Exploring Neutrino Interaction Physics with MicroBooNE

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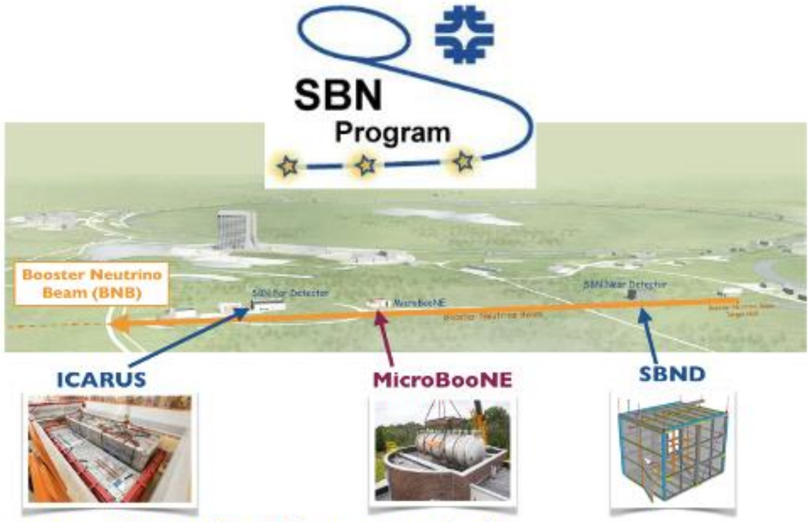
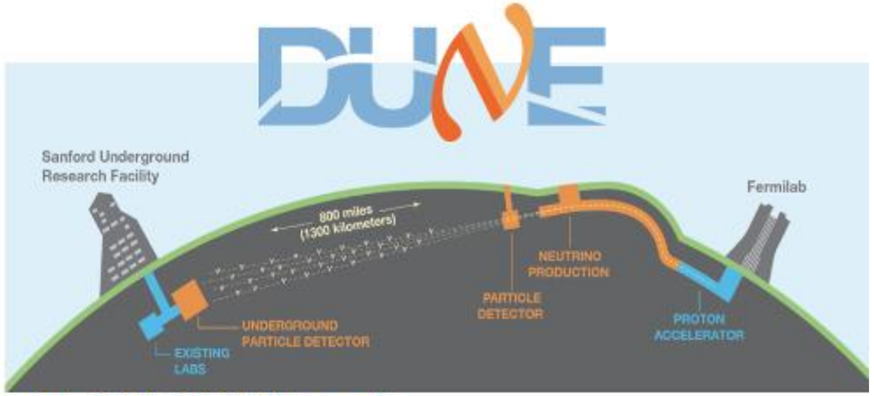
On behalf of MicroBooNE collaboration

Neutrino-nucleus interactions in LArTPC

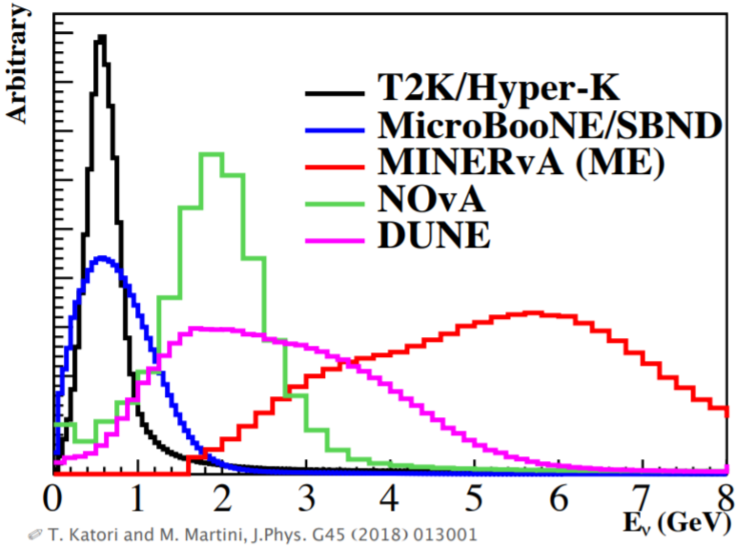
- Liquid Argon Time Projection Chamber (LArTPC) is one key technology in the current and future neutrino oscillation experiments
- Understanding ν-Ar cross sections is critical in reducing systematic uncertainties to reach desired precision of these experiments



arXiv:1503.01520 [physics.ins-det]



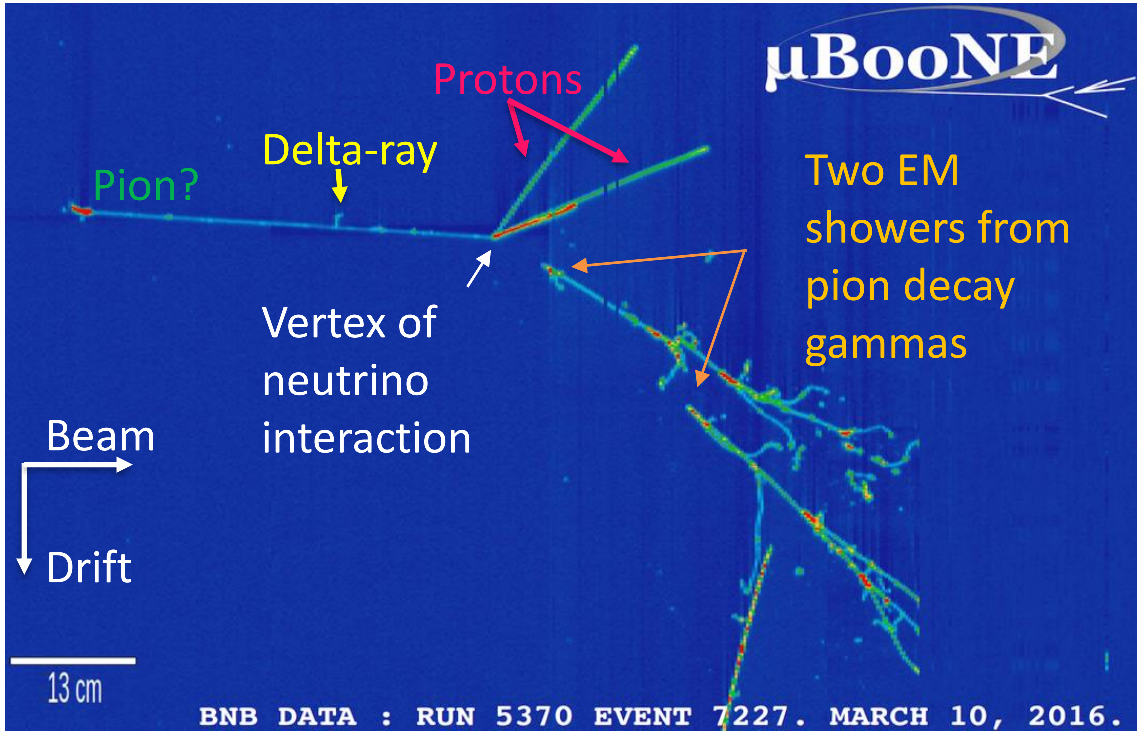
arXiv:2002.03005 [hep-ex]

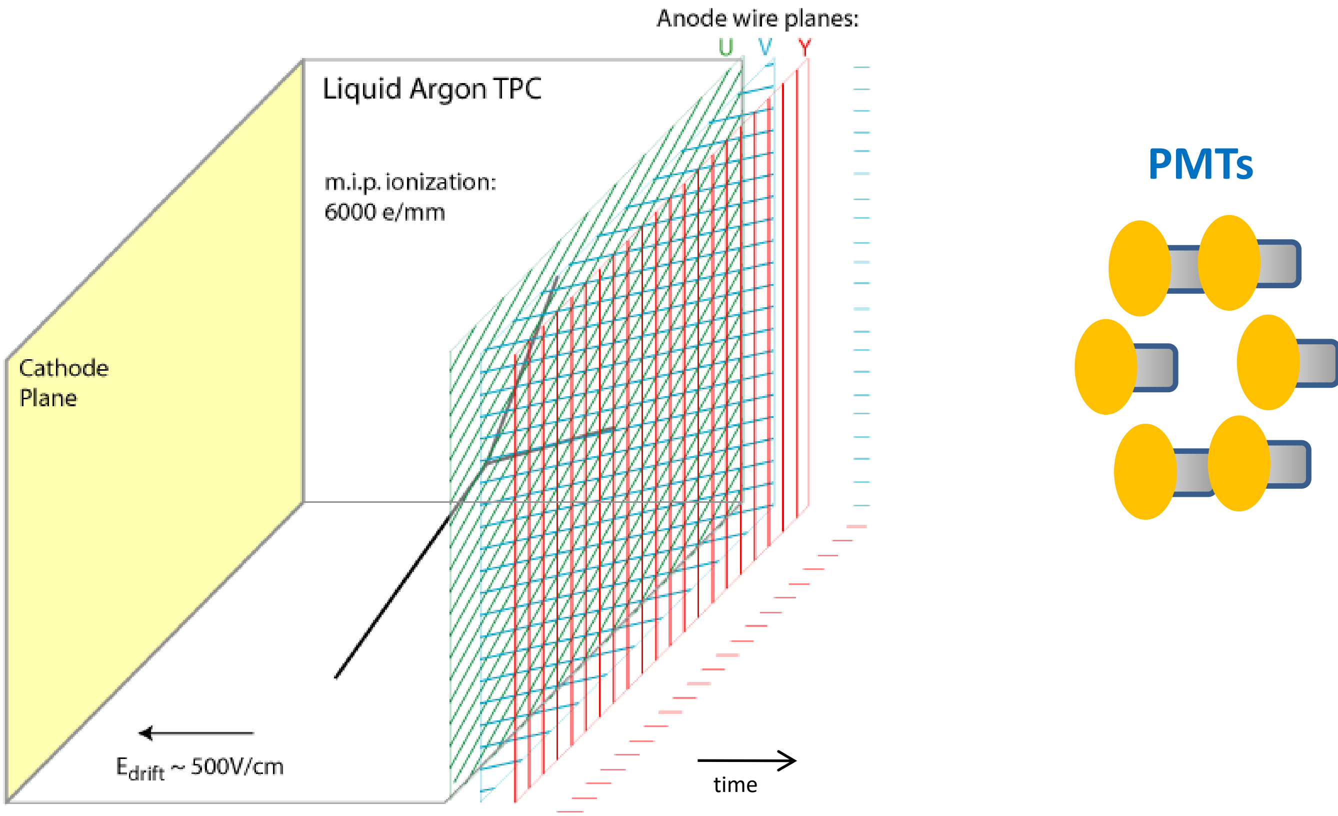


T. Katori and M. Martini, J.Phys. G45 (2018) 013001

LArTPC: fully active tracking calorimeter

Made by Bo Yu (BNL)



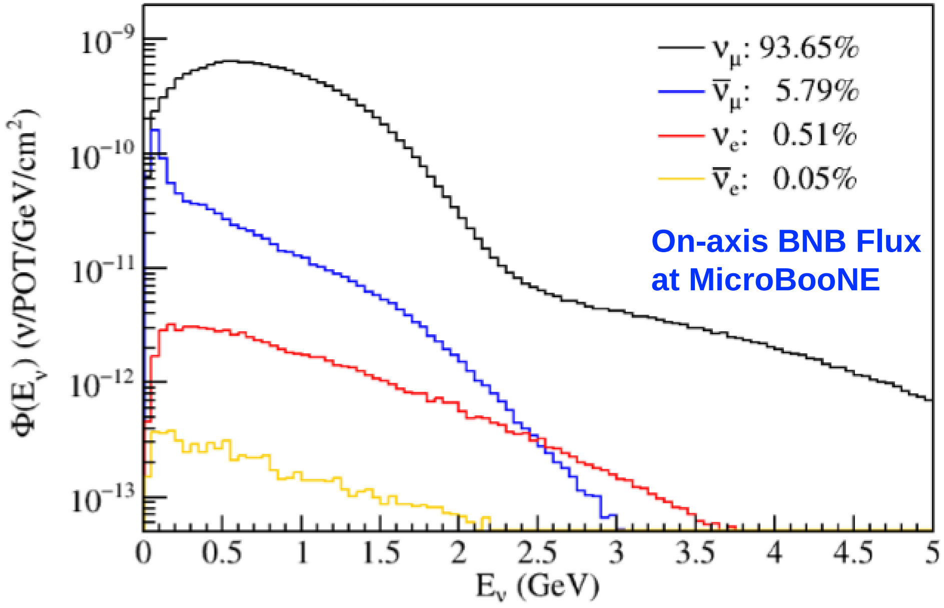


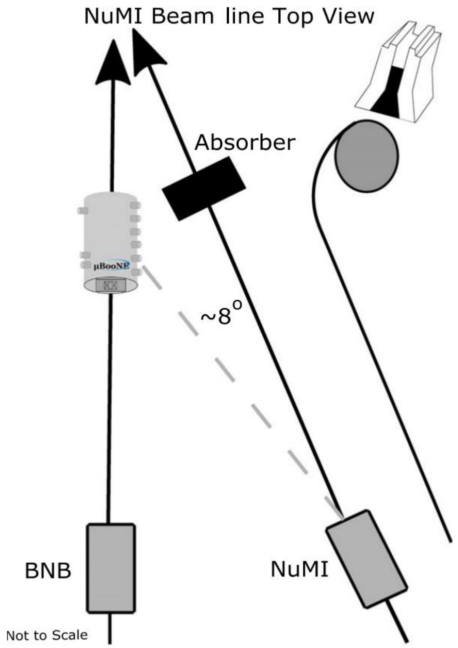
A candidate of neutral-current interaction

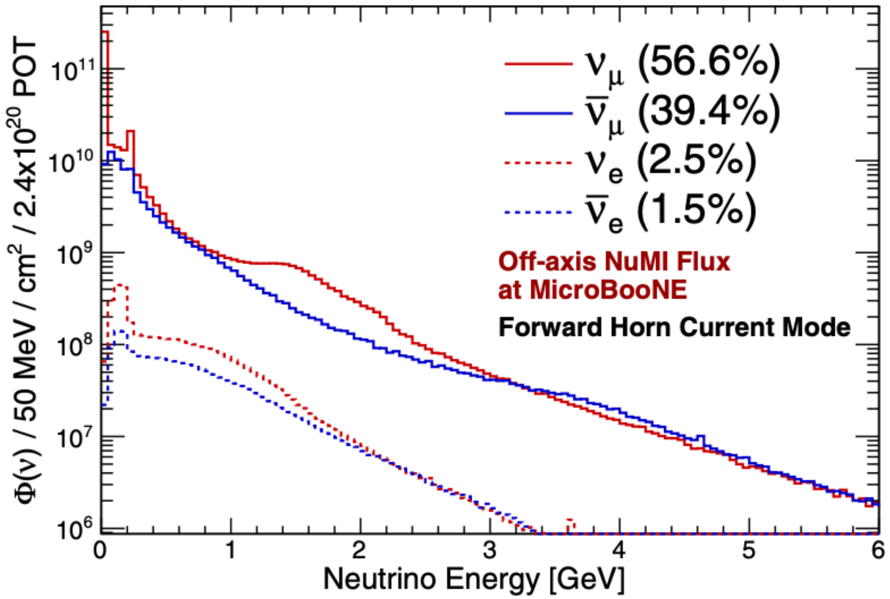
Drift velocity 1.6 mm/μs → several ms drift time

