

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

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On behalf of the MicroBooNE collaboration  
APS DPF21

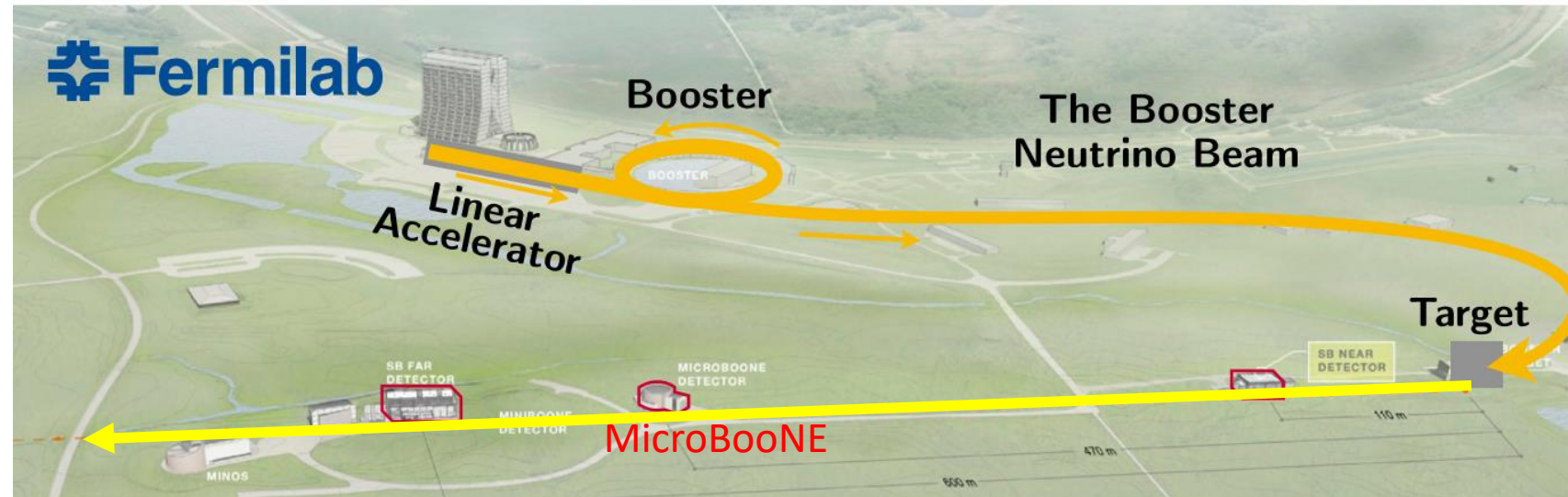
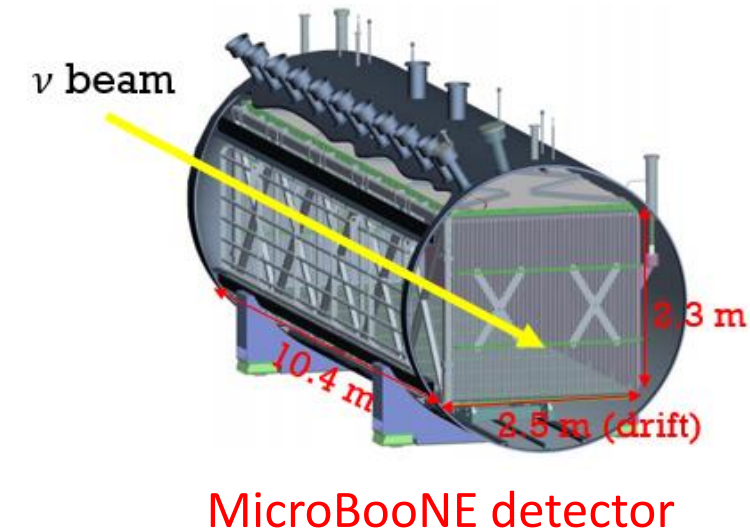
# MicroBooNE Overview

- Micro Booster Neutrino Experiment

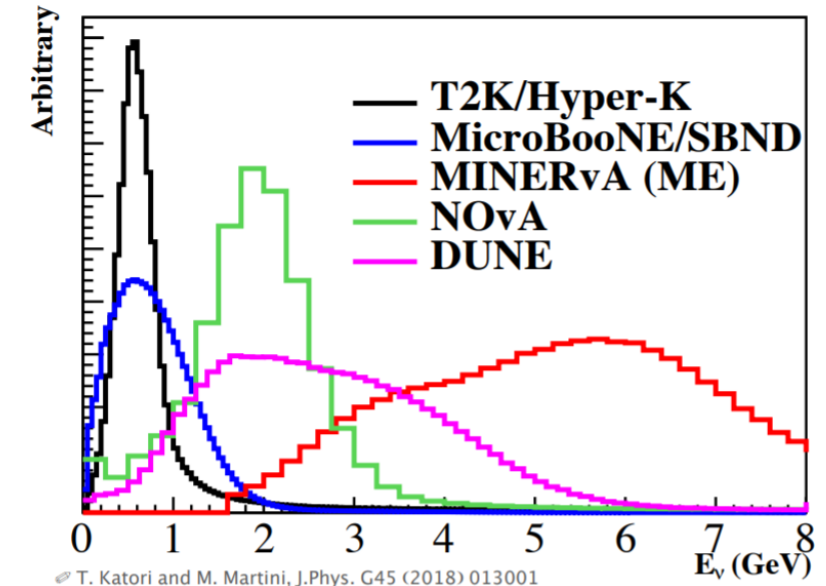
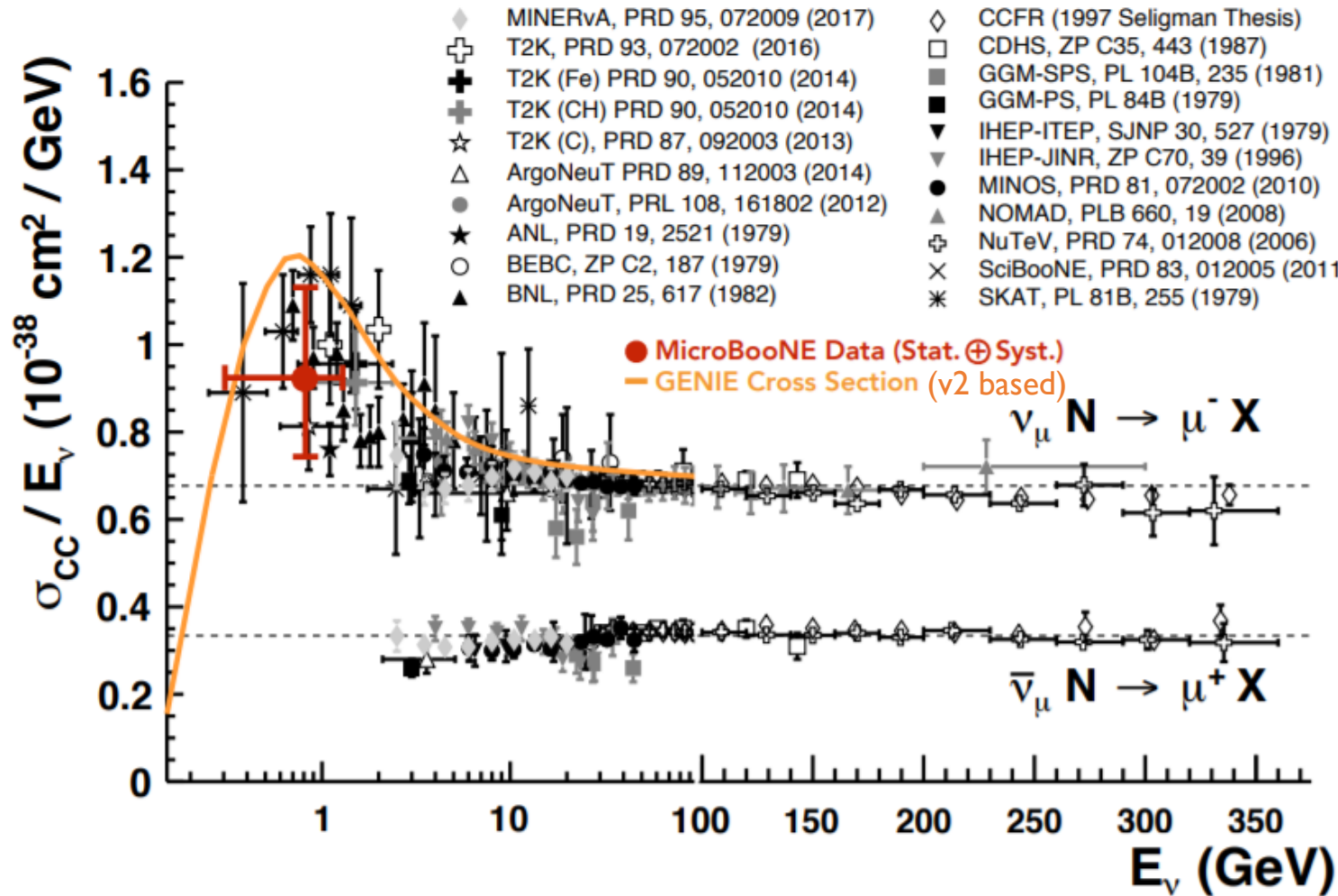
- Accelerator  $\nu$  experiment at Fermilab
- LArTPC with 85 ton active mass
- Near-surface operation

