Recent neutrino cross-section results from MicroBooNE

Wenqiang Gu

On behalf of MicroBooNE collaboration

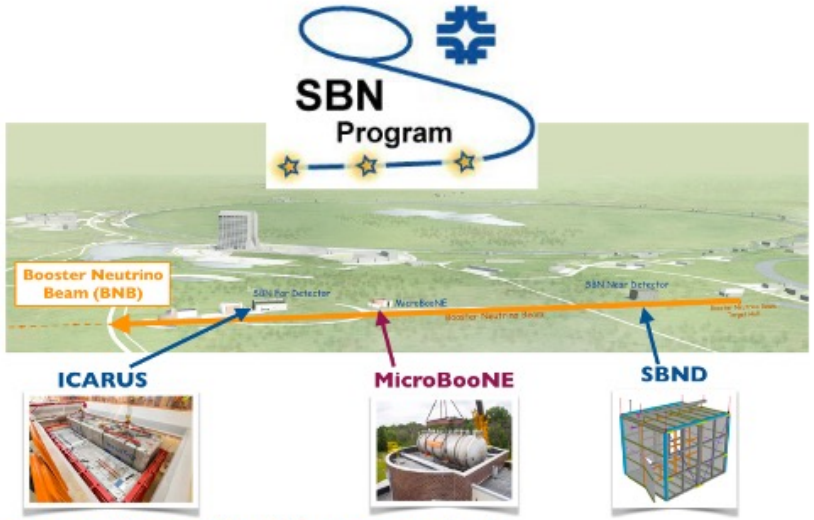
Interested in more about MicroBooNE?

Investigation on LEE by Nicholas Kamp (Tue 11/1)

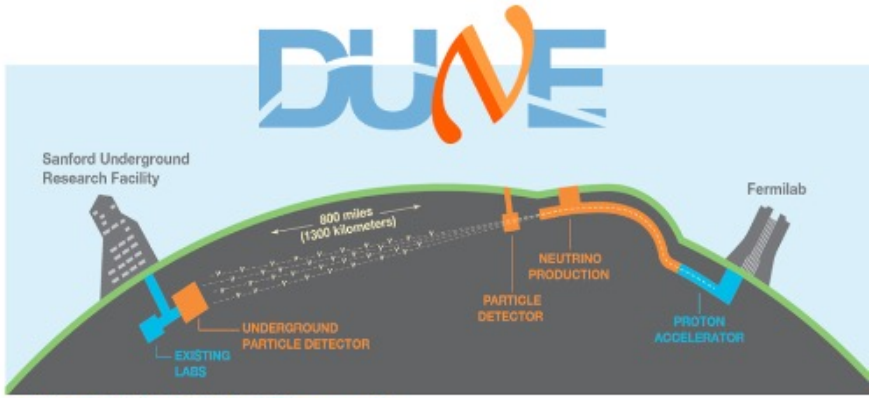
Astroparticle and BSM by Anyssa Navrer-Agasson (Wed 12/1)

Neutrino-nucleus interactions in LArTPC

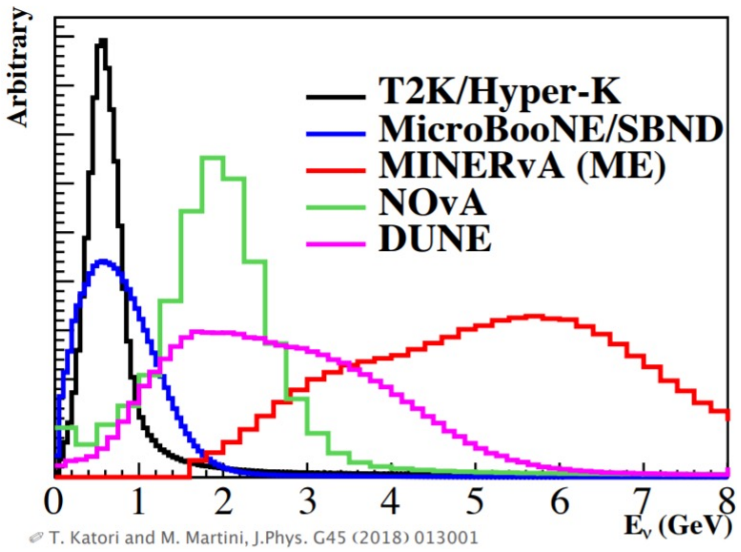
- Liquid Argon Time Projection Chamber (LArTPC) is one key technology in the current and future neutrino oscillation experiments
- Understanding ν-Ar cross sections is critical in reducing systematic uncertainties to reach desired precision of these experiments



arXiv:1503.01520 [physics.ins-det]

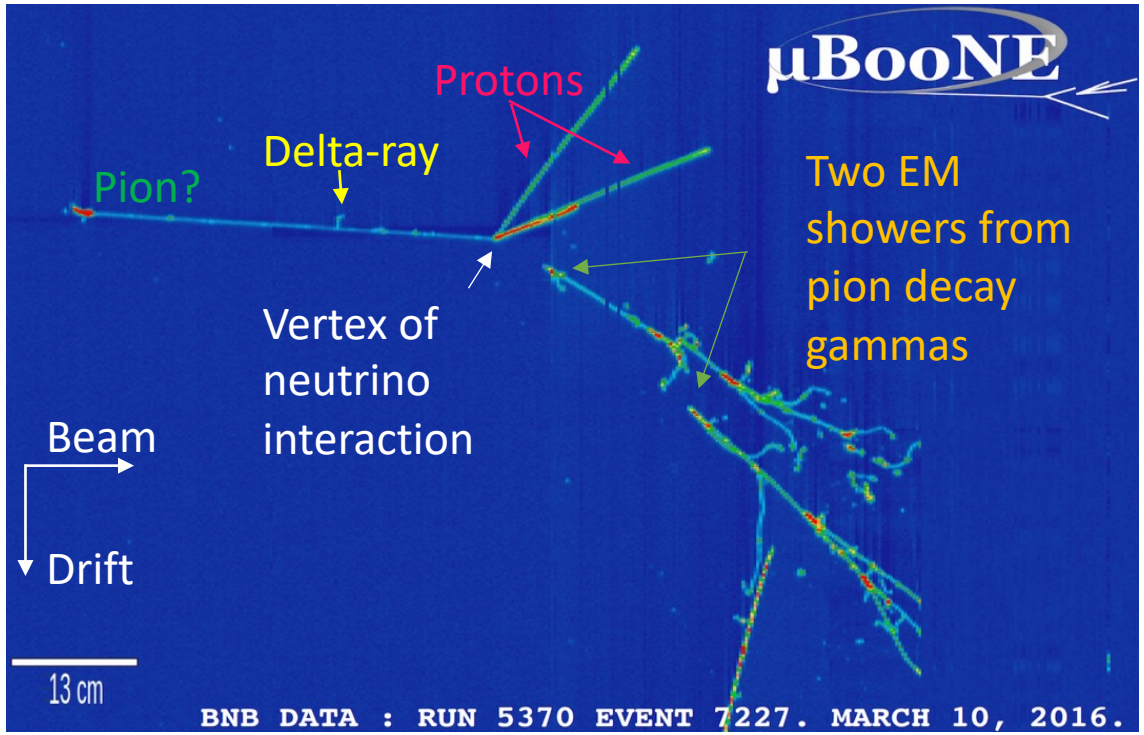


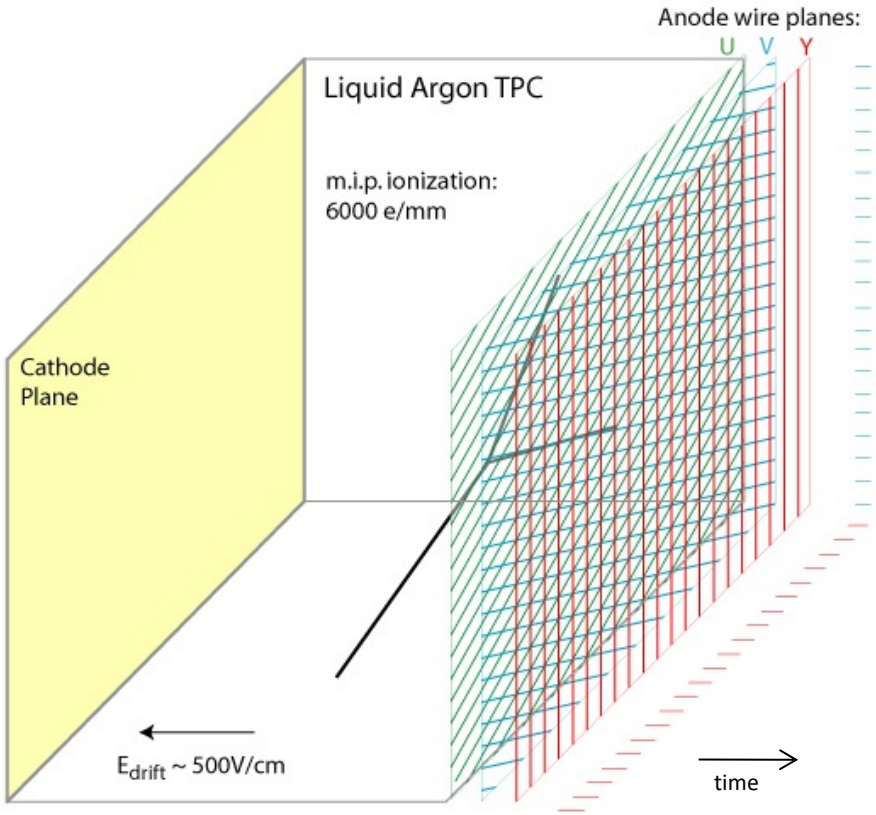
arXiv:2002.03005 [hep-ex]



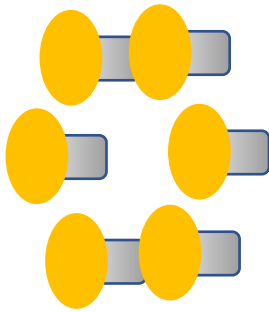
LArTPC: fully active tracking calorimeter

