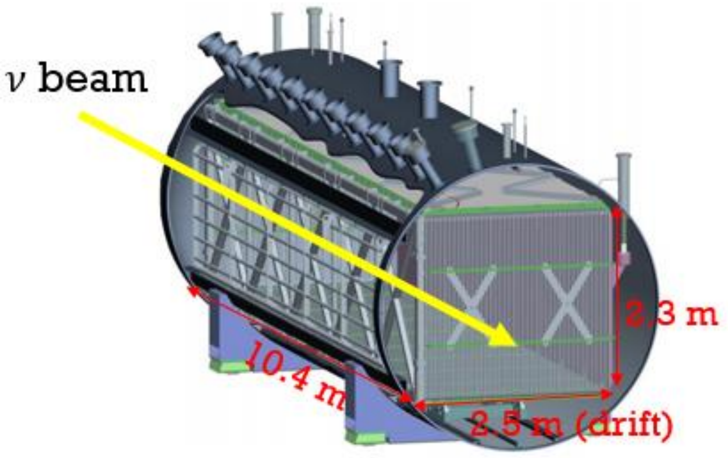
Model Validation in Extraction of the Inclusive Muon Neutrino Charged Current Cross Section at MicroBooNE

Xiangpan Ji and Wenqiang Gu (BNL)
On behalf of the MicroBooNE collaboration
APS April Meeting 2021

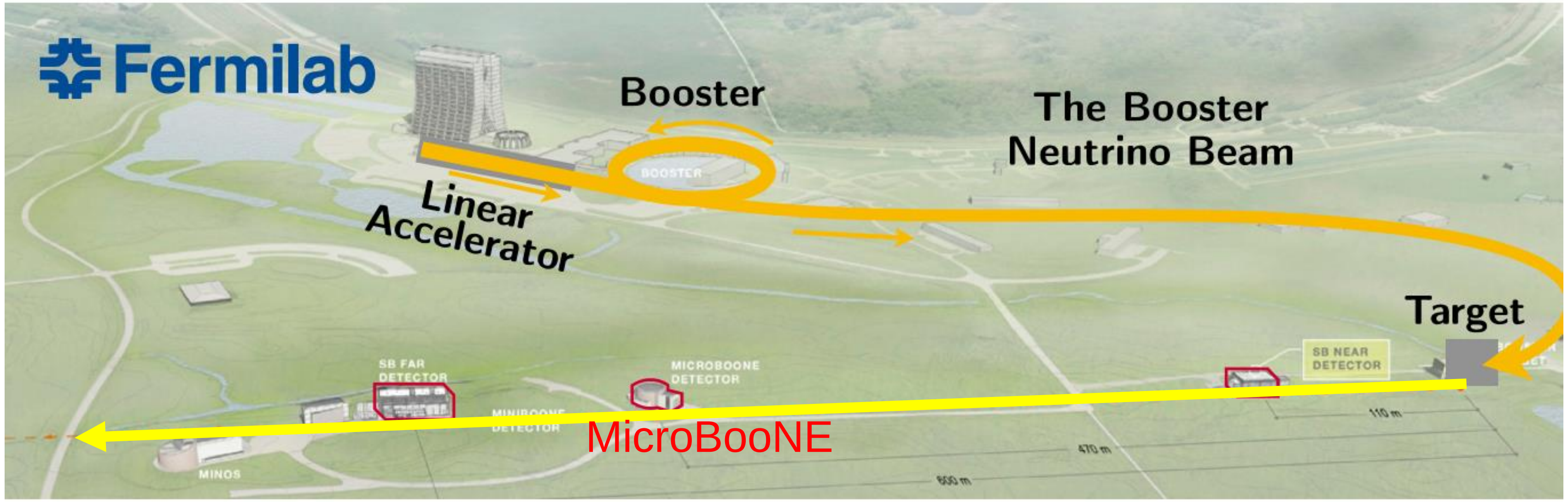
MicroBooNE Overview

- <u>Micro</u> <u>Boo</u>ster <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
  - Measure ν-Ar interaction cross-sections

