Recent π^0 production measurements from MicroBooNE

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on behalf of the
MicroBooNE Collaboration

NuINT 24

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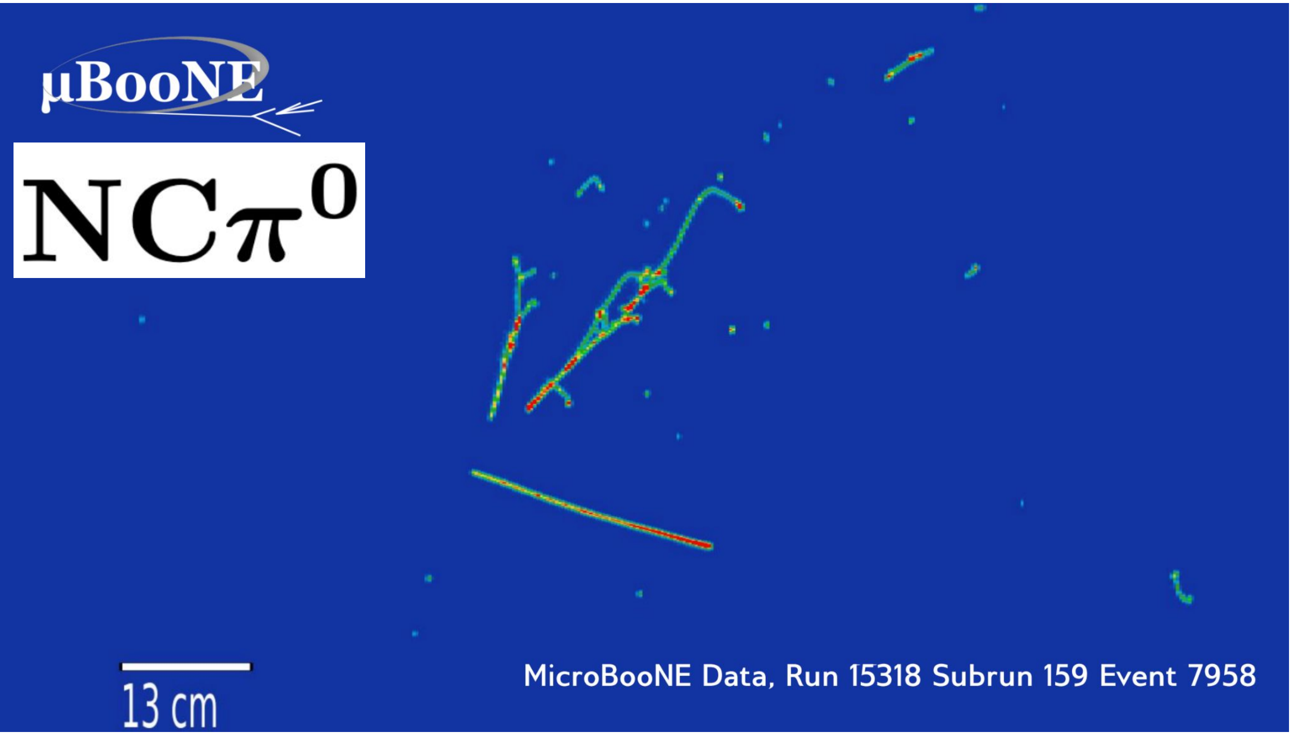
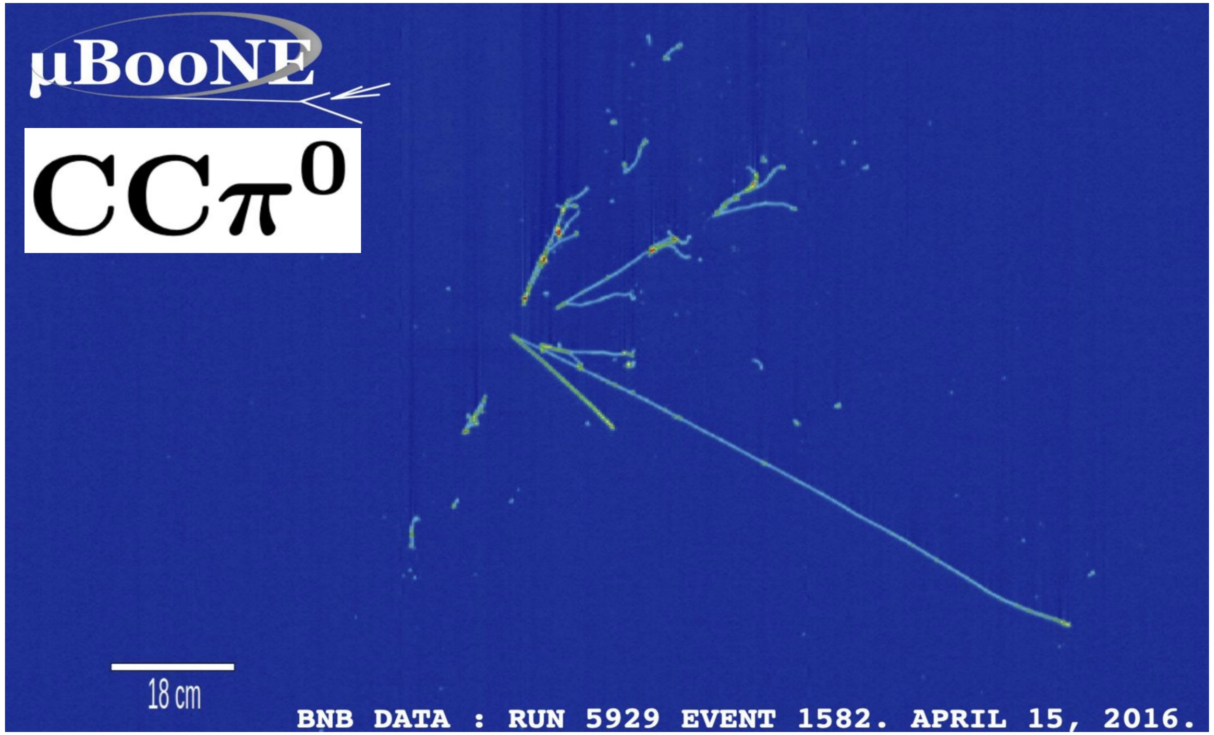
Recent π^0 production measurements from MicroBooNE

- Two recent π^0 production results from MicroBooNE.
  - Semi-inclusive CCπ^0 without charged pions: arXiv:2404.09949
  - Semi-inclusive NCπ^0: arXiv:2404.10948



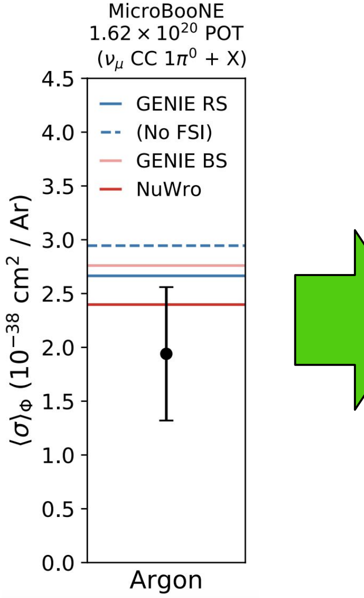
$$\nu_x + Ar \rightarrow \nu_x + \pi^0 + X$$



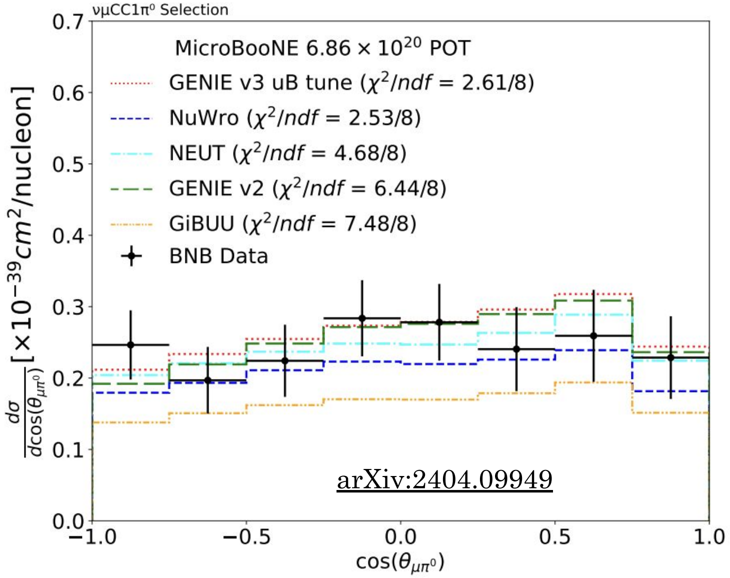
$$\nu_\mu + \mathrm{Ar} \rightarrow \mu^- + \pi^0 + 0\pi^\pm + \mathrm{X}$$

Recent π^0 production measurements from MicroBooNE

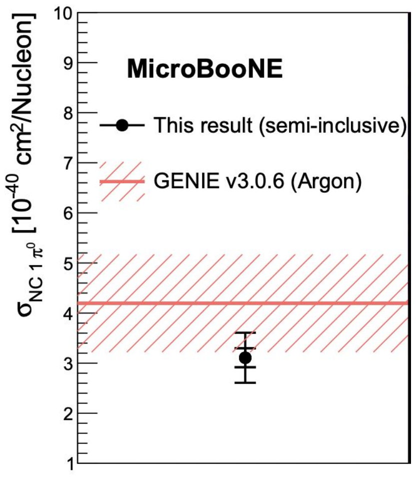
- New differential measurements expand upon previous total cross section results.
- CCπ^0 results reported as a function of the:
  - muon kinematics.
  - π^0 kinematics.
  - muon-pion opening angle.
- NCπ^0 results reported as a function of the π^0 kinematics and include:
  - a double-differential measurement.
  - simultaneous measurements of final states with (Np) and without (0p) protons*.

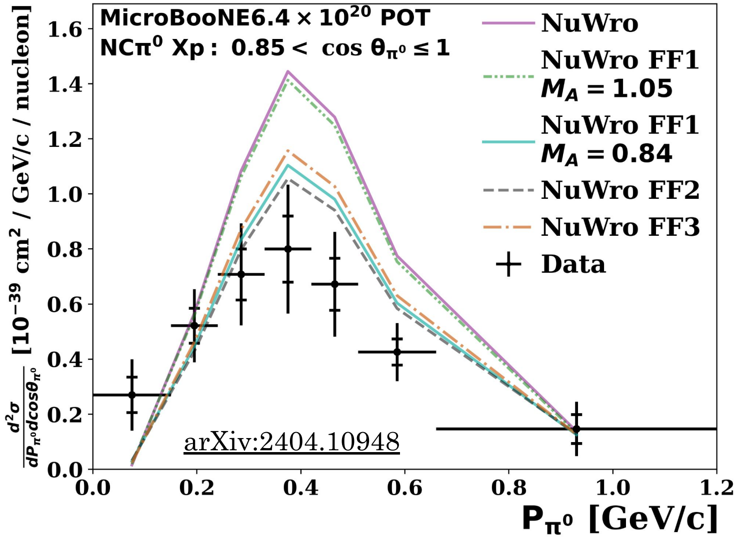


Phys. Rev. D 99, 091102 (2019)



Phys. Rev. D **107**, 012004 (2023)

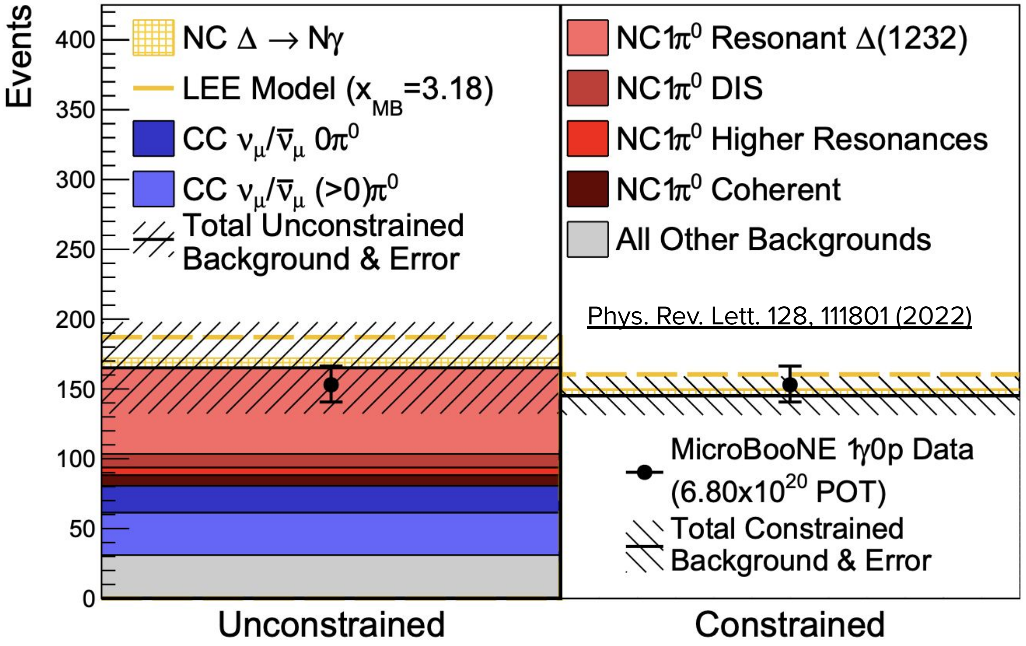




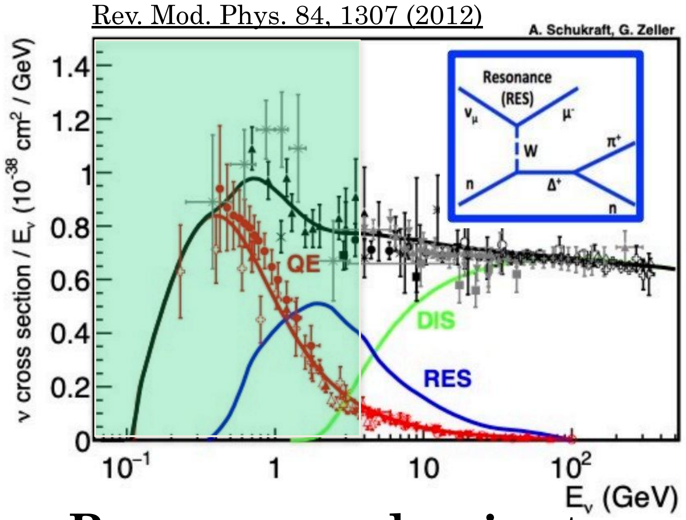
*35MeV proton kinetic energy threshold applied to 0pNp measurements motivated by MicroBooNE's ~1cm track detection threshold.

Motivation

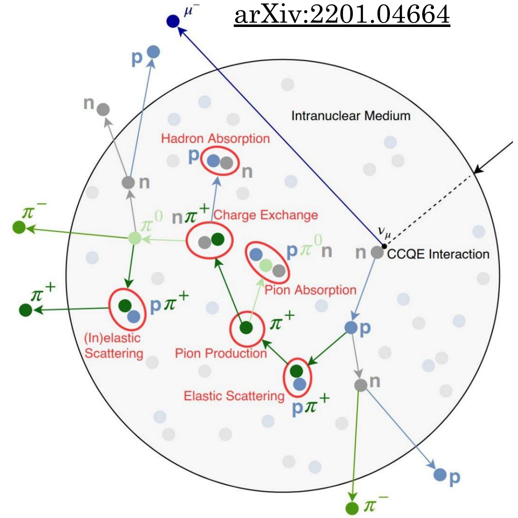
- Measurements are motivated by the
  - prominence of π^0 in single shower selections.
  - challenges associated with holistically modeling both initial interaction and FSI.
  - a need for more data, measurement for both CC and NC channels on argon are sparse.
    - Only two NCπ^0 measurements on argon thus far, one from MicroBooNE and one from ArgoNeuT.
    - Only one CCπ^0 measurements on argon from MicroBooNE.



CC and NC pi0 is a prominent background.



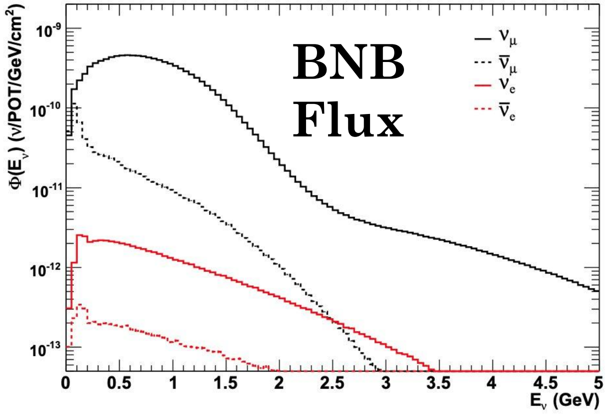
Resonances dominate pion production at MicroBooNE energies.

