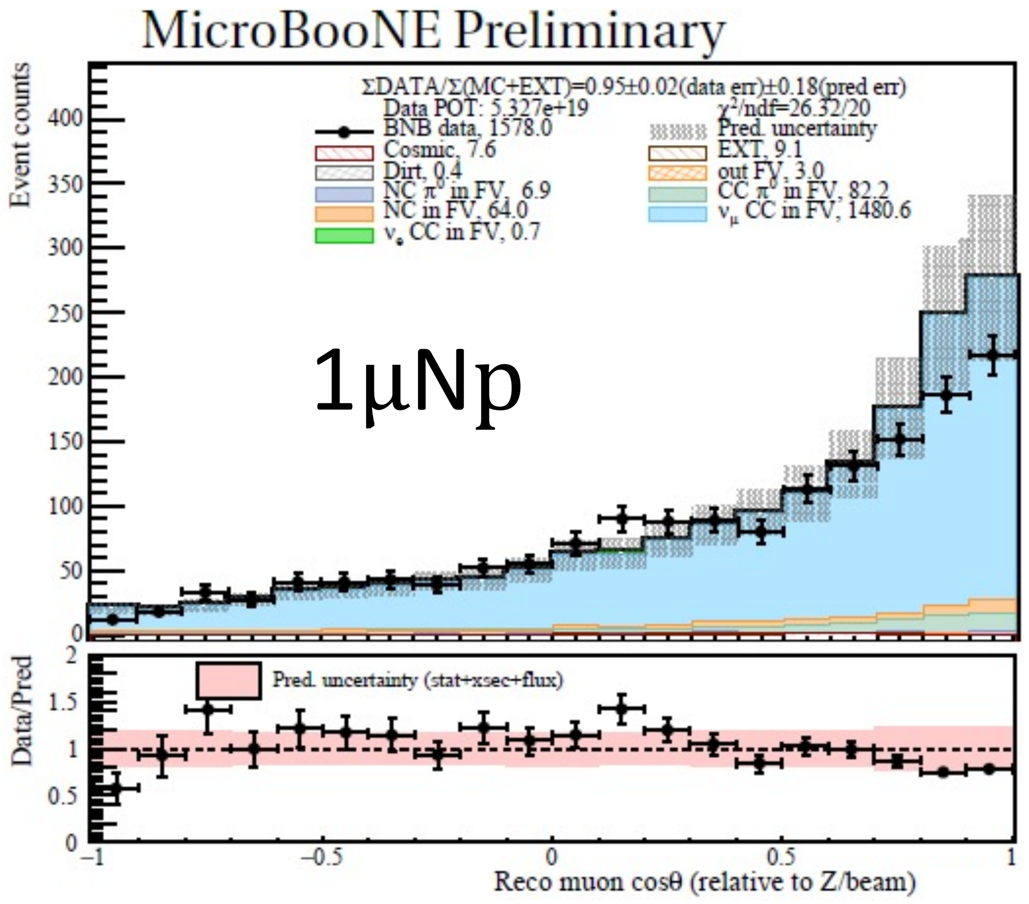


(c) FC ν_μ CC, $NpX\pi$

Model Comparison in High Dimension



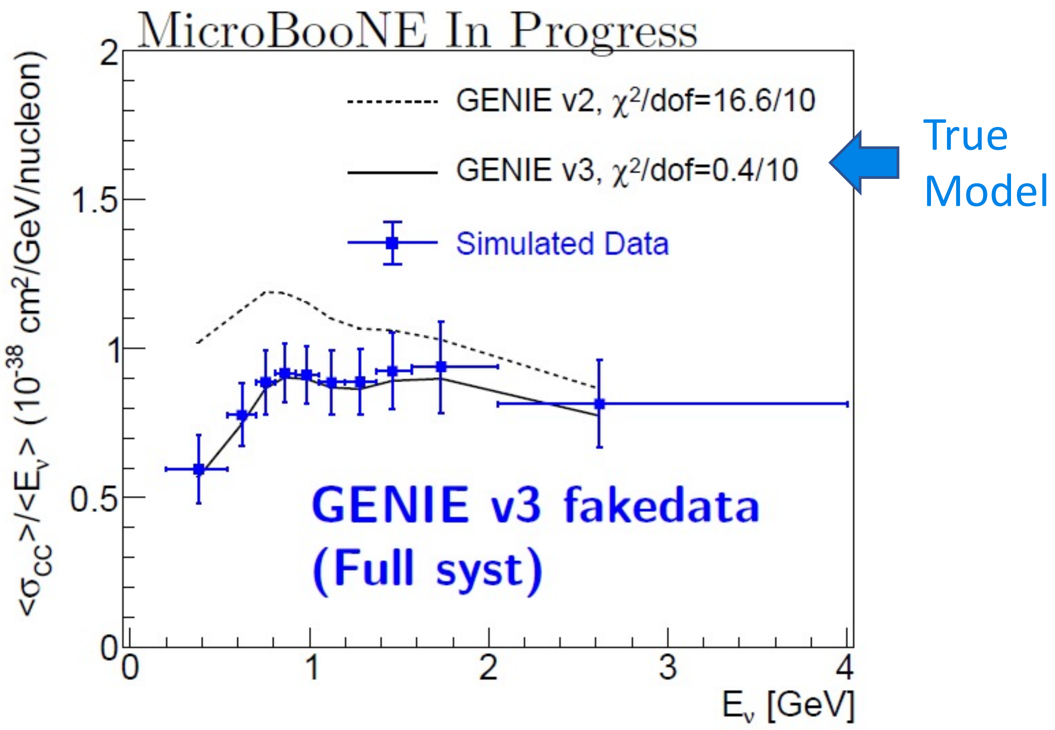
