Advancing Neutrino-Nucleus Interaction Physics for Precision Oscillation Studies: Insights from MicroBooNE

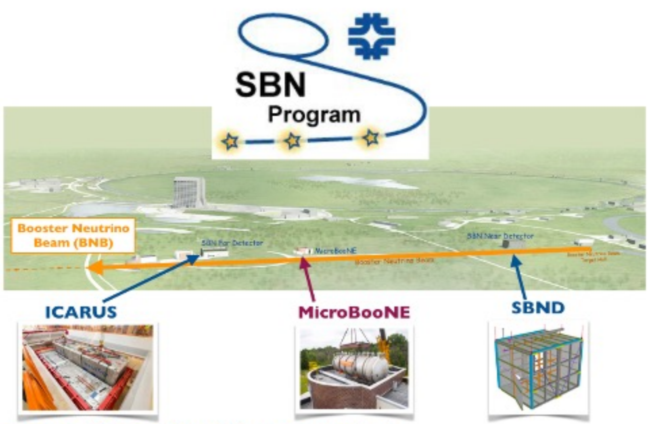
Xin Qian

Brookhaven National Laboratory

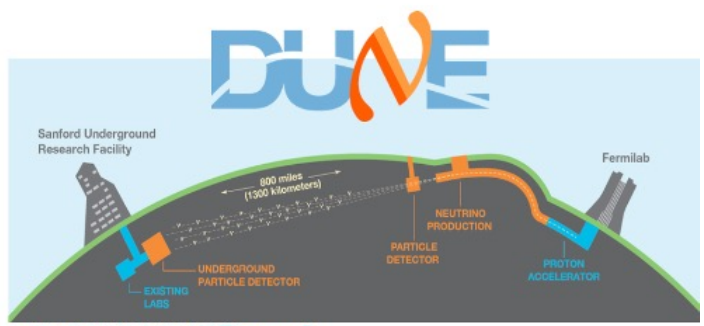
On behalf of MicroBooNE collaboration

Neutrino-nucleus interactions in LArTPC

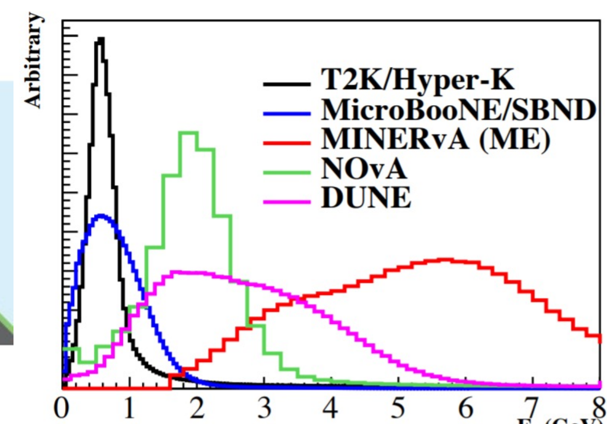
- Liquid Argon Time Projection Chamber (LArTPC) is one key technology in the current and future neutrino oscillation experiments
- Understanding ν-Ar cross sections in GeV energy range is critical in reducing systematic uncertainties to reach desired precision of these experiments



arXiv:1503.01520 [physics.ins-det]



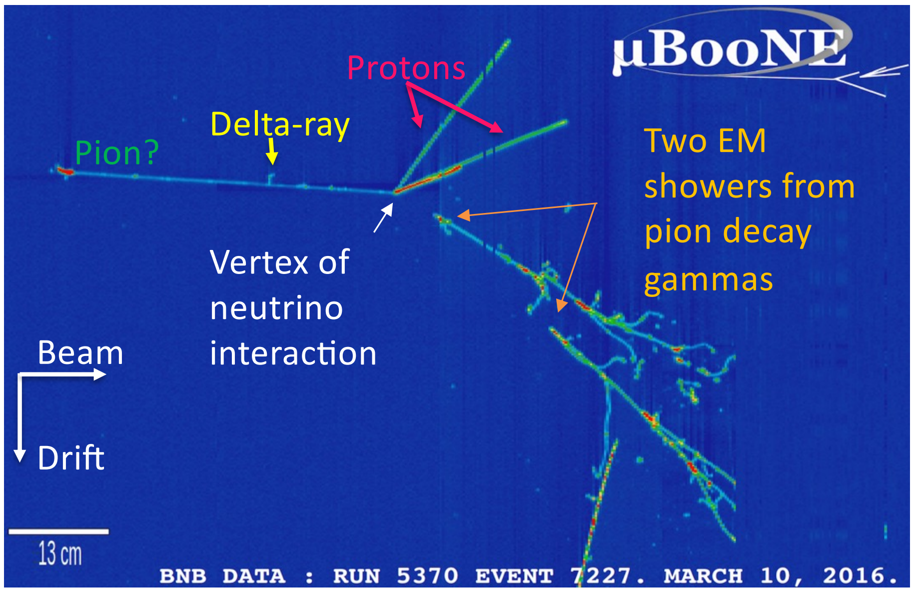
arXiv:2002.03005 [hep-ex]

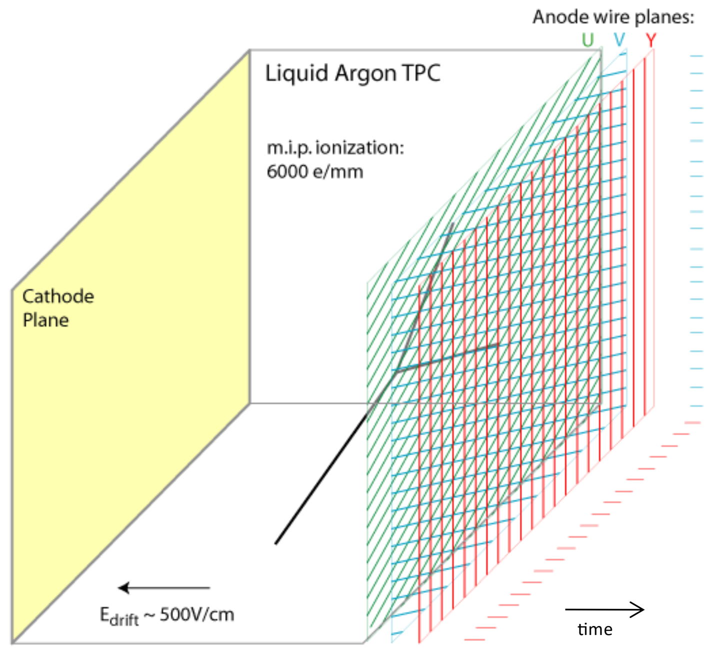


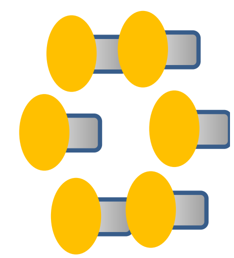
T. Katori and M. Martini, J.Phys. G45 (2018) 013001

LArTPC: Fully Active Tracking Calorimeter

Made by Bo Yu (BNL)





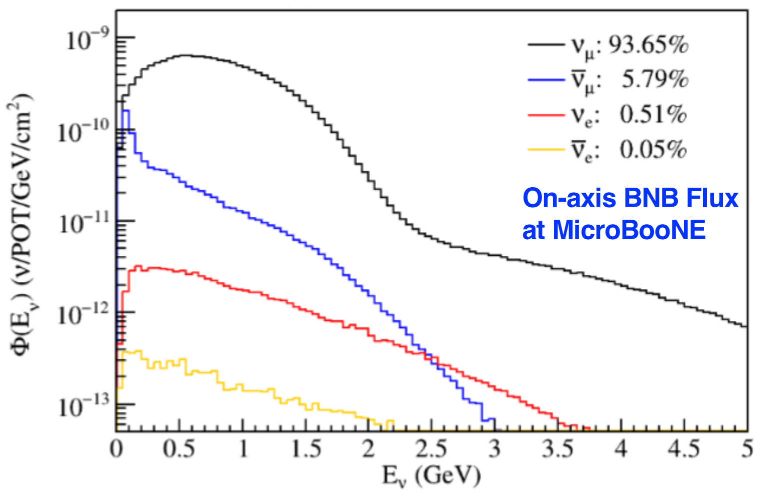


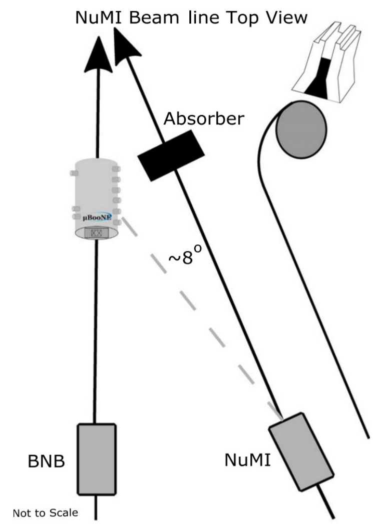
A candidate of neutral-current interaction

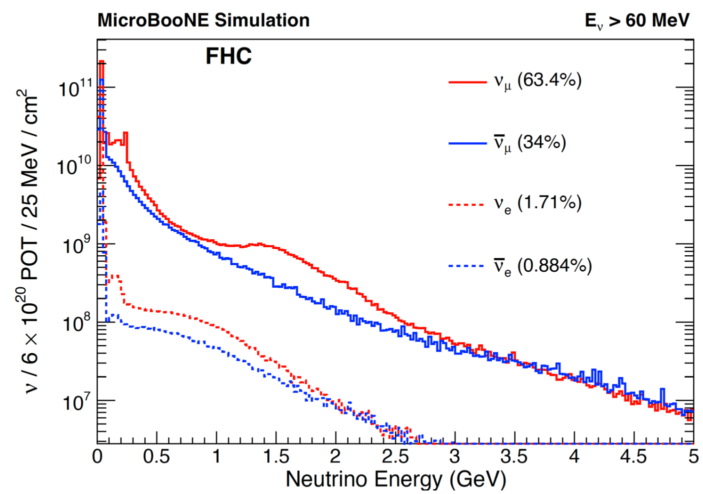
Drift velocity 1.6 mm/μs → several ms drift time

~mm position resolution with sub MeV energy threshold and ~ns timing resolution

MicroBooNE Experiment



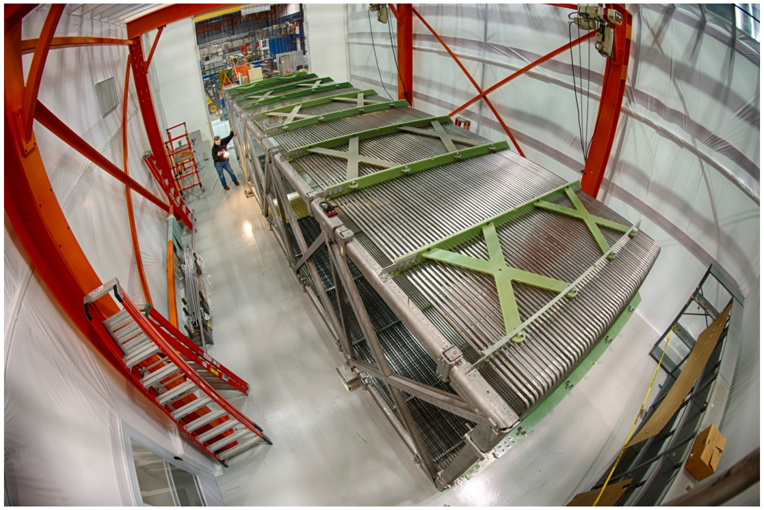


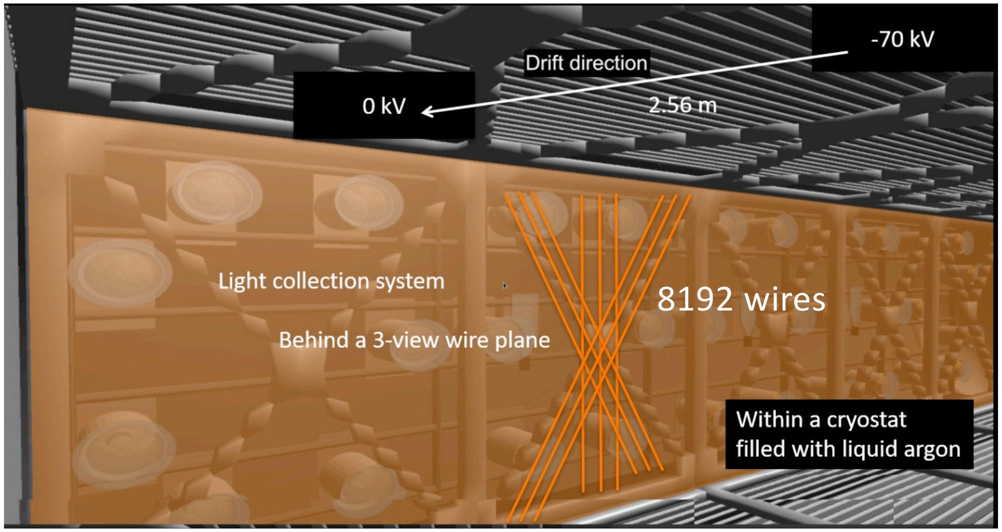


- Both ν_μ and ν_e cross sections are important for oscillation measurements
- At MicroBooNE, two beamlines are available:
  - Booster Neutrino Beamline (BNB): **on-axis**, 99.5% $\nu_\mu + \bar{\nu}_\mu$ **&** 0.5% $\nu_\mathrm{e} + \bar{\nu}_\mathrm{e}$
  - Main injector neutrino beam (NuMI): **off-axis**, 3% $\nu_\mathrm{e} + \bar{\nu}_\mathrm{e}$

MicroBooNE Detector: An 85-ton LArTPC

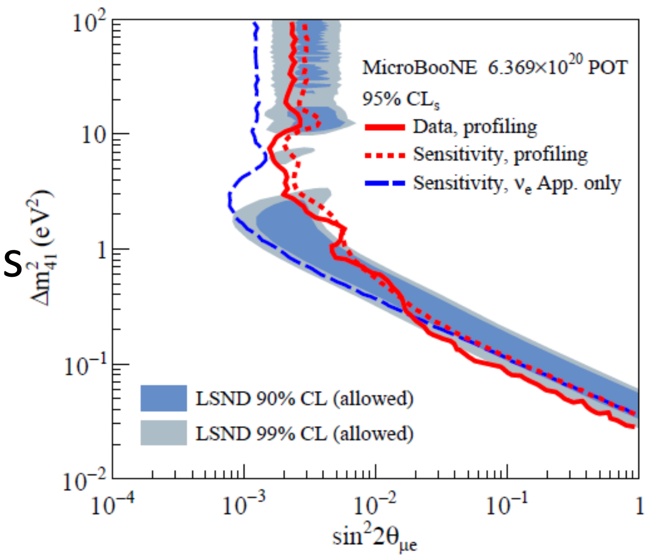
- 8192 wire channels to detect ionization charge
- 32 8-inch PMTs to detect scintillation light
- Physics Motivation:
  - **Address MiniBooNE Low Energy Excess & BSM**
  - **LArTPC hardware & software R&D**
  - **Study ν-Ar interactions**
    - ~0.5 M events in 2016-2021 ν-Ar data set

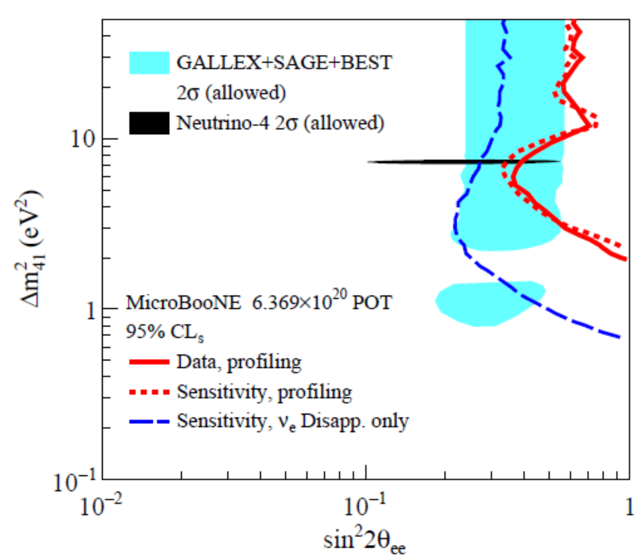




Search for a Light Sterile Neutrino in a 3+1 Model

- No evidence of ν_s oscillation
- ν_μ to ν_e app. and ν_e dis. can cancel, creating degeneracies
- A combined BNB+NuMI search can probe the full phase space in a single experiment
  (soon to be released)
  - Two neutrino beams + One detector
  - ~10× difference in ν_e/ ν_μ flux ratio breaks degeneracy





Phys. Rev. Lett. 130, 011801

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} + (-1)^{\delta_{\alpha\beta}} \boxed{\sin^2 2\theta_{\alpha\beta}} \cdot \sin^2(1.267 \frac{\Delta m^2_{41} L}{E})$$

ν_e disappearance $\boxed{\sin^2 2\theta_{ee} = \sin^2 2\theta_{14}}$

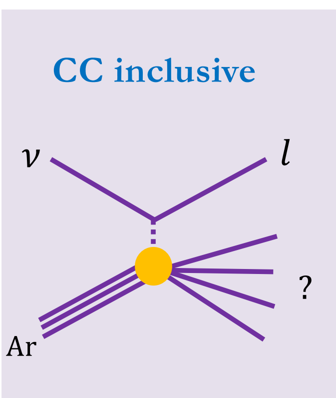
ν_μ disappearance $\boxed{\sin^2 2\theta_{\mu\mu} = 4\cos^2\theta_{14}\sin^2\theta_{24}\left(1-\cos^2\theta_{14}\sin^2\theta_{24}\right)}$

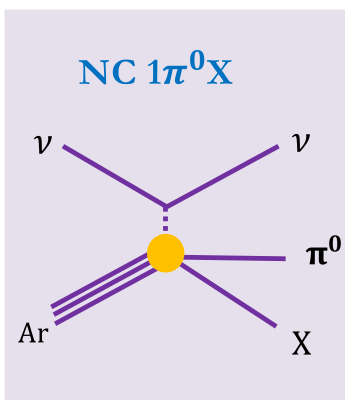
ν_e appearance $\boxed{\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14}\sin^2\theta_{24}}$

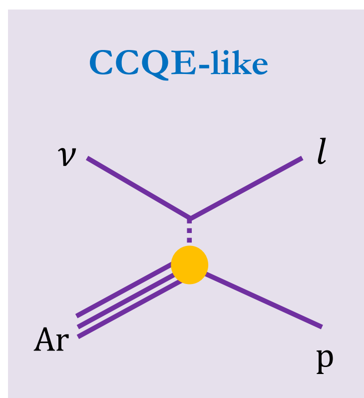
- non-zero ν_e appearance requires both ν_e and ν_μ disappearances

