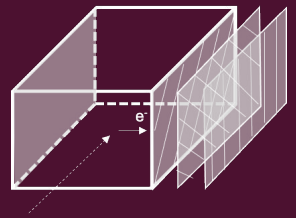


Measuring the ***Neutral Current*** π^0 ***Cross-Section*** on Argon in MicroBooNE

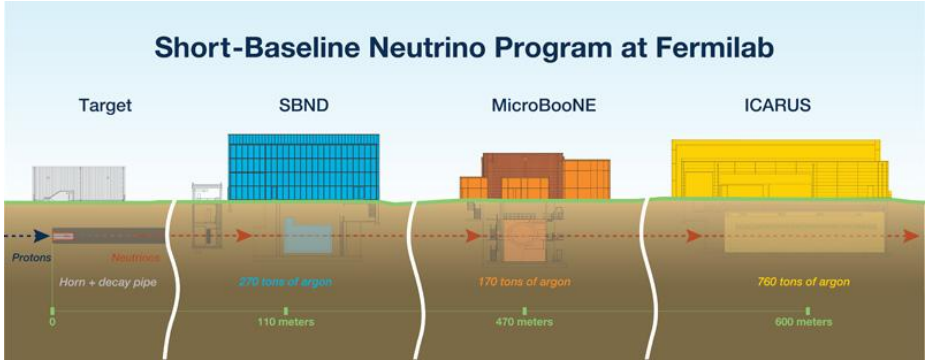
Nupur Oza (LANL)
on behalf of the MicroBooNE Collaboration

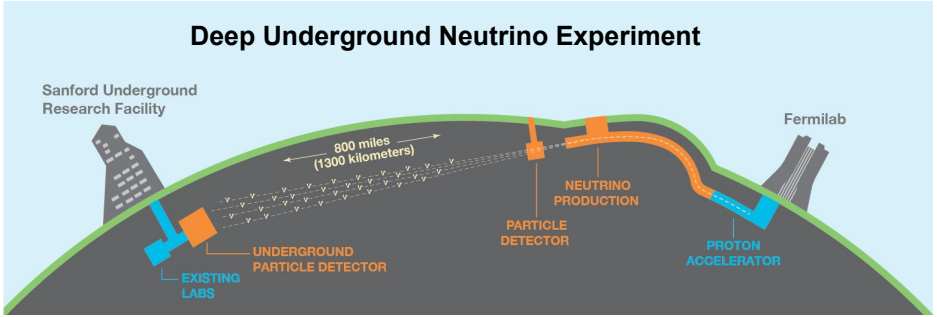
New Perspectives 2022
June 17th, 2022

Los Alamos NATIONAL LABORATORY

μBooNE

Measuring Cross Sections with MicroBooNE





Illustrations courtesy of Fermilab

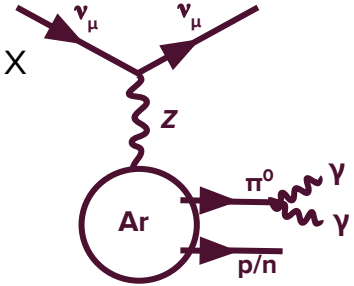
1. Large scale liquid argon time projection chamber (LArTPC) exposed to neutrinos with $\langle E_\nu \rangle \sim 0.8$ GeV
   - Highly relevant to the SBN and DUNE programs
2. 3D event reconstruction capability with **high spatial resolution & calorimetry**
   - Well suited to measure a wide range of final states
3. **Highest-statistics measurement** of neutrino-argon interactions to date

Cross-section measurements in MicroBooNE will improve our understanding of neutrino-argon interactions and have implications on **future neutrino oscillation and charge-parity violation studies**

Neutral Current (NC) π^0 Interactions

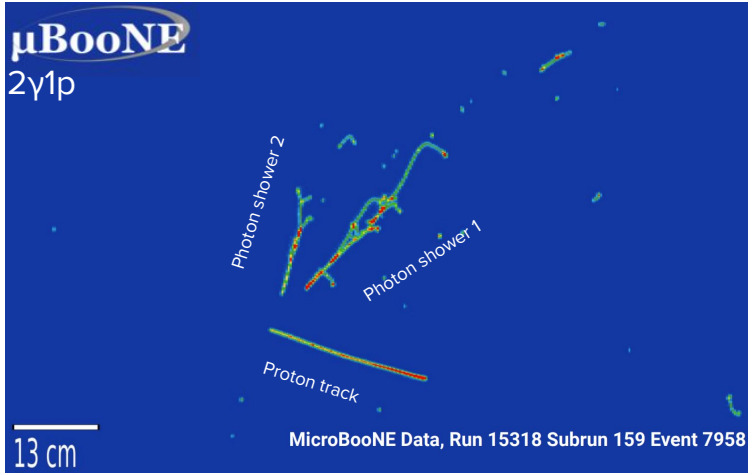
$\nu + Ar \rightarrow \nu + Ar' + \pi^0 + X \rightarrow \nu + Ar' + 2\gamma + X$