- Main physics goals:

- Investigate MiniBooNE low-energy excess
- Measure  $\nu$ -Ar interaction cross-sections



# Measurements of Inclusive $\nu_\mu$ CC Cross Section



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

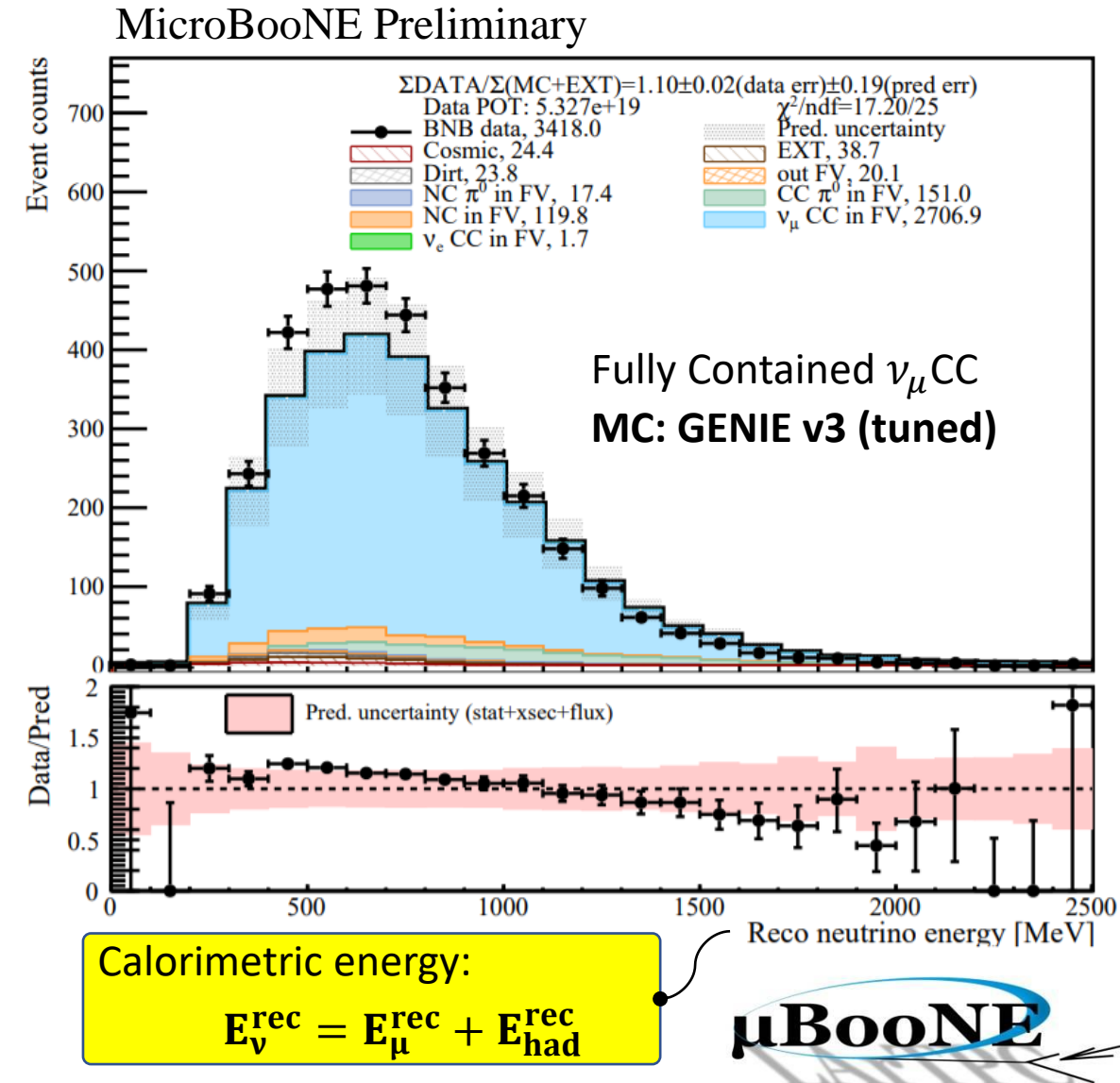
- Inclusive cross section is a good test of overall modeling of all the interaction processes

# Selection of Inclusive Charged-Current $\nu_\mu$ Interactions



	Efficiency	Purity	Cosmic- $\mu$ rejection
Trigger	1	5e-5	1
Generic- $\nu$ detection	80%	65%	7e-6
<b><math>\nu_\mu</math> CC</b> (Fully & Partially Contained)	<b>64%</b>	<b>93%</b>	7e-7