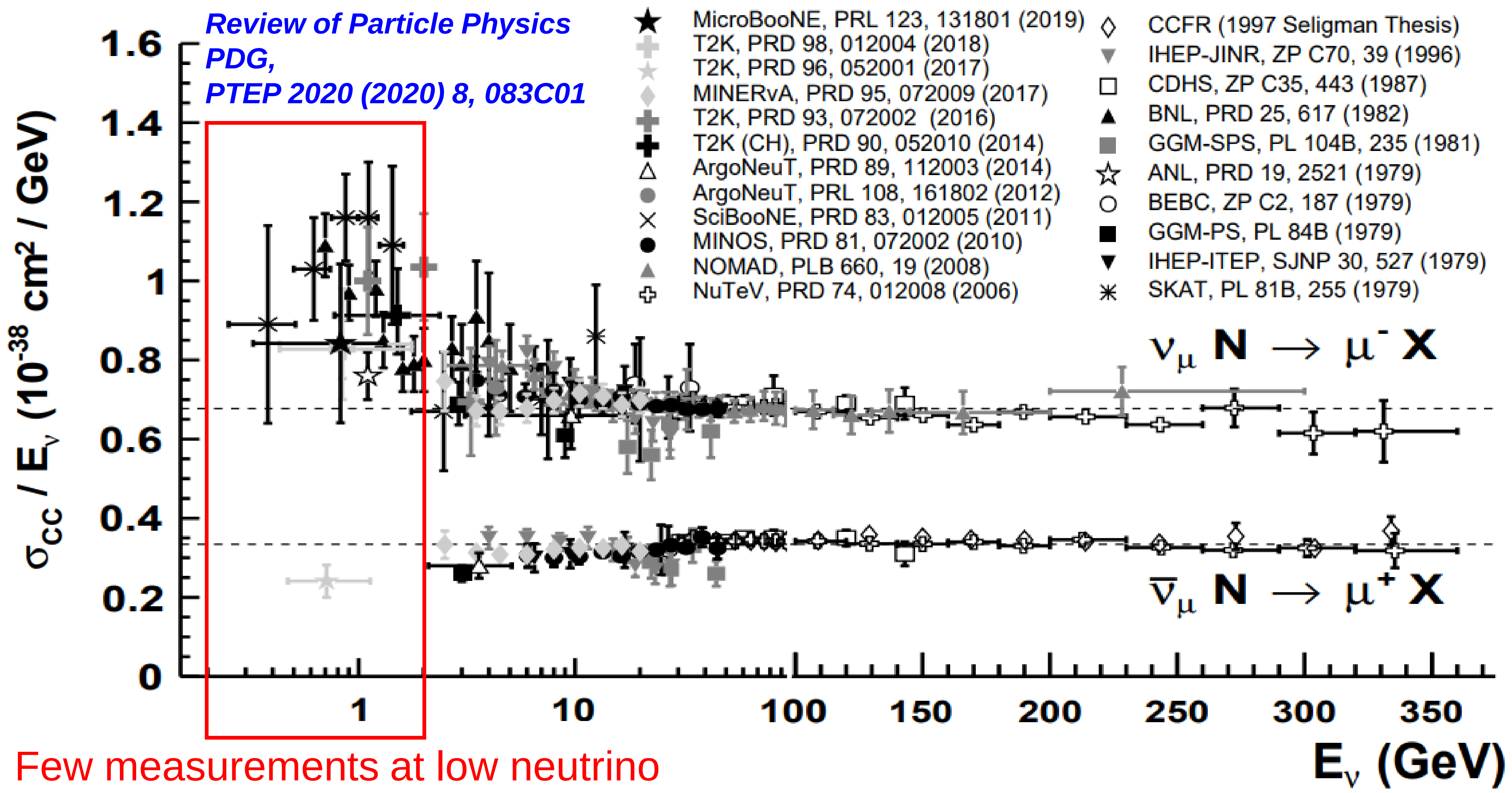


MicroBooNE detector



There are 16 presentations given by MicroBooNE at this meeting!