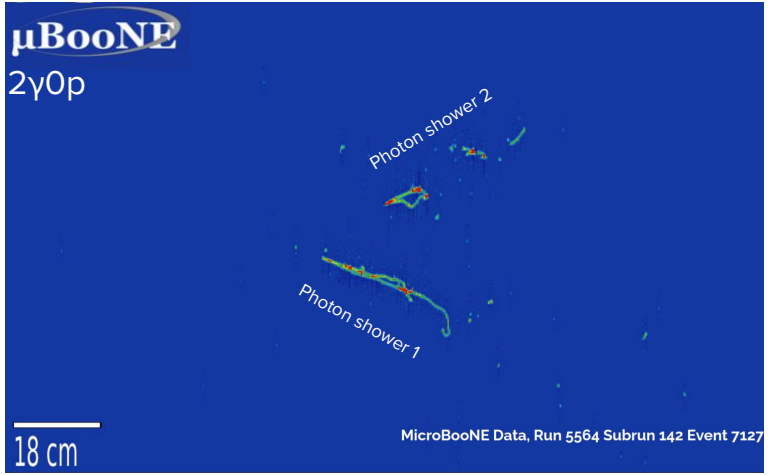
- X : **1 or 0 protons**, any number of neutrons



Background for rare and beyond the Standard Model processes, such as:

- NC Δ radiative decay[1], NC coherent single-photon production[2]
- "Dark sector" e^+e^- production





[1] *Phys. Rev. Lett.* 128, 111801 (2022) [2]MICROBOONE-NOTE-1103-PUB

NC π^0 Backgrounds

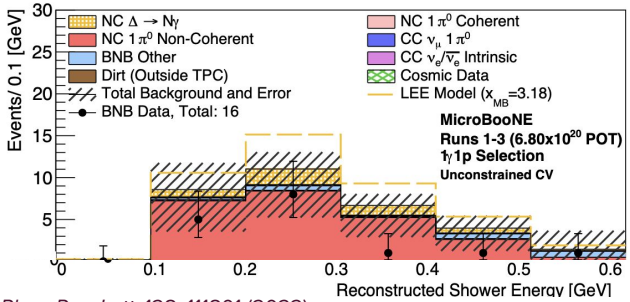
π^0 events can be mis-reconstructed as a single shower and **mimic a single photon signal**

- E.g. photon escapes volume of detector, overlapping showers, asymmetric π^0 decay with a very low energy shower
- NC π^0 events dominate 1γ0p & 1γ1p backgrounds by 41% and 87%, respectively[1]

NC π^0 cross sections can be used to **improve modeling of NC final states** and **constrain background** in future analyses

MicroBooNE presents the **first measurements of NC 1π^0 production on Argon at mean neutrino energy $\lesssim$ 1 GeV**

- ArgoNeuT has reported measurements at higher beam energies[3]



Phys. Rev. Lett. 128, 111801 (2022)

[1] *Phys. Rev. Lett.* 128, 111801 (2022) [3] *Phys. Rev. D* 176, 012006 (2017)

NC π^0 Signal Selection

Selection Stage	$2\gamma 1p$ eff.	$2\gamma 0p$ eff.
Topological	10.5%	6.60%

1. **Topological Selection[1]**
   a. **Select all 2 shower, 1 or 0 track events after Pandora[4] reconstruction**
2. Secondary Selection
3. Boosted Decision Tree-Based Selection

