Extraction of the Inclusive Muon Neutrino Charged Current Cross Section at MicroBooNE using Wiener SVD Unfolding

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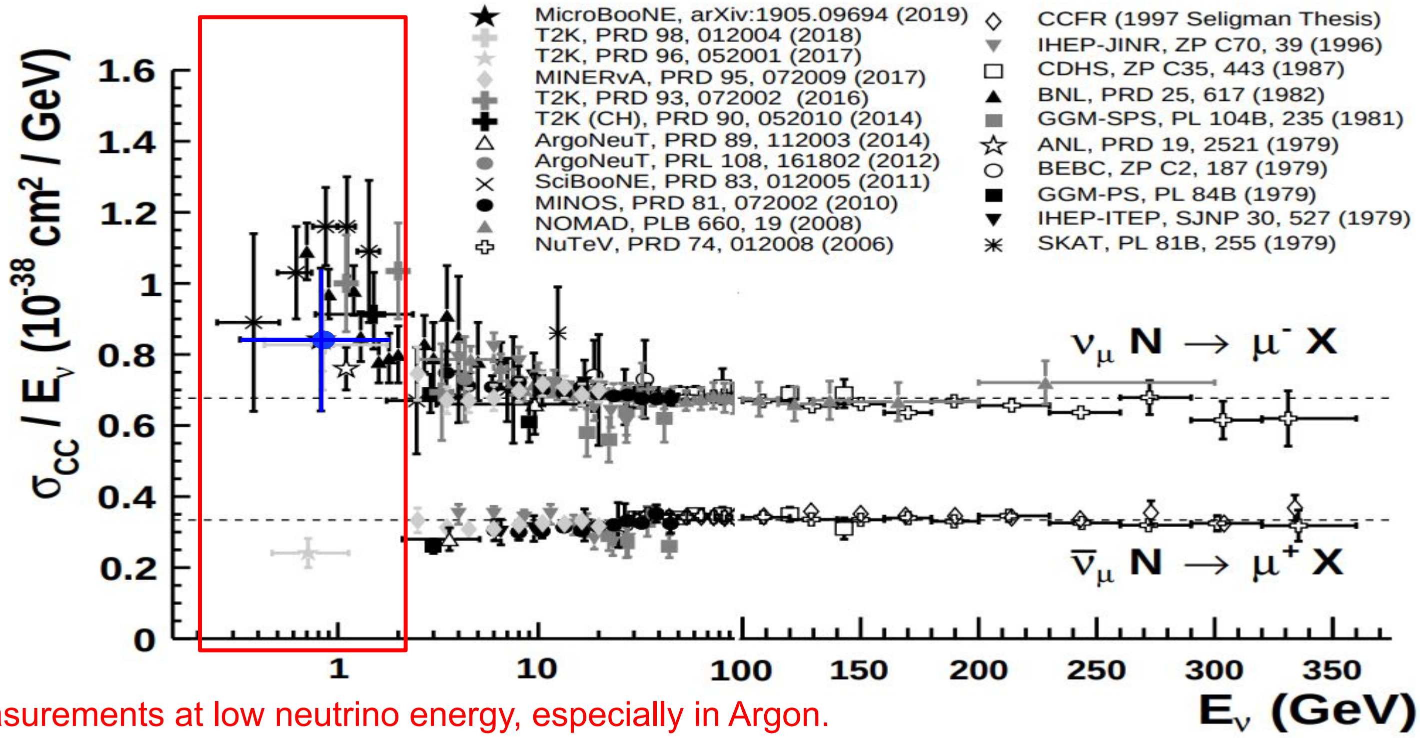
Neutrino Cross Section Measurements