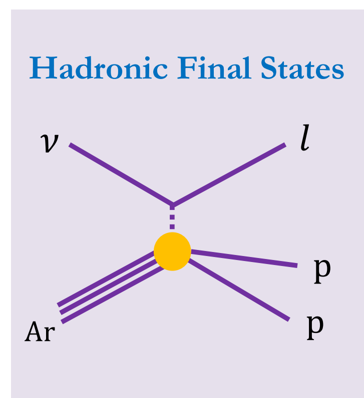
Neutrino-Nucleus Interaction Physics

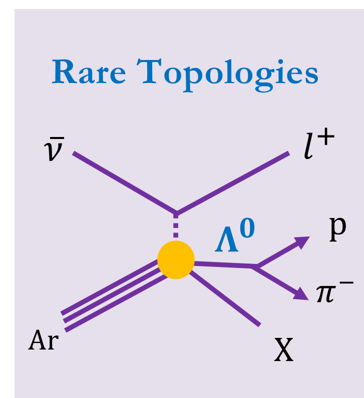
- Precision oscillation studies require a detailed understanding of neutrino-nucleus interactions:
  - Xs quantify the nuclear response to a neutrino probe
  - Interaction rates impact statistical power
  - Final-state particles enable event identification and tagging
  - Energy mapping from reconstructed to true neutrino energy for accurate oscillation modeling





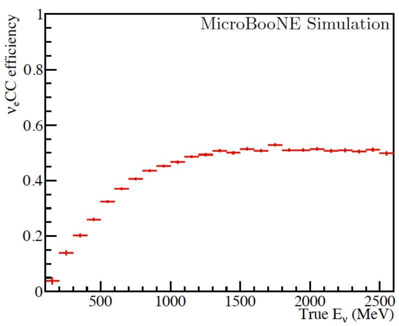




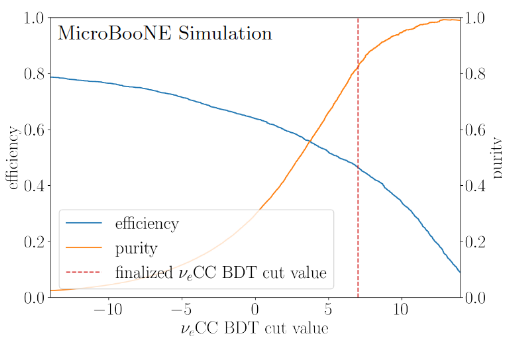


Impact of Neutrino-Nucleus Cross Sections on Oscillation Analysis

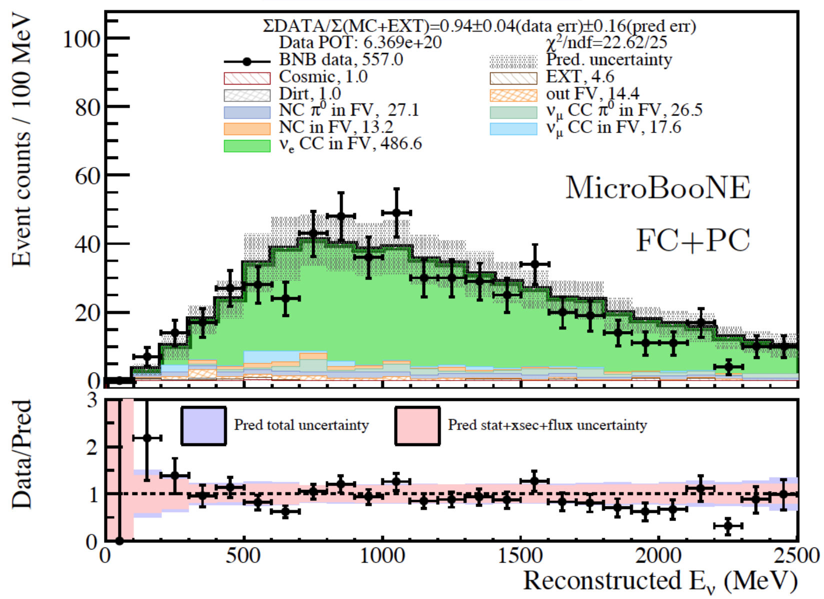
Signal efficiency



Background prediction (aka signal purity)

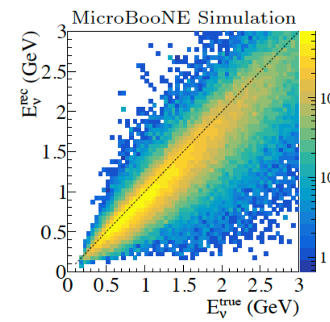


[PRD 105 112005]



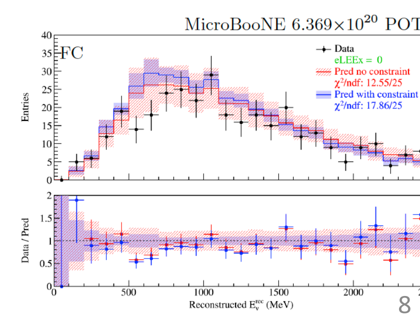
Requires **an end-to-end model** combining flux prediction, *interaction cross sections*, detector response, event reconstruction/selection among others

Mapping between true and reconstructed neutrino energy



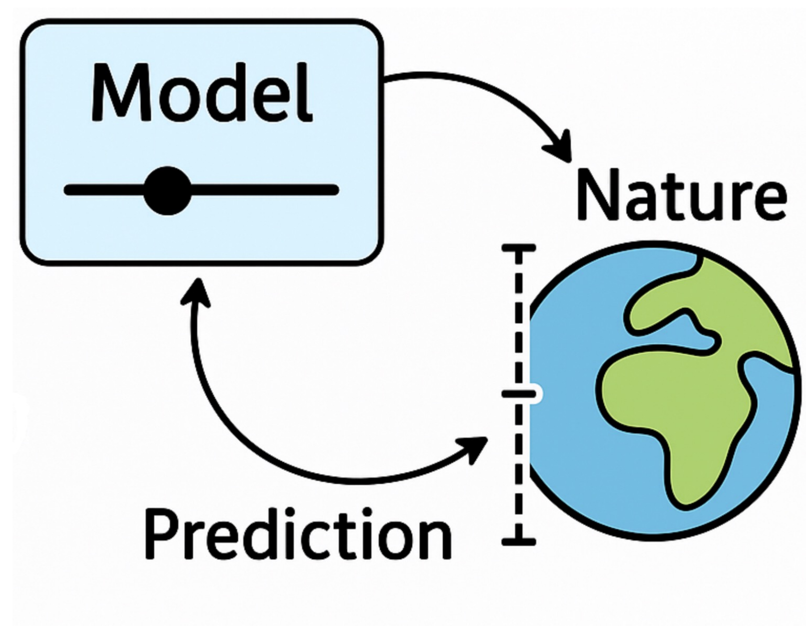
(c) ν_e CC candidates, FC

Signal prediction



What is a Model?

- A **model** is an approximation of nature that captures essential physical behavior
  - Includes **effective degrees of freedom** (or **knobs**) to represent underlying dynamics
  - Each **knob** represents a **tunable parameter** (e.g., nuclear response shape) → Central-Value (CV)
  - Every knob is associated with a **quantified uncertainty** to reflect modeling limitations



Model Limitations

- The number of degrees of freedom in a model is often underestimated

- Meanwhile, parameter uncertainties tend to be overestimated
  - Reflects a conservative approach→ **Absorb potential model deficiencies within larger uncertainties**
  - Achieves the goal → Ensure that **discrepancies from missing physics** remain **statistically insignificant** relative to total uncertainty

J. Taylor
"An introduction to Error Analysis"

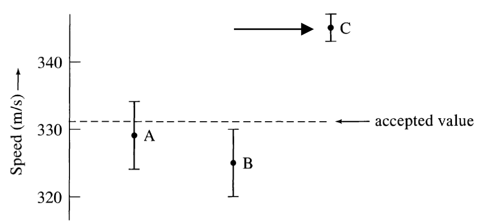


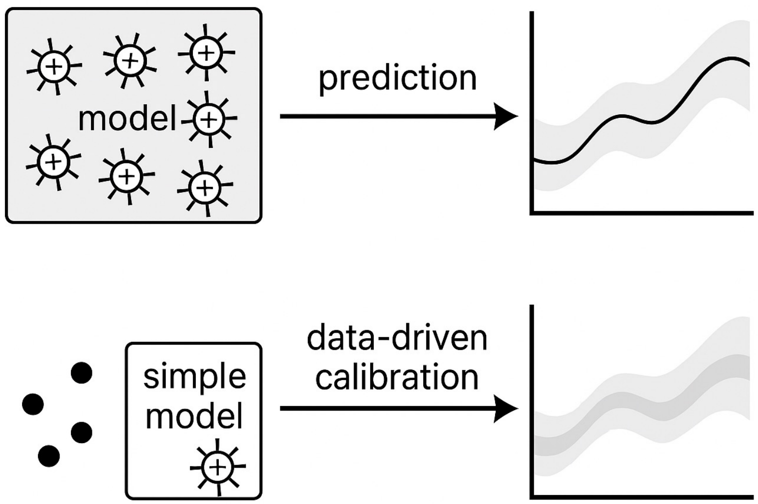
Figure 2.2. Three measurements of the speed of sound at standard temperature and pressure. Because the accepted value (331 m/s) is within Student A's margins of error, her result is satisfactory. The accepted value is just outside Student B's margin of error, but his measurement is nevertheless acceptable. The accepted value is *far outside* Student C's stated margins, and his measurement is definitely unsatisfactory.

•✅ **A and B**: Conservative uncertainties absorb possible modeling deficiencies — results remain acceptable even if some physics is missing

•❌ **C**: Small uncertainty fails to cover a large discrepancy — suggests underestimation despite possibly using a more complex model

How to Improve Model?

Data-driven Calibration



Data-driven calibration

Part of systematic uncertainties are replaced by the data statistical uncertainties

Model Validation

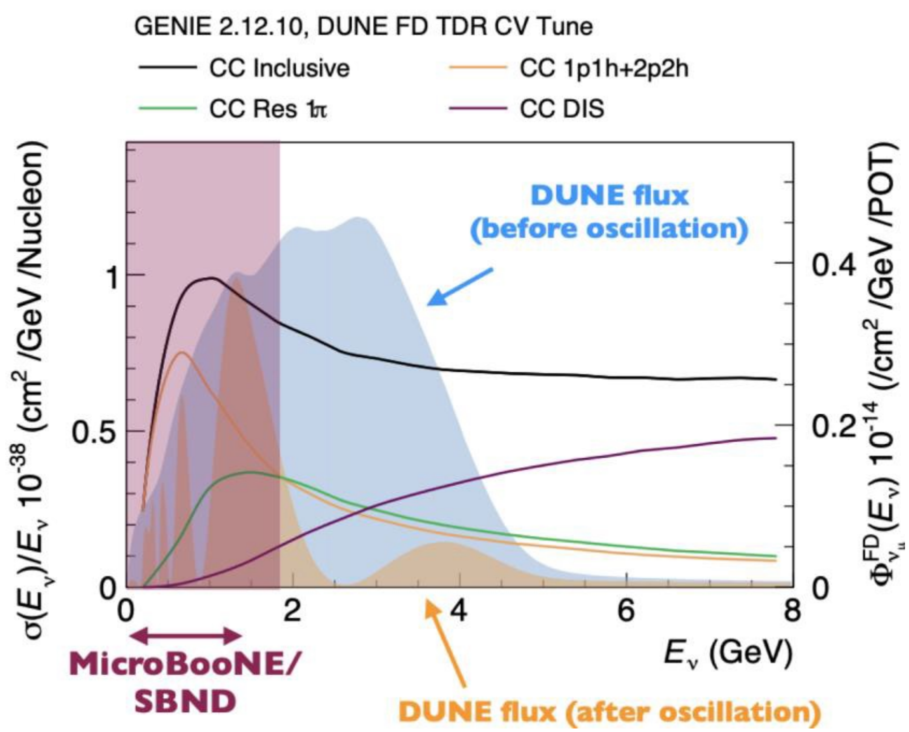
- Follows the **same philosophy as data calibration**, but applies when no dedicated calibration dataset exists
  - Involves **checking compatibility between model predictions and real data**
- A successful validation means the model is **consistent with data within its stated uncertainties**
- ⚠️ **Caution**: Agreement with data does **not imply the model is complete** across the entire phase space — limitations (e.g. missing degrees of freedom) may still exist

Apply the Philosophy to Neutrino Oscillation

- Direct Calibration of Nuclear Response to **ν** Probes
  - **Provides neutrino energy–dependent cross sections: $\boldsymbol{\sigma(E_\nu)}$**
  - Includes differential Xs across a wide range of final-state topologies
  - **Improve/tune the event generators**

- Energy Mapping in Broad-Band Neutrino Beams
  - E_ν is not known event-by-event
  - Accurate neutrino oscillation predictions require **validating the mapping between $\boldsymbol{E_{rec}}$ vs. $\boldsymbol{E_\nu}$**
    - Also essential for extracting energy-dependent $\sigma(E_\nu)$

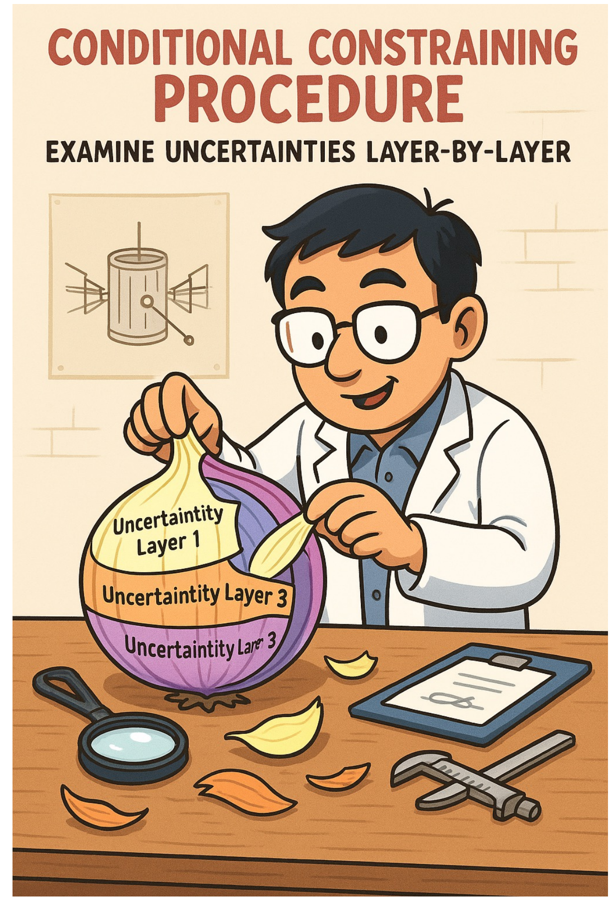
- **Better energy resolution,** higher efficiency, lower background, detector calibrations, side-band constraints …



Model Validation

&

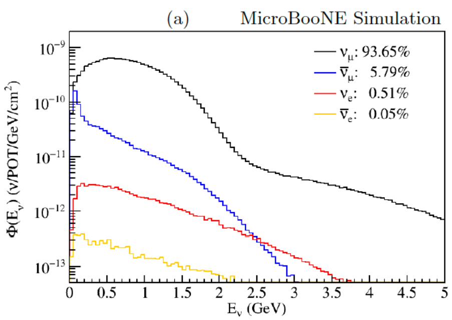
Inclusive $\nu_\mu - Ar$ charged-current interaction Cross Sections



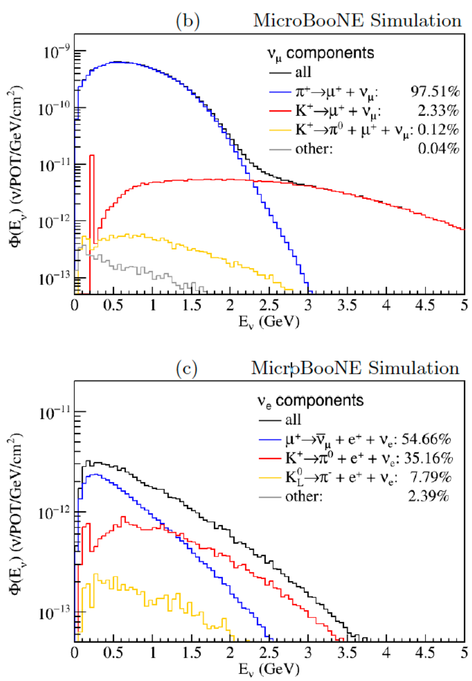
MicroBooNE Model (I)

- Neutrino Flux Simulation
  - Based on GEANT4 simulation following the earlier work by MiniBooNE

[PRD 79, 072002](#)



Strong correlations between ν_μ and ν_e given the decays from charged pions and kaons



- Neutrino-Nucleus Interaction
  - GENIE-v3 + Tune to T2K CC0**π** data
  - Full Valencia model assuming local Fermi gas, CCQE, CC2p2h interactions
  - RPA, Coulomb interactions, FSI improvements

[PRD 105, 072001](#)

TABLE VIII. Summary of parameters for which MicroBooNE analyses adopt a different central value and/or uncertainty than recommended in the GENIE v3.0.6 G18_10a_02_11a model set.