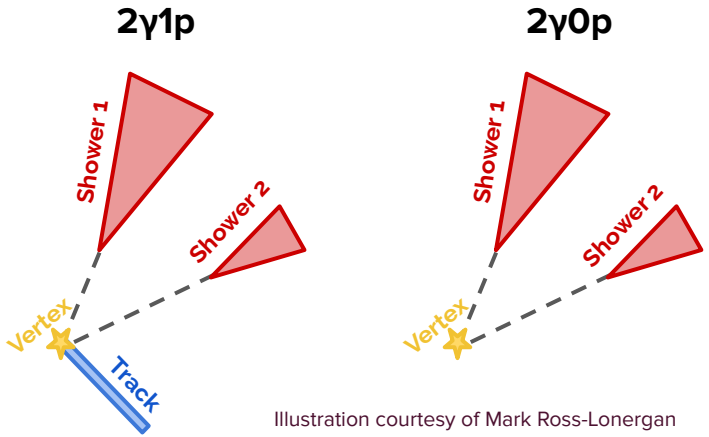


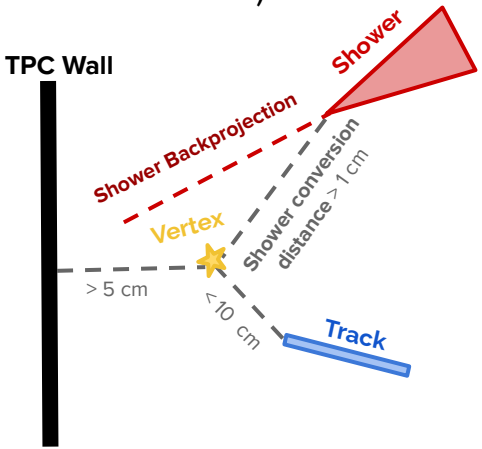
Illustration courtesy of Mark Ross-Lonergan

[1] *Phys. Rev. Lett.* 128, 111801 (2022) [4] *Eur. Phys. J. C* 78, 82 (2018)

NC π^0 Signal Selection

Selection Stage	$2\gamma 1p$ eff.	$2\gamma 0p$ eff.
Topological	10.5%	6.60%
Secondary	59.4%	77.3%

1. Topological Selection
2. **Secondary Selection[1]**
   a. **Shower energy thresholds > 30 MeV for leading shower and > 20 MeV for subleading shower**
   b. **Reconstructed neutrino vertex > 5 cm from TPC walls** (reduce tracks that exit detector)
   c. **Shower conversion distance > 1 cm** (minimize electron showers)
   d. **Track begins < 10 cm from reconstructed neutrino vertex**
3. Boosted Decision Tree-Based Selection



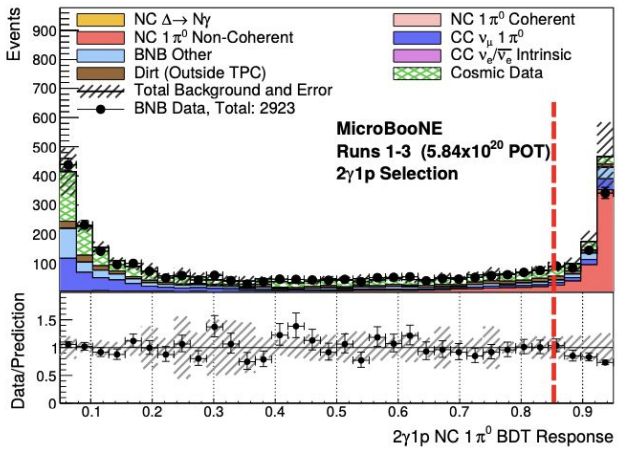
[1] *Phys. Rev. Lett.* 128, 111801 (2022)

NC π^0 Signal Selection

1. Topological Selection
2. Secondary Selection
3. **Boosted Decision Tree-Based (BDT) Selection[1]**
   a. **1 BDT trained on 10 kinematic, geometric and calorimetric variables for each signal definition**
      i. E.g. shower impact parameter, reco energy of higher energy shower candidate, reco track length (only 2γ1p)
      ii. Useful in rejecting cosmic muon tracks and charged current π^0 interactions
   b. **Each event assigned BDT score, cuts placed to maximize signal efficiency x purity**

Selection Stage	$2\gamma 1p$ eff.	$2\gamma 0p$ eff.
Topological	10.5%	6.60%
Secondary	59.4%	77.3%
BDT Selection	69.9%	54.8%
Final Efficiencies	4.36%	2.81%
Final Purity	63.4%	57.6%

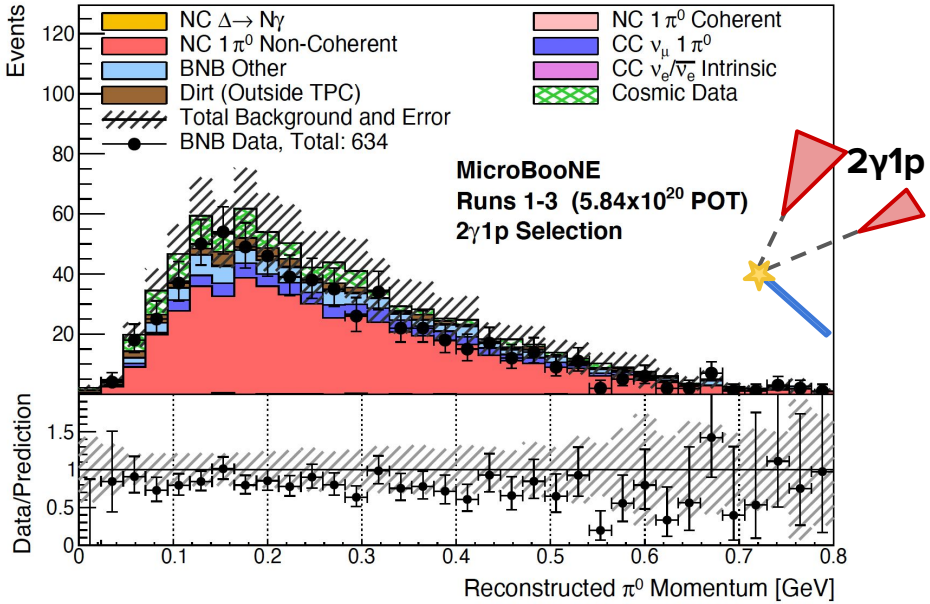
Reco particle track in 2γ1p selection helps tag interaction and improve selection purity/efficiency