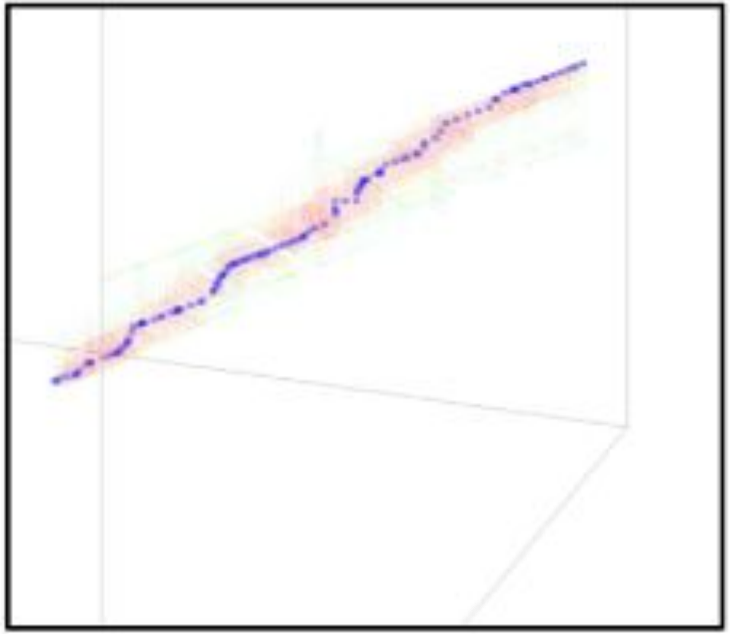
Few measurements at low neutrino energy, especially in Argon.

MicroBooNE total cross section measurement in blue.

Wire-Cell Reconstruction

- Wire-Cell is a fully 3D event reconstruction that arranges charge in a graph structure.
- Use of 2D deconvolution allows for accurate charge reconstruction.
- Many-to-many flash-charge matching allows for accurate cosmic ray tagging.
- Trajectory fit and particle flow create robust particle identification capabilities.

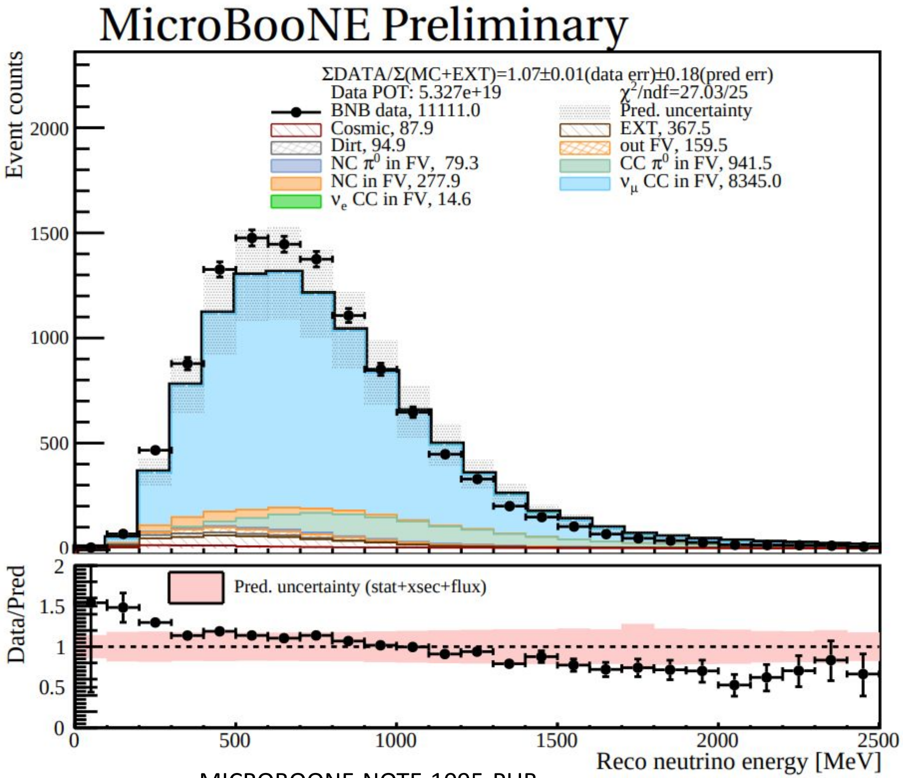
MicroBooNE Preliminary



A muon charge deposition (red) with trajectory fit overlaid (blue).

Wire-Cell Generic Neutrino Selection

- Wire-Cell has reconstructed an inclusive neutrino selection with high efficiency (64%) and high purity (93%).
- This high efficiency is maintained across the full range of three important kinematic variables for differential cross sections: E_{ν}, E_{μ}, and $E_{transfer}$ (aka ν).