- Achieved excellent cosmic- $\mu$  rejection
  - Wire-Cell reconstruction: JINST 16 (2021) 06, P06043
  - Generic- $\nu$  detection:
    - arXiv:2012.07928, Phys. Rev. Applied 15, 064071 (2021)
- The **high-statistics** event selection allows for high-precision/multi-dimensional cross-section measurements
  - MICROBOONE-NOTE-1095-PUB



# Towards $\sigma(E)$ with Unfolding

- Understanding the cross section as a function of energy,  $\sigma(E)$ , is crucial for oscillation measurements
- We plan to measure  $\sigma(E)$  using Wiener-SVD unfolding

Measurements

$\nu_\mu$  Neutrino Flux

$\nu_\mu$  CC cross section

Detector response matrix

Selection efficiency

Background

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

detector response matrix

model expectation in reco space

model expectation in truth space

$$\text{model expectation in reco space} = \text{detector response matrix} \times \text{model expectation in truth space}$$

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

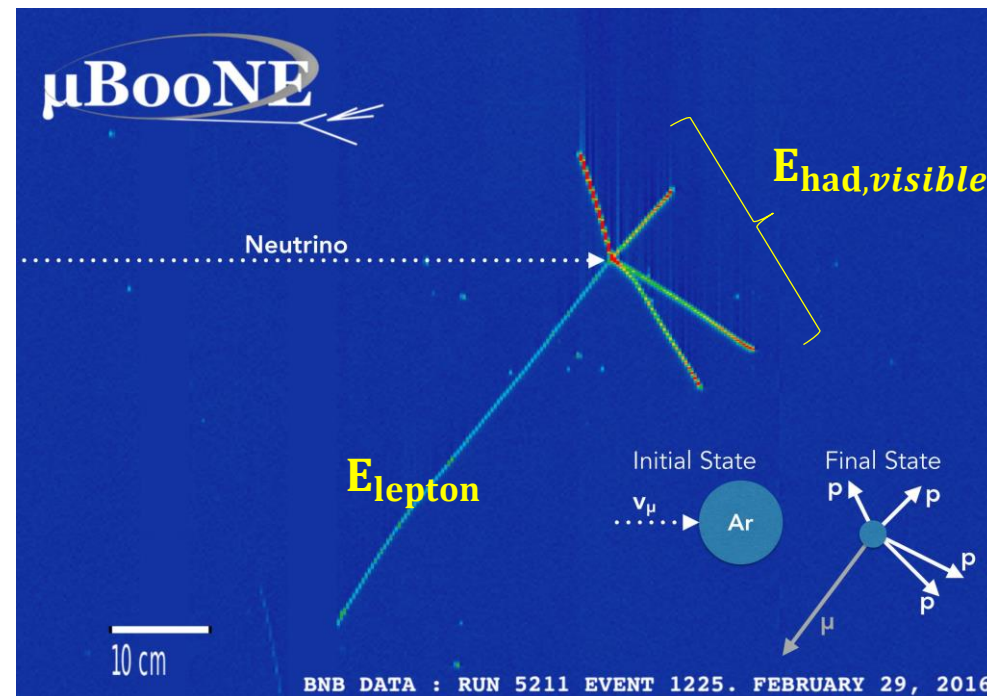
$i$ : bin in  $E_{rec}$   
 $j$ : bin in  $E_\nu$



# Energy Model Validation: $E_{\nu}^{\text{true}}$ to $E_{\nu}^{\text{rec}}$

- Neutrino energy modeling is crucial to neutrino oscillation measurements
- Key challenge: understanding  $\nu$ -Ar cross section as a function of energy

$$E_{\nu} = E_{\text{lepton}} + E_{\text{had,visible}} + E_{\text{had,missing}}$$

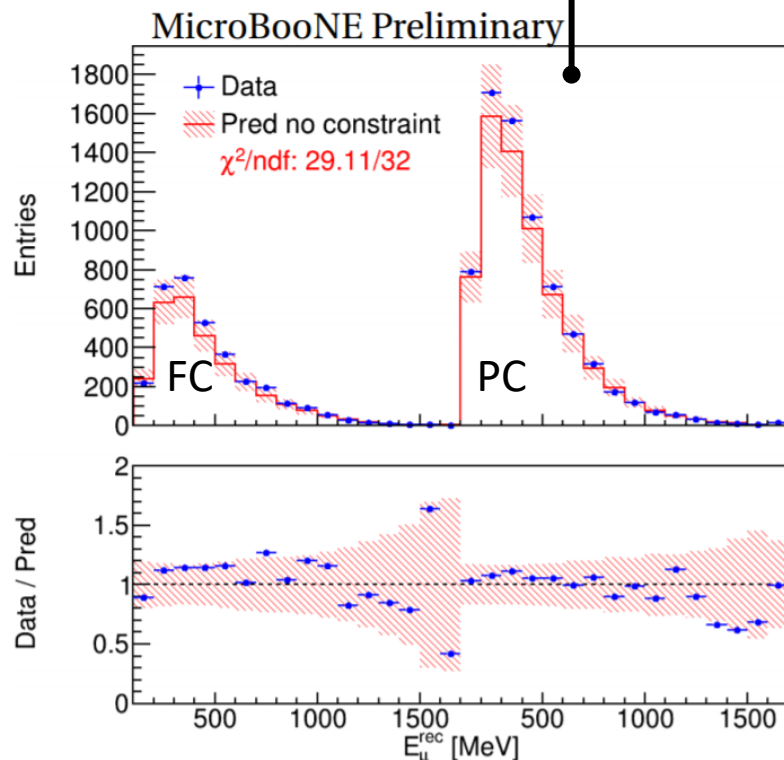


[Fermilab News](#)  
[@ Anne Schukraft,](#)  
[Marco Del Tutto](#)