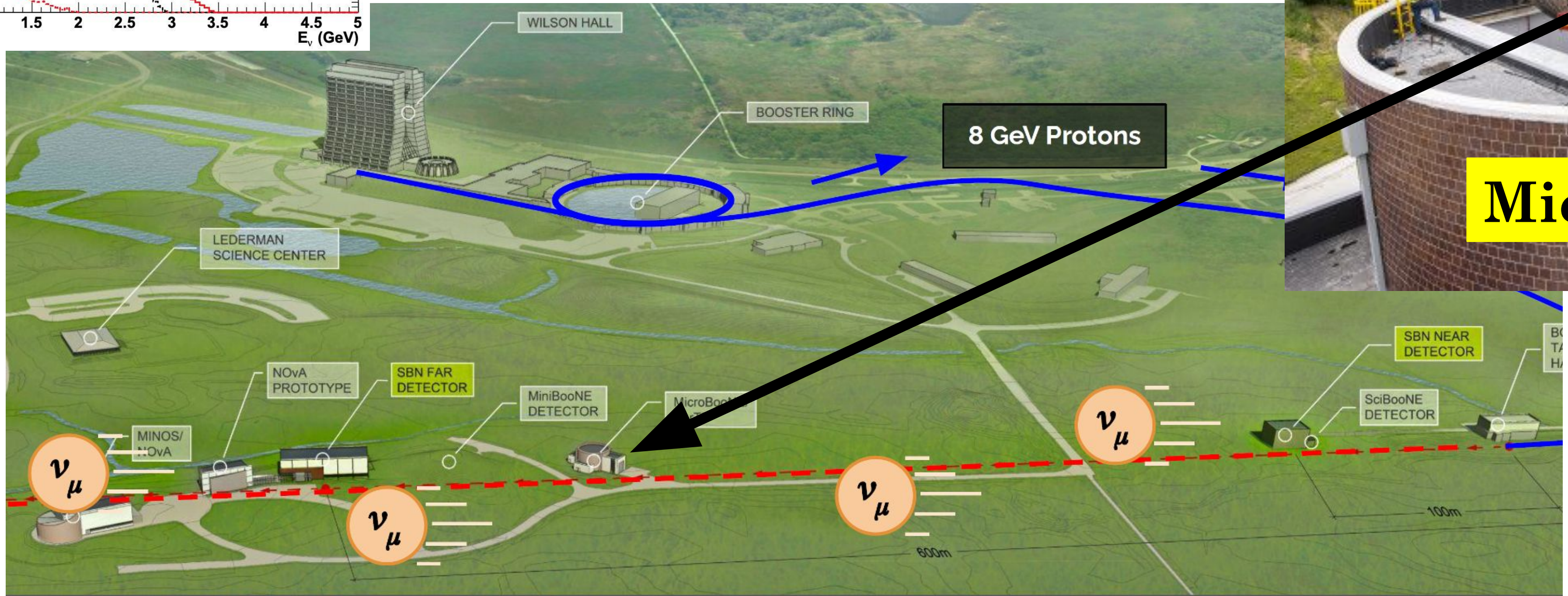


FSI and nuclear effects play a prominent role.

MicroBooNE

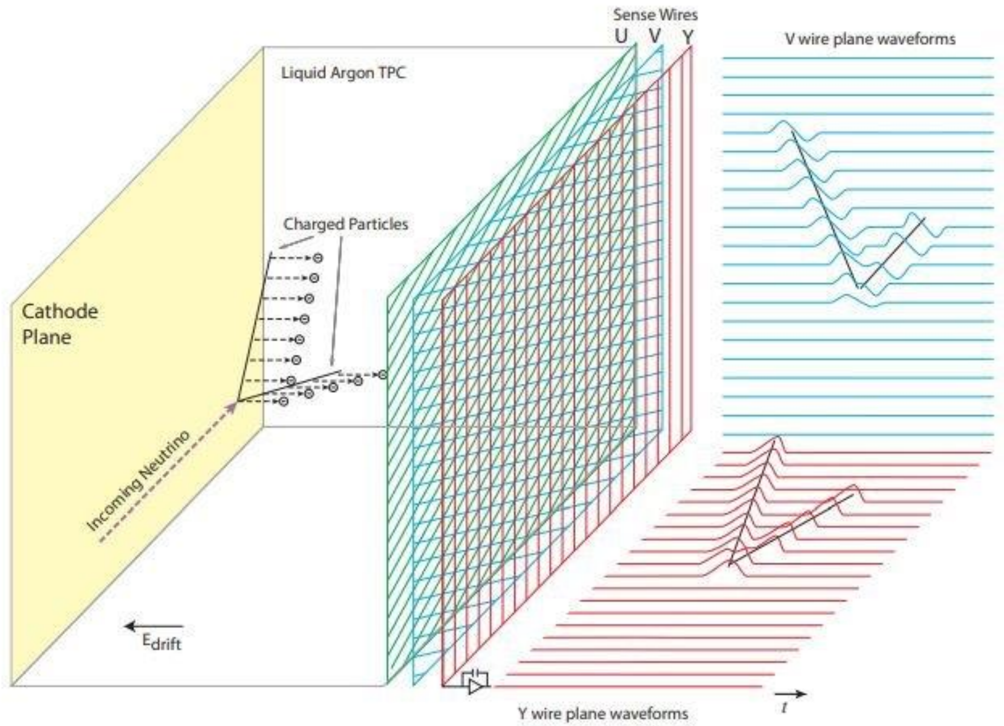
- MicroBooNE detector is a liquid argon time projection chamber (LArTPC).
- Located in Booster Neutrino Beam (BNB) at Fermilab.
- Collected data from 2015-2021. These results use ½ this data.
- Physics goals:
  - Test the Low Energy Excess (LEE).
  - **Study neutrino-Ar interactions.**
  - Demonstrate the capabilities of LArTPC.
  - Explore BSM physics.



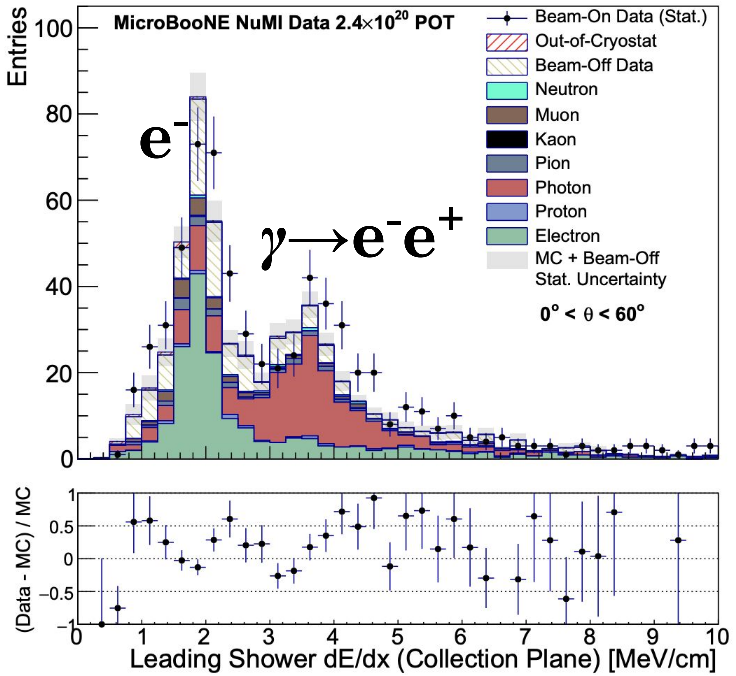


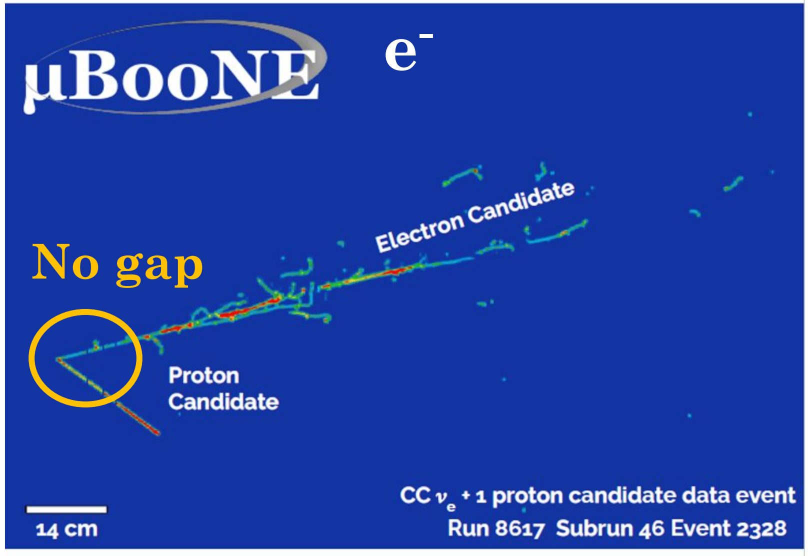
LArTPC and π^0 identification

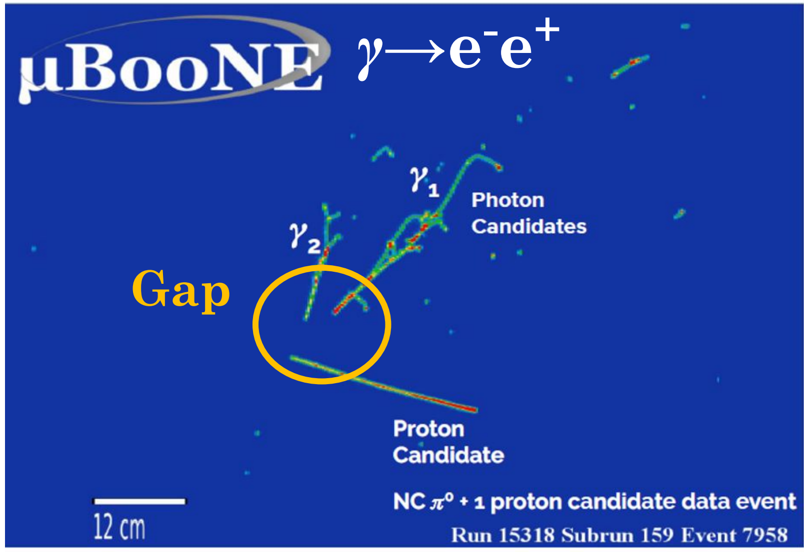
- In LArTPCs, interactions produce ionization electrons and scintillation light.
  - PMTs provide timing measurement from light.
  - High voltage field draws electrons to wire planes enabling calorimetry and mm resolution 3D imaging.
- π^0 are identified via their two decay photons.
  - Topological and dE/dx information used to distinguish photons and electrons.



Phys. Rev. D 104, 052002 (2021)

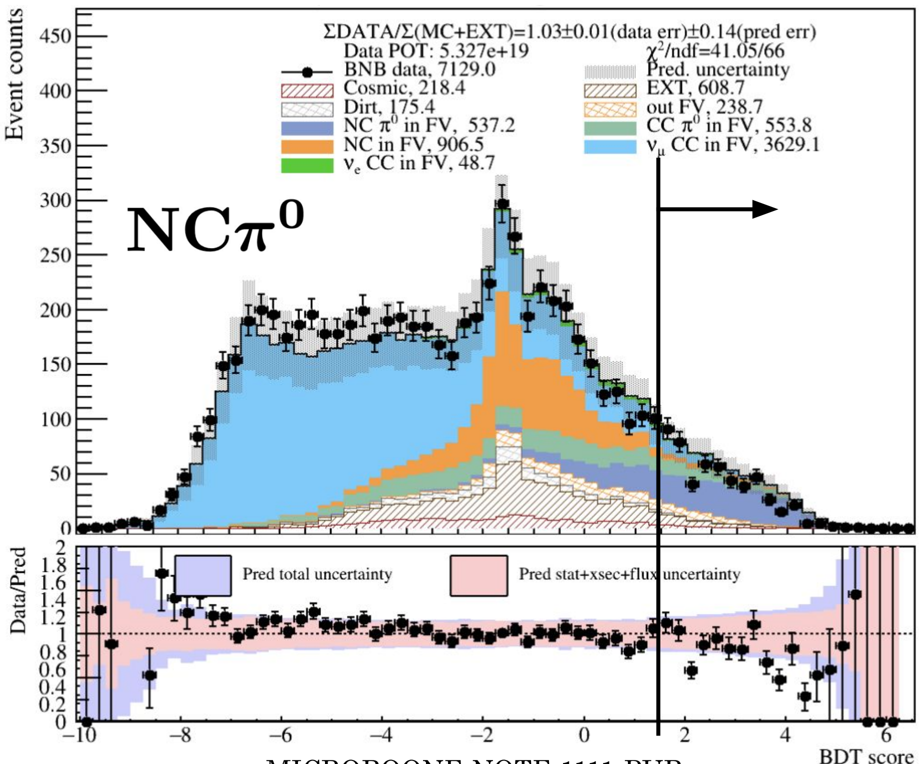




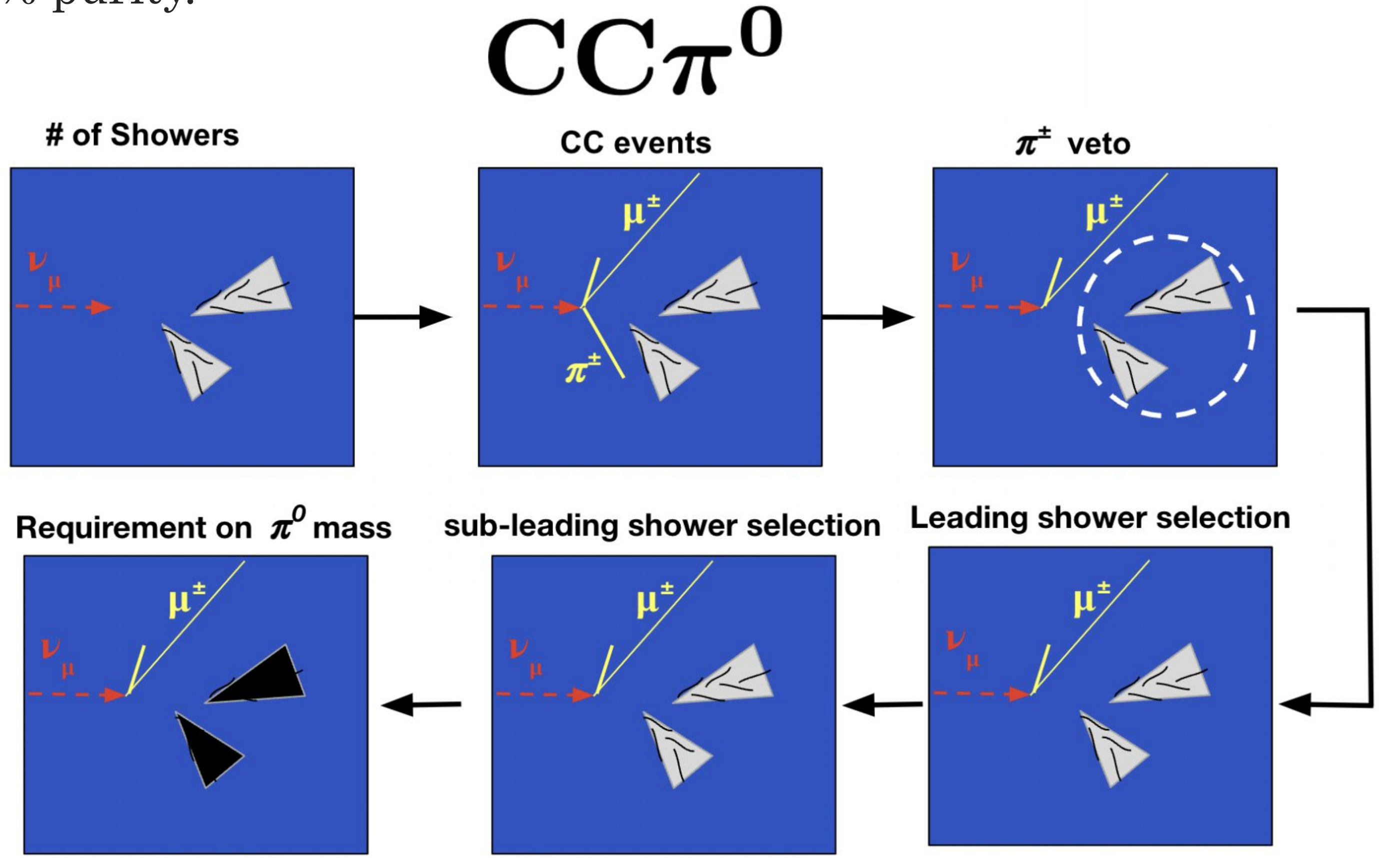


Event Selections

- $NC\pi^0$ analysis utilizes a Boosted Decision Tree based event selection.
  - Trained on "tagger" variables designed to characterize ν_μCC, ν_eCC and $NC\pi^0$ events.
  - Selection achieves 35% efficiency and 54% purity.
- $CC\pi^0$ analysis utilizes a cut-based event selection.
  - Selection achieves a 8.1% efficiency and 69% purity.