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

MicroBooNE experiment

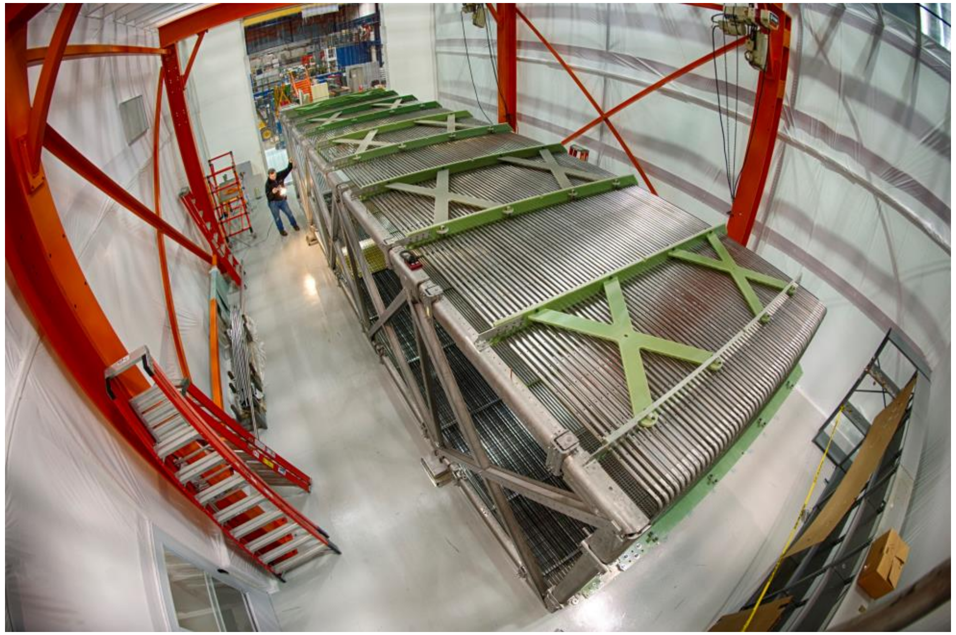






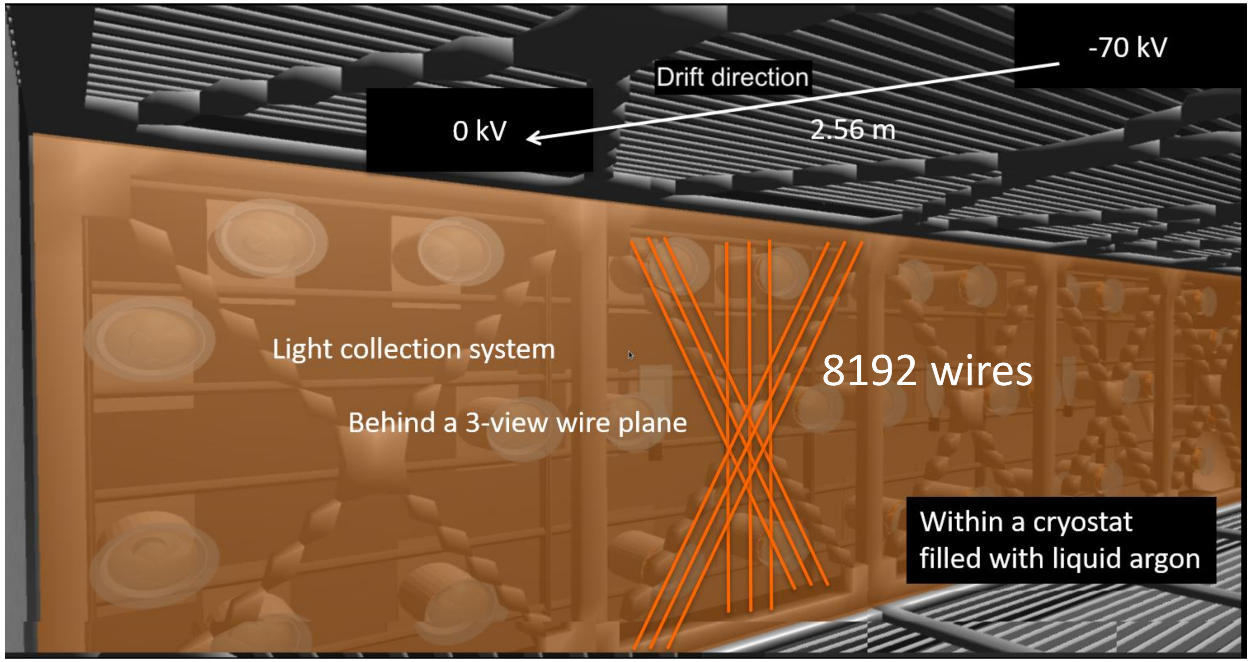
- Both ν_μ and ν_e cross sections are important for oscillation measurements
- At MicroBooNE, two beamlines are available:
  - Booster Neutrino Beamline (BNB): **on-axis**, >99% $\nu_\mu + \bar{\nu}_\mu$
  - Main injector neutrino beam (NuMI): **off-axis**, 4% $\nu_e + \bar{\nu}_e$

MicroBooNE Detector: An 85-ton LArTPC



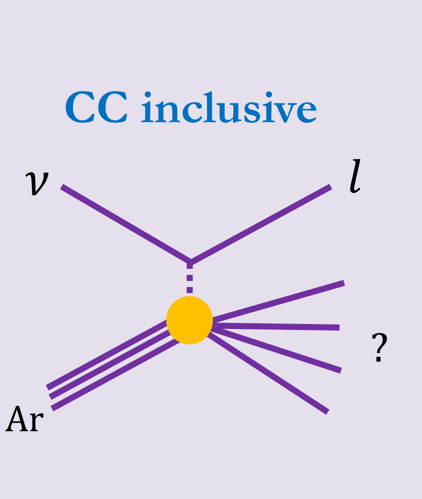
- 8192 wire channels to detect ionization charge
- 32 8-inch PMTs to detect scintillation light

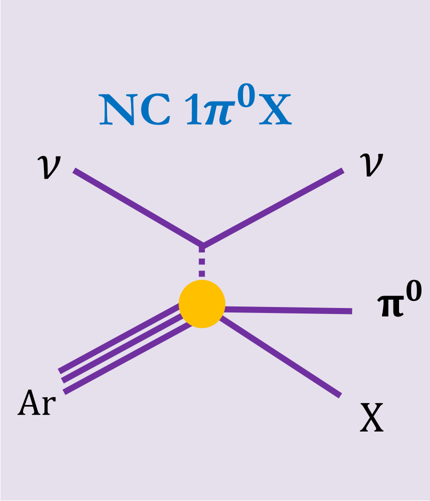
- Physics Motivation:
  - **Address MiniBooNE Low Energy Excess**
  - **LArTPC hardware & software R&D**
  - **Study ν-Ar interactions**
    - Largest ν-Ar data set (~0.5 M in 2016-2021)

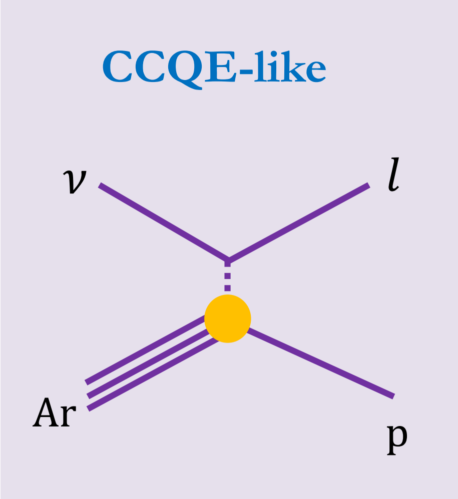


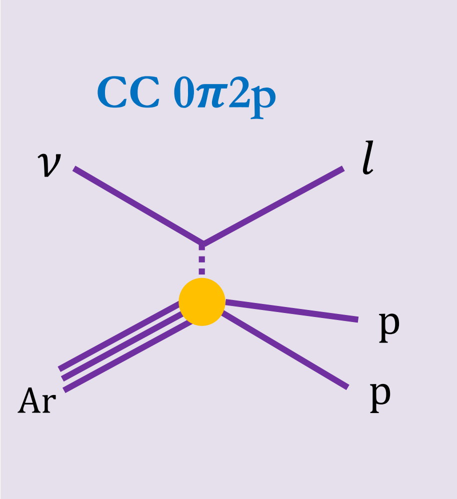
Studying ν-Ar cross sections at MicroBooNE

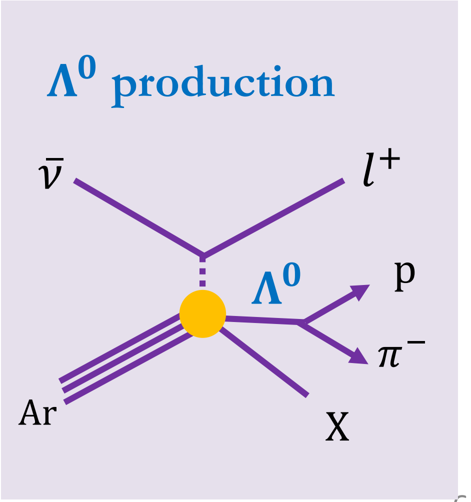
- Leveraging LArTPC's excellent capability of tracking calorimetry
  - Understanding of charged-current (CC) **inclusive** and neutral-current (NC) π^0 cross section is desired for oscillation measurements
  - **Exclusive** cross sections further guide event generators to pin down underlying reaction mechanisms
  - Explore neutrino-argon cross sections for **rare processes**





