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

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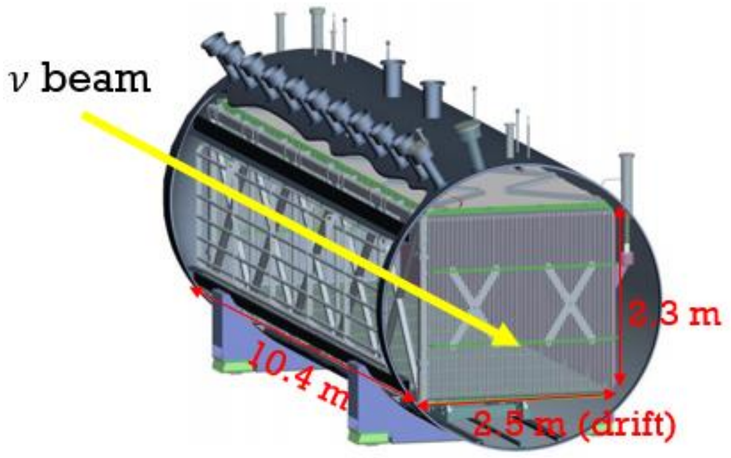
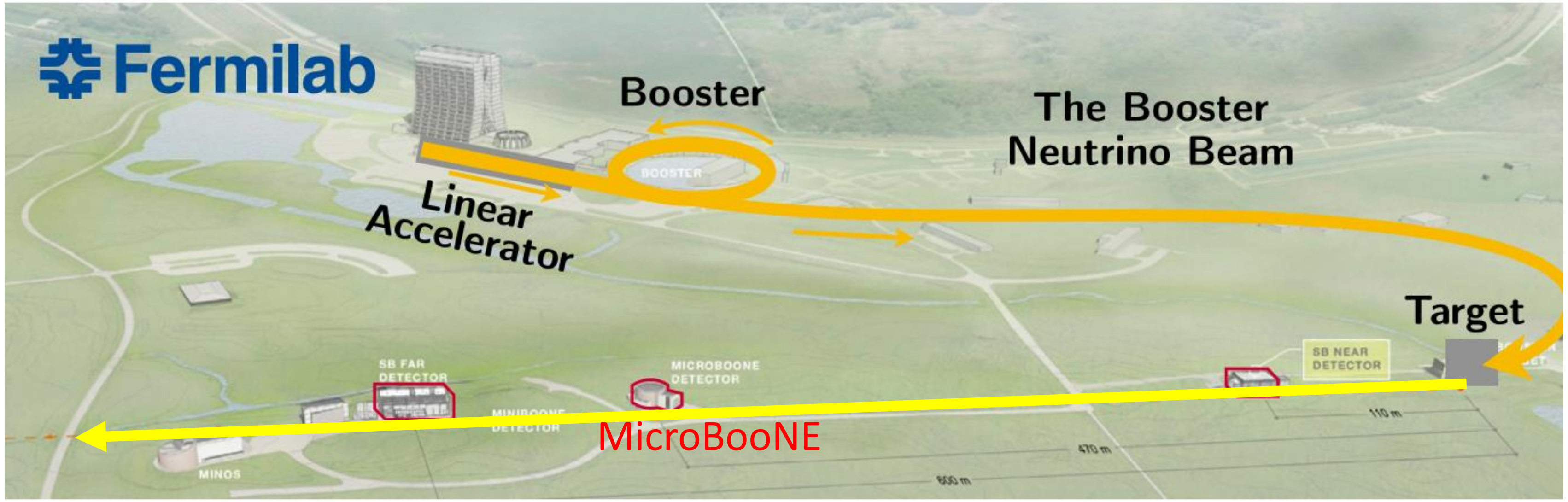
MicroBooNE Overview

- Micro Booster Neutrino Experiment
  - Accelerator ν experiment at Fermilab
  - LArTPC with 85 ton active mass
  - Near-surface operation

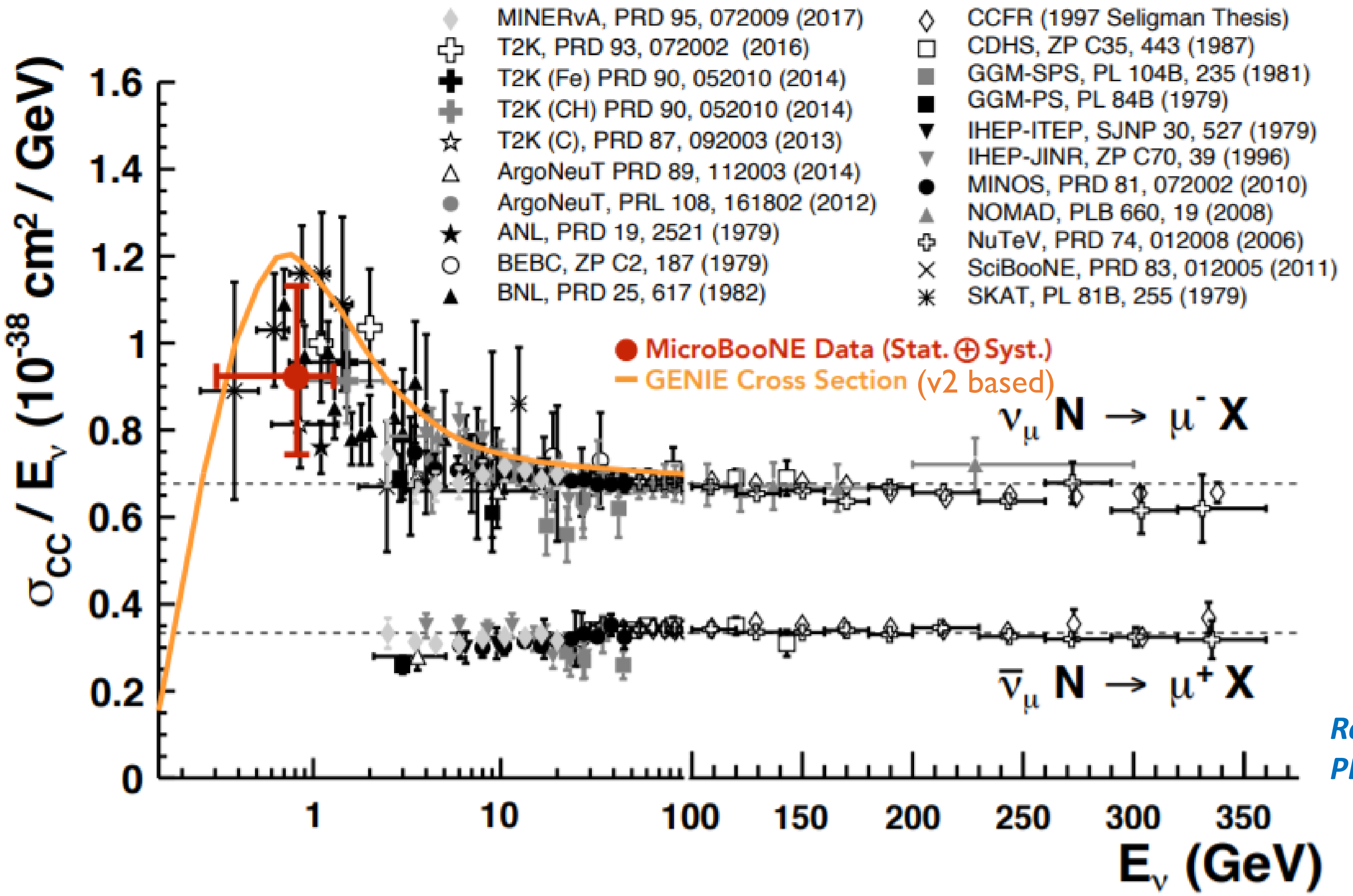
- Main physics goals:
  - Investigate MiniBooNE low-energy excess
  - Measure ν-Ar interaction cross-sections