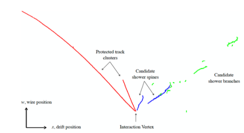
	"MicroBooNE Tune"		
Parameter	Central value	+1σ	-1σ
MaCCQE[a]	1.10 GeV	+0.1 GeV	-0.1 GeV
RPA_CCQE[b]	85%	+40%	-40%
NormCCMEC	166%	+50%	-50%
XSecShape_CCMEC	Empirical[c]	N/A	Valencia[d]
Coulomb_CCQE	Nominal	+30%	-30%
DecayAngMEC	Isotropic	Alternative[e]	N/A
FracPN_CCMEC	Valencia	+20%	-20%
FracDelta_CCMEC	Valencia	+30%	-30%
NormNCMEC	Nominal	+100%	-100%
ThetaDelta2NRad	Isotropic	Alternative[e]	N/A
NormCCCOH	Nominal	+100%	-100%
NormNCCOH	Nominal	+100%	-100%

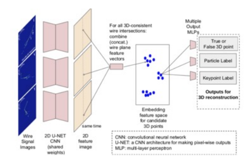
MicroBooNE Model (II)

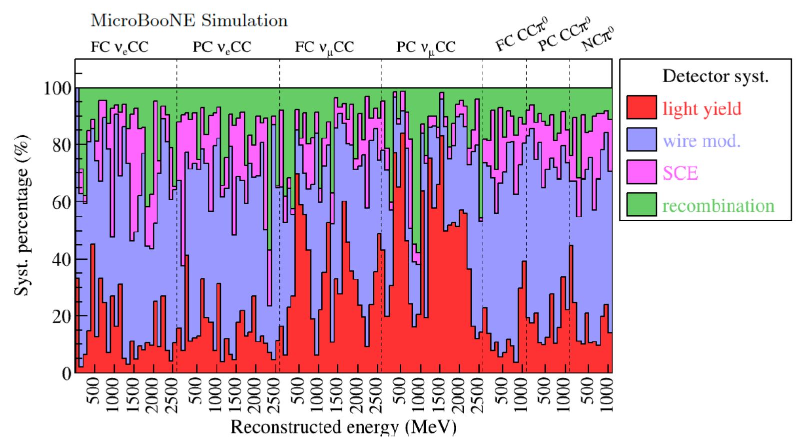
- Detector Simulation
  - GEANT4: Secondary Interactions
  - LArSoft: Conversion from energy deposition to ionization charge
  - Wire-Cell: from ionization charge to observed waveform
- Detector Systematics
  - Variations in Light Yield, Space Charge Effect (SCE), recombination model, discrepancies in detector response between data and CV MC (WireMod)

PRD 105 112005

- Event Reconstructions
  - Wire-Cell tomographic reconstruction
  - Pandora
  - Deep-Learning







Model Validation: Goodness-of-Fit Test

- χ^2**/ndf** calculated from the full systematics and statistics → combine all information to a single number

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

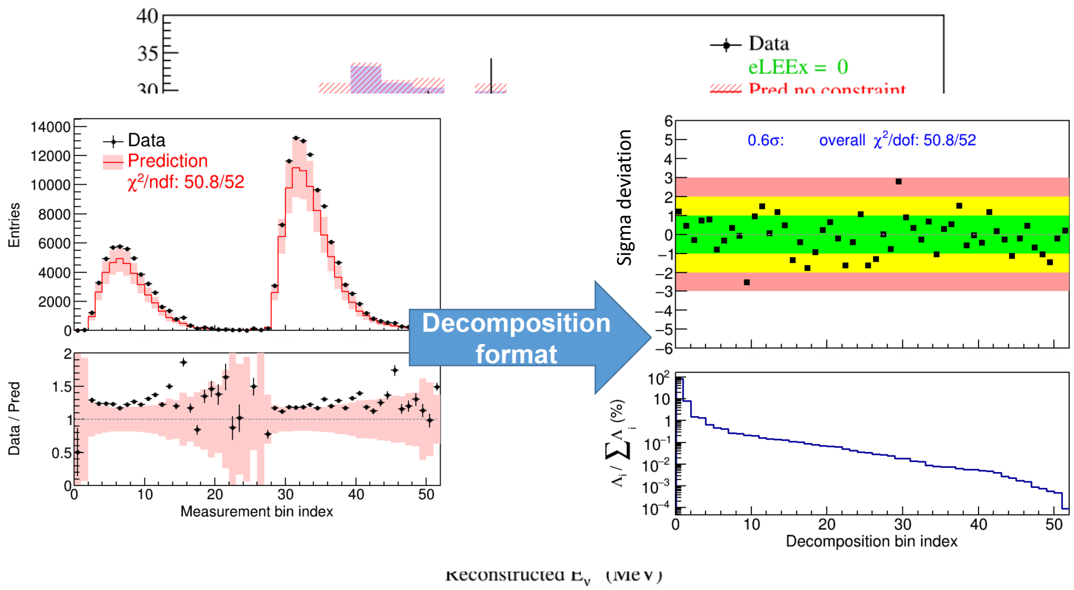
- Differential Goodness-of-Fit Test
  - Allow examine local structure
- Conditional constraining Procedure
  - Examine uncertainties layer-by-layer

Conditional expectation & covariance

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

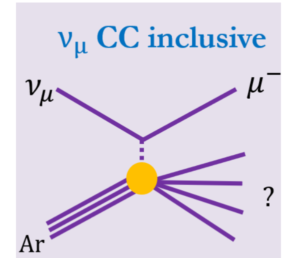
$$\mu_{Y|X} = \mu_Y + \Sigma_{YX}\Sigma_{XX}^{-1}(X - \mu_X)$$

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



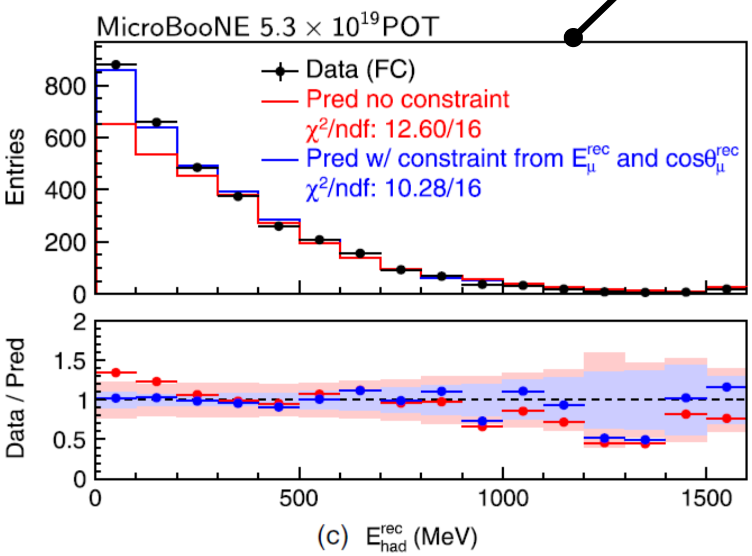
arXiv:2411.03280, to be published in PRD

Validation of Model of Neutrino Energy Reconstruction
& Inclusive ν_μCC Cross Sections

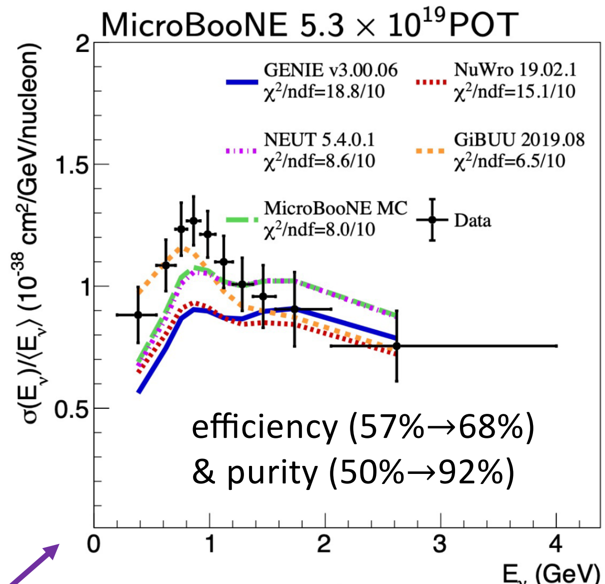


- Comparison $M(\mathbf{E}_{\mathbf{had}}^{\mathbf{rec}})$ vs. $\mu(\mathbf{E}_{\mathbf{had}}^{\mathbf{rec}} \mid \mathbf{E}_\nu, \mathbf{E}_{\boldsymbol{\mu}}^{\mathbf{rec}})$ is sensitive to the modeling of missing energy given the overall energy conservation and separated lepton and hadronic energy measurements in LArTPC

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



- No sign of mis-modeling of the **missing hadronic energy** → validating the model of E_ν reconstruction
- Enable energy-dependent cross sections & eLEE & ν oscillation measurements

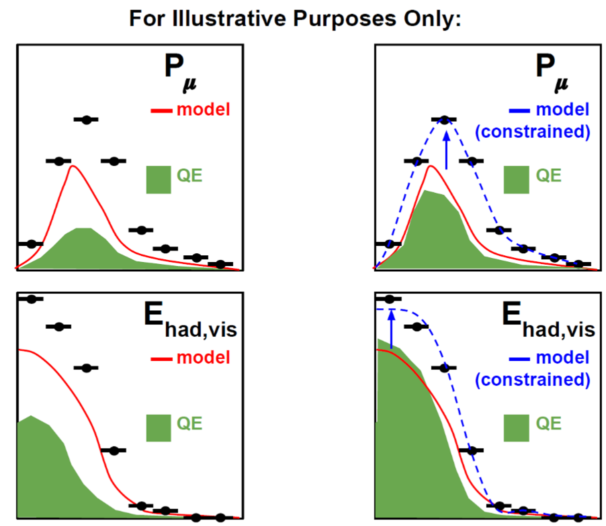


PRL 128, 151801

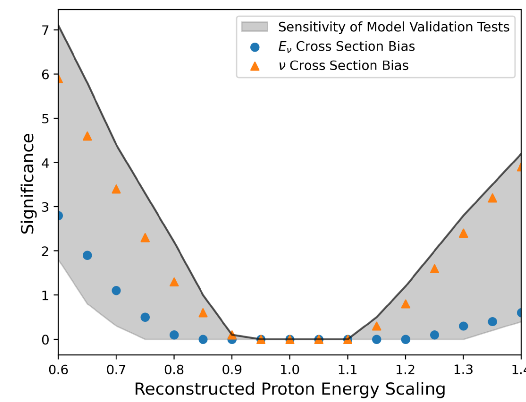
Procedure also demonstrated by the fake data studies

Model Validation of Missing Hadronic Energy

- Conditional constraint procedure akin to reweighting based on P_μ measurement
- QE, RES, DIS predict different $P_\mu, E_{had}^{missing}$, and E_{had}^{vis} distributions
  - The constrained prediction of E_{had}^{vis} is thus sensitive to the modeling of $E_{had}^{missing}$ in each process

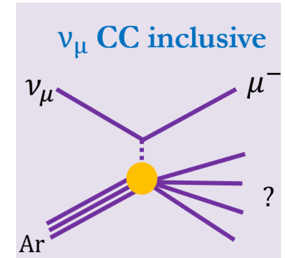


- Constrained E_{had}^{vis} is thus sensitive to the model of $E_{had}^{missing}$ → validation of the mapping between the true and reconstructed E_ν
  - Greater sensitivity than Xs owing to reduced uncertainties

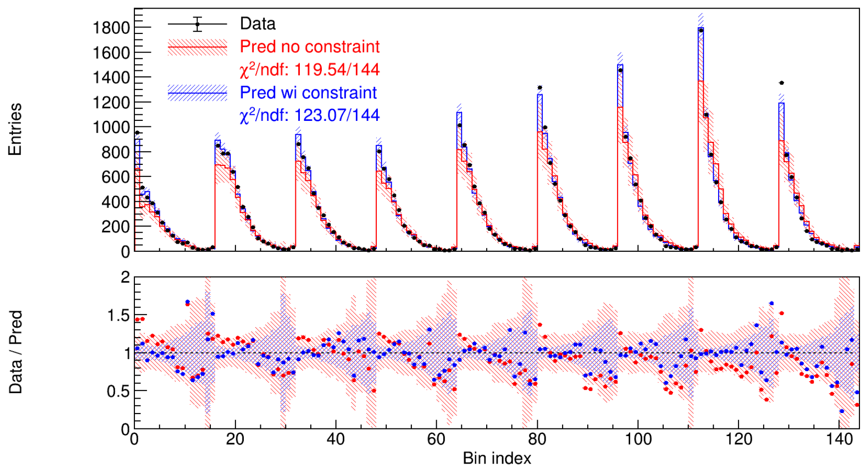


More details @ [Lee Hagaman's NuSTEC seminar]

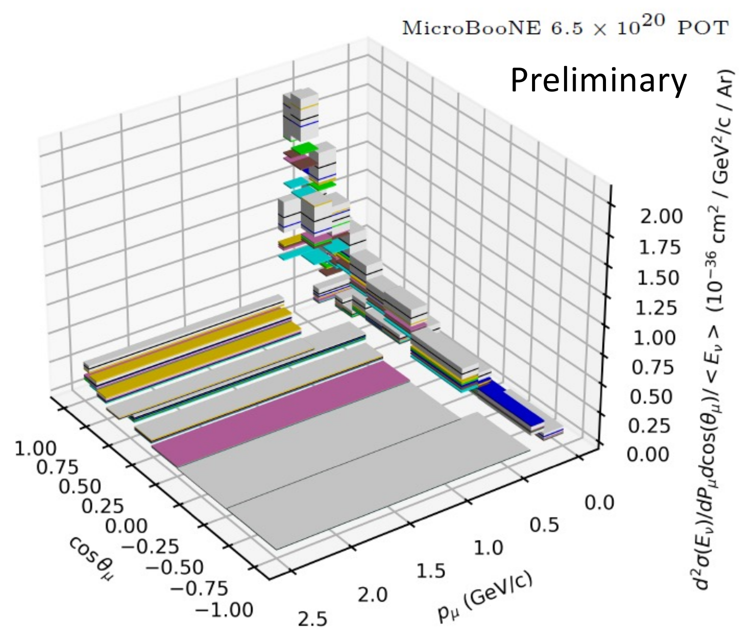
Validation of Model of E_ν Reconstruction in 2D & 3D Inclusive ν_μCC Cross Sections

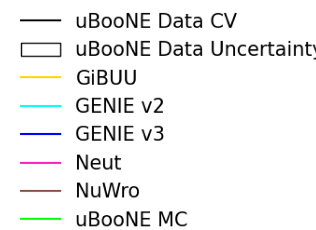


{E_{had}, cos(θ_μ)} Distribution



0.705 GeV $\leq E_\nu \leq$ 1.05 GeV



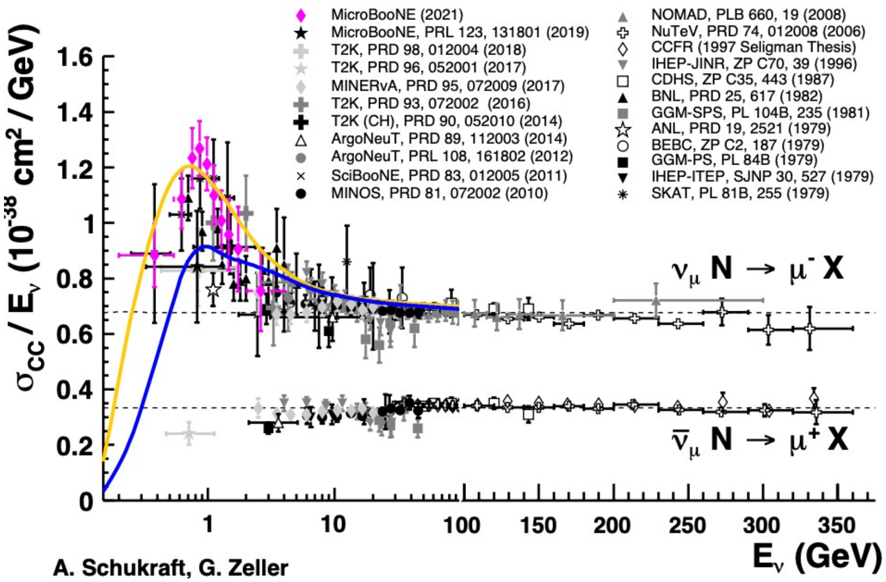


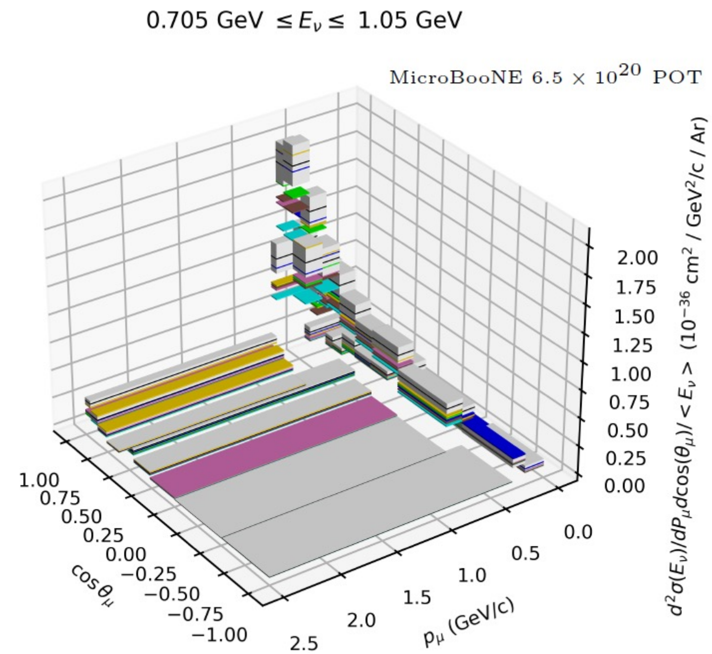
Model Generator	χ^2/ndf
Genie v2	740.8/138
Genie v3 (MicroBooNE Tune)	313.9/138
Genie v3 (Default Tune)	309.7/138
GIBUU	265.6/138
NEUT	233.1/138
NuWro	200.9/138

- Validation of model of E_ν reconstruction was successfully demonstrated in 2D {E_{had}, cos(θ_μ)}
- Enabled extraction of triple differential cross sections for inclusive ν_μCC in {E_ν,P_μ,cos(θ_μ)}
    - *Large wealth of information*

arXiv:2307.06413, London Cooper-Troendle's Wine & Cheese

1D → 3D inclusive ν_μCC cross sections





$\sigma(E_\nu)$ @ PDG

Focus on the lepton kinematics

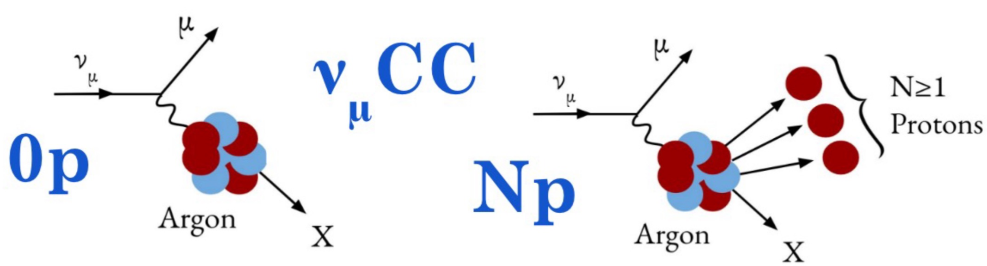
Successful Model Validations so far

$\sigma(E_\nu, p_\mu, \theta_\mu)$
arXiv:2307.06413

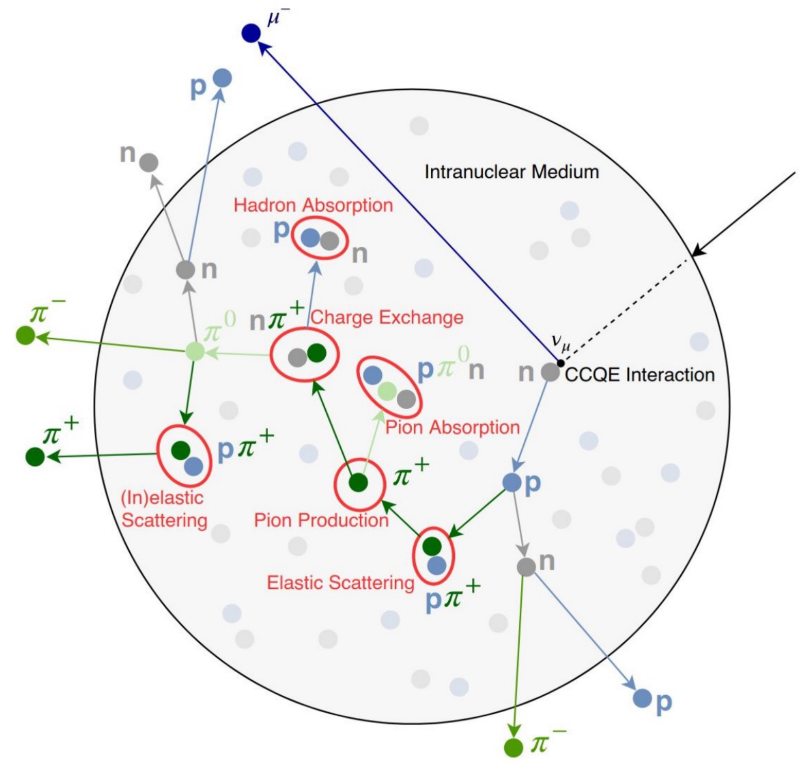
Hadronic Final State of ν_μCC

- Despite the lack of a first-principle theory, hadronic final states offer valuable insight into neutrino–nucleus (ν–A) interactions