Made by Bo Yu (BNL)





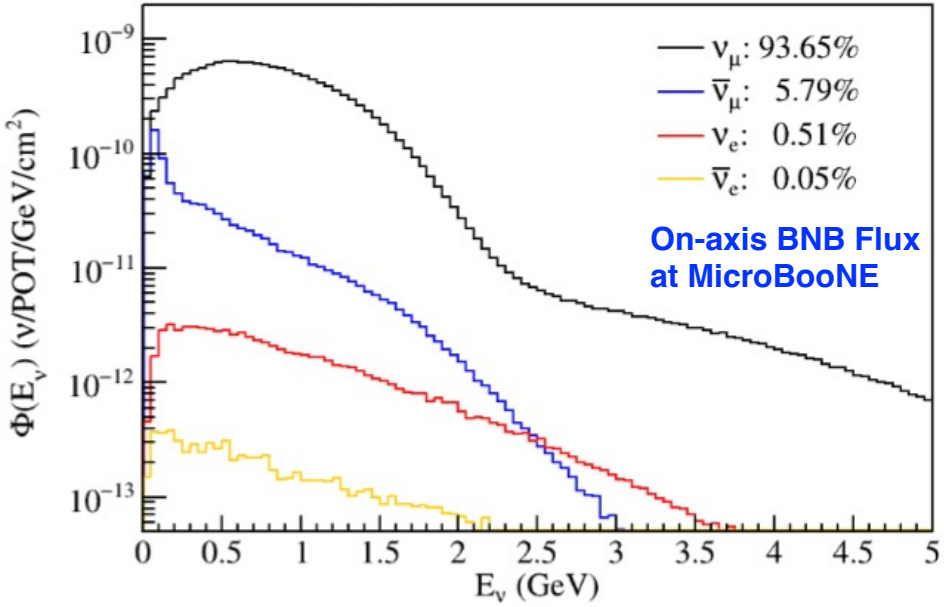
PMTs

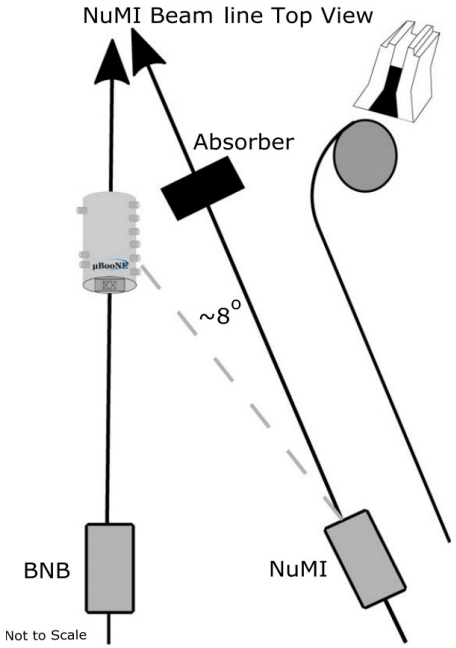


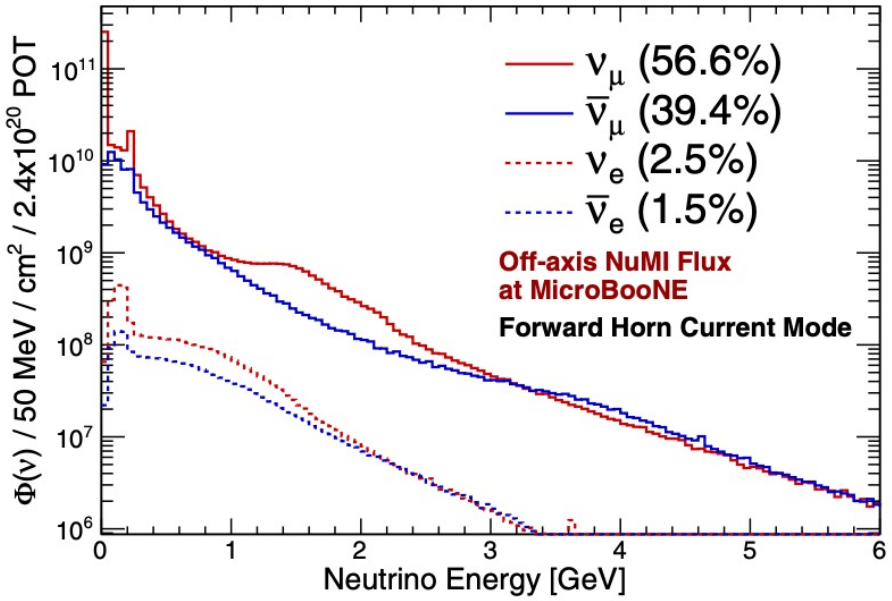
A candidate of neutral-current interaction

Drift velocity 1.1 mm/μs → several ms drift time

MicroBooNE experiment



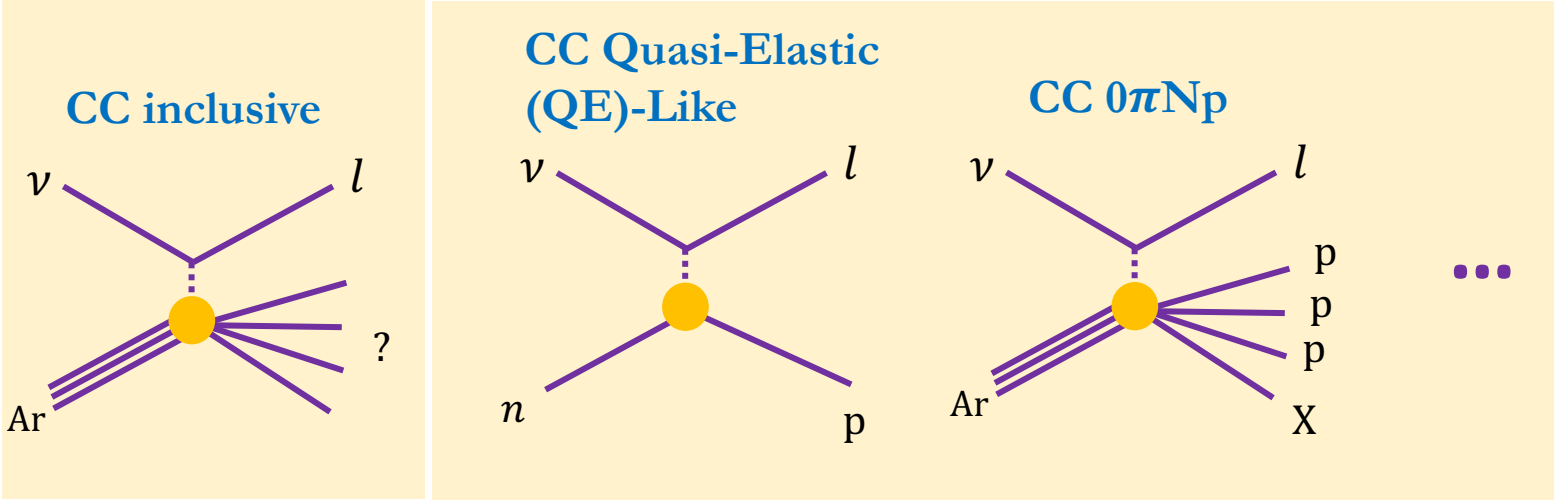




- Both ν_μ and ν_e cross sections are important for oscillation measurements
- At MicroBooNE, two beamlines are available:
  - Booster Neutrino Beamline (BNB): **on-axis**, >99% $\nu_\mu + \bar{\nu}_\mu$
  - Main injector neutrino beam (NuMI): **off-axis**, 4% $\nu_e + \bar{\nu}_e$

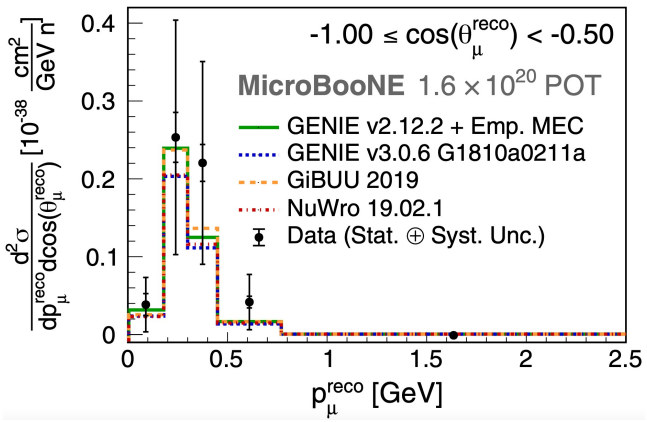
Studying ν-Ar cross sections at MicroBooNE

- Understanding of charged-current (CC) **inclusive** cross section on argon is desired for oscillation measurements
- **Exclusive** cross sections could further guide event generators to pin down underlying reaction mechanisms
- Leveraging LArTPC's excellent capability of tracking calorimetry

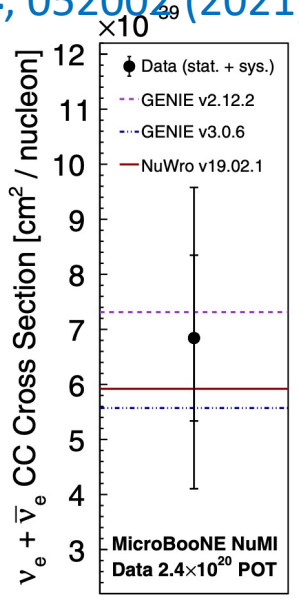


Previous results from MicroBooNE

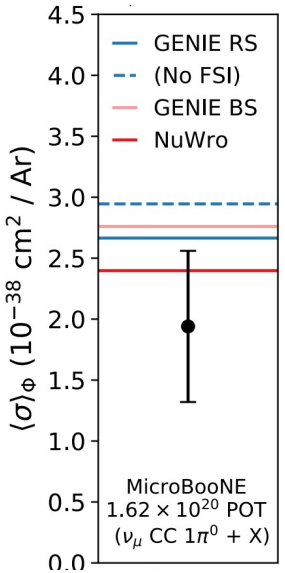
PRL **123**, 131801 (2019)