Overall excess

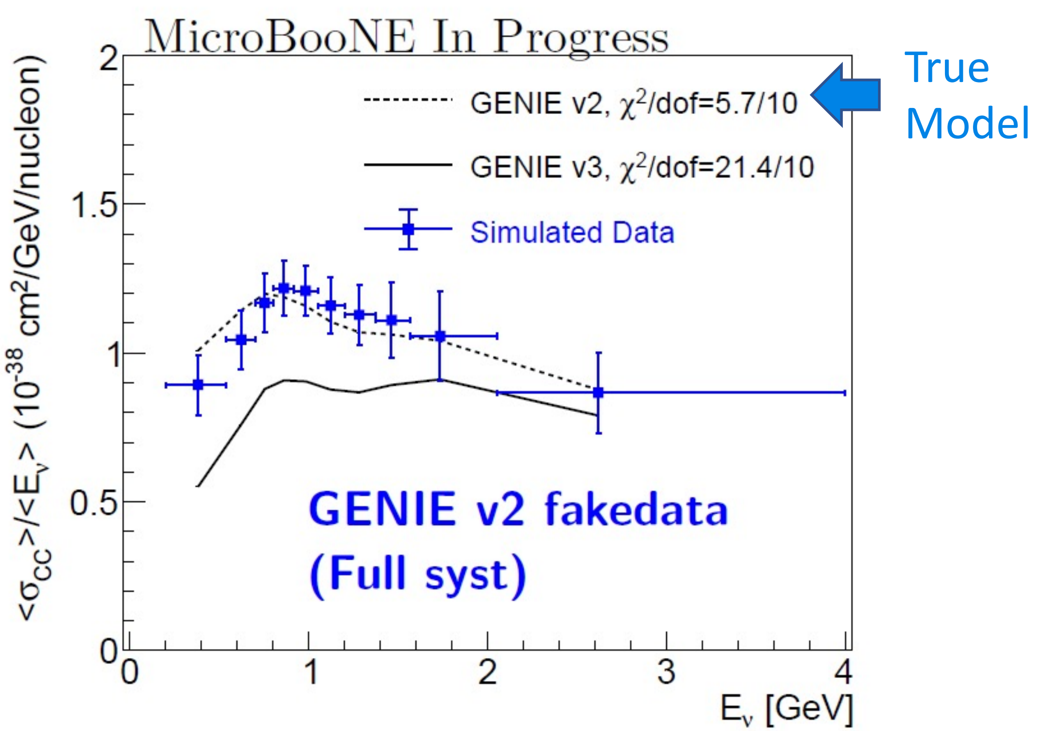


Deficit at muon forward angle

- High-statistics ν_μCC allows