- First simultaneous measurements of final states with (Np) and without (0p) protons
  - 0p events are defined by a 35-MeV kinetic energy threshold, and include interactions with no detected final-state proton



[PRL 133, 041801](PRL 133, 041801) [PRD 110, 013006](PRD 110, 013006)

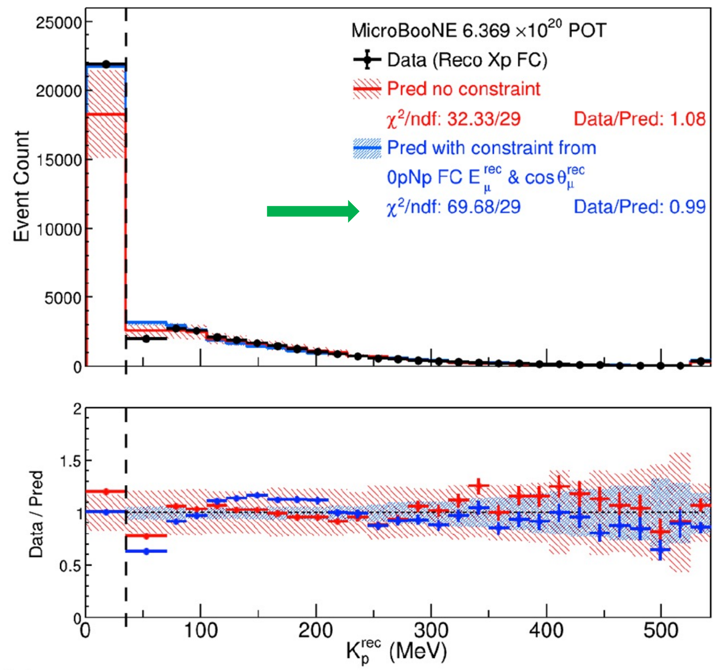


arXiv:2201.04664

Hadronic Final States: Exposing Model Limitations Through Validation

- While (GENIE-v3) model works well for inclusive channel,
  - its limitations become apparent when including detailed hadronic final states

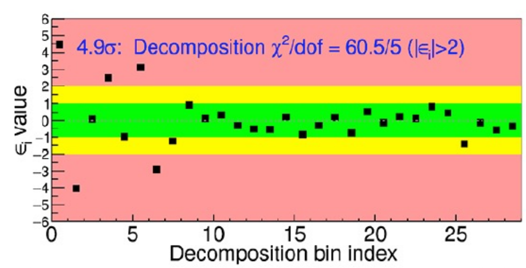
- Introducing reweighting uncertainties based on leading proton kinetic energy
  - restores agreement in a comprehensive, multi-dimensional model validation procedure
  - See Ben Bogart's Wine & Cheese Talk



(c) Reconstructed FC leading proton kinetic energy constrained by the 0pNp FC muon kinematics.

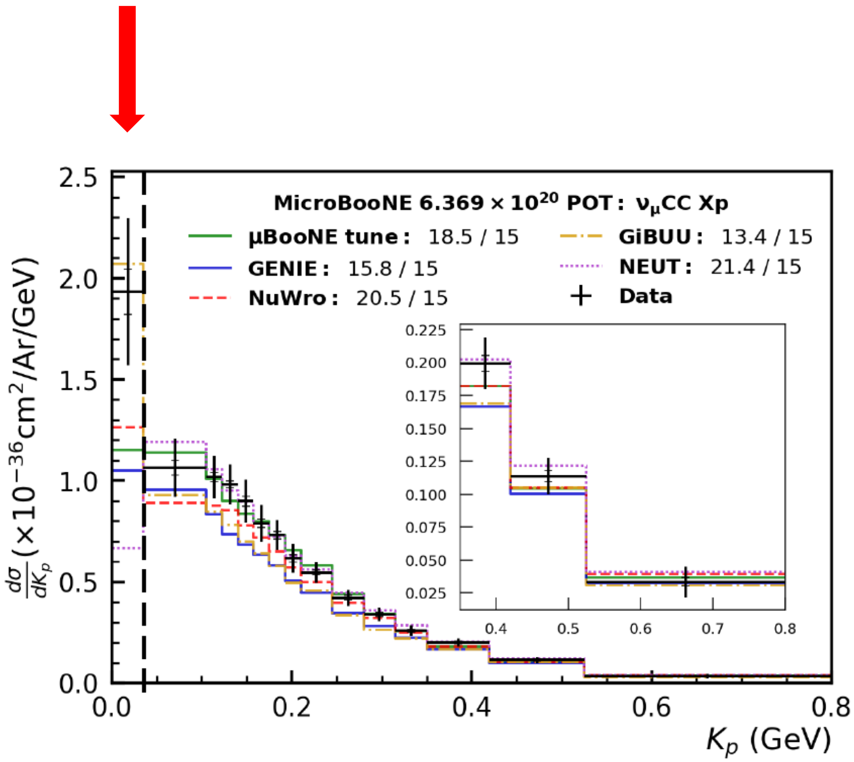
PRL 133, 041801

PRD 110, 013006



(g) Decomposition χ^2 for (c).

Comprehensive Results for Event Generator "Calibration"

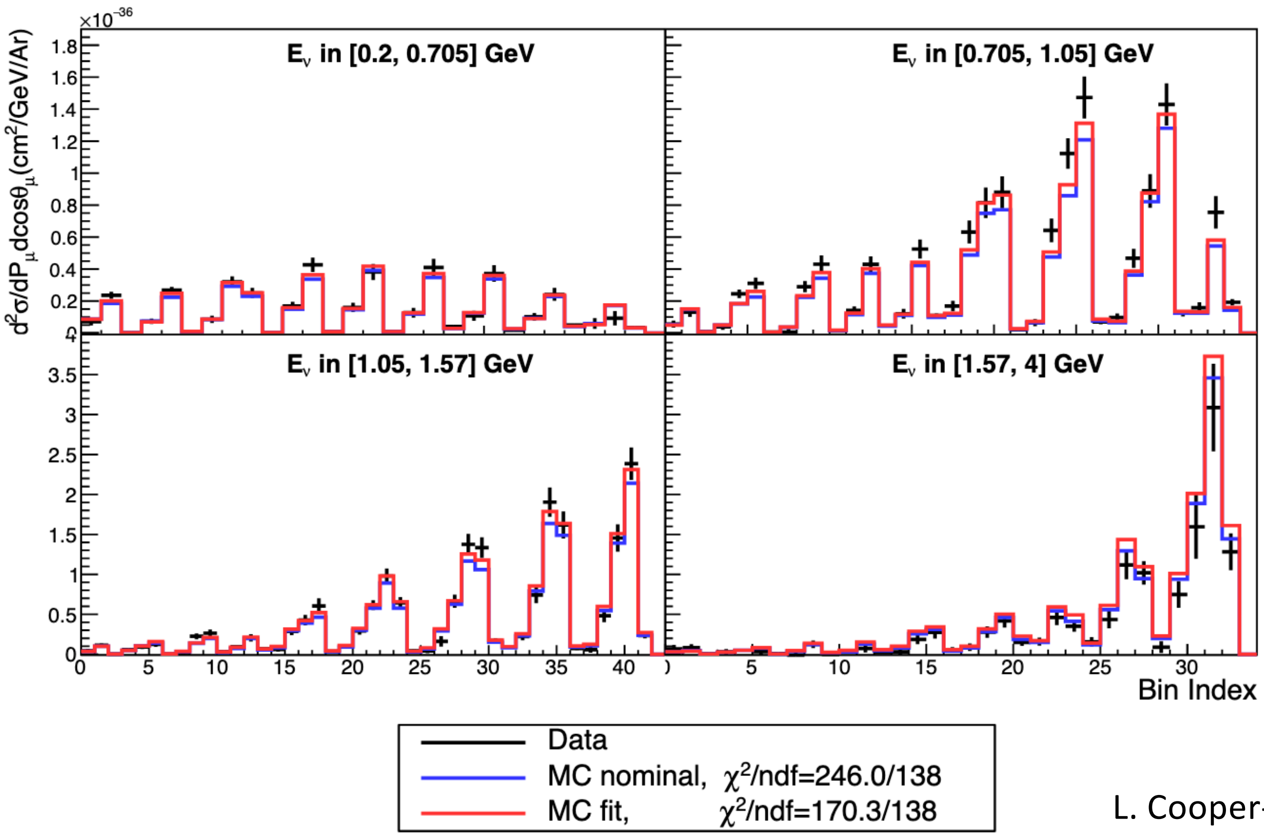


PRL 133, 041801

Measurement	Channel	*ndf*	μBooNE tune	GENIE	NuWro	NEUT	GiBUU
$\frac{d\sigma}{dE_\mu}$	0p	11	38.3	41.8	29.5	56.2	13.5
	Np	11	16.5	27.2	20.2	13.0	25.3
	0pNp	22	50.8	61.5	46.4	65.7	37.6
$\frac{d\sigma}{d\cos\theta_\mu}$	0p	17	25.6	28.3	13.2	44.7	9.9
	Np	17	34.2	34.2	42.0	19.9	27.3
	0pNp	34	64.3	62.1	55.7	70.3	44.6
$\frac{d\sigma}{d\nu}$	0p	3	37.5	45.1	28.8	91.4	9.2
	Np	6	12.7	24.3	20.6	20.7	26.3
	0pNp	9	63.3	66.2	52.1	153.5	59.0
$\frac{d\sigma}{dE_{avail}}$	0p	5	32.8	39.5	29.9	71.7	0.8
	Np	9	12.7	22.2	13.7	25.7	12.1
	0pNp	14	43.3	56.8	40.4	85.1	14.3
$\sigma(E_\nu)$	0p	10	21.5	29.7	17.5	56.4	15.4
	Np	10	6.4	20.1	13.7	5.5	15.1
	0pNp	20	29.6	41.4	29.2	72.1	43.4
$\frac{d\sigma}{dK_p}$	Xp	15	18.5	15.8	20.5	21.4	13.4
	Np	14	15.4	13.8	13.4	15.8	10.6
$\frac{d\sigma}{d\cos\theta_p}$	Np	20	16.0	22.4	9.9	28.4	48.0
Proton Multiplicity	Xp	4	7.1	19.8	9.9	22.2	10.5
$\frac{d^2\sigma}{d\cos\theta_\mu dE_\mu}$	0p	55	129.8	140.9	109.7	180.3	102.8
	Np	69	203.1	189.7	196.9	192.7	192.1
	0pNp	124	287.5	266.4	263.7	298.8	249.8
	Xp	69	129.6	140.4	169.3	104.7	161.5
$\frac{d^2\sigma}{d\cos\theta_p dK_p}$	Np	96	144.2	138.8	120.3	204.4	274.1
$\frac{d^3\sigma}{dE_{avail} d\cos\theta_\mu dE_\mu}$	Xp	249	274.2	336.9	309.4	330.6	313.9

PRD 110, 013006

Using MicroBooNE 3D $(E_\nu, E_\mu, Cos\theta_\mu)$ inclusive $\nu_\mu CC$ Xs to tune Event Generators



- Robust fits with both GENIE and NEUT event generators → *No observation of "PPP" (aka normalization issue)*
- Good fits with both small and large amount of model parameters

L. Cooper-Troendle et al. under preparation

Tuning of Event Generator

&

Peelle's Pertinent Puzzle (PPP)

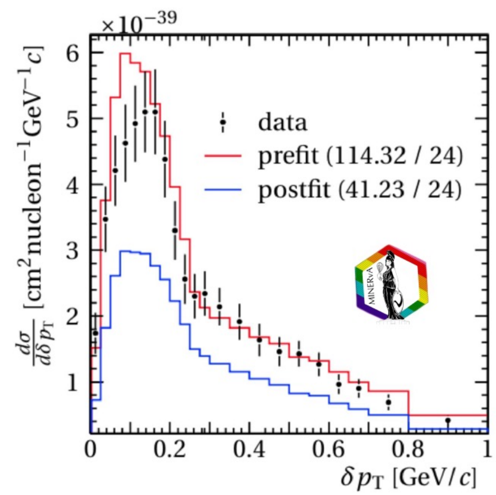
&

Wiener-SVD Xs Extraction

Peelle's Pertinent Puzzle (PPP)

- Common Challenges in Model Fitting
  - Fits often fail or yield non-physical best-fit parameters (e.g. normalization)
- Typical responses include:
  - Ignoring correlations between data points (e.g. in obtaining MicroBooNE tune in fitting T2K cross-sections)
  - Modifying the covariance matrix in ad-hoc ways
    - Absolute → relative → transformation → relative → absolute

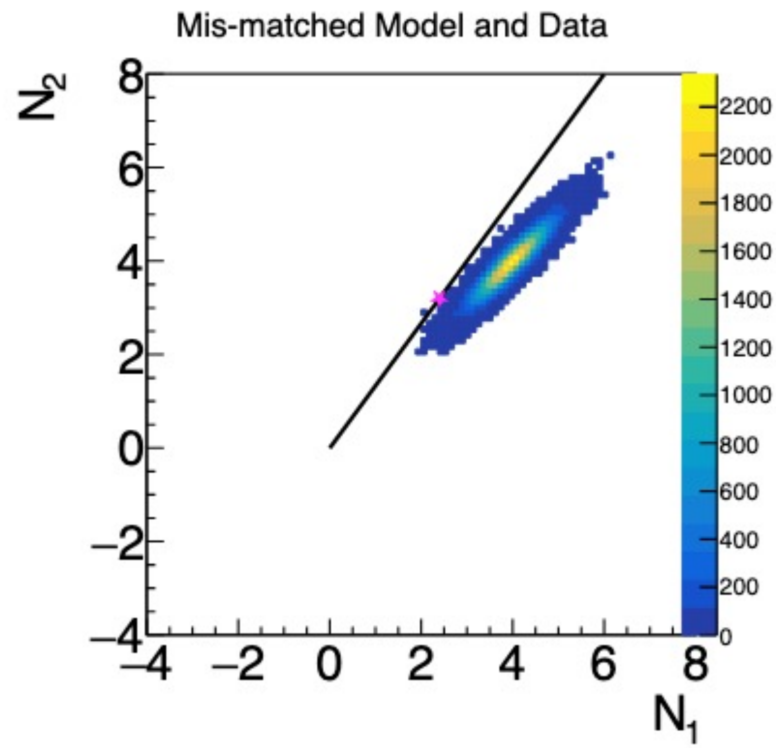
- Peelle's pertinent puzzle in one picture



PRD 109, 072006

Origin of PPP: Mismatch between Data and Model

- Incorrect models ???
- Apples Vs. Oranges
  - Impact of A_C matrix with unfolding
  - (unknown) real vs. nominal flux
  - Profiling vs. marginalization of model parameters
- Let's review the data unfolding



L. Cooper-Troendle, N. Nayak et al. under preparation

Introduction to Data Unfolding Problem

True distribution : S(x) on variable x with dimension d_S
Measured distribution : M(y) on variable y with $\bar{y} = R(\mathrm{x})$ and dimension d_M
Unfolding problem is M(y) $\rightarrow$ S(x)

Special Case of $d_M \geq d_S$: Weighted Least Squares

$T = (M - R \cdot S)^T \cdot C^{-1} \cdot (M - R \cdot S)$
M : (vector) measurement
S : (unknown vector) signal
R : response matrix connecting signal to measurement
C : Covariance matrix describing uncertainties

$\rightarrow$

Minimizing T leads to a solution with Linear Algebra of

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

and

$$C_S = (R^T \cdot C^{-1} \cdot R)^{-1}$$

A. C. Aitken Proc. R. Soc. Edinburgh 55, 42 (1935)

- Since measurements are around the expectation
  - $M = R \cdot S + N \rightarrow \hat{S} = S + (R^T \cdot C^{-1} \cdot R)^{-1} \cdot R^T \cdot C^{-1} \cdot N$
  - N : statistical and systematic uncertainties

Large fluctuations → Regularization (e.g. Wiener-SVD) is needed for intuitive results

Wiener-SVD: Uncertainties and Regularization

- Regularization language
  - Minimizing $\phi(s) = \chi^2(s) + \Lambda(s)$
- Tikhonov regularization
  - $\Lambda(s) = \tau \cdot \int \left(\frac{d^k s}{dE^k}\right)^2$
  - k=0, 1, 2 ~ amplitudes, slopes, smoothness of S
- Wiener-SVD
  - $\Lambda(s) = \frac{1}{2}\sum_i \log \frac{M_{U\,i}^2}{N^2}$

Signal in the effective frequency domain

Noise in the effective frequency domain

JINST 12 P10002

- Unfolded results
  - $\hat{S} = A_C \cdot (S + (R^T R) \cdot R^T \cdot Q \cdot N)$
  - **Expectation $\bar{\hat{S}} = A_C \cdot \bar{S}$ (truth expectation)**
- Difference between unfolded results w.r.t. truth depends on the (often known) A_C matrix
  - **A_C must be applied on the predictions, ensuring consistent comparison with data**

Application: Cross Section Extraction Procedure

- Case study: extraction of total ν_μCC cross section as neutrino energy

Measurements

ν_μ Neutrino Flux

ν_μCC cross section

Detector response matrix

Selection efficiency

background

$$M\left(E_{rec}\right) = POT \cdot T \cdot \int F\left(E_\nu\right) \cdot \sigma$$

E_ν: true neutrino energy E_{rec} :