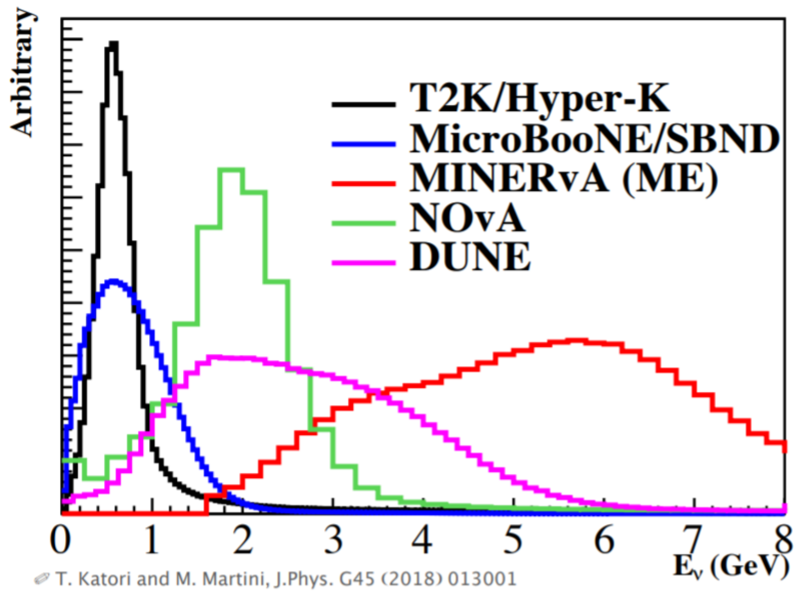


MicroBooNE detector



Measurements of Inclusive ν_μCC Cross Section





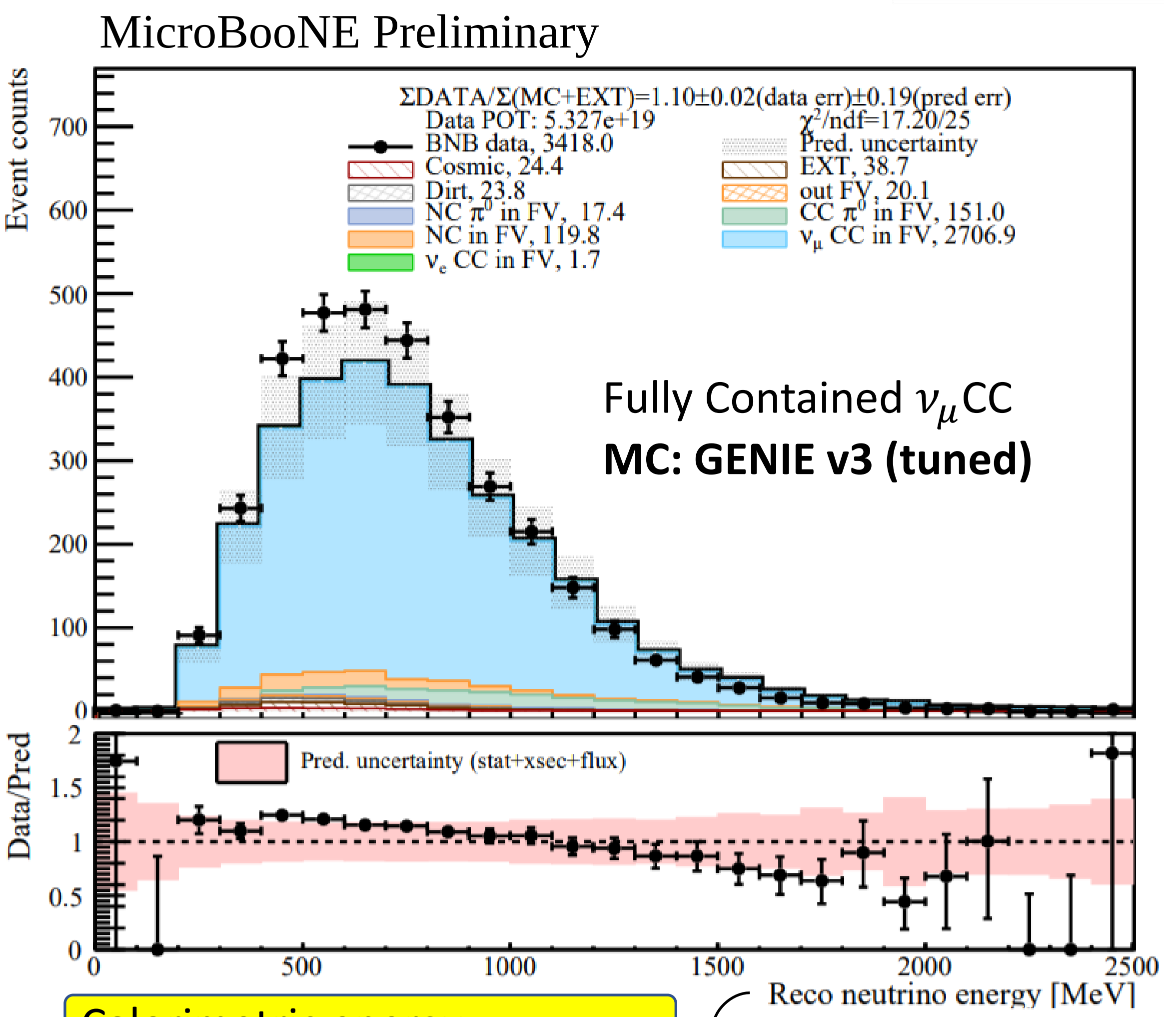
Review of Particle Physics
PDG, PTEP 2020 (2020) 8, 083C01

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

Selection of Inclusive Charged-Current 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)**	**64%**	**93%**	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
  - MICROBOONE-NOTE-1095-PUB