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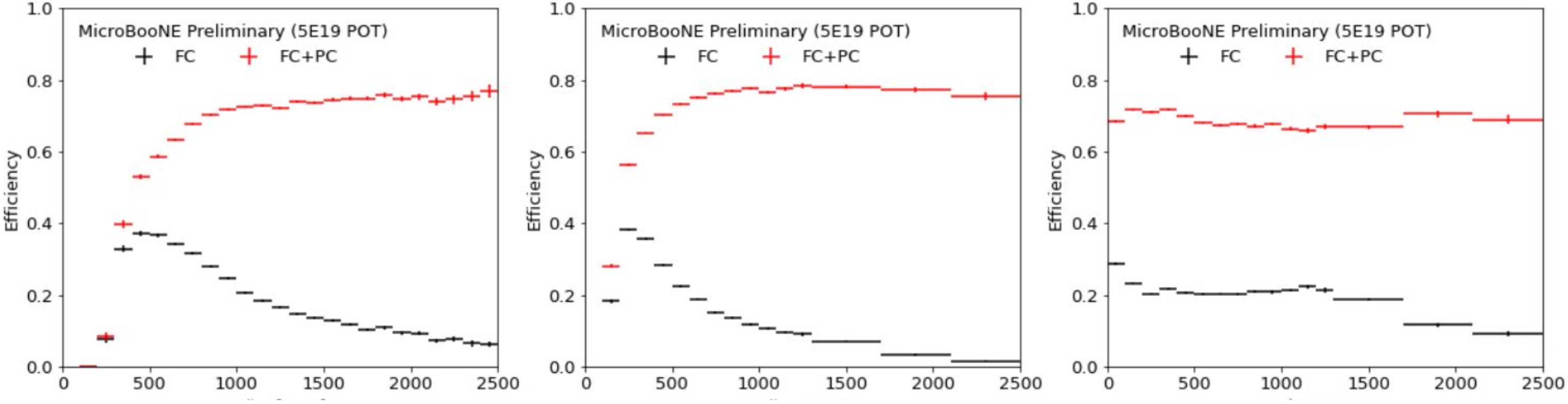
Kinematic Variables for Differential Cross Sections

Fully contained (FC) events begin and end inside the detector.
Partially contained (PC) events enter or leave the detector.



E_{ν}^{true}(MeV) **E_{μ}^{true}(MeV)** **$E_{transfer}^{true}$(MeV) = E_{ν}-E_{μ}**

ν_{μ}CC selection efficiency as a function of true neutrino energy, true muon energy, and true transferred energy to Ar, respectively.

The Purpose of Unfolding

- Allows for direct comparison with other experimental measurements.
- Allows data to help refine generator predictions by favoring and disfavoring existing predictions / underlying assumptions.
- Both the above are of key importance when considering the upcoming SBN and DUNE programs.

Wiener Unfolding in MicroBooNE with Wire-Cell

- Can we Unfold?
  - MC model accurately describes data within uncertainties.
  - Robust data event selection allows for rigorous validation of model.

- Why Wiener Unfolding:
  - Reduced instability compared to simple unfolding.
  - Wiener filter maximizes signal-to-noise ratio in frequency domain.
  - Does not depend on choice of regularization strength parameter.

Measuring the ν_μ CC Cross Section Using Unfolding

Measurement M

Background B

Response matrix R

Signal S

Covariance matrix C

Test statistic $T = (M-B-R\cdot S)^T \cdot C^{-1} \cdot (M-B-R\cdot S)$

$$M-B = R\cdot S$$

Minimize T

$$S = (R^T \cdot C^{-1} \cdot R)^{-1} \cdot R^T \cdot C^{-1} \cdot (M-B)$$

Allows for cross section to be computed as a function of truth variables.

This standard weighted least squares approach suffers from instability in the computation.

Wiener SVD Unfolding

Measurement M

Background B

Response matrix R

Signal S

Covariance matrix C

Test statistic $T = (M-B-R\cdot S)^T\cdot C^{-1}\cdot(M-B-R\cdot S)+T_{reg}$

$$M-B = R\cdot S$$

Minimize T

$$S = A_C\cdot(R^T\cdot C^{-1}\cdot R)^{-1}\cdot R^T\cdot C^{-1}\cdot(M-B)$$

T_{reg} is generated from the MC truth expectation, and helps the fit stability.