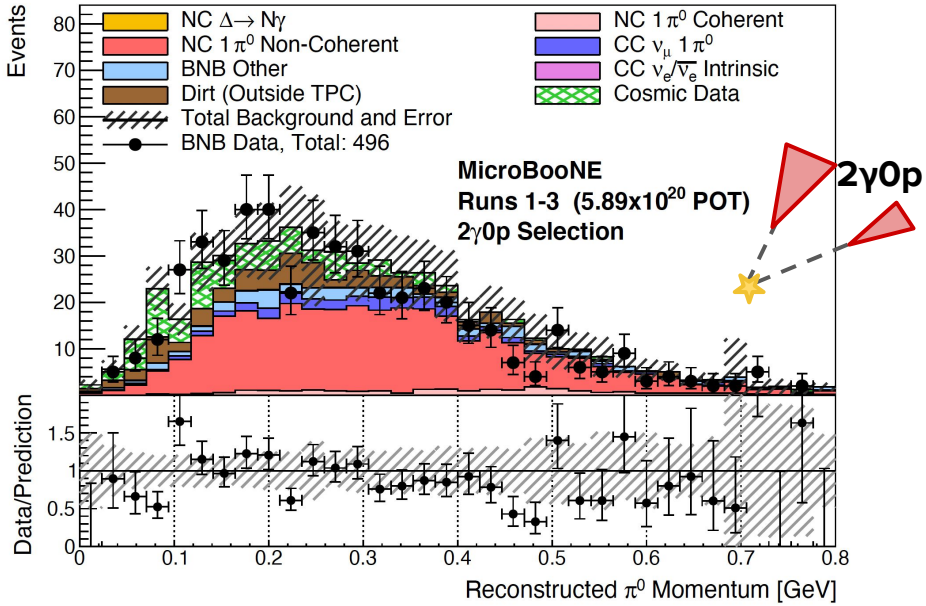


[1] *Phys. Rev. Lett.* 128, 111801 (2022)

NC π^0 Signal

First high statistics measurement of NC π^0 - Argon interaction : 1,130 total observed signal events!





Good agreement between the shape of the data and MC distributions

systematic deficit in total events selected in the data → a cross section measurement is well motivated!

data-MC ratio (2γ1p): 0.717

Calculating NC π^0 Cross Sections

A flux-integrated cross section is calculated from the selected events:

$$\sigma_{NC1\pi^0} = \frac{N^{\text{obs}}_{NC1\pi^0} - N_{BNBext} - N_{bkg}}{\epsilon_{NC1\pi^0}\Phi N_{targets}}$$

$N_{NC1\pi0}$: Number of events in selection (data)

N_{BNBext}: Number of off-beam cosmic events (data)

N_{bkg} : Number of expected background events (MC)

$\epsilon_{NC1\pi0}$: Efficiency of selecting *NC 1π*^{0} events (MC)

ϕ : Integrated flux
➔ Summed for each neutrino species

$N_{targets}$: Number of target argon atoms

Proton energy threshold > 50 MeV

	$\mathbf{NC\pi^0}$ **(semi-inclusive)**	$\mathbf{NC\pi^0 + 1p}$ **(exclusive)**	$\mathbf{NC\pi^0 + 0p}$ **(exclusive)**
Samples Used	$2\gamma(0+1)p$ Selection	$2\gamma 1p$ Selection	$2\gamma 0p$ Selection
$\sigma_{NC1\pi^0}$ $[10^{-38}\text{cm}^2/\text{Ar}]$	$1.243 \pm 0.185 \pm 0.076$	$0.444 \pm 0.098 \pm 0.047$	$0.624 \pm 0.131 \pm 0.075$