Calorimetric energy:

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

Towards σ(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

ν_μ Neutrino Flux

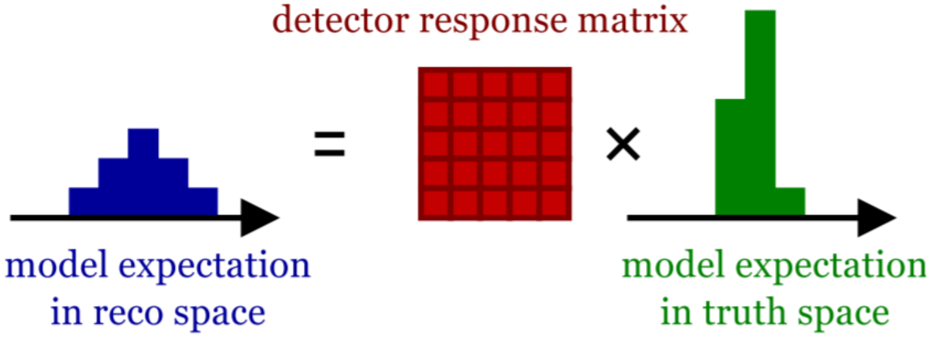
ν_μCC cross section

Detector response matrix

Selection efficiency

Background

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



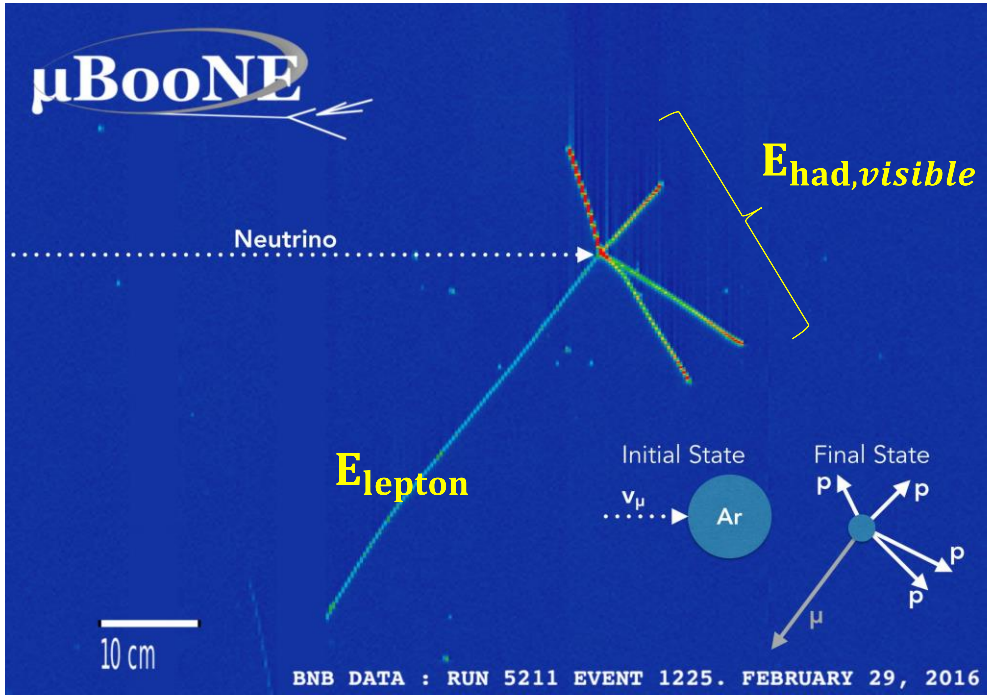
$$\boldsymbol{M_i = \sum_j R_{ij} \cdot S_j + B_i}$$

i: bin in E_{rec}
j: bin in E_ν

Energy Model Validation: $\mathbf{E}_{\boldsymbol{\nu}}^{\mathbf{true}}$ to $\mathbf{E}_{\boldsymbol{\nu}}^{\mathbf{rec}}$

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

$$\mathbf{E}_{\boldsymbol{\nu}} = \mathbf{E}_{\mathbf{lepton}} + \mathbf{E}_{\mathbf{had,visible}} + \mathbf{E}_{\mathbf{had,missing}}$$

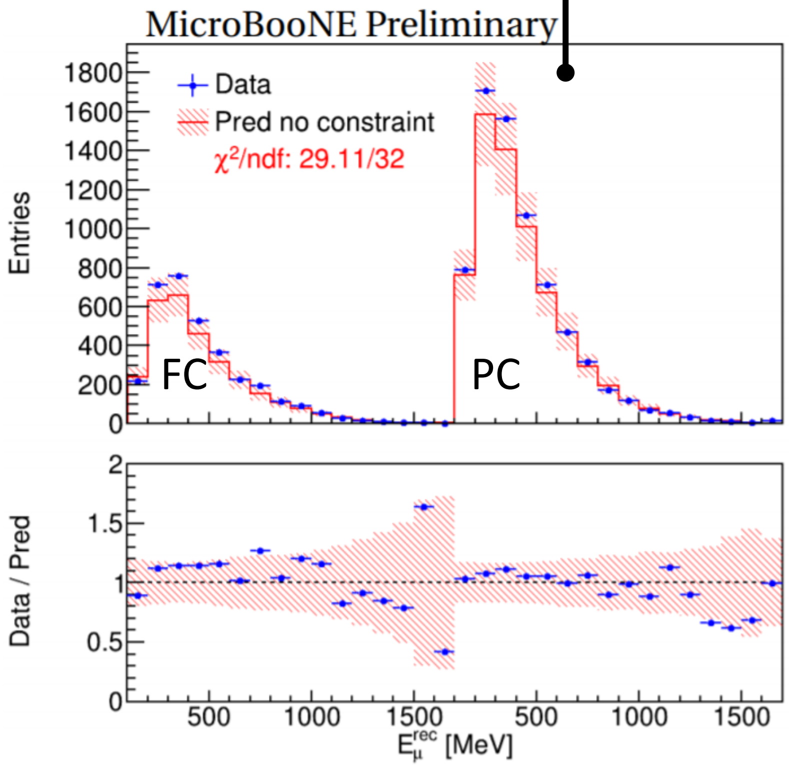


[Fermilab News @ Anne Schukraft, Marco Del Tutto]