POT: proton on target

T: number of target nucleons

$$\boxed{M_i = \sum_j S_{ij} + B_i}$$

With the nominal ν_μ flux prediction $\overline{F}\left(E_{\nu\,j}\right)$, we have

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

$$S_{ij} = \Delta_{ij} \cdot F_j \cdot S_j = R_{ij} \cdot S_j$$

$$\Delta_{ij} = \frac{(\text{Selected no. of events in reco. energy bin i from true energy bin j after event weights})}{(\text{Generated no. of events in truth energy bin j after event weights})}$$

Can be directly calculated with existing Monte Carlo simulations

$$F_j = POT \cdot T \cdot \int_j \overline{F}\left(E_{\nu\,j}\right) \cdot dE_{\nu\,j}$$

A constant for each reco. energy j bin related to POT, T, and nominal flux

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

Nominal flux averaged cross section in the truth energy bin j
for pros, also see discussions in L. Koch and S. Dolan PhysRevD.102.113012

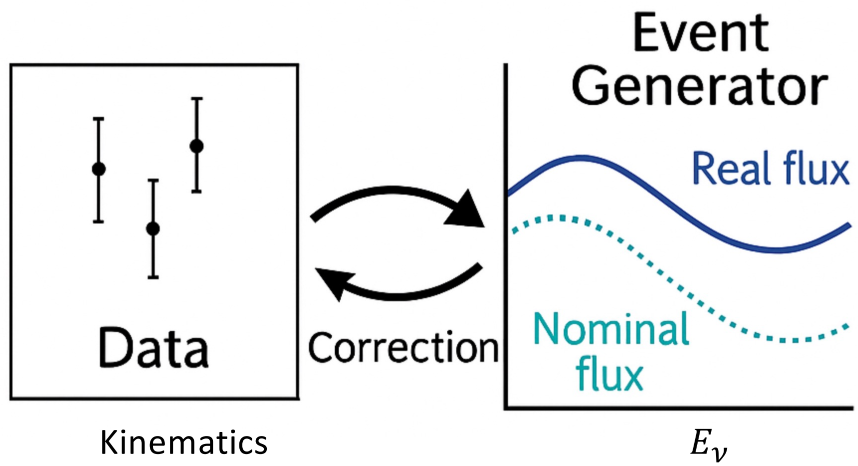
This choice is crucial in simplifying the uncertainty calculation and comparisons with model calculations

Application: Cross Section Extraction Procedure

- Event generator predictions (e.g., for tuning) are typically made at the **nominal neutrino flux & spectrum**
- Extracted cross sections—based on the **true (unknown) flux**—must be corrected to the nominal flux for fair comparison

- This correction depends on a mapping between kinematic variables and the neutrino energy spectrum

- ✅ Validating this mapping is essential to ensure reliable model-data comparisons



Real vs. Nominal Neutrino Flux Issue

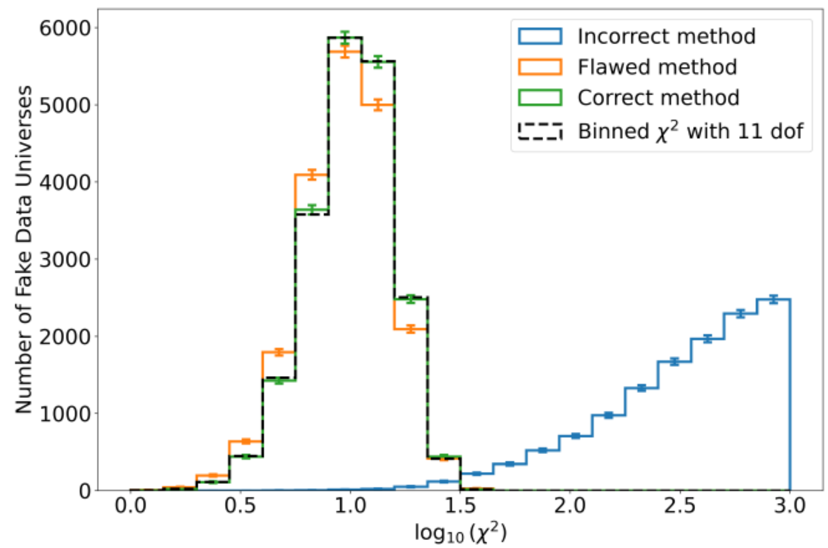
@ Real flux

$$\left(\frac{d\sigma}{dp_\mu}\right)_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{\text{target}} \cdot \Phi_{\nu_\mu} \cdot (\Delta p_\mu)_i}$$

N_i (B_i): # of candidate (bkgd) in reco bin i
$\mathrm{N}_{\text{target}}$: # of argon nuclei
Φ_{ν_μ}: integrated neutrino flux
$(\Delta p_\mu)_i$: width for reco bin i
$\tilde{\epsilon}_i$: effective efficiency for reco bin i

Additional correction steps are required to infer nominal-flux–averaged (differential) cross sections from data

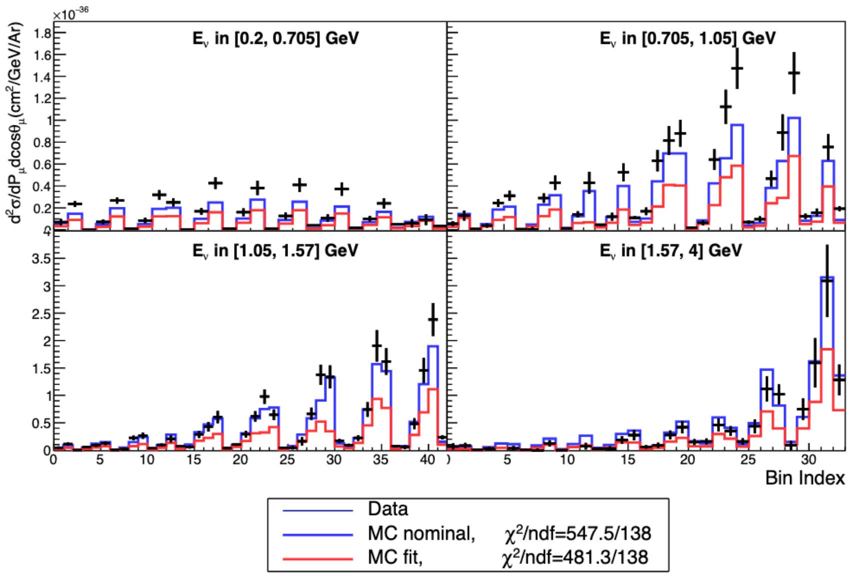
arXiv:2411.03280 (to be published @ PRD)



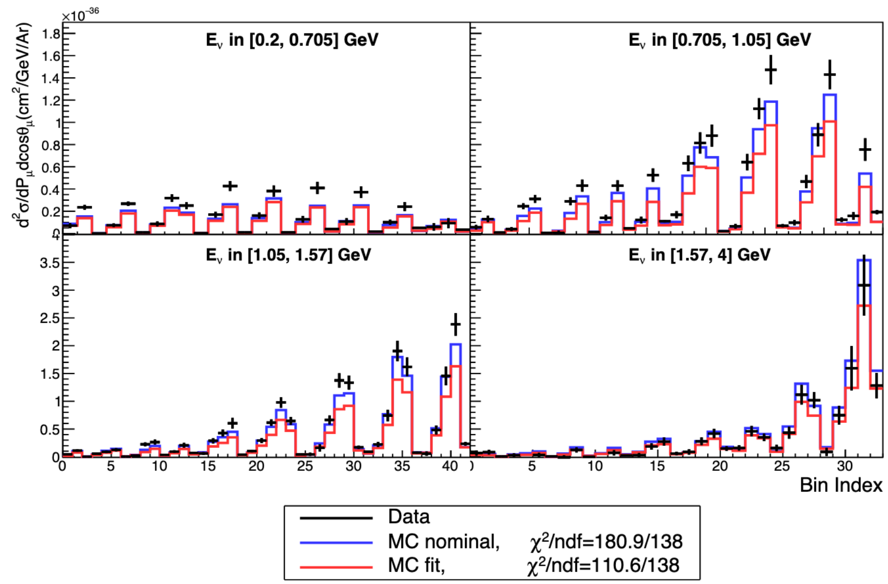
- ❌ **Incorrect**: Comparing Xs extracted at the **real (unknown) flux** with model predictions at the **nominal flux**, **without including flux uncertainties**
- ⚠️ **Flawed**: Model predictions include flux uncertainties, but **ignore correlations** with the extracted cross section
- ✅ **Correct**: **Correlated flux uncertainties** between the extracted cross section and model prediction are properly accounted for

PPP Observed in various Apple vs. Orange Cases

Missing A_C: Treating unfolded Xs as truth



Fitting Xs @ Real with Predictions @ nominal neutrino flux



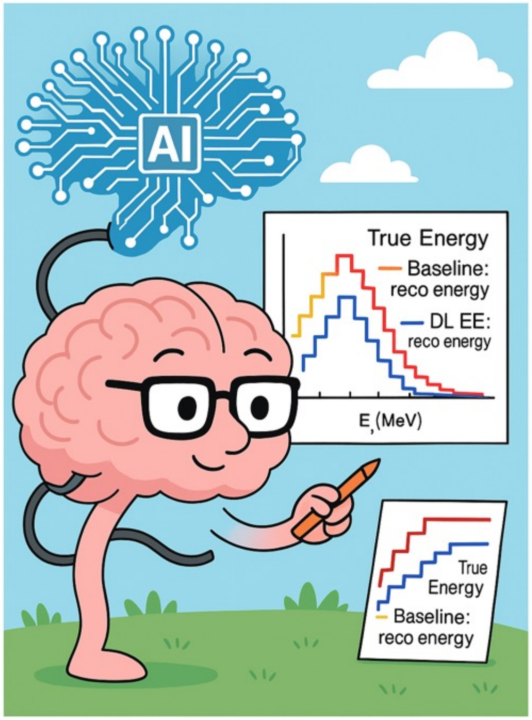
L. Cooper-Troendle, N. Nayak et al. under preparation

Key Take-away Points

- To properly calibrate (tune) an event generator, avoid **apple-to-orange** comparisons between data and predictions
  - Unfolded results CANNOT be treated as true values without caution
  - Be explicit about cross section definitions:→ Comparing results extracted at the real (unknown) flux vs. predictions at the nominal flux is problematic

- Emphasize **model validation of the mapping between true E_ν and kinematic observables** → essential for obtaining nominal-flux–averaged cross sections for fair model comparison

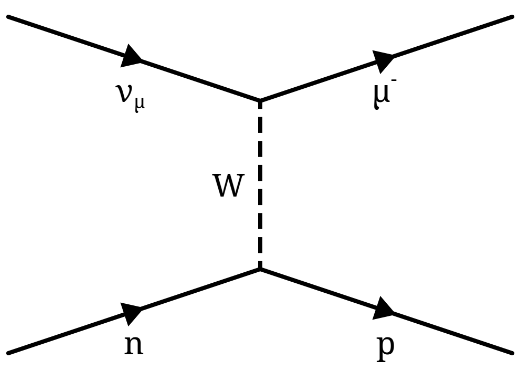
Deep-Learning Neutrino Energy Reconstruction



Neutrino Energy Reconstruction

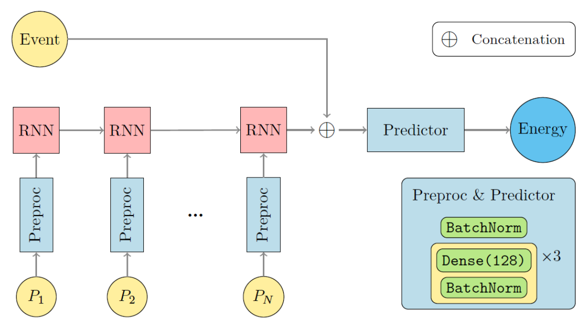
Kinematics Reconstruction

$$E_\nu^{\mathrm{QE}} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)},$$



- Assuming 2-body scattering kinematics under energy and momentum conservation

Deep-Learning Neutrino Energy Estimator



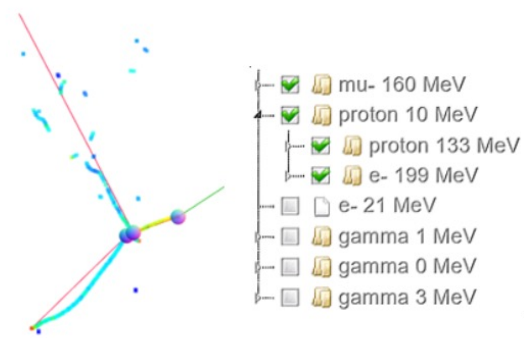
Recurrent Neural Network (RNN) to effectively leverage the reconstructed particle flow information, which encapsulates both the calorimetric energy and the kinematic properties of the final-state particles

Calorimetric Reconstruction

$$E_\nu^{\mathrm{rec}} = \sum_i \left(K_i^{\mathrm{rec}} + m_i + B_i\right),$$

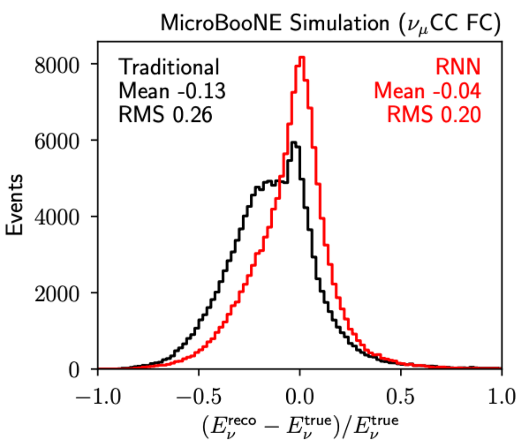
- K: kinetic energy
- M: mass
- B: binding energy

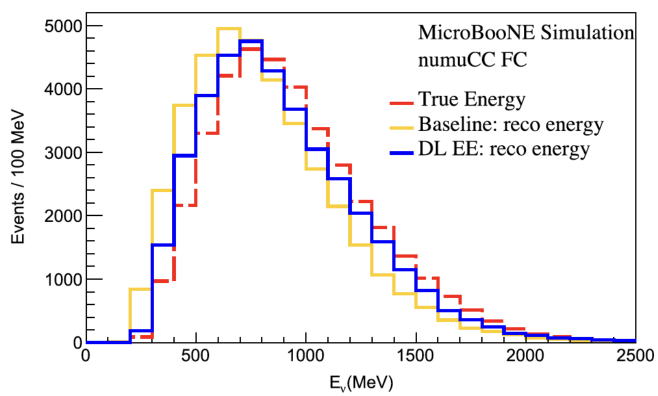
(e) Particle flow starting from neutrino vertex

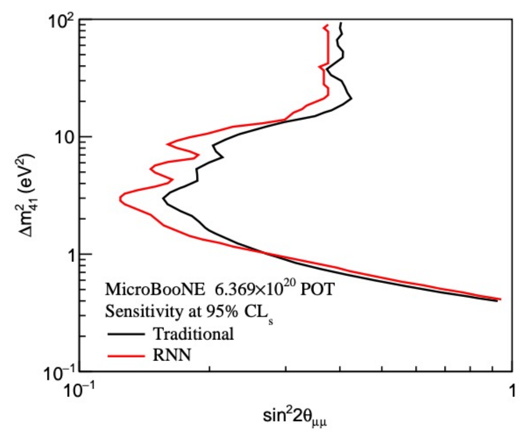


Neutrino Energy Estimator with RNN

- Motivated by NOvA and applied to LArTPC; Use long short-term memory (LSTM) cells for stable training (Phys. Rev. D 110, 092010).
- Successfully demonstrated in MicroBooNE data to improve resolution and reduce bias
  - leads to sensitivity improvement in sterile neutrino search







- Trained with simulation (e.g., GENIE v3 with MicroBooNE tune), will it successfully infer on data?

Model Validation Results on Data

Conditional expectation & covariance

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

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

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

- Successful model validation suggests that any **inaccuracies in modeling** the final-state kinematics in the event generators are **insignificant** compared to the overall uncertainties

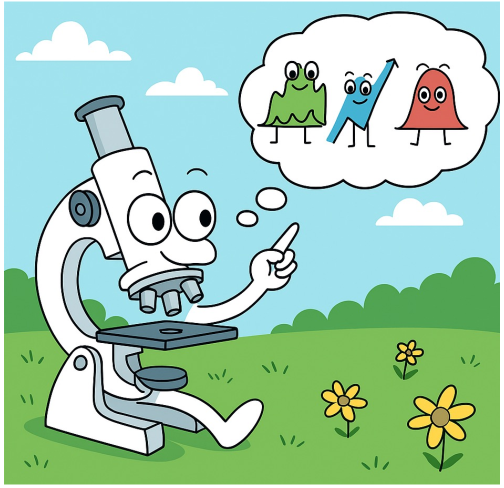
- More precise data with reduced systematic uncertainties—and higher statistics—will naturally lead to more stringent model validation, potentially revealing issues in models

TABLE II. Data vs MC validation results of the reweighted RNN energy estimator. The first column of the table shows the label of the statistical test that was performed. The second and third columns indicate p values returned by the test for the traditional and RNN energy estimators respectively. A p value above 0.05 indicates that the respective test was passed.

	p value	
Test	Traditional	RNN
$P(E_\mu)$	0.89	0.92
$P(E_{\mathrm{had}})$	1.00	0.99
$P(E_\nu)$	1.00	0.97
$P(E_\mu^{\mathrm{PC}} \mid E_\mu^{\mathrm{FC}})$	0.95	0.70
$P(E_{\mathrm{had}}^{\mathrm{PC}} \mid E_{\mathrm{had}}^{\mathrm{FC}})$	1.00	0.96
$P(E_\nu^{\mathrm{PC}} \mid E_\nu^{\mathrm{FC}})$	1.00	0.84
$P(E_\mu \mid \cos\theta_\mu)$	0.45	0.50
$P(E_{\mathrm{had}} \mid \cos\theta_\mu)$	1.00	0.99
$P(E_\nu \mid \cos\theta_\mu)$	1.00	0.97
$P(E_{\mathrm{had}} \mid E_\mu)$	1.00	0.97
$P(E_\nu \mid E_\mu)$	1.00	0.99
$P(E_{\mathrm{had}} \mid E_\mu, \cos\theta_\mu)$	1.00	0.99
$P(E_\nu \mid E_\mu, \cos\theta_\mu)$	1.00	1.00
$P(E_\nu \mid E_\mu, \cos\theta_\mu, E_{\mathrm{had}})$	1.00	0.97