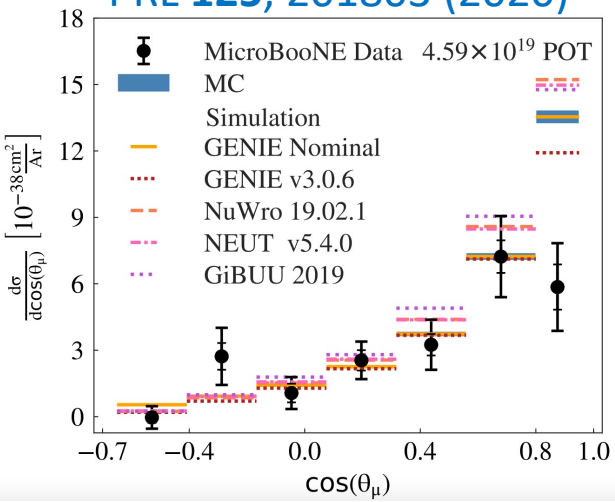
PRD **104**, 052002 (2021)



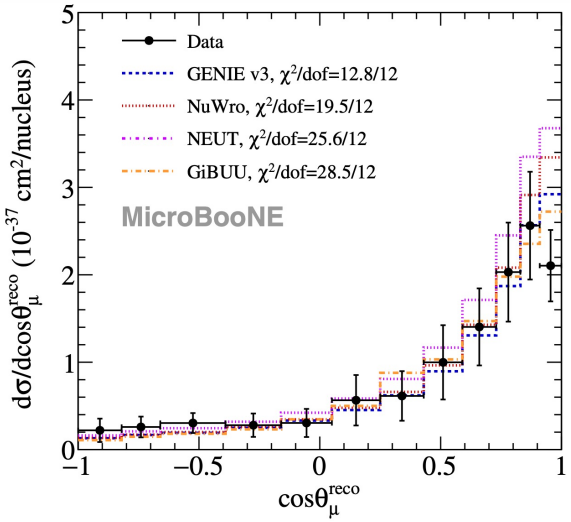
PRD **99**, 091102 (2019)



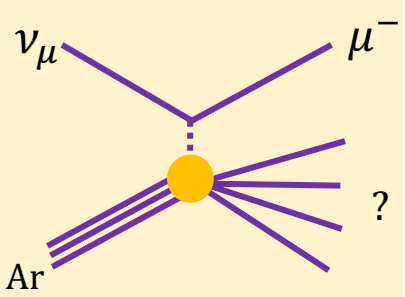
PRL **125**, 201803 (2020)



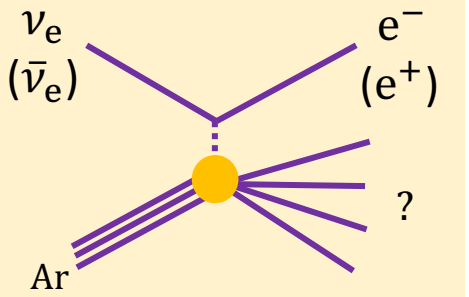
PRD **102**, 112013 (2020)



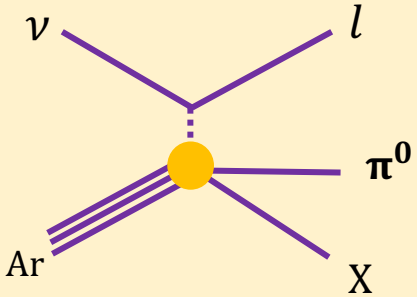
ν_μ CC inclusive



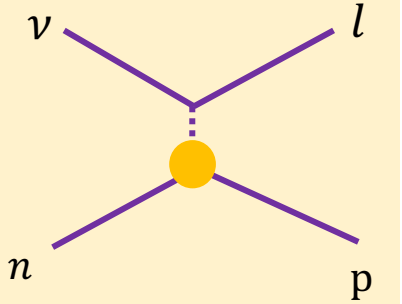
$\nu_e(\bar{\nu}_e)$ CC inclusive



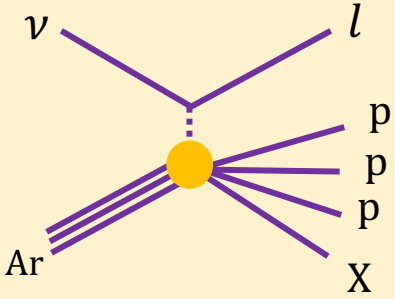
CC $1\pi^0$X



CC Quasi-Elastic (QE)-Like

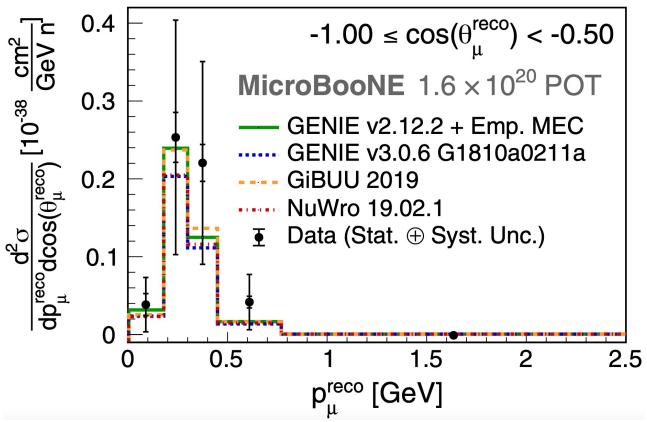


CC 0πNp

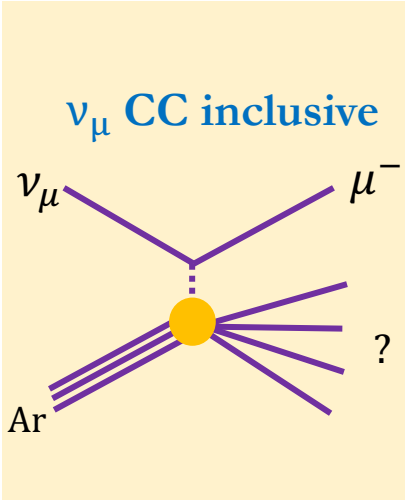


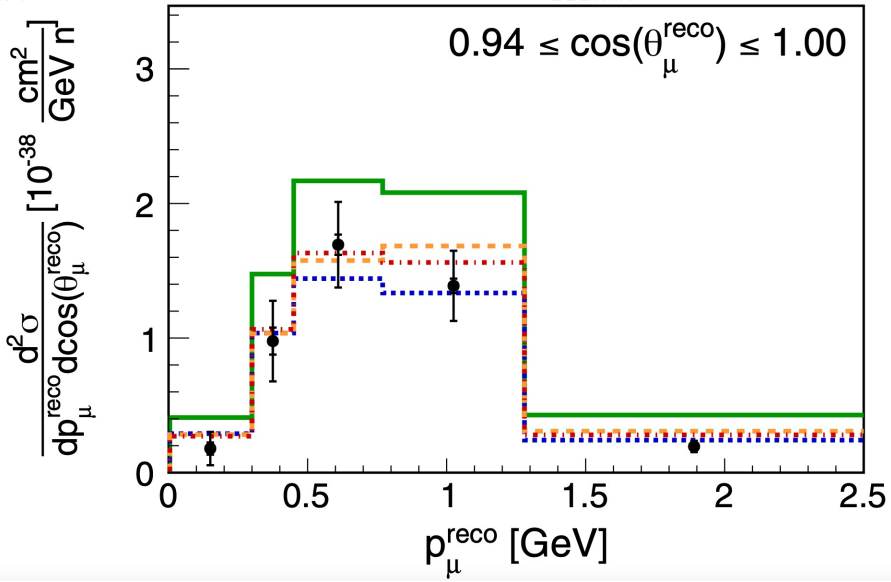
Previous results from MicroBooNE

PRL **123**, 131801 (2019)



- 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





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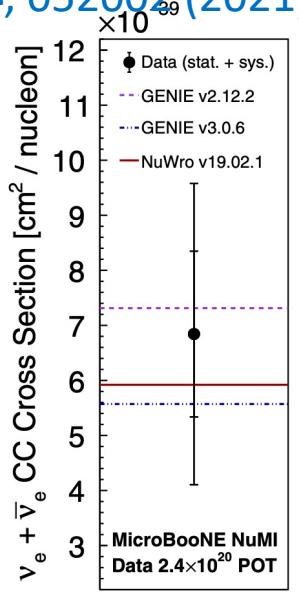
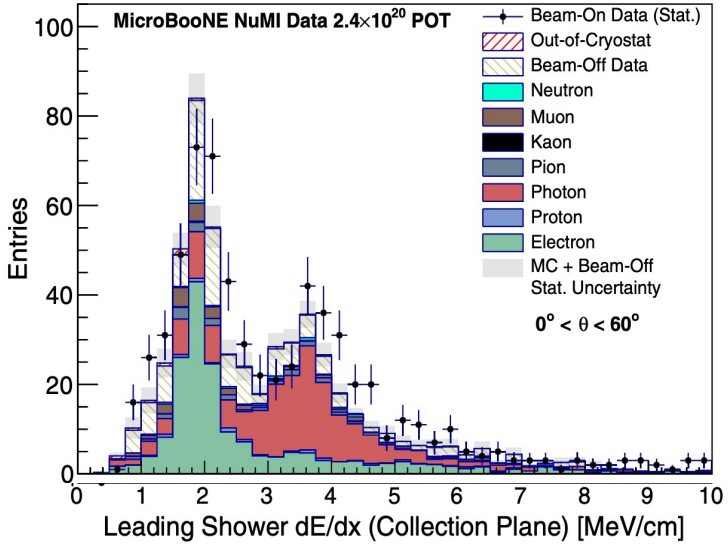
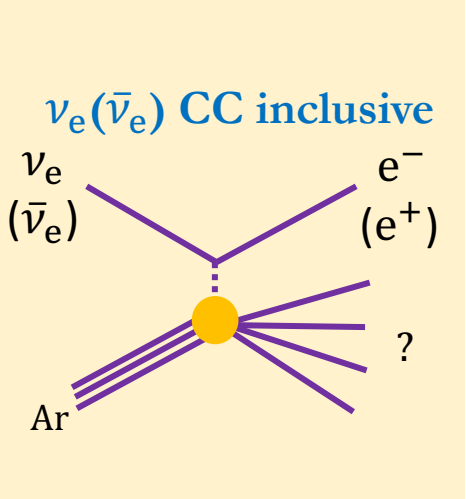