MICROBOONE-NOTE-1111-PUB



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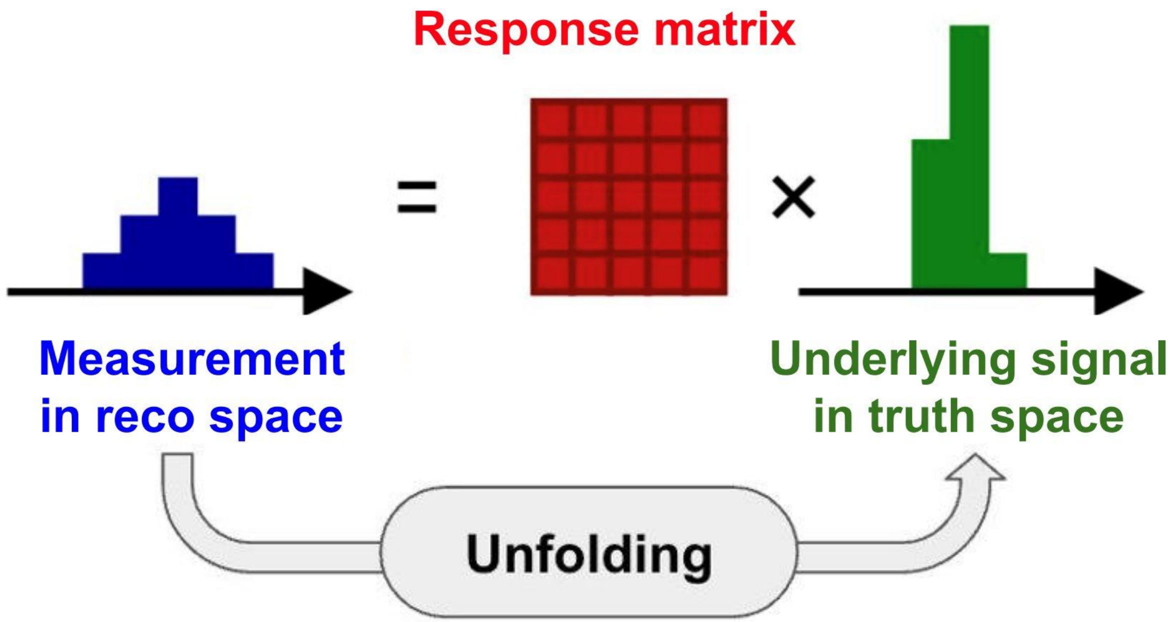
Wiener-SVD Unfolding

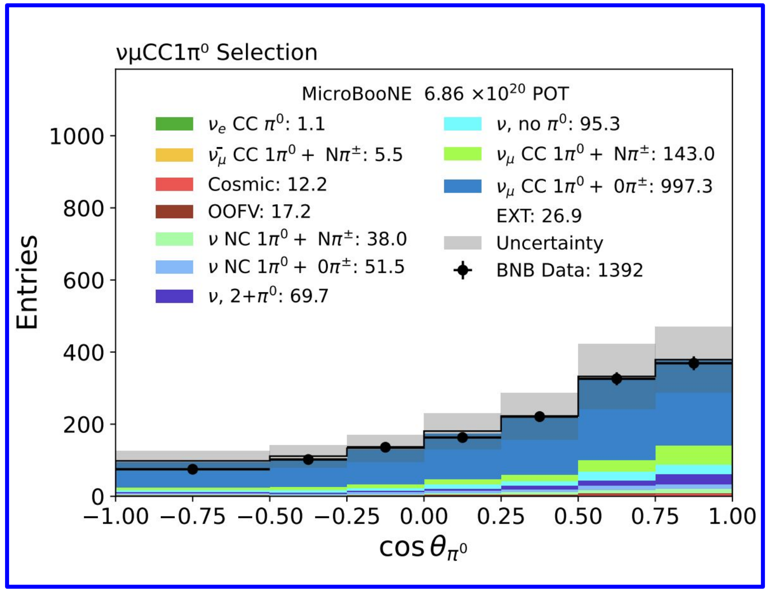
- Cross sections are extracted from the reconstructed distributions with the Wiener-SVD unfolding method.
  - Analogous to digital signal processing with a Wiener Filter.
- Maximizes the signal to noise ratio in an effective frequency domain.

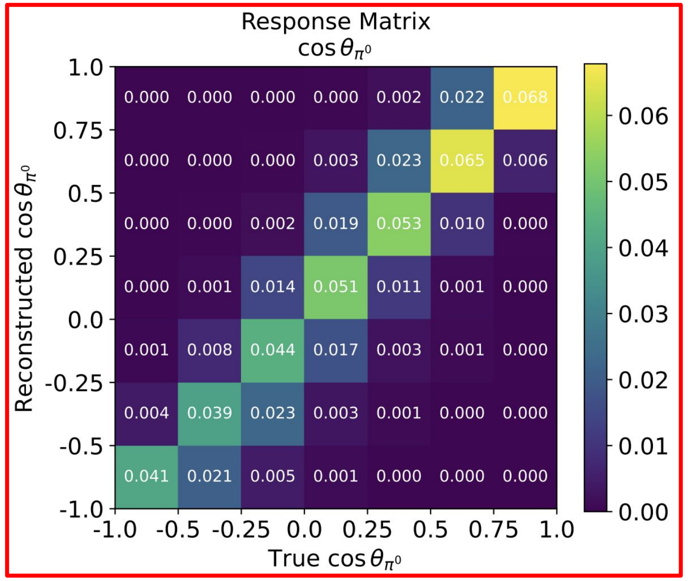


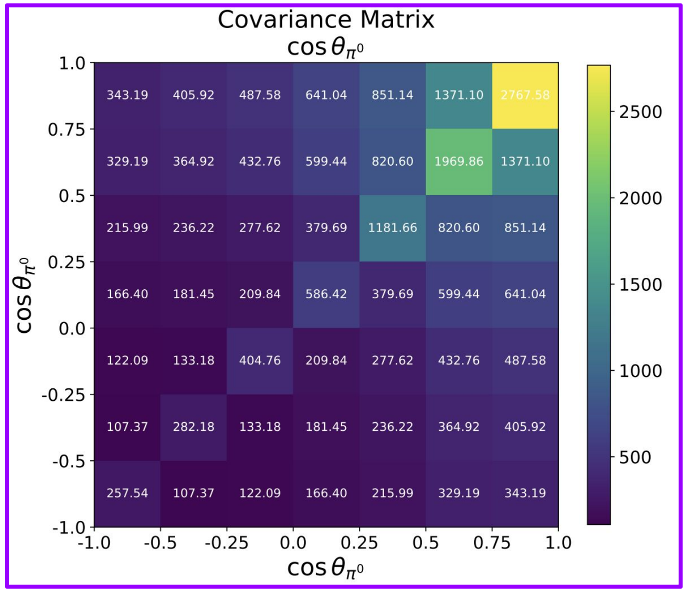
JINST, Volume 12, October 2017

Wiener-SVD Unfolding

- **Input Quantities:**
  - **Data measurement**.
  - **Response matrix:** mapping between true and reconstructed distributions.
  - **Total Covariance matrix:** uncertainties of the model.







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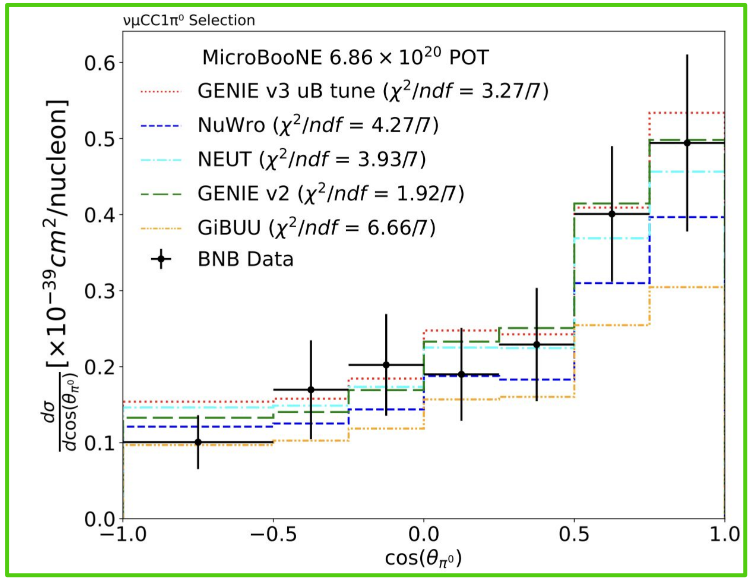
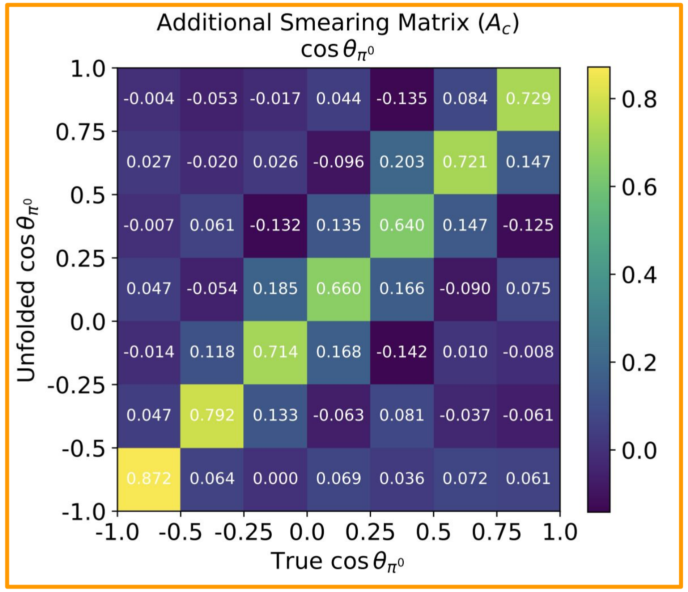
Wiener-SVD Unfolding

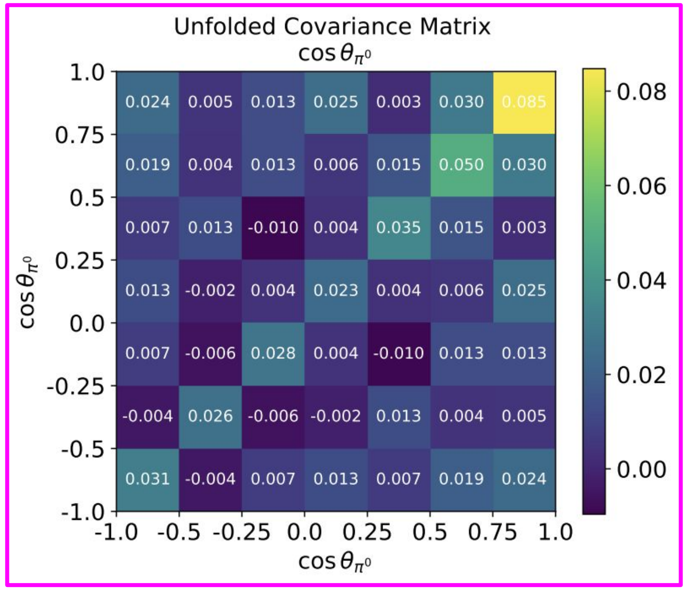
Prediction should be multiplied by the additional smearing matrix when comparing to these results.

- Input Quantities:
  - Data measurement.
  - Response matrix: mapping between true and reconstructed distributions.
  - Total Covariance matrix: uncertainties of the model.
- **Output Quantities:**
  - **Extracted cross section.**
  - **Extracted covariance matrix**: uncertainties on the extracted results.
  - **Additional smearing matrix:** describes bias induced by regularization.





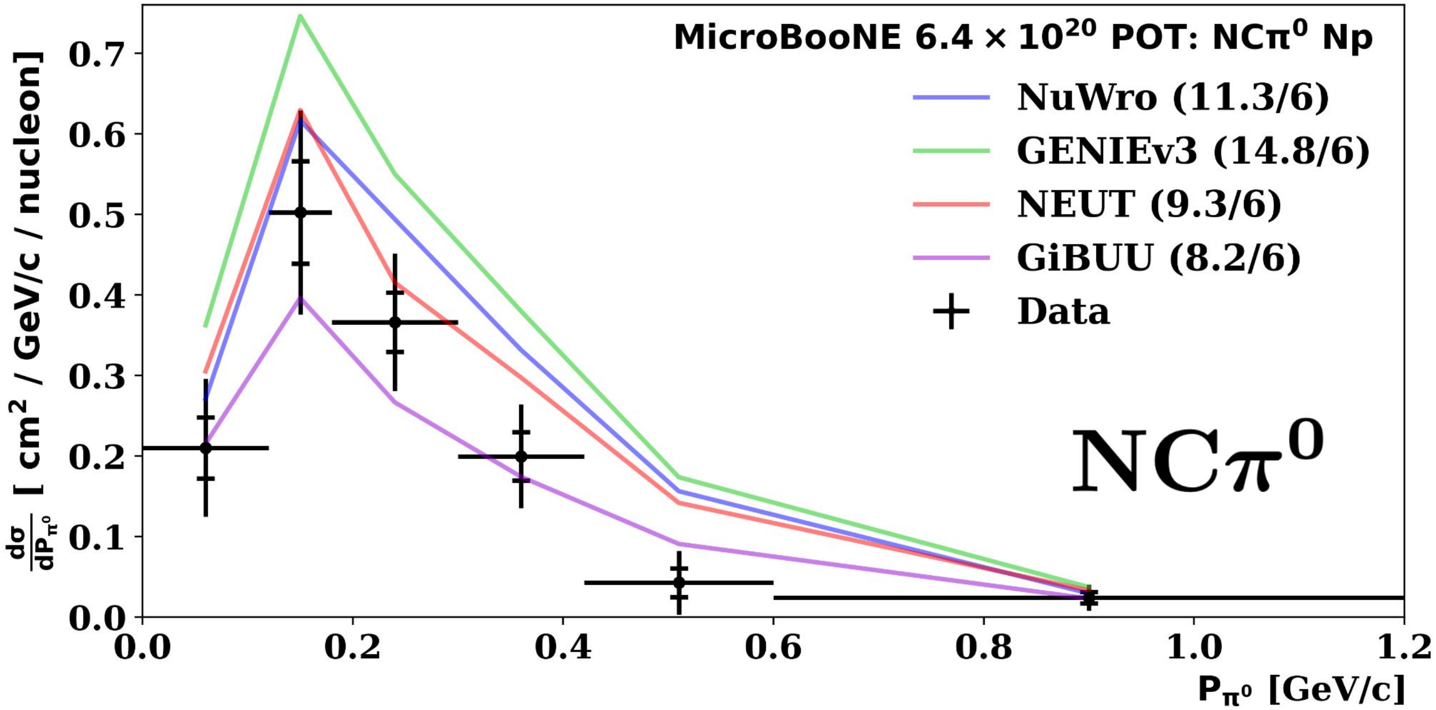
-0.004	-0.053	-0.017	0.044	-0.135	0.084	0.729
0.027	-0.020	0.026	-0.096	0.203	0.721	0.147
-0.007	0.061	-0.132	0.135	0.640	0.147	-0.125
0.047	-0.054	0.185	0.660	0.166	-0.090	0.075
-0.014	0.118	0.714	0.168	-0.142	0.010	-0.008
0.047	0.792	0.133	-0.063	0.081	-0.037	-0.061
0.872	0.064	0.000	0.069	0.036	0.072	0.061

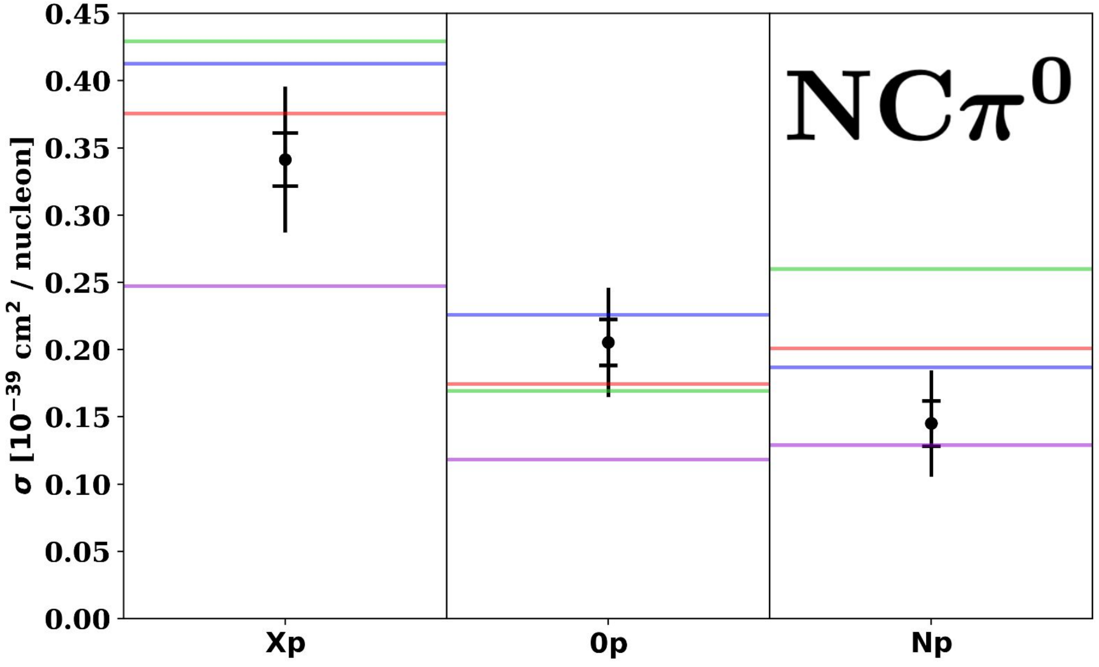


0.024	0.005	0.013	0.025	0.003	0.030	0.085
0.019	0.004	0.013	0.006	0.015	0.050	0.030
0.007	0.013	-0.010	0.004	0.035	0.015	0.003
0.013	-0.002	0.004	0.023	0.004	0.006	0.025
0.007	-0.006	0.028	0.004	-0.010	0.013	0.013
-0.004	0.026	-0.006	-0.002	0.013	0.004	0.005
0.031	-0.004	0.007	0.013	0.007	0.019	0.024

Results: NCπ^0

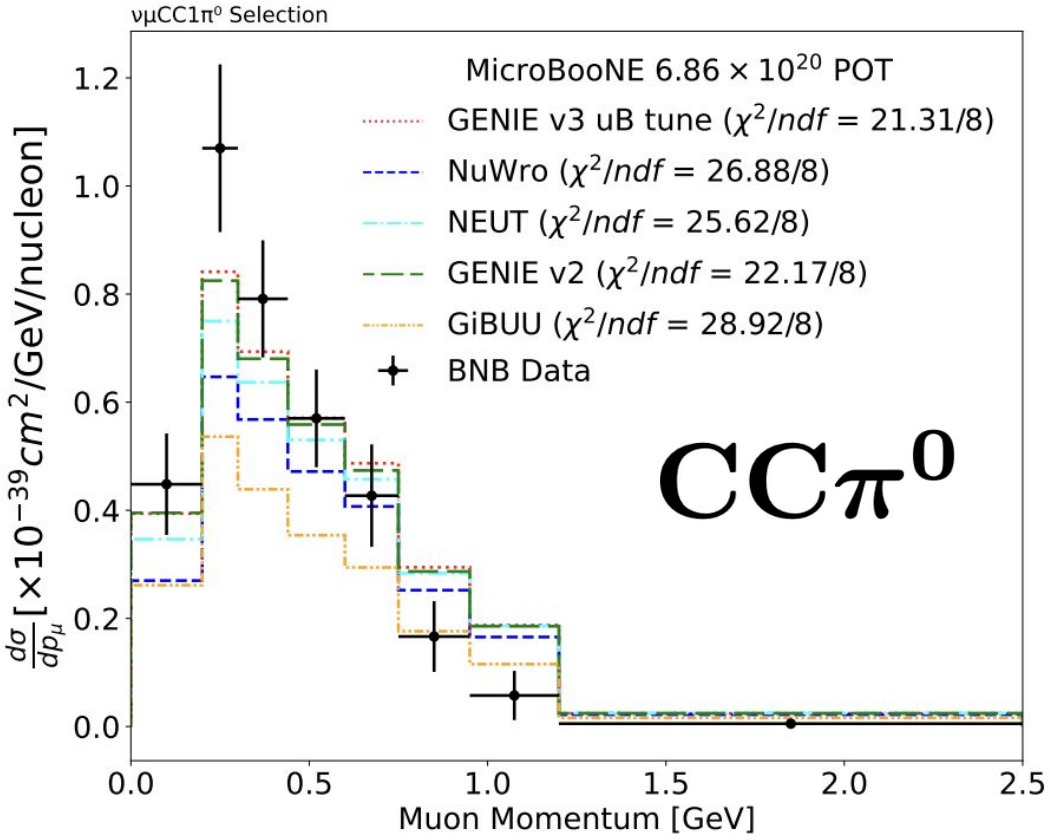
- Generators tend to overestimate the NCπ^0 cross section.
- Most prominent around 0.2 to 0.5 GeV/c of momentum and when a proton is present in the final state.
    - **GiBUU** is the exception and shows better agreement in these regions but an underprediction elsewhere.