for multi-dimensional cross-section measurements

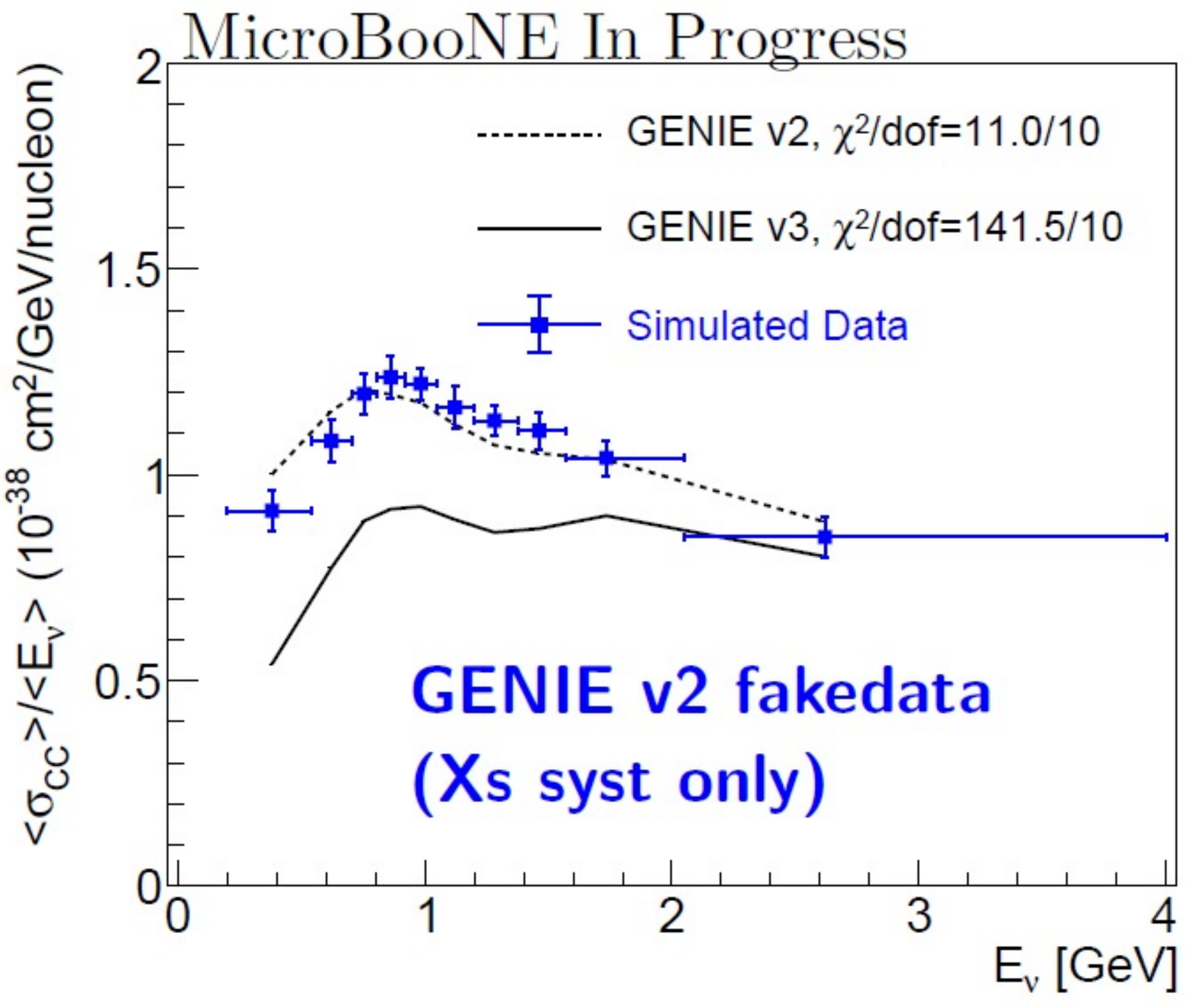
Procedure Validation with Simulated Data