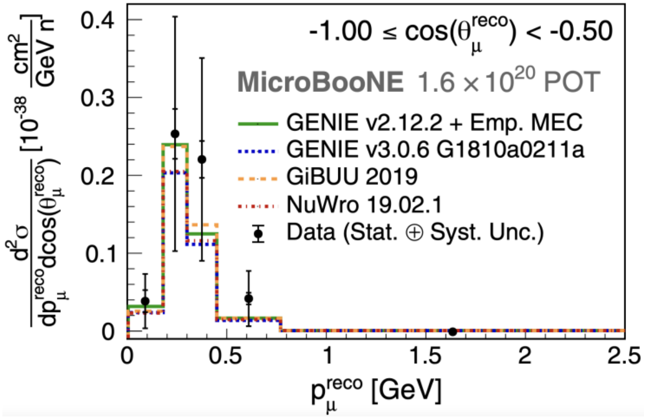




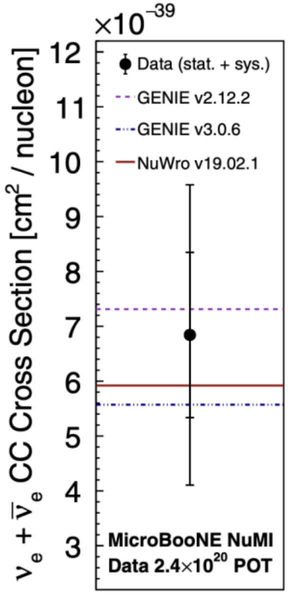


First-generation Cross Section Measurements

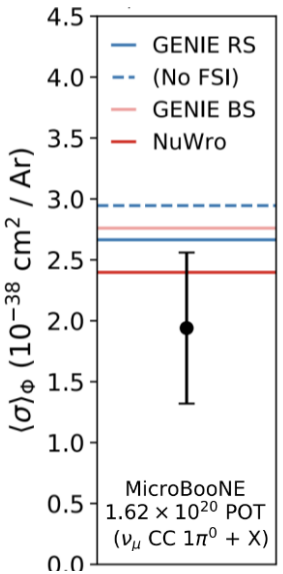
PRL **123**, 131801



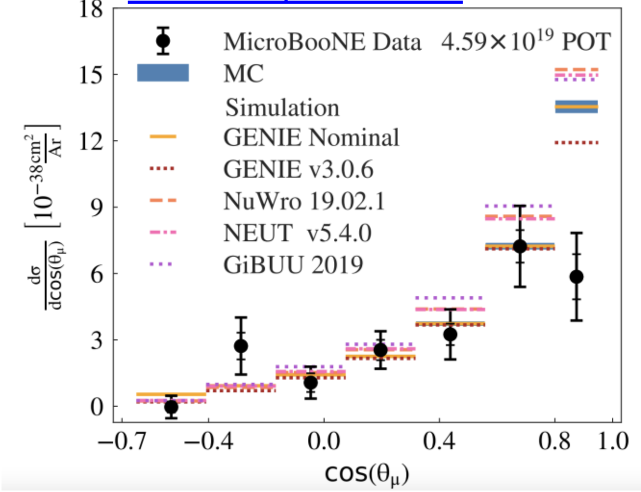
PRD **104**, 052002



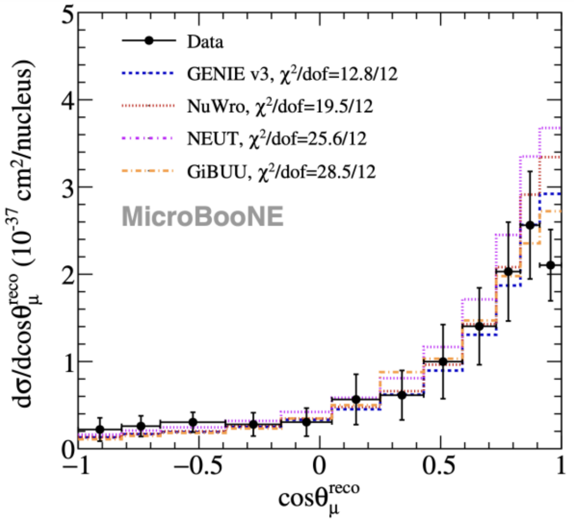
PRD **99**, 091102



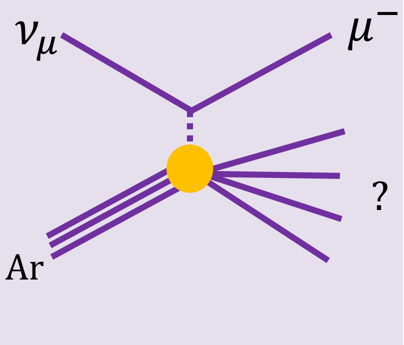
PRL **125**, 201803



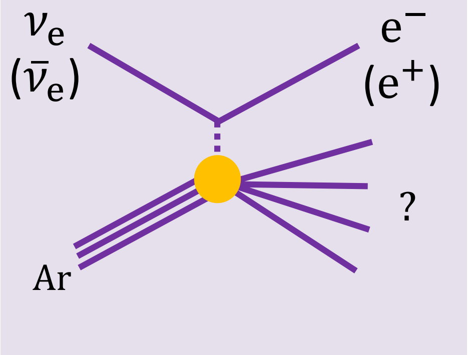
PRD **102**, 112013



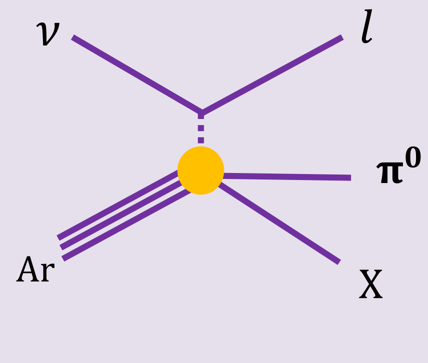
ν_μ CC inclusive



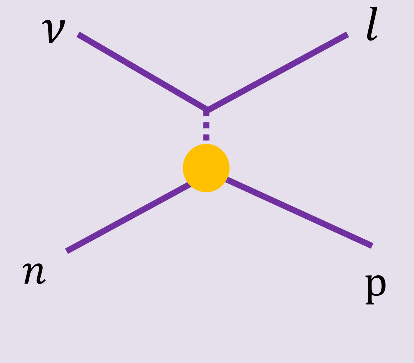
$\nu_e(\bar{\nu}_e)$ CC inclusive



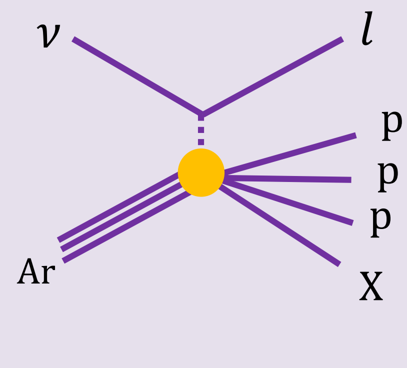
CC $1\pi^0$X



CC Quasi-Elastic (QE)-Like

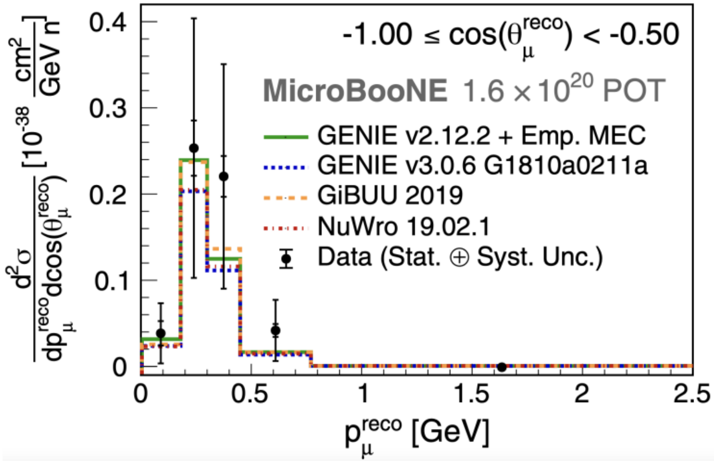


CC 0πNp

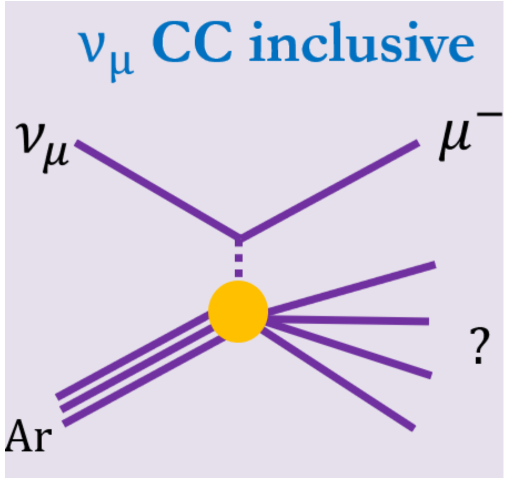


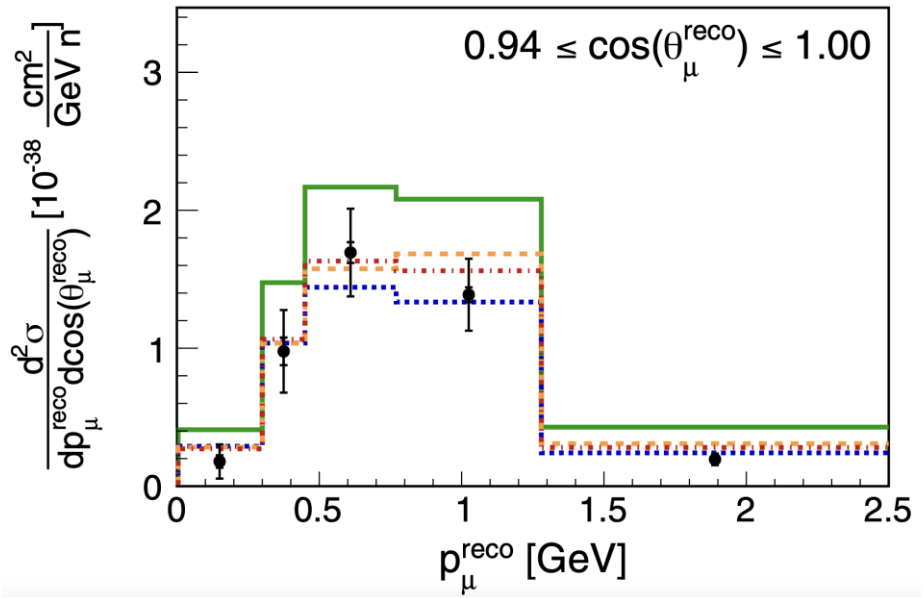
1^{st} generation inclusive ν_μCC

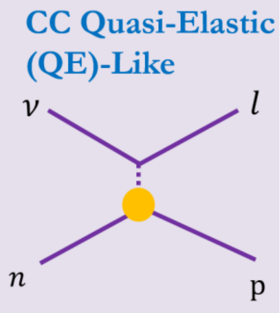
PRL **123**, 131801



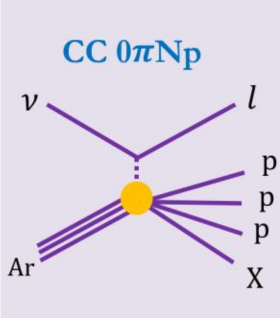
- First **double differential** cross section measurement on argon
  - Model overpredictions observed in high-momentum, most **forward-going** muon angle
    - nucleon-nucleon correlation (e.g., RPA effect) is a possible explanation



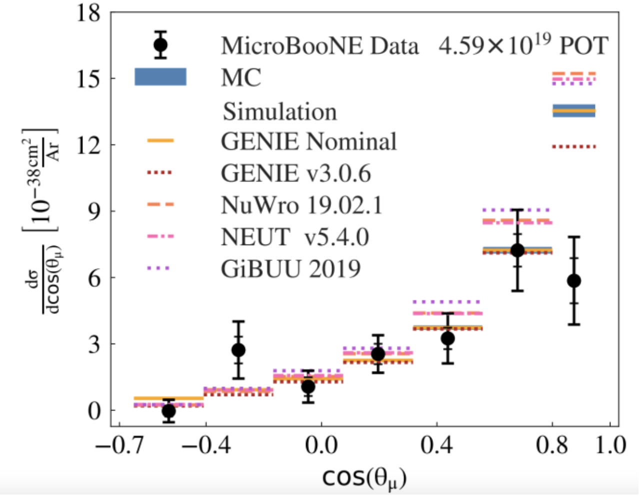




1st generation: ν_μCCQE & ν_μCC 0π Np

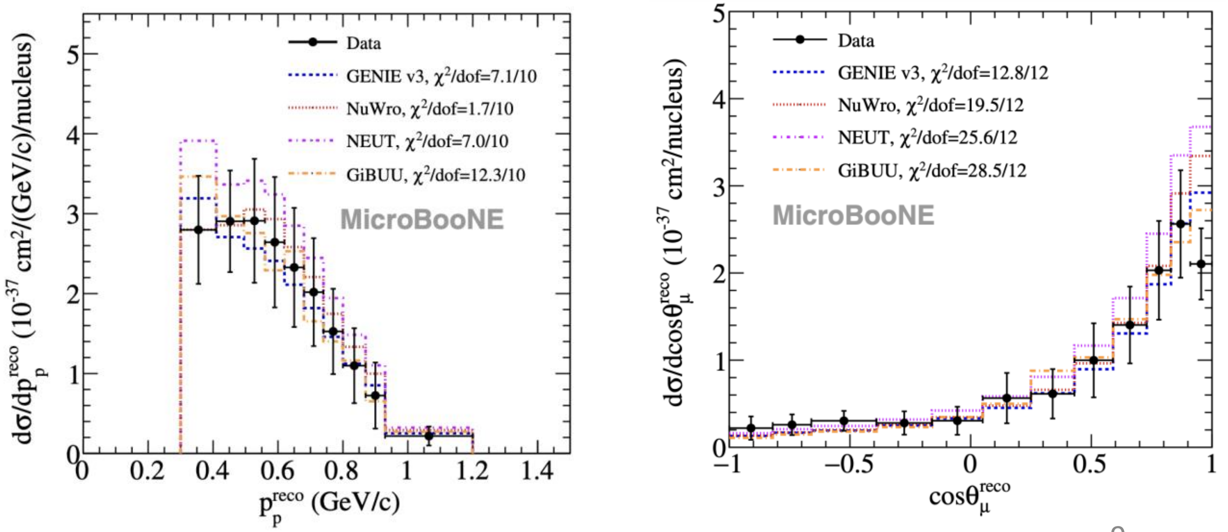


PRL **125**, 201803

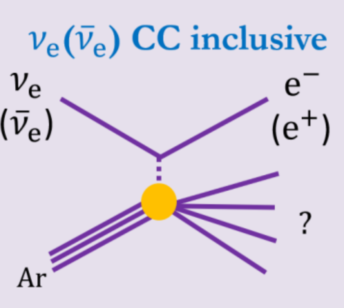


- Model overpredictions at most forward-going muon angle
  - ➡ Consistent with CCQE-like results
- Low proton momentum region is sensitive to Final State Interaction (FSI) and *2p2h* effect

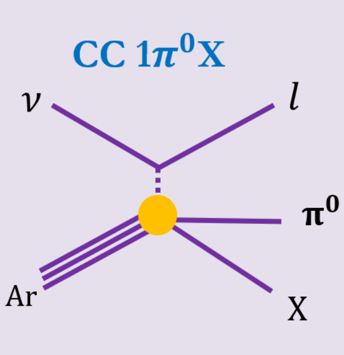
- First measurement of ν-Ar CCQE-like single differential cross section
- Model overprediction observed at most forward-going muon angular bin
  - ➡ More significant than inclusive measurement



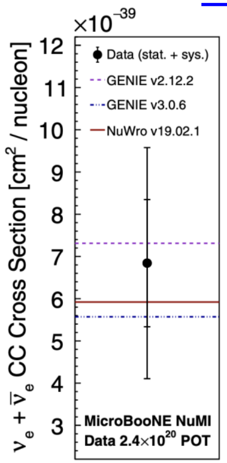
PRD **102**, 112013

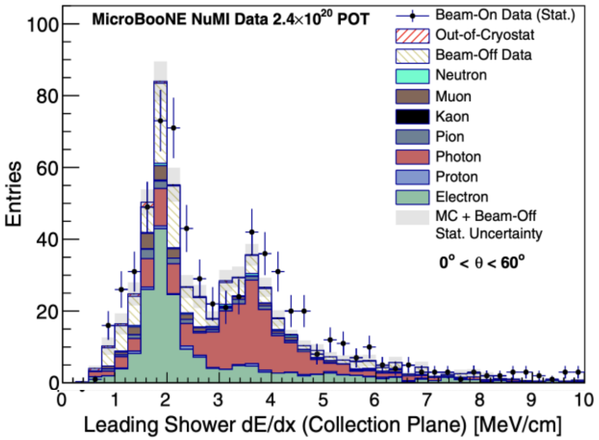


1[st] generation: $(\nu_e+\bar{\nu}_e)$CC & ν_μCC π^0



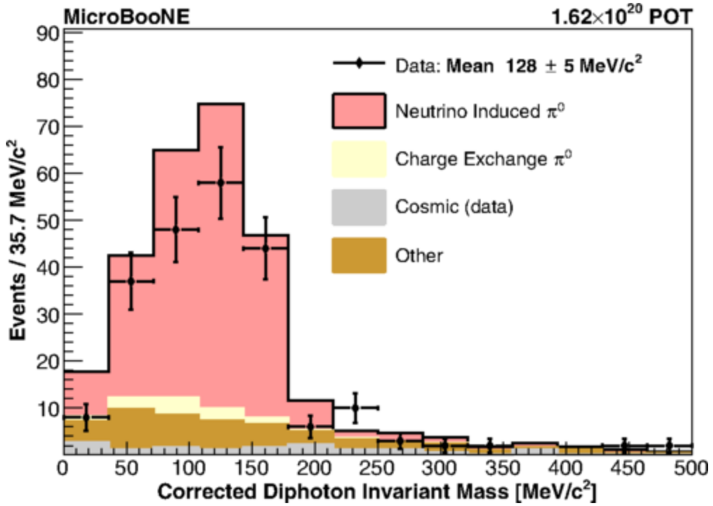
PRD **104**, 052002

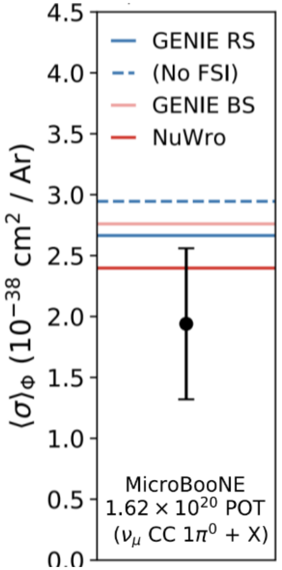




- ν_e+$\bar{\nu}_e$ measurement using the NuMI off-axis beam at MicroBooNE
  - Successful demonstration of e/γ separation and electron-neutrino reconstruction
  - Consistent with model predictions within uncertainties

- First measurement of the flux-integrated cross section of ν_μ CC single π^0 production on argon



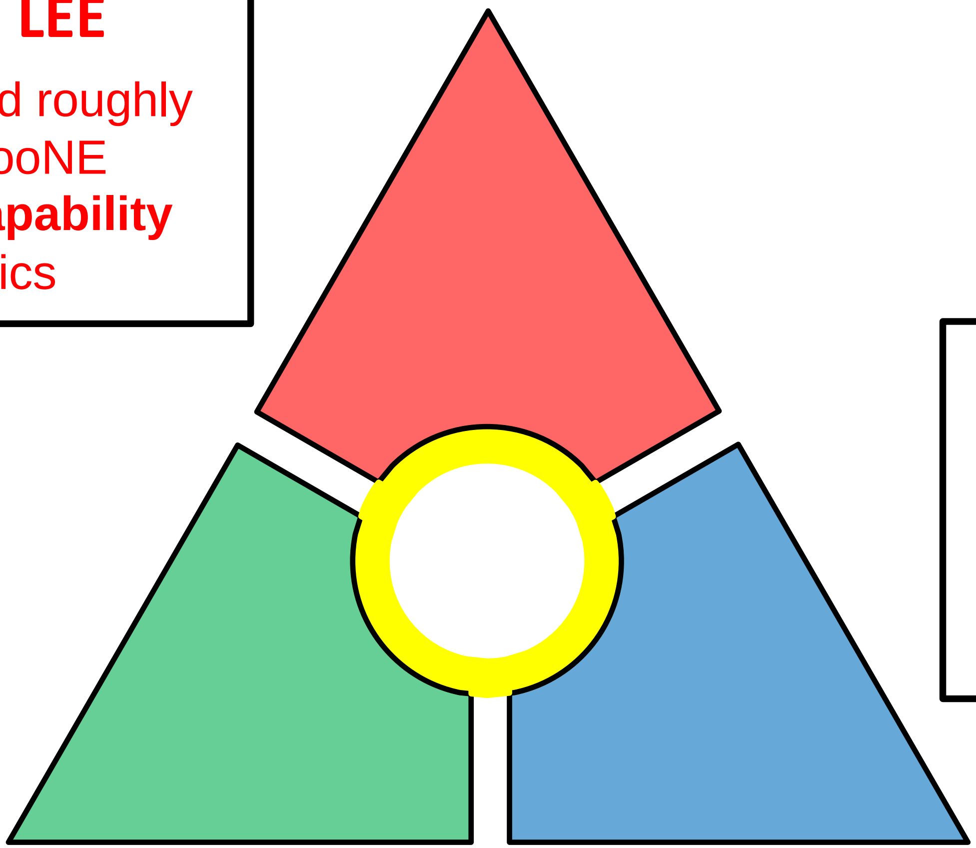


PRD **99**, 091102

MicroBooNE Science Goals (Physics + R&D)

Address MiniBooNE LEE

Same neutrino beamline and roughly same location as MiniBooNE
Unique e/γ separation capability
Search for BSM physics



Study ν-Ar interactions

Inclusive & exclusive cross section measurements,
Validation of modeling of neutrino energy

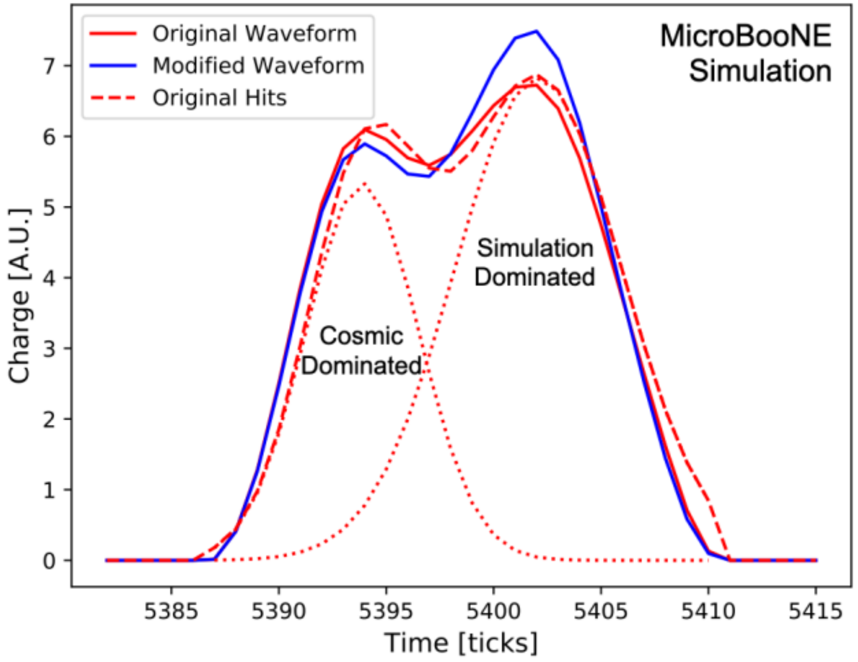
LArTPC hardware & software R&D

LArTPC design, cryostat, cold electronics ...
Noise filtering, TPC signal processing, detector physics,
event reconstruction

Second-generation MicroBooNE cross section measurements benefits from significant progresses in the other two directions