- First $\nu_e + \bar{\nu}_e$ measurement using the NuMI off-axis beam at MicroBooNE
  - ➡ Successful demonstration of e/γ separation and electron-neutrino reconstruction

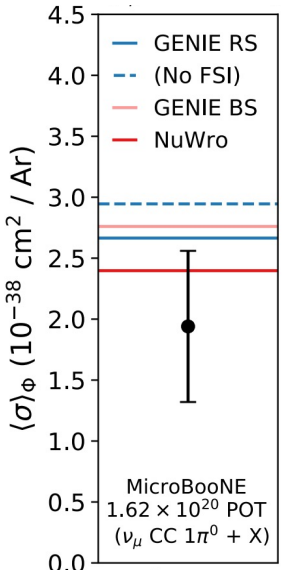




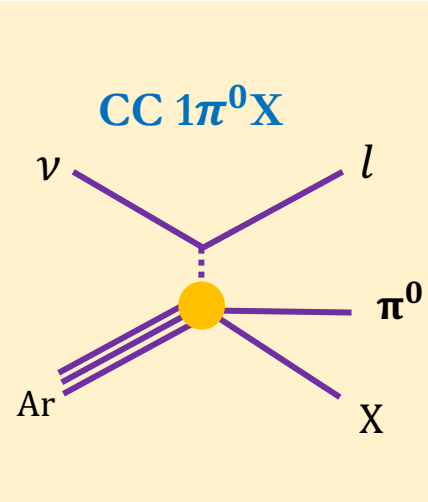
- ➡Consistent with model predictions within uncertainties

Previous results from MicroBooNE

PRD **99**, 091102 (2019)



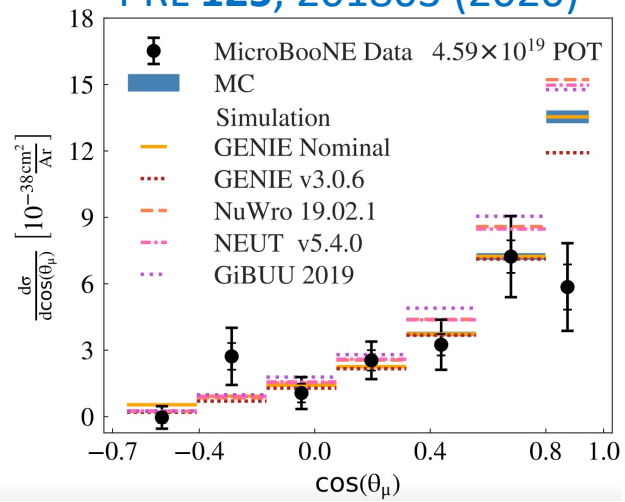
- First measurement of the flux-integrated cross section of ν_μ CC single π^0 production on argon



Previous results from MicroBooNE

- 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

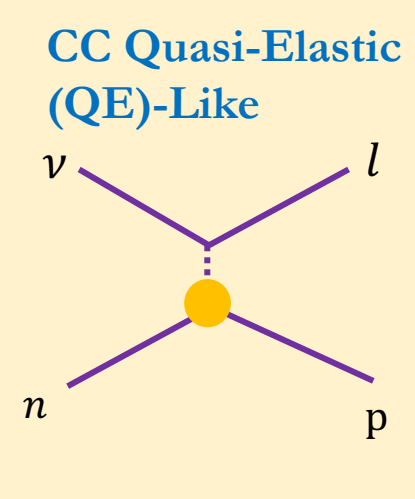
PRL **125**, 201803 (2020)



GENIE Nominal's goodness-of-fit

χ^2/dof = 33.8/7

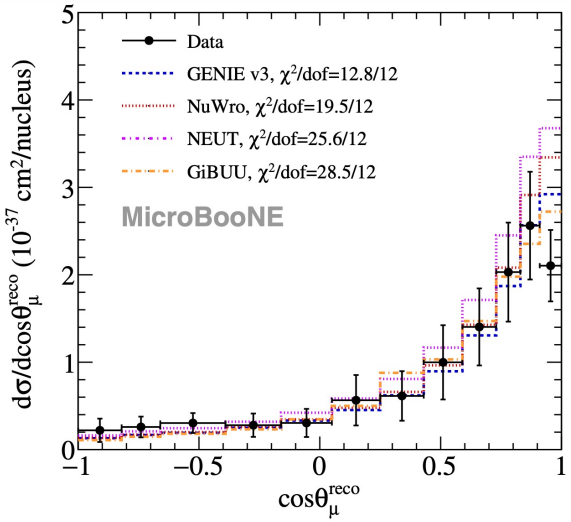
χ^2/dof = 7.3/6 (cosθ<0.8)

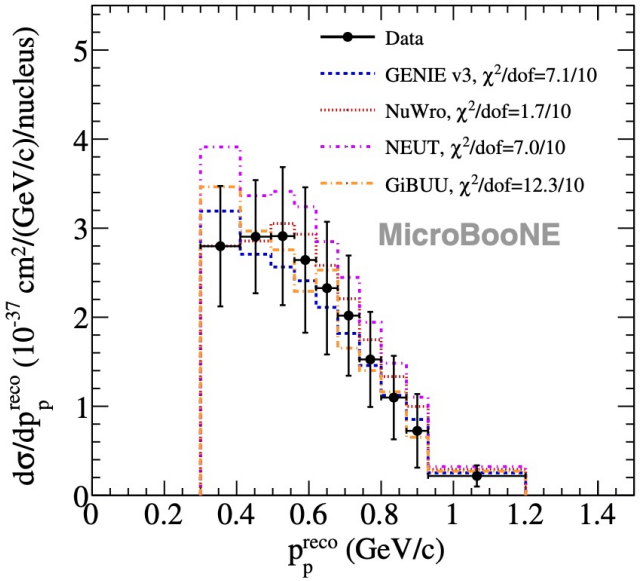


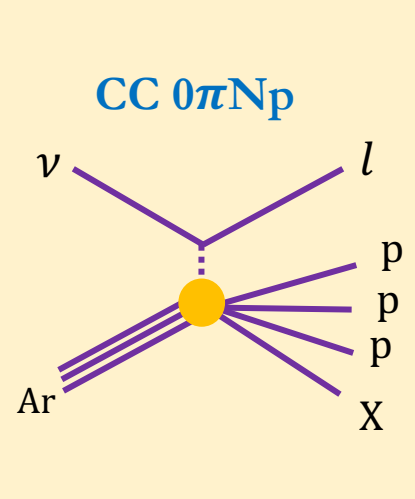
Previous results from MicroBooNE

- 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

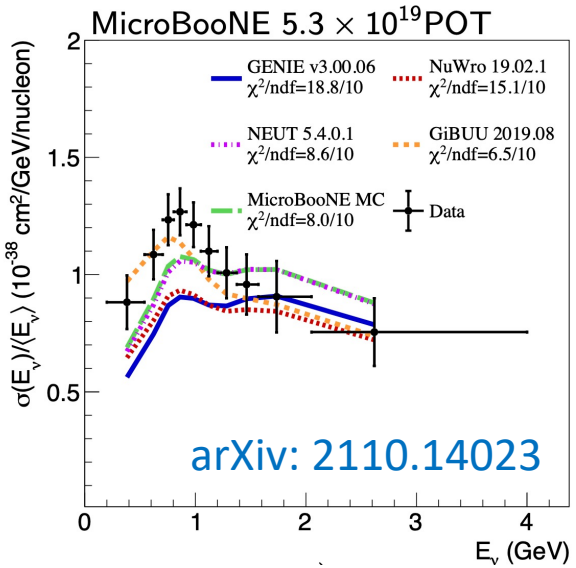
PRD **102**, 112013 (2020)