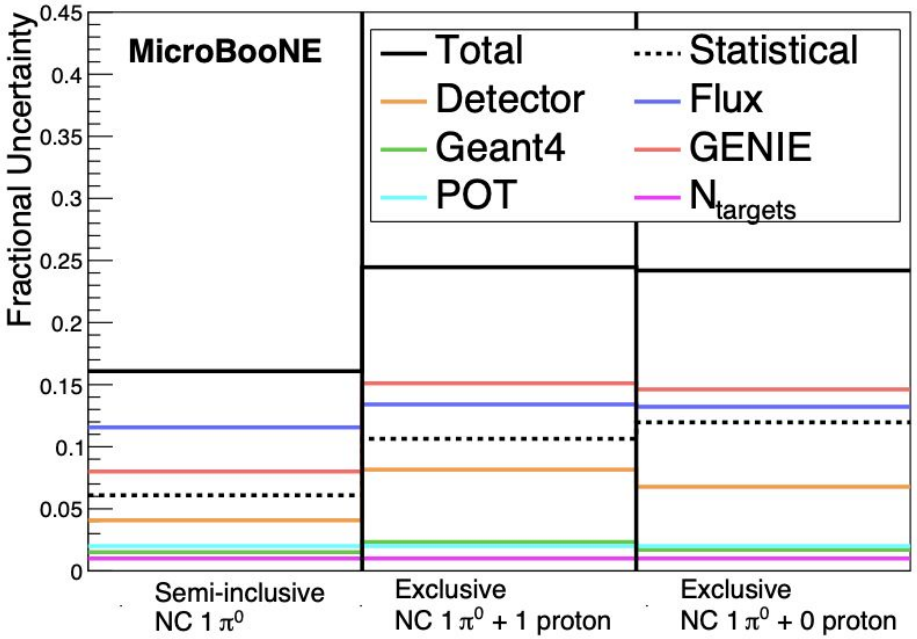
2γ(0+1)p semi-inclusive definition
- Combines exclusive 2γ1p & 2γ0p events after scaling by POT
- Efficiency corrected to include 2+ proton final states

NC π^0 Cross Section Uncertainties

Uncertainties were evaluated for each cross section component in every "systematic universe"

Relevant Systematics:

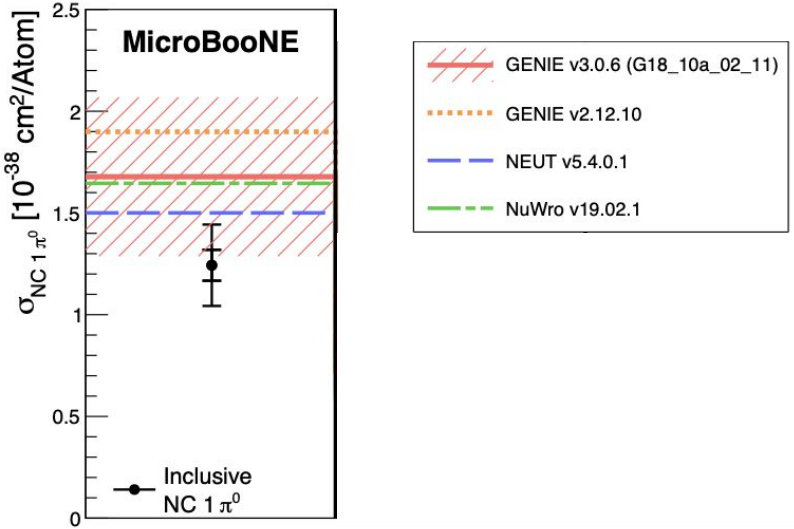
- Modeling of final state interactions and resonant pion production (GENIE)
- Light yield modeling and detector response
- Neutrino flux
- Hadron re-interactions (GEANT4)



Dominant GENIE contribution enters through background subtraction

Systematics limited → motivates a differential measurement

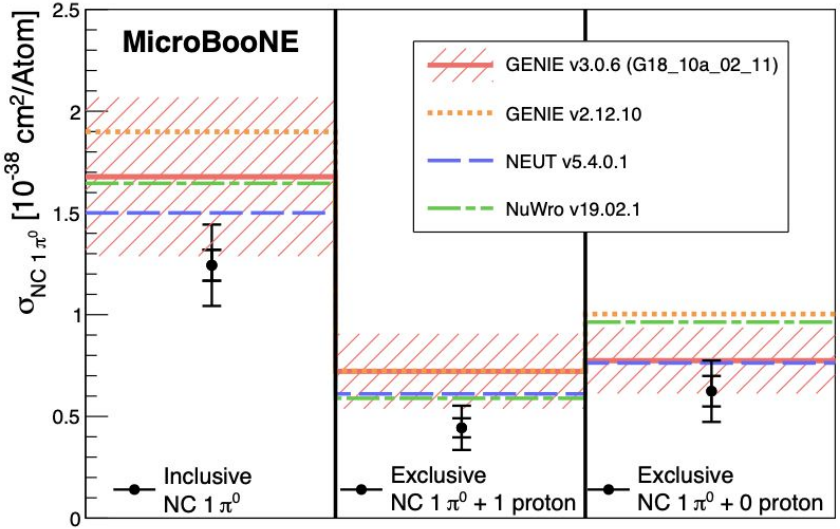
NC π^0 Cross Section Measurement vs. Predictions