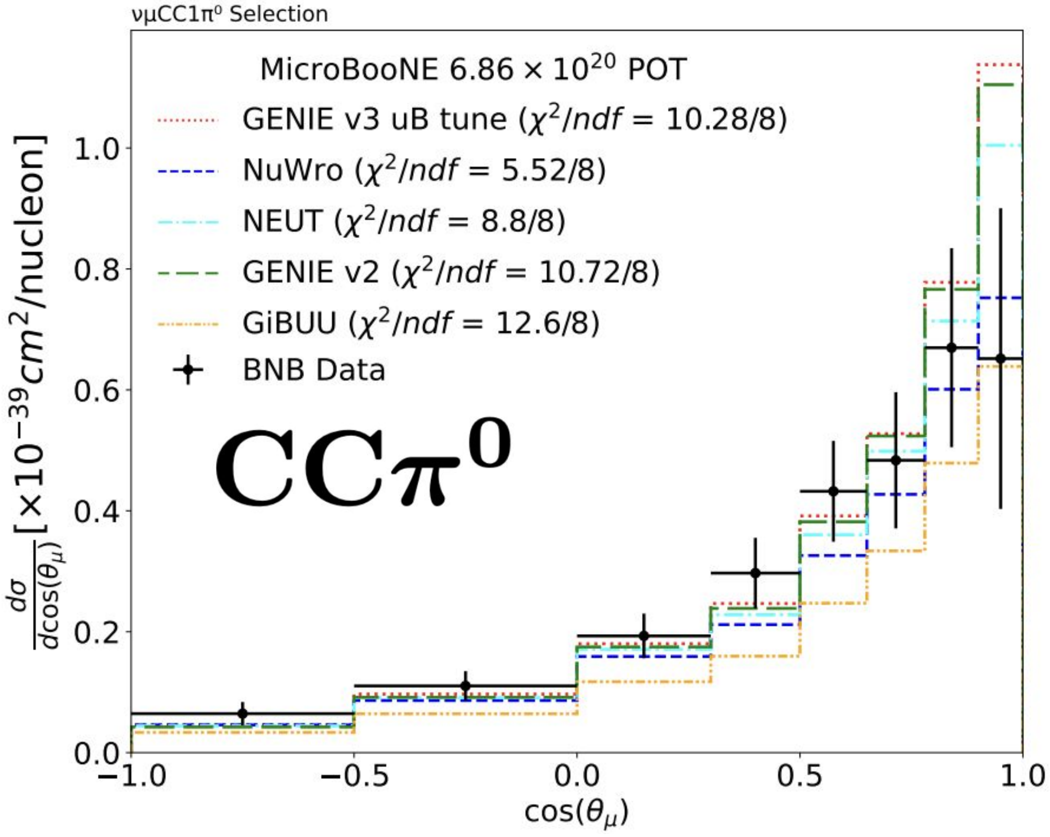




Results: $CC\pi^0$

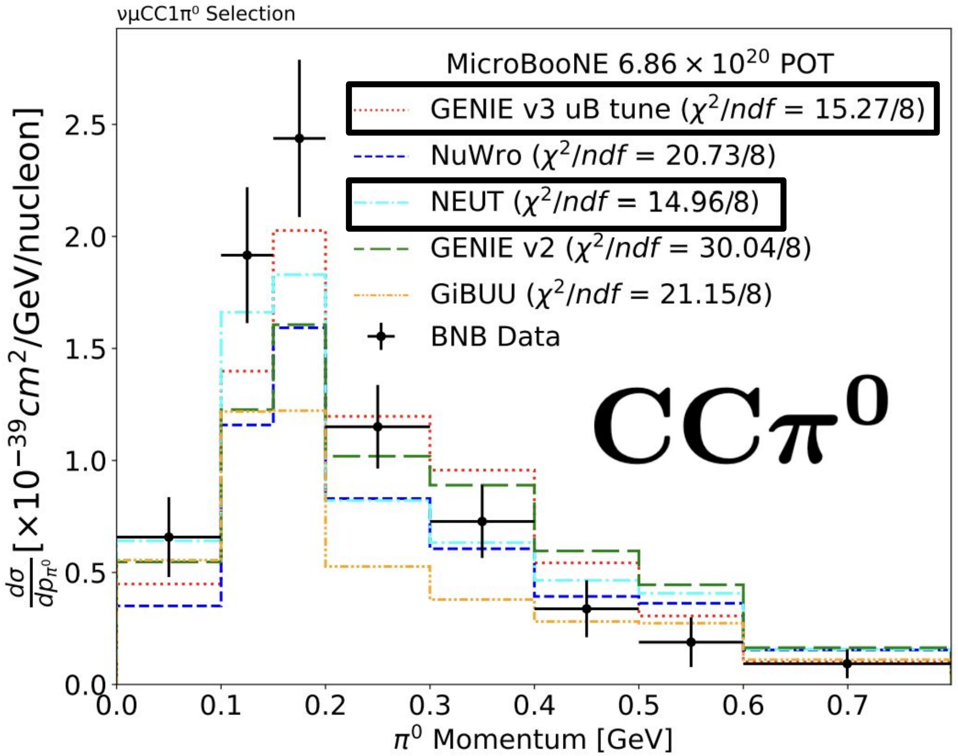
- Generators underestimate the $CC\pi^0$ cross section for both the muon and π^0 momentum around the peak of the distribution.
  - Similar trend in the muon momentum is seen in other MicroBooNE CC measurements: arXiv:2403.19574, arXiv:2402.19216
- Muon and π^0 angular distributions are described well, except at forward muon angles.

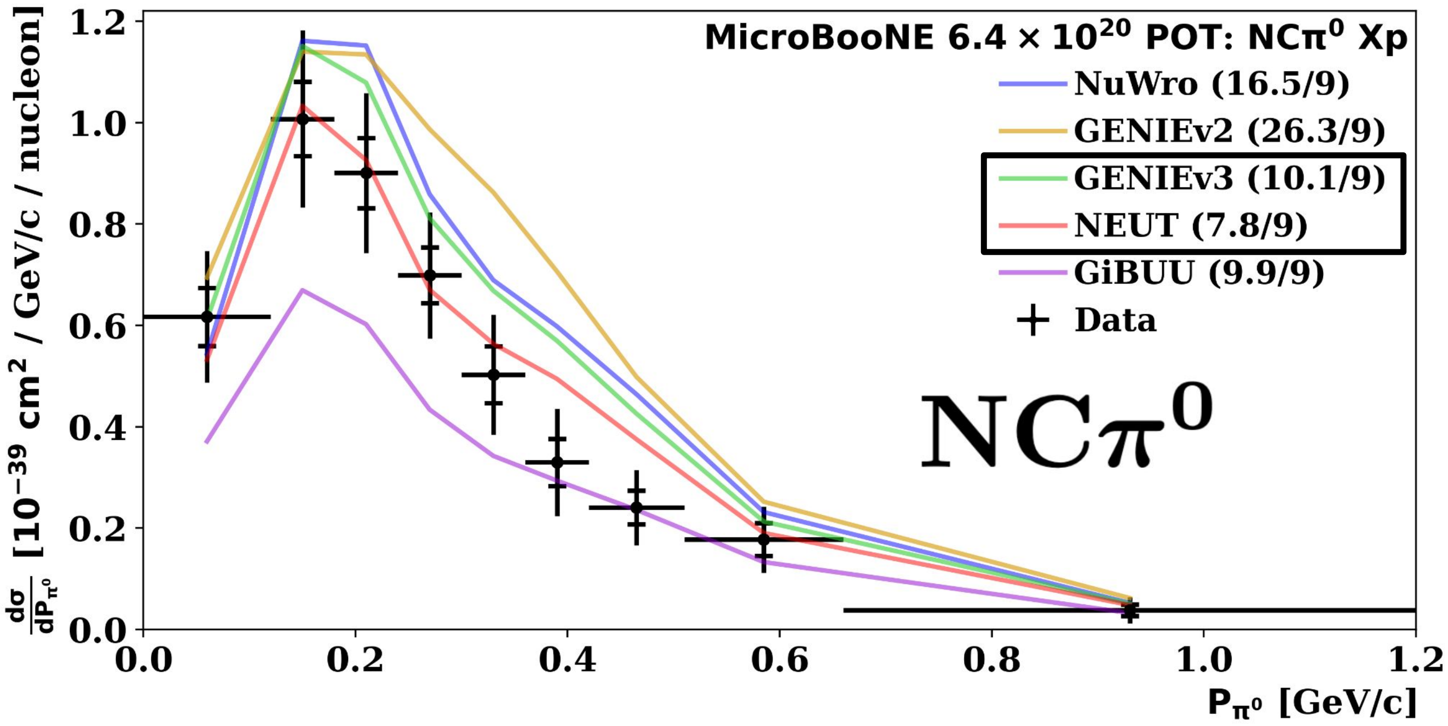




Results: NCπ^0 and CCπ^0 Comparison

- Both measurements are relatively consistent in the hierarchy of generators when it comes to the π^0 momentum:
  - **NEUT** offers the best description of the data, follow closely by **GENIEv3**.





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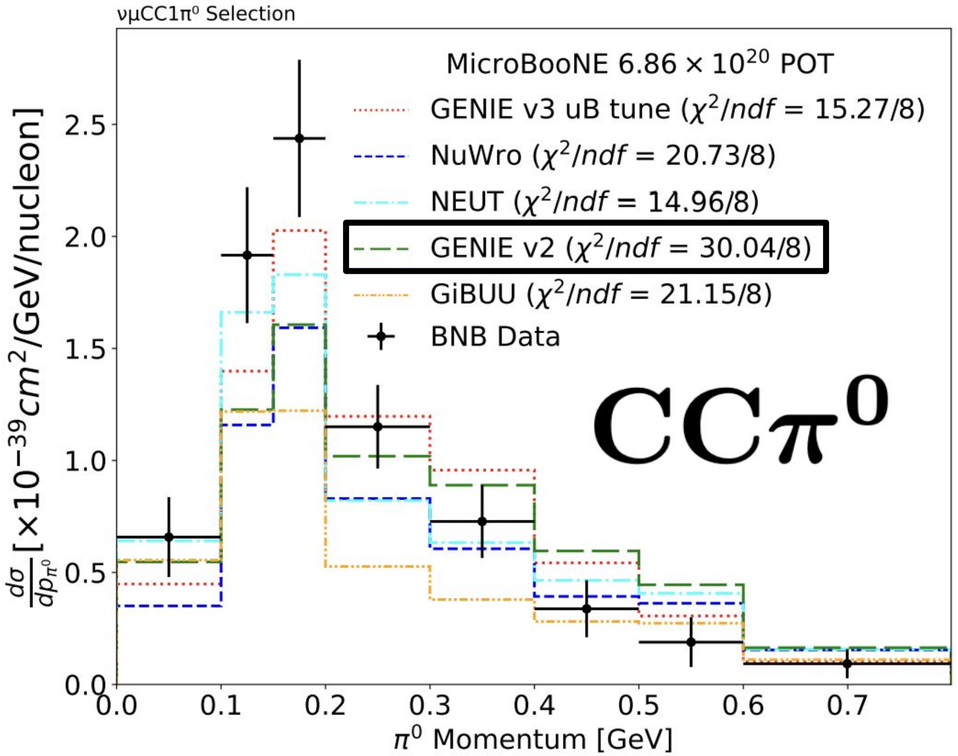