Measurements of ν_μCC Inclusive Cross Section



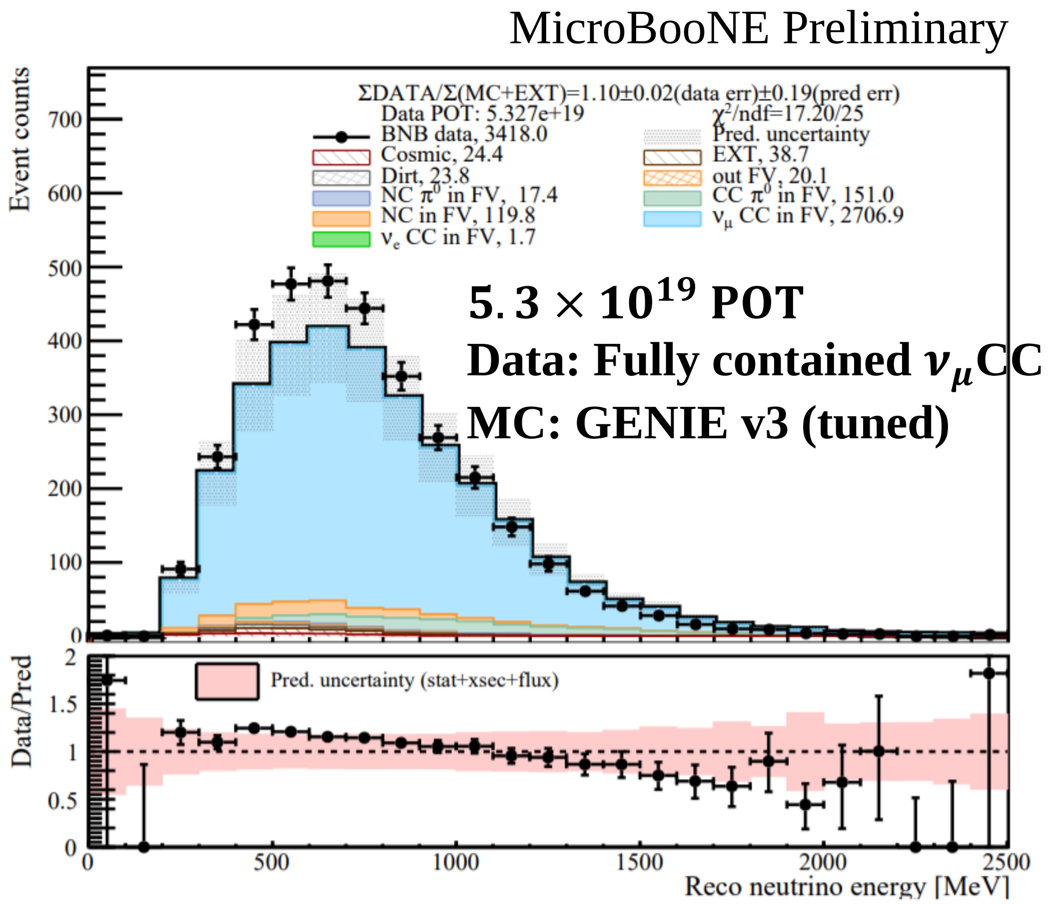
Few measurements at low neutrino energy, especially in Argon target

Selection of Inclusive ν_μCC Interactions

- The Wire-Cell 3D event reconstruction for LArTPC are used, achieving a high rejection of cosmic-ray backgrounds, a high-performance generic neutrino detection (arXiv:2011.01375, arXiv:2011.01375, arXiv:2101.05076)

- The high-statistics event selection allows for high-precision cross-section measurements (MICROBOONE-NOTE-1095-PUB)

- The selected events of inclusive ν_μCC interactions: 93% purity and 64% efficiency



Selection of Inclusive ν_μCC Interactions

London Cooper-Troendle's talk on Wire-Cell generic neutrino detection (E18.2)

- The Wire-Cell 3D event reconstruction for LArTPC are used, achieving a high rejection of cosmic-ray backgrounds, a high-performance generic neutrino detection

Hai Wang Yu's talk on Wire-Cell pattern recognition (Z19.1)