The Wiener filter used to generate A_C maximizes signal/noise ratio in the relevant frequency domain.

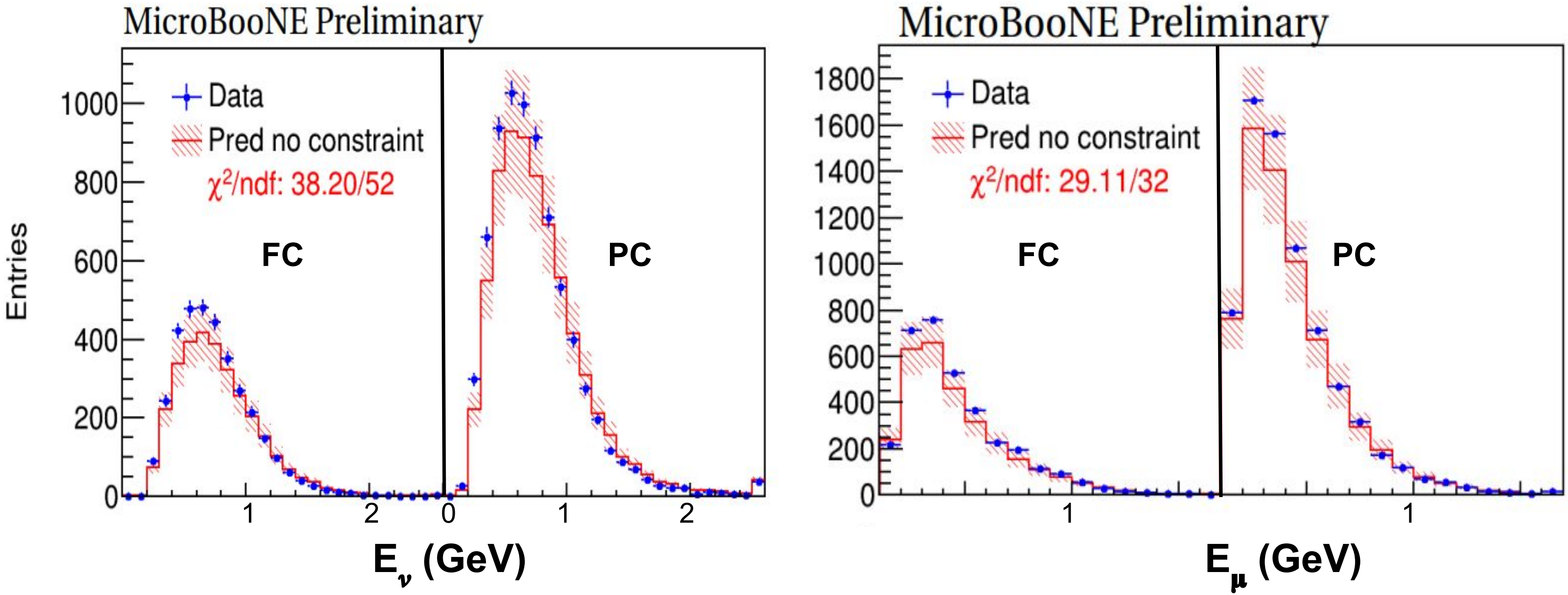
Assumptions of Wiener SVD Unfolding

- The model used for the regularization term T_{reg} / smearing matrix A_C in unfolding must accurately predict data

- Covariance matrix formalism should accurately describe systematic uncertainties, and these uncertainties should cover any data/MC difference.