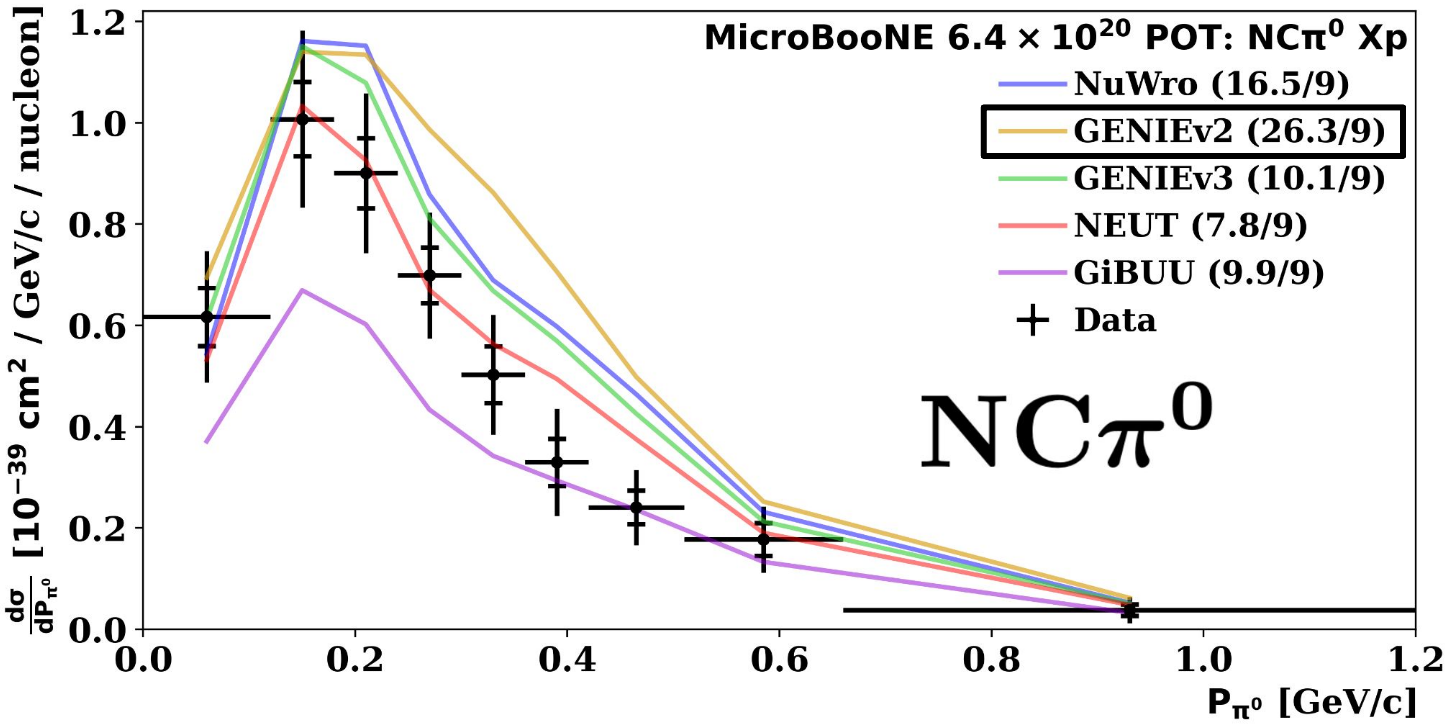

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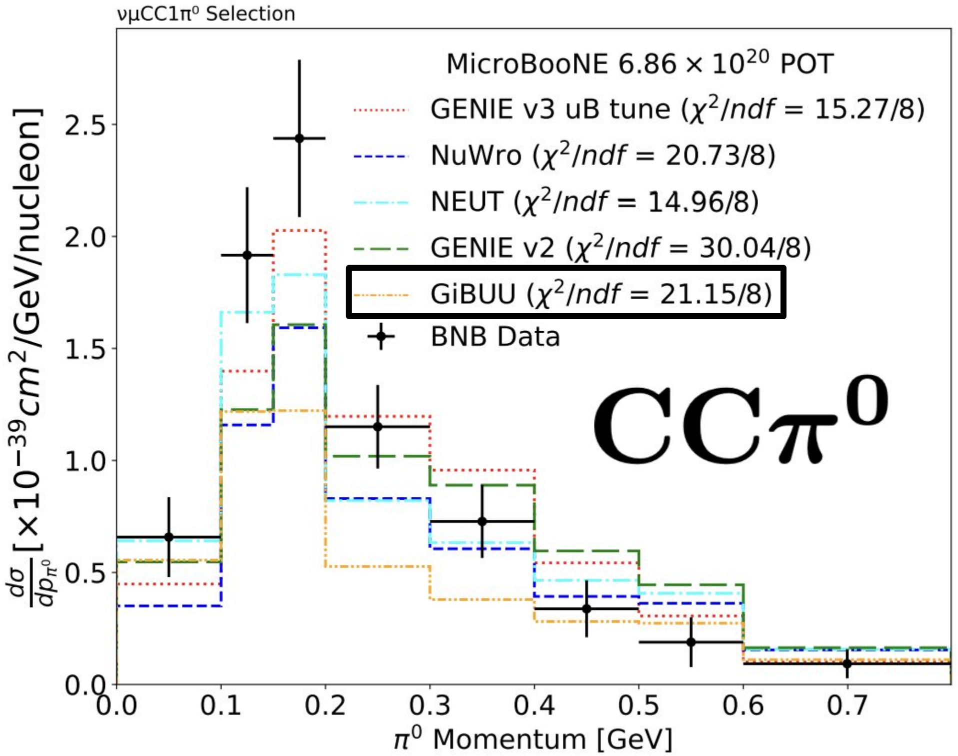
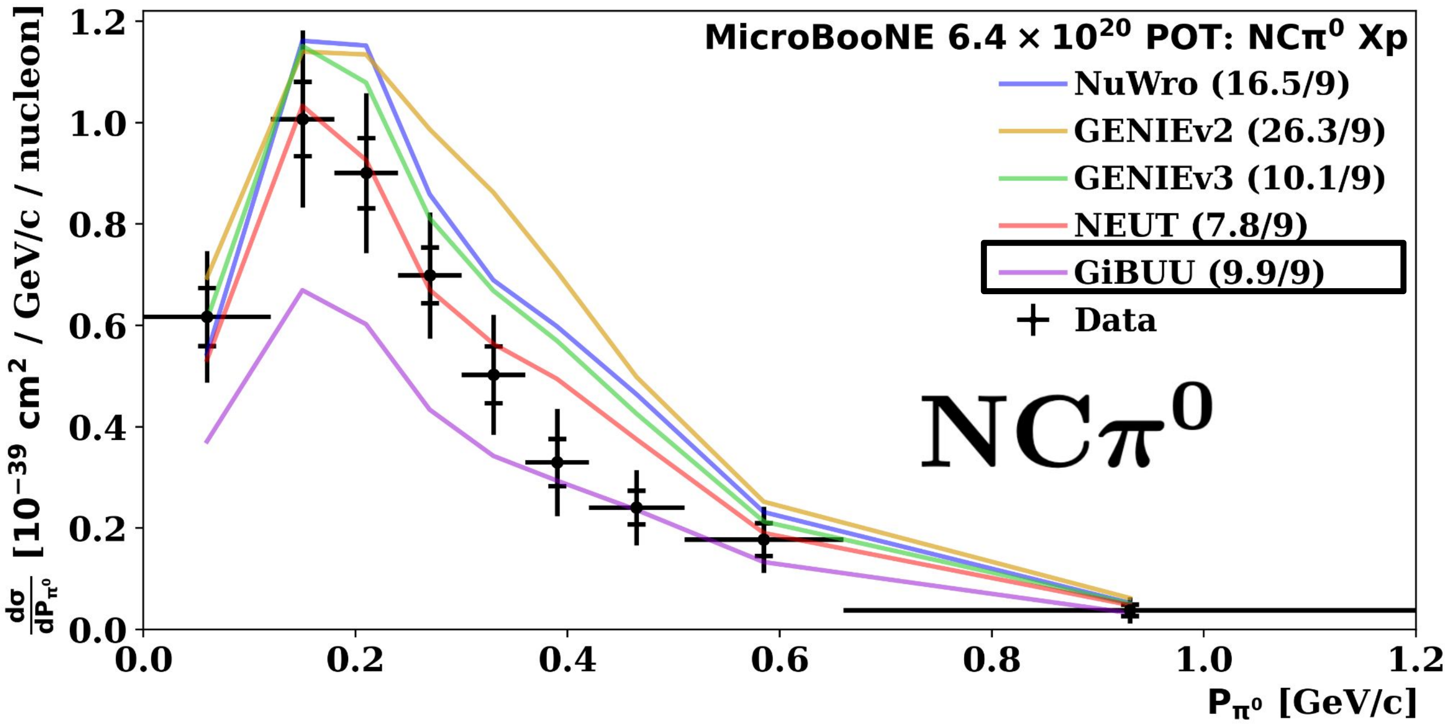
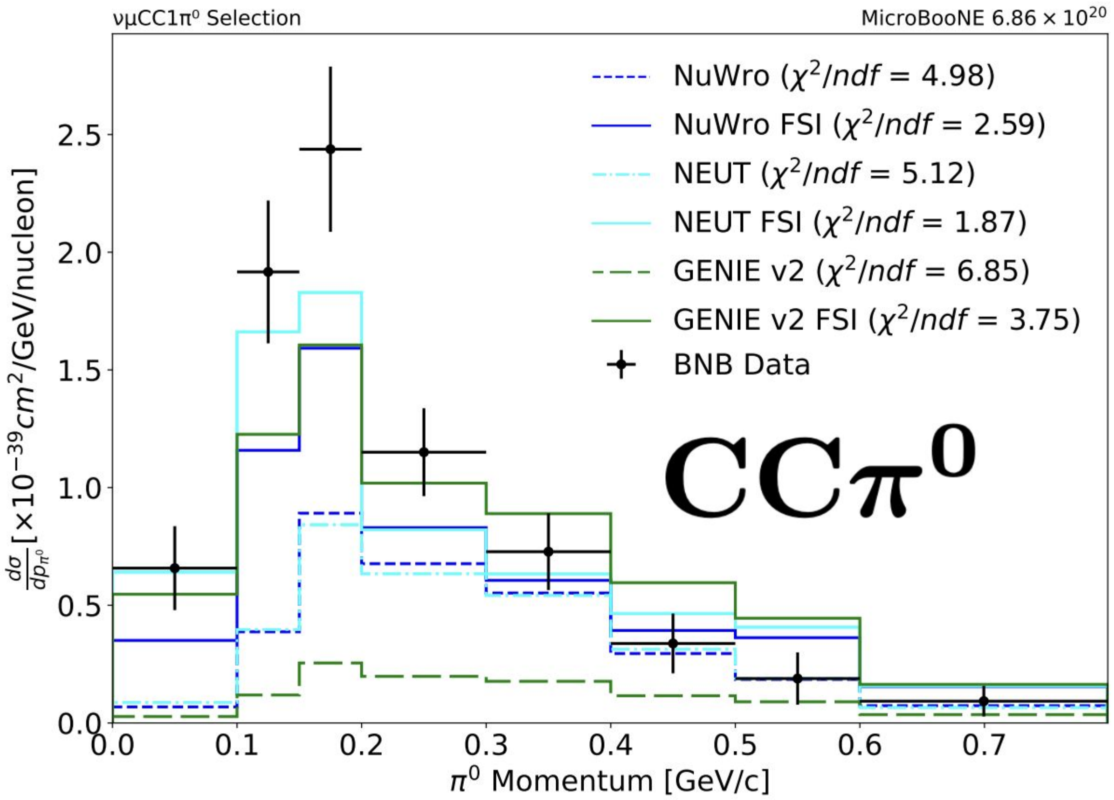




Result interpretation: FSI

$\mathbf{CC\pi^0}$

- FSI increases the CCπ^0 cross section.
    - Dominant CCπ^+ channel feeds the CCπ^0 channel through charge exchange FSI.
- FSI shifts the π^0 momentum distributions towards lower values.
- An underprediction by generators is seen in the medium momentum ranges.
    - Possibly related to the treatment of FSI, which is prominent in this regime.
    - Similar trends in CCπ^0 results from MiniBooNE and MINERvA.



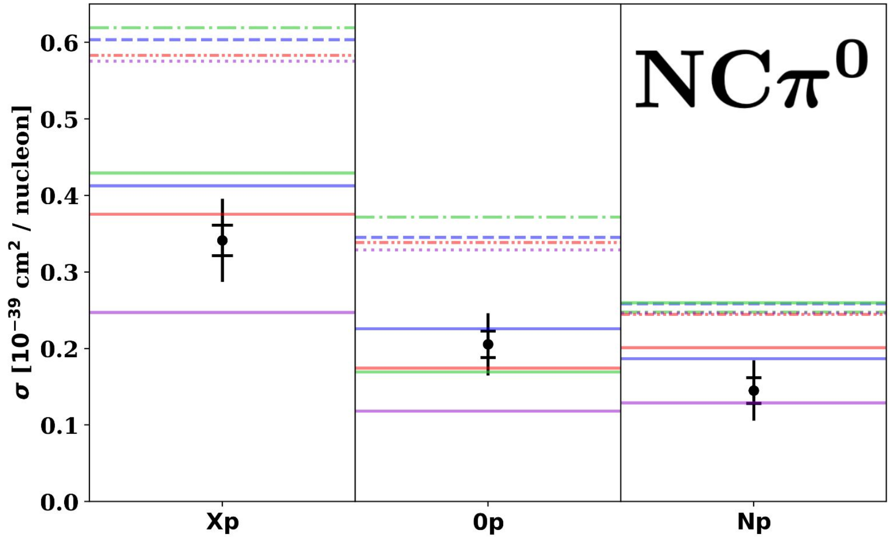
MiniBooNE: Phys. Rev. D **83**, 052009 (2011)

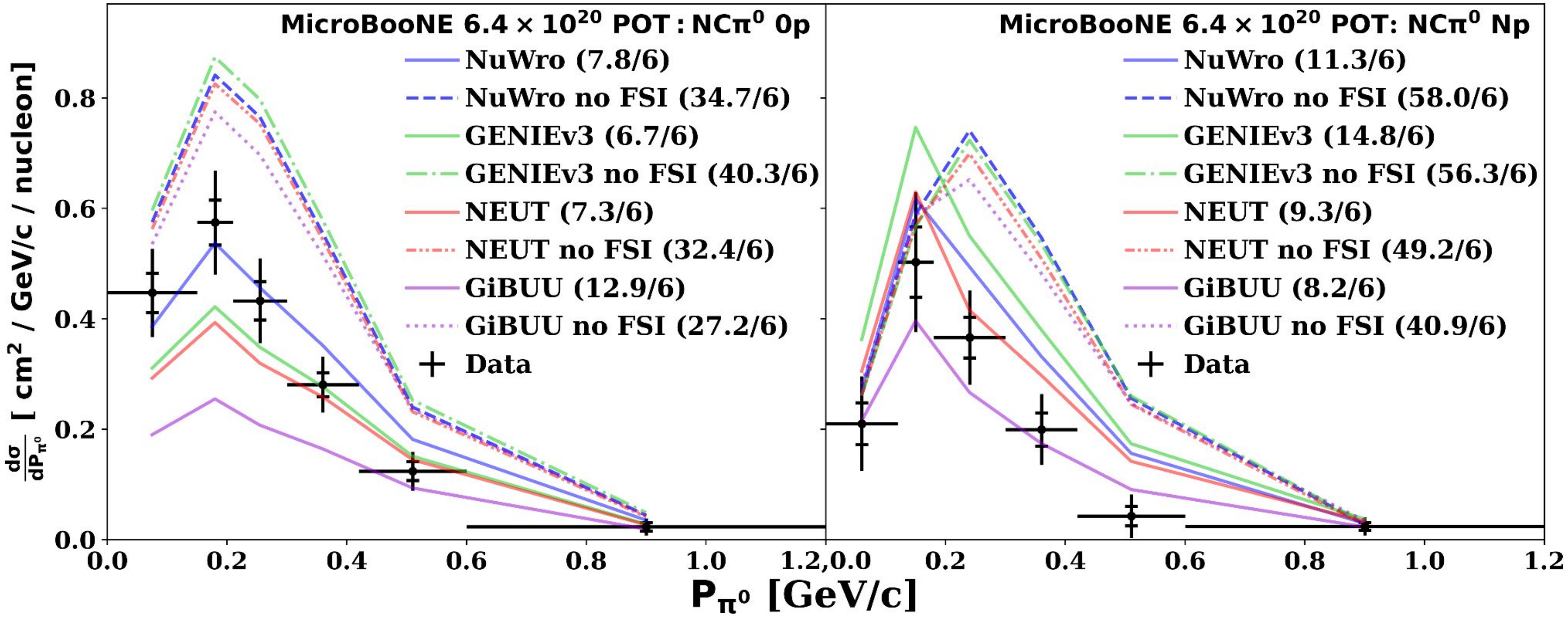
MINERVA: Phys. Rev. D **96**, 072003 (2017)

Result interpretation: FSI

$\mathbf{NC\pi^0}$

- For $NC\pi^0$ production, FSI **reduces** the cross section instead.
  - π^0 production dominates for the NC channel, so feeding to the $\pi^\pm$ channels through charge exchange FSI reduces the cross section.
- FSI shifts 0p to Np ratio.





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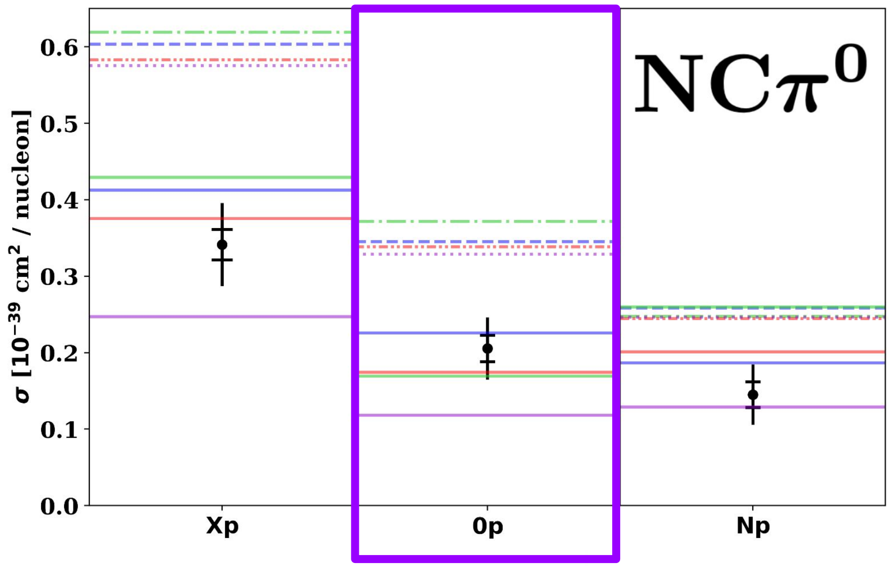
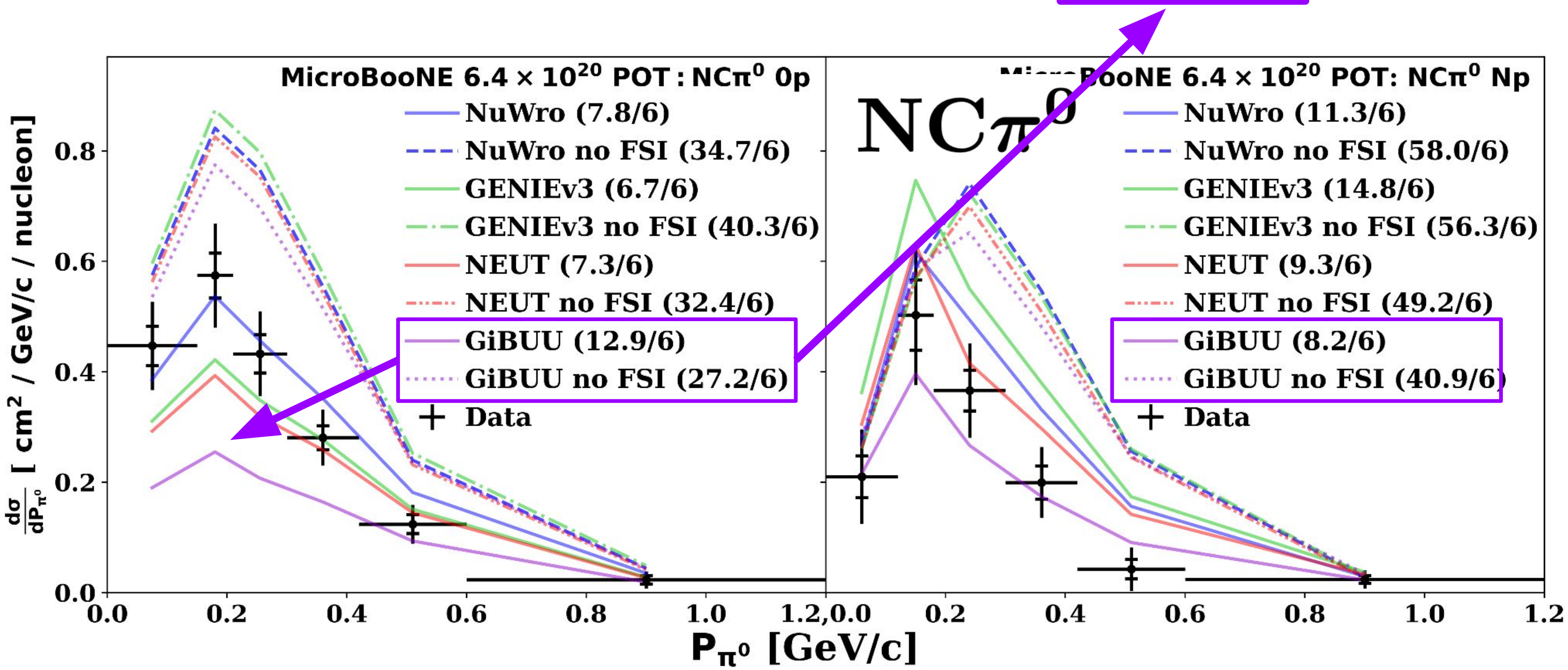
- **GiBUU** reduces the total cross section the **most,** especially in the 0p channel.
  - Large underprediction of the 0p cross section.