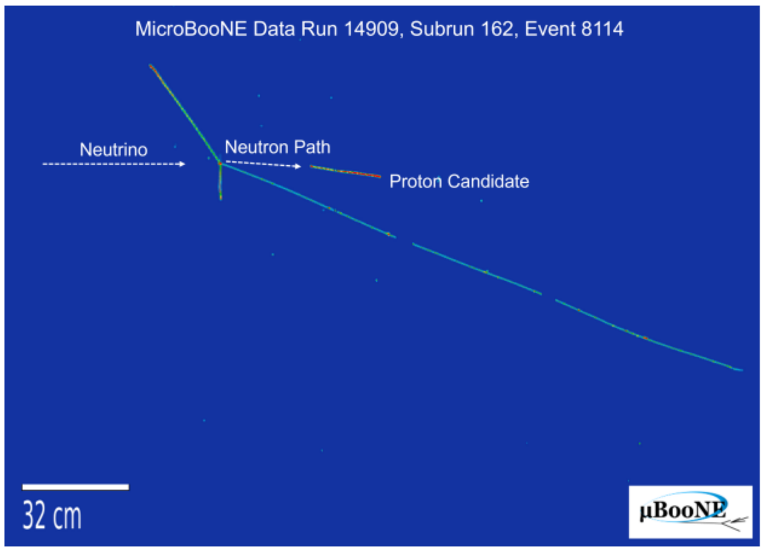
$$P(X|Y) \coloneqq \mu_{Y|X}\ vs.\ data$$

Broader Look at MicroBooNE's Recent Cross Section Measurements



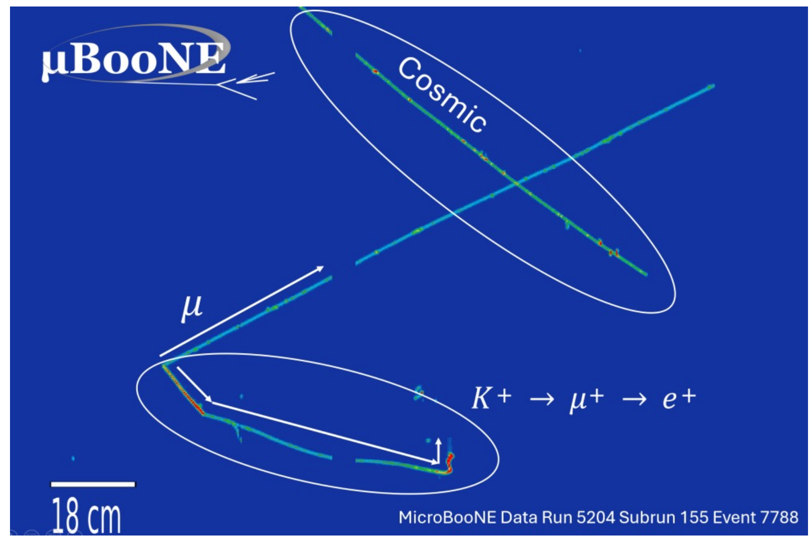
Rarer Topologies

Neutron Tagging [Eur. Phys. J. C84, 1052 (2024)]



- Further improve missing energy reconstruction

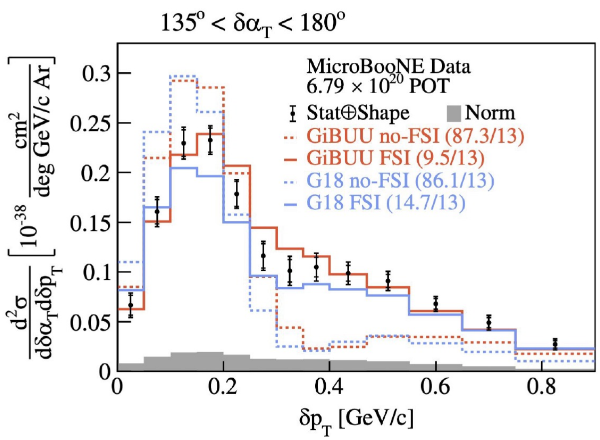
Kaon identification [arXiv: 2503.00291]



- Constraining Background for Proton Decay Searches

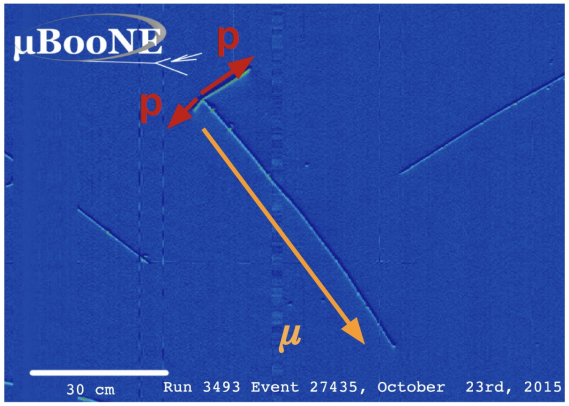
Dive into Hadronic Final State

- Kinematics Imbalance



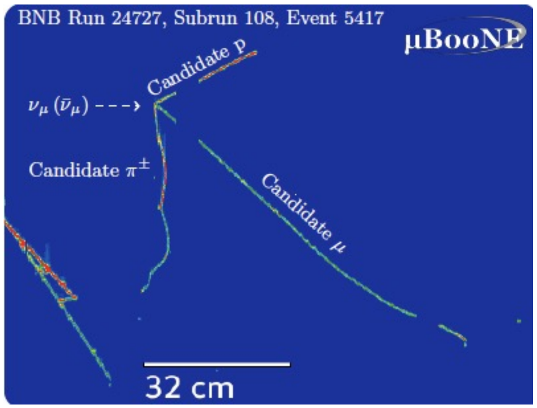
TKI: PRL 131, 101802, PRD 108, 053002
GKI: PRD 109, 092007

- CC2p0**π** → sensitive to NN correlations and FSI



arXiv:2211.03734

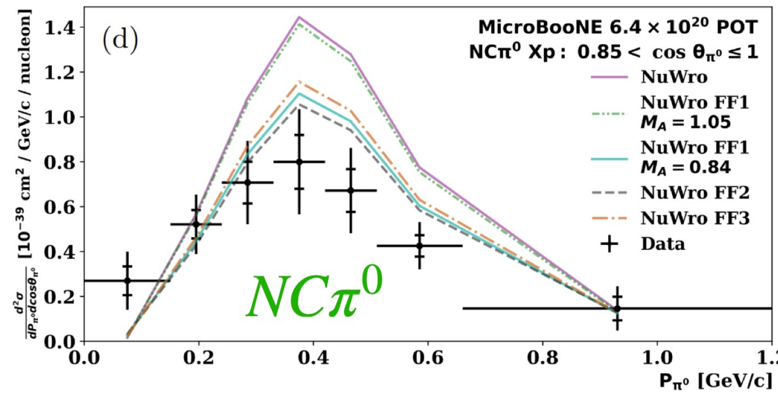
- CC $1\pi^{\pm}$ → resonance, μ/π separation



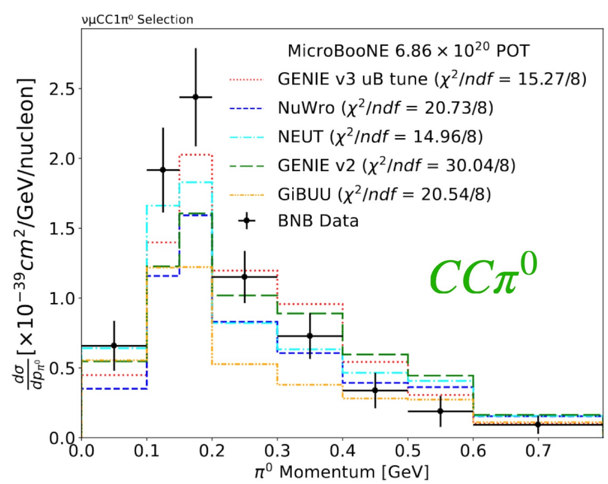
Coming soon

ν_eCC and π^0 productions

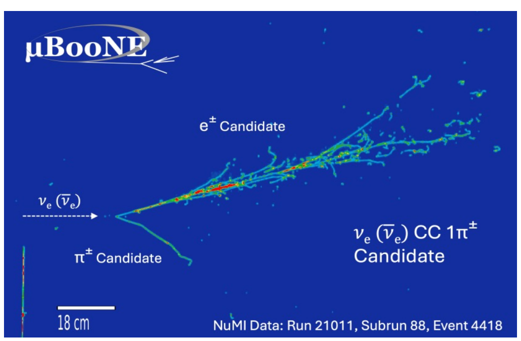
- Recent focus on exclusive channels, especially coming from RES (Δ-decay)
  - First differential and double-differential in π^0
  - NC π^0 (Major background for ν_eCC oscillation signal)
  - ν_eCC $\pi^{\pm}$ (Utilizing off-axis NuMI beam)



arXiv:2404.10948
Accepted by PRL



Phys. Rev. D. 110, 092014



arXiv: 2503.23384

uBooNE Cross-section Program

MICROBOONE-NOTE-1069-PUB

Single-differential cross section with updated detector and interaction models
Phys. Rev. Lett. 128, 151801 (2022)

Energy-dependent single-differential cross section

Triple-differential cross section arXiv:2307.06413 [hep-ex]
Phys. Rev. Lett. 133 (4), 041801

Multi-differential with proton multiplicity
Phys. Rev. D 110 (1), 013006

Data-driven Model Validation Techniques arXiv:2411.03280

Charged particle multiplicity Eur. Phys. J. C79, 248 (2019)

Double-differential cross section Phys. Rev. Lett. 123, 131801 (2019)

ν_μ CCQE-like differential cross section

ν_μ CCπ1p double differential TKI cross section
Phys. Rev. Lett. 131, 101802 (2023)

ν_μ CC0pi1p multi-differential cross sections Phys. Rev. D 108, 053002 (2023)

ν_μ CC0pi1p generalised kinematic imbalance Phys. Rev. D 109, 092007 (2024) (PRD Editor's suggestion)

ν_μ CC0$\pi\geq$1p differential cross section Phys. Rev. D 102, 112013 (2020)

ν_μ CC0$\pi\geq$1p double-differential cross section arXiv:2403.19574 [hep-ex]

Total inclusive $\nu_e+\bar{\nu}_e$ cross section Phys. Rev. D 104, 052002 (2021)

Inclusive differential $\nu_e+\bar{\nu}_e$ cross section Phys. Rev. D 105, L051102 (2022)

ν_μ CC0π2p differential cross section
arXiv:2211.03734 [hep-ex]

ν_μ CCπ^0 differential cross section
Phys. Rev. D. 110 (9), 092014 (2024)

ν_μ NCπ^0 total cross section
Phys. Rev. D 107, 012004 (2023)

ν_μ NCπ^0 double-differential cross section arXiv:2404.10948 [hep-ex]

ν_μ CC kaon production
arXiv: 2503.00291

ν_μ CC Λ^0 production
Phys. Rev. Lett. 130, 231802 (2023)

ν_μ eta production
Phys. Rev. Lett. 132, 151801 (2024)

ν_μ NC1p differential
MICROBOONE-NOTE-1067-PUB

ν_μ NC elastic differential
MICROBOONE-NOTE-1101-PUB

ν_μ Neutron tagging
Eur. Phys. J. C84, 1052 (2024)

Theory-driven tune of cross-section models
Phys. Rev. D 105, 072001 (2022)

Differential ν_e CC0π cross section Phys. Rev. D 106, L051102 (2022

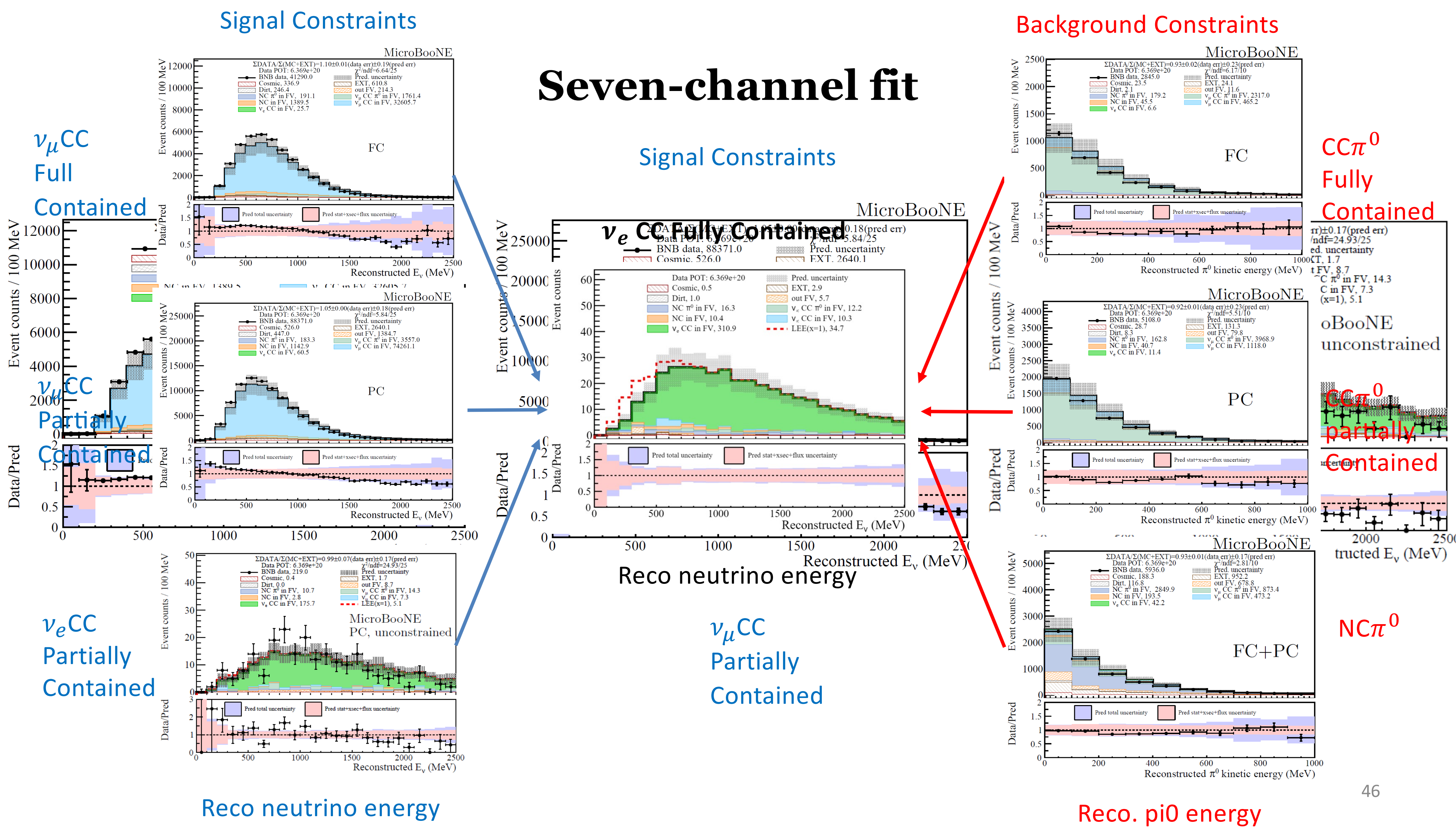
Differential ν_e CC$\pi^{\pm}$ cross section arXiv: 2503.23384

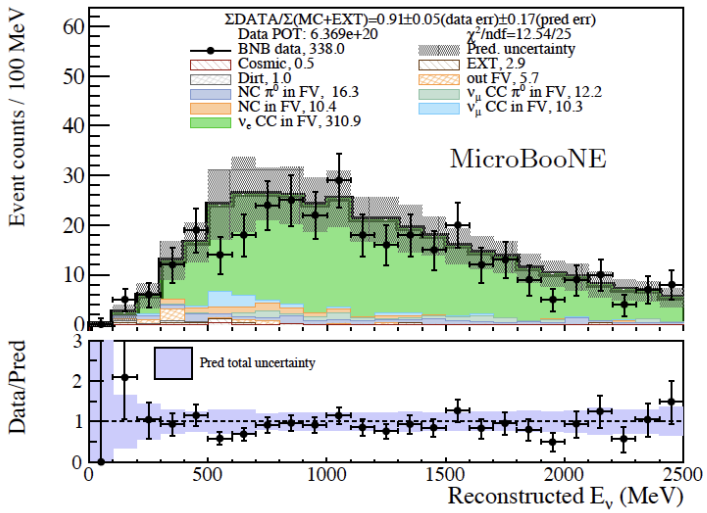
- ✓ Comprehensive ν – Ar program, includes the most detailed cross-sections
- ✓ Also want to focus on solving issues for users, model-benchmarking for DUNE

Summary

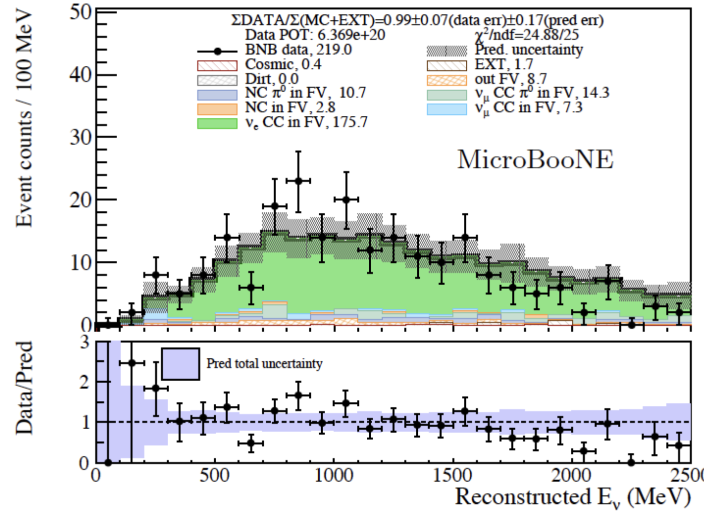
- MicroBooNE has a comprehensive cross-section program focused on neutrino-argon interactions
  - Inclusive, dynamics in hadronic final-states, rare topologies …
- MicroBooNE's cross-section results are expected to provide valuable input for next-generation precision neutrino oscillation measurements
  - Care must be taken when tuning event generators to avoid 'apples-to-oranges' comparisons
  - Particularly in the context of **data unfolding** and discrepancies between **real and nominal neutrino fluxes**
- **Model validation** is a critical step to ensure that theoretical models and simulations are compatible with experimental data within model uncertainties