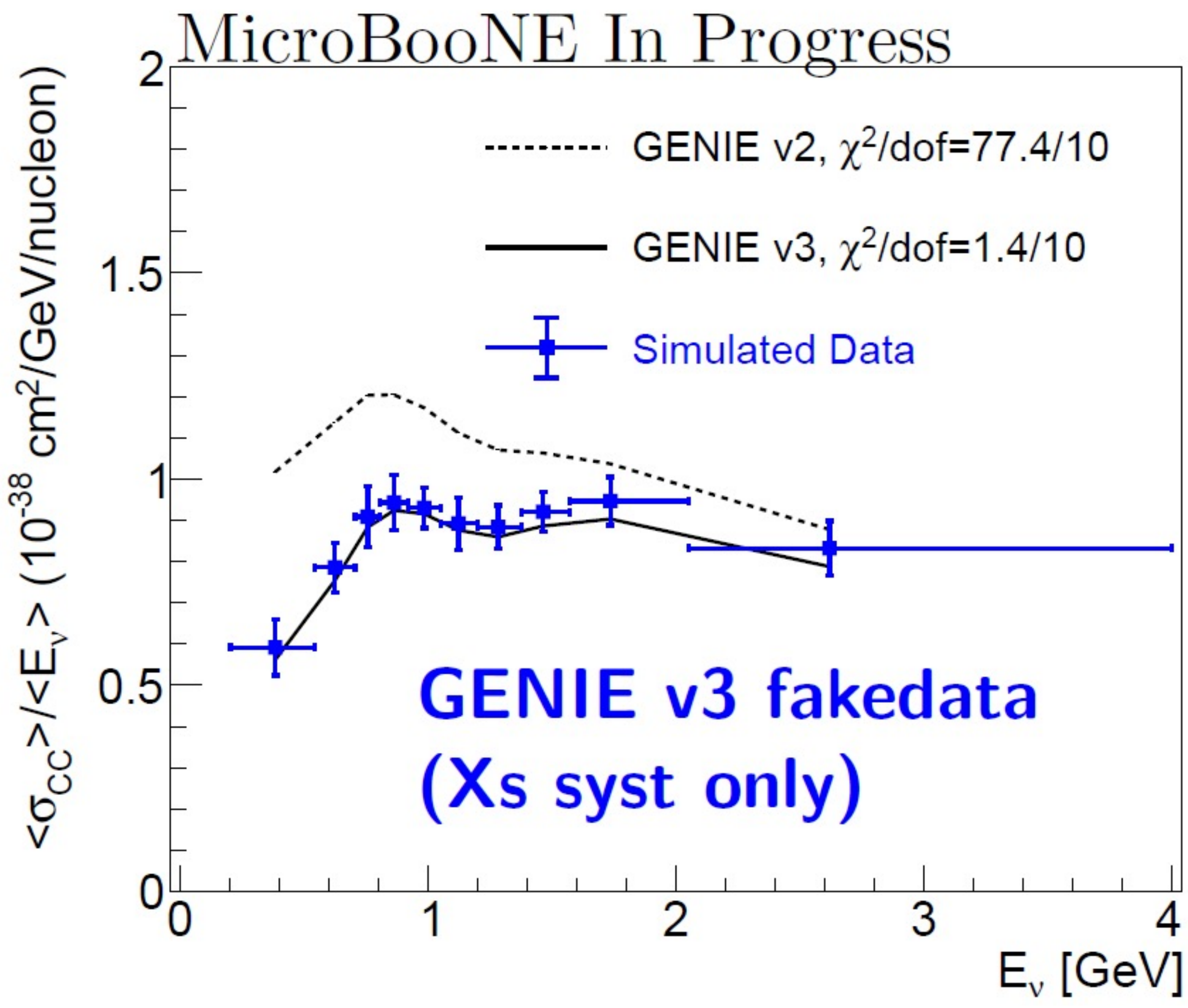




- MicroBooNE's nominal MC is used to extract the cross section from the "fake dataset" – same treatment as data
- Analyses of cross-section extraction from two simulated data sets justify the unfolding procedure