Evolved detector simulation & signal processing

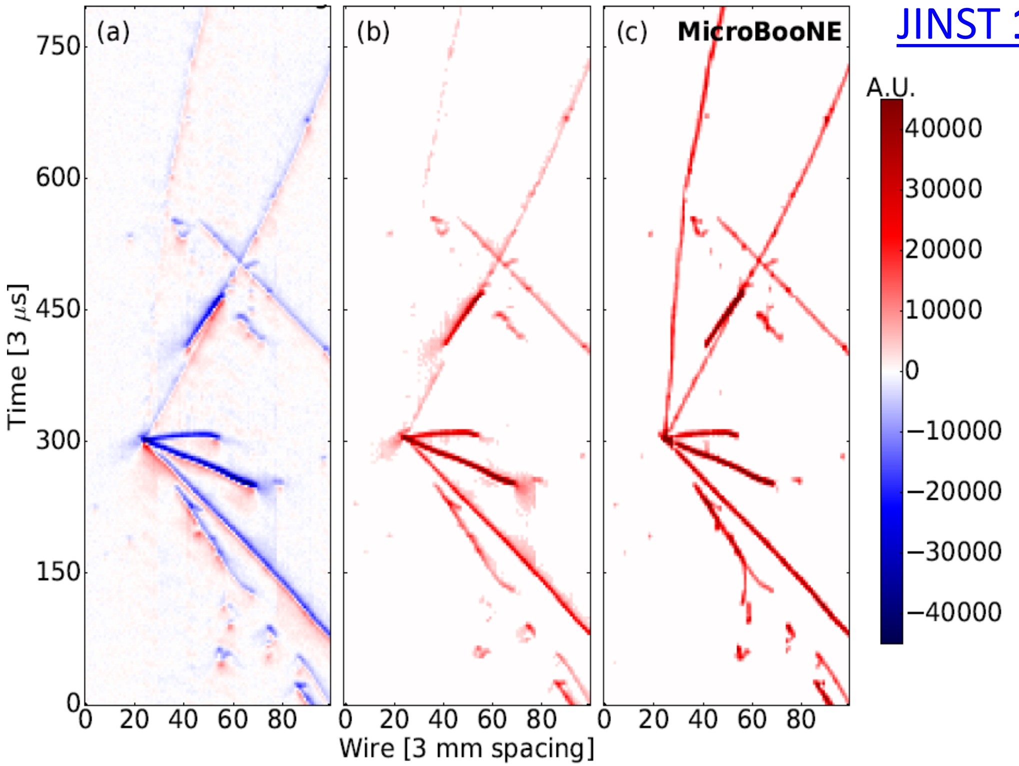
[Eur. Phys. J. C82 454]



- Improved evaluation of **detector systematic uncertainties** with changes to detector modeling

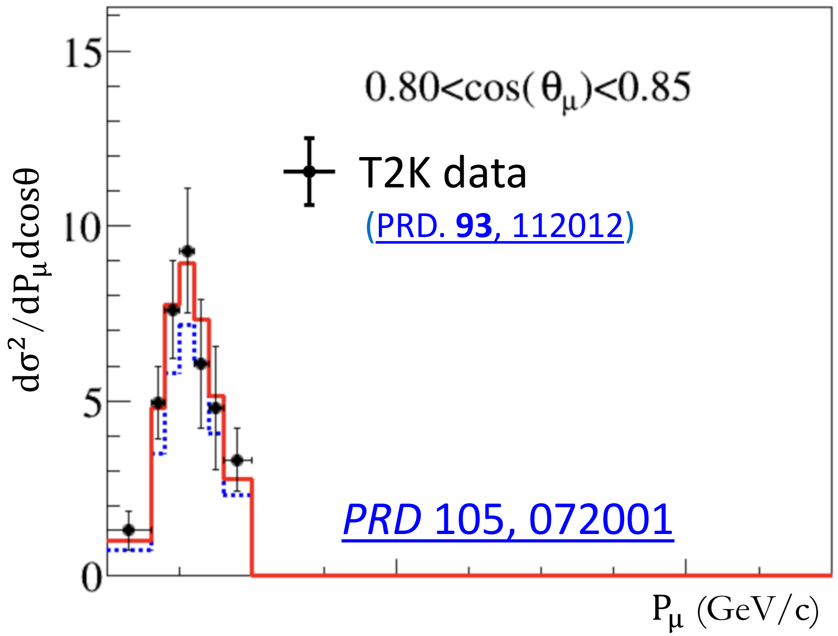
Original | 1D deconvolution | 2D deconvolution

[JINST **13** P07006]



- Advanced **2D deconvolution** with consideration of long-range induction effect

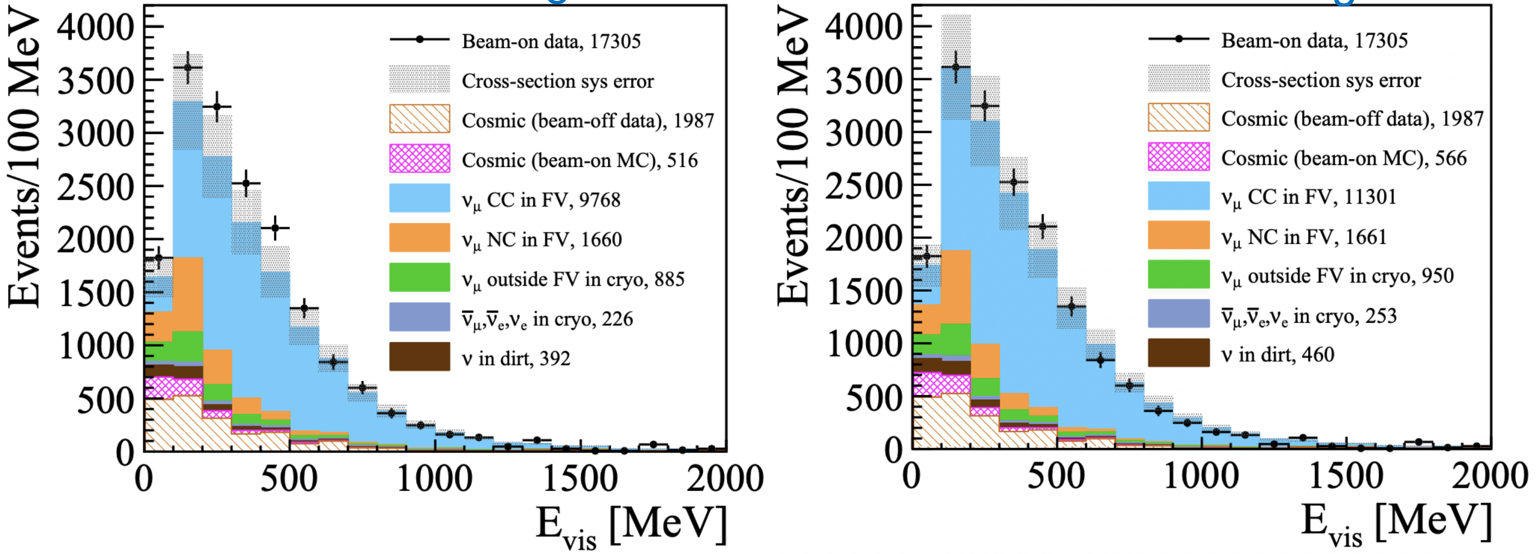
Evolved neutrino interaction model



Generic neutrino preselection

Before tuning

After Tuning



- MicroBooNE's interaction model evolved from GENIE v2 to GENIE v3
- New cross section model is tuned through fitting to T2K's ν_μ CC0π data (CH) at similar beam energy
  - ➥ Tune 4 key parameters and their uncertainties related to Valencia treatments of CCQE (axial mass, RPA) and 2p2h (shape and normalization) models based on LFG
  - ➥ No additional fit to MicroBooNE data (Ar)

Expanded cross section extraction method

- Forward-folding

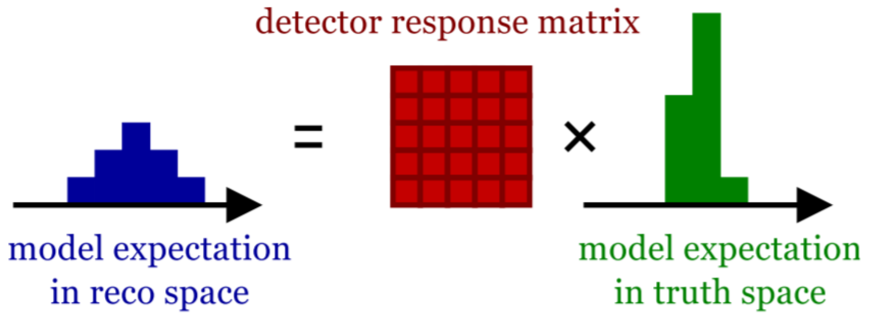
$$\left(\frac{d\sigma}{dp_\mu}\right)_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{\text{target}} \cdot \Phi_{\nu_\mu} \cdot (\Delta p_\mu)_i}$$

N_i (B_i): # of candidate (bkgd) in reco bin i
N_{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

- (Wiener-SVD & Iterative) unfolding

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

N_i (B_i): # of candidate (bkgd) in reco bin i
R_{ij}: response (smearing) matrix
S_j: cross section to be extracted in **true bin j**

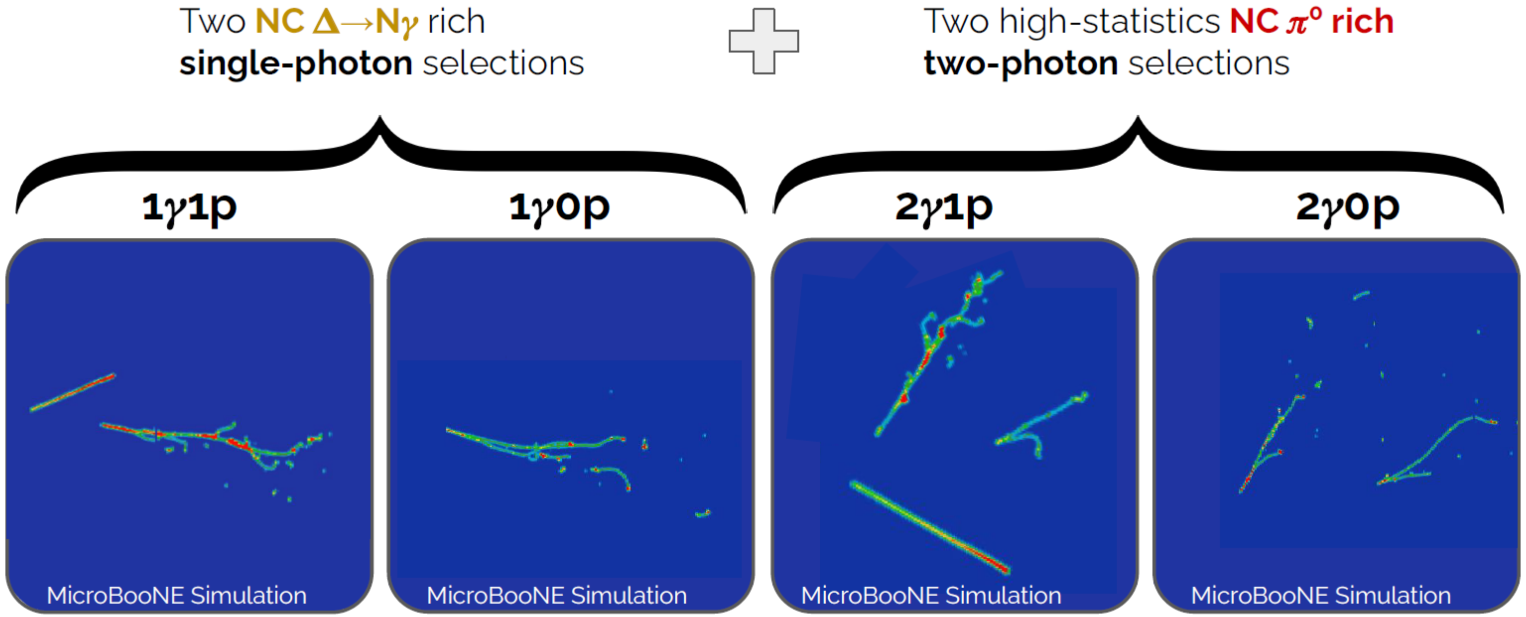


Wiener-SVD: JINST 12 (2017) 10, P10002

‡ : Phys. Rev. D 102 (2020) 113012

➡ Flux shape uncertainty properly treated ‡

Search for Excess in NC Δ Radiative Decay



PRL 128, 111801

1γ1p

Unconstr. bkgd.	27.0 ± 8.1
Constr. bkgd.	20.5 ± 3.6
NC $\Delta \to N\gamma$	+ 4.88
LEE ($x_{\rm MB} = 3.18$)	+ 15.5

16 Data Events Observed

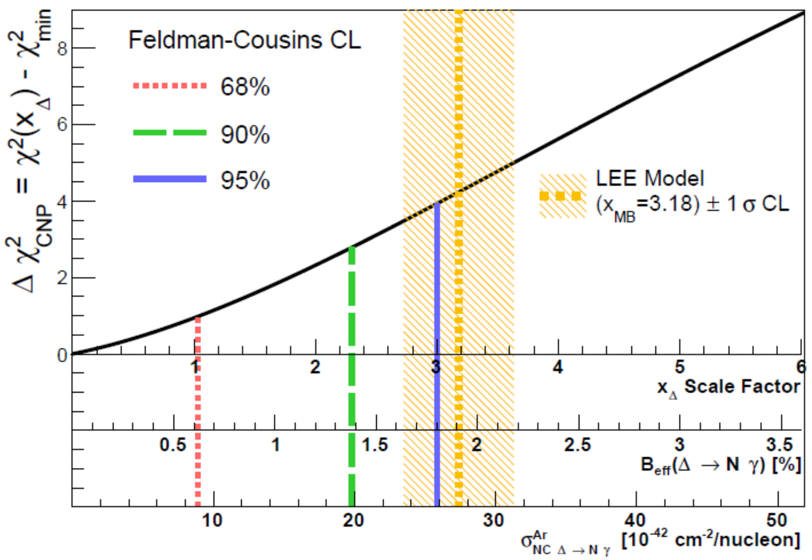
1γ0p

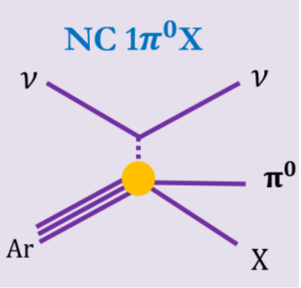
Unconstr. bkgd.	165.4 ± 31.7
Constr. bkgd.	145.1 ± 13.8
NC $\Delta \to N\gamma$	+ 6.55
LEE ($x_{\rm MB} = 3.18$)	+ 20.1

153 Data Events Observed

No Excess Observed in NC Δ Radiative Decay

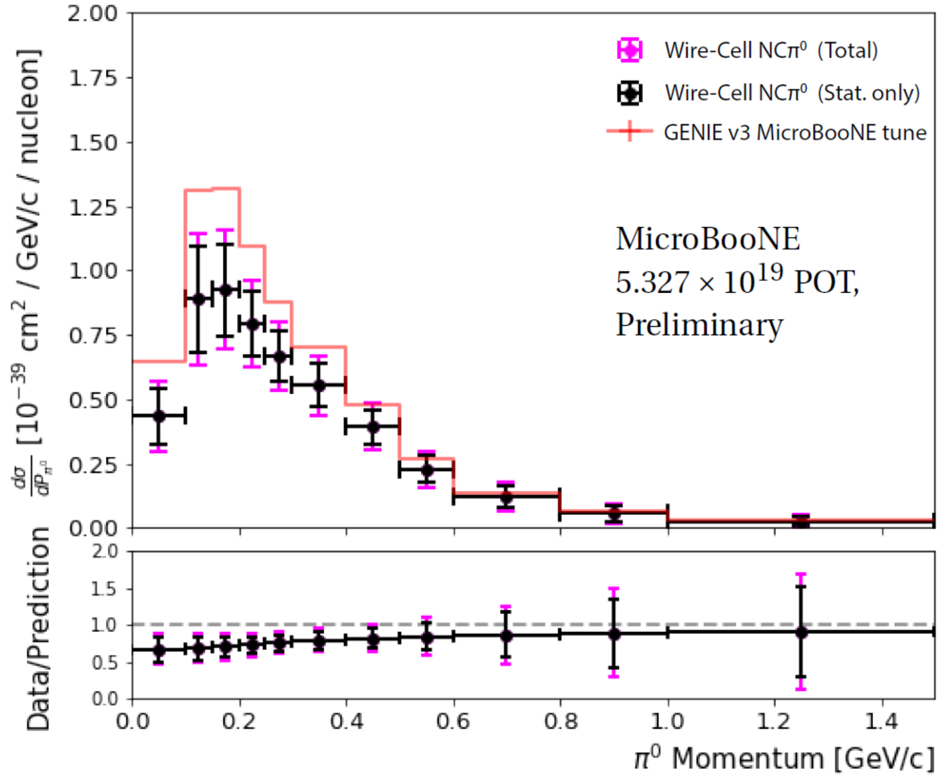
- 90% CL limit on the branching ratio is 1.38%
  - Consistent with expectation
- x50 fold improvement over the world's best limit at O(1 GeV) region