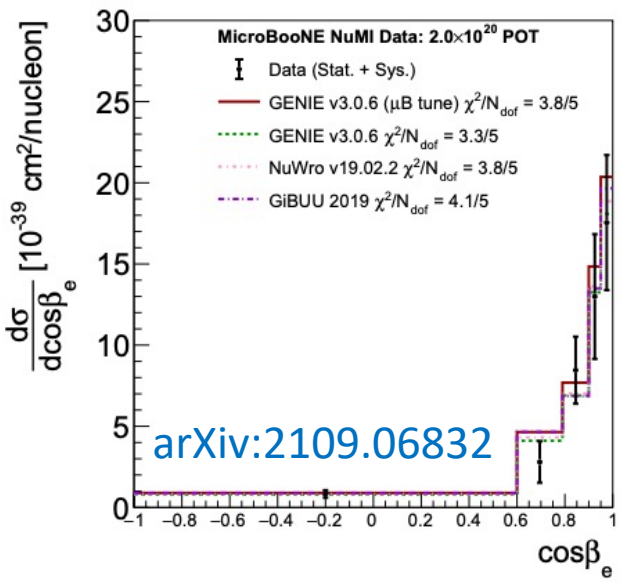


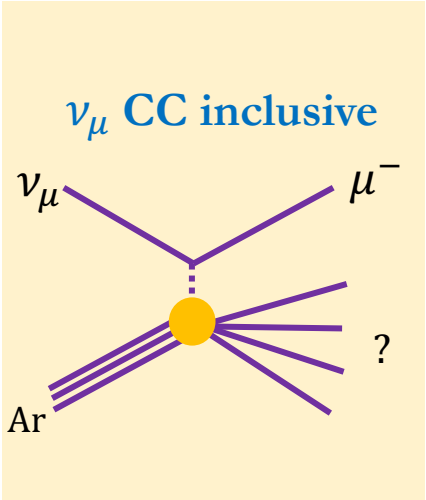


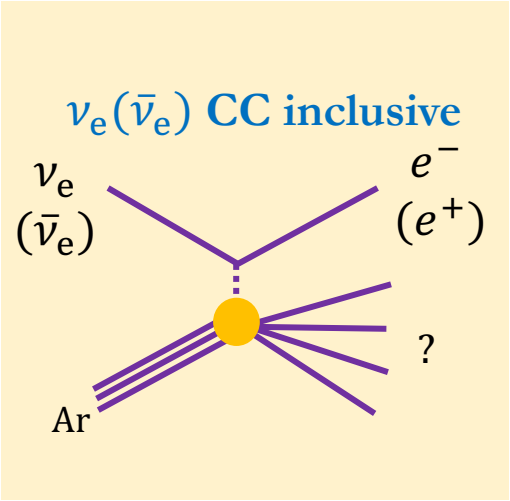


New results from MicroBooNE



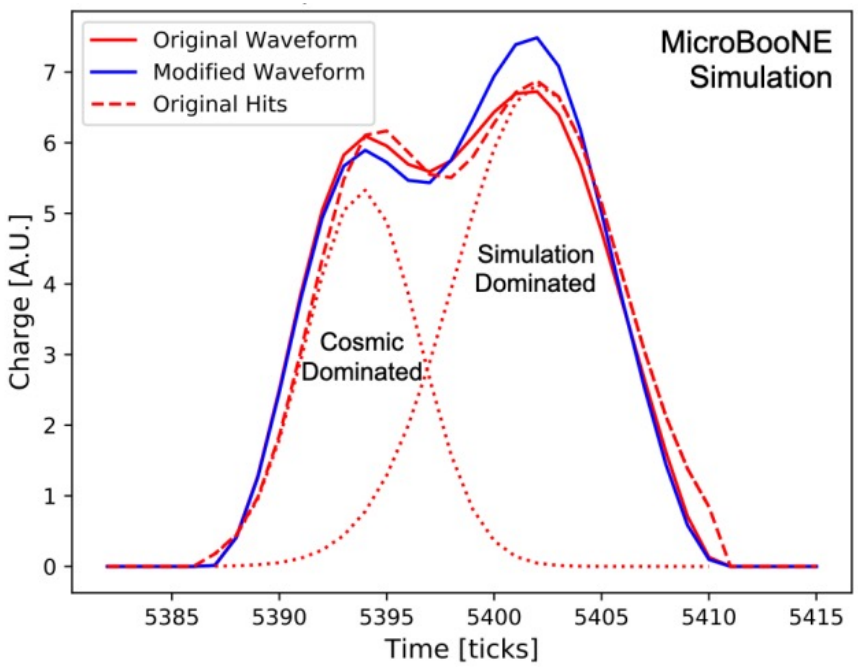


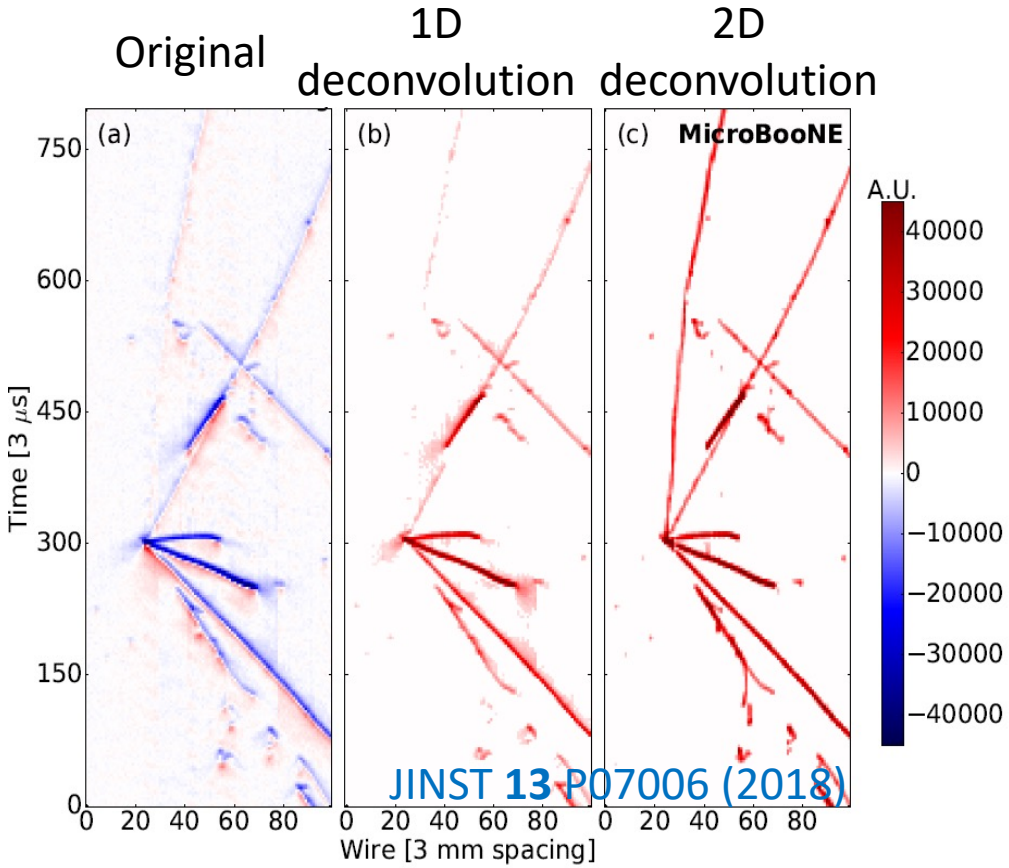




Evolved detector simulation & signal processing

arXiv:2111.03556

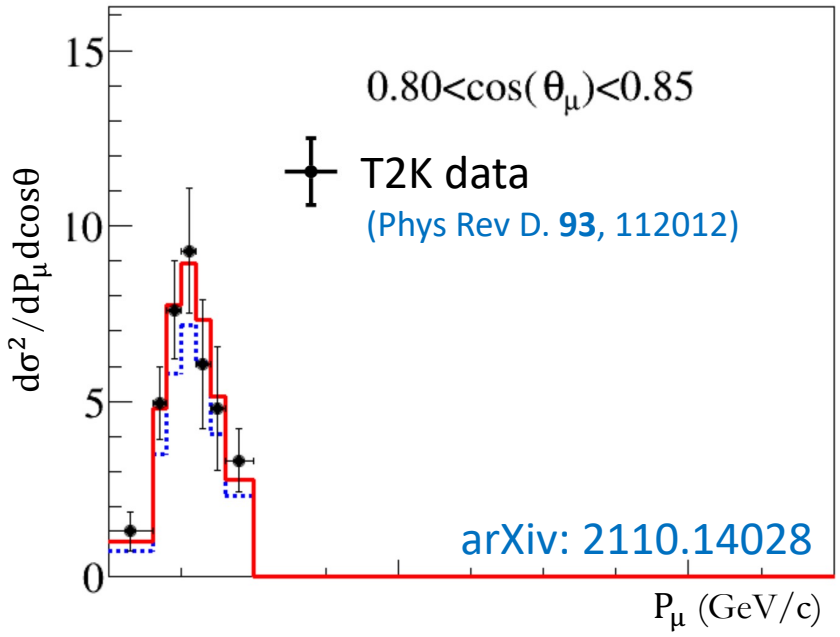




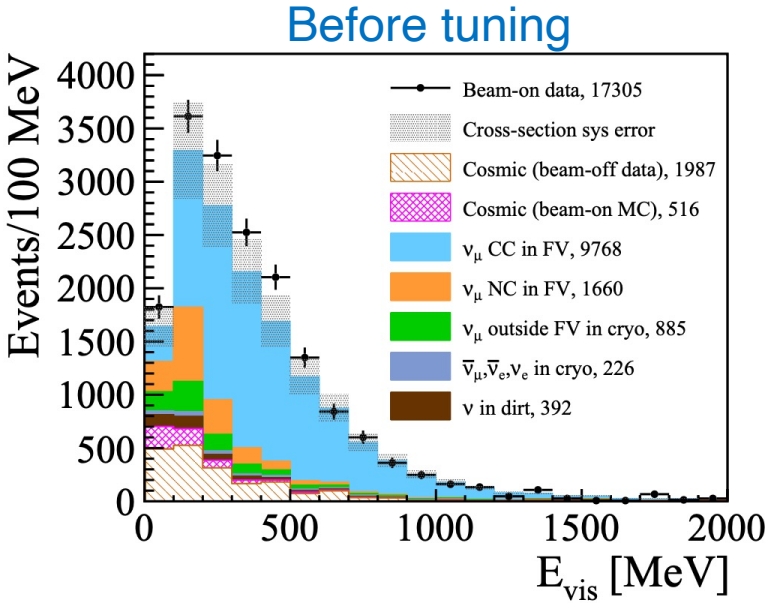
JINST **13** P07006 (2018)

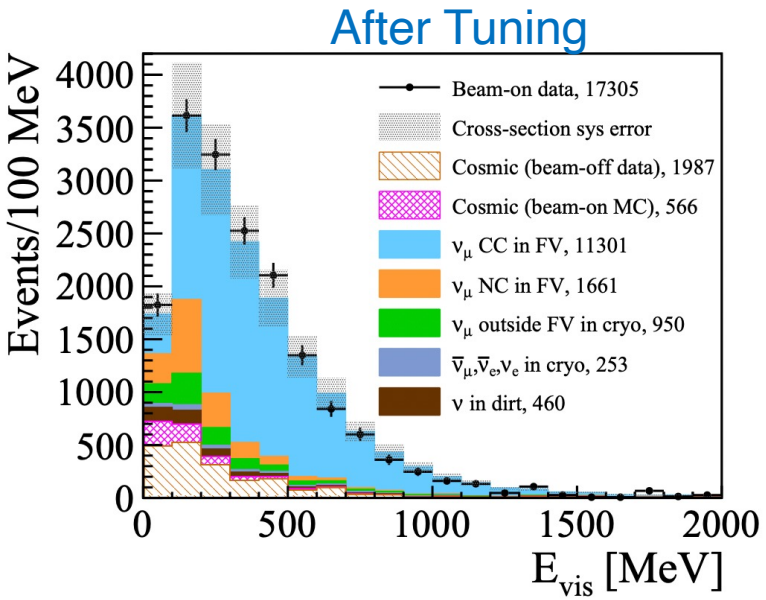
- Improved evaluation of **detector systematic uncertainties** with changes to detector modeling
- Advanced **2D deconvolution** with consideration of long-range induction effect