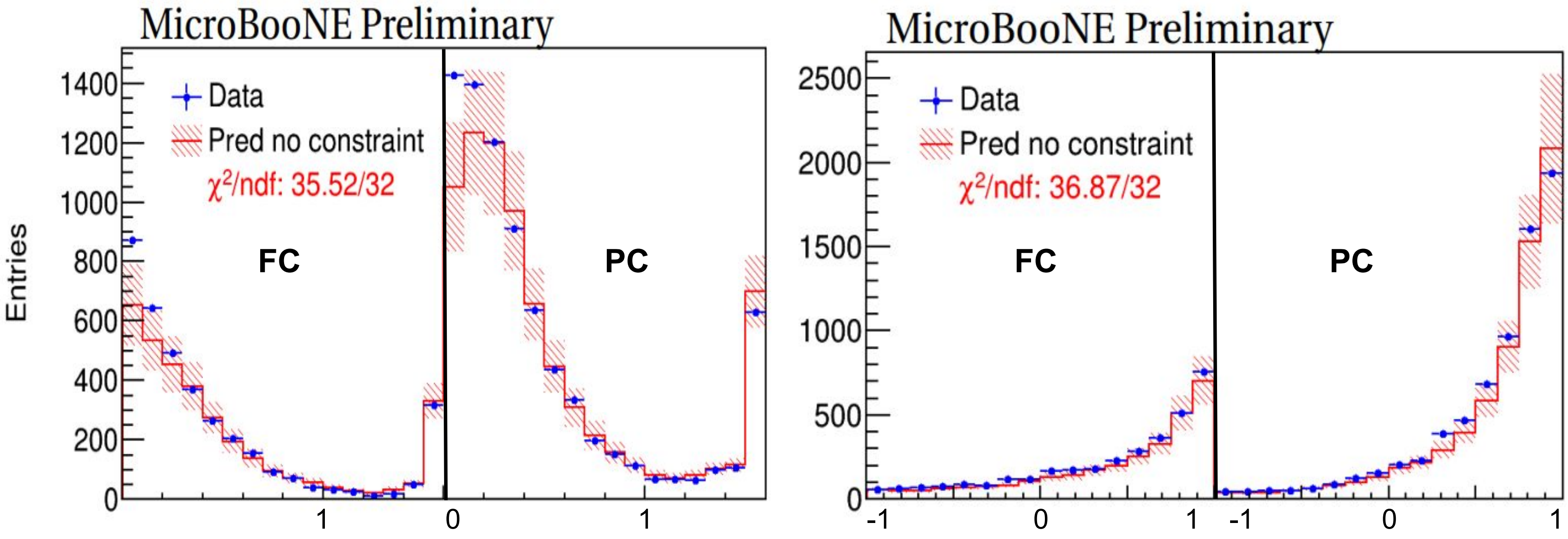
- There must be no data reconstruction gap in phase space across kinematic variables. (Strength of LArTPC and Wire-Cell).

Validation of Model with Goodness of Fit



Fully contained (left) and partially contained (right) events are shown for each variable.
Data from 5e19 POT open dataset.

Validation of Model with Goodness of Fit

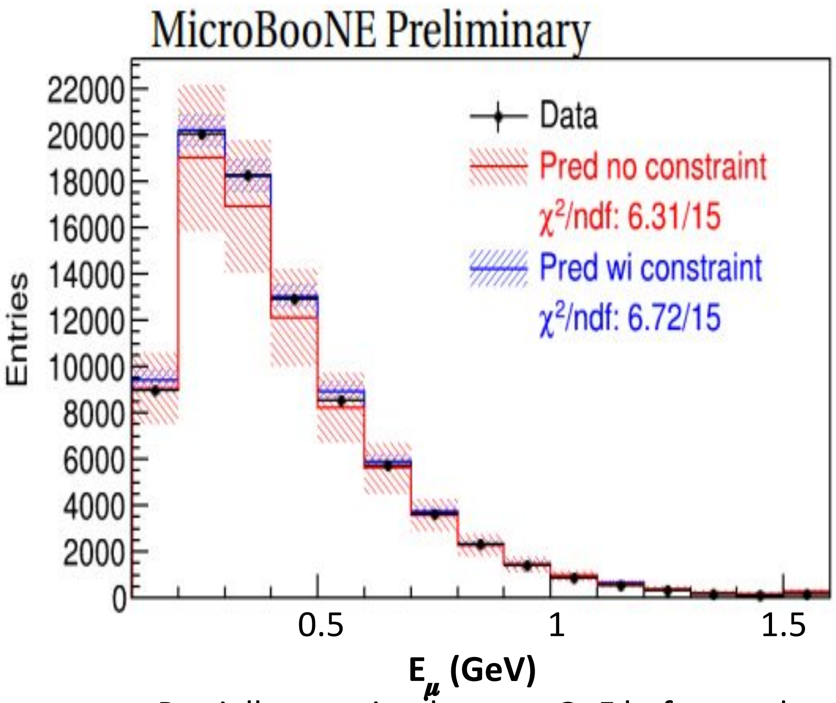


$E_{transfer}$ (GeV) cos θ_{μ}

Fully contained (left) and partially contained (right) events are shown for each variable.
Data from 5e19 POT open dataset.