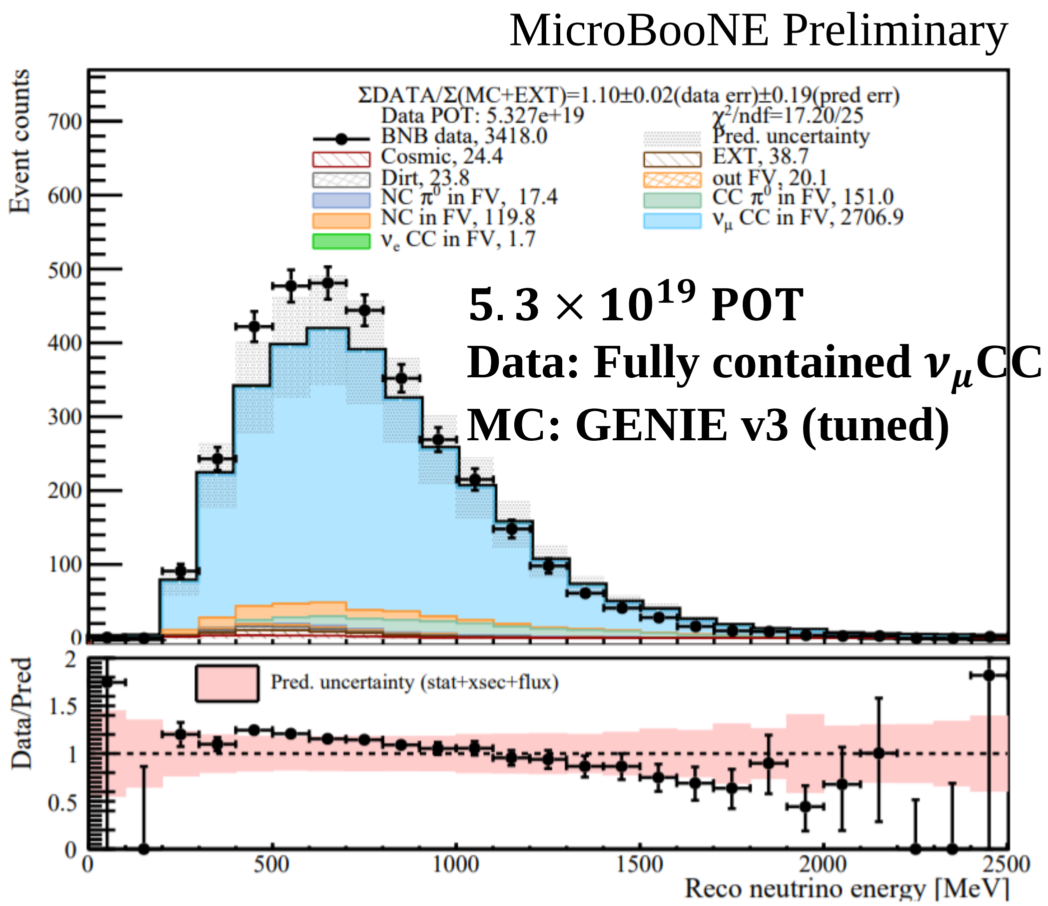
- The high-statistics event selection allows for high-precision cross section measurements (*MICROBOONE-NOTE-1095-PUB*)

Lee Hagman's talk on Wire-Cell ν_eCC selection (H13.1)

Jay Hyun Jo's talk on Wire-Cell eLEE search (H13.2)

- The selected events of inclusive ν_μCC interactions: 93% purity and 64% efficiency

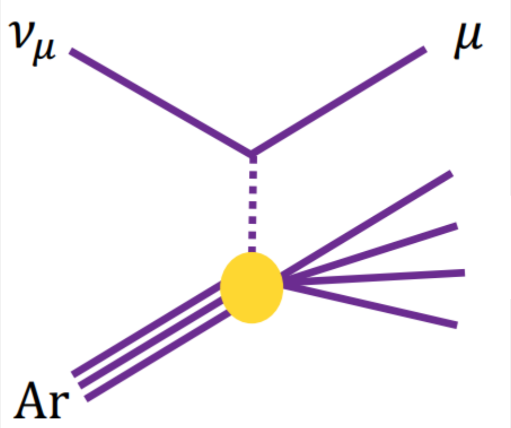
Giacomo Scanavini's talk on Wire-Cell ν_μCC selection (S11.8)



Validation of Neutrino Energy Modeling: E_ν to $\mathrm{E}_\nu^{\mathrm{rec}}$

- Neutrino energy modeling is crucial to neutrino oscillation measurement
- Key challenge: understanding ν-Ar cross section as a function of energy
- A method: validate $\mathrm{E}_{\mathrm{had}}^{\mathrm{rec}}$ after applying the constraint of muon kinematics distribution
  - Common systematics are suppressed, providing a more stringent validation

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



muon kinematics $\Rightarrow X$

total reco energy of hadrons $\mathrm{E}_{\mathrm{had}}^{\mathrm{rec}} \Rightarrow Y$