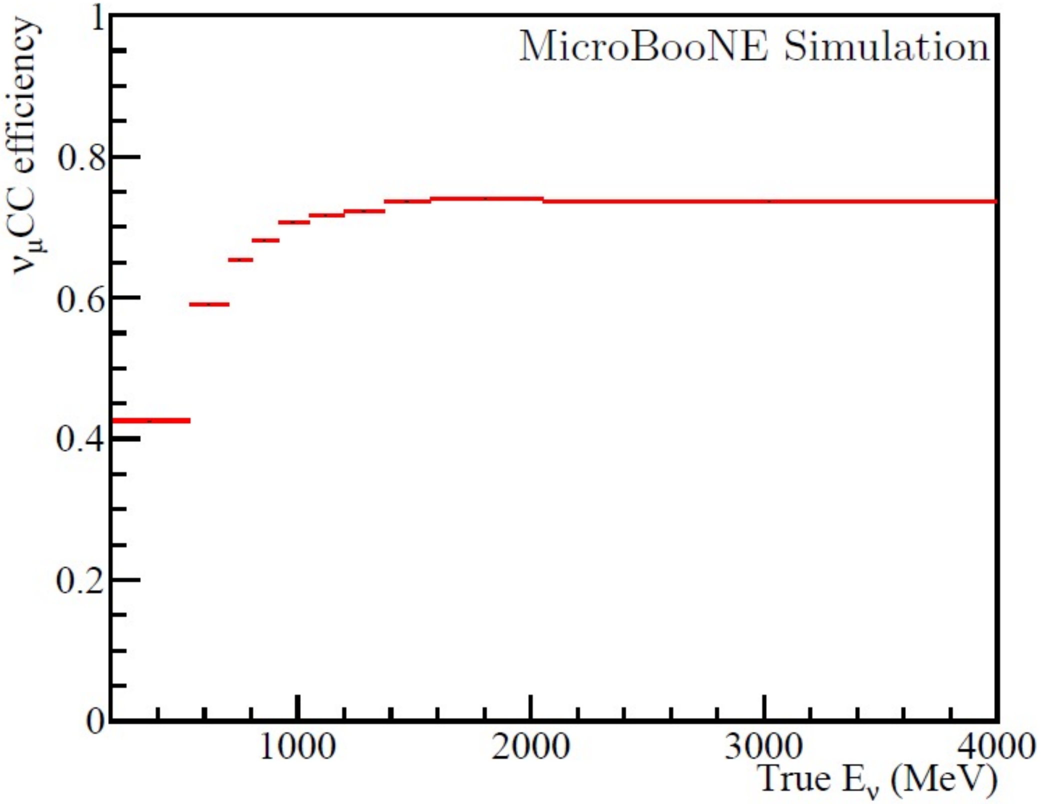
Validation with Simulated Data





ν_μCC and ν_eCC Event Selection

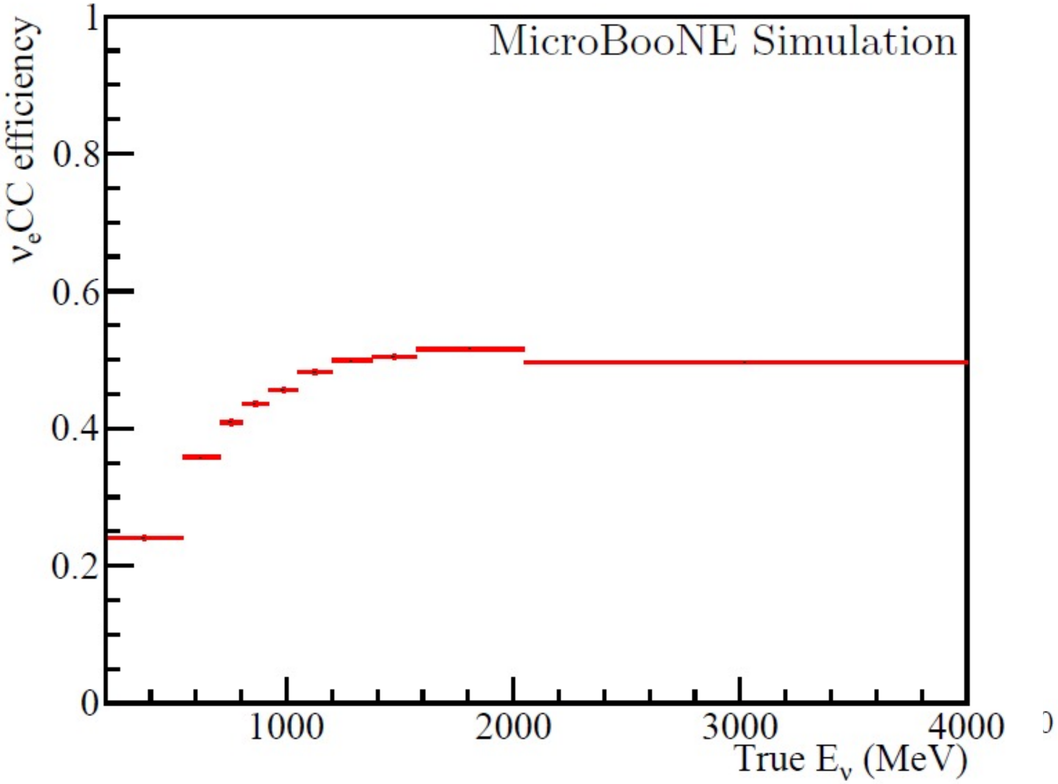
arXiv:2110.13978



Efficiency: 68%