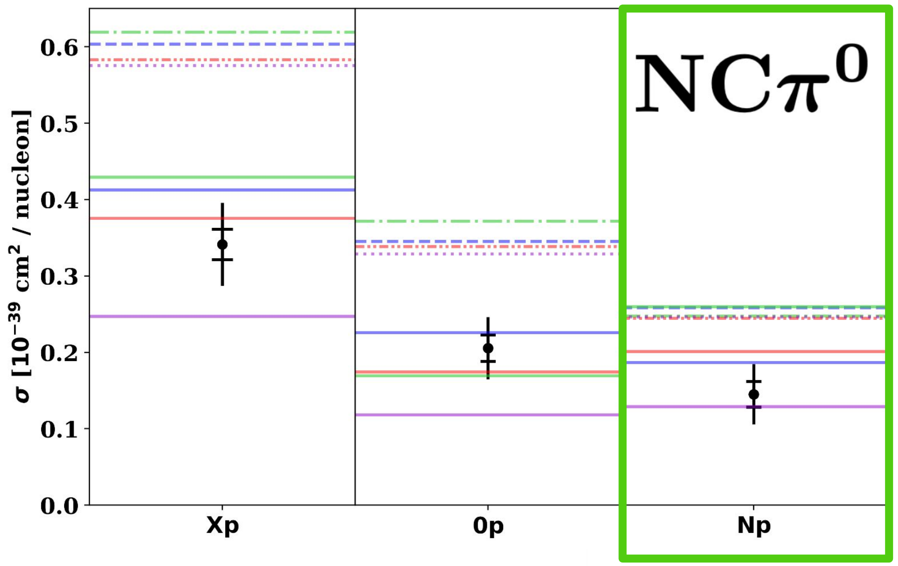


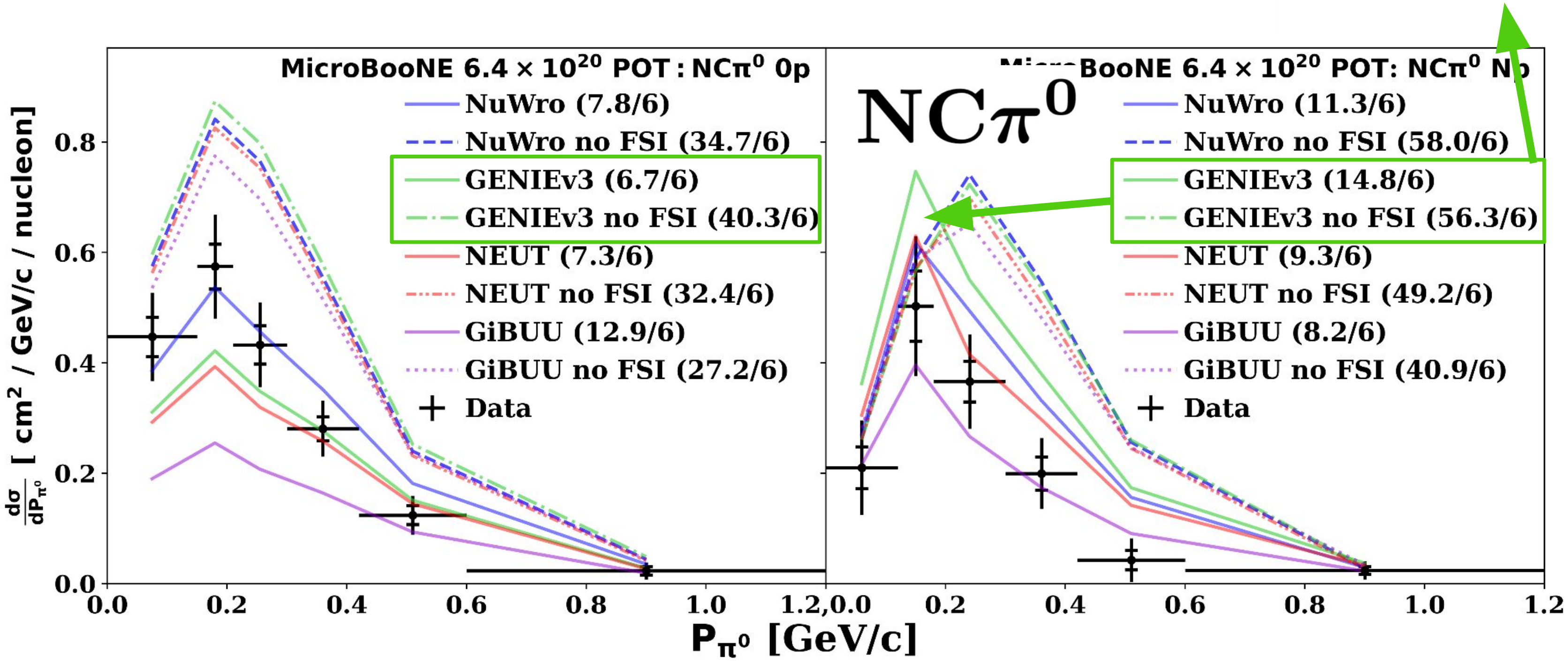


Result interpretation: FSI

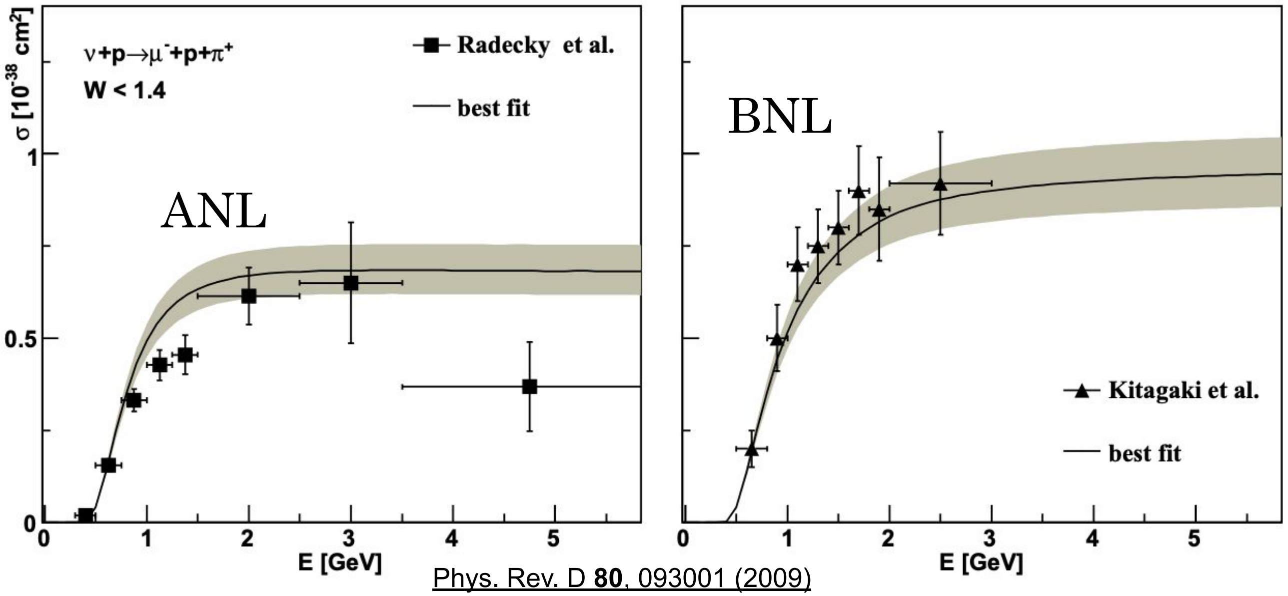
$NC\pi^0$

- For $NC\pi^0$ production, FSI **reduces** the cross section instead.
  - π^0 production dominates for the NC channel, so feeding to the $\pi^\pm$ channels through charge exchange FSI reduces the cross section.
- FSI shifts 0p to Np ratio.
- **GiBUU** reduces the total cross section the **most,** especially in the 0p channel.
  - Large underprediction of the 0p cross section.
- **GENIEv3** reduces the total cross section the **least**, especially in the Np channel.
  - Large overprediction of the Np cross section.





Interpreting the Results: Axial Form Factors



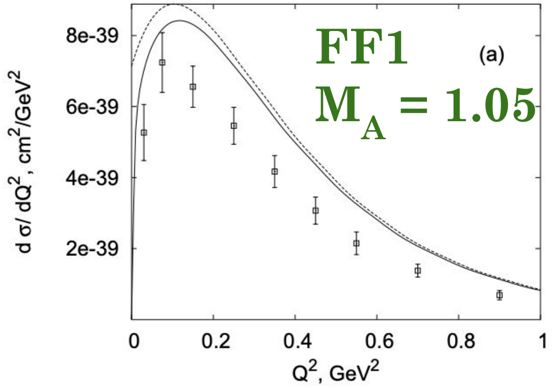
Phys. Rev. D **80**, 093001 (2009)

$$C_5^A(Q^2) = \frac{C_5^A(0)}{(1+Q^2/M_A^2)^2}\frac{1}{1+Q^2/3M_A^2}$$

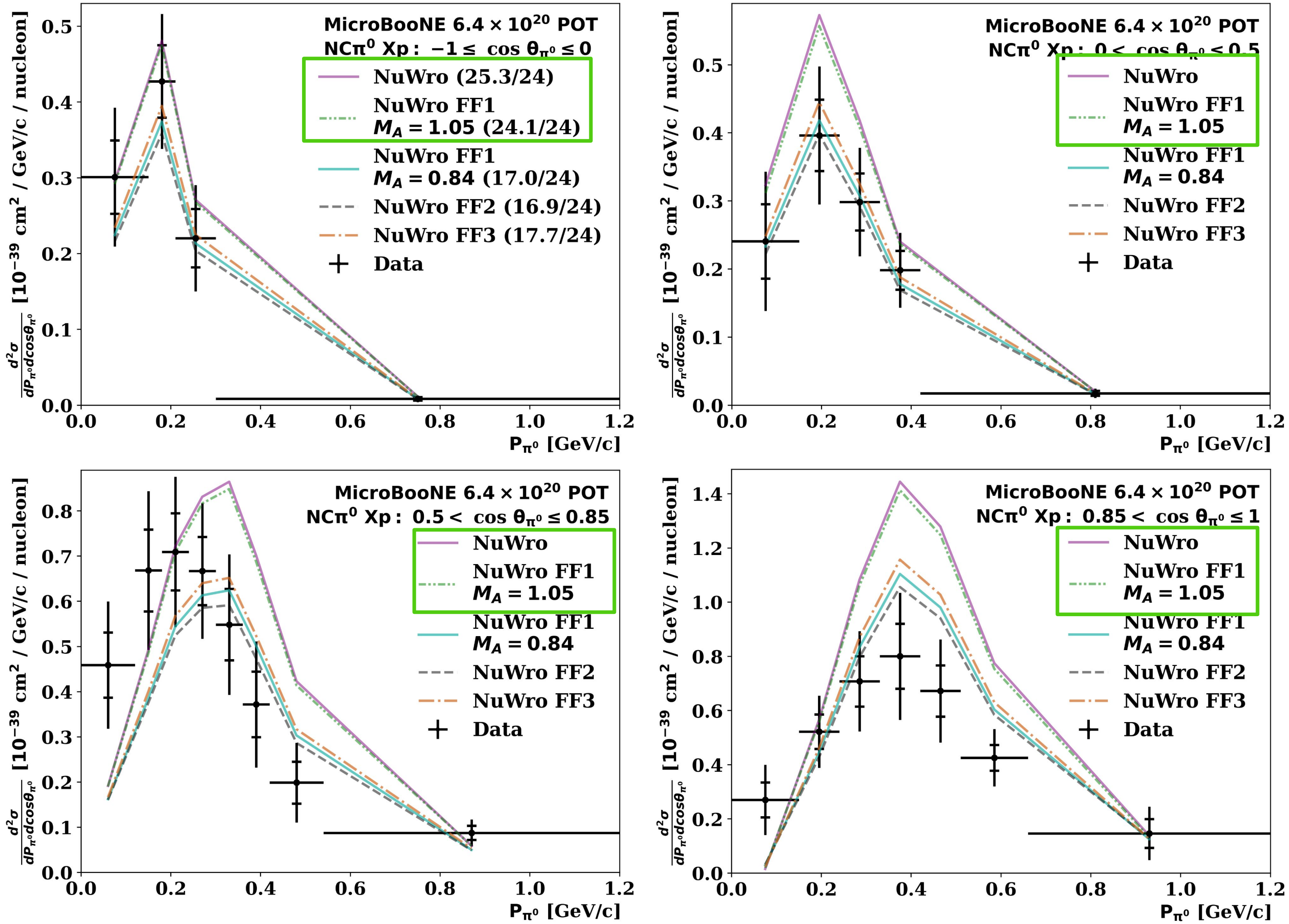
Axial form factors must be fit to neutrino data!

- Initial neutrino-nucleus production of resonances parameterized with axial and vector form factors obtained from fits to data.
- Axial form factors commonly fit using two (very old) bubble chamber $CC\pi^+$ data sets.
  - One from ANL and one from BNL.
  - Data sets differ in normalization by **~30%** leading to large theoretical uncertainties.
- Our π^0 data provide an invaluable benchmark.

Form Factors $NC\pi^0$



Comparison to ANL data
Phys.Rev. D71 074003 (2005)

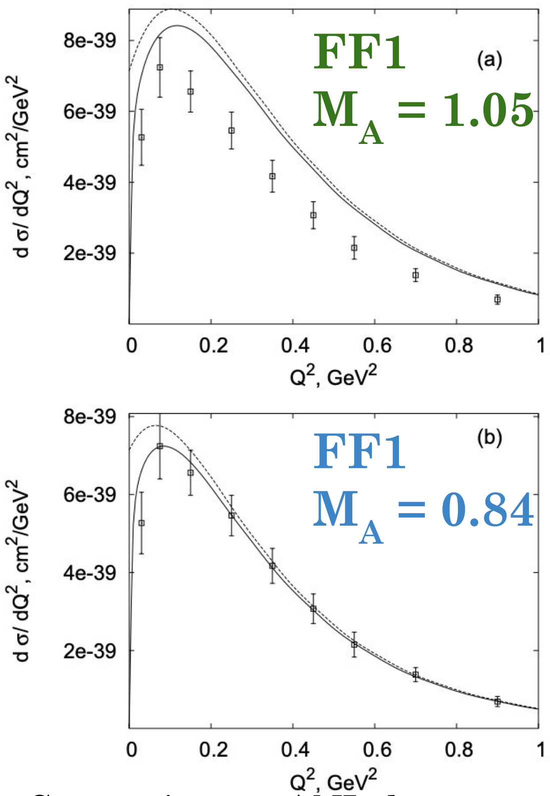


Form factors from:
Phys.Rev. D71 074003 (2005)
Phys. Rev. D **80**, 093001 (2009)

- $NC\pi^0$ data compared to predictions with 5 different form factors using **NuWro**.
  - **NuWro** and **NuWro FF1 M_A = 1.05** agree with BNL data but overpredict ANL data.