Applying Constraints to Goodness of Fit

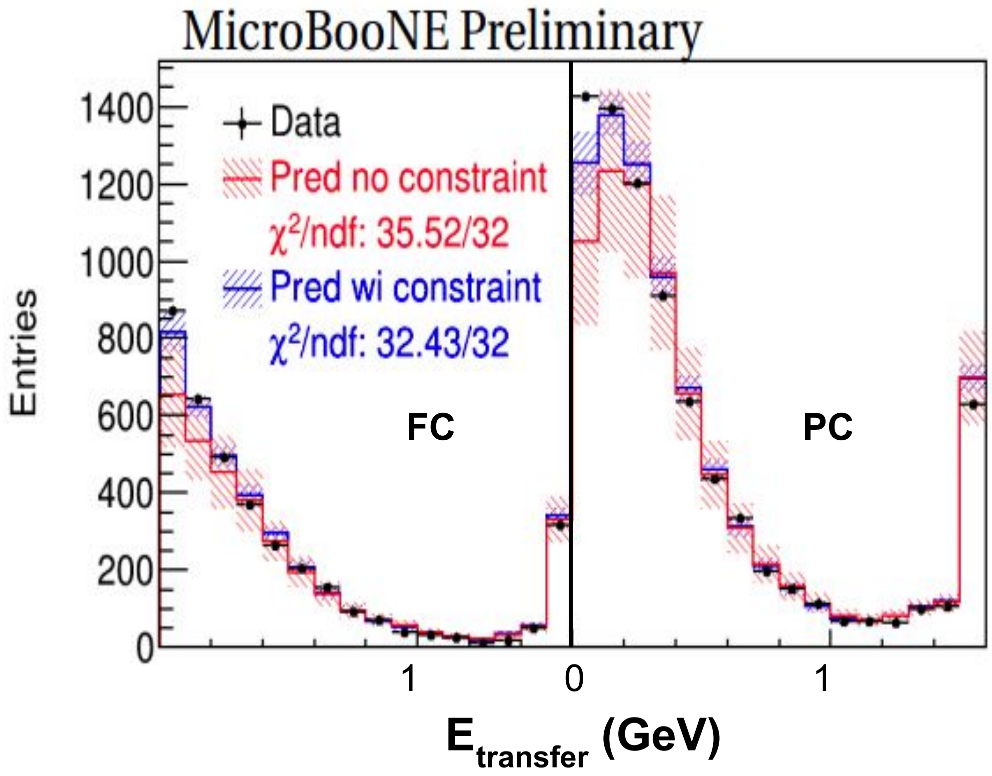
- Goodness of fit of partially-contained events E_μ compared before and after constraining by fully contained events.
- The constraint reduces uncertainties but also shrinks data/MC difference, maintaining GoF value.
- This validates our energy reconstruction model for partially contained events.



Partially contained events GoF before and after constraint from fully contained events.

Constraining Hadron Energy with Muon Energy

- Muon energy measurement constraint significantly reduces uncertainty.
- Constrained measurements agree better with MC, improving X^2/ndf.
- This helps reduce worry of hadronic-specific reconstruction issue in data.



Summary

- Wire-Cell's high-efficiency, inclusive ν_μ selection provides high statistics for numerous differential cross sections.
- Unfolding allows for cross sections to be measured as a function of truth variables.
- The interaction model is validated with data/MC GoF comparisons to ensure accurate unfolding.
- Multiple cross section measurements are in progress and hope to be published soon!

References

- Wire-Cell Software Package for LArTPC: https://lar.bnl.gov/wire-cell/
- Neutrino Interaction Model and Uncertainties for MicroBooNE Analyses. MICROBOONE-NOTE-1074-PUB
- Wire-Cell Neutrino Selection MICROBOONE-NOTE-1095-PUB
- Data Unfolding with Wiener SVD Method