# Energy Model Validation: $E_v^{\text{true}}$ to $E_v^{\text{rec}}$

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

$$E_v = E_{\text{lepton}} + E_{\text{had,visible}} + E_{\text{had,missing}}$$



**FC:** fully-contained events in the fiducial volume (FV)

**PC:** partially contained events in the FV

**Goodness-of-fit test:**

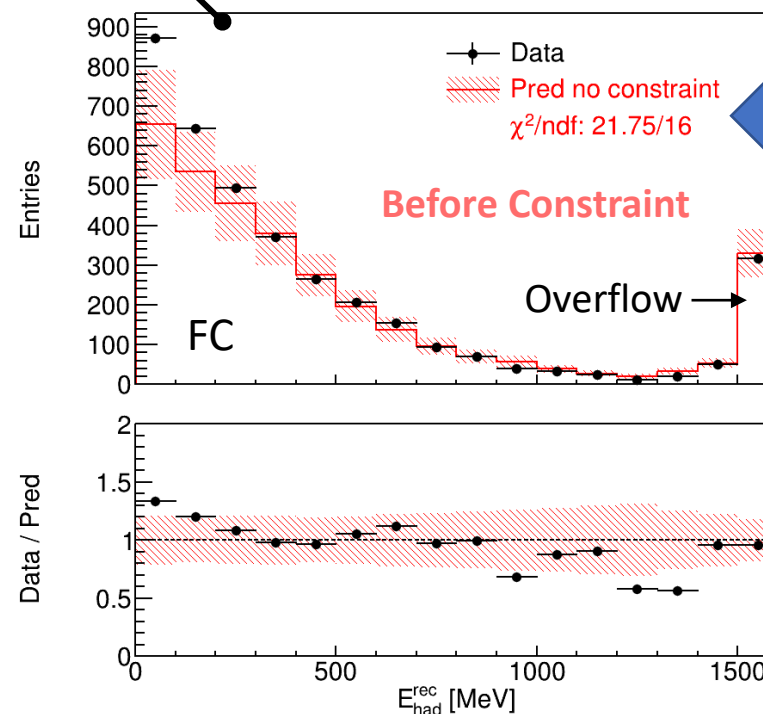
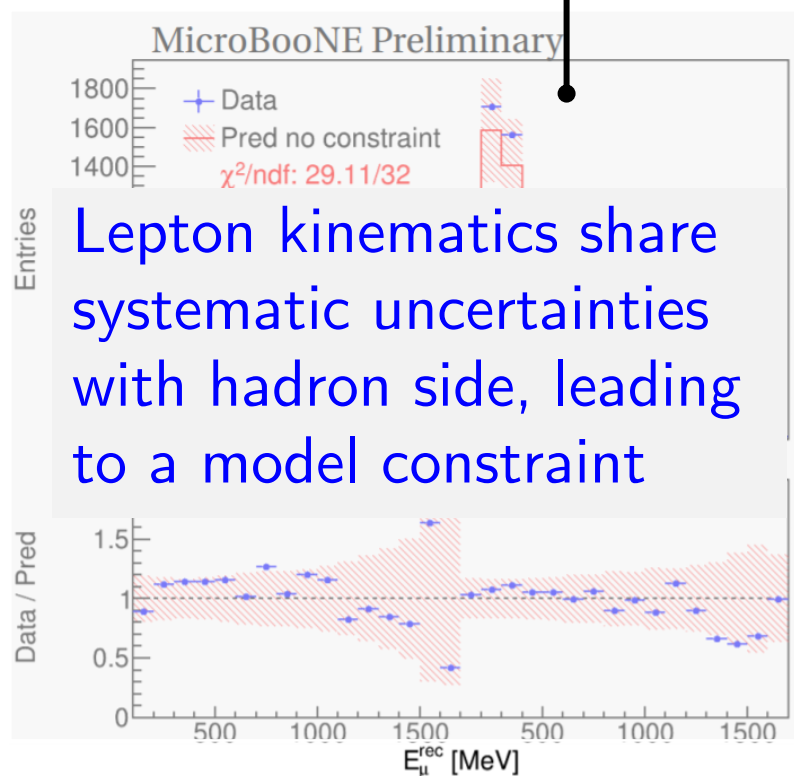
$$\chi^2 = (m - \mu)^T \cdot \Sigma^{-1} \cdot (m - \mu)$$

- Good agreement within model uncertainty given that  $\chi^2/\text{ndf} = 29.11/32$

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

$$E_v = E_{\text{lepton}} + E_{\text{had,visible}} + E_{\text{had,missing}}$$



Reasonable GoF value

- Although excess at low hadronic energy, uncertainty can cover it
- However, more biases hidden by large uncertainty?
- Indicates mis-modeling of missing energy?



# Conditional expectation & variance

## Conditional expectation & variance

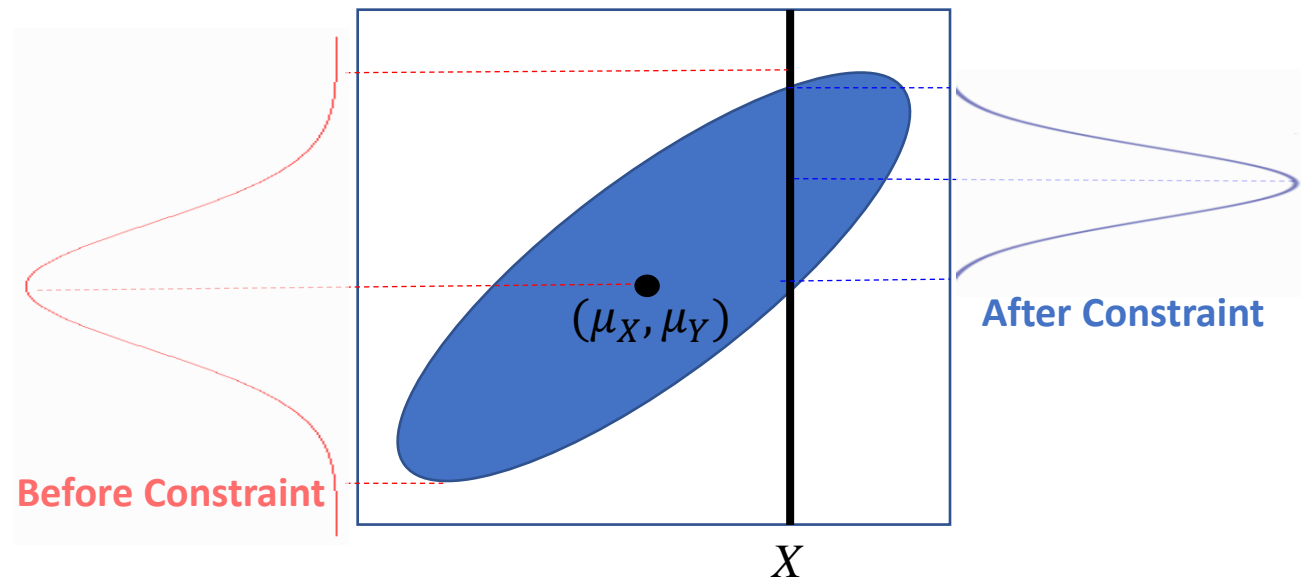
$$\mu_{X,Y} = \begin{pmatrix} \mu_X \\ \mu_Y \end{pmatrix}, \quad \Sigma_{X,Y} = \begin{pmatrix} \Sigma_{XX} & \Sigma_{XY} \\ \Sigma_{YX} & \Sigma_{YY} \end{pmatrix}$$