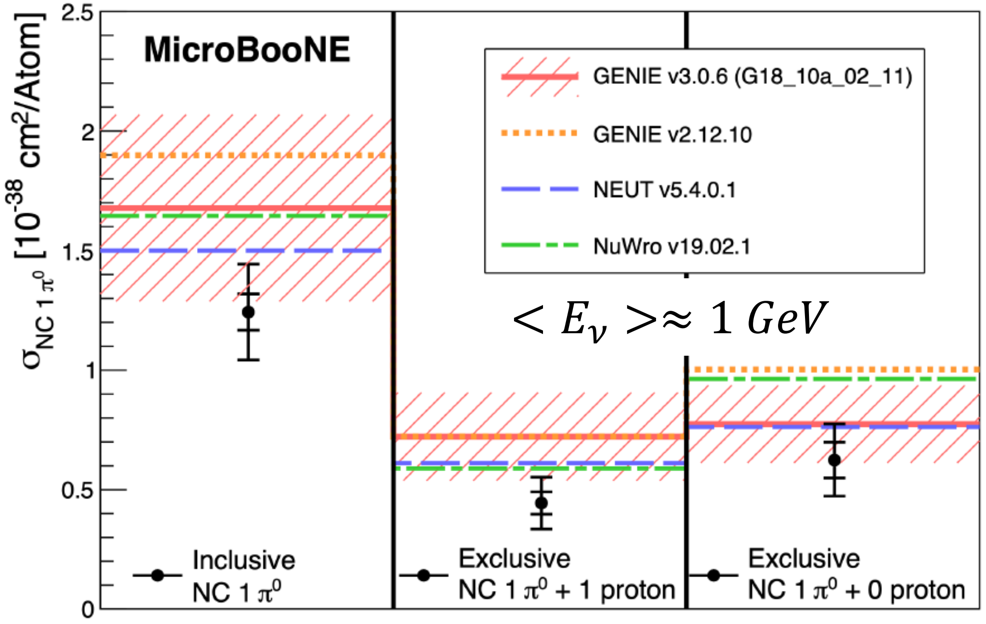


NC π^0 Cross Section

[MicroBooNE-NOTE-1111-PUB](#)



- Inclusive NC 1 π^0 measurement on argon
  - First exclusive measurements in the 0p and 1p channels
- Deficits seen compared to all model studied

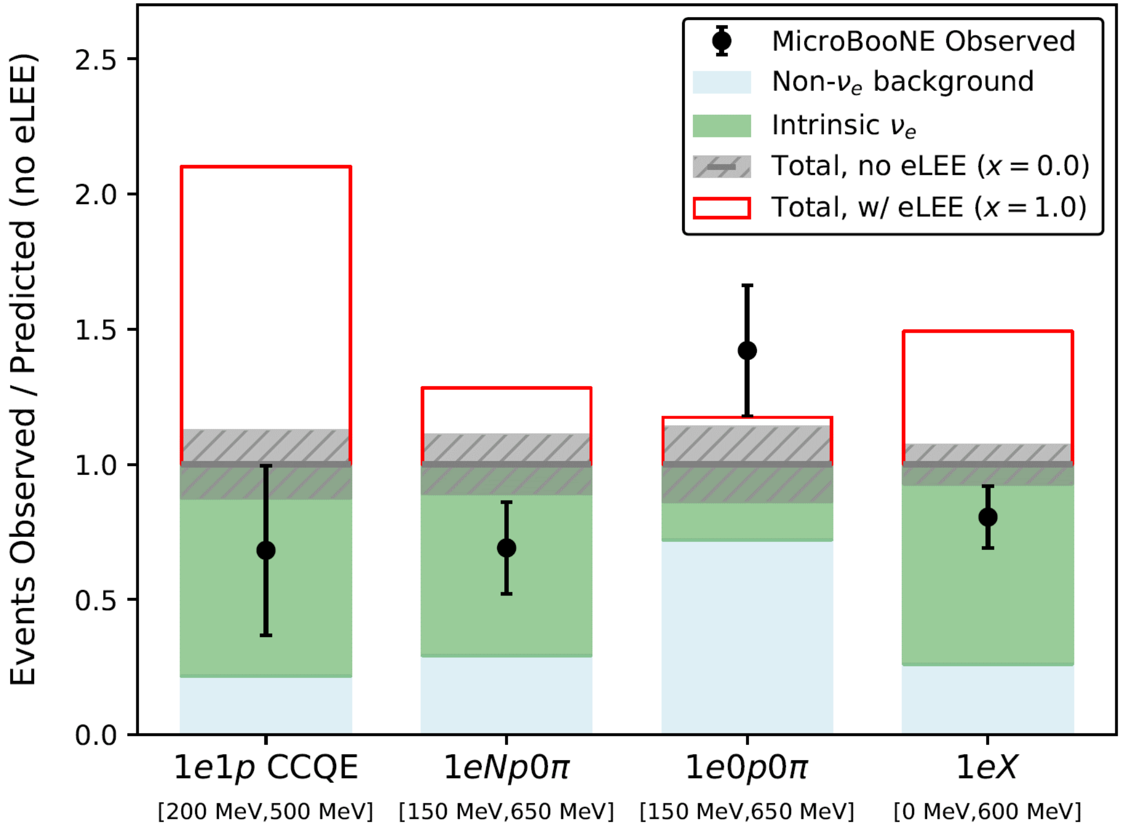


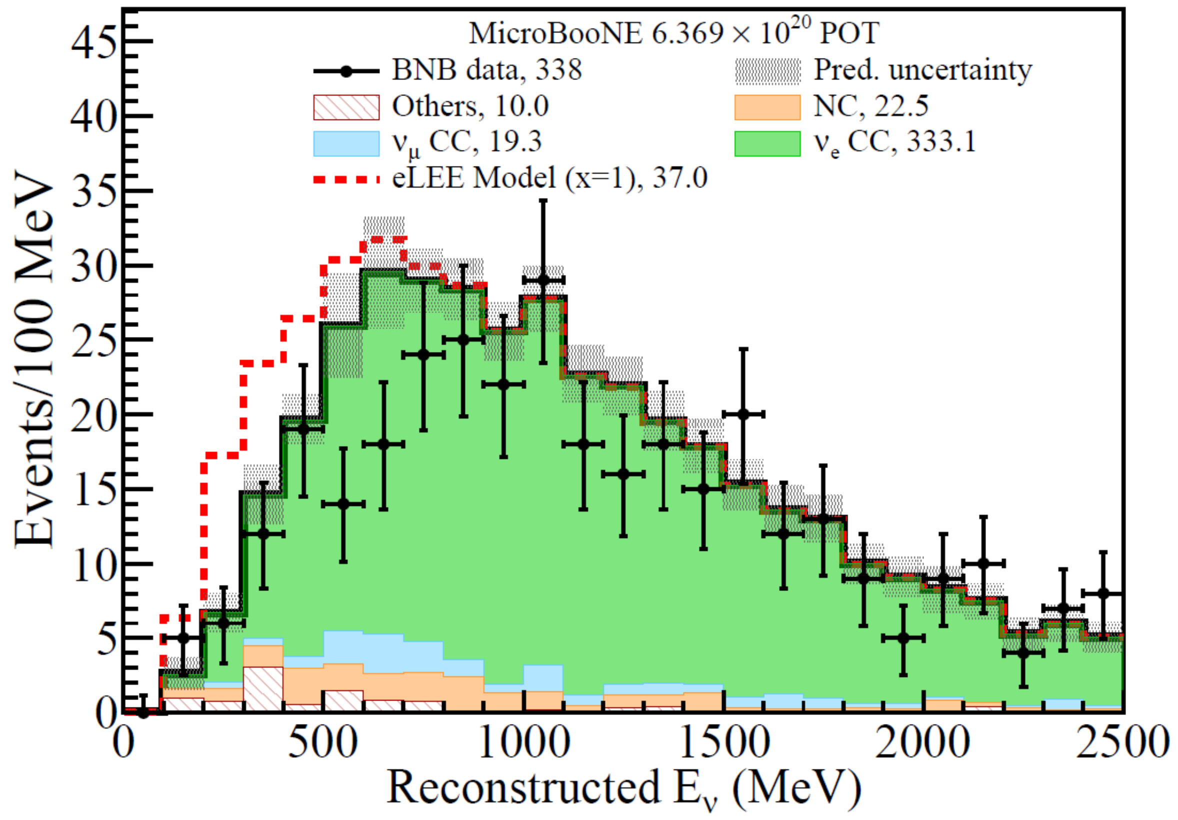
[arXiv:2205.07943](#), submitted to PRD

- Ongoing analysis to extract differential cross sections
- ~ 1σ deficit over much of the phase space in π^0 momentum with an interesting slope

See R. Fine's talk

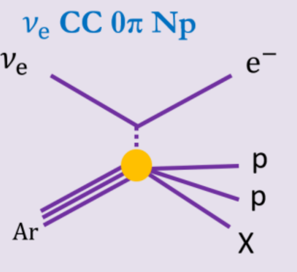
Search for Low-Energy Excess (LEE) in ν_eCC



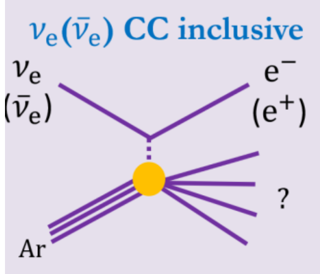


PRL 128, 241801 (2022)

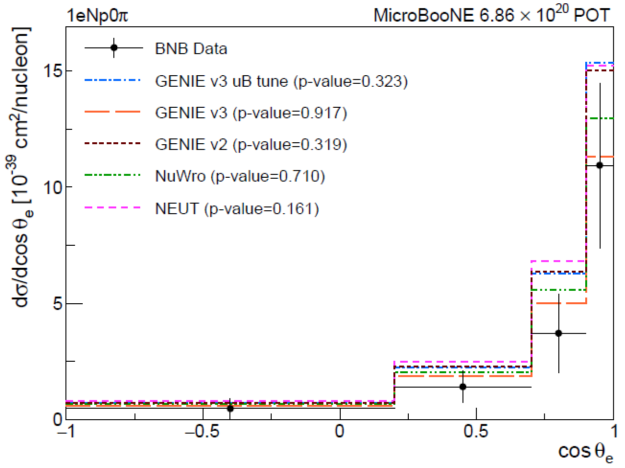
- Except for the background-limited 1e0p0π channel, all other channels do not observe low-energy excess. Slight deficits observed in the signal region
- **eLEEx=1 hypothesis excluded a high significance** (min. p-value 9×10^{-5})

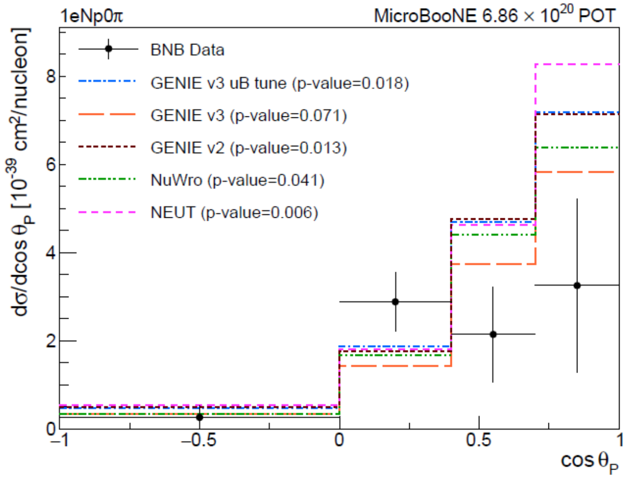


ν_eCC Cross Section (BNB vs. NuMI)



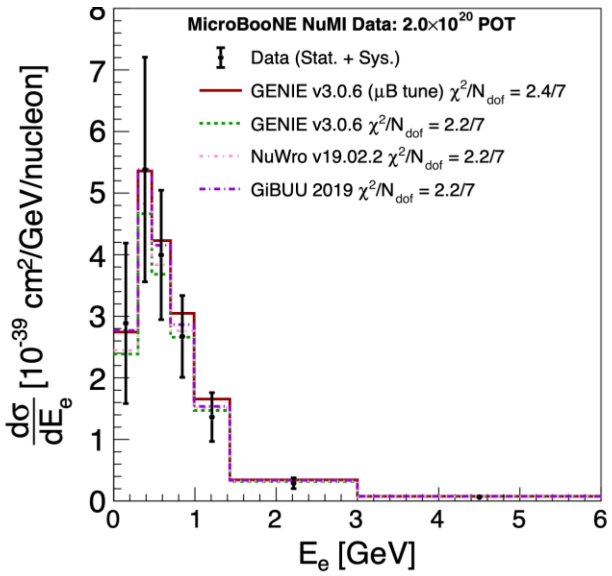
PRD 106, L051102

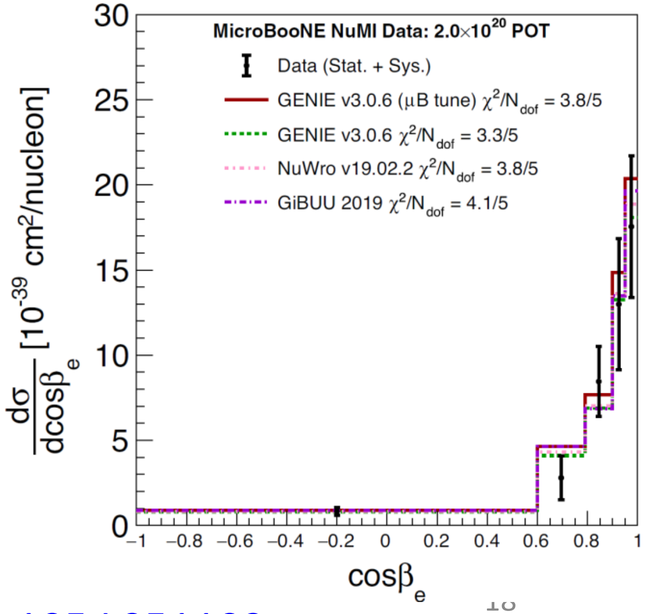




- Differential **inclusive** ν_e+$\bar{\nu}_e$ CC cross section
  - Enhanced event selection efficiency (9% → 21%) and purity (39% → 72%)
  - Consistent results with model predictions within uncertainties

- First differential **exclusive** ν_e CC cross section without pions
  - Categorize the proton final state with low energy threshold
  - Consistent results with model predictions within uncertainties, slightly favor predictions of a lower overall cross section