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

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

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



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

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

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

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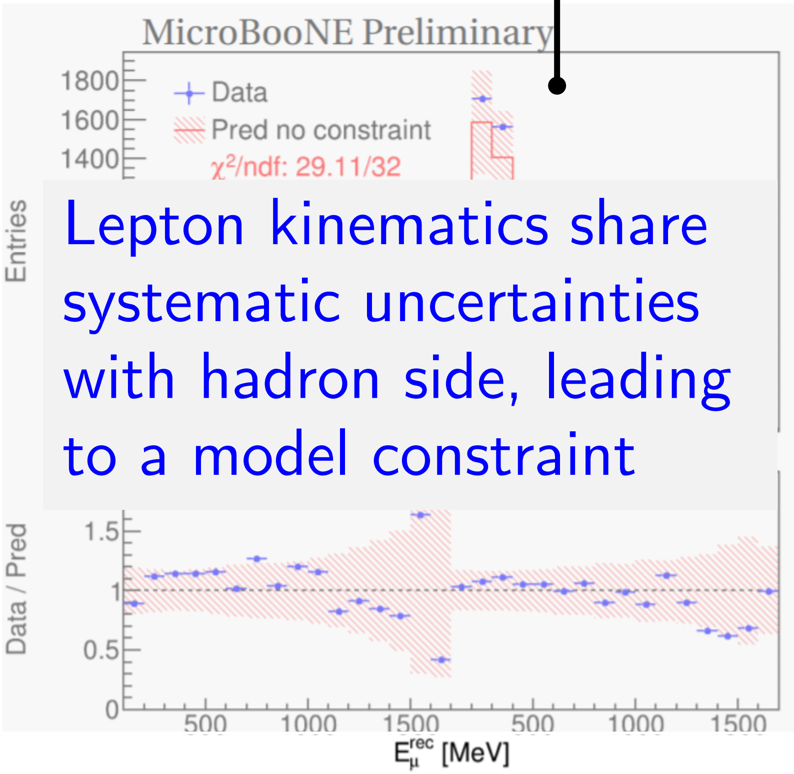
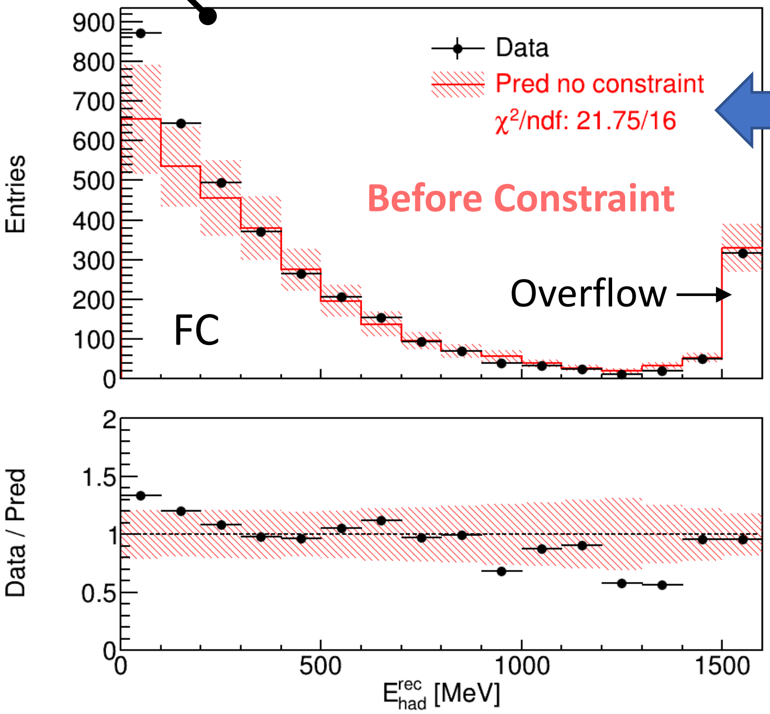


Lepton kinematics share systematic uncertainties with hadron side, leading to a model constraint



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

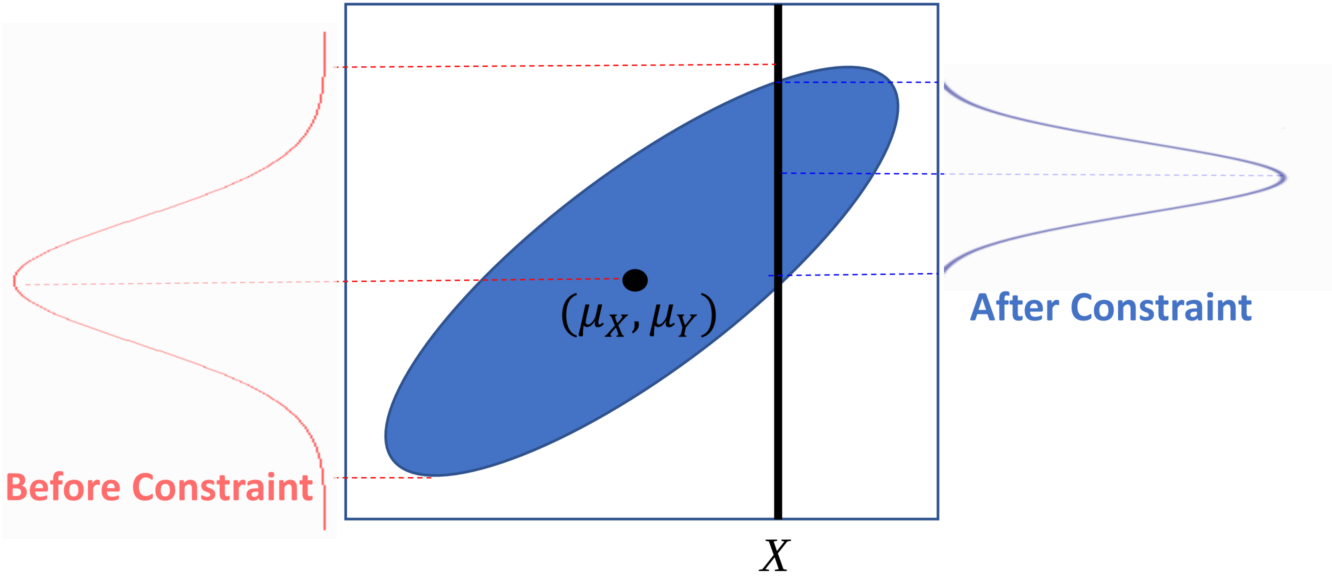
$$\mu_{X,Y} = \begin{pmatrix} \mu_X \\ \mu_Y \end{pmatrix}, \qquad \Sigma_{X,Y} = \begin{pmatrix} \Sigma_{XX} & \Sigma_{XY} \\ \Sigma_{YX} & \Sigma_{YY} \end{pmatrix}$$