Form Factors

NCπ⁰



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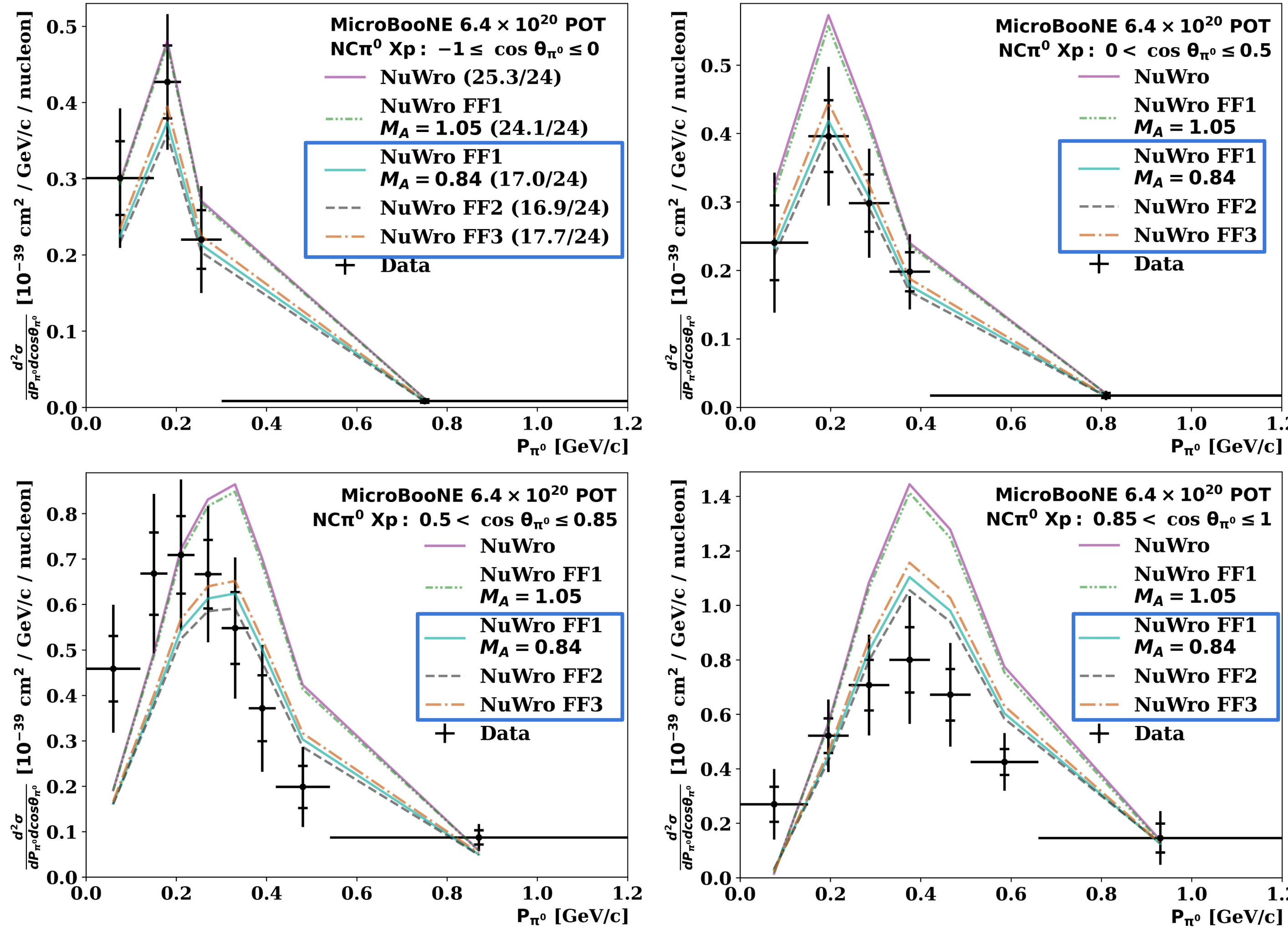

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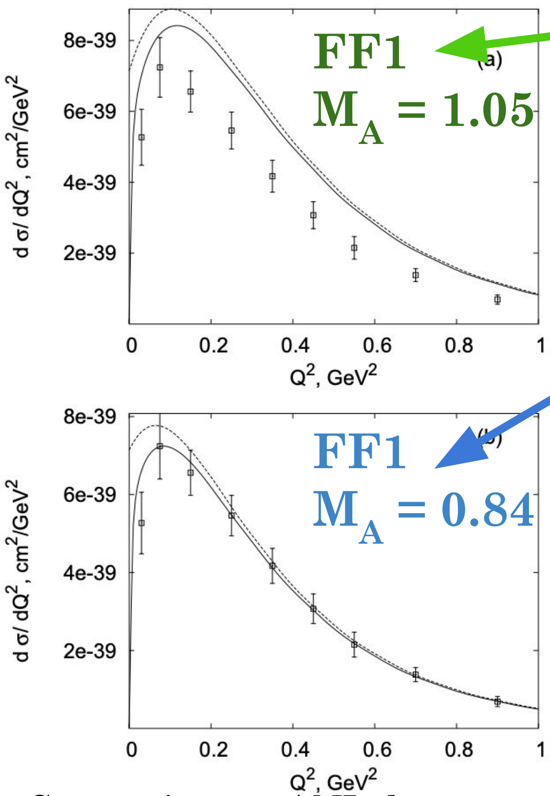
- NCπ^0 data compared to predictions with 5 different form factors using **NuWro**.
  - **NuWro** and **NuWro FF1 M_A = 1.05** agree with BNL data but overpredict ANL data.
  - **NuWro FF1 M_A = 0.84** , **NuWro FF2**, and **NuWro FF3** show better agreement with ANL data, but underpredict BNL data.

Form Factors

NCπ⁰



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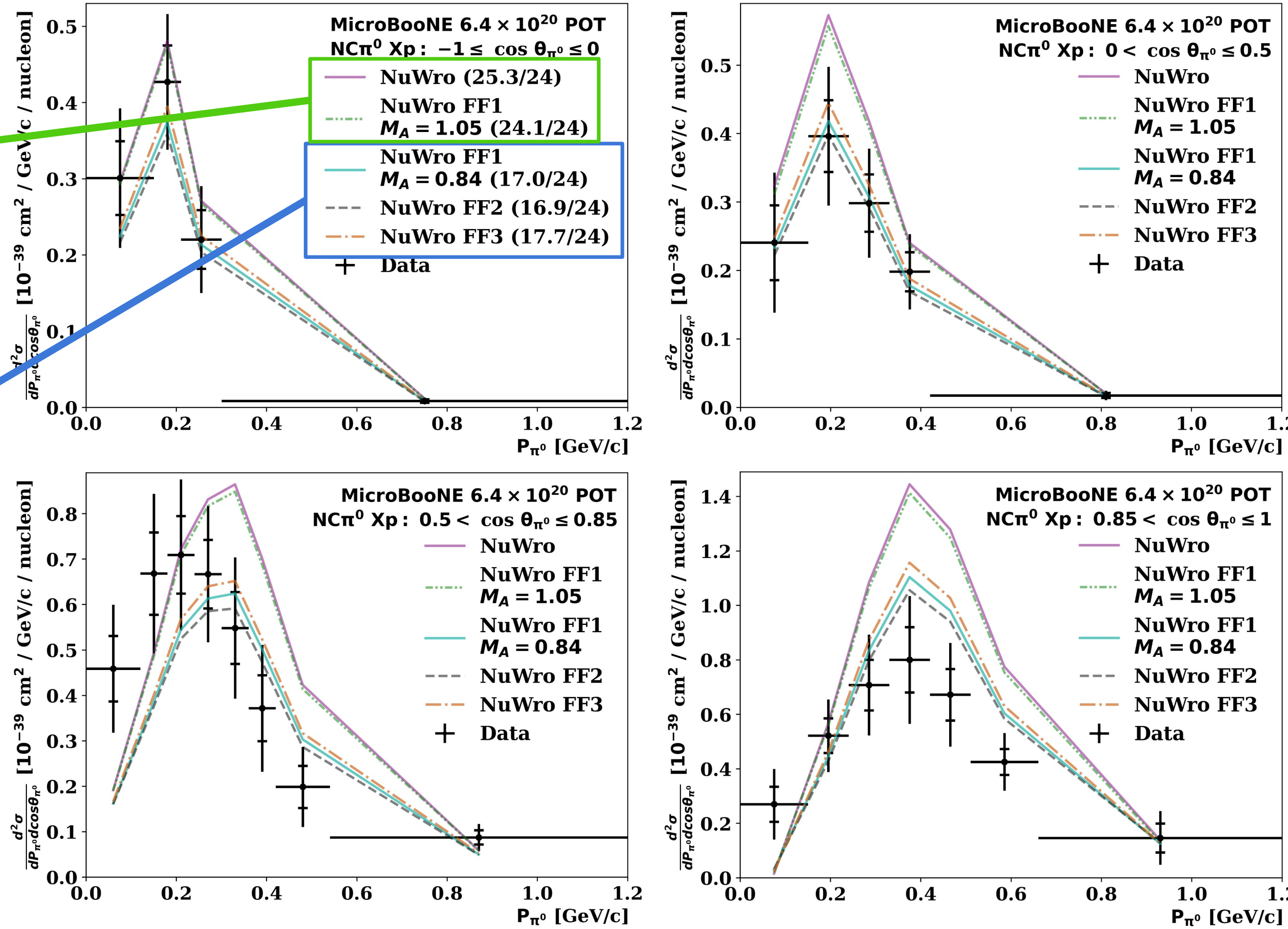

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Phys. Rev. D **80**, 093001 (2009)

- $NC\pi^0$ data compared to predictions with 5 different form factors using **NuWro**.
  - **NuWro** and **NuWro FF1 M_A = 1.05** agree with BNL data but overpredict ANL data.
  - **NuWro FF1 M_A = 0.84** , **NuWro FF2**, and **NuWro FF3** show better agreement with ANL data, but underpredict BNL data.
- **Our $NC\pi^0$ data prefers the predictions that agree better with ANL data.**

Summary

- New CCπ^0 and NCπ^0 differential cross section measurements from MicroBooNE expand upon previous total cross section results.
- Provide novel information about neutral pion production on argon useful for improving event generator modeling.
  - Generators overpredict the NCπ^0 cross section, especially at moderate π^0 momentum and when a proton is present in the final state.
  - Generators underpredict the CCπ^0 cross section especially around the peak of the muon and pion momentum distributions.

$$C_5^A(Q^2) = \frac{C_5^A(0)}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$

M_A = 0.94: NuWro default

Phys. Rev. D 90, 112017 (2009)

$$C_5^A(Q^2) = \frac{C_5^A(0)}{(1 + Q^2/M_A^2)^2} \frac{1}{1 + Q^2/3M_A^2}$$

FF1

M_A = 1.05 or M_A = 0.84

Phys.Rev. D71 074003 (2005)

$$C_5^A(Q^2) = \frac{C_5^A(0)}{(1 + Q^2/M_A^2)^2} \frac{1}{1 + 2Q^2/M_A^2},$$

FF2

with $M_A = 1.05$ GeV or

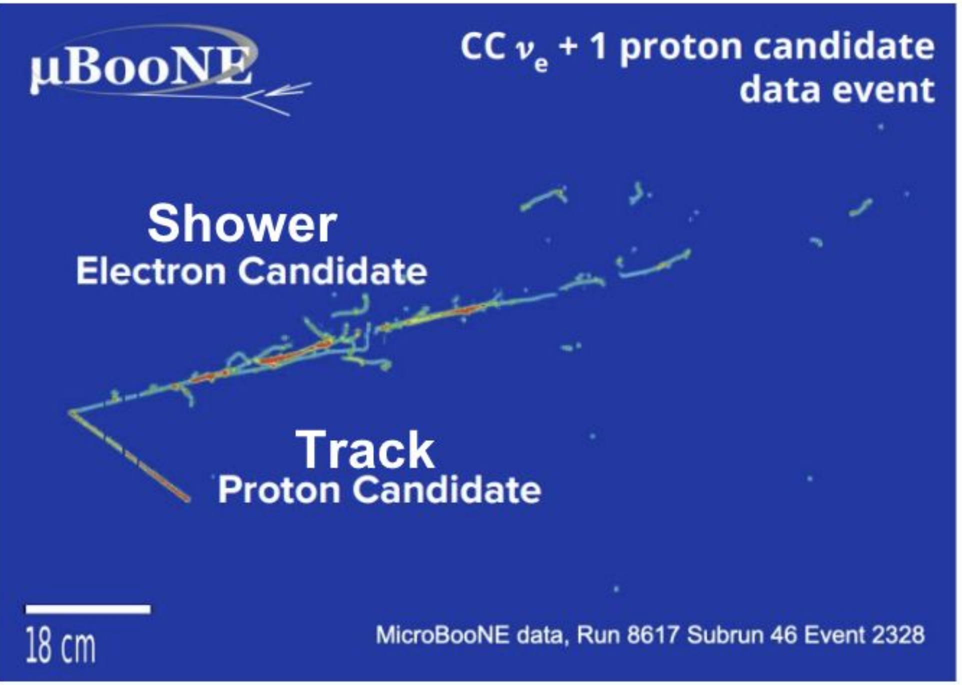
$$C_5^A(Q^2) = \frac{C_5^A(0)}{(1 + Q^2/M_A^2)^2} \left(\frac{1}{1 + Q^2/3M_A^2}\right)^2,$$

FF3

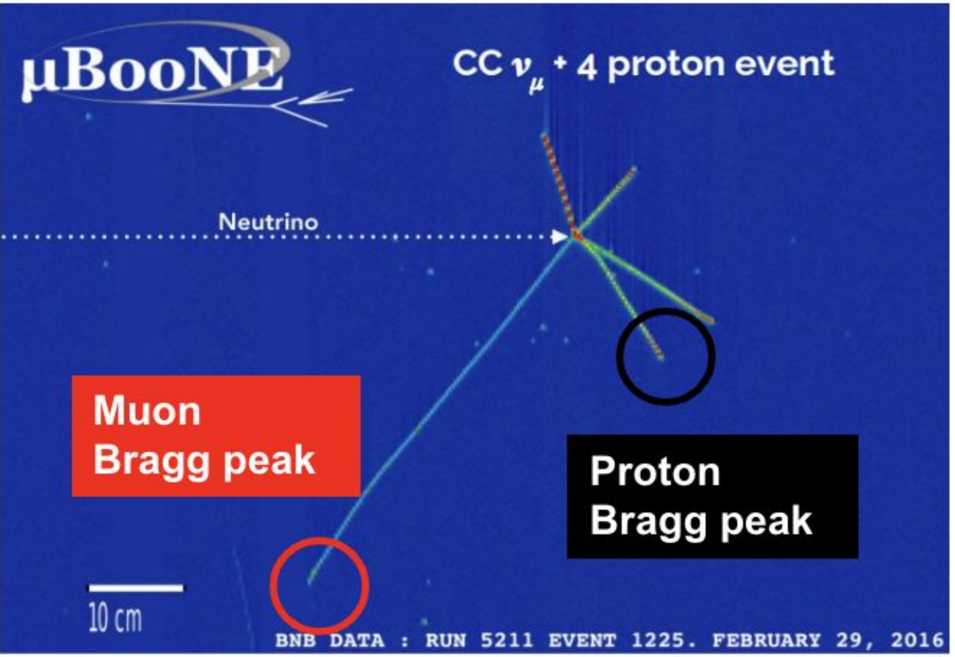
with $M_A = 0.95$ GeV

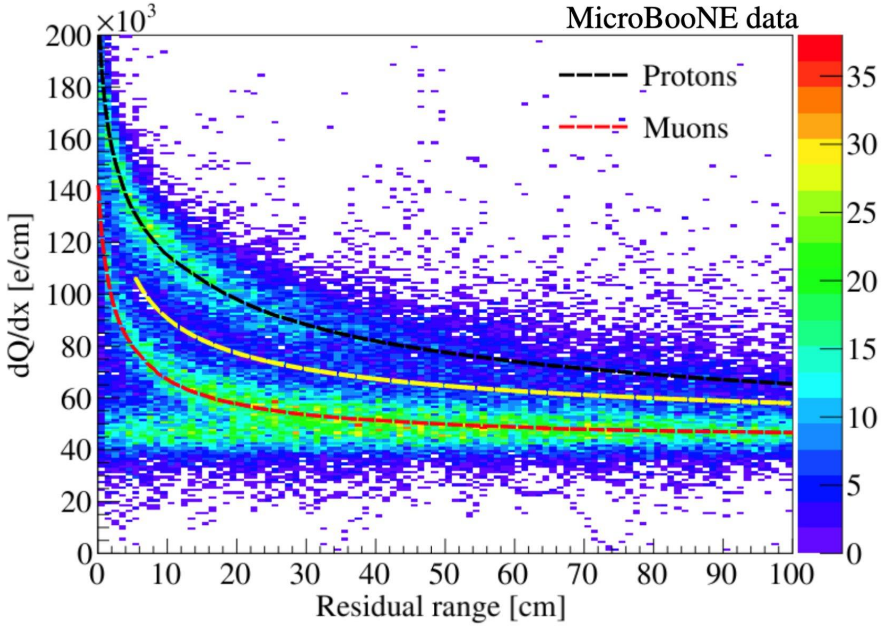
https://nuwro.github.io/user-guide/getting-started/parameters/

Track/shower and Muon/Proton Separation



- Two distinct particle topologies:
  - Showers produced by electrons and photons.
  - Tracks produced by charged pions, muons and protons.
- Proton and muon tracks are distinguished based on differences in their dQ/dx profile.
  - Protons have a sharper Bragg peak than muons.