NEUT neutrino generator shows closest agreement with data-extracted cross-section for all signal definitions

Extracted Cross Section is 26% lower than GENIE prediction
(1.68 [10^{-38}cm^2/Atom]) for 2γ(0+1)p

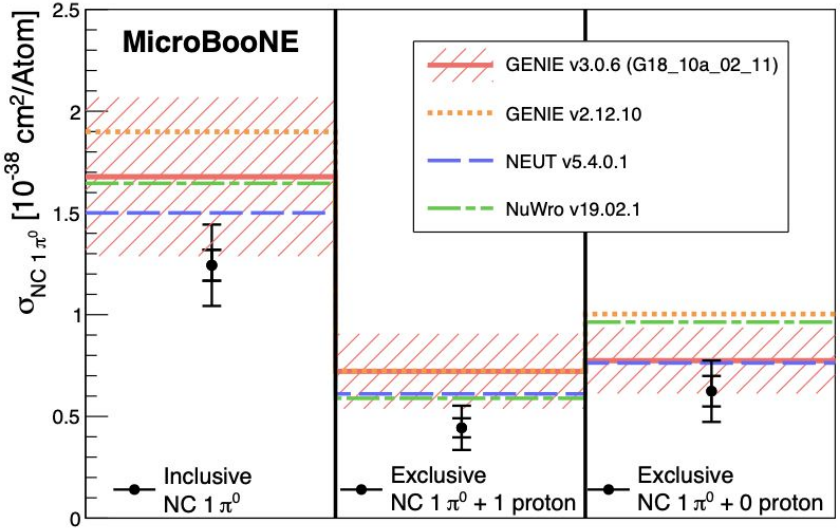
NC π^0 Cross Section Measurement vs. Predictions



NEUT neutrino generator shows closest agreement with data-extracted cross-section for all signal definitions

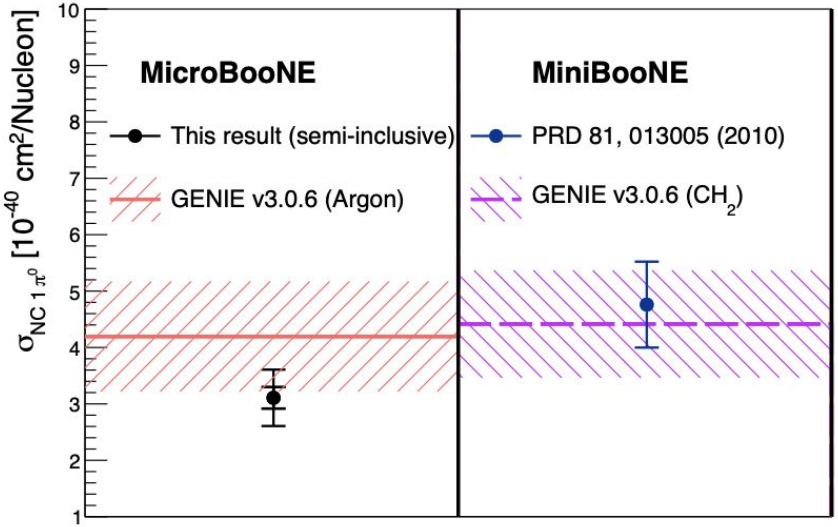
Extracted Cross Sections are 26%, 32%, and 17% lower than GENIE predictions (1.68, 0.72, and 0.78 [10^{-38}cm^2/Atom]), for 2γ (0+1)p, 2γ1p, and 2γ0p respectively

NC π^0 Cross Section Measurement vs. Predictions



NEUT neutrino generator shows closest agreement with data-extracted cross-section for all signal definitions

Both our inclusive result and MiniBooNE's agree with GENIE v3.0.6 **within assigned uncertainties**

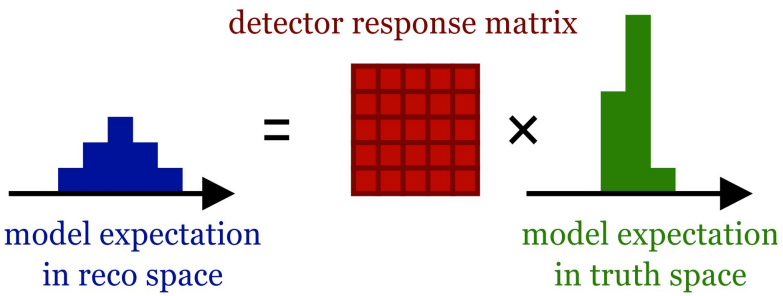


Extracted Cross Sections are 26%, 32%, and 17% lower than GENIE predictions (1.68, 0.72, and 0.78 [10^{-38}cm^2/Atom]), for 2γ (0+1)p, 2γ1p, and 2γ0p respectively