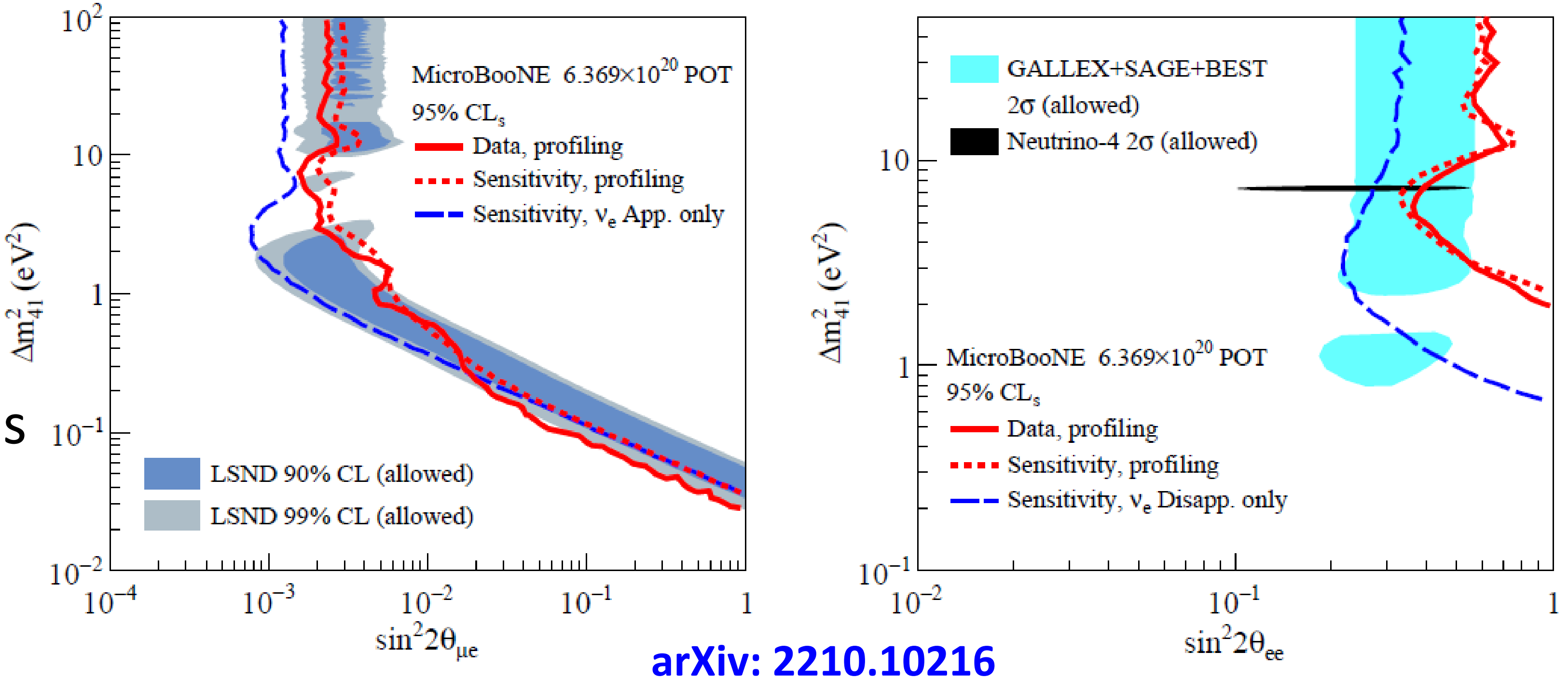


See A. Szelc's talk

PRD 105 L051102

Search for a Light Sterile Neutrino in 3+1 Model

- No evidence of light sterile neutrino oscillation
- Cancellation of ν_e appearance and ν_e disappearance with full 3+1 model leads to degeneracies in determining the oscillation parameters
- Neutrino oscillation analysis requires good understanding of the mapping between reconstructed and true neutrino energy



arXiv: 2210.10216

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

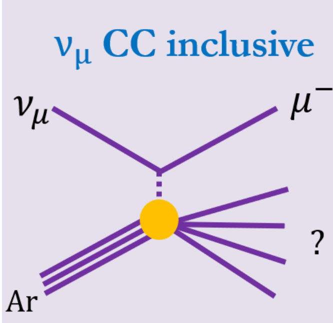
ν_e disappearance: $\sin^2 2\theta_{ee} = \sin^2 2\theta_{14}$

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

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

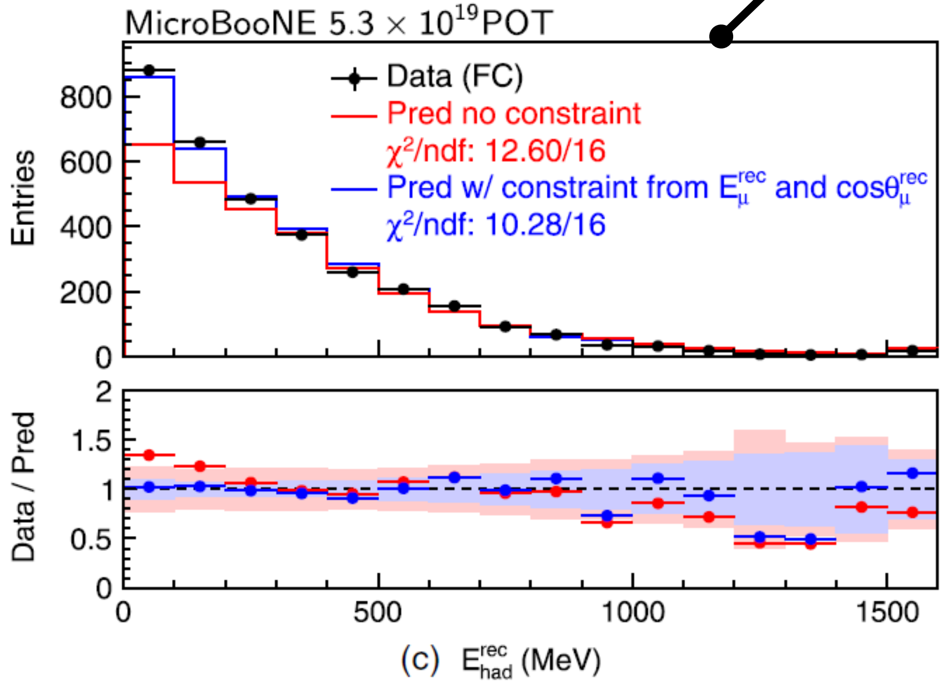
- non-zero ν_e appearance requires both ν_e and ν_μ disappearances

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

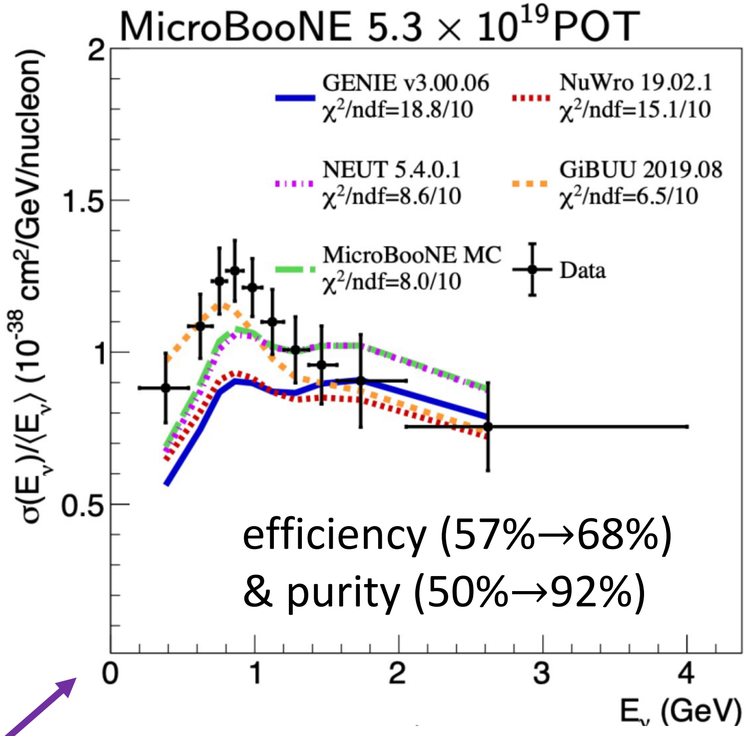


- Comparison $M(\mathbf{E}_{\mathbf{had}}^{\mathbf{rec}})$ vs. $\mu(\mathbf{E}_{\mathbf{had}}^{\mathbf{rec}} \mid \mathbf{E}_\nu, \mathbf{E}_{\mu}^{\mathbf{rec}})$ is sensitive to the modeling of missing energy given the overall energy conservation and separated lepton and hadronic energy measurements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

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



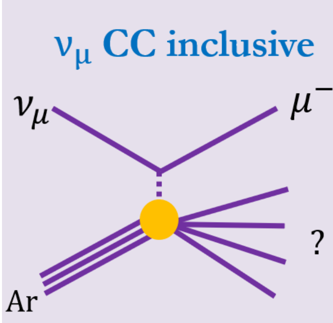
- No sign of mis-modeling of the **missing hadronic energy** → validating the model of E_ν reconstruction
- Enable energy-dependent cross sections & eLEE & ν oscillation measurements



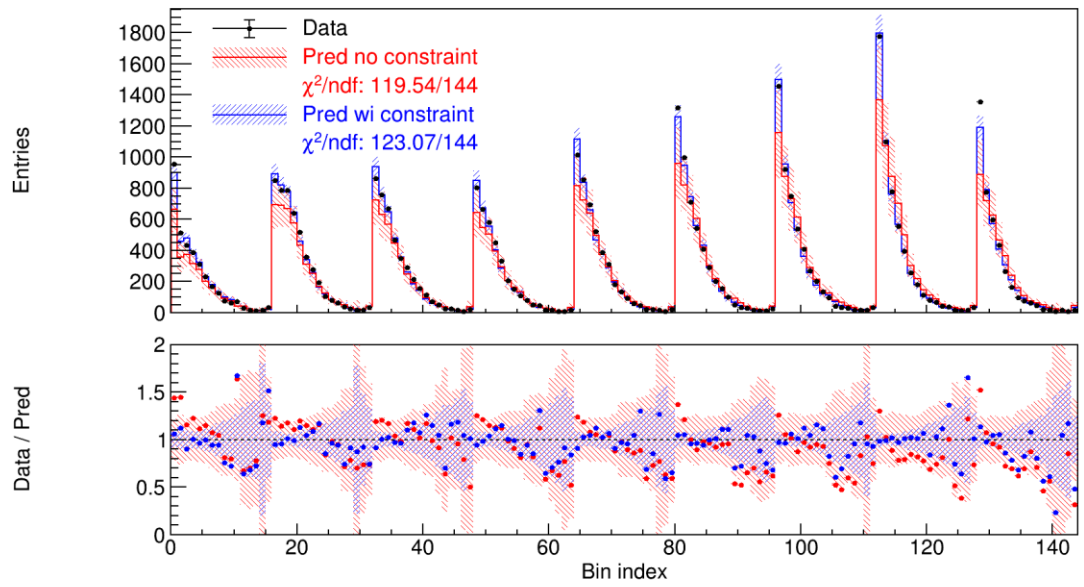
PRL 128, 151801

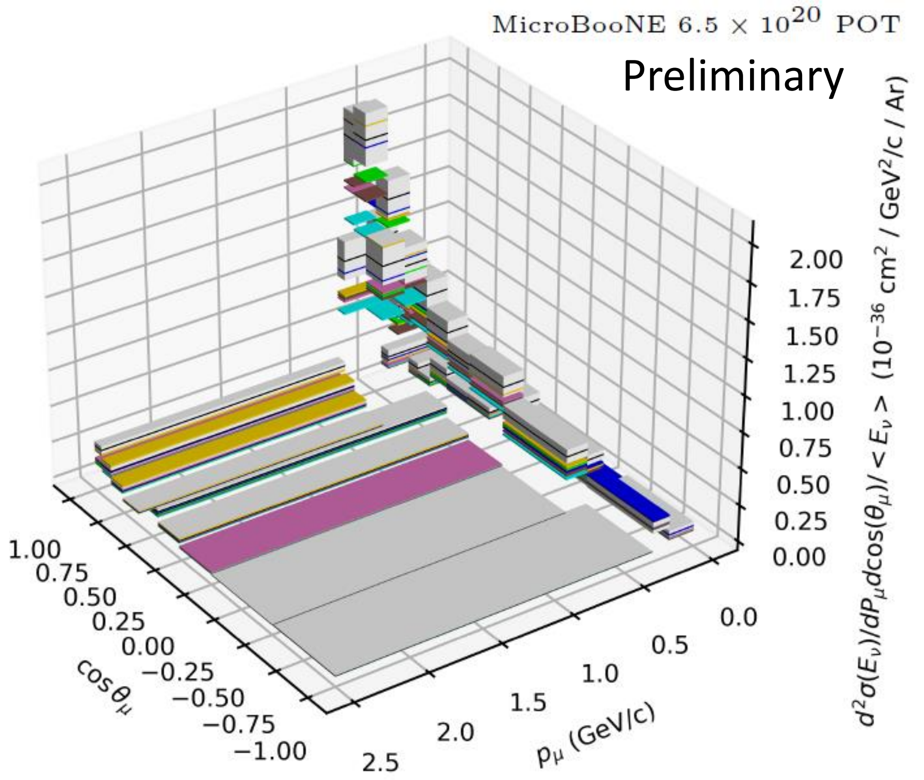
See L. Cooper-Troendle's talk

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



$\{E_{had}, \cos(\theta_\mu)\}$ Distribution





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 $\{E_{had}, \cos(\theta_\mu)\}$
- Enabled extraction of triple differential cross sections for inclusive ν_μCC in $\{E_\nu, P_\mu, \cos(\theta_\mu)\}$
  - *Large wealth of information*

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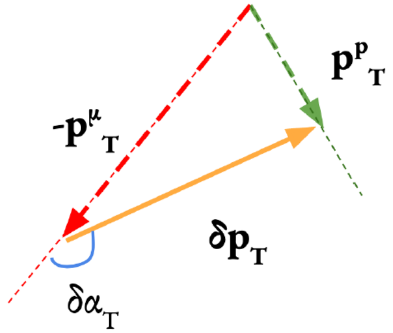
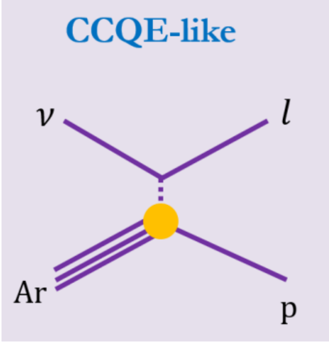
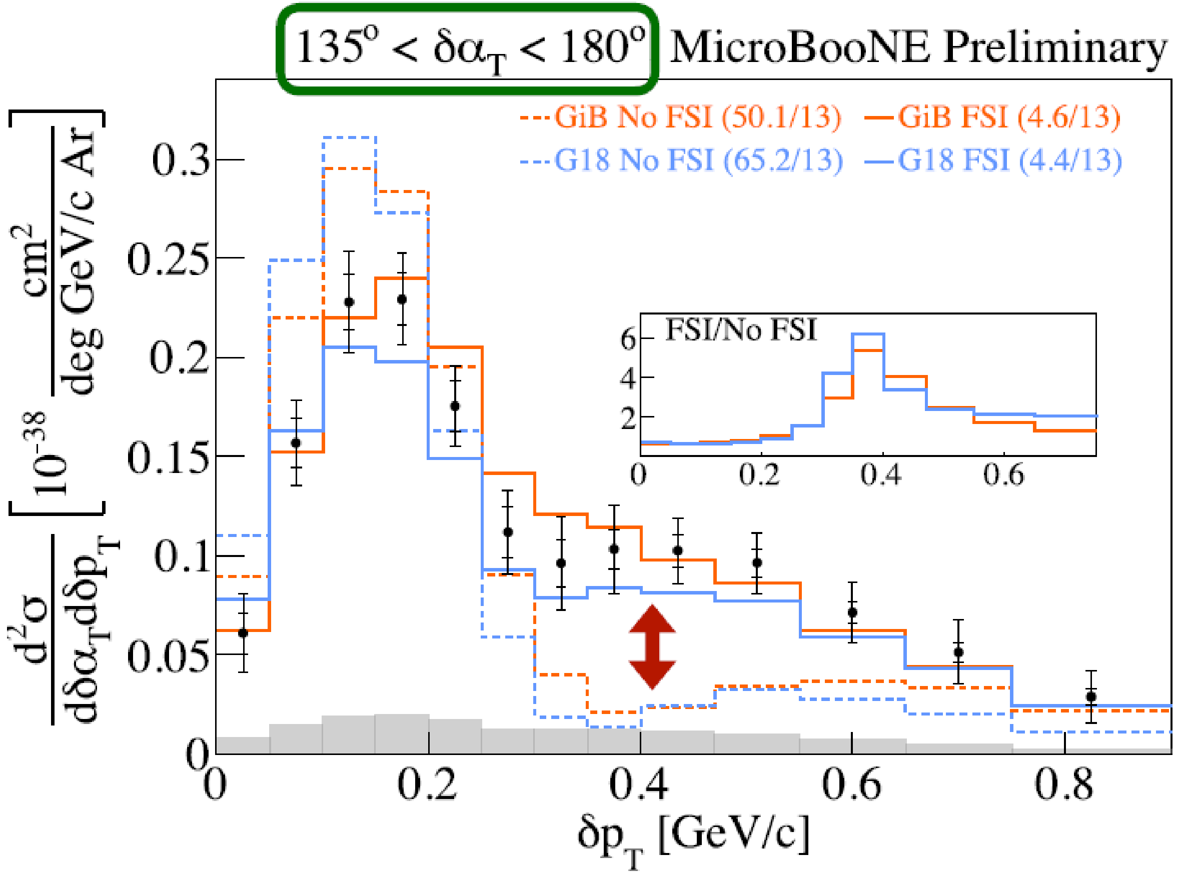
See L. Cooper-Troendle's talk