w.r.t to all ν_μCC w. vertex in fiducial volume

Purity: 92% (**>5** improvement)



Efficiency: 46%

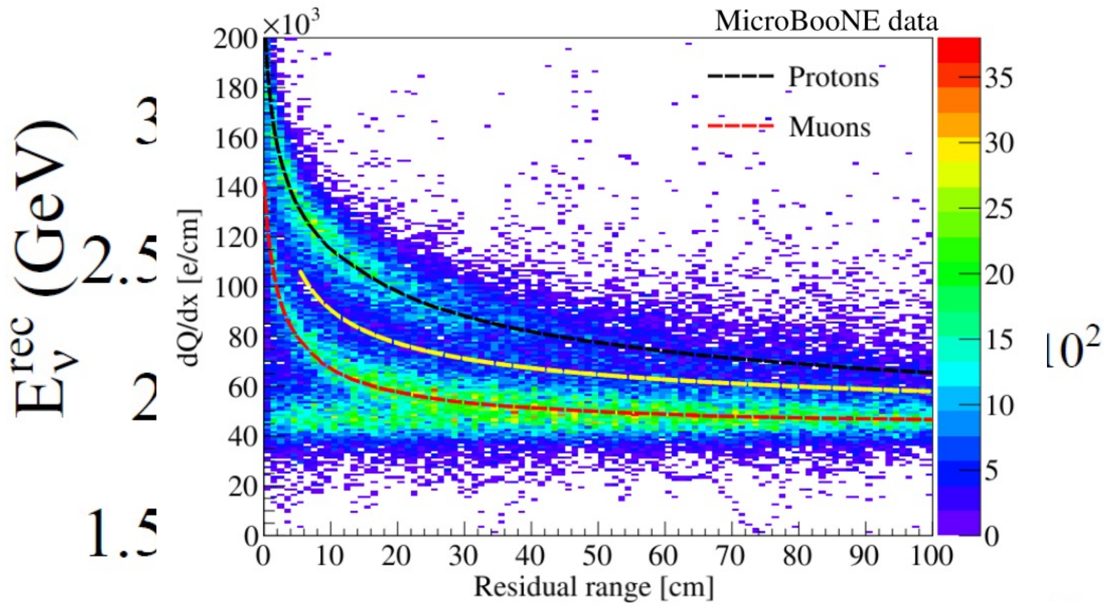
w.r.t to all ν_eCC w. vertex in fiducial volume

