Latest Neutral Pion Production Measurements from MicroBooNE

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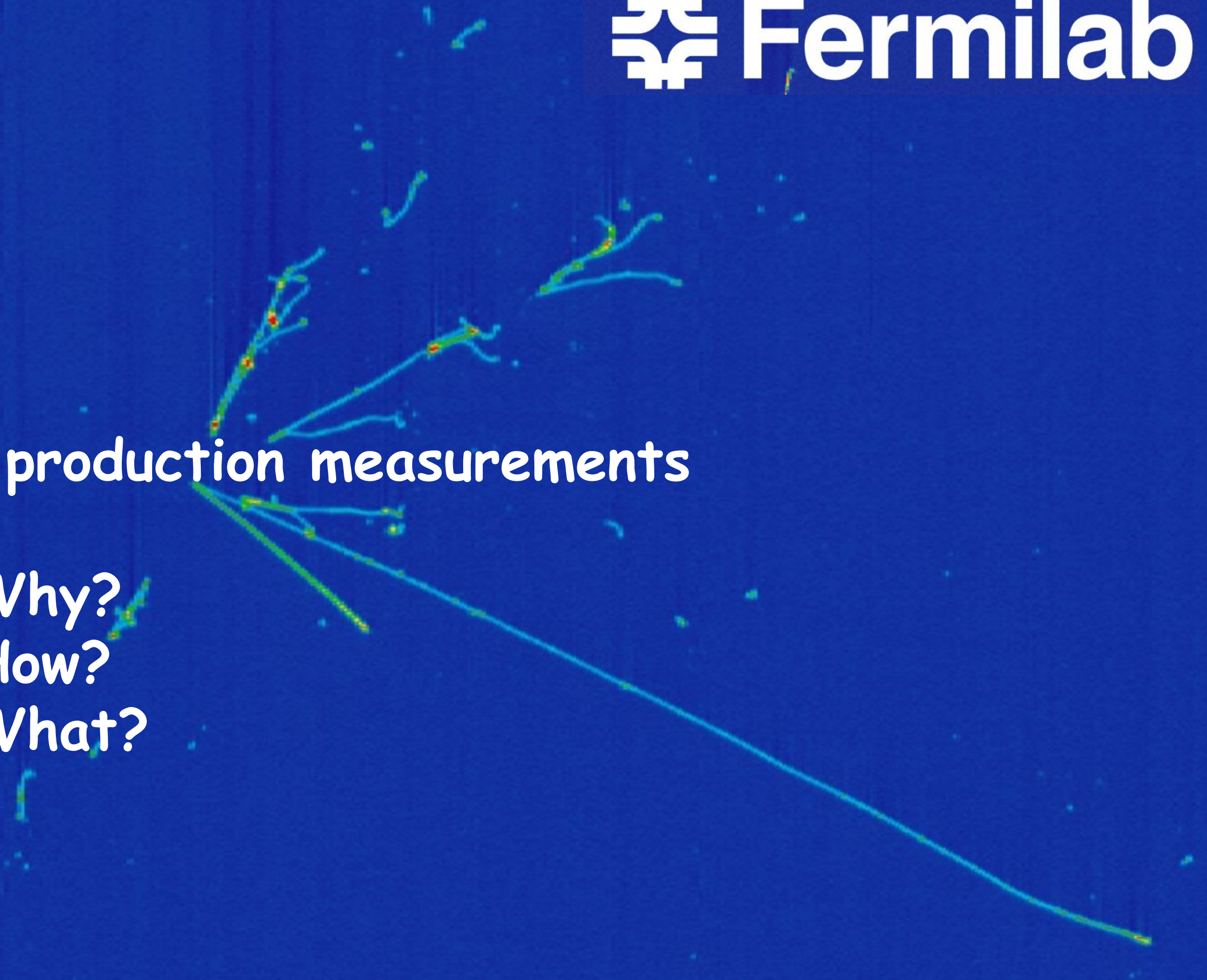
For the MicroBooNE Collaboration
October 4th, 2024
Fermilab Wine & Cheese Seminar

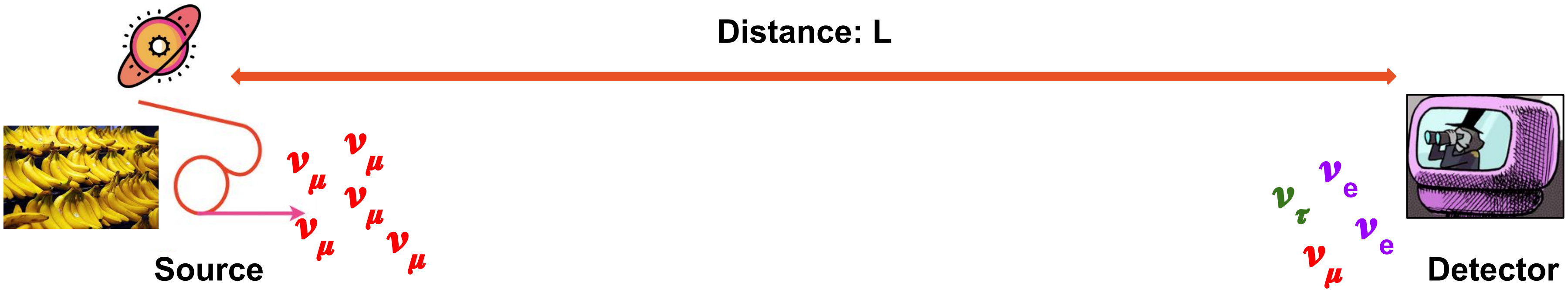
Physics Motivation

Pion production measurements

Why?
How?
What?



Neutrinos Oscillate:



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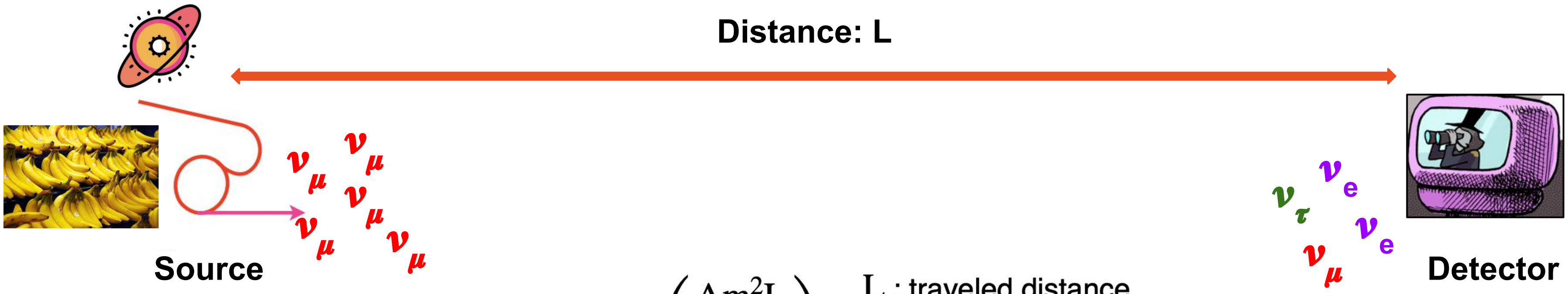

$$P(\nu_\alpha \to \nu_\beta) \sim \sin^2(2\theta)\sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right),$$

L : traveled distance

E : energy

$\Delta m_{ij}^2 = m_i^2 - m_j^2$

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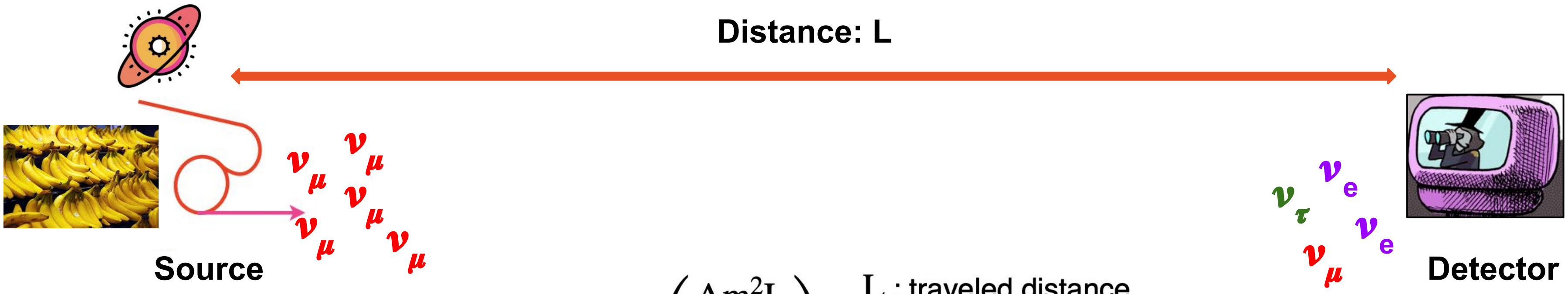
Neutrinos Oscillate:



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$\Delta m_{ij}^2 = m_i^2 - m_j^2$

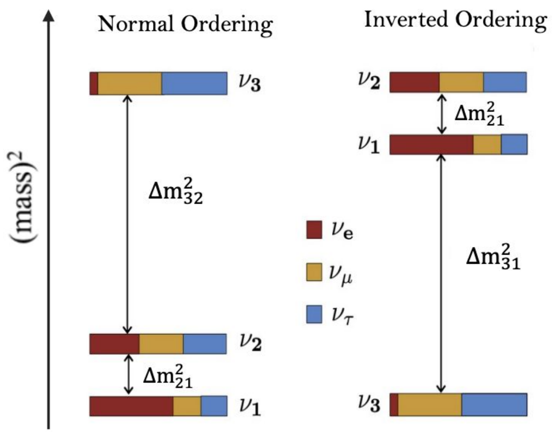
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \text{PMNS} \\ \text{matrix} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{pmatrix} \text{PMNS} \\ \text{matrix} \end{pmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$

Goals for next-generation experiments:

Determine the neutrino mass ordering



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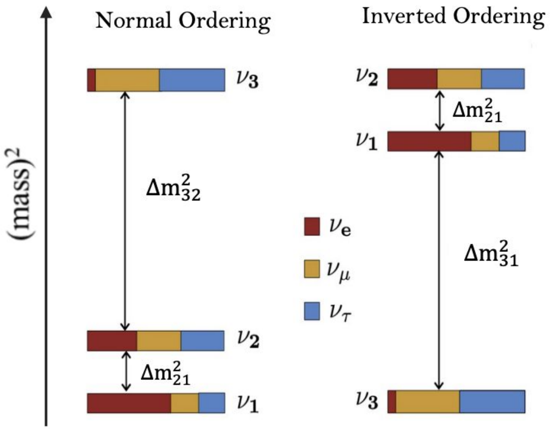
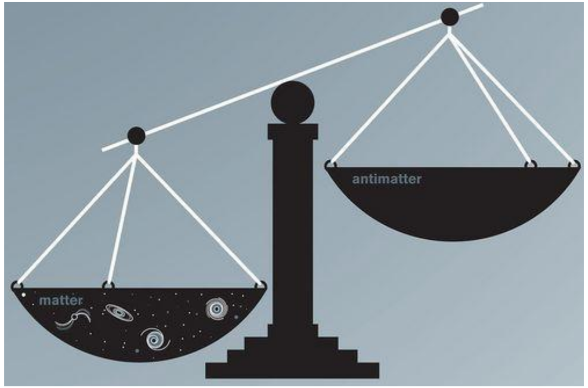


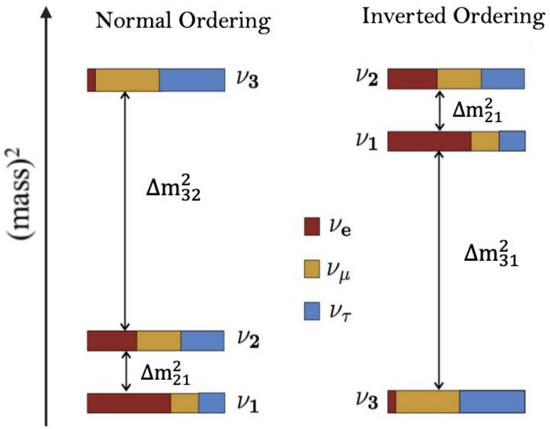
More matter in the universe - why?



Measure δ_{CP} and determine if CP is violated

Goals for next-generation experiments:

Determine the neutrino mass ordering



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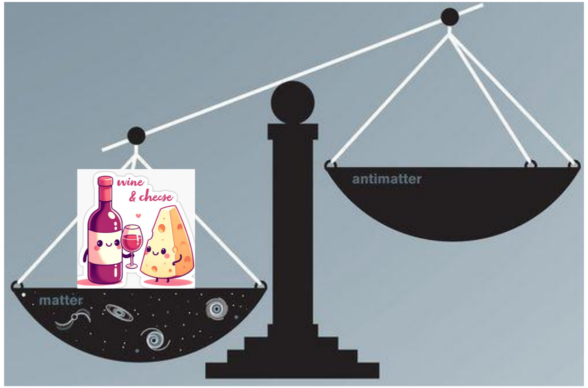

Measure δ_{CP} and determine if CP is violated

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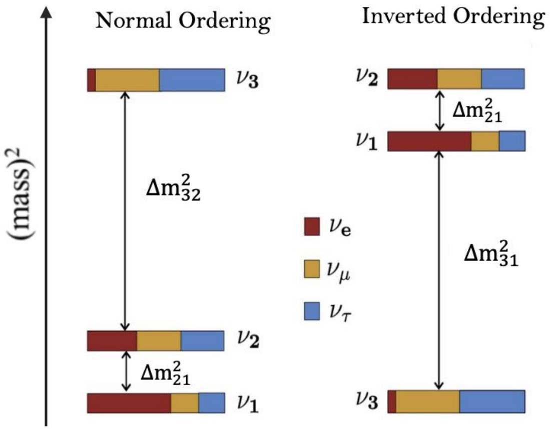

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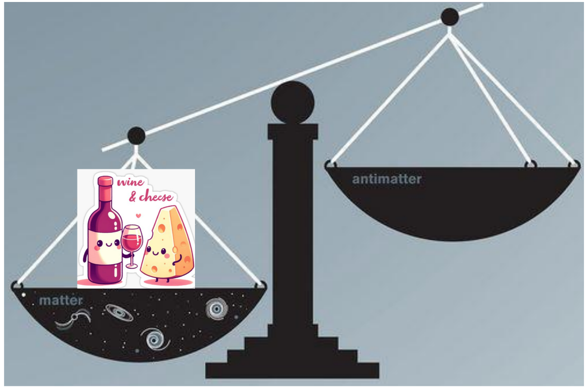
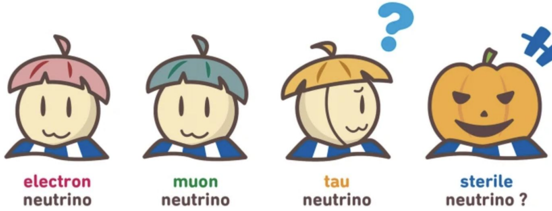


Measure δ_{CP} and determine if CP is violated

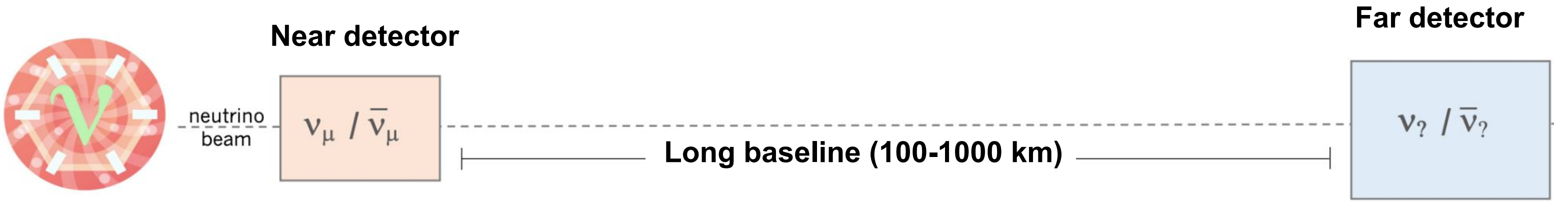
Is the 3-flavor model complete?



Credit: Nature

Sterile neutrino & BSM searches

Long-baseline measurements:



Count the neutrinos at Near and Far Detector

Measured event rate

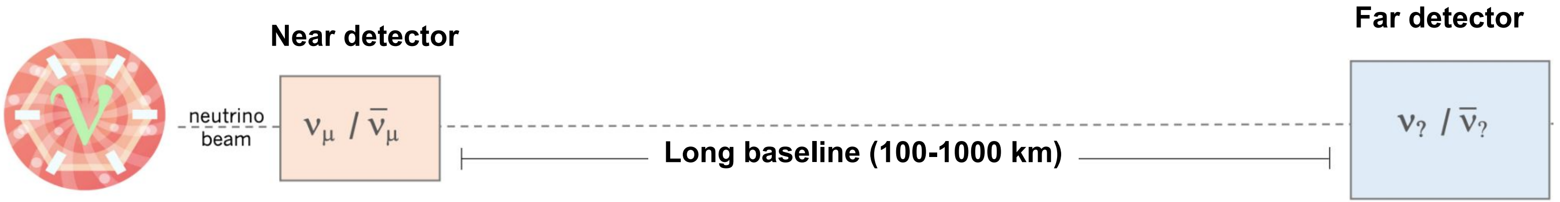
Interaction cross section

$$N_\mu(E_\nu) = \Phi(E_\nu) \times \sigma(E_\nu) \times \epsilon(E_\nu)$$

Neutrino flux

Detector efficiency

Long-baseline measurements:



Interaction cross section

Measured event rate

$$N_\ell(E_\nu) = \Phi(E_\nu) \times \sigma(E_\nu) \times \epsilon(E_\nu) \times P(\nu_\alpha \rightarrow \nu_\beta)$$

Oscillation probability

Neutrino flux

Detector efficiency

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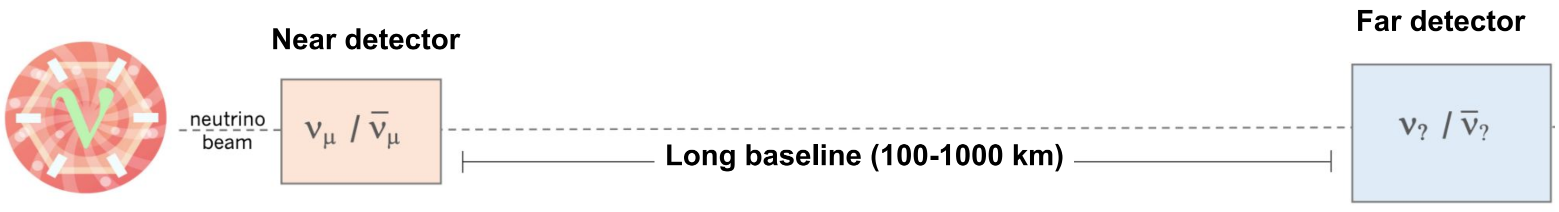

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$$N_\ell(E_\nu) = \Phi(E_\nu) \times \sigma(E_\nu) \times \epsilon(E_\nu) \times P(\nu_\alpha \to \nu_\beta)$$

Oscillation probability

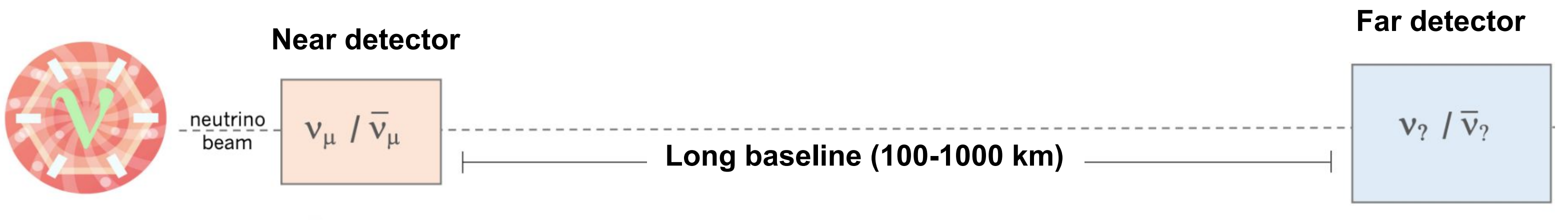
Neutrino flux

Detector efficiency

$$P(\nu_\alpha \to \nu_\beta) \sim \sin^2(2\theta)\sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$

Precise modeling input needed to interpret $N_\ell(E_\nu)$ as $P(\nu_\alpha \to \nu_\beta)$

Long-baseline measurements:

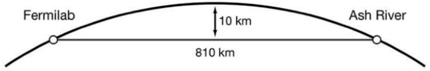


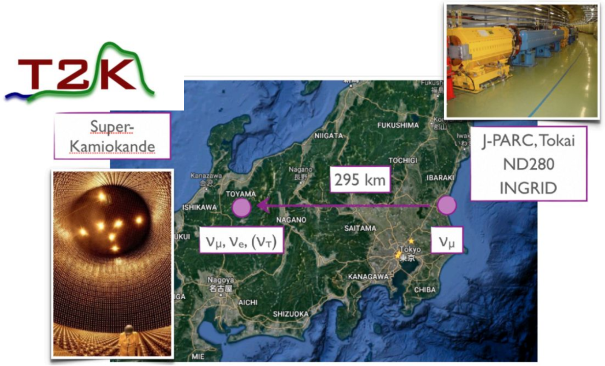
Measured event rate

$$N_\ell(E_\nu) = \underbrace{\Phi(E_\nu) \times \sigma(E_\nu) \times \epsilon(E_\nu)}_{\text{Sources of Systematic Uncertainty}} \times P(\nu_\alpha \rightarrow \nu_\beta)$$

Oscillation probability

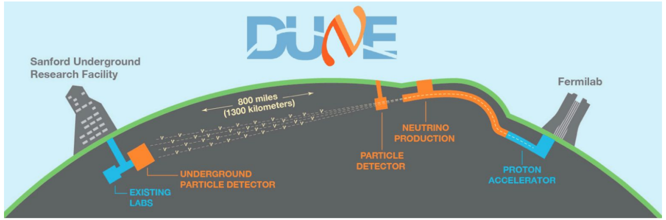
Current Generation

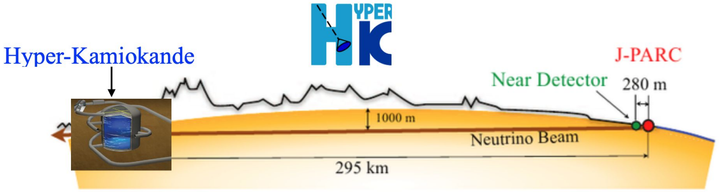




Entering the precision era where systematics play a more important role

Next Generation





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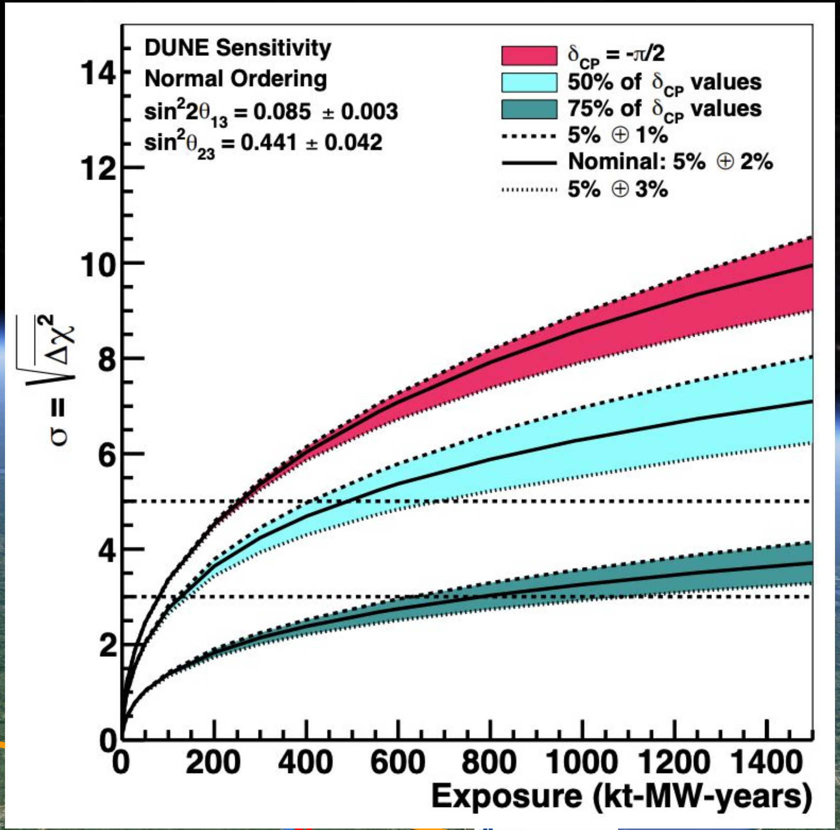
Deep Underground Neutrino Experiment (DUNE)

Next-generation international neutrino experiment hosted in the US

Credit: google earth

Eur. Phys. J. C 80, 978 (2020)



Credit: google earth

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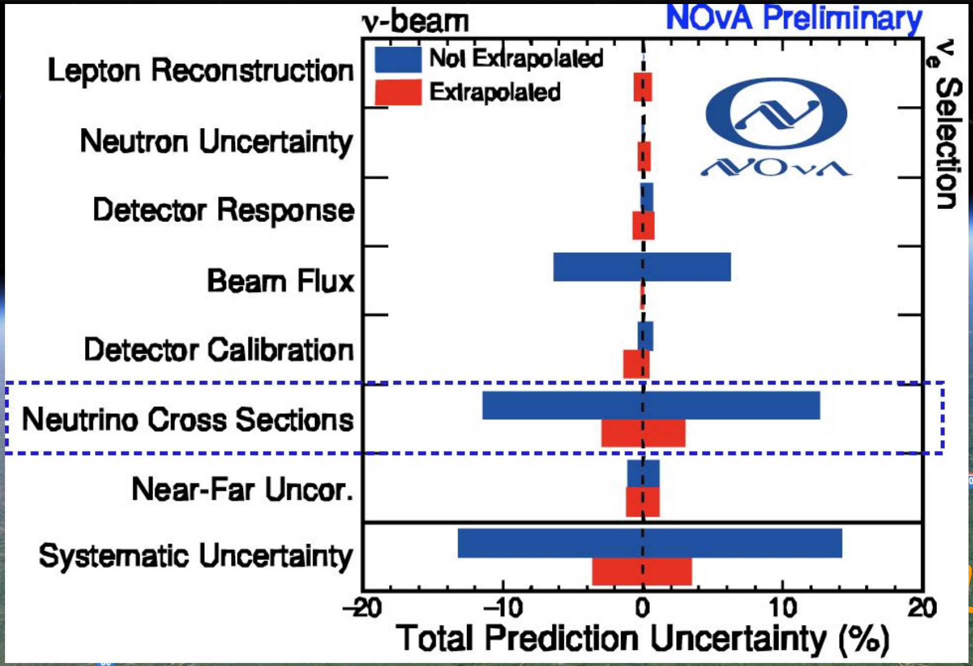
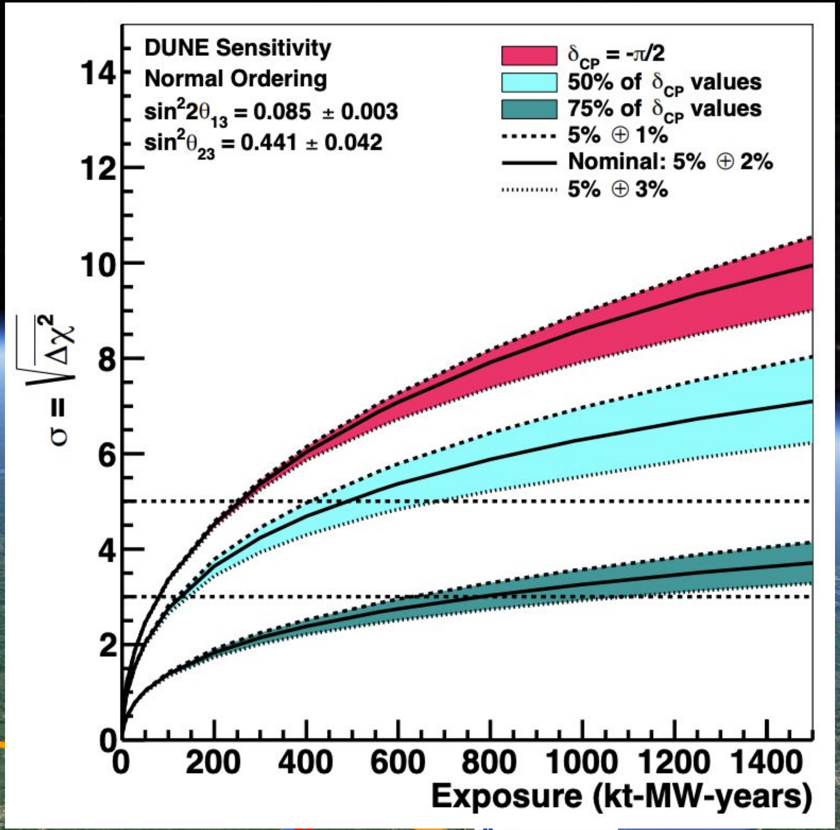




Fermilab

Credit: google earth

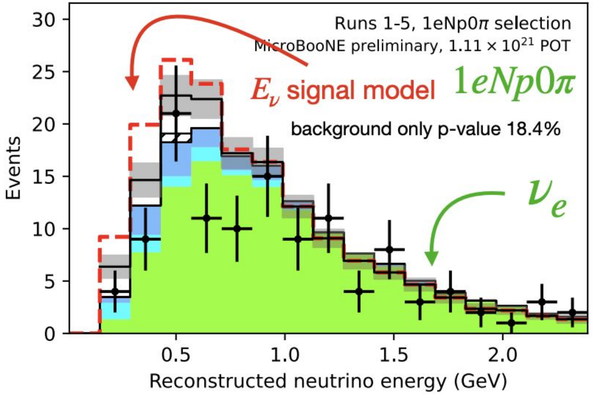
Understanding neutrino nucleus interactions are key to oscillation measurements

MicroBooNE: Understanding Neutrinos through a LArTPC Lens

Data taking 2015 - 2020

MicroBooNE: Understanding Neutrinos through a LArTPC Lens

Low Energy Excess



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MicroBooNE: Understanding Neutrinos through a LArTPC Lens

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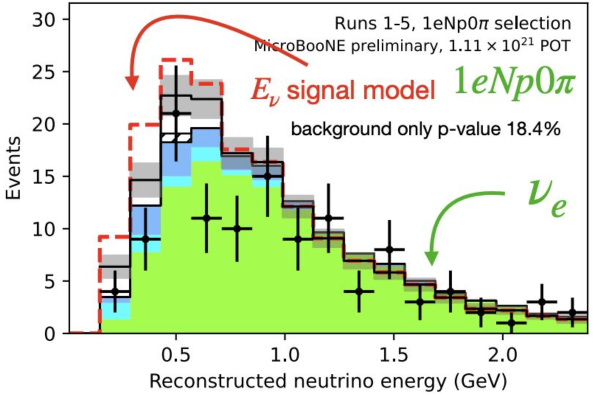
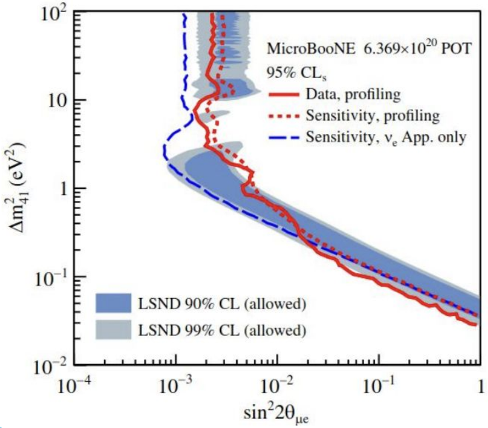


Beyond Standard Model Search



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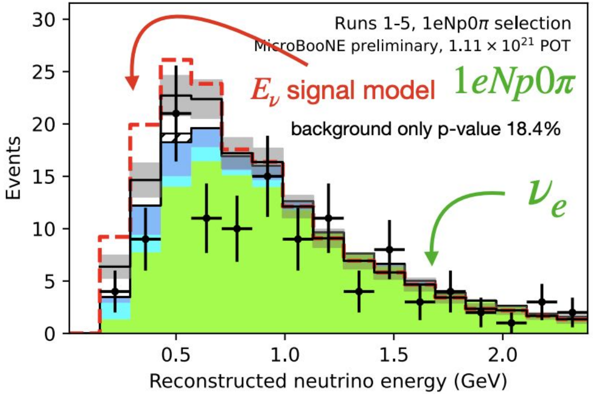

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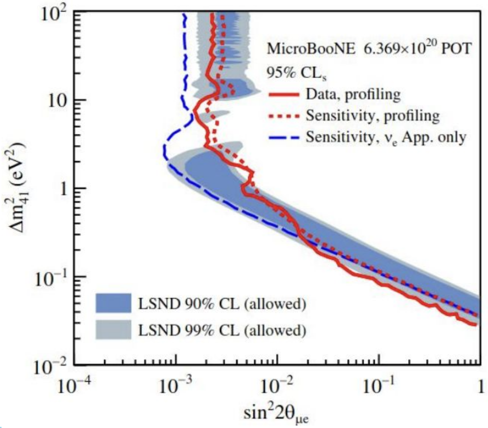
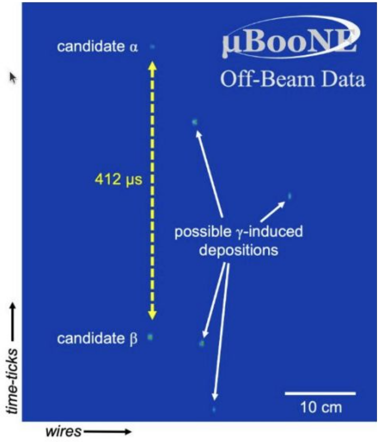