Evolved neutrino interaction model



Generic neutrino preselection





- MicroBooNE's interaction model evolved from GENIE v2 to GENIE v3
- New model is tuned through fitting to T2K's ν_μ CC0π data (CH) at similar beam energy
  - ➡ Tune 4 key parameters related to CCQE and 2p2h models
  - ➡ No additional fit to MicroBooNE data (Ar)

Evolved cross section extraction method

- Forward-folding

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

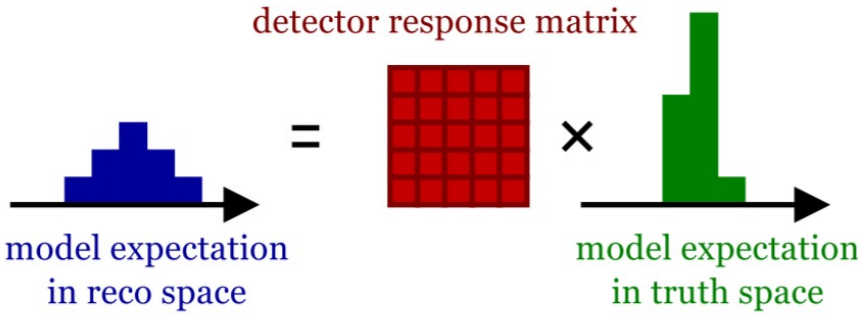
N_i (B_i): # of candidate (bkgd) in reco bin i
$\mathrm{N_{target}}$: # of argon nuclei
Φ_{ν_μ}: integrated neutrino flux
$(\Delta p_\mu)_i$: width for reco bin i
$\tilde{\epsilon}_i$: effective efficiency for reco bin i

- (Wiener-SVD) 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**

➡ Flux shape uncertainty properly treated ‡

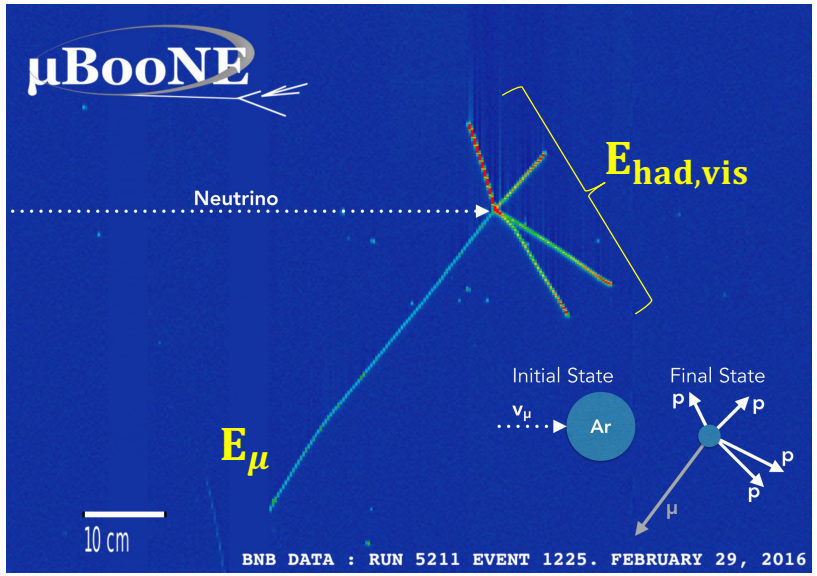


Wiener-SVD: JINST 12 (2017) 10, P10002

‡ : Phys. Rev. D 102 (2020) 113012

Evolved inclusive ν_μCC measurement

- Enhanced event selection efficiency (57%→68%) and purity (50%→92%)
- Extracted neutrino energy-dependent inclusive ν_μCC cross section
- **Challenge**: 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**

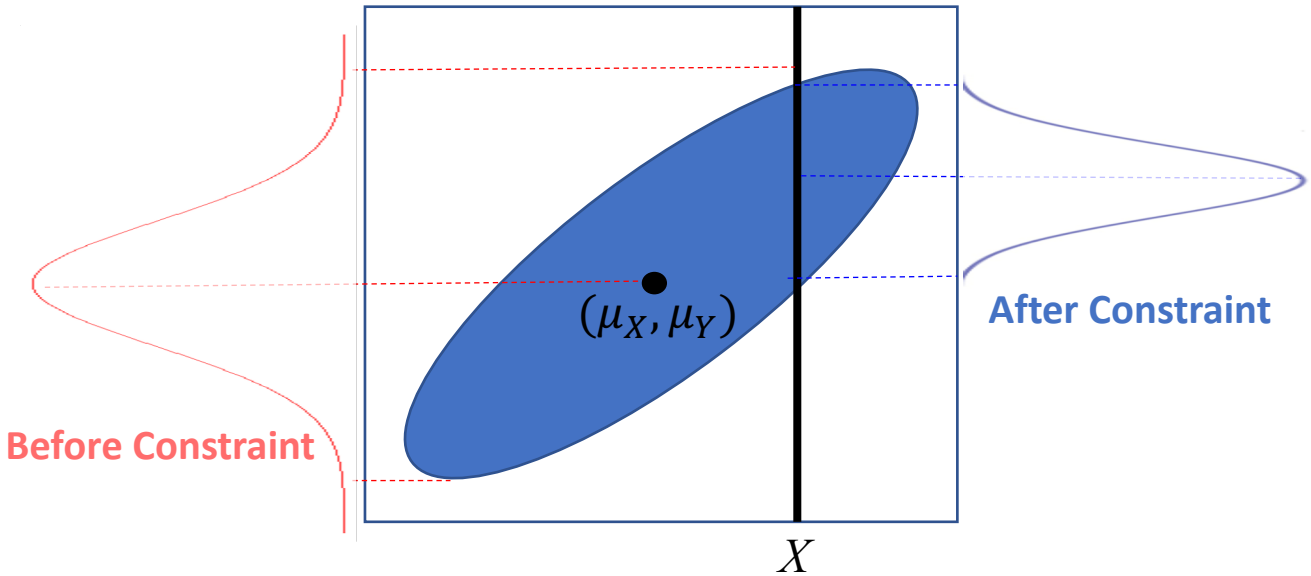
Conditional expectation & covariance

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

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

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

* A variant of Gaussian Process regression



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

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

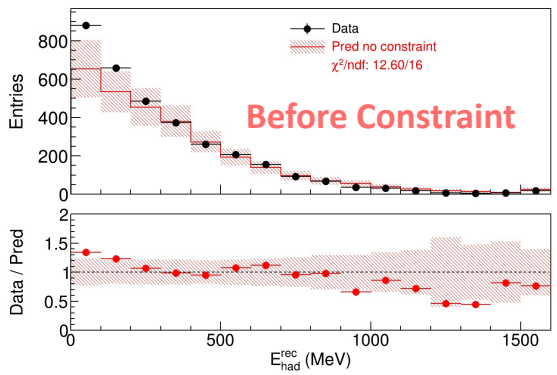
Prior model Sideband Posterior model

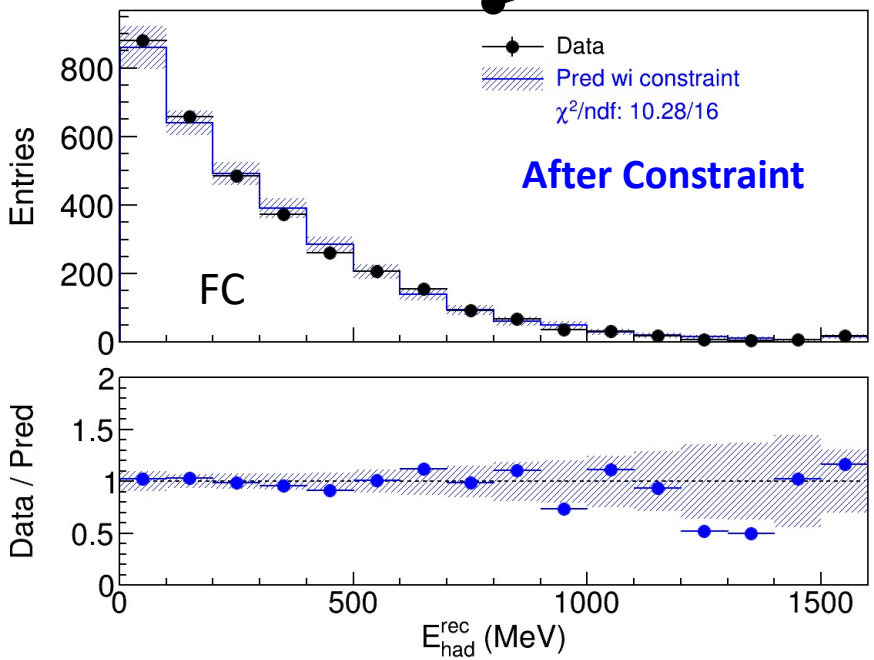
$$\mathrm{E}_{\nu} = \mathrm{E}_{\mu} + \mathrm{E}_{\mathrm{had,vis}} + \mathrm{E}_{\mathrm{had,missing}}$$

Energy model validation: $M(E_{had}^{rec})$ vs. $\mu(E_{had}^{rec} \mid E_{\mu}^{rec}, \cos\theta_{\mu}^{rec}, E_{\nu})$