Seven-channel fit

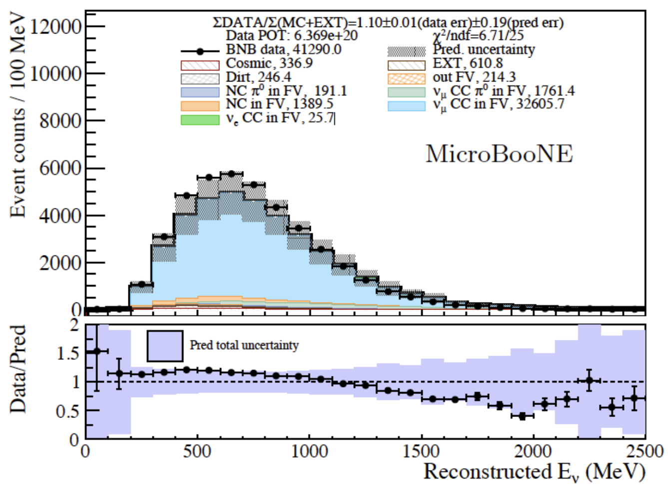




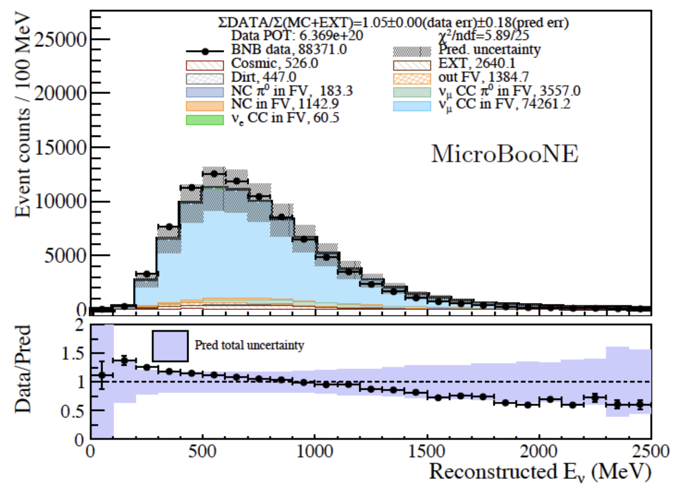
(a) FC ν_e CC



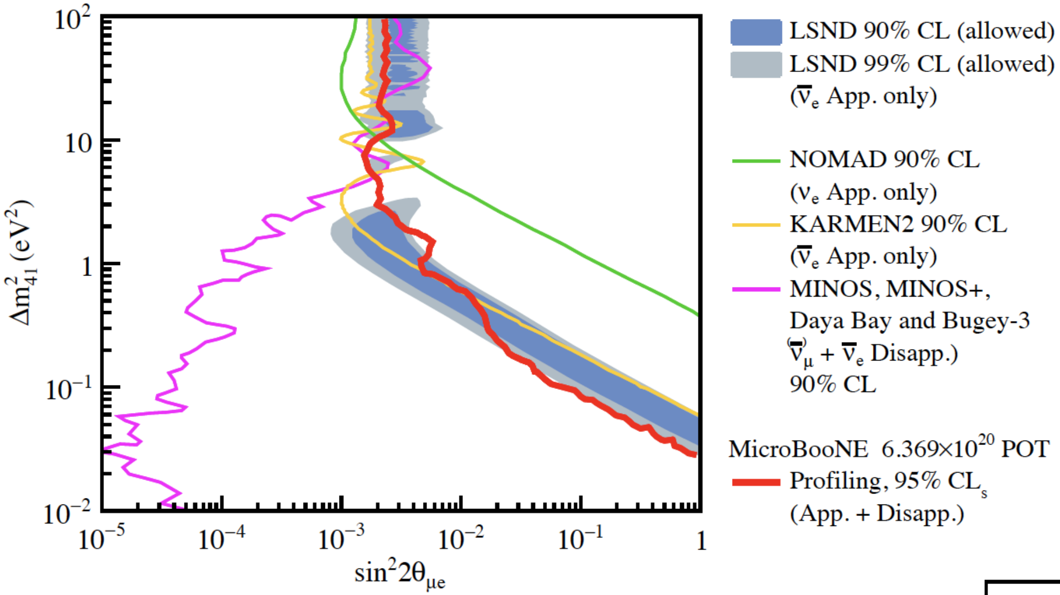
(b) PC ν_e CC



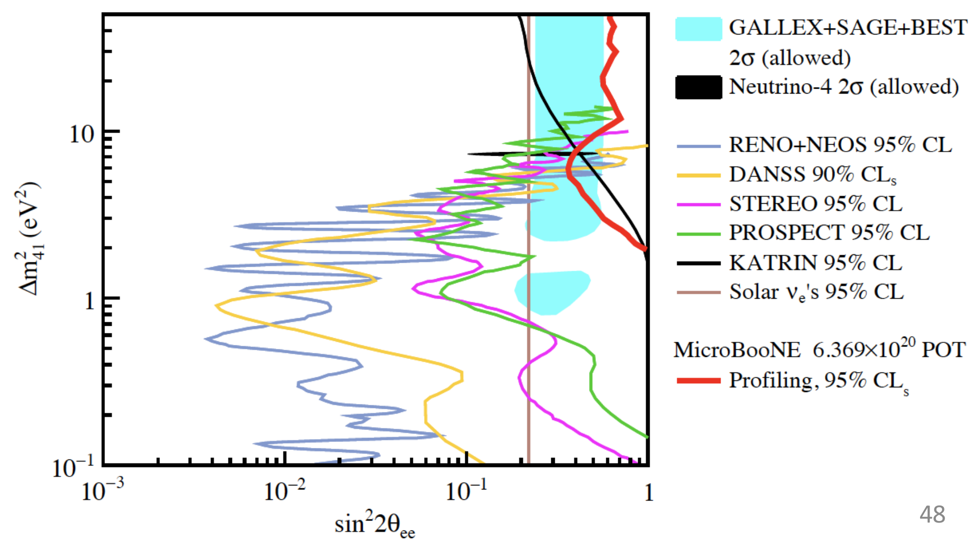
(c) FC ν_μ CC



(d) PC ν_μ CC



LSND 90% CL (allowed)
LSND 99% CL (allowed)
($\bar{\nu}_e$ App. only)
NOMAD 90% CL
(ν_e App. only)
KARMEN2 90% CL
($\bar{\nu}_e$ App. only)
MINOS, MINOS+,
Daya Bay and Bugey-3
($\overset{(-)}{\nu}_\mu$ + $\bar{\nu}_e$ Disapp.)
90% CL
MicroBooNE 6.369×10^{20} POT
Profiling, 95% CL$_s$
(App. + Disapp.)
Δm^2_{41} (eV^2)
$\sin^2 2\theta_{\mu e}$
10^{-2}
10^{-1}
1
10
10^2
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1



GALLEX+SAGE+BEST
2σ (allowed)
Neutrino-4 2σ (allowed)
RENO+NEOS 95% CL
DANSS 90% CL$_s$
STEREO 95% CL
PROSPECT 95% CL
KATRIN 95% CL
Solar ν_e's 95% CL
MicroBooNE 6.369×10^{20} POT
Profiling, 95% CL$_s$
Δm^2_{41} (eV^2)
$\sin^2 2\theta_{ee}$
10^{-1}
1
10
10^{-3}
10^{-2}
10^{-1}
1

Model Validation Tools: Goodness-of-Fit Tests

Global/Local or Differential GoF Tests

- χ^2**/ndf** calculated from the full systematics (flux, Xs, detector, MC statistics) and statistics

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

- Perform decomposition on the $\mathrm{Cov}_{\mathrm{full}}$ so that one can examine deviation on each (independent) eigen vectors
  - $Cov_{full} = Q^T \cdot D \cdot Q$ D: diagonal, Q: unitary
  - $\chi^2 = [Q \cdot (M-P]^T \cdot D^{-1} \cdot [Q \cdot (M-P)]$

$$\boxed{\chi^2 = \sum_i \chi_i^2 = \sum_i \frac{(m_i - p_i)^2}{d_i^2}}$$

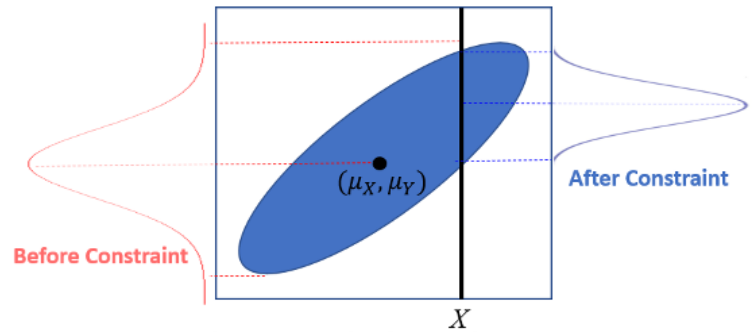
Conditional Constraining Procedure

Conditional expectation & covariance

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

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

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



* Estimate correlated statistical uncertainty with bootstrapping (sampling w/ replacement)

Fake-Data Closure Testing

- In traditional fake-data closure tests, we try to ensure that the cross section model used for the extraction is consistent with other cross section models in the relevant phase space

Phase Space Of All Models

(Made up for illustration, very high dimensional in reality)

Data-driven Model Validation

- In data-driven model validation, we try to ensure that the cross section model used for the extraction is consistent with real data in the relevant phase space

Phase Space Of All Models

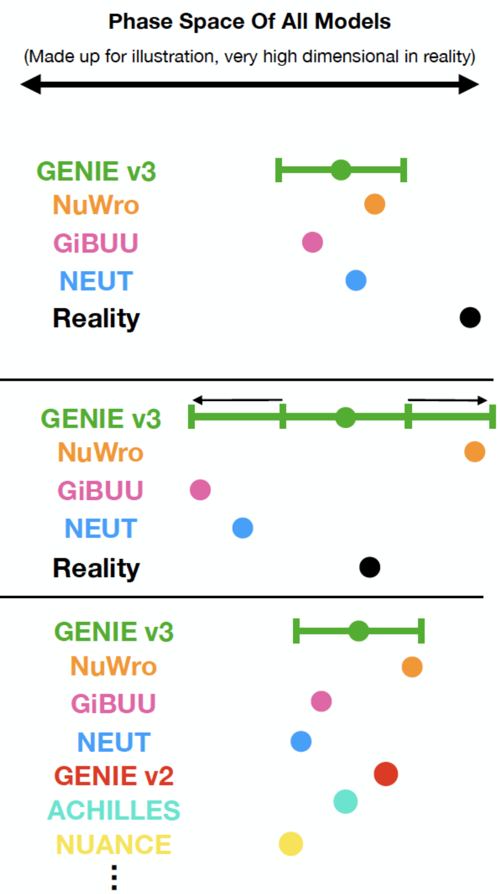
(Made up for illustration, very high dimensional in reality)

Fake-Data Closure Testing

- This procedure has some limitations
  - 1: What if the spread of models included in fake data tests do not describe the real cross section?

  - 2: What if the spread of models included in fake data tests is very large, and makes you expand to very large uncertainties, even when your original model is good?

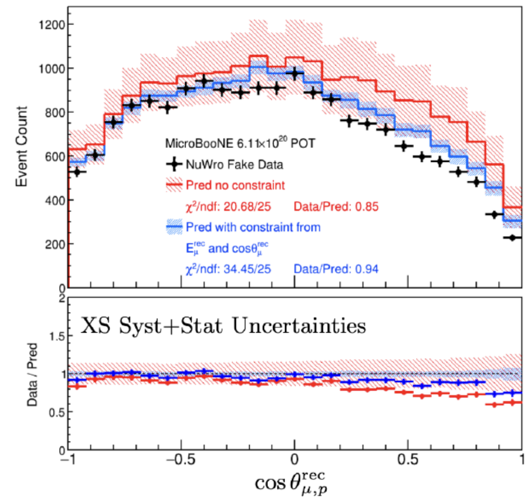
  - 3: How do you know when to stop? There are many generators, and many configurations and tunes, is testing just one or a few alternate generators enough?

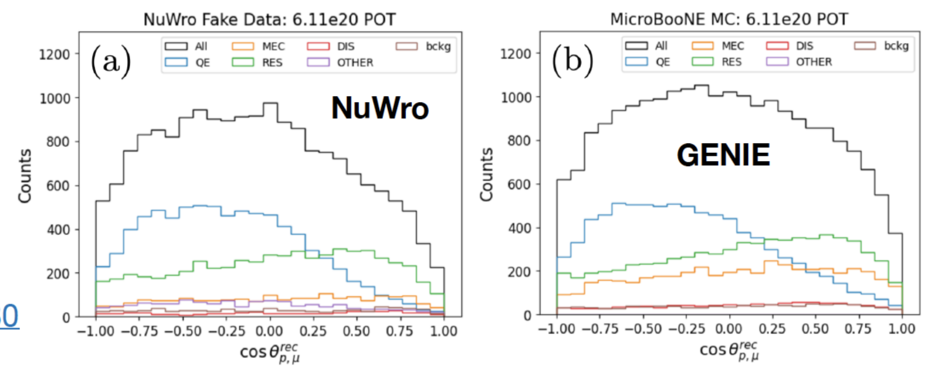


The Conditional Constraint Isn't A Black Box!

NuWro Fake Data: MEC Rate and $\theta_{\mu,p}$

- The effect of a conditional constraint can be easily interpreted in some cases
- As an example, with NuWro fake data, we use muon kinematics to constrain the muon-proton opening angle distribution
- NuWro has a much smaller MEC prediction relative to GENIE
- After the update from the constraint, this difference is reflected in the muon-proton opening angle distribution
  - Good agreement for the QE-dominant (large angle) region
  - Bad agreement for the MEC/RES-dominant (small angle) region
- This tells us that the NuWro MEC prediction seems to be outside of GENIE uncertainties (more on NuWro/GENIE comparisons later)

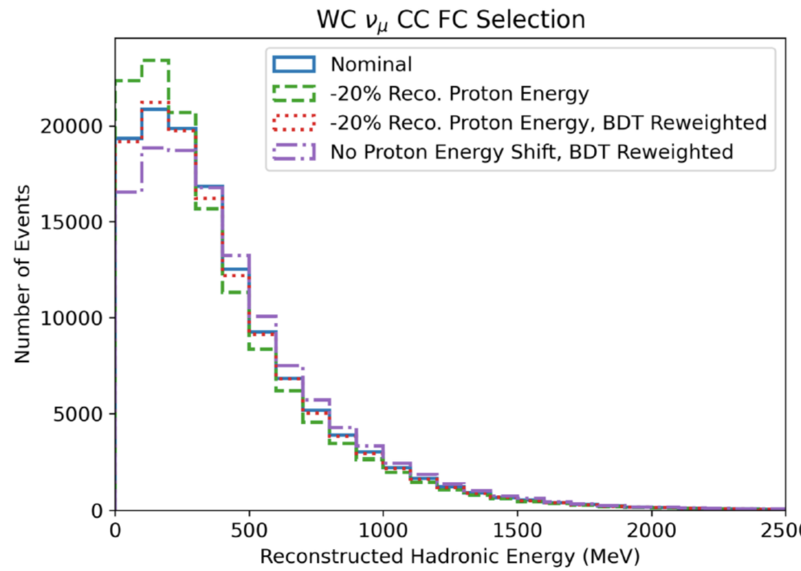


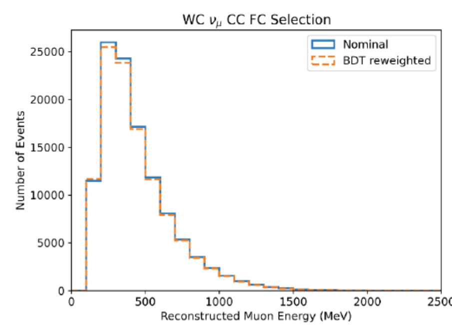


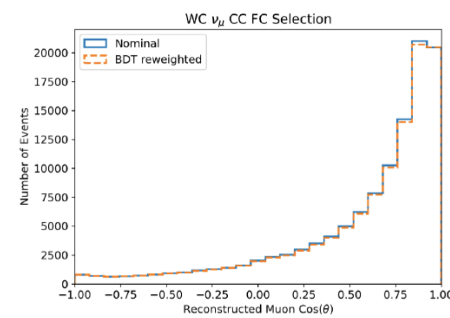
arXiv:2411.03280

Recreating DUNE-ND Proton Energy Scaling Fake Data

- For illustration, we recreate a similar scenario using MicroBooNE simulation
- We shift the reconstructed proton energy down by 20%
- Then, we have a multivariate BDT reweighting to restore the distributions of E_μ^{true}, $\cos\theta_\mu^{\mathrm{true}}$, and $\nu = E_\nu - E_\mu^{\mathrm{true}}$
  - Simulating a mis-modeled cross section that happens to cancel out the proton energy shift
- This reweighting results in good distributions of E_μ^{rec}, $\cos\theta_\mu^{\mathrm{rec}}$, and $E_{\mathrm{had}}^{\mathrm{rec}}$



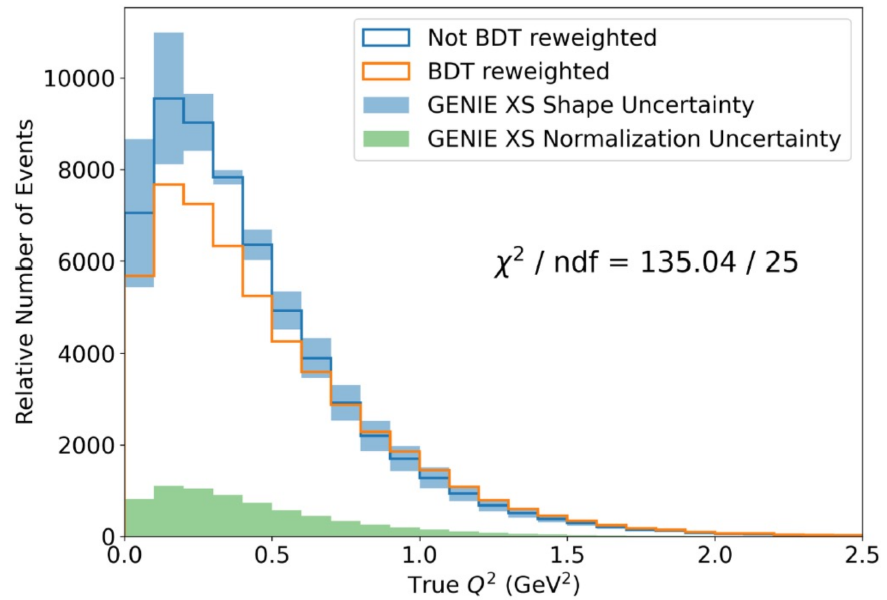




arXiv:2411.03280

Recreating DUNE-ND Proton Energy Scaling Fake Data: QE Events

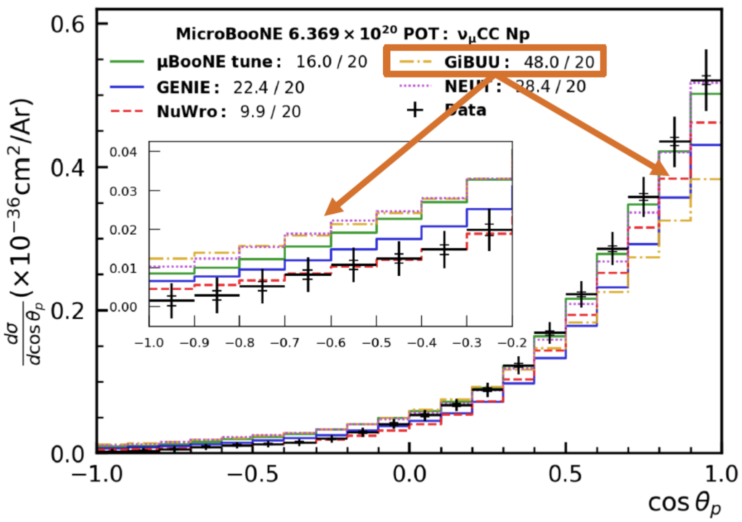
- The cross section for QE events as a function of Q^2 is among the most well understood parts of our cross section models
    - Constrained by theoretical modeling and electron scattering data
- Looking at this distribution, the BDT reweighting results in a cross section very far outside of theoretical uncertainties
- Such a large change that could cancel out the proton energy scaling seems implausible