CCQE-like ν_μCC with Transverse Kinematic Imbalance (TKI)

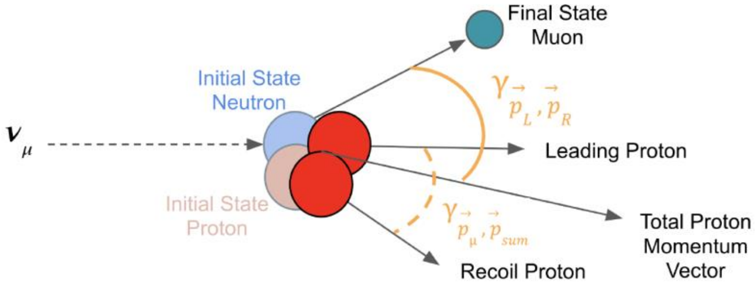


- First ν-Ar differential Xs on TKI variables
  - Sensitive to details of proton FSI modeling and the initial-state Fermi motion
- Extension to double differential Xs $\{\delta\alpha_T, \delta P_T\}$ for the first time (any neutrino target)
  - Probe regions with greatest model discrimination power

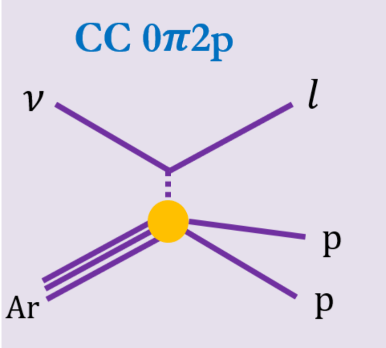


See A. Papadopoulou's talk

MICROBOONE-NOTE-1108-PUB

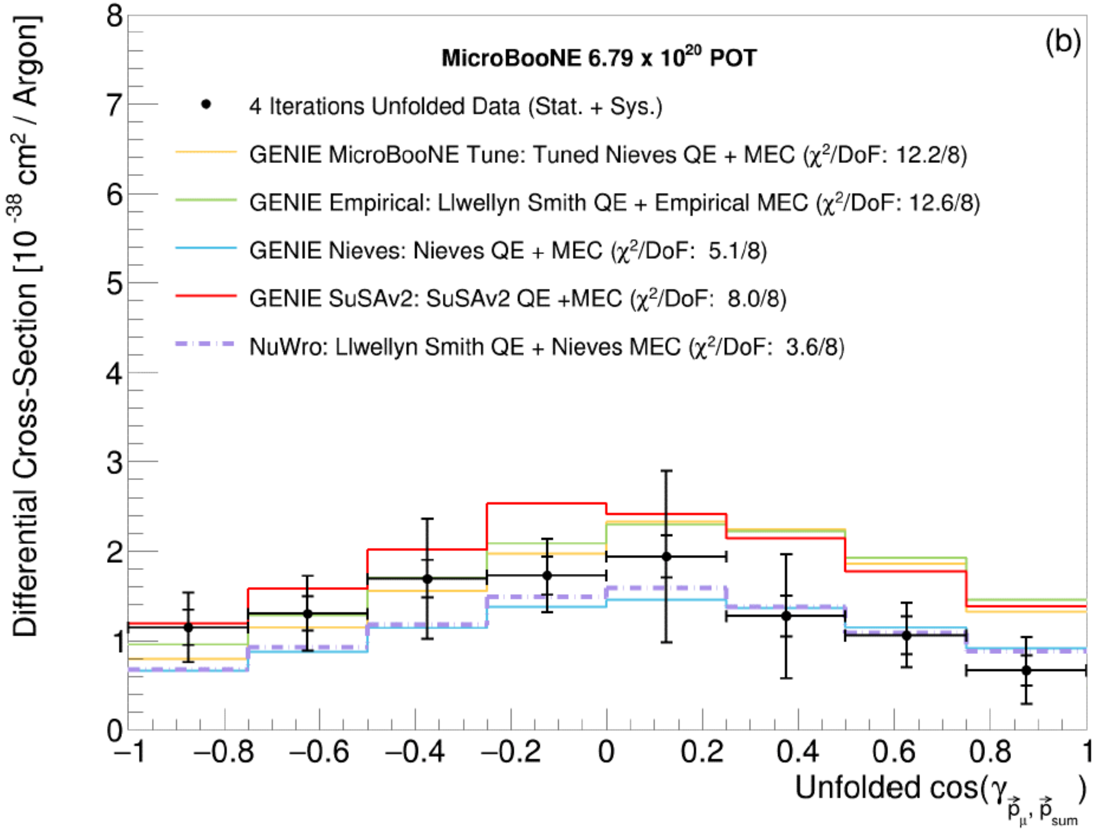


Differential Cross Sections for ν_μCC 2p Final State



- First-time cross section measurements on this topology
  - Sensitive to the Meson Exchange Current (MEC) interactions

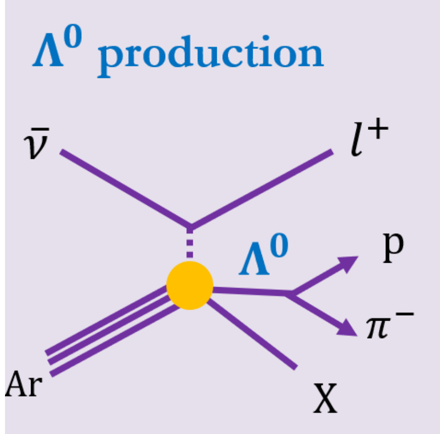
- Differential cross section w.r.t proton-proton kinematics are sensitive to treatment of correlated proton-neutron pair (e.g. back-to-back in the initial state in NuWro)



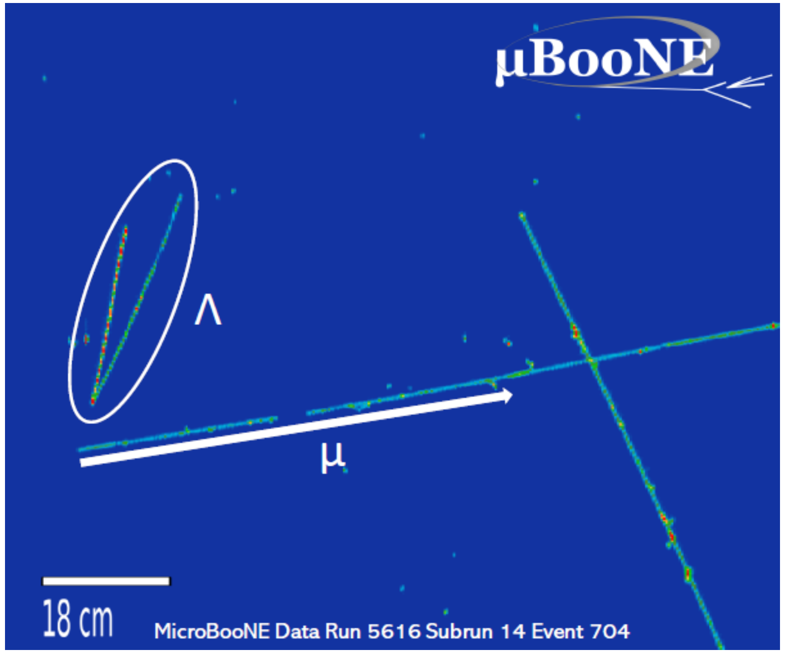
See M. Kirby's talk

Paper coming soon, [MICROBOONE-NOTE-1117]

Rare Process: Quasi-elastic Λ Baryon Production with NuMI

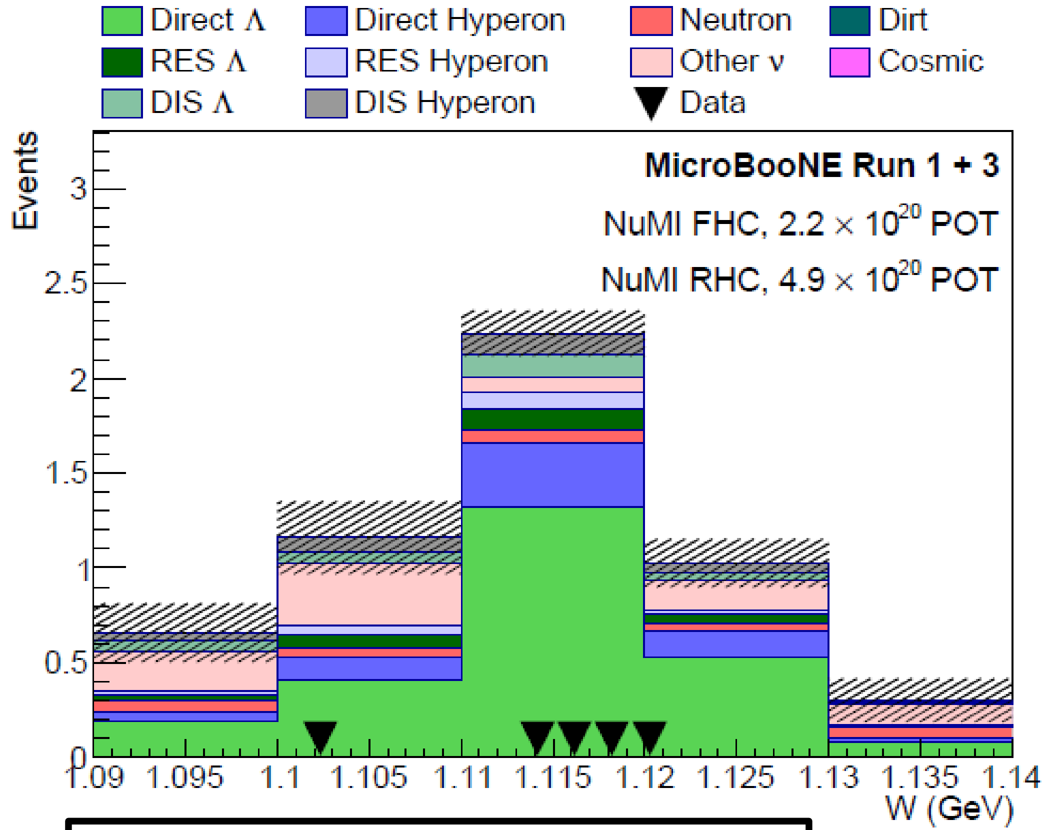


- First observation of Λ in LArTPC
  - Background for Proton Decay



- Additional results with other rare processes: kaons, eta …

Paper coming soon
MicroBooNE-NOTE-1112-PUB



See C. Thorpe's talk

Wealth Of Results → Better Understanding of ν-Ar Interactions

CC inclusive

- ν_e CC inclusive @ NuMI (Wed.)
- ν_μ CC inclusive @ NuMI
- ν_μ CC inclusive @ BNB (Wed.)
- ν_e / ν_μ ratios @ NuMI
- E_ν, E_μ, hadronic energy @ NuMI & BNB

Much more coming from 30+ active analyses

Pion production

- ν_μ CC1π^+ @ BNB
- ν_μ CC-Coherent @ BNB
- ν_μ CCπ^0 @ BNB
- ν_μ NCπ^0 @ BNB (Fri.)
- ν_μ CC/NC π^0 @ BNB

CC0π

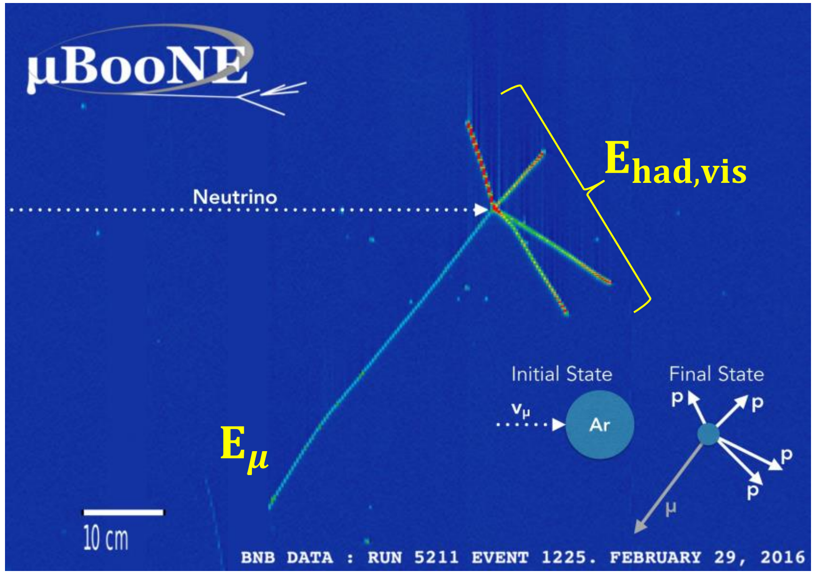
- ν_μ Single Transverse Variables @ BNB (Wed.)
- ν_μ CC2p topologies @ BNB (Wed.)
- ν_μ CC0π inclusive @ BNB
- ν_μ CC0π0p @ BNB
- ν_e CC0πNp @ NuMI

Rare channels

- ν_μ CC Kaon @ BNB
- ν_μ CC Kaon @ NuMI
- η production @ BNB
- Hyperon (Λ,Σ) production @ NuMI (Fri.)
- MeV-scale Physics in MicroBooNE

Challenge in validating energy model $\mathbf{D}(E_\nu \rightarrow E_{reco})$

- How to verify the modeling of the undetected **missing hadronic energy**?
  - ➥ Mapping of $E_\nu \rightarrow \mathrm{E}_\nu^{\mathrm{rec}}$



True energy components:

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

Calorimetric energy reconstruction:

$$\mathrm{E}_\nu^{\mathrm{rec}} = \mathrm{E}_\mu^{\mathrm{rec}} + \mathrm{E}_{\mathrm{had,vis}}^{\mathrm{rec}}$$

Conditional constraining procedure

- Overcome the challenge by leveraging LArTPC's simultaneous measurements of **lepton energy** and **visible hadronic energy**

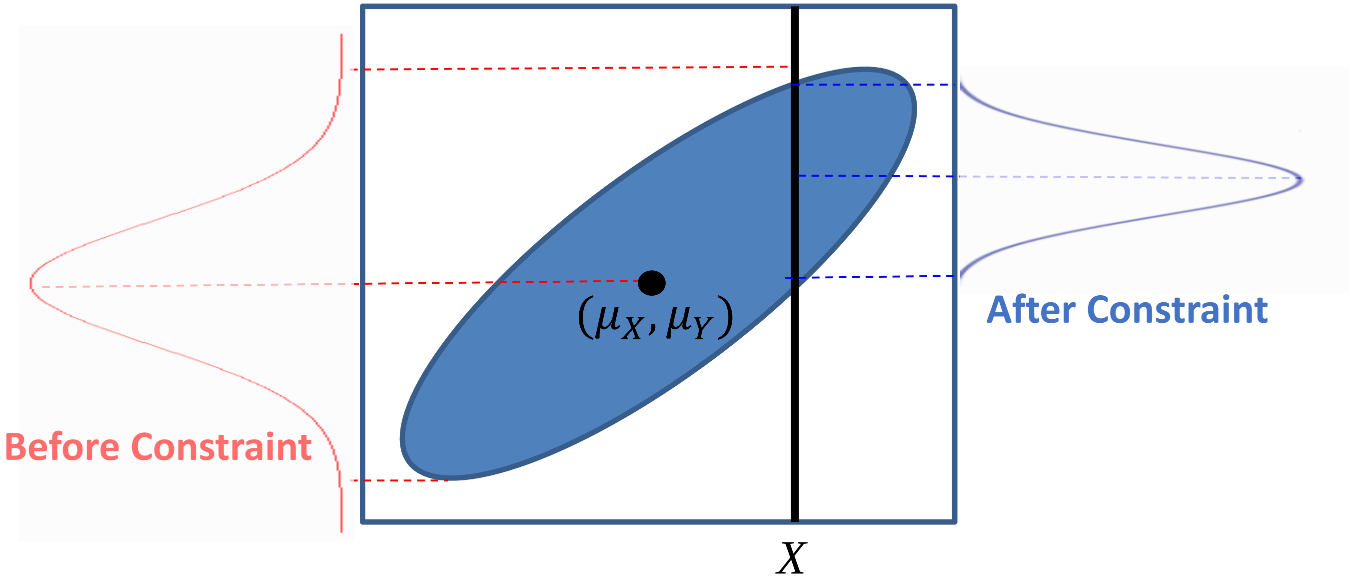
Conditional expectation & covariance

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

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

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

* A variant of Gaussian Process regression



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

$$\begin{matrix} \mu(E_{had}^{rec}) \\ \Sigma(E_{had}^{rec}) \end{matrix} + M(E_{\mu}^{rec}) = \begin{matrix} \mu(E_{had}^{rec} \mid E_{\mu}^{rec}, E_\nu) \\ \Sigma(E_{had}^{rec} \mid E_{\mu}^{rec}, E_\nu) \end{matrix}$$