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

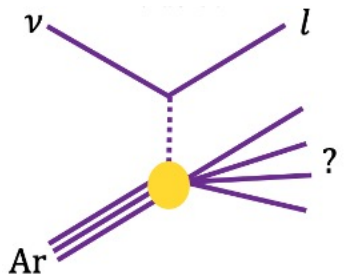
$$E_{\nu} = E_{\mu} + \underbrace{E_{had,vis} + E_{had,missing}}$$

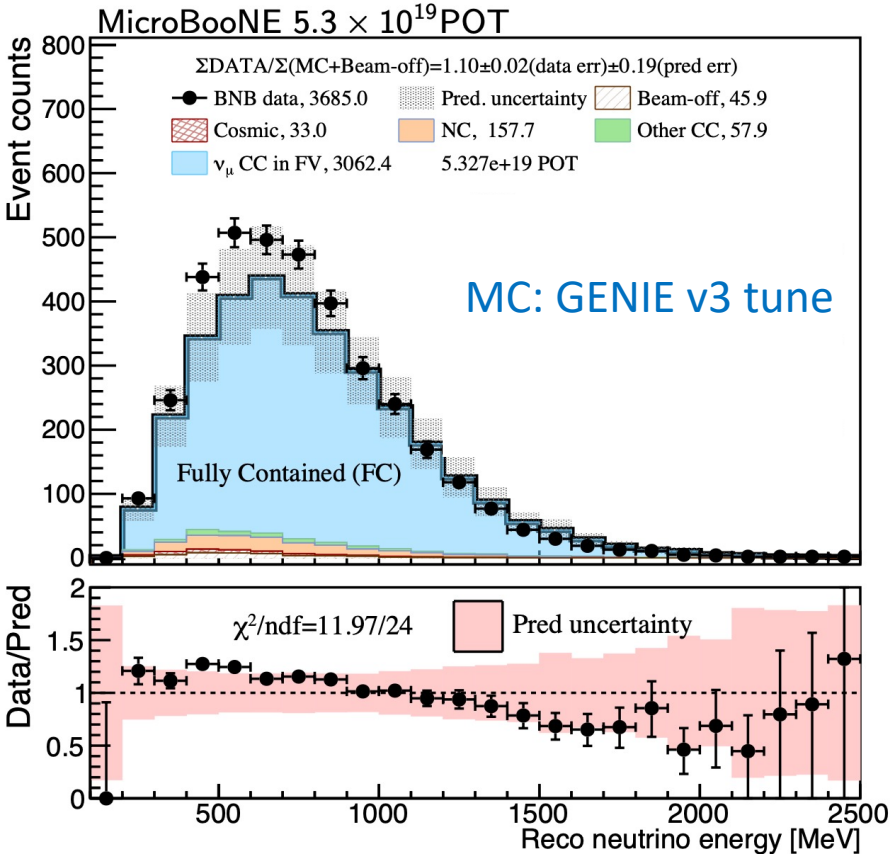


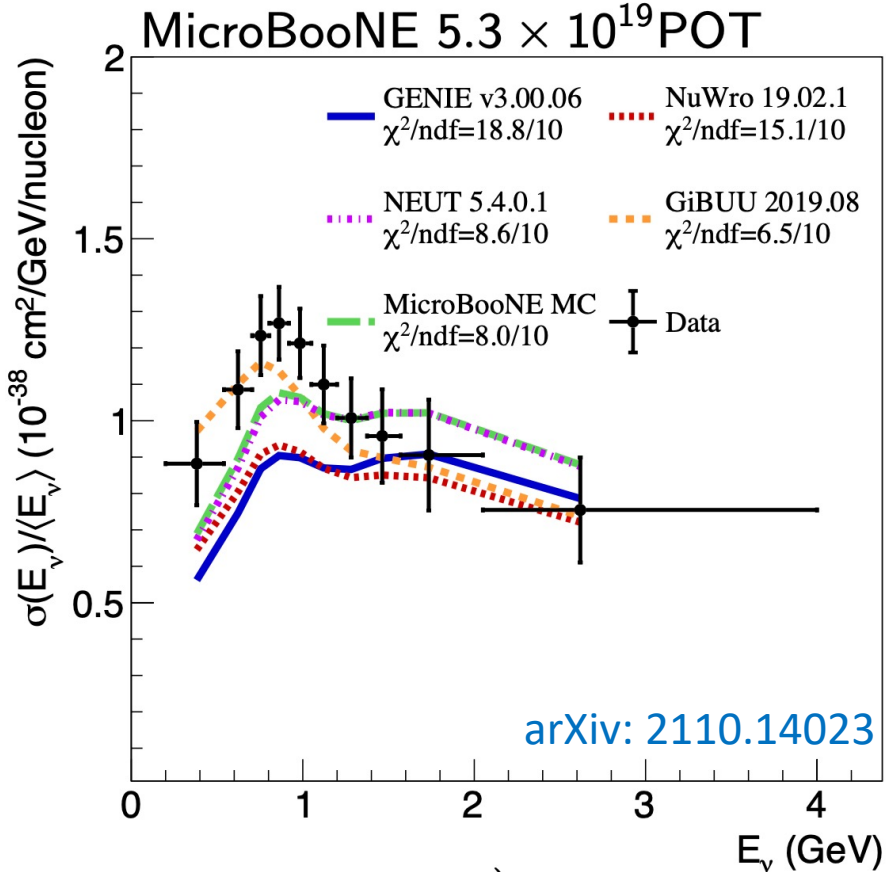


- Significant reduction in overall systematic uncertainties (20% → 5%)
- No sign of mis-modeling of the **hadronic missing energy**
  - $E_{\nu} \rightarrow E_{\nu}^{rec}$ mapping is good!

Inclusive ν_μCC: energy-dependence



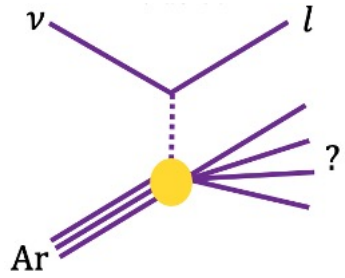




- Improved cosmic-μ rejection
  - Phys. Rev. Applied 15, 064071; arXiv:2012.07928
  - JINST 16 (2021) 06, P06043 (Wire-Cell reconstruction)

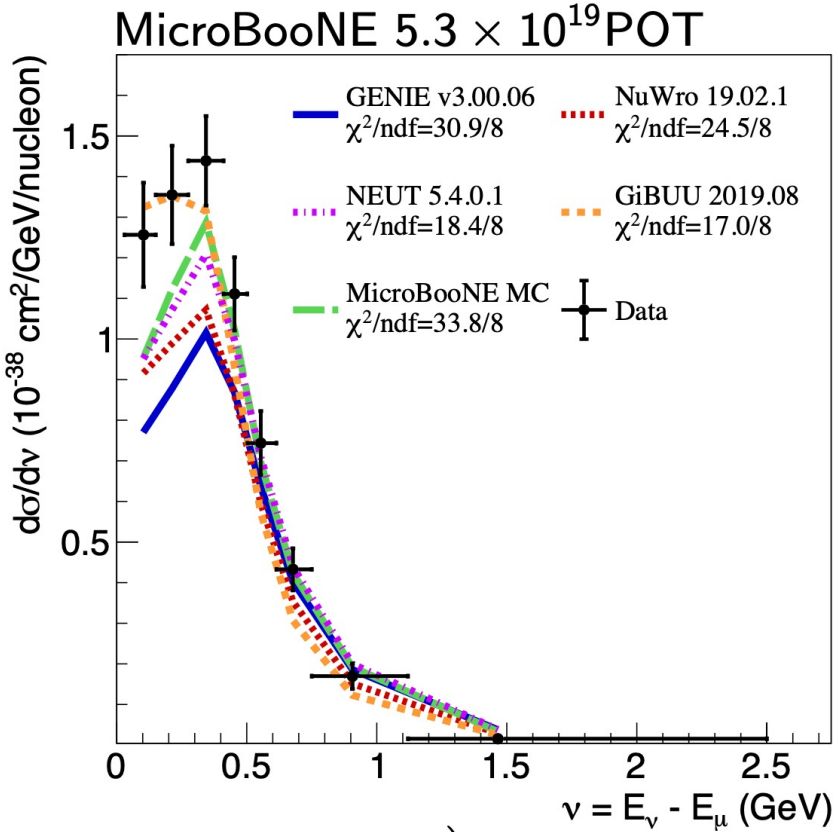
- New model validation procedure for E_ν reconstruction enables unfolding of $\sigma(E_\nu)$

Differential inclusive ν_μCC: hadronic energy transfer



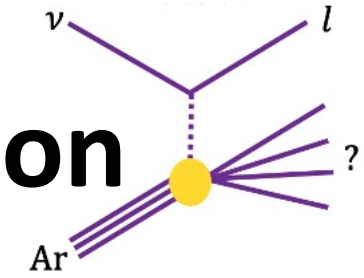
- New model validation procedure for E_ν reconstruction also enables **differential cross section** as a function of hadronic energy transfer on argon
- Good separation power of model predictions from different generators
- GiBUU's central prediction gives best agreement at low energy transfer