Method Description*

Given the vector of variable X, Y with their mean and covariance matrix

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

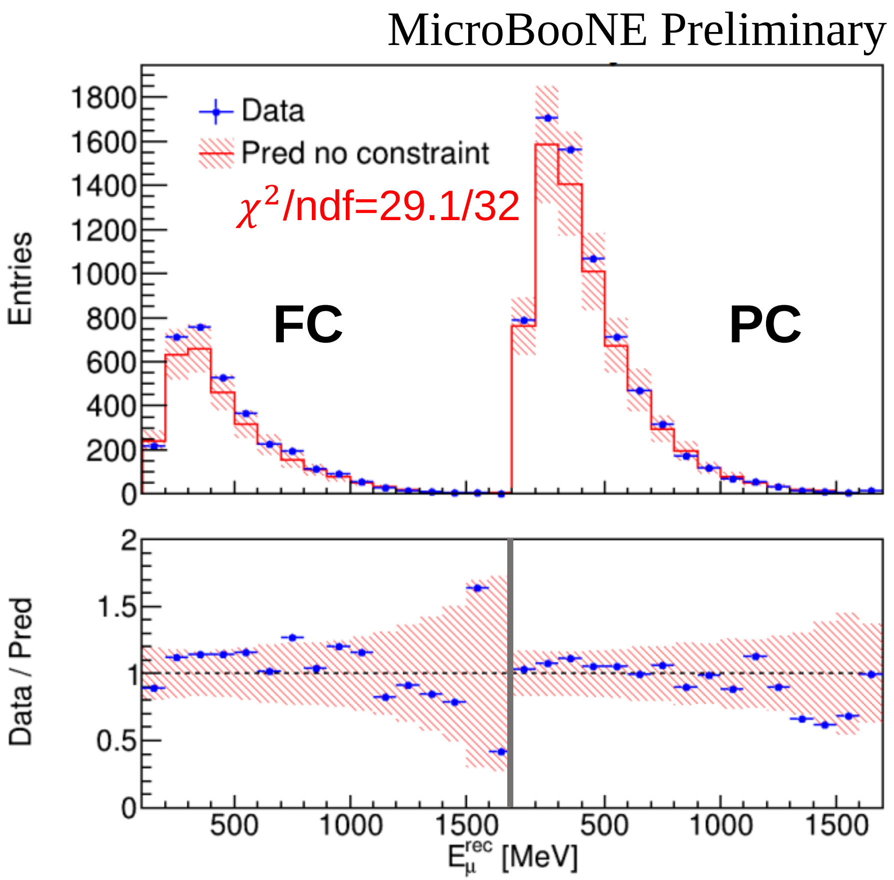
We can calculate the conditional mean and conditional variance

$$\mu_{Y|X}^{\mathrm{constrained}} = \mu_Y + \Sigma_{YX}\Sigma_{XX}^{-1}(m_X - \mu_X)$$ **Expectations on Y**

$$\Sigma_{Y|X}^{\mathrm{constrained}} = \Sigma_{YY} - \Sigma_{YX}\Sigma_{XX}^{-1}\Sigma_{YX}$$ **Uncertainties on Y**

**E. L. Morris "Multivariate Statistics: a Vector Space Approach" 1983*

Muon Kinematics: Total Reconstructed Energy of the Muon ($\mathbf{E_{\mu}^{rec}}$)