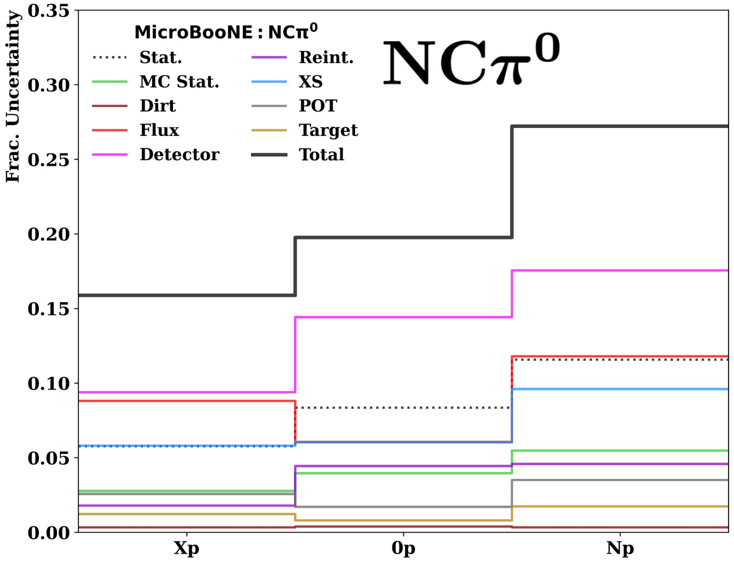


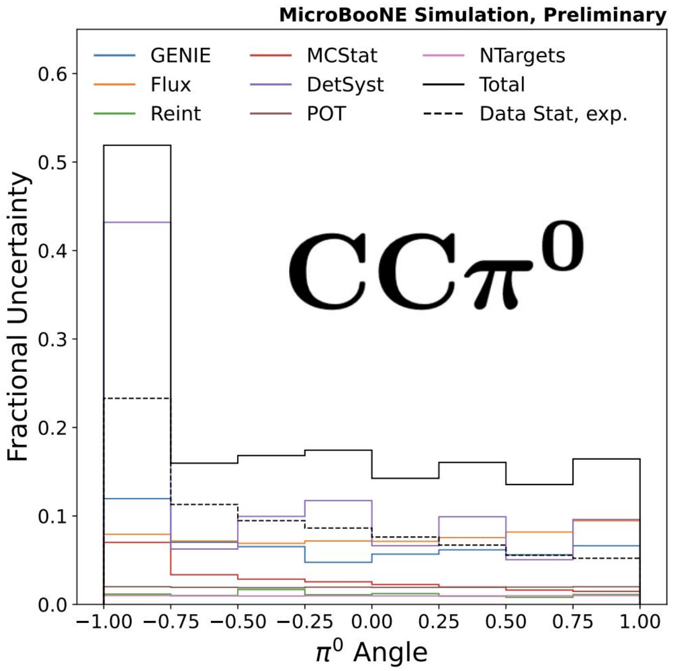


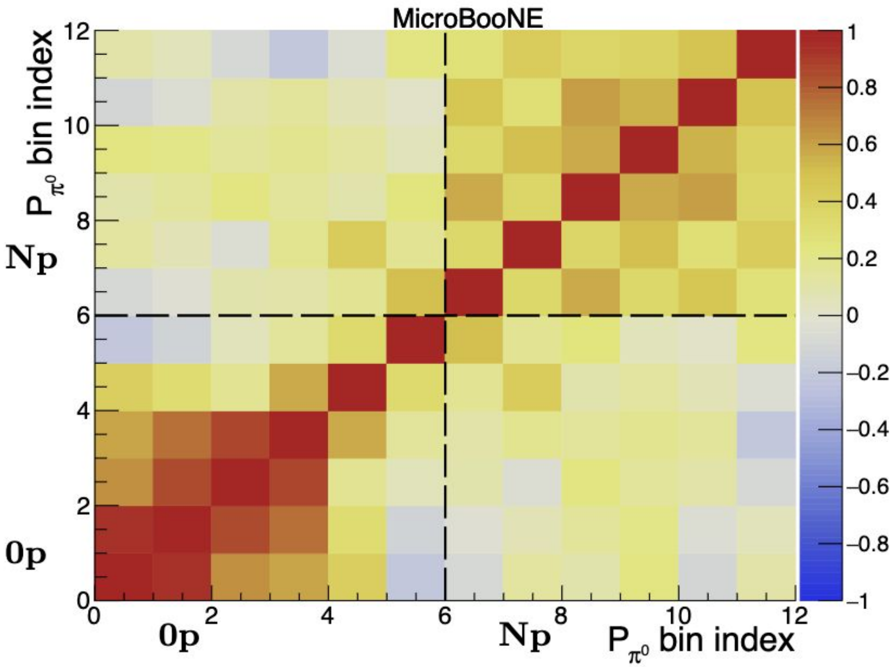
Systematics

$$V_{ij} = \frac{1}{N}\sum_{k}^{N}(M_i^k - M_i^{CV})(M_j^k - M_j^{CV})$$

- Uncertainties are evaluated with the covariance matrix formalism.
- Consider systematic uncertainties from detector response, neutrino flux, cross section modeling, and secondary interactions outside the target nucleus.
- Both measurements are systematics limited.
  - Detector uncertainties tend to be the most prominent, particularly for the NCπ^0 analysis.



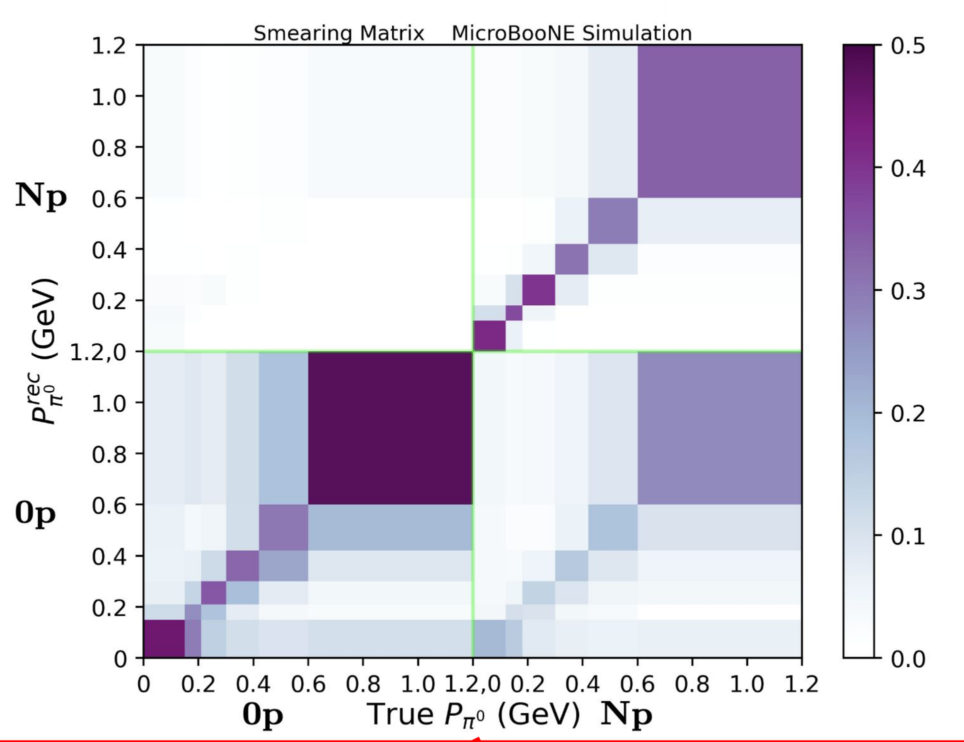




NCπ^0 correlation matrix for the 0pNp π^0 momentum measurement.

0p and Np NCπ^0 Measurements

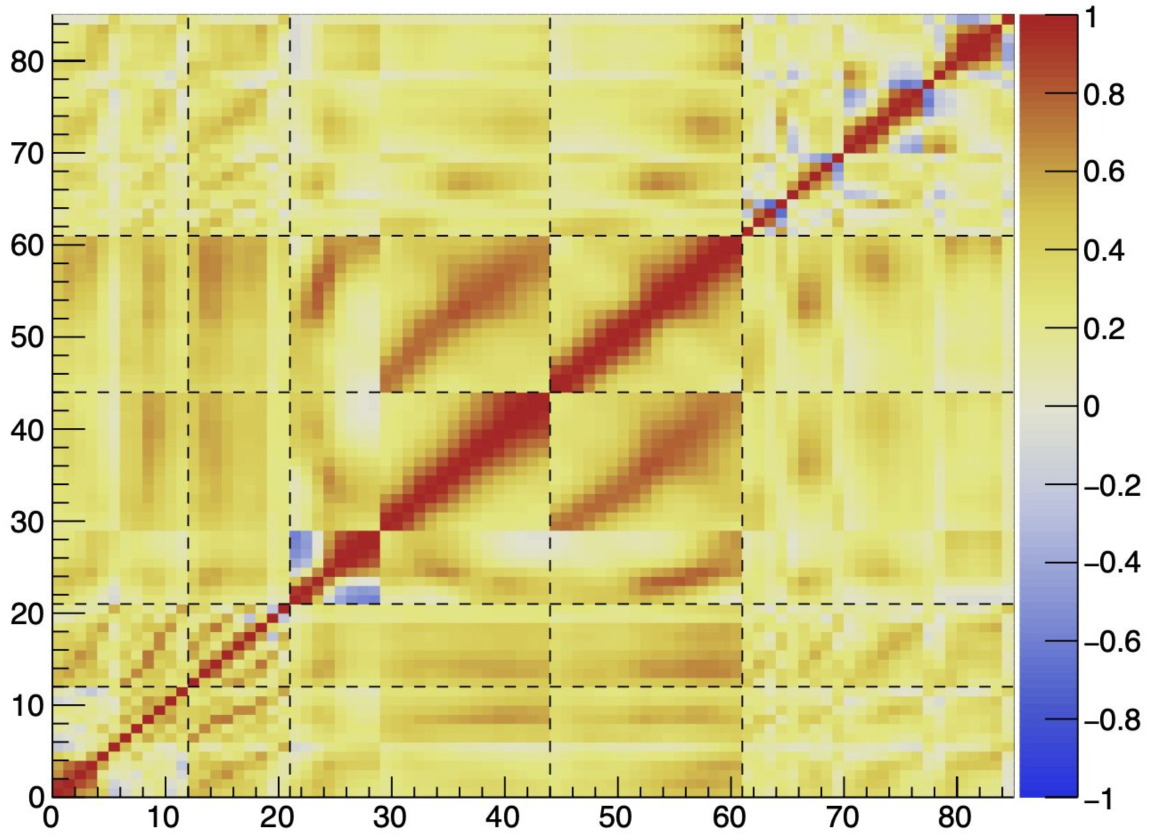
- 0p and Np results are extracted simultaneously*.
- Response matrix to have off-diagonal blocks describing the true (0p) Np contribution to the Np (0p) selection.
  - Analogous to a double differential measurement.
- Allows the Np background in the 0p selection to be informed by the Np selection and vice versa.
  - Reduces the dependance on the model for background subtraction.
- 92% of NCπ^0 signal events passing the Np selection satisfy the Np signal criteria.
- 54% of NCπ^0 signal events passing the Np selection satisfy the Np signal criteria.



$$\begin{pmatrix} M_{0p} \\ M_{Np} \end{pmatrix} = \begin{pmatrix} R_{0p0p} & R_{0pNp} \\ R_{Np0p} & R_{NpNp} \end{pmatrix} \cdot \begin{pmatrix} S_{0p} \\ S_{Np} \end{pmatrix} + \begin{pmatrix} B_{0p} \\ B_{Np} \end{pmatrix}$$

*35MeV proton kinetic energy threshold applied to 0pNp measurements motivated by MicorBooNE's ~1cm track detection threshold. This is applied to both the signal and the selection.

Blockwise Unfolding



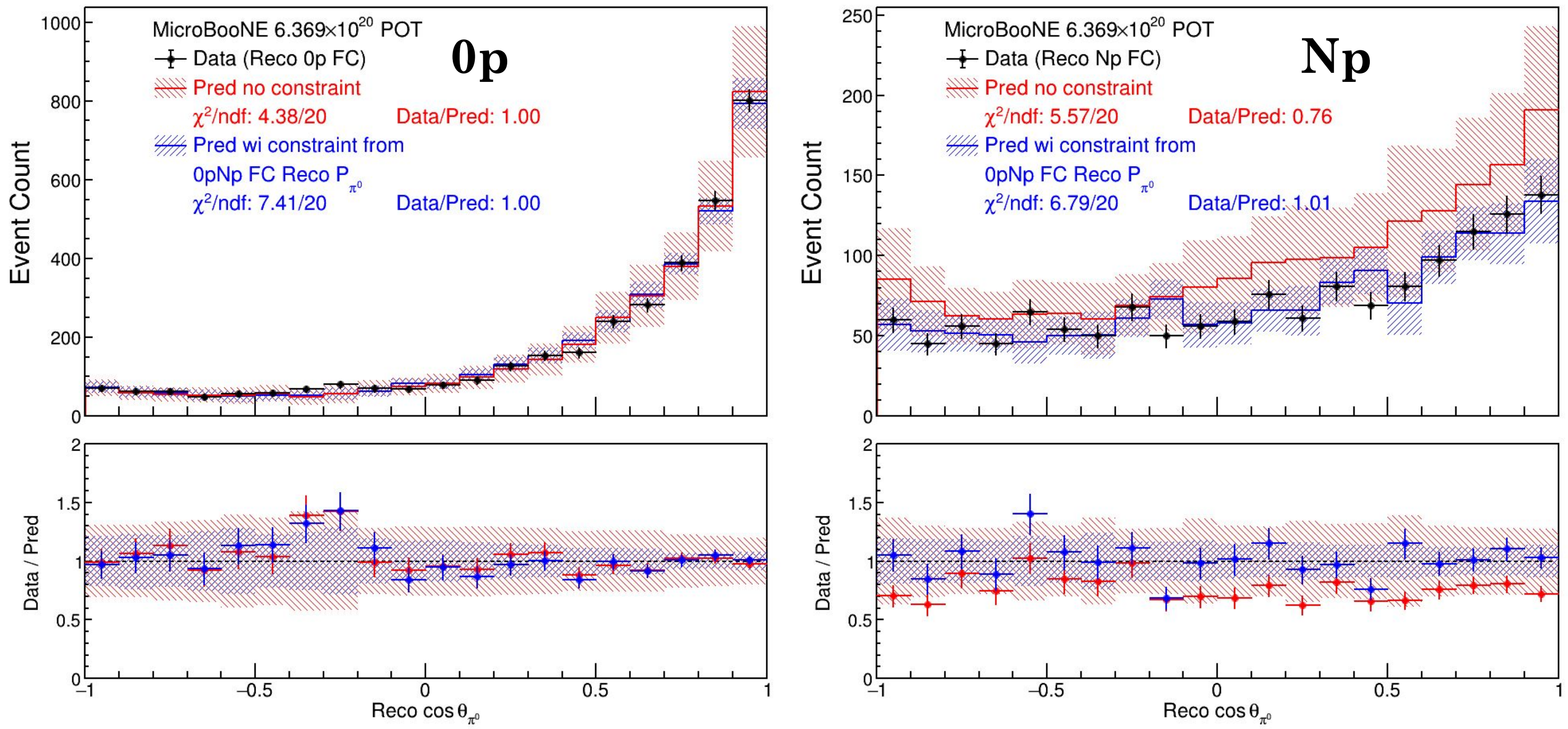
Measurement	Channel	ndf	NuWro	GENIEv2	GENIEv3	NEUT	GiBUU
All Bins	0p	14	12.2	17.4	14.6	10.7	16.8
	Np	21	16.9	30.3	20.0	14.0	13.8
	0pNp	35	24.5	39.9	30.3	23.0	28.9
	Xp	50	36.0	44.1	25.0	23.6	27.7
	0pNpXp	85	82.2	68.8	47.8	53.9	58.5

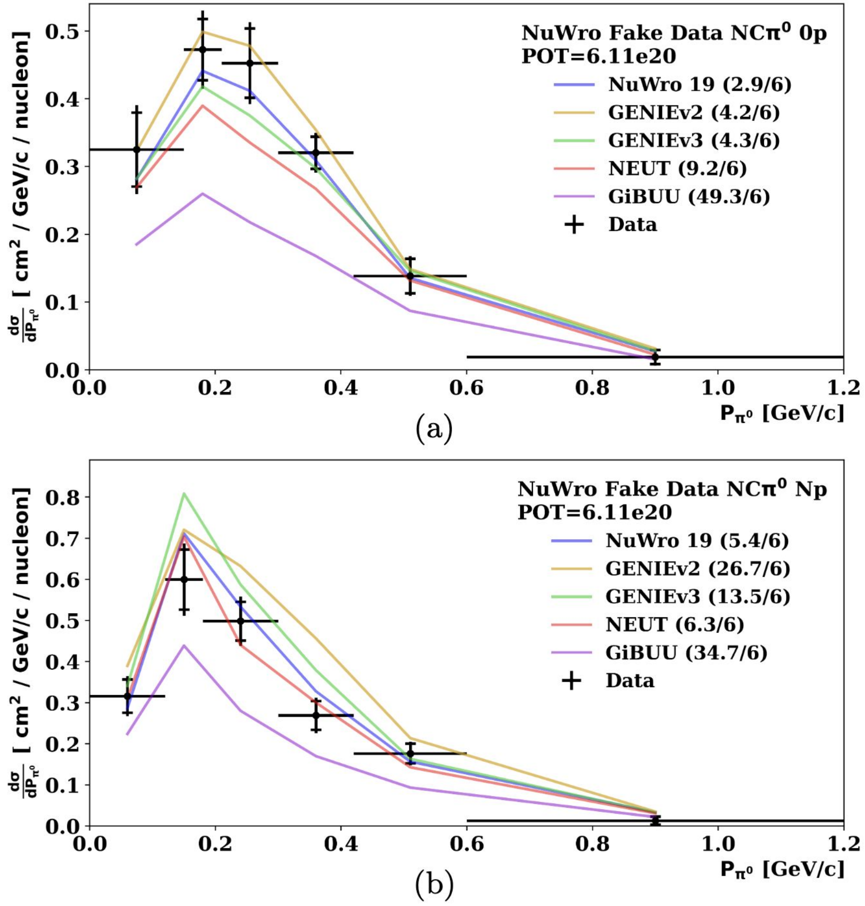
Data release for the NCπ^0 analysis reports correlations between individual measurement through the use of blockwise unfolding.

For more discussion on this method, see: https://arxiv.org/abs/2401.04065

Order of blocks: 1.) 0pNp π^0 momentum, 2.) Xp π^0 momentum, 3.) 0pNp π^0 scattering angle, 4.) Xp π^0 scattering angle, 5.) Xp double-differential π^0 momentum and scattering angle

Model Validation and Fake Data Studies





(a)

(b)

- Cross section measurements rely on model predictions to estimate the rate of background events, selection efficiencies, and detector smearing.
- Utilized fake data studies and data-driven model validation analogous to other MicroBooNE analyses to ensure that the model is sufficient for extracting unbiased cross section results.
  - Relies on GoF tests and the conditional constraint formalism.
  - Tailored to investigate the modeling of each hadronic final state and the π^0 kinematics in the context of a double-differential measurement.