  ⇒ more contribution of *2p2h*

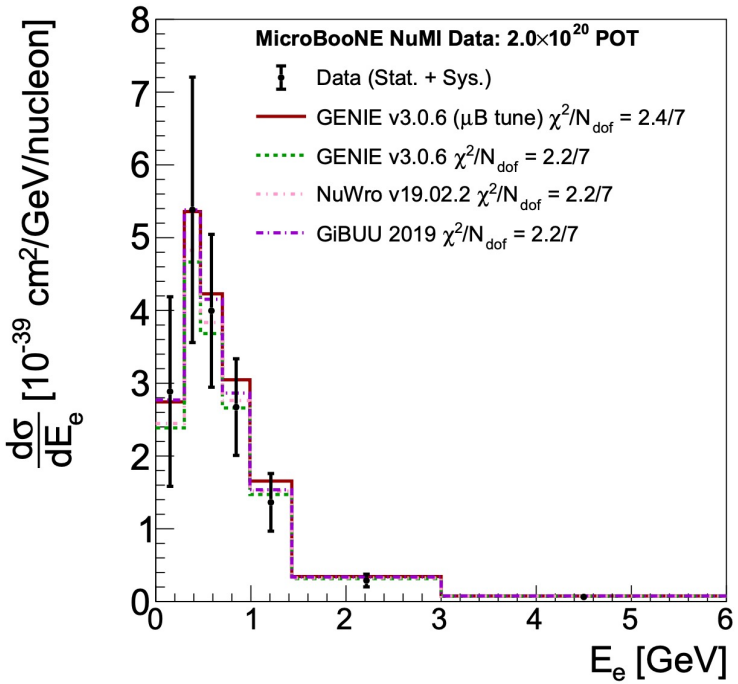


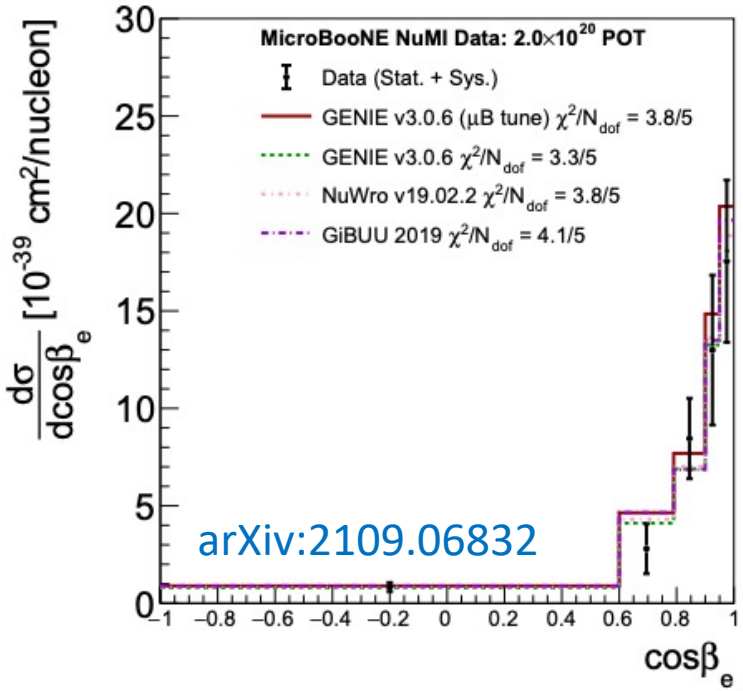
arXiv: 2110.14023

Differential inclusive $\nu_e + \bar{\nu}_e$ CC cross section



- Enhanced event selection efficiency (9%→21%) and purity (39%→ 72%)
- **Differential** cross sections as a function of electron/positron's energy and angle are extracted using unfolding techniques
- Consistent results with model predictions within uncertainties

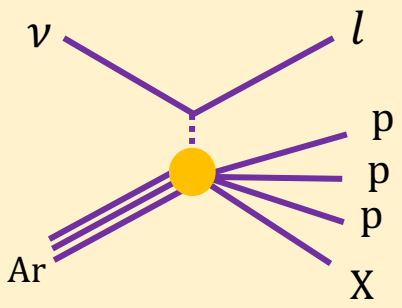




arXiv:2109.06832

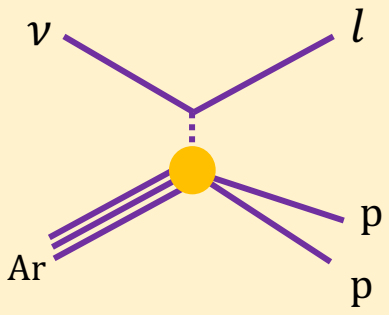
More cross-sections in progress

CC0πNp 2D differential



MICROBOONE-NOTE-1099-PUB

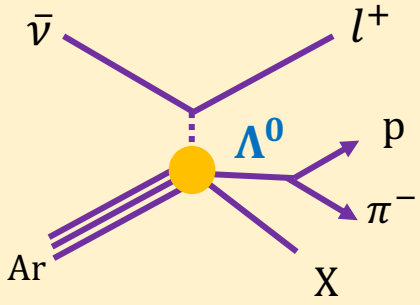
CC 0π2p



MICROBOONE-NOTE-1096-PUB

- *2p2h* effect

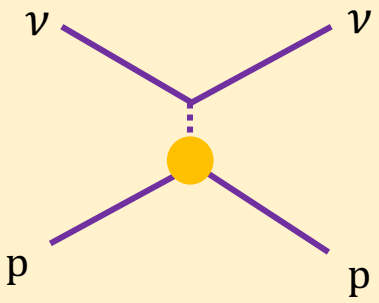
Λ^0 production



MICROBOONE-NOTE-1097-PUB

- driven by anti-neutrinos

NC Elastic

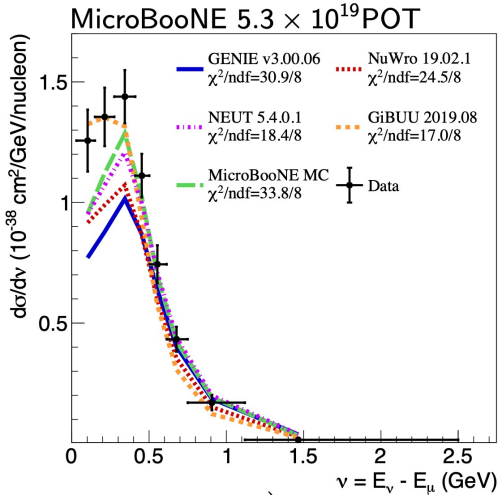


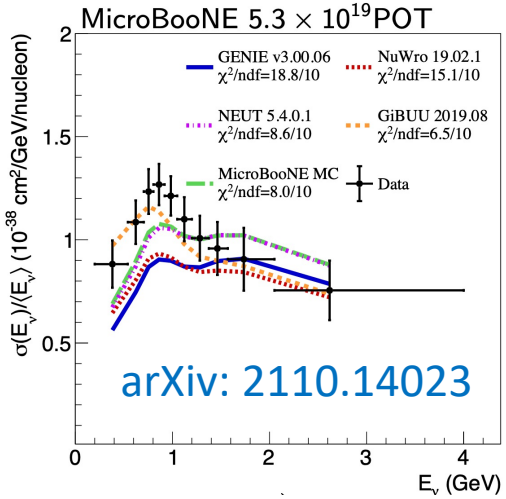
MICROBOONE-NOTE-1101-PUB

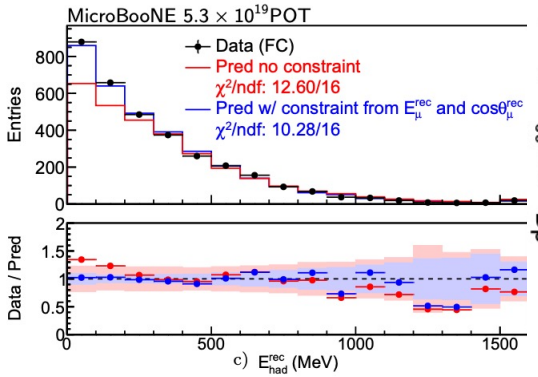
- $Q^2 \rightarrow 0.1\text{GeV}^2$
- sensitive to strange quark contribution to proton spin

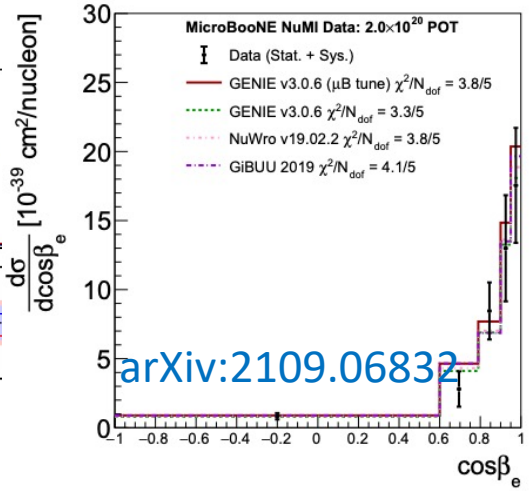
Summary

- Understanding of ν-Ar cross section is vital for LArTPC-based precision neutrino oscillation experiments
- MicroBooNE has produced numerous ν-Ar cross section measurements
  - ➡ ν_e vs. ν_μ, inclusive vs. exclusive (CCQE-like, CC0πNp, …)
  - ➡The only high-stat ν-Ar observatory before SBND is online
- New validation method of neutrino energy modeling enables the energy-dependent inclusive ν_μ CC cross section
  - ➡ Good separation power of model predictions from different generators





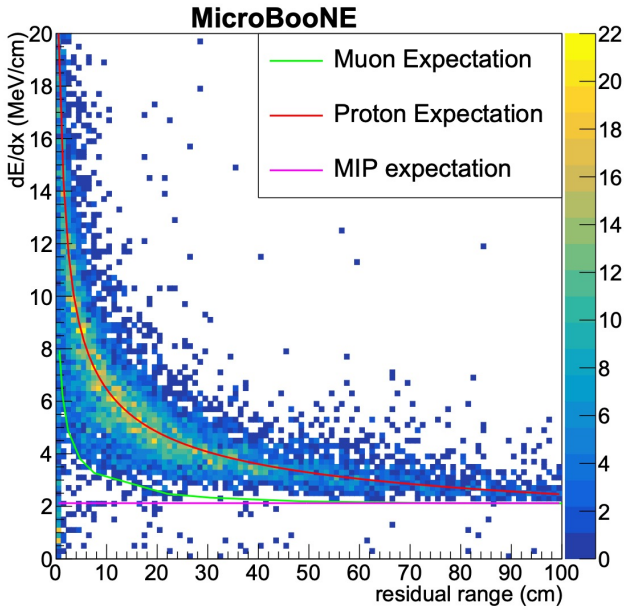




Backup Slides

Protons in LArTPC

- Low-momenta protons give access to **exclusive** channels of ν-Ar interaction, as well as probes of nuclear effects (2p2h, FSI, etc.)
- LArTPC has excellent proton detection by identifying a Bragg peak in dE/dx at end of particle trajectories



JINST 15, P03022 (2020)