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

$$\Sigma_{Y|X} = \Sigma_{YY} - \Sigma_{YX}\Sigma_{XX}^{-1}\Sigma_{XY}$$

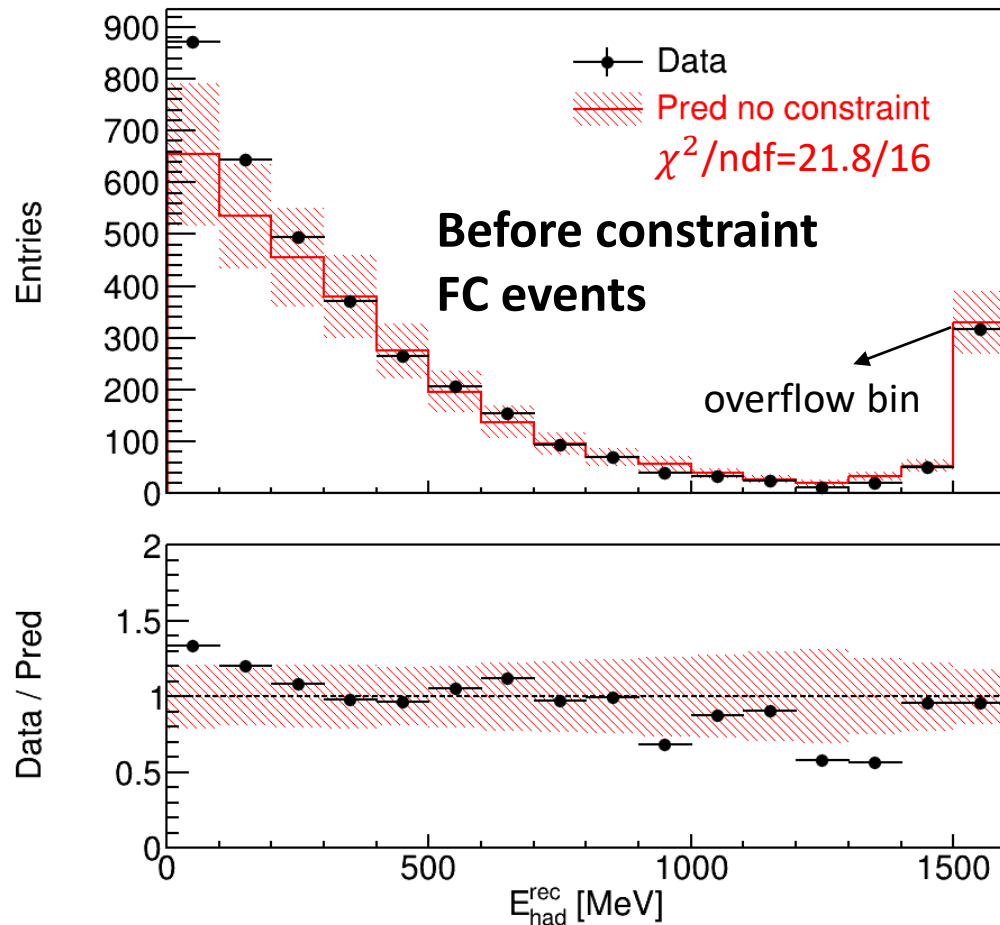
- In-situ model correction: both  $\mu$  and  $\Sigma$
- Avoid over-tuning and time-consuming of MC model tuning (flux, cross section, reinteraction, etc.)

- Perhaps a more famous variant of this method is known as **Gaussian Process Regression**
  - $\Sigma_{YX}\Sigma_{XX}^{-1}$ : linear regression coefficient



# Validation of Hadronic Energy Reconstruction

MicroBooNE Preliminary

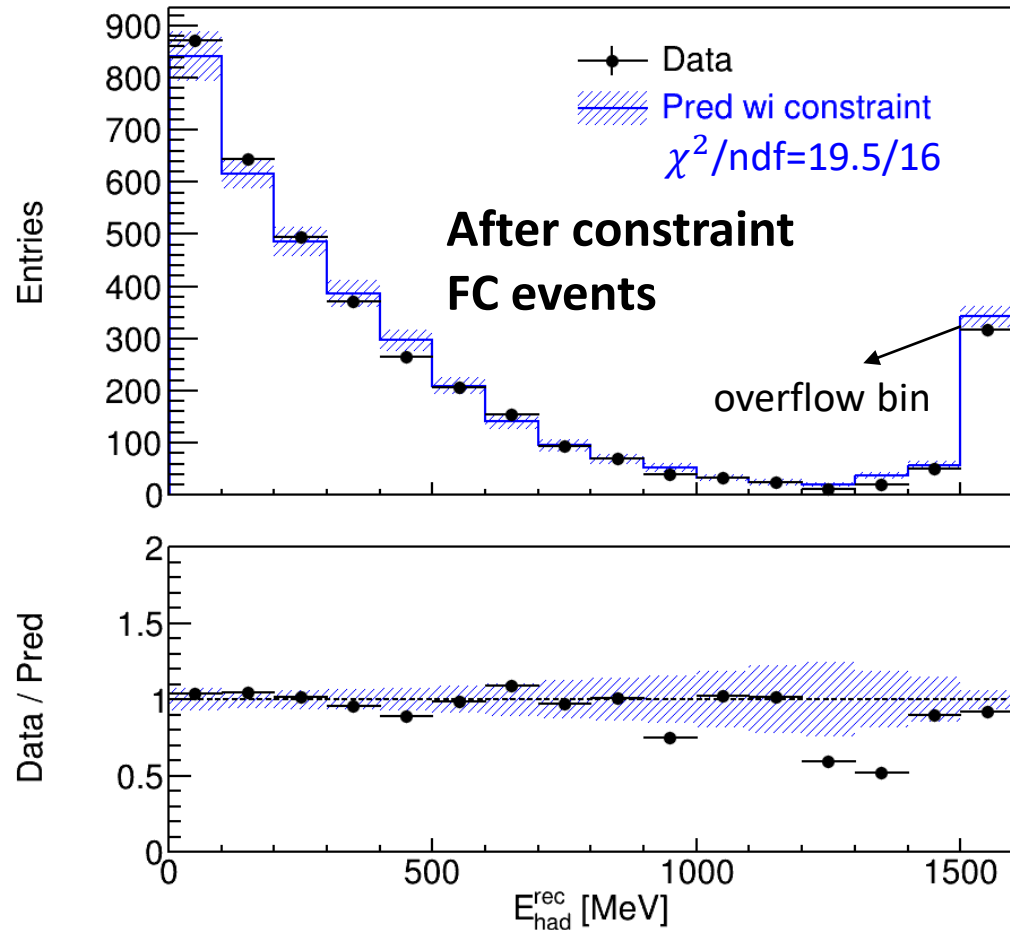


\* Similar result of PC events

- **Before constraint: Excess observed at low hadronic energy**
  - Mis-modeling of missing energy in the hadron final states?
- **After constraint with  $E_{\mu}^{\text{rec}}$  and  $\cos\theta_{\mu}^{\text{rec}}$ :**
  - No sign of mis-modeling of the **hadron missing energy**
  - Reduction in overall uncertainties (20%  $\rightarrow$  5%)
- We also found this validation procedure can
  - Identify shifts of  $\sim 15\%$  in the hadronic energy fraction allocated to protons
  - distinguish GENIE-v2 based MC from MicroBooNE nominal MC (GENIE v3 based)