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

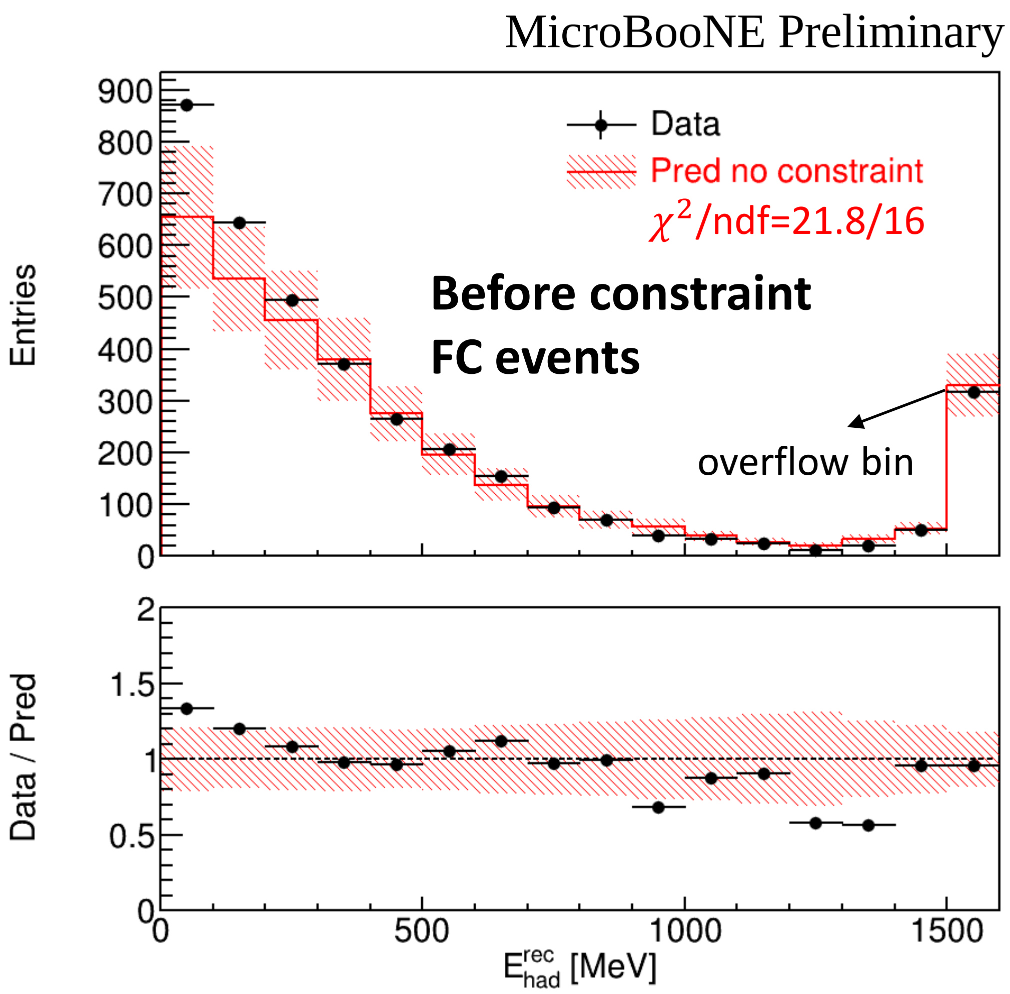
$$\boldsymbol{\Sigma_{Y|X} = \Sigma_{YY} - \Sigma_{YX}\Sigma_{XX}^{-1}\Sigma_{XY}}$$

- In-situ model correction: both μ and Σ
- 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



** 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_μ^{rec} and $\cos\theta_\mu^{rec}$:**
  - No sign of mis-modeling of the **hadron missing energy**
  - Reduction in overall uncertainties (20% → 5%)
- We also found this validation procedure can
  - Identify shifts of ~15% in the hadronic energy fraction allocated to protons
  - distinguish GENIE-v2 based MC from MicrroBooNE nominal MC (GENIE v3 based)

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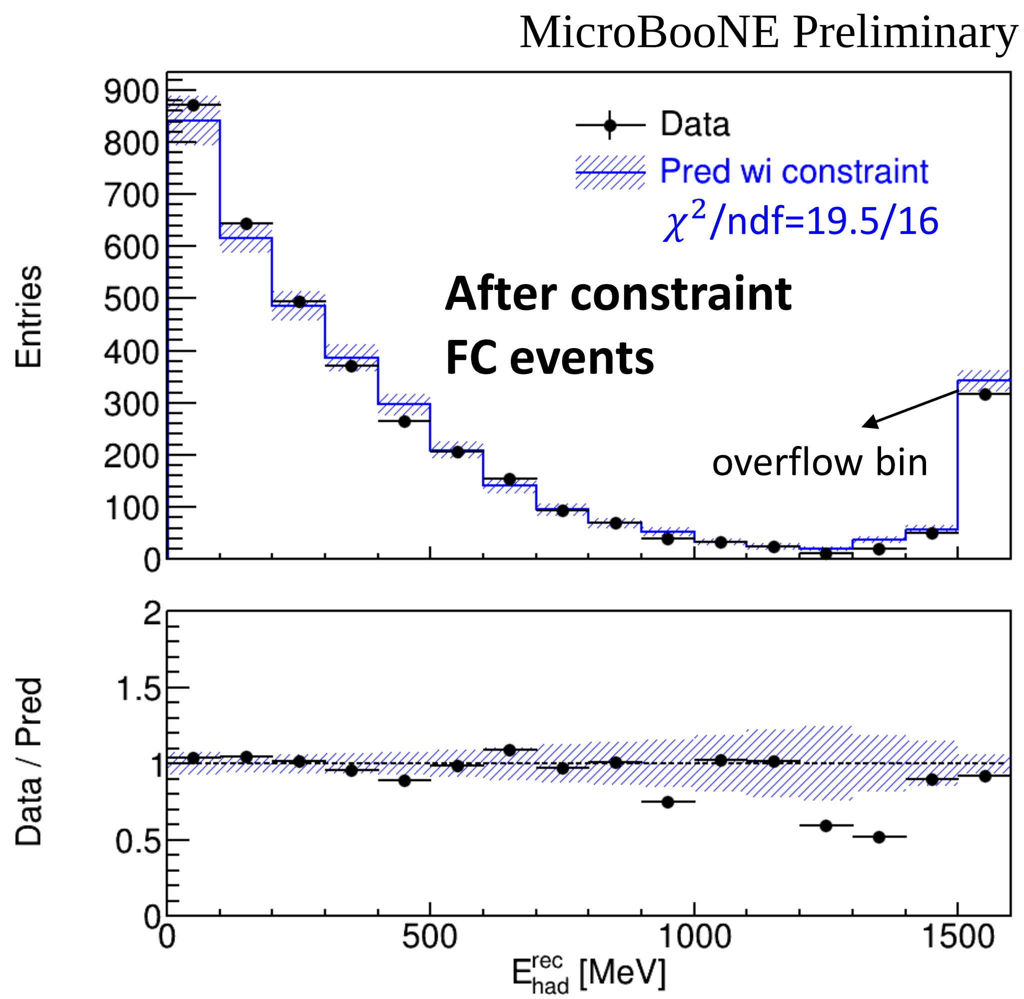