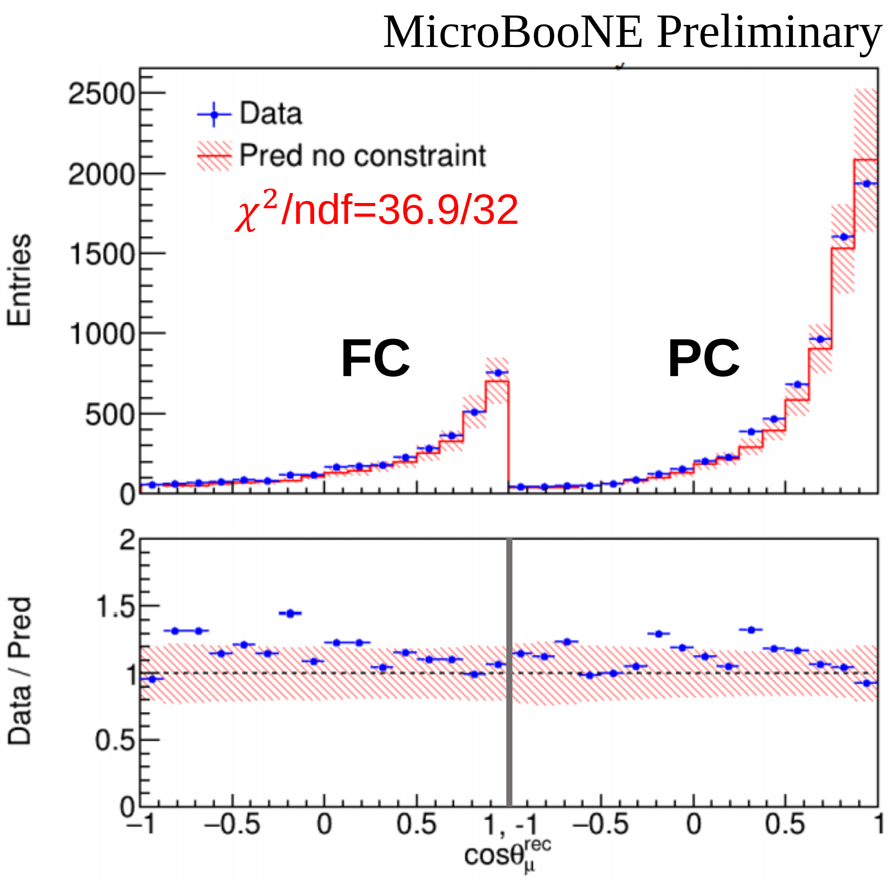


FC: fully contained events in the fiducial volume
PC: partially contained events in the fiducial volume
Goodness-of-fit test:
$\chi^2 = (m-\mu)^{T} \cdot \Sigma^{-1} \cdot (m-\mu)$

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

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



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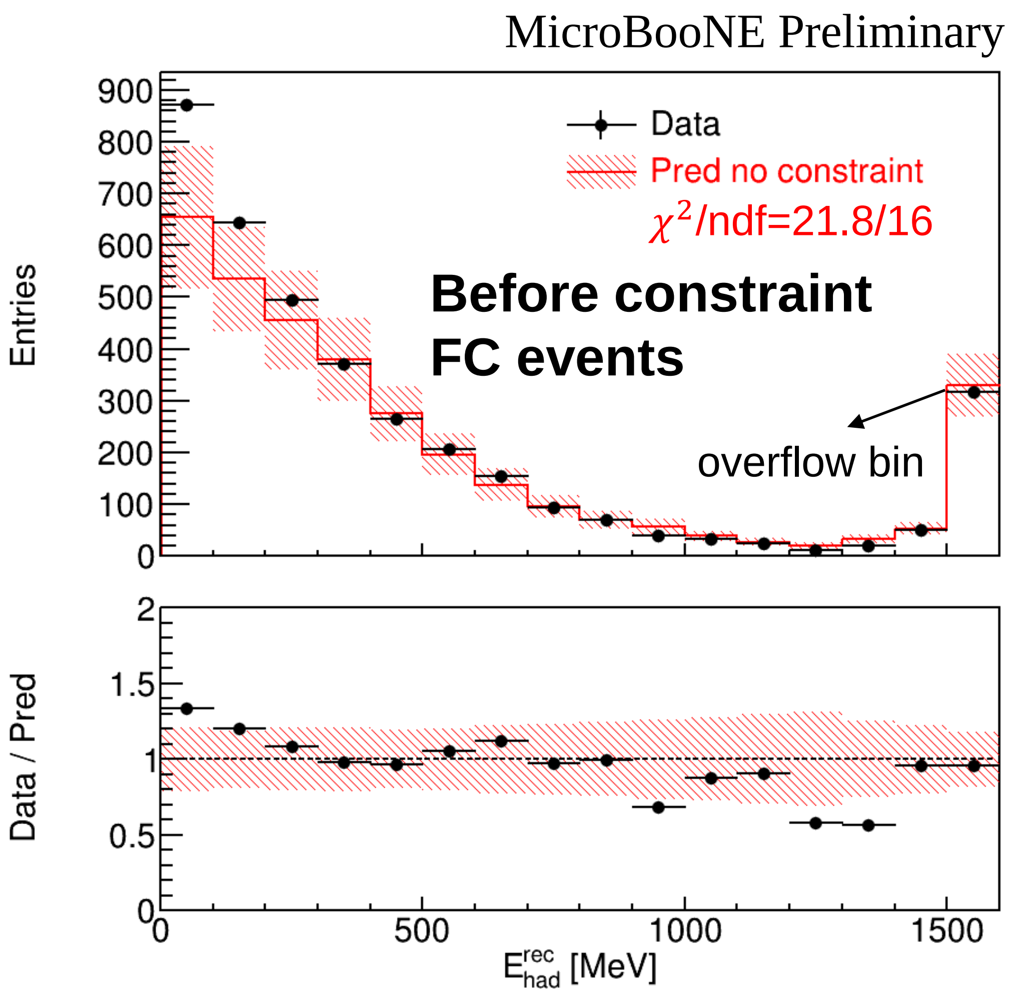
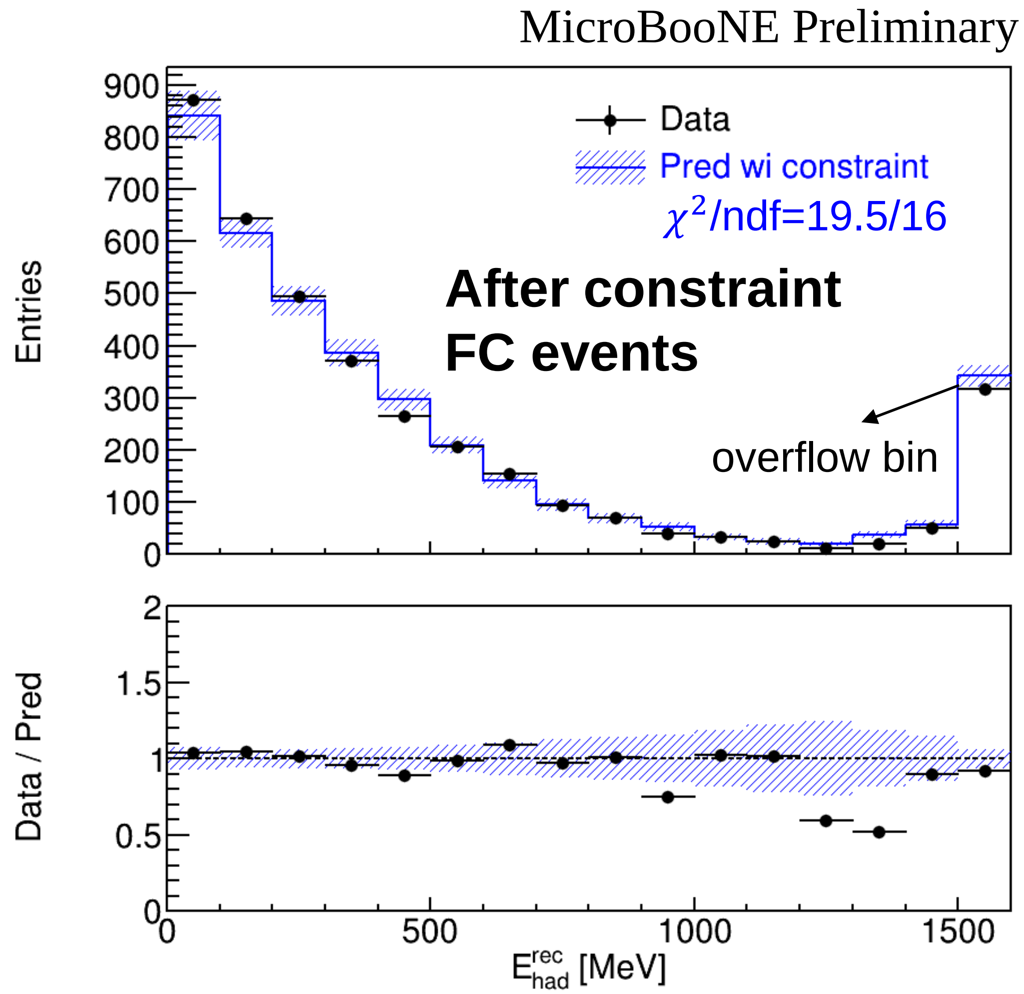
Validation of Hadronic Energy Reconstruction