Data taking 2015 - 2020

Liquid Argon R&D



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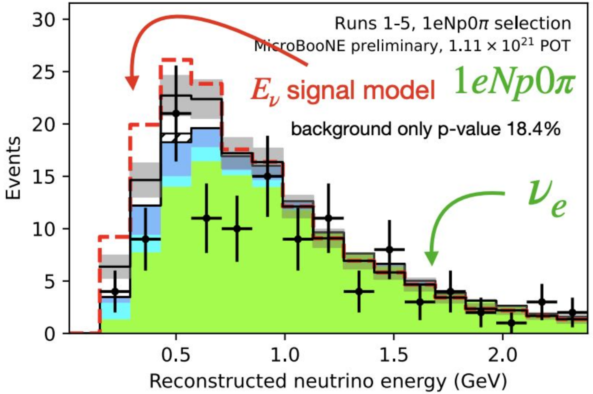

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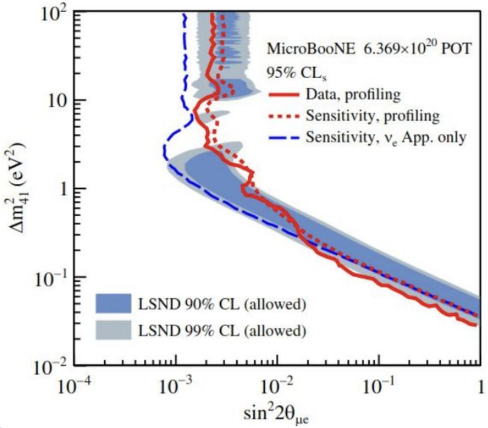

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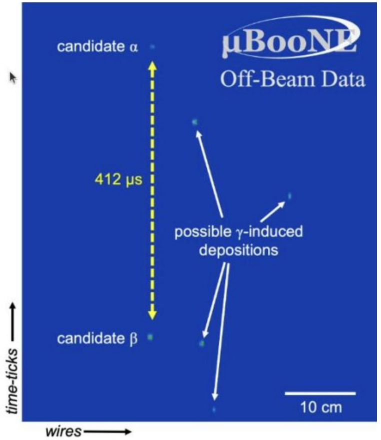
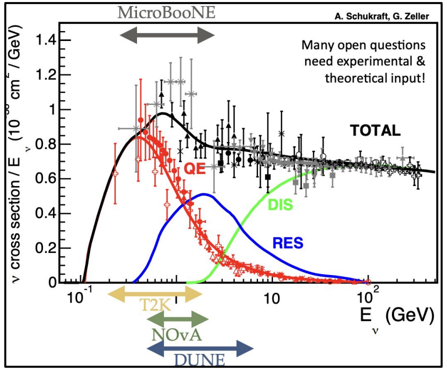
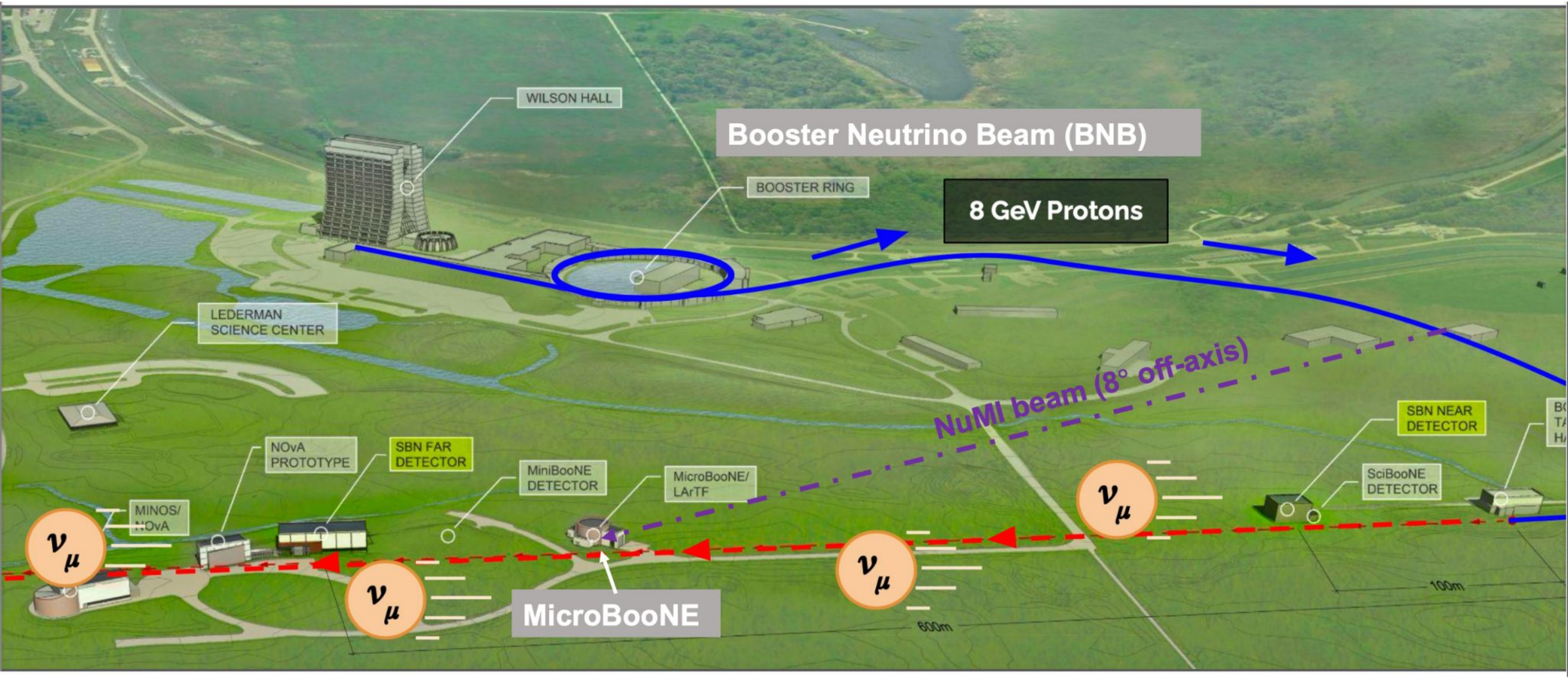


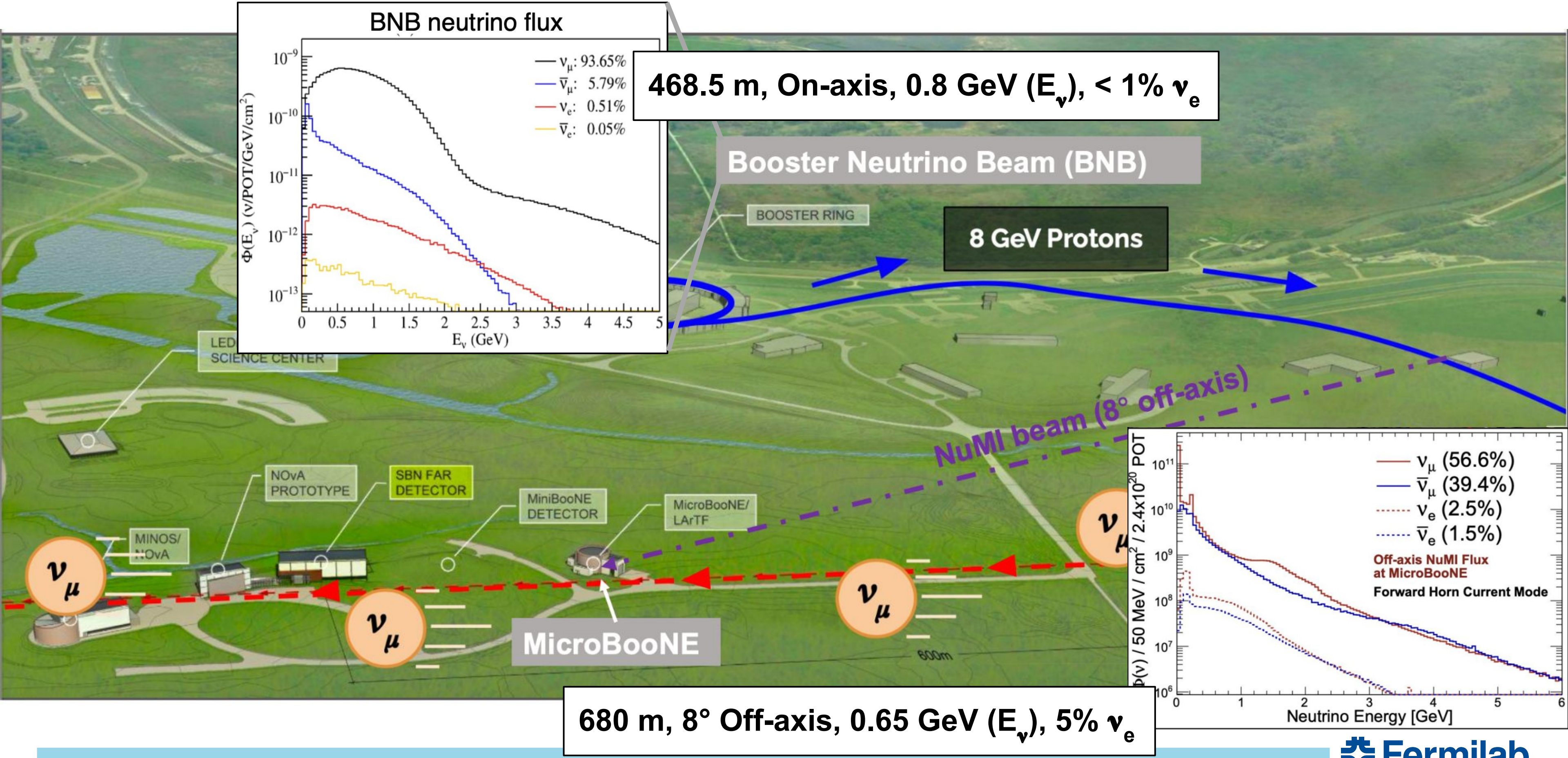
Neutrino-Ar cross section



Neutrinos Towards MicroBooNE



Neutrinos Towards MicroBooNE



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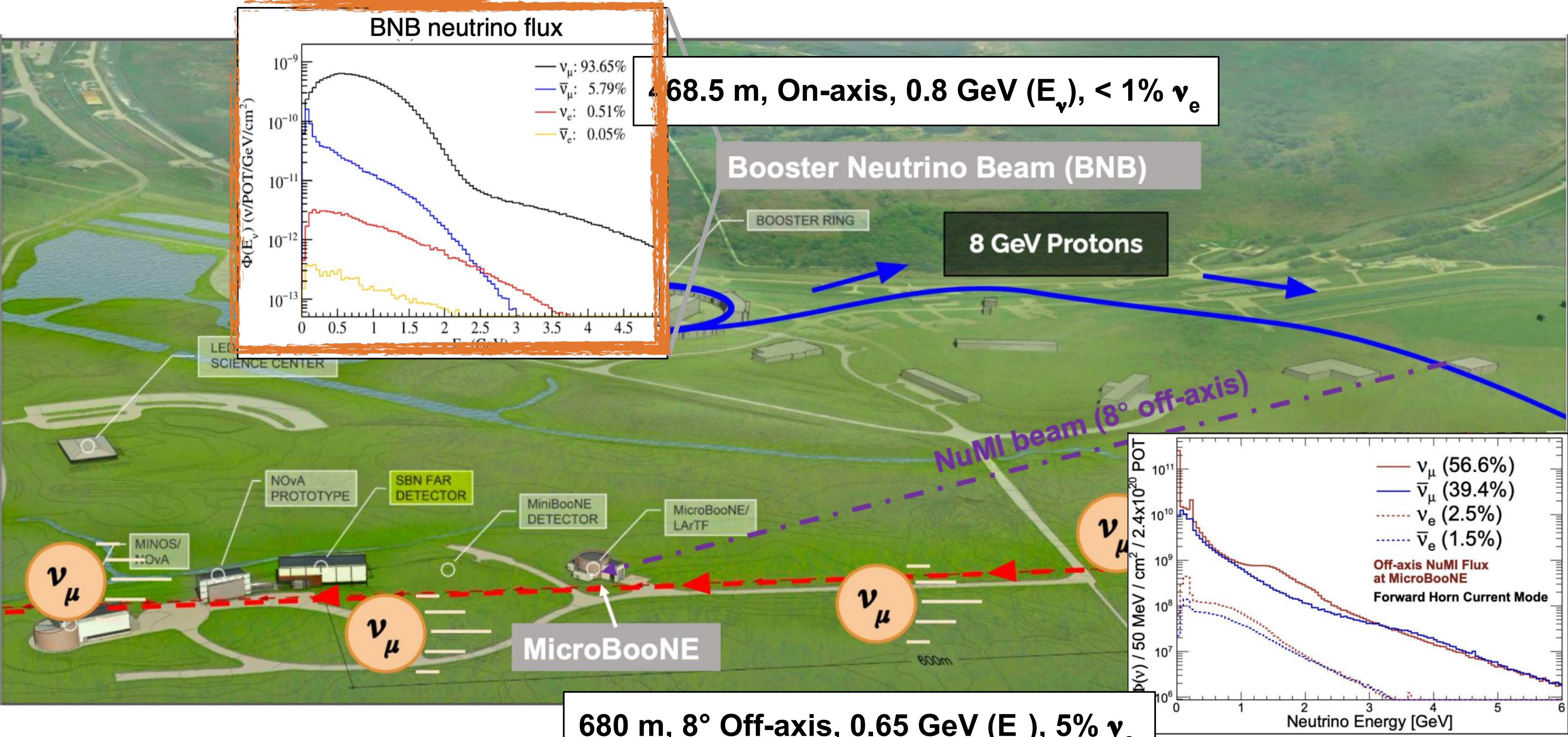
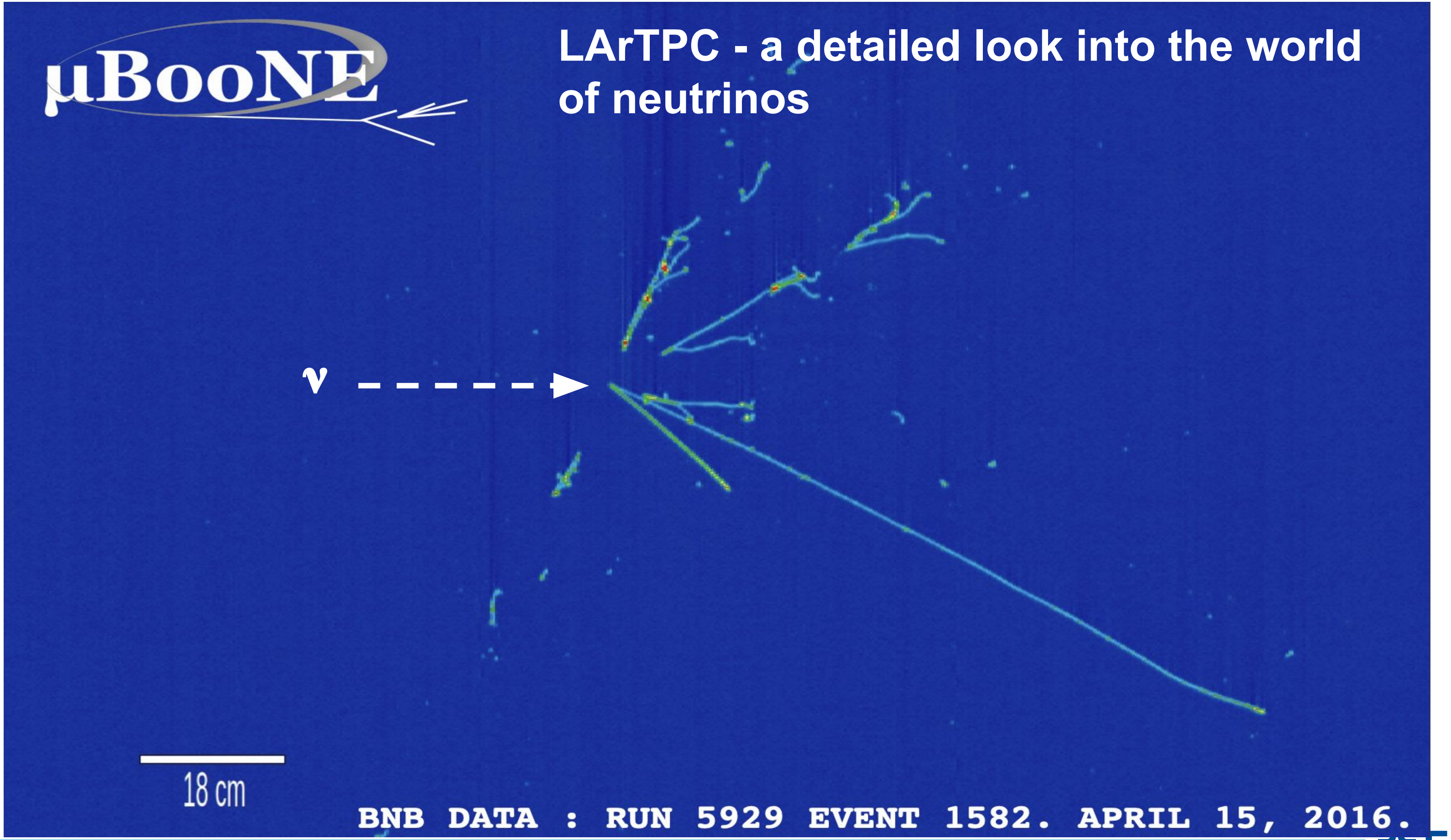


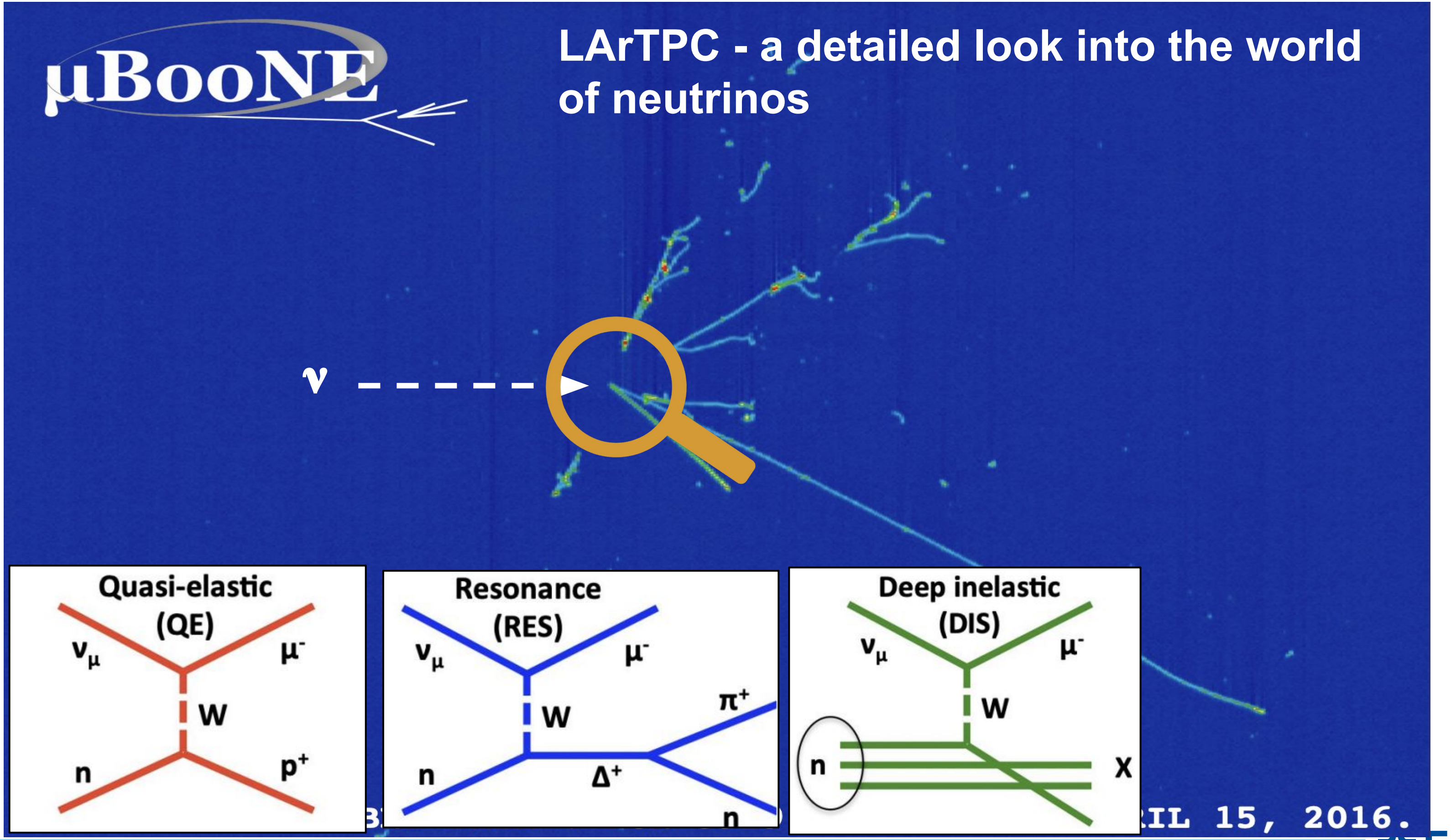
468.5 m, On-axis, 0.8 GeV (E_ν), < 1% ν_e

680 m, 8° Off-axis, 0.65 GeV (E_ν), 5% ν_e

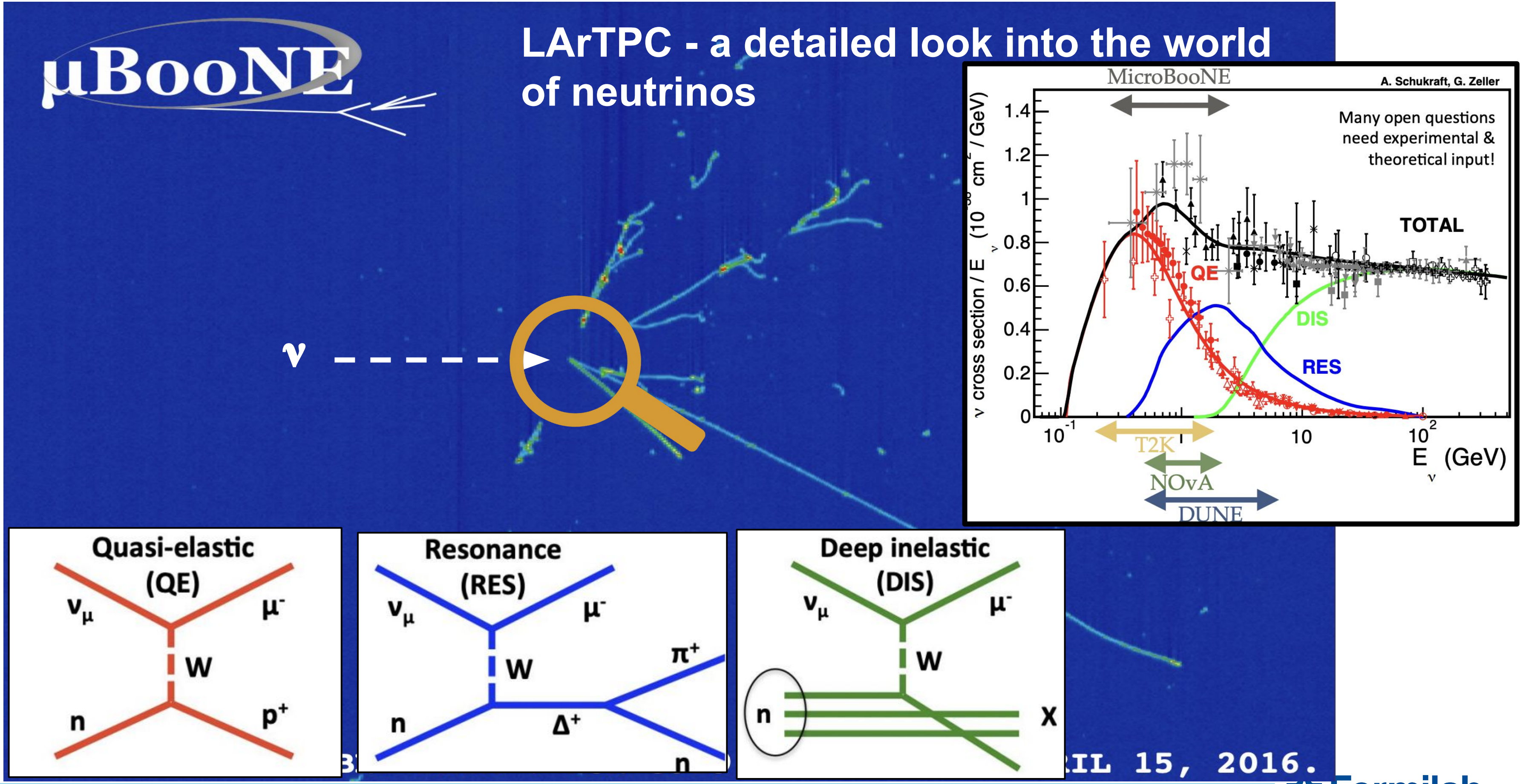
Neutrino Nucleus interactions :



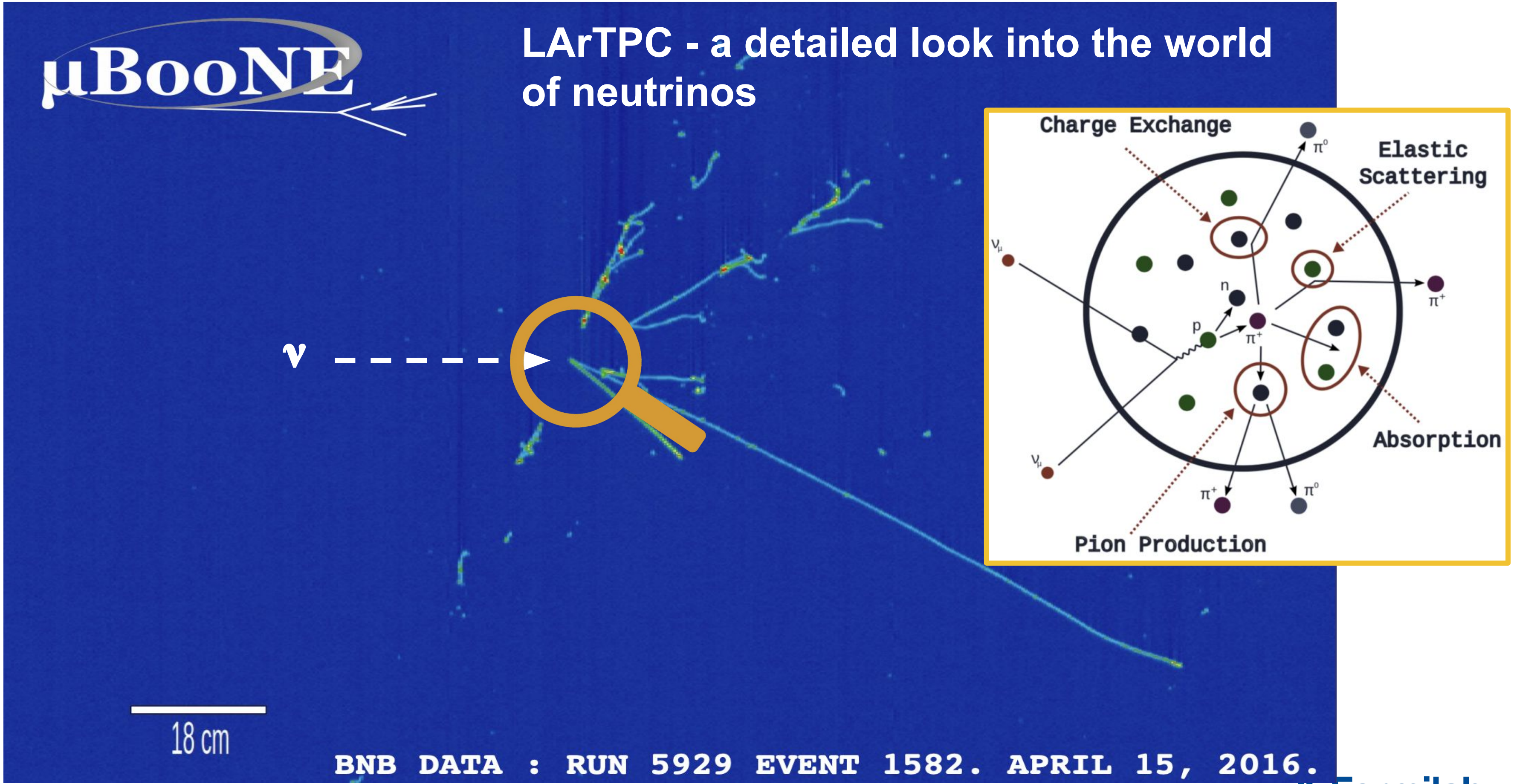
Neutrino Nucleus interactions :



Neutrino Nucleus interactions :



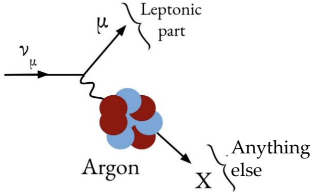
Neutrino Nucleus interactions :



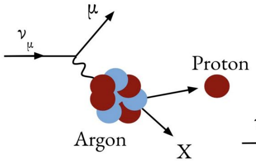
MicroBooNE’s Cross Section Campaign:

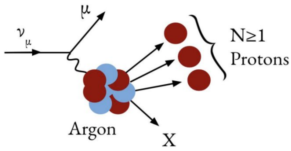
Inclusive

- 1D ν_μ CC inclusive @ BNB
  Phys. Rev. Lett. 123, 131801 (2019)
- 1D ν_μ CC E_ν @ BNB
  Phys. Rev. Lett. 128, 151801 (2022)
- 1D ν_e CC inclusive @ NuMI
  Phys. Rev. D105, L051102 (2022)
  Phys. Rev. D104, 052002 (2021)
- 2D ν_μ CC0pNp inclusive @ BNB
  PhysRevD.110.013006,
  PhysRevLett.133.041801



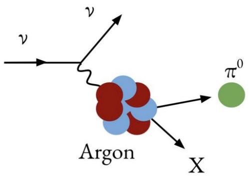
Pionless

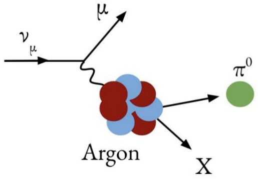




- 1D ν_e CCNp0π @ BNB
  Phys. Rev. D 106, L051102 (2022)
- 1D & 2D ν_μ CC1p0π Kinematic Imbalance @ BNB
  Phys. Rev. Lett. 131, 101802, Phys. Rev. D 108, 053002
- 1D & 2D ν_μ CC1p0π generalized imbalance @ BNB
  Phys. Rev. D 109, 092007
- 1D ν_μ CC1p0π @ BNB
  Phys. Rev. Lett. 125, 201803 (2020)
- 1D ν_μ CCNp0π @ BNB
  Phys. Rev. D102, 112013 (2020)
- 2D νμ CCNp0π @ BNB, arXiv:2403.19574

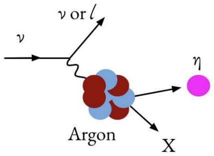
Pion production

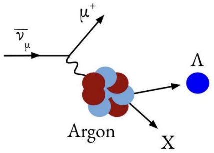




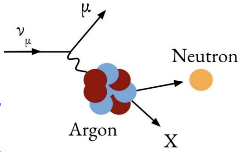
- ν_μ NCπ^0 @ BNB, Phys. Rev. D 107, 012004 (2023)
- 2D ν NCπ^0 @ BNB, arXiv:2404.10948
- ν_μ CCπ^0 @ BNB, arXiv:2404.09949

Rare channels



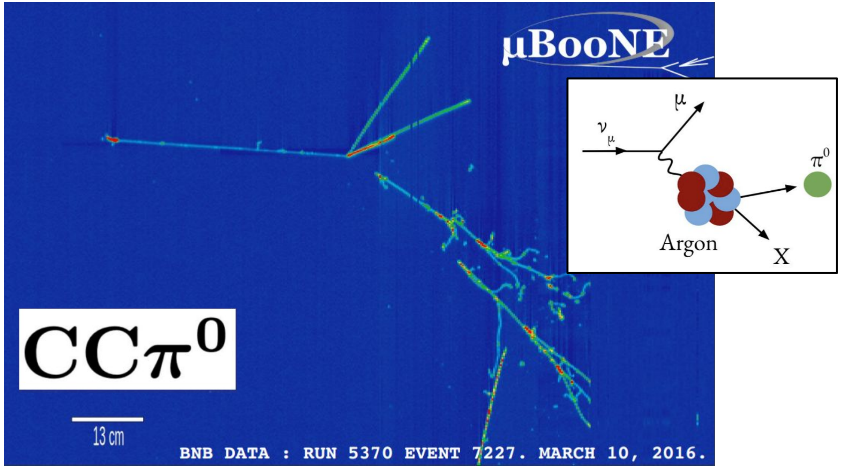


- η production @ BNB
  PhysRevLett.132.151801
- Λ production @ NuMI
  PhysRevLett.130.231802
- Neutron identification, arXiv:2406.10583

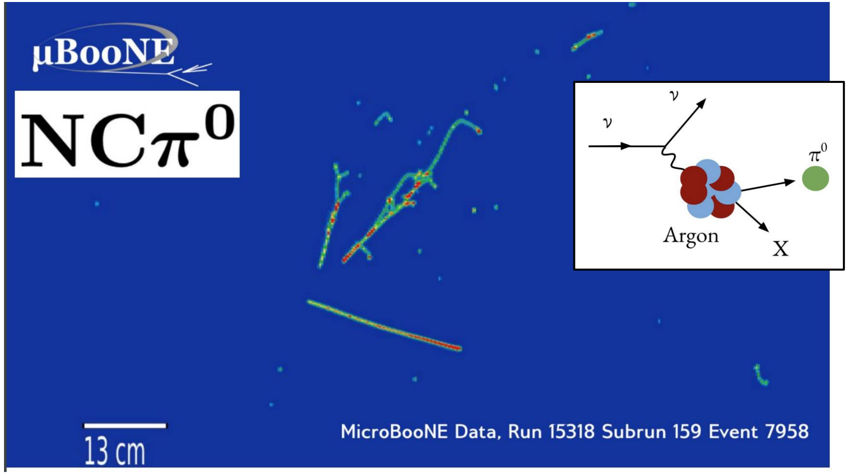


Topics Today:

- Two recent π^0 production results from MicroBooNE
  - Using ~50% of available MicroBooNE data sets and Booster Neutrino Beam (BNB)

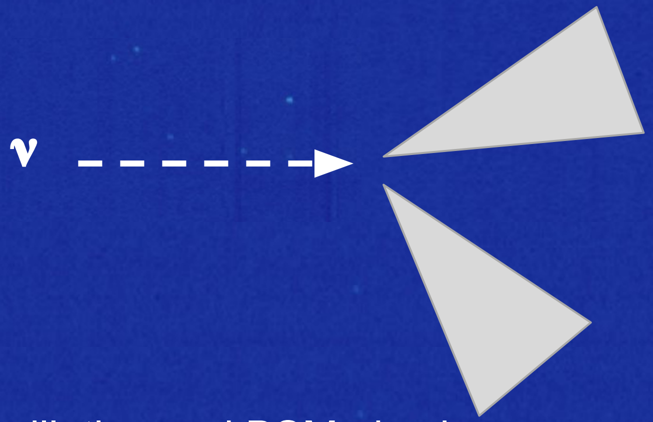


arXiv:2404.09949

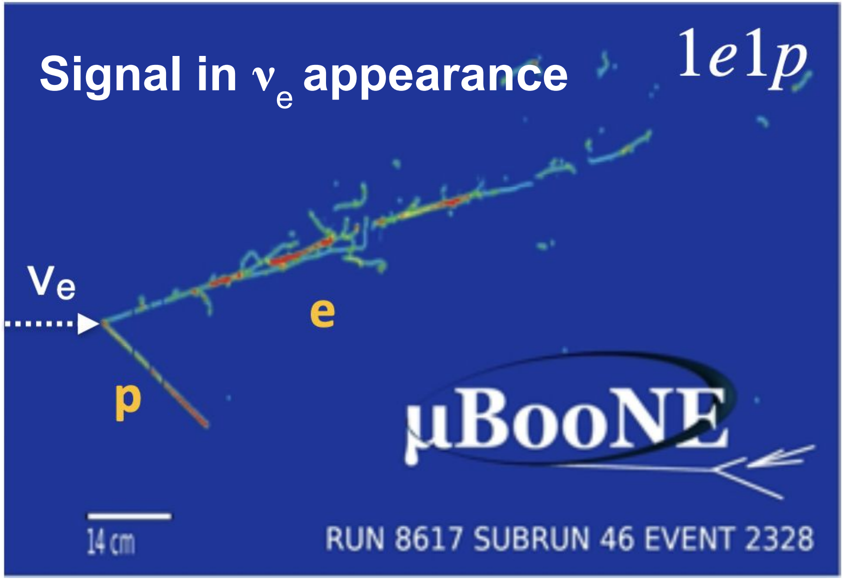


arXiv:2404.10948

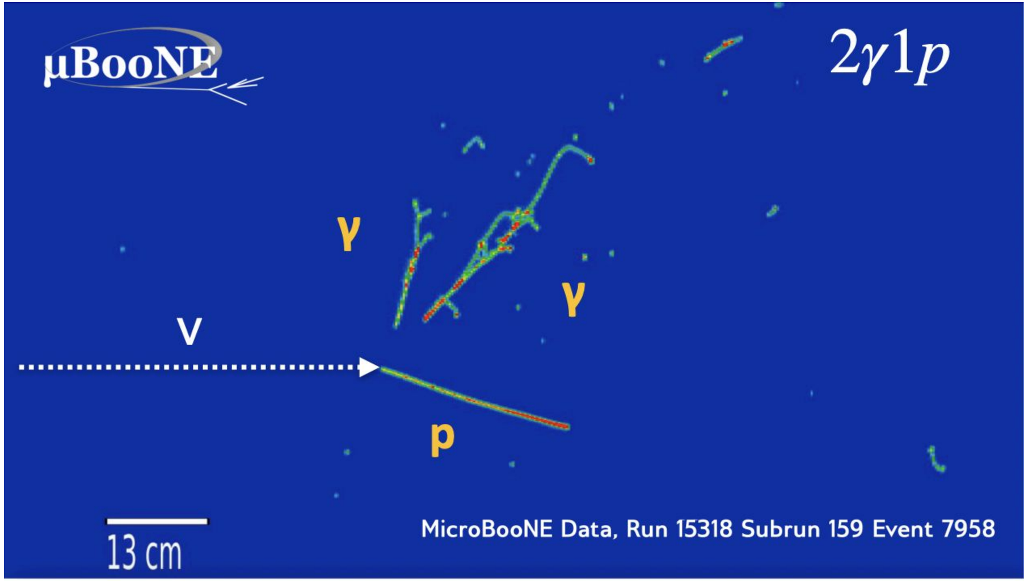
Neutral pion production in LArTPC



- Crucial for oscillation and BSM physics
- Benchmark event generators
  - More insights into modeling

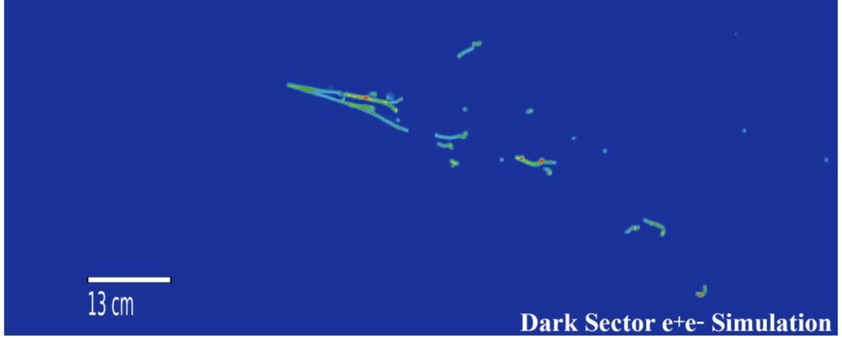


π^0 mimics signal if 1γ shower is missed

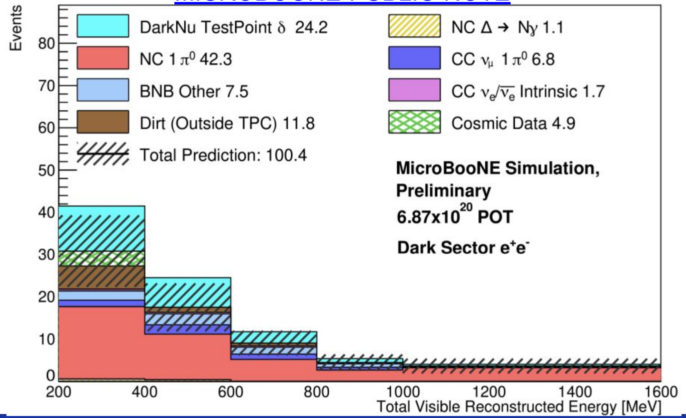


- LArTPCs provide powerful e/γ discrimination, but it is not perfect
- Remaining π^0 background must be estimated via simulation

Rare BSM Search with e^+e^- as the signal



MICROBOONE-PUBLIC-NOTE



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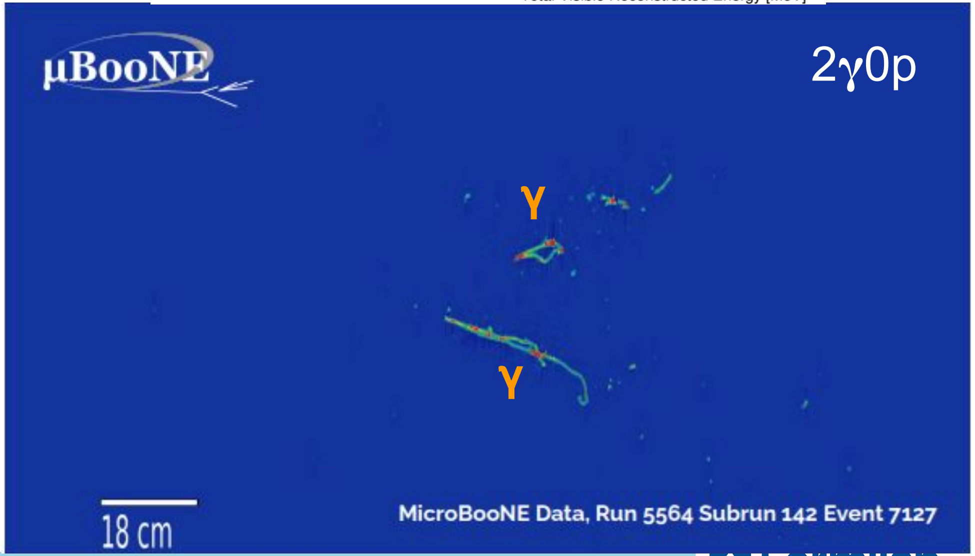
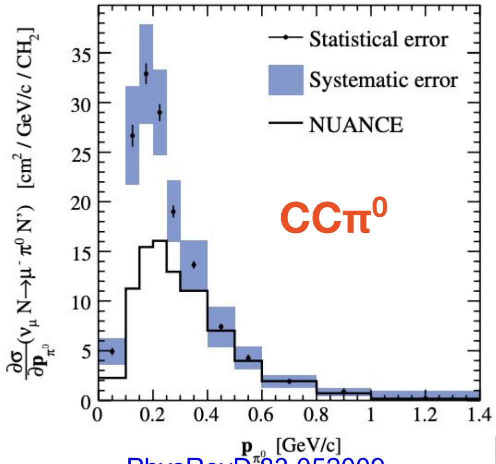


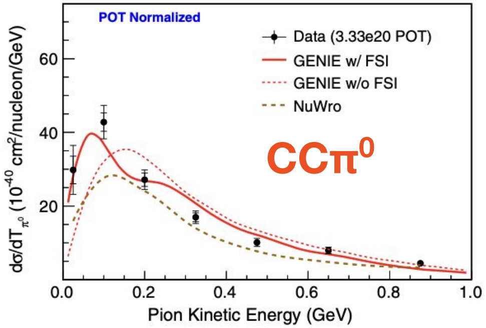
Status quo:

MiniBooNE (2011)



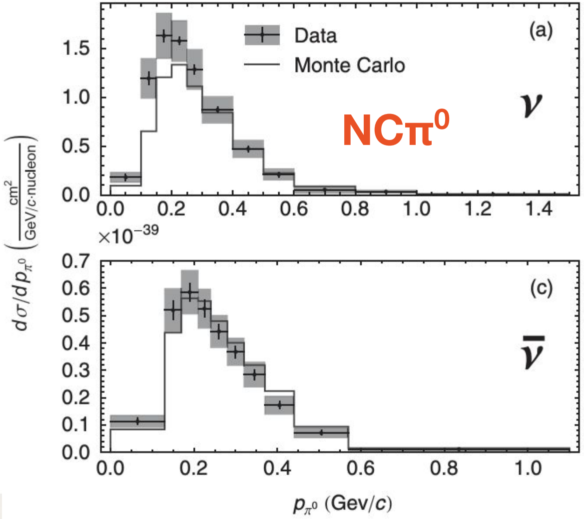
PhysRevD.83.052009

MINERvA (2017)



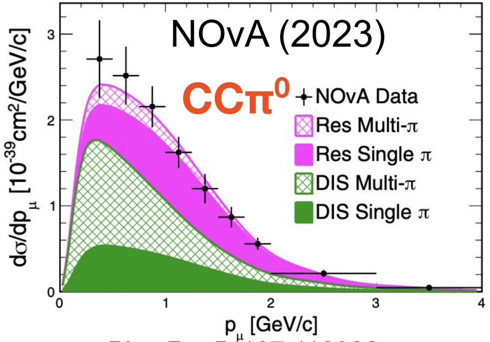
PhysRevD.96.072003

MiniBooNE (2010)



PhysRevD.81.013005

NOvA (2023)



PhysRevD.107.112008

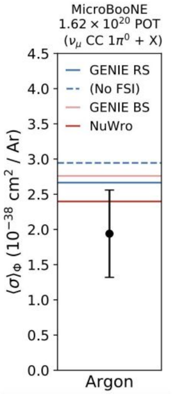
Joanna Sobczyk (NuFact 2024)

Fermilab

World Measurements of ν-Ar Neutral Pion Production:

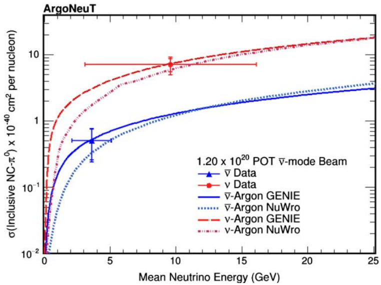
$CC\pi^0$

ν_μ $CC\pi^0$ total cross section (PhysRevD.99.091102)

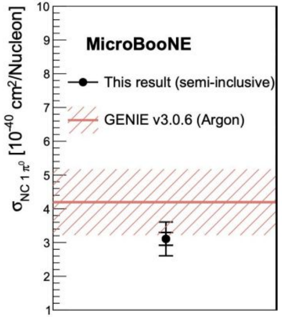


$NC\pi^0$

ν_μ and $\bar{\nu}_\mu$ $NC\pi^0$ production (PhysRevD.96.012006)



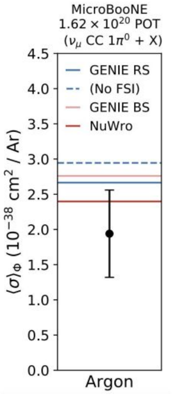
ν $NC\pi^0$ total cross section (PhysRevD.107.012004)



World Measurements of ν-Ar Neutral Pion Production:

CCπ^0

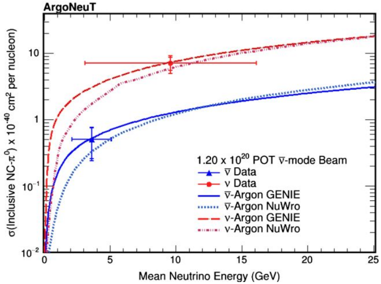
ν_μ CCπ^0 total cross section
(PhysRevD.99.091102)



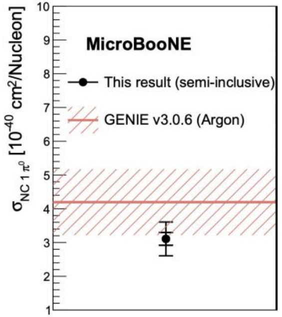
ν_μCCπ^0 single-differential cross section
(This talk, arXiv:2404.09949)

NCπ^0

ν_μ and $\bar{\nu}_\mu$ NCπ^0 production
(PhysRevD.96.012006)



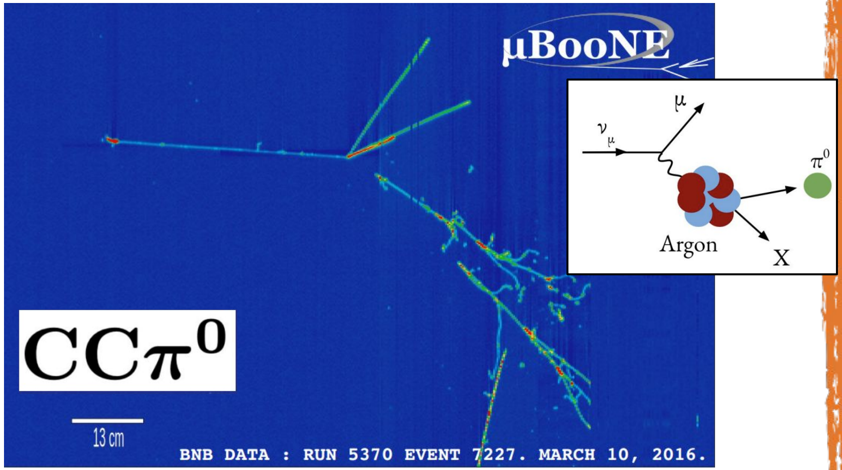
ν NCπ^0 total cross section
(PhysRevD.107.012004)



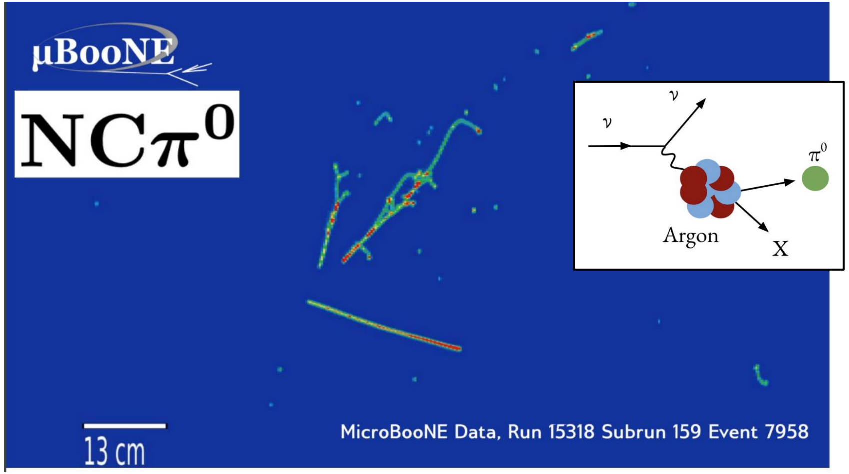
ν NCπ^0 double-differential cross section
(This talk, arXiv:2404.10948)

Topics Today:

- Two recent π^0 production results from MicroBooNE
    - Using ~50% of available MicroBooNE data sets and Booster Neutrino Beam (BNB)

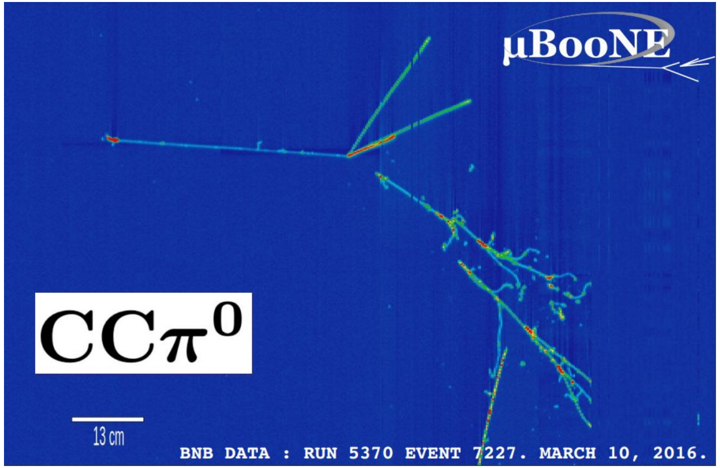


arXiv:2404.09949



arXiv:2404.10948

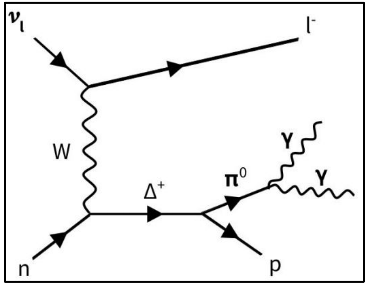
ν_μ CC Single π^0 Differential Cross Section Measurement

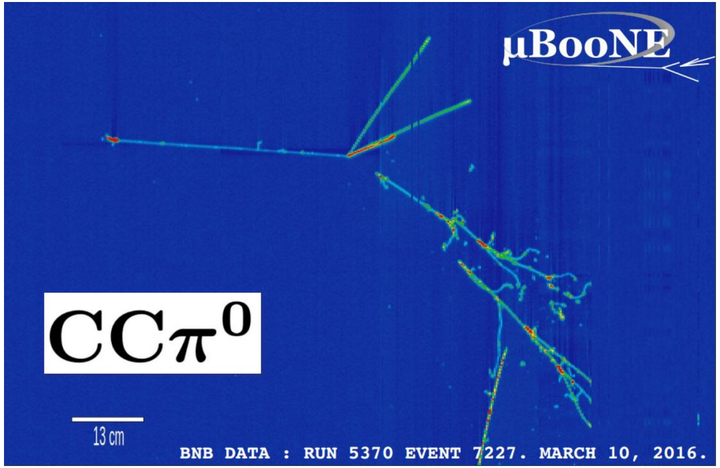


arXiv:2404.09949

- First single-differential cross section measurement on argon with π^0 in the final state
- CCπ^0 results reported as a function of 5 kinematic variables:
  - π^0 kinematics
  - muon kinematics
  - muon-pion opening angle
- Additional kinematic information on π^0 production beyond what we measure in the NC channel

Signal Definition :

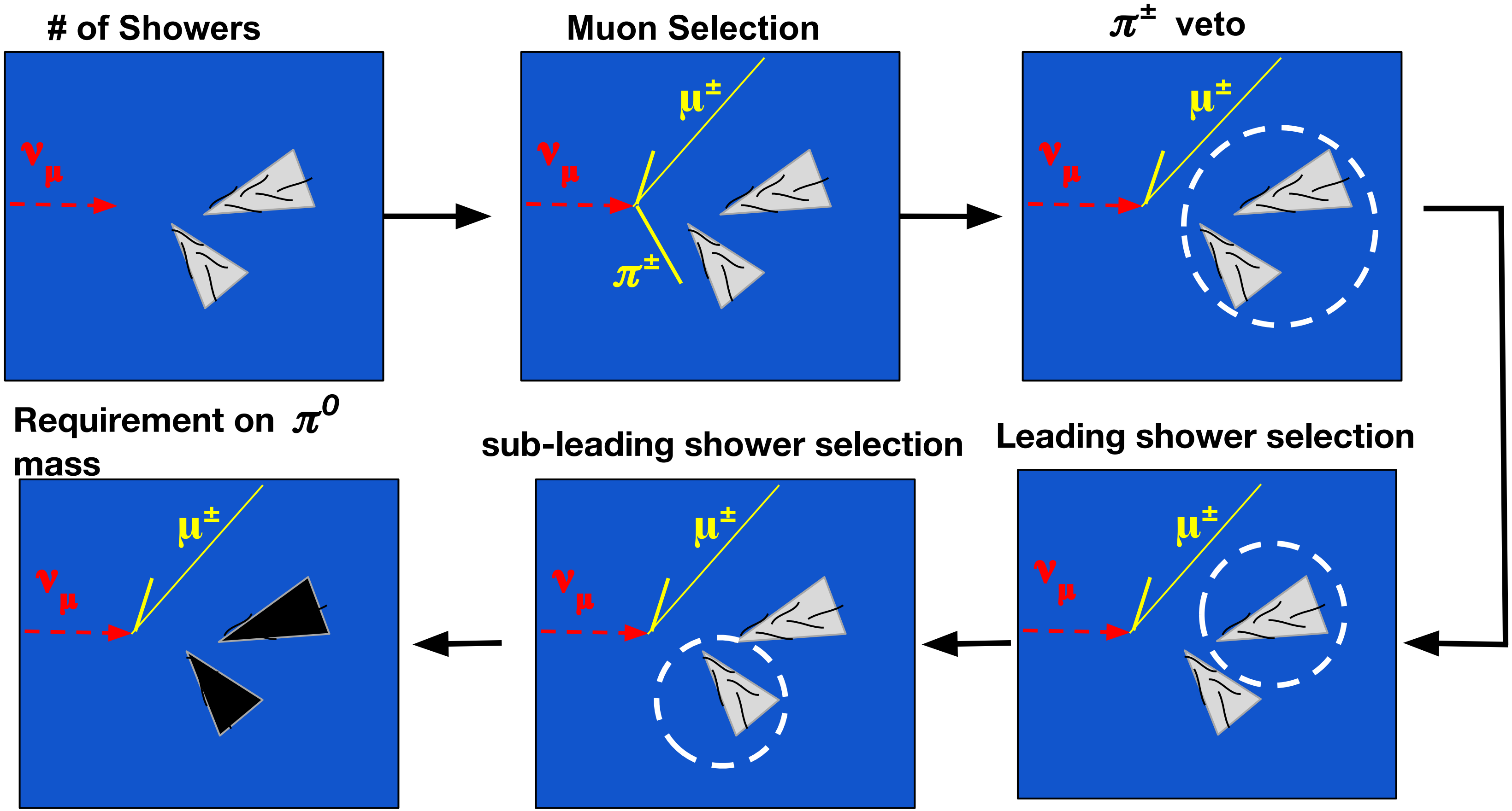




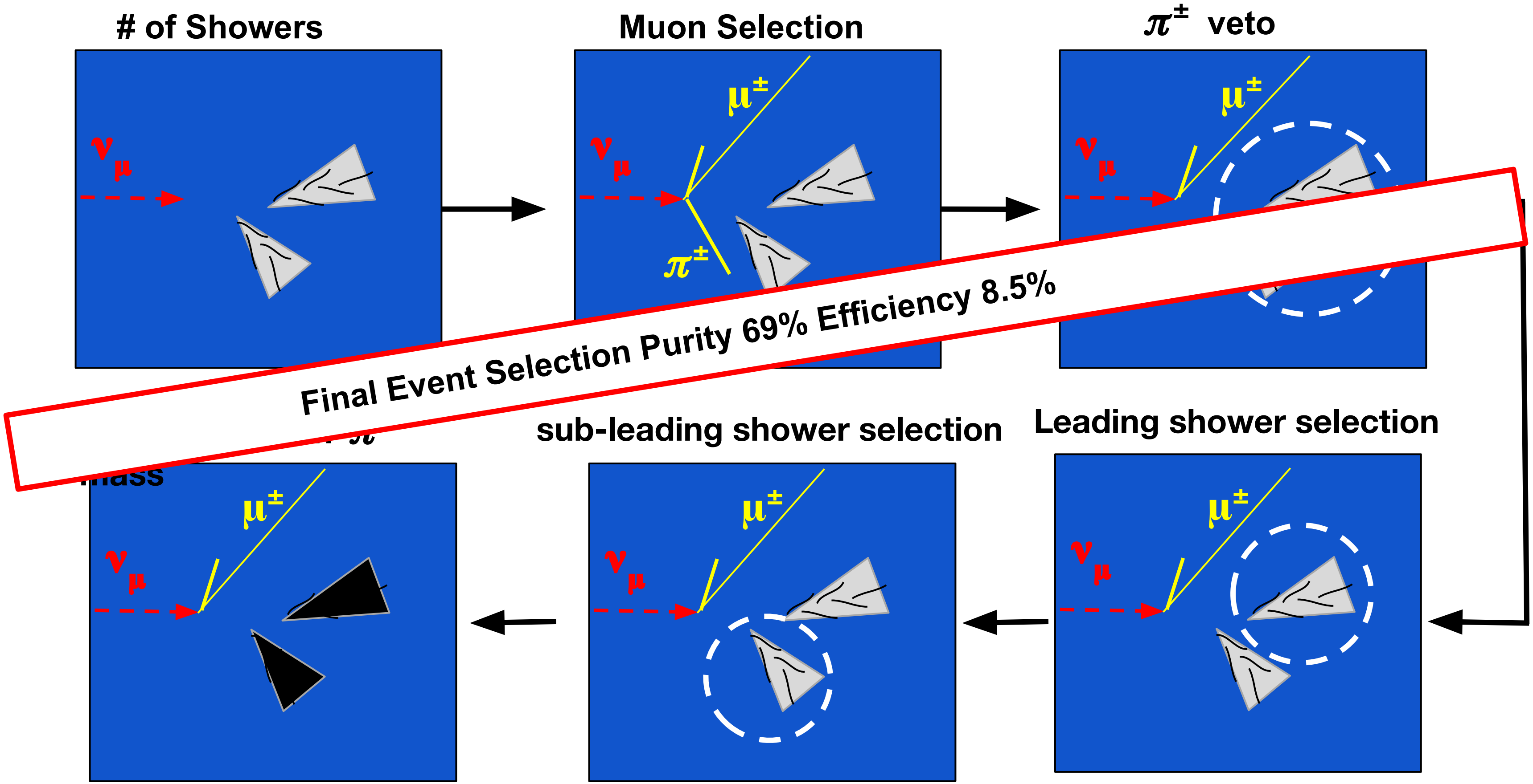
Signal: ν_μ +Ar $\rightarrow$ 1 μ + 1 π^0 + 0 $\pi^\pm$ + X (nucleons)
↳$\gamma\ \gamma$

- 1 μ candidate (K.E. > 20 MeV)
- neutrino event contains 1 π^0
- No $\pi^\pm$ (K.E. > 40 MeV)
- No requirements on presence(or absence)of X