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Cross Section Extraction

Measurements

ν_μ Neutrino Flux

ν_μCC cross section

Detector response matrix

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Background

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

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

Nominal-flux weighted cross section

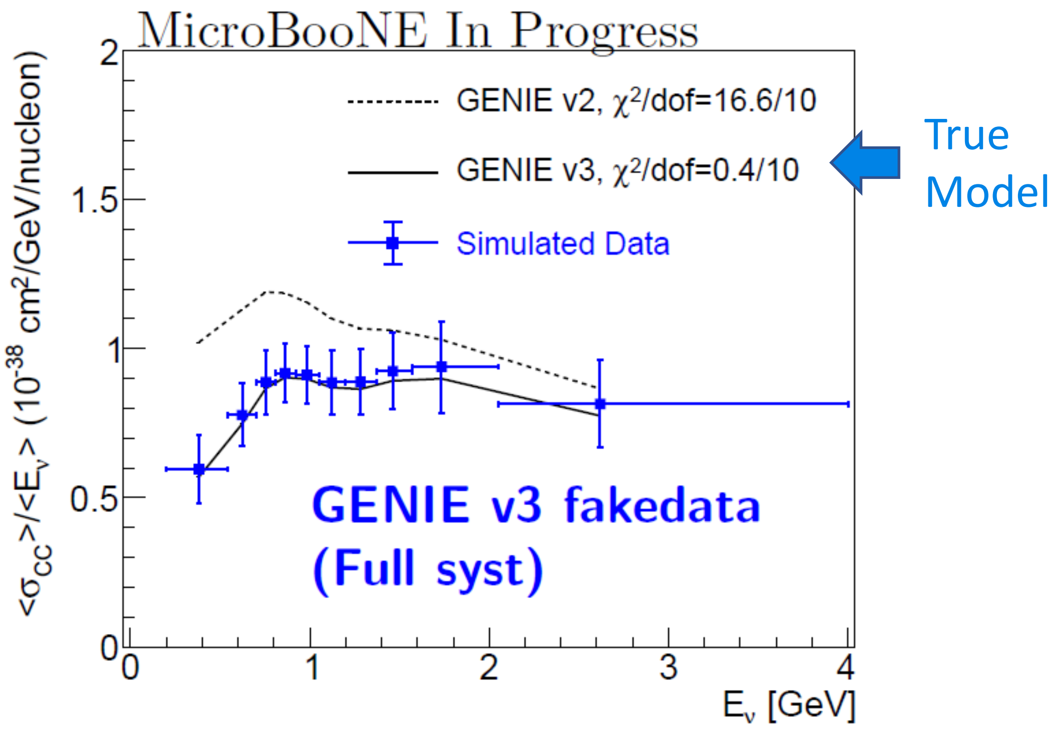
$$R_{ij} = \widetilde{\Delta}_{ij}\,\boldsymbol{\widetilde{F}_j} \qquad \boldsymbol{\widetilde{F}_j = POT \cdot T \cdot \int_j \overline{F}\left(E_{\nu\,j}\right) \cdot dE_{\nu\,j}}$$

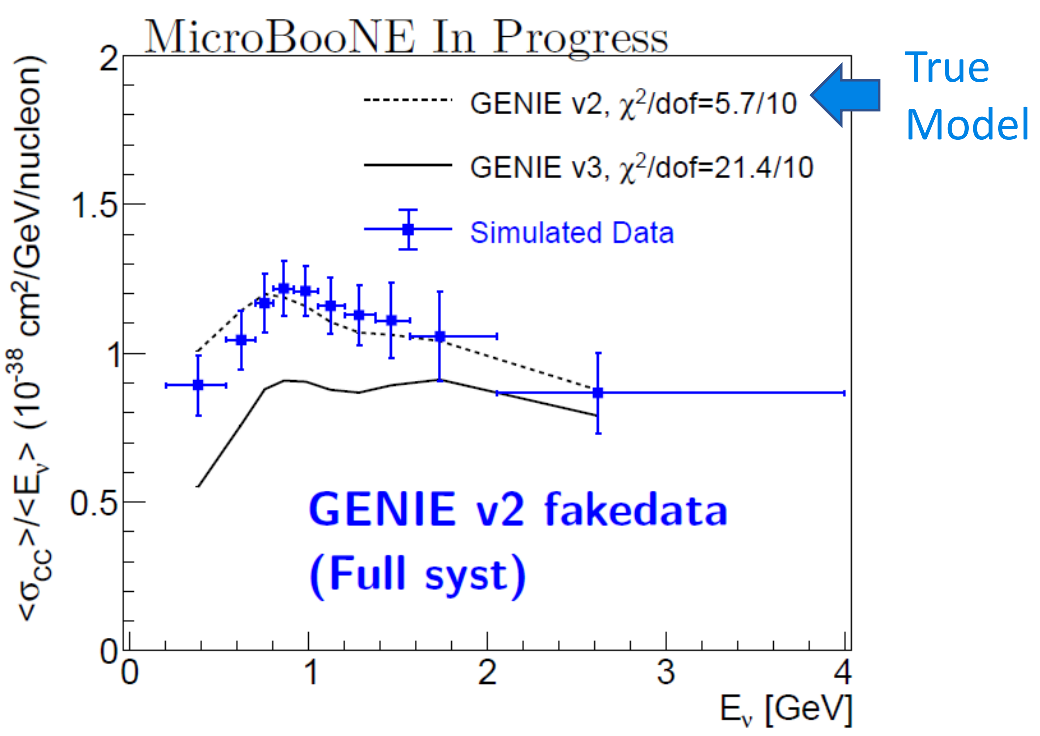
$$\widetilde{\Delta}_{ij} = \frac{POT \cdot T \cdot \int_j F\left(E_{\nu\,j}\right) \cdot \sigma\left(E_{\nu\,j}\right) \cdot D\left(E_{\nu\,j}, E_{rec\,i}\right) \cdot \varepsilon\left(E_{\nu\,j}, E_{rec\,i}\right) \cdot dE_{\nu\,j}}{POT \cdot T \cdot \int_j \overline{F}\left(E_{\nu\,j}\right) \cdot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