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

Validation of Hadronic Energy Reconstruction



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

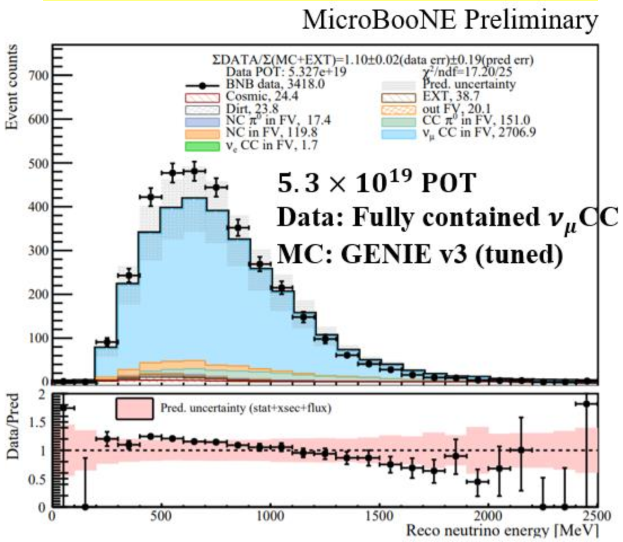
$$\Sigma_{Y|X}^{constrained} = \Sigma_{YY} - \Sigma_{YX}\Sigma_{XX}^{-1}\Sigma_{YX}$$