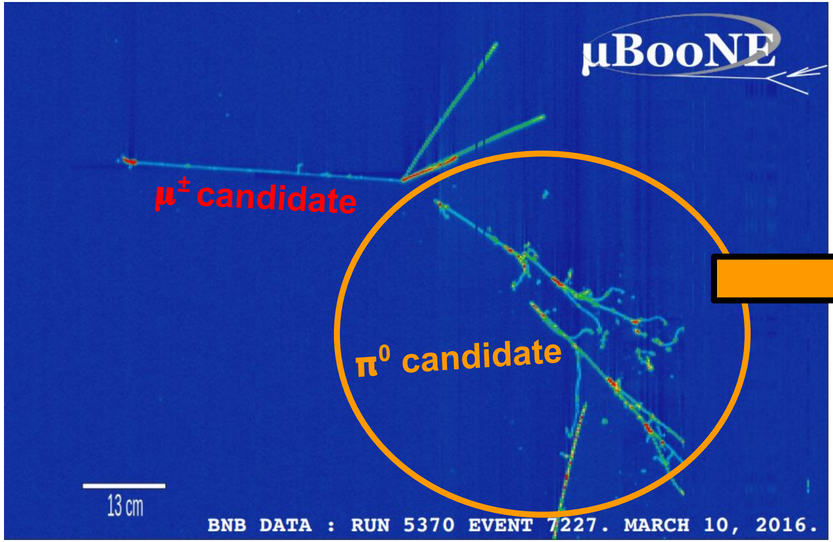
Event selection

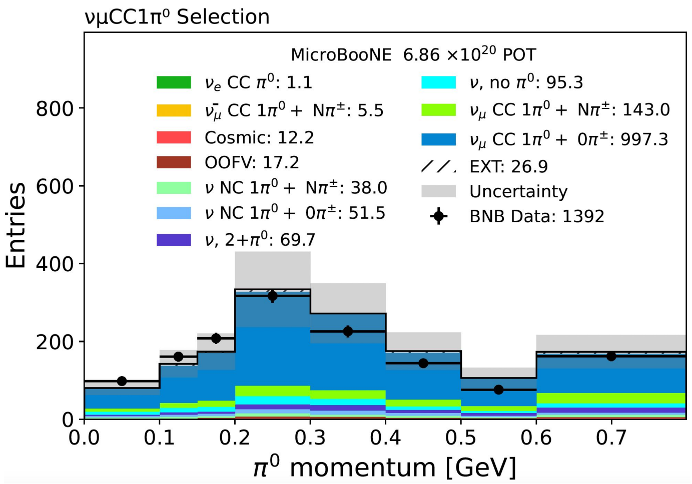


Event selection



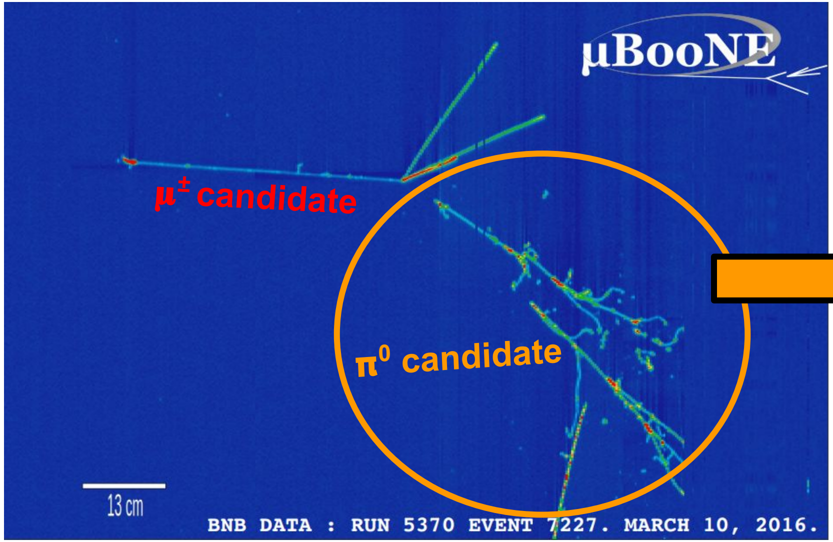
Pion Kinematic Variables

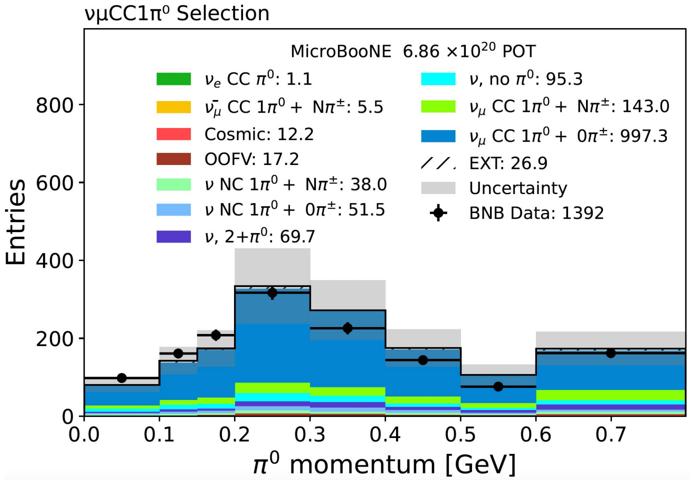


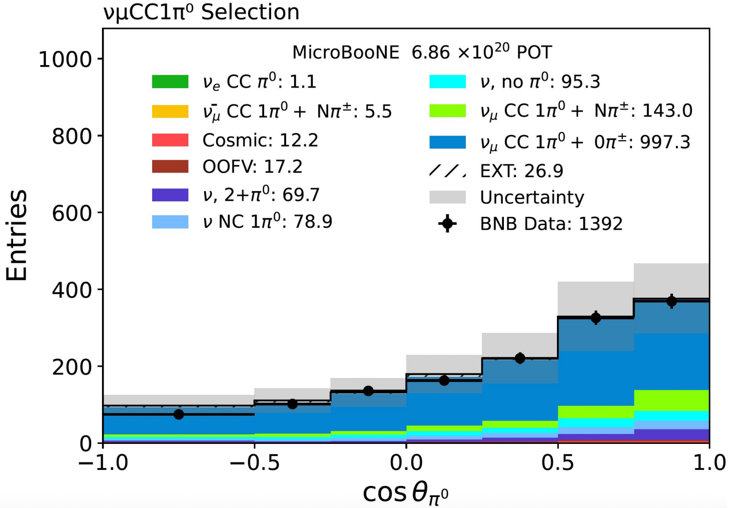


1392 candidate data events

Pion Kinematic Variables

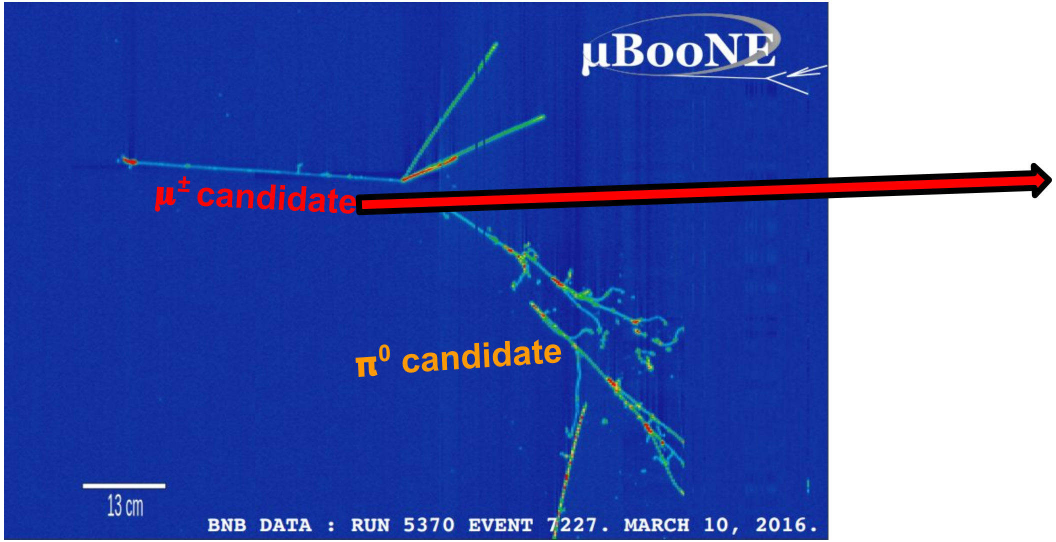


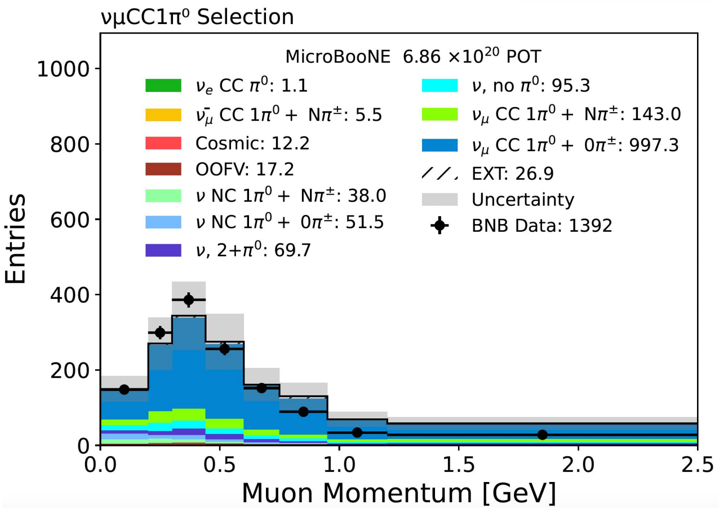


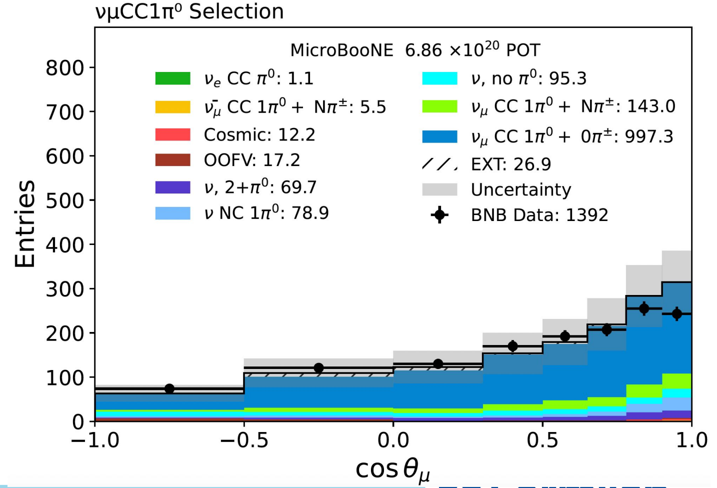


Data and MC agree within the uncertainty

Muon Kinematic Variables







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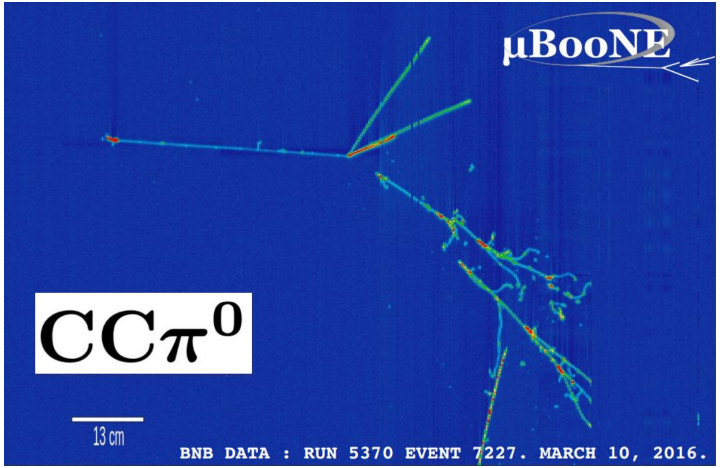
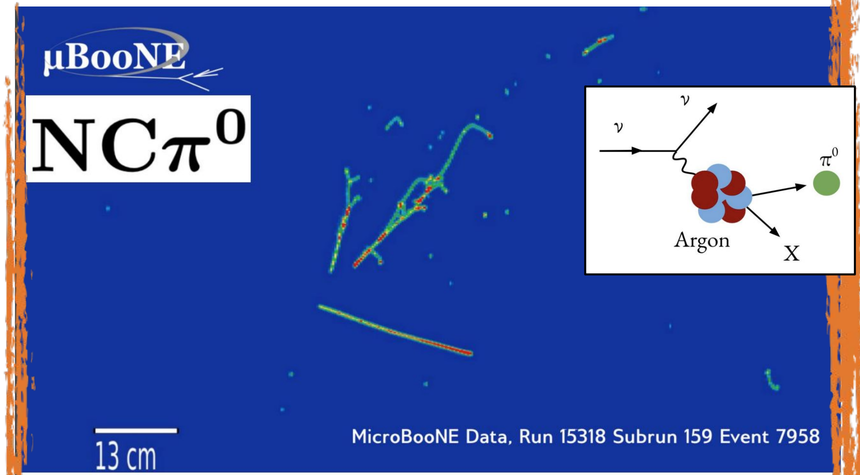
  - Using ~50% of available MicroBooNE data sets and Booster Neutrino Beam (BNB)

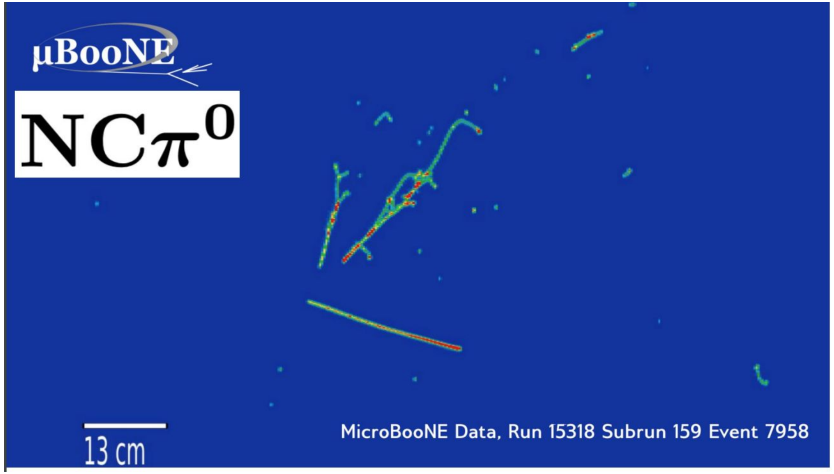


arXiv:2404.09949



arXiv:2404.10948

Topics Today:



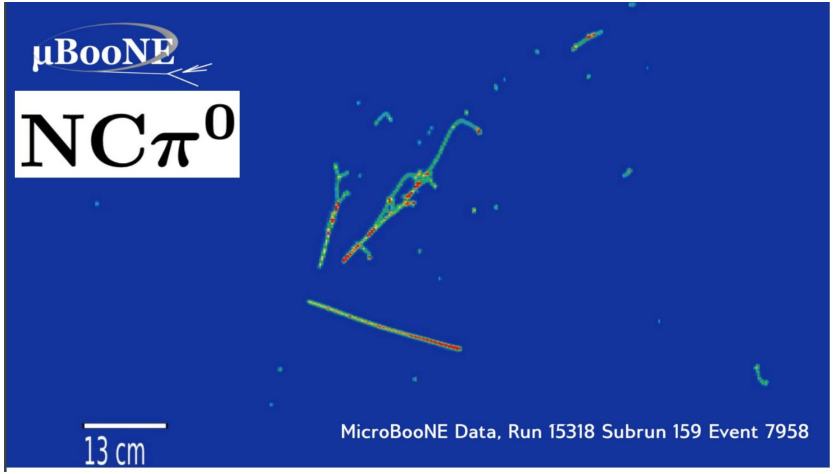
[arXiv:2404.10948](https://arxiv.org/abs/2404.10948)

- First double-differential cross section measurement of neutral-current π^0 production on argon
- Simultaneous single-differential measurements of final states with (Np) and without (0p) protons
- NCπ^0 results reported as a function of the π^0 kinematics

Benjamin Bogart

https://inspirehep.net/authors/2117345

Signal Definition:



arXiv:2404.10948

Signal: $\nu_x + Ar \rightarrow \nu_x + 1\ \pi^0 + X$
↳ $\gamma\ \gamma$ ↳ (nucleons + hadrons)

- Neutrino event contains 1 π^0 ($P_{\pi 0} < 1.2$ GeV/c)
- All neutrino flavors are included
- Any hadronic final state
- 0p and Np (K.E. > 35 MeV)

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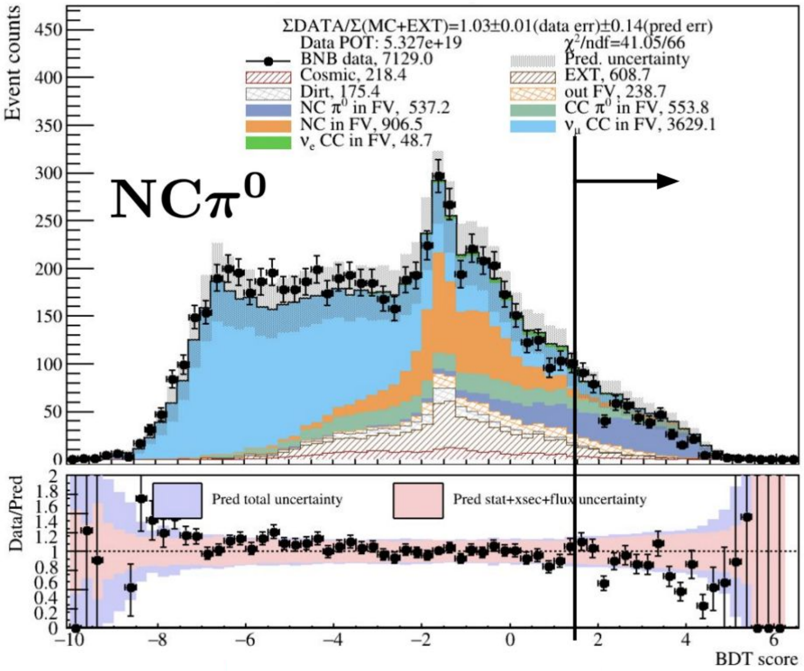
Event Selection :



arXiv:2404.10948

- NC π^0 analysis utilizes a Boosted Decision Tree based event selection
- Trained on “tagger” variables designed to characterize ν_μCC, ν_e CC and NC π^0 events
- Selection efficiency 35% and Purity 54%

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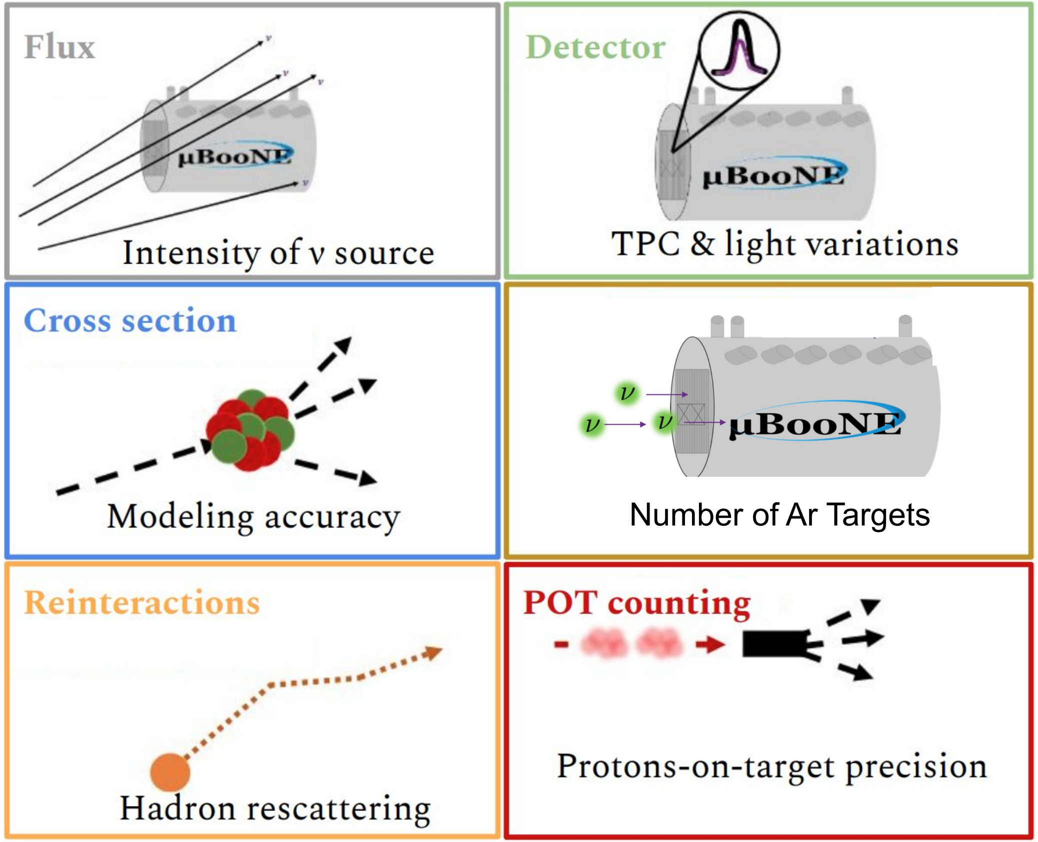
Uncertainties:

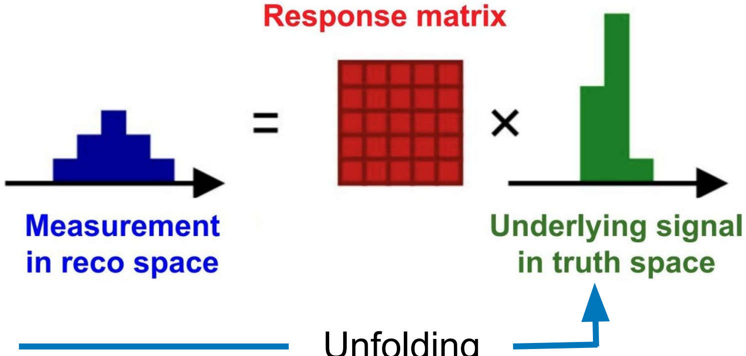


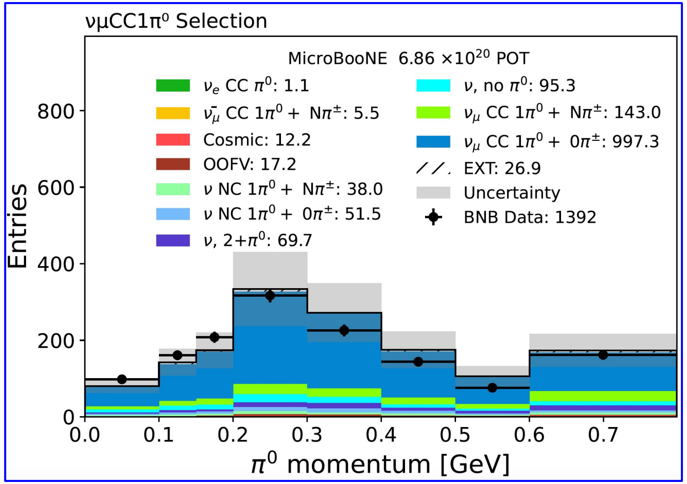
- Both $CC\pi^0$, $NC\pi^0$ measurements are systematics dominated
- Dominant sources of systematic uncertainties
  - Detector response
  - Neutrino flux

Cross Section Extraction with Wiener SVD Unfolding:

From event distributions to cross sections→ unfolding

JINST 12 P10002 (2017)





- Data measurement
- Background (Cosmics + MC)

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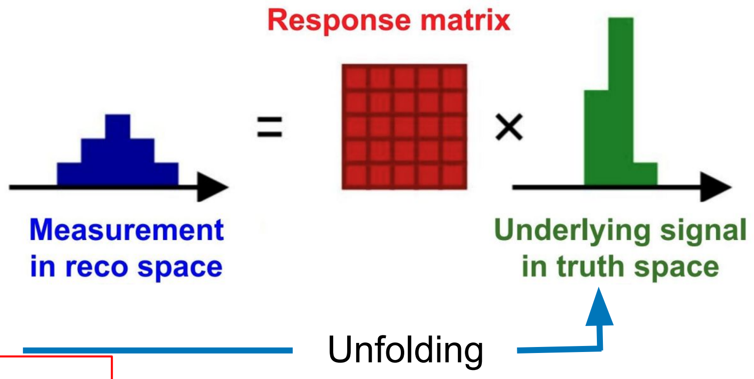
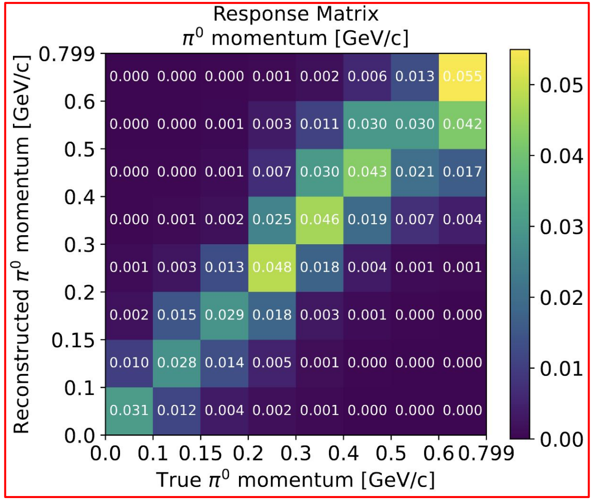
Cross Section Extraction with Wiener SVD Unfolding:

From event distributions to cross sections→ unfolding

JINST 12 P10002 (2017)





- Response Matrix
  - Mapping between true and reconstructed distributions
  - Accounts for bin migration effects due to limitations of the reconstruction and the inefficiencies

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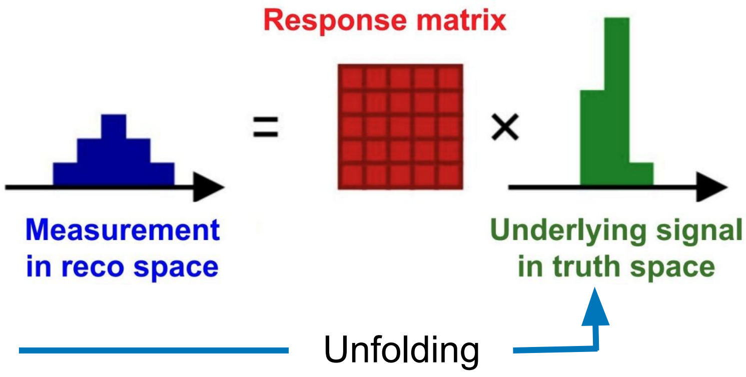
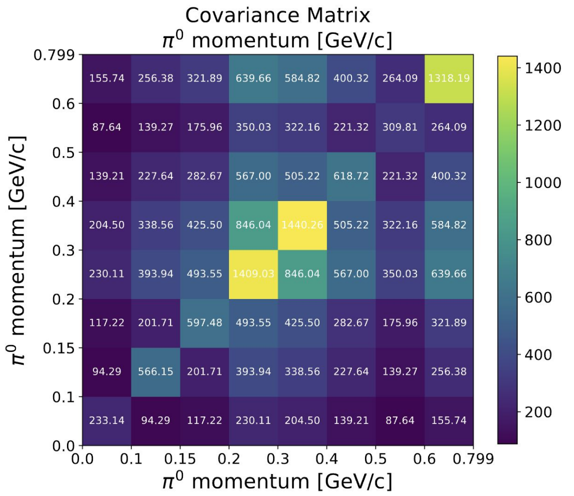
Cross Section Extraction with Wiener SVD Unfolding:

From event distributions to cross sections→ unfolding

JINST 12 P10002 (2017)



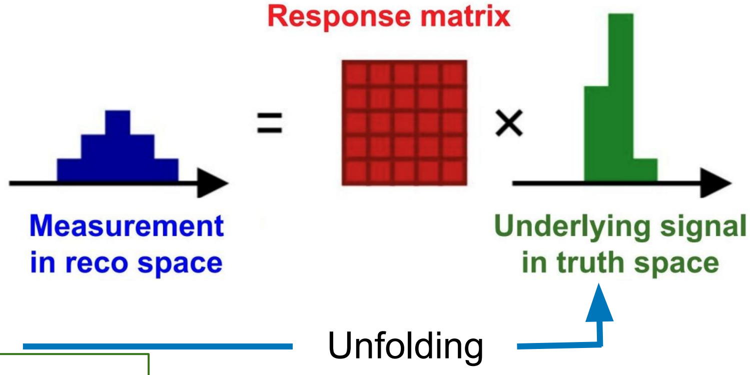


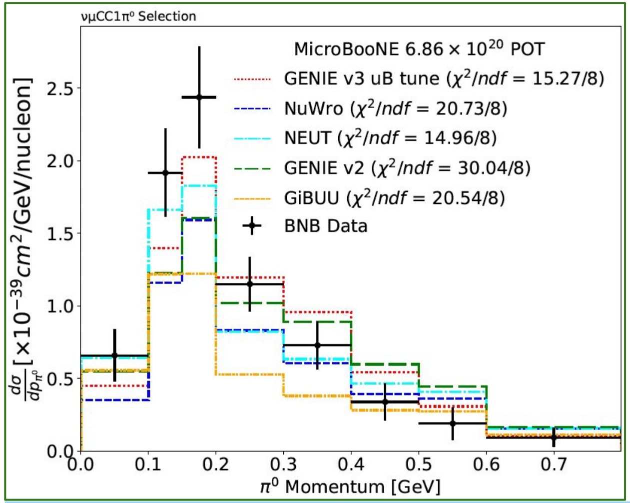
- Total Covariance Matrix
    - Statistical and systematic uncertainties

Cross Section Extraction with Wiener SVD Unfolding:

From event distributions to cross sections→ unfolding

JINST 12 P10002 (2017)





- Extracted cross section

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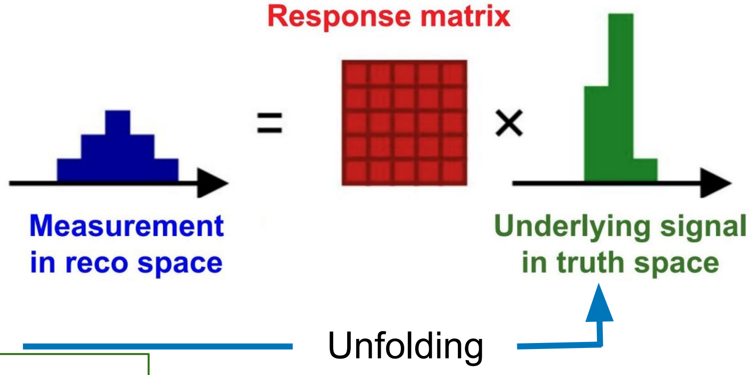
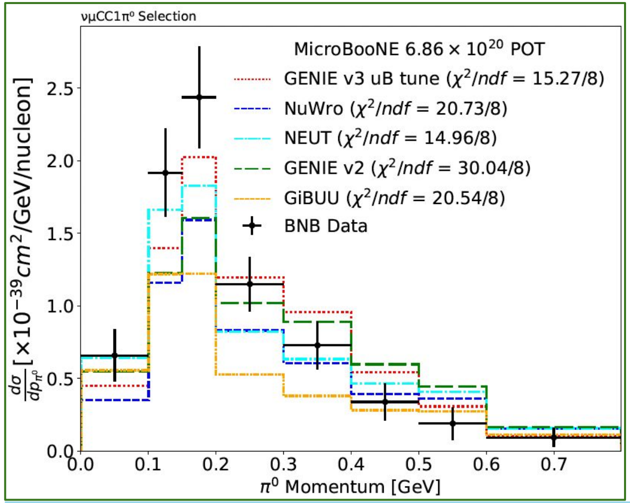
Cross Section Extraction with Wiener SVD Unfolding:

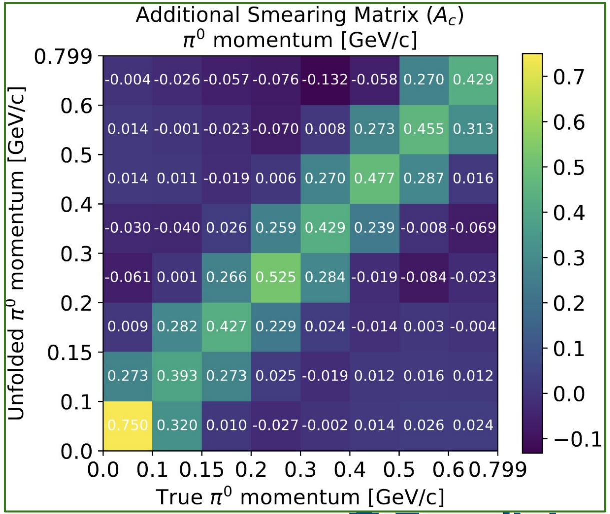
From event distributions to cross sections→ unfolding

[JINST 12 P10002 (2017)](#)



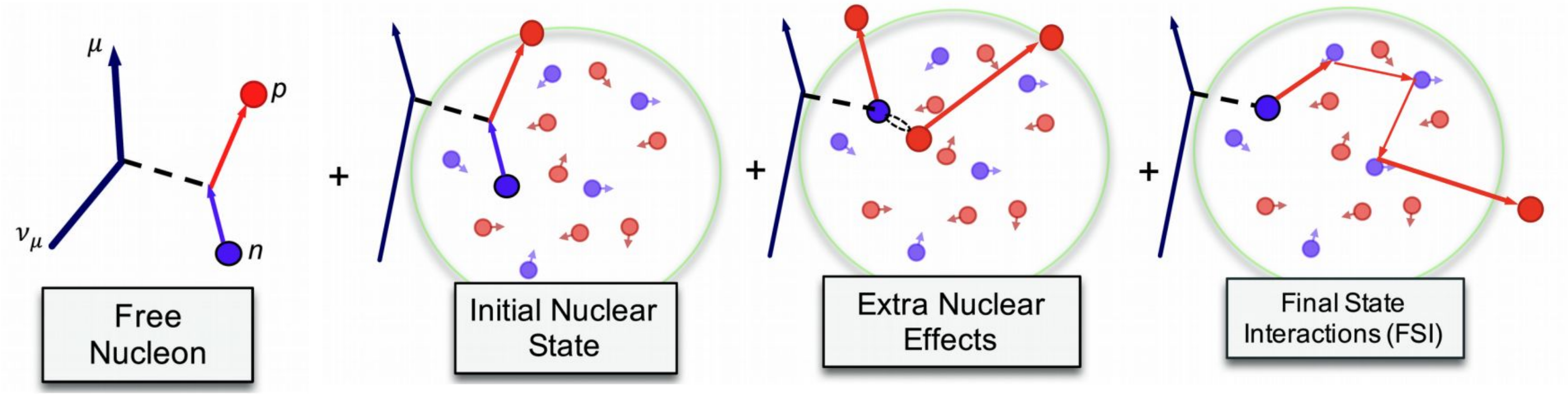


- Additional Smearing Matrix:
  - Applied on theory predictions and info included in data release



Anatomy of Neutrino Nucleus Interaction:

The nucleon isn't stationary inside a nucleus → initial momentum



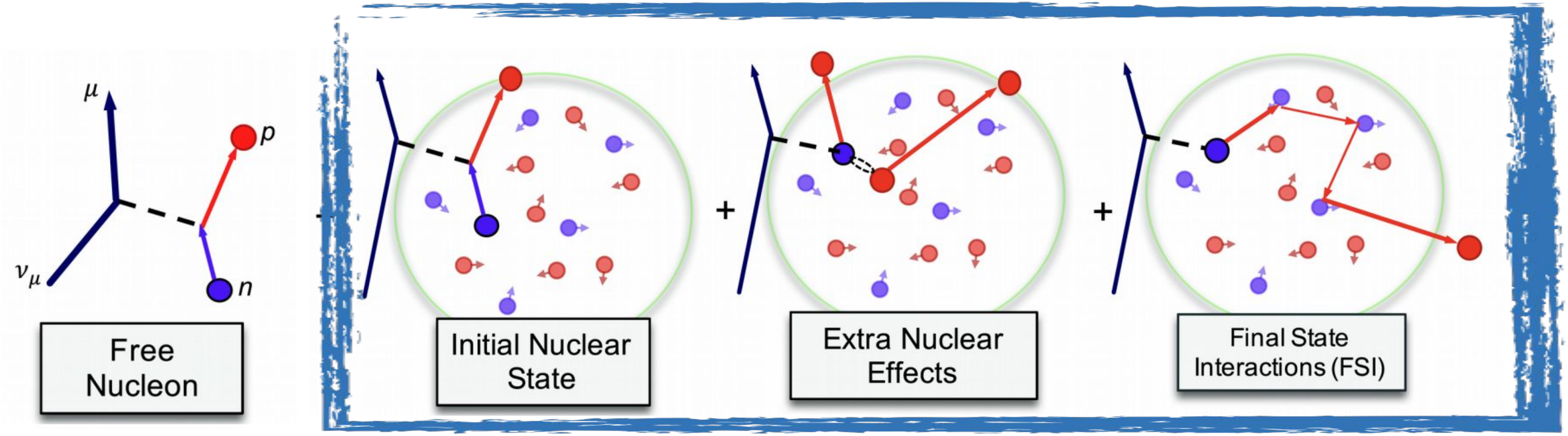
The neutrino can interact with multiple nucleons, and additional processes can occur inside the nucleus

[Cartoon Credit Callum Wilkinson at NNN 2017]

Anatomy of Neutrino Nucleus Interaction:

The nucleon isn't stationary inside a nucleus → initial momentum

Model differences



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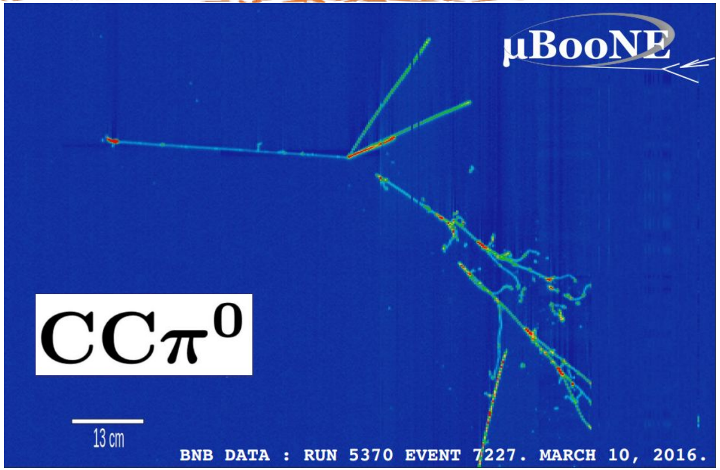
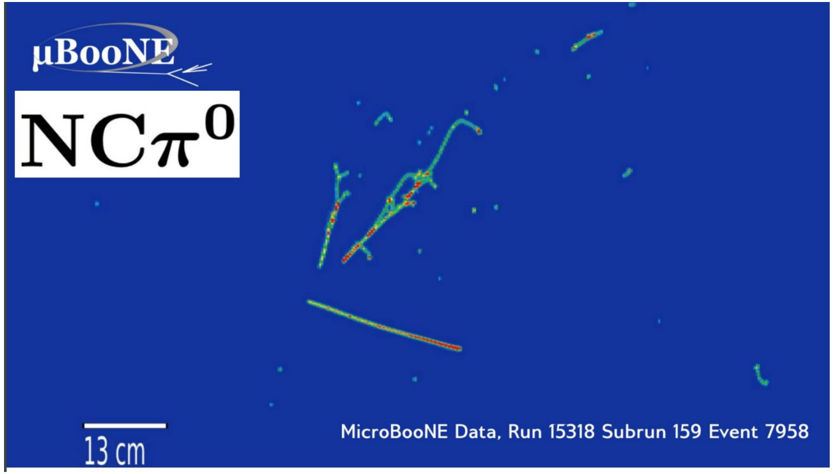
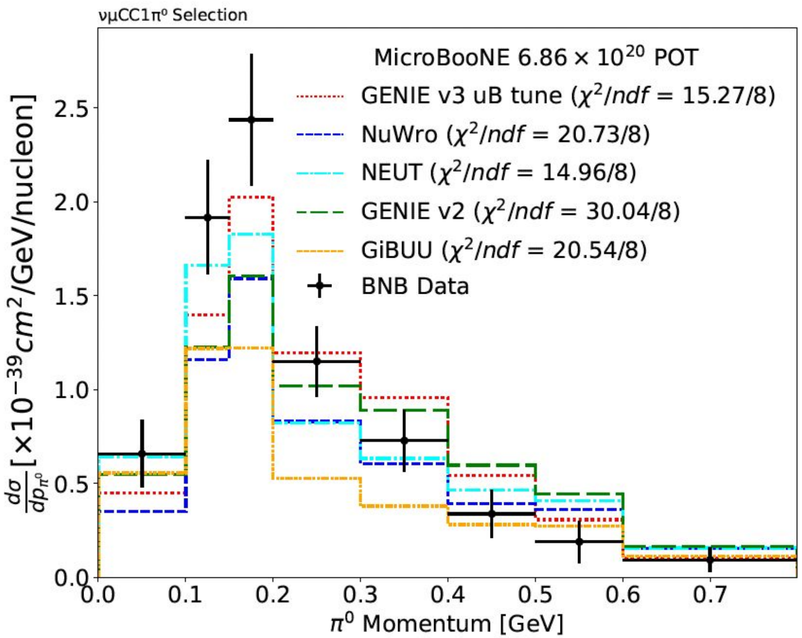


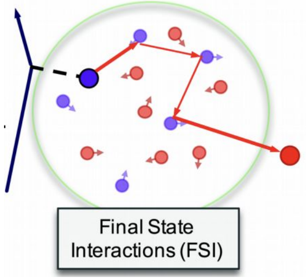
arXiv:2404.09949



arXiv:2404.10948

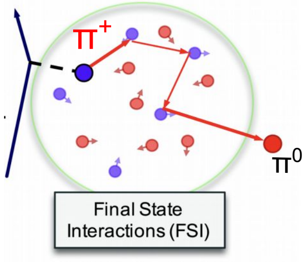
Cross Section Results: $CC\pi^0$

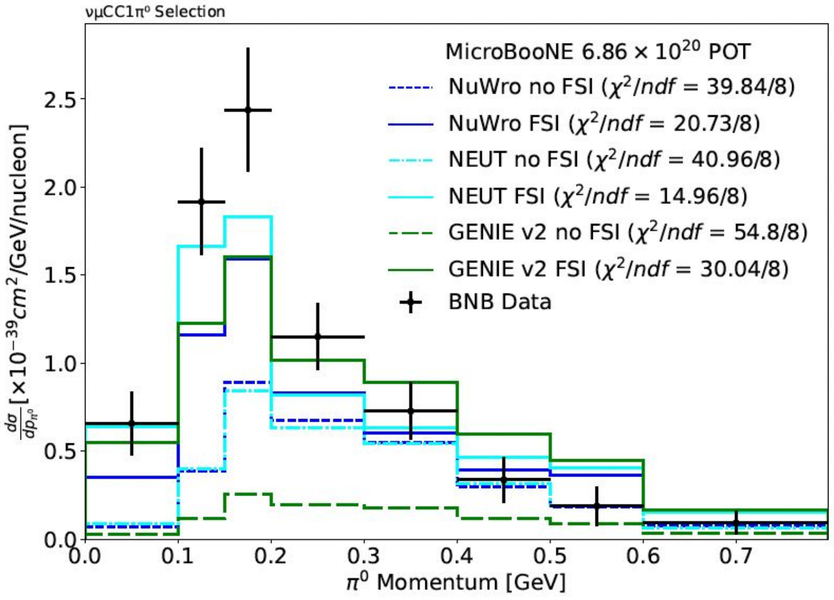




- Pions interacting with nuclear medium shift momentum to lower values, contribute to buildup of peak
- Generators underestimate data extracted cross section in the peak (FSI dominated region)

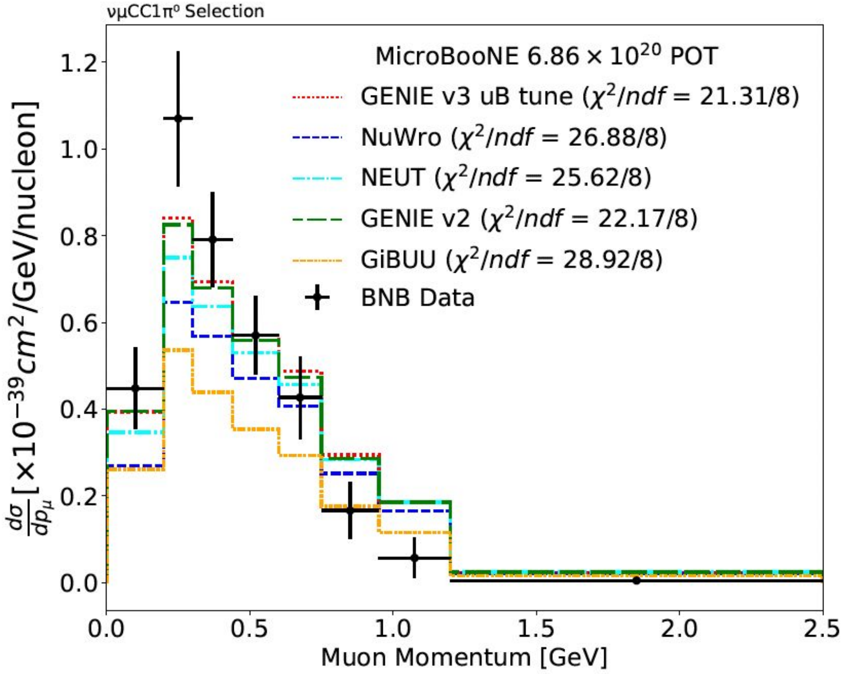
Cross Section Results: CCπ^0 FSI Effects





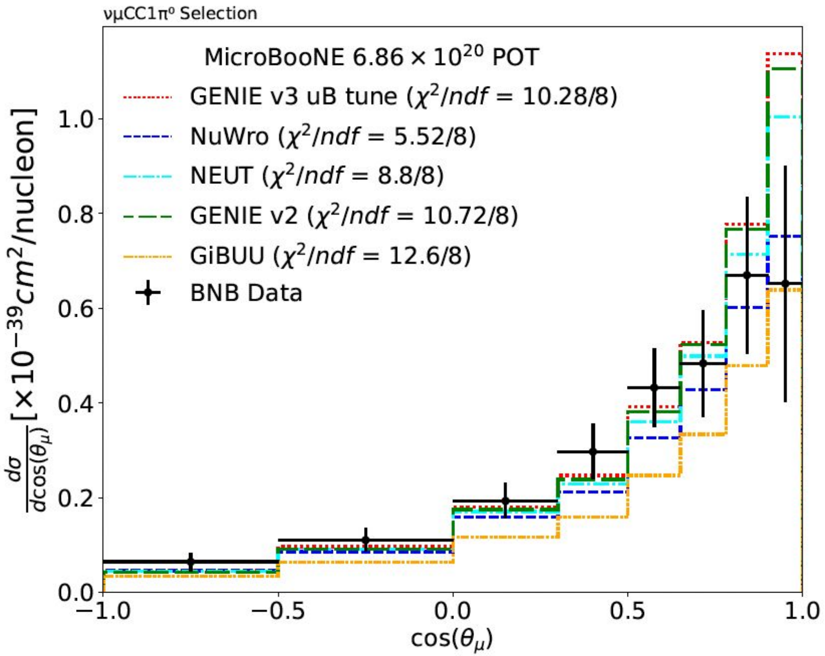
- E.g., CCπ$^+$ production feeding to the π^0 channels through charge exchange → FSI increases the cross section

Cross Section Results: $CC\pi^0$



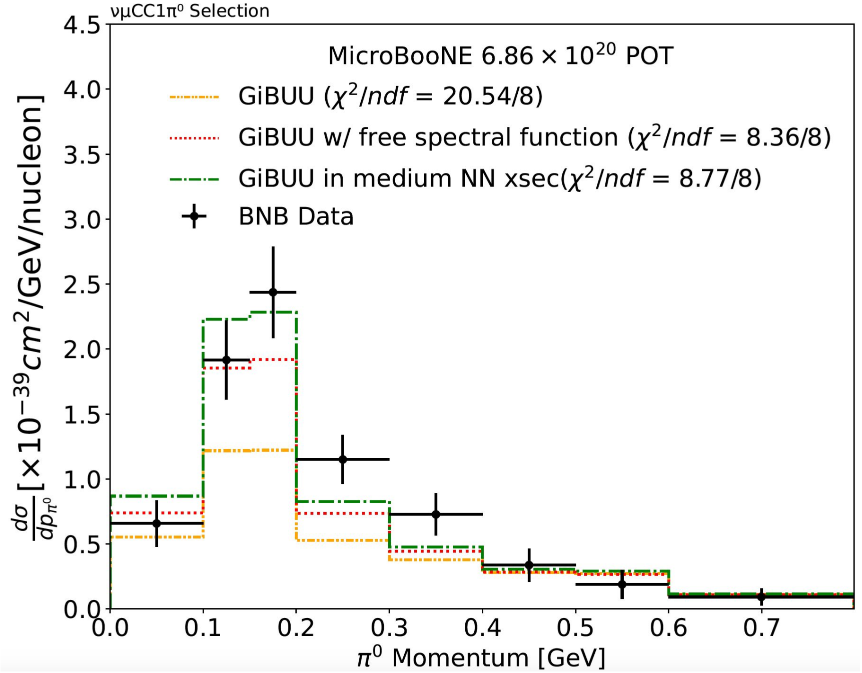
- Similar trend as π^0 momentum
  - Suppressed generator predictions in lower momenta (~200 - 400 MeV)
  - In higher momenta, generator predictions are higher than the data

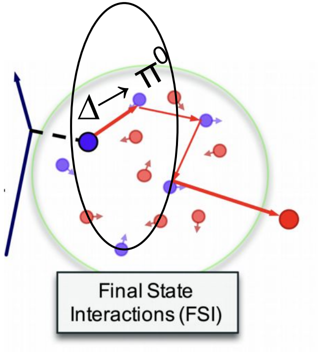
Cross Section Results: CCπ^0



- Generators overpredict cross section at cos(θ_μ) > 0.9
  - Indicates shortcomings of models
- The forward angle corresponds to low momentum transfer (Q^2) events, not well reproduced by models in MINERvA, MiniBooNE measurements

More Insights into Modeling:



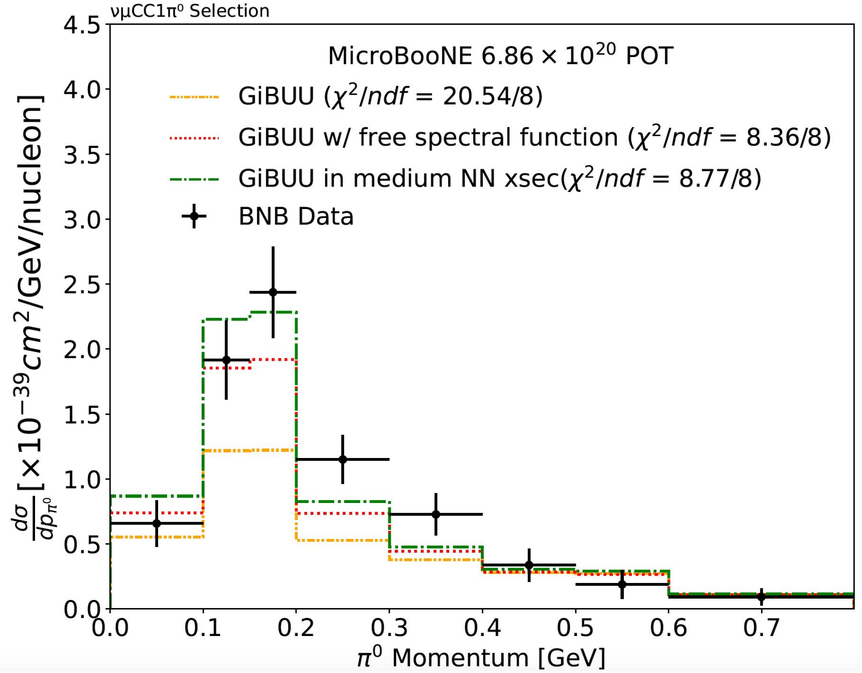


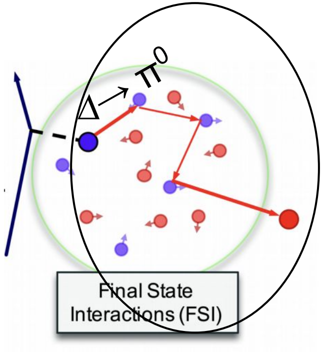
- GiBUU 2023 (default)
  - Valencia-Oset collisional broadening for the Δ resonance → increases Δ decay width

    ⇩

    Reduced Δ production + increased Δ absorption
- GiBUU with free spectral function for Δ resonance

More Insights into Modeling:



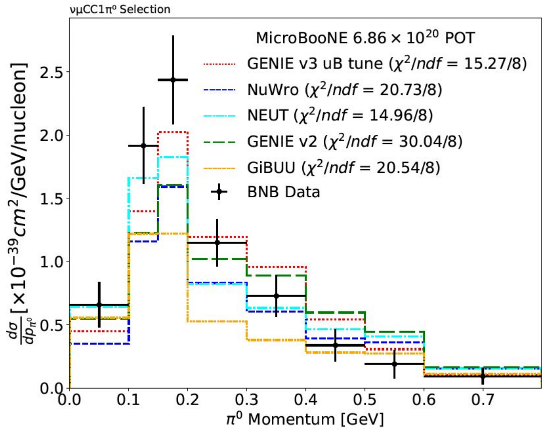


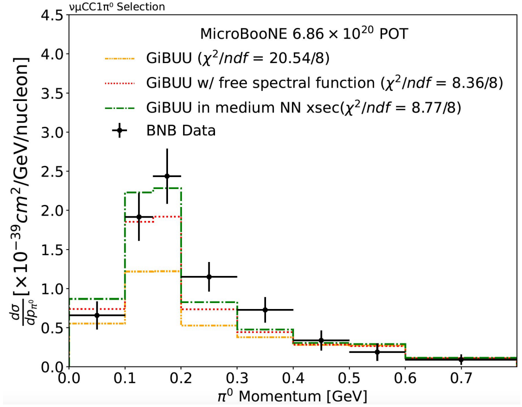
- GiBUU 2023 (default)
  - Valencia-Oset collisional broadening for Δ resonance
  - Nucleon-nucleon (NN) cross sections in vacuum while evaluating FSI

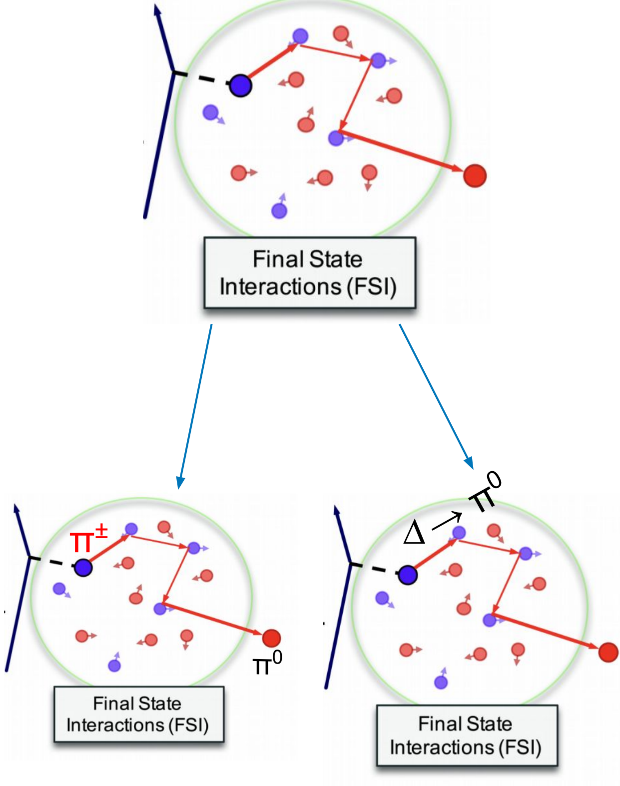
- GiBUU in medium NN xsec
  - Free spectral function for Δ resonance
  - NN cross section calculated in medium

CCπ^0 Takeaways:

- First single differential measurements of CCπ^0 on argon
- Sensitive to Final State Interactions
  - Effect on Δ decay width and hence pion production
  - Effect on pion re-interaction







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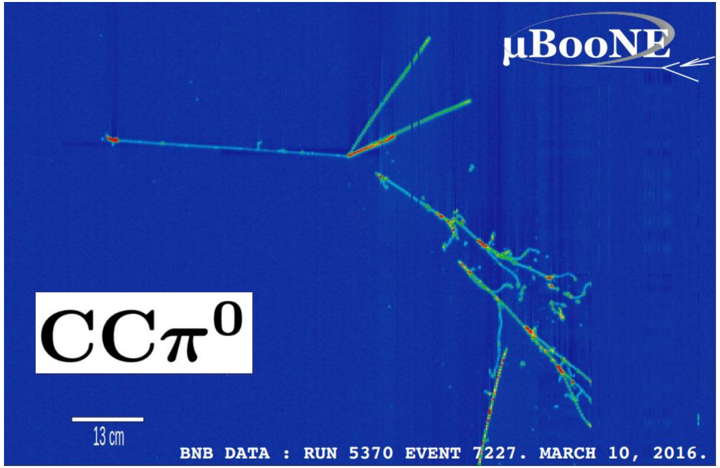
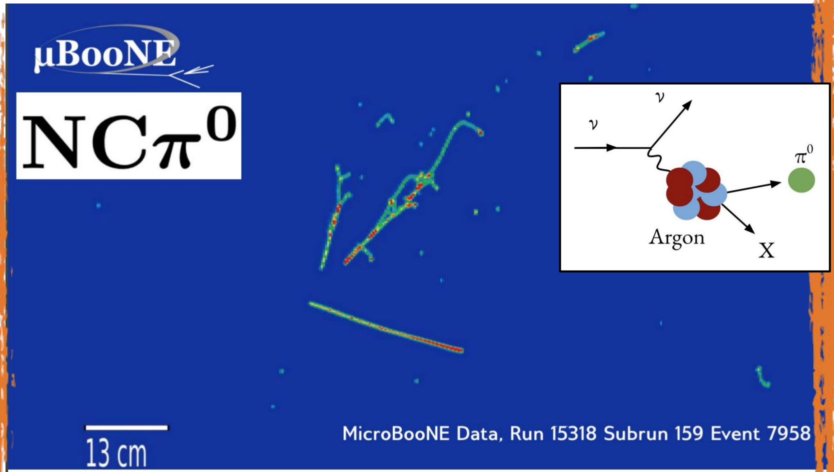
Topics Today:

- Two recent π^0 production results from MicroBooNE
  - Using ~50% of available MicroBooNE data sets and Booster Neutrino Beam (BNB)

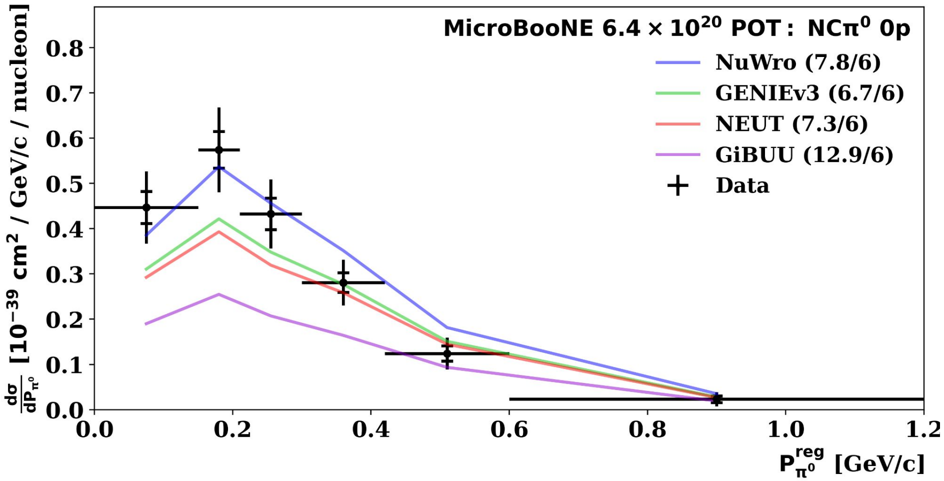


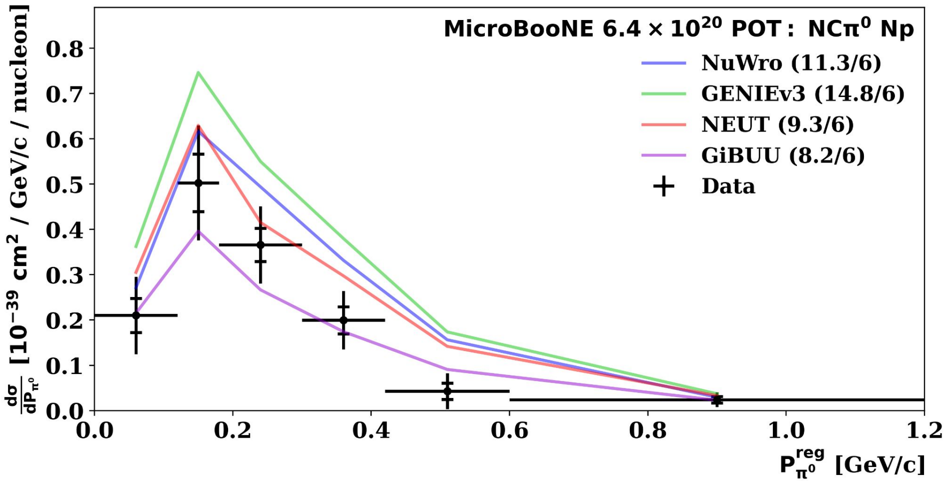
arXiv:2404.09949



arXiv:2404.10948

Cross Section Results: NCπ^0

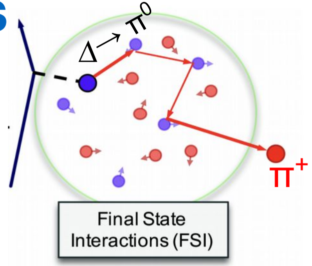


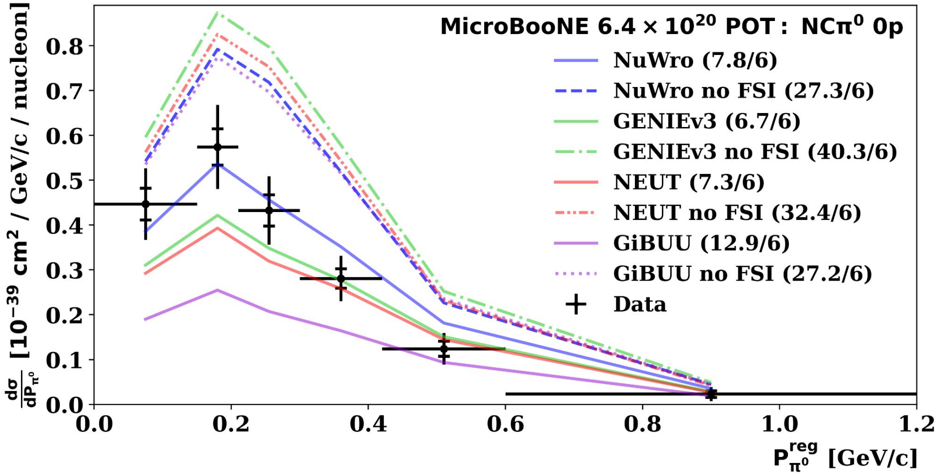


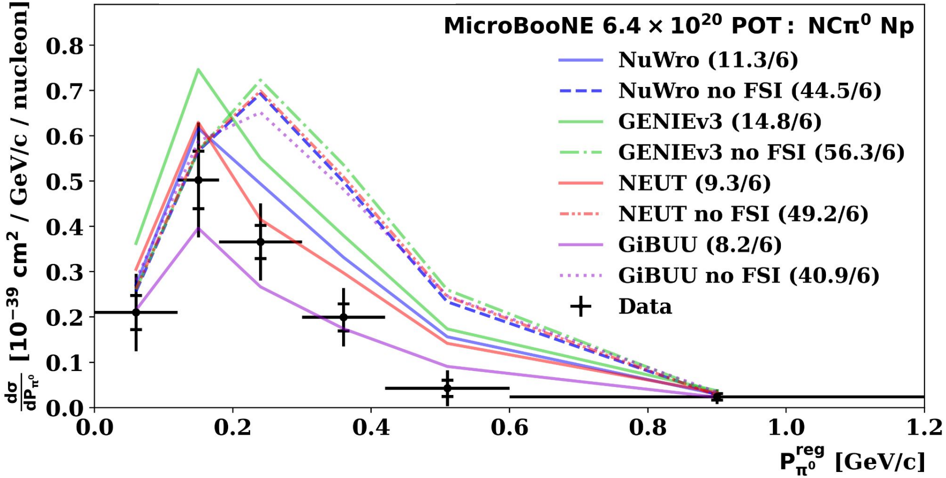
Predictions overestimate measured Np NCπ^0 cross section, around the peak (0.2-0.5 GeV/c momentum range)

GiBUU underestimates the cross section around the peak of the distribution in both the 0p and Np channels

Cross Section Results: NCπ^0 FSI Effects







- π^0 production feeding to the $\pi^\pm$ channels through charge exchange → FSI reduces the cross section
- FSI shifts 0p to Np ratio

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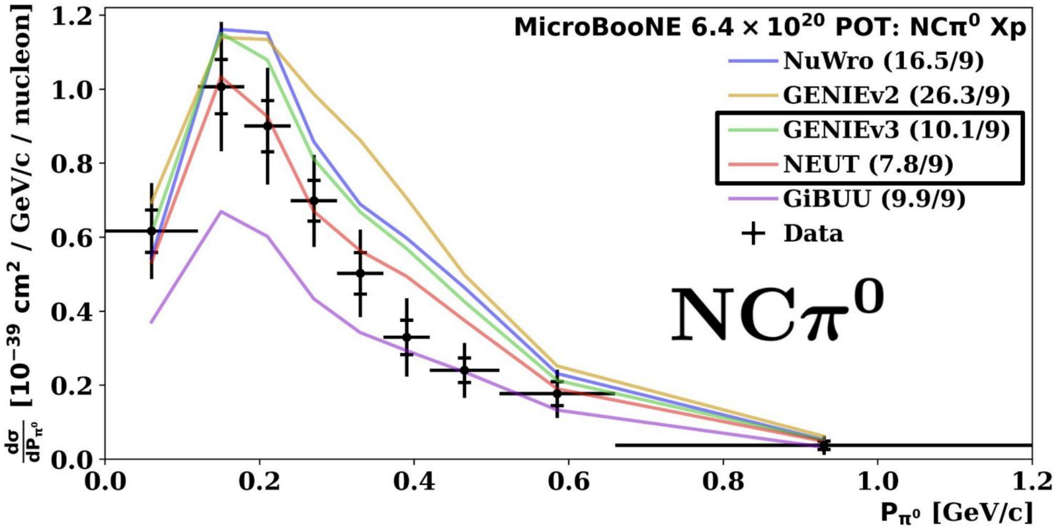
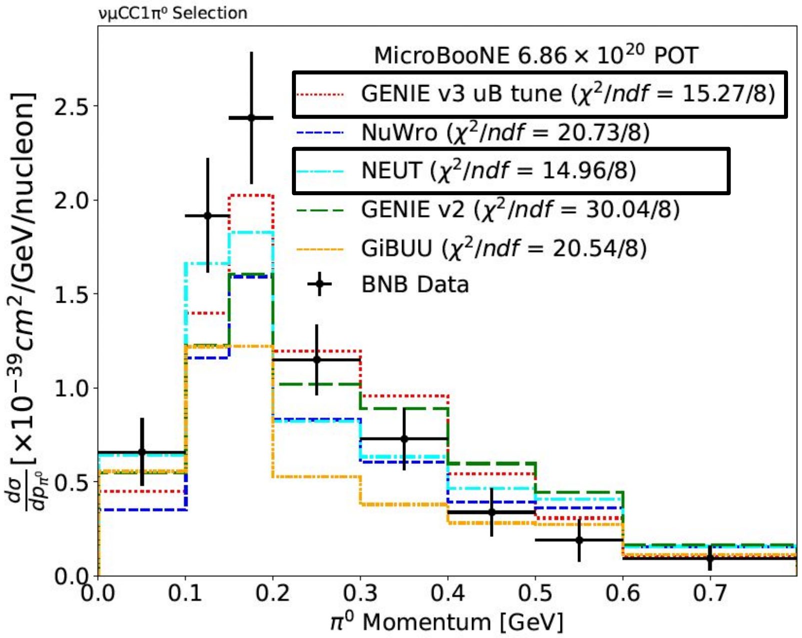
Comparing Cross Section Results:

π^0 momentum: Relatively consistent in the hierarchy of generators

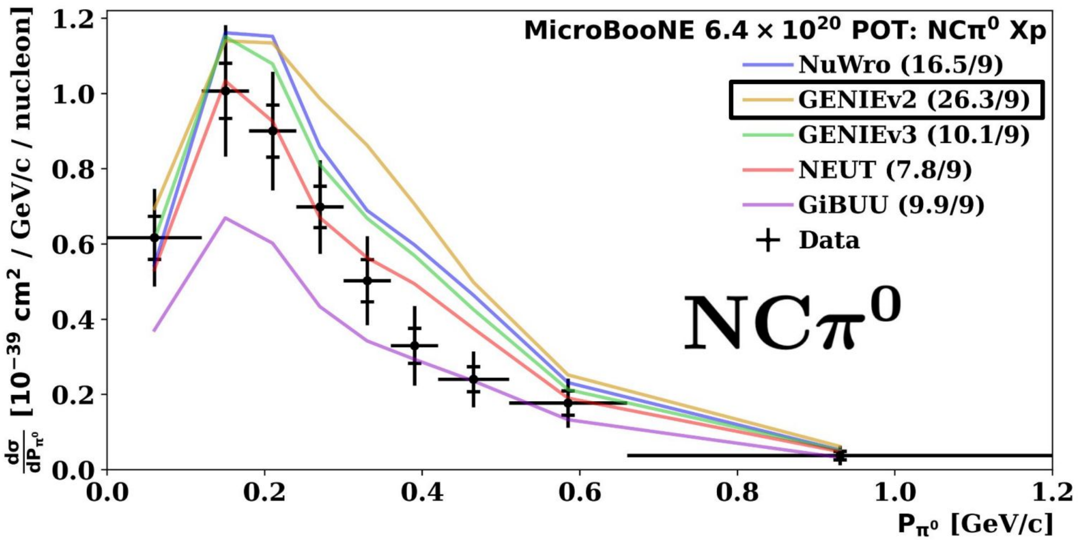


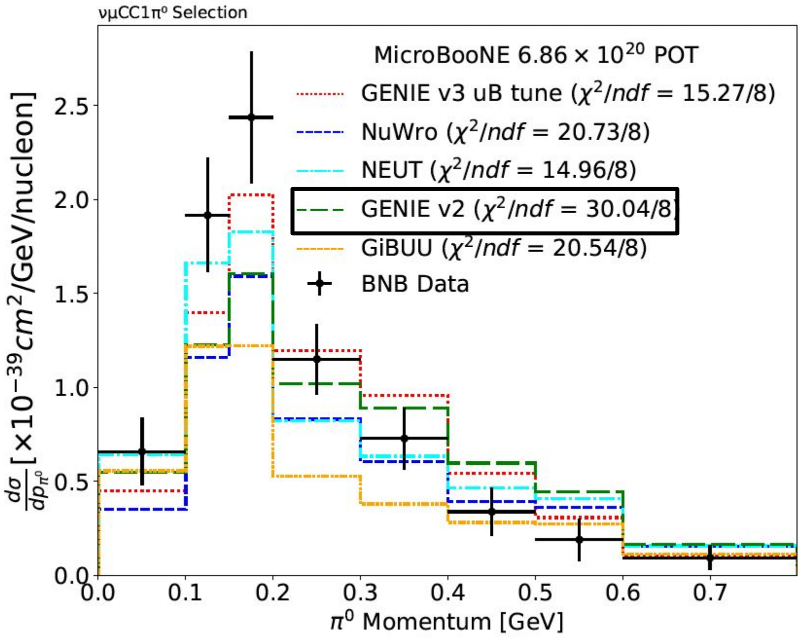


- Best agreement with data: NEUT, followed by GENIEv3

Comparing Cross Section Results:

π^0 momentum: Relatively consistent in the hierarchy of generators





- Best agreement with data: NEUT, followed by GENIEv3
- Poor performance: GENIEv2

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Comparing Cross Section Results: NCπ^0