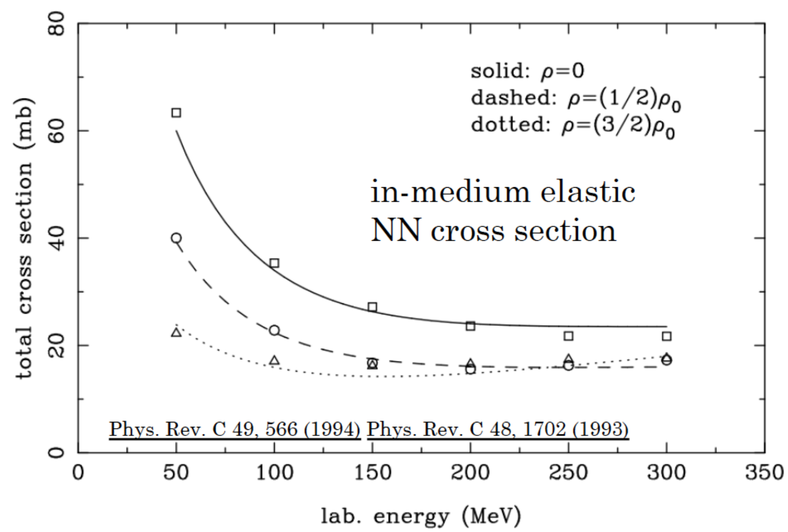


arXiv:2411.03280

Utilizing the Data: In-medium Modifications

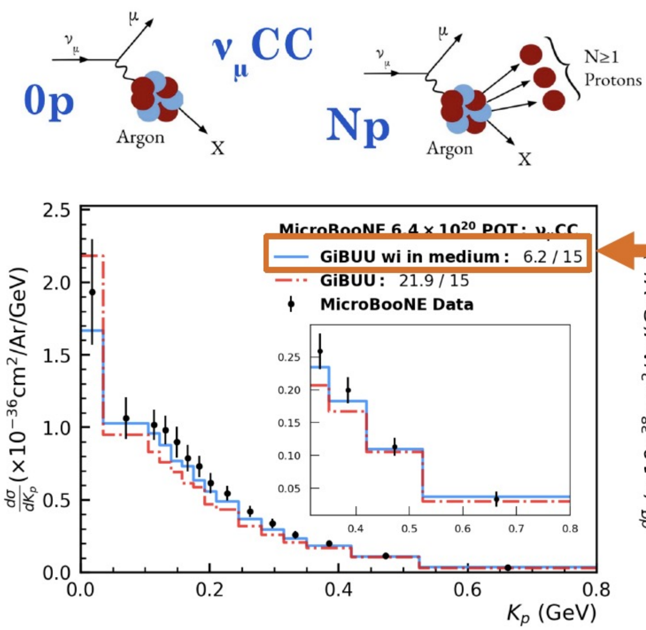
- The free parameters of **GiBUU**'s FSI model are the binding potentials and elementary cross sections of each particle species.
- Theoretical investigation suggest a lowering of nucleon-nucleon (NN) cross sections inside the nuclear medium.
  - **GiBUU** nominally uses the vacuum cross section in its FSI model.
- Features of the data suggest a need for in-medium modifications.
  - Underestimation of the proton spectra at forward angles, overestimation at backwards angles.

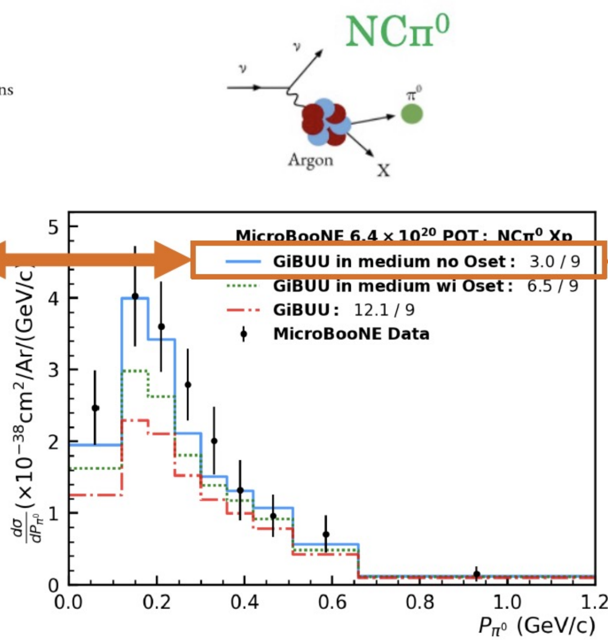




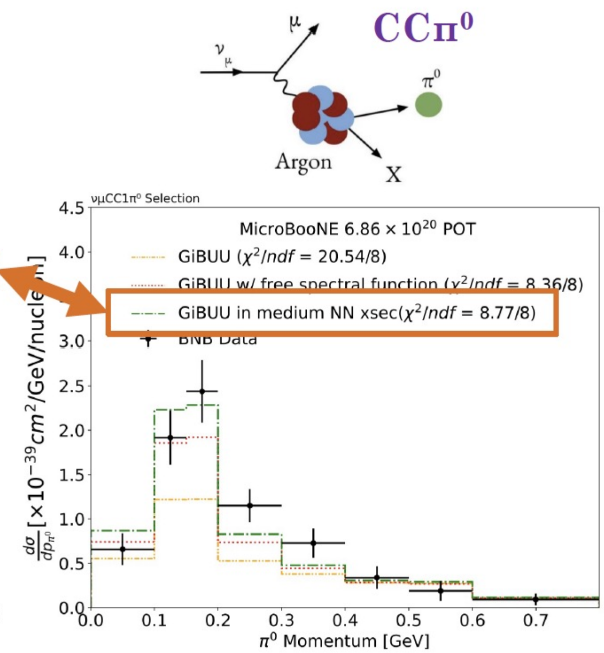
Nuclear Physics in MicroBooNE Data

- Analogous trends seen in other MicroBooNE data.
  - Meghna’s W&C highlights in-medium effects in neutral pion production.
  - Accounting for in-medium effects is essential in obtaining a satisfactory description of the data.
- MicroBooNE data are sensitive to nuclear physics modeling!





arXiv:2404.10948



Phys. Rev. D 110, 092014 (2024)

Meaning of Wiener filter

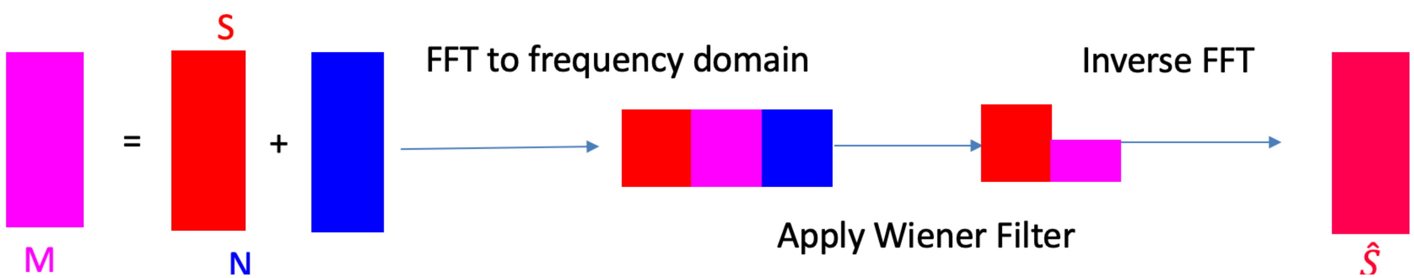
- Wiener filter was determined by minimizing the expectation of

$$E\left[\left(F(\omega)\cdot M(\omega)-\overline{S(\omega)}\right)^2\right]$$
$$=E\left[\left(F(\omega)\cdot\left(\bar{S}(\omega)+N(\omega)\right)-\overline{S(\omega)}\right)^2\right]$$

M: measurement
$\bar{S}$: expectation of the signal

$$\boxed{F(\omega)=\frac{\overline{S(\omega)}^2}{\overline{S(\omega)}^2+\overline{N^2(\omega)}}}$$

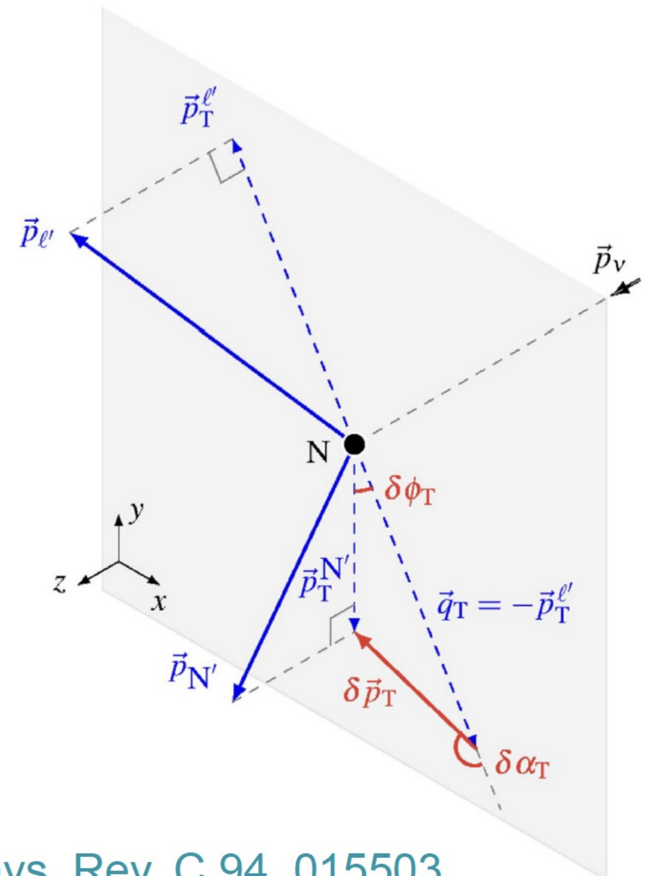
Wiener filter is by construction to minimize the total
mean squared error (MSE = bias^2 + variance) in the frequency domain



How to find a (frequency) 'domain' to maximize separating signal and noise?

Title:	Year	Notes	arXiv
First Measurement of Dierential Charged Current Quasielastic-like {ArgonScattering Cross Sections with the MicroBooNE Detector	2020	QE	2006.00108
Multi-Differential Cross Section Measurements of ν_μ-Argon Quasielastic-like Reactions with the MicroBooNE Detector	2023	QE, Mmulti-dimension	2301.03700
First double-differential measurement of kinematic imbalance in neutrino interactions with the MicroBooNE detector	2023	TKI	2301.03706
Measurement of nuclear effects in neutrino-argon interactions using generalized kinematic imbalance variables with the MicroBooNE detector	2023	GKI	2310.06082
First study of neutrino angle reconstruction using quasielastic-like interactions in MicroBooNE	2025	QE, neutrino angle	2504.17758
First Measurement of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon at Ev~0.8 GeV with the MicroBooNE Detector	2019	first inclusive CC	1905.09694
First Measurement of Energy-Dependent Inclusive Muon Neutrino Charged-Current Cross Sections on Argon with the MicroBooNE Detector	2021	Wire-Cell inclusive 1D	2110.14023
Measurement of three-dimensional inclusive muon-neutrino charged-current cross sections on argon with the MicroBooNE detector	2023	Wire-Cell inclusive 3D	2307.06413
Inclusive cross section measurements in final states with and without protons for charged-current νμ-Ar scattering in MicroBooNE	2024	Wire-Cell inclusive 0p vs. Np	2402.19216
First simultaneous measurement of differential muon-neutrino charged-current cross sections on argon for final states with and without protons using MicroBooNE dat	2024	Wire-Cell PRL	2402.19281
New CC0 GENIE Model Tune for MicroBooNE	2021	Model tuning	2110.14028
Improving neutrino energy estimation of charged-current interaction events with recurrent neural networks in MicroBooNE	2024	Wire-Cell neutrino energy	2406.10123
Data-driven model validation for neutrino-nucleus cross section measurements	2024	model validation	2411.03280
Measurement of neutral current single pi0 production on argon with the MicroBooNE detector	2022	NC pi0 first	2205.07943
First double-differential cross section measurement of neutral-current π0 production in neutrino-argon scattering in the MicroBooNE detector	2024	Wire-Cell NC pi0	2404.10948
Measurement of the differential cross section for neutral pion production in charged-current muon neutrino interactions on argon with the MicroBooNE detector	2024	CCpi0	2404.09949
Measurement of the Flux-Averaged Inclusive Charged-Current Electron Neutrino and Antineutrino Cross Section on Argon using the NuMI Beam and the MicroBooNE D	2021	NuMI nueCC (both nue and antinue)	2101.04228
First Measurement of Inclusive Electron-Neutrino and Antineutrino Charged Current Dierential Cross Sections in Charged Lepton Energy on Argon in MicroBooNE	2021	NuMI nueCC (both nue and antinue)	2109.06832
Differential cross section measurement of charged current e interactions without final-state pions in MicroBooNE	2022	BNB nue	2208.02348
First measurement of ν_e and .ν_e charged current single charged pion production differential cross sections on argon using the MicroBooNE detector	2025	NuMI nueCC charged pion	2503.23384
Comparison of νμ-Ar multiplicity distributions observed by MicroBooNE to GENIE model predictions	2018	multiplicity	1805.06887
Measurement of Dierential Cross Sections for -Ar Charged-Current Interactions with Protons and no Pions in the Final State with the MicroBooNE Detector	2020	CC0piNp	2010.0239
Measurement of double-differential cross sections for mesonless charged-current muon neutrino interactions on argon with final-state protons using the MicroBooNE	2024	CC0piNp	2403.19574
First measurement of differential cross sections for muon neutrino charged current interactions on argon with a two-proton final state using the MicroBooNE detector	2022	2p final-state	2211.03734
First measurement of quasi-elastic Λ baryon production in muon anti-neutrino interactions in the MicroBooNE detector	2022	Lambda, rare process	2212.07888
First measurement of η production in neutrino interactions on argon with MicroBooNE	2023	eta. Rare process	2305.16249
Demonstration of neutron identification in neutrino interactions in the MicroBooNE liquid argon time projection chamber	2024	neutron identifciation	2406.10583
First Measurement of Charged Current Muon Neutrino-Induced K_+ Production on Argon using the MicroBooNE Detector	2025	K+	2503.00291

Nuclear effects with pionless analyses



Phys. Rev. C 94, 015503

We know initial momentum perpendicular to beam direction is zero:

- Measuring non-zero transverse momentum tells us about missing momentum

$$\delta P_T = | \mathbf{P}_T^{\mu} + \mathbf{P}_T^{P} |$$

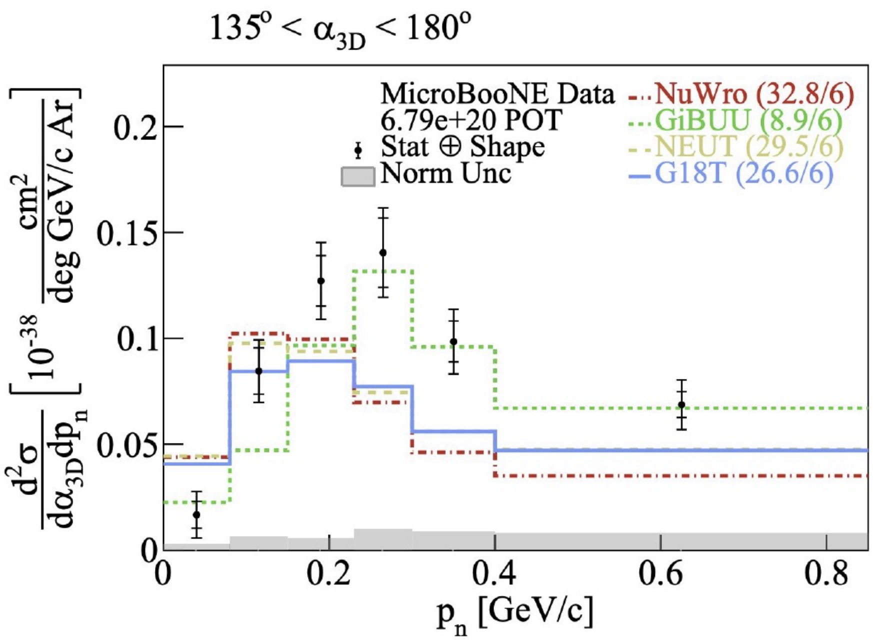
Imbalance due to initial nucleon motion or hadronic final state interactions (FSI)

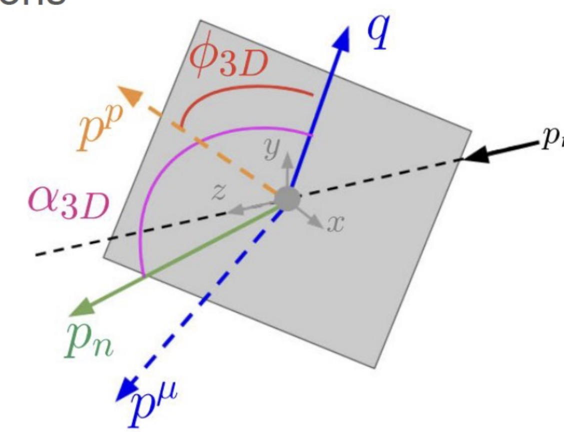
In the absence of FSI, the transverse kinematic imbalance (TKI) parameters:

- $\boldsymbol{\delta P_T}$: momentum of the struck momentum
- $\boldsymbol{\delta\alpha_T}$: angle between momentum transfer and initial state nucleon momentum

CC1p0π Selection - GKI

Generalise kinematic imbalance (GKI) variables to three dimensions by considering longitudinal component of missing momentum:





First measurement using novel GKI variables:

- Enhanced sensitivity to ground state modeling and hadron re-interactions

Region of α_{3D} > 135° contains large fraction of events which undergo FSI interactions