Purity: 82% (**>800** improvement)

As a near-surface detector, performance close to DUNE's requirement in a wide energy range

Neutrino Energy Reconstruction

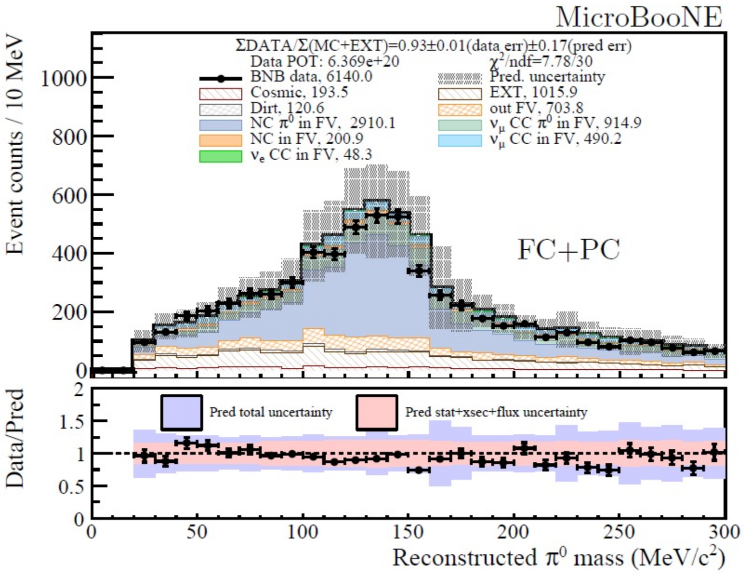
- Calorimetry energy reconstruction with particle mass and binding energy included
  if PID can be done
  - Track: Range, dQ/dx → dE/dx correction
    - Calibrated by stopped muons/protons
  - EM shower: scaling of charge
    - Calibrated by π^0 invariance mass

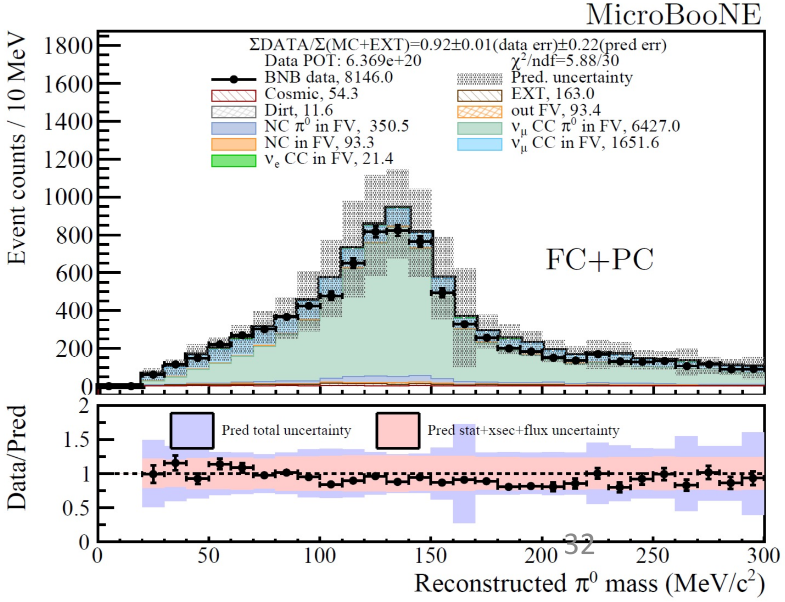


- Fully contained events

$\nu_e CC$ 10-15% resolution ~7% bia

$\nu_\mu CC$ 15-20% resolution ~10% bias





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