Current Status

Expand this total measurement to a **differential cross-section** measured in terms of various kinematic variables i.e. **pion momentum, opening angle**

- **Unfolding** = Measured ➔ "True" parameter space
  - **Removes distortions caused by detector effects & noise**
  - Allows **direct comparisons to theory**
  - Methods:
    i. Wiener-SVD ii. D'Agostini



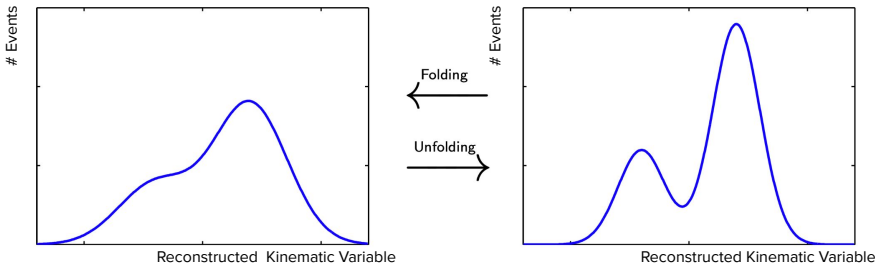


Figure : Smeared density

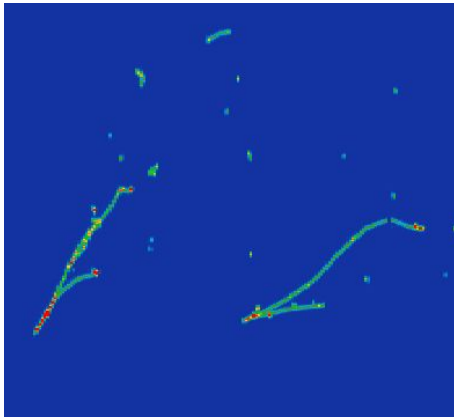
Figure : True density

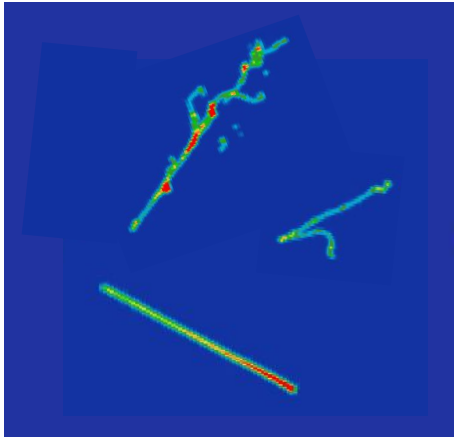
Summary

Future neutrino oscillation analyses will rely on improved understanding of neutrino-argon interactions

- Reported the **first cross section measurement of NC π^0 production on argon at $\lesssim$ 1 GeV** in MicroBooNE
- Made use of a **high-statistics, high-purity** measurement of NC π^0
- Can improve tuning of NC π^0 production in neutrino-argon scattering models & background constraints in future analyses

MicroBooNE's first NC π^0 publication is available on arXiv:2205.071743 and submitted to *Physical Review D.*





Backup Slides

The MicroBooNE Experiment

85-tonne active volume liquid argon time projection chamber (LArTPC) experiment at Fermilab

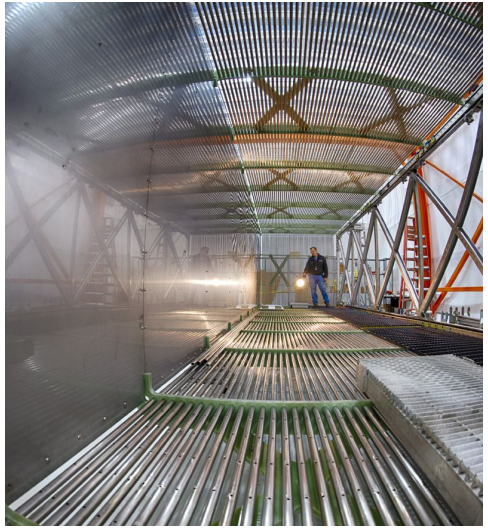
- Reconstructs 3D images of neutrino interactions

Goals:

- Investigate anomalous excess of electromagnetic shower-like low energy events observed in MiniBooNE
- Measure neutrino cross sections and search for rare and new physical processes
- Inform the design/interpretation of future LArTPCs

Status:

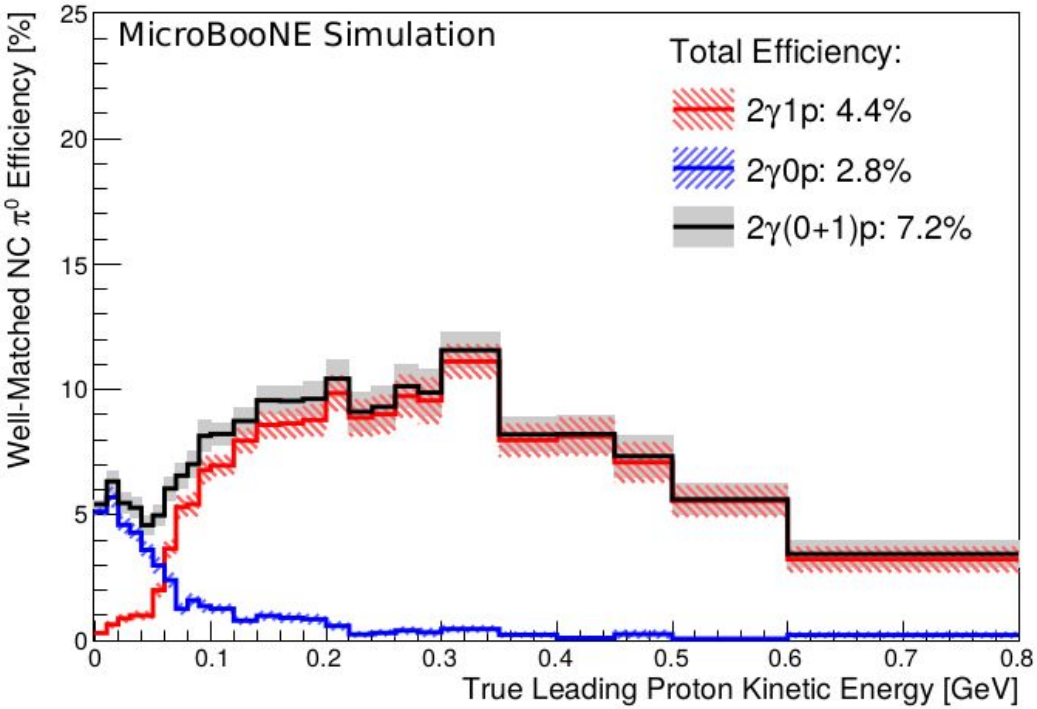
- Completed 5 years of data-taking (2015-2021)
- **First tests have not revealed an explanation for the MiniBooNE anomaly[5][1]**



Images courtesy of Fermilab

[5] *Phys. Rev .Lett.* 128, 241801 (2022) [1] *Phys. Rev. Lett.* 128, 111801 (2022)

Efficiency vs. True Proton Kinetic Energy



Events start to shift between the 2γ0p and 2γ1p selections at a a threshold of ≈ 50 MeV proton kinetic energy.

Events with no exiting proton are in the first bin.

NC π^0 Cross Section Components

	NCπ^0 (semi-inclusive)	**NC$\pi^0 + 1p$ (exclusive)**	**NC$\pi^0 + 0p$ (exclusive)**
Samples Used →	$2\gamma(0+1)p$ Selection	$2\gamma 1p$ Selection	$2\gamma 0p$ Selection
# Targets [10^{30} Ar atoms]	$1.187 \pm 0.119 \pm 0.00$		
Flux [10^{-10} ν/POT/cm^2]	$7.876 \pm 0.902 \pm 0.00$		
POT of Sample [10^{20} POT]	$5.84 \pm 0.12 \pm 0.00$	$5.84 \pm 0.12 \pm 0.0$	$5.89 \pm 0.12 \pm 0.00$
Efficiency	$0.090 \pm 0.003 \pm 0.001$	$0.128 \pm 0.007 \pm 0.002$	$0.076 \pm 0.004 \pm 0.002$
Selected Data [evts]	$1125.9 \pm 0.0 \pm 33.5$	$634.0 \pm 0.0 \pm 25.2$	$496.0 \pm 0.0 \pm 22.3$
BNBext [evts]	$177.0 \pm 0.0 \pm 8.9$	$96.1 \pm 0.0 \pm 6.5$	$81.5 \pm 0.0 \pm 6.1$
Bkg [evts]	$332.1 \pm 49.0 \pm 8.9$	$194.7 \pm 30.1 \pm 6.3$	$138.5 \pm 22.2 \pm 6.3$
Bkg subtracted rate [evts]	$616.9 \pm 49.0 \pm 35.8$	$343.2 \pm 30.1 \pm 26.8$	$275.9 \pm 22.2 \pm 23.9$
$\sigma_{NC1\pi^0}$ [10^{-38}cm^2/Atom]	$1.250 \pm 0.182 \pm 0.075$	$0.490 \pm 0.077 \pm 0.039$	$0.657 \pm 0.098 \pm 0.059$