Prior model | Sideband | Posterior model

$$E_\nu = E_\mu + E_{had,vis} + E_{had,missing}$$

Model Validation: $M(\mathbf{E}_{\mathrm{had}}^{\mathbf{rec}})$ vs. $\mu(\mathbf{E}_{\mathrm{had}}^{\mathbf{rec}} \mid \mathbf{E}_{\nu}, \mathbf{E}_{\mu}^{\mathbf{rec}})$

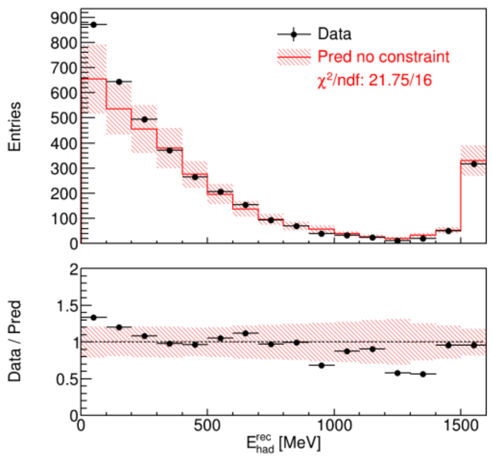
$\mathbf{E}_{\nu}$ → Neutrino flux modeling

$\mathbf{E}_{\mu}^{\mathbf{rec}}$ → Measurement of muon kinematics

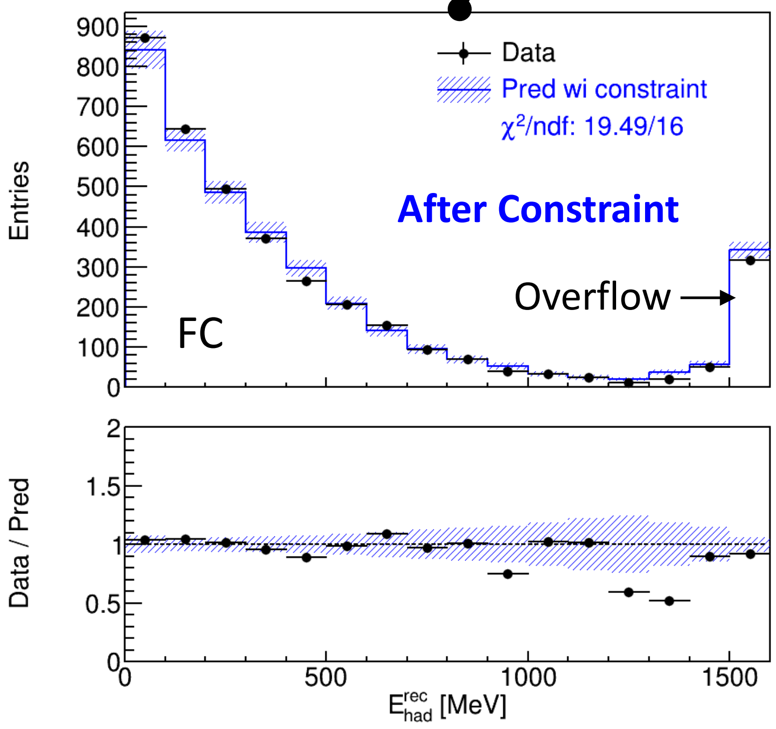
- New method to <u>validate modeling of neutrino energy</u> reconstruction given separated lepton and hadronic energy measurements in LArTPC

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

Before Constraint



Excess at low hadronic energy indicates mis-modeling of missing energy?

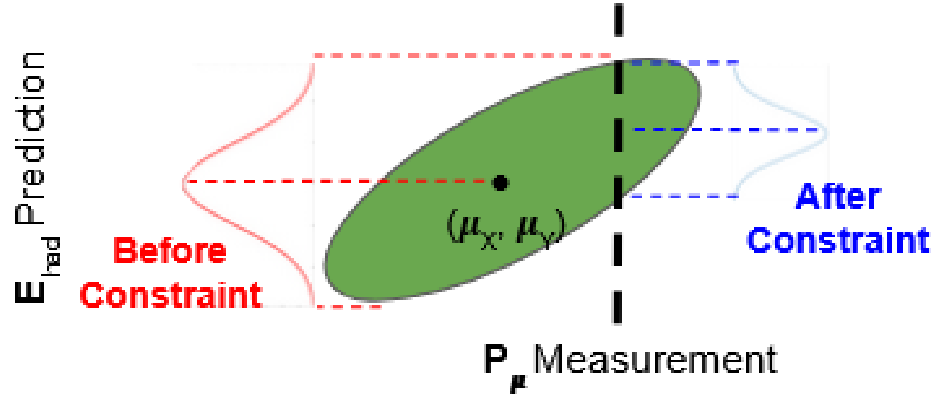


Measured muon kinematics are used to constrain the overall model (flux, cross section, etc.) for hadronic energy

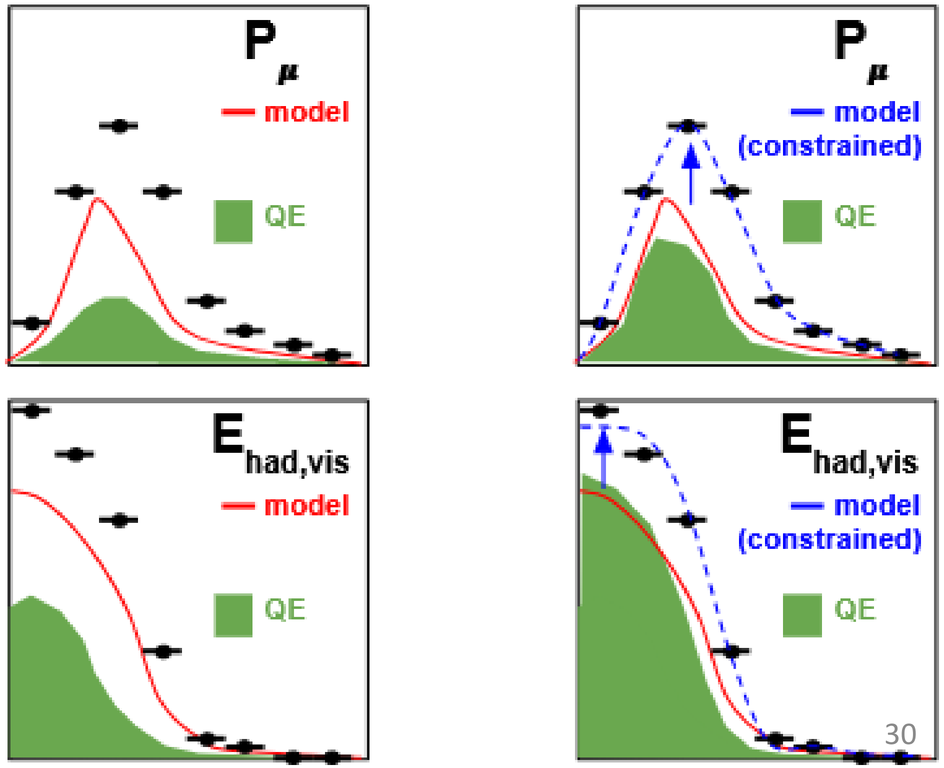
- Systematic uncertainties 20% → 5% in performing model validation
- No sign of mis-modeling of the **missing hadronic energy**
  - $\mathbf{D}(E_{\nu} \rightarrow E_{reco})$ is good!

Model Validation of Missing Hadronic Energy

- Conditional constraint procedure akin to reweighting based on P_μ measurement
- QE, RES, DIS predict different P_μ, $E_{had}^{missing}$, and E_{had}^{vis} distributions
  - The constrained prediction of E_{had}^{vis} is sensitive to the modeling of $E_{had}^{missing}$ in each process
- Measurement of constrained E_{had}^{vis} is thus sensitive to the model processes used in $E_{had}^{missing} \rightarrow$ validation of **the mapping between true and reconstructed E_ν**

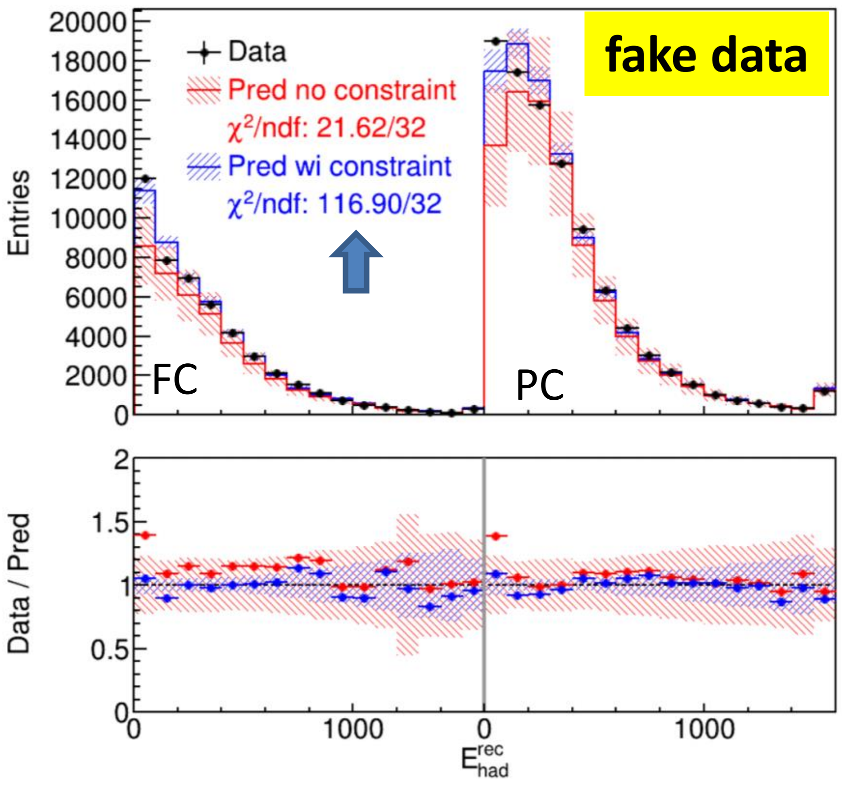


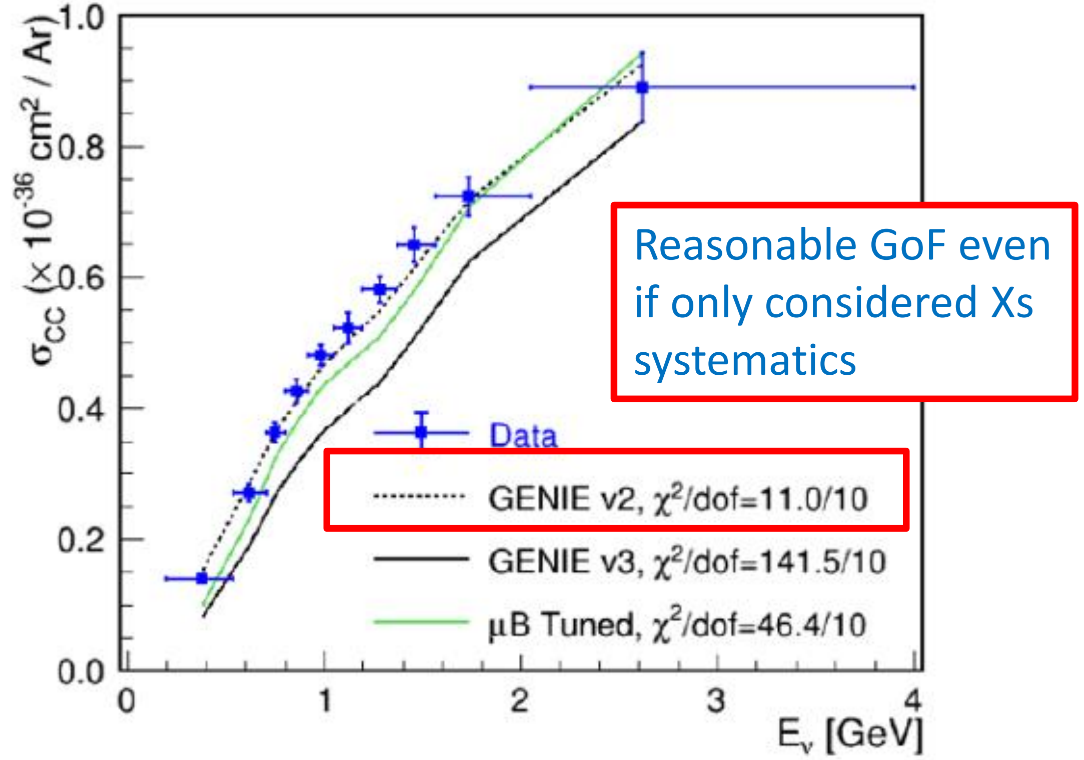
For Illustrative Purposes Only:



Constraint only used for validation, not unfolding

Fake Data: GENIE v2





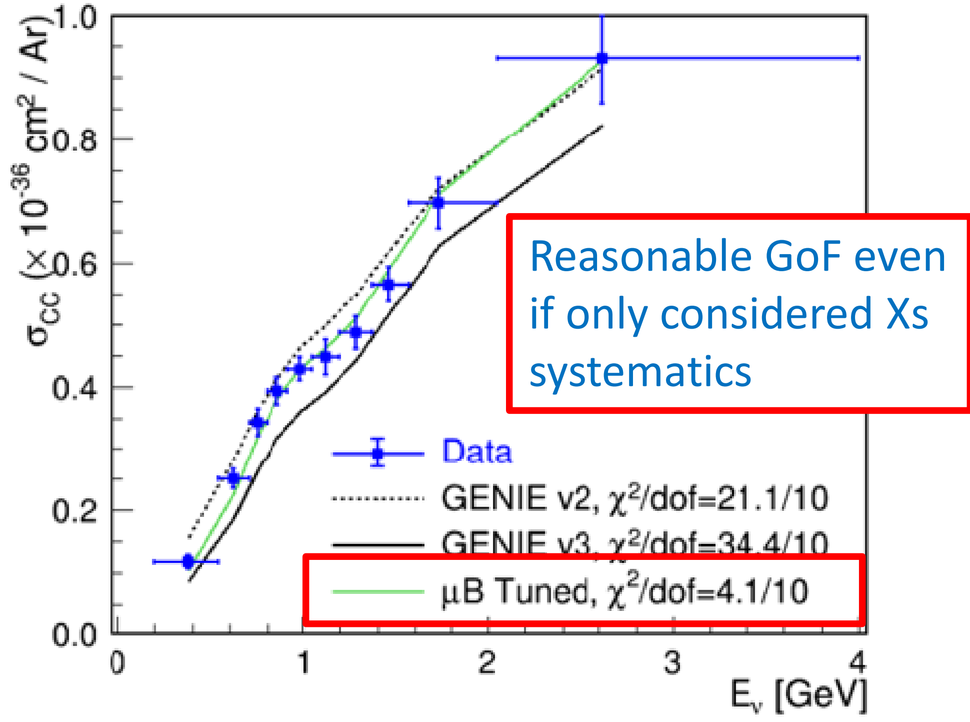
- Fake data (GENIE v2) shows a very poor χ^2/ndf for $E_{\text{had}}^{\text{rec}}$ after constraint to muon kinematics

- Model validation procedure is much more sensitive (stringent) to the model defects than the extraction of energy-dependent Xs

Fake Data: Enhance Missing Hadronic Energy

E_p^{rec} scaling factor	FC events (ndf=16)	PC events (ndf=16)	FC+PC (ndf=32)
0.95	2.55 (1.00)	4.08 (1.00)	5.34 (1.00)
0.90	8.90 (0.92)	17.13 (0.38)	21.05 (0.93)
0.85	18.66 (0.29)	39.45 (0.00)	47.01 (0.04)
0.80	32.95 (0.01)	67.88 (0.00)	80.60 (0.00)

χ^2 P-value



- χ^2/ndf has a significant increase with a shift of ~15% in the hadronic energy fraction allocated to protons (mimicking a variation of the proton-inelastic cross section)

- Model validation procedure is much more sensitive (stringent) to the model defects than the extraction of energy-dependent Xs