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

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

Procedure Validation with Simulated Data

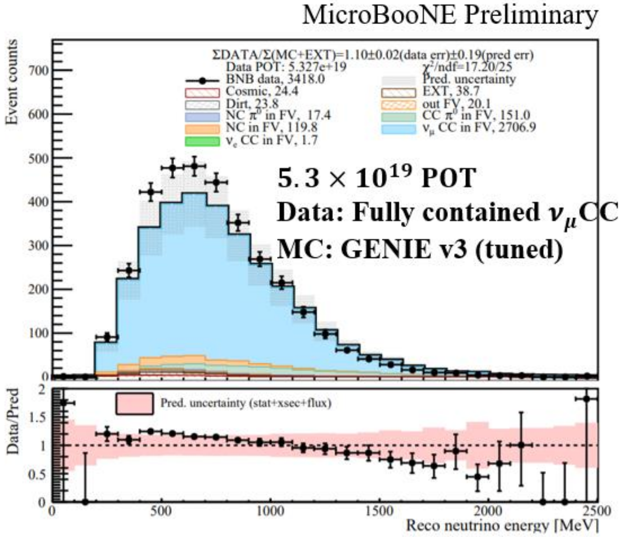




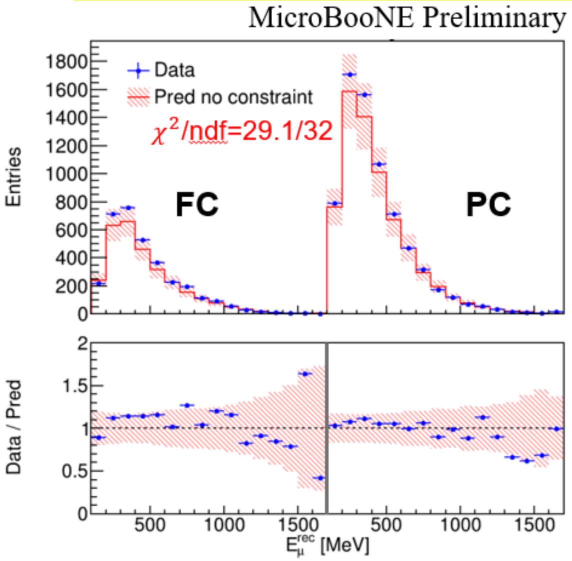
- MicroBooNE's nominal MC is used to extract the cross section from the "fake dataset" – same treatment as data
- Analyses of cross-section extraction from two simulated data sets justify the unfolding procedure

To measure the cross section

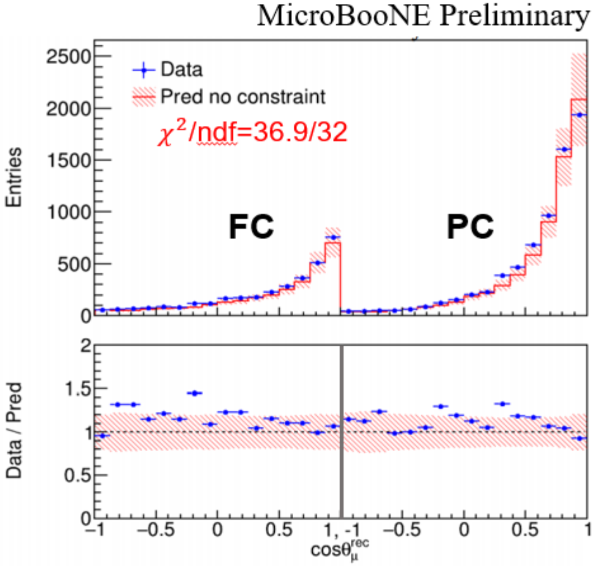
Reco neutrino energy



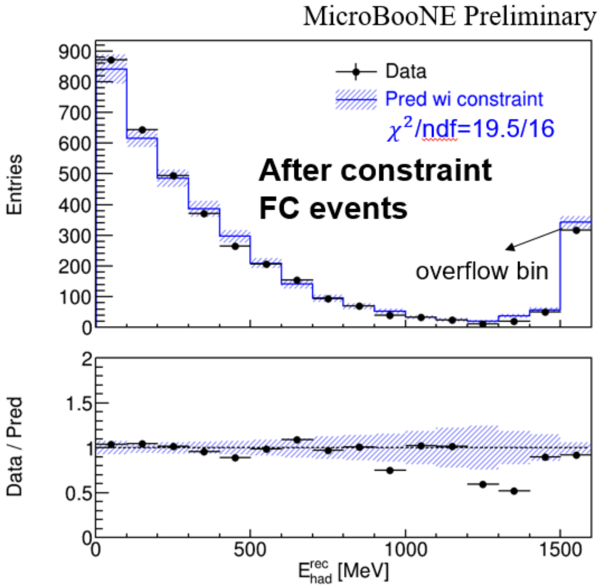
Reco muon energy



Reco polar angle



Reco hadronic energy



- Measure the cross section
  - σ/E_ν: total cross section as a function of neutrino energy
  - $d\sigma/dE_\mu$: differential cross section as a function of muon energy
  - $d\sigma/d\nu$: 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

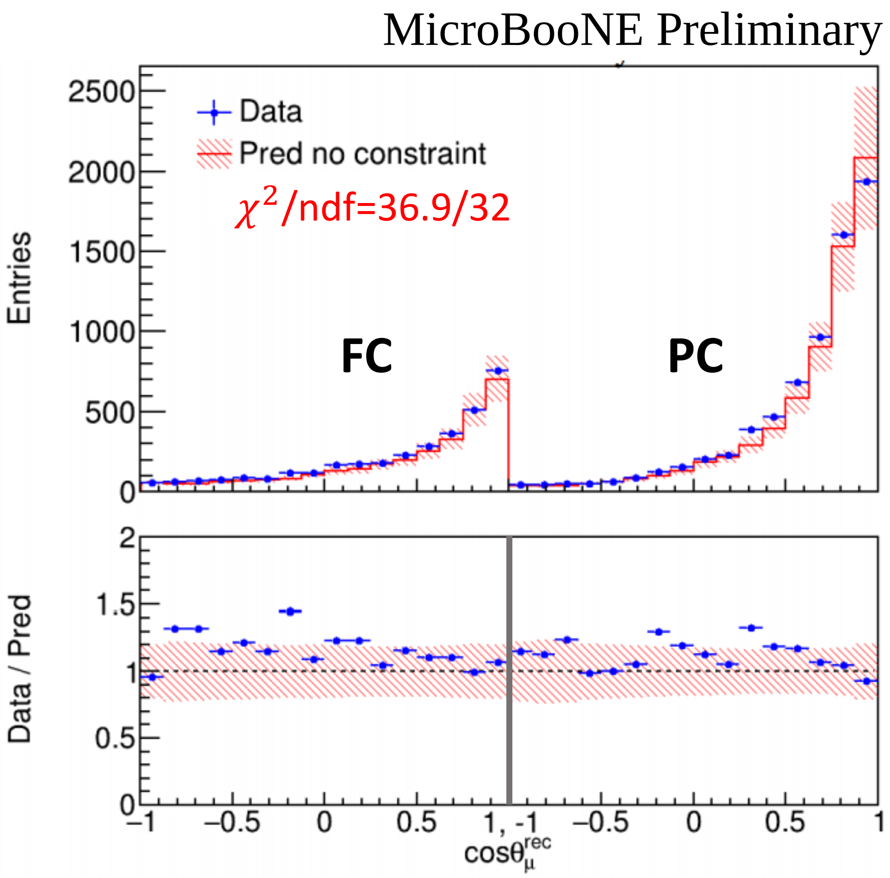
- A high-performance inclusive ν_μCC selection (**93% purity, 64% efficiency**) has been achieved using Wire-Cell reconstruction at MicroBooNE