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# Cross Section Extraction

Measurements  $\downarrow$   $\nu_\mu$  Neutrino Flux  $\searrow$   $\nu_\mu$  CC cross section  $\downarrow$  Detector response matrix  $\swarrow$  Selection efficiency  $\swarrow$  Background  $\swarrow$

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

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

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

Nominal-flux weighted cross section

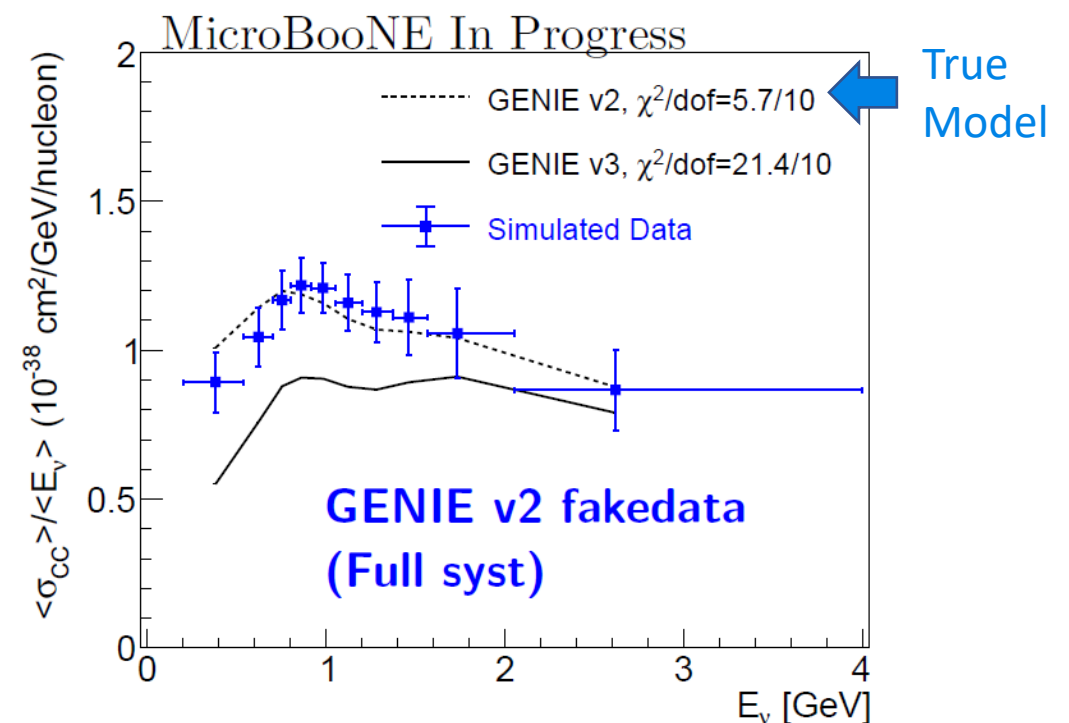
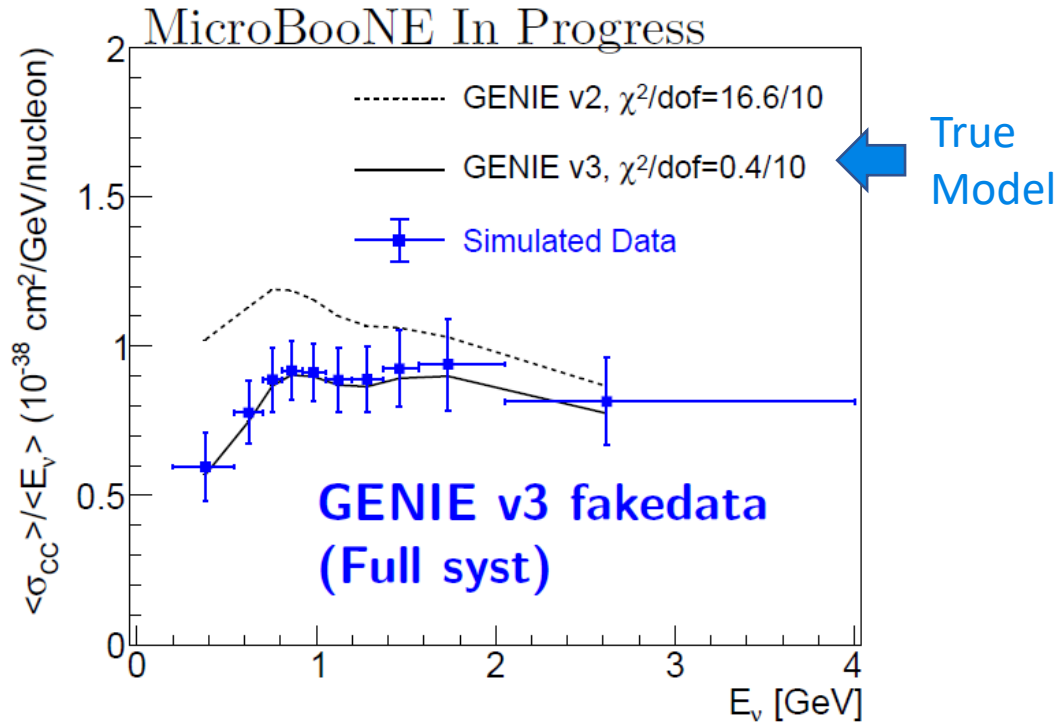
$$R_{ij} = \tilde{\Delta}_{ij} \tilde{F}_j \quad \tilde{F}_j = POT \cdot T \cdot \int_j \bar{F}(E_{\nu j}) \cdot dE_{\nu j}$$

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

$i$ : bin in  $E_{rec}$      $j$ : bin in  $E_\nu$

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

# Procedure Validation with Simulated Data

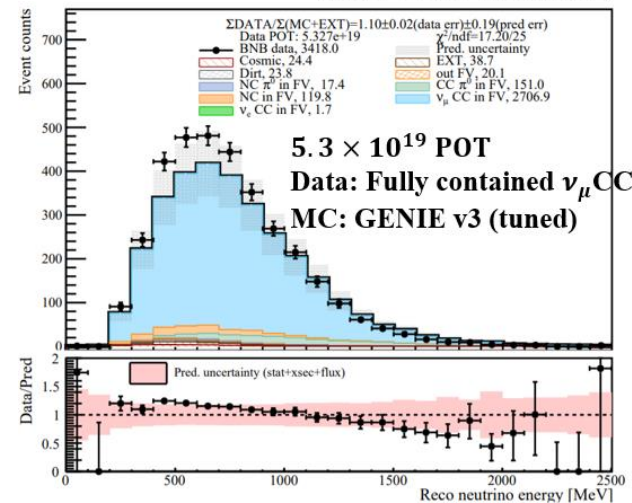


- MicroBooNE's nominal MC is used to extract the cross section from the “fake dataset” – same treatment as data
- Analyses of cross-section extraction from two simulated data sets justify the unfolding procedure