Y: E_{had}^{rec}

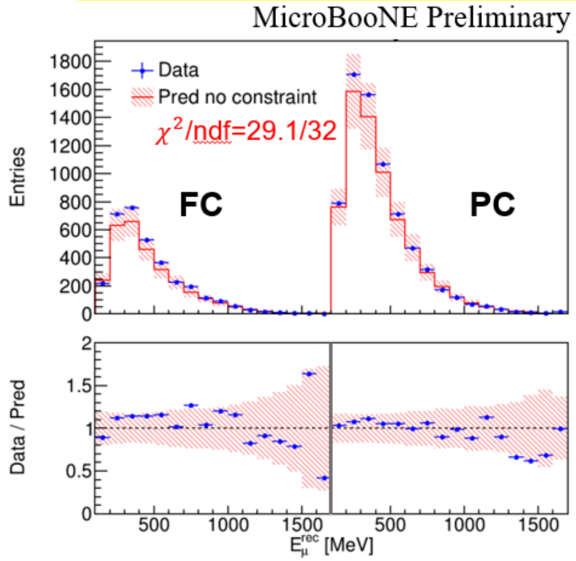
X: E_μ^{rec} **and** $\cos\theta_\mu^{rec}$

To measure the cross section

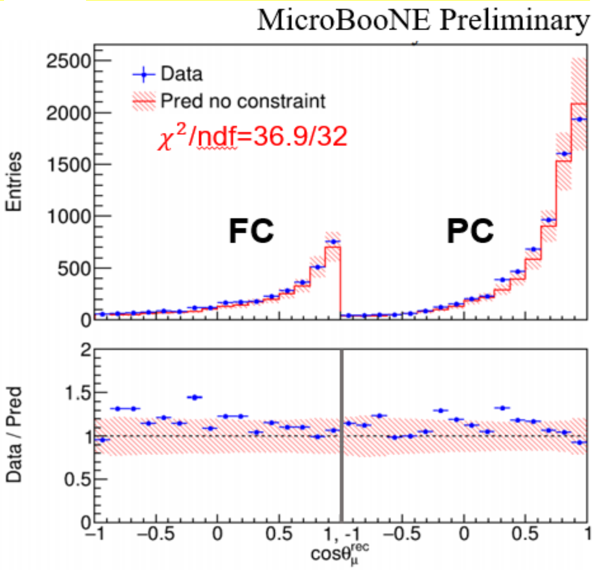
Reco neutrino energy



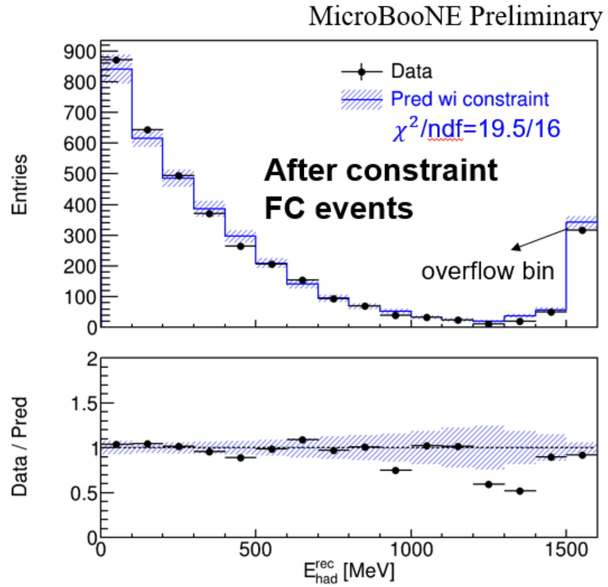
Reco muon energy



Reco polar angle



Reco hadrons energy



- Measure the cross section:
  - σ_{CC}/E_ν: total cross section as a function of neutrino energy
  - $d\sigma_{CC}/dE_\mu$: differential cross section as a function of muon energy
  - $d\sigma_{CC}/d\nu$: differential cross section as a function of energy transfer to Ar
- It enables us to do the multi-dimension differential cross-section measurements
  - E.g. $d\sigma_{CC}/dE_\mu d\theta_\mu$

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 constraint 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 constraint by muon kinematics explains the observed low-hadronic-energy excess

- High-statistics ν_μCC event selection (**≈225k expected for $\mathbf{1.2 \times 10^{21}}$ POT**) for precision cross-section measurements
  - Stay tuned for the initial measurement of cross section (by Wiener-SVD unfolding method *arXiv:1705.03568*)

Thank you!