- 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 ν_μ CC event selection (**≈225k expected for 1.2E21 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 ($\cos\theta_\mu^{rec}$)

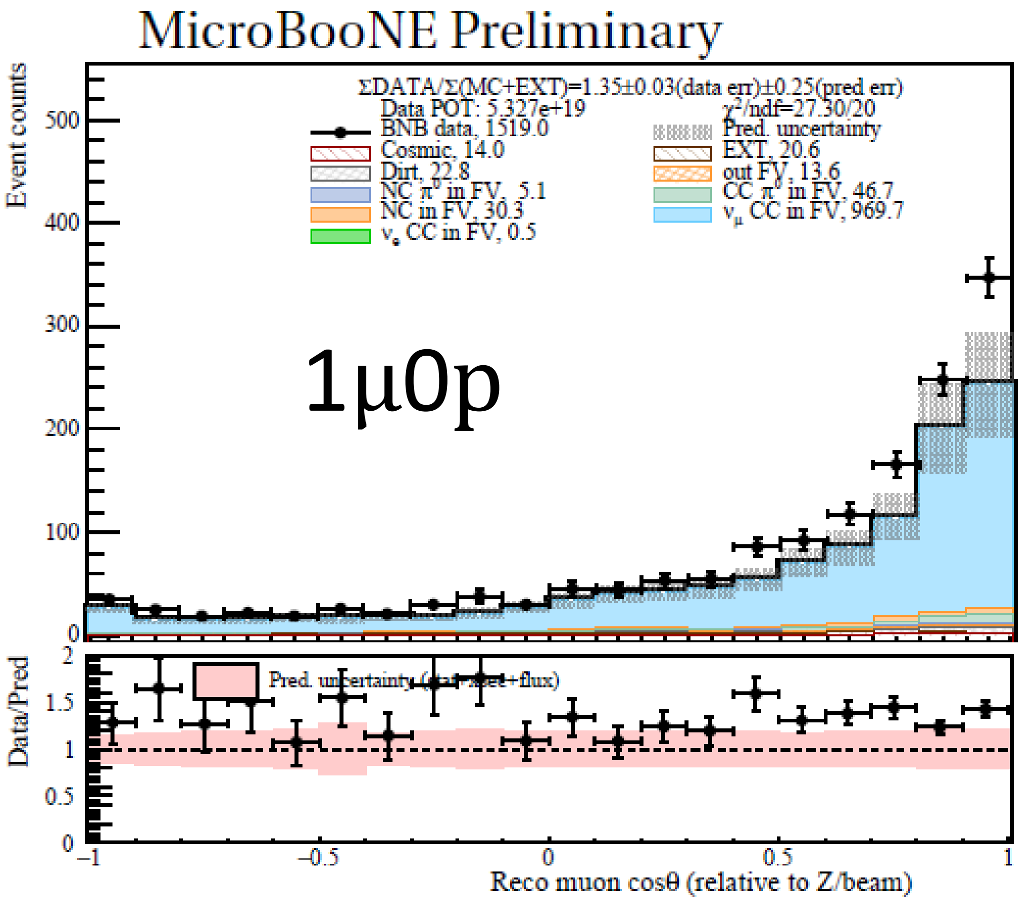


FC: fully contained events in the fiducial volume
PC: partially contained events in the fiducial volume
Goodness-of-fit test:
$\chi^2=(m-\mu)^{\mathsf{T}}\cdot \Sigma^{-1}\cdot(m-\mu)$

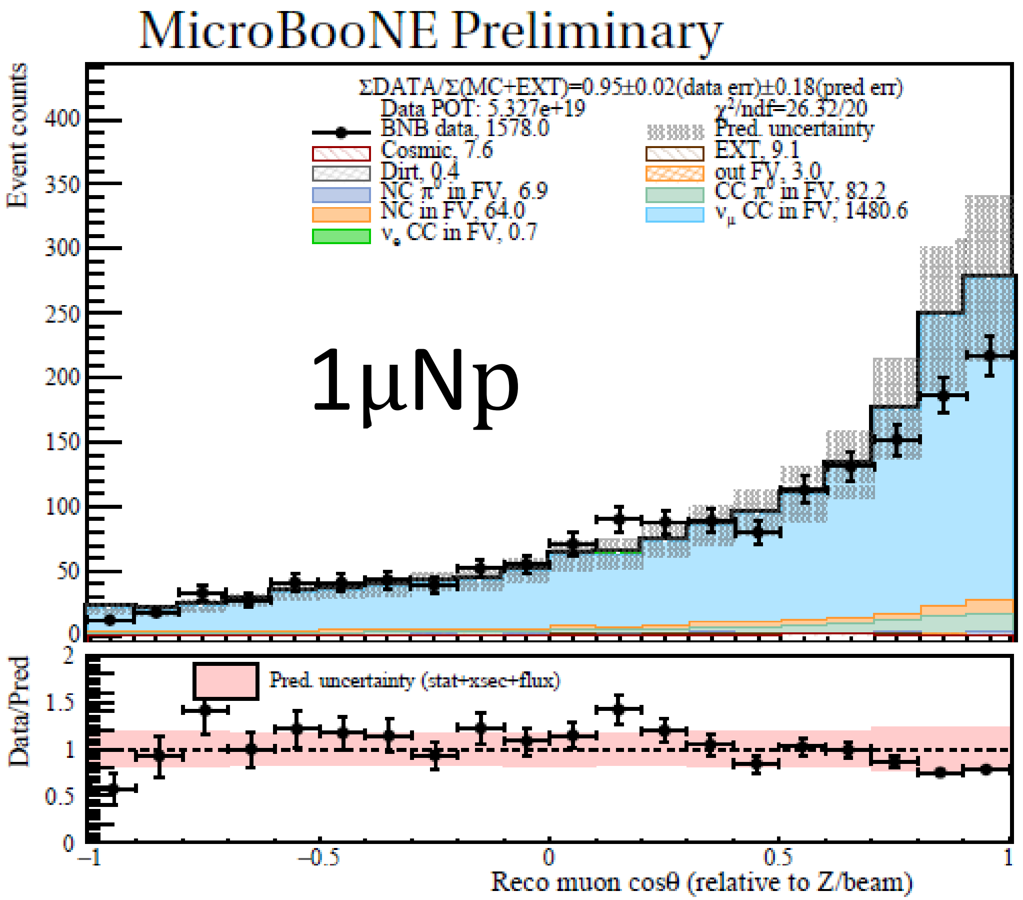
Error band for statistic, flux and cross section systematic uncertainties

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 ν_μCC allows for multi-dimensional cross-section measurements

Validation with Simulated Data