# To measure the cross section

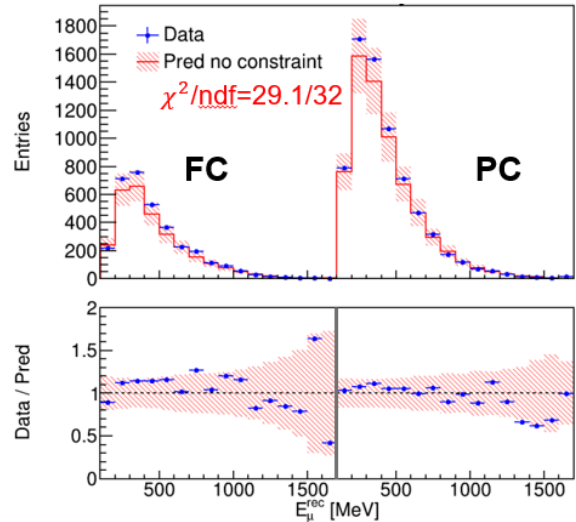
## Reco neutrino energy

MicroBooNE Preliminary



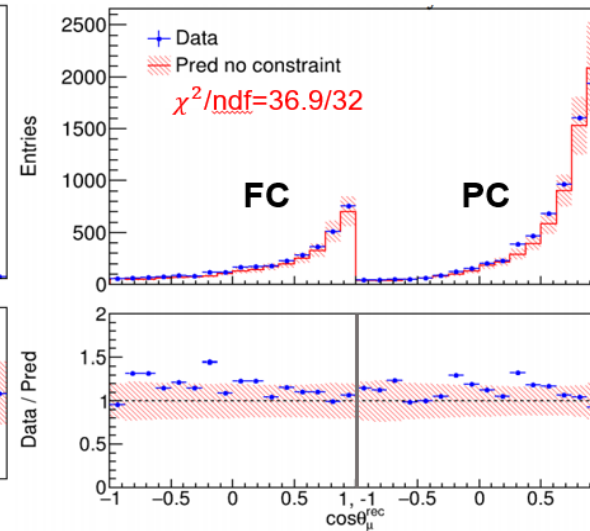
## Reco muon energy

MicroBooNE Preliminary



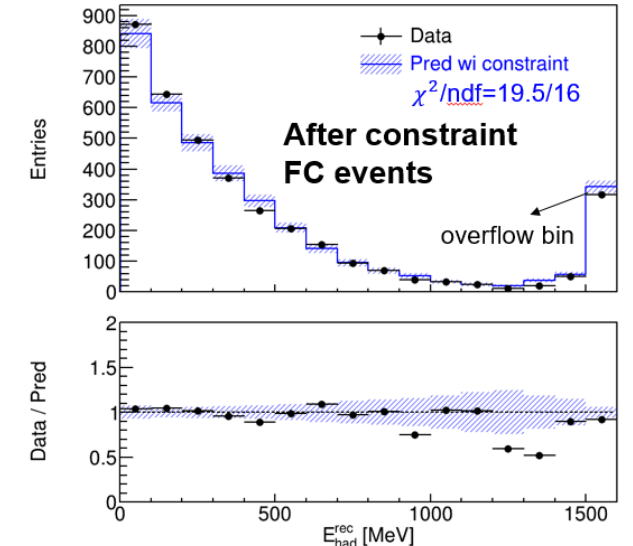
## Reco polar angle

MicroBooNE Preliminary



## Reco hadronic energy

MicroBooNE Preliminary



### • Measure the cross section

- $\sigma/E_\nu$ : total cross section as a function of neutrino energy
- $d\sigma/dE_\mu$ : differential cross section as a function of muon energy
- $d\sigma/dv$ : differential cross section as a function of energy transfer to Ar
- Future plans: extend to energy-dependent multi-dimension differential cross-section
  - e.g.,  $d\sigma/dE_\mu d\theta_\mu$  as a function of neutrino energy

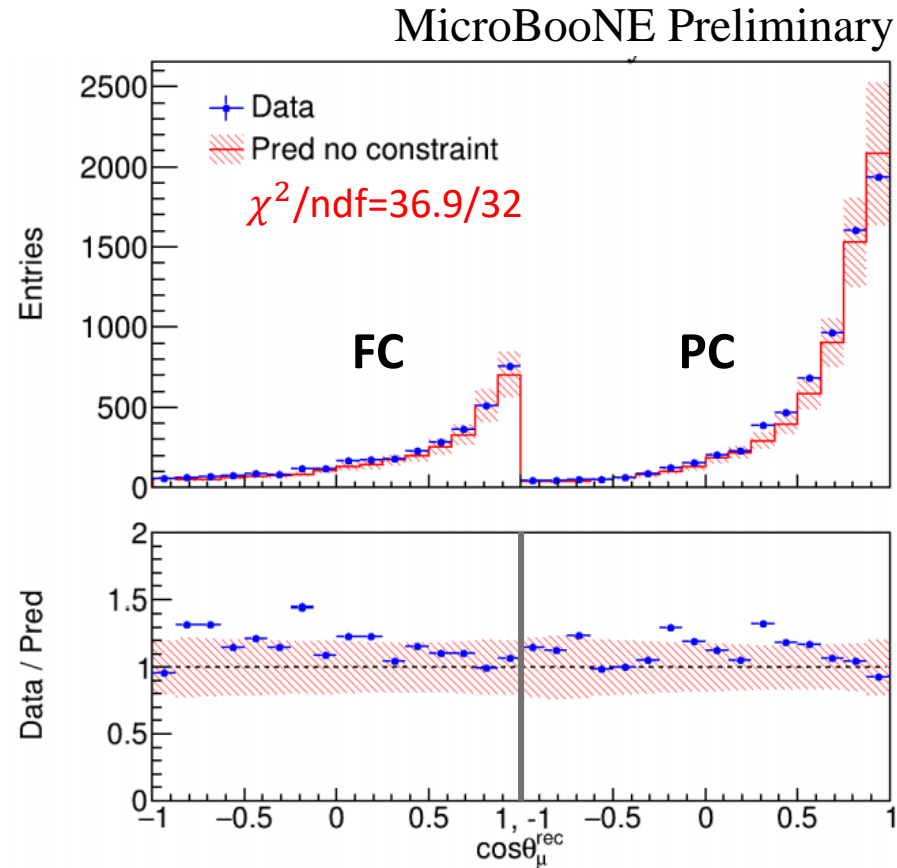


# Summary

- A high-performance inclusive  $\nu_\mu$  CC selection (**93% purity, 64% efficiency**) has been achieved using Wire-Cell reconstruction at MicroBooNE
- New technique with conditional variance allows for more stringent validations of the **cross-section modeling** and **neutrino energy reconstruction** for oscillation and cross section measurements
  - Examination of hadronic energy distribution after constraining to muon kinematics explains the observed low-hadronic-energy excess
- High-statistics  $\nu_\mu$  CC event selection ( **$\approx 225\text{k}$  expected for  $1.2\text{E}21$  POT**) for multi-dimensional differential cross-section measurements
  - Stay tuned for the energy-dependent cross section measurement (Wiener-SVD unfolding arXiv:1705.03568)

# Backup Slides

# Muon Kinematics: Reconstructed Polar Angle between of Muon and Neutrino Beam ( $\cos\theta_{\mu}^{\text{rec}}$ )



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**PC:** partially contained events in the fiducial volume

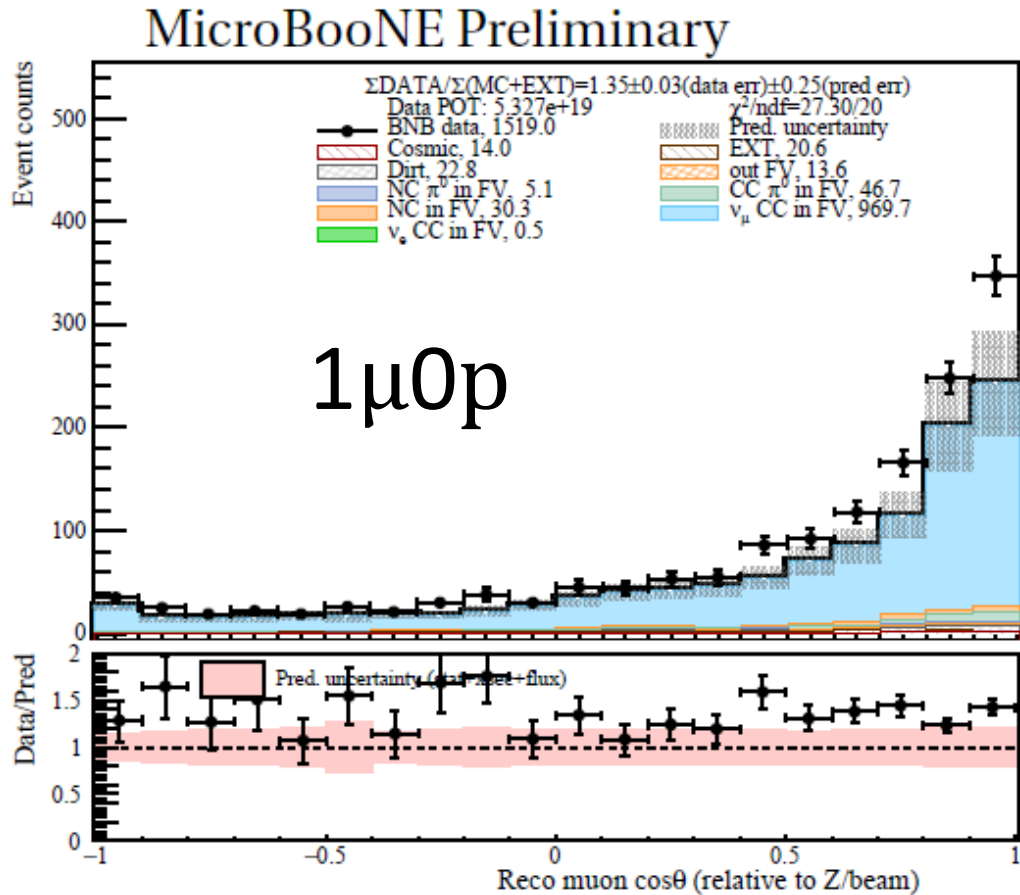
**Goodness-of-fit test:**

$$\chi^2 = (m - \mu)^T \cdot \Sigma^{-1} \cdot (m - \mu)$$

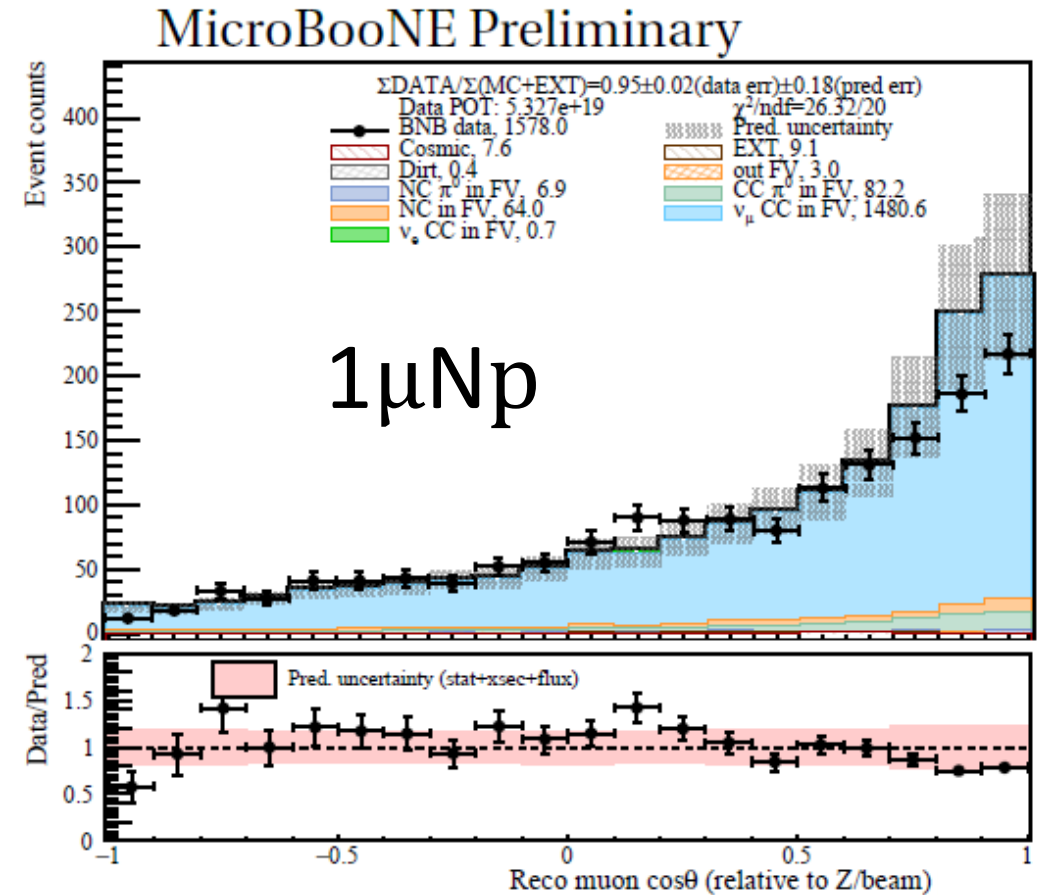
Error band for statistic, flux and cross section systematic uncertainties

The reasonable value of goodness-of-fit test show good agreement between data and model prediction

# Model Comparison in High Dimension



Overall excess



Deficit at muon forward angle

- High-statistics  $\nu_\mu$  CC allows for multi-dimensional cross-section measurements

# Validation with Simulated Data