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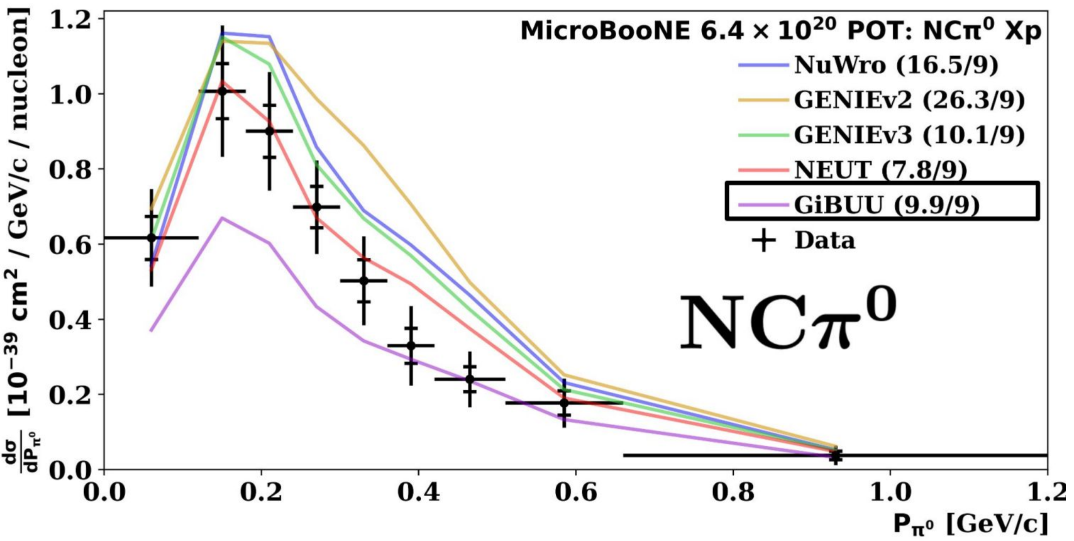
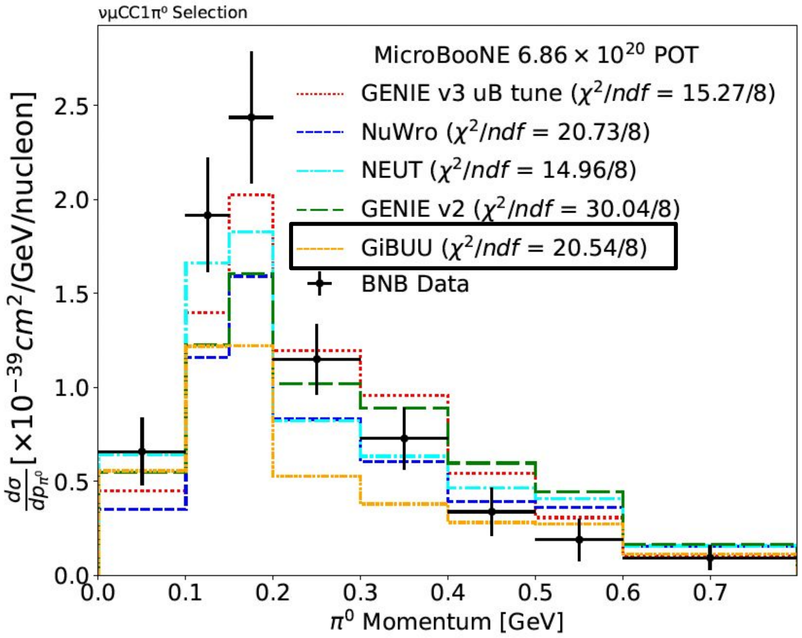
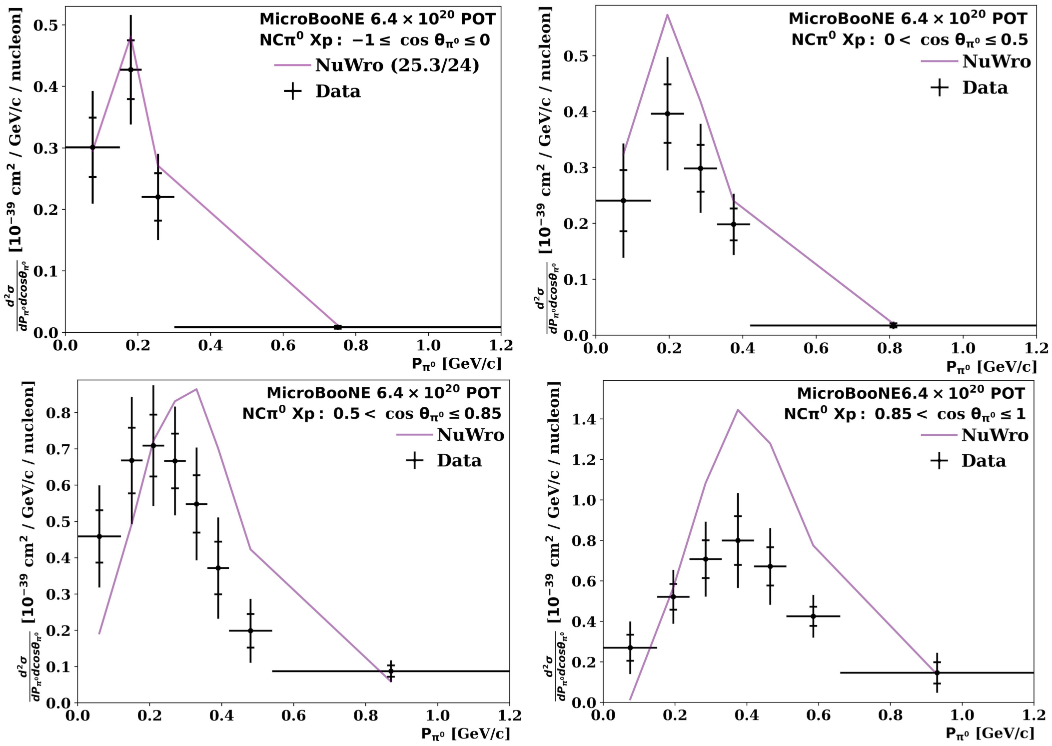




- Best agreement with data: NEUT, followed by GENIEv3
- Poor performance: GENIEv2
- GiBUU shows low normalization, around the peak (FSI dominated region)

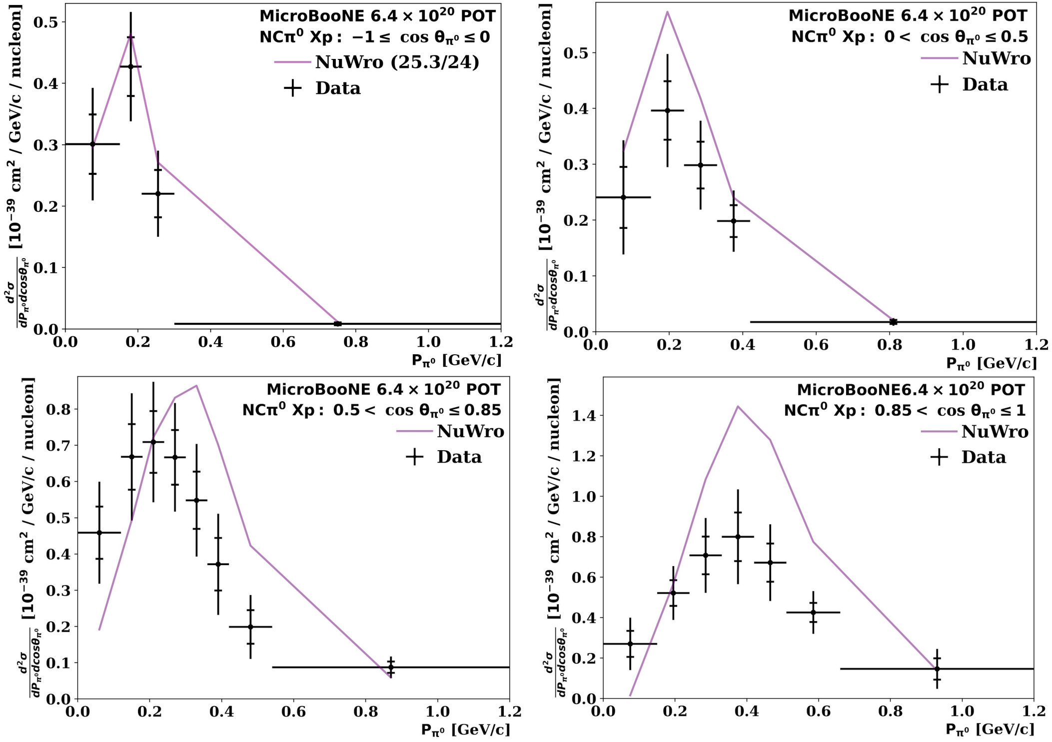
Cross Section Results: NCπ^0

- First double-differential cross-section measurement
  - sensitive to mis-modeling in different regions of phase space

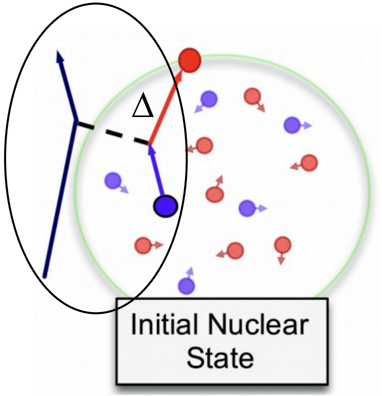


Cross Section Results: $NC\pi^0$

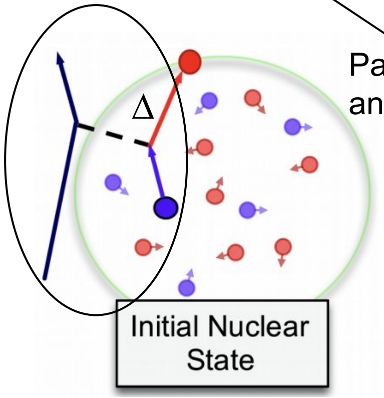
- First double-differential cross-section measurement
  - sensitive to mis-modeling in different regions of phase space
  - sensitive to Δ production modeling

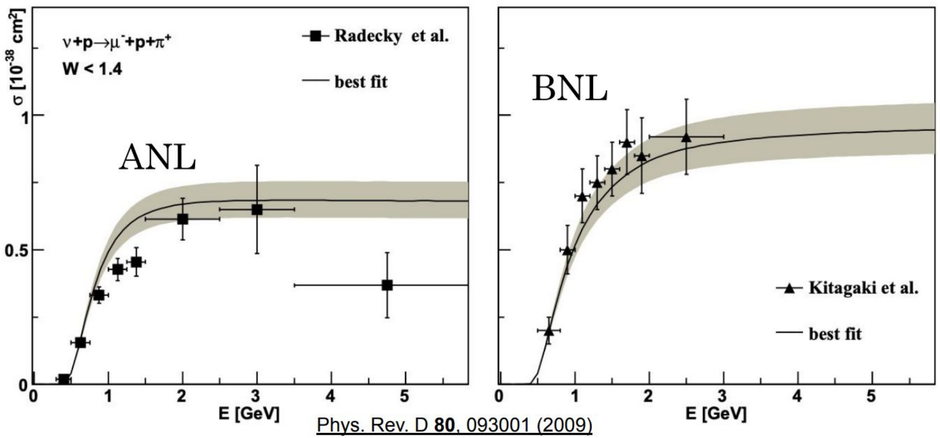


Δ production

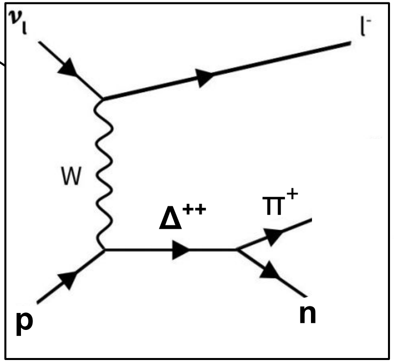


Axial Form Factors:





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



- Axial and vector form factors obtained from fits to data
- Axial form factors commonly fit using two bubble chamber CCπ^+ data sets
  - One from ANL and one from BNL
  - Data sets differ in normalization by ~30% leading to large theoretical uncertainties

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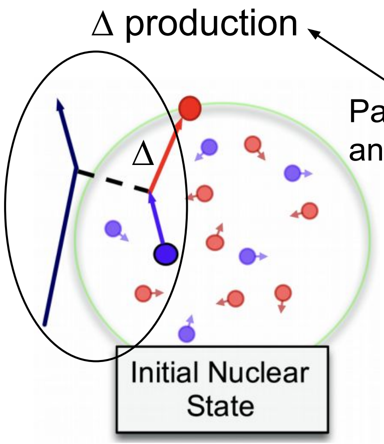
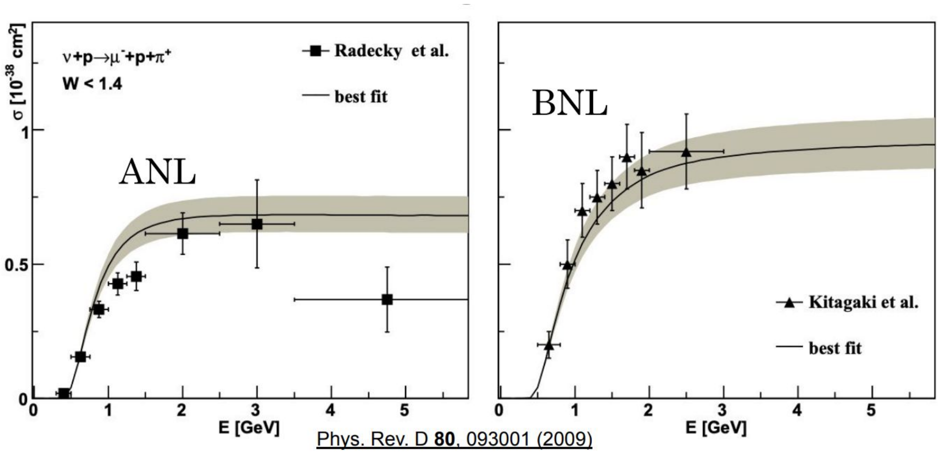
Axial Form Factors:



Parameterized with axial and vector form factors



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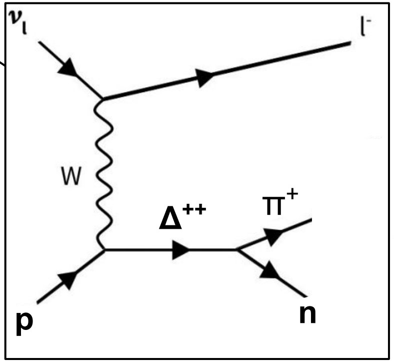

- Axial and vector form factors obtained from fits to data
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  - One from ANL and one from BNL
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NCπ^0 measurements provide an invaluable benchmark

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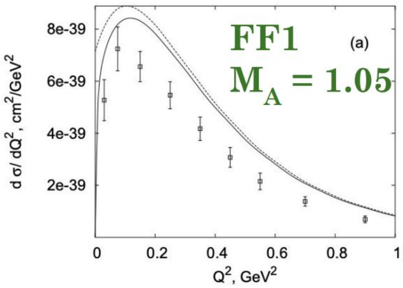
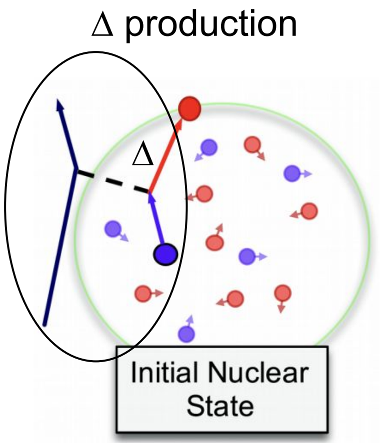
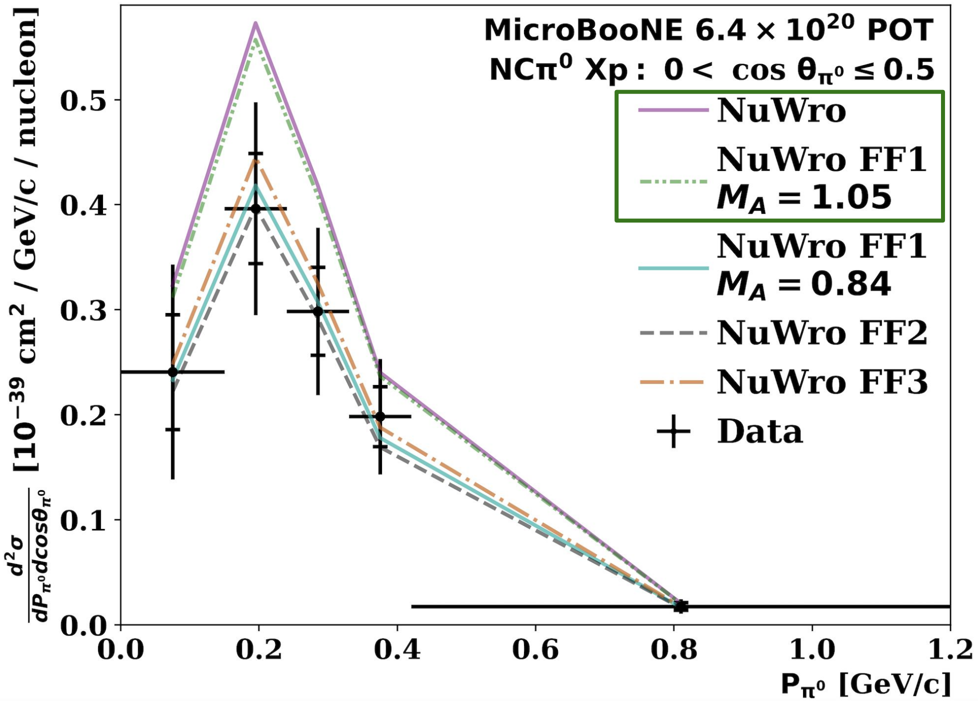
Cross Section Results: NCπ^0



Comparison to ANL data





- NCπ^0 data compared to predictions with 5 different form factors using NuWro
- NuWro and NuWro FF1 M_A = 1.05 favor BNL data

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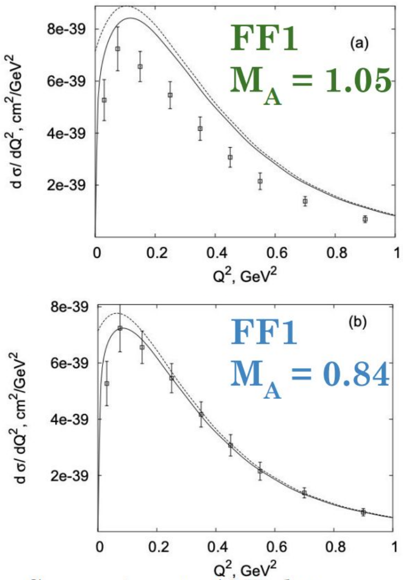
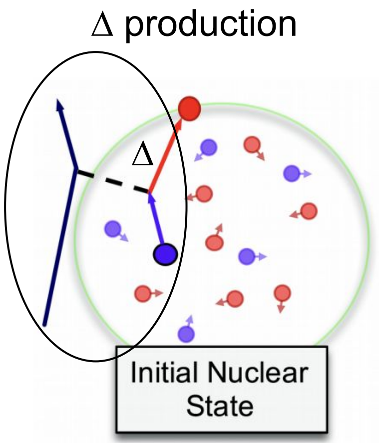
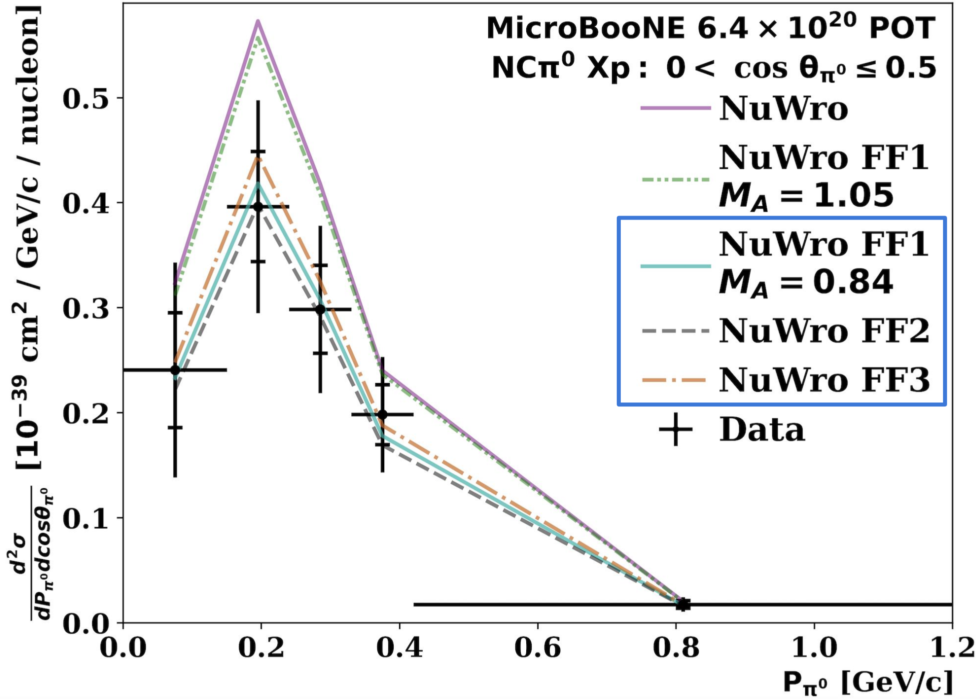
Cross Section Results: NCπ^0



Comparison to ANL data

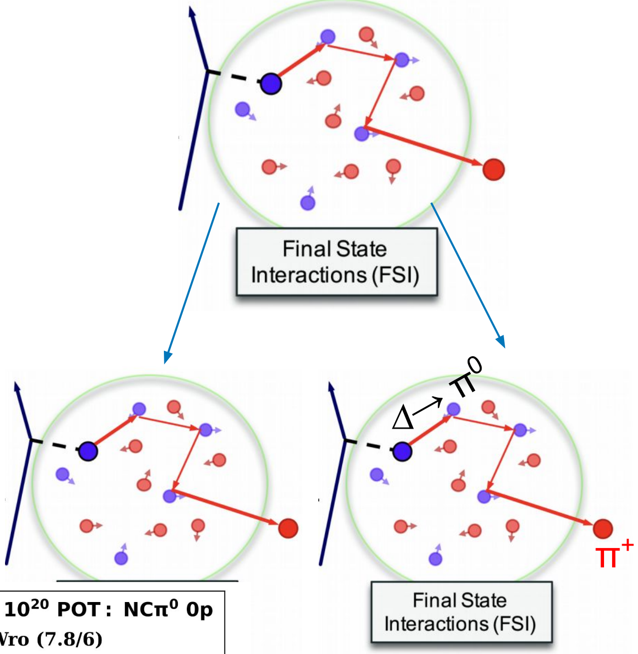


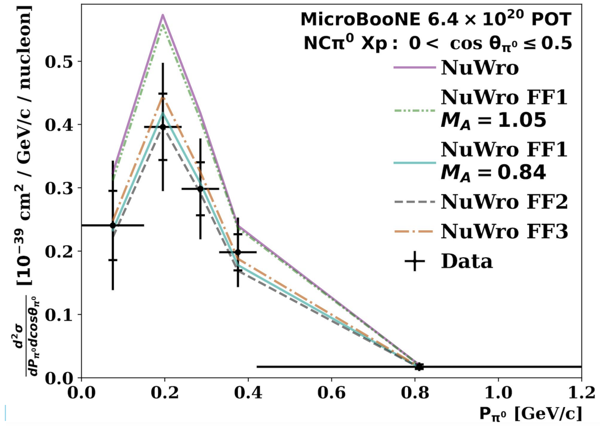


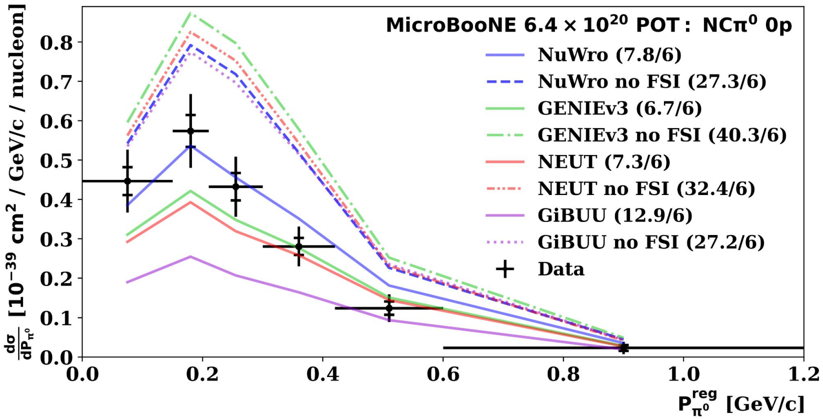
- NCπ^0 data compared to predictions with 5 different form factors using NuWro
- NuWro and NuWro FF1 M_A = 1.05 favor BNL data
- NCπ^0 data prefers the predictions that agree better with ANL data

NCπ^0 Takeaways:

- First double differential measurements of NCπ^0 on argon
- Sensitive to Δ production modeling
- Sensitive to Final State Interactions
    - Effect on pion re-interaction
    - Effects on with (Np) and without (0p) proton final states







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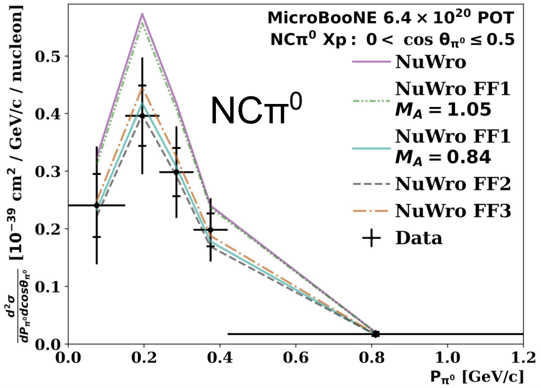
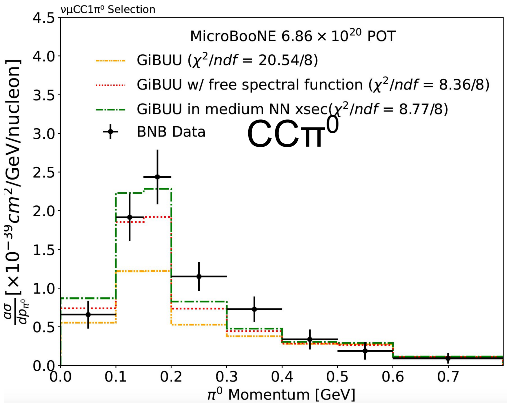
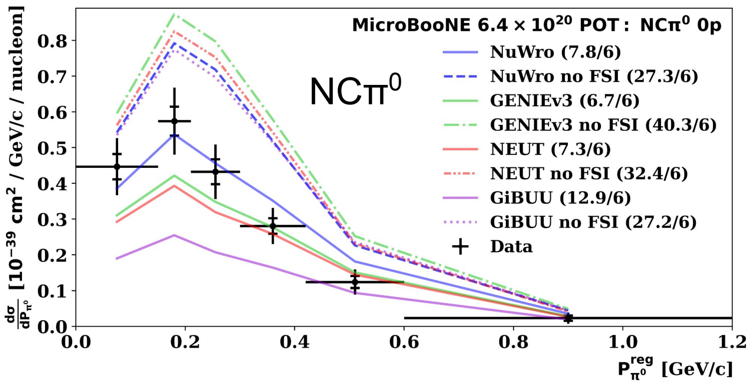
Summary:

- Two MicroBooNE analyses providing novel information about neutral pion production on argon with single and double-differential cross section measurements [arXiv:2404.09949](https://arxiv.org/abs/2404.09949), [arXiv:2404.10948](https://arxiv.org/abs/2404.10948)

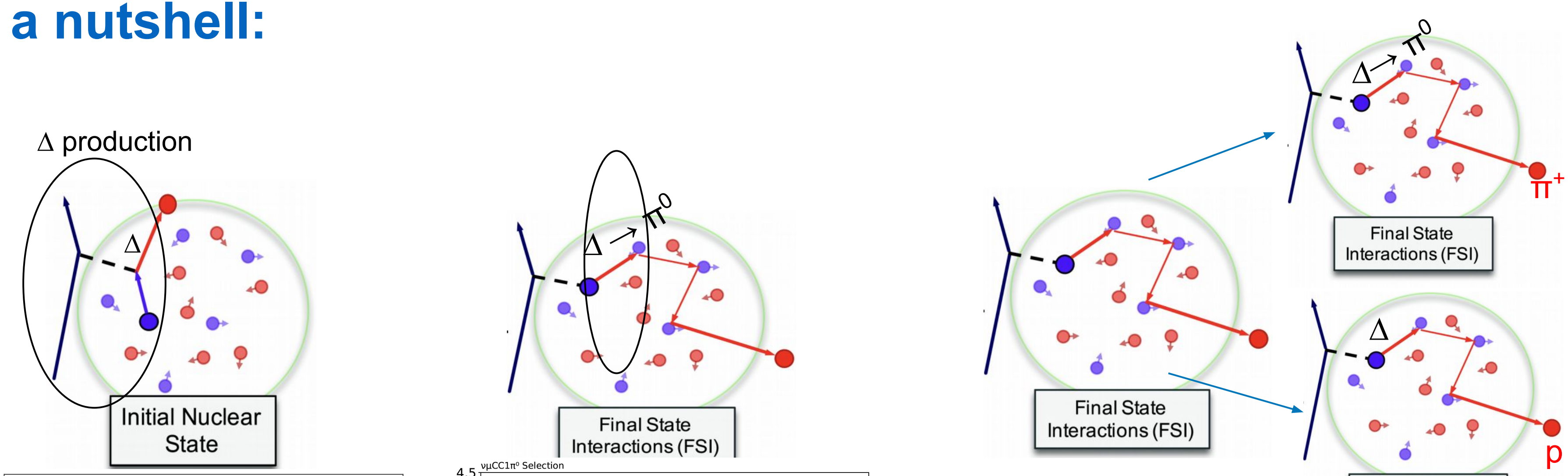
- These are sensitive to the initial nuclear state, multi-nucleon effects, and FSI

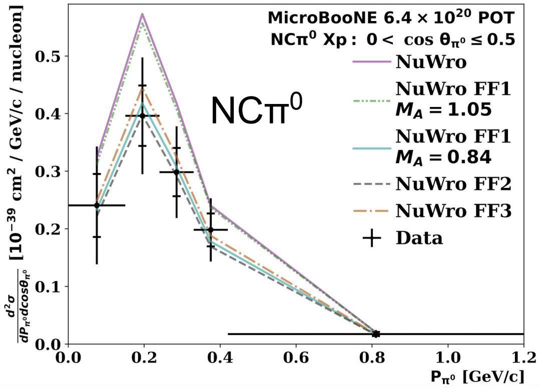


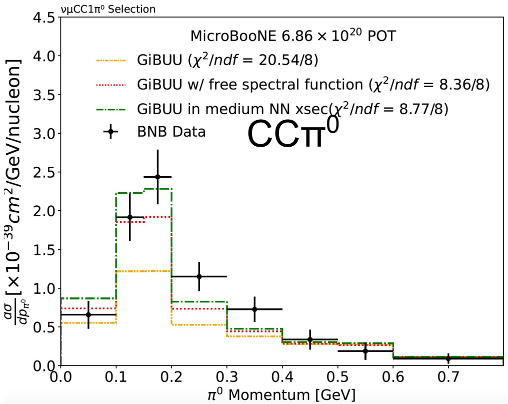


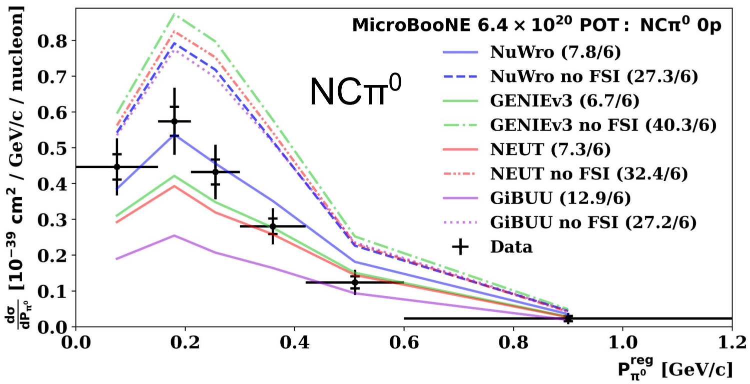


In a nutshell:

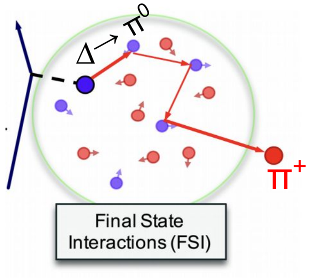


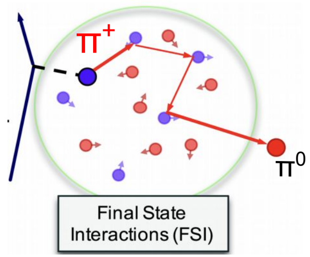


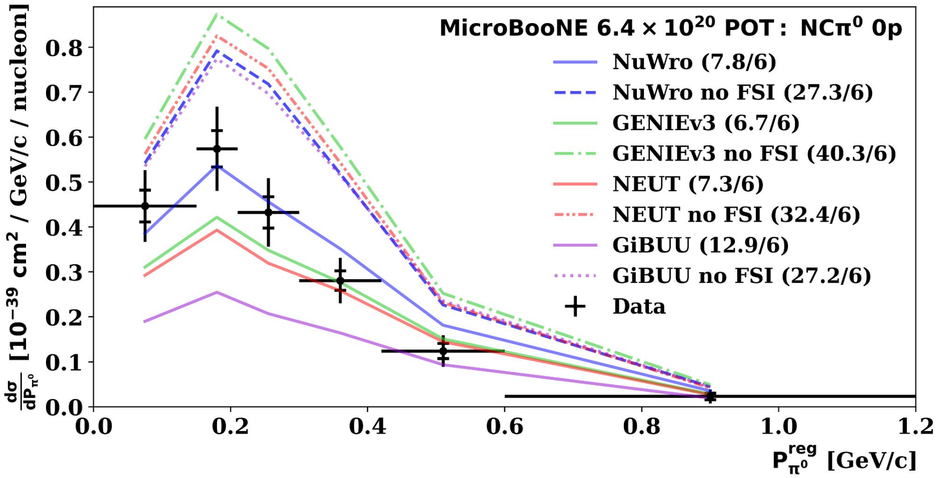


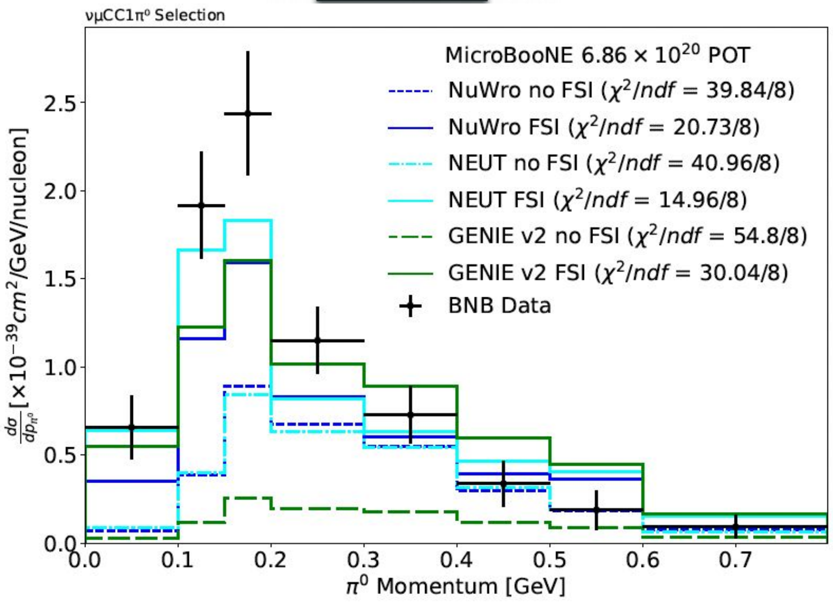


Outlook:









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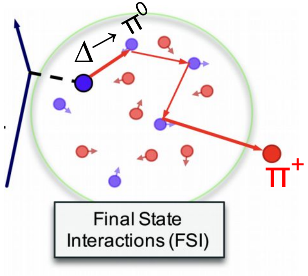
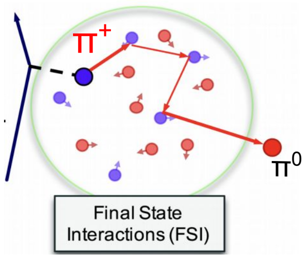
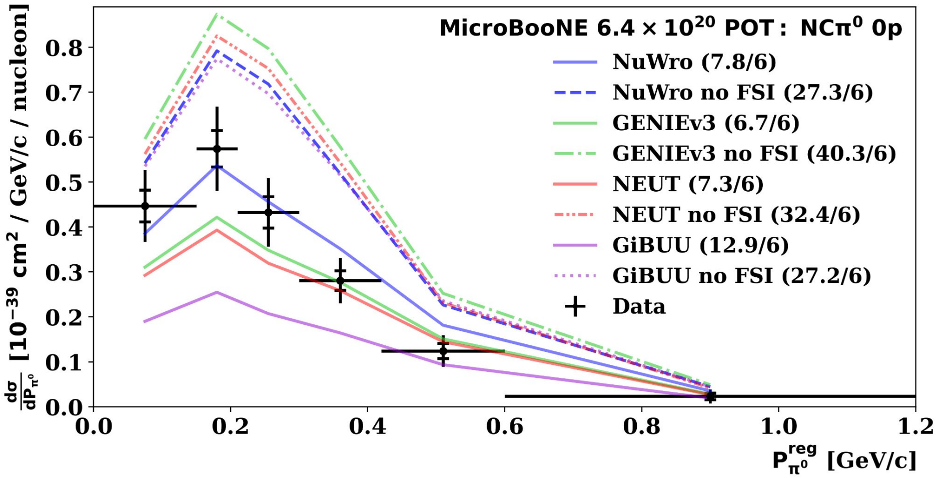
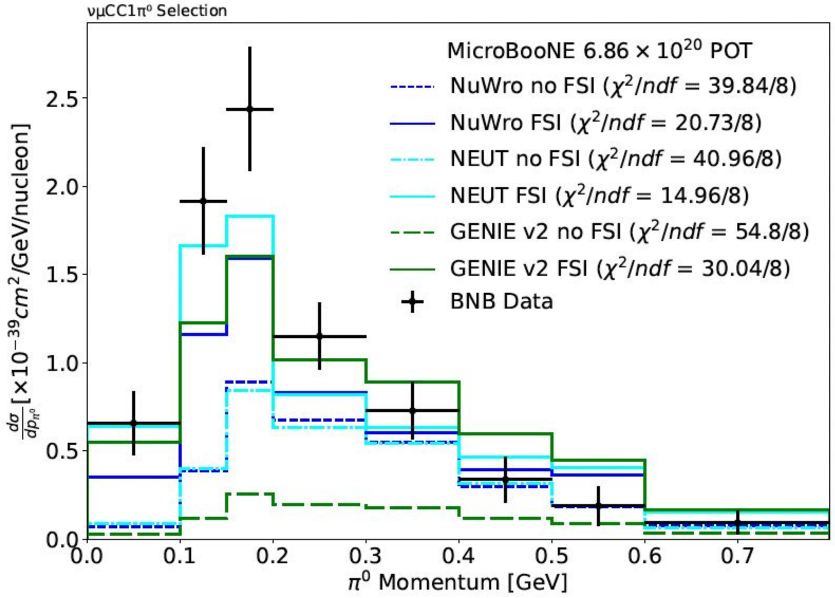


Stay tuned for π⁺ measurements!

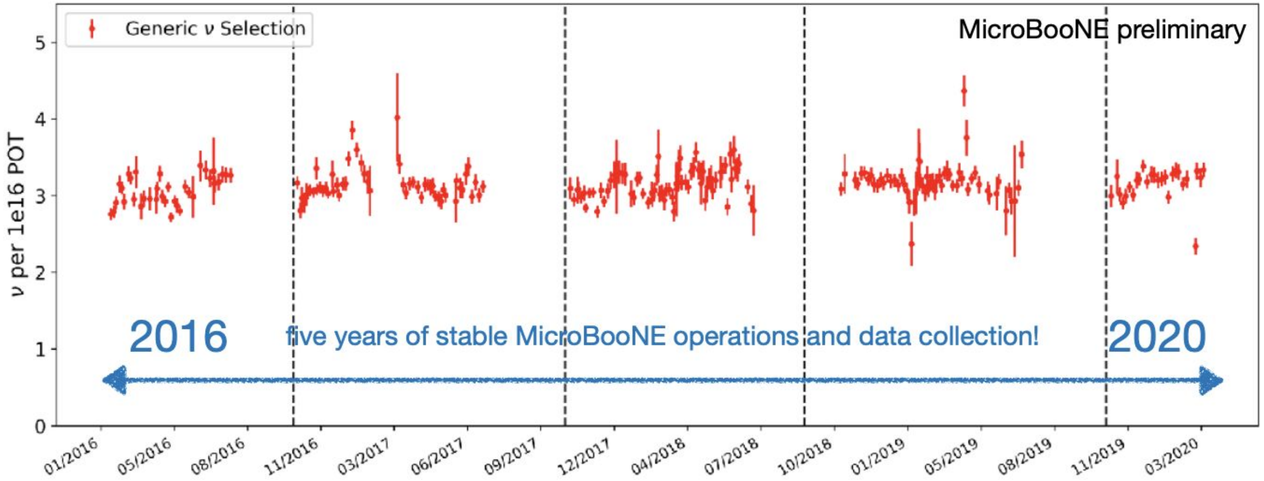






Outlook:

- A deeper dive in neutral pion productions currently being explored
  - NC π^0 measurement that compares directly to CCπ^0 production
- Exploring variety of analysis techniques and demonstrating sensitivity to understand mismodeling effects
- Analyses using our full data set (2x stats), electron neutrinos, and charged pions to follow soon!



Thank you!

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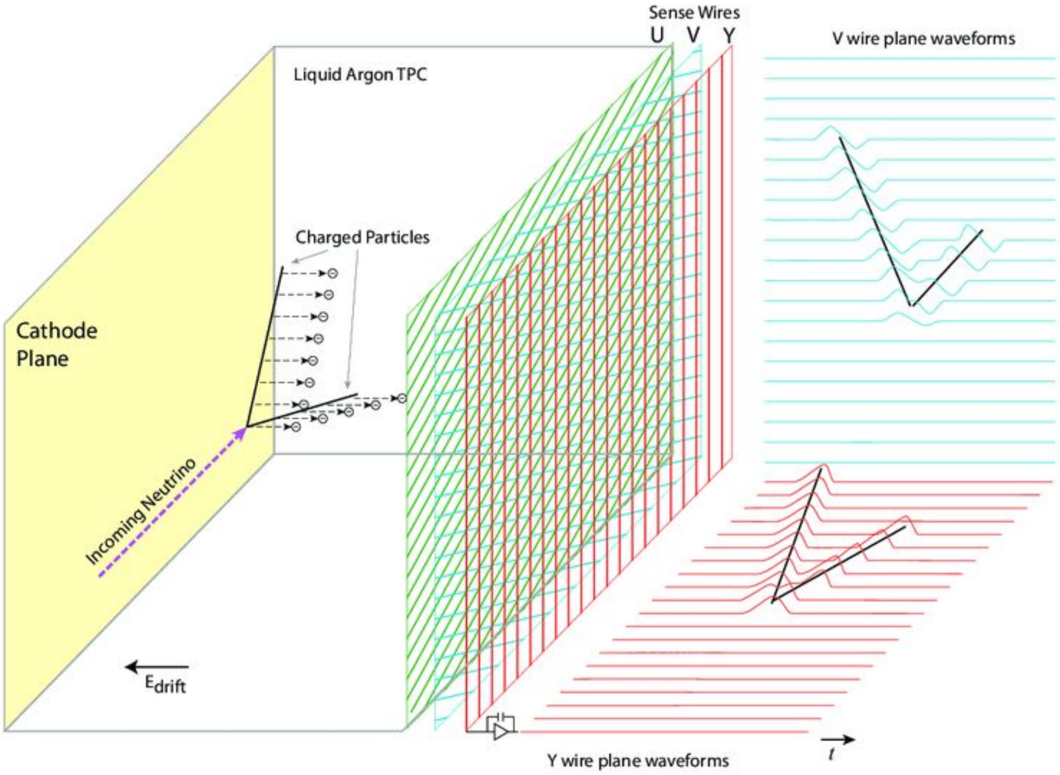
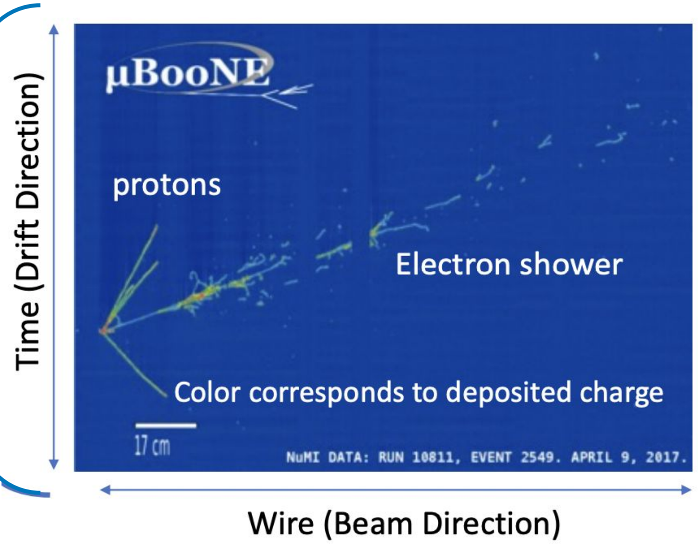
The Crux of LArTPC





- Excellent particle imaging detector
- mm scale spatial resolution
- Light signal by PMTs Current generation LArTPCs

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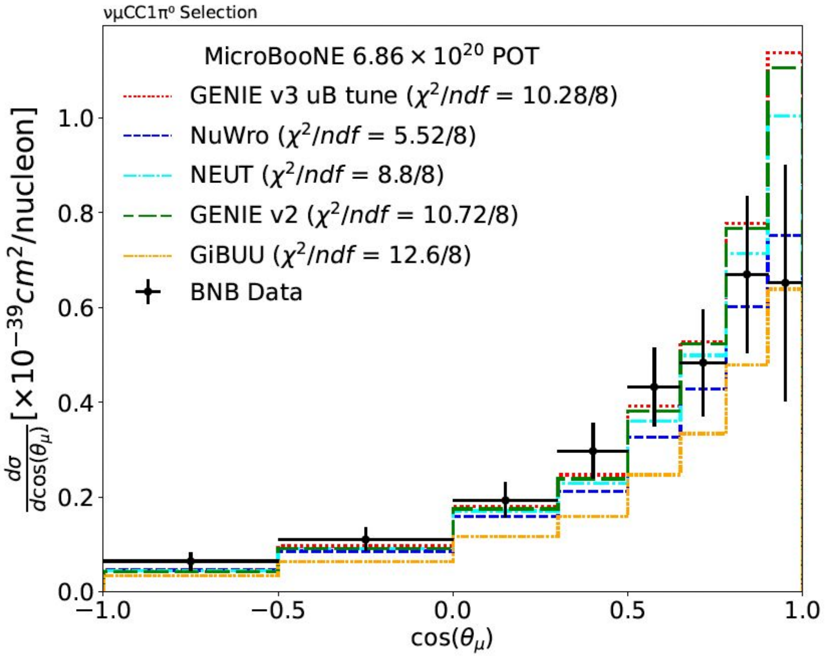
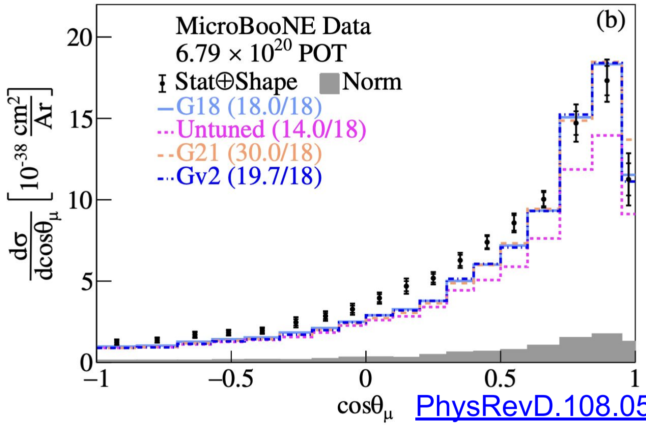
Cross Section Results: CCπ^0



- Generators overpredict cross section at $\cos(\theta_\mu) > 0.9$
  - Indicates shortcomings of models
- The forward angle corresponds to low momentum transfer (Q^2) events, not well reproduced by models in MINERvA, MiniBooNE measurements
- MicroBooNE CCQE measurements show good agreement with models with low-Q^2 suppression implemented



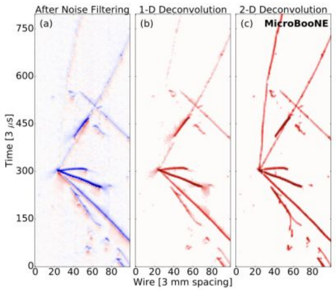
PhysRevD.108.053002

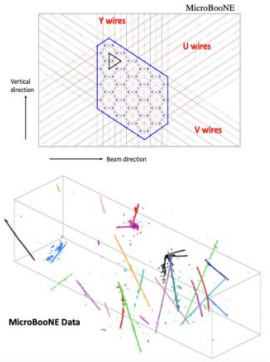
- Tuning GENIE pion production model with MINERvA data reported by MINERvA → improvement in χ^2 values for π^0 production

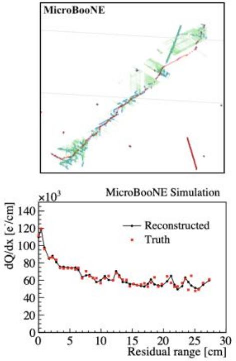
Reconstruction:

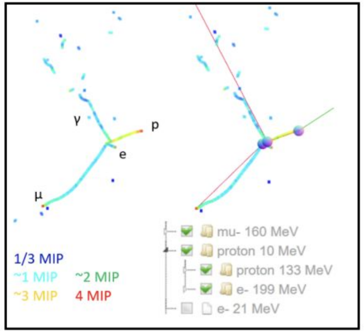
- Wire-Cell reconstruction paradigm
  - forms 3D images of particle-induced electron ionization tracks and showers via 1D wire position tomography
  - The 3D images are then processed by clustering algorithms and matched to light signals for cosmic rejection, before a deep neural network is used to determine the neutrino candidate vertex.
  - The events are characterized in terms of energy deposit, topology, and kinematics, for eventual event building, classification (e.g., νe CC, νμ CC, π0, cosmic), and neutrino energy reconstruction

noise filtering signal processing	3D imaging clustering charge-light matching	3D trajectory & dQ/dx fitting cosmic muon tagger	multi-track fitting 3D vertexing particle identification









Reconstruction:

Neutrino energy reconstruction is performed based on calorimetry with particle ID information -

15-20% resolution for fully contained ν_μ CC

10-15% resolution for fully contained ν_e CC

noise filtering

signal processing

3D imaging

clustering

charge-light matching

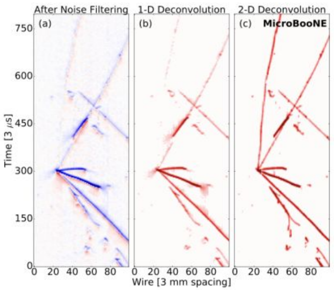
3D trajectory & dQ/dx fitting

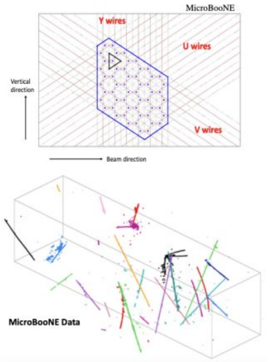
cosmic muon tagger

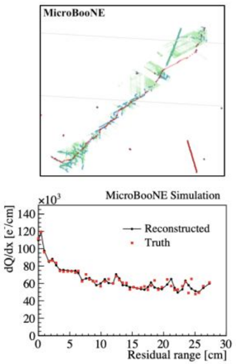
multi-track fitting

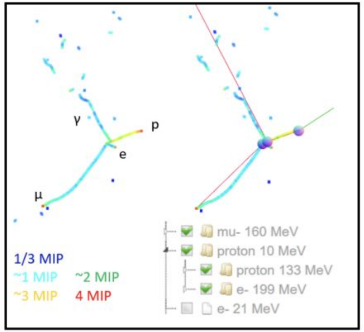
3D vertexing

particle identification









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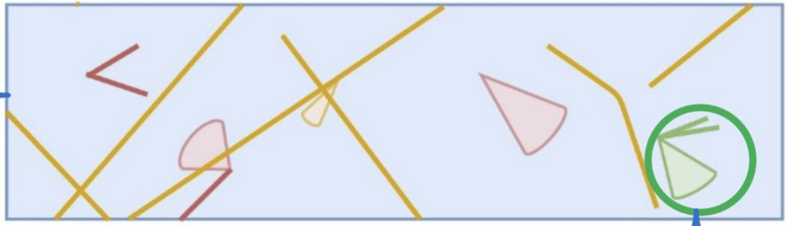
Reconstruction:

Select a neutrino candidate and remove cosmic backgrounds with Pandora event reconstruction: Eur.Phys.J.C 78 (2018) 1, 82

1. Cluster and remove "obvious" cosmic activity
2. Decide on the sets of charge that comprise regions of interest
3. Optical information is used to find the neutrino candidate most consistent with the beam timing to reduce cosmics.



- This classifies reconstructed particles as either tracks or showers:

Track-like	Shower-like
p, μ, $\pi^{\pm}$, $K^{\pm}$	e, γ

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Resolution:

particle	kinetic energy resolution
proton	4% at 100 MeV, 1% at 200 MeV
muon (range)	3%
muon (MCS)	25% at 100 MeV, $<$ 10% above 400 MeV
electron	15%

Table 4: Energy resolution for different particle species.

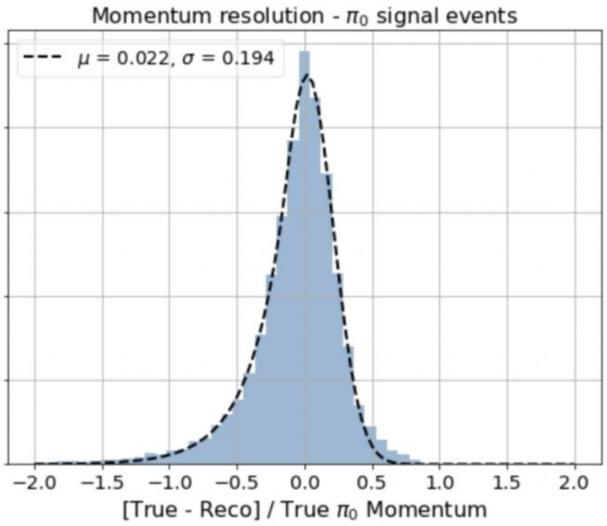


Figure 24: π^0 average momentum resolution

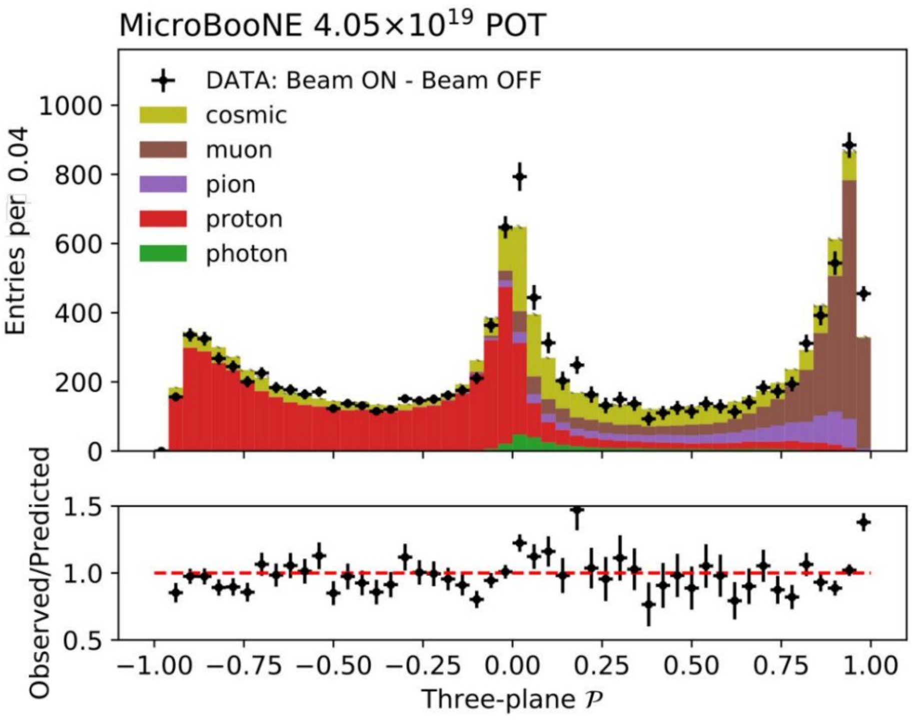
The NC π0 resolution ranges from about 15% at low momenta to about 40% at high momenta

Reconstruction:

- MIPs = minimally ionising particles = muons and charged pions.
- Compare dE/dx profiles along tracks, with corrections for non-isotropy of detector.
- Calculate likelihood ratio:

$$\text{LLR PID} = \frac{2}{\pi}\arctan\left(\ln\frac{\mathcal{L}(\mu|dE/dx,r,\theta)}{\mathcal{L}(p|dE/dx,r,\theta)}\right)$$

Figure from JHEP 12 (2021) 153.

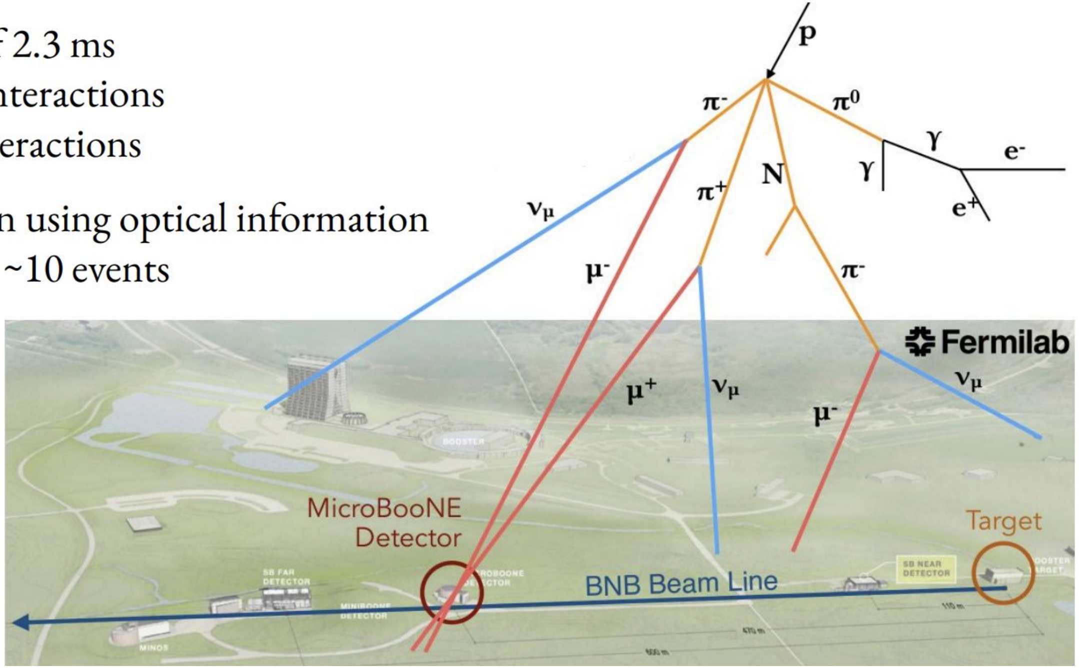


Because of its near-surface location, the MicroBooNE detector is exposed to a significant amount of cosmic rays resulting as backgrounds. Cosmic ray events recorded during off-beam data taking are used to estimate the background arising from such events. The event selection requirement is applied to this off-beam data to estimate the background. To model the background from cosmic rays in neutrino induced triggers, we overlay unbiased data collected in a beam-off environment onto a simulated neutrino interaction.

Readout window of 2.3 ms

- ~20 cosmic interactions
- ~0.0017 ν interactions

Significant reduction using optical information to 1 ν interaction in ~10 events



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

M_A = 0.94: NuWro default

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

FF1
M_A = 1.05 or M_A = 0.84

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

FF2

with $M_A = 1.05$ GeV or

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

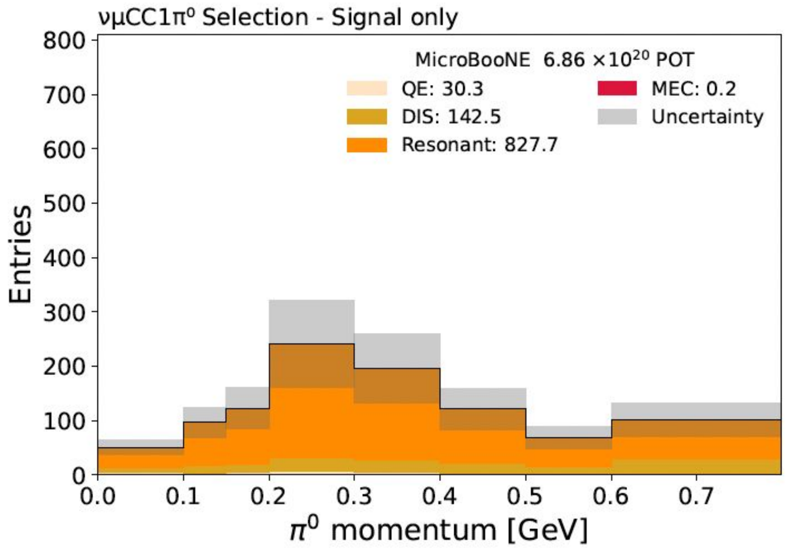
FF3

with $M_A = 0.95$ GeV

Phys.

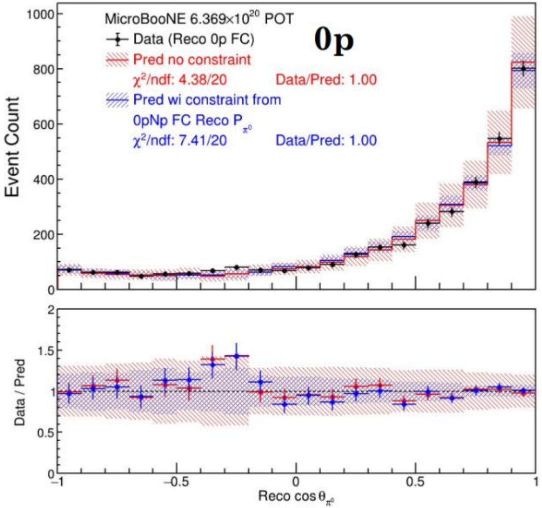
regions. `NuWro` predictions with various parameterizations of the $C_5^A(Q^2)$ axial form factor [82, 83] used to describe the neutrino-nucleon Δ excitation cross section are also shown. Free parameters of these form factors are fit to ANL [84, 85] and BNL [86] CCπ^+ bubble chamber data. Though demonstrated to be consistent within flux uncertainties [82, 87], these data sets differ in normalization by approximately 30% leading to large theoretical uncertainties. The default `NuWro` prediction uses a dipole form factor with an axial mass, M_A, of 0.94 GeV/c^2 as obtained in [82] with a fit to both the ANL and BNL data. The predictions labeled `NuWro FF1` $\texttt{M}_\texttt{A}$`=1.05` and `NuWro FF1` $\texttt{M}_\texttt{A}$`=0.84` use the modified dipole form factor given in Eq. (II.12) of [83] with $M_A = 1.05$ GeV/c^2 and $M_A = 0.84$ GeV/c^2, respectively. Two additional predictions with steeper Q^2 dependence for $C_5^A(Q^2)$ are also included. These are labeled `NuWro FF2` and `NuWro FF3` and correspond to the form factors in [83] with steeper Q^2 dependence and $M_A = 1.05$ GeV/c^2 and $M_A = 0.95$ GeV/c^2, respectively.

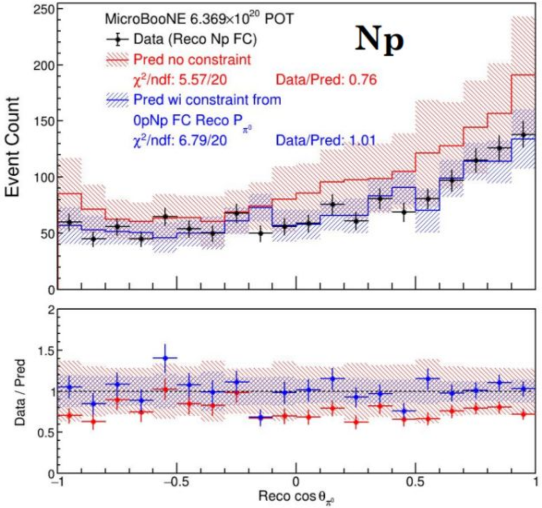
Interactions:

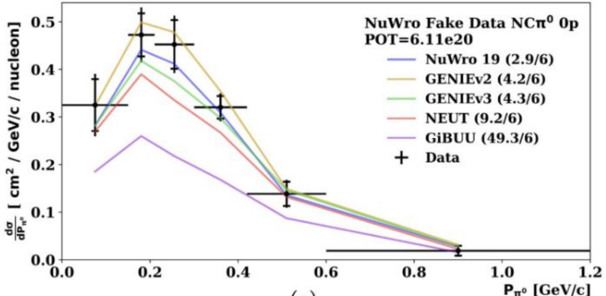


- ~83% of predicted signal events from RES
- 14.3% contribution from deep inelastic scattering (DIS) interactions

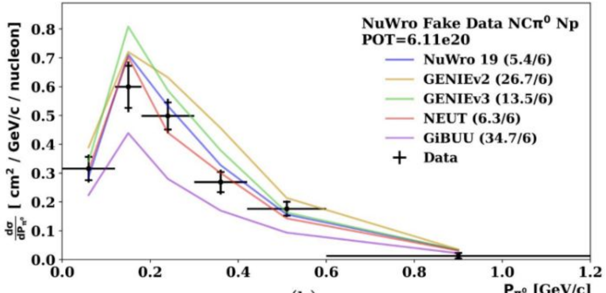
Model Validation and Fake Data Studies







(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.

Model Configurations:

BNB data extracted cross sections are shown in Fig. 2 along with a series of generator predictions; the MicroBooNE tuned version of GENIE v3.0.6 (GENIE v3 uB tune) [18], GENIE v2.12.2 (GENIE v2) [43, 44], NuWro 19.02.1 (NuWro) [45, 46], Neut v5.4.0 (NEUT) [47, 48] and GiBUU 2023 (GiBUU) [49]. The difference in prediction from these generators comes from the different underlying models. Several MicroBooNE publications describe these models in detail [50–52]. The generators have different initial state nuclear models (GENIE v2 uses a relativistic Fermi gas, while the others use a local Fermi gas) and resonant pion production models. The NuWro generator implements the Adler-Rarita-Schwinger formalism [53] to explicitly calculate the $\Delta(1232)$ resonance, and the non-resonant background is estimated using a quark-parton model. GENIE v2 uses the Rein and Sehgal model [54], while NEUT and the tuned version of GENIE v3 follow the Berger and Sehgal approach [20–22].

GiBUU employs the MAID analysis [55] for modeling the RES interactions. The different generators also differ in their treatmeant of final state interactions (FSI). NuWro employs intranuclear cascade models [46], NEUT uses the FSI cascade approach with nuclear medium corrections for pions [56]. GiBUU uses numerical solution from the Boltzmann-Uehling-Uhlenbeck equation to model the intranuclear hadron transport. As a result, the initial state and the FSI effects are described in a consistent nuclear potential. The GENIE generator versions used here applies the hA FSI model [57, 58]. The differences among various generators are presented in a tabular format in [59]. The comparison between generator predic-

ArgoNeuT
pathfinder, low statistics

↓

MicroBooNE
high statistics, but initial measurements had large systematic uncertainties

↓

Precision MicroBooNE
improved detector understanding → high statistics, low uncertainties

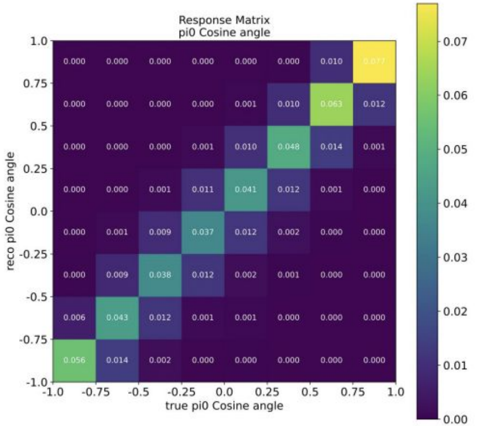
↓

Future experiments: higher statistics (**SBND**, **ICARUS**, **DUNE-ND**) and lower systematics due to measurements by **LArIAT**, **ProtoDUNEs**

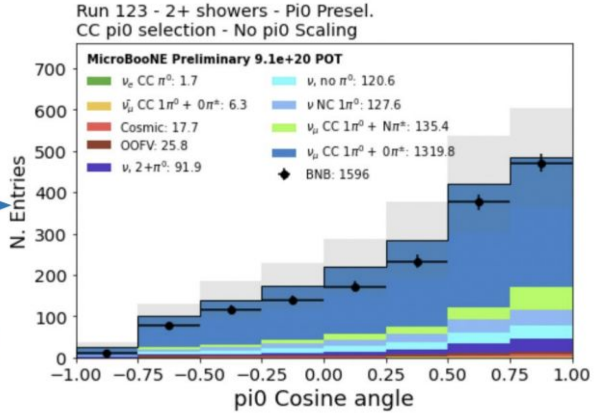
THE ROAD TO DUNE

- Now in the era of **precision MicroBooNE analyses**
  - Large amounts of data
  - Detailed neutrino interaction images
  - Well-understood detector
- Vital input to model development for DUNE
- Technical advances also important for DUNE: reconstruction, event selections, simulations
- Future experiments will continue improvements until (and during) DUNE data-taking

Measurement of the Differential Cross Section:



Event selection



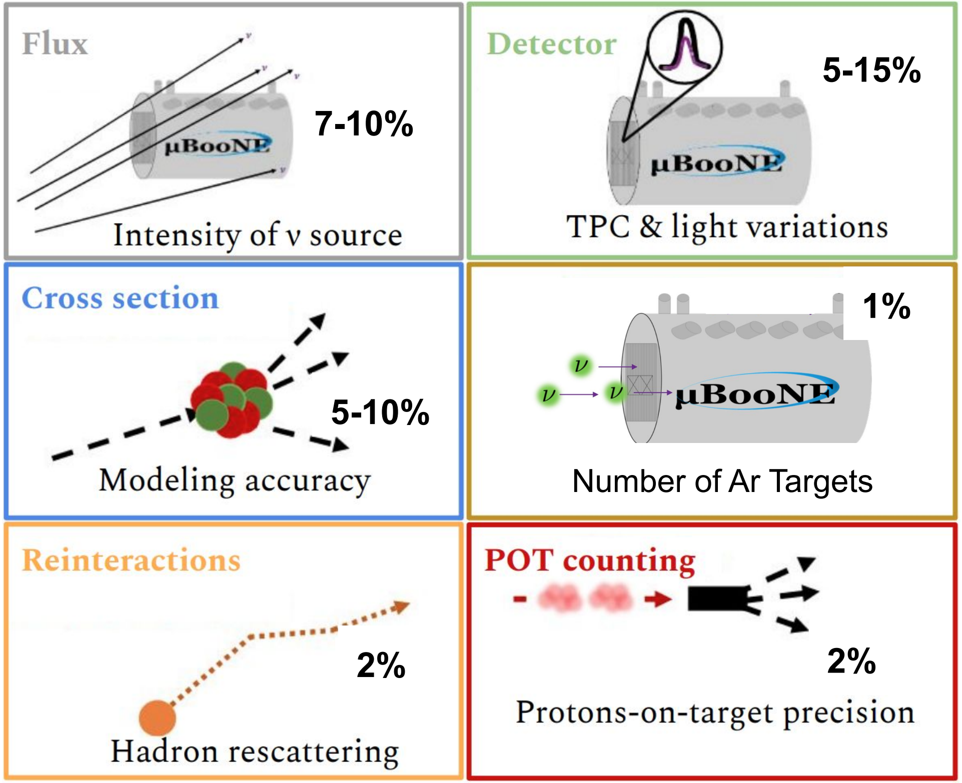
$$< \frac{d\sigma}{dp} >_i = \frac{\sum_j U_{ij}(N_j - B_j)}{N_{\text{target}} \times \phi \times (\Delta p)_i}$$

Kinematic variables

Fermilab

Uncertainties:

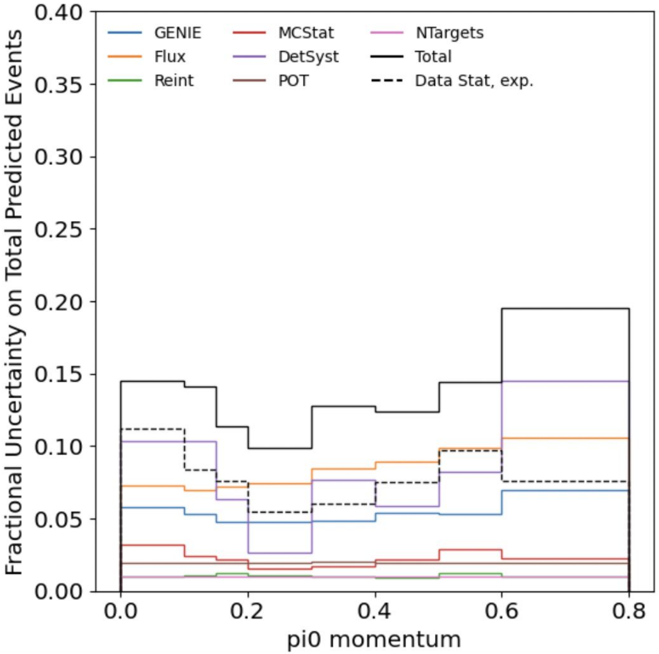
$CC\pi^0$

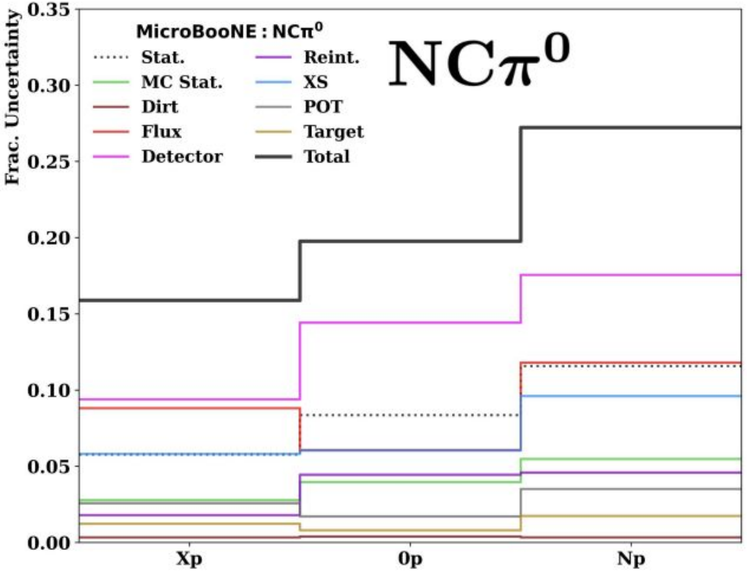


Systematics:

As the differential cross section is measured across multiple correlated bins, we utilize a covariance matrix to incorporate the uncertainties in the final calculation of cross sections. The covariance matrix for each source of systematic uncertainty is determined by considering multiple systematic variations

$$V_{ij} = \frac{1}{N}\sum_{k=1}^{N}(n_i^{\rm CV} - n_i^k)(n_j^{\rm CV} - n_j^k)$$





Systematics: Flux

we use the MiniBooNE flux with its uncertainties, updated for MicroBooNE's baseline

Considers hadron production and beamline geometry uncertainties

Hadron production dominates

Systematics: Cross Section

- GENIE unisim : allows for a single variation of the cross-section model and a single alternate universe is constructed.

- GENIE multisim : On the contrary to unisim, the multisim universes are produced by simultaneously varying multiple model parameters. 500 universes were used for this.

Systematics: Reinteraction

Secondary interactions outside the Ar nucleus. MicroBooNE uses Geant4Reweight, combined with fits to pion data

Systematics:

The detector systematic uncertainties are estimated using dedicated samples that are generated by changing model parameters in the nominal simulation

Variation	Description
Wire Mod x position	Wire modification of x position
Wire Mod (y,z) position	Wire modification of (y,z) position
Wire Mod θ_{XZ}	Wire modification of angle in XZ plane
Wire Mod θ_{YZ}	Wire modification of angle in YZ plane
Light Yield Attenuation	Attenuation of LY response in detector over time
Light Yield Down	Turn down the light yield in the detector by 25%
Light Yield Rayleigh	Increase Rayleigh scattering length from 60 cm to 90 cm
Recombination	Reduce value of β' in the Modified Box Model
SCE	Use an alternative Space Charge Map

- Wire modification : data driven transformations are applied while deconvolving the simulated TPC wire waveforms. Separate variation samples are produced based on the transformations on x, y, z, θ_{xz}, and θ_{yz}.

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Systematics:

The detector systematic uncertainties are estimated using dedicated samples that are generated by changing model parameters in the nominal simulation

Variation	Description
Wire Mod x position	Wire modification of x position
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Light Yield Rayleigh	Increase Rayleigh scattering length from 60 cm to 90 cm
Recombination	Reduce value of β' in the Modified Box Model
SCE	Use an alternative Space Charge Map

- Light yield : Three variations of the light yield from the photomultiplier tubes are considered. The Light Yield Attenuation introduces position dependent effects by using a 10 m absorption length, whereas in the Light Yield Down variation the overall light yield of energy depositions is reduced by 25%. The Light Yield Rayleigh on the other hand studies the effect by increasing the rayleigh scattering length by 50%.

- Space Charge and Recombination : The simulated electric field and the ionization electron drift trajectories are distorted in this variation. In the Recombination variation, the parameter values used for ionization simulation are modified.

Xsec Systematics:

Cross section model uncertainties on signal events are incorporated by evaluating the effect of model variations on the smearing and efficiency of the predicted event rate, and on the rate of predicted neutrino backgrounds.

- GENIE unisim : allows for a single variation of the cross-section model and a single alternate universe is constructed.

- GENIE multisim : On the contrary to unisim, the multisim universes are produced by simultaneously varying multiple model parameters. 500 universes were used for this.

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

- The motivation for data unfolding is to estimate the true signal (e.g. energy spectrum) given a measurement that is affected by the detector response as well as statistical (e.g. associated with signal and backgrounds) and systematic uncertainties (e.g. associated with backgrounds, mis-modeling of detector response due to imperfect calibration or finite statistics in simulations). In many applications, data unfolding is not necessarily required

- unfolded results are convenient to compare results from different experiments that have different detector responses

- SVD approach -unfolding problem is expressed as a minimization of a chi-square function comparing the measurement with the prediction. The large fluctuations (also called variance) in the unfolded results are regularized by adding a penalty term into the chi-square function. The penalty term can be chosen to regularize the strength or the curvature (second derivative) of the unfolded results, among other possible choices. A parameter commonly known as the regularization strength can be adjusted freely to control the power of the penalty term relative to the chi-square

Unfolding:

The data unfolding problem generally starts with a $\chi^2(s)$ function defined as

$$\chi^2(s) = (\mathbf{m} - \mathbf{r} \cdot s)^T \cdot \mathrm{Cov}^{-1} \cdot (\mathbf{m} - \mathbf{r} \cdot s)\,.$$

- $\boldsymbol{m}$: measured spectrum, *m*-dimensional vector
- $\boldsymbol{s}$: unknown spectrum, to be unfolded, *n*-dimensional vector
- $\boldsymbol{r}$: smearing (response) matrix, *m X n* and $m \geq n$
- *Cov* : covariance matrix containing all statistical and systematic uncertainties associated with $\boldsymbol{m}$ and $\boldsymbol{r}$.

- Cholesky decomposition: $Cov^{-1} = Q^T Q$, Q is a lower triangular matrix

$$\chi^2(s) = (M - R \cdot s)^T \cdot (M - R \cdot s)$$

Pre-scaling
- $M \coloneqq Q \cdot \boldsymbol{m}$
- $R \coloneqq Q \cdot \boldsymbol{r}$

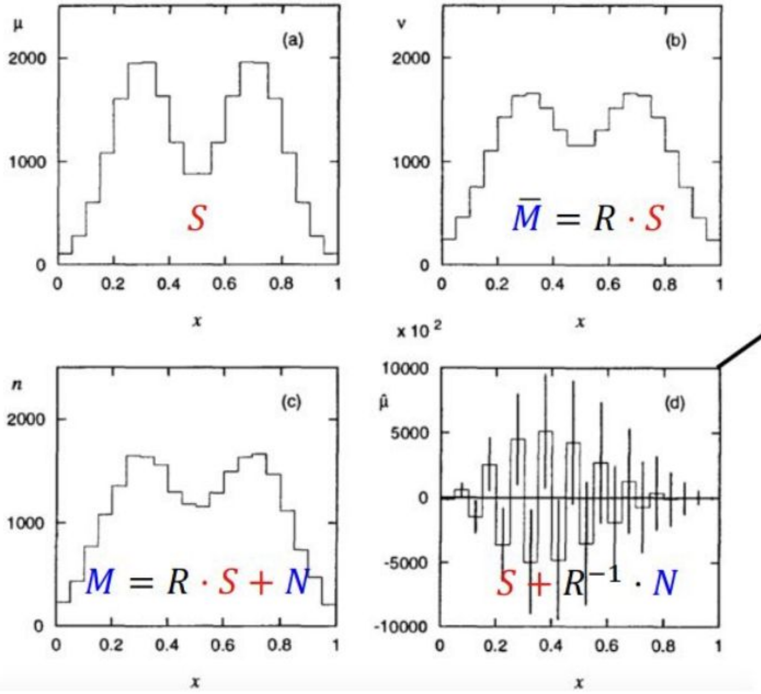
Solution (direct inversion)

$$\hat{s} = (R^T R)^{-1} R^T M$$

$$\hat{s} = (R^T R)^{-1} R^T (R \cdot s_{true} + N)$$

The response matrix R is unnecessary to be a square matrix

Unfolding:



This is one unbiased solution (direct inversion) to an unfolding problem. However, it has catastrophic oscillations, i.e. huge variance, in the unfolded spectrum.

- Decrease the number of bins to suppress the "oscillation" --> Nyquist theorem
- Trade-off **bias** and **variance** to suppress the "oscillation" --> e.g. **regularization [unfolding method]**

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Wiener-SVD Unfolding:

- To automatically minimize the Mean Square Error (MSE) given a model S

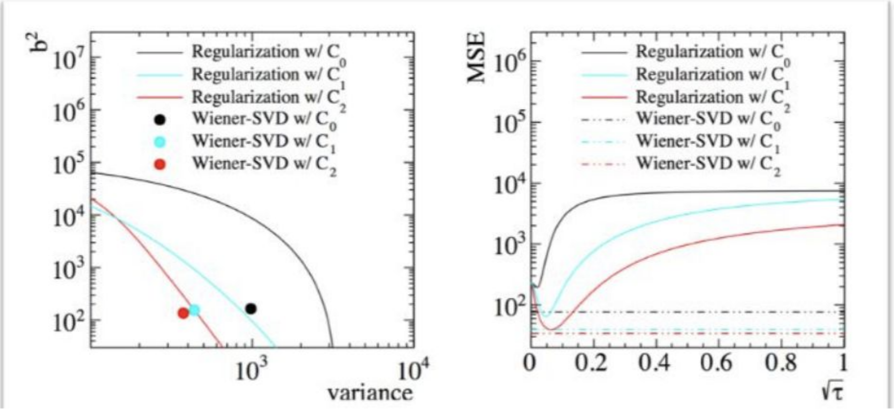
$$MSE = E\left[(\hat{S} - S)^2\right] = E\left[\left(F \cdot \frac{M}{R} - S\right)^2\right] = E\left[\left(F \cdot S + F \cdot \frac{N}{R} - S\right)^2\right]$$

$$= E\left[((F - I) \cdot S)^2 + \left(F \cdot \frac{N}{R}\right)^2\right]$$

Bias

Variance

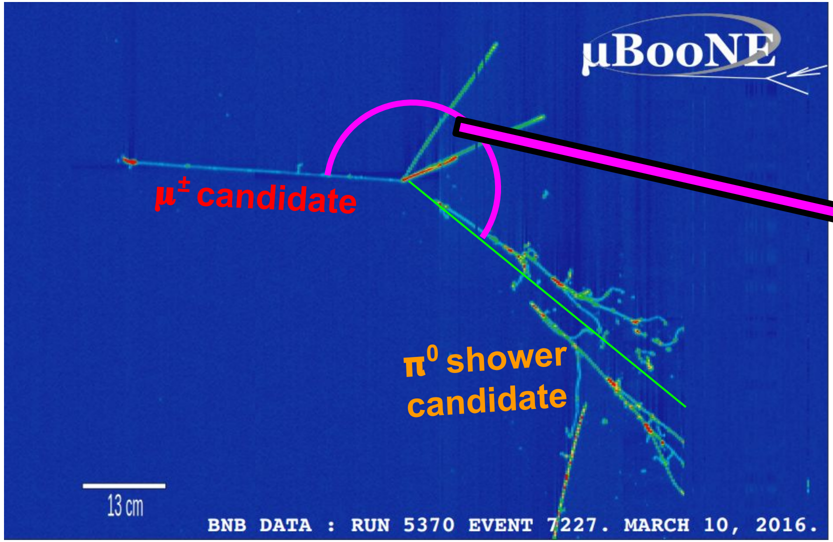
F = "filter" = additional smearing matrix = regularization

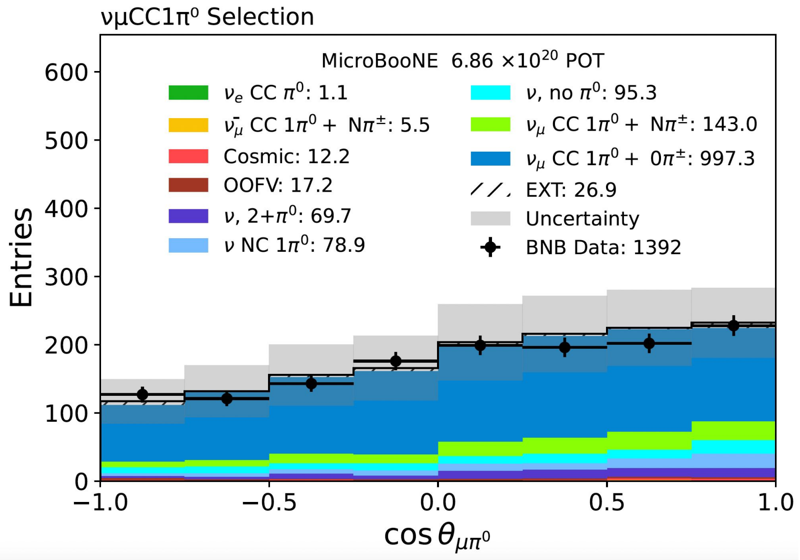


Given one model S

- General regularization, e.g. Tikhonov regularization, needs to "tune" a regularization strength parameter [curve in the left plot]
- Wiener-SVD regularization corresponds to a fixed point in the phase space of bias versus variance with **minimum MSE**

Pion Muon Opening Angle:





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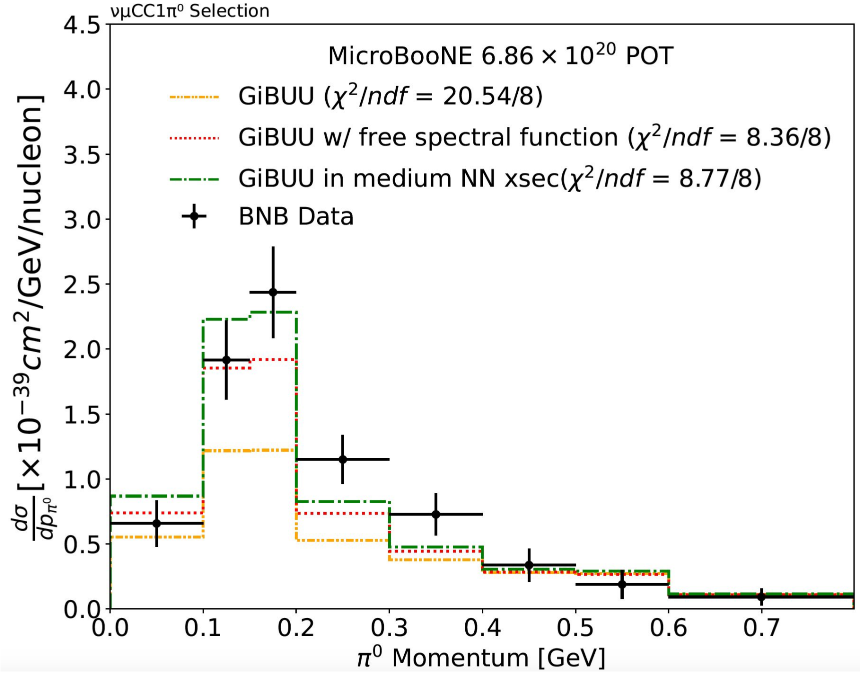
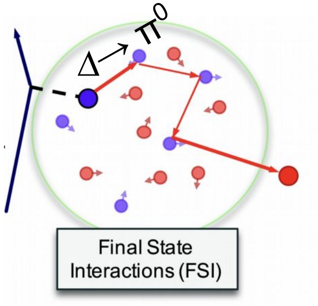
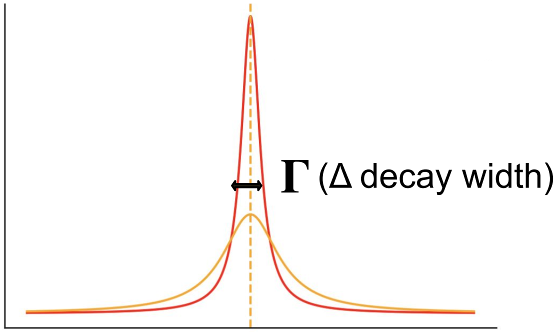
More Insights into Modeling:







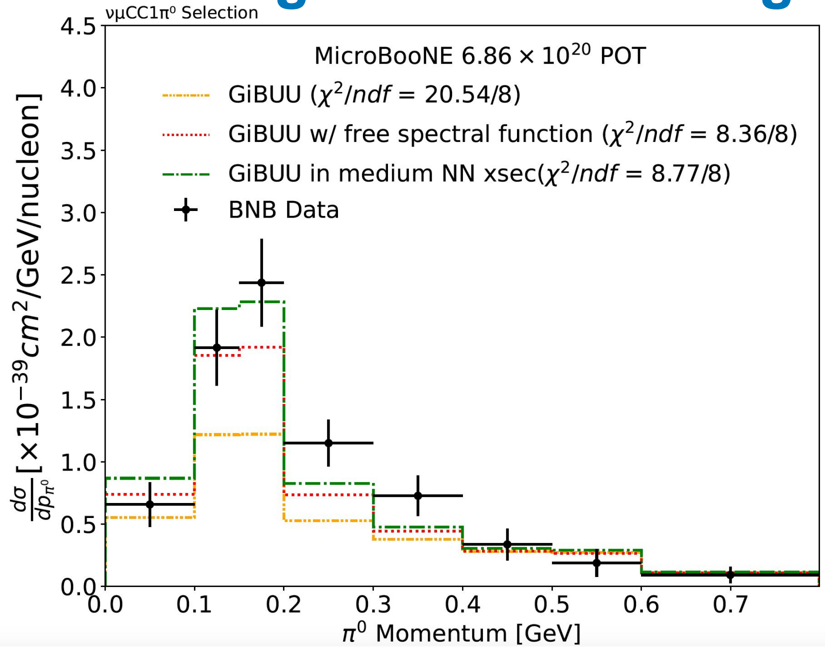
(Not to scale, just for visual aid)

- GiBUU 2023 (default)
  - Valencia-Oset collisional broadening for the Δ resonance → increases Δ decay width

    ⇩

    Reduced Δ production + increased Δ absorption
- GiBUU with free spectral function for Δ resonance

More Insights into Modeling:



$$\Gamma^{med}_{tot} = \tilde{\Gamma} + \Gamma_{coll}$$

Oset collision broadening increases the Δ width as a function of momentum and density. It requires some extrapolation in this context, can vie

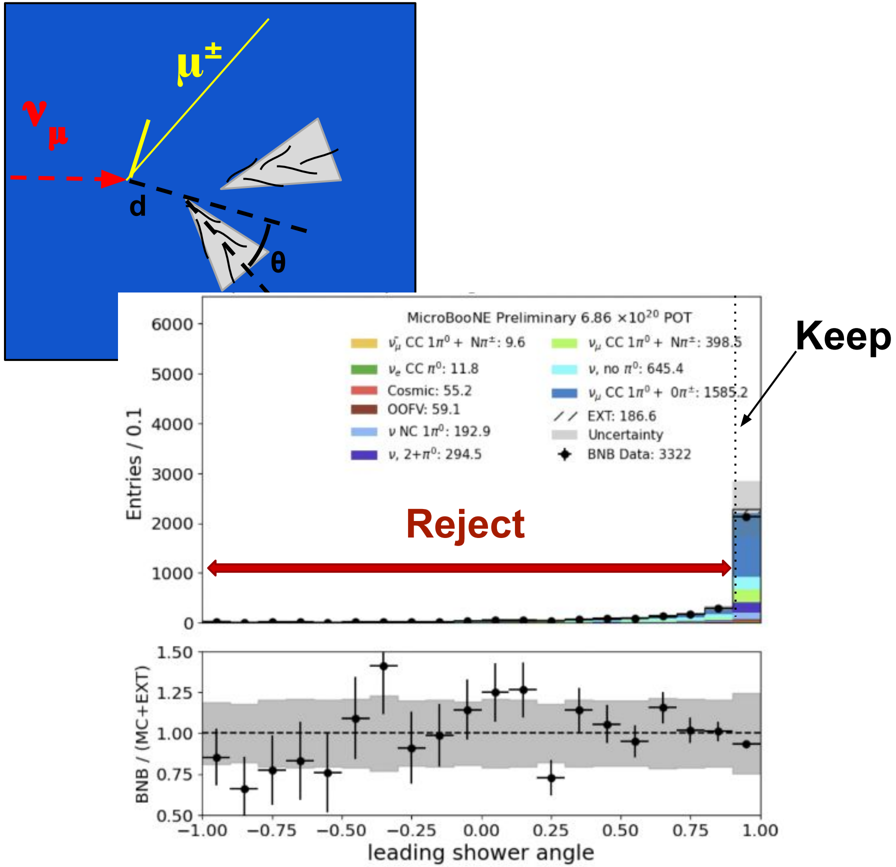
Phys. Rev. C 87, 014602 (2013)
Nucl. Phys. A 468, 631-652 (1987)
Phys. Rev. D 97, 013004 (2018)

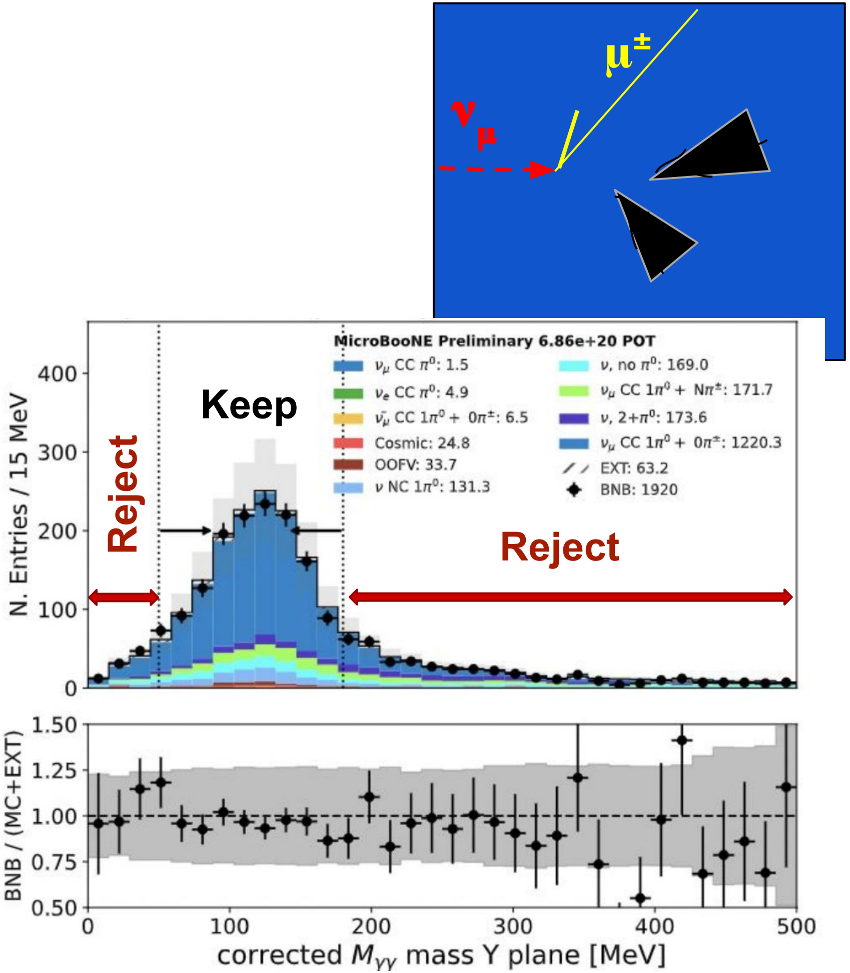
Absorption processes in collisional broadening ΔN → NN or ΔNN → NNN

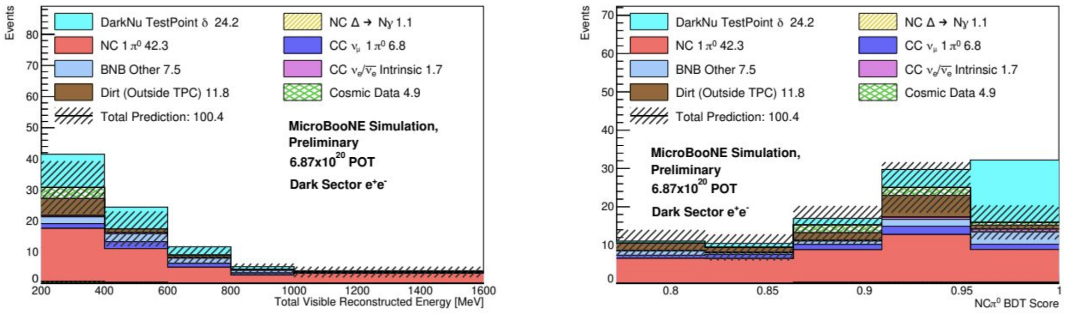
Δ can disappear without producing a pion

Elastic scattering, ΔN → ΔN contributes to broadening

Event Selection:







(a) *Reconstructed visible energy of e^+e^- pair* ***(b)*** *Neutral-current π^0 BDT score*

Figure 3: *The final predicted distributions for the e^+e^- selection from MicroBooNE Runs 1–3, corresponding to a 6.87×10^{20} POT exposure. This figures shows the total reconstructed visible energy of the e^+e^- pair (a) as well as the neutral-current π^0 BDT score (b), an important variable for rejecting backgrounds. Shown stacked on top of the backgrounds is a representative parameter point for the dark sector e^+e^- model, chosen to be on the edge of our expected sensitivity achievable at MicroBooNE. This test point consists of an 800 MeV Z', with two sterile neutrinos of 210 and 107 MeV respectively. We note that this representative point predicts a smaller rate of events in MiniBooNE compared to the observed anomaly. In general, model points that accurately match the rate of the anomaly in MiniBooNE predict $\mathcal{O}(100)$ e^+e^- events in MicroBooNE for this selection. This is primarily due to the coherent upscattering cross-section scaling proportional to neutron number squared, N^2, and moving from Mineral Oil ($N = 6$) to Argon ($N = 22$) targets*

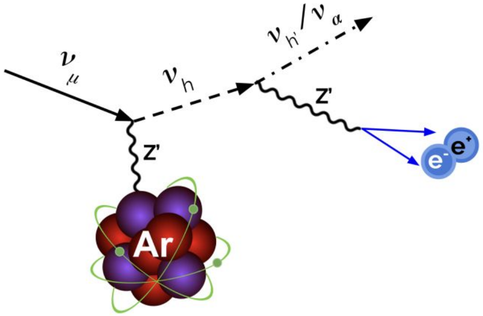


Figure 1: *A representative example of the upscattering dark neutrino models being searched for at MicroBooNE. An incoming muon-neutrino upscatters off an argon target, producing a heavy sterile neutrino (or dark neutrino, ν_h). Depending on the dark-sector content, the decay of the dark neutrino (ν_h) can be to a lighter dark-sector sterile neutrino ($\nu_{h'}$) or to an active neutrino (ν_α). Similarly, depending on the relative mass of the dark neutrino and the dark photon (Z'), the decay